Modeling the Architecture and Composition of Exoplanetary Systems from Pebble Accretion

ExoExplorers 2023 - 3rd Cohort

Sean McCloat

Advisors:

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About Me

- 4^{th} year PhD student at UND – Space Studies + Masters
- lots of amateur observation work
  - 7 years maintaining, operating, using observatory; teaching; master's theses

- published! McCloat, von Essen, Fieber-Beyer (Astron. J. ,2021)
  - detected Na in atmosphere KELT-10b using synthetic telluric correction

- North Dakota Space Grant STEM Ambassador, instructor

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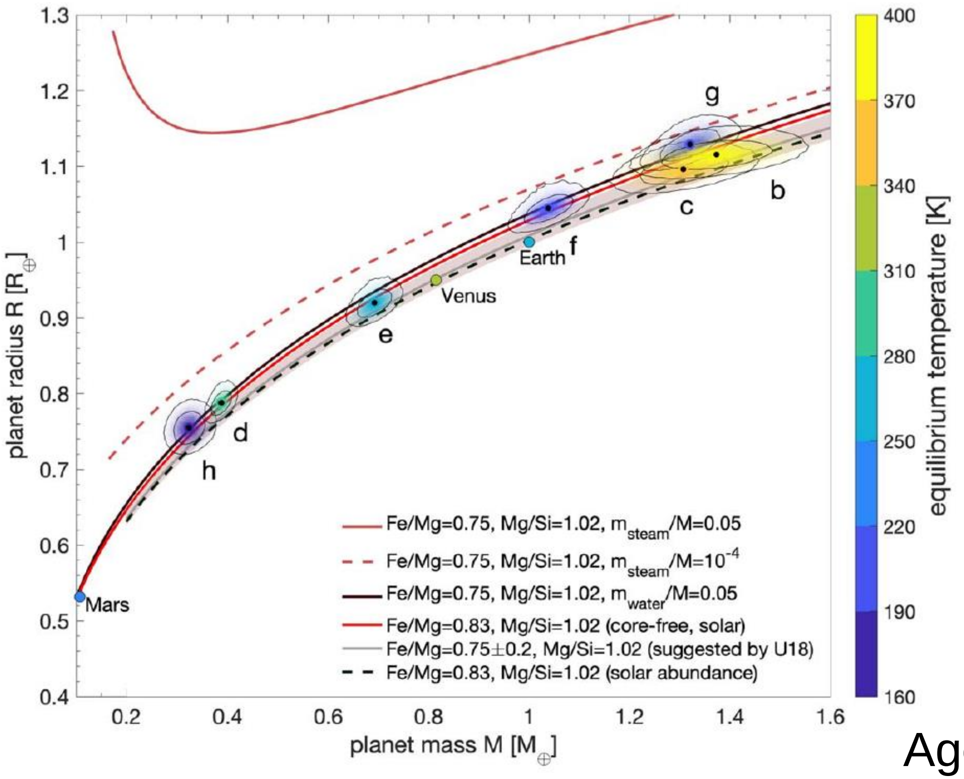
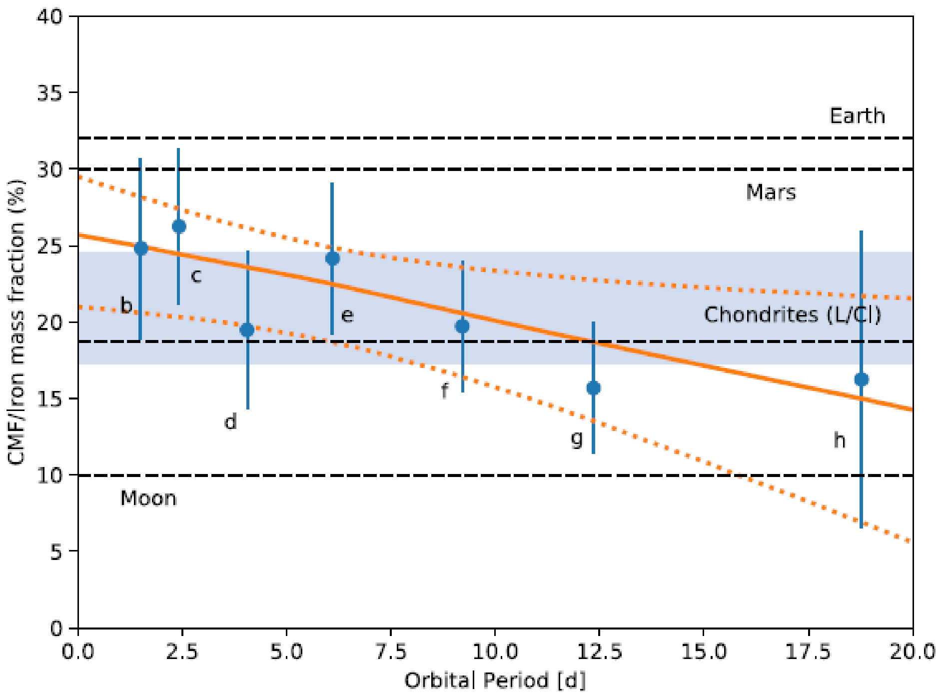
Dissertation – Under Construction

- model planet formation by pebble accretion and track the composition
- investigate trends in bulk composition within exoplanetary systems

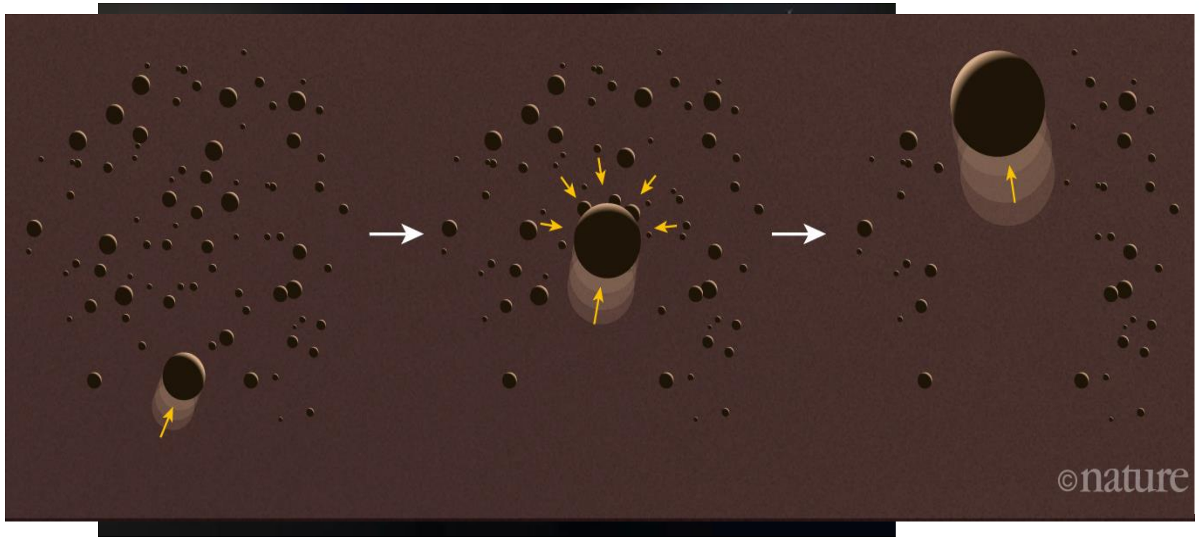


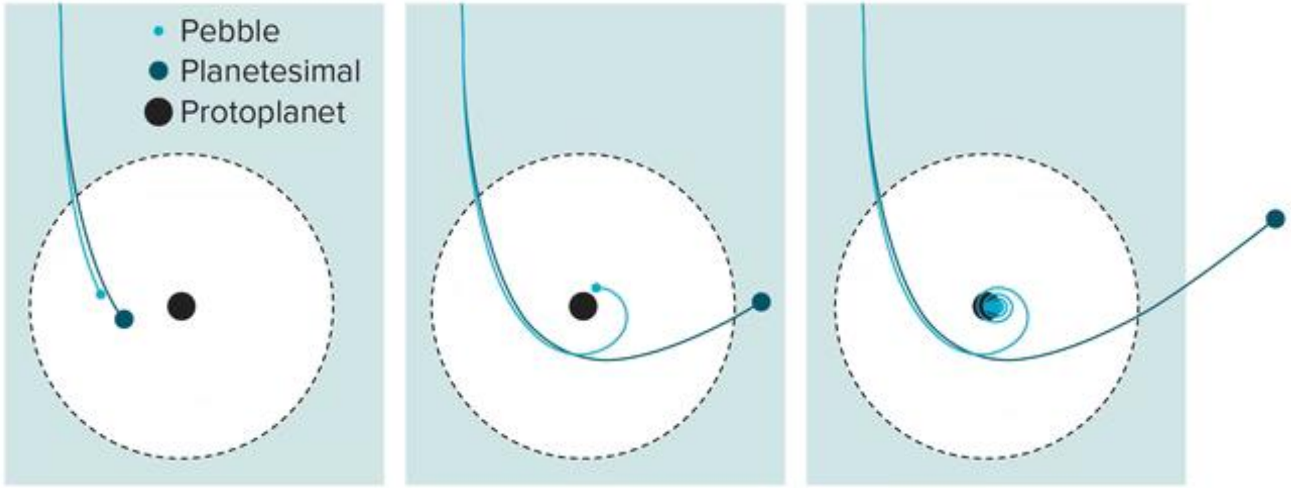


Agol+ 2021

Pebble Accretion I

- instead of piecewise collisions of planetesimals, protoplanets grow (primarily) by accreting mm-cm sized pebbles
- pebbles form gradually throughout disk and drift in towards the star
- “aerodynamically assisted accretion”, gravity + gas drag





Lambrechts & Johansen

Pebble Accretion II

- pebbles form (coagulate) out of dust disk material according to disk conditions (e.g. solid-to-gas ratio, gas and dust surface density, viscosity, fragmentation velocity)
- pebbles move inward (a mass flux) from gas drag, *some* accrete onto a seed mass until "pebble isolation mass" reached
  - prevents pebbles from drifting inward, quenches mass flux
- pebbles described by Stokes number
  - dimensionless quantity, "aerodynamic size", reflects radius, density, gas conditions

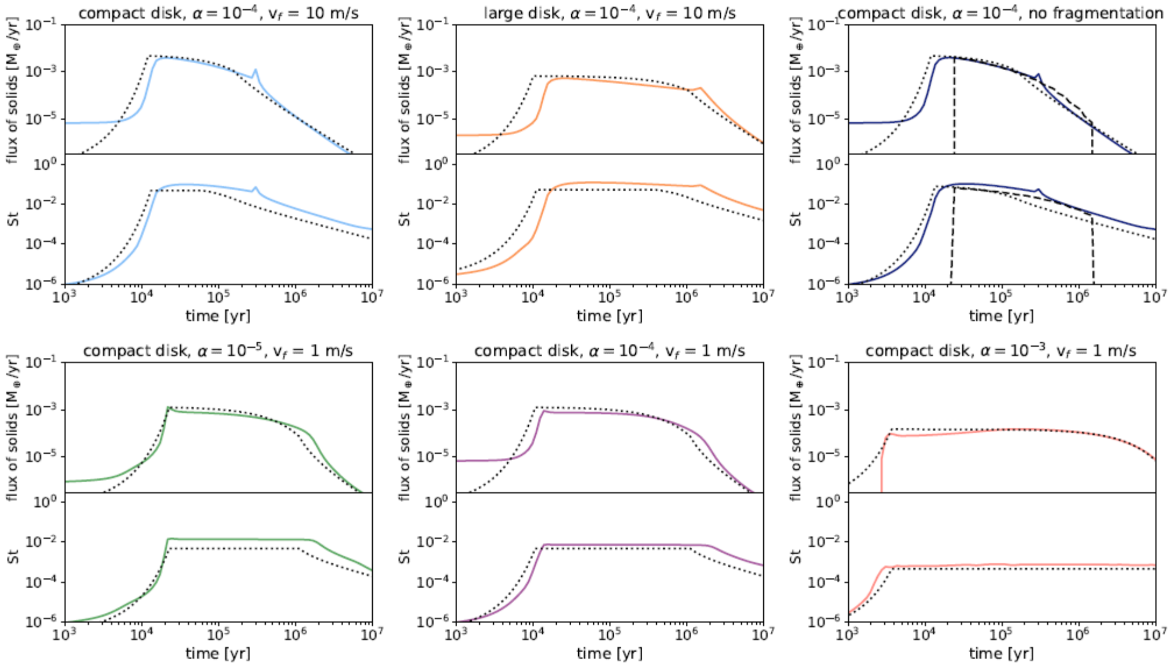
Building the Model

- combination of “pebble-predictor” (Drazkowska+ 2021) and “epsilon” (Ormel & Liu 2018; Liu & Ormel 2018)
- PP coagulates pebbles from dust and disk conditions
- OL describes accretion efficiency onto a seed mass in presence of pebble flux

- together I call it PPOL, or … “the PPOL’s model”

pebble-predictor (Drazkowska et al. 2021)

- PP determines Stokes number and mass flux of pebbles at any point/time in a user-specified disk
- simplified pebble-growth model – single representative St number
- tracks decrease in solid mass inventory over timespan of disk, but no gas evolution



outputs of PP (black dotted) compared against DustPy (color solid); St values and mass flux at 10 AU

Inputs I (PP)

- User-inputs:
  - time/space range
  - stellar mass
  - gas, dust surface density
  - temperature (profile)
  - alpha viscosity
  - fragmentation velocity threshold
  - pebble internal density

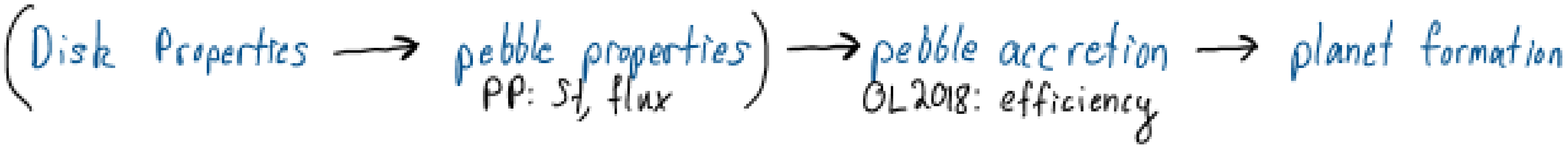
Disk properties → pebble properties

Symbol	Description
M_{star}	Stellar mass
M_{disk}	Solid mass inventory of disk
Z	Solid-to-gas mass ratio
$\Sigma_{gas,0}$	Initial surface density of gas
$\Sigma_{dust,0}$	Initial surface density of dust
α	Alpha viscosity, turbulence parameter
v_f	Fragmentation velocity threshold: maximum velocity up to which a pebble will survive after collision
ρ	Internal pebble density
St	Stokes number (stopping time in OL2018)
c_s	Sound speed
v_η	Maximum velocity of radial drift
η	Pressure gradient parameter

OL2018

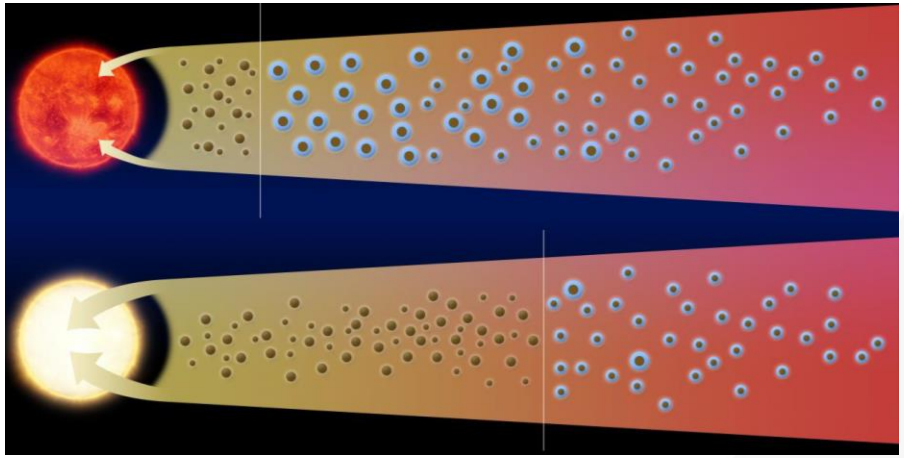
- “epsilon”, OL2018, from Ormel & Liu 2018; Liu & Ormel 2018
- determines <u>accretion efficiency</u> of pebbles onto a seed mass
  - seed mass is an input to OL

- based on analytical fits to three-dimensional n-body simulations of pebbles near a seed mass



Power to the PPOL

- typically see these explore how one planet will grow, or how one affects another in two planet example (e.g. Mulders+ 2021)
- adding many more seed masses
- incorporating composition by implementing snow line in disk
- two effects:
  - composition (density) of pebble by location
  - key disk properties change across the snow line



Composition-Based Disk Properties

- examples of parameterization of snow line, and PPOL parameters changing across snow line:

Parameter	Function	Source
Snow line location	T = 150 K (with T ~ $280a^{-0.5} M_s^{0.5}$)	Mulders et al. 2021
Snow line location	$r_{ice} \propto \alpha^{0.61} \Sigma_{g,0}^{0.8} f_{DG}^{0.37}$	Savvidou et al. 2021
	Inside → Outside Snow line	
Solid mass inventory (fraction of total)	0.5 M_{disk} → 1.0 M_{disk}	Mulders et al. 2021
Fragmentation velocity threshold (v_{frag})	100 cm/s → 1000 cm/s	Mulders et al. 2021
Dust-to-gas ratio (fraction of total)	0.4 → 0.64	Savvidou et al. 2021

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Checkpoint

Parameter	Function	Source
Snow line location	T = 150 K (with T ~ $280a^{-0.5} M_s^{0.5}$)	Mulders et al. 2021
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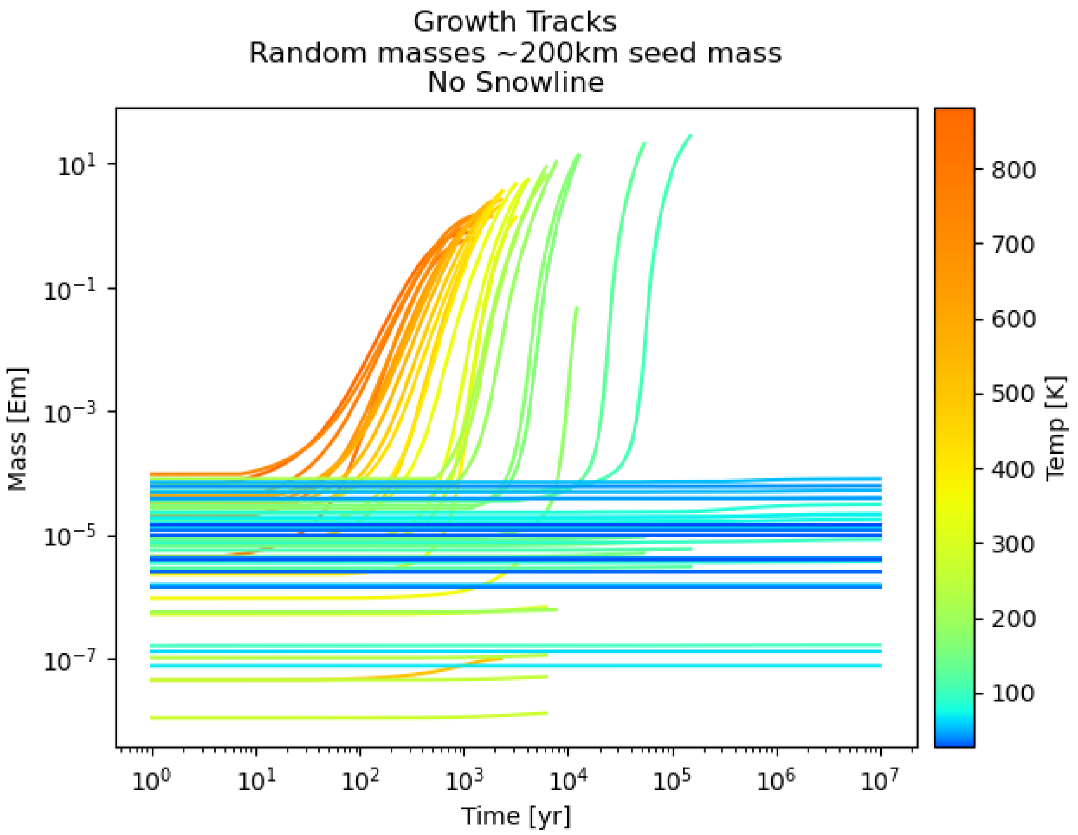
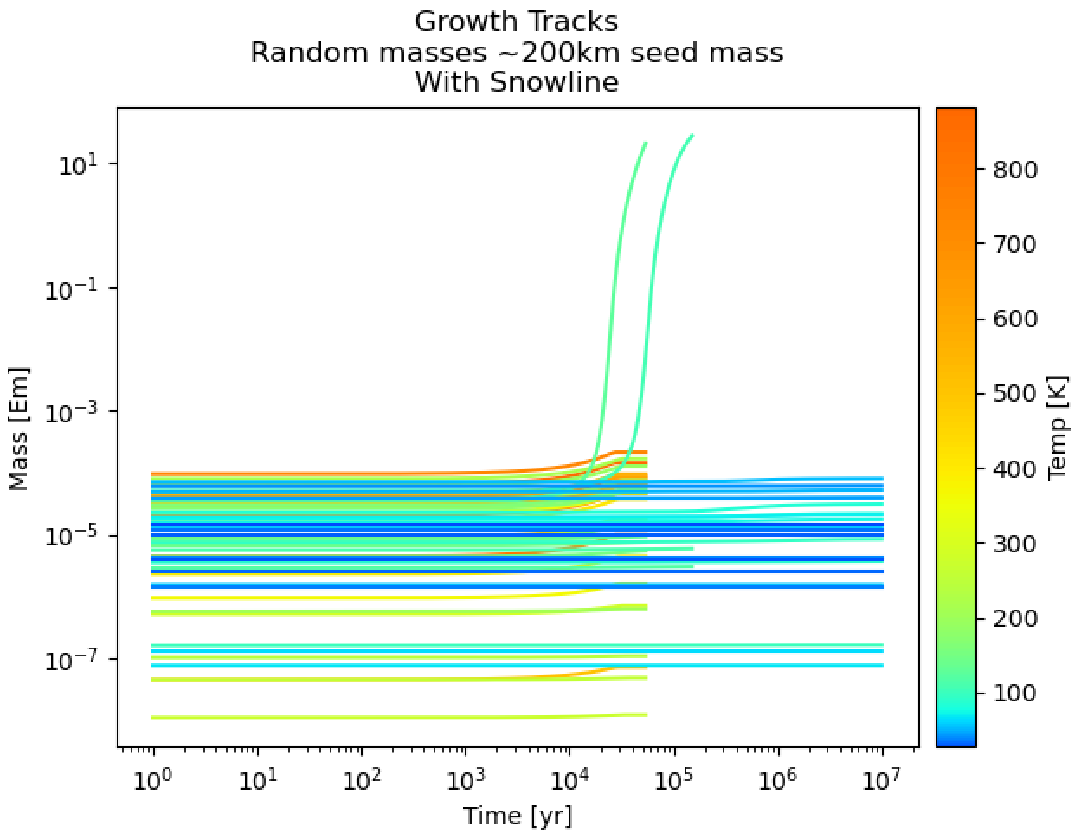
Note: random seed mass scattered around mass of asteroid 3 Juno, a 200-km asteroid





X = initial ● = final

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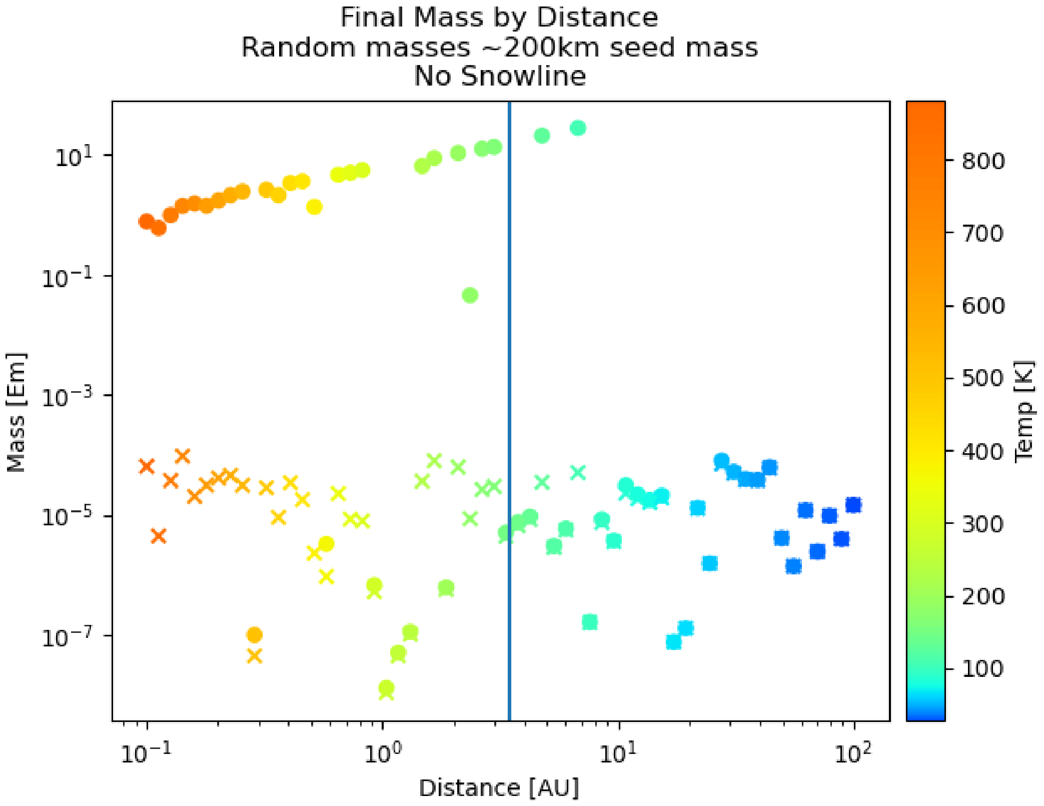

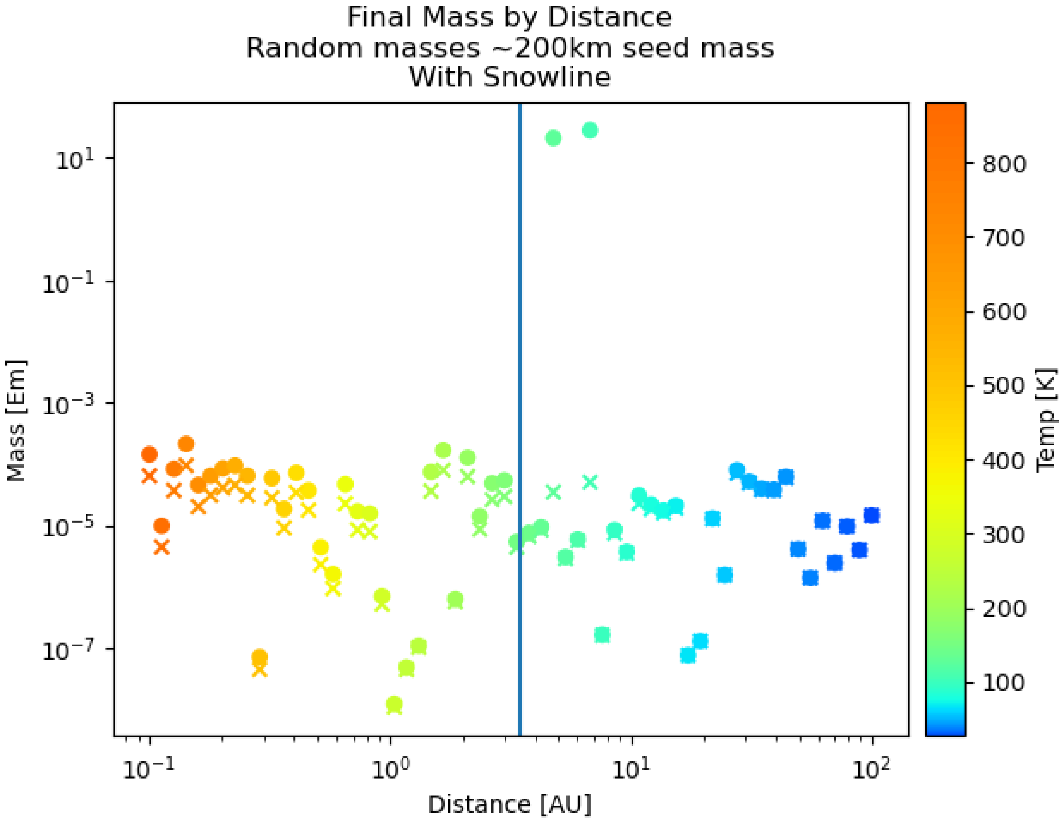

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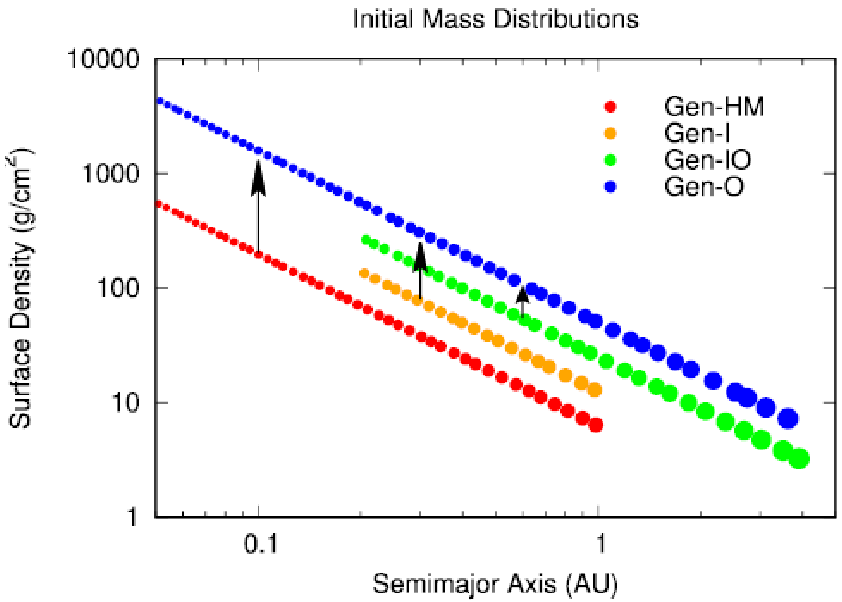
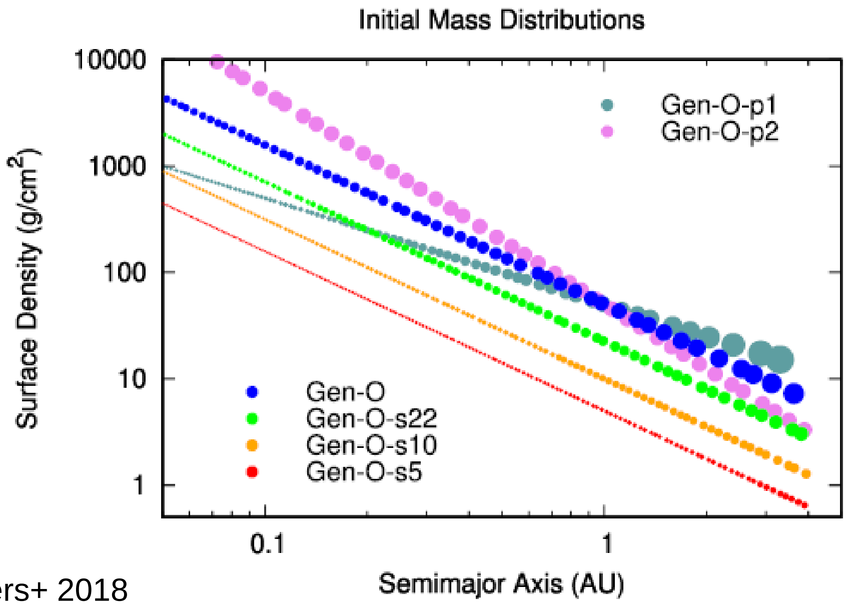
Next Steps

- PPOL will produce systems of protoplanets with mass, radius, location, and composition (“architecture & composition”) up to time when gas disk dissipates
- late stages of accretion: gravitational interaction, collisions, a battle royale
- Mulders+ 2018: *n*-body simulations performed and recorded in *genesis* database

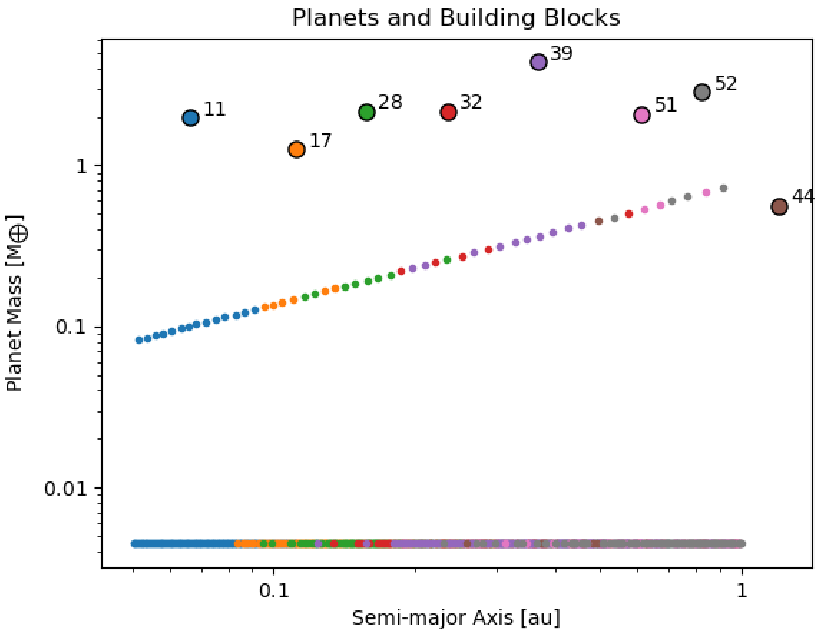


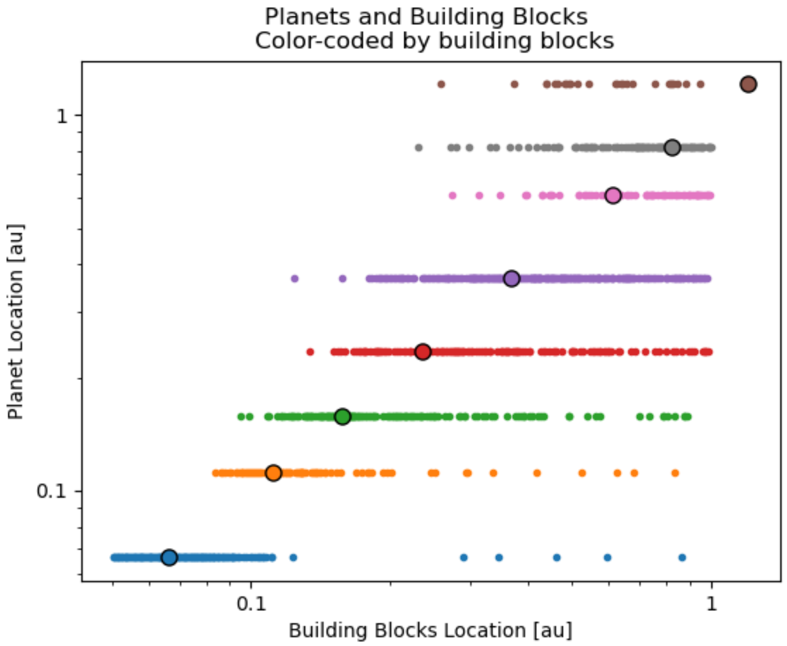
Mulders+ 2018



“collision trees”

- building blocks that compose final planets (location, mass) are recorded



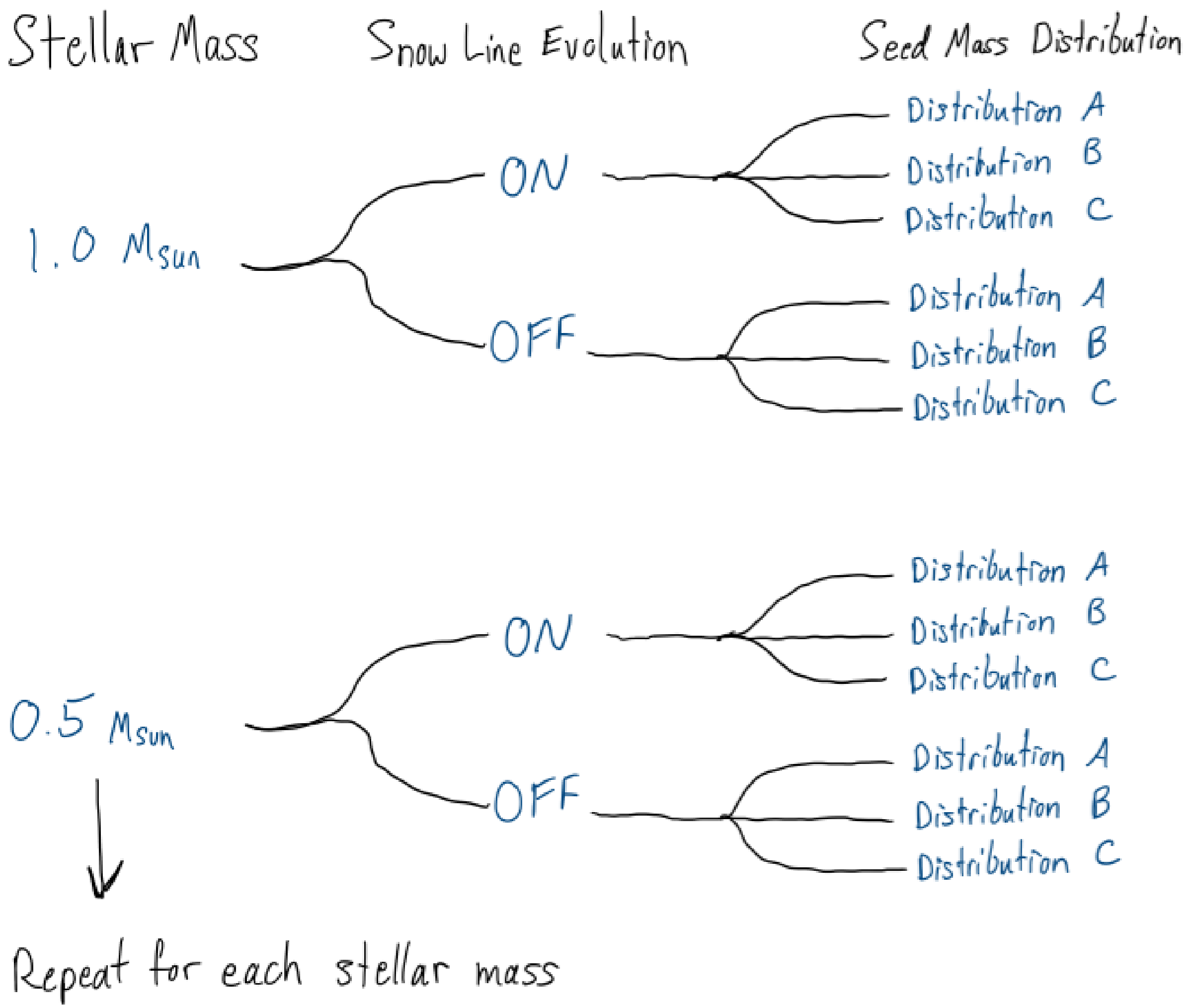


- goal is to align outputs of PPOL to inputs of *genesis* to make use of collision trees, yield composition of building blocks

Gen-P: planetesimals included

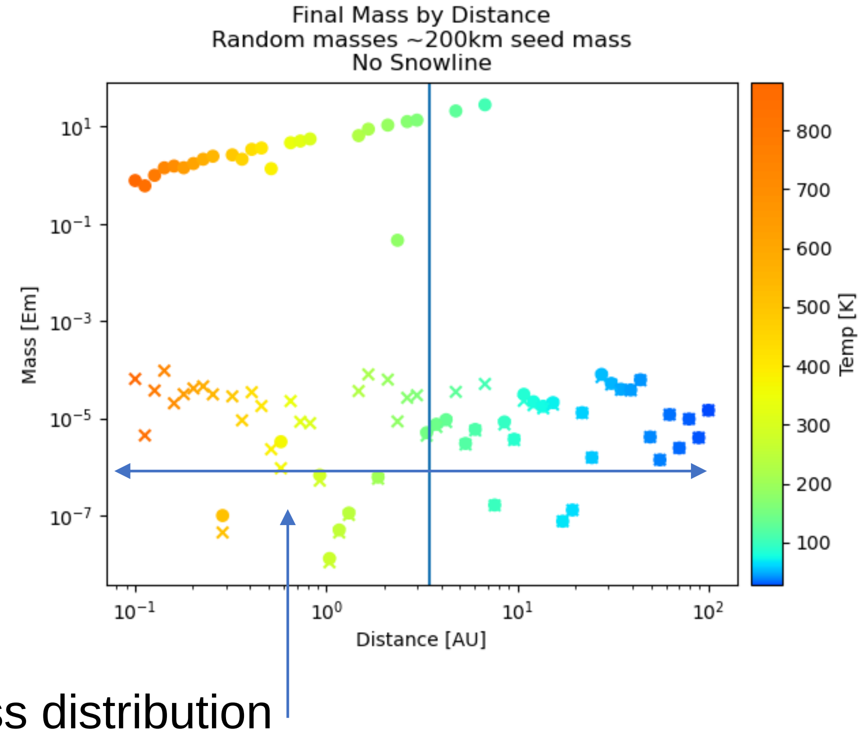
Range of Models

- stellar mass
  - assume disk mass is function of stellar mass (solid mass inventory)
  - (0.1 – 2.0 M_{Sun})
- evolution of the snow line
  - position of snow line changes with time as disk conditions change
  - possibly a mechanism to supply water to inner planets
  - also include silica line
- seed mass distribution...



Seed Mass Distribution

- pebble weakness: requires sufficiently massive seed to be efficient
- location, size, quantity, and timing of planetesimal/seed masses is open question
- yet, some distribution must be assumed
- possibilities:
  - simple geometric functions re: spacing, mass
  - anticipating connection with genesis models
  - “informed” from SS small bodies research



seed mass distribution

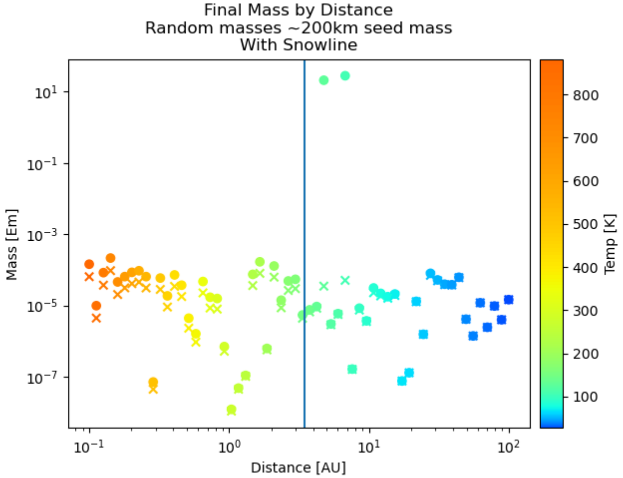
Limitations

- no n-body interactions, migration, during the pebble accretion phase

- BUT it is not clear including these effects yields improvement
  - Lambrechts et al. (2019), Izidoro et al. (2021) include “the kitchen sink”
  - model result: planets systematically ice-rich
  - observations: Kepler planets are predominantly rocky

Conclusion

- PPOL models pebble accretion and outputs protoplanets up to gas disk dissipation
- by connecting to late-stage n-body simulations, make use of collision trees to see what material ends up where
- contribute to describing/quantifying context and formation scenarios of planetary systems, biosignature assessment?



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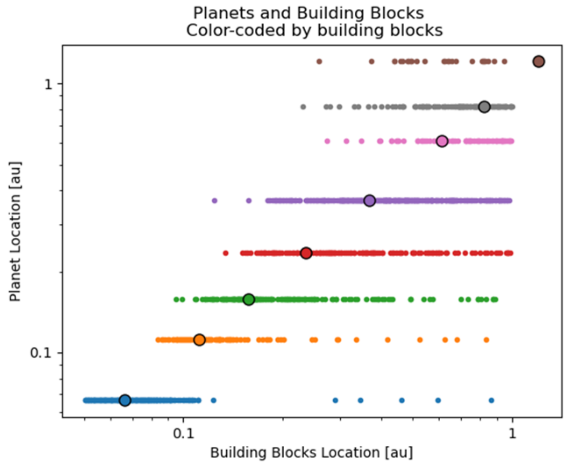

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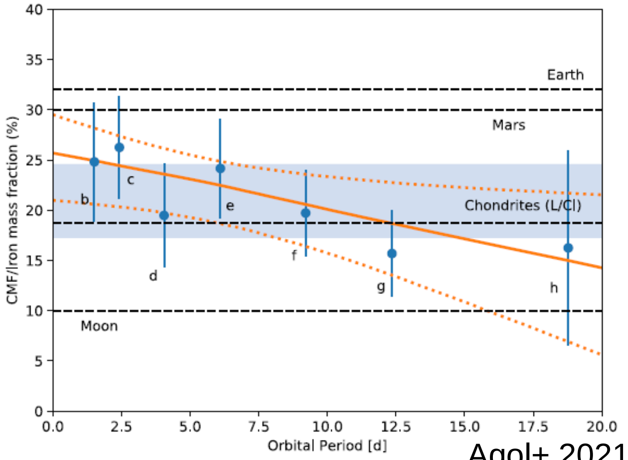
Mulders+ 2018



Agol+ 2021

Thank You!

Questions?
Comments?
Suggestions?
Cautionary Tales?