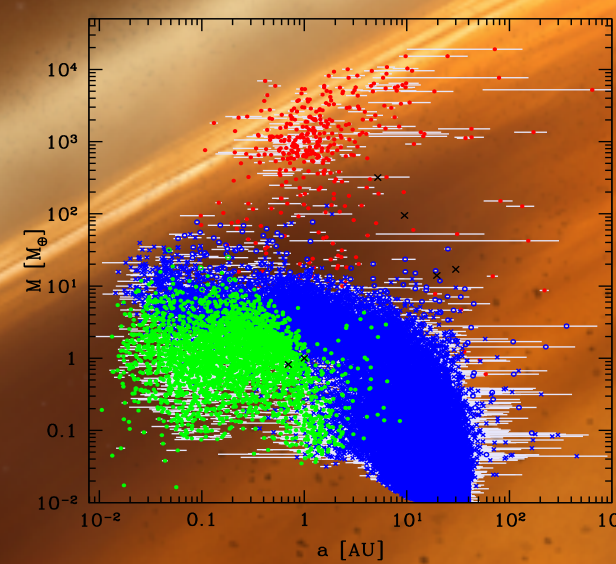
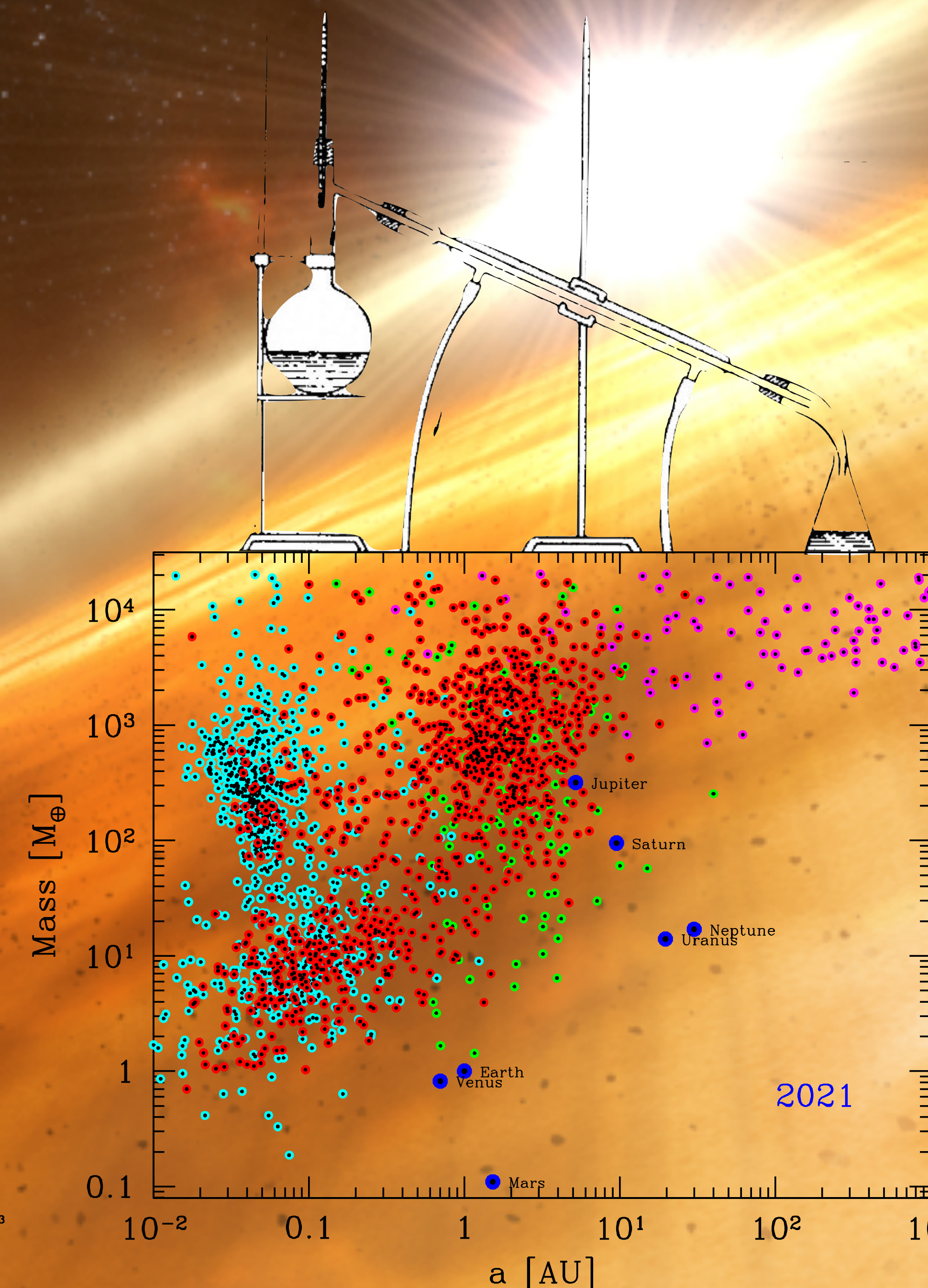
Planetary population synthesis - comparing theory and observation

Sagan Summer Workshop

19.-23.7.2021





Christoph Mordasini

Division of Space Research and Planetary Sciences

Physics Institute

University of Bern, Switzerland

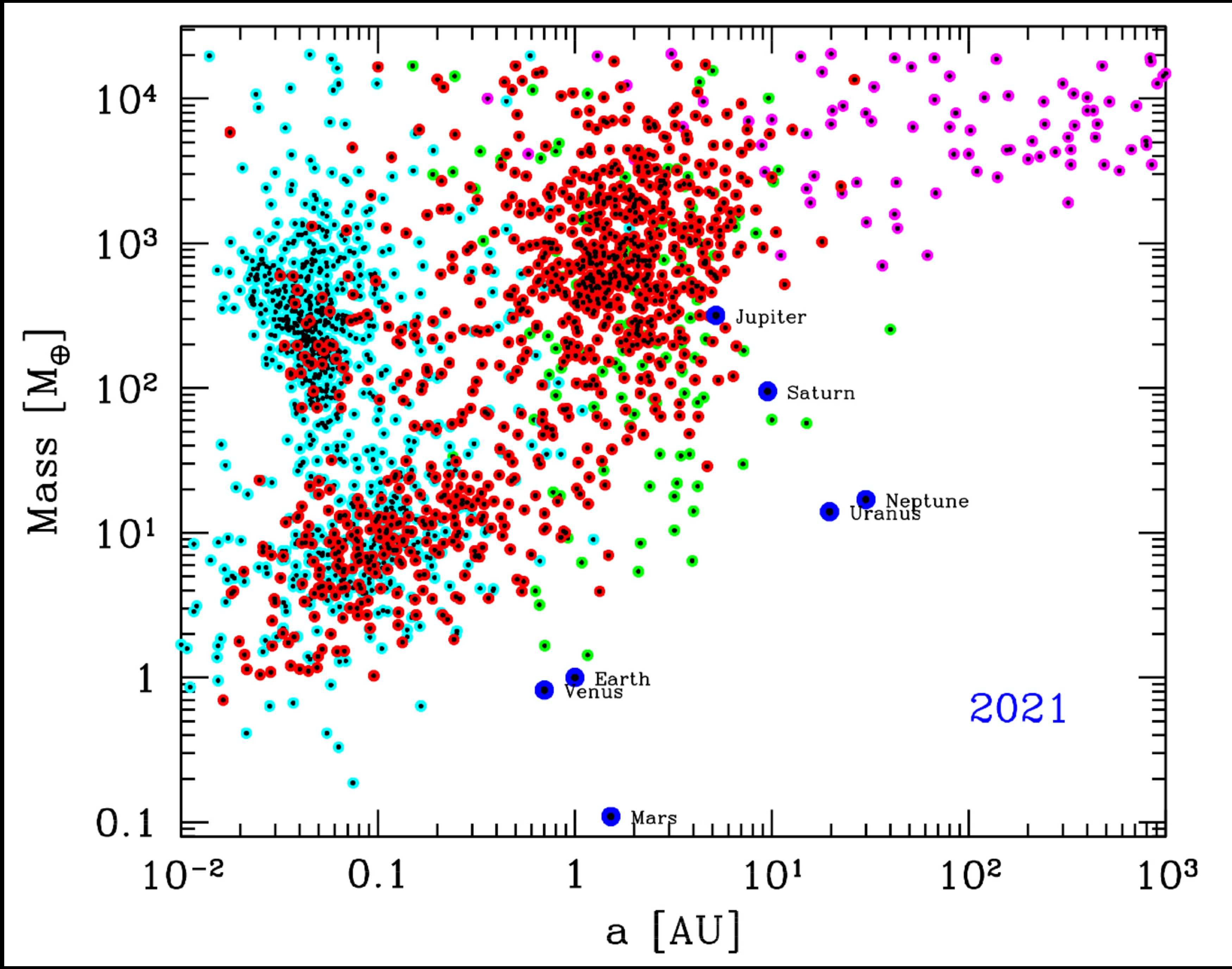
Talk contents

Part A: Introduction and methods

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

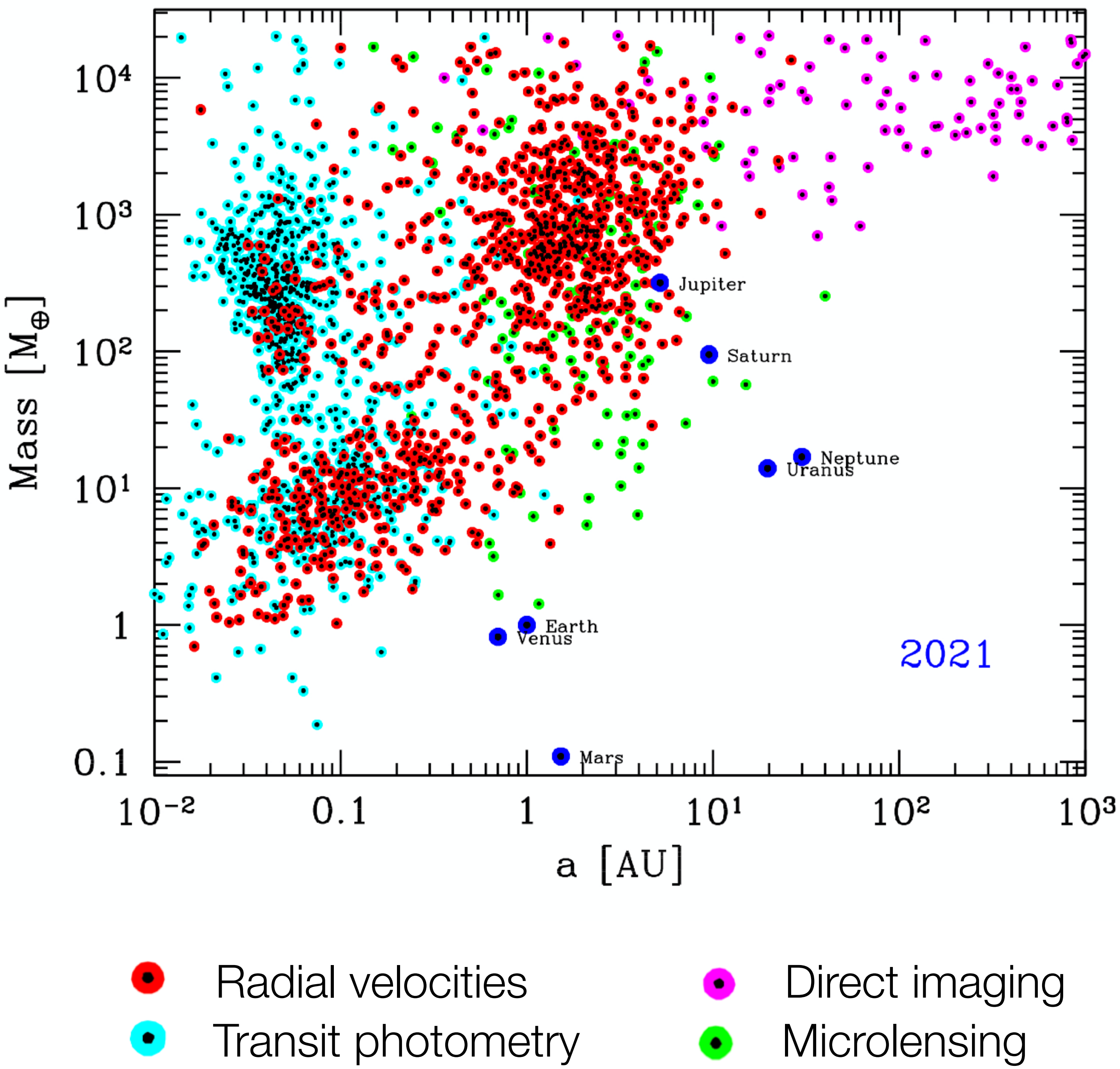
Part B: Results and perspectives

1. Classes of planetary systems
2. Overview of statistical results
3. Comparisons with observations
4. Perspectives and conclusions



1. Observational motivation

Observational motivation

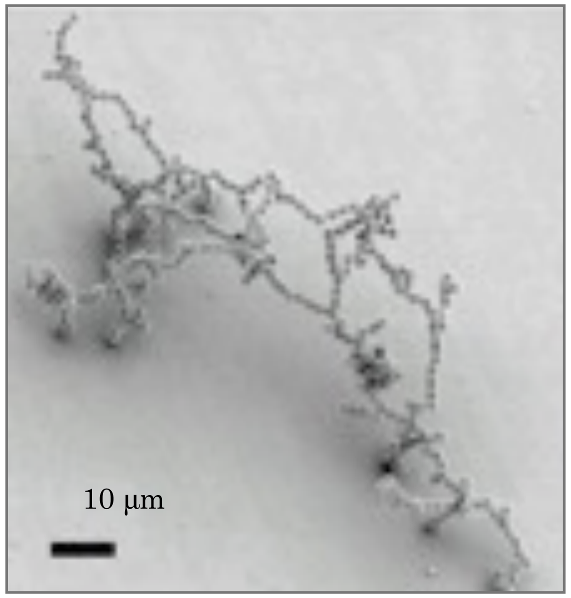


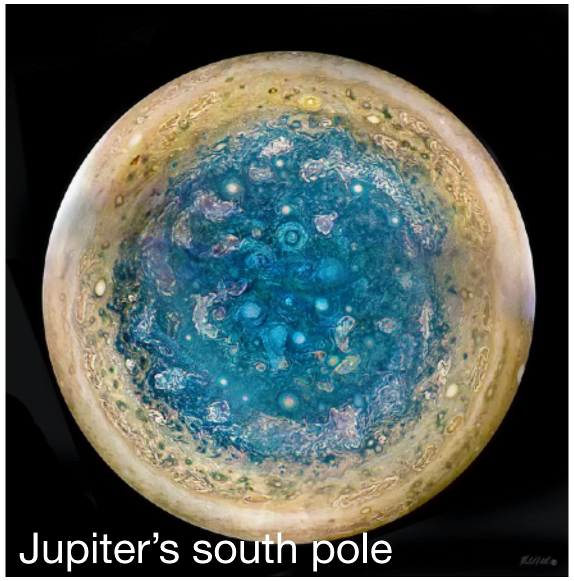
- Enormous increase in observational data on exoplanets since 1995. Detections from ground and space (HARPS, HIRES, Kepler, TESS, NGTS, SPHERE, GPI, CARMENES, CHEOPS, ESPRESSO, WASP…)
- More to come soon (JWST, Gaia, PLATO, Roman ST, ARIEL, ELT, …)

Diversity in exoplanet properties

We would like to use all these observations to better understand planet formation and evolution. But the field remains observationally driven, theory struggles to keep up. Why?

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
- Complete 3D radiation-magnetohydrodyamic numerical simulations too expensive

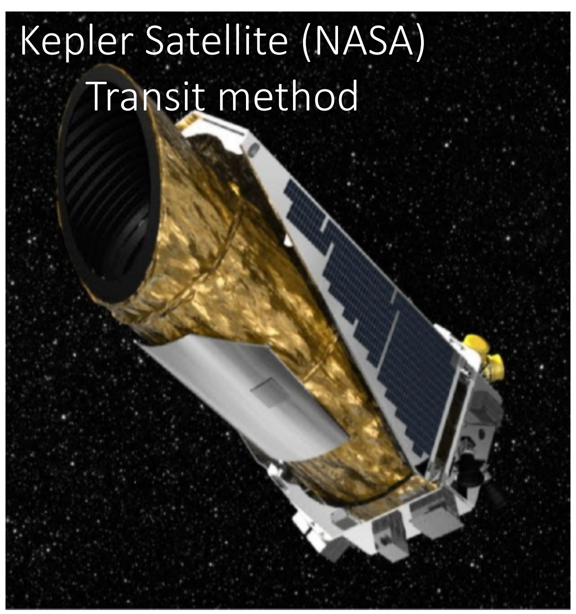
Cannot build theory based on first principles of physic only.

⇒ Theory needs observational guidance via comparison of observations and theoretical predictions

Comparing theory and observations

Compelling comparisons not so easy in practice:

- models for specific processes: difficult to test directly with observations. Each physical mechanism intermingles with many others. Only result of non-linearly combined action of all mechanisms observable.
- Often only limited knowledge about an individual exoplanet system (like period and radius / minimum mass).



But: very high number of exoplanets: they can be treated as a population.

- statistical constraints
- data from many different techniques: much more stringent constraints on theoretical models by combining M, a, e, R, L, spectra, …

We need a tool to use this wealth of constraints.

Population synthesis as a tool

Population synthesis is a tool to:

- use all known exoplanets to constrain planet formation and evolution models
- test the implications of theoretical concepts
- predict the yield of future instruments
- provide a link between theory and observations

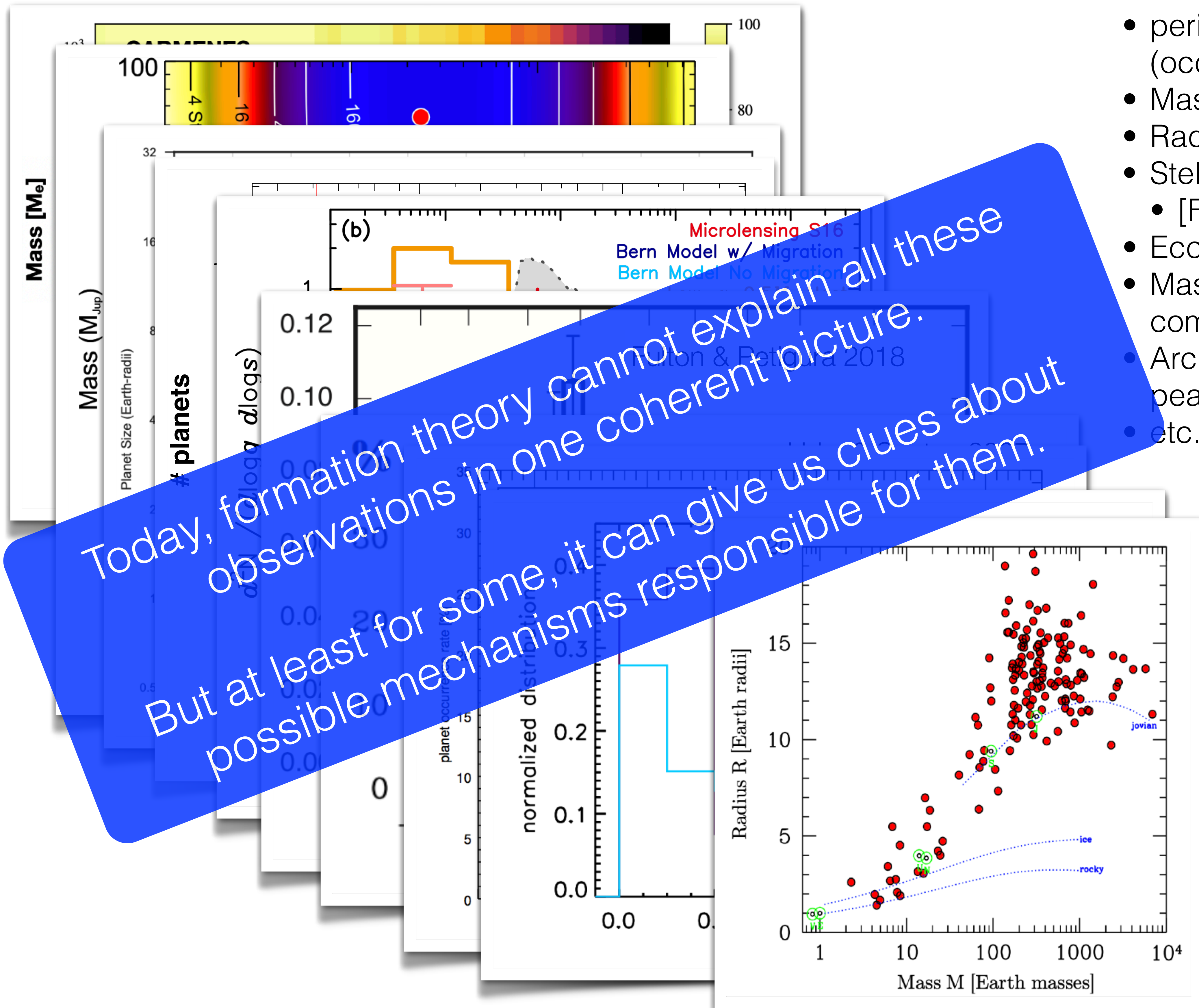
Statistical approach rather than comparing individual systems

- need to compute the formation of many planetary systems
- the approach and the physics must be simplified (typically low-dimensional)
- but it must capture the key effects

⇒ builds on all detailed studies of specific physical mechanism, combining them into a global end-to-end formation & evolution model

- depends on / reflects the general progress of the field

Essential statistical constraints

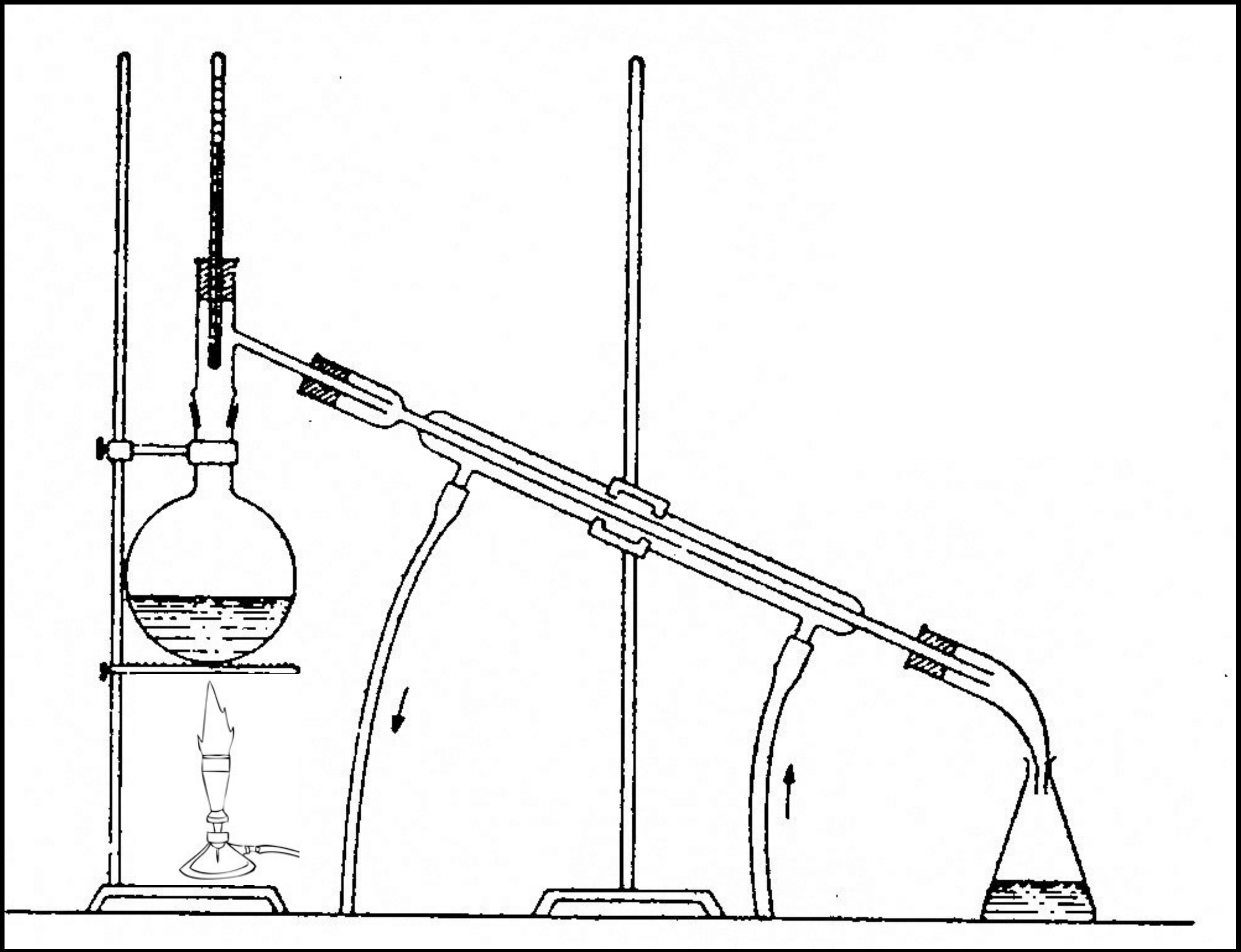


Today, formation theory cannot explain all these observations in one coherent picture.

But at least for some, it can give us clues about possible mechanisms responsible for them.

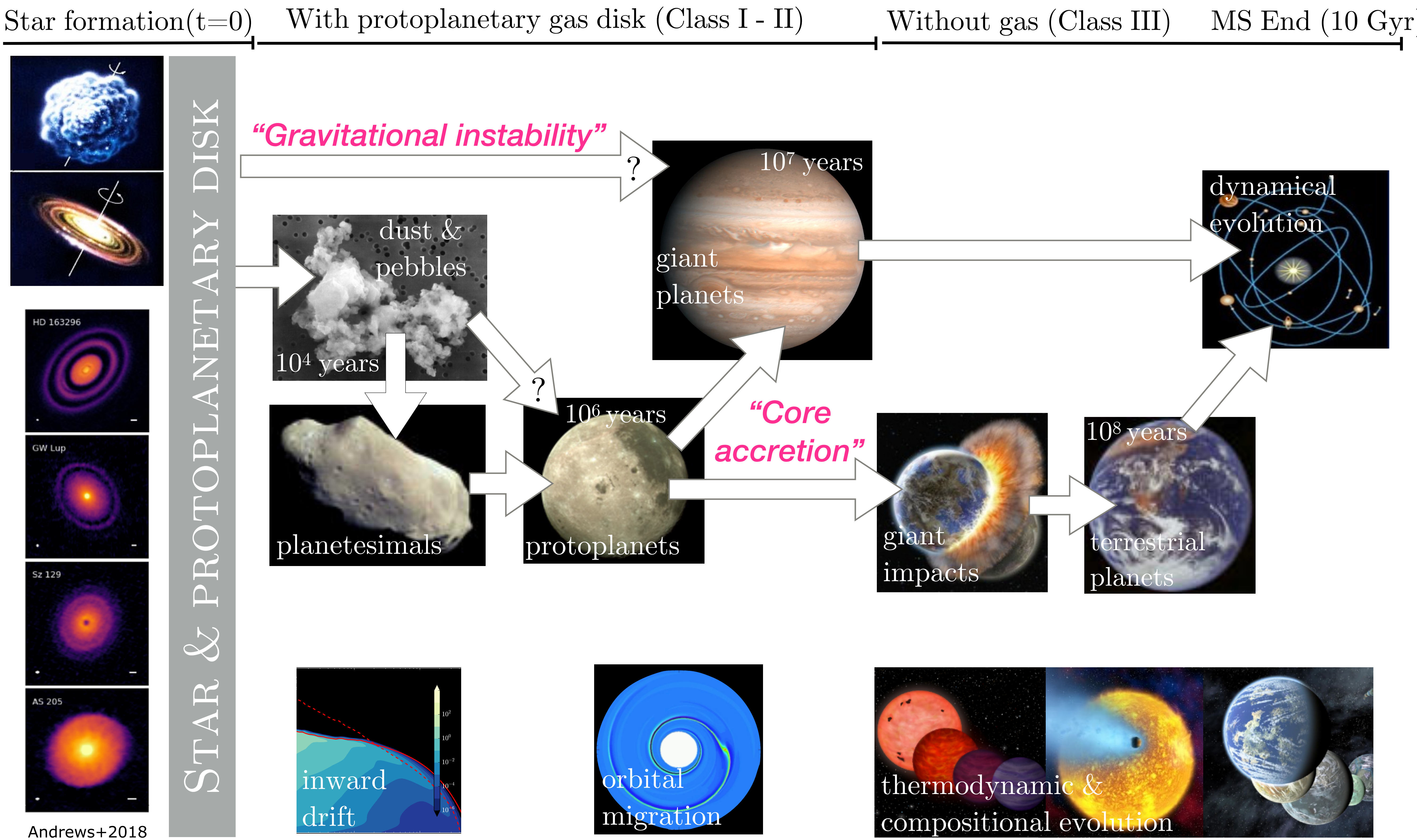
- period-M/R/mag diagrams (occurrences of planet types)
- Mass function P-IMF
- Radius distribution, Fulton gap
- Stellar dependencies
  - [Fe/H], mass, cluster origin
- Eccentricity distribution
- Mass-radius relation, bulk composition
- Architecture (multiplicity, peas-in-a-pod, SE-CJ relation)
- etc.

Combine constraints from all major detection methods plus Solar System



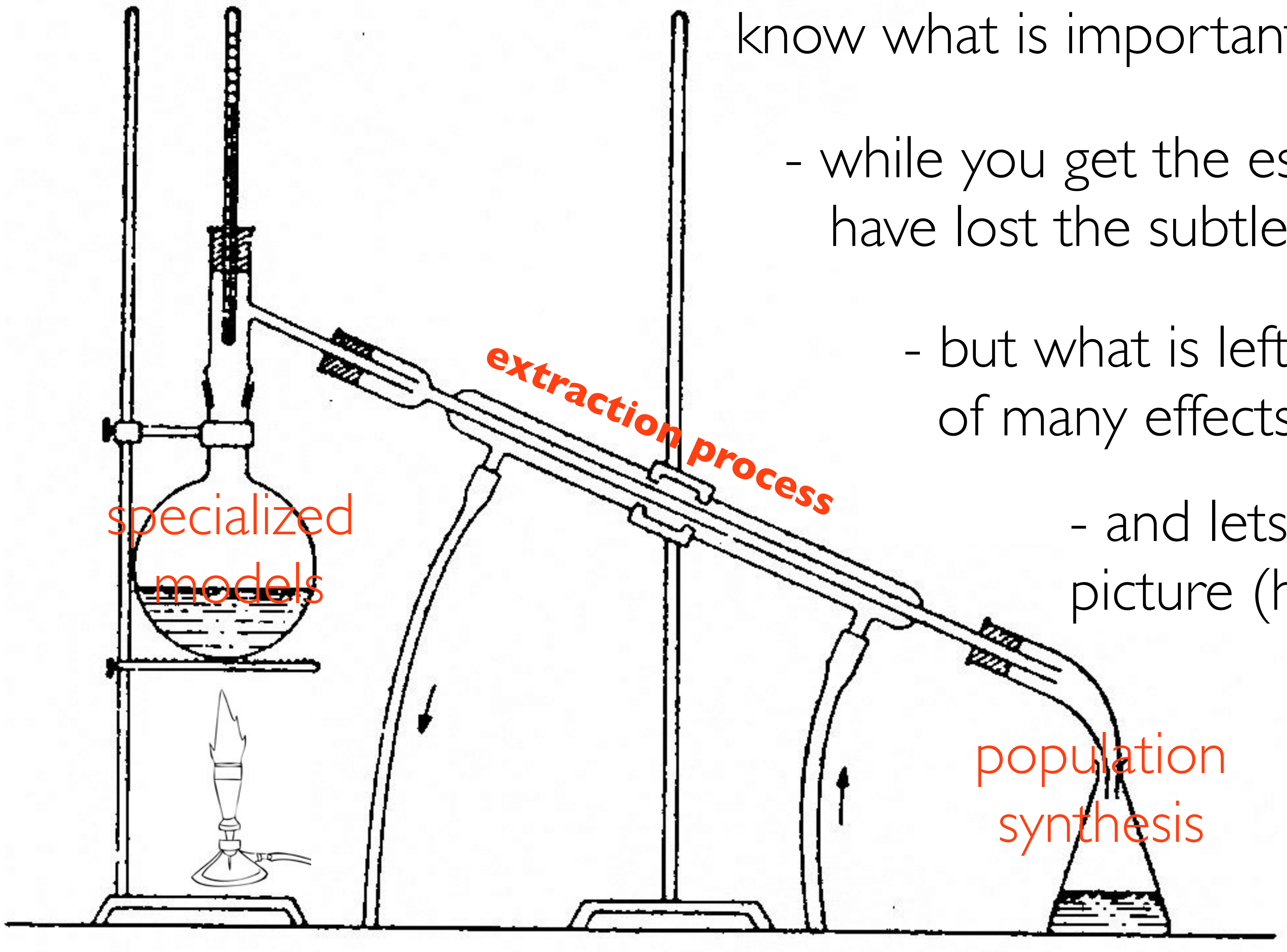
2.
Population synthesis principle

The sequential planet formation paradigm



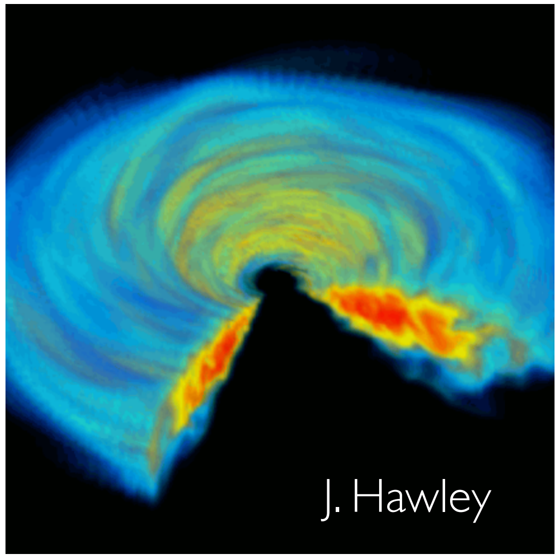
Global end-to-end models should -in principle- include all these effect… a formidable task

The essence of the method



- you need specialised models to know what is important
- while you get the essence, you have lost the subtlety of the original
- but what is left is a concentrate of many effects
- and lets you see the big picture (hopefully)

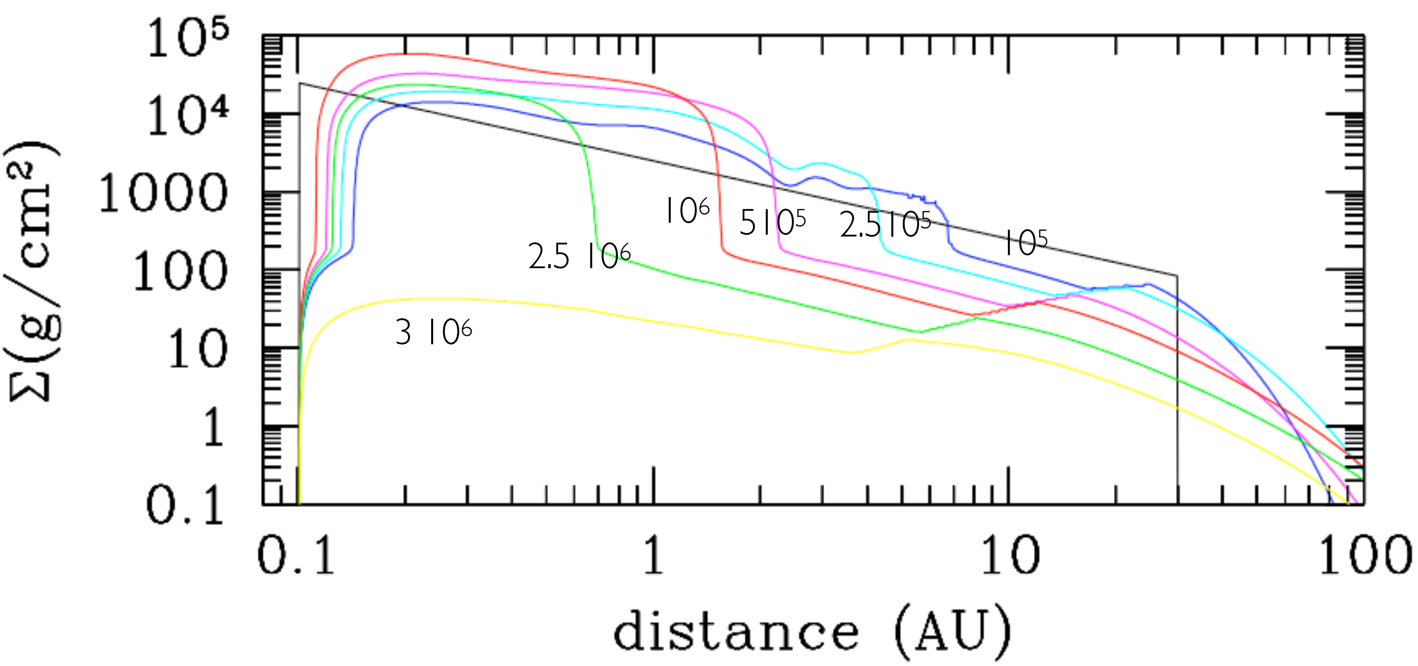
Distill how strongly?



$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + (\rho \mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla \left(P + \frac{B^2}{8\pi} \right) - \rho \nabla \Phi + \left(\frac{\mathbf{B}}{4\pi} \cdot \nabla \right) \mathbf{B} + \eta_V \left(\nabla^2 \mathbf{v} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{v}) \right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta_B \nabla \times \mathbf{B})$$

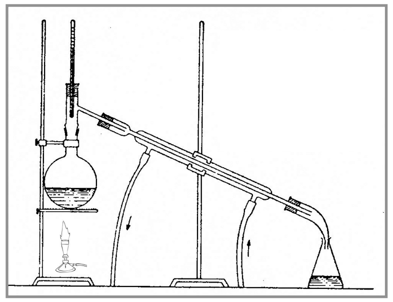


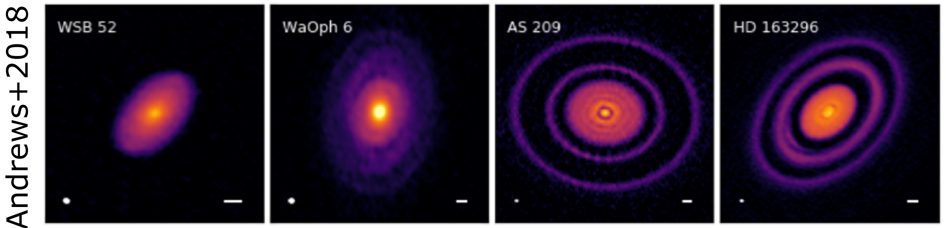
$$\frac{d\Sigma}{dt} = \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} \tilde{\nu} \Sigma r^{1/2} \right] + \dot{\Sigma}_w(r)$$

How simple is still good enough?

$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0} \right)^{-\alpha} e^{-t/\tau}$$

The population synthesis method





Andrews+2018

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

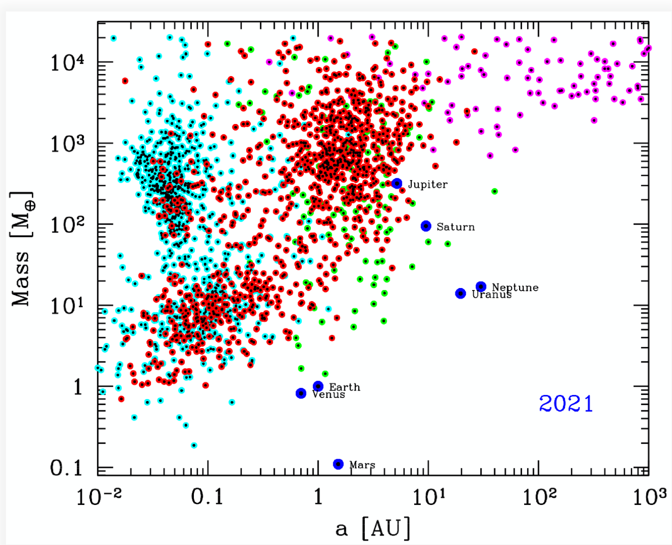
From observations

Draw and compute synthetic population

New instrumentation

better observational constraints

Apply observational detection bias



Observed population

Predictions

(going back to the full synthetic population)

Stat. Comparison:

Observable sub-population
- Frequencies
- Orbits, masses, radii, luminosities
- Architecture, multiplicity
- Correlations

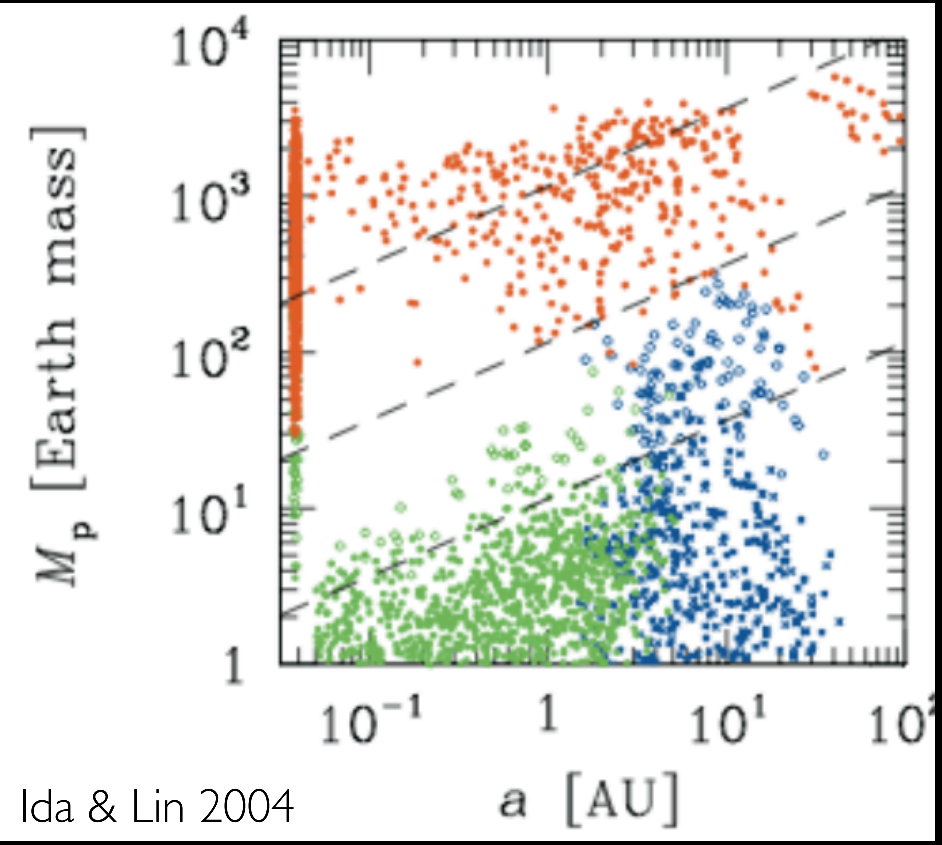
…..

No match: change parameters, improve model, reject model

Match

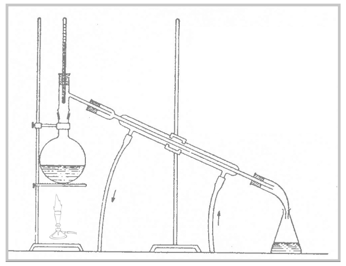
Model solution found

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

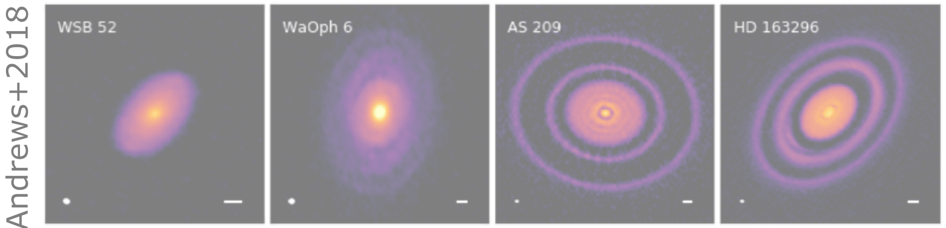


3.
Input physics: global models

Global end-to-end models



Andrews+2018



Models of individual processes

Accretion, migration, …

Global end-to-end formation & evolution model

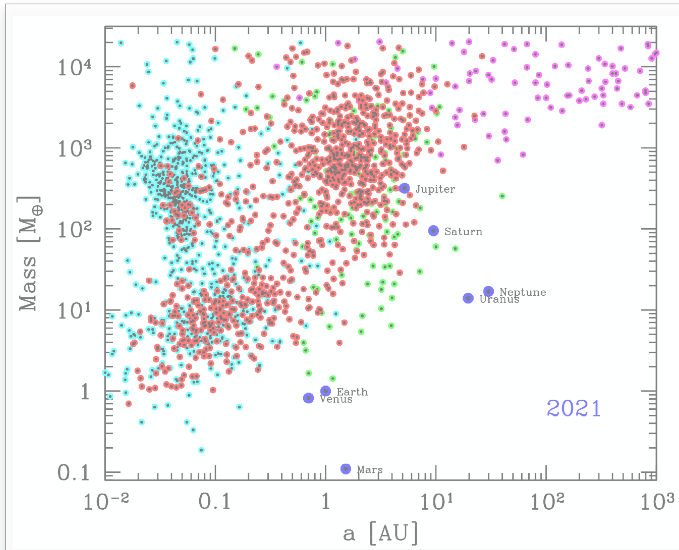
Disk properties ⇒ planet properties

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:

Observable sub-population
- Frequencies
- Orbits, masses, radii, luminosities
- Architecture, multiplicity
- Correlations

.....

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!

An early (earliest?) population synthesis

Computer Simulation of the Formation of Planetary Systems

STEPHEN H. DOLE

The Rand Corporation
Santa Monica, California 90406

Received January 25, 1970; revised July 30, 1970

One of the many hypotheses about the formation of the solar system postulates that the planets were formed by the aggregation of particulate matter within a cloud of dust and gas surrounding the newly-formed sun. A test of the validity of one version of this hypothesis was obtained in a computerized Monte Carlo simulation of the process.

In the model used, nuclei are "injected" into the cloud one at a time, on elliptical orbits. The dimensions of the semimajor axis and the eccentricity of the orbit of each nucleus are determined by using random numbers. As the nuclei orbit within the cloud they grow by aggregation and gradually sweep out dust-free annular lanes. If they grow larger than a specified critical mass they can begin to accumulate gas from the cloud as well. If the orbit of a planet comes inside a certain interaction distance from a planet that was formed earlier, or if the orbits cross one another, the two bodies coalesce to form a single, more massive planet which may then continue to grow by aggregation. The process of injecting nuclei is continued until all the dust has been swept from the system. At this point the run is terminated and the machine output displays the masses and orbital parameters of the planets remaining in the final configuration.

Each planetary system produced by using a different random number sequence is unique. However, all the systems so produced share the major regular features of our solar system. The orbital spacings have patterns of regularity suggestive of "Bode's law." The innermost planets are small rocky bodies; the midrange planets are large gaseous bodies; the outermost planets are generally small. The general pattern of planetary mass distribution is similar to that in our solar system with masses ranging from less than that of Mercury to greater than Jupiter's.

Based on nebular hypothesis and core accretion paradigm: first accretion of solid cores, then accretion of gas if sufficiently massive

An early approach

- **Disk model:** static in time, exponential profile
- **Accretion of solids:** limited by feeding zone (restricted 3 body)
- **Accretion of gas:** if $M_{core} > k_{crit} \times M_{crit}$ found from $v_{therm} < v_{esc}$
- **Termination of gas accretion:** ~arbitrary parametrization
- **Coalescence of embryos:** if feeding zones overlap,
- **Orbits:** fixed (in situ formation, no migration, no N-body)
- <u>Parameters:</u> stellar mass, disk profile, seed mass, k_{crit}, max M.
- <u>Monte Carlo variables:</u> position and eccentricity of seed, disk mass, disk dust-to-gas ratio

"Monte carlo computer synthesis"

Dole 1970

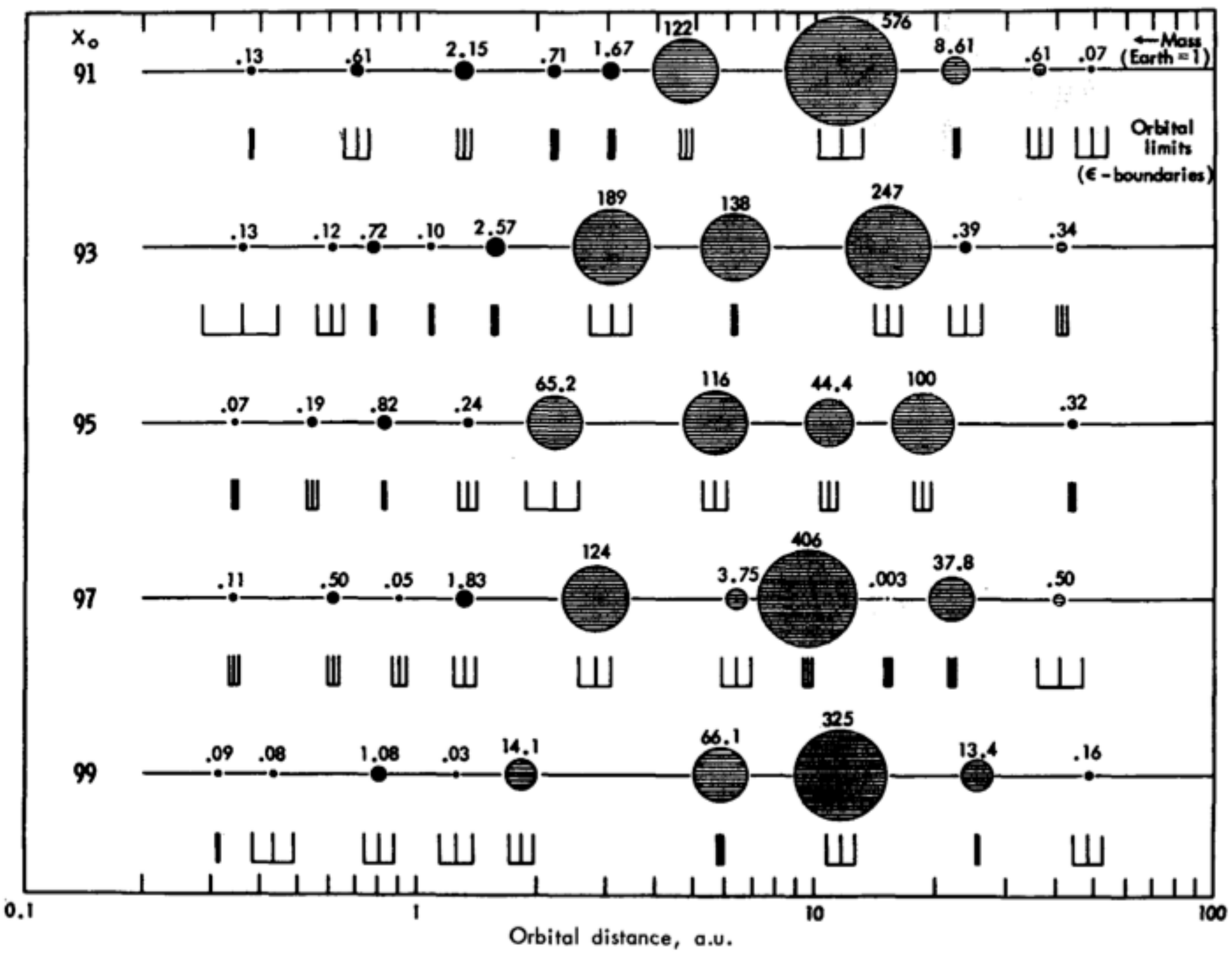


FIG. 1. Examples of planetary systems generated in computer synthesis. X_0 is initiating number for random number series used in program. Positions of circles along line indicate mean orbital radius; numbers above circles and sizes of circles indicate planetary masses (radius of circle ~ planetary mass$^{1/3}$); solid circles are terrestrial bodies; horizontal shading designates gas giants.

~isolation mass

~critical mass

Pre-viscous-accretion disk theory (Lynden-Bell & Pringle 1974)

Pre-planetesimal accretion theory (Safronov 1972)

Pre-1D planetary structure theory (Mizuno 1978)

Pre-orbital migration theory (Goldreich & Tremaine 1979)

-Solar System-like with ~uniform spacing in log

-no close-in planets, no distant giant planets

Reliance of global models on models for specific processes … and on observations

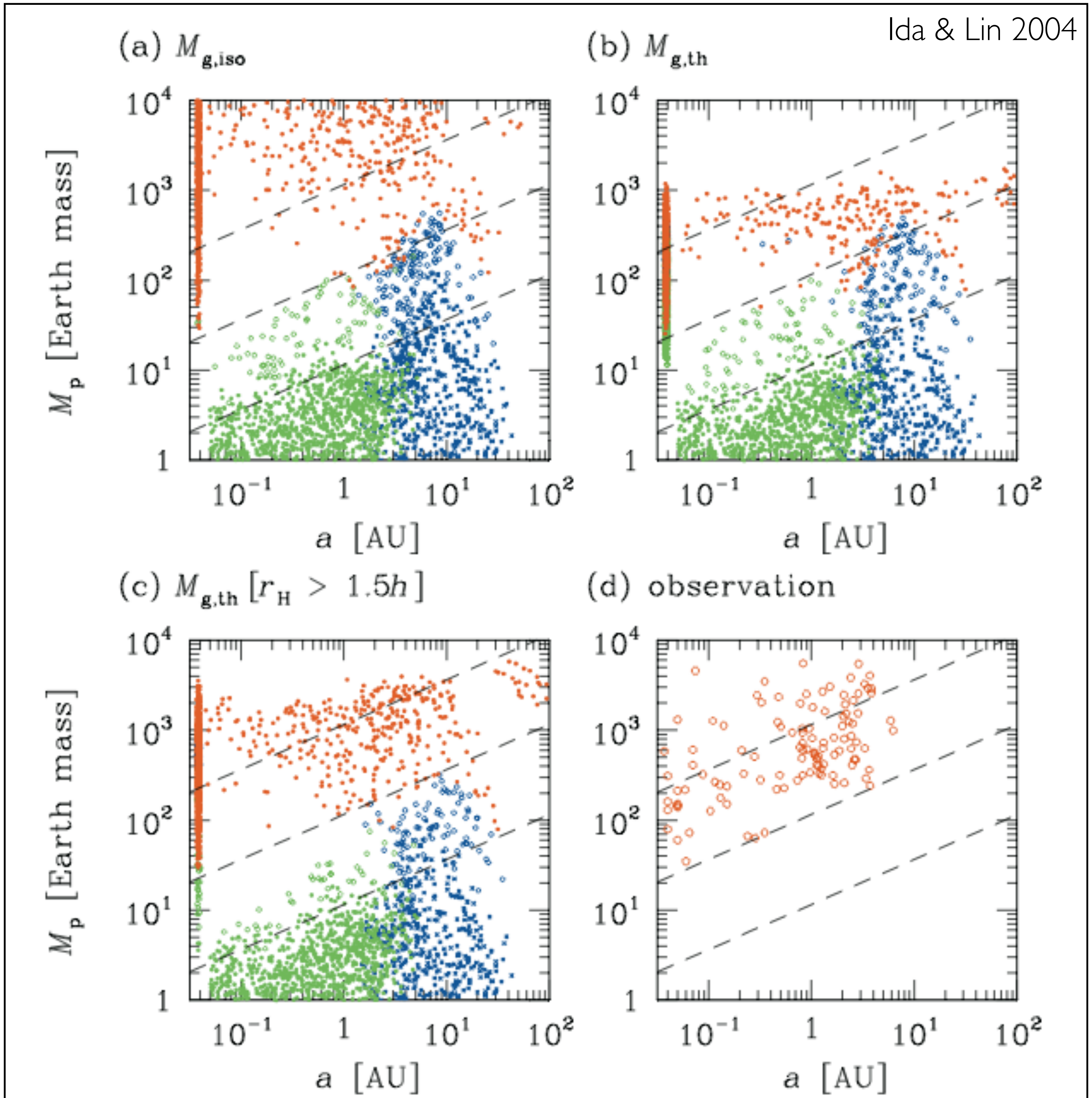
First modern model: Ida & Lin 2004

Ida & Lin (2004, 2005, 2008, 2010, 2013) building on Kokubo & Ida 2002, Ida & Makino 1993, …

- Disk model: powerlaw, exponential decrease
- Accretion of solids: Safonov rate equation, isolation mass
  Safronov 1969, Greenzweig & Lissauer 1992, Ida & Makino 1993
- Accretion of gas: Parameterized KH-contraction, fitted M_{crit}
  Perri & Cameron 1974, Mizuno et al. 1978, Ikoma et al. 2000
- Termination of gas accretion: Gap formation, disk dissipation
  Lubow 1999, Kley & Dirksen 2006
- Coalescence of embryos: 1 embryo per disk, later semi-analytical prescription (orbit crossing)
- Orbits: type I and II disk migration
  Goldreich & Tremaine 1979, Lin & Papaloizou 1986, Paardekooper et al. 2010, …
- <u>Monte Carlo variables:</u> position of embryo, disk mass, dust-to-gas ratio, disk lifetime

Later several improvements: dead zones, local enhancement of solids, new type II mig., …

First modern pop. synthesis



- $M_{env}/M_{core} \leq 1$ (rocky)
- $M_{env}/M_{core} \leq 1$ (icy)
- $1 < M_{env}/M_{core} \leq 10$ (rocky)
- $1 < M_{env}/M_{core} \leq 10$ (icy)
- $M_{env}/M_{core} > 10$

- aM: diversity
- Planetary desert
- Metallicity effect (correlation between metallicity and giant planet detection probability)
-termination of gas accretion
-effects of type II migration

Overview of some population synthesis models

Core accretion

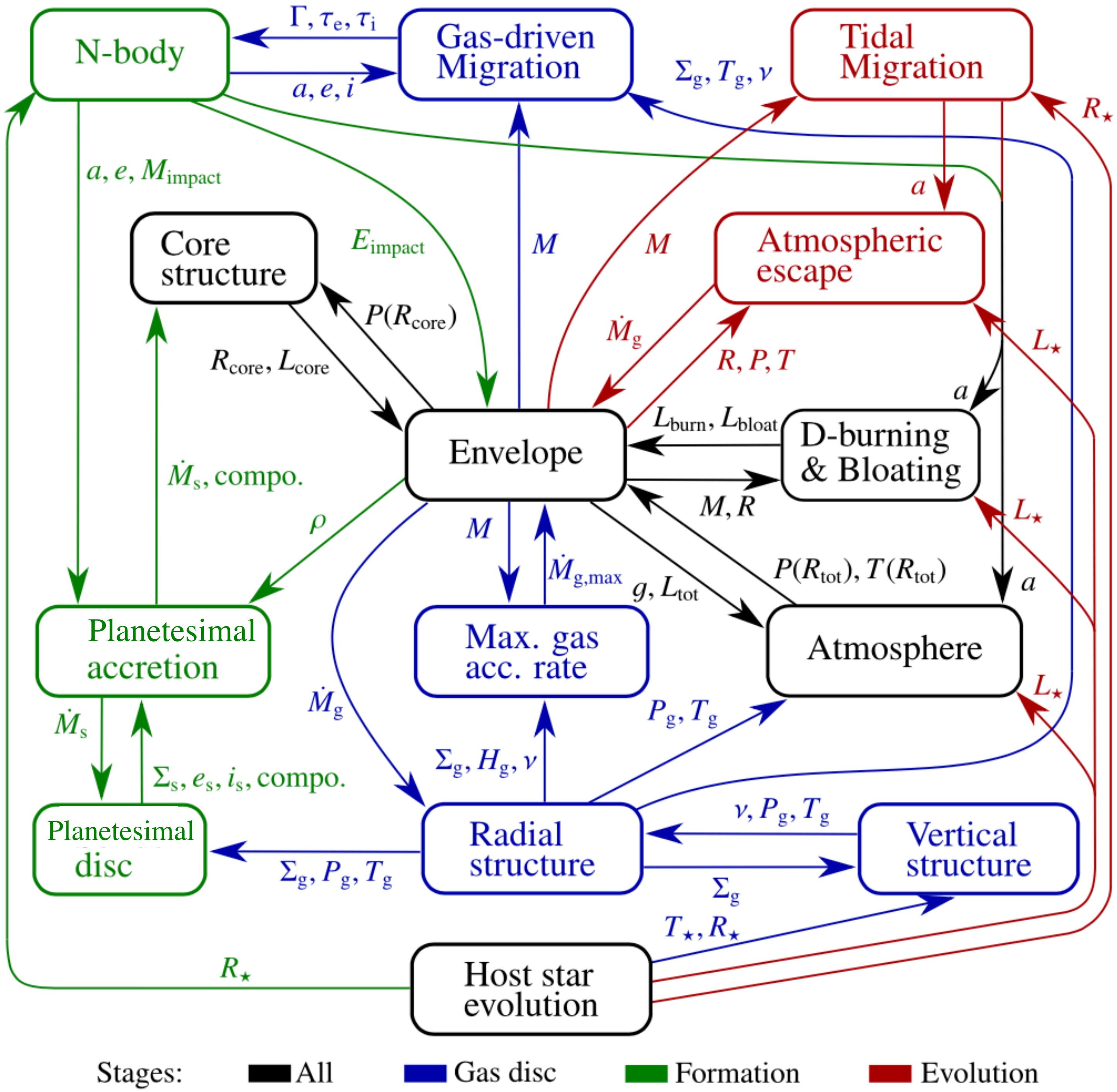
- *Ida & Lin Model*: with planetesimals. Fast, customised for pop. synthesis. First one-embryo per disk, then w. statistical N-body interactions.
  - Similar open source model available online at https://nexsci.caltech.edu/workshop/2015/
- *Bern Model:* with planetesimals. Combined formation and long-term evolution. Explicit N-body integrator. Explicit solution of underlying diff. equations. Interior structure model.
- *Lund Model* (Bitsch, Johansen, Ndugu, Liu and collaborators): with pebbles. Single embryo per disk. 2D-disk model.
- *Mc Master Model* (Pudritz, Alessi, Cridland, Hasegawa et al.): with planetesimals. Disk traps, astrochemistry, interior structures.

Gravitational instability

- *Forgan, Rice at al.; Nayakshin, Humphries et al.; Müller, Helled & Mayer*
- Fragmentation criteria, tidal downsizing, migration, clump contraction, …

Ida & Lin 2004-2013; Mordasini et al. 2009-2015: Miguel et al. 2008, 2009; Forgan & Rice 2013; Alibert et al. 2013; Benz et al. 2014 (review); Nayakshin et al. 2015, 2016; Alessi & Pudritz 2018; Mordasini 2018 (review); Chambers 2018, Ida et al. 2018; Forgan et al. 2018; Müller et al. 2018; Liu et al. 2019; Ndugu et al. 2018, 2019; Alessi et al. 2020; Emsenhuber et al. 2021ab; Schlecker et a. 2020, 2021; Burn et al. 2021, Mishra et al. 2021, ….

Bern Generation 3 formation & evolution model



Core accretion paradigm

Alibert et al. 2005, 2013, Mordasini et al. 2009, 2012 Benz et al. 2014, Mordasini 2018, Emsenhuber et al. 2021a,b Schlecker et al. 2021a,b, Burn et al. 2021, Mishra et al. 2021

Emphasis of Generation III

- direct prediction of all important observable quantities
- ability to simulate planets ranging in mass from of Mars to super-Jupiters, at all orbital distances

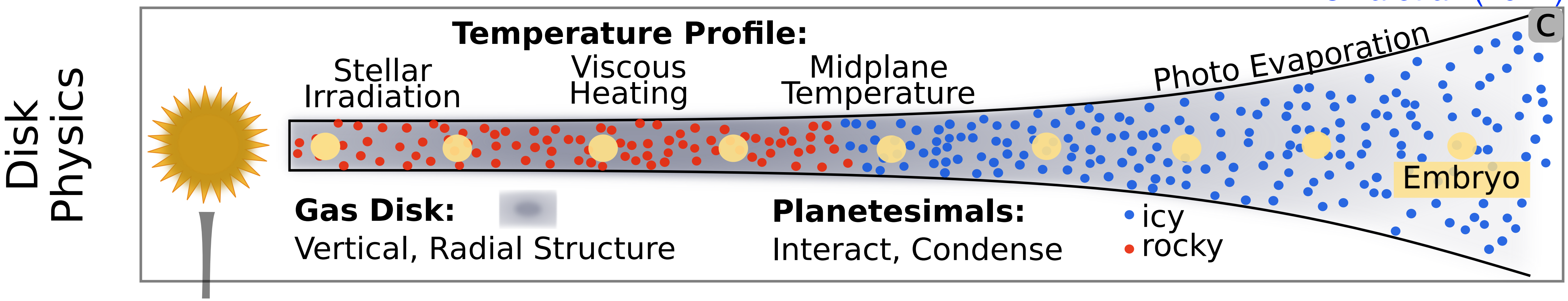
Sub-models

Form. & evolution phase (0-10 Gyr)
Gas disk (0-τ_{disk} Myr)
Formation phase (0-20 Myr)
Evolution phase (20 Myr - 10 Gyr)

- 1D axisym. cst. α-model w. photoevap. & irradiation (Lynden-Bell & Pringle, Hollenbach, Chiang & Goldreich, …)
- Planetesimals as a surface density with dynamical state: eccentricity, inclination (Adachi, Ohtsuki, Chambers, ..)
- Rate equation à la Safronv for planetesimal accretion rate (Safronv, Greenzweig & Lissauer, Ida & Makino, Inaba, …)
- Solution of 1D radially symmetric planetary structure equations to calculate H/He envelope internal structure and thus gas accretion rate, radius and luminosity (Bodenheimer & Pollack), w. D burning & XUV driven atm. escape
- Outer boundary conditions for envelope structure: attached, detached, isolated (Eddington gray)
- Internal structure and radius of the solid core (modified polytropic EOS, Seager)
- Type I & type II gas disk-driven orbital migration (Lin & Papaloizou, Tremaine, Paardekooper, …)
- N-body interaction among protoplanets: scattering, collisions, capture in MMR (Newton, Chambers,…)

The Gen III Bern Model of planet formation and evolution

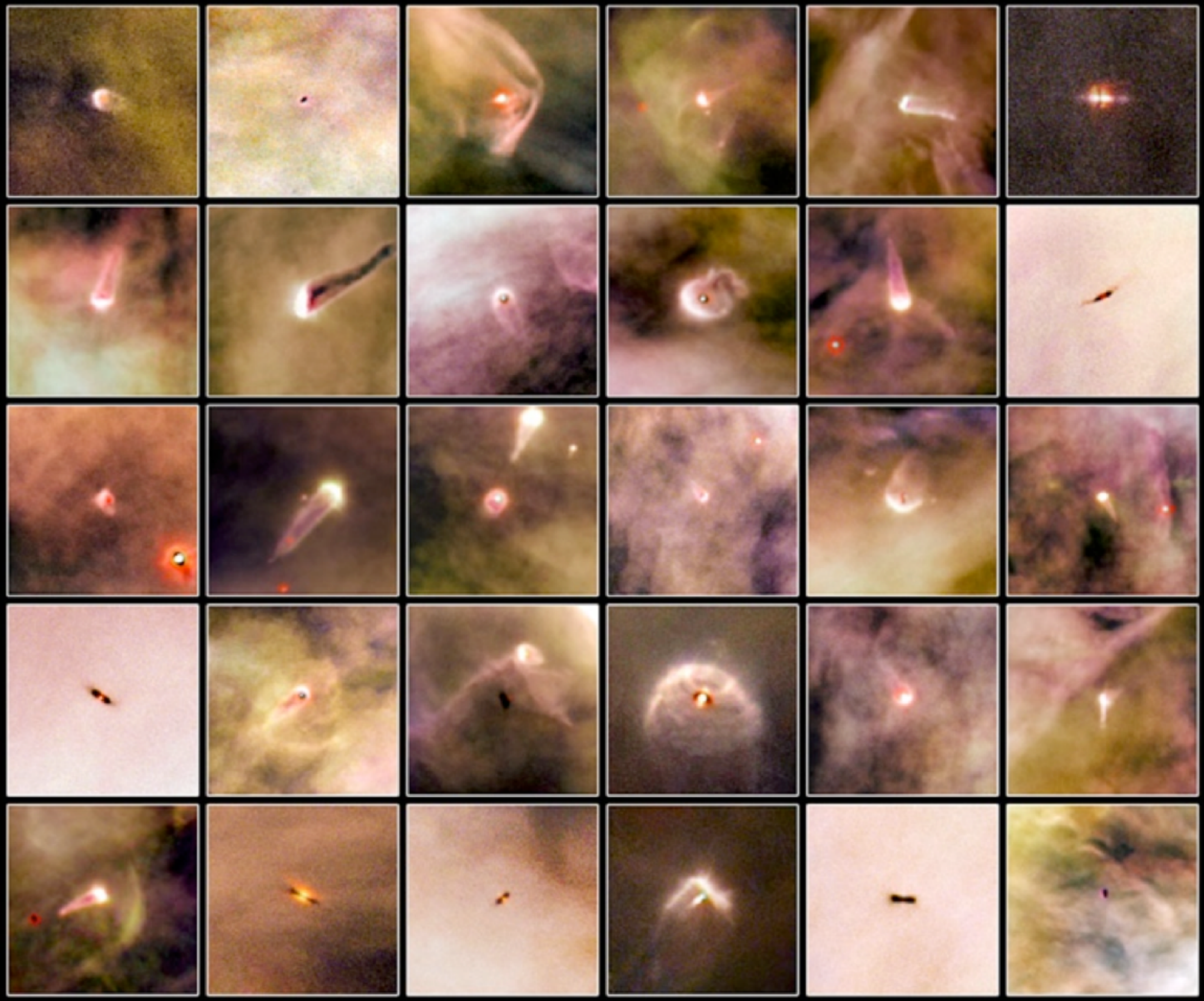
Mishra et al. (2021)



Simplification: rich in (micro)physics, but low dimensionality:
-Planets: spherically symmetric (internal structure resolved radially in 1D)
-Disks: rotationally symmetric (resolved 1+1D, radial and vertical direction)

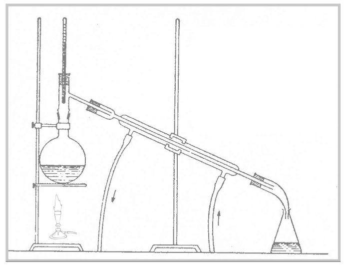
Still many effects neglected: early phases for solids (e.g., Voelkel+2020), disk winds (e.g., Suzuki et al. 2010), …

Numerical simulation of 1 planetary system starting from 100 lunar mass embryos : about 3 months (mostly N-body and planetary internal structure calculation). Long calculation time makes parameter optimisation difficult (Chambers 2018).



4.
Initial conditions

Initial conditions



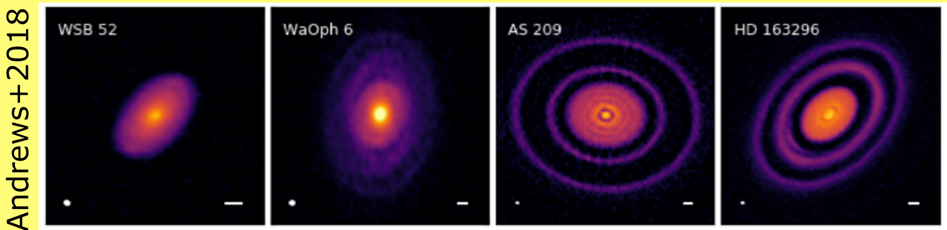
Models of individual processes

Accretion, migration, …

Global end-to-end formation & evolution model

Disk properties ⇒ planet properties

Andrews+2018

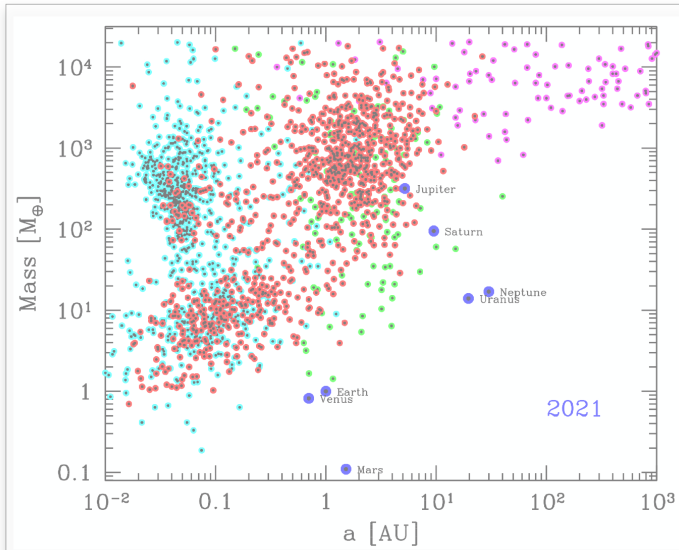


Initial Conditions: Probability distributions of disk properties

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:

Observable sub-population
- Frequencies
- Orbits, masses, radii, luminosities
- Architecture, multiplicity
- Correlations

…..

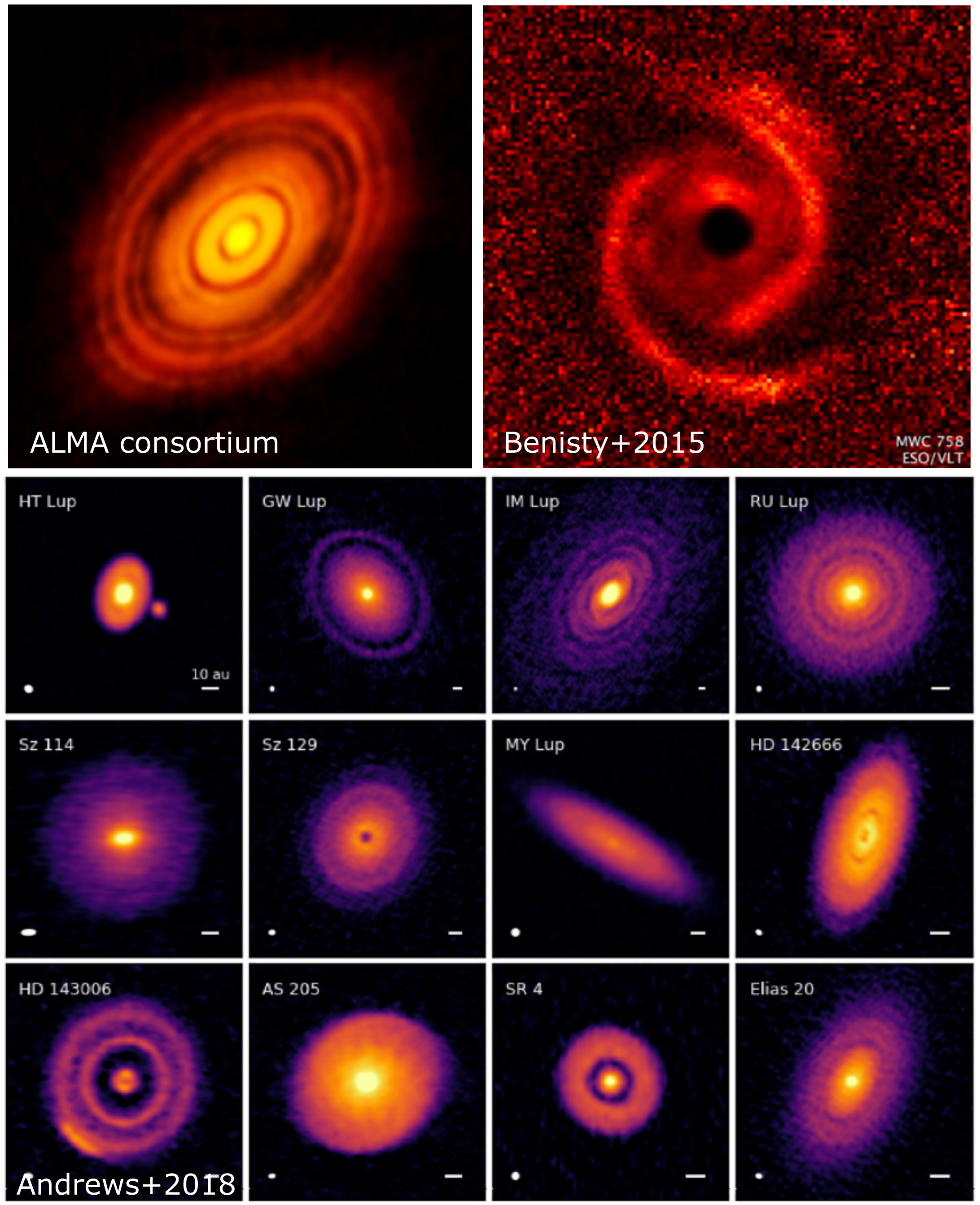
No match: change parameters, improve model, reject model

Match

Model solution found

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

The imprint of disk properties



The ALMA revolution

Planet-forming disks: large diversity too.
Observational determination of distributions of

- Disk lifetimes (stellar cluster environ.)
- Disk gas masses
- Disk dust masses
- Disk sizes

Diversity of disks (Initial conditions)

⇩

Diversity of planets (End products)

Statistically reproducible with a population synthesis model ?

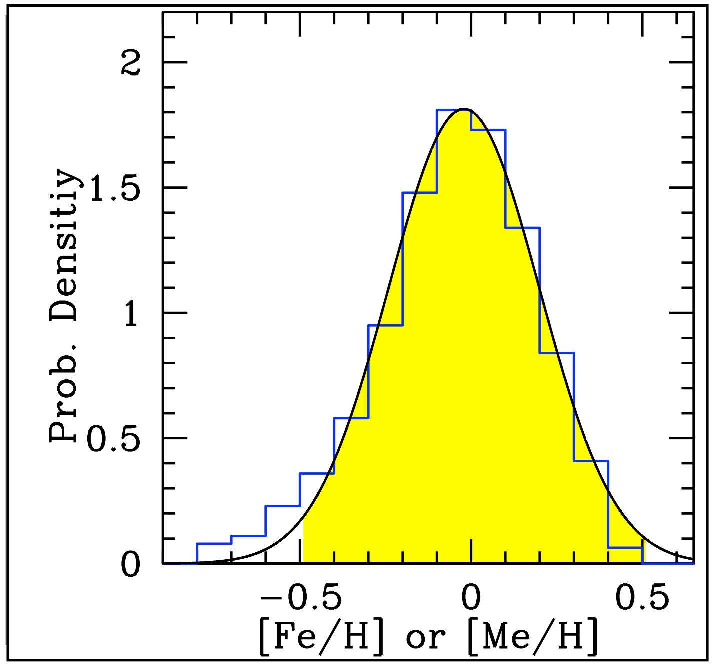
Monte Carlo initial conditions

1 Metallicity

assume same in star and disk

Stellar [Fe/H] from spectroscopy. Gaussian distribution for [Fe/H] with μ ~0.0, σ~ 0.2. (e.g. Santos et al. 2003)

$$f_{\mathrm{dg}} = 0.0149 \times 10^{[\mathrm{Fe/H}]}$$

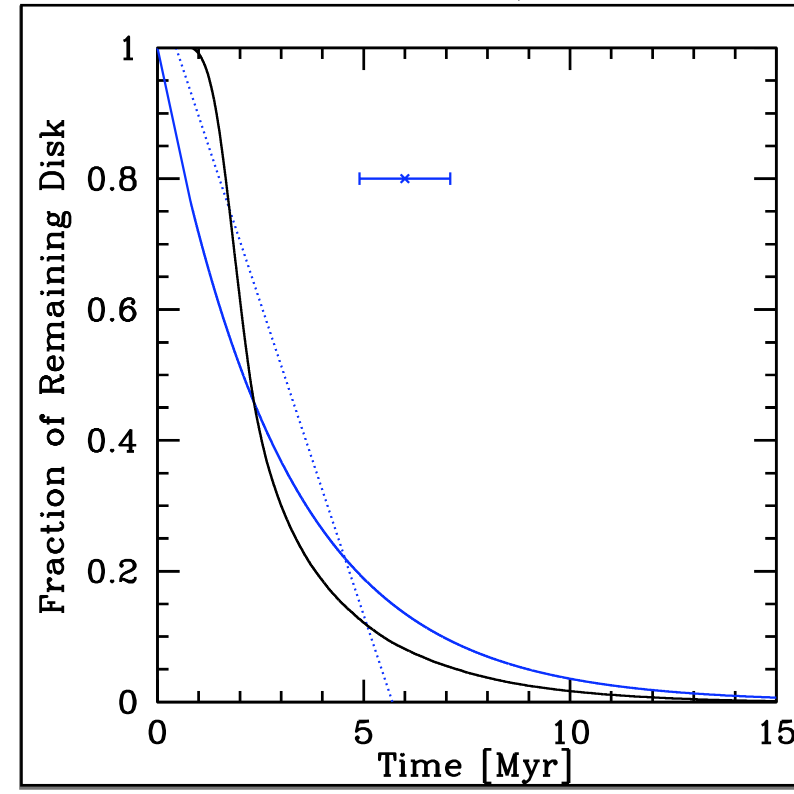


3 Disk lifetime

IR excess

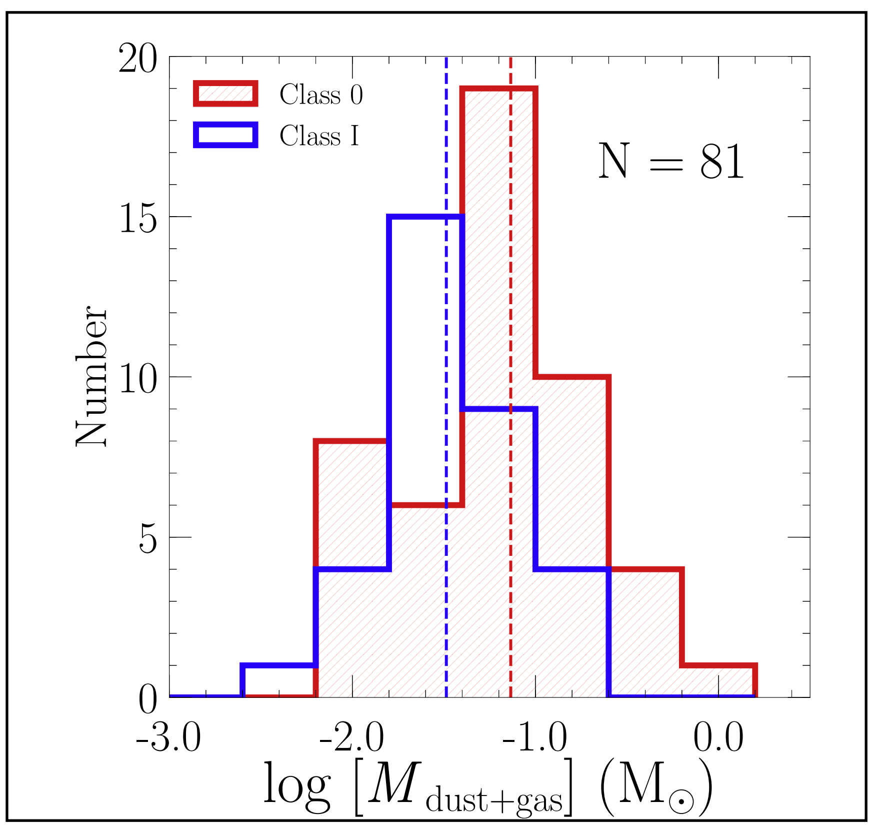
vary lifetime via photoevaporation rate alpha=2×10^{-3}

Haisch et al. 2001, Fedele et al. 2010



2 Disk (gas) masses

From VANDAM survey of Perseus Class I disks (Tychoniec et al. 2018)



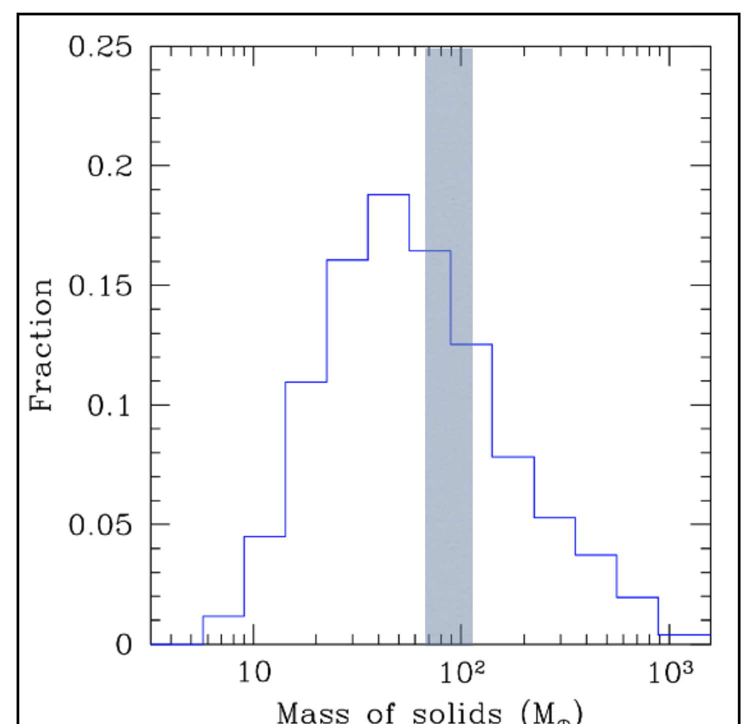
4 Inner disk edge

At corotation radius. Venuti+2017 rotation periods in NGC 2264 (~3 Myr): log-normal distribution with mean of 4.74 days and σ of 0.3 dex.

Initial solid mass

Initial mass of solids in the disks.

Gray: sum of metals in Solar System planets today

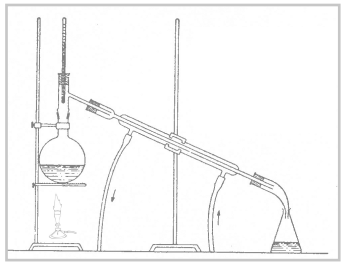


It is not trivial to derive these distributions

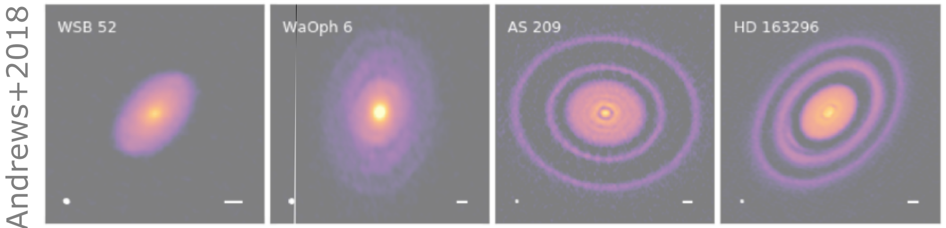
OHP 1.93 m - 51 Peg b discovery

5. Detection biases

Detection bias



Andrews+2018



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

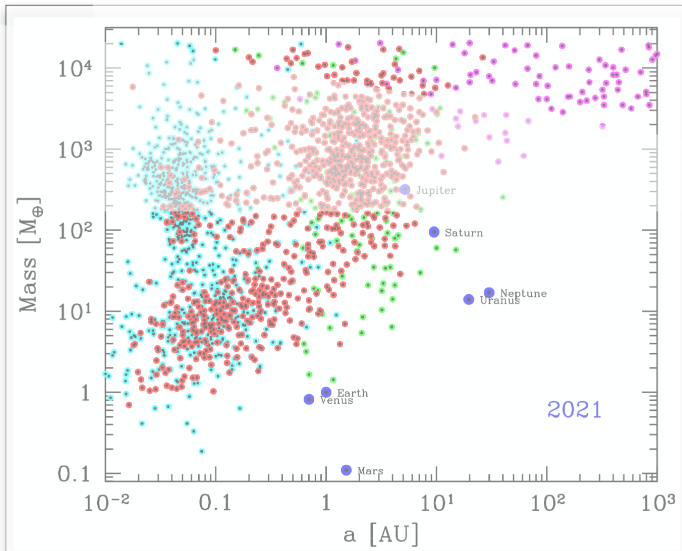
From observations

Draw and compute synthetic population

New instrumentation

better observational constraints

Apply observational detection bias



Observed population

Predictions

(going back to the full synthetic population)

Stat. Comparison:

Observable sub-population

- Frequencies
- Orbits, masses, radii, luminosities
- Architecture, multiplicity
- Correlations

.....

No match: change parameters, improve model, reject model

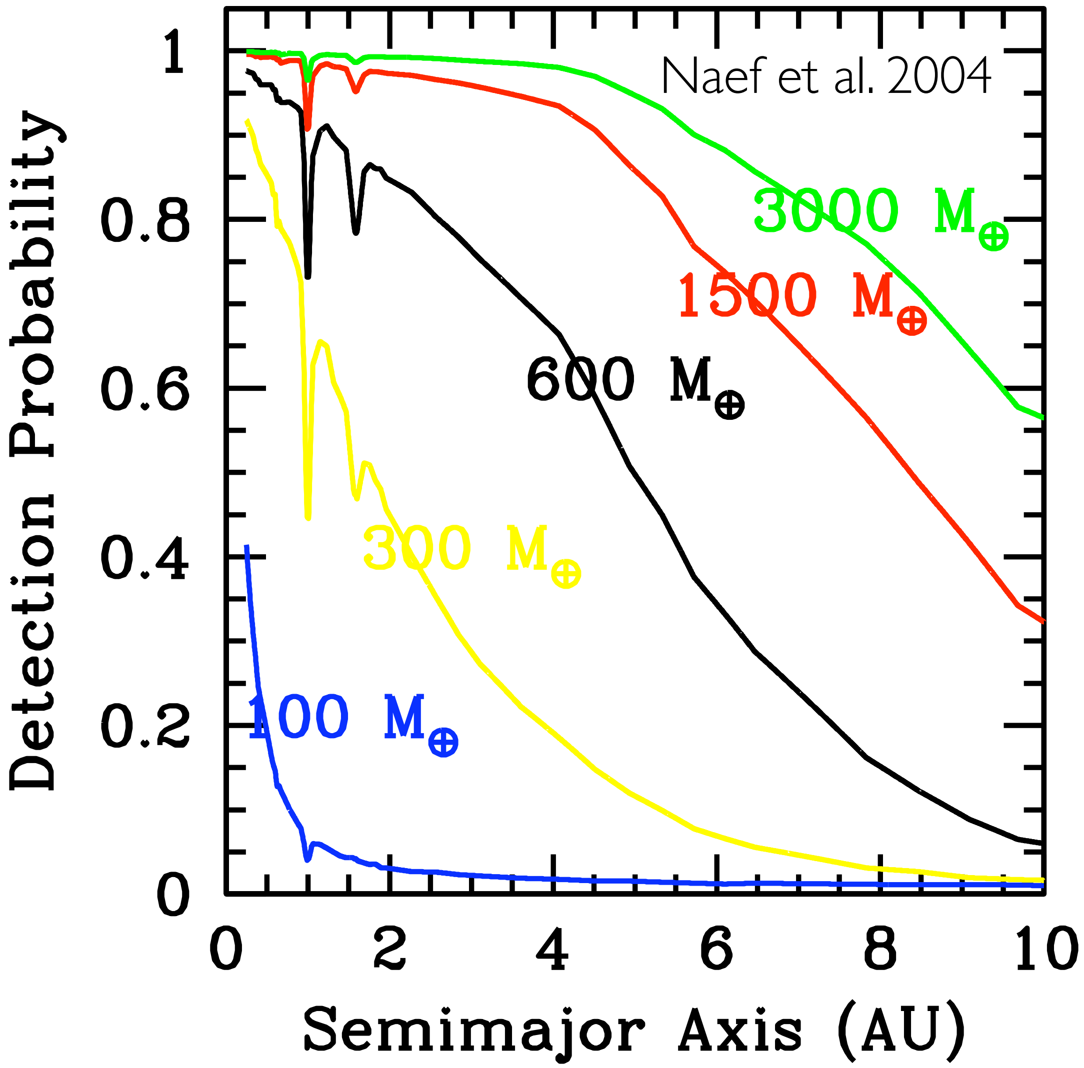
Match

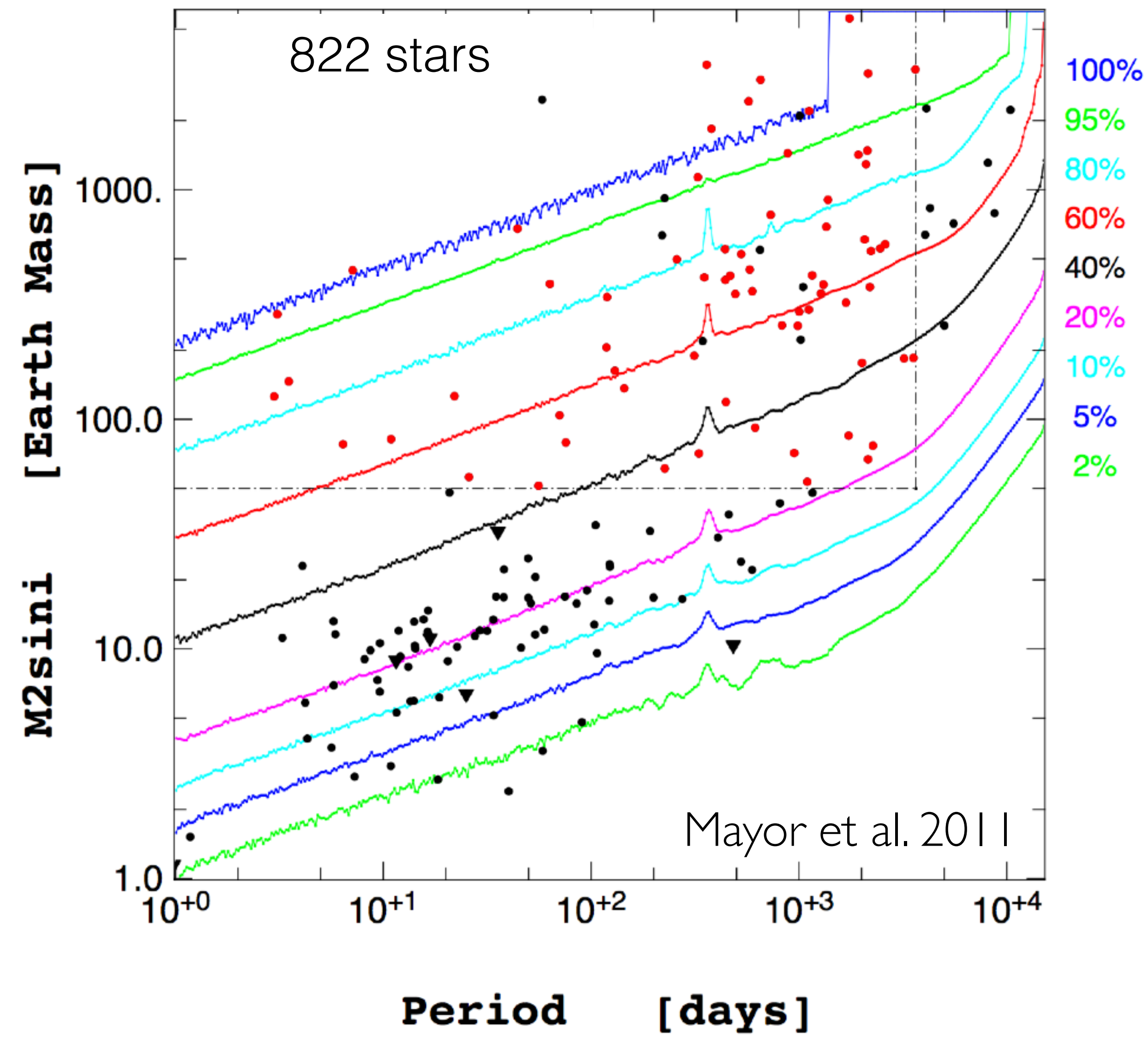
Model solution found

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

Radial velocity detection bias

Get sub-population of *observable* synthetic planets



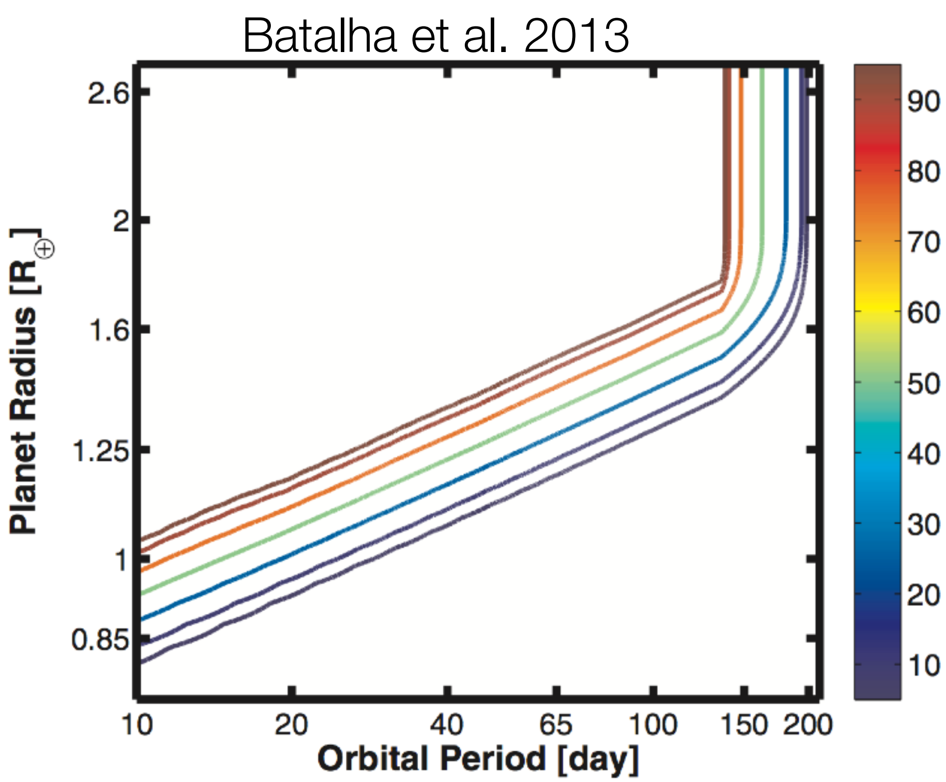


Elodie ~10 m/s Instrumental precision HARPS ~1 m/s

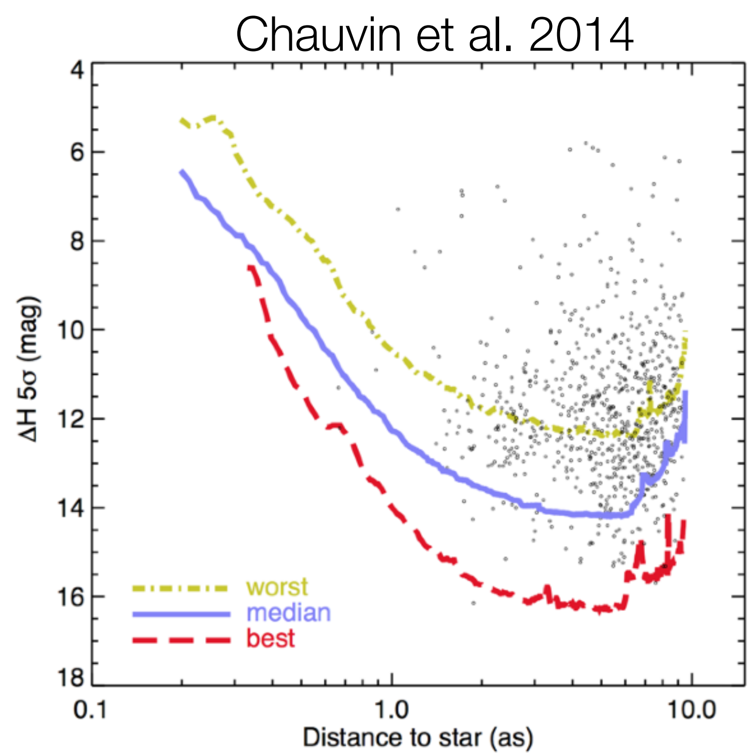
Includes effects of

- Orbital eccentricity
- Stellar metallicity, rotation rate, and jitter
- Actual measurement schedule

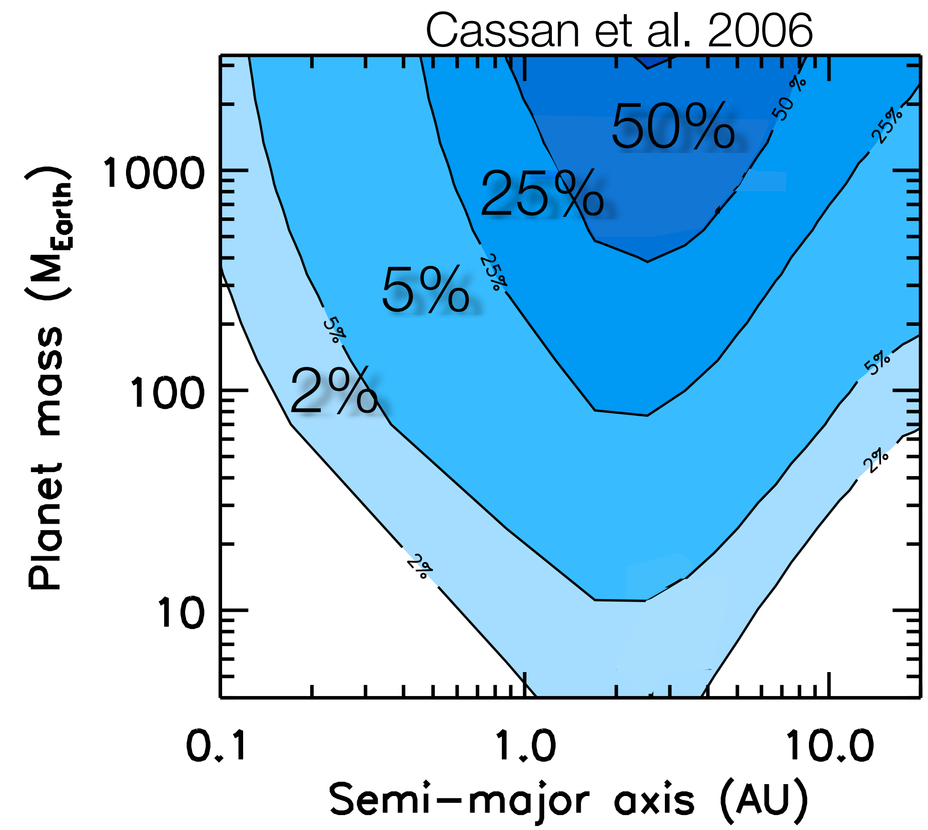
Transits, direct imaging, microlensing



Transits
probe radii of close-in planets



Direct imaging
probe luminosities of distant giant planets



Microlensing
probe cold planets around M dwarfs

- Accounting properly for biases is important. Otherwise, the picture might be distorted (e.g. Hot Jupiters)
- Models need to predict not only masses and orbits but also radii and magnitudes
- Each technique probes different aspects of the theory: helps to beat the parameter dependency of global models, a weakness of this approach.
- Once we have the detectable sub-population, we can compare it with the actual observed one and learn if the model disagrees/agrees with the observations

Large surveys with a well defined bias are suited best for statistical comparisons

End of part A