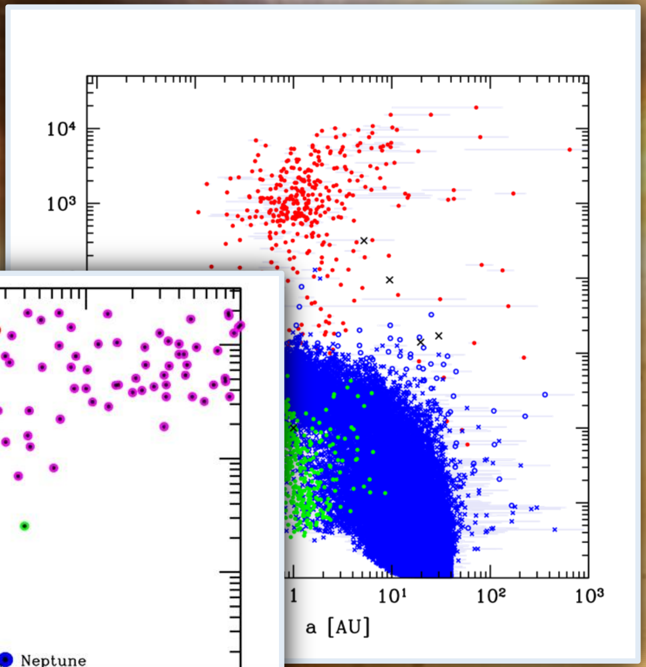
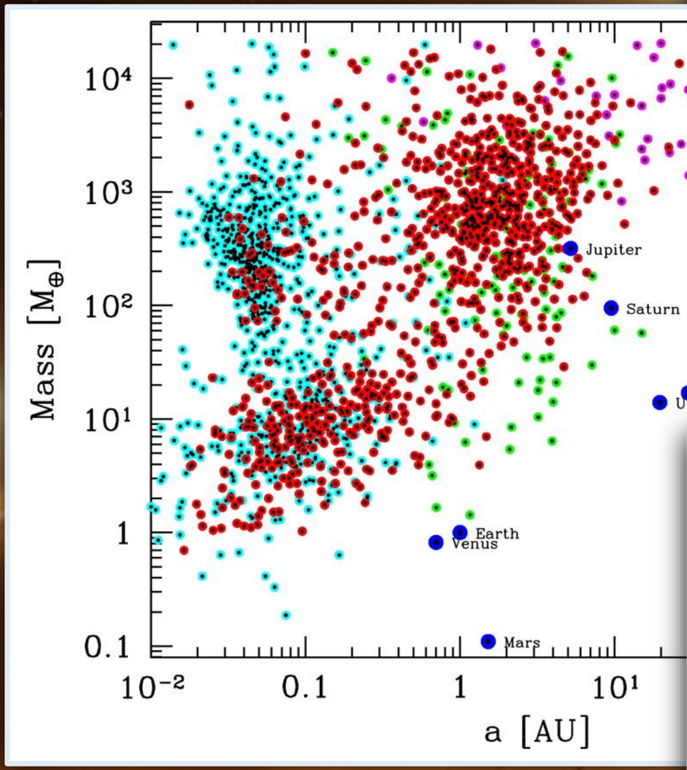
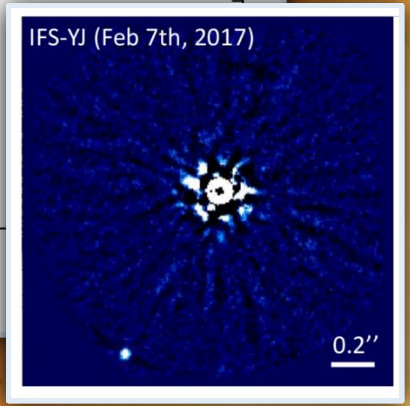
Planet demographics







Cool giants and their systems

30th anniversary of the discovery of
51 Peg b

Observatoire de la Haute-Provence

06.10.2025

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Caltech

UNIVERSITÄT BERN

PlanetS

Swiss National Science Foundation

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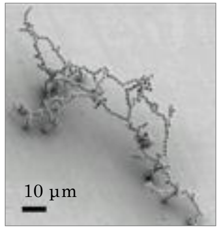
The underlying goal

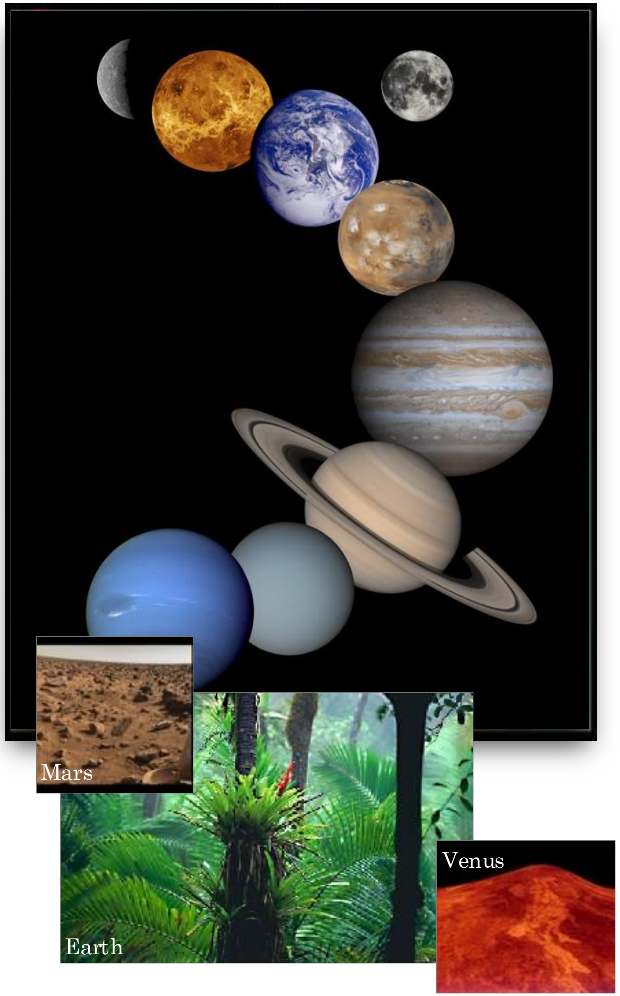
Understanding planet formation and evolution - and potentially the origin of life in the universe



5 Billion

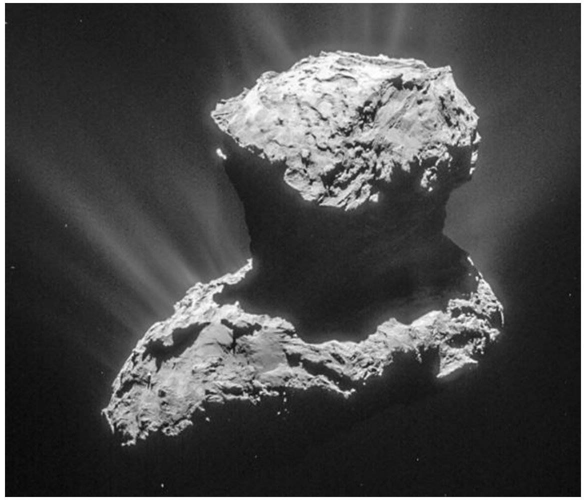
years

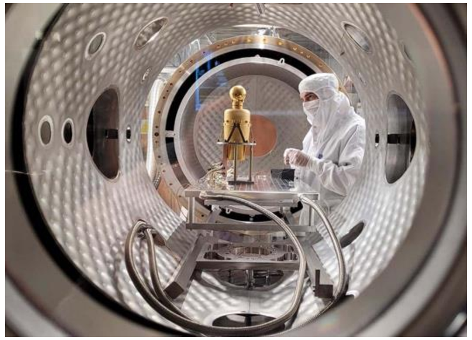
How?



From the origins to present day: a formidable task

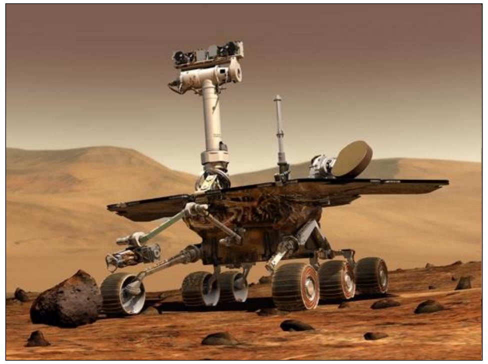
Observational constraints: the Solar System

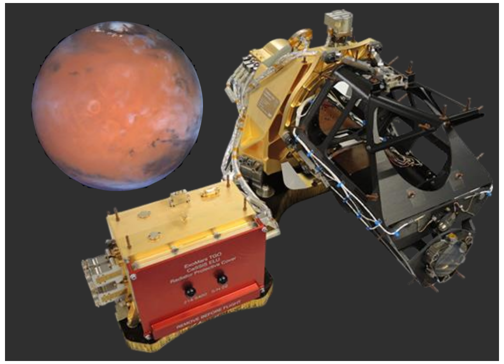




Centuries of solar system studies...

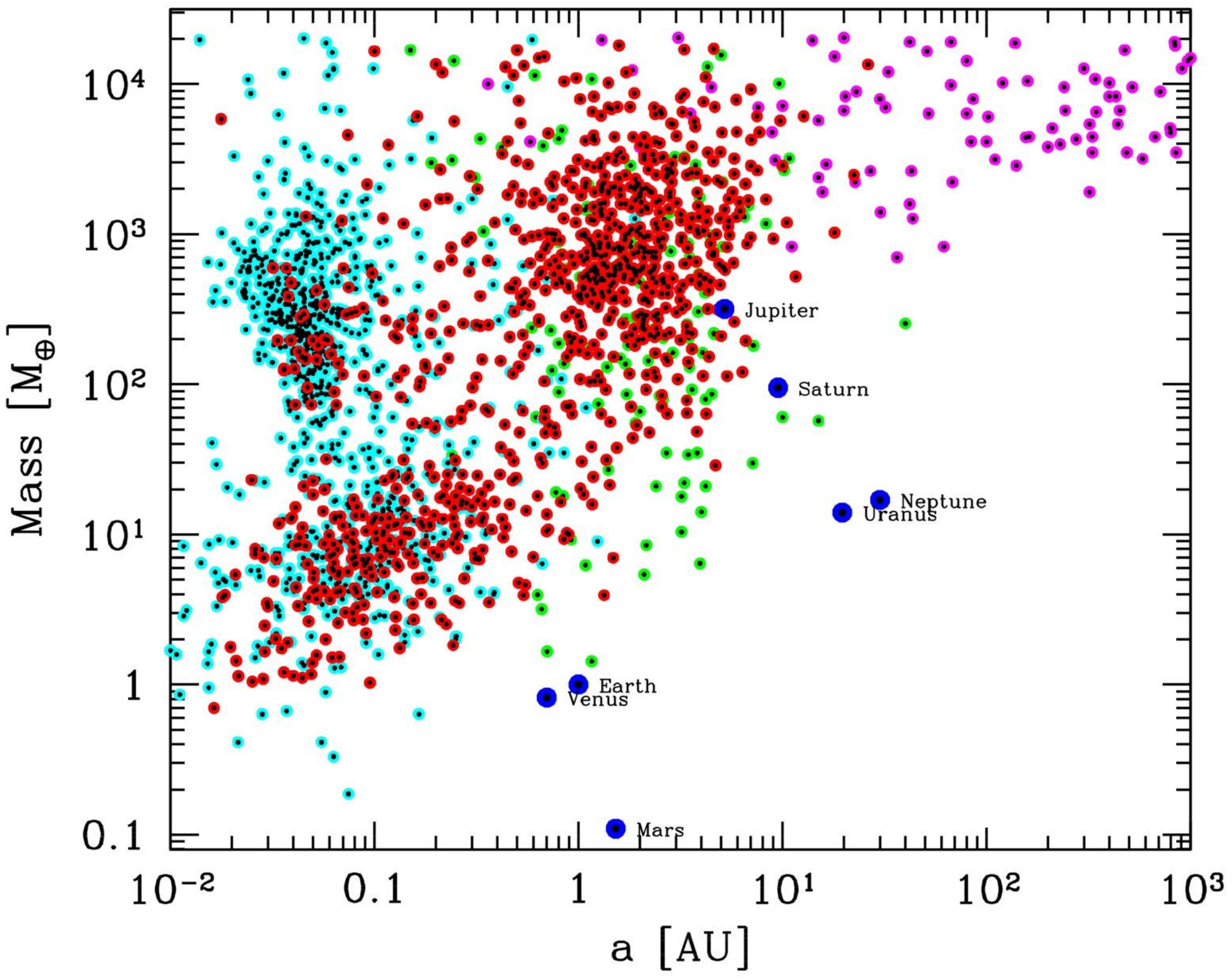
- *remote observations*
- *laboratory experiments*
- *in-situ measurements*
- *sample returns*





The benchmark system for theoretical models: detailed constraints

Observational constraints: extrasolar planets



Radial velocities
Transit photometry
Direct imaging
Microlensing

…30 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, …)

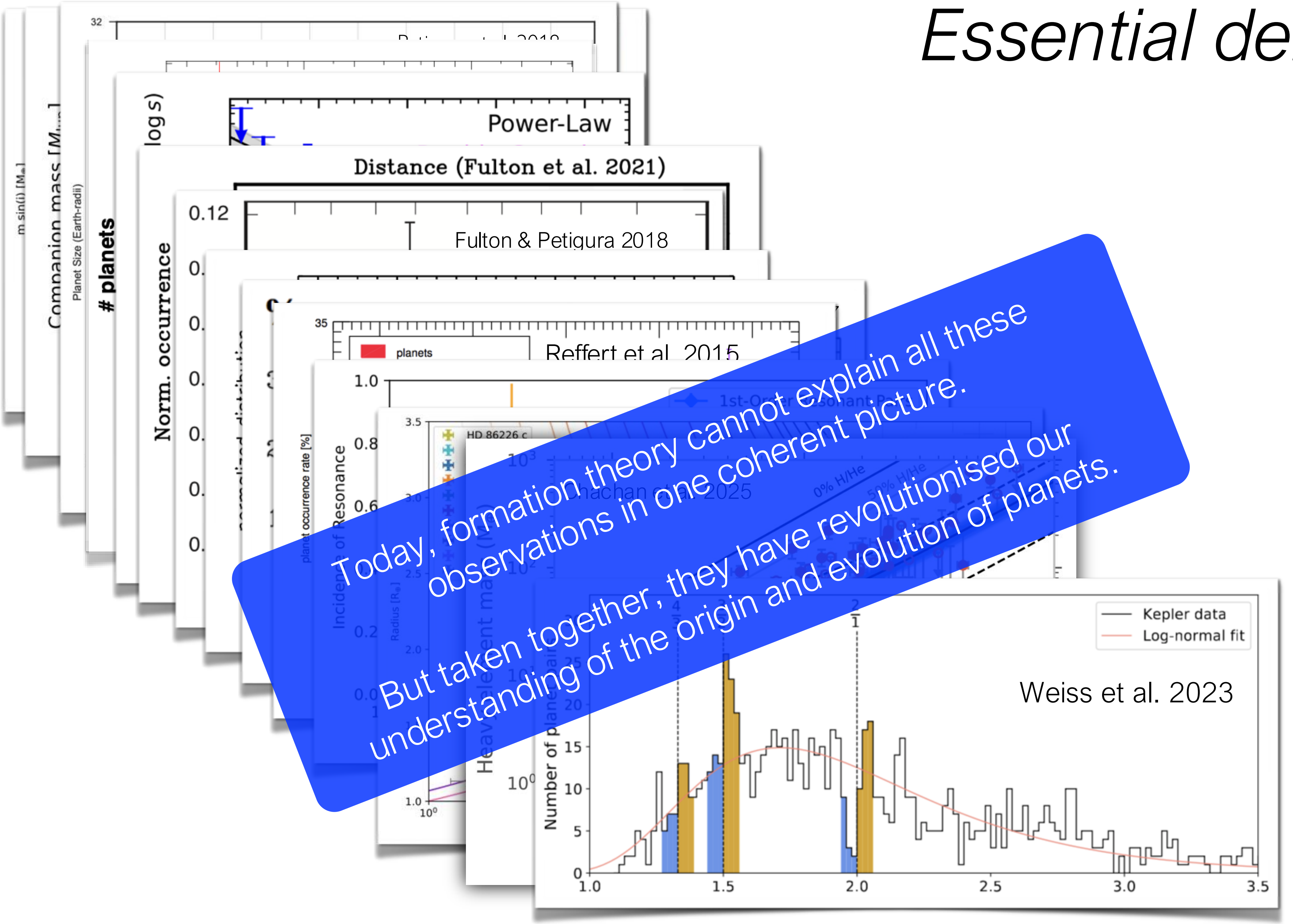
Little knowledge about individual systems, but *demographical constraints*:

-frequencies
-distributions
-correlations

A satisfactory theory must explain both aspects.

Essential demographics

- Occurrence rates of planet types
- period-M/R/mag diagrams
- Distributions: mass, distance, eccentricity
- Radius distribution, radius valley
- Stellar dependencies
  - [Fe/H], stellar mass, age, binarity
- Mass-radius relation, bulk composition
- Architecture (multiplicity, peas-in-a-pod, resonances, SE-CJ relation, composition)
- Atmospheric composition (JWST)



Today, formation theory cannot explain all these observations in one coherent picture.

But taken together, they have revolutionised our understanding of the origin and evolution of planets.

Combine constraints from all exoplanet observation methods plus Solar System and protoplanetary discs

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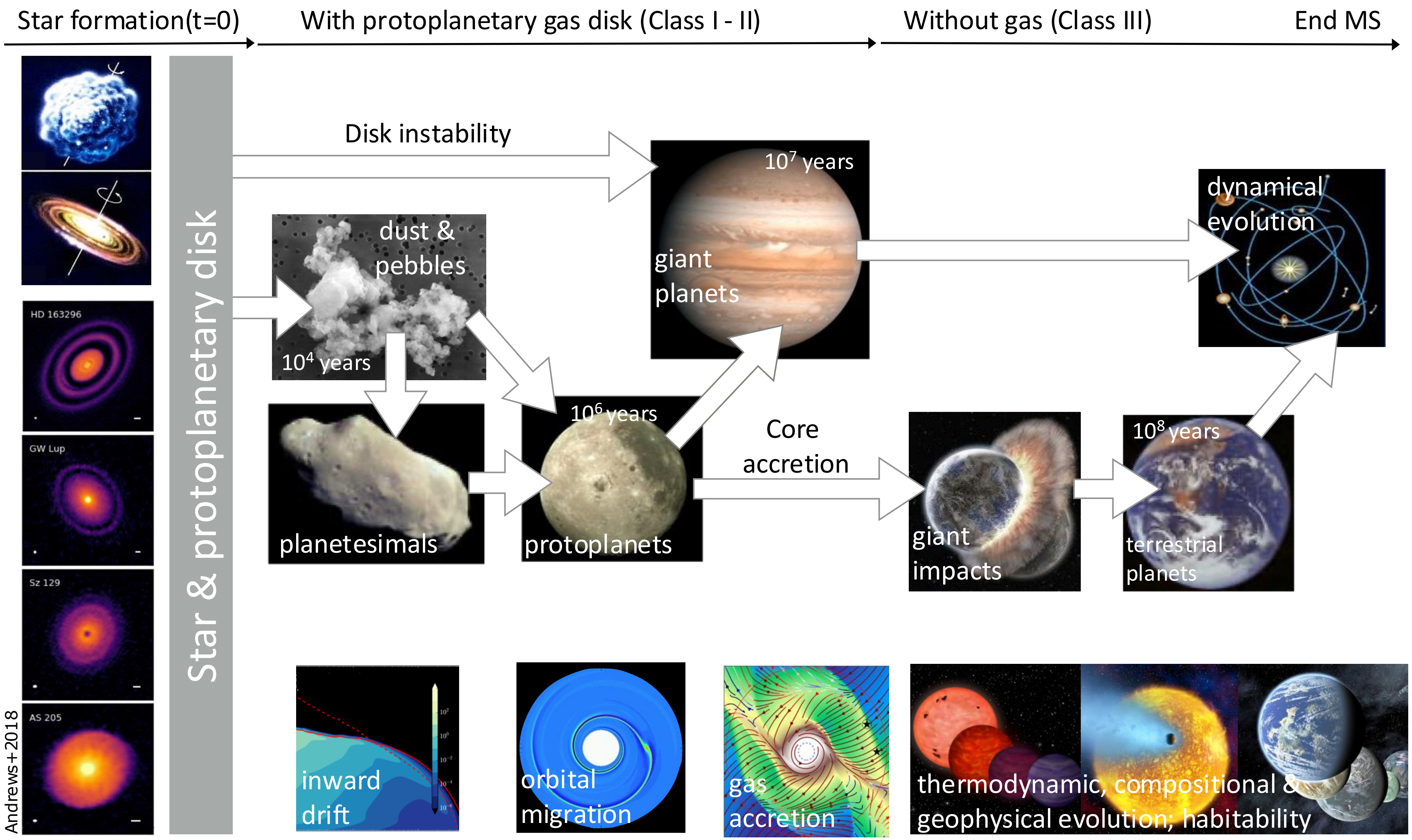
Planet formation - an evolving picture



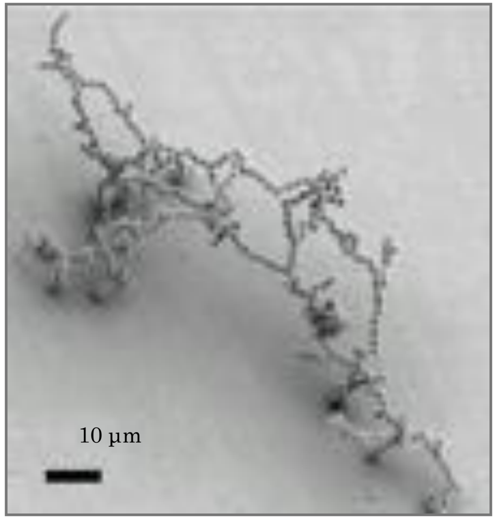
Shifts of paradigms

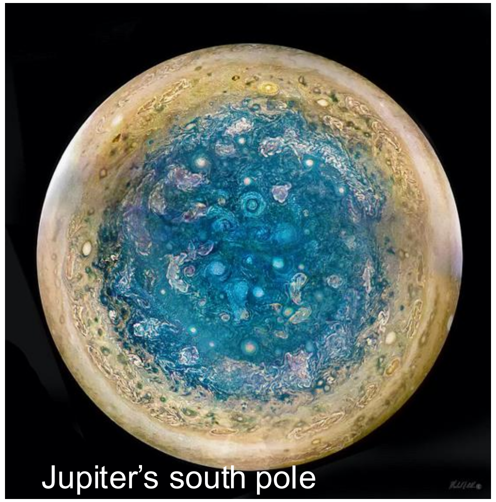
(relative to original Solar System formation theory)

- Mobility (both at pebble drift and planet migration level)
- Complexity of solid accretion (pebbles, planet-esimals, giant impacts)
- Disks: structures, MHD-winds, open system (link to star formation)

A lot of open questions remain….

Challenges in planet formation and evolution theory





Planet formation is a complex process

- Huge range in spatial scales: dust grains to giant planets
- Millions of dynamical timescales
- Multiple input physics: gravity, hydrodynamics, thermodynamics, radiative transport, magnetic fields, high-pressure physics,…
- Strong non-linear mechanisms and feedbacks

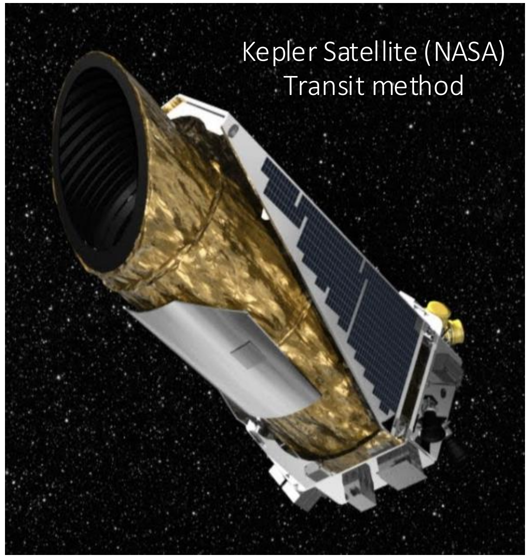
- Laboratory experiments only for special regimes
- Long-term 3D radiation-magnetohydrodyamic simulations too expensive

Cannot build theory based on first principles of physic only. Needs observational guidance via comparison with observations.

Compelling comparisons not so easy in practice:

- theoretical models for specific processes: difficult to test directly. Only result of non-linearly combination of all mechanisms observable.
- different observational methods probe only a given parameter space and/or only a few planet properties

Comparing theory and observations

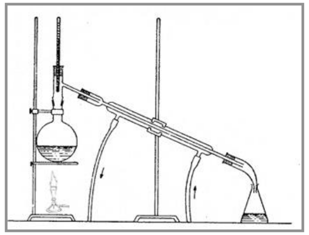


But: very high number of exoplanets know: they can be treated as a population with rich demographical constraints

Important needs for comparing theory and statistical observations

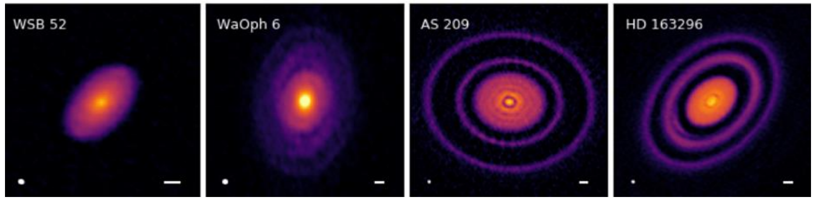
- detailed theoretical models to understand key individual physical mechanisms
- global end-to-end model predicting directly many observable properties
- large surveys with well-defined detection limits and host star samples
- different observational methods to get a more complete picture
- quantitative comparisons of observations and models with same cuts in planet properties, same host star samples in terms of metallicity, mass, age, binarity, etc.
- confronting same theoretical models with multi-data / multi-method observational constraints to fight parameter degeneracy and model uncertainty

Planetary population synthesis is a tool to use the wealth of demographic data and to build a bridge between theory an observation.



The principle

Andrews+2018

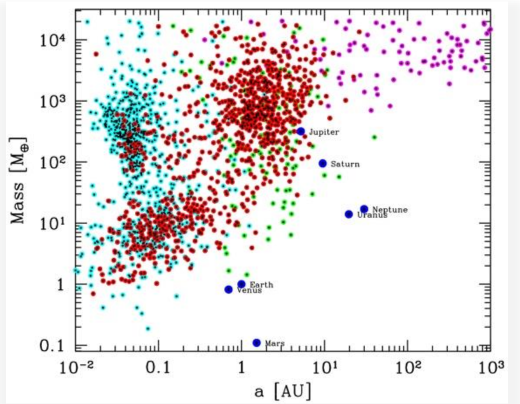


Models of individual processes
Accretion, migration, interiors, …

Global end-to-end formation & evolution model
Link 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 planet population



Observed population

Building Instrumentation
most compelling future observations

Apply observational detection bias

Predictions
(going back to the full synthetic population)

Stat. Comparison:
Observable sub-population
- Frequencies
- Orbits, masses, radii, luminosities
- Architecture, multiplicity
- Correlations

.....

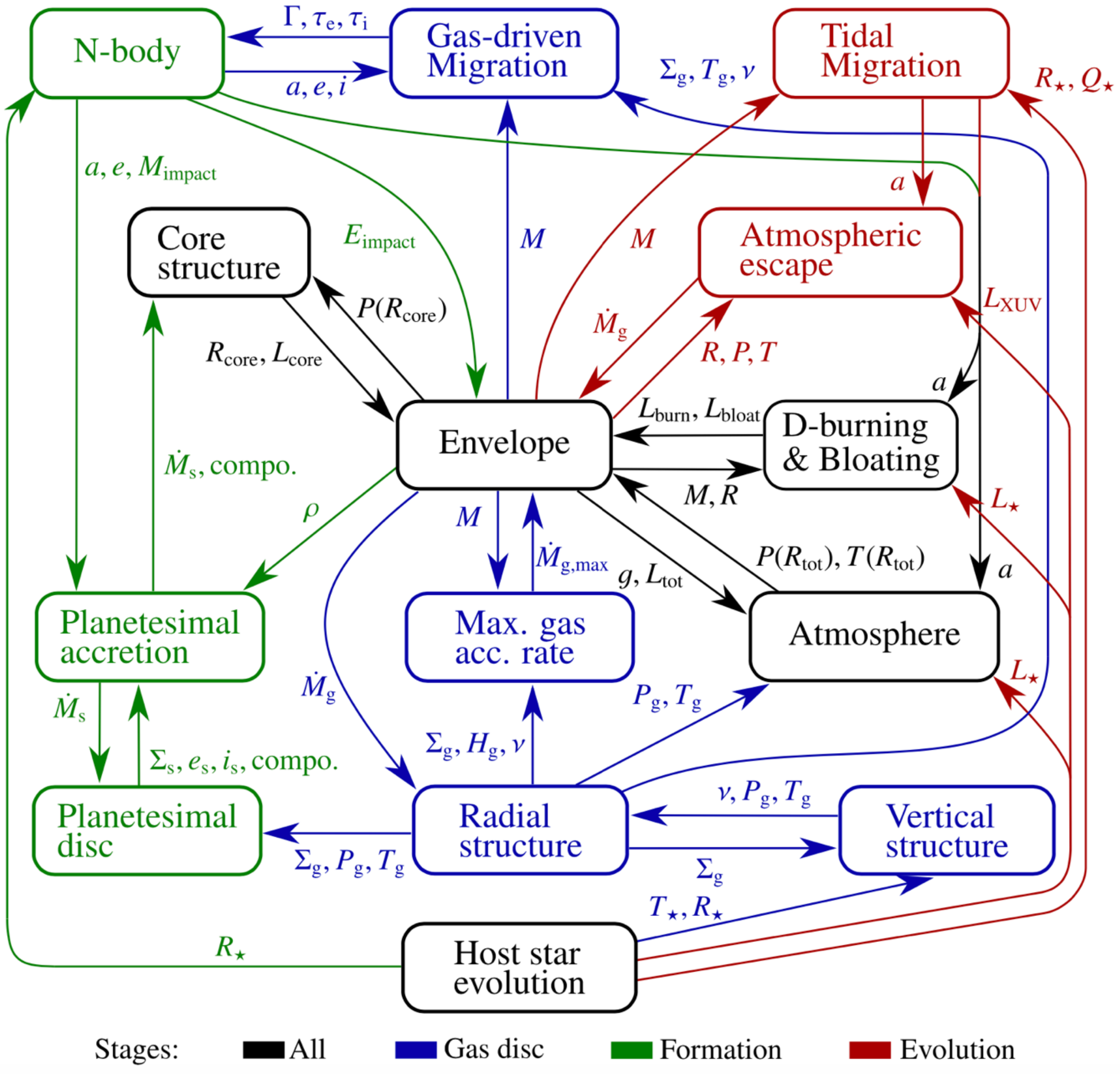
Match

Model solution found

No match: improve, change parameters, new approaches

Ida & Lin 2004, Benz+2014, Burn & Mordasini 2025

One example: the Generation III Bern Model



Core accretion paradigm

The Generation III Bern model: among the most *comprehensive* end-to-end models of planetary system formation and evolution to date

It combines

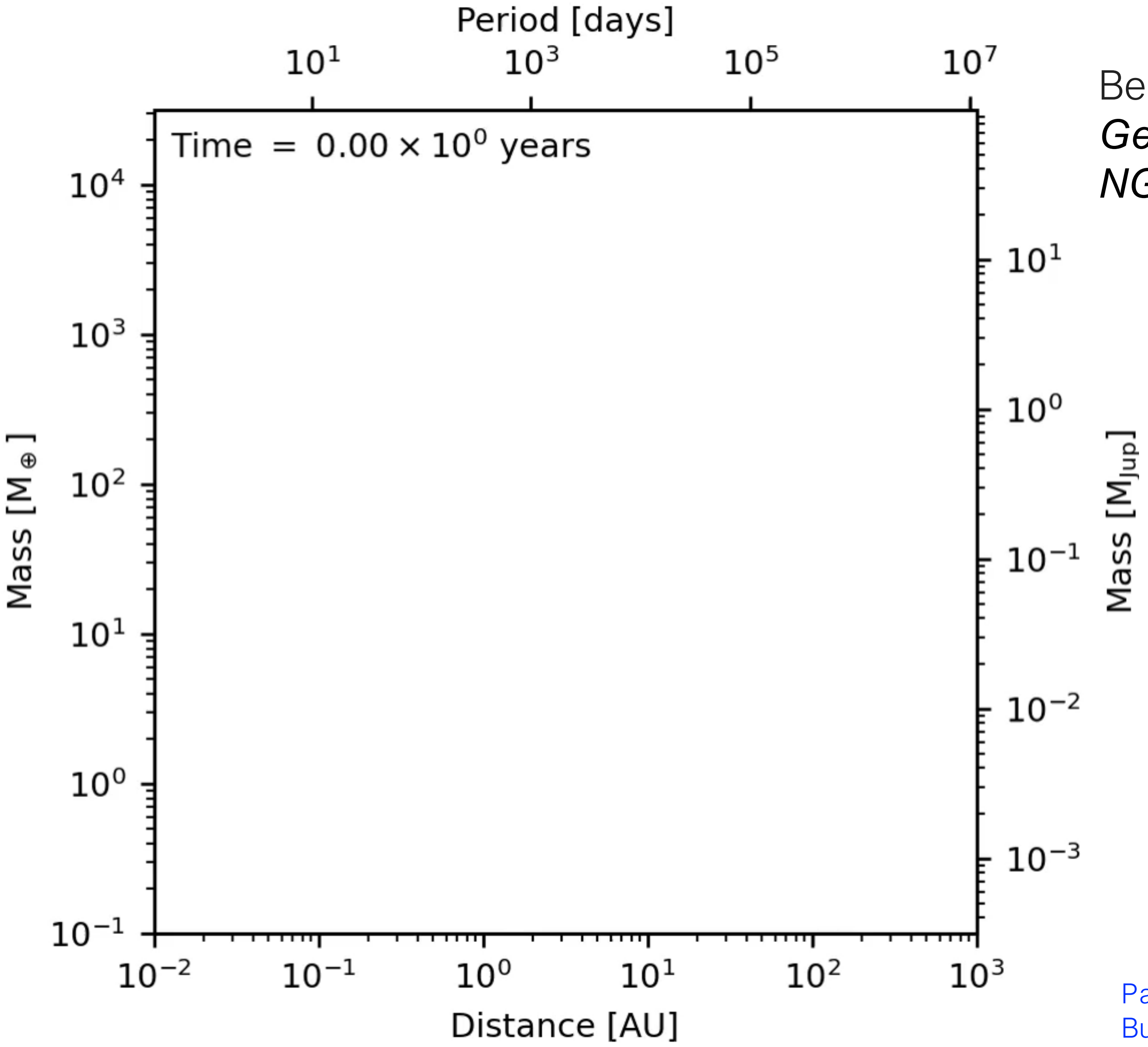
- *formation* (disk evolution, accretion of gas and solids, orbital migration, N-body interactions, internal structure calculation; first ~100 Myr)
- *long-term evolution* (internal structure, atmospheric escape, tides; following ~5 Gyrs).

A high number of coupled physical processes - modelled by direct solution of governing differential equations, but in low-dimensional approximation (axisymmetric disk; spherical planets; only N-body is 3 dimensional).

Direct prediction of all important directly observable quantities for (exo)planets (orb. elements; mass, radius, magnitudes).

Main publications: Alibert et al. 2005, 2013; Mordasini et al. 2009, 2012; Benz et al. 2014; Emsenhuber et al. 2021, 202[illegible]

NGPPS population synthesis 1 M⊙

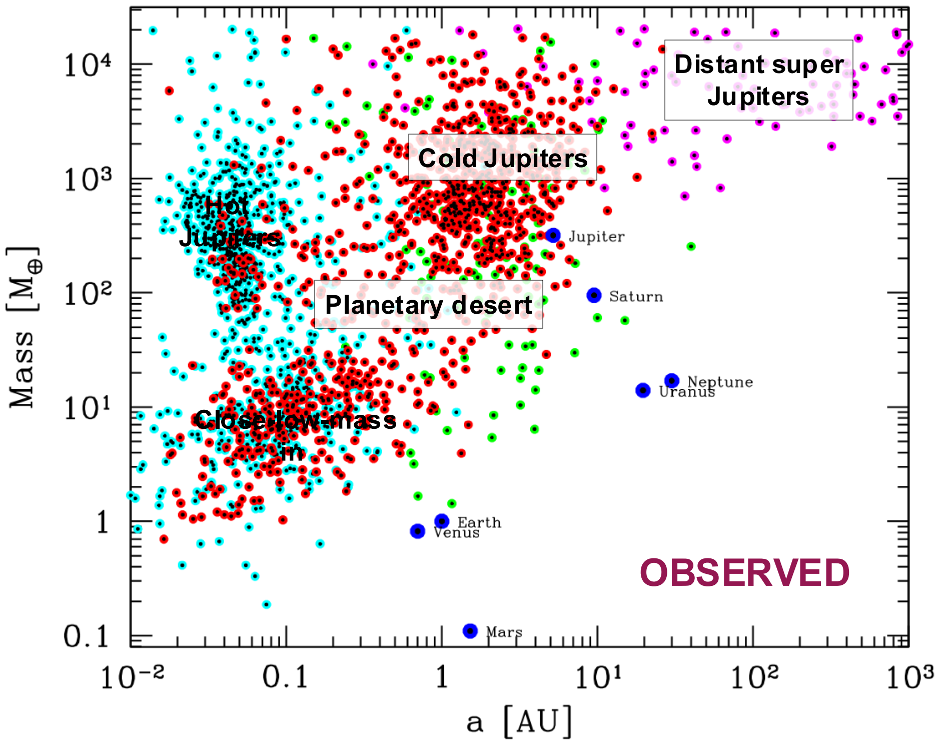


Bern Gen III model used to generate the *New Generation Planetary Population Synthesis, NGPPS*

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

Papers: NGPPS I-VIII: Emsenhuber+2021a,b; Schlecker+2021a,b, Burn+2021, Mishra+2021, Chengplus Emsenhuber+2023, Burn+2024, …

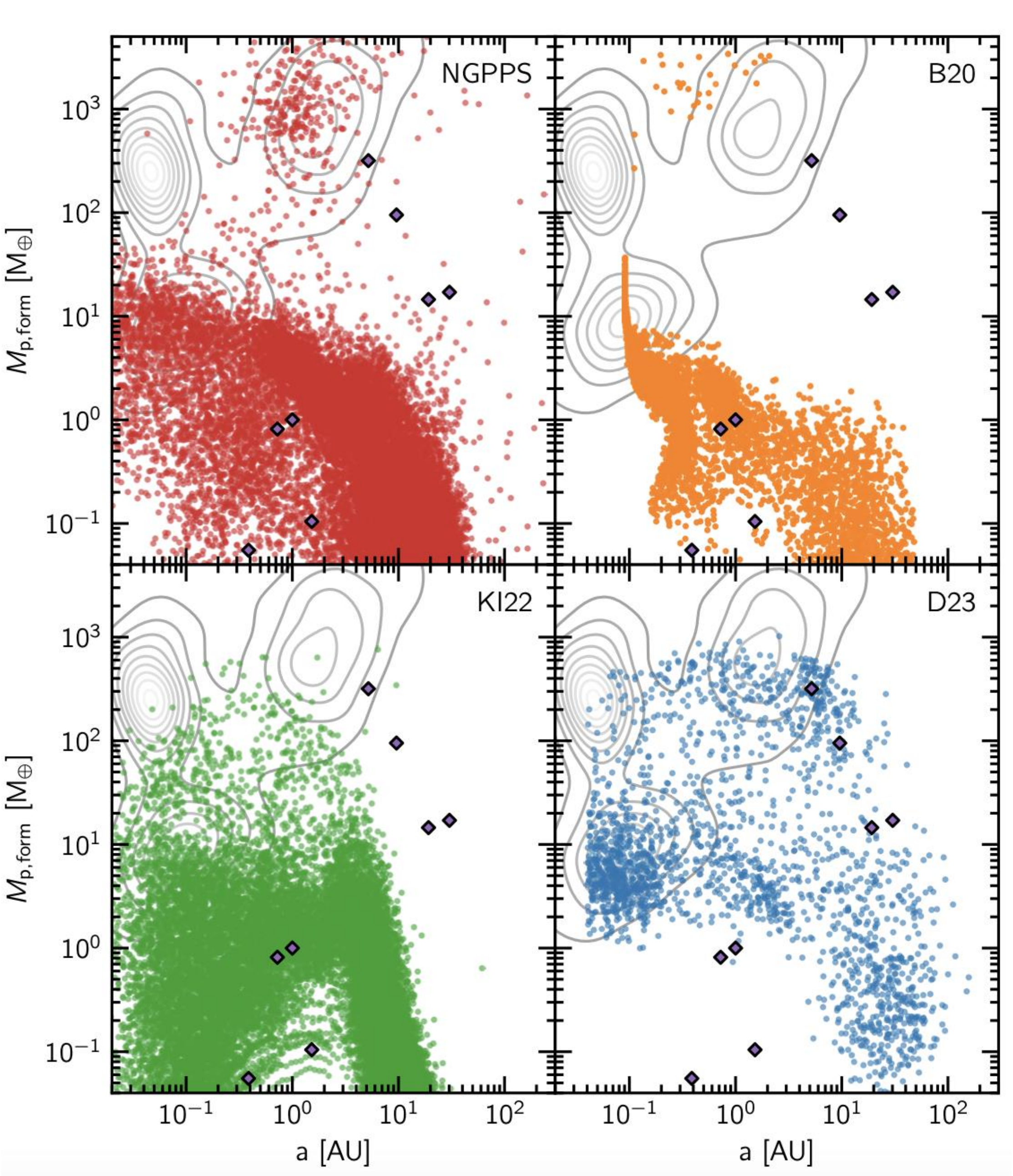
Overall result



Diversity of initial conditions (disk properties) leads to diversity of planetary systems similar as observed.

But how well does it compare quantitatively to observations?

- Kepler (Mulders+2019, Burn+2024, Dichang+2025)
- SPHERE SHINE (Vigan+2020)
- Microlensing (Suzuki+2018, Zang+2025)
- radial velocities (Emsenhuber+2025, NGPPS VII)



Comparison of pop. synth models in Burn & Mordasini (2024)

- NGPPS
- Bruegger+2020
- Kimura & Ikoma 2022
- Drazkowska+2023

See also models of

- Bitsch+2015, 2022
- Chambers 2018
- Alessi & Pudritz 2022
- Pan, Liu+2024
- Guo, Ogihara, Ida+2025

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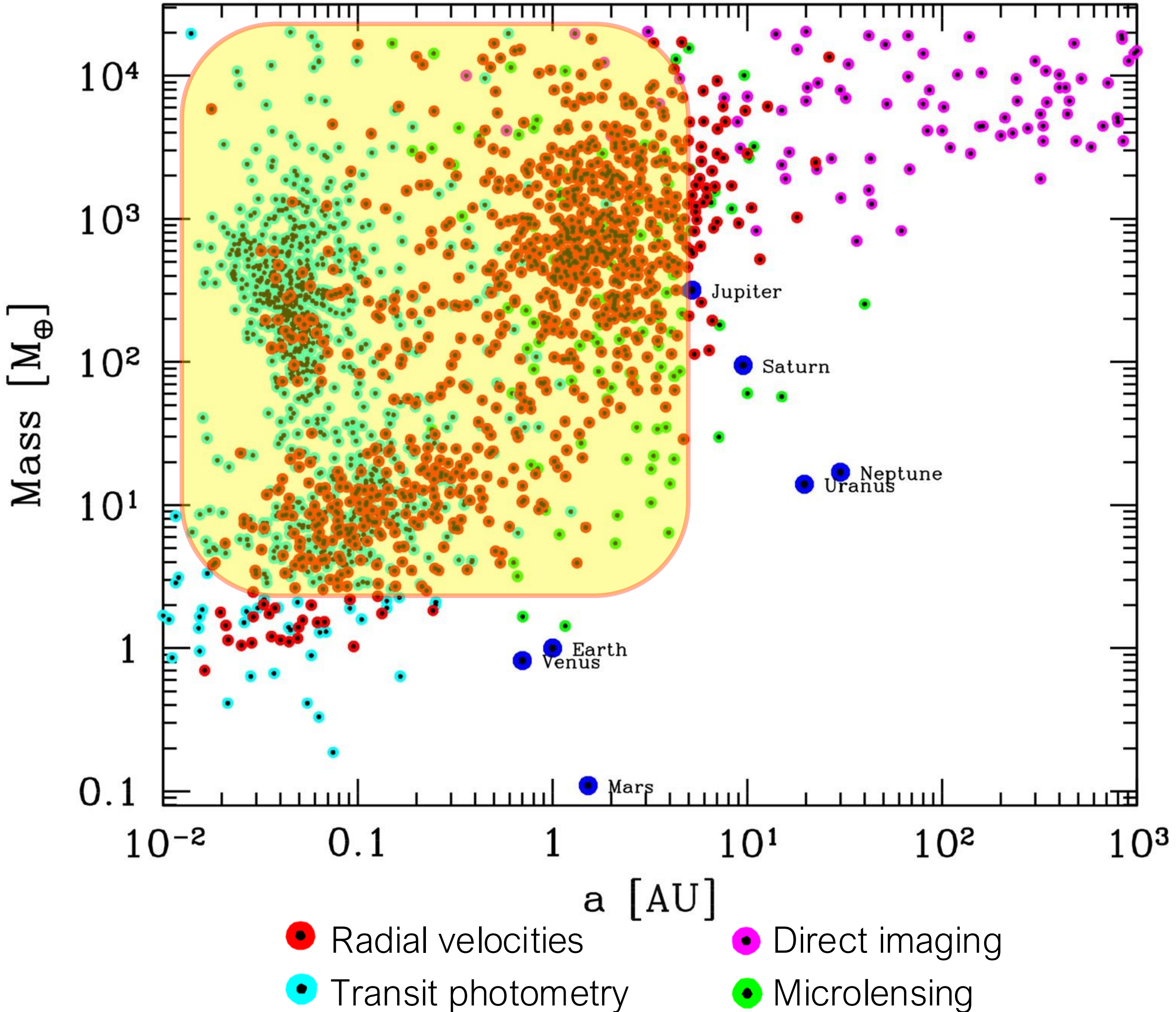
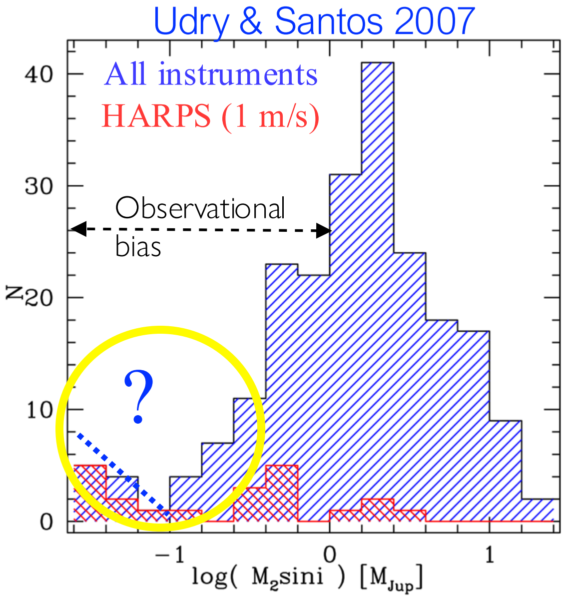
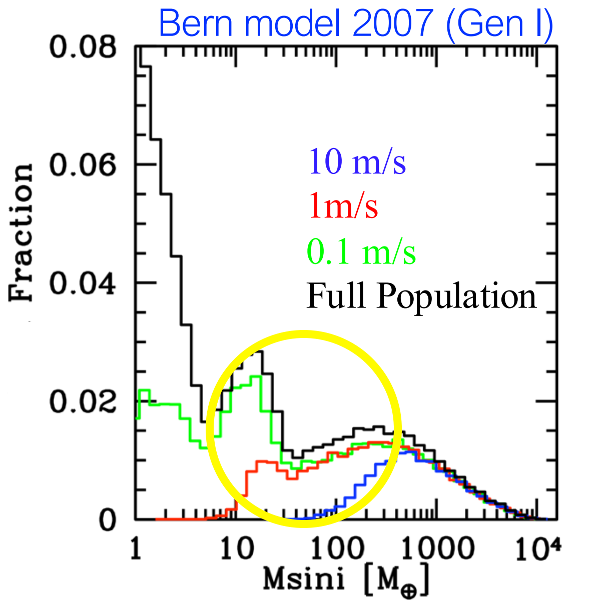
Confronting long-term RV surveys and predictions from the core accretion paradigm





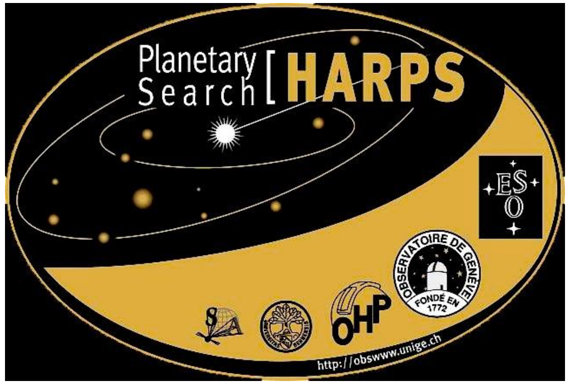


Population synthesis models then had too many limitations to address all HARPS obs. results.

NGPPS VII - Statistical comparison with the HARPS/Coralie survey

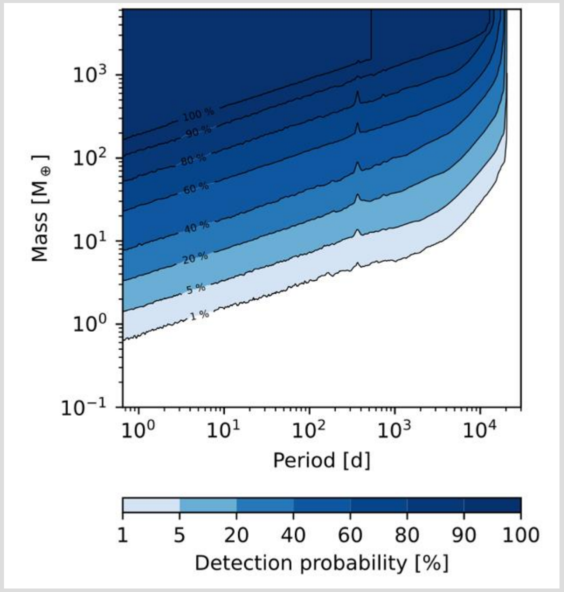
Emsenhuber et al. (incl. M. Mayor) 2025

The HARPS GTO survey



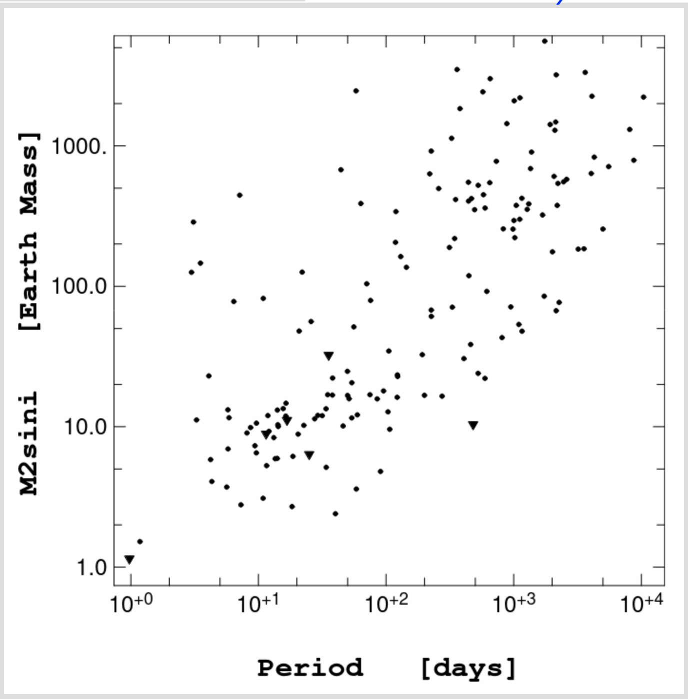
- HARPS: High Accuracy Radial velocity planet searcher (spectrograph for radial velocity measurements) at ESO 3p6 (Mayor et al. 2003)
- RV accuracy of ~1 m/s: first detection of low-mass exoplanets
- Volume-limited sample within 50 pc with 822 low-activity solar-like stars
- Combined w. Coralie survey for longer baseline (Udry et al. 2000)
- Known mean detection bias from signal injection and recovery tests
- Statistical analysis in Mayor+2011

Mayor+ 2011



Importance of large surveys with well-defined bias (like Kepler or direct imaging surveys; in future PLATO, NIRPS GTO, GAIA, Roman Space Telescope, …)

Mayor+ 2011



Nb of discovered exoplanets: 161

See also results of California Legacy Survey (Rosenthal+2021, Fulton+2021, Rosenthal+2024….)

Comparison frequencies and aM diagram

- Same approach as Mordasini+2009: "observe" NGPPS with HARPS GTO
- Draw randomly 882 synthetic systems out of 1000 NGPPS systems
- Draw system inclination assuming random orientations of systems to get system sin(i)
- Include effects of inter-planet inclinations (model output)
- Apply mean detection bias from Mayor+2011
- Compare ***quantitatively*** a-M, multiplicity, mass function, eccentricity, period ratio, [Fe/H] dependency

Observed (Mayor+2011)

Nb of planets: 161

Nb of stars w. planets: 102

Mean obs. multiplicity: 1.58

Synthetic biased

Nb of planets: 294^{+30}_{-27}

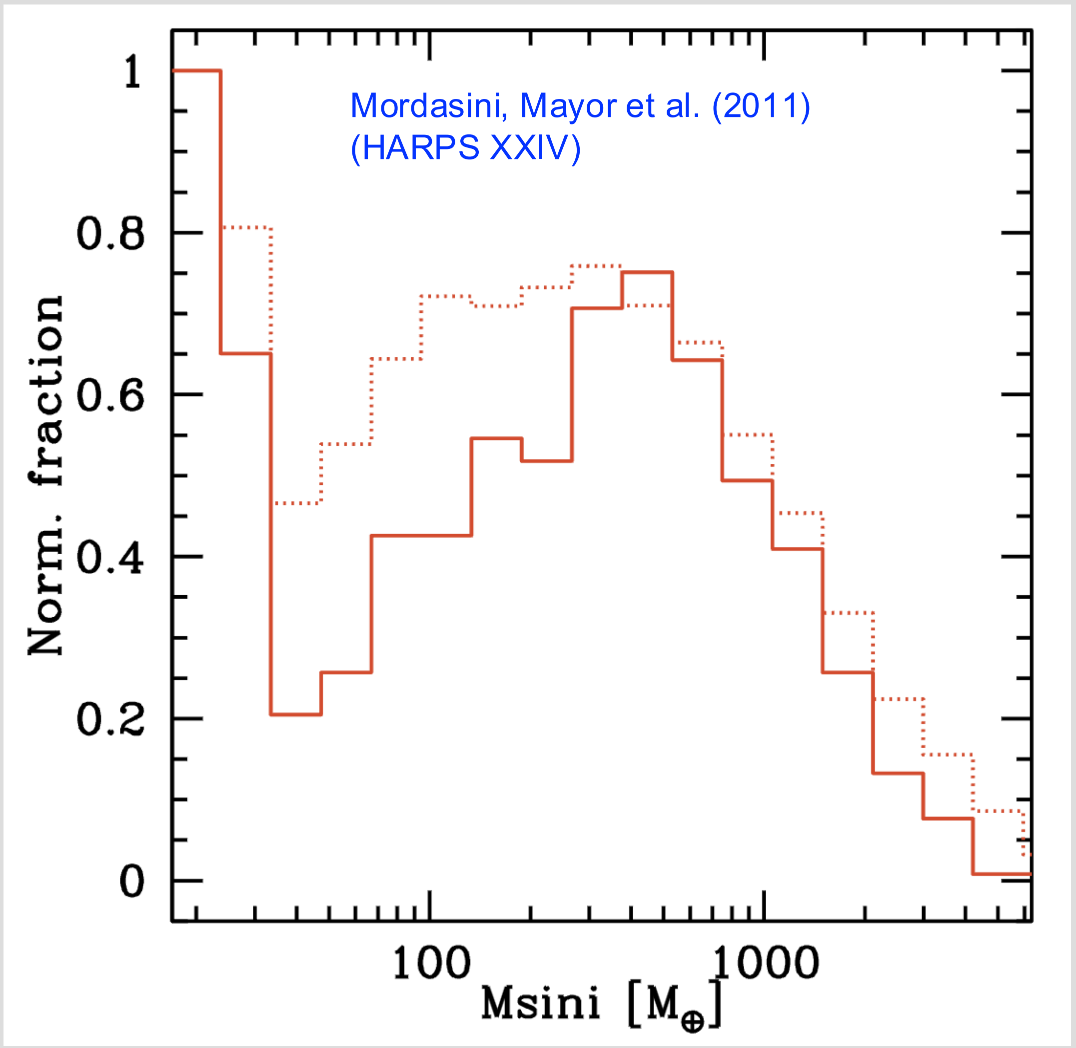
Nb of stars w. planets: 200^{+18}_{-17}

Mean obs. multiplicity: $1.47^{+0.3}_{-0.25}$

- Agreement: similar global structure: relative distribution (concentrations, voids)
- Agreement: Mean multiplicity ⇒ system architect.
- Disagreement: Factor ~2 in absolute number. Poss. explanations: Initial conditions? Cluster environment (cf. Winter+2020)? Not optimised!
- Disagreement: Hot Jupiters. Poss. explanation: a) Kozai /scattering plus tidal circularisation channel missing in model. There are proto-Jupiters. b) type II rates

Adapted from Emsenhuber, Mordasini, Mayor, Marmier, Udry et al. 2025 (NGPPS VII)

Planetary mass function (distribution of Msini)



Mass distribution actual and synthetic detected planets

- Agreement: bimodal structure
- Agreement: Change ~30 $M_\oplus$: smoking gun of CA: runaway gas accretion Mcore~Menve~15 $M_\oplus$ (see also Bennet+2021, but also Bertaux & Ivanova 2022, Zang+2025, Thomas+2025).
- Disagreement: Giants too massive (~400 vs ~700 $M_\oplus$) & too many by ~45%
- Disagreement: Too few intermediate mass planets by ~60% (plan. desert, Ida & Lin 2004, Mayor & Udry 2008, Bouchy+2009).

Obs. constrain on onset of rapid gas accretion and gas accretion rate in runaway and disk-limited phase.

⇒ current models: too fast and too long gas accretion (cf. Nayakshin+2019) Similar for gas accretion rate derived from several 3D hydrodynamic models (Machida+2010, Bodenheimer+2013, Choksi+2023…)

Possible explanations: low viscosity disks (Ginzburg & Chiang 2019) with efficient gap formation (Aoyama & Bai 2023), magnetic regulation (Batygin 2018, Cridland 2018), angular momentum barrier (Takata & Stevenson 1996), 3D circulation (Szulagyi et al. 2014), ….

Observational side: need 20-200 $M_\oplus$ planets at several AU (RV)

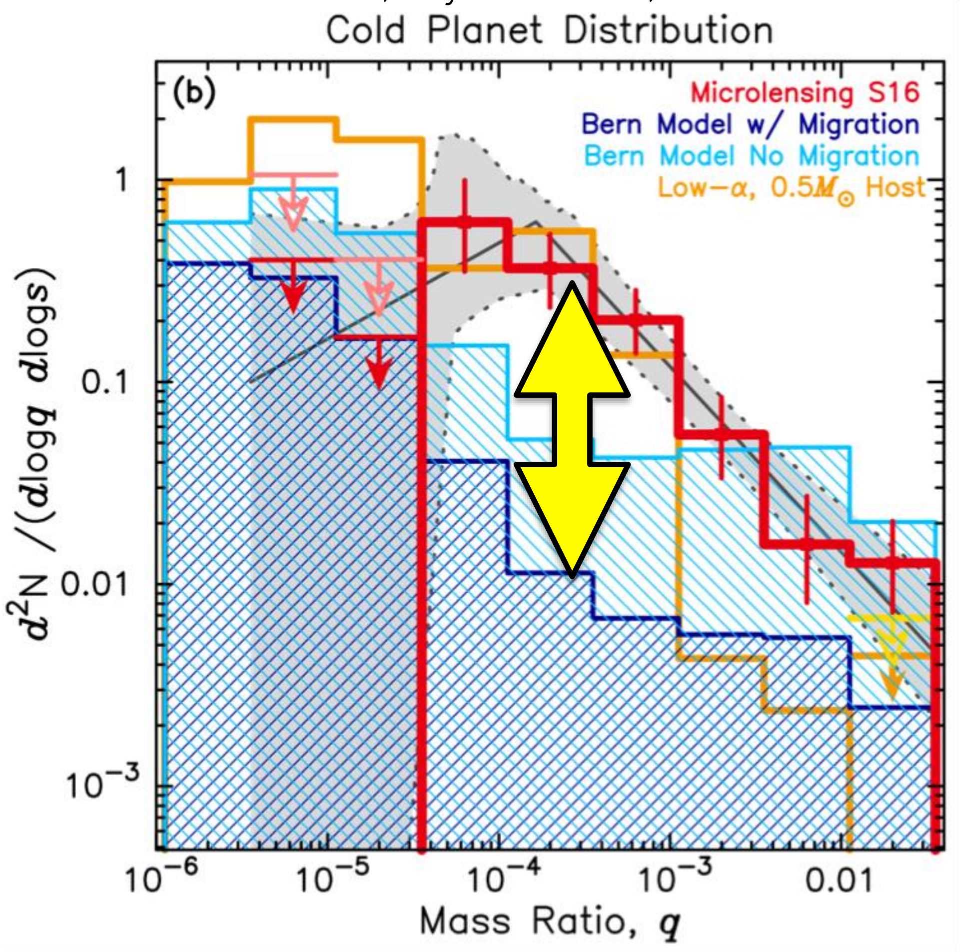
Inset: Comparison with microlensing

Imprints of core accretion are visible in mass distribution

-solid accretion
-critical core mass
-runaway gas accretion
->break in mass function
->planetary desert

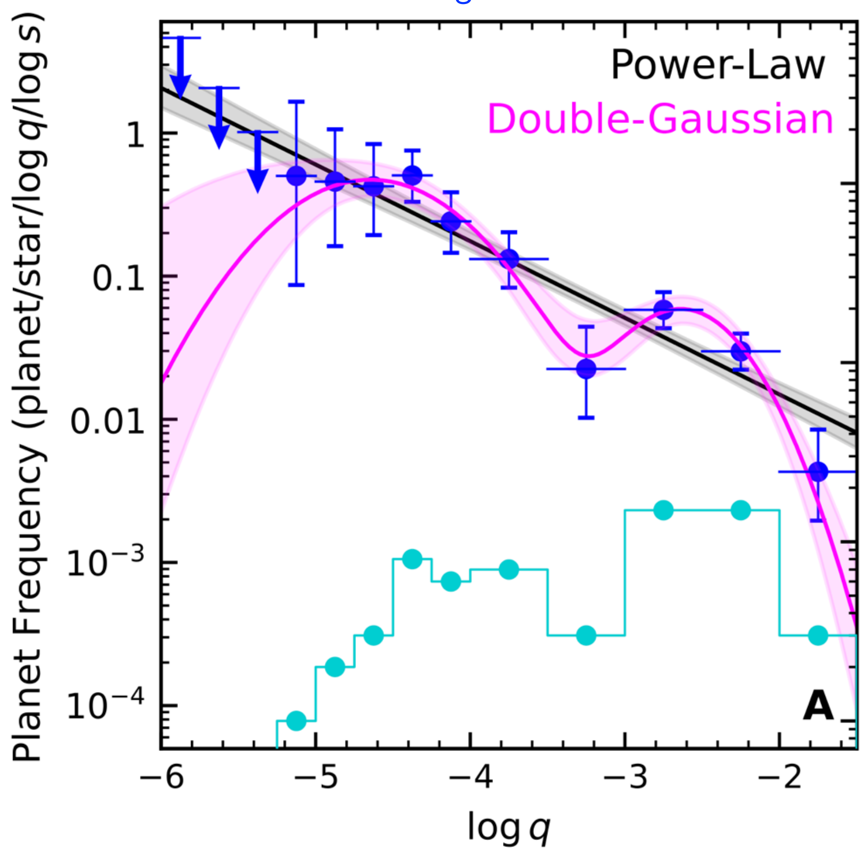
Past ML studies challenged these fundamental predictions of the core accretion theory (Suzuki+2018, Bennet+2021)

M-dwarfs, beyond iceline, Suzuki+2018



-maximum (?) at ~20-50 M_{Earth}
-much higher frequency than synthetic
-one single power-law
-low disk viscosity seems to help

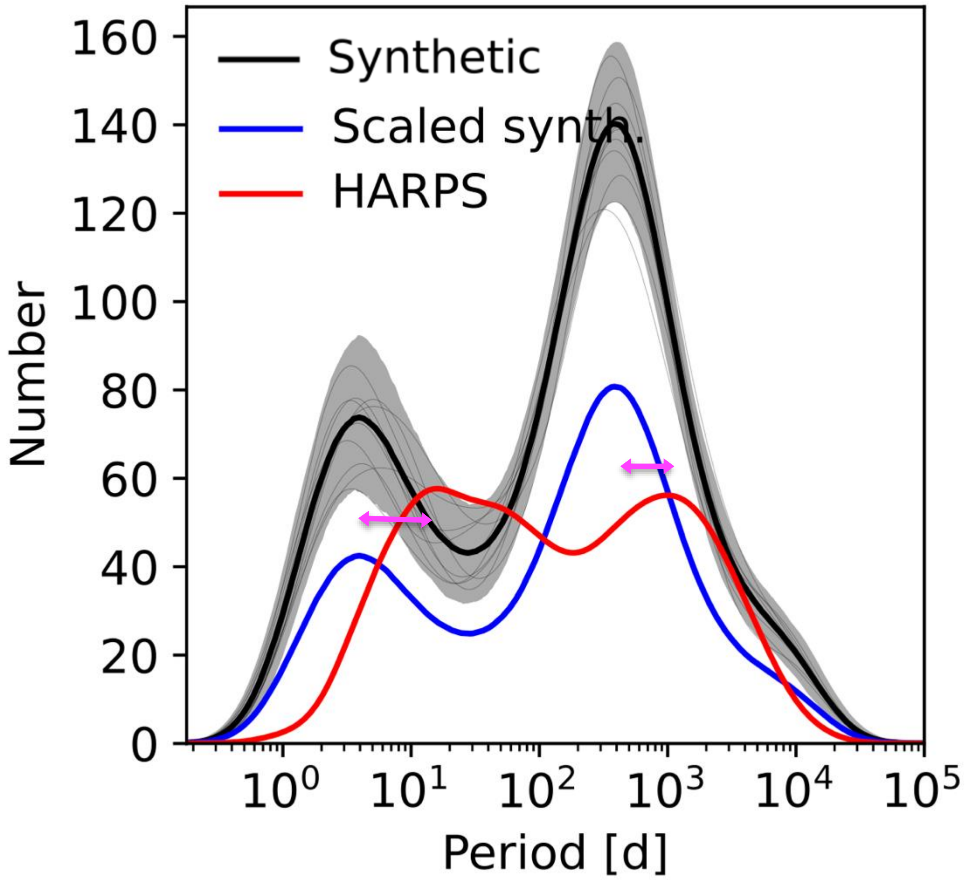
Observed (Microlensing, 2025)
Zang+2025

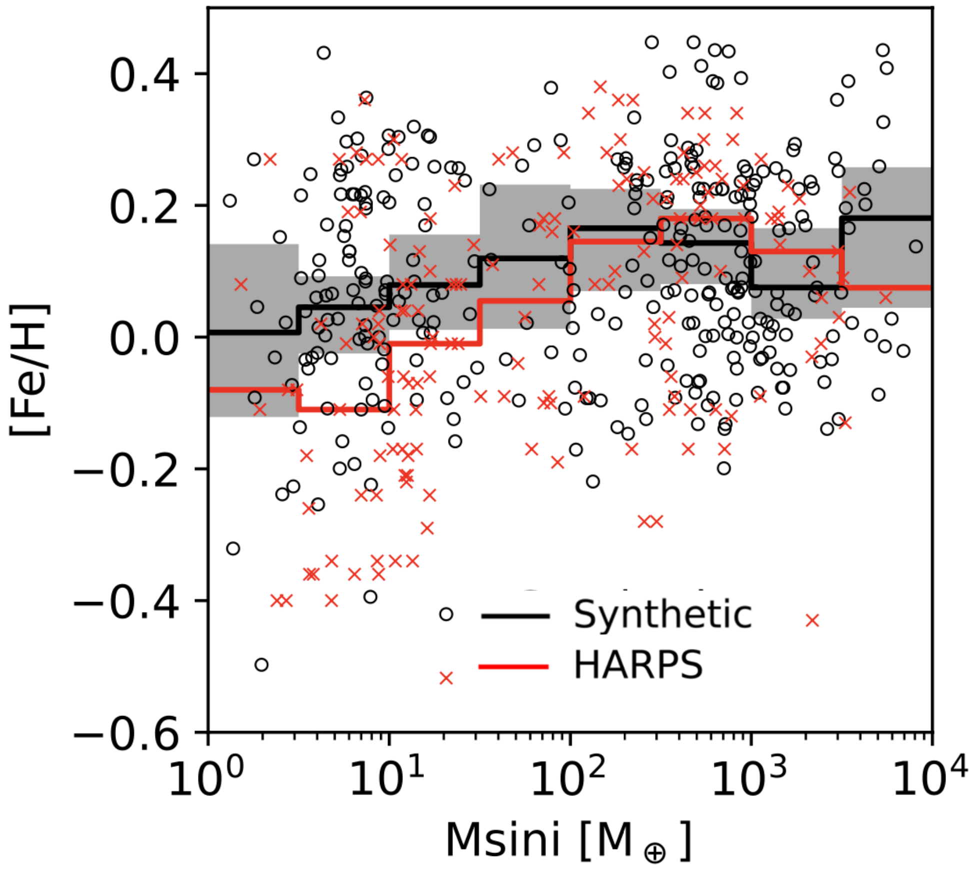


-new data points at a potential minimum
-detailed comparison necessary

Roman ST will be a game-changer

Orbital period and mass-metallicity correlation

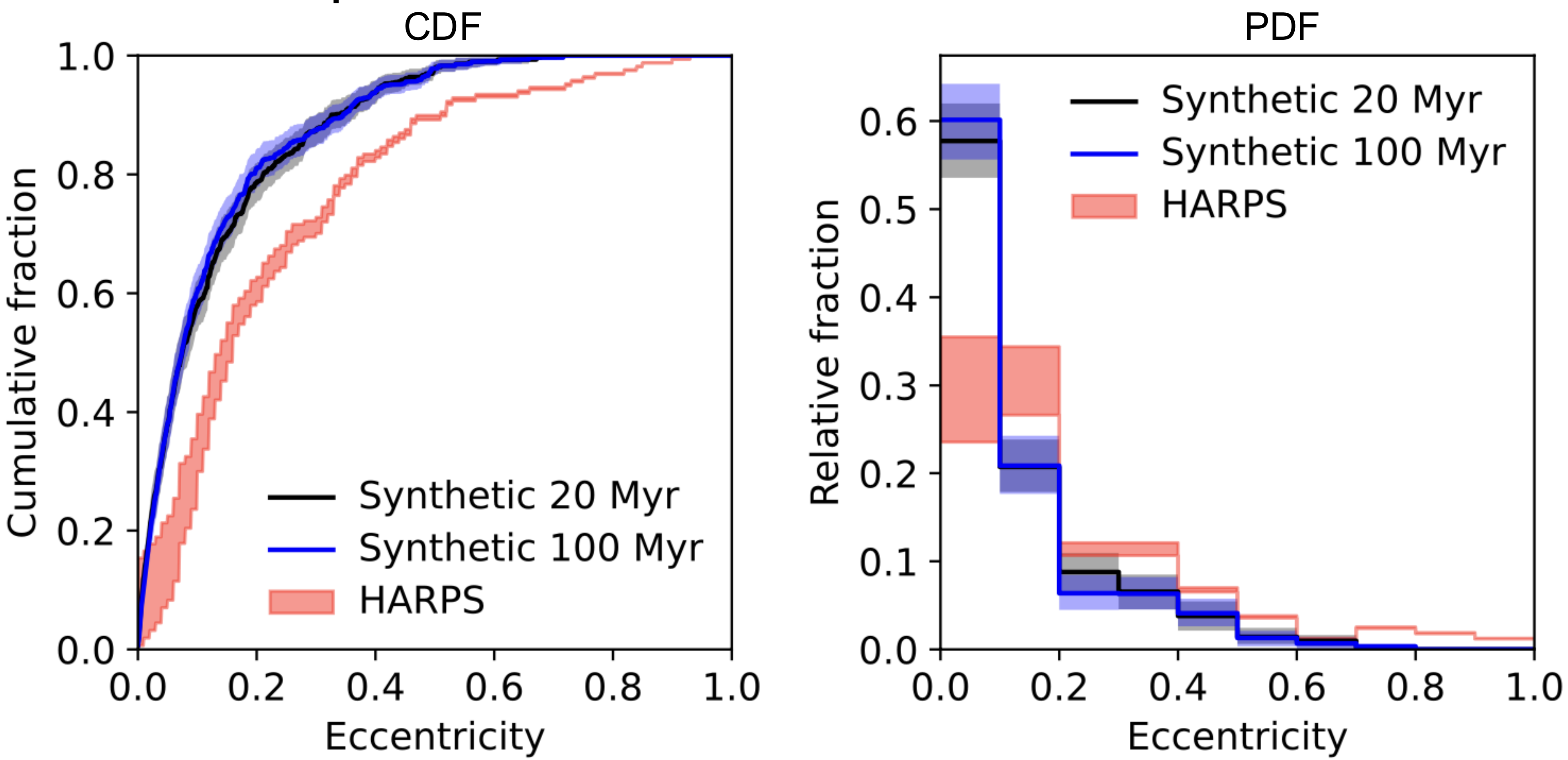




- Agreement: two maxima: inner low mass planets, outer giants
- Disagreement: both types are too close in
- SuperEarth/sub-Neptunes: ~3 d instead of 10 d. Halting at inner edge: viscosity transition (Flock+2019)?
- Giants: too fast migration (MHD-wind driven disks or starting further out e.g. via pebble accretion in structured disks (Lau+2022)?

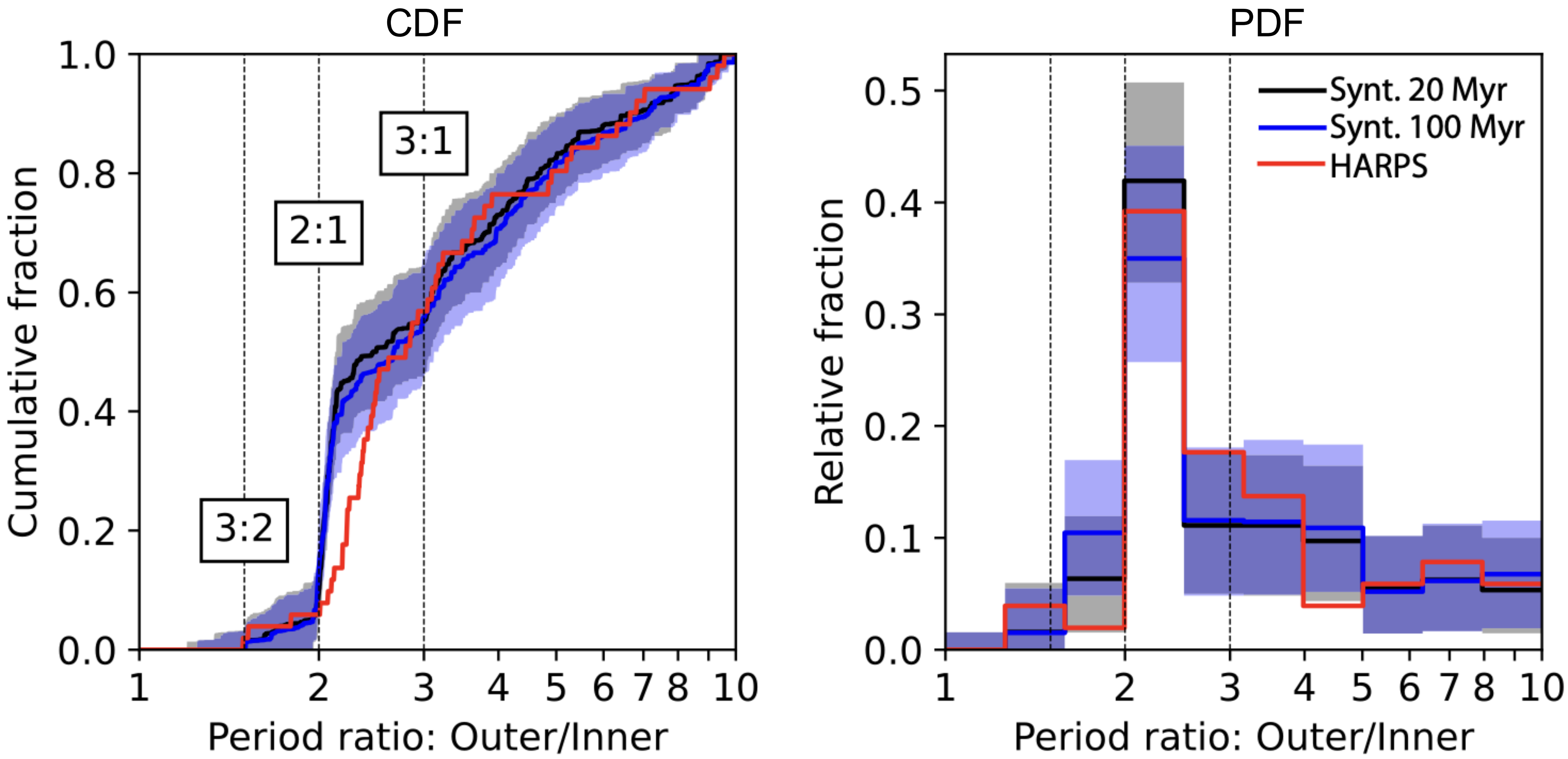
- Agreements: Increase of mean [Fe/H] with increasing mass
- Disagreement: trend weaker than observed at low masses
  - Effects during earlier stages not included in model (during planetesimal formation stage)?
  - At highest masses: pollution by BD/GI formation? Low number statistics (Adibekyan+2013, 2019)

Distribution of planet eccentricities



- Agreement: similar intermediate values (planet-planet scattering, cf. Juric & Tremaine 2008; Ford & Rasio 2008)
- Disagreement: offset by ~0.07 towards higher eccentricities in HARPS rel. to synthetic
- Disagreement: no very high e > 0.7 planets in synthesis
  - Model: Too strong damping? Other mechanisms increasing ecc.? External perturbers / binaries ? Excitation by gas disk for massive planets (Kley & Dirksen 2006)
  - Observations: overestimation of e (known bias of RV method, Lucy & Sweeney 1971, Hara+2019)

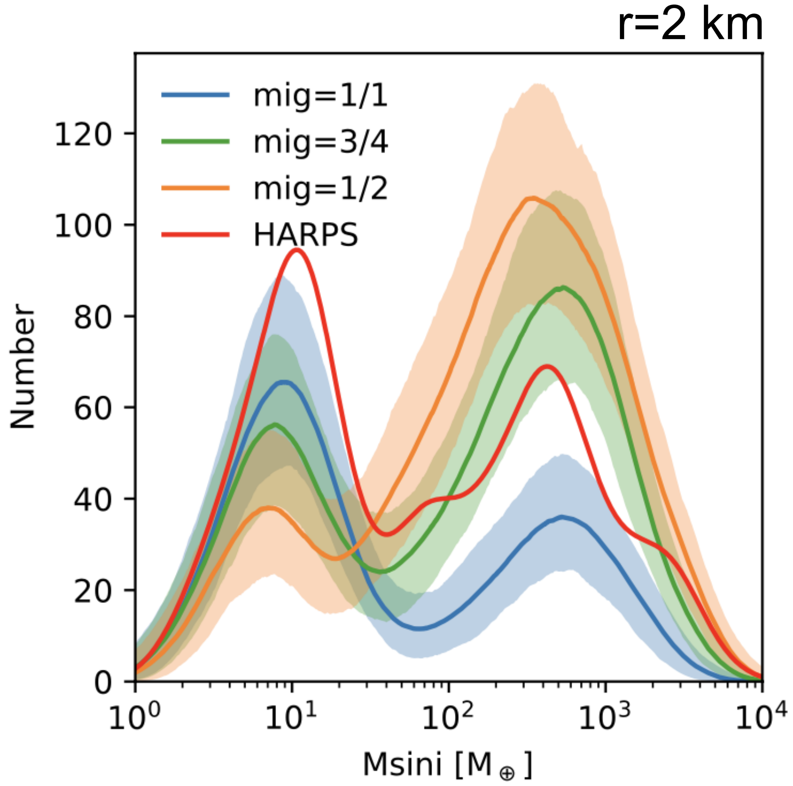
Period ratio of adjacent planet pairs



- Agreement: good agreement of shape in most parts, range, both high and low ratios
- Disagreement: too many very close to / in 2:1 MMR in synth. pop. compared to observations
  - Model: Stochastic migration? Too much orbital migration overall? Effect of tides (missing in model)?
  - Observations: two planets in 2:1 interpreted as singe eccentric planet?
- Extending the N-body integration time from 20 to 100 Myr only slightly changes the result

"Optimised" populations

- Introduce free scaling factors for solid accretion rate, gas accretion rate, migration rate
- Vary as free parameters to better fit HARPS
- Result: difficult to fit at the same time
  - mass of giants planets (should be smaller than in nominal pop.)
  - semimajor axis distribution (should be further out)
  - while having observed ratio of sub-Neptunes to giant planets
- Example: reduction of migration also leads to too many giants relative to sub-Neptunes



- Coupled nature of the processes in global model
- Generally difficult to "force" outcome into one direction without also changing (negatively) many other outcomes

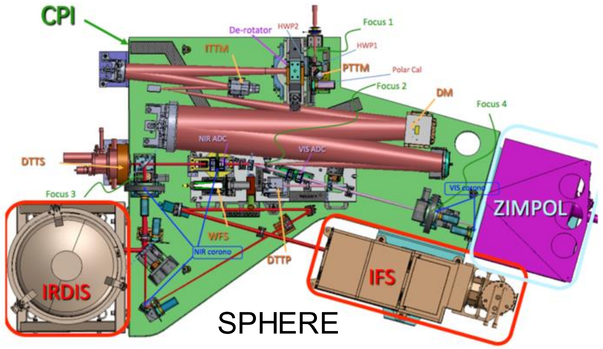
Conclusions

- Many key findings of HARPS GTO can be recovered from the included physics
- Many qualitatively, several also quantitatively
- Unable to concurrently match all key constraints
- Differences point at missing / different physics

Inset: Comparison with direct imaging

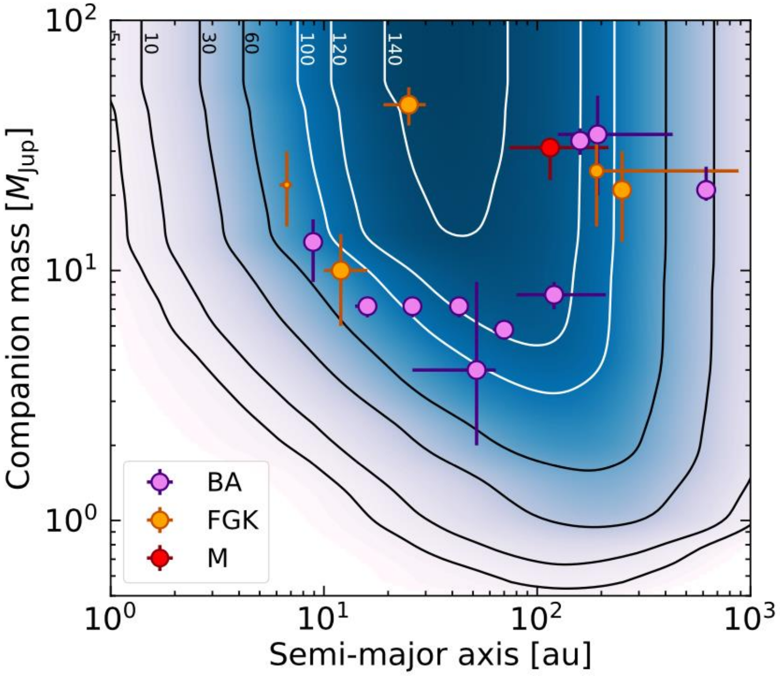
SPHERE@VLT SHINE GTO survey (Vigan et al. 2020)
150 stars

cf. Nielsen et al. 2019 GPIES

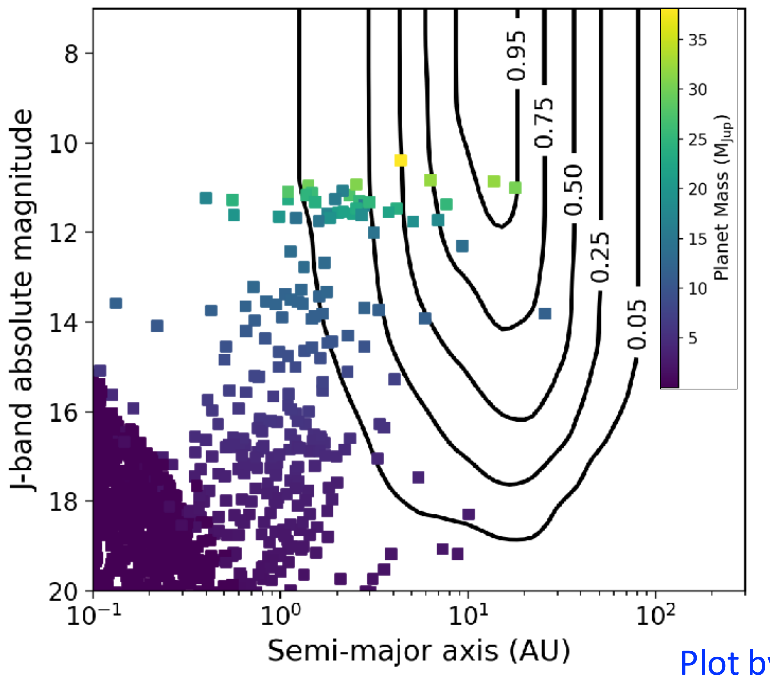


Probes very different kind of planets and a different observable (magnitudes / luminosity)

Actual detections & sensitivity maps



Synthetic population & sensitivity maps



Plot by Clemence Fontanive

Fraction of FGK stars w. planets (M=1-75 MJ, 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 core a accretion 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 ~circular orbits
- Structured disks? Formation by **gravitational instability**?

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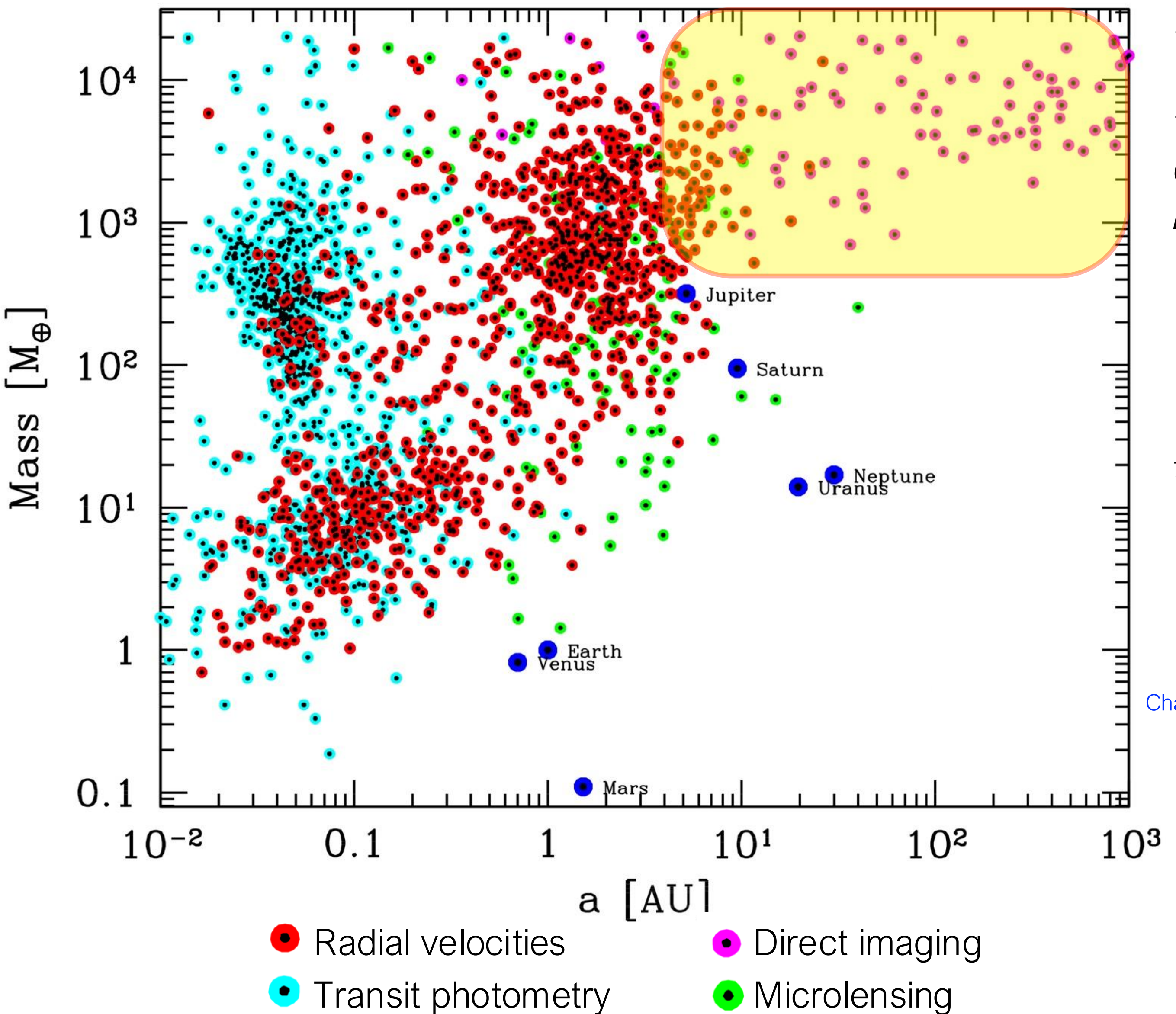
Population resulting from disk instability



DIPSY - a new Disc Instability Population SYnthesis

Oliver Schib, Christoph Mordasini, Alexandre Emsenhuber, Ravit Helled

Paper I and II on arXiv today (A&A acc.)
https://arxiv.org/pdf/2510.02436
https://arxiv.org/abs/2510.02437

<u>Where core accretion struggles</u>

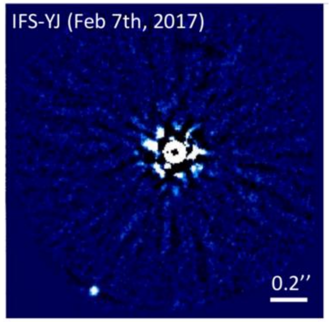
Very distant giants, very early ages

Giant planets around very low mass stars (<~ 0.2 M_{sol})

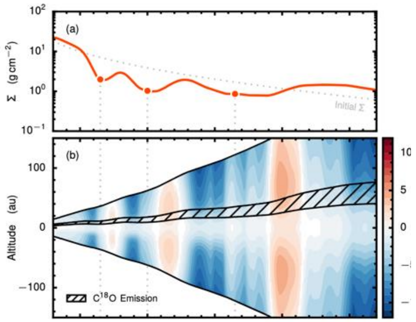
Giants around low [Fe/H] stars

<u>Is there a parameter space for disk instability to form planets?</u>

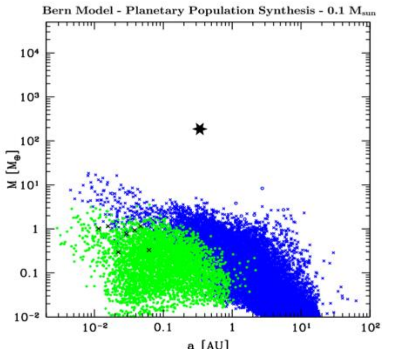
Chauvin+ 2017 HIP 65426



Teague+2018 HD163296

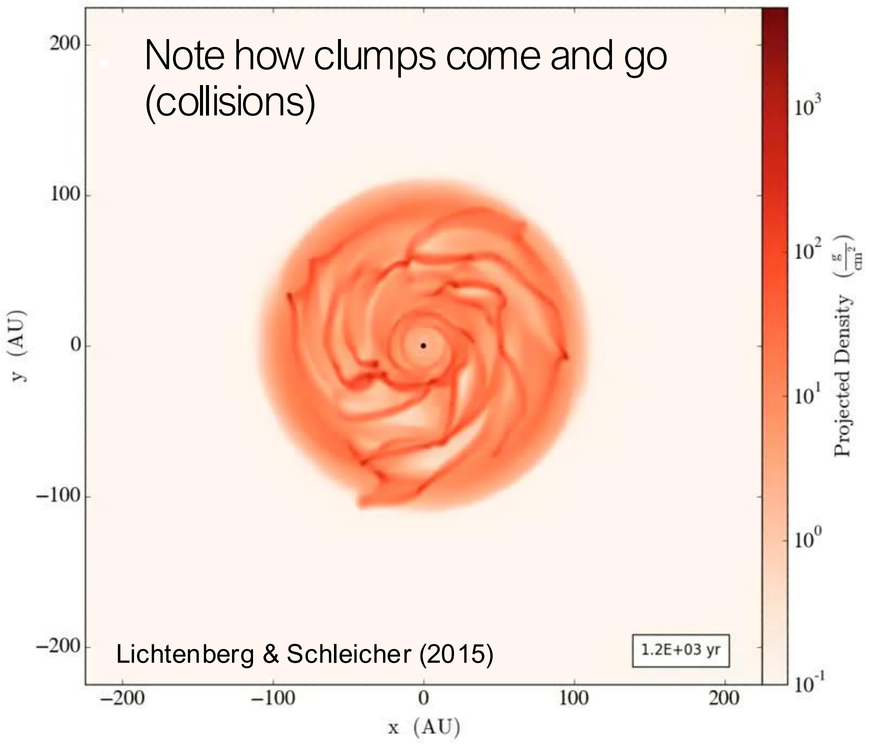


Morales+2019 (GJ3512b)



New global DI formation model

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 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 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 (cooling & infall frag. 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

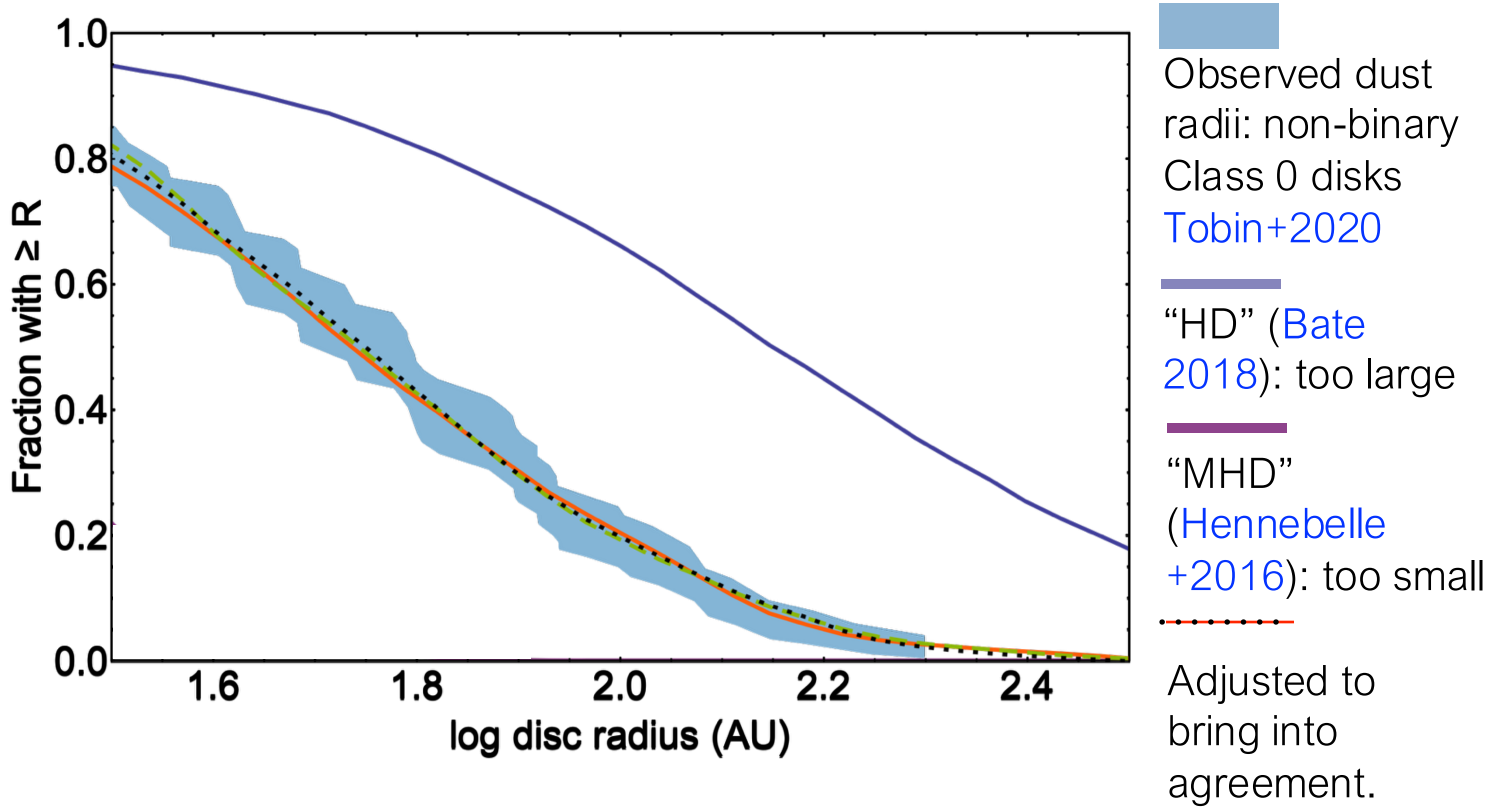
Hueso & Guillot 2005, Kratter+2010, Kimura+2016, Nakamoto & Nakagawa 1994, Toomre 1964, Gammie 2001, Vazan & Helled 2012, D'Angelo & Lubow 2010, Kratter+2021, Humphries +2019, Boley+2010, Ida+2020, Chambers 1999

Initial conditions and Monte Carlo variables

- Star and disk built up by infall from MCC from small initial values
  - $M_{star,init}$ = 0.05 M_{sun}
  - $M_{star,ini}$= 0.015 M_{sun}
- Final host star masses: 0.1 to 5 M_{sun}
- Distribution infall rates from hydrodynamic simulation (Bate 2018). Average 3×10^{-5} M_{sun}/yr.
- 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

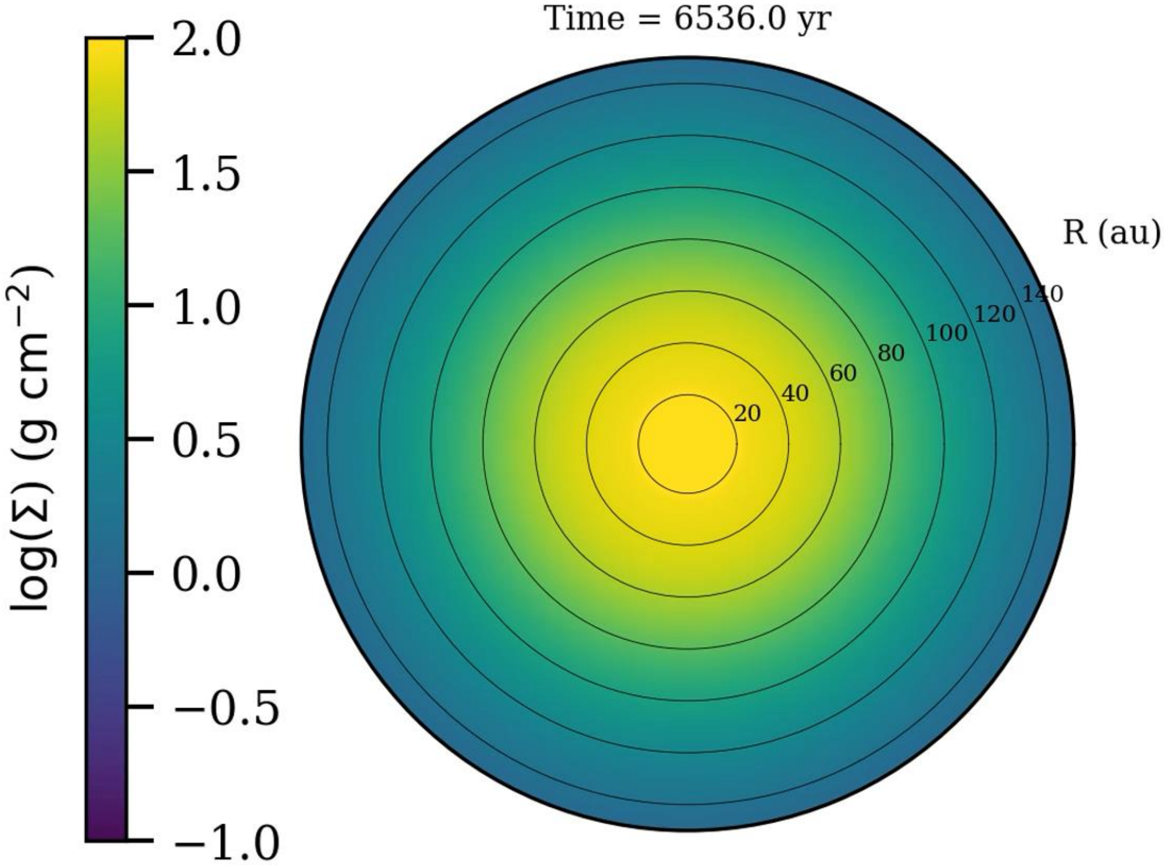
- Distribution of infall locations onto disk: such that synthetic disk radii fit observed class 0 disk sizes (observationally informed)

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

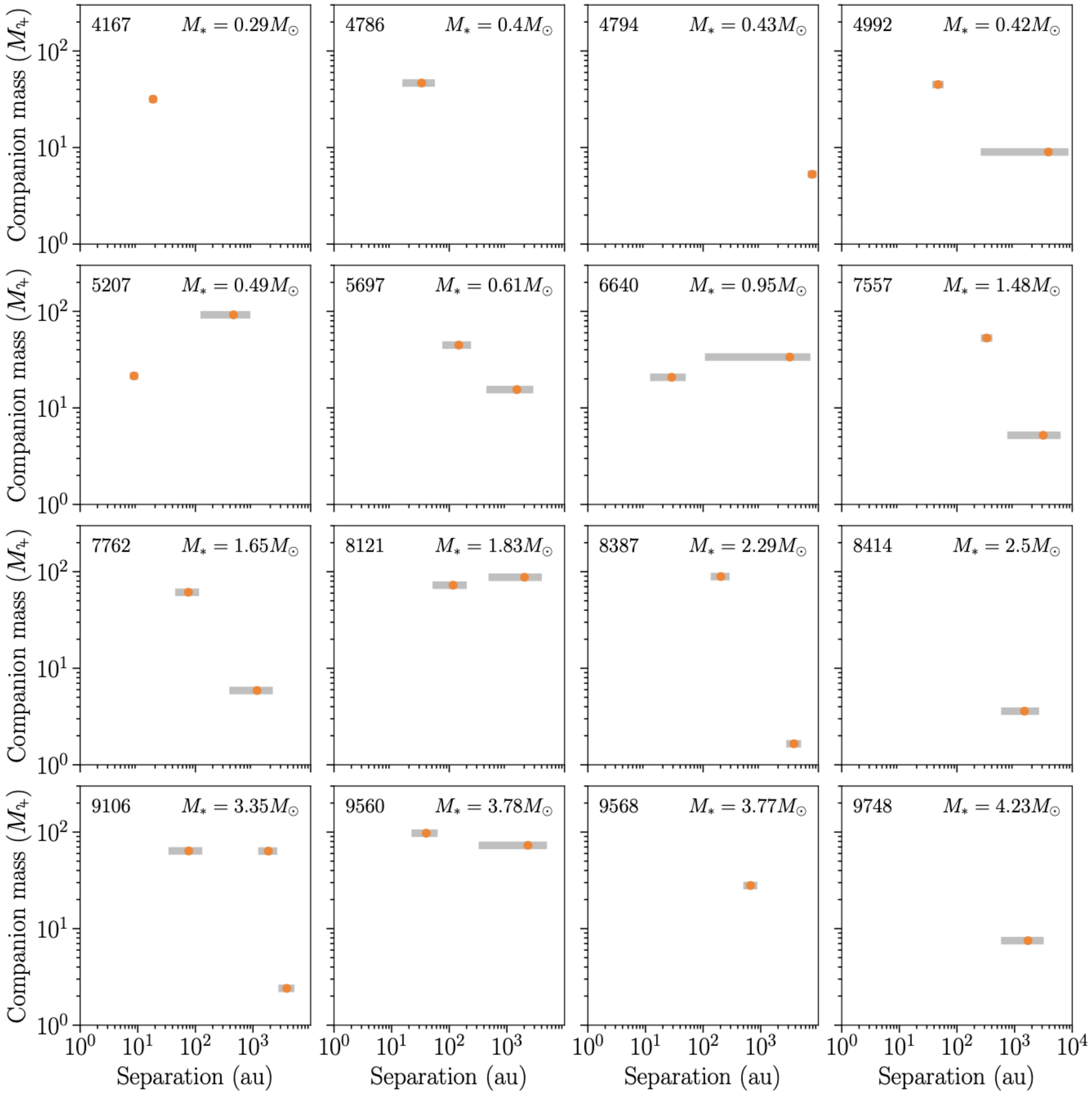


High number of clumps formed per fragmenting disk

- typical number ~10-30 initial clumps / disk
- reason: continuing infall

Strong dynamical interactions among clumps

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



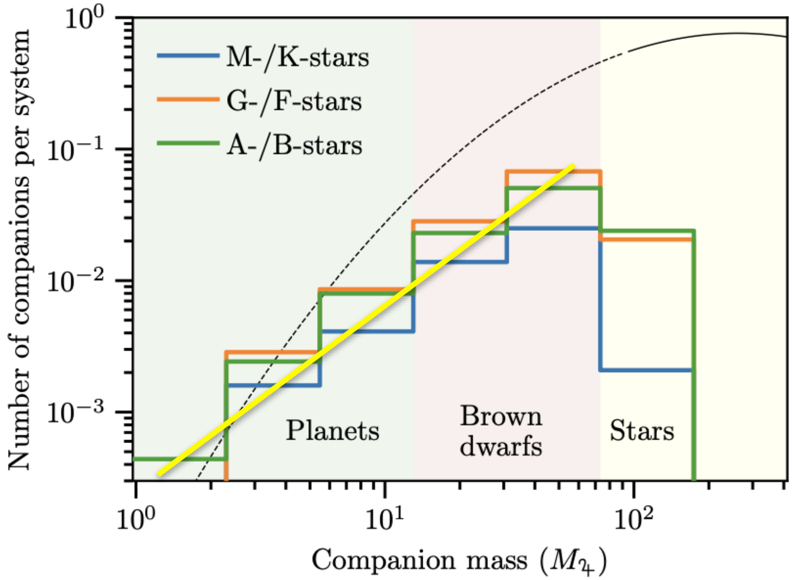
Final architecture: Usually one, sometimes two, rarely 3 companion.
Very low survival rate for initially formed clumps

Essential demographic distributions

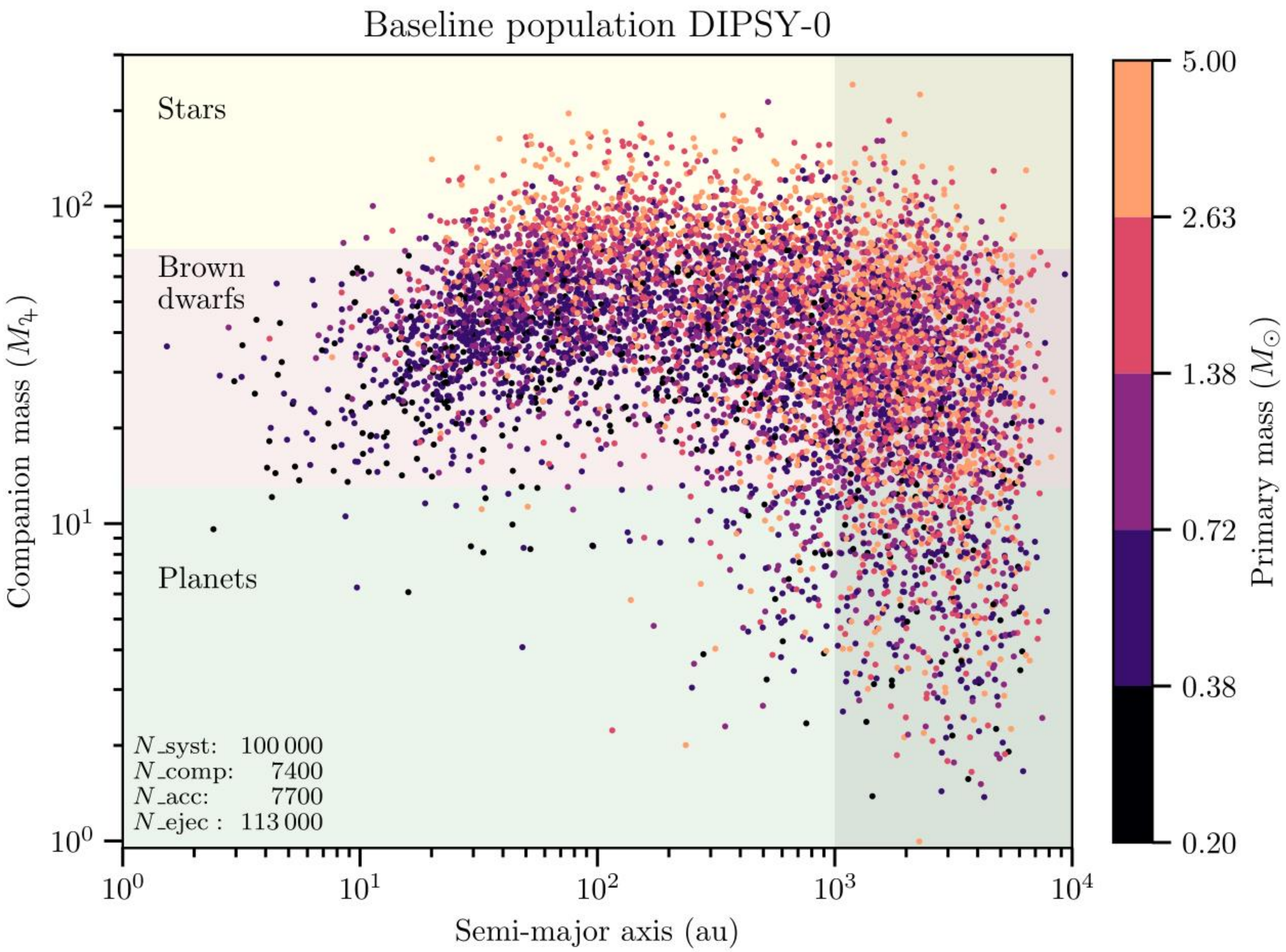
Mass distribution

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

Unimodal, peak at ~50 MJup, $N \propto M^{1.1}$



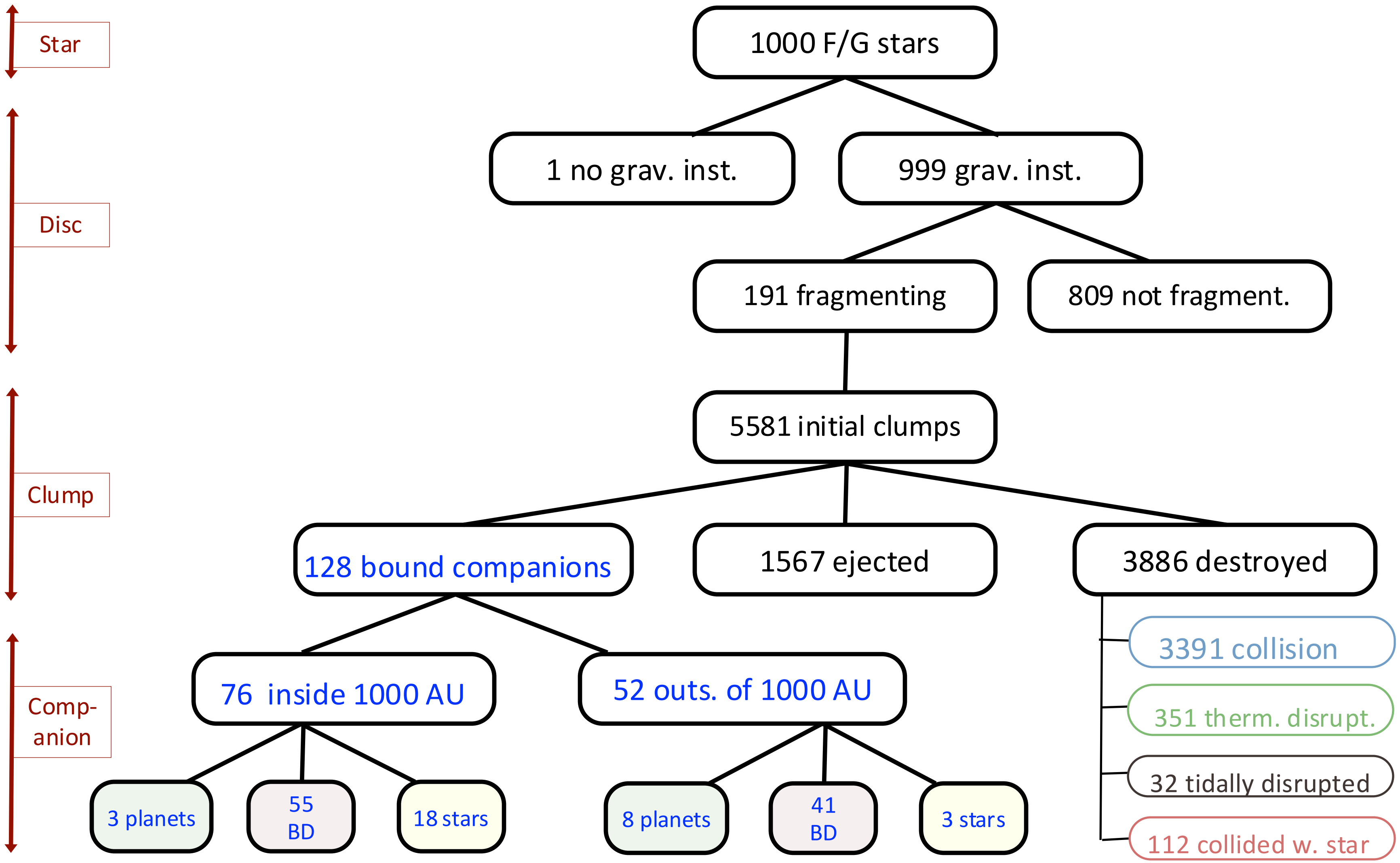
Predicted mass-distance diagram



- Inverted and rotated **'L' shape** with remarkable rareness 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



Conclusions

- New DIPSY populations allows to quantitatively compare DI with surveys.
- Distances less than 100-1000 AU companion frequency:
  - -planets: per-mill
  - -BD: low percent
  - -~1:1 ratio stars:ejected objects
- Caveat: DI overall less developed than CA and thus also DIPSY despite its complexity compared to previous attempts (no solids, no magnetic fields, …).

Talk contents

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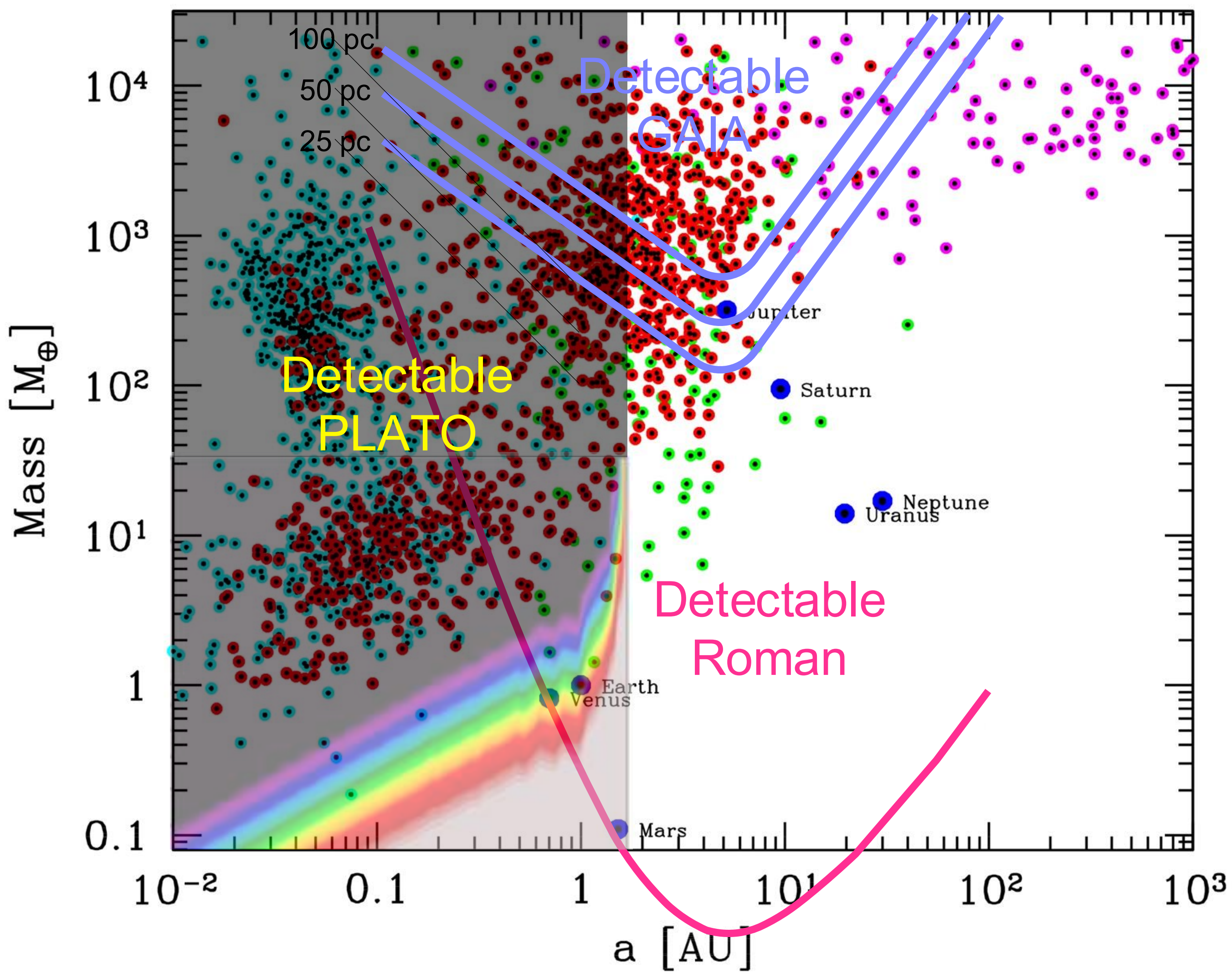
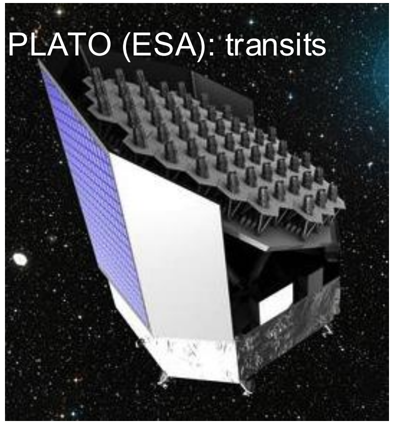
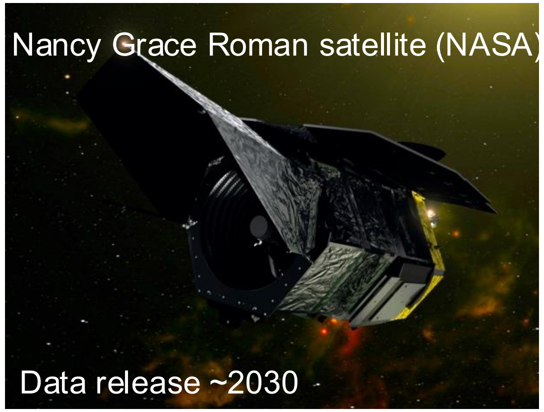
Outlook: future statistical exoplanet missions



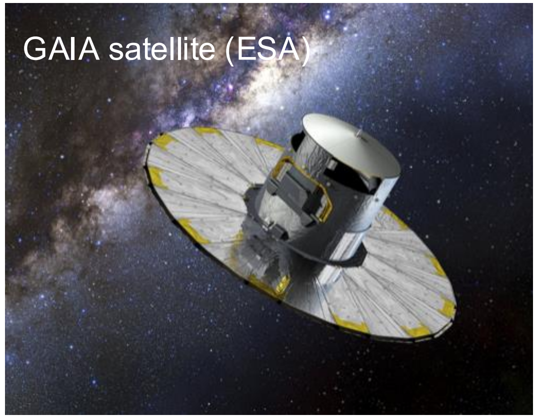
Blue lines: 5 σ detection limits for GAIA (Courtesy D. Segransan, Geneva Obs.)



Expected yield: 4000-12000 planets



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



Astrometric technique
Expected yield: thousands of giant exoplanets

Hundreds of atmospheres characterised

But also ground-based (e.g. NIRPS GTO, EXPRES, SPECULOOS, ...)

A bright future

2025

2030ies

An enormous increase in exoplanet demographics in the last 30 years. For the future, exoplanets are key science cases for several of the largest observational projects in the coming years and decades - uncovering unexplored processes and parameter spaces: key to understand if our understanding really captures the governing physics. In this, combined demographics from surveys with well-defined large samples and known biases are of paramount importance.