Planetary population synthesis

Statistical tests of and constraints on planet formation

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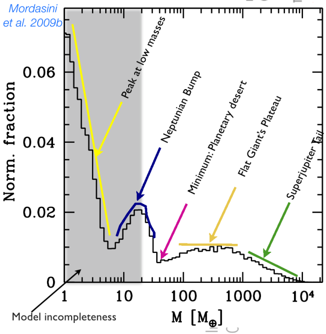
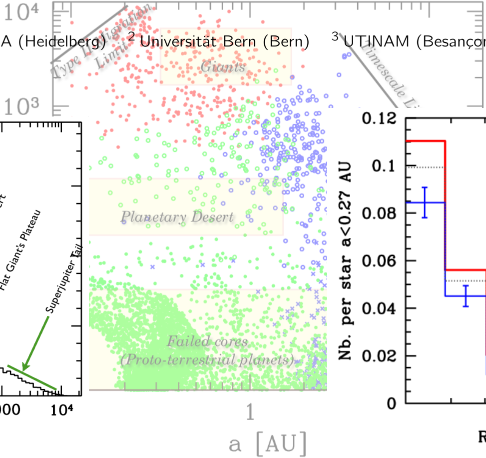
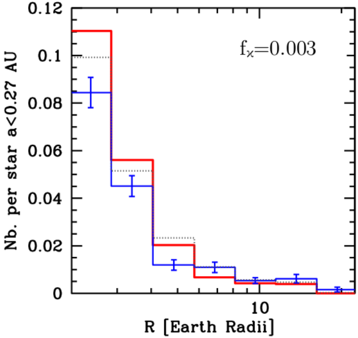
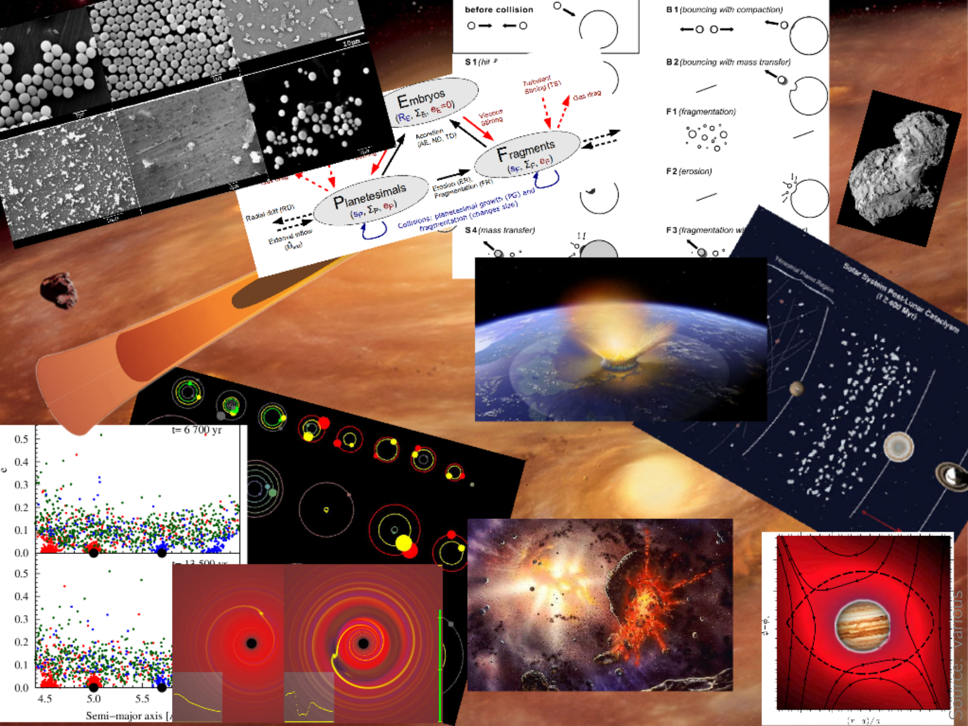
A. Fortier[2], D. Swoboda[2], Y. Alibert[2,3], W. Benz[2]

[1] MPIA (Heidelberg) [2] Universität Bern (Bern) [3] UTINAM (Besançon)









before collision
B 1 (bouncing with compaction)
B 2 (bouncing with mass transfer)
F 1 (fragmentation)
F 2 (erosion)
S 4 (mass transfer)
Embryos
Fragments
Planetesimals
Viscous Stirring
Turbulent Stirring (TS)
Gas drag
Radial drift (RD)
External inflow
Collisions: planetesimal growth (PG) and fragmentation (changes size)
Solar System Post-Lunar Cataclysm
t= 6 700 yr
Semi−major axis
Source: Various

The essence of population synthesis

Planet formation: Many processes from many domains

- Gravity, (M)HD, radiation transport, convection, microphysics, . . .
- Large range of temporal and spatial scales

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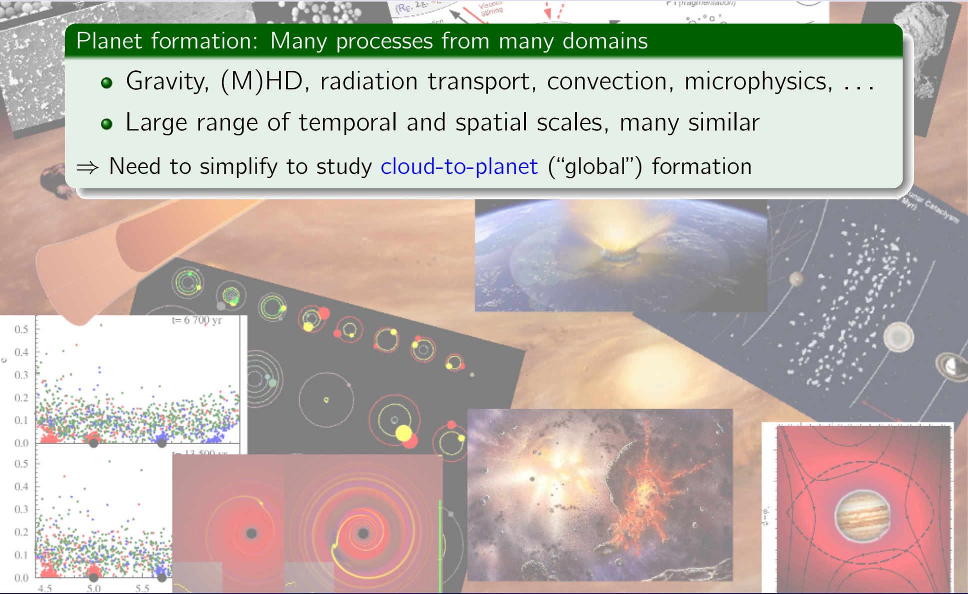
⇒ Need to simplify to study cloud-to-planet (“global”) formation



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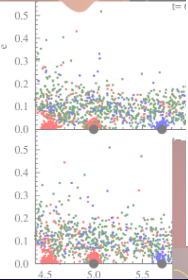

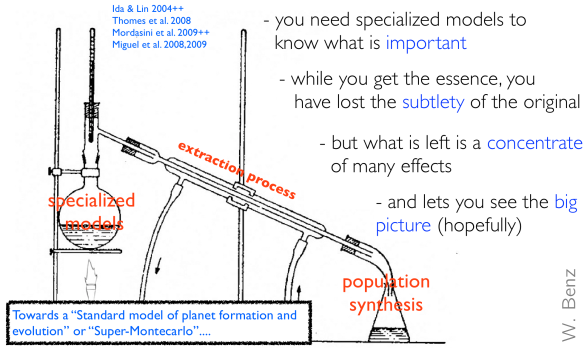

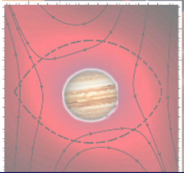

Schematic principle of population synthesis

Diversity of planets: same physics + diversity of initial conditions

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Planet formation & evolution model
Link disk properties ⇒ planet properties

Protoplanetary disk
Vertical structure
Radial structure
Disk of solids

Interactions
Orbital migration
N-body

Planet
Accretion rate
Gas envelope
Atmosphere
Planetesimal infall
Core structure
Atmospheric escape

Mordasini et al. (2014c)

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Initial Conditions: Probability distributions
Disk gas mass
Disk dust mass
Disk lifetime
From observations of protoplanetary disks

Mordasini et al. (2014c)

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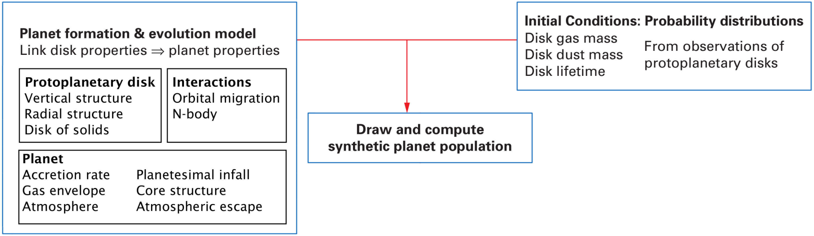

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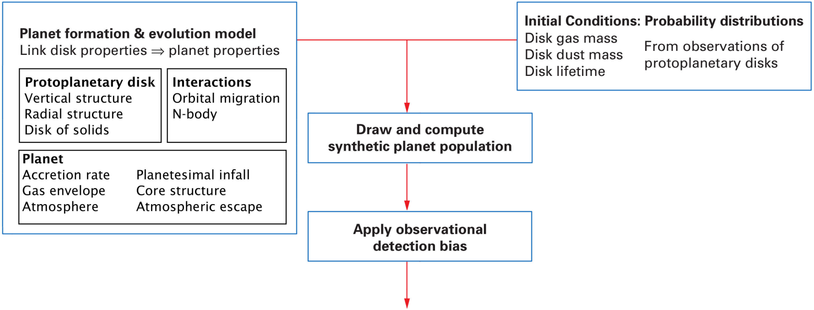

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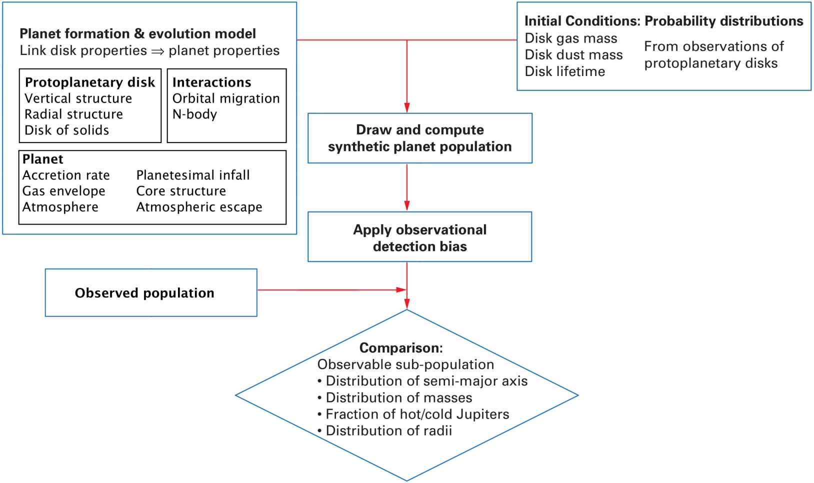

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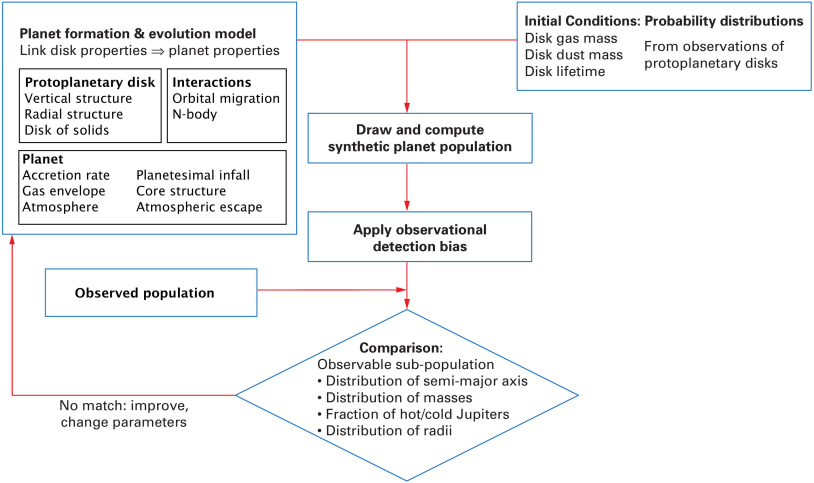

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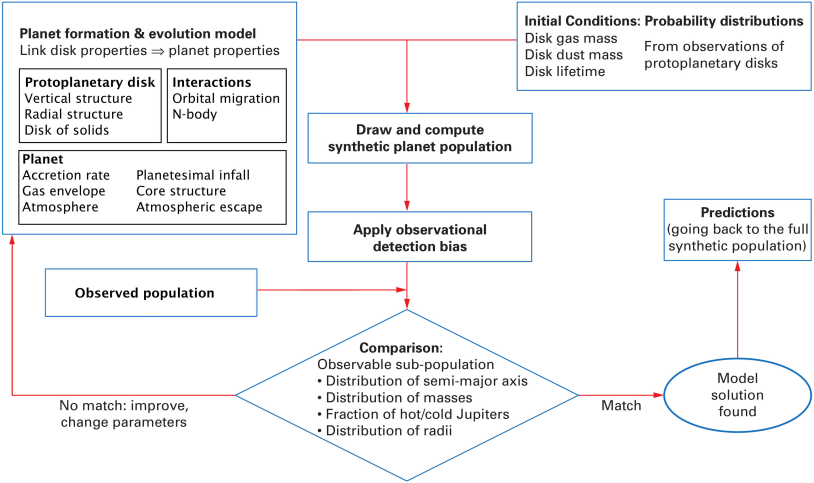
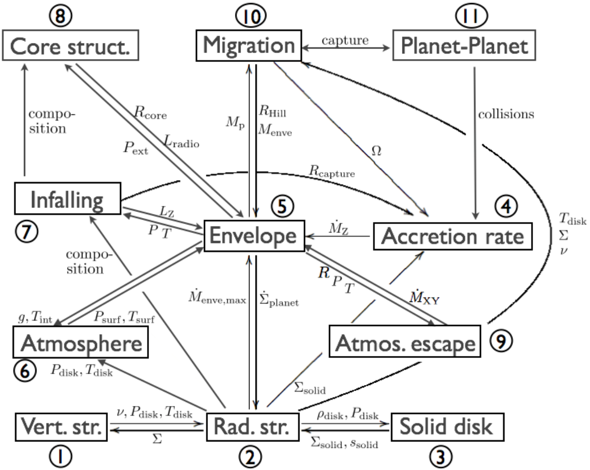


Mordasini et al. (2014c)

The main modules



(Alibert et al. 2005, Fouchet et al. 2011, Mordasini et al. 2012b, Alibert et al. 2013, Fortier et al. 2013, Dittkrist et al. 2014, Jin et al. 2014, Marleau et al. in prep.)

(Incomplete!) relevant literature

Pioneering and recent work:

- ⋆ Ida & Lin et al. (2004–. . .). *Toward a deterministic formation model. I–VII*
- ⋆ Alibert, Mordasini, Benz & Winisdoerffer (2005). *Models of giant planet formation with migration and disc evolution*

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- Thommes et al. (2008), Hasegawa & Pudritz (2013), Galvagni & Mayer (2013), Coleman & Nelson (2014), **etc.**

Reviews:

- ★ Benz, Alibert, Ida, Lin & Mordasini (2014). *Protostars & Planets VI*
- ★ Mordasini, Mollière, Dittkrist, Jin & Alibert (2014). *J. Astrobiology*

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This talk

Focus on core accretion

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Overview

Overview

1. Selected physical ingredients
   - Disc-related modules
   - Planet-related modules

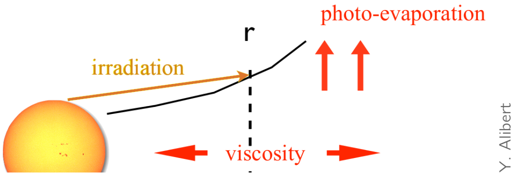
2. Comparisons to observations: constraints
   - General comments
   - Mass–semi-major axis diagram (M_p–a)
   - Mass–radius relationship (M_p–R_p)

3. Summary

Contents

Disc structure and evolution

- Standard α-viscosity, 1+1D disc (parametrised/numerical)
- Internal (central star) + external (cluster stars) photoevaporation
- Initial profile: theory/observations



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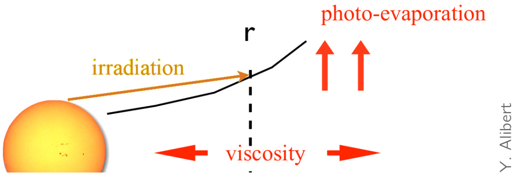

Open question: Growth of solids from µm to ∼ km

- Two-body coagulation/self-gravity, high τ_{runaway} dependence on turbulence, . . .
- Start with bimodal: 0.6 $M_\oplus$ protoplanet + 100-km planetesimals

⇒ Need more results from specialised models

(Birnstiel et al. 2010, Ormel & Okuzumi 2013, Johansen et al. 2009, 2014, etc.)

Disc structure and evolution

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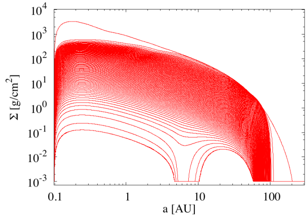
on

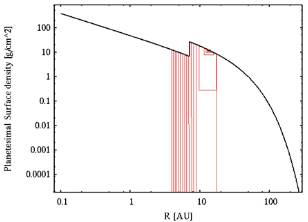
Y. Alibert

Numerical model

Gas surface density $\Sigma_g(r, t)$:



Solids surface density $\Sigma_d(r, t)$:



Open question: Grow

- Two-body coagu ... e on turbulence, . . .
- Start with bimod ... imals

$\Rightarrow$ Need more resul

sen et al. 2009, 2014, etc.)

Orbital migration

Planet–disk interaction → migration + e, i damping

- 2/3D rad.-hydro simulations expensive
- Migration rates: simulations / theory

(e.g. Kley & Nelson 2012, Dittkrist et al. 2014, Paardekooper et al. 2011, 2014)

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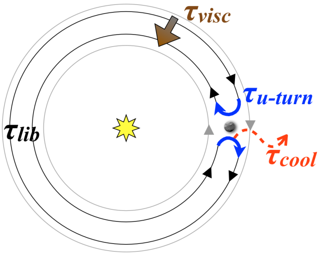
⇒ Motivated theoretical developments

- Find: thermal structure is crucial

⋆ Compare timescales → which regime



Dittkrist et al. (2014)

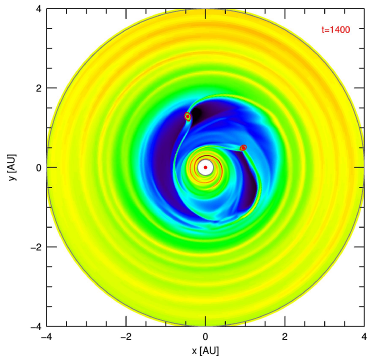
(e.g. Kley & Nelson 2012, Dittkrist et al. 2014, Paardekooper et al. 2011, 2014)

Contents

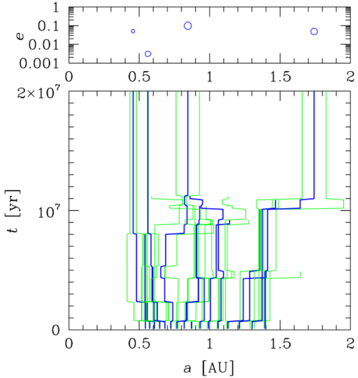
Planet-planet interactions

- Effects: competitive accretion, MMR, collisions, ejections, ...
- Computation: explicit N-body / statistical (timescales) approach

(Ida & Lin 2010, Ida et al. 2013, Alibert et al. 2013)



Kley & Nelson (2012)



Ida & Lin (2010)

Planetary structure

Gas accretion rate: $\min(\dot{M}_{\mathrm{thermal}}, \dot{M}_{\mathrm{disc}})$

- Semi-analytical approach (Ida & Lin): $\dot{M}_{\mathrm{thermal}} \simeq M_p/\tau_{\mathrm{KH}} \propto {M_p}^{4-5}$
- Solution of standard structure equations (Alibert, Benz, Mordasini)

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Key for structure and $\dot{M}_{\mathrm{thermal}}$: atmospheric opacity $\kappa_{\mathrm{atm}} \ll \kappa_{\mathrm{ISM}}$

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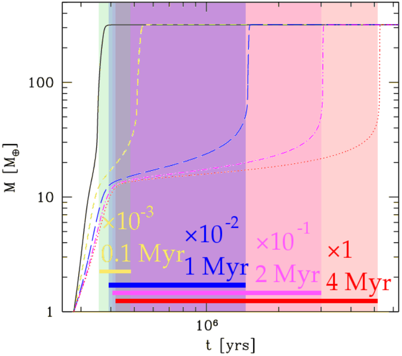

Mordasini et al. 2014a

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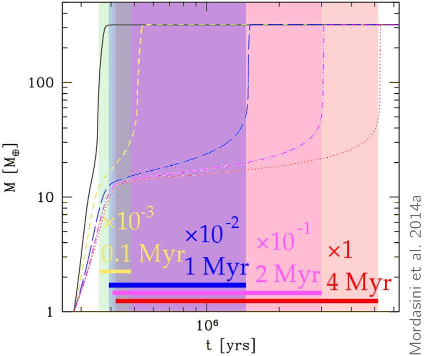
- Analytical grain evolution model

  (Mordasini 2014b, Ormel 2014)



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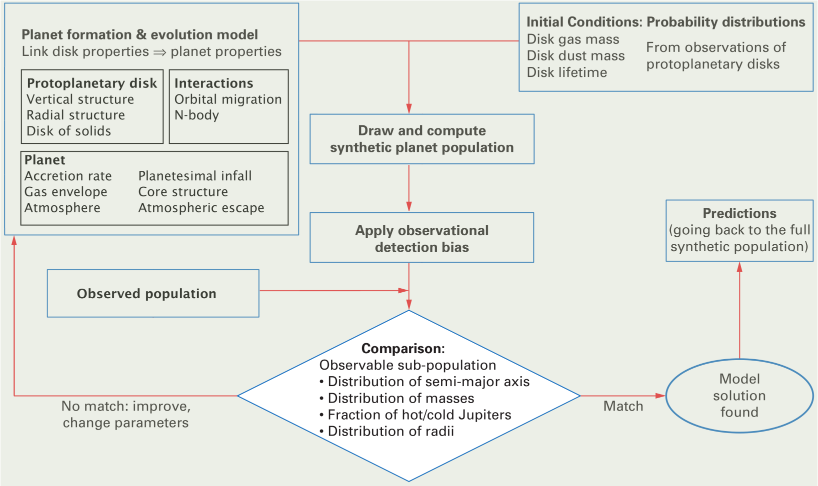
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Initial Conditions: Probability distributions
Disk gas mass
Disk dust mass
Disk lifetime
From observations of protoplanetary disks
Draw and compute synthetic planet population
Apply observational detection bias
Observed population
Predictions
(going back to the full synthetic population)
Comparison:
Observable sub-population
• Distribution of semi-major axis
• Distribution of masses
• Fraction of hot/cold Jupiters
• Distribution of radii
No match: improve, change parameters
Match
Model solution found

Contents

Comparing population synthesis to data

- Need to simultaneously satistify constraints on:
  1. Frequencies: overall, by planet type, f(stellar type), f([Fe/H])
  2. Planet properties: M_p, R_p, composition, spectrum
  3. Syst. architectures: a_P, e, planet type as $f(a_P)$, multiple-planet

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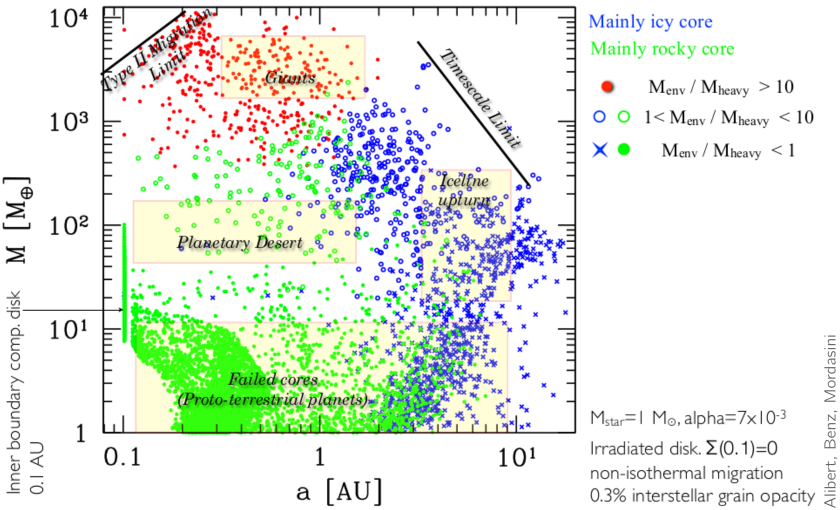
Key point

★ With population synthesis: can compare specialised models to data! ★

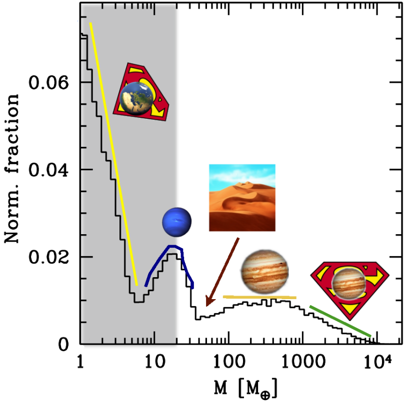
Contents

Main features



Planetary Initial Mass Function (PIMF)

Solid + gas accretion rate → PIMF



Mordasini et al. 2009b

Predictions of CA (features):

- Decreasing $N_{\text{super-jupiters}}(M_p)$
- Gas-giant plateau
- Planet desert at $\approx 30\ M_\oplus$
- Neptunian bump
- Large rise towards low masses

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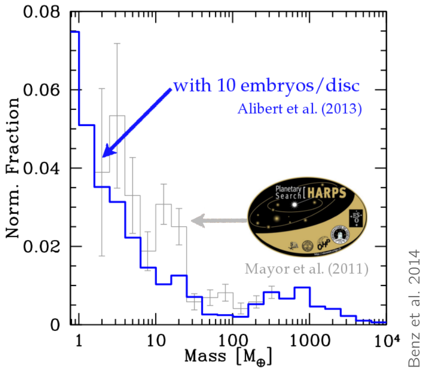

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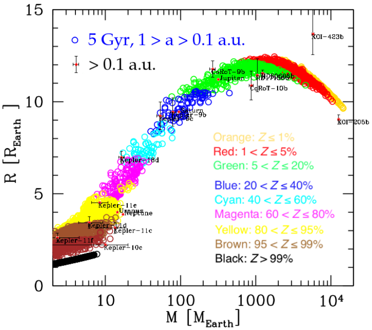
Mass–radius relationship and composition

Late-time mass–radius relationship



- Good overall agreement
- Shape: prediction of CA

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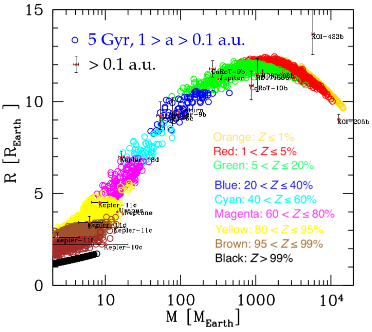

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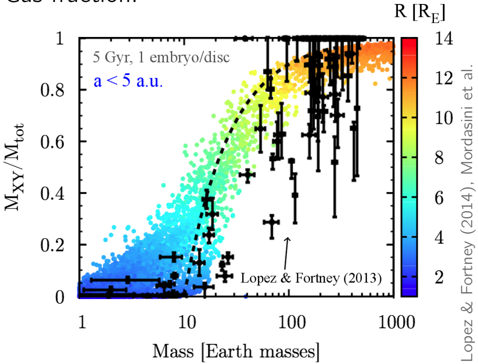

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- "See" runaway accretion!

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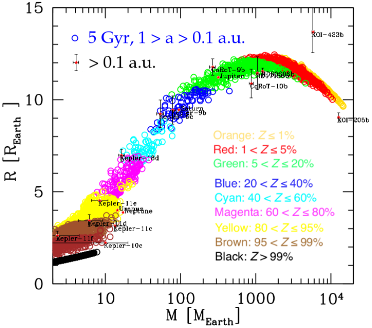

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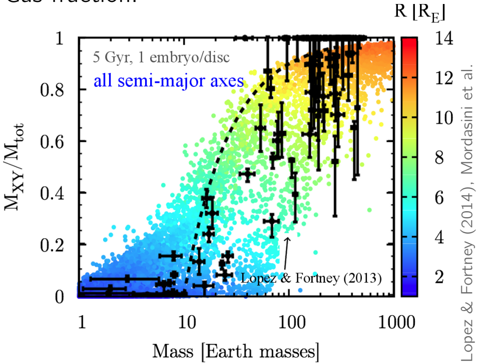
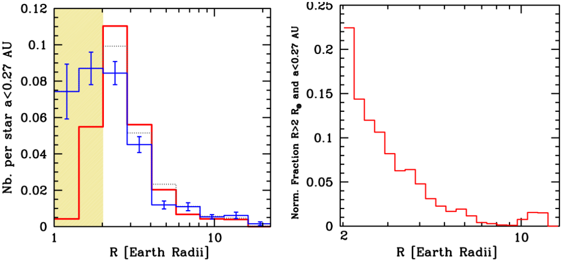


- Simulation: ≈ 10-$M_\oplus$-core line?
- "See" runaway accretion!
- Need planet–planet scattering

Radius distribution

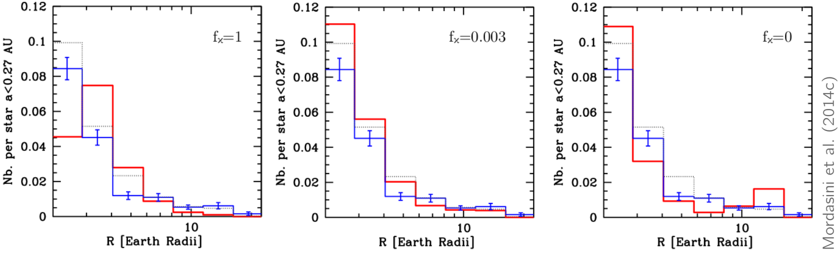


Mordasini et al. (2012b)

$P < 50$ days ($a_P < 0.3$ AU for 1 $M_\odot$), *Kepler* data

- Only H/He-atmospheres → ignore $< 2\ R_p$
- Increase at low M_p + solid-dominated → increase at small R_p
- Using smaller bins: see Jovian peak (from flat $M_p(R_p)$ at 3 M_J)

Radius distribution II



⇒ Constraints on atmospheric opacity

Overview

Summary

The main power of population synthesis

With population synthesis: can compare specialised models with data

- Type I migration rate
- Grain opacity

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★ Predictions for the Planetary Initial Mass Function

1. Change of slope at $\approx 30\ M_\oplus$
2. Large increase at low masses

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Summary

Thank you for your attention!

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Additional material

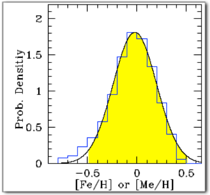
Additional material

Initial conditions

1 Metallicity

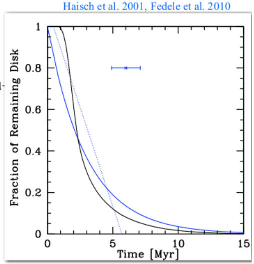
assume same in star and disk

Stellar [Fe/H] from spectroscopy. Gaussian distribution for [Fe/H] with μ ~0.0, σ~ 0.2. (e.g. Santos et al. 2003)



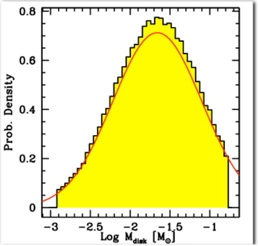
3 Disk lifetime

L-band (3.4 μm) photometry:
- excess caused by μ-sized dust @ ~900K
... ok to < 10 AU



2 Disk (gas) masses

Thermal continuum emission from cold dust at mm and submm wavelengths (Ophiuchus nebula).



4 Initial semimajor axis of the seed embryo:

Analytical work (Lissauer & Steward 1992) and numerical simulations (Kokubo & Ida 2000): spacing between bodies Δ ∝ a

$$p(a)da \propto \frac{da}{\Delta} \propto \frac{da}{a} = dlog(a) \propto const.$$

5 Stellar mass

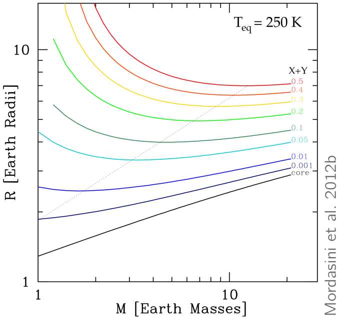
C. Mordasini

Additional material

Planetary structure II

Differentiated solid core (Fe & Ni + silicates + ices, from formation)

- Modified polytrope: $\varrho(P) = \varrho_0 + cP^{0.5-0.6}$ (Seager et al. 2007)



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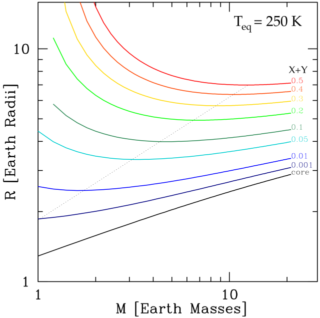
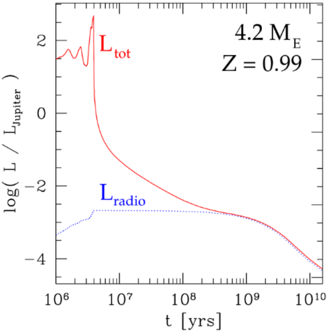
- Modified polytrope: $\varrho(P) = \varrho_0 + cP^{0.5\text{—}0.6}$ (Seager et al. 2007)
- Luminosity → cooling:
  - Radioactive decay important at late times (and early?)



Mordasini et al. 2012b



Mordasini et al. 2012b

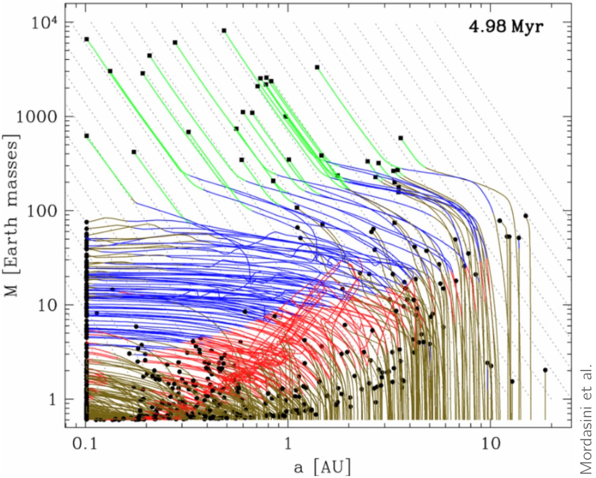
Planetary structure III

Recent and coming developments:

- Atmospheric escape
- Bloating mechanisms
- Detailed equation of state for the core
- Cooling of the core

Additional material

Formation tracks

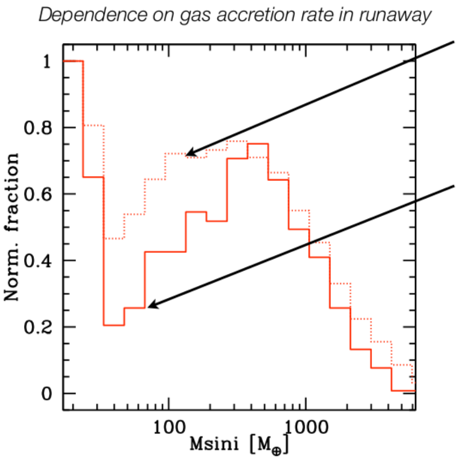


Locally isothermal
Type I, unsaturated
Type I, saturated
Type II
$(d \ln M / d \ln a = -\pi)$

1 $M_\odot$, $\alpha = 7 \times 10^{-3}$, non-isothermal Type I (no reduction), 1 seed per disc

Additional material

Accretion rate effect

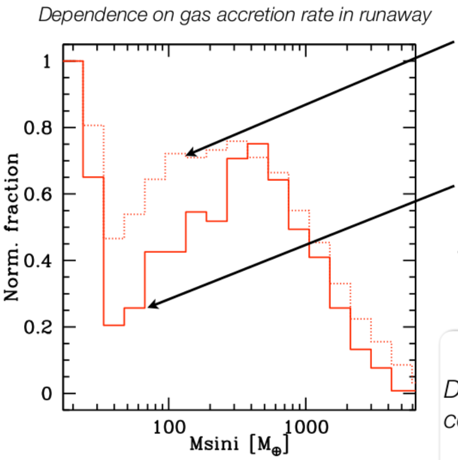


Mordasini et al. 2011

Planetary gas accretion rate limited to slow viscous disk accretion rate.
Shallow minimum.

Planetary gas accretion rate not limited to disk accretion rate for gas already in the planet's hill sphere (fast accretion).
Deep minimum.

Accretion rate effect



Mordasini et al. 2011

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Detections important for directly constraining formation theory.