FORMATION OF THE TRAPPIST-1 SYSTEM

– A PEBBLE APPLICATION STORY –

I. METHODOLOGY (MONASH)

II. SCIENCE (PALM COVE)

I. A (NEW?) LAGRANGIAN MODEL FOR PLANET FORMATION

Chris Ormel, University of Amsterdam

Netherlands Organisation for Scientific Research

with

Sebastiaan Krijt (Arizona), **Djoeke Schoonenberg** (Amsterdam)

Disc-ussion workshop, Monash University, Melbourne, Down Under

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TSINGHUA UNIVERSITY

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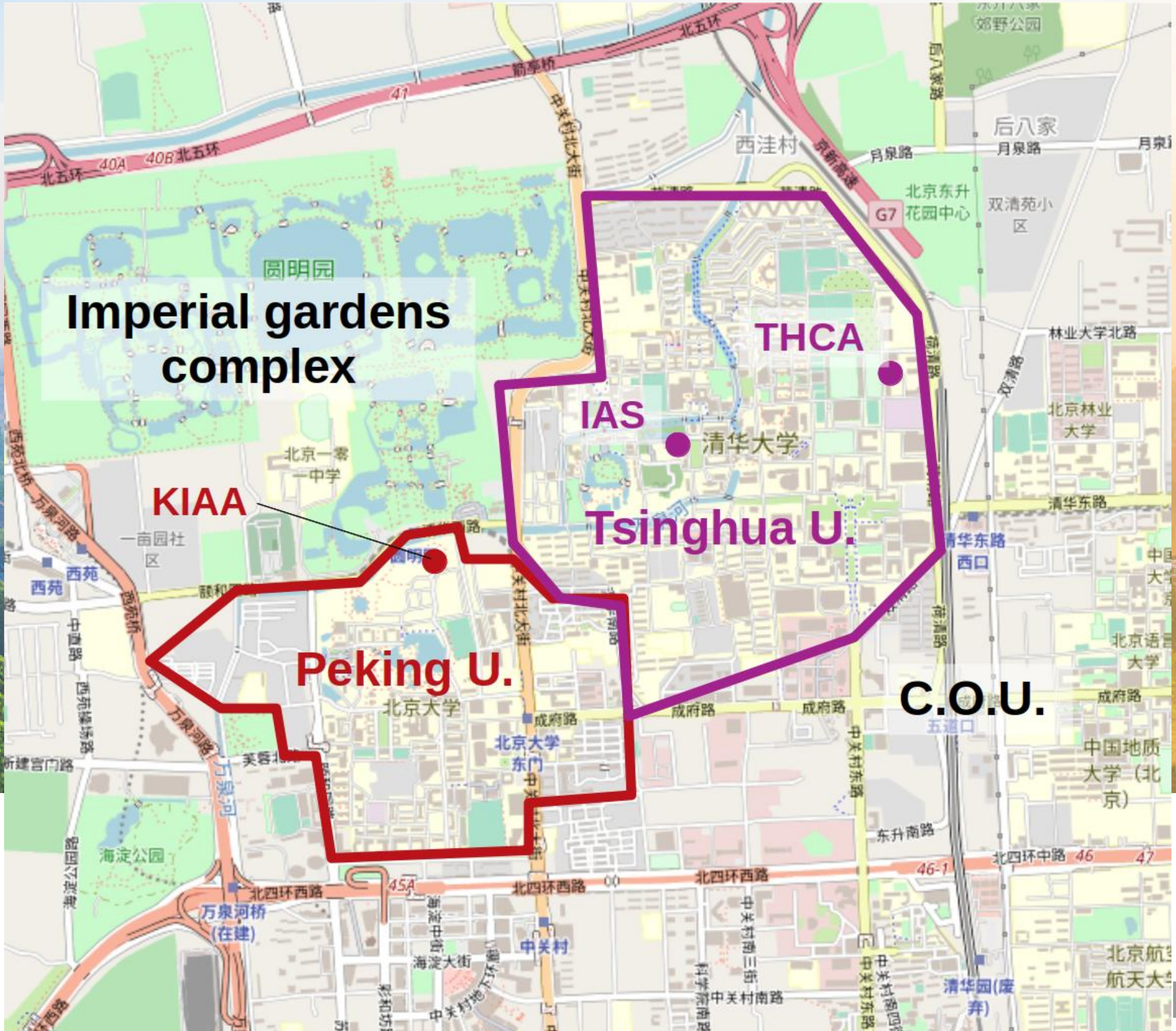
University, NW-Beijing

- KIAA
  Kavli Institute Astronomy & Astrophysics
  Greg Herczeg
- IAS
  Institute for Advanced Studies
  Doug Lin, Xuening Bai
- TsingHua Center for Astrophysics
  Shude Mao, Xuening Bai, CWO



TSINGHUA UNIVERSITY

Tsinghua Department of Astronomy (DoA)

- rapidly expanding
- opportunities for PD and faculty positions

please, visit!

GOAL

Present a planet *system* formation model from A-Z

- evolutionary timescales
- model entire planet formation process

  dust –> pebbles –> planetesimals –> planets

- Lagrangian representation dust

  composition, coupling to N-body

KRIJT'S BATCH METHOD

Krijt, Ormel, Dominik, Tielens (2016)

Lagrangian:

$$\frac{\mathrm{D}m}{\mathrm{D}t} = \frac{m}{t_{\mathrm{grow}}},$$

and radial drift

$$\frac{\mathrm{D}r}{\mathrm{D}t} = -\frac{r}{t_{\mathrm{drift}}},$$

Idea: follow *lifeline* of batches.

- disk radius
- mass (characteristic size)
- composition, porosity

t_{drift}=f(m,r,t)

t_{growth}=f(m,r,t, Σ)

KRIJT'S BATCH METHOD

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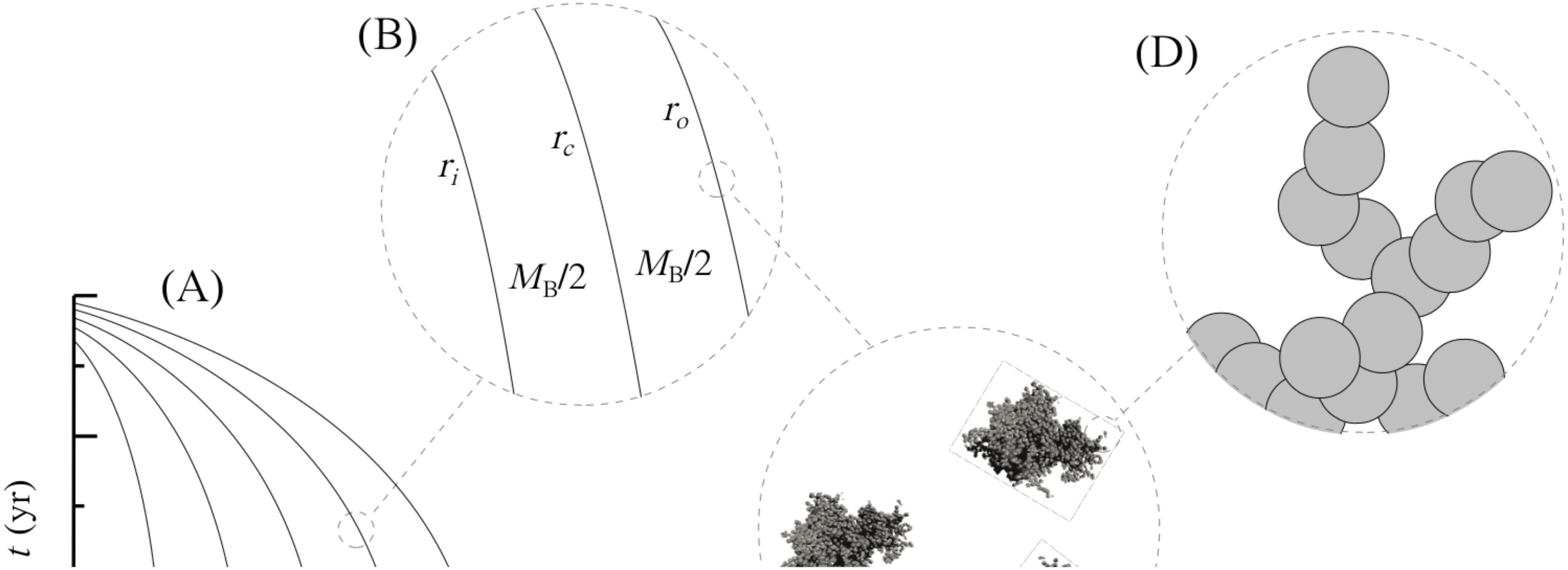
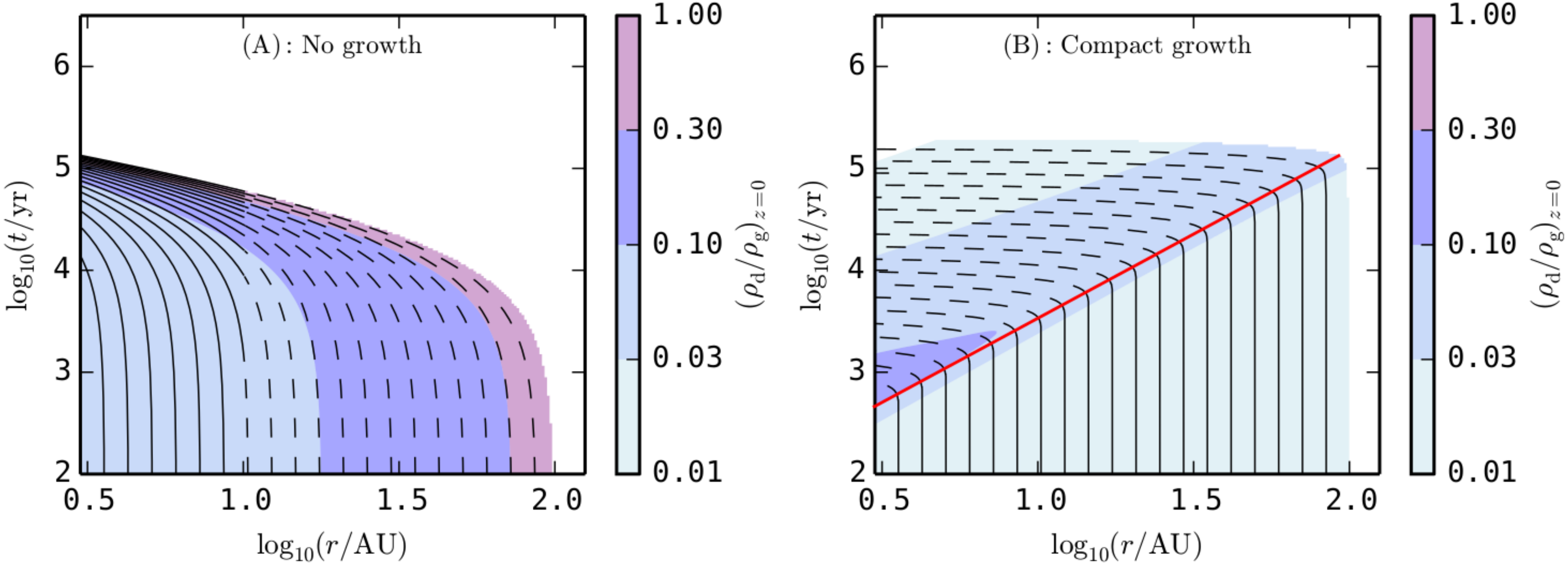
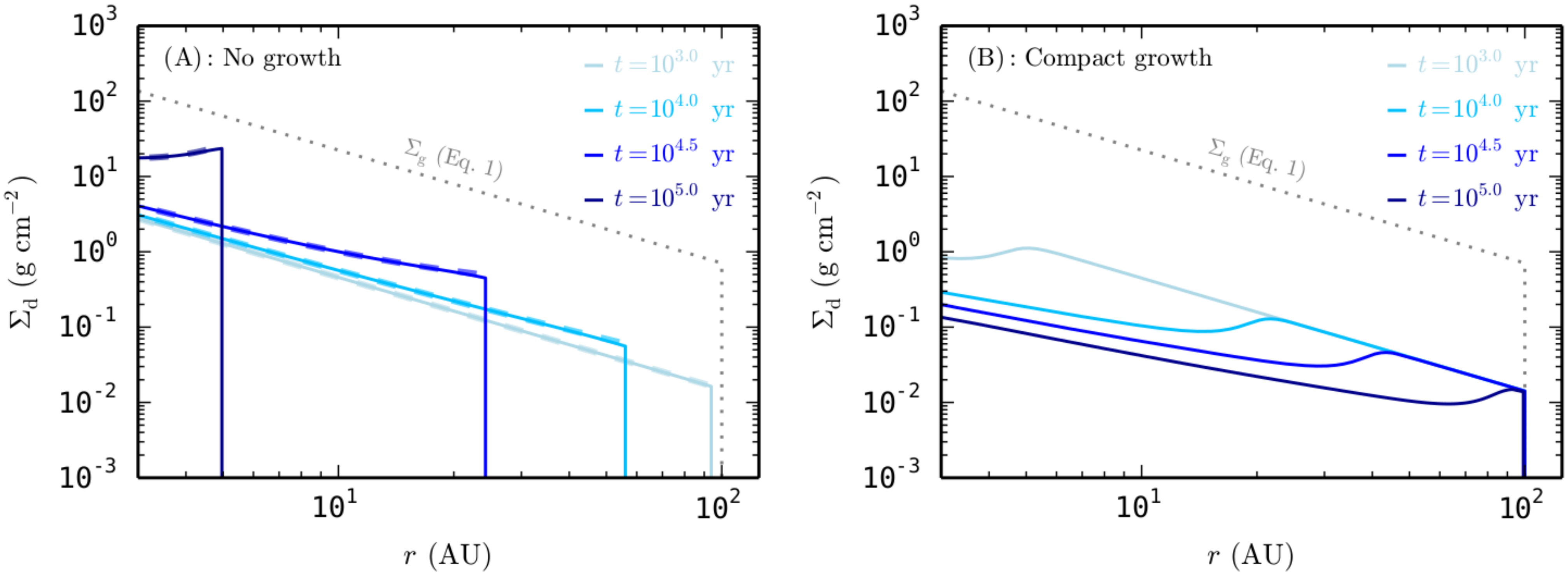


RESULTS



Krijt et al. (2016) – compact models. Note: size is not shown!

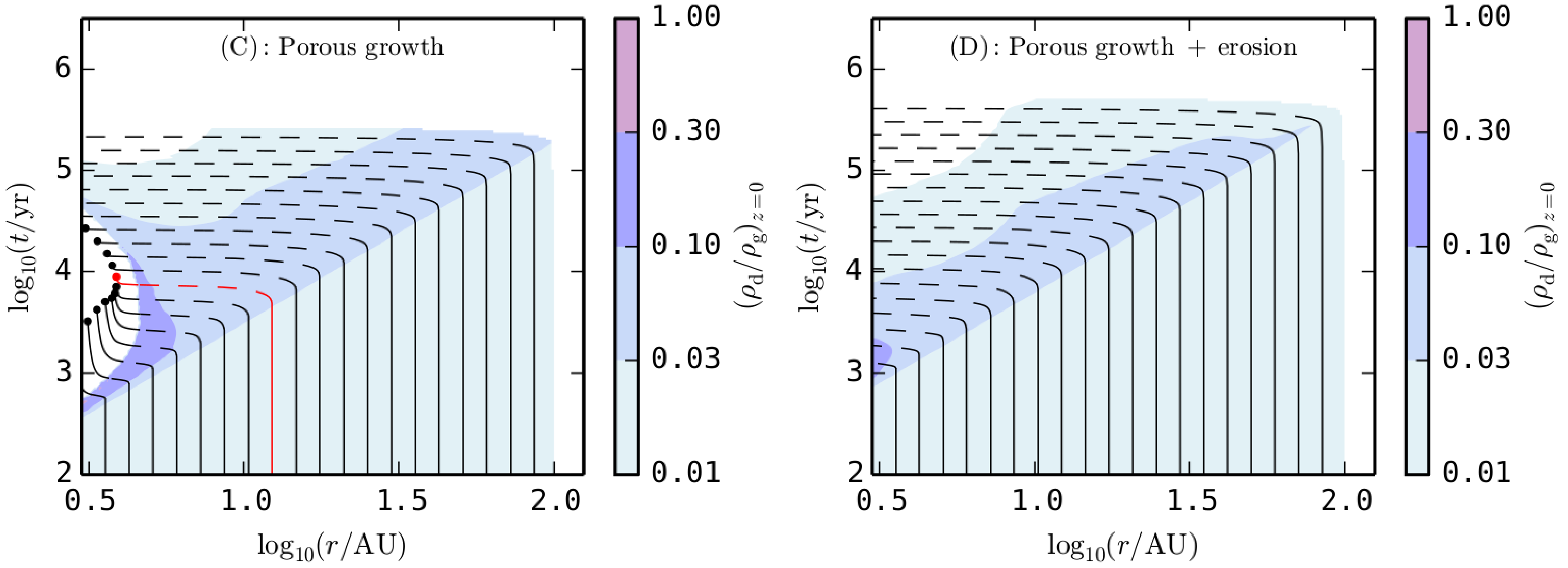
RESULTS



Krijt et al. (2016) – compact models. Note: size is not shown!

- in (a) we get strong pileup, similar to Youdin & Shu (2002)

RESULTS

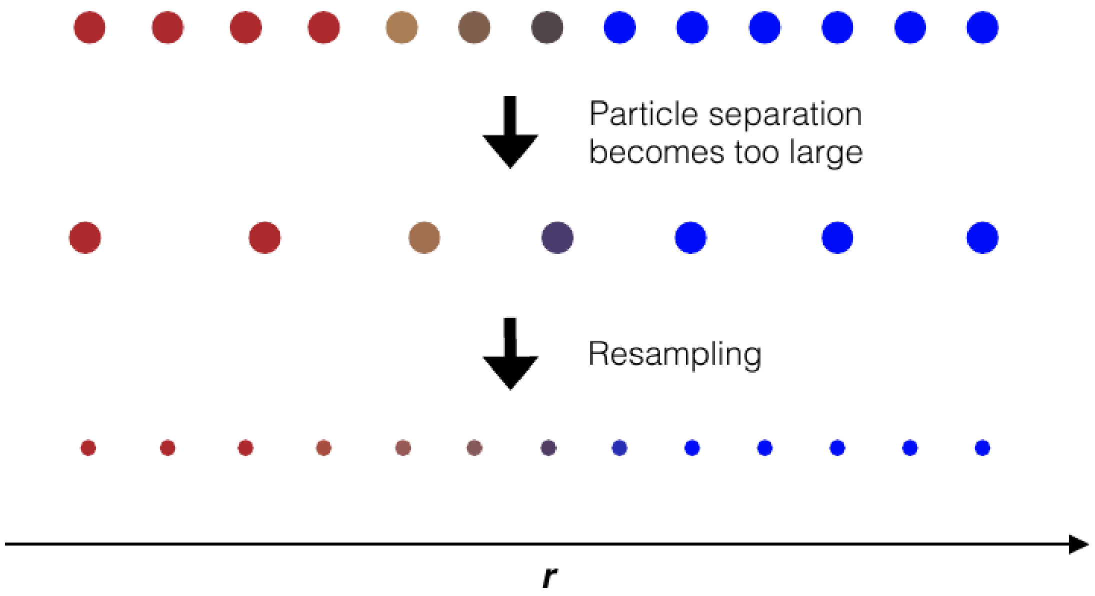


Krijt et al. (2016) – porous models. Note: size is not shown!

SCHOONENBERG'S SPH METHOD

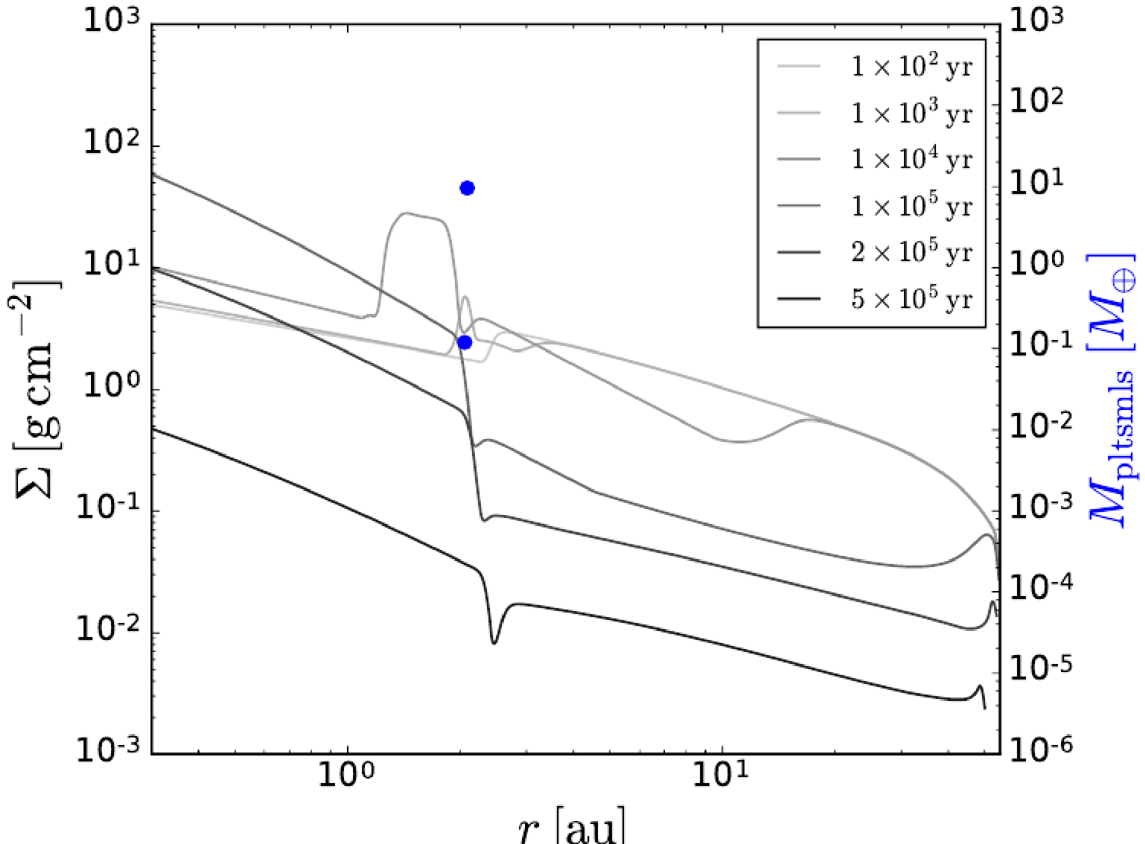
Schoonenberg, Ormel, & Krijt (2018)

$$\Sigma(x_i) = \frac{1}{2\pi x_i} \sum_{j\in\text{support}} M_j W(|x_i - x_j|, h_i),$$



- particles different mass, compositions
- 5 particles in the support Kernel
- resample when relative distance exceeds 20%

PLANETESIMAL FORMATION



- no pressure bumps
- rapid evolution
- pileup interior to snowline

  but dust:gas>1 not reached

- planetesimals form at iceline

  Schoonenberg & Ormel (2017)

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further evolution *not* followed

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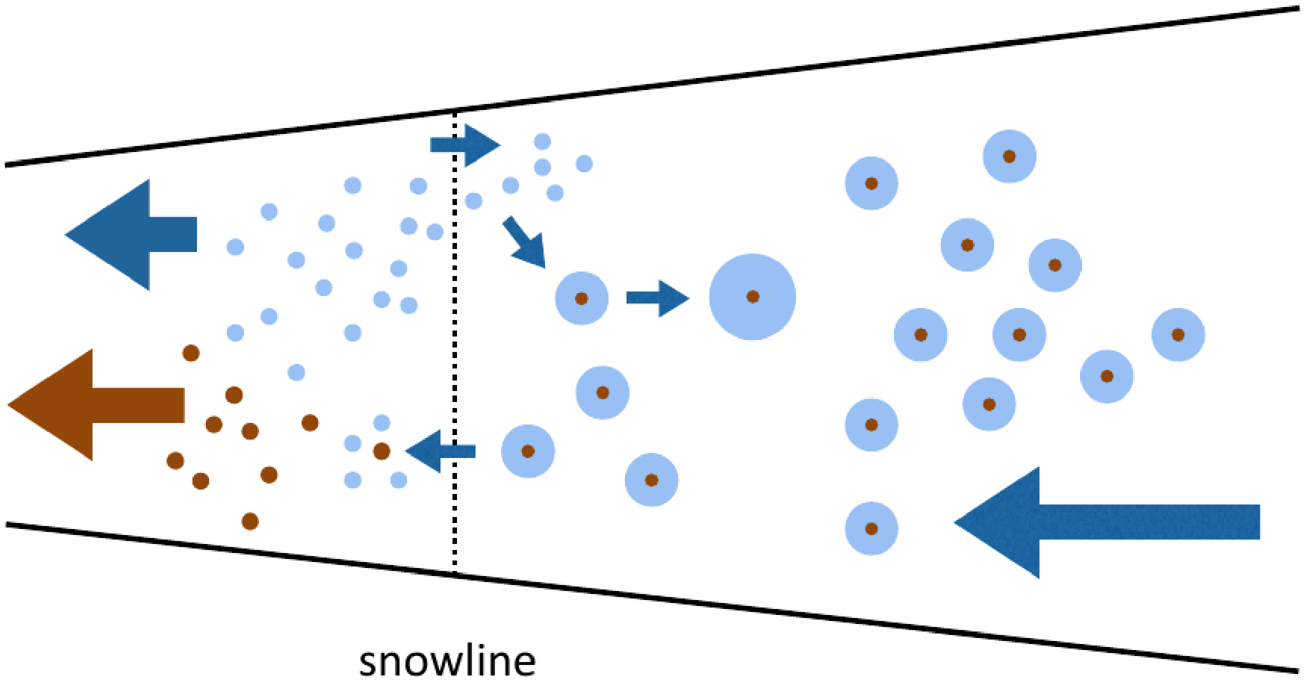

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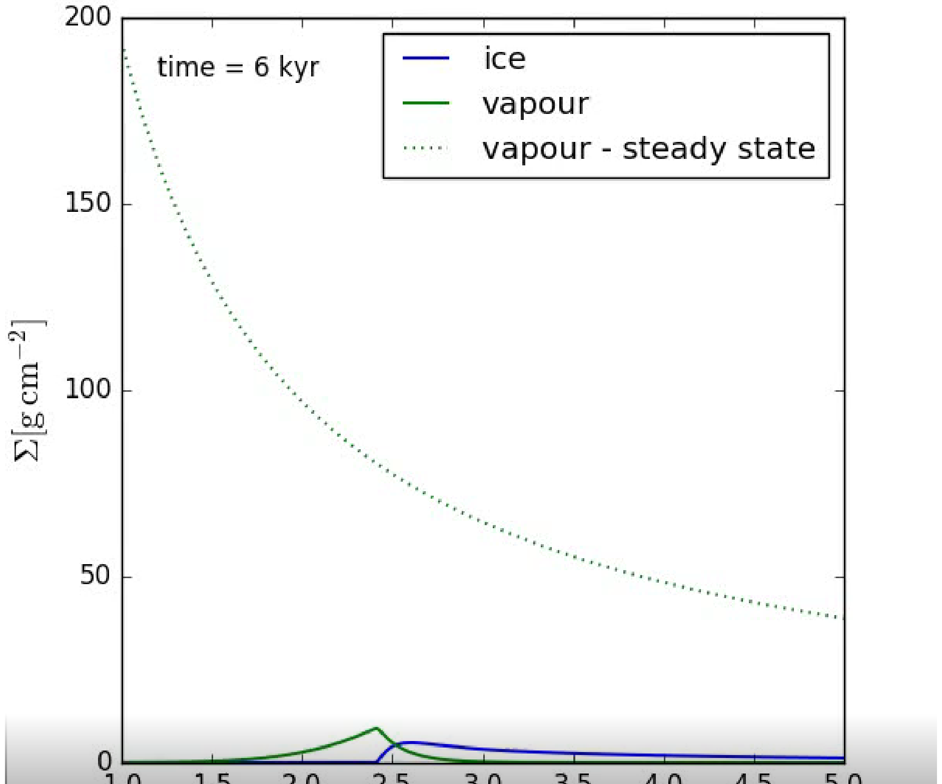

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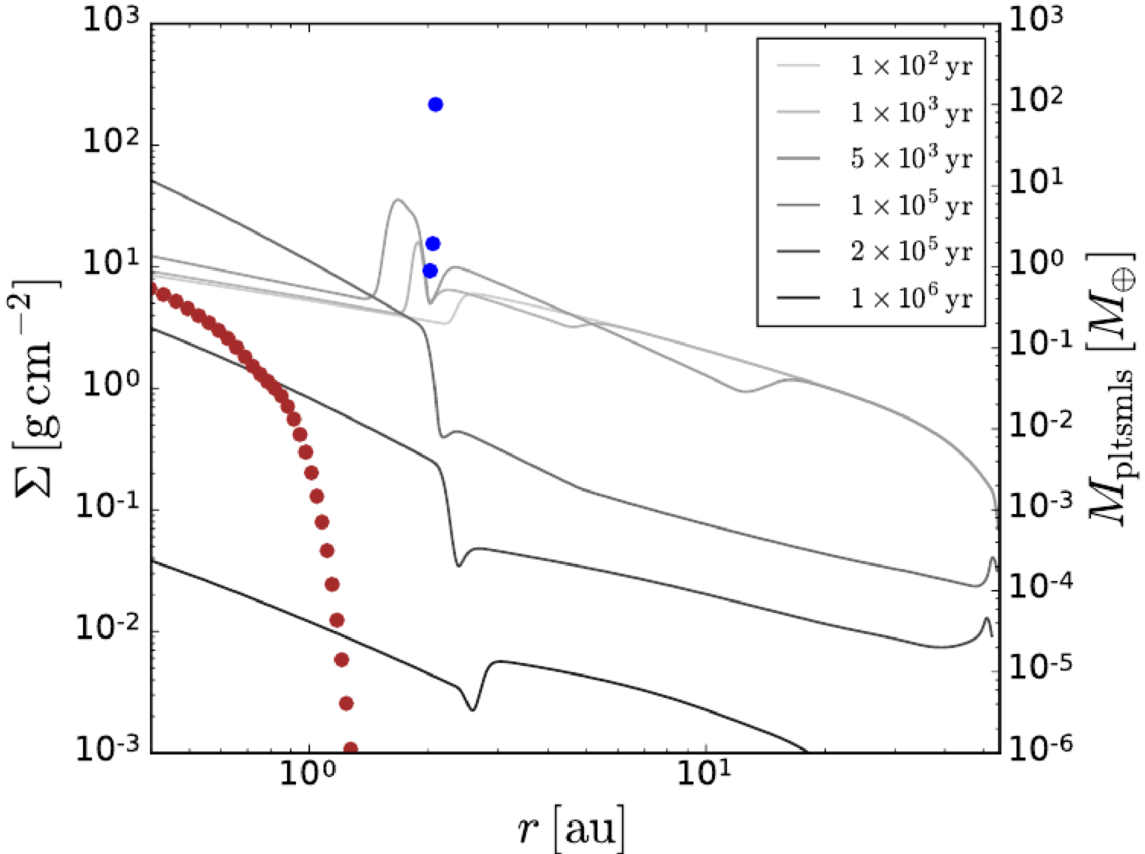
FINDINGS

Schoonenberg, Ormel, & Krijt (2018)



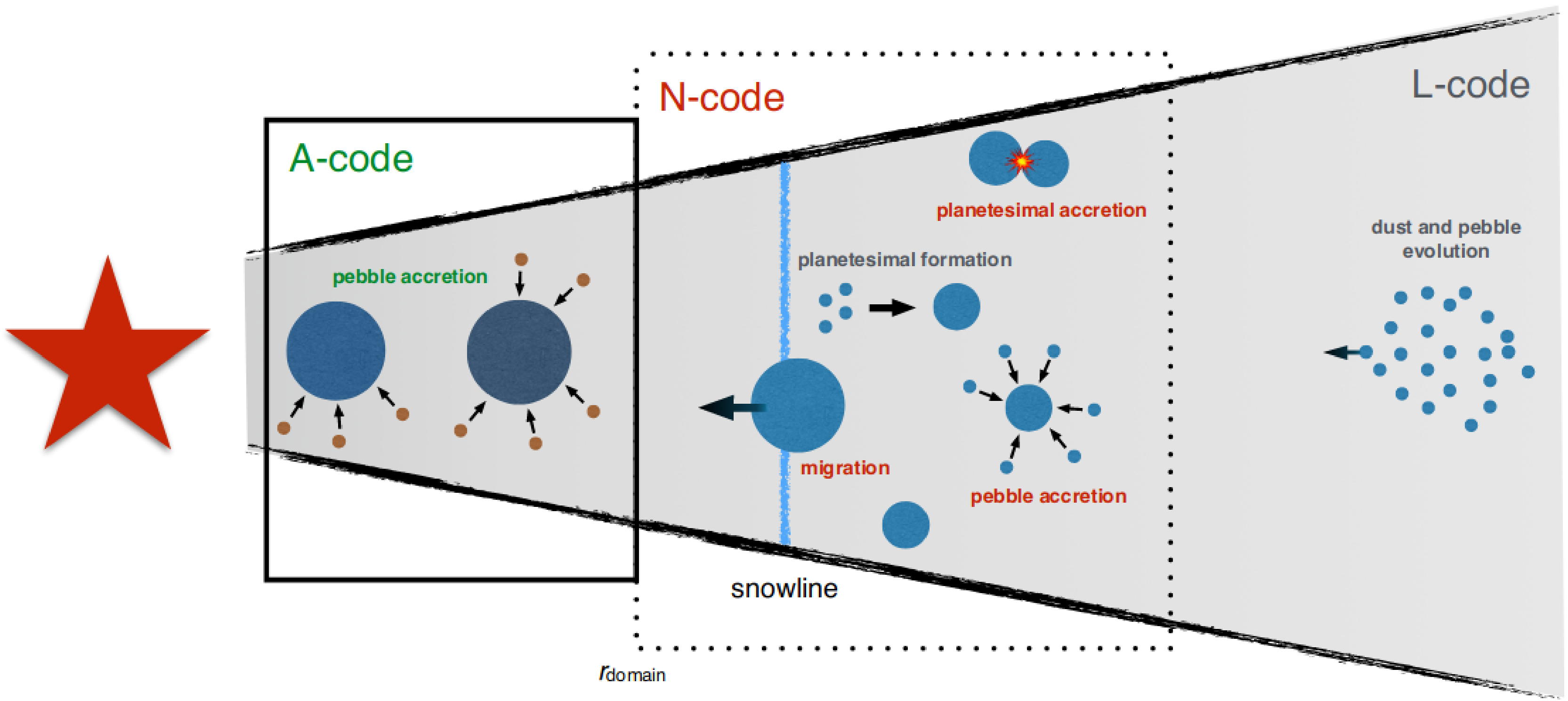
model for first "burst" of planetesimal formation

- rapid disk evolution -> rapid formation
- planetesimals tend to form preferentially near snowline
- efficient for high Z, around low mass stars

NEXT STEPS (NEXT WEEK)

We have coupled three codes:

- L-code
- N-code
- A-code



Schoonenberg et al. (2019) – model overview

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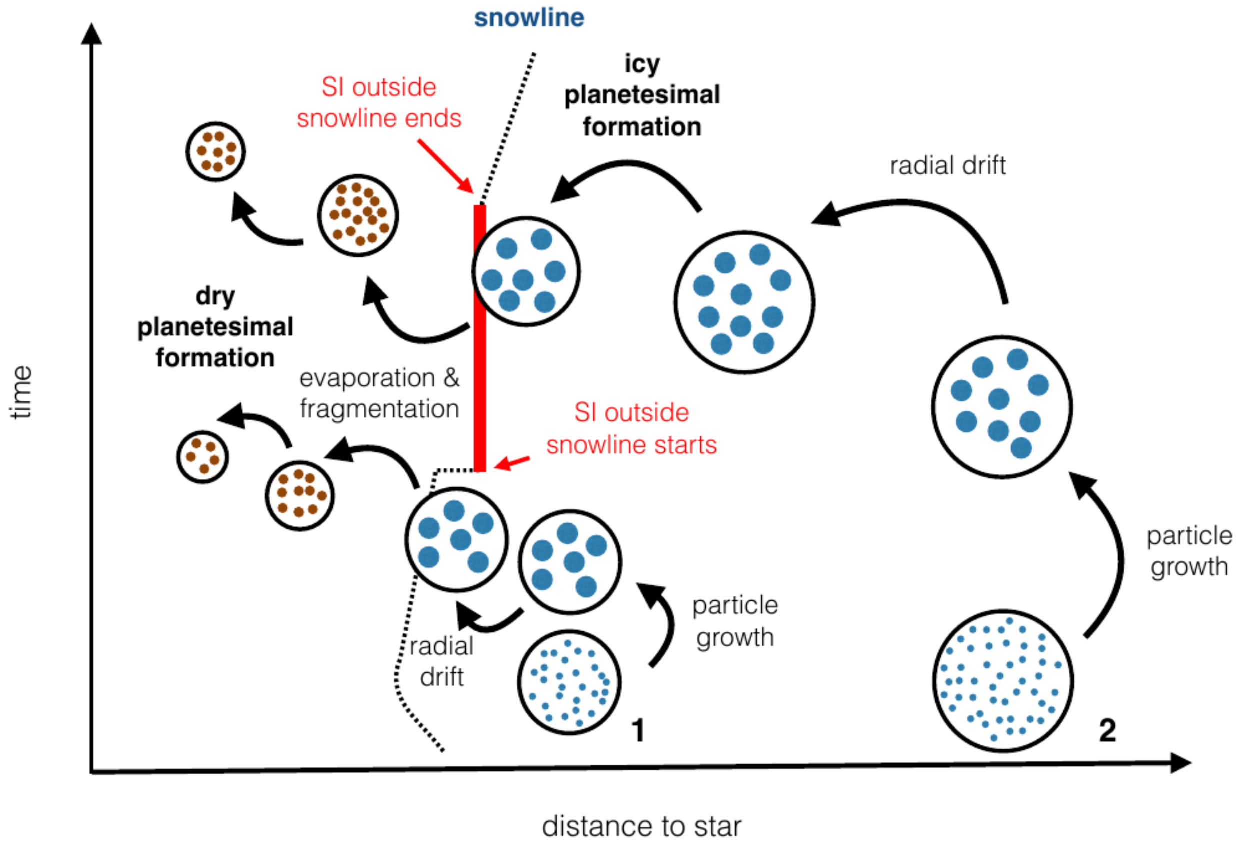
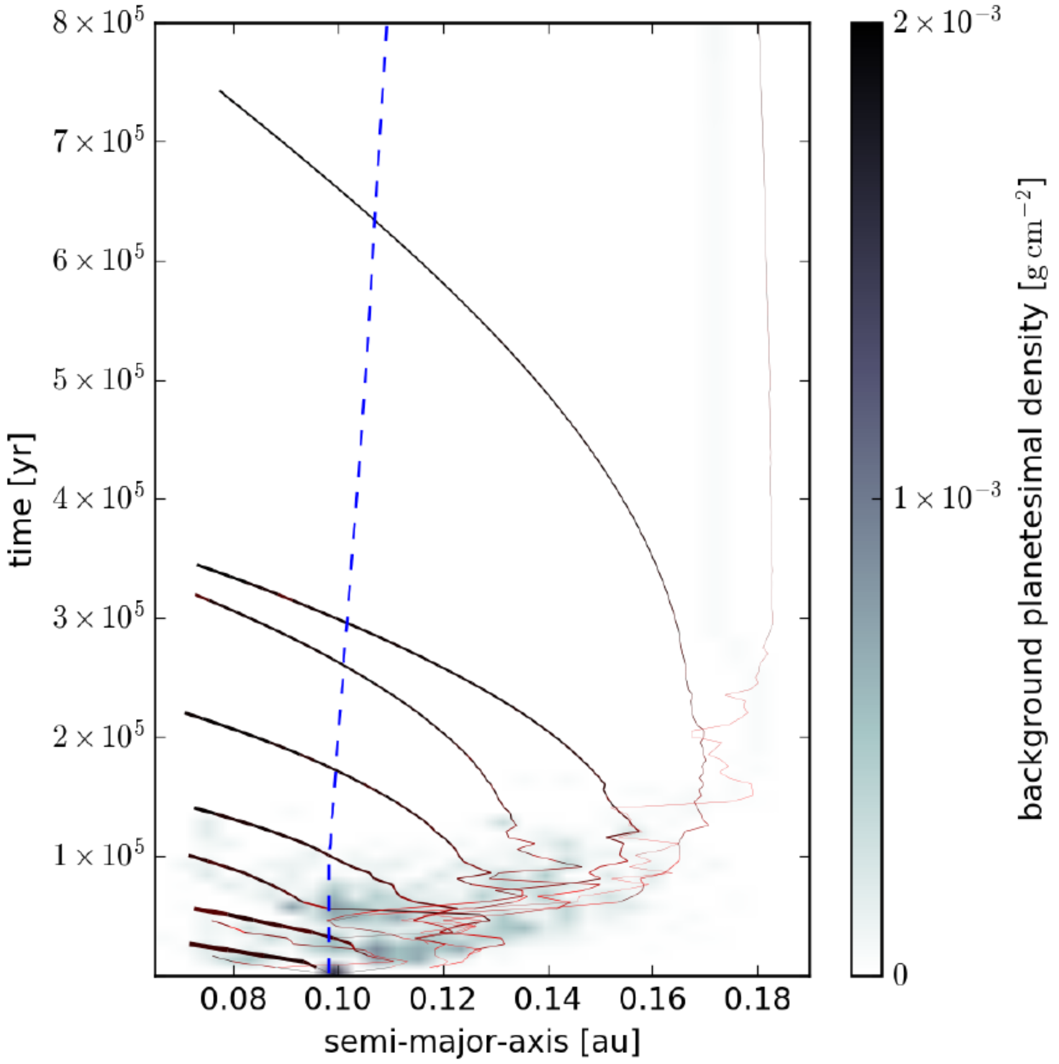
- L-code
  –> **Lagrangian** code for evolution of dust/pebbles, planetesimal formation
- N-code
- A-code



NEXT STEPS (NEXT WEEK)

We have coupled three codes:

- L-code
- N-code
  –> **N-body** code for self-coagulation of planetesimals, pebble accretion
- A-code



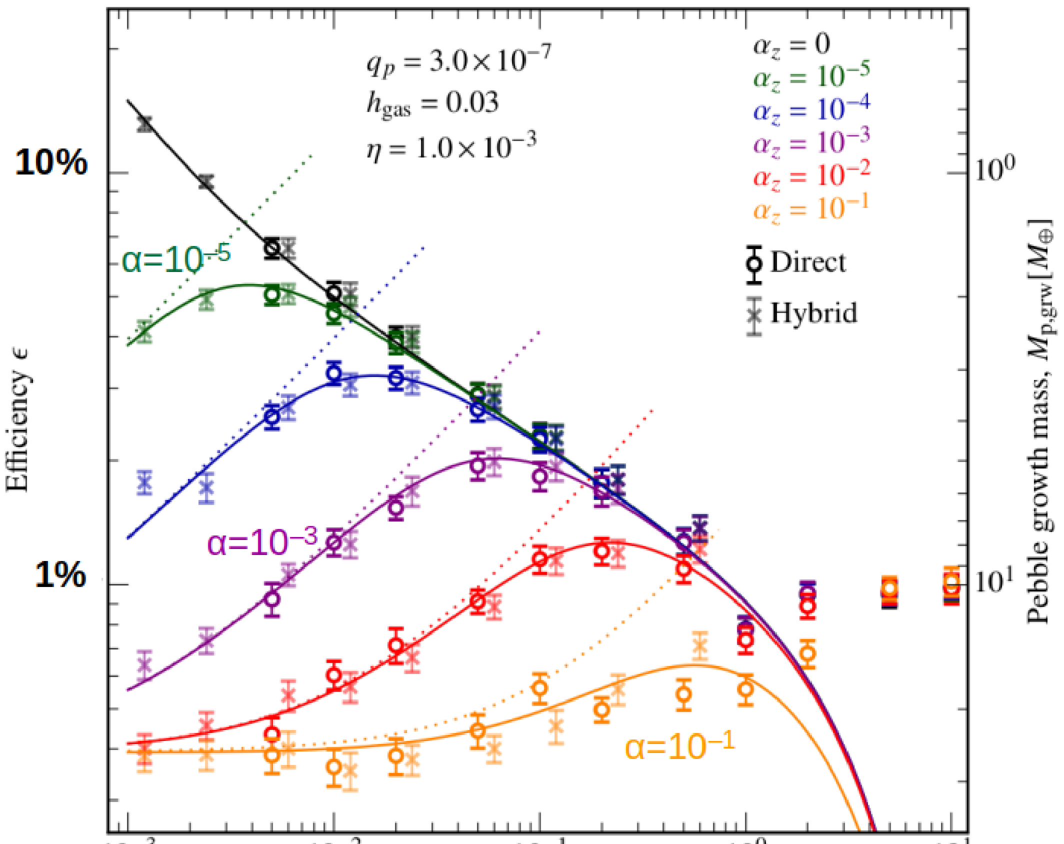
Schoonenberg et al. (2019) – **N-body** calculation

NEXT STEPS (NEXT WEEK)

We have coupled three codes:

- L-code
- N-code
- A-code

  –> Analytical code for pebble accretion efficiencies



NEXT STEPS (NEXT WEEK)

We have coupled three codes:

- L-code
- N-code
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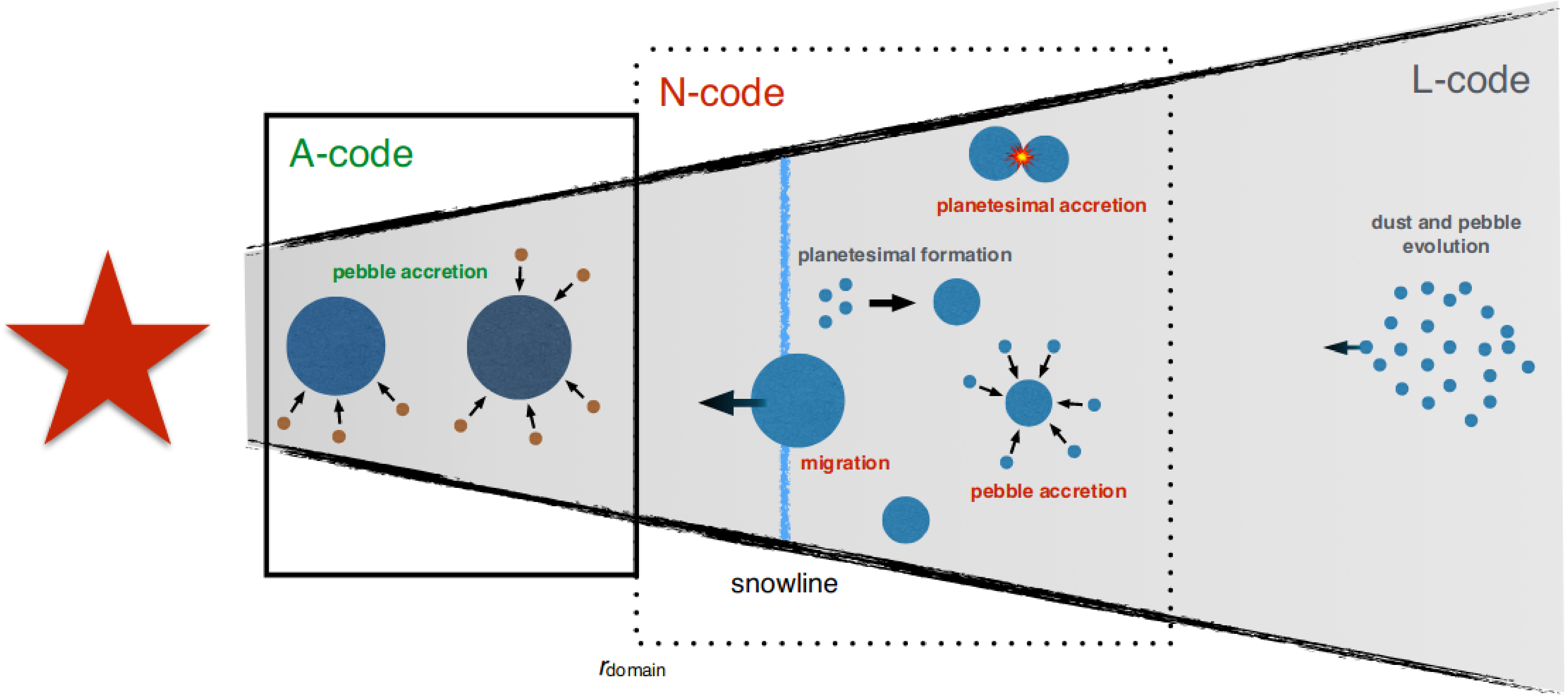
Caveats:

- No connection to star formation phase
- No link to final dynamics



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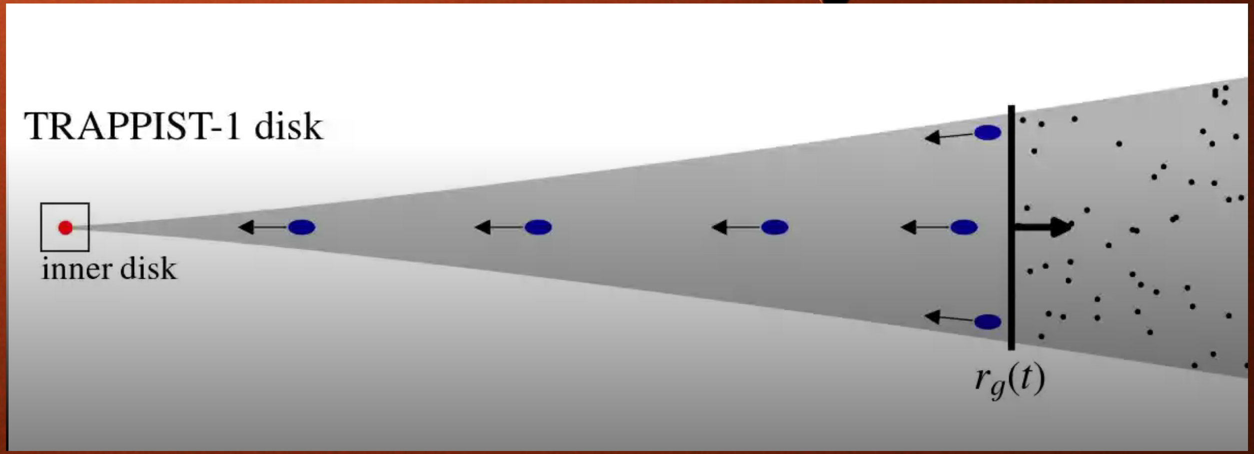
II. FORMATION OF THE TRAPPIST-1 SYSTEM

CHRIS ORMEL

University of Amsterdam

with

Djoeke Schoonenberg (Amsterdam) **Beibei Liu** (Lund) **Caroline Dorn** (Zürich)



Ormel et al. (2017)

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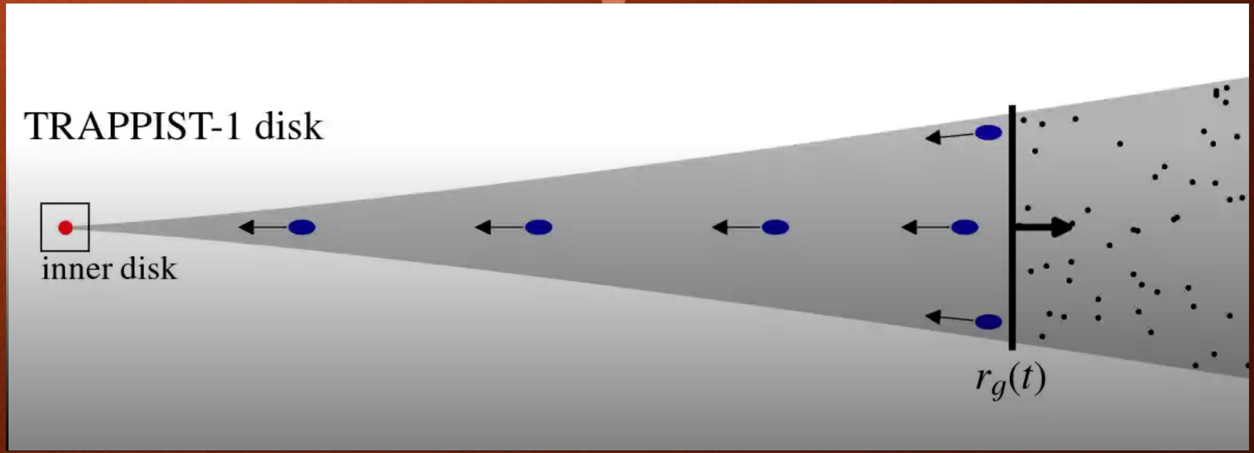
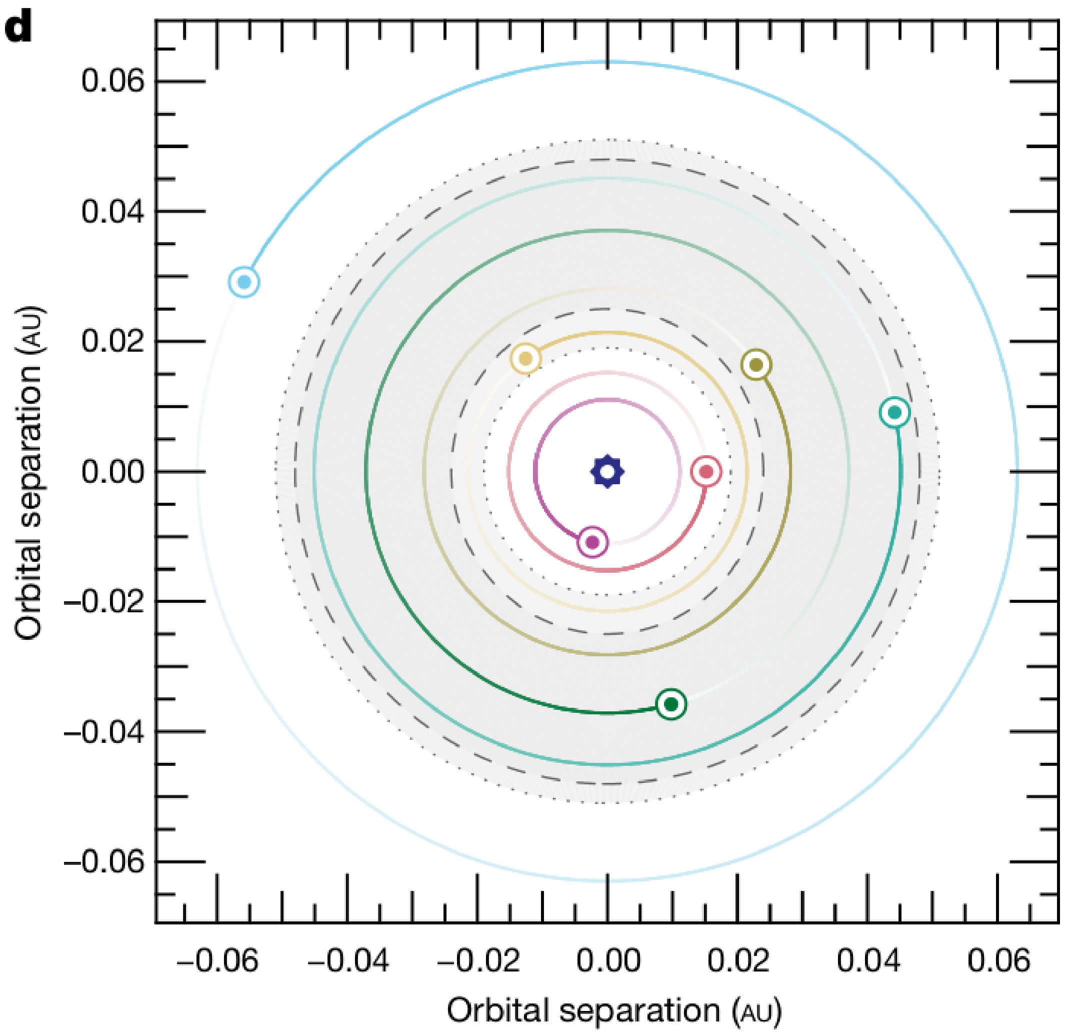


TRAPPIST I SYSTEM



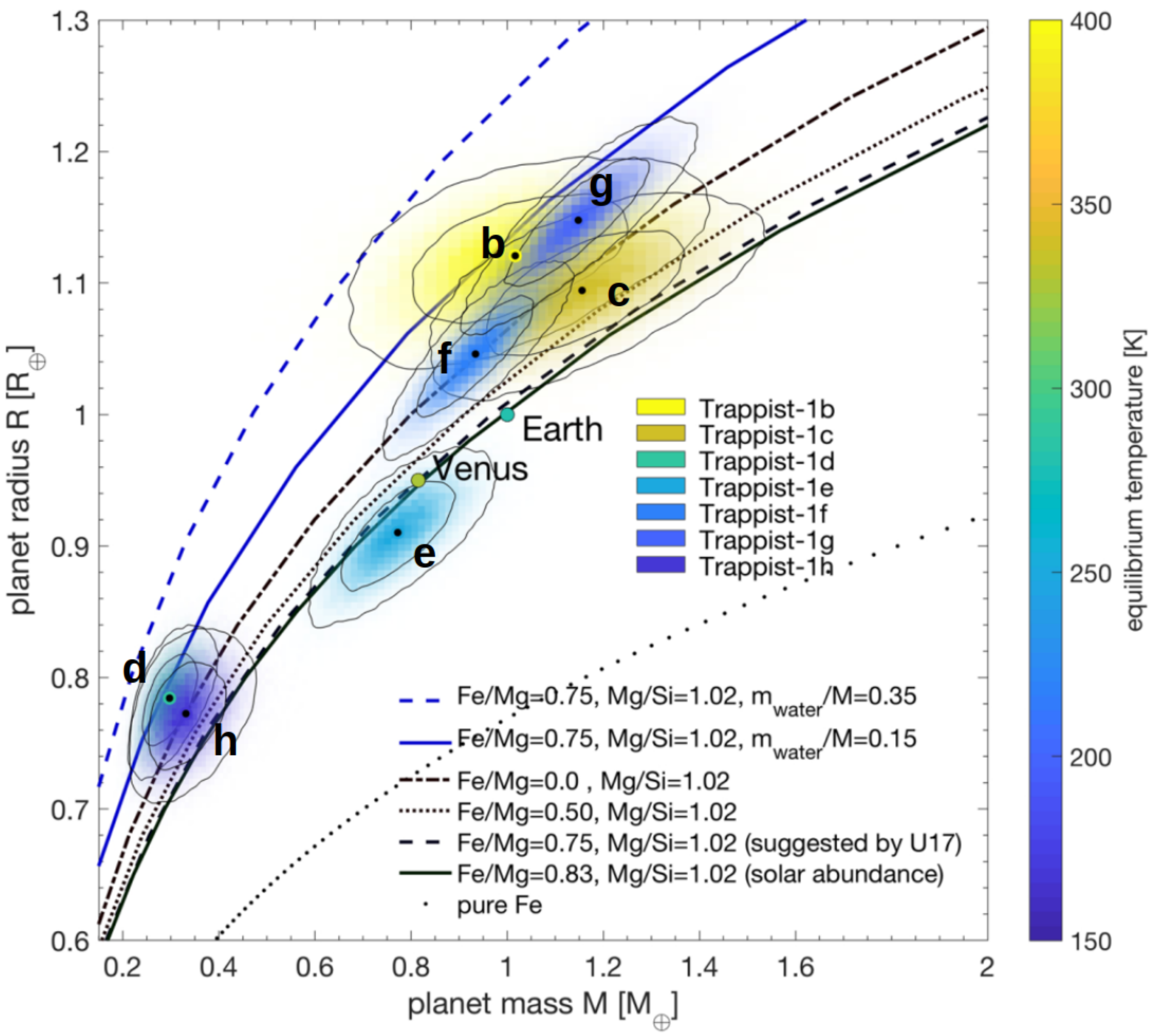
Gillon et al. (2017)

- M8 dwarf, 12.1 pc,
  mass = 0.09 M_{sun},
  age = 7.6 +- 2.2 Gyr

  Van Goortel (2017), Burgasser & Mamajek (2017)

- 7 planets, all around 1 Earth radius
- compact; 0.01 – 0.07 au
- resonances, many close to 3:2

COMPOSITION



Grimm et al. (2018)

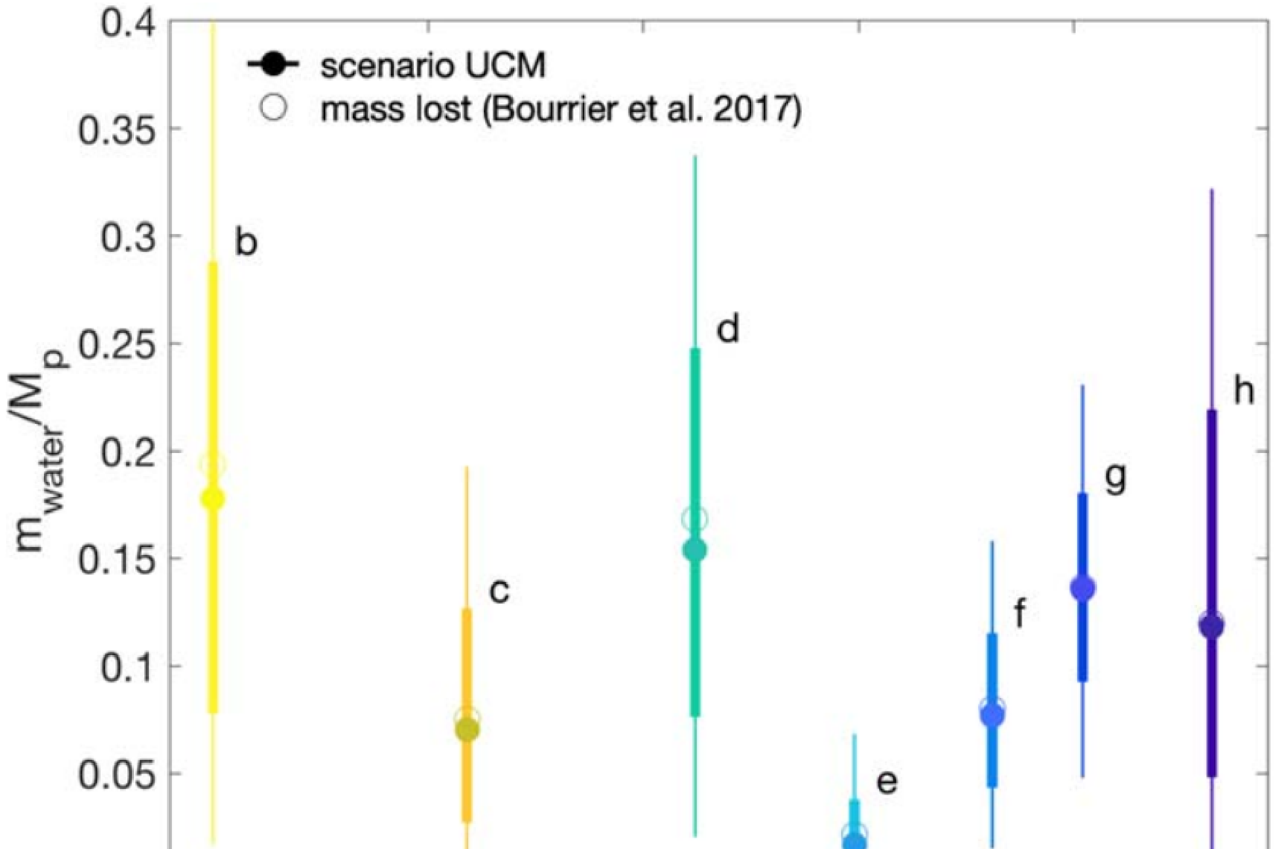
Mass-radii relationships indicate:

- planets lie above the rock line
- moderate H_2O fraction (~10%)

Dorn et al. (2018)

Properties hard to explain with "standard" planet formation scenarios

COMPOSITION



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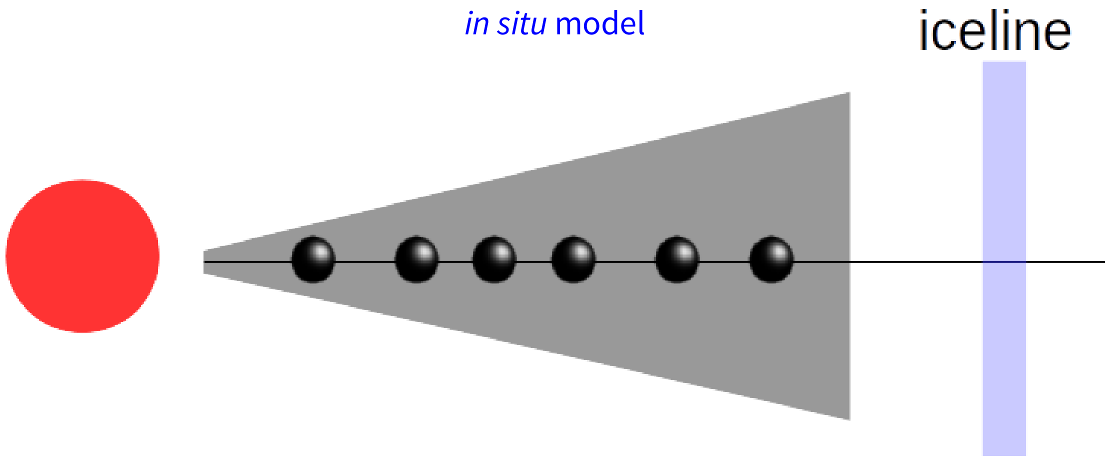
CLASSICAL FORMATION SCENARIOS



IN SITU SCENARIO

- requires an unusually massive disk (unstable)
- no (easy) explanation for ice contents planets
- no resonances

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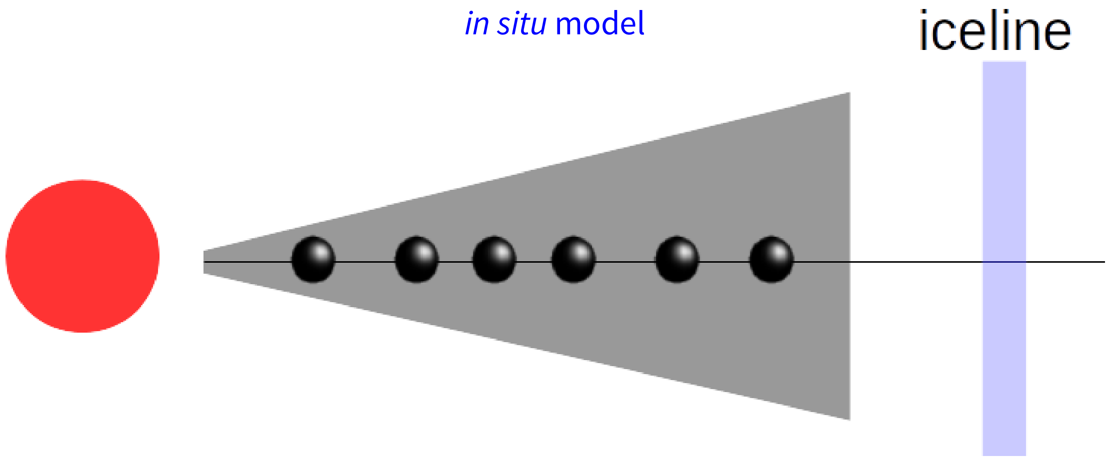

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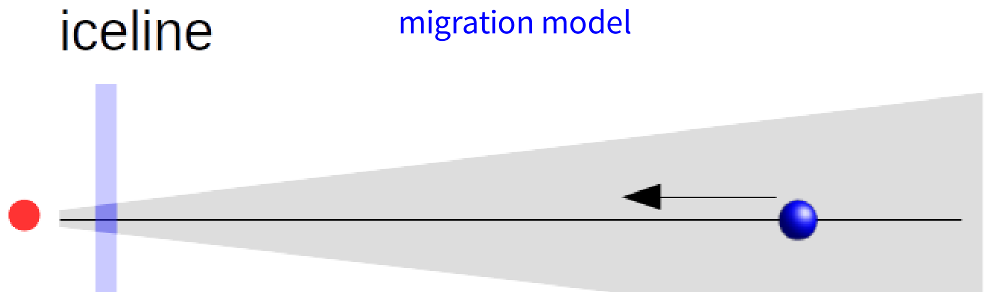
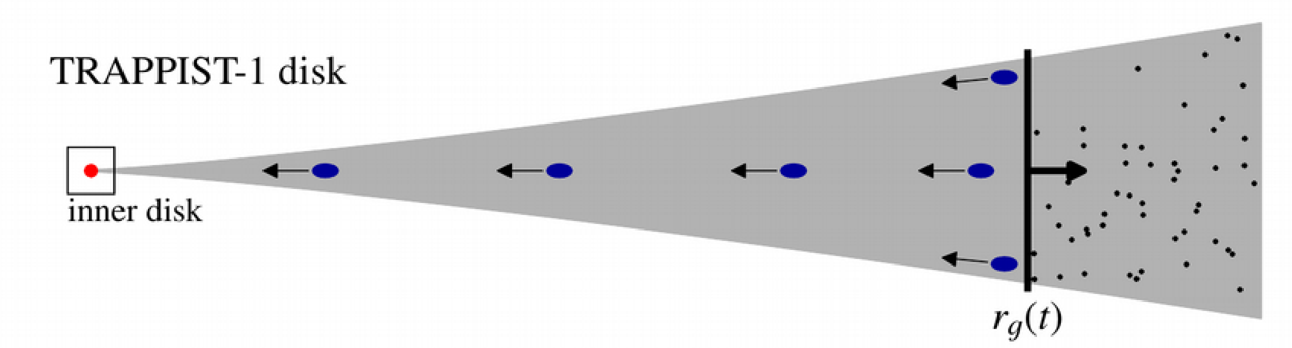


MIGRATION SCENARIO

- formation time long
- expected composition icy

PEBBLE-DRIVEN FORMATION

Ormel, Liu, Schoonenberg (2017)

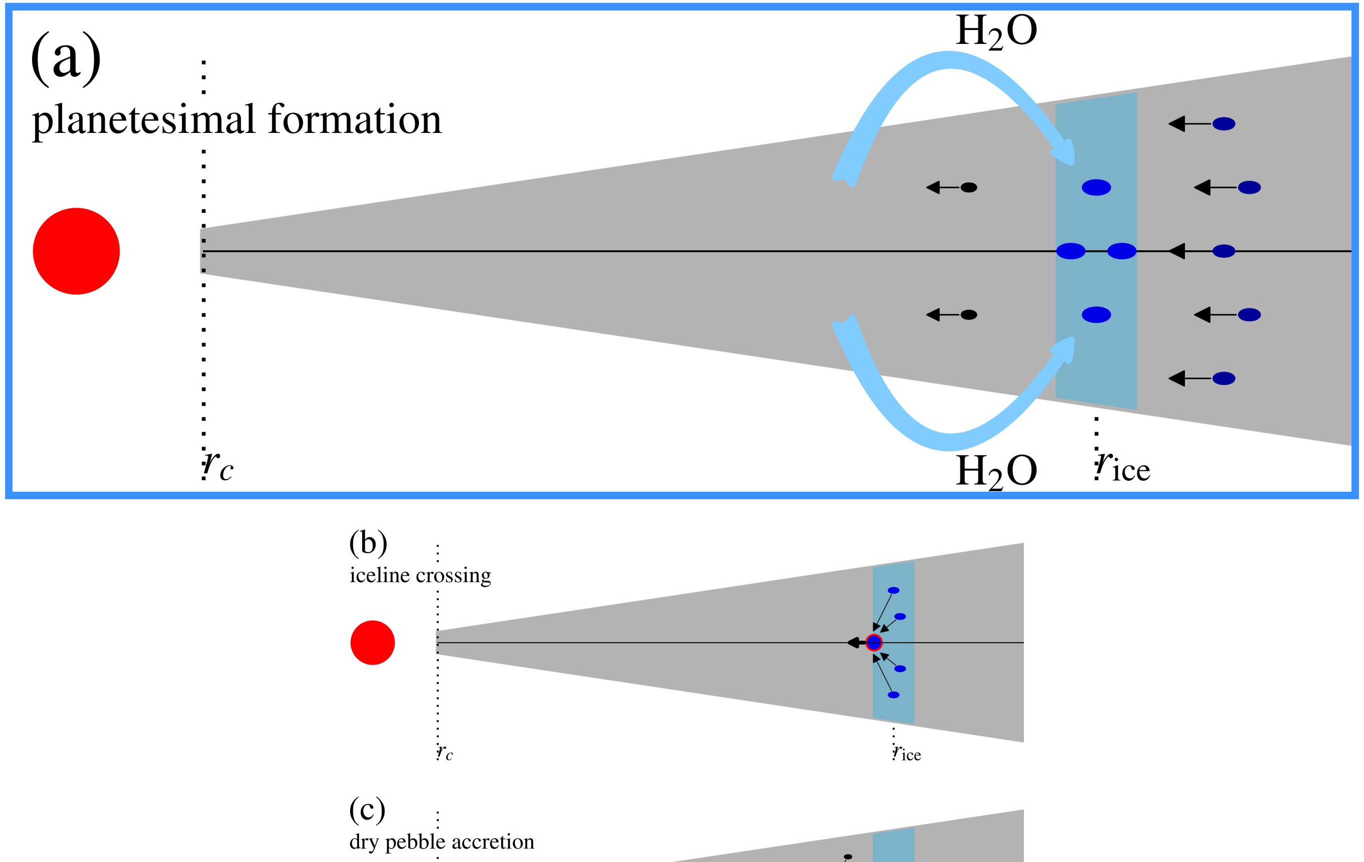


large disk; **dust** growth to pebbles; drift to inner disk

see Birnstiel et al. (2012), Lambrechts & Johansen (2014)
cf. inside-out formation by Chatterjee & Tan (2017)

SYNOPSIS

Ormel, Liu, Schoonenberg (2017)



- icy pebbles cross snowline
- H_2O vapor diffuses back across snowline
- midplane dust:gas=1 exceeded
- planetesimal formation at iceline

  by streaming instability (Schoonenberg & Ormel 2017)

SYNOPSIS

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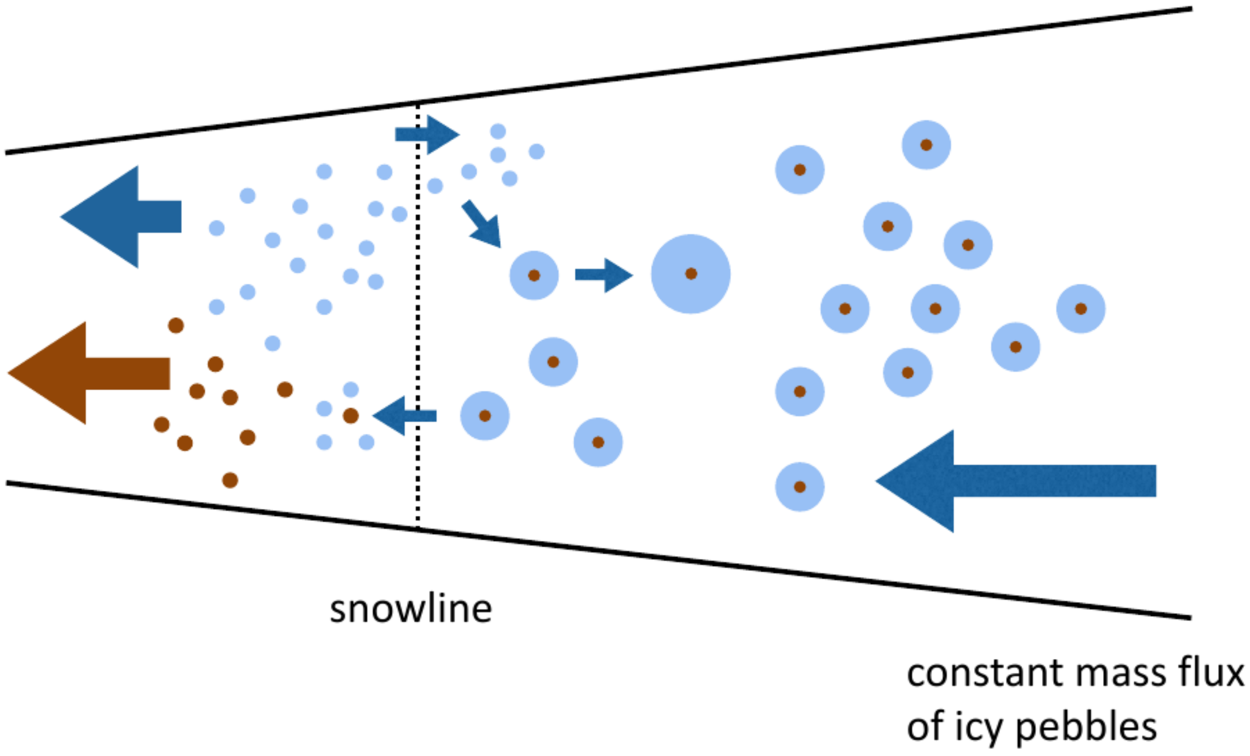

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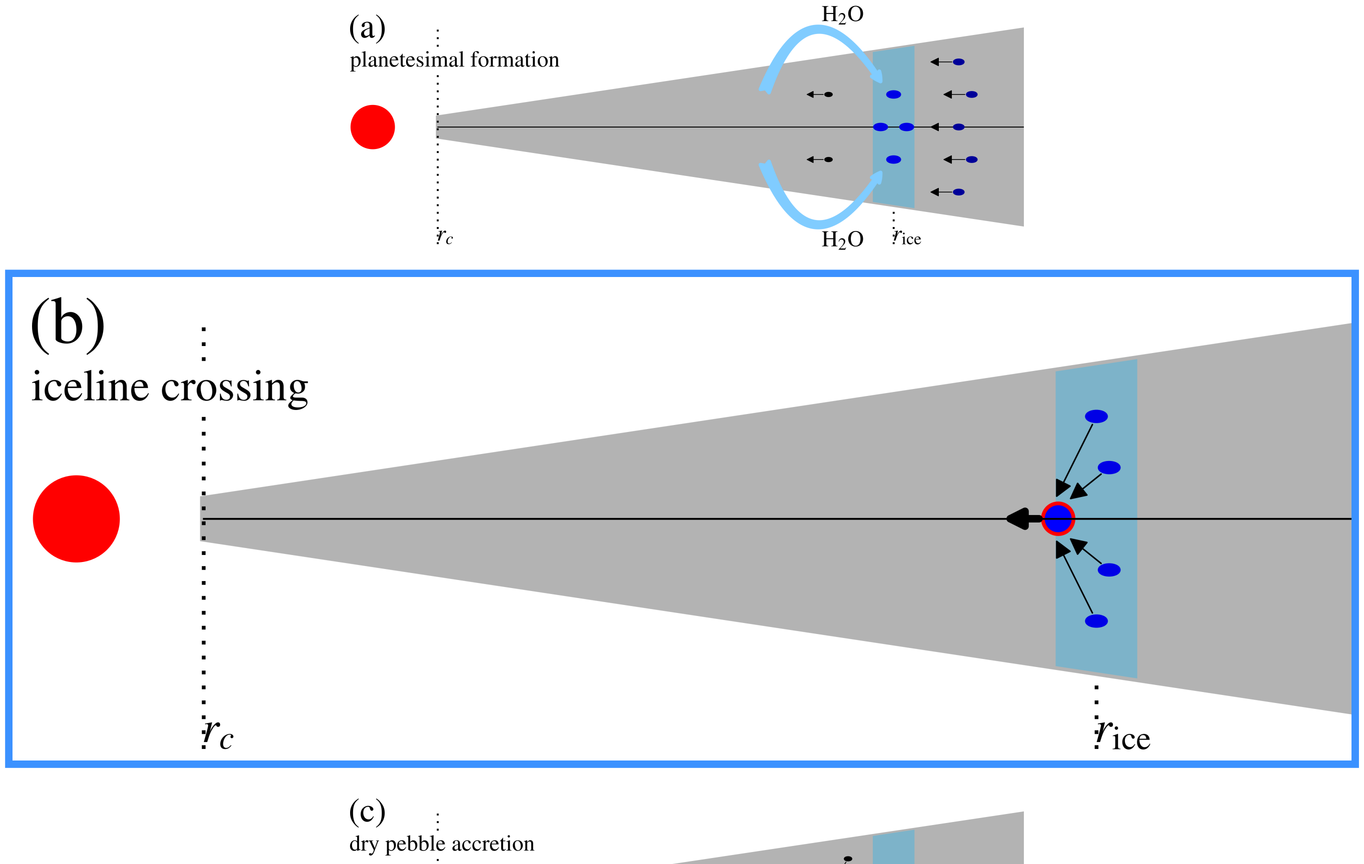
Schoonenberg & Ormel (2017): growth by recondensation

SYNOPSIS

Ormel, Liu, Schoonenberg (2017)



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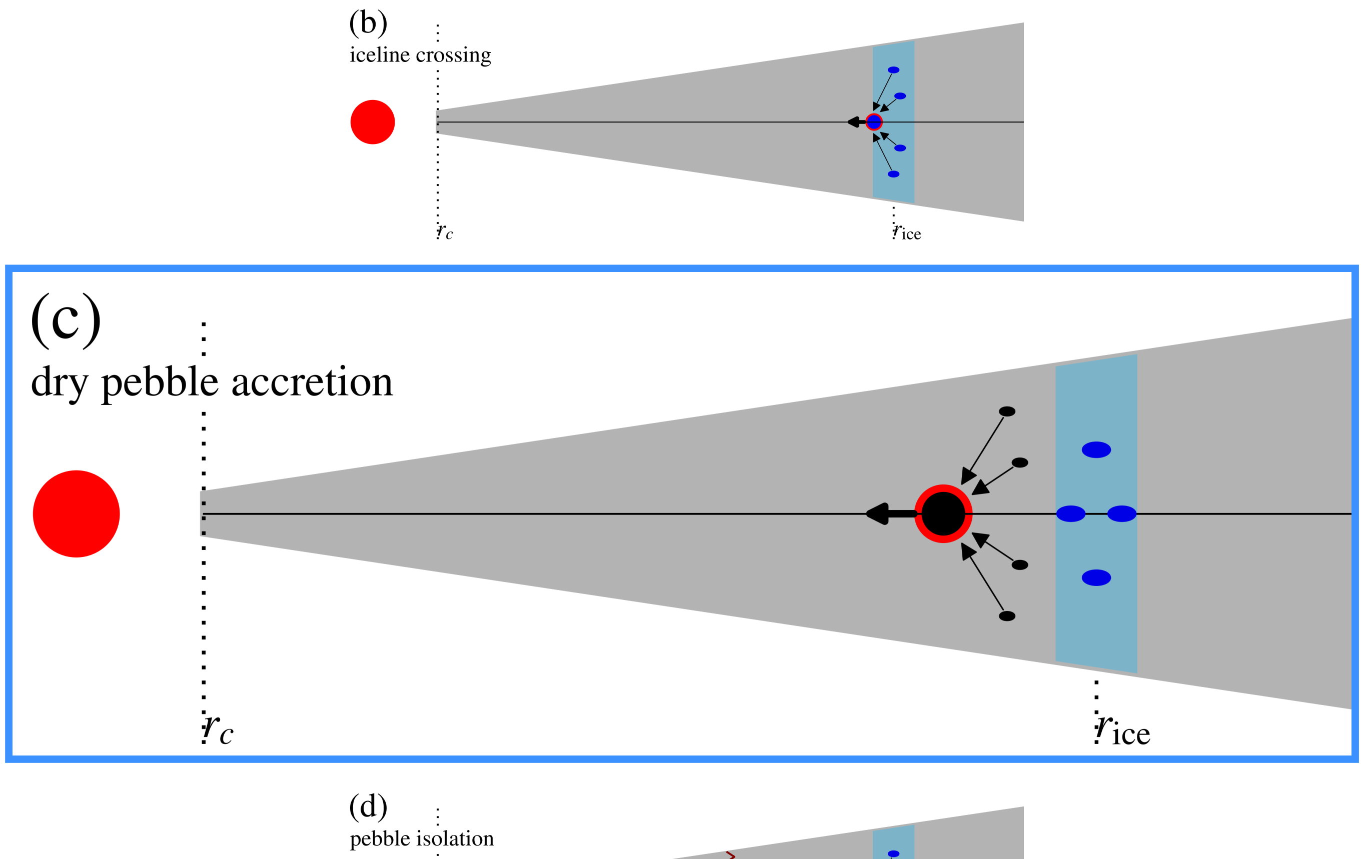
- planetesimals coagulate (**wet** accretion)

  The water contents is set (Schoonenberg et al. in prep)

SYNOPSIS

Ormel, Liu, Schoonenberg (2017)

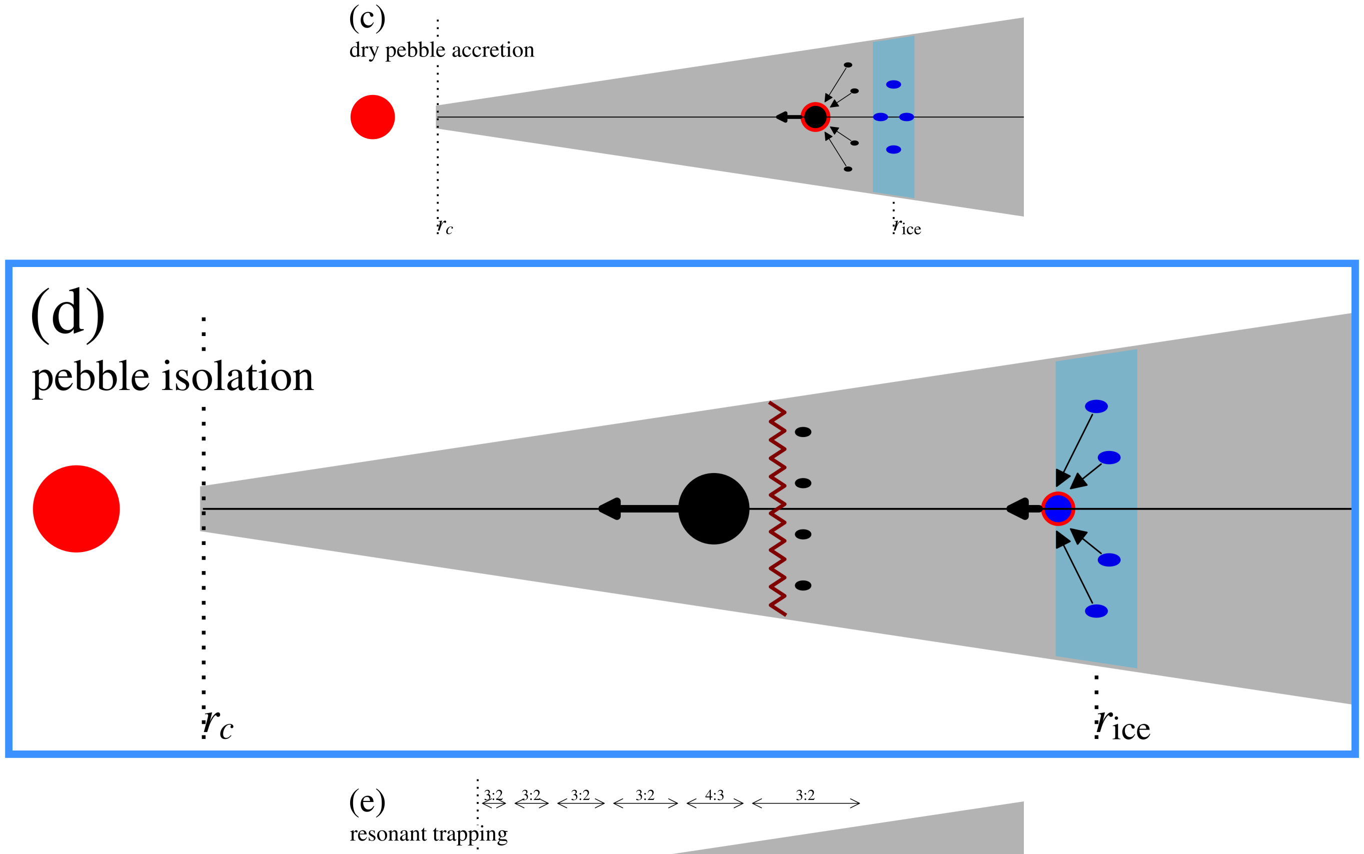


- icy pebbles cross snowline
- H_2O vapor diffuses back across snowline
- midplane dust:gas=1 exceeded
- planetesimal formation at iceline
- planetesimals coagulate (**wet** accretion)
- migration and accretion of **dry** pebbles

  H_2O fraction decreases

SYNOPSIS

Ormel, Liu, Schoonenberg (2017)



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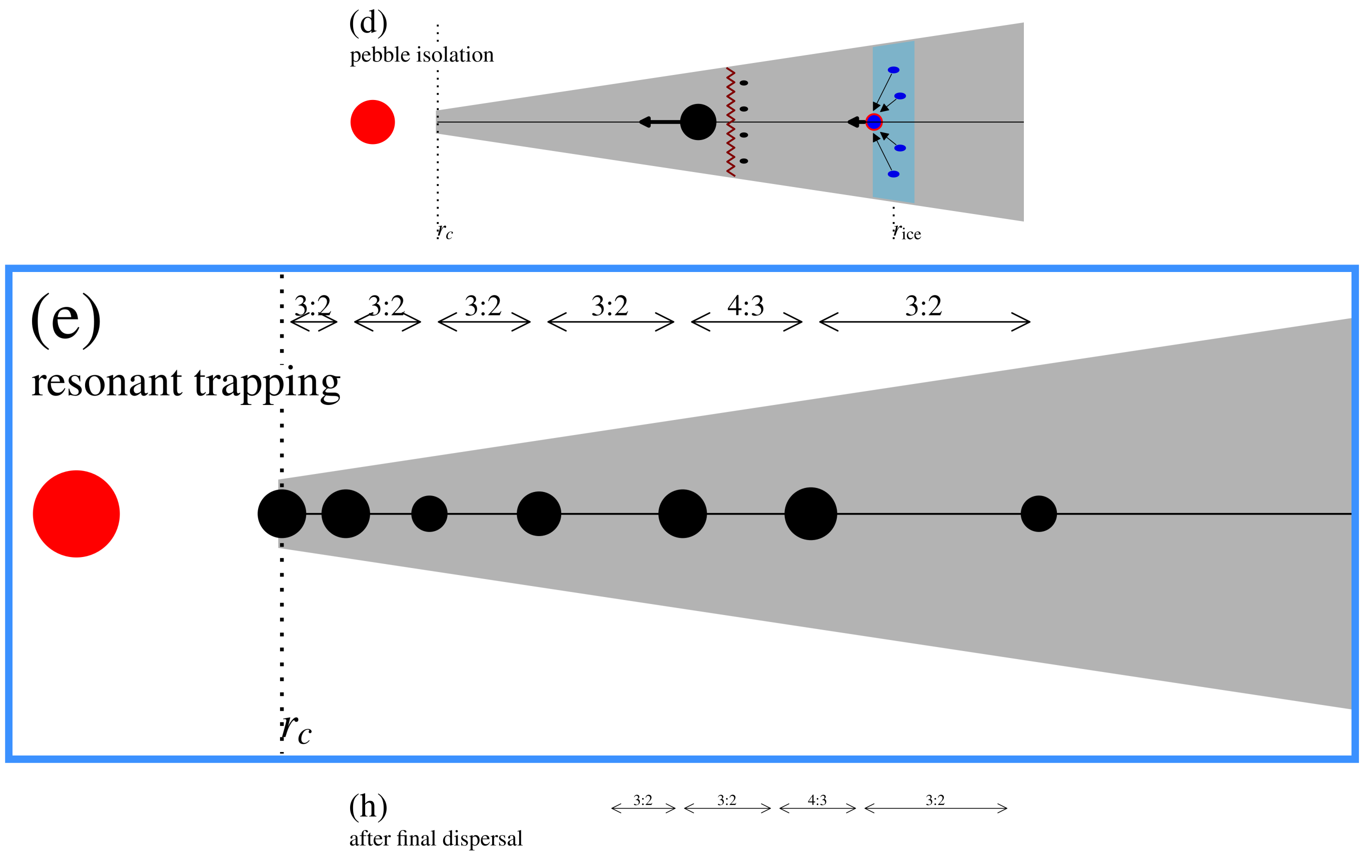
- migration and accretion of **dry** pebbles
- accretion ceases at *pebble isolation mass* $h^3 M_\star$

Lambrechts et al. (2014), Atteiee et al (2018), Bitsch et al. (2018)

The process repeats

SYNOPSIS

Ormel, Liu, Schoonenberg (2017)



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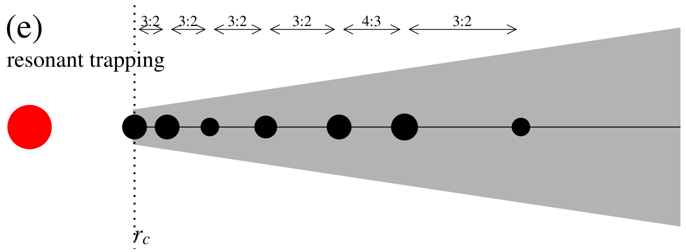
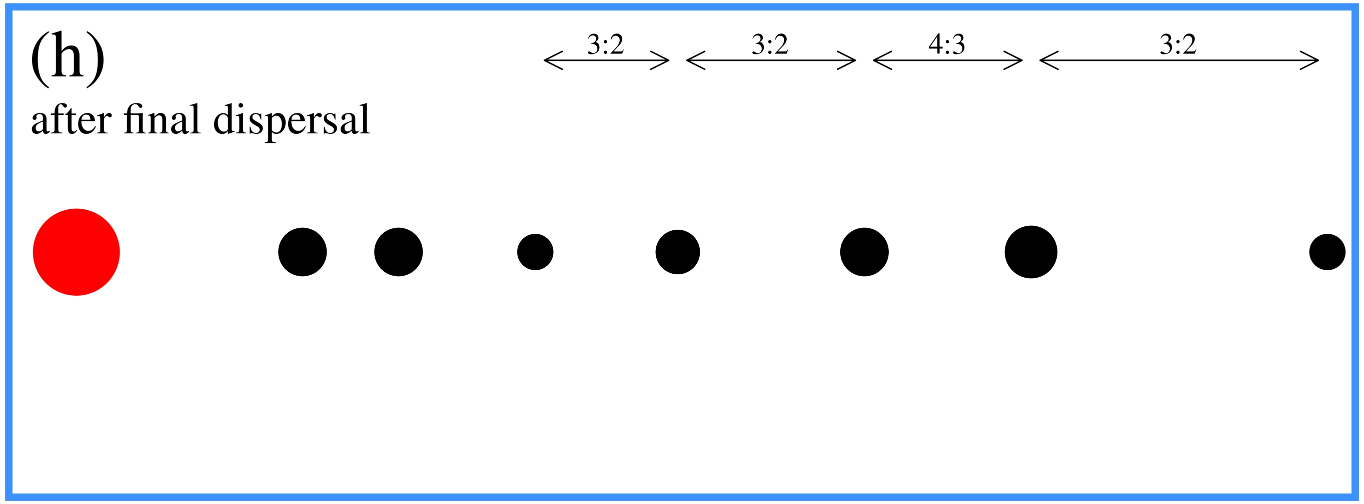
- migration and accretion of **dry** pebbles
- accretion ceases at *pebble isolation mass* $h^3 M_\star$
  - 7 planets form; end up in resonances

    migration stall at the magnetospheric cavity radius r_c

SYNOPSIS

Ormel, Liu, Schoonenberg (2017)





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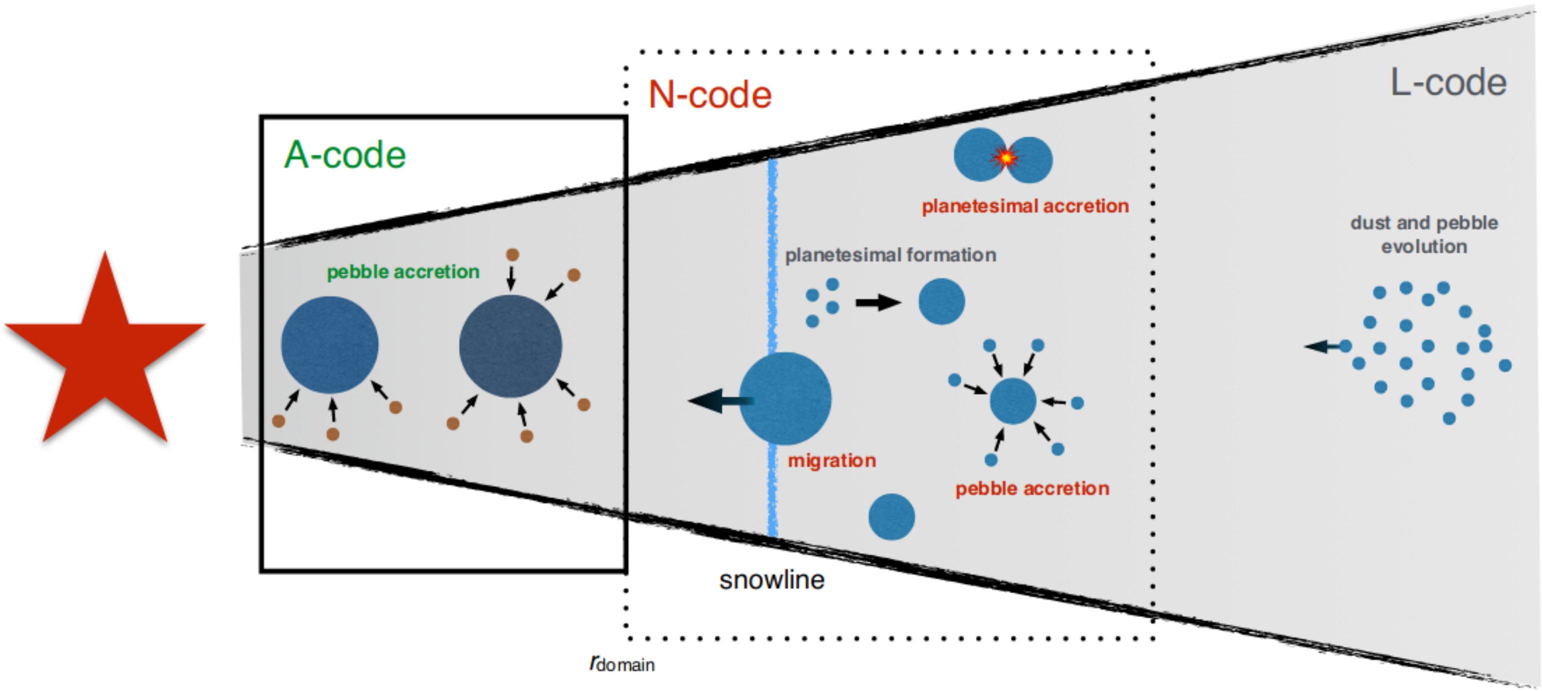
  - 7 planets form; end up in resonances
  - Planets re-arrange after disk dispersal

NEW RESULTS

Schoonenberg, Liu, Ormel, Dorn (2019)



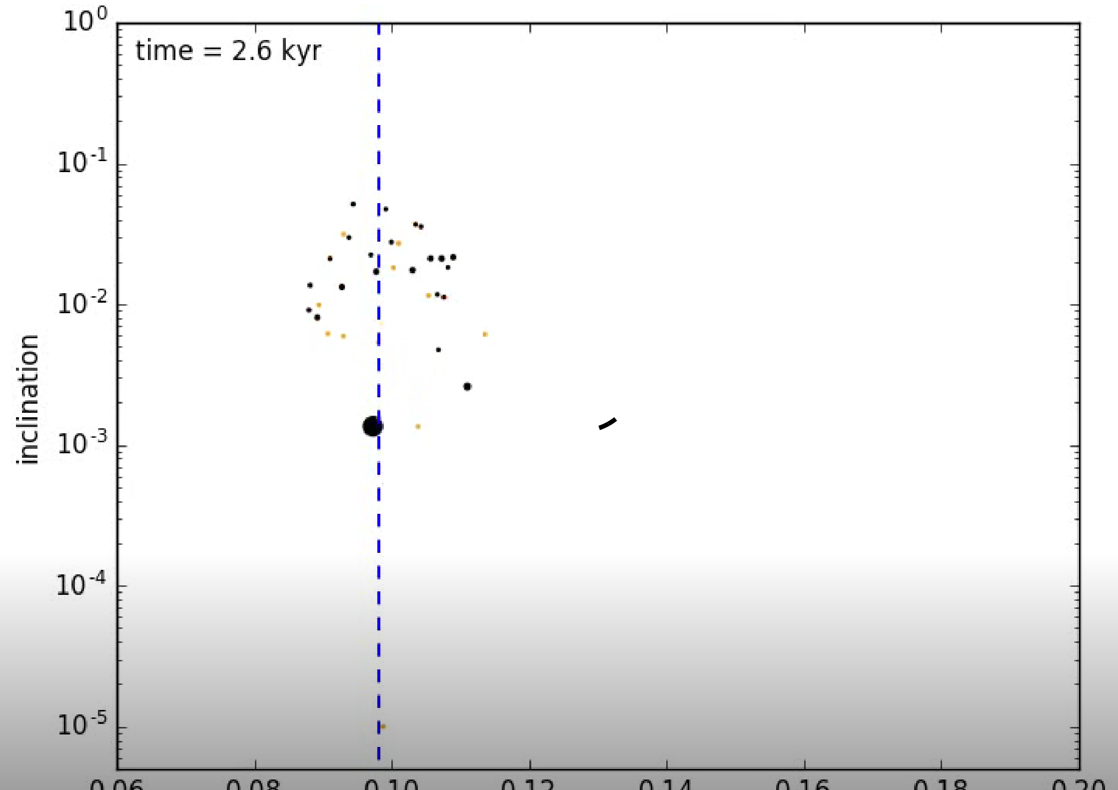
Schoonenberg et al. (2019) – model overview

Developed an integrated numerical model combining three codes:

- a **L**agrangian code for the dust/pebbles
  Schoonenberg et al. (2018)
- an **N**-body code for the planetesimal dynamics/coaguation at the snowline
  Liu et al. (2019)
- an **A**nalytical code to calculate pebble accretion efficiencies

NEW RESULTS

Schoonenberg, Liu, Ormel, Dorn (2019)



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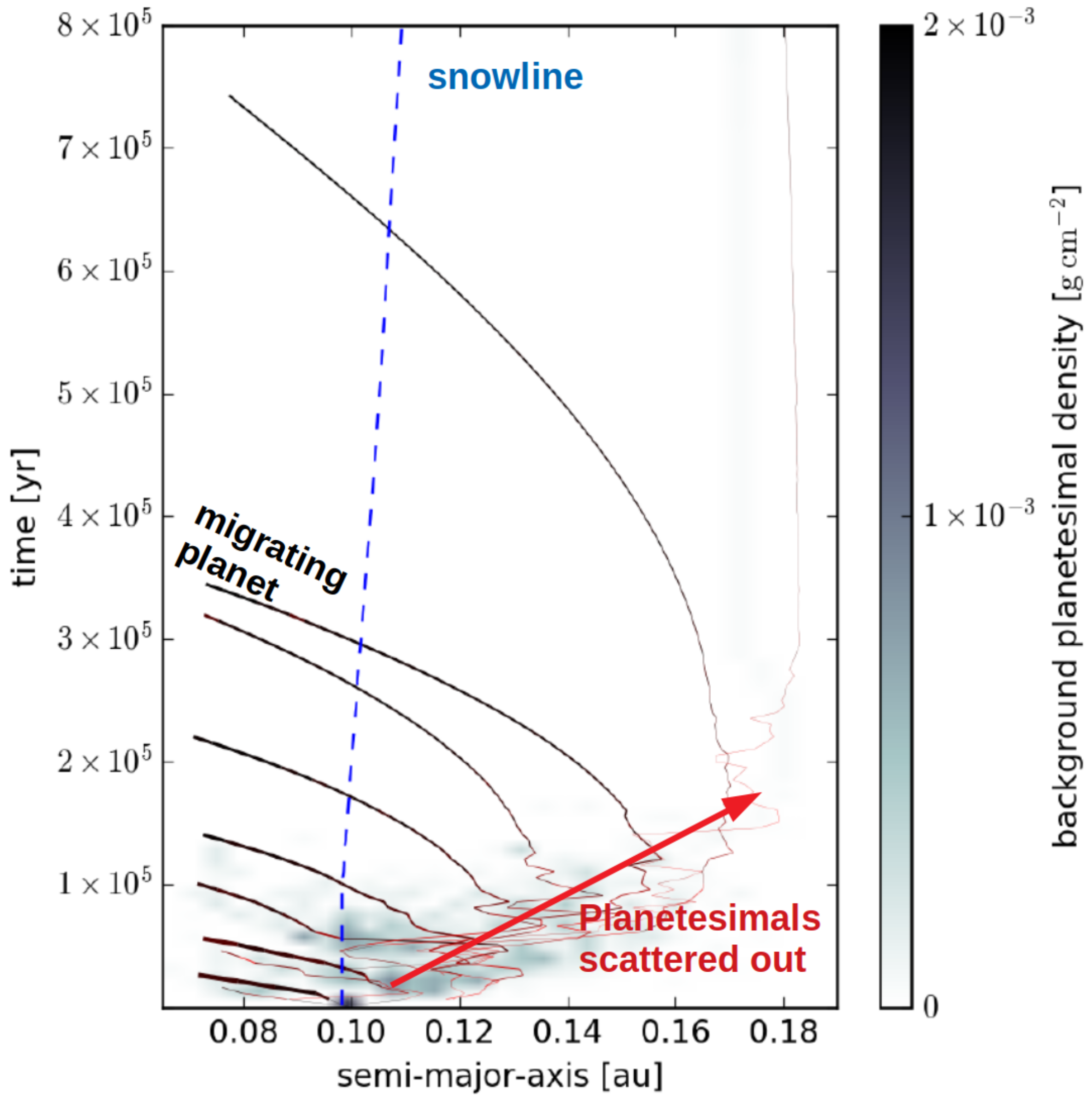
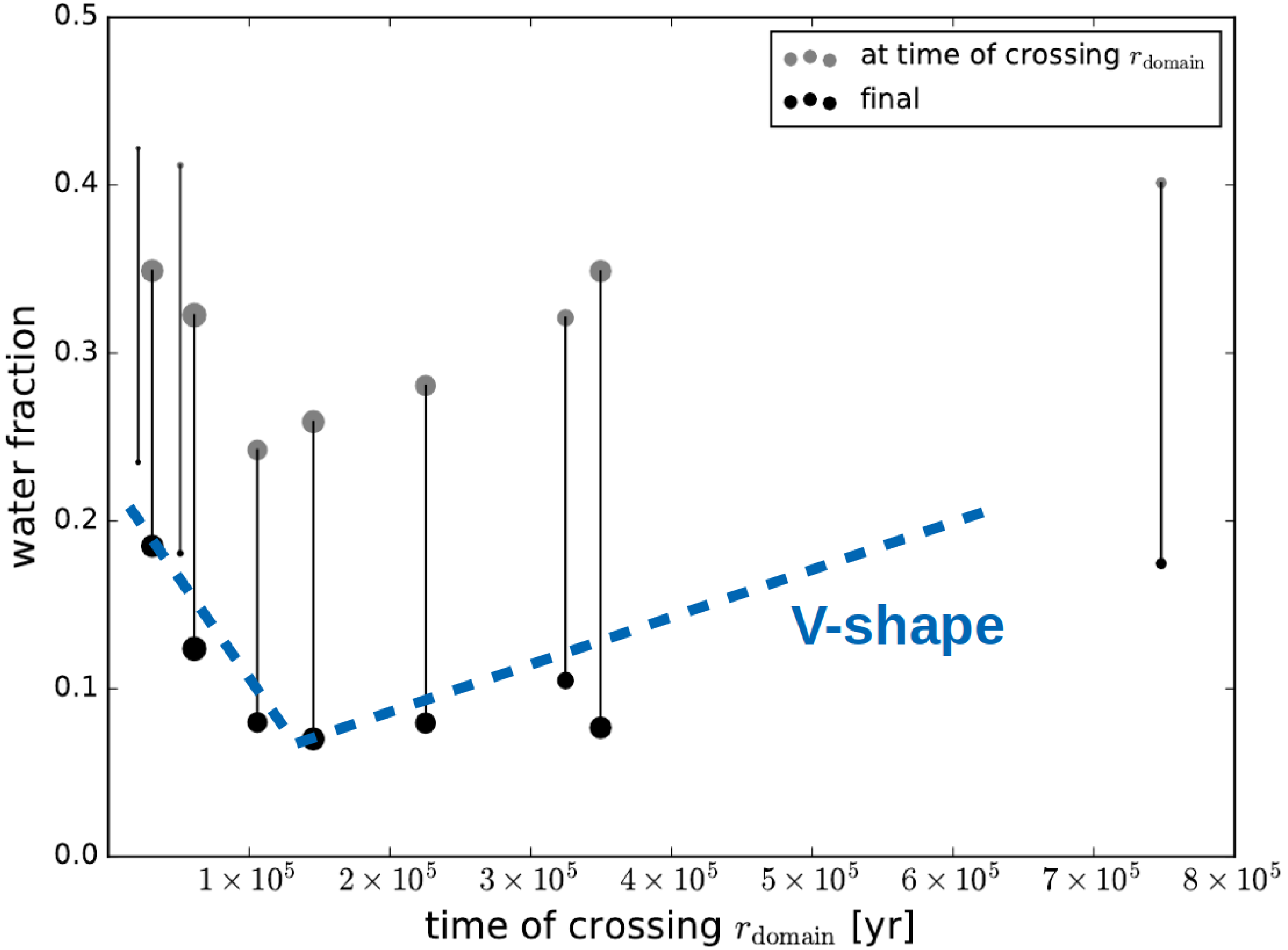
- an **A**nalytical code to calculate

NEW RESULTS



Single (initial) burst of planetesimal formation, quick spreading

NEW RESULTS



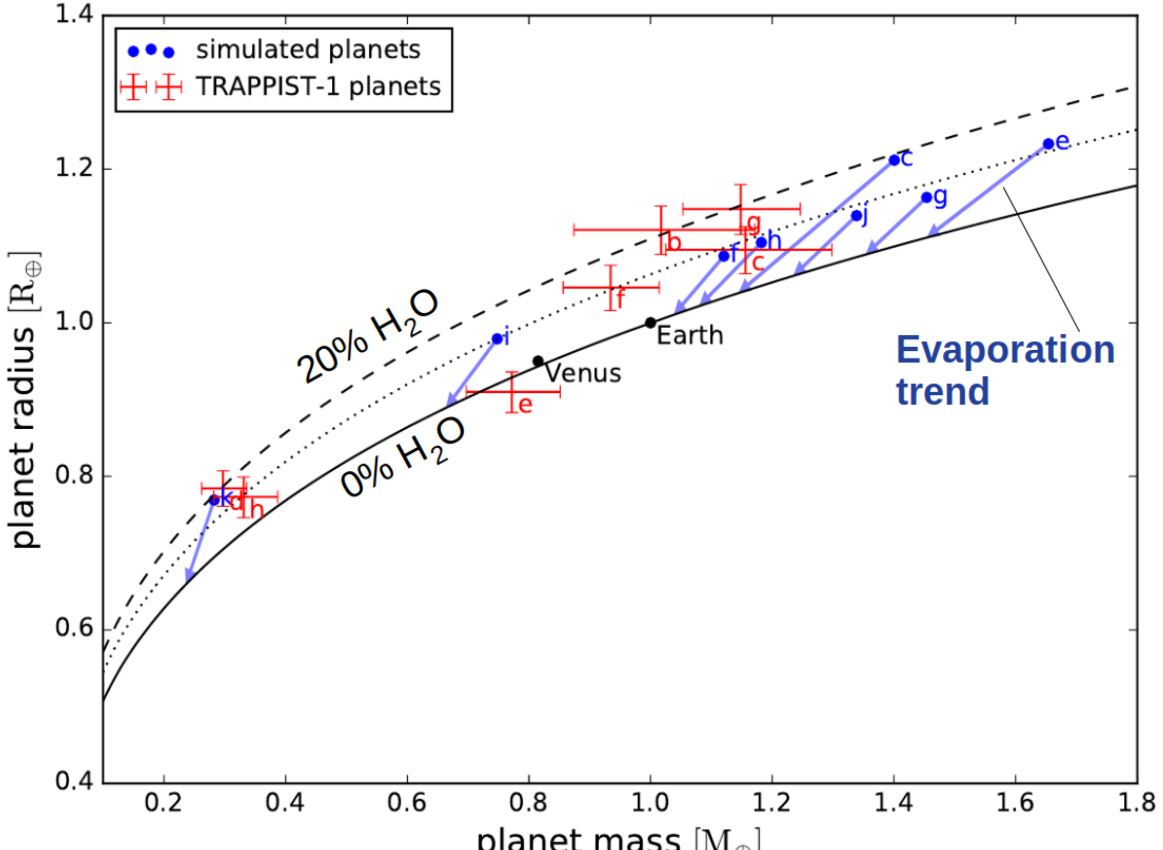
A **V-shape** in the H2O mass fraction of the planets

PARAMETER STUDY

	Model description	$\sum M_{pl}$ $[M_\oplus]$	M_{SI} $[M_\oplus]$	$\overline{M_{pl}}$ $[M_\oplus]$	$\overline{f_{H_2O}}$
1.	Fiducial (see Table 1)	9.3 ± 0.08	1.4 ± 0.02	1.74 ± 0.89	0.10 ± 0.05
2.	With a pebble isolation mass of 1 $M_\oplus$	5.5 ± 0.56	1.4 ± 0.02	0.84 ± 0.29	0.19 ± 0.08
3.	Larger initial pltsml size (1500 km)	9.3 ± 0.2	1.4 ± 0.04	1.84 ± 0.92	0.10 ± 0.05
4.	Smaller initial pltsml size (1000 km)	9.4 ± 0.08	1.4 ± 0.03	1.74 ± 0.73	0.10 ± 0.05
5.	$\alpha = 5 \times 10^{-4}$	14.8 ± 0.06	5.9 ± 0.01	0.67 ± 0.28	0.39 ± 0.09
6.	$\alpha = 2 \times 10^{-3}$	8.7 ± 0.17	1.5 ± 0.01	1.43 ± 0.71	0.14 ± 0.05
7.	$\dot{M}_{gas} = 5 \times 10^{-11}$ $M_\odot$ yr^{-1}	10.8 ± 0.46	3.0 ± 0.01	1.06 ± 0.50	0.16 ± 0.09
8.	$\dot{M}_{gas} = 2 \times 10^{-10}$ $M_\odot$ yr^{-1}	7.1 ± 0.1	1.4 ± 0.04	1.57 ± 0.93	0.13 ± 0.06
9.	Higher disk mass (r_{out} = 300 au)	14.5 ± 0.49	1.4 ± 0.03	2.56 ± 1.53	0.07 ± 0.05
10.	Lower disk mass (r_{out} = 100 au)	4.3 ± 0.04	1.3 ± 0.02	1.10 ± 0.49	0.17 ± 0.05
TRAPPIST-1	UCM model, Dorn et al. (2018)	$5.66^{+0.65}_{-0.61}$		0.95 ± 0.26	0.10 ± 0.05

Schoonenberg, Liu, Ormel, Dorn (2019)

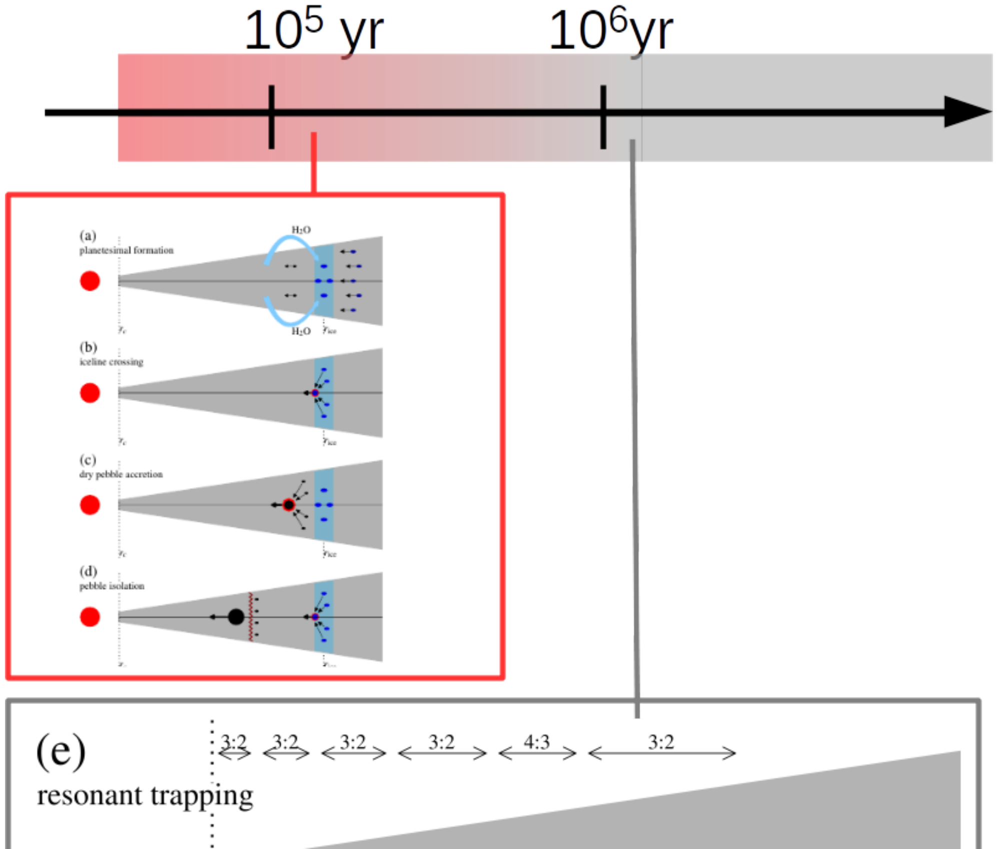
AFTERTHOUGHTS



H_2O FRACTION ~10% IS SPECIAL

- too much to change by delivery, evaporation
- hard to understand from theory
- ... but result strongly depends on TTV measurement/modeling!

AFTERTHOUGHTS



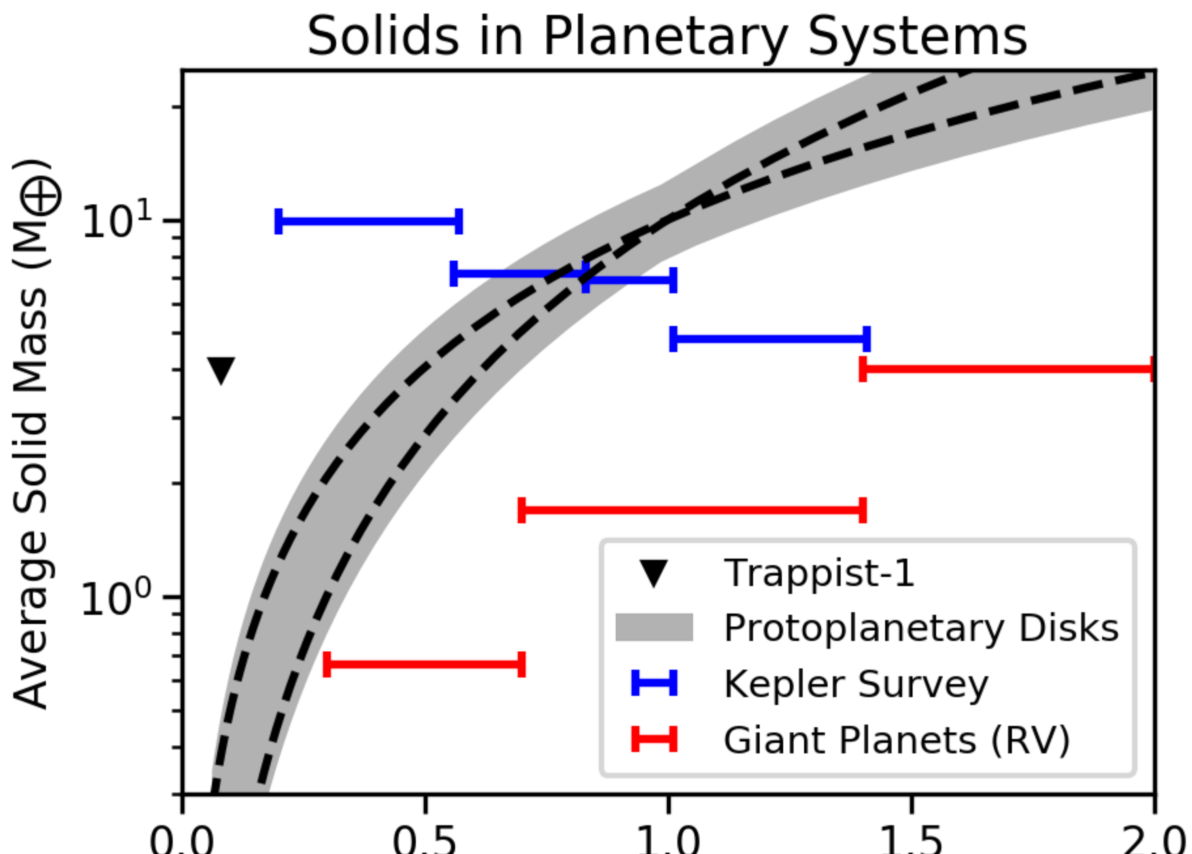
- H_2O fraction ~10% special

PLANETS FORM VERY FAST (~10^5 YR)

- Observational evidence for early formation?
- Fast disk clearing

(Sheehan & Eisner 2017, Tychoniec et al. 2018, Manara et al. 2018)

AFTERTHOUGHTS

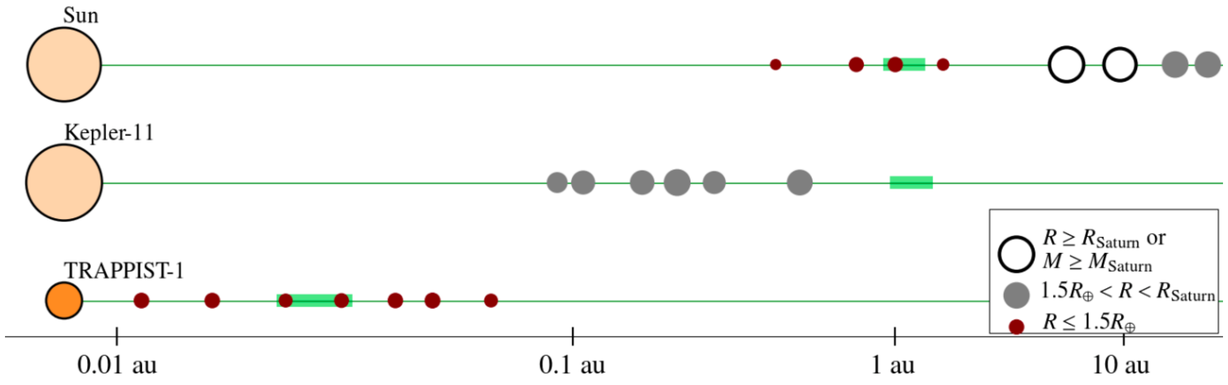


- H_2O fraction ~10% special
- Planets form very fast (~10^5 yr)

SCENARIO APPLICABLE TO LOW MASS STARS?

- many close-in planets around M-stars
  (Mulders et al. 2015)
- Pebble accretion efficient for low-mass stars
  (Ormel & Liu et al. 2018)
- Scenario aided by lack of an outer giant planet

AFTERTHOUGHTS



planetet systems design

- H_2O fraction ~10% special
- Planets form very fast (~10^5 yr)
- Scenario applicable to low mass stars

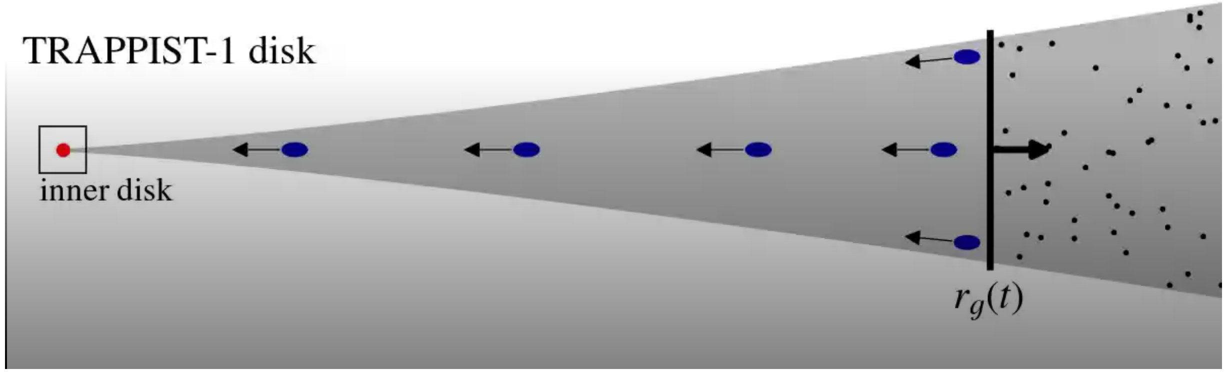
SCENARIO APPLICABLE TO SOLAR-TYPE STARS?

- Kepler systems are thermal mass M ~ h^3 $M_\bigstar$

  (Wu 2018)

- intra-system uniformity natural outcome of our model

AFTERTHOUGHTS



Ormel et al. (2017)

- H_2O fraction ~10% special
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THANK YOU