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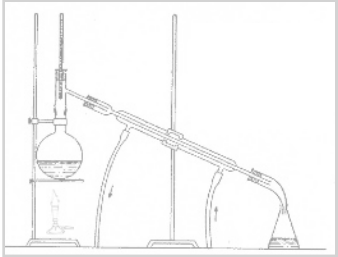
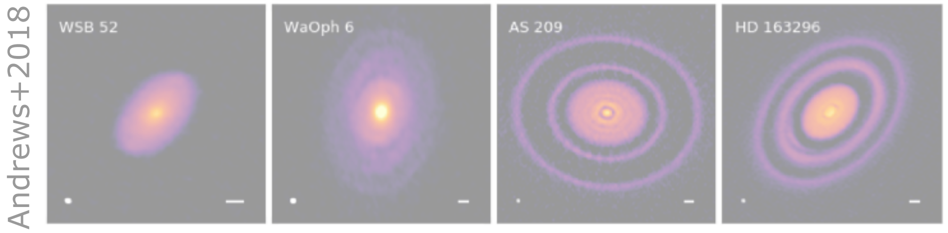
2. Population synthesis principle
3. Input physics: global models
4. Initial conditions
5. Observational biases

Part B: Results and perspectives

1. Compute the population: individual systems
2. Overview of statistical results
3. Comparisons with observations
4. Perspectives and conclusions

Compute the synthetic population





Models of individual processes

Accretion, migration, …

Global end-to-end formation & evolution model

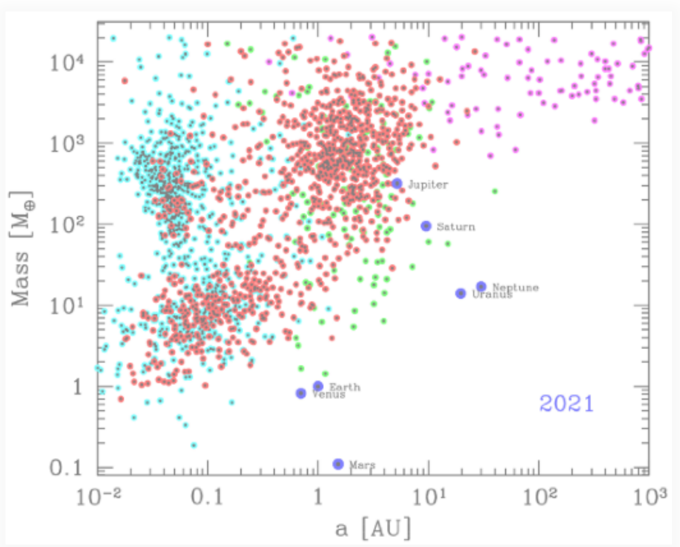
Disk properties ⇒ planet properties

Initial Conditions: Probability distributions of disk properties

Disk gas mass
Disk dust mass
Disk lifetime

From observations

Draw and compute synthetic population



Observed population

New instrumentation
better observational constraints

Apply observational detection bias

Predictions
(going back to the full synthetic population)

Stat. Comparison:

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- Frequencies
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- Correlations

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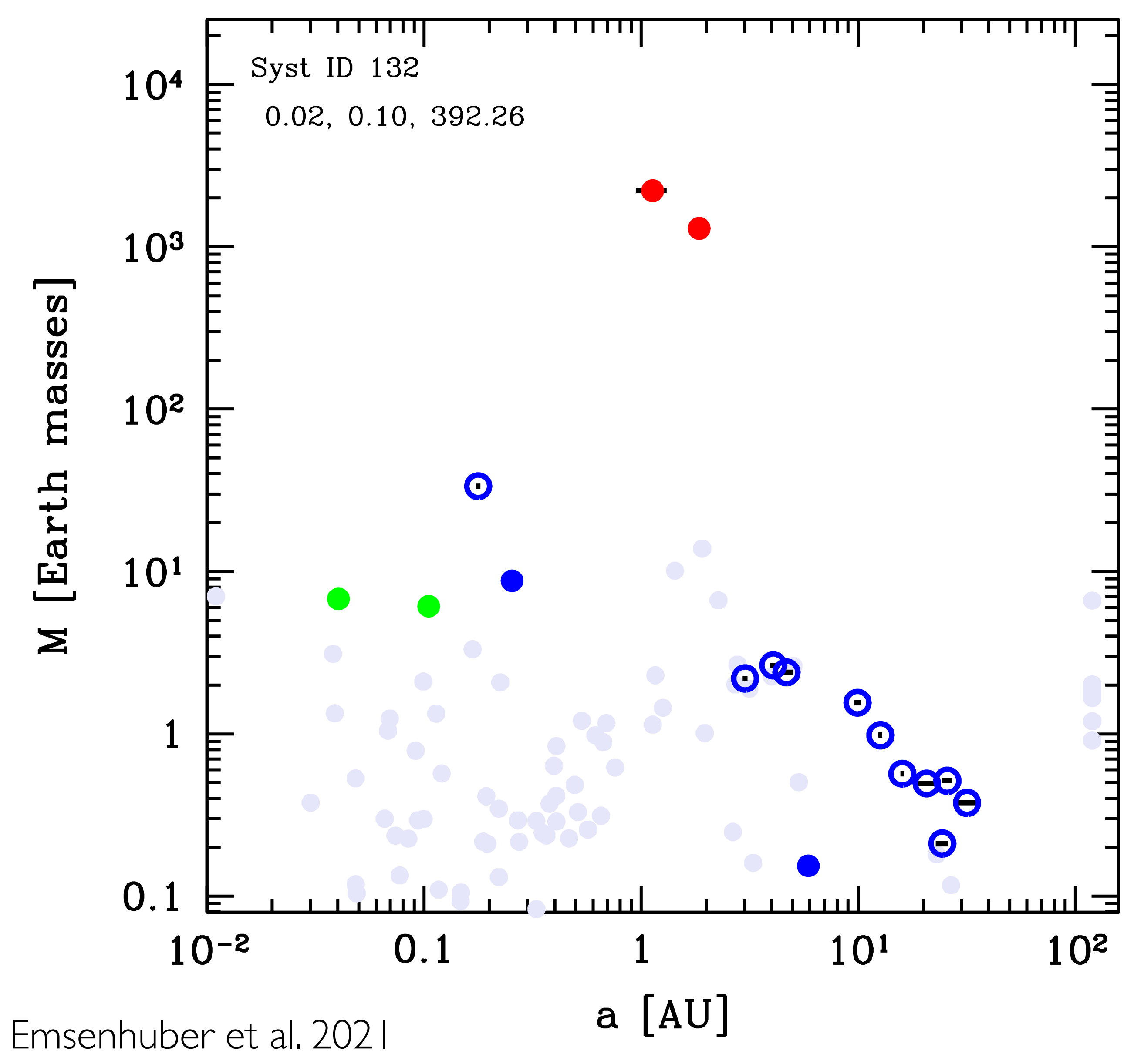
No match: change parameters, improve model, reject model

Match

Model solution found

One learns a lot even if a synthetic population does not match the observed one!



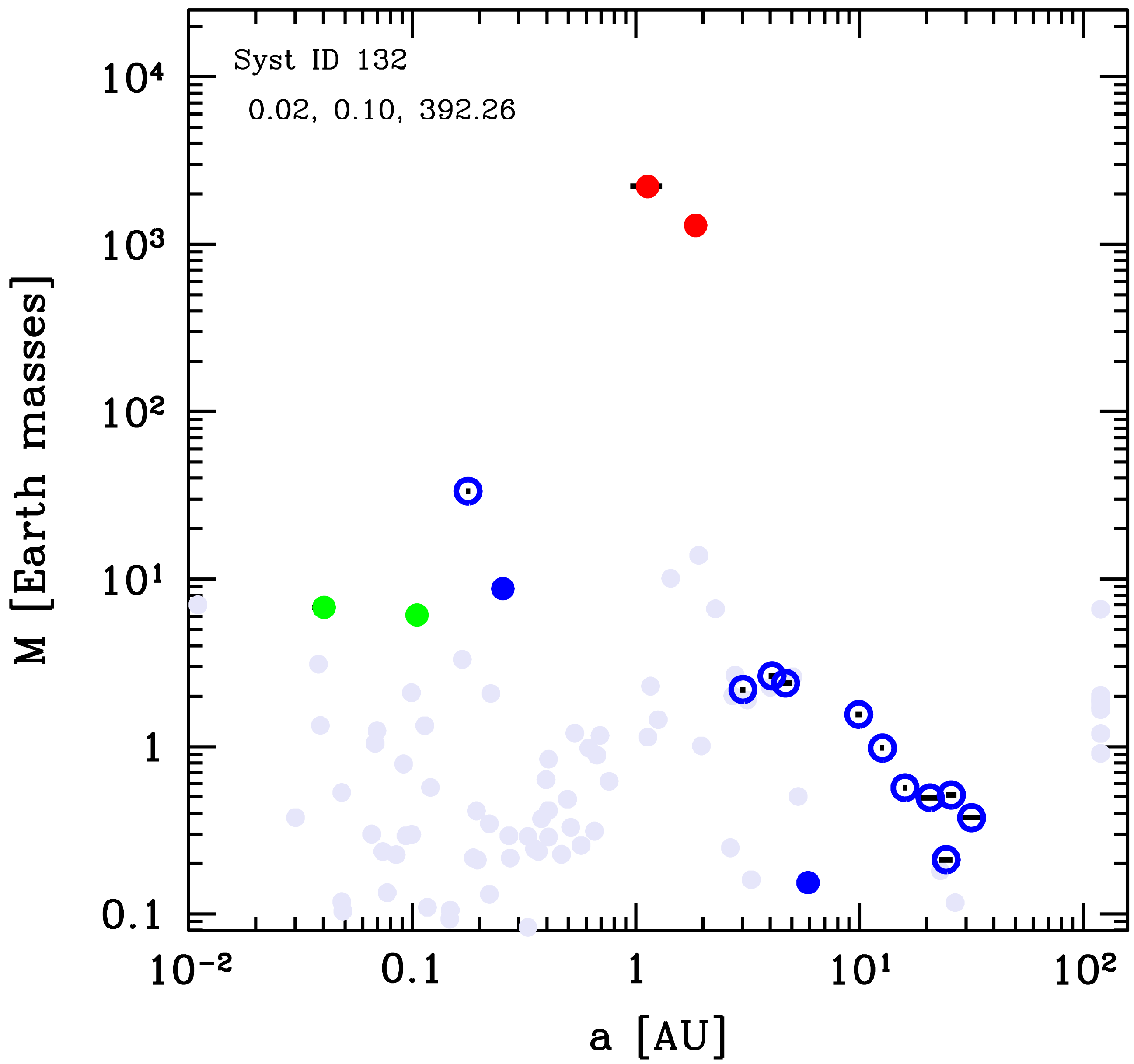
Emsenhuber et al. 2021

1. Compute the population: individual systems

Global model: Example outcome

Bern Generation III model

Setup/parameters
- -solar-mass stars
- -1000 systems (stars)
- -100 initial embryos per system
- -embryo mass 1 M_{luna}
- -uniform in log out to 40 AU at t=0.
- -viscosity α=0.002
- -opacity red. factor 0.003



Numbers are
- -[Fe/H]
- -$M_{gaz,0}$ [M_{Sun}]
- -$M_{solids,0}$ [M_{Earth}]

● Gas-dominated giant (M_{enve}/M_{core} >=1) ("Jovian")

○ Volatile rich planet, with H/He ("Neptunian")

● Volatile rich planet, without H/He ("water world")

○ Iron/silicate planet with H/He ("H/He terrestrial")

● Iron/silicate planet without H/He ("Earth-like")

● Protoplanet lost during formation and evolution process (accreted by another more massive protoplanet, ejected, collided with the star).

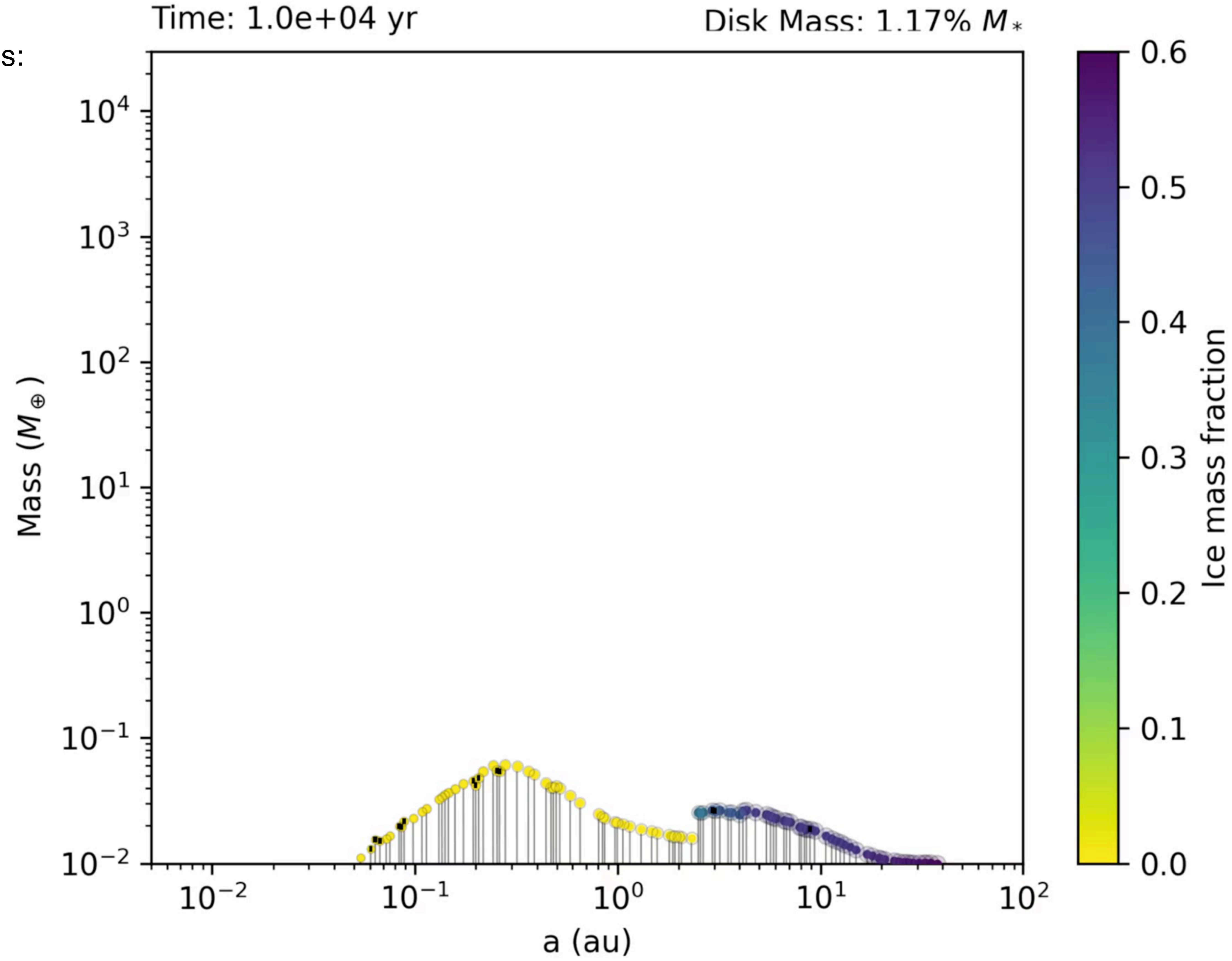
—●— Black bar: peri- to apoastron distance (showing eccentricity)

A global model in action: low solid mass

Initial conditions

-initial disk gas mass:
0.017 M_{sun}

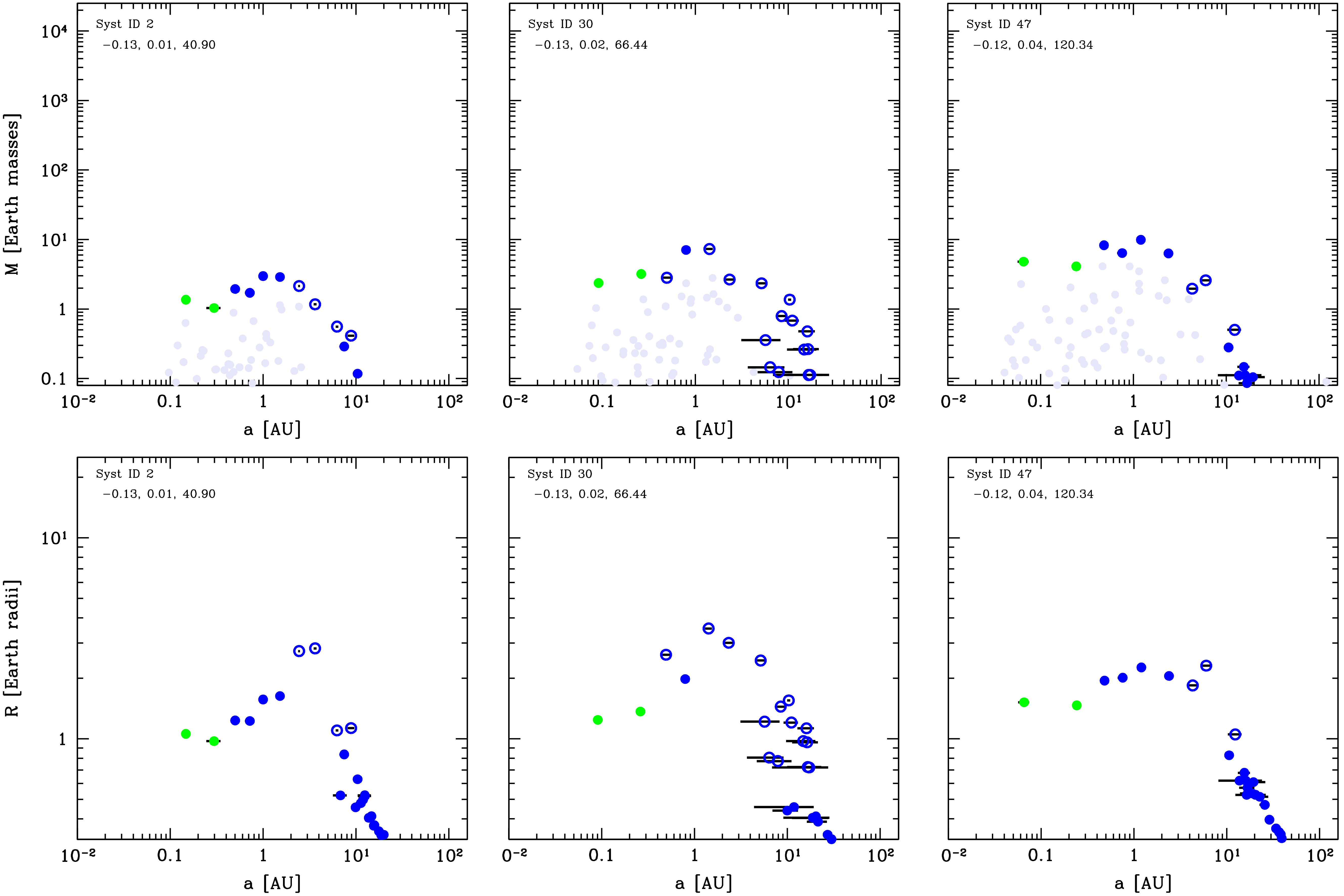
-initial solid mass:
57 M_{Earth}



Class 1
architecture

Class 1. The in situ Earths and ice worlds systems

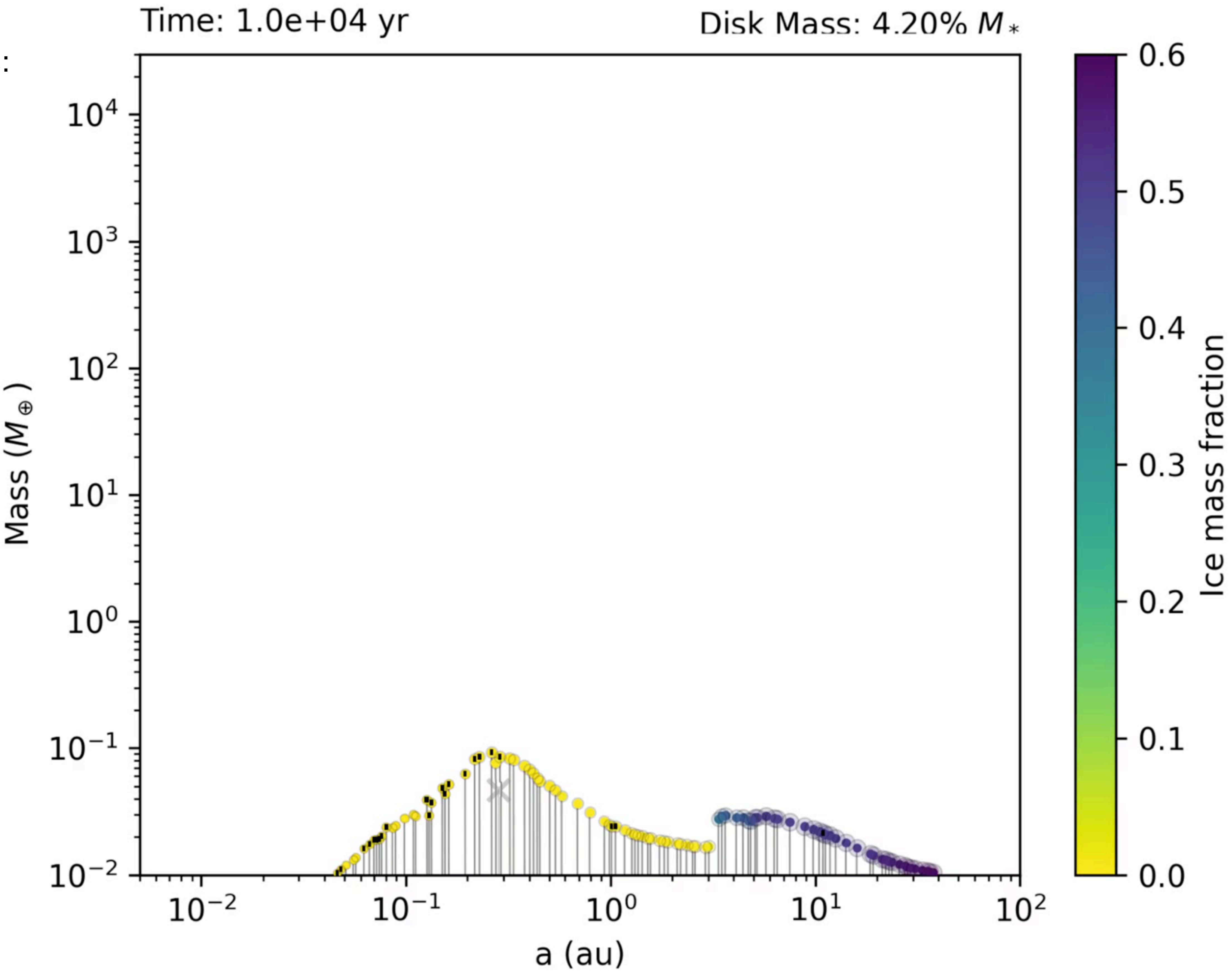
t=5 Gyr



A global model in action: mid solid mass

Initial conditions

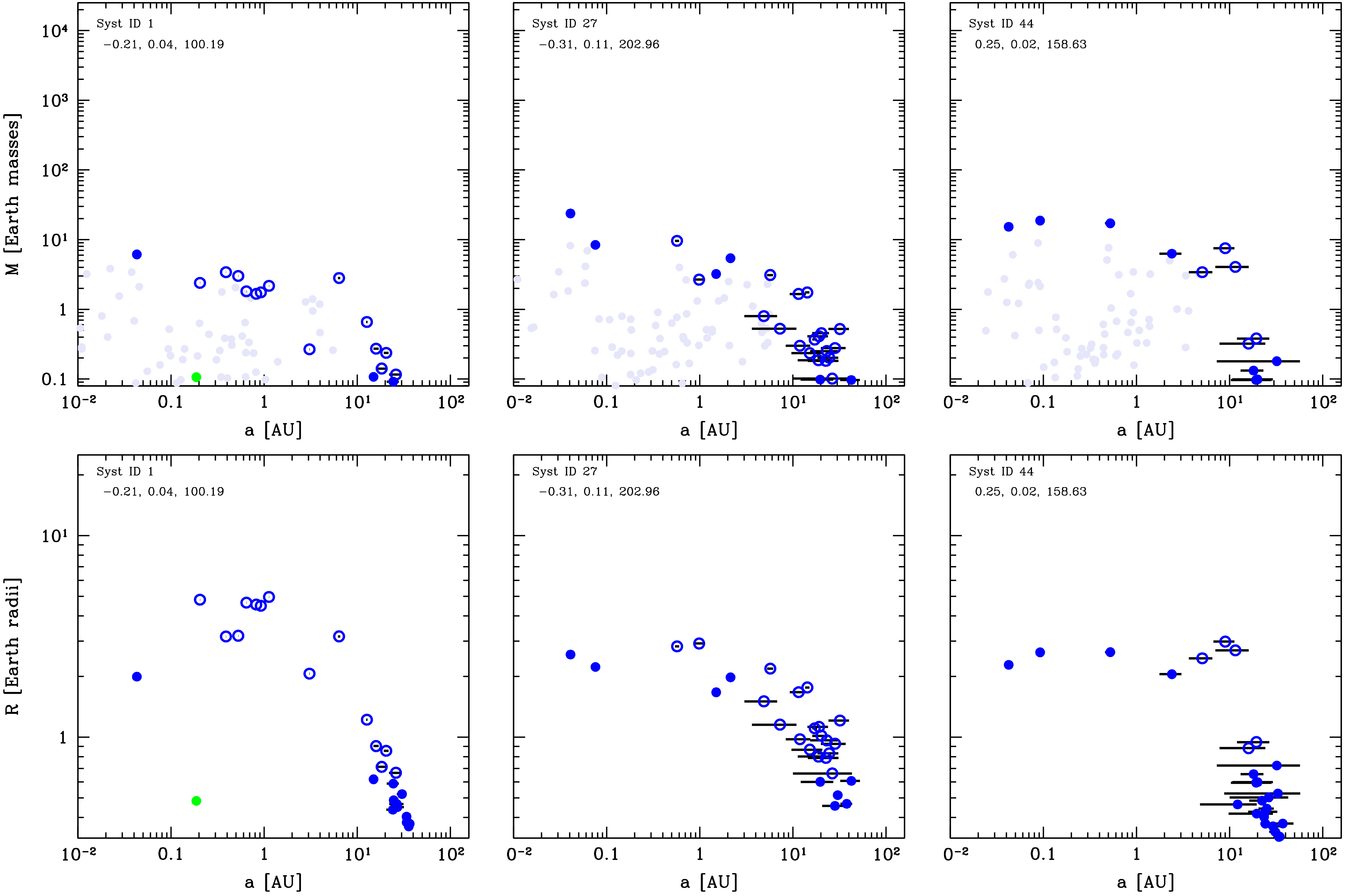
-initial disk gas mass:
 0.042 M_{sun}
-initial solid mass:
 100.1 M_{Earth}



Class 2
architecture

Class 2. The migrated sub-Neptune systems

t=5 Gyr



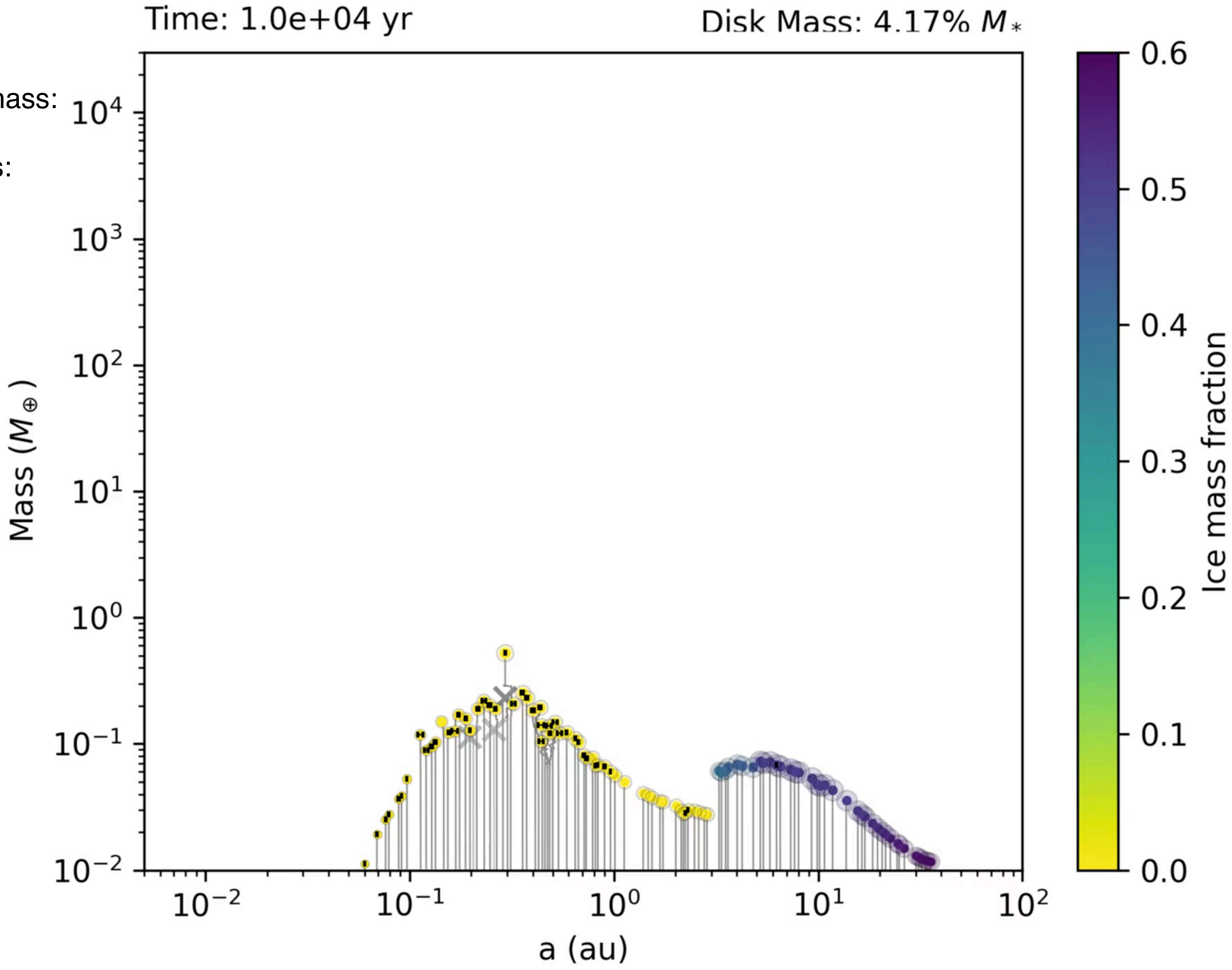
Peas-in-a-pod (Weiss+2018, Millholland+2017): Misra+2021

A global model in action: high solid mass

Initial conditions

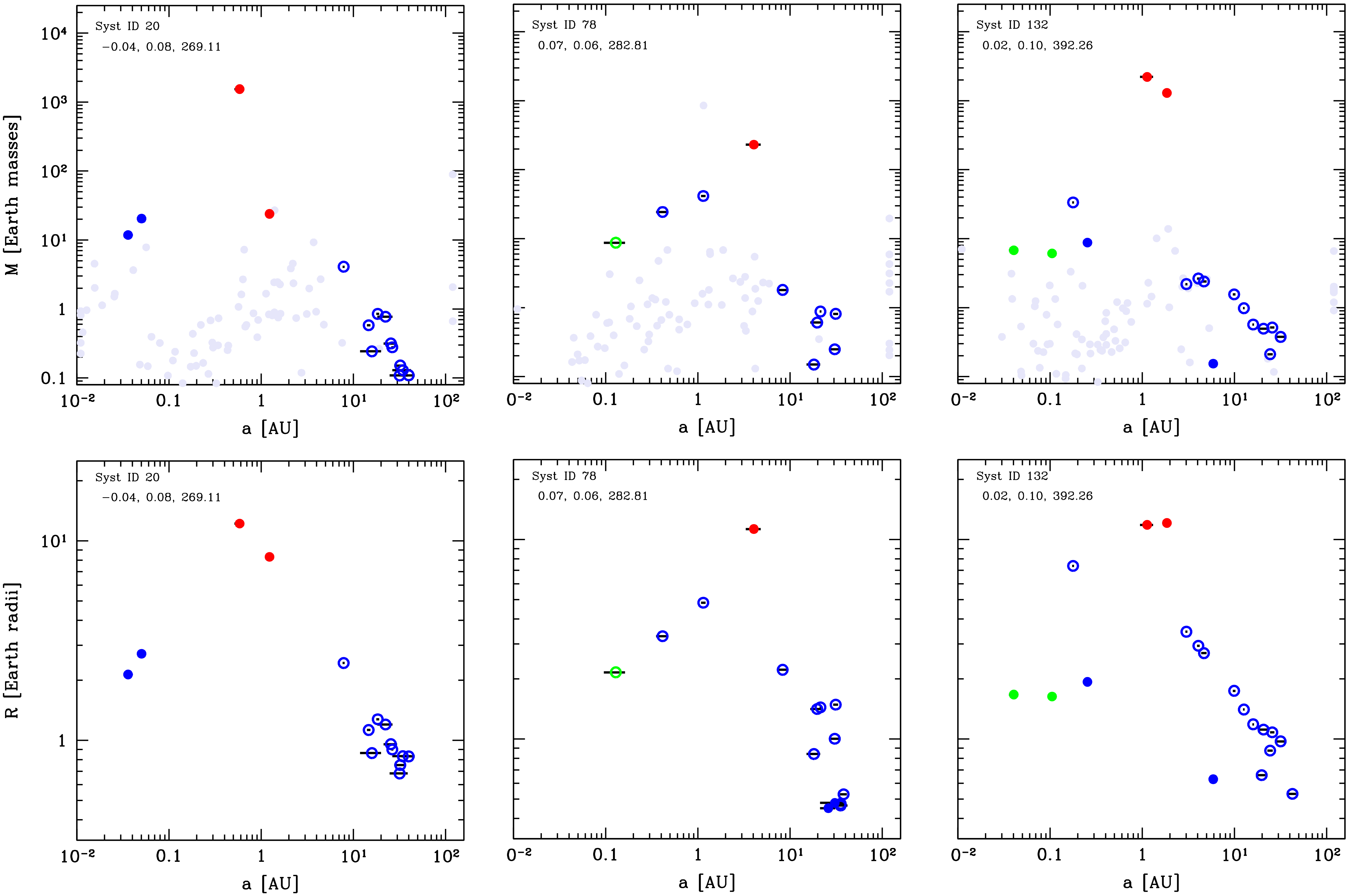
-initial disk gas mass:
0.042 M_{sun}

-initial solid mass:
245 M_{Earth}



Class 3
architecture

Class 3. The mixed systems

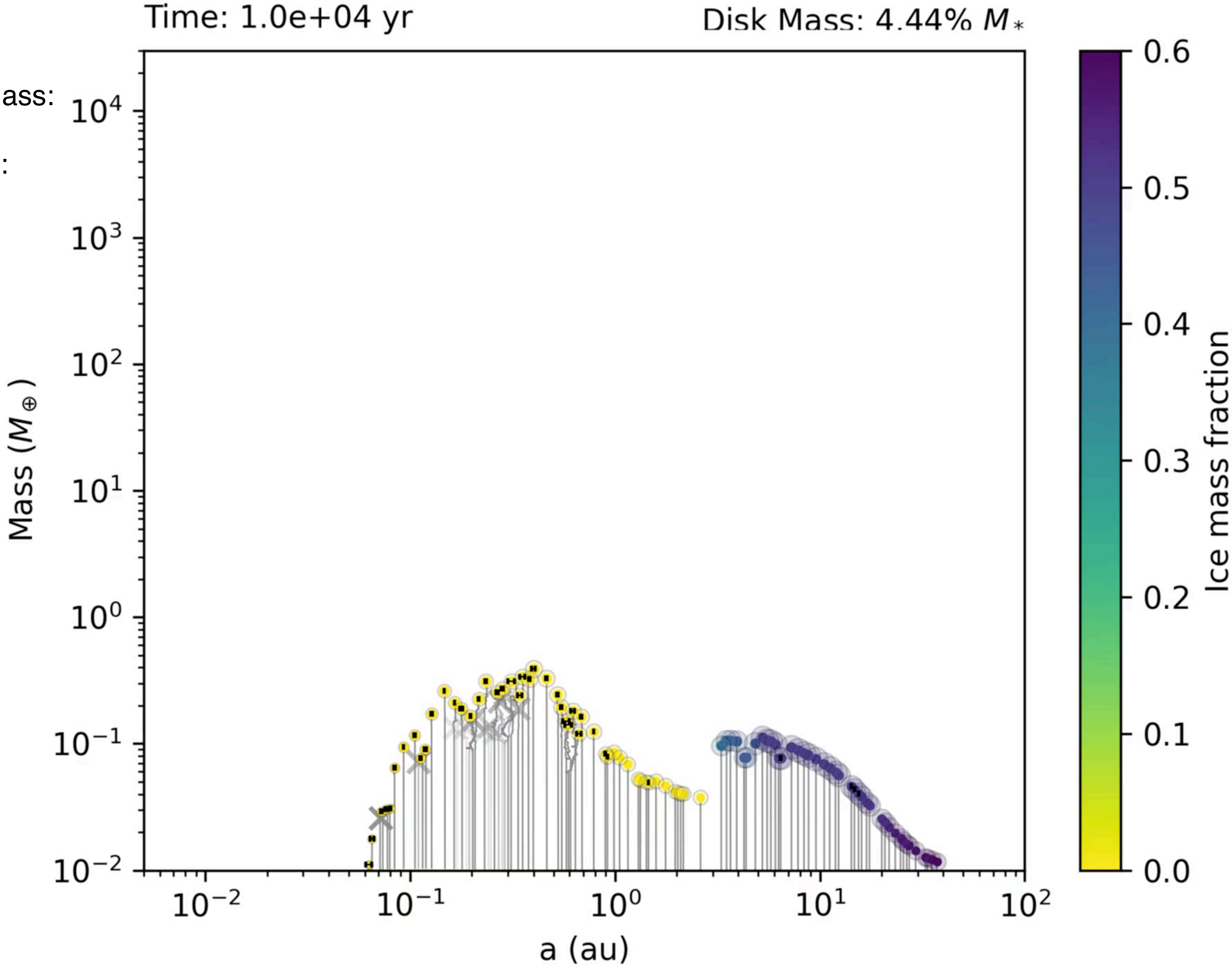


A global model in action: very high solid mass

Initial conditions

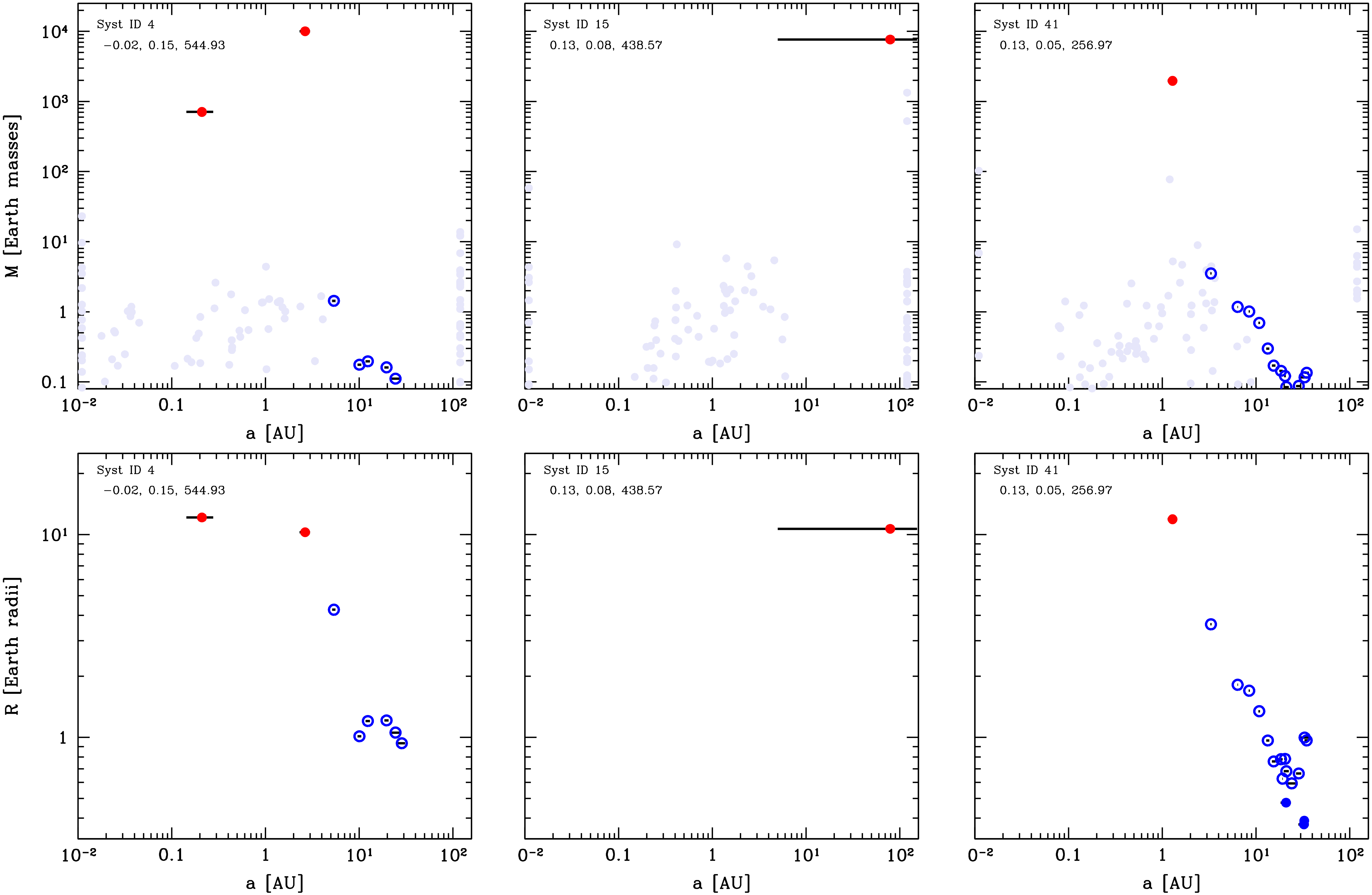
-initial disk gas mass: 0.044 M_{sun}

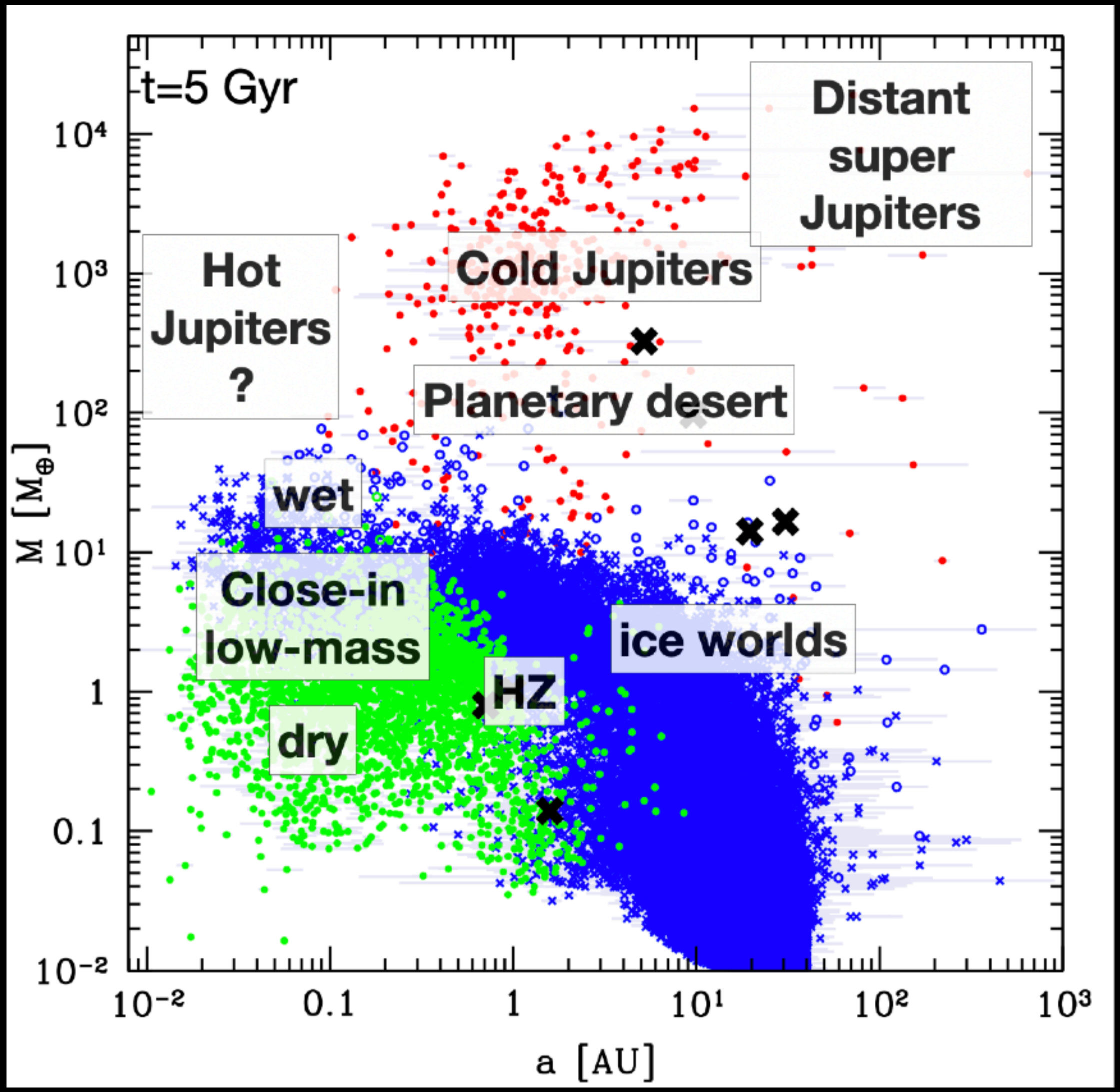
-initial solid mass: 327 M_{Earth}



Class 4 architecture

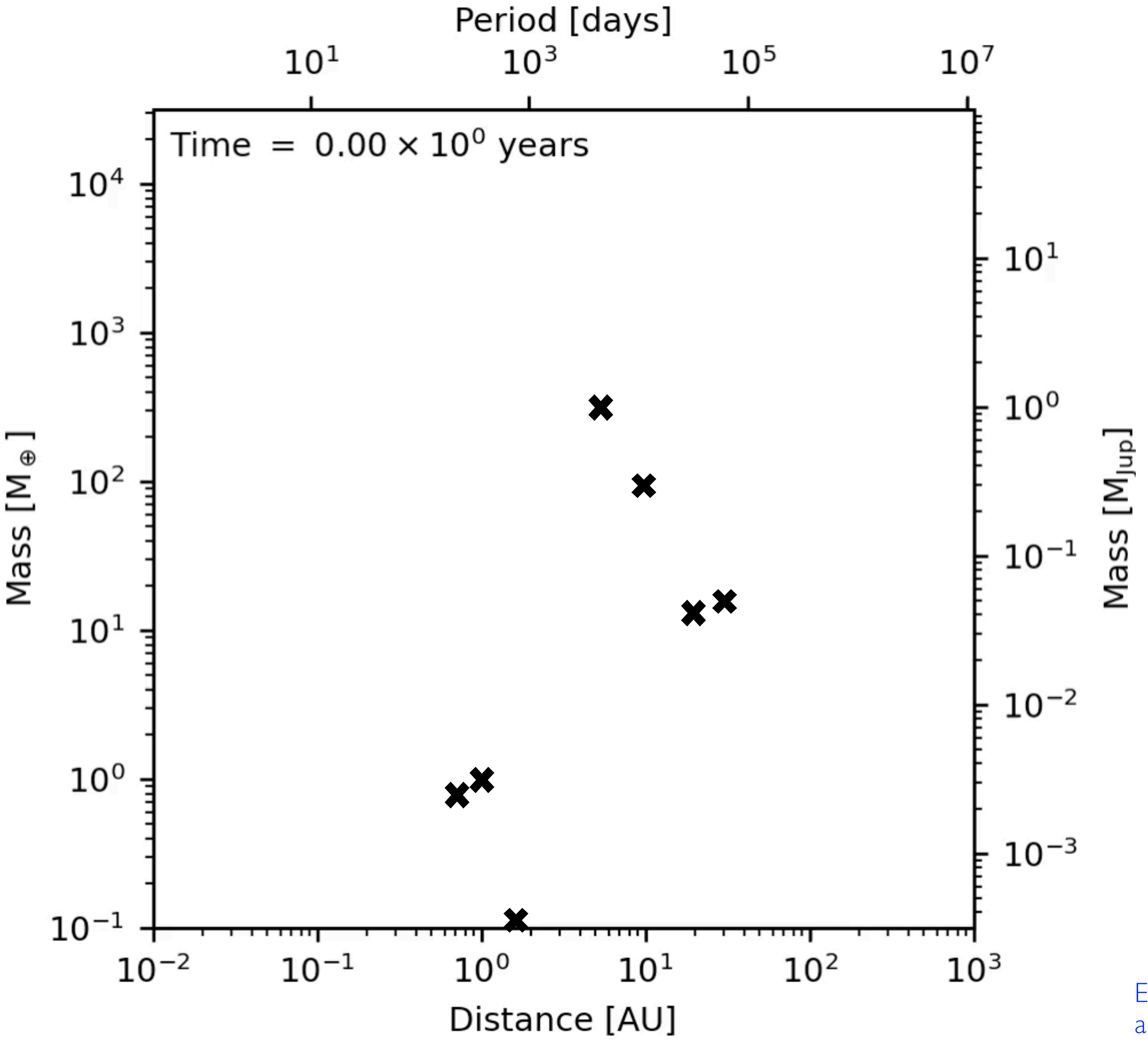
Class 4. The dynamically active giants





2.
Overview of statistical results

Formation of the a-M diagram

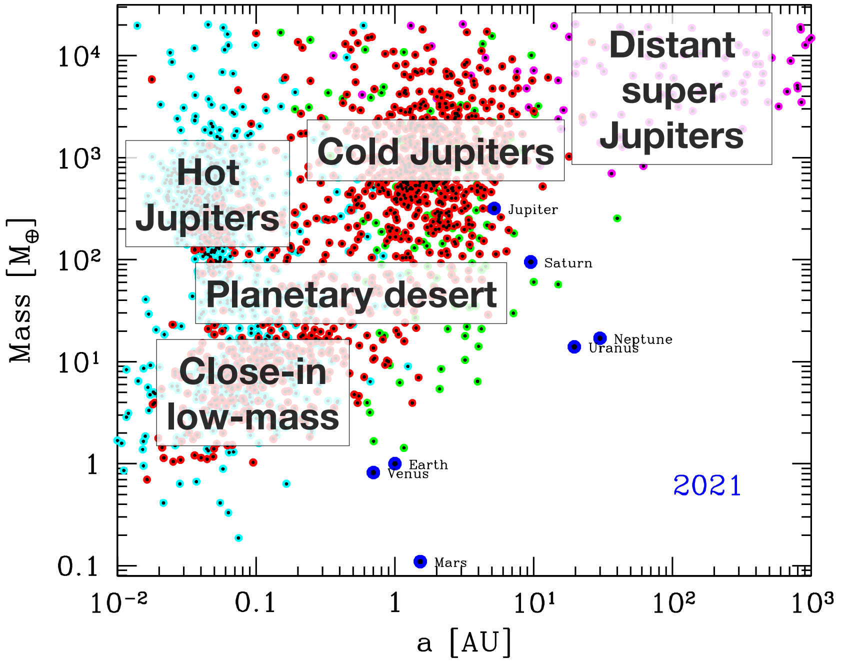


Initial conditions

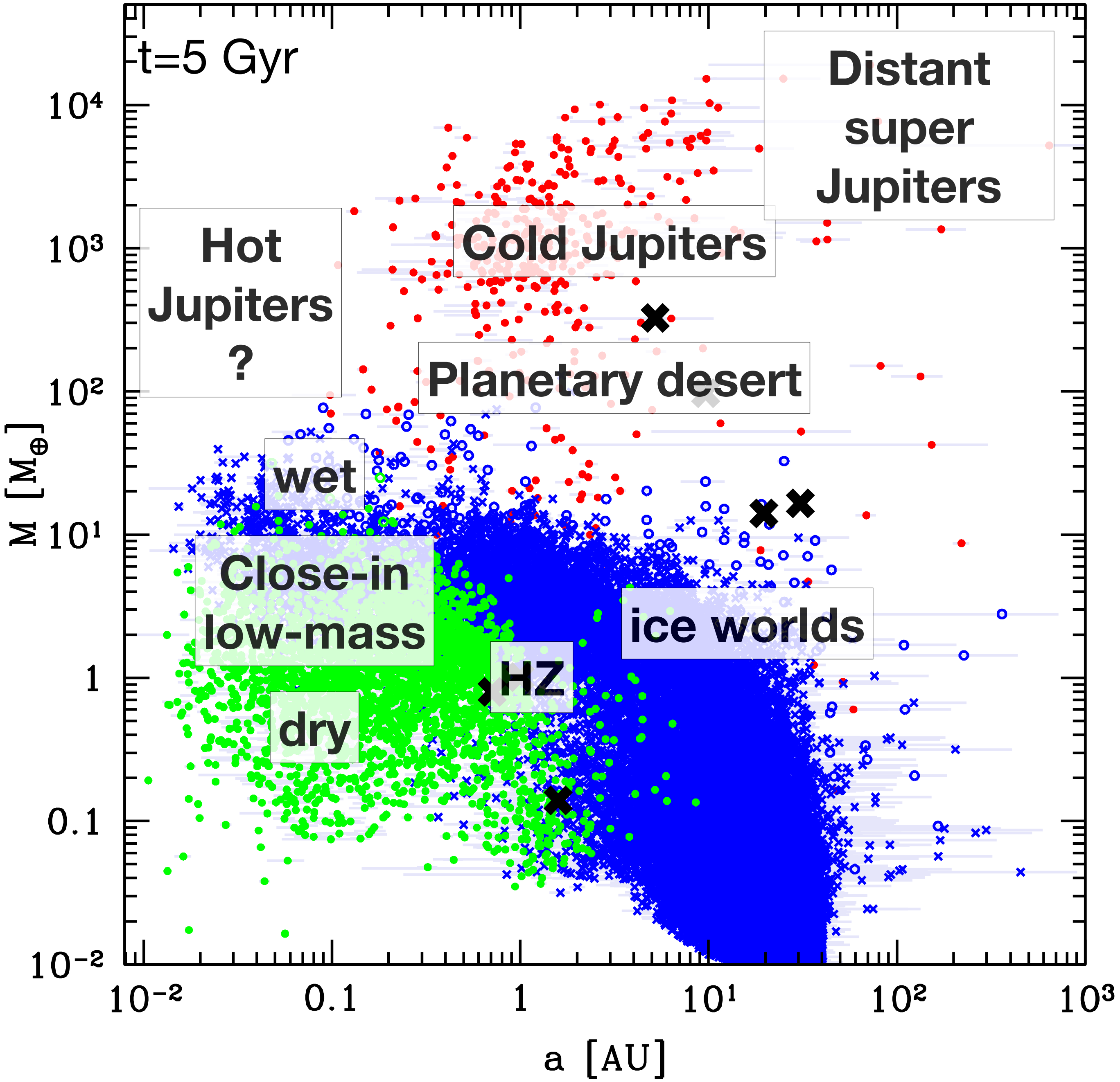
- -solar-mass stars
- -1000 systems (stars)
- -100 initial embryos per system
- -initial mass 1 M_{luna}

Emsenhuber et al. 2021b (NGPPS II, arXiv: 2007.05562)

Nominal population 1 $M_\odot$



Several fundamental features of the observed population can be recovered.

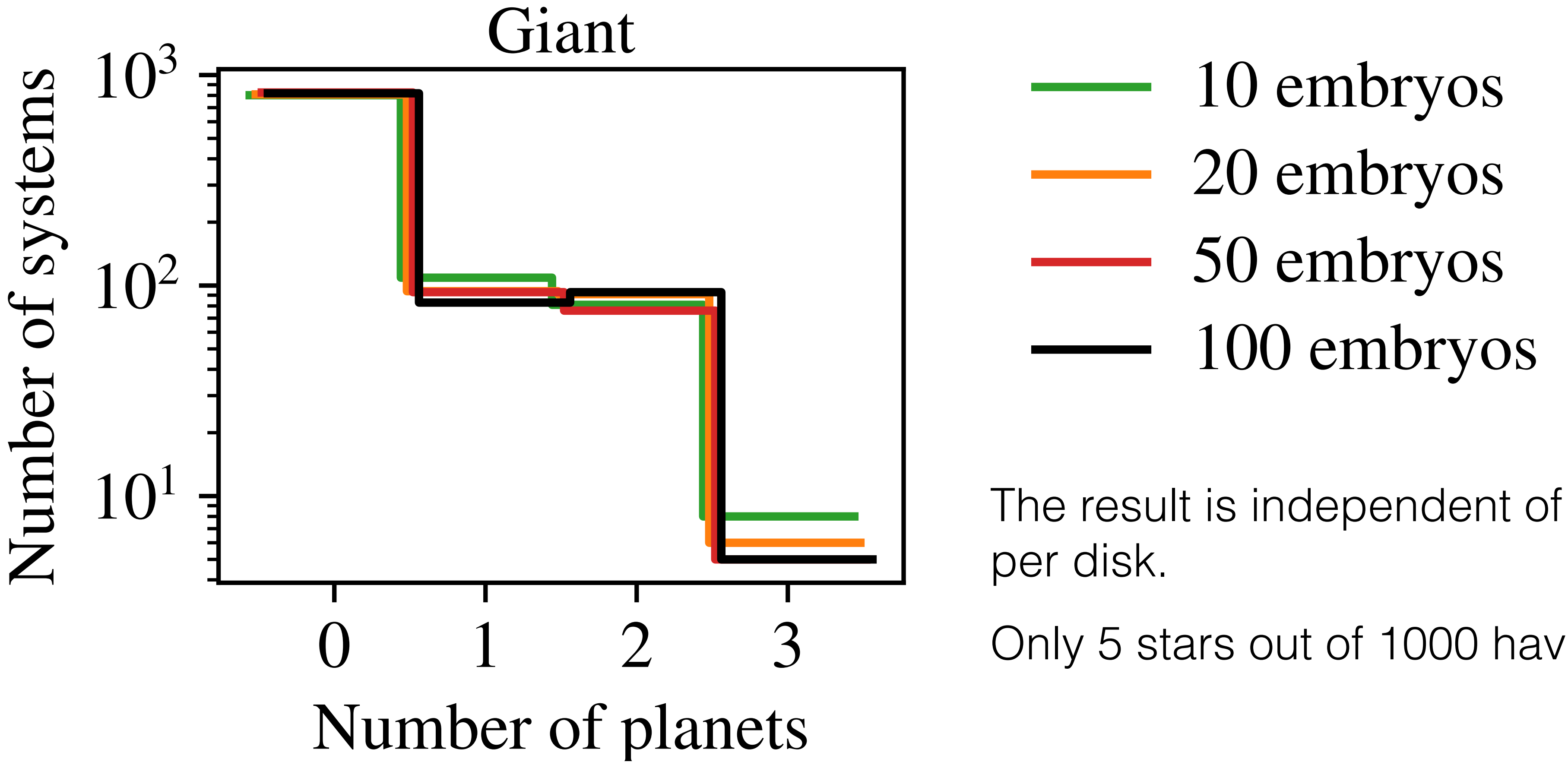


The variations of the disk initial conditions over a range likely occurring in nature leads to a large diversity of planetary systems, similar as observed.

Statistical overview for 1 $M_\odot$

Fundamental demographical results

- Synthetic planetary system contain on average **8** planets more massive than 1 $M_\oplus$ including all orbital distances (no obs. constraints yet).
- Fraction of systems with giants planets: **18 %** (all orbital distances), only 1.6 % at >10 AU.
- Systems with giants contain on average **1.6** giant planets.



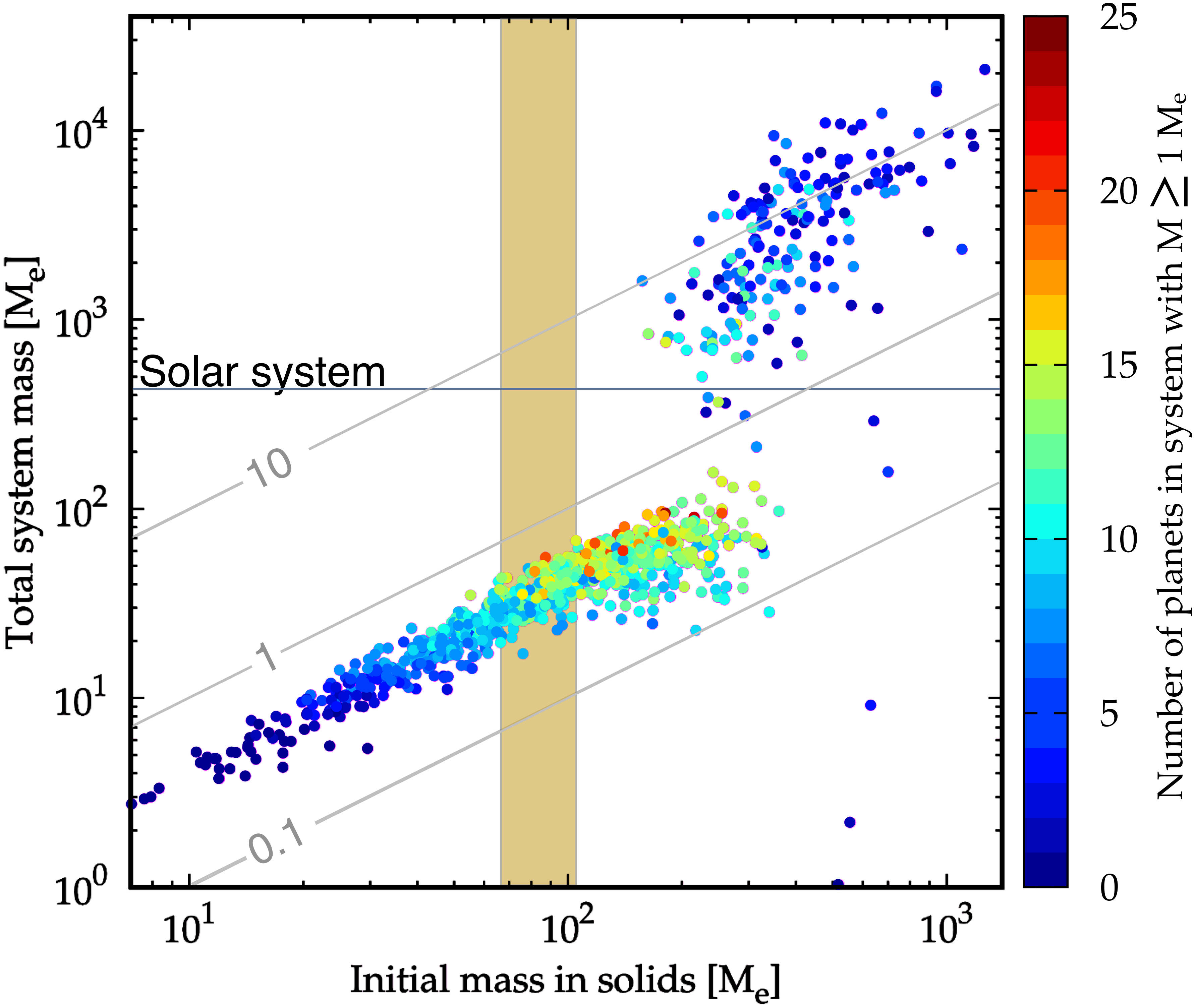
Initial number of embryos per disk

The result is independent of the initial nb of embryos per disk.

Only 5 stars out of 1000 have 3 giant planets.

- Low-mass planets (0.3-3 $M_\oplus$) in habitable zone: 44 % of stars. Mean multiplicity 1.3 (rather low). Mean [Fe/H] of stars with habitable planets -0.11. Different from Solar System.

What sets the outcome?



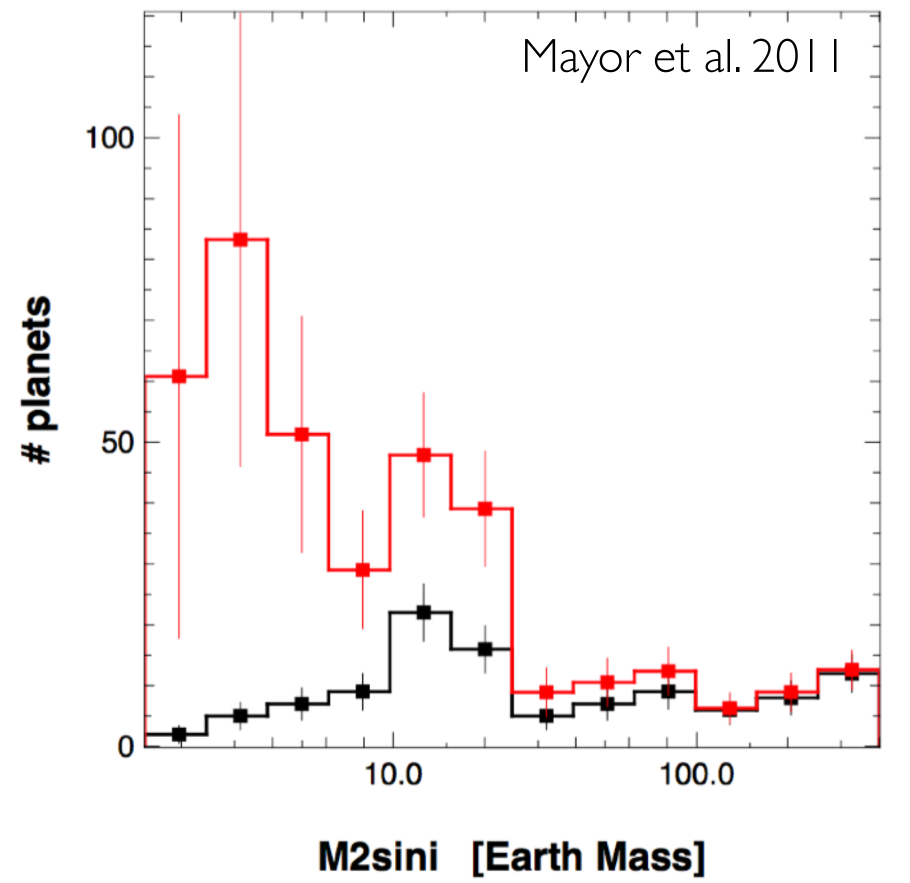
The most important initial condition is the mass of solids initially present in the disk.

Grey lines: efficiency of planetary system formation(including H/He) per system

We need 2-3 MMSN to form the Solar System mass.

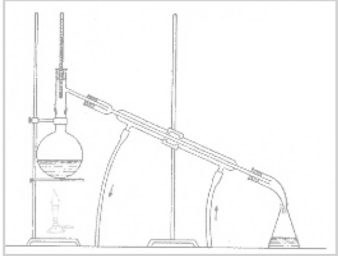
Adapted from Mordasini+ in prep.

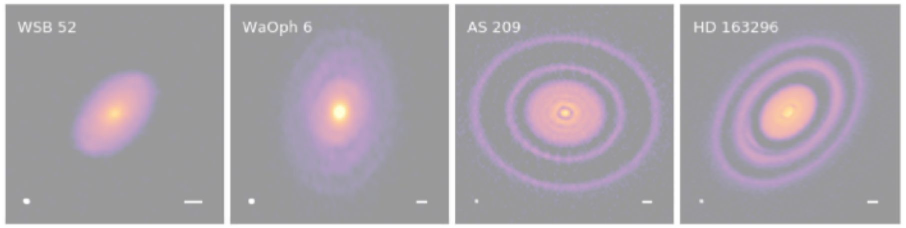
Another important initial condition is external disk photoevaporation, setting the disk lifetime. It depends on stellar birth environment and affects the emerging system architecture (e.g., Winter et al. 2020).



3.
Comparisons with observations

Comparisons with observations





Andrews+2018

Models of individual processes

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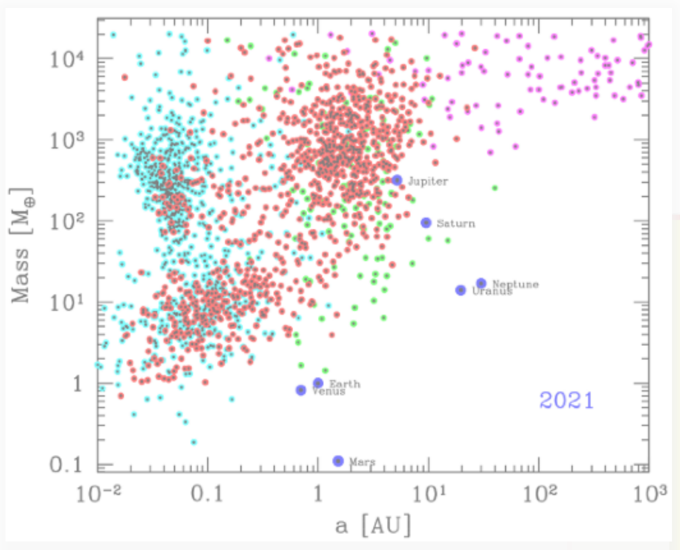

Observed population

New instrumentation
better observational constraints

Apply observational detection bias

Predictions
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Stat. Comparison:

Observable sub-population
- Frequencies
- Orbits, masses, radii, luminosities
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…..

No match: change parameters, improve model, reject model

Match

Model solution found

One learns a lot even if a synthetic population does not match the observed one!

Statistical comparison with HARPS survey

HARPS: high accuracy radial velocity planet searcher.

GTO Survey: 822 solar-like stars. Known bias.

See also recent results of California Legacy Survey (Rosenthal+2021, Fulton+2021)

Observed

Nb of planets: 161
Nb of stars w planets: 102
Multiplicity: 1.6

Synthetic biased

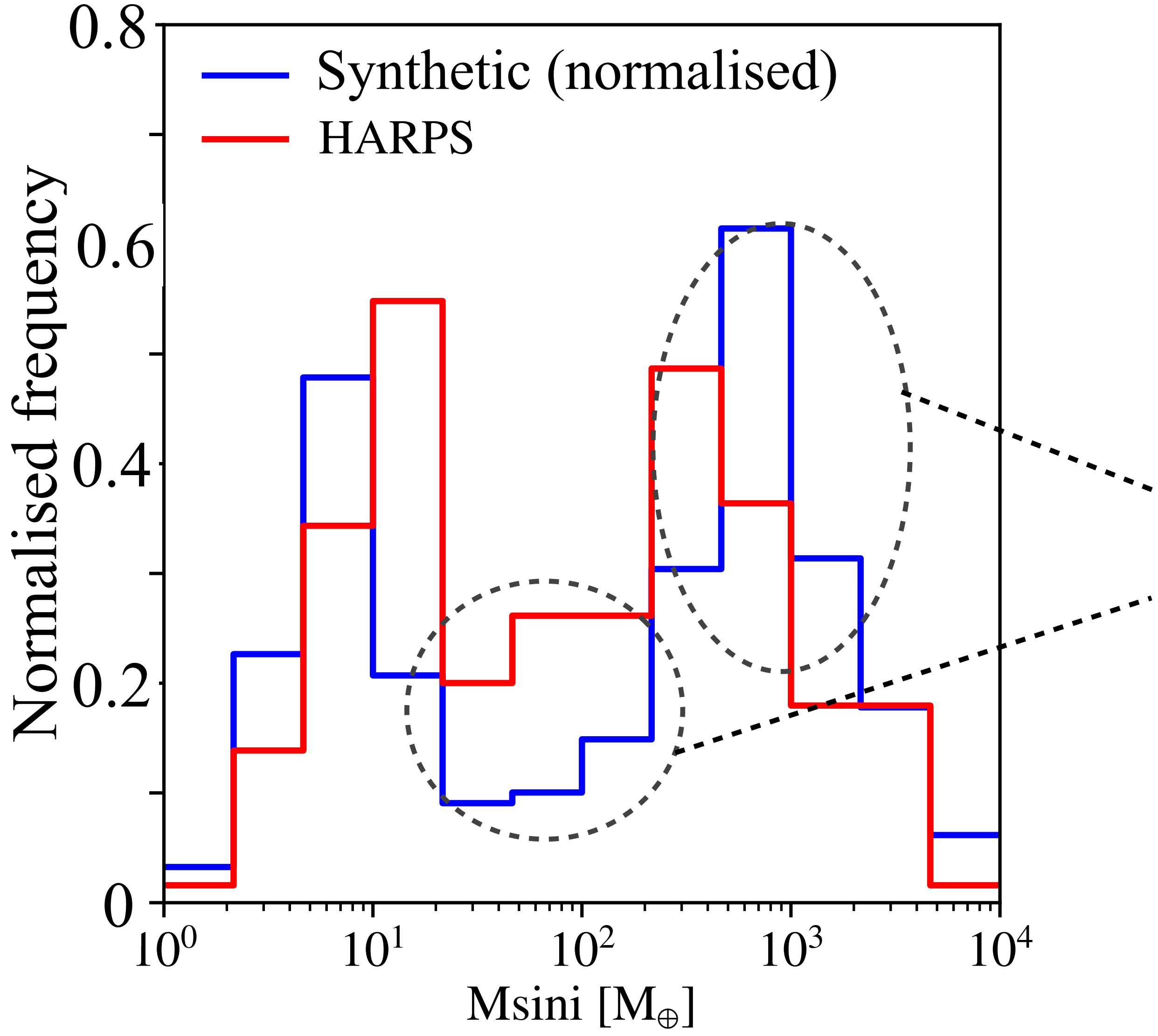
Nb of planets: 317
Nb of stars w planets: 204
Multiplicity: 1.6

- Agreement: similar global structure: relative distribution (concentrations, voids)
- Agreement: Mean multiplicity ⇒ system architecture.
- Disagreement: Factor 2 in absolute number. Poss. explanations: Initial conditions? Cluster environment (cf. Winter et al. 2020)?
- Disagreement: Hot Jupiters. Poss. explanation: Kozai plus tidal circularisation channel missing in model.

Adapted from Emsenhuber, Mordasini, Udry, Mayor, Marmier + in prep. (NGPPS VII)

Quantitative comparison mass distribution

Mass distribution detected planets



- Agreement: Fundamental bimodal structure
- Agreement: Change in regime at ~20 $M_\oplus$: smoking gun of core accretion: runaway gas accretion M_{core}~M_{enve}~10 $M_\oplus$ (but see also Bennet et al. 2021).
- Disagreement: Giant planets factor 2-3 too massive
- Disagreement: Too few intermediate mass planets by factor ~2-3 (planetary desert, Ida & Lin 2004).

⇒ too fast gas accretion (cf. Nayakshin et al. 2019)

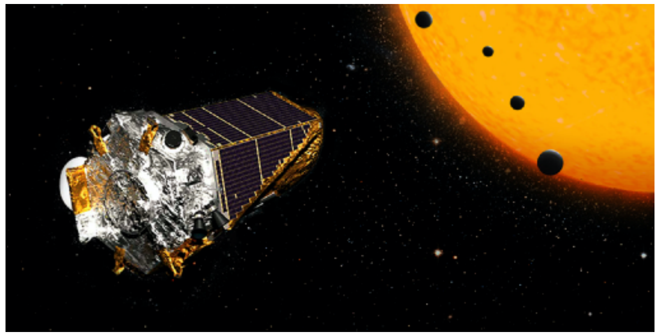
Similar for gas accretion rate derived from several 3D hydrodynamic models (Machida et al. 2010, D'Angelo et al. 2010, Bodenheimer et al. 2013)

Possible explanations: low viscosity disks (Ginzburg & Chiang 2019a), magnetic regulation (Batygin 2018, Cridland 2018), angular momentum barrier (Takata & Stevenson 1996), 3D circulation (Szulagyi et al. 2014), ….

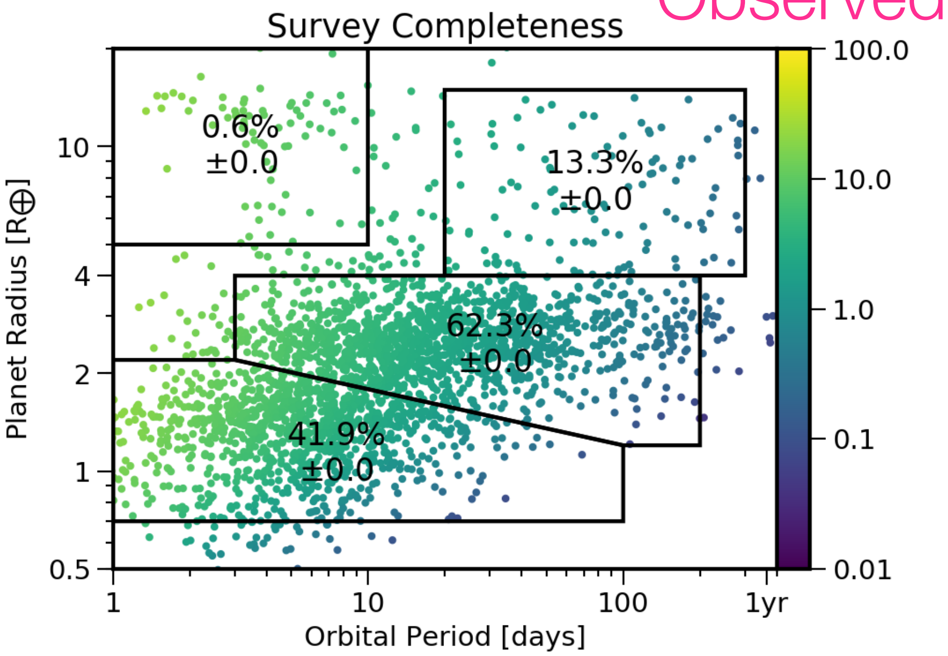
Population synthesis makes it possible to *quantify* discrepancies between theory and observations.

Statistical comparison with Kepler survey

NASA Kepler space telescope (transits)



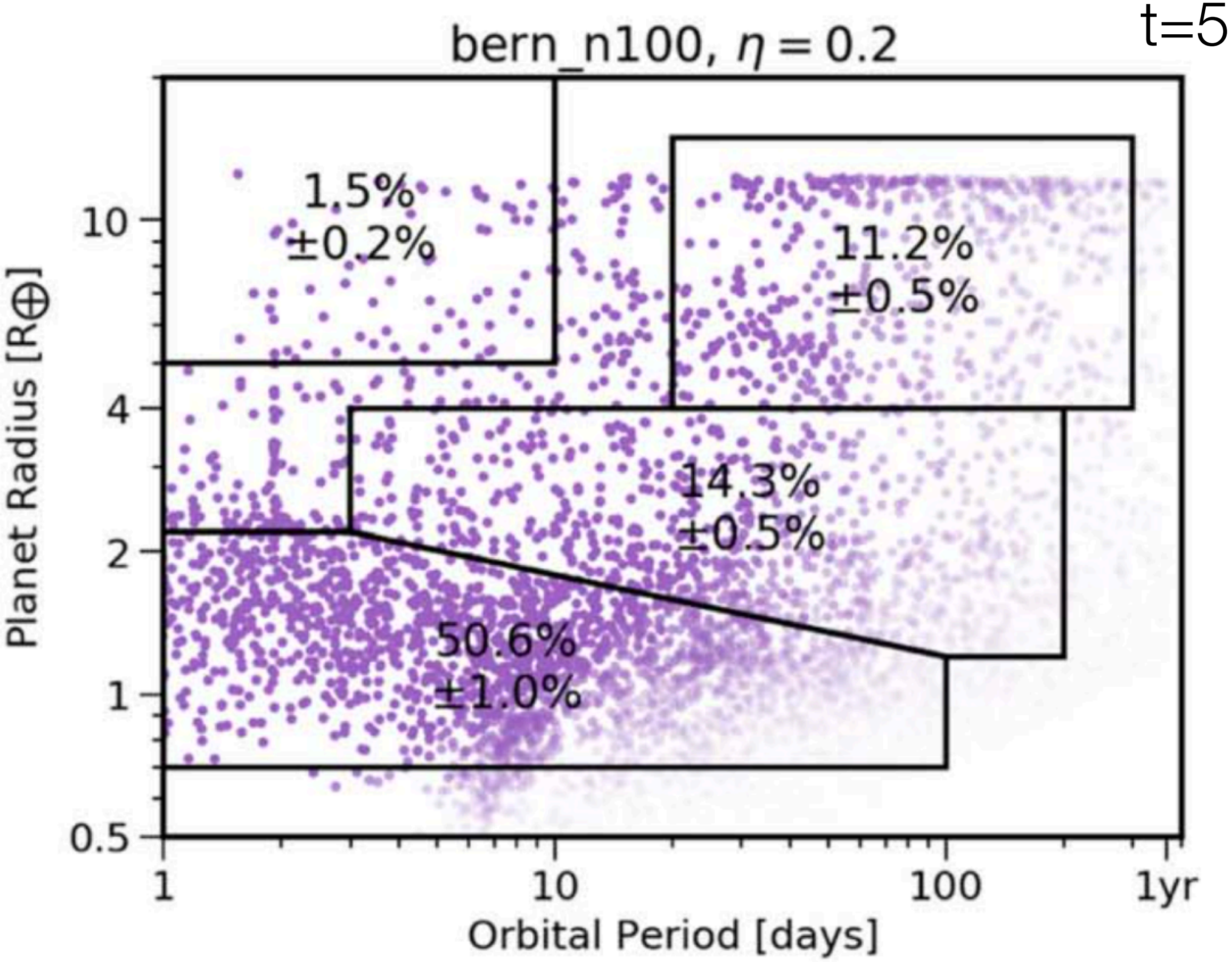
Observed



Mulders et al. (2019)

Synthetic

t=5 Gyr



Numbers: Bias corrected occurrence rates (Nb of planets in area / Nb of stars x 100)

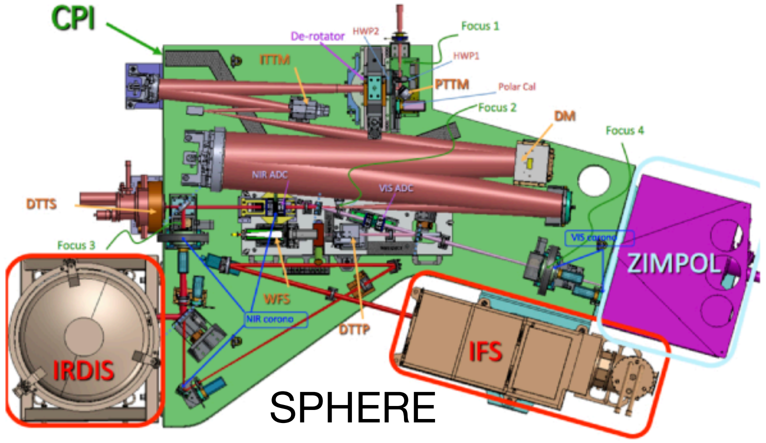
For a direct comparison, the end-to-end model should include the long term evolution / internal structure calculation including atmospheric escape -> R and L/mag.

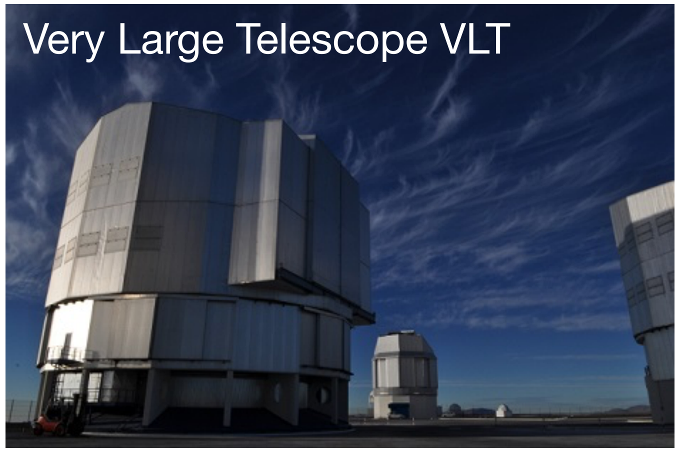
- Agreement: relative occurrence, except for (sub)-Neptunes (2-4 R⊕)
- Disagreement: absolute occurrence: too high again (x 5)
- Radius valley not clearly visible for high number of initial embryos: Impact stripping? Water-rich planets? Enriched envelopes?

Statistical comparison with direct imaging

SPHERE@VLT SHINE GTO survey (Vigan et al. 2020)
150 stars

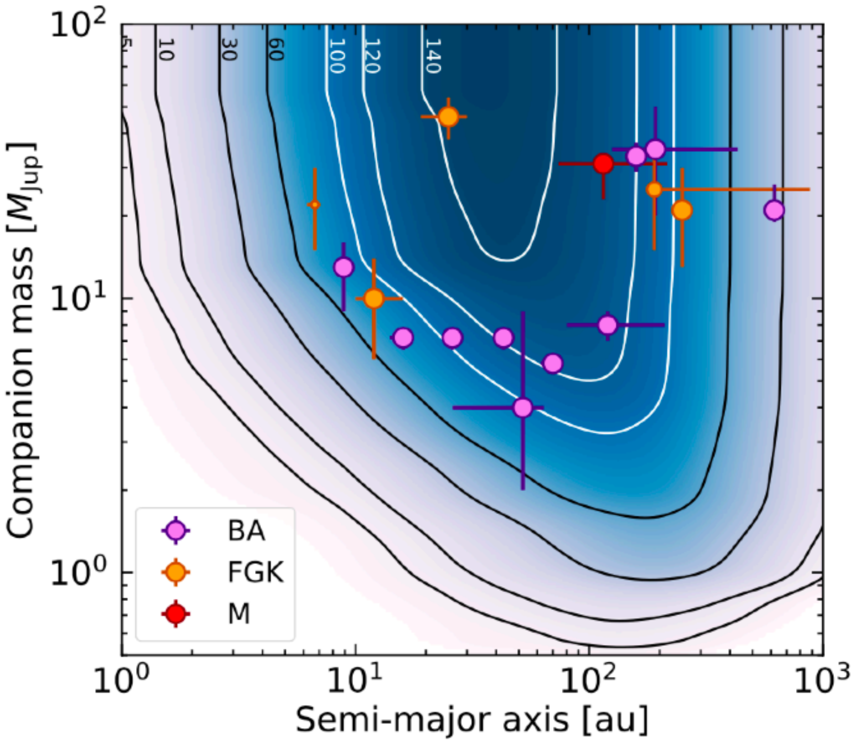
cf. Nielsen et al. 2019 GPI




Very Large Telescope VLT

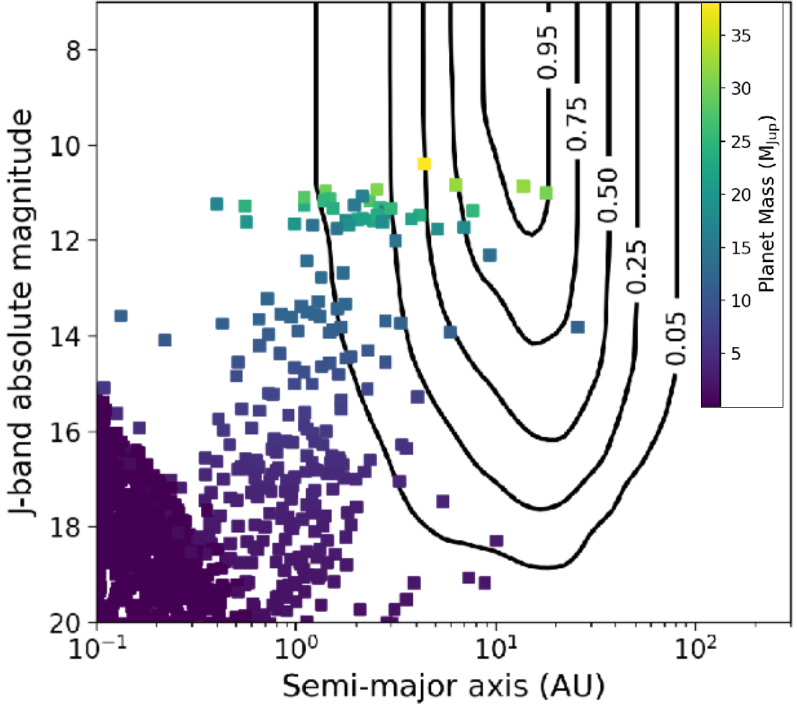
Probes very different kind of planets and a different observable (luminosity).

Actual detections & sensitivity maps



Synthetic population & sensitivity maps

Plot by Clemence Fontanive



Fraction of FGK stars w. planets (M=1-75 M_J, a=5-300 AU)

Observed: $5.8^{+4.7}_{-2.8}$ %

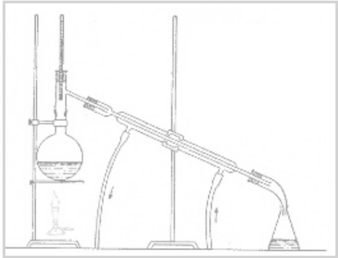
Synthetic: $3.4^{+0.5}_{-0.5}$ %

- Agreements: overall frequency, mass-luminosity relation (β Pic b)
- Distant giants in synthesis: Single, massive, eccentric planets from scattering events (see Marleau+2019b), mean eccentricity: 0.39
- Disagreement: No HR 8799-like systems: 4 distant massive giants on rather circular orbits

- Structured disks? Formation by gravitational instability?

4.
Perspectives and conclusions

Comparisons with observations



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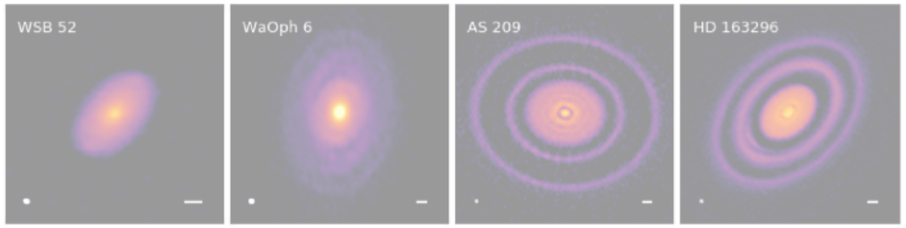

Andrews+2018

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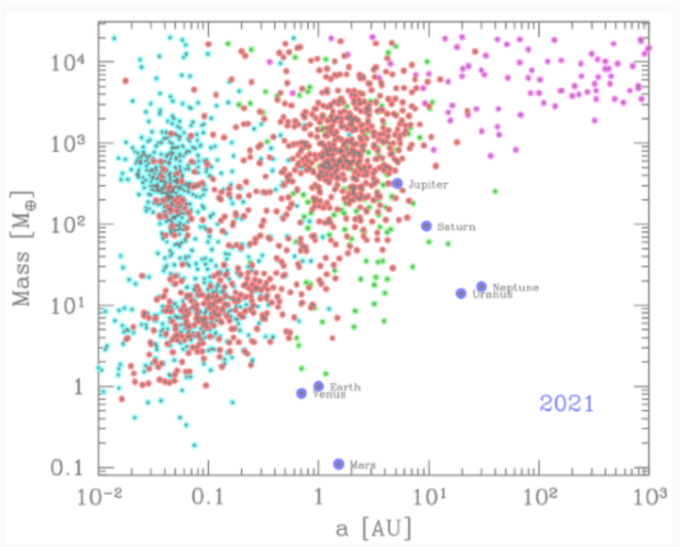

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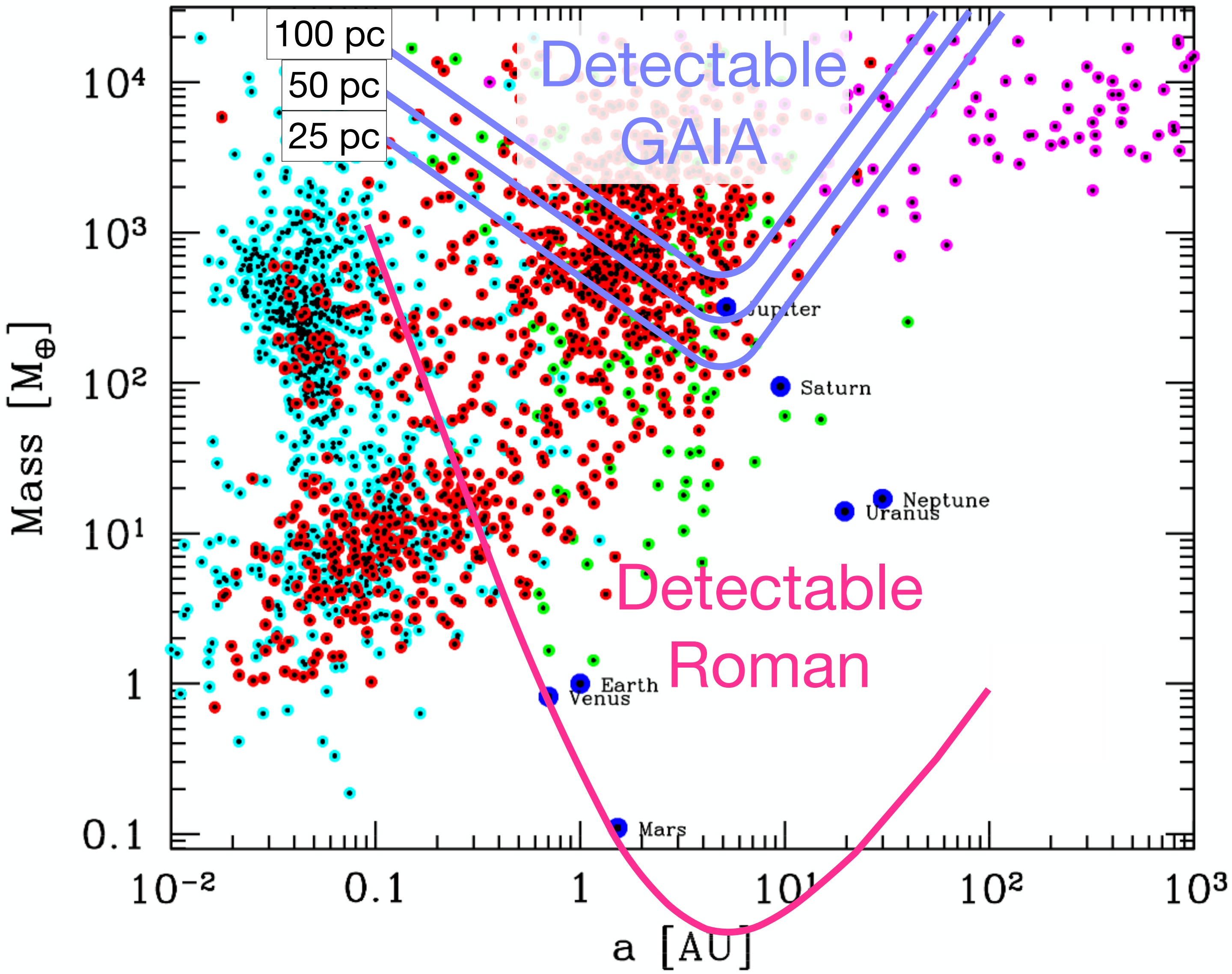
Perspectives and conclusions

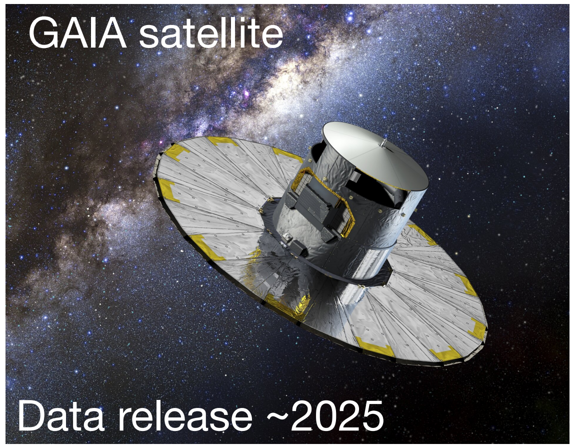


Observationally driven field: consider coming missions

The future is bright regarding new statistical observational constraints.

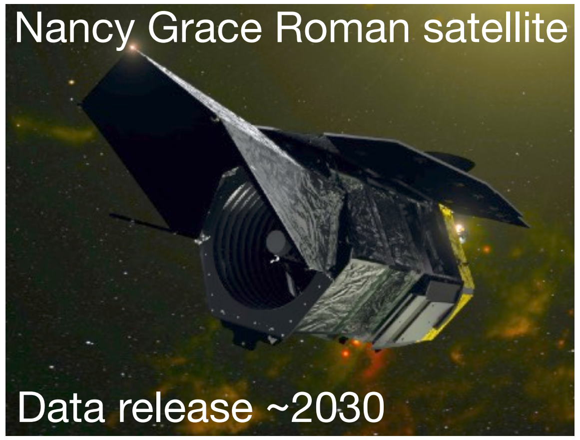
Exquisite knowledge of planet mass distribution and demographics in giant and low-mass regime. Ideal to investigate mechanisms of gas and solid accretion.

Blue lines: 5 σ detection limits for GAIA (Courtesy D. Segransan, Geneva Obs.)


GAIA satellite

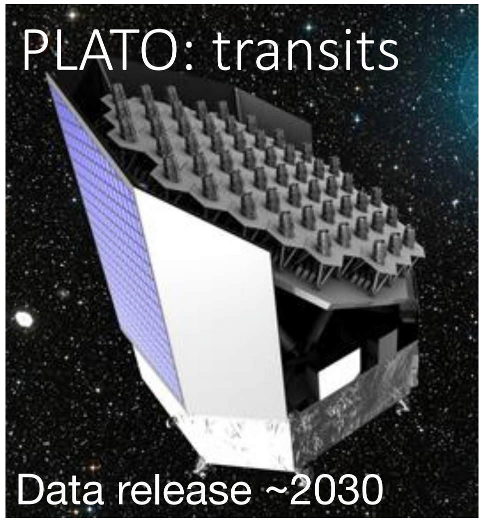
Data release ~2025

Astrometric technique
Expected yield: 20’000 to 70’000 giant planets (!)


Nancy Grace Roman satellite

Data release ~2030

Microlensing technique
Expected yield: 2000-3000 cold low-mass planets


PLATO: transits

Data release ~2030

Transit technique
Hab. zone planets
Temporal evolution


ARIEL: atmospheric spectroscopy

Launch ~2029

Atmo. spectroscopy
Statistics of atmo. compositions

Terra incognita as litmus test

2021

~2030

Cross-checking the same theoretical model with population synthesis in many different and especially unexplored parameter spaces:

Key to understand whether theory really captures the governing underlying physics and is not merely a sophisticate fit tweaked to explain already known observations.

Much to do on the theoretical side: initial conditions & early phases, disk models (beyond α-models), hybrid pebble-planetesimal models, link formation-atmospheric composition, gas accretion,…

Observing planet formation as it happens as a new direct constraint on planet formation

Conclusions

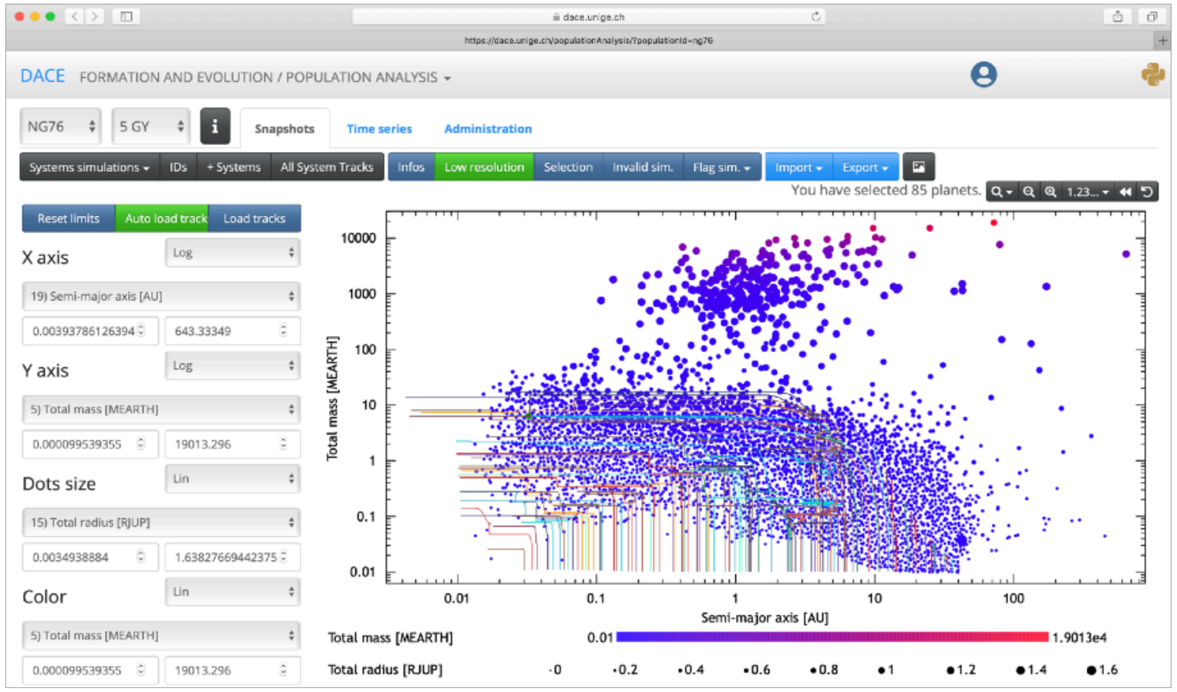
- Population synthesis is a tool to compare theory and observation to improve understanding of planet formation
  - use full wealth of observational constraints
  - put detailed models to the test
  - see global statistical consequences: which processes are key?
- Observational constraints on many processes
  - solid and gas accretion rate
  - N-body dynamics
  - orbital migration rate
- See link between disk and planetary properties
- Predict yield of future instruments/space missions
- Continuously improving models
  - population syntheses depend on progress of formation theory as a whole
  - many new theoretical developments to test, many new obs. constraints to come

Resources

Population synthesis review papers

- -Benz et al., Protostars & Planets VI, 691, 2014
- -Mordasini et al., IJA, 201, 2015
- -Mordasini, Handbook of Exoplanets, 143, 2018

DACE data base: Bern population synthesis models
https://dace.unige.ch/evolution/index



NG76 | 5 GY

You have selected 85 planets.

X axis: Log
19) Semi-major axis [AU]: 0.00393786126394 | 643.33349

Y axis: Log
5) Total mass [MEARTH]: 0.000099539355 | 19013.296

Dots size: Lin
15) Total radius [RJUP]: 0.0034938884 | 1.63827669442375

Color: Lin
5) Total mass [MEARTH]: 0.000099539355 | 19013.296

All NGPPS data publicly available via dedicated interactive online tool on DACE website

Freely available toy population synthesis model
http://nexsci.caltech.edu/workshop/2015/#handson