

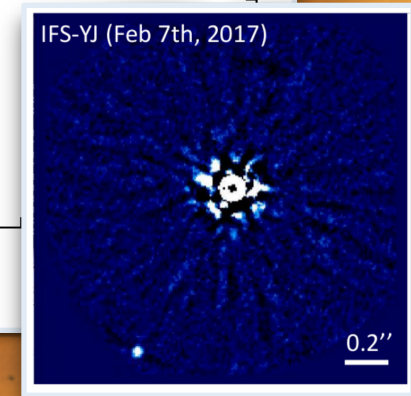
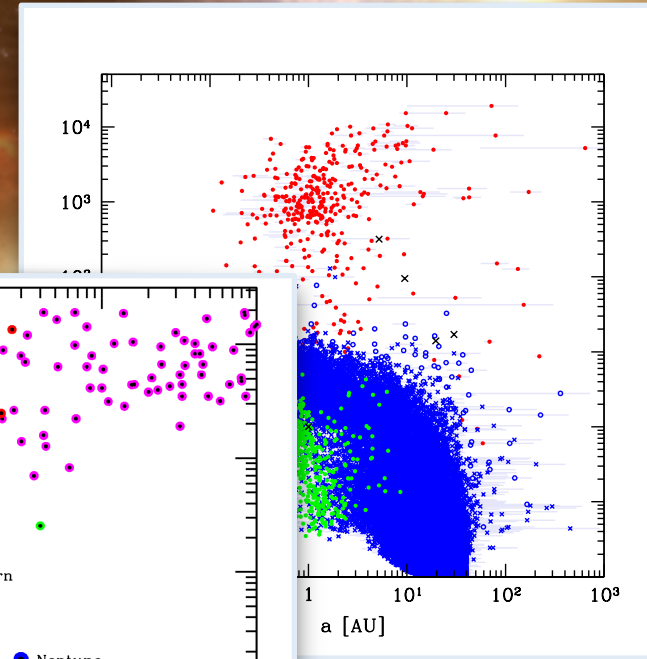
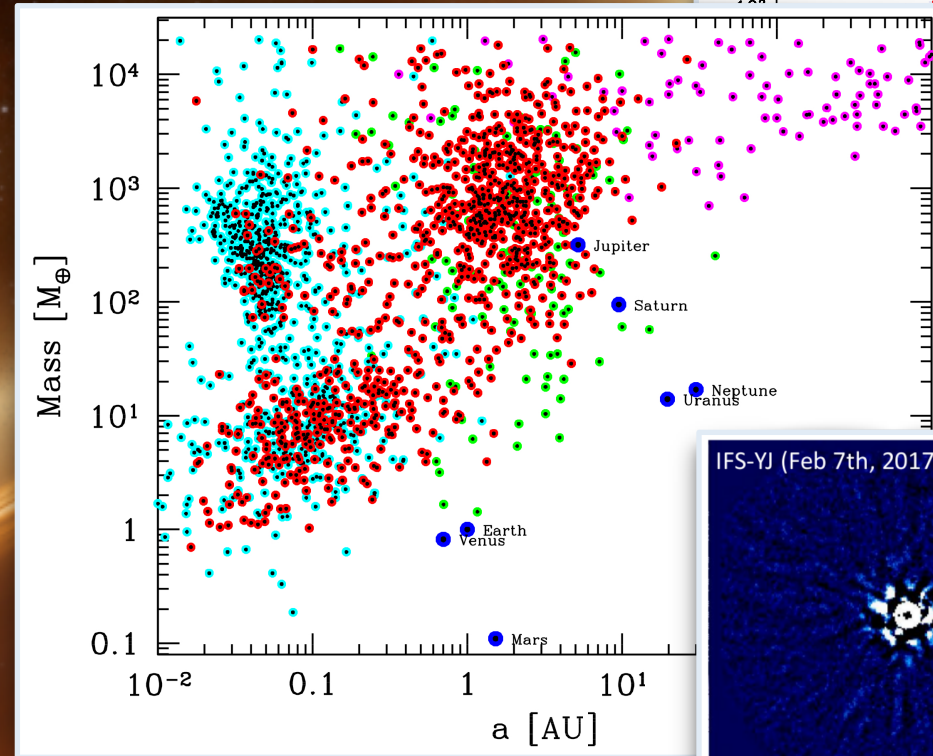
Confronting planet formation theory and observations with planetary population synthesis

Perspectives of Planet and Star Formation

70th birthday of Prof. Thomas Henning

MPIA, Heidelberg

23.06.2026



Christoph Mordasini

Division of Space Research and Planetary Sciences,
University of Bern, Switzerland

u^b

^b
UNIVERSITÄT
BERN

Talk contents

1. Introduction

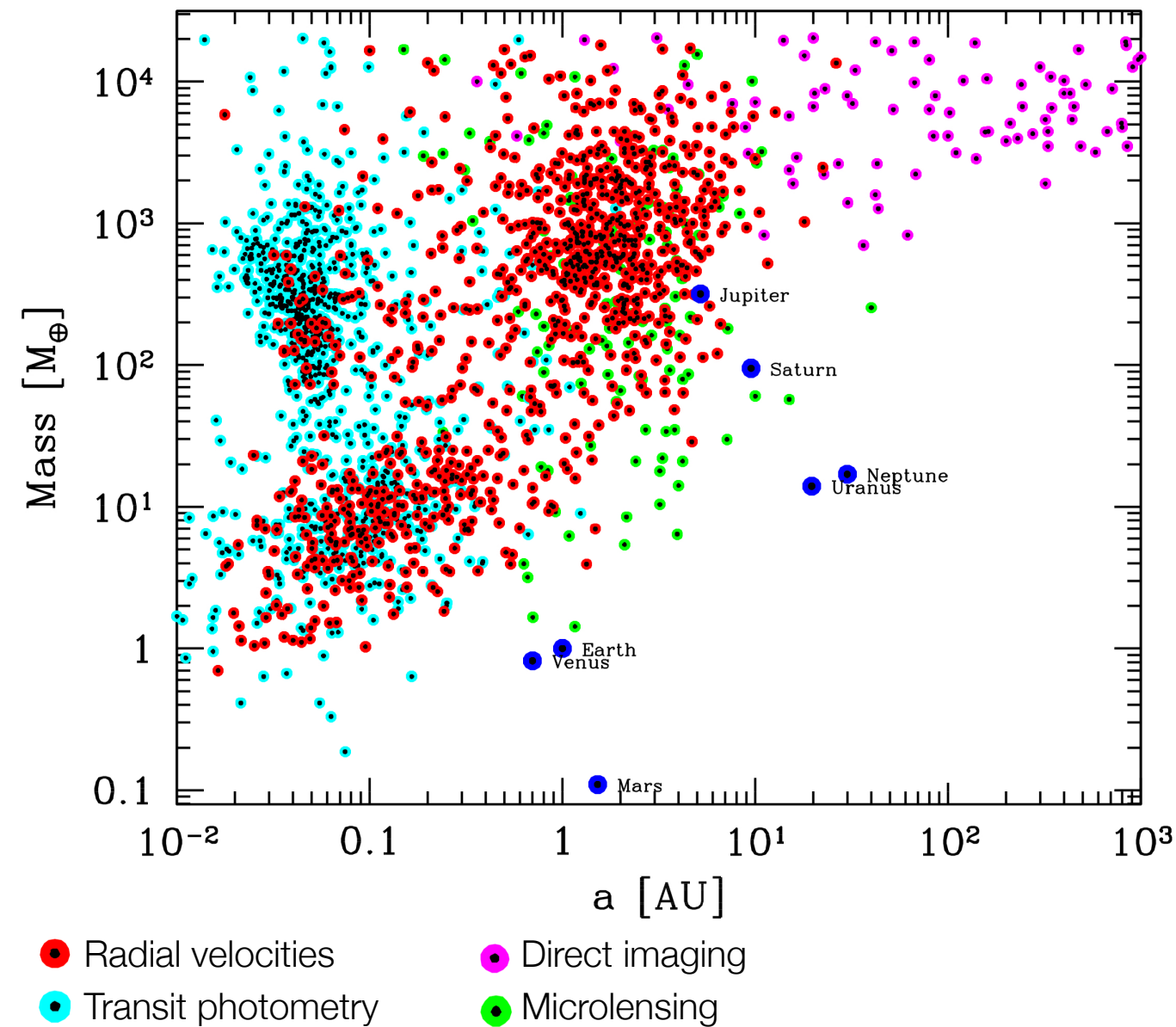
2. Selected results on the long-term impact of Thomas and MPIA

a) transit photometry - radii - system architectures

b) direct imaging - luminosities - disk instability

3. Conclusions and future steps

Observational constraints



Centuries of solar system exploration
and 31 year of exoplanet studies

Diversity in exoplanet properties

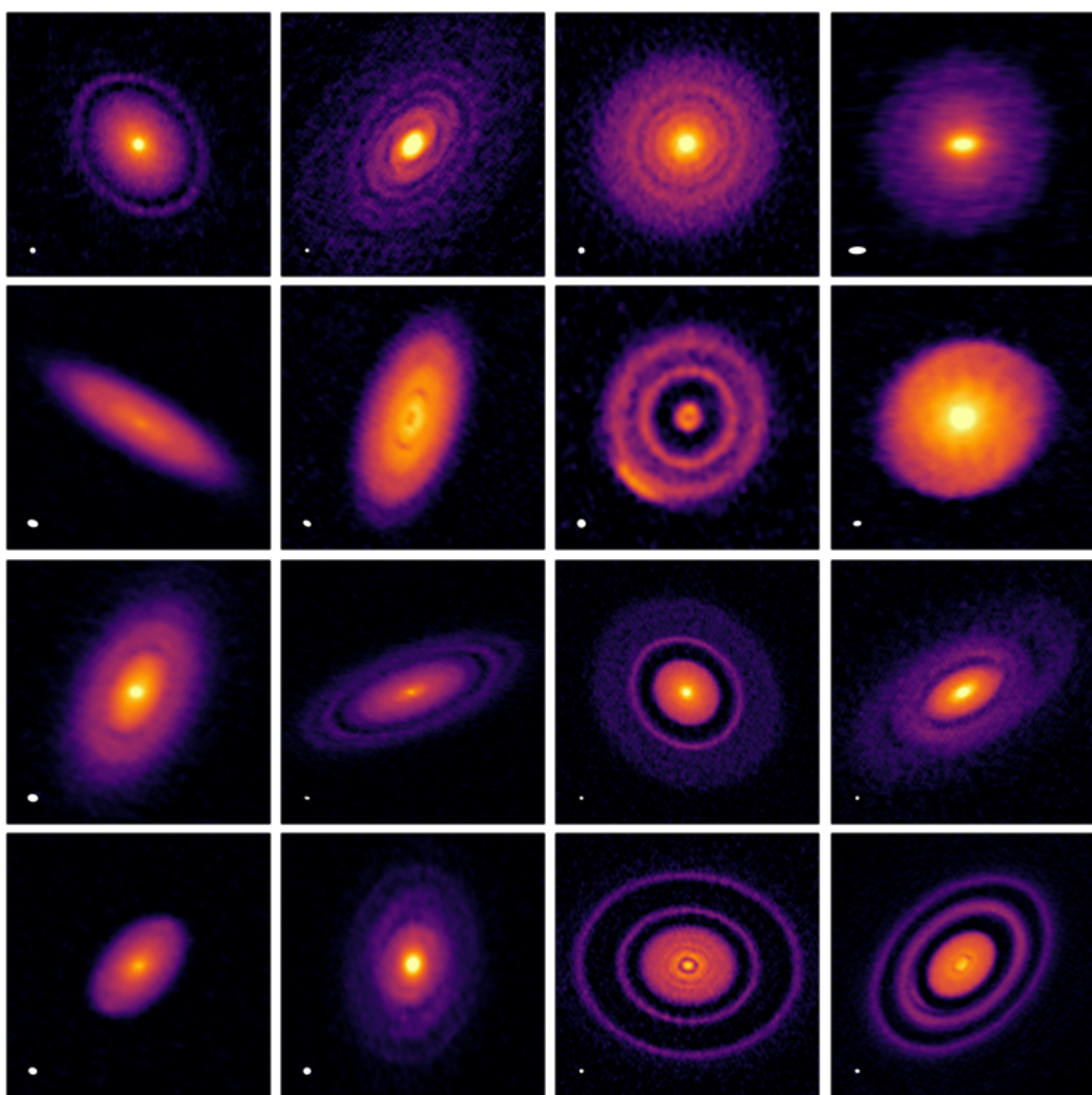
- Enormous increase in observational data on exoplanets since 1995. Multi-method detections from ground and space.
- More to come soon (Gaia DR4, PLATO, Roman ST, ARIEL, ELT, ...)

Little knowledge about individual systems, but *demographical constraints*:

- frequencies
- distributions
- correlations

Use the exoplanet population to statistically constrain planet formation processes.

Diversity of disks and planets



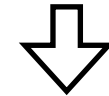
Protoplanetary disks: initial and boundary conditions in which planetary systems form

The ALMA revolution: A huge increase in knowledge and **diversity** as for exoplanets

Observational determination of distributions of

- Disk gas masses
- Disk dust masses
- Disk sizes
- Disk lifetimes (->stellar environment)

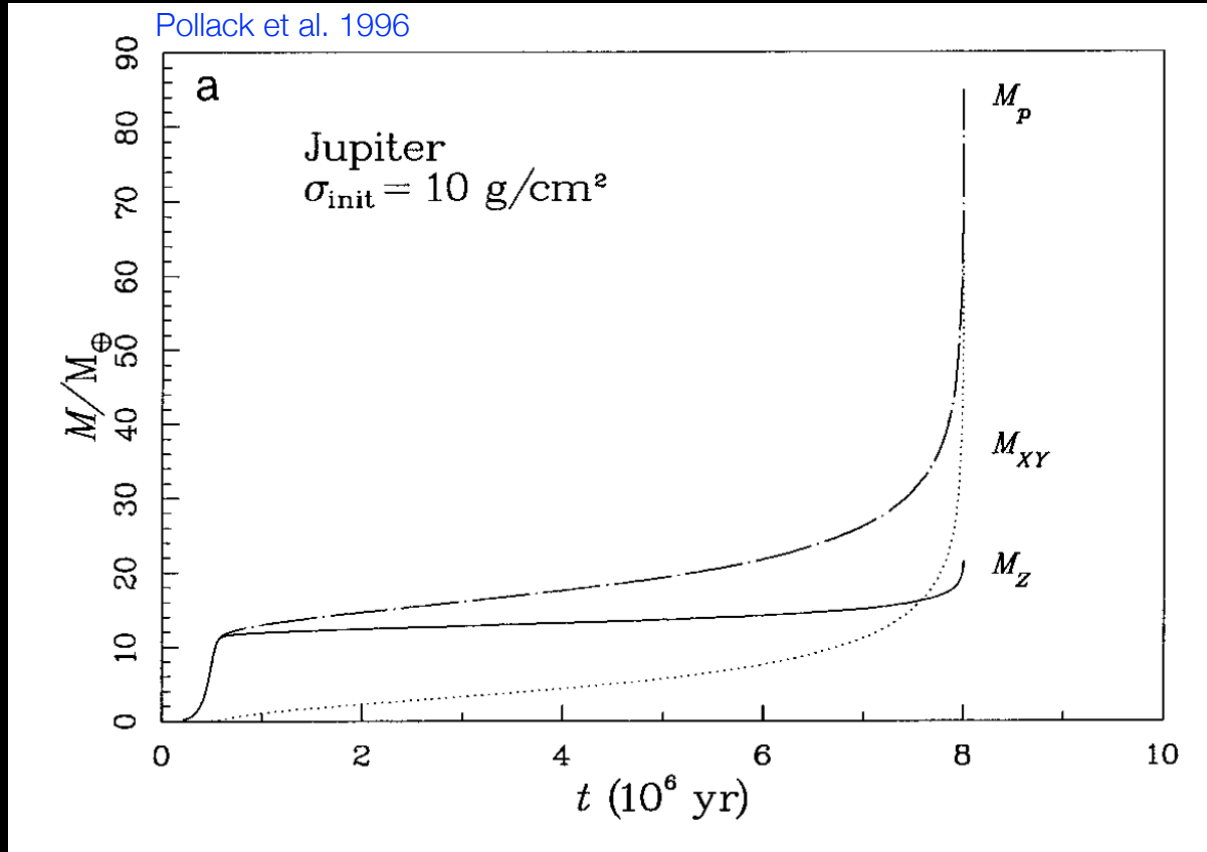
Diversity of disks (Initial conditions)



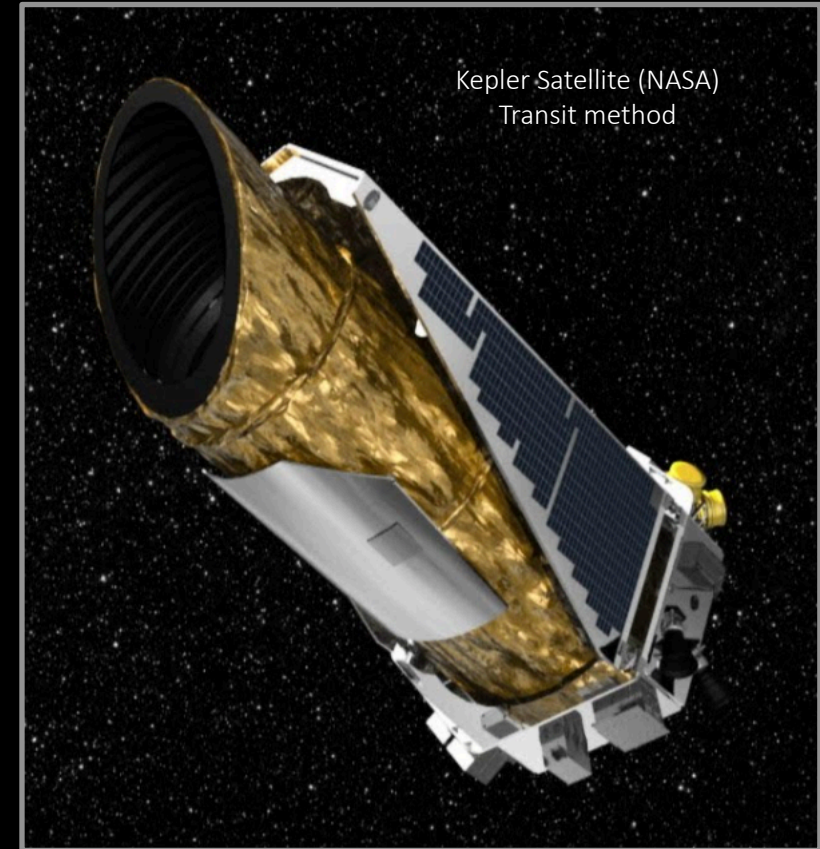
Diversity of planets (End products)

Statistically reproducible with a global planet formation model and if not, why?

2a. Transit photometry - planetary radii - system architectures

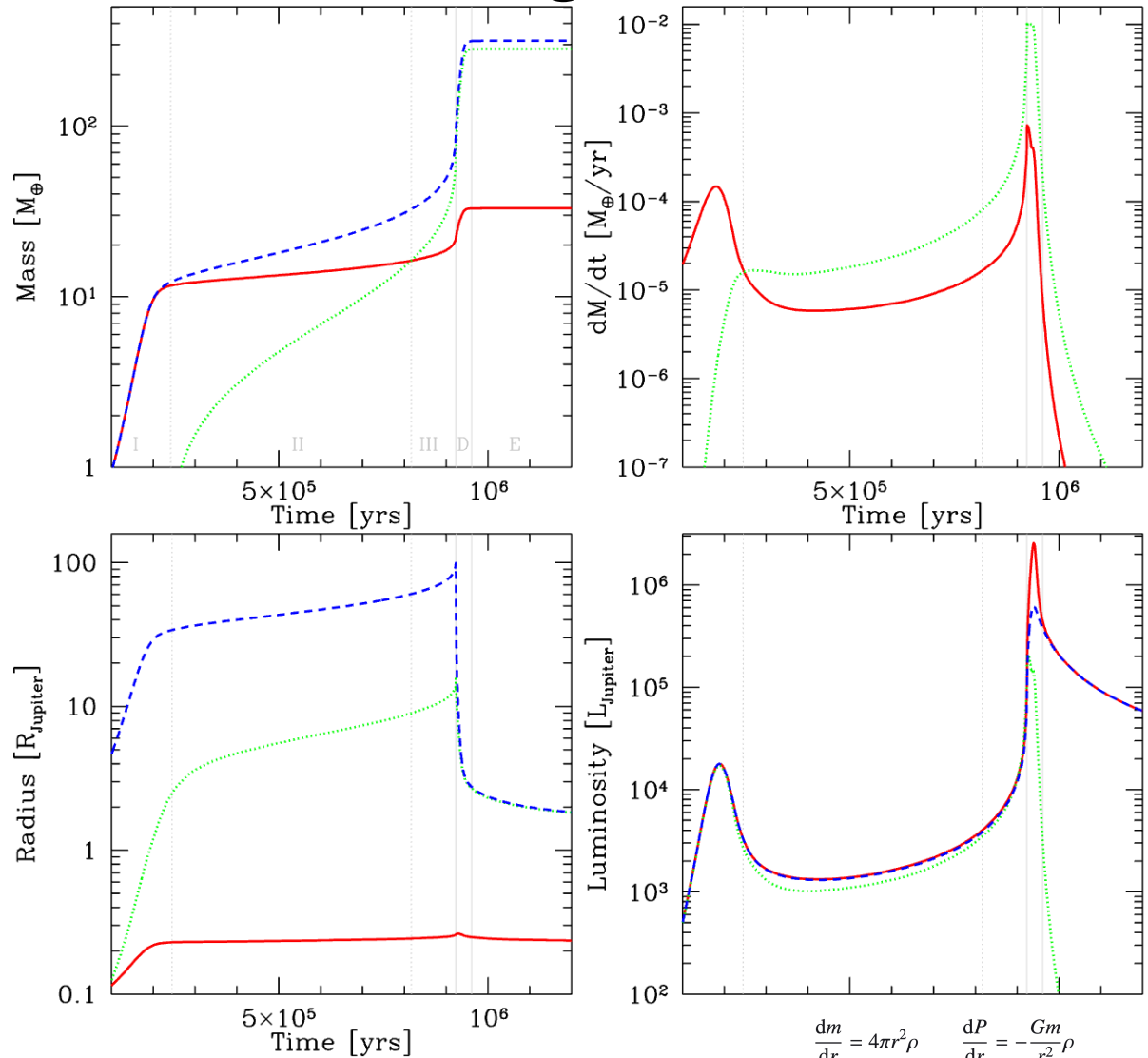


Early models: prediction of the mass, but not the radius and the luminosity



Kepler Prime Mission (2009–2013): Survey of ~150,000 stars in the Cygnus-Lyra region

Adding the detached and evolutionary phase



A&A 547, A111 (2012)
DOI: 10.1051/0004-6361/201118457
© ESO 2012

**Astronomy
& Astrophysics**

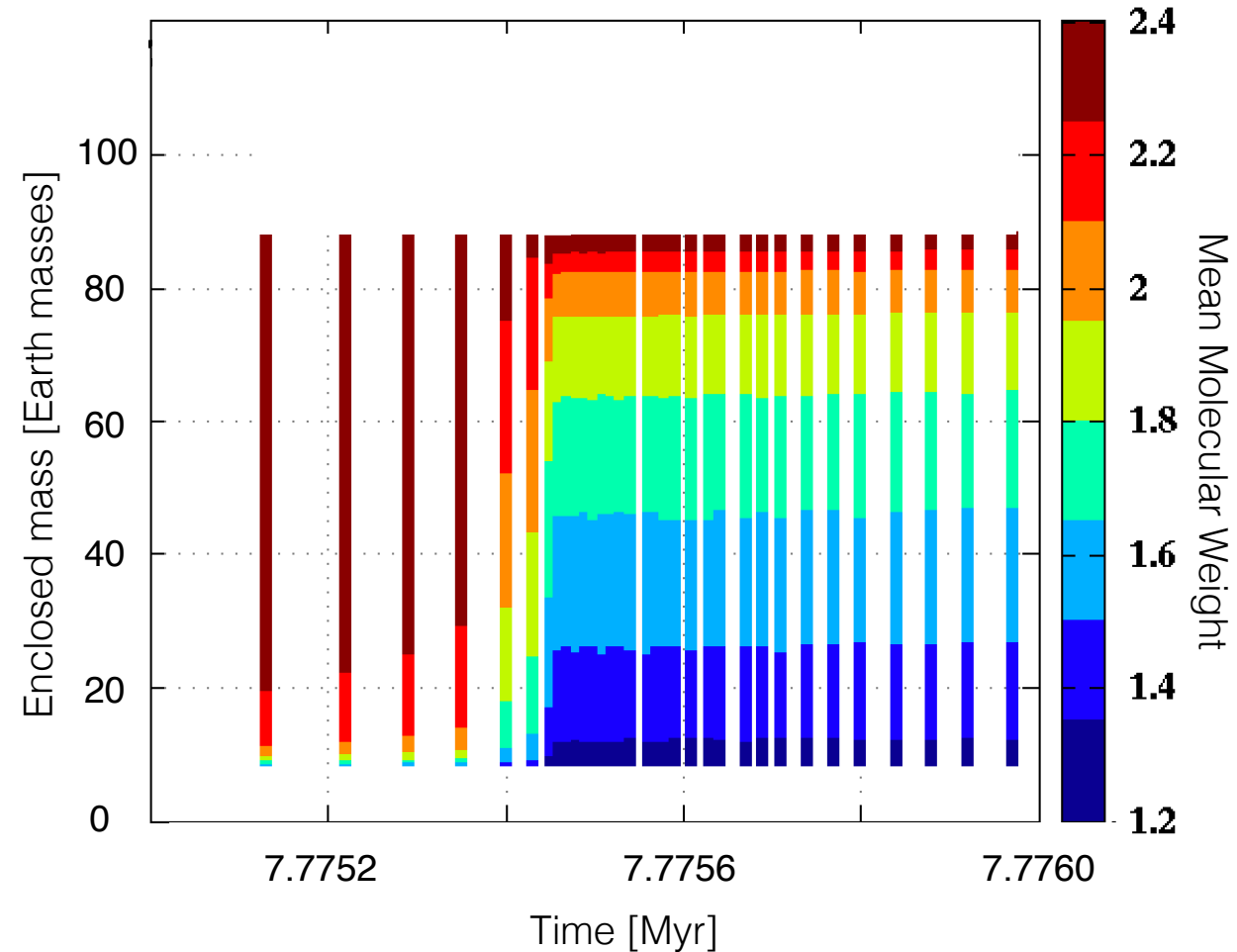
Characterization of exoplanets from their formation

I. Models of combined planet formation and evolution

C. Mordasini¹, Y. Alibert², H. Klahr¹, and T. Henning¹

$$\begin{aligned} \frac{dm}{dr} &= 4\pi r^2 \rho & \frac{dP}{dr} &= -\frac{Gm}{r^2} \rho \\ \frac{dl}{dr} &= 0 & \frac{dT}{dr} &= \frac{T}{P} \frac{dP}{dr} \nabla(T, P) \end{aligned}$$

Attached, detached,
evolutionary phase

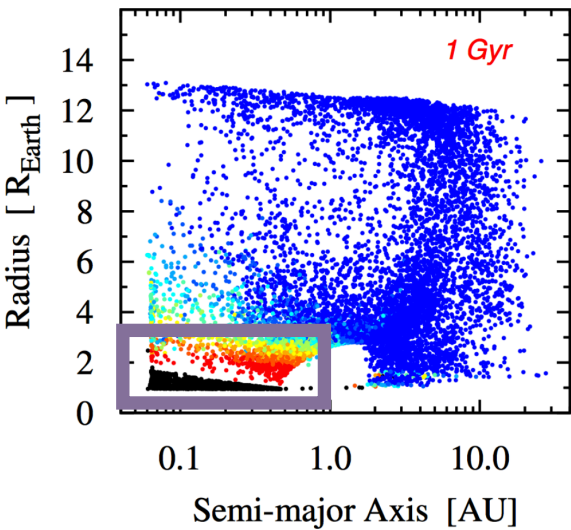


Envelope dissociates on a $\sim$ year timescale

Stability criterion for gas spheres $\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \varrho} \right)_s$

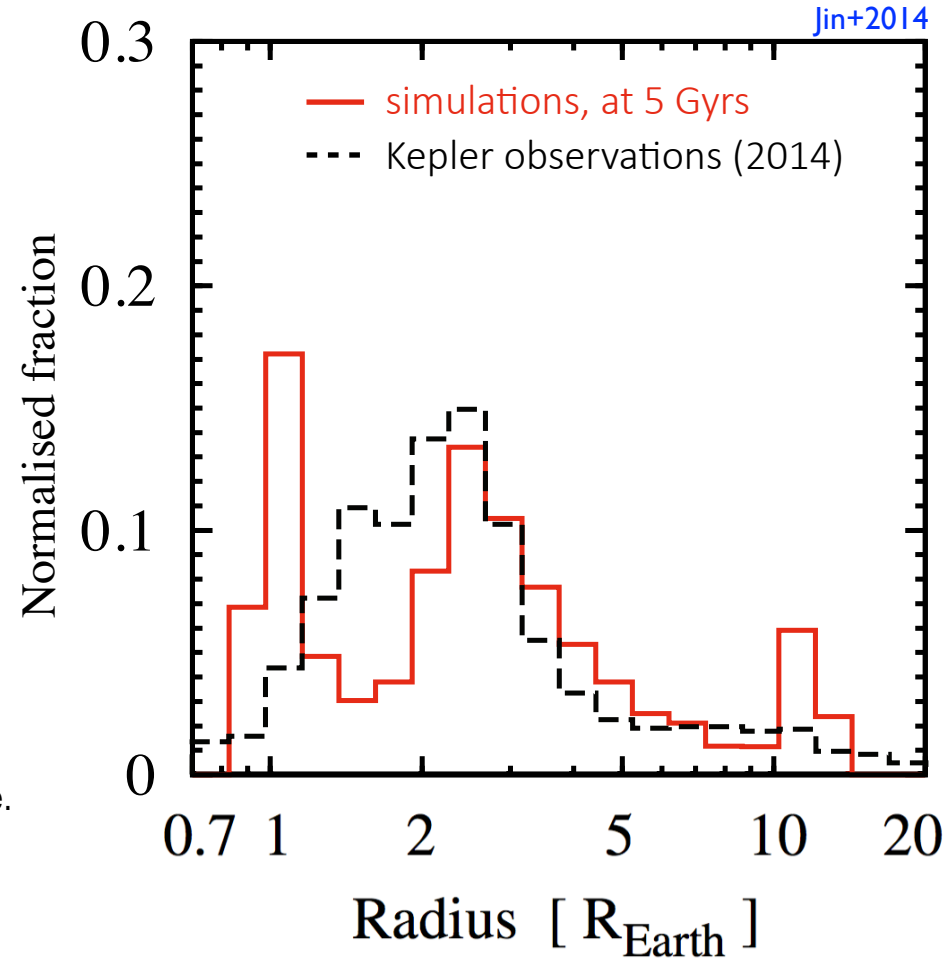
Dynamic or not - still no general agreement in literature

A look back: application for the origin of the radius valley



Early one-embryo per-disk pop. synthesis - but with radii and atmospheric escape

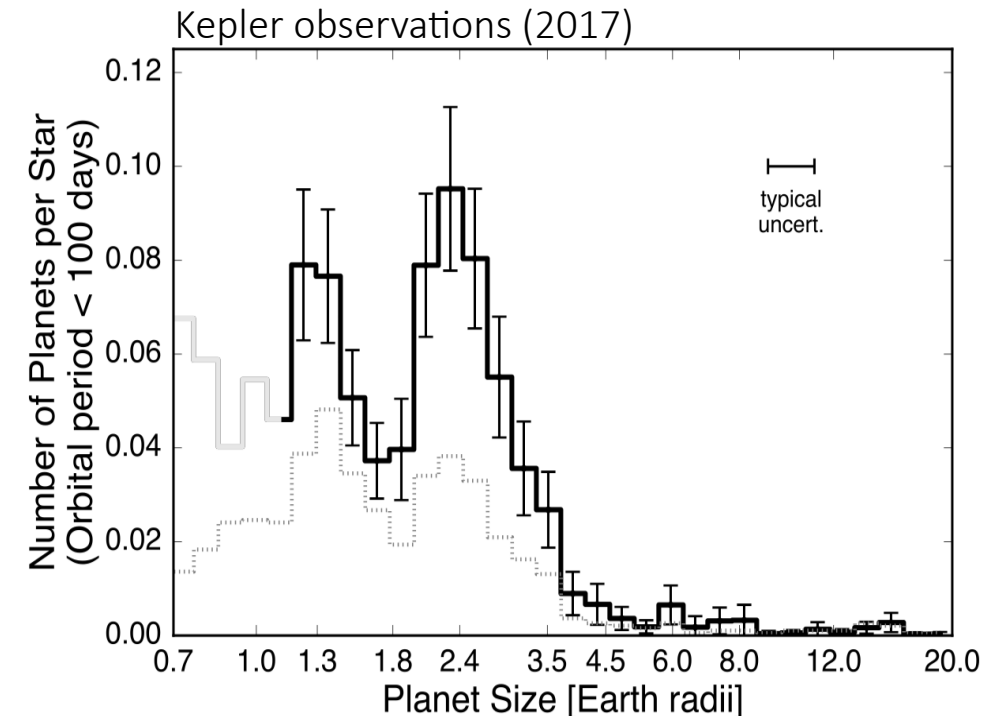
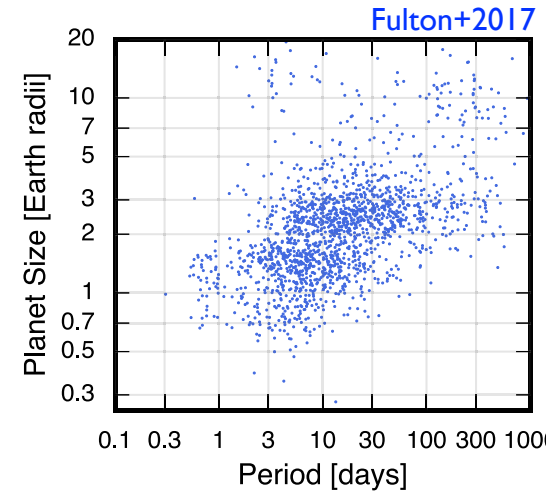
Black: planets having lost all H/He.



Observed radius distribution (before 2017): no bimodal distribution

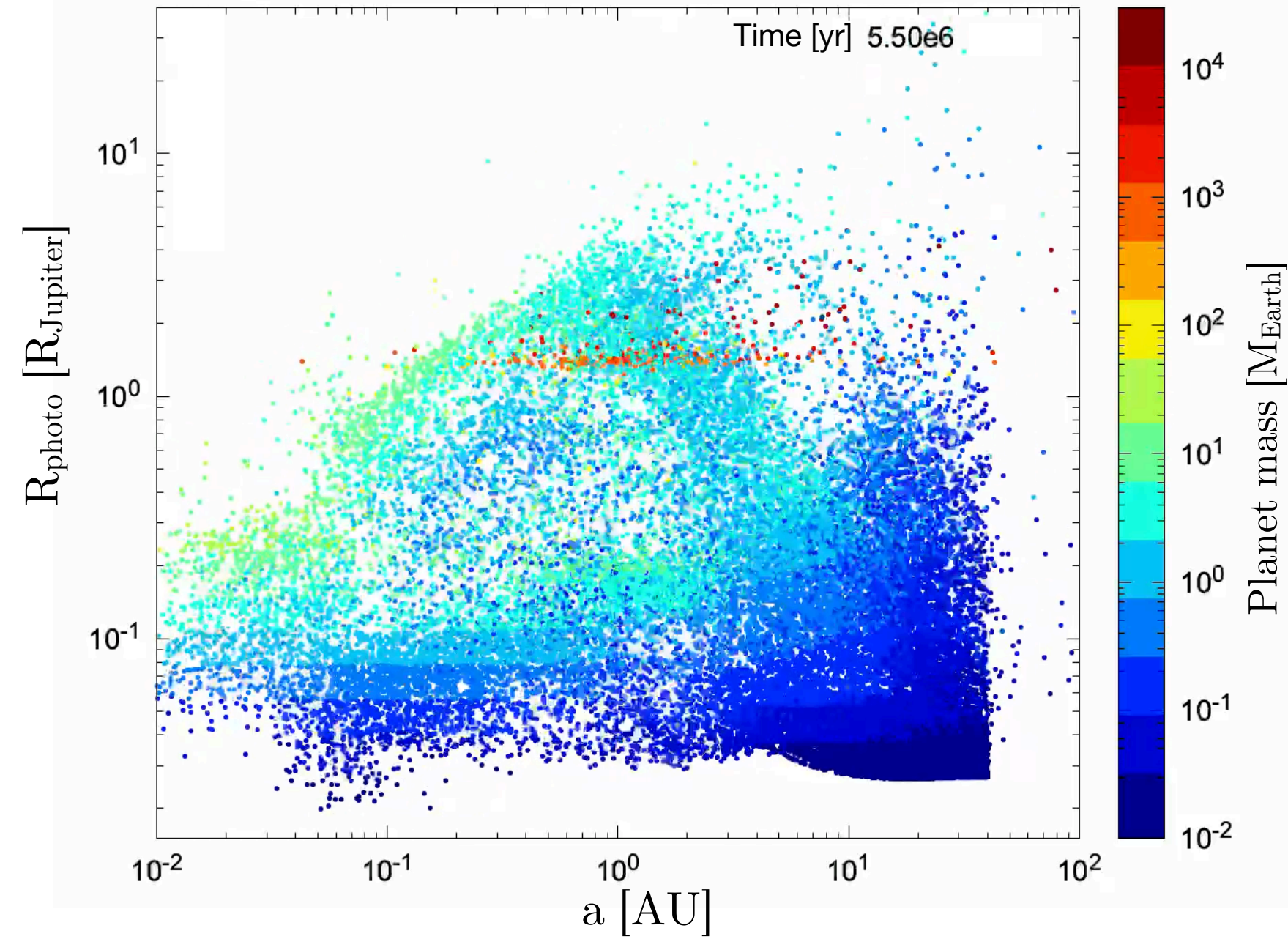
cf. Owen & Wu 2013, 2018,, Lopez & Fortney 2013,

- Improved stellar $R \Rightarrow$ improved planet R
- There is a valley: predictive power



Jin (shared PhD student at MPA),
Mordasini, Parmentier, van Boekel
Henning & Ji 2014

New results: NGPPS population synthesis 1 $M_{\odot}$: a-R tracks



Gen III model used to generate the *New Generation Planetary Population Synthesis, NGPPS*

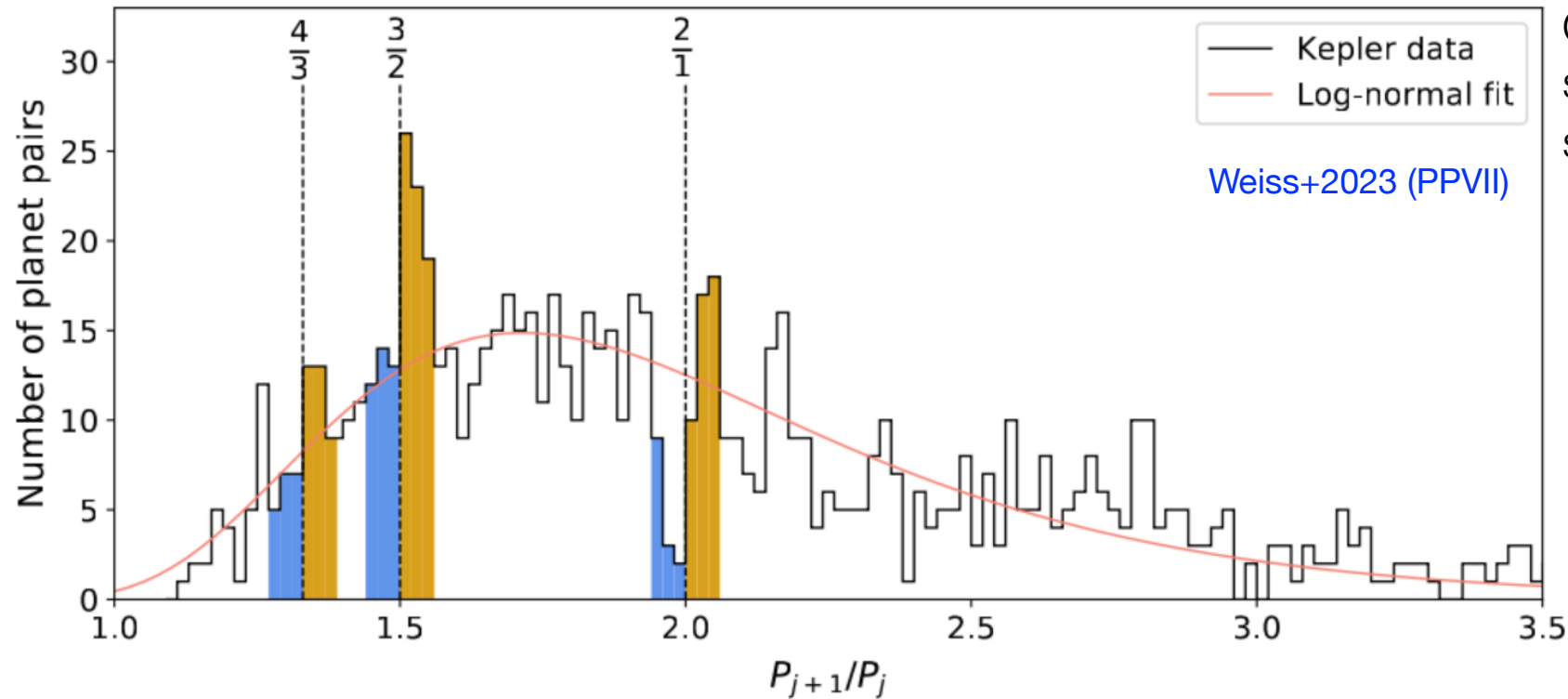
- 1000 systems (stars); solar-like host stars
- 100 initial embryos per system of 1 M_{Jupiter}
- 4 Monte Carlo variables: [Fe/H], initial disk gas mass, external photoevaporation rate, disk inner edge

Classical physics, but comprehensive & direct predictions. N-body integration to 100 Myr, thermodynamic evolution to 10 Gyr.

Papers: NGPPS I-VIII: [Emsenhuber+2021a,b](#); [Schlecker+2021a,b](#), [Burn+2021](#), [Mishra+2021](#), [Cheng+2025](#), [Emsenhuber+2025](#)

Insights in formation pathways

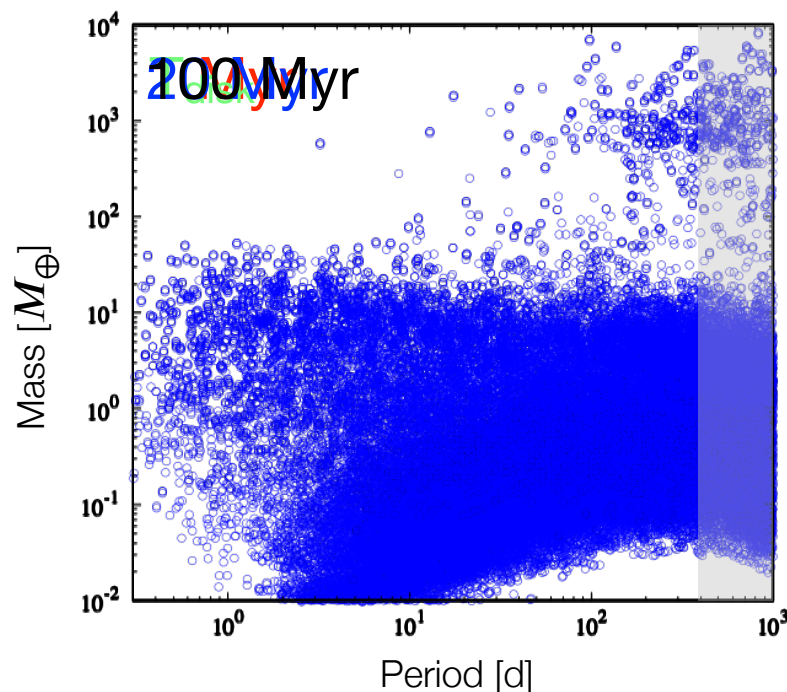
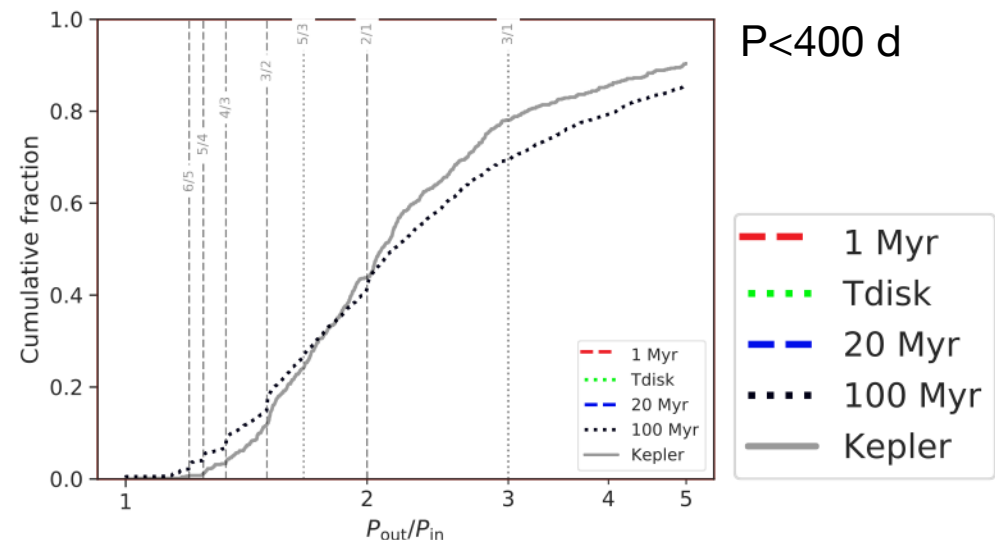
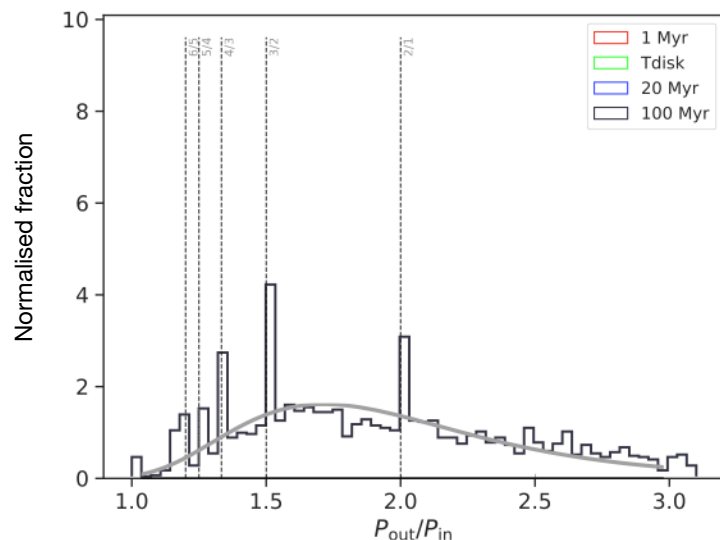
Somewhat unexpected (but see [Mayor+2011](#)), Kepler also brought a plethora of multi-planet systems:
Novel constraints for formation and in particular migration models (presence of resonances)



Observed period ratio histogram for small “Kepler planets” ($R < 4 R_{\oplus}$, short periods)

How does this look like in the synthetic population?

Temporal evolution
of period ratio
distribution in
synthetic NGPPS
population



1 Myr (in gas disk): majority $P_{\text{out}}/P_{\text{in}} < 1.2$. Gas damps eccentricities, stabilises orbits (Kley & Nelson 2012). Tight packing from oligarchic planetesimal growth phase (relative spacing ~ 10 mutual Hill radii, Kokubo & Ida 1998) and convergent migration.

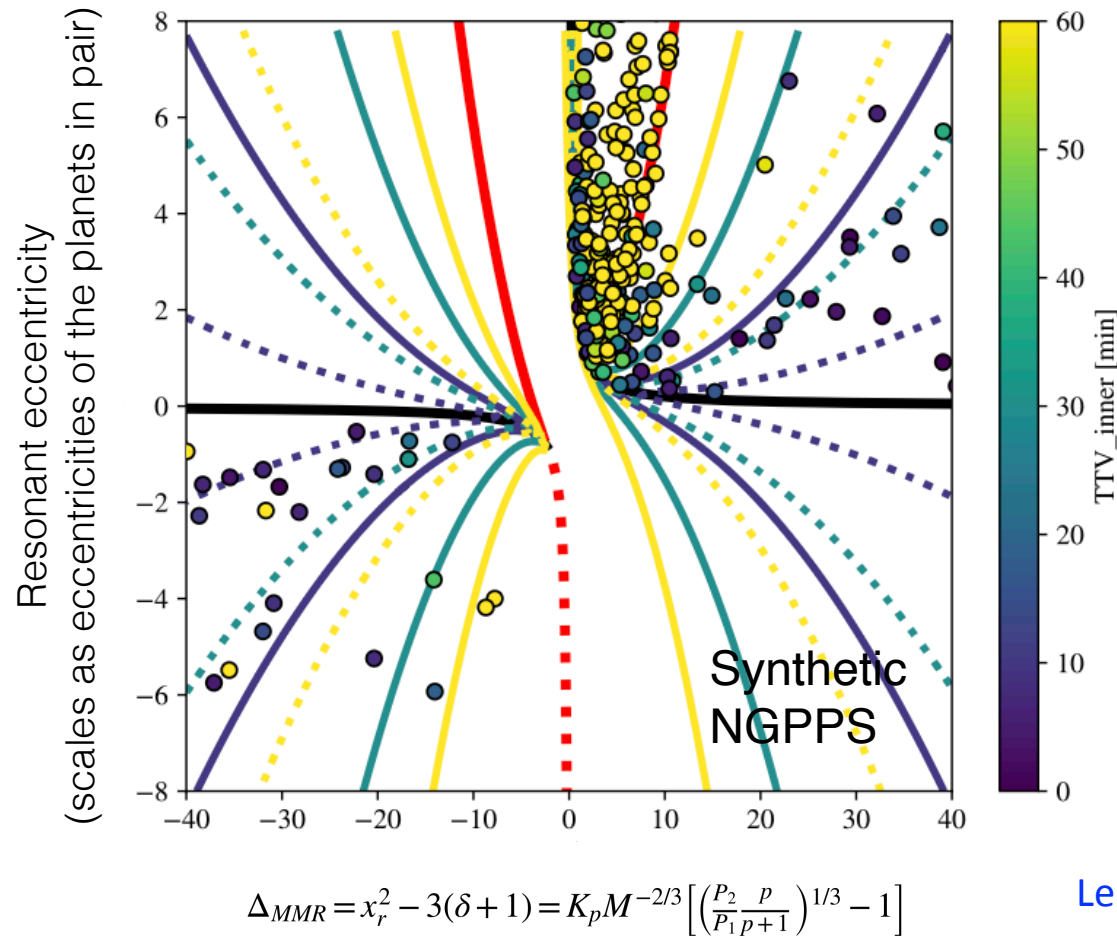
T_{disk} (~3 Myr): Damping vanishing, the frequency of pairs with $P_{\text{out}}/P_{\text{in}} < 1.2$ decreases. MMRs like 6/5, 5/4, 4/3 strongly populated. Pairs with $P_{\text{out}}/P_{\text{in}} > 2$ still rare.

20 Myr: Large change between T_{disk} and 20 Myr: many resonances break, a lot of giant impacts (Ida & Lin 2010; Izidoro et al. 2017)

100 Myr: Between 20 and 100 Myr, fraction of planets in and near the resonances, especially in tighter ones, decreases more. Fraction of resonant systems at 100 Myr, however, still larger than observed in Kepler data (~ 5 Gyr).

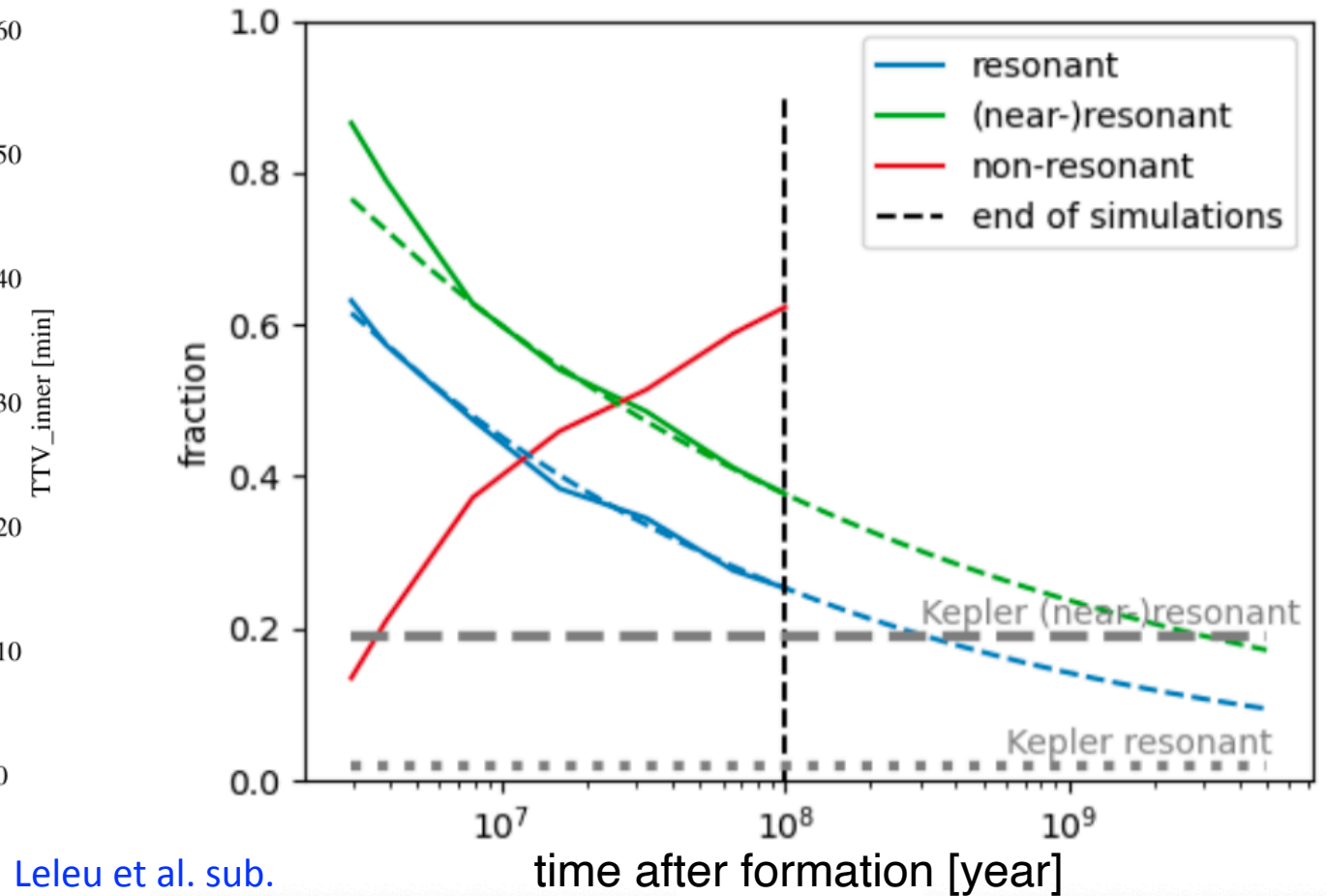
The synthetic population (yielding all dynamic information) can be used to study the dynamics of synthetic multi planet systems, in particular with respect to their resonant state.

Evolution of fraction of resonant pairs



distance to commensurability of the period ratio
Also constraints for strength of disk turbulence.

Use to study fraction of resonant and non-resonant pairs as a function of time (integration time NGPPS: 100 Myr)

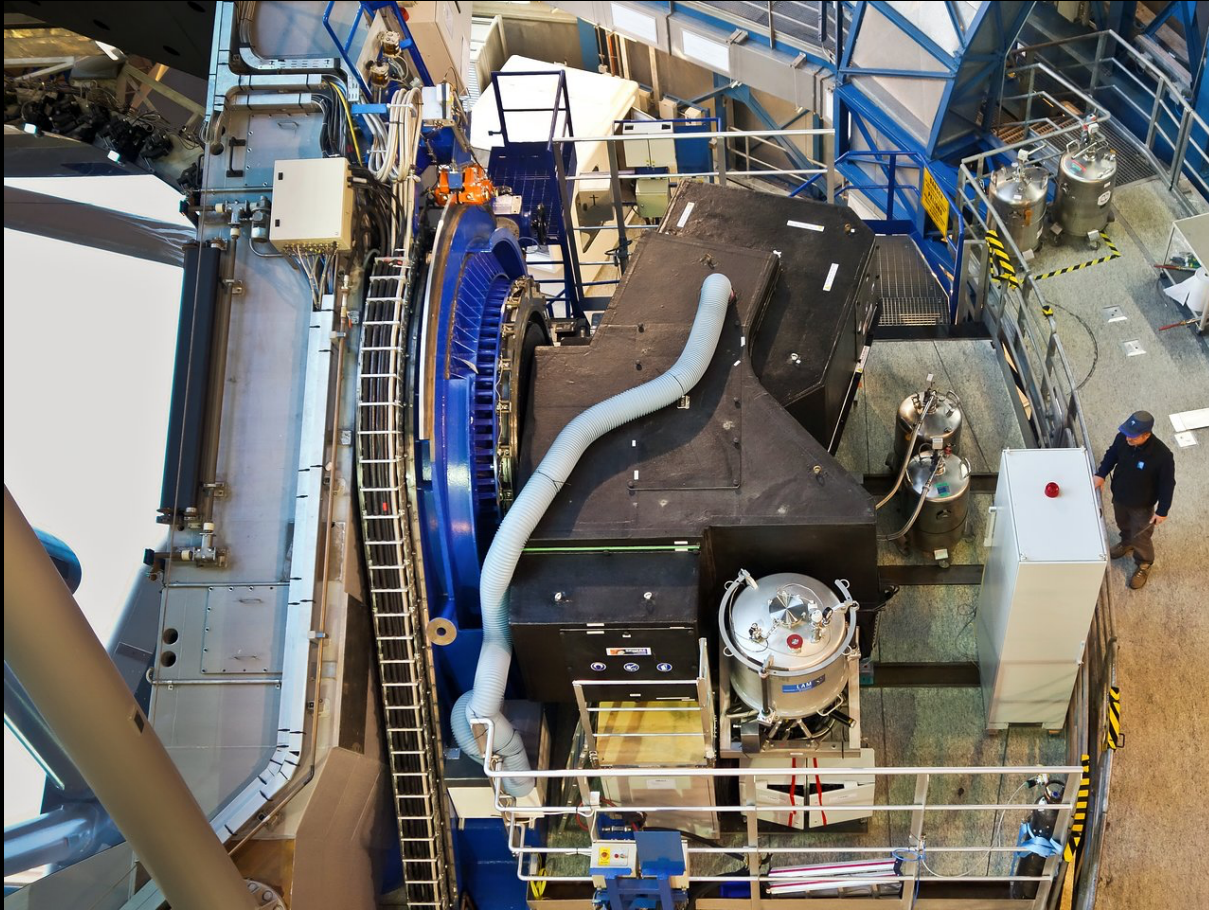


Leleu et al. sub.

“A major point of contention for population synthesis [with migration] has been to over produce resonant pairs. However, by extrapolating the rate at which resonance broke during the first 100 Myr of post disk evolution [...], we have shown that we expect less than ~9% of resonant pairs by 5 Gyr, which is closer to the observed rate of a few percent, as well as the overall occurrence of resonances as function of stellar age”

One of strongest statistical evidences to date that orbital migration is widespread & key constraint for sub-Neptune and super-Earth formation models (not in situ)

2b. Direct imaging - luminosities - CA and DI



SPHERE-SCIENCE 25 March 2010 at 13:09



Markus Feldt

[Science] Science with SPHERE - Special Meeting Thu, Apr 2nd, 10:30, MuFu

To: science@mpia.de



This message is from a mailing list.

Dear All,

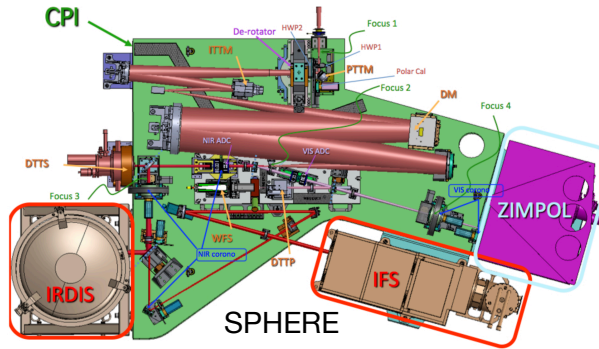
as described in the recent house colloquium, the planned first light of the SPHERE instrument is drawing nearer. dedicated instrument for direct exoplanet rese



A look back: early comparison with SPHERE GTO

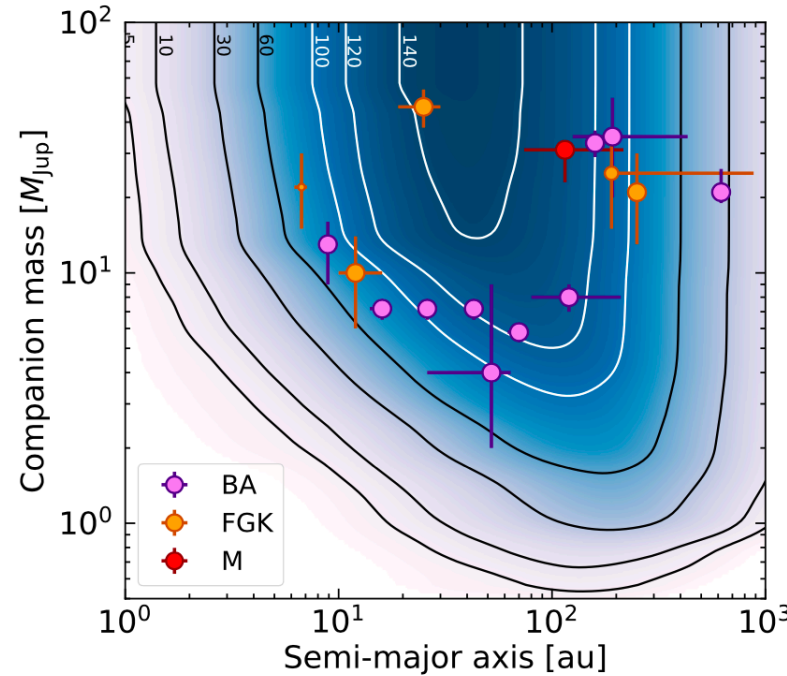
SPHERE@VLT SHINE GTO
survey (Vigan et al. 2020)
150 stars (initial analysis)

cf. Nielsen et al. 2019 GPIES

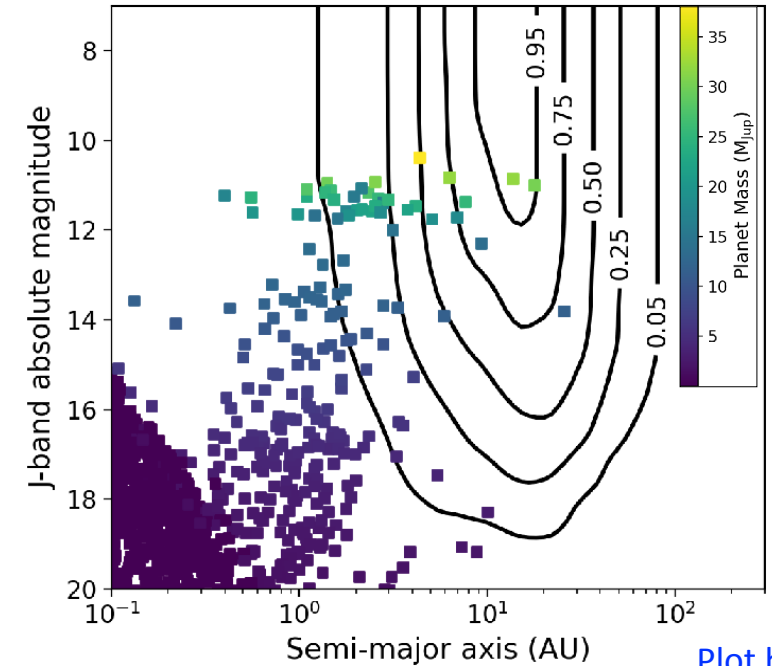


Probes very different kind of planets
and a different observable
(magnitudes / luminosity)

Actual detections & sensitivity maps



Synthetic population & sensitivity maps

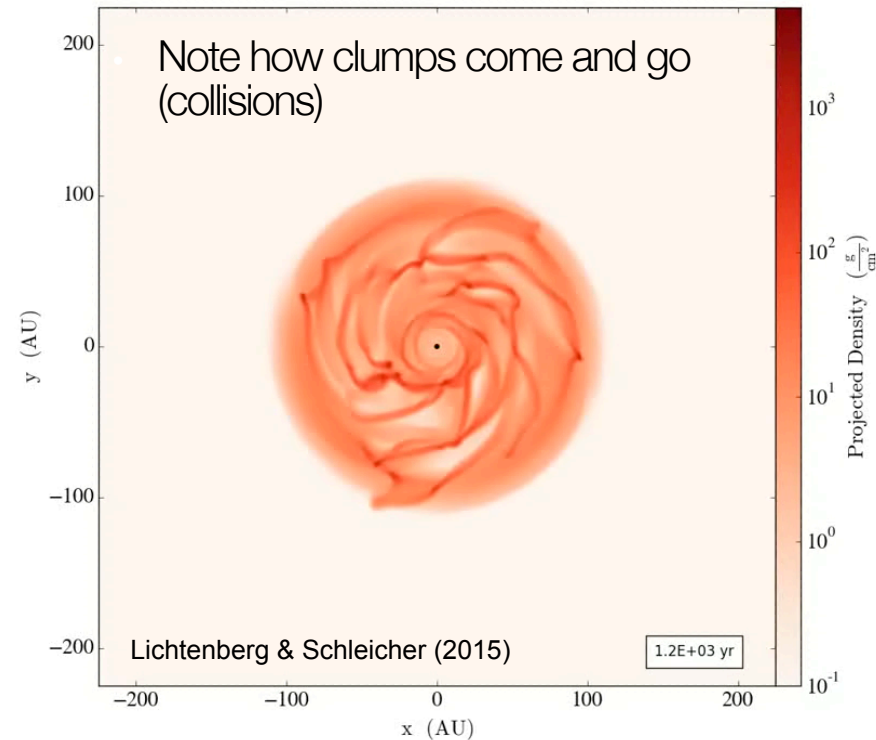


Comparison of synthetic CA population with SPHERE SHINE results

- Distant giants in core accretion synthesis: Single, massive, eccentric planets from scattering events (see Marleau+2019b)
- **Disagreement:** too few distant giant planets especially around M-dwarfs
- **Disagreement:** No HR 8799-like systems: 4 distant massive giants on ~circular orbits
- Structured disks? Formation by **gravitational/disk instability?**

New global GI formation model and population synthesis: (Disk Instability Population Synthesis DIPSY)

Hydrodynamic models: no statistics



Previous global models & disk instability syntheses (e.g., Forgan, Rice+2013, 2018, Nayakshin+2015):

- start from unstable disks: no predictions of absolute companion occurrence rates
- less linked to observational constraints on disk properties
- less recent input physics

Our approach (DIPSY, [Schib+2021](#), [2022](#), [2023](#), [2025a,b](#))

Take a step back: start from infalling star+disk system, track fraction of disk becoming unstable, follow fragmentation and clump formation and evolution.

Make quantitative comparisons with observations possible: DIPSY as first GI pop. synth. able to predict absolute frequencies of companions.

DIPSY model: 3 linked parts

Disk Model

- 1-D (radial) viscous disk
- Infall, photoevaporation
- Variable α (background, global instability, Q-dependent)
- Auto-gravitation for Ω and H
- Vertical temperature model (viscous heating, stellar irradiation, shock heating)

Clump formation and evolution

- Dyn. inserted in fragmenting parts (Toomre & cooling criteria)
- Initial clump mass (spiral arm dens. perturbations)
- Clump interior evolution tracks: cooling, contraction, second collapse (H_2 dissociation)
- Growth by gas accretion (Bondi)
- Clump destruction: thermal, tidal

Interactions

- Clump-gas disk: orbital migration, e/i damping (torque dens & dyn. friction)
- Clump-clump: explicit 3D N-body integration (Mercury), collision detection

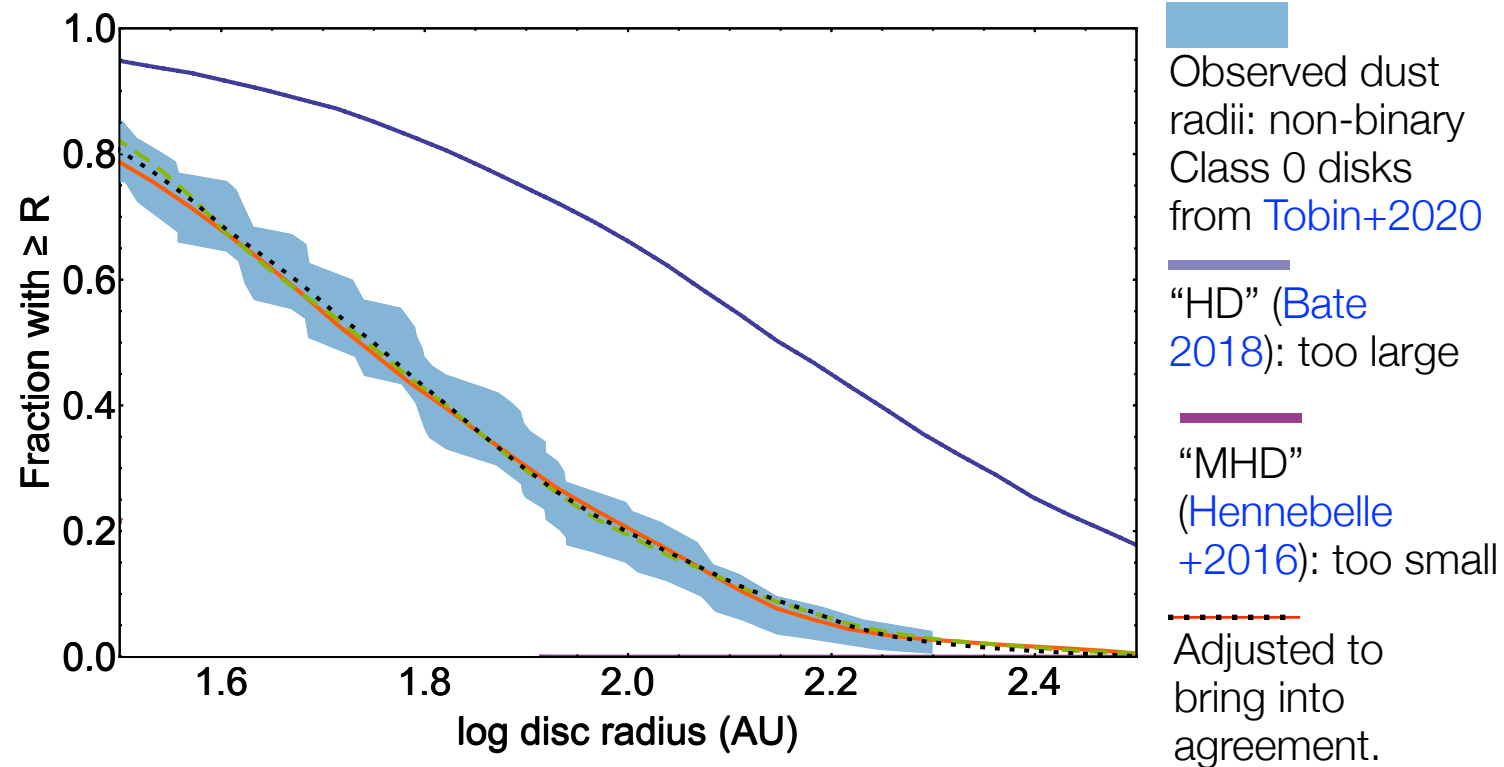
[Hueso & Guillot 2005](#), [Kratter+2010](#), [Kimura+2016](#), [Nakamoto & Nakagawa 1994](#), [Toomre 1964](#), [Gammie 2001](#), [Vazan & Helled 2012](#), [D'Angelo & Lubow 2010](#), [Kratter+2021](#), [Humphries +2019](#), [Boley+2010](#), [Ida+2020](#), [Chambers 1999](#)

Initial conditions and Monte Carlo variables

- Star and disk built up by infall from molecular cloud core from small initial values
 - $M_{\text{star,init}} = 0.05 M_{\text{sun}}$
 - $M_{\text{disk,ini}} = 0.015 M_{\text{sun}}$
- Final host star masses: 0.1 to 5 M_{sun}
- Distribution infall rates from hydrodynamic simulation (Bate 2018). Average $3 \times 10^{-5} M_{\text{sun}}/\text{yr}$. Constant in time.
- Distribution of infall durations chosen such that get initial mass function IMF for host stars (Chabrier 2005). Average 30 kyr.
- Fixed parameters:
 - Background viscosity
 - External photoevaporation rate

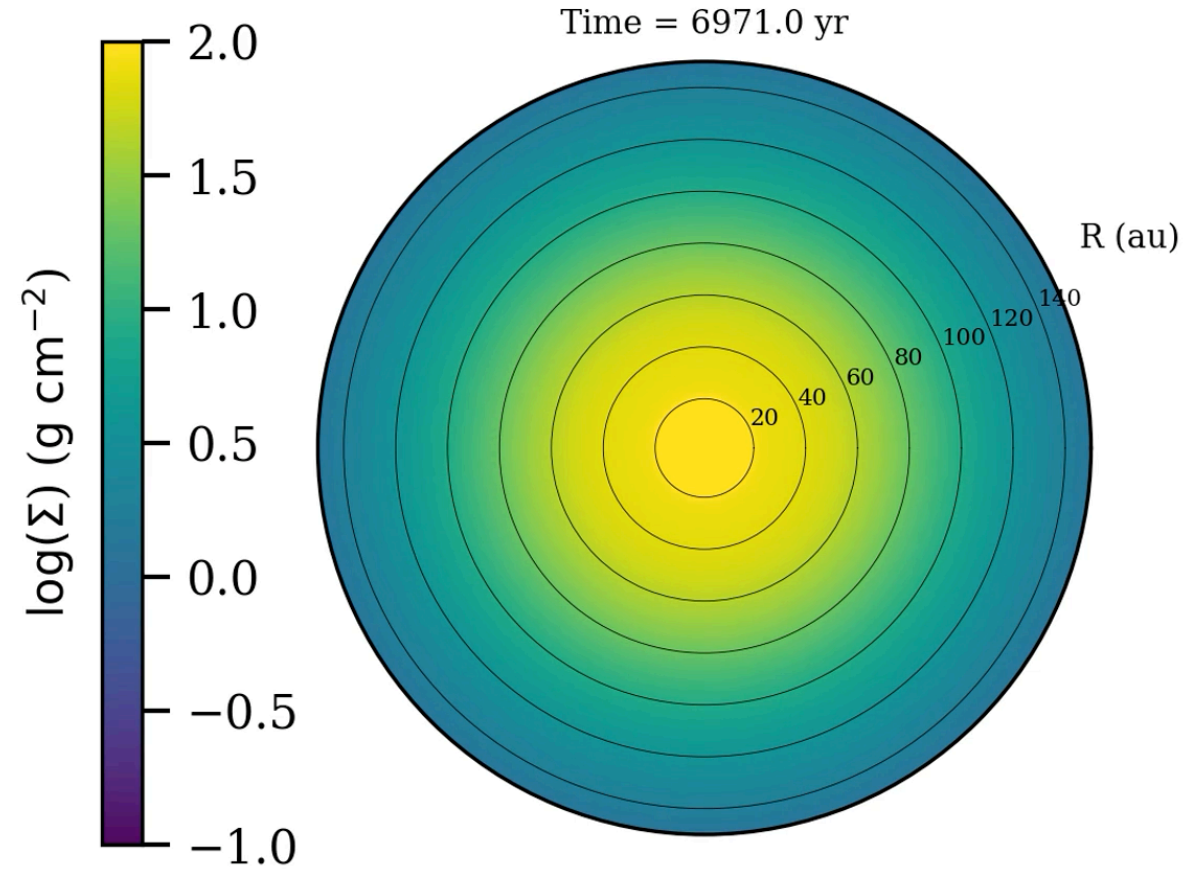
- Distribution of infall locations onto disk: such that synthetic disk radii fit observed class 0 disk sizes (observationally informed)

Distribution of disk outer radius in synthetic disk populations at end of infall phase for different infall location prescriptions (Schib+2023).



Almost all discs have self-gravitating phase, but only 10-20% fragment.

Some example synthetic systems

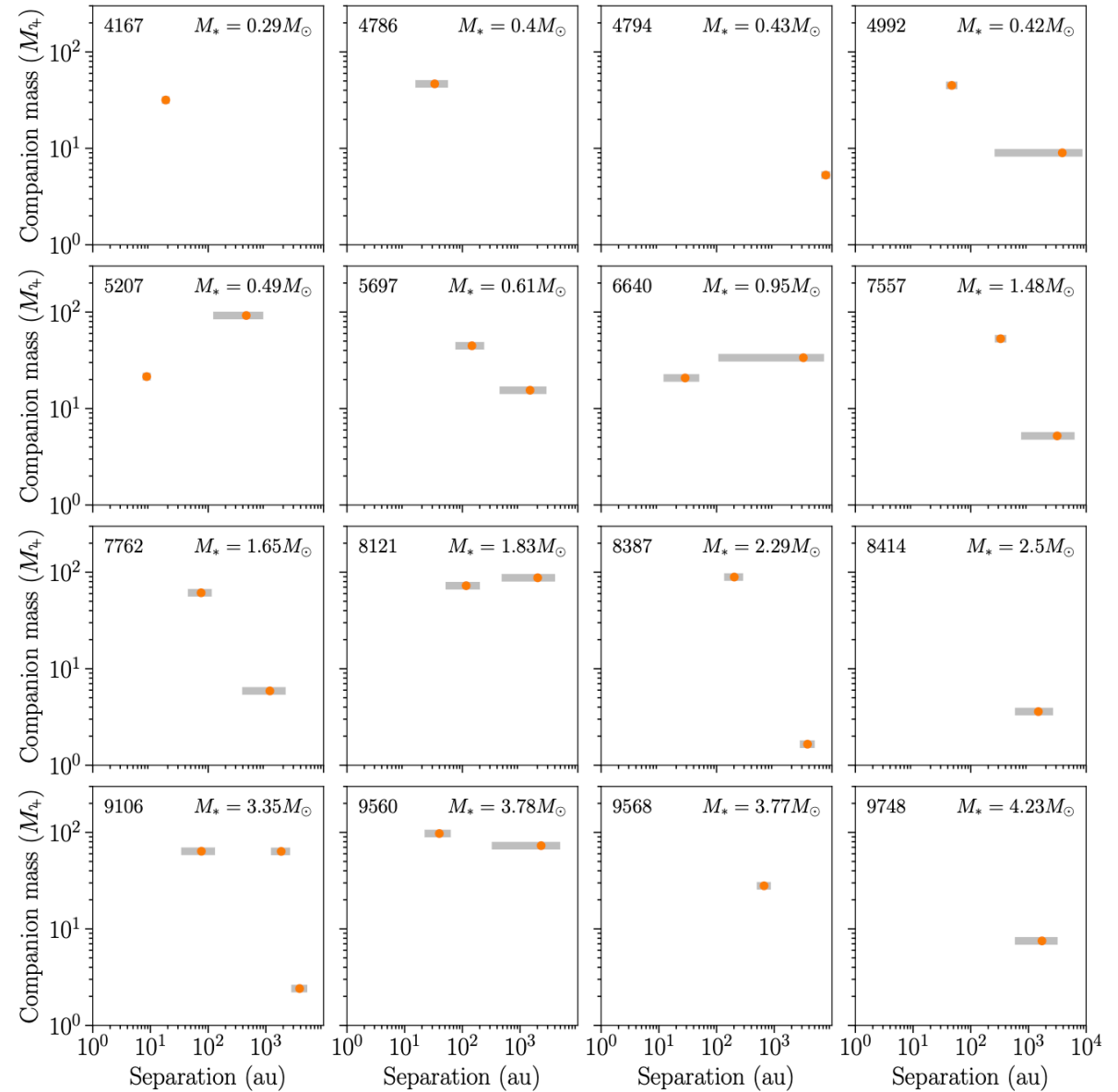


High number of clumps formed per fragmenting disk

- typical number $\sim 10\text{-}30$ initial clumps / disk
- reason: continuing infall

Strong dynamical interactions among clumps

- Collisions (AU-size before 2nd collapse!)
- Scatterings
- Ejections



Final architecture: Usually one, sometimes two, rarely 3 companion.
Very low survival rate for initially formed clumps

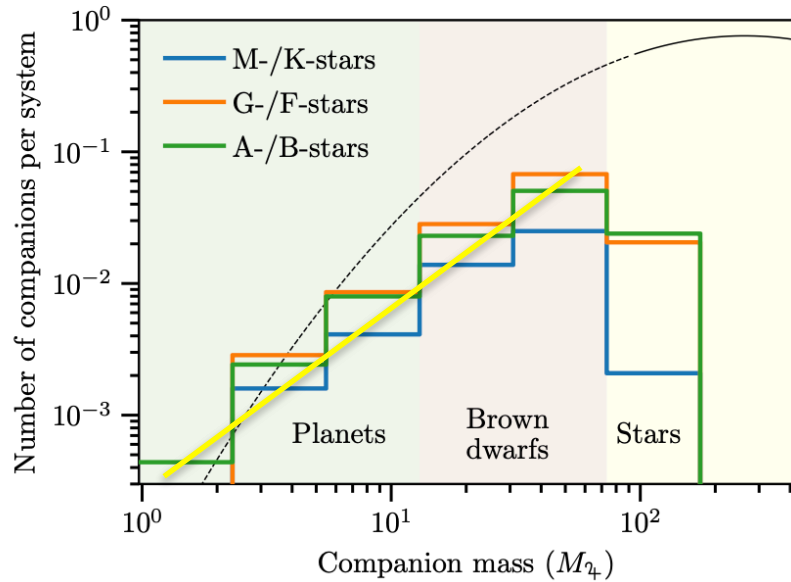
Essential demographic distributions (synthetic)

Mass distribution

LMS (15 %), BD (75 %), PMO (10 %)

Unimodal, $N \propto M^{1.1}$

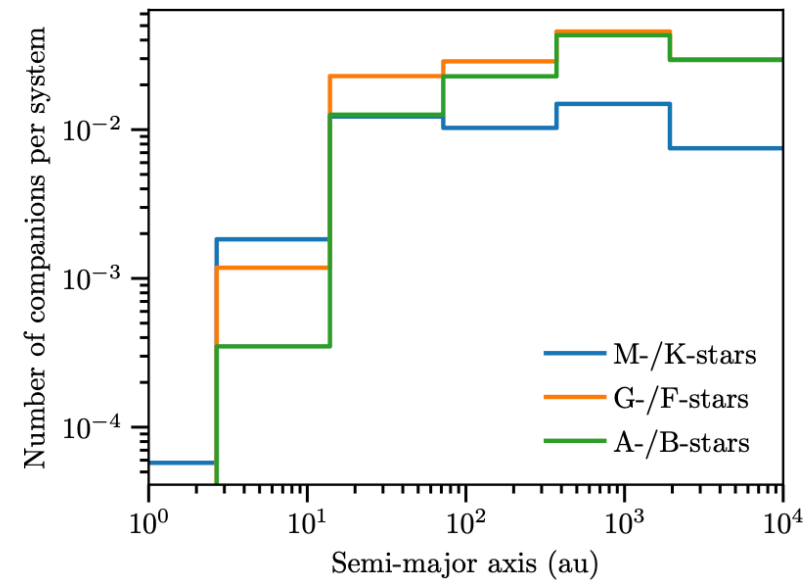
Opposite to CA.



Distance distribution

Strong drop inside of ~ 20 AU.

Uniform in log outside

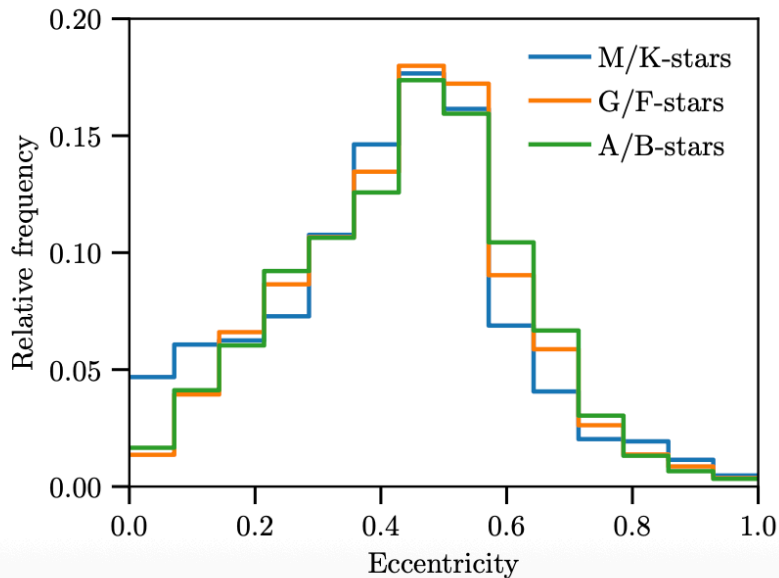


Eccentricity distribution

Wide range

High average value, peaking at ~ 0.5

Scattering events

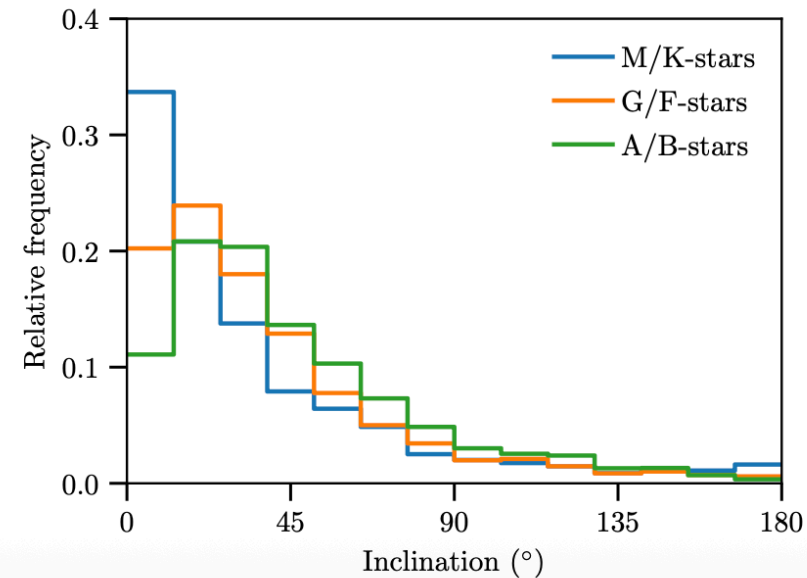


Inclination distribution

Significant inclinations

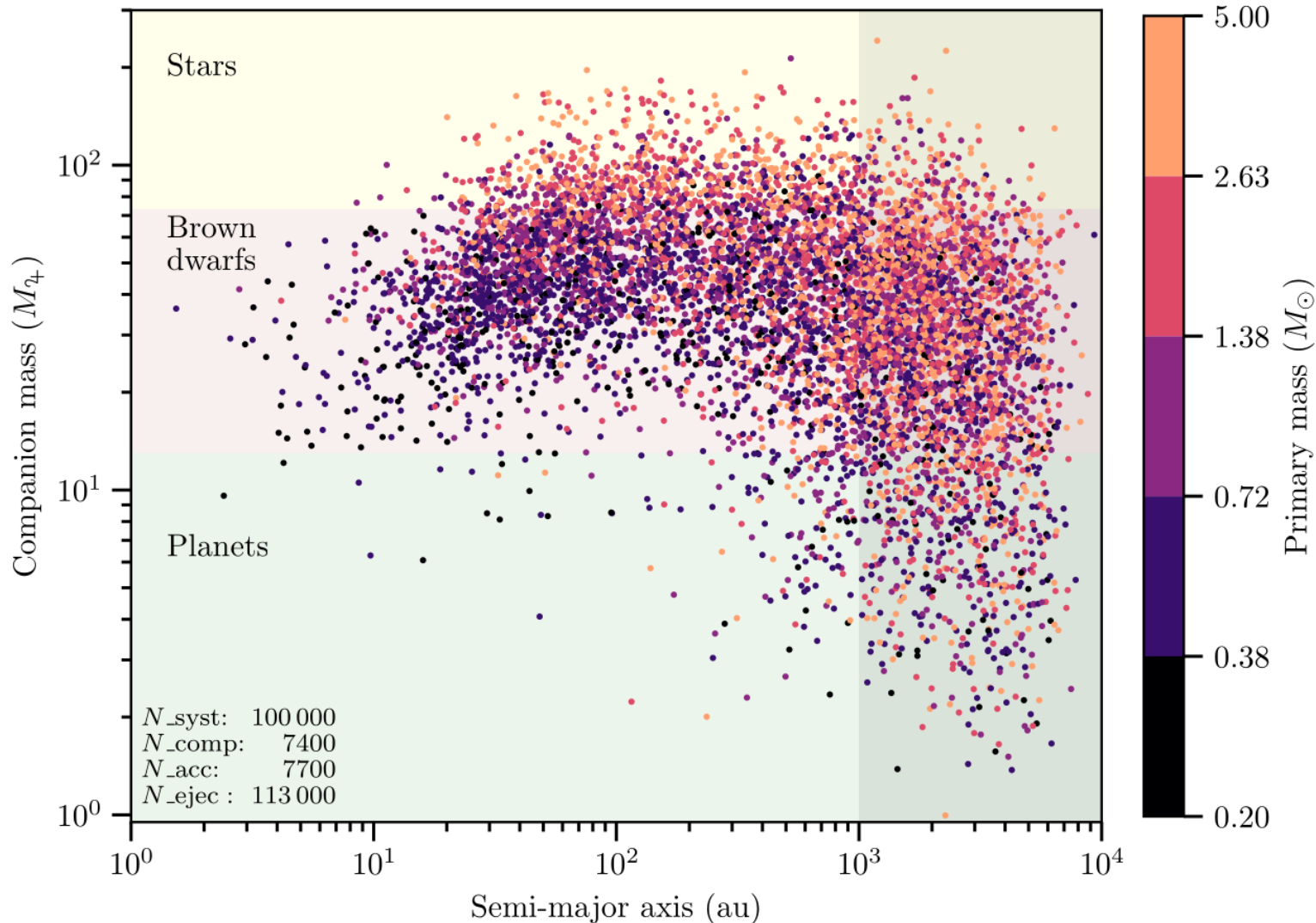
Tail to polar/retrograde

Trends with host star mass, but generally rather weak.



Predicted mass-distance diagram

Baseline population DIPSY-0 Schib+2025a,b

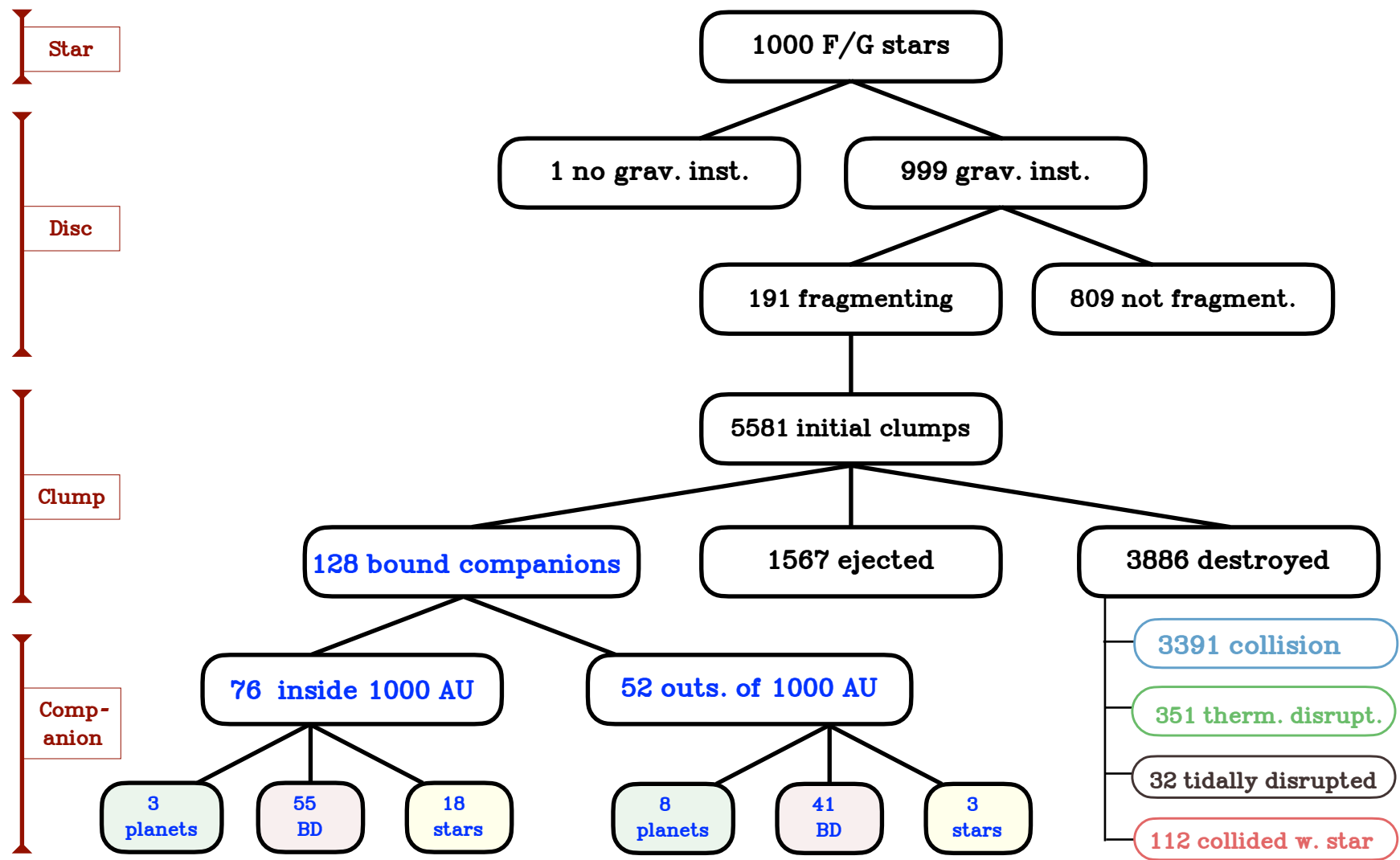


- Inverted and rotated **'L' shape** with remarkable paucity of planetary-mass companions inside 100-1000 AU
- If fragmenting, in disk enough surrounding mass to grow to BD regime (Kratter+2010)
- To stay at lower (planetary) mass, must be scattered out of gas disk
- Analogy to (former) picture of low-mass star formation via ejection (Luhman 2012).

Synthetic population can be downloaded at

https://www.space.unibe.ch/research/research_groups/theoretical_astrophysics_and_planetary_science/taps/numerical_data/index_eng.html

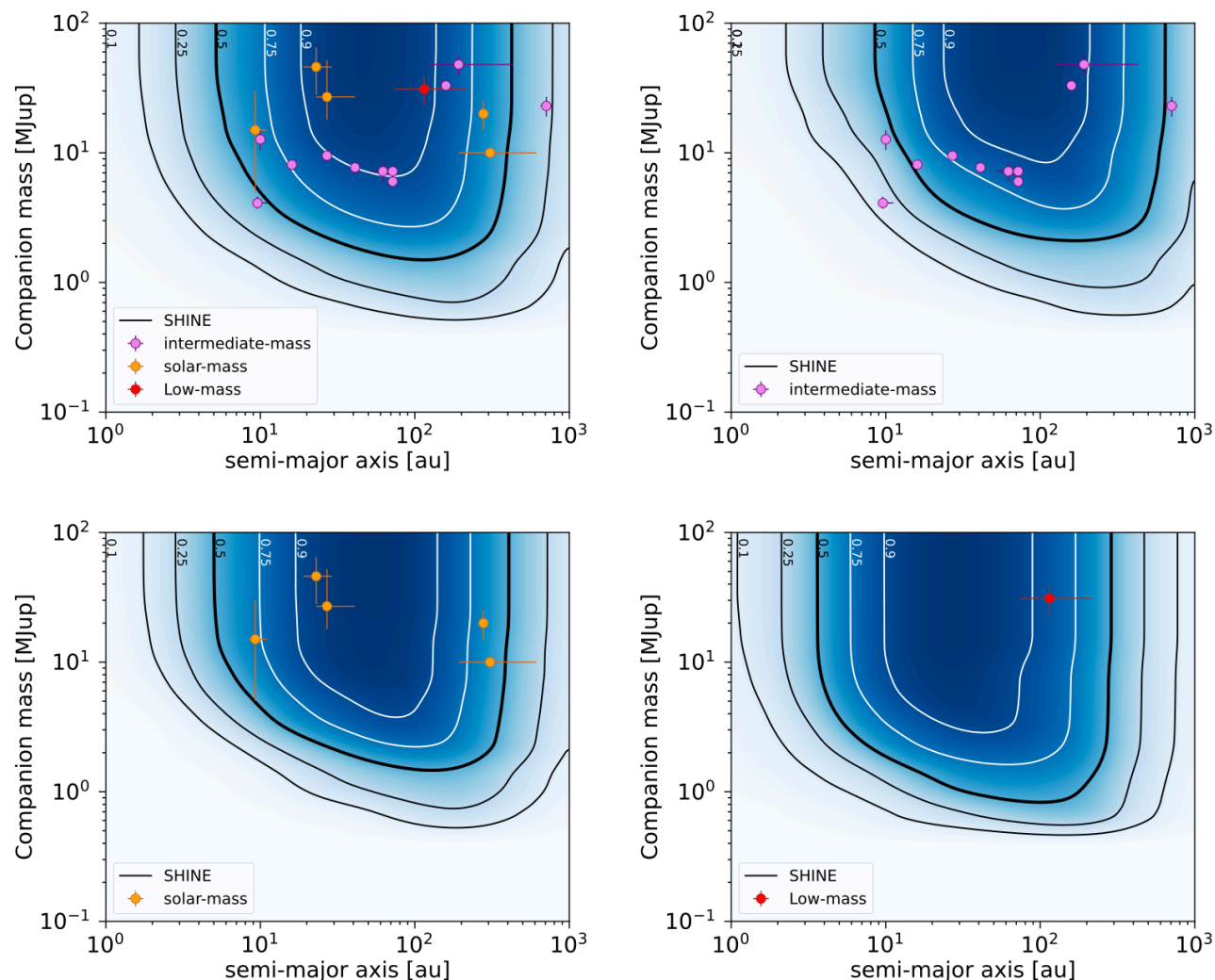
Quantitative outcome for F/G hosts



But how does this compare with reality?

Comparison with SPHERE (full sample)

Final survey analysis with 333 stars, along with survey discoveries and detection completeness



Observed occurrence rates w. BEX-COND-hot
a=5-500 AU, M=1 - 75 M_J

Population	intermediate-mass [>1.5 M _☉]	solar-mass [0.8–1.5 M _☉]	low-mass [<0.8 M _☉]
Full	13.2 ^{+6.8} _{-4.6} %	4.1 ^{+2.6} _{-1.8} %	2.9 ^{+2.7} _{-1.6} %
Planet-like	7.7 ^{+6.3} _{-4.2} %	< 4.9 %	< 5.1 %
BD-like	4.1 ^{+2.6} _{-1.8} %	2.7 ^{+2.0} _{-1.3} %	1.4 ^{+2.0} _{-1.1} %

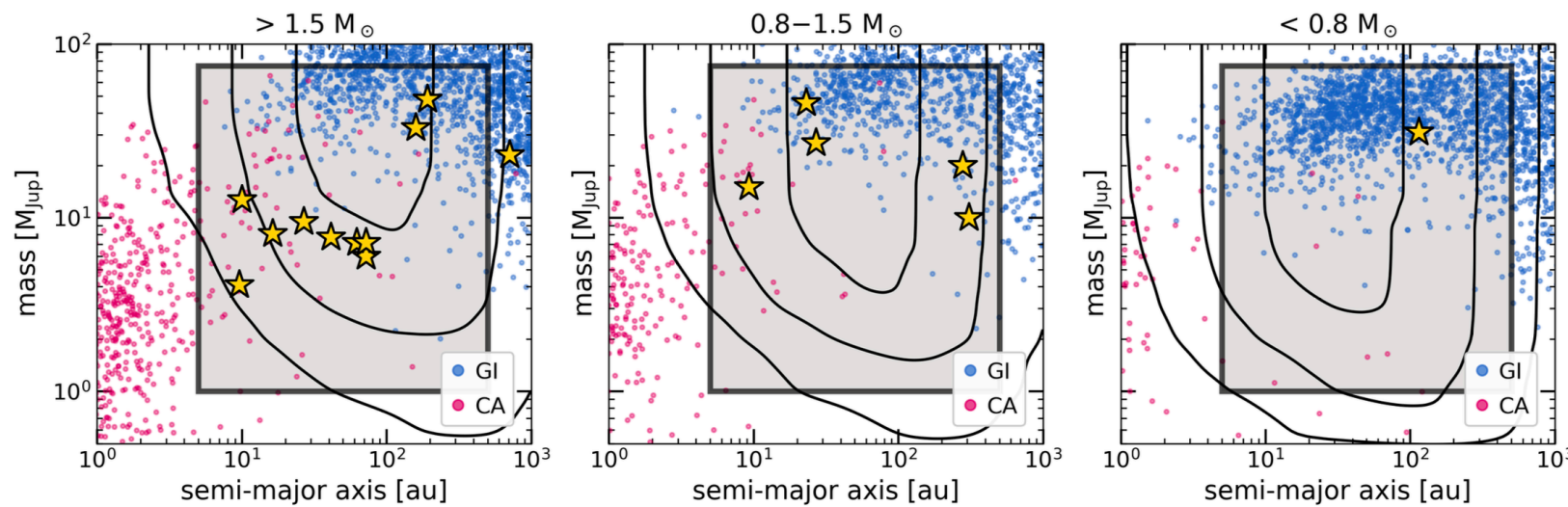
- Total substellar companion frequency decreases with decreasing host star mass
- Relative contributions of components (parametric models) vary with host star mass
 - bottom-up component (planet-like) dominates around intermediate-mass stars
 - Top-down pathway (BD-like) main contributor for solar-mass and low-mass hosts.

Comparing combined NGPPS + DIPSY with SHINE

Apply survey detection bias to combined core accretion (NGPPS, CA, red points) and disk instability (DIPSY, GI, blue points) populations.

What would SHINE have detected?
How does this compare to reality?

Shine collaboration (Fontanive, Chauvin, ...) in prep.



Model	intermediate-mass [>1.5 M _⊙]	solar-mass [0.8–1.5 M _⊙]	low-mass [<0.8 M _⊙]
CA (NGPPS)	6.4%	3.2%	0.6%
GI (DIPSY)	2.0%	4.2%	4.6%
Total synth.	8.4%	7.4%	5.2%
Total obs.	8.6-20.1%	2.3-6.7%	1.3-5.6%

Frequencies Combined synth. populations recover observed frequencies at all stellar masses at 1–1.5σ. Both in

- absolute frequencies as function of stellar mass
- relative contributions of CA & GI as fct of stellar mass

Non-trivial. Neither pop. optimised. Important factors:
CA: Planetesimal size chosen to get ~10⁵ yr core growth timescales; GI: disk sizes from observations.

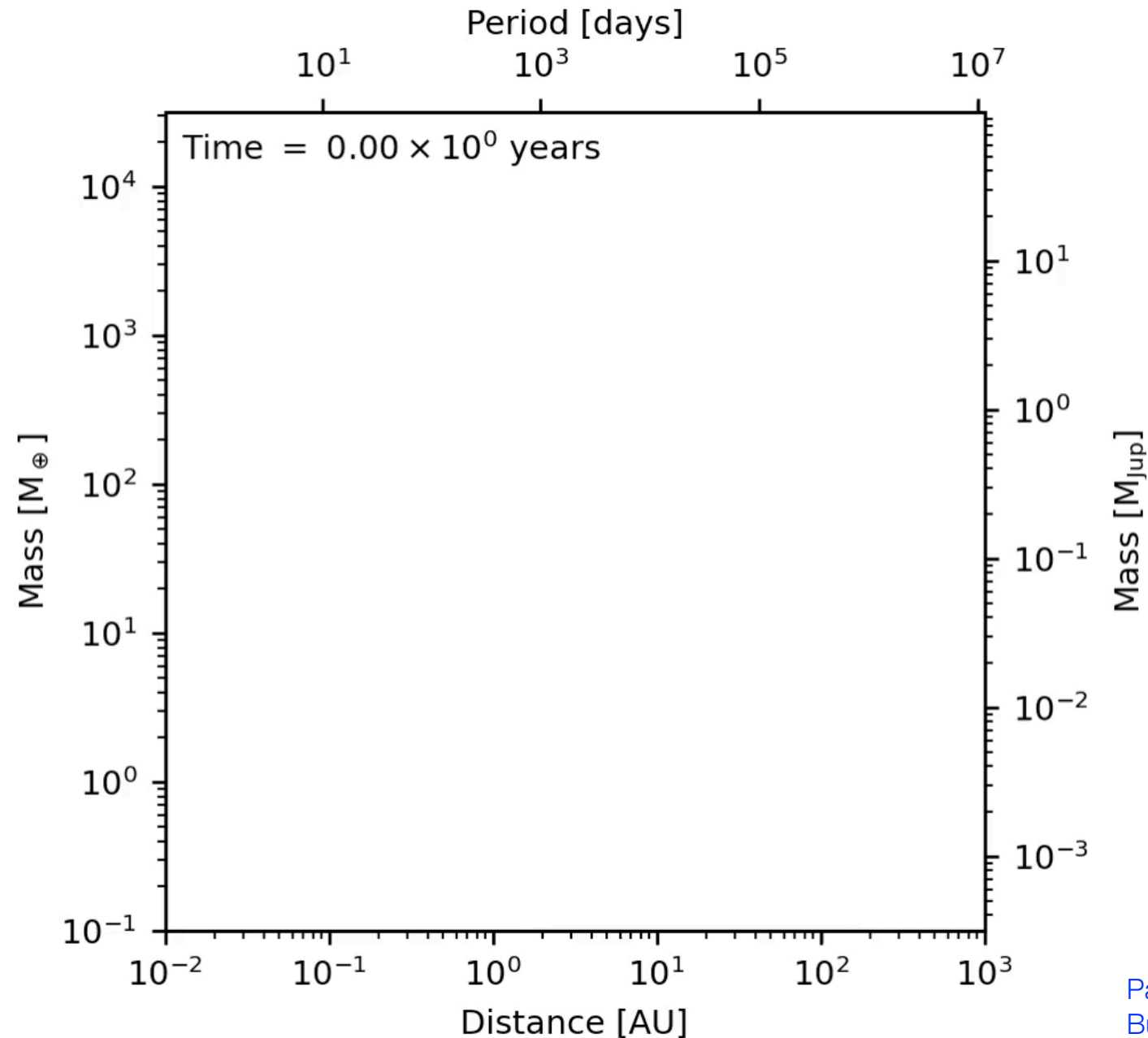
Comparing same CA population to RV HARPS GTO survey (Emsenhuber+2025) and Kepler (Matuszewski+2023): too many planets (factor ~2)! Would scale together.

Conclusion: Gen 3 Model lacks giant planet formation at large distances. Candidate processes: pebble accretion, structured disks, lower disk viscosities. ⇒ *Gen 4 model*.

Distribution in a-M plane

- null hypothesis of the combined GI+CA populations cannot be ruled out for any stellar subsets
 - CA alone always ruled out
 - GI-alone only ruled out for intermediate-mass stars
- But still no HR8799-like systems.

NGPPS population synthesis 1 M_⊙



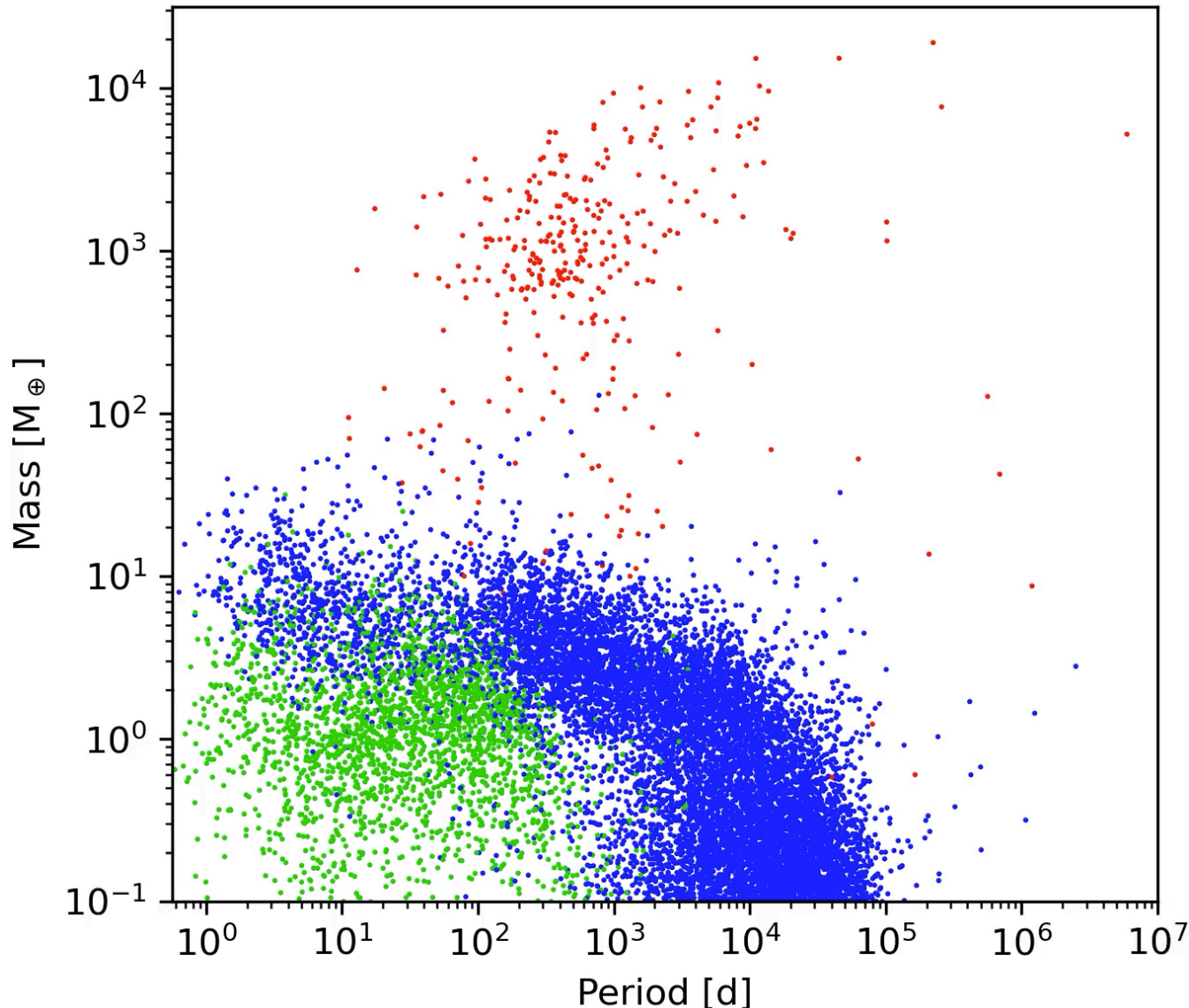
Bern Gen III model used to generate the *New Generation Planetary Population Synthesis, NGPPS*

- 1000 systems (stars); solar-like host stars
- 100 initial embryos per system of $1 M_{\text{luna}}$
- 4 Monte Carlo variables: $[M/H]$, initial disk gas mass, external photoevaporation rate, disk inner edge

- Gas-dominated
- silicate/iron
- with volatiles
- Lost
- Eccentricity
- ⊗ Solar system

Papers: NGPPS I-VIII: [Emsenhuber+2021a,b](#); [Schlecker+2021a,b](#),
[Burn+2021](#), [Mishra+2021](#), [Chengplus](#) [Emsenhuber+2023](#), [Burn+2024](#), ...

Mass-distance diagram



- **Agreement:** similar envelope of points: variation of initial conditions over observed range sufficient to produce similar diversity as observed in HARPS
- **Agreement:** similar global structures: relative distribution (concentrations, voids) with two main groups: close-in low mass and distant giants
- **Disagreement:** Synthetic population still does not have as much diversity as observed
 - Too much concentration into the two groups
- **Disagreement:** Absence of Hot Jupiters. Not formed in model by disk migration (slowing down in disk-dominated regime - to be checked by torque-based Type II migration model)
 - Planet scattering or Kozai-Lidov plus tidal circularisation partially missing in model (2nd formation channel)
 - There are actually “proto-HJ” in the population (some with high obliquities)