Time: a new dimension of constraints for planet formation and evolution theory
“Stellar masses and ages will be tightly constrained by the systematic use of asteroseismology. …
Ages will be known to 10% for solar-like stars.”

For the first time with PLATO: population-wide and accurate planet evolution in time as a measurable quantity on the observational side.

On the theoretical side: temporal evolution: a fundamental and omnipresent concept.
Radius evolution and formation

Radius evolution in time depends on

- initial thermodynamic state (how hot initially / entropy)
- Bulk composition (H/He, silicates, Fe, ices)
- Energy transport in the interior (convection)
- Atmosphere & opacity
- Atmospheric escape/evaporation
- Bloating mechanisms

Implication for planet formation

- (Giant) planet formation mode, gas accretion shock structure
- Formation location, migration, opacity in the protoatmosphere, planetesimal / pebble accretion
- Accretion history, planetesimal size
- Enrichment, formation location
- Efficiency of H/He accretion
- Migration mechanism (Kozai, disk migration)

New constraints to better understand planet formation
Temporal evolution: giant planets

Atmospheric model

Inflation

Energy transport

Composition M [M_\odot] Init. cond.
Temporal evolution low-mass planet

**Mini-Neptune**
- $a=0.05$ AU
- $M_{\text{core}}=4$ $M_{\text{Earth}}$
- $M_{\text{env}}=0.1$ $M_{\text{Earth}}$
- $L_{\text{init}}=0.1$ $L_J$
- Earth-like core (0.33 iron, 0.66 silicate)
- X-rays & EUV evaporation
- Solar-composition opacity

- Fast decrease from $\sim 2$ $R_{\text{Earth}}$ to $R=R_{\text{core}}$ when envelope totally lost

All these $R$(time) curves are not directly observationally constrained
Temporal evolution of the a-M diagram

Output of core accr. population synthesis

Thermodynamic evolution (cooling & contraction) in time w. atmos. escape

Close-in, low-mass lose the envelope.

Most of the action early on.

a-M does not change much. (a>0.06 AU)

M$_{\text{star}}$=1 M$_{\odot}$, isothermal type I migration rate x 0.1, cold accretion. 1 embryo/disk, no special inflation mechanisms.

Jin et al. 2013

Thermodynamic evolution (cooling & contraction) in time w. atmos. escape

Black: Bare rocky cores (a>0.06 AU)
Temporal evolution of the a-R diagram

- Contraction
- Evaporation
- Empty valley below 1-2 $R_{\text{Earth}}$

Artifact of using $M_{\text{min}}=1 \, M_{\text{Earth}}$

$M_{\text{star}}=1 \, M_{\text{Sun}}$ Isothermal Type I rate x 0.1. Cold accretion. 1 embryo/disk, no special inflation mechanisms.

Black: Bare rocky cores

a-R does change!
Radius distribution as a function of time:

Key constraint for planet formation and evolution theory

Radius alone sufficient
No mass needed

Observed version by PLATO come back in 2030 :-)
Have this in 2030 not from theory, but from PLATO data!
Transition solid - gas rich planets

- Kepler: numerous close-in small planets: 49% of stars (P<100 d, R<4 R\text{Earth})
- Many are low-density planets (likely with a few percent of H/He)
  - Important for formation theory, but also habitability
- At which mass and orbital distance is the transition? In principle, with time dimension:
  - Solid planets: mean density \sim constant in time
  - Gaseous planets: mean density increases: contraction, evaporation
- Comparison with spectroscopy and dynamics of multiple planet systems

Not only giants planets
Transition solid - gas rich planets

Search for the transition in the $M$-$\rho$-$t$ space

Giants: hotter less dense: bloating

Low mass: hotter denser: evaporation

1 $M_{\odot}$ star. Initial conditions from population synthesis.
Origin of close-in low-mass planets

- Essential open question for planet formation theory
  - Rapid migration from beyond the iceline: ice-rich interior
  - In situ formation or slower migration: rocky interior

- Mass-radius relation degenerate: iron/silicate/ice/H-He

- If we can rule out (observationally) that a sub-population of planets can have a significant H/He atmosphere, break degeneracy
Origin of close-in low-mass planets

Planets with density of 2-3 g/cm³ in the “static” part of the a-R (no time evolution i.e. no H/He envelope) must be icy
Conclusions

- PLATO’s ability to accurately determine the ages of the host stars adds a new class of constraints for formation theory

- With the time dimension, it should become possible to observationally see
  - the transition from solid to gas-rich planets
  - the composition of close-in low-mass planets

- This constrains several key concepts of planet formation theory like
  - efficiency of H/He accretion
  - orbital migration

- The mass is sometimes not necessary for these new constrains: the radius and the age are sufficient