Exploring the Accretion History of Terrestrial Planets in the Grand Tack Model

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Overview

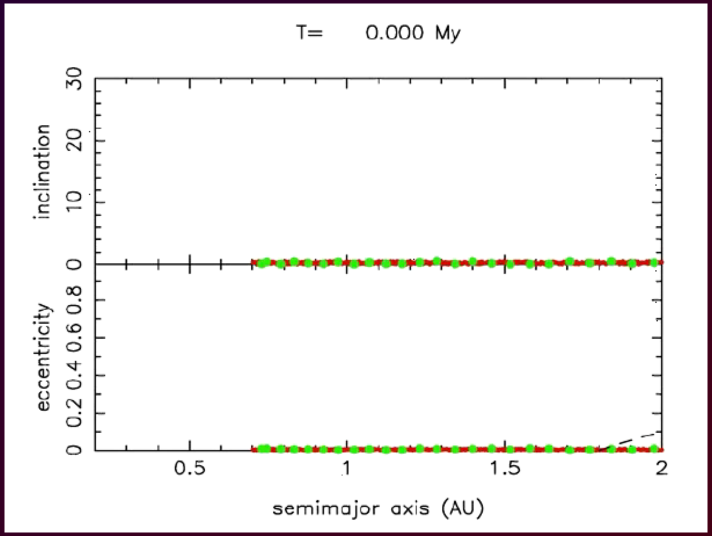
- 'Grand Tack' scenario described by Morbidelli in previous talk
  - Jupiter experiences early inward and outward migraion
  - Significant amounts of material are scattered or shepherded inwards by Jupiter
  - Terrestrial planets form from a truncated disk of planetesimals and embryos
- Initial simulations produce reasonable terrestrial planets (eg. Walsh et al. 2011)
  - Small mars, etc.

Overview

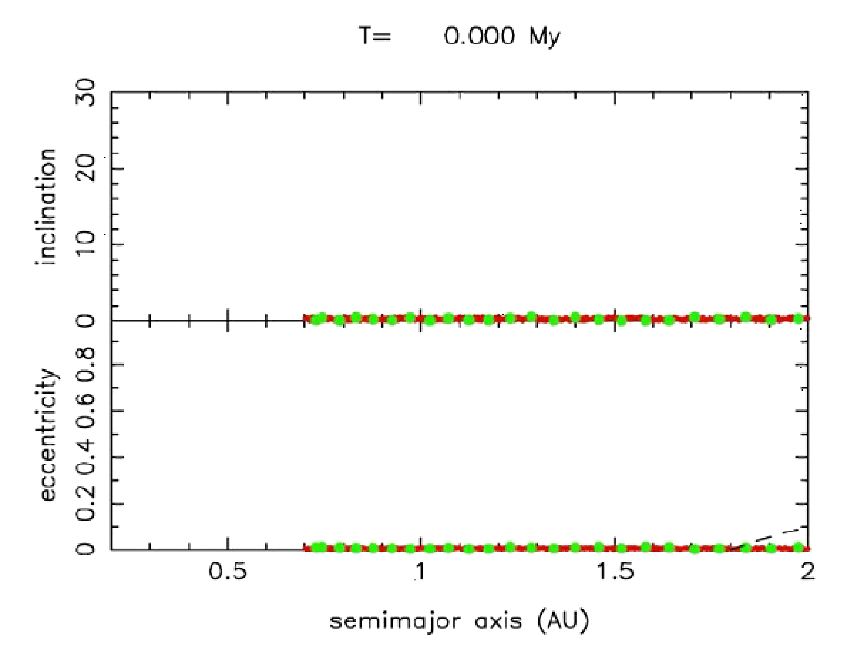
- What is the detailed evolution of the planets?
  - Mass accretion history
    - Timescales of growth
    - Where does the material come from?
    - When is it delivered?
  - Specific focus on water delivery
  - Late giant impacts (Moon forming events)
- Following slides discuss how we analyze the simulations and what we're finding in the first new set of simulations

Simulation Parameters

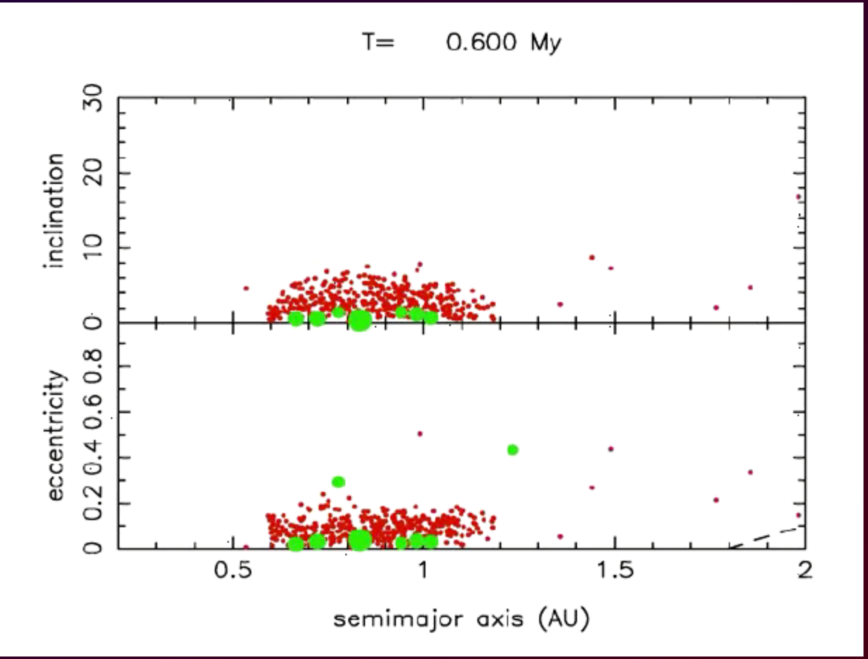
- Equal mass placed in large embryos and small planetesimals
- Embryos are either ¼ or ½ of a Mars mass (~0.025 or 0.05 Earth mass)
- Simulations run with SyMBA integrator for 150 Myr, including effects of migrating giant planets



Simulations

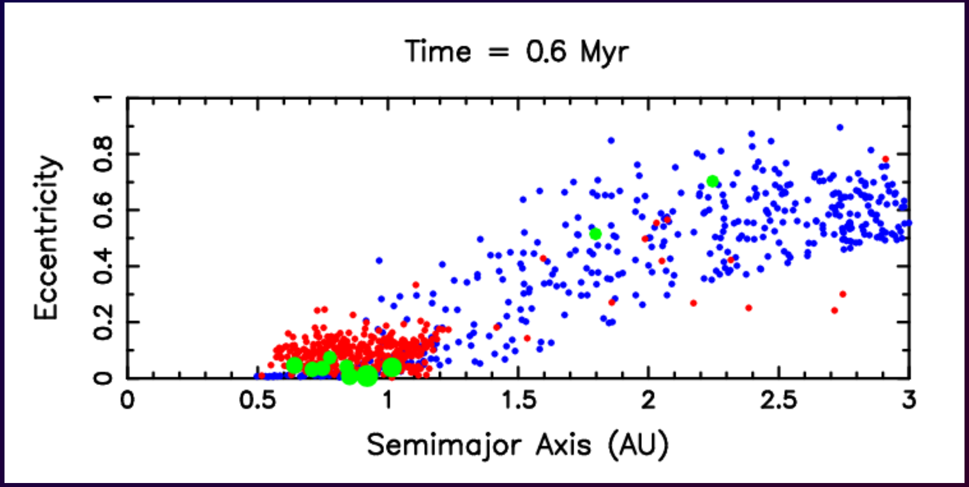


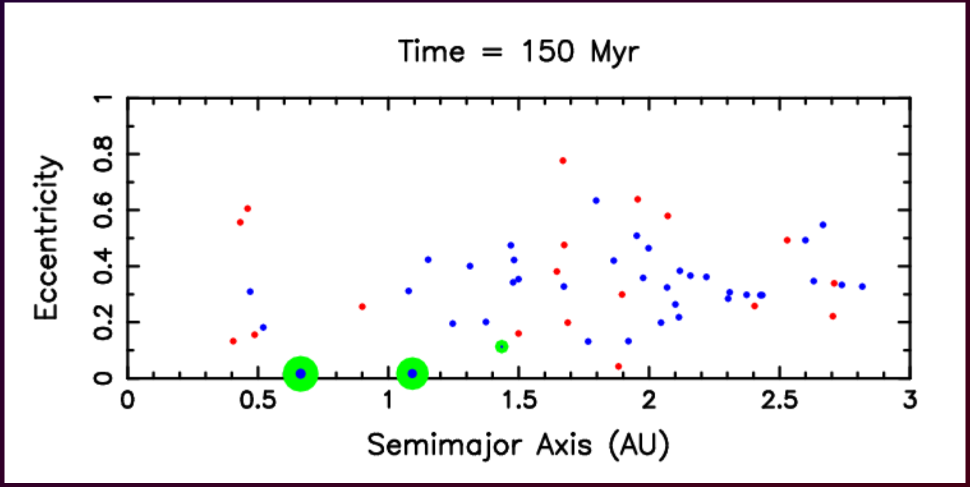
Initial conditions
(actually extends to 3 AU)



Following Jupiter's inward and
outward migration

Simulations



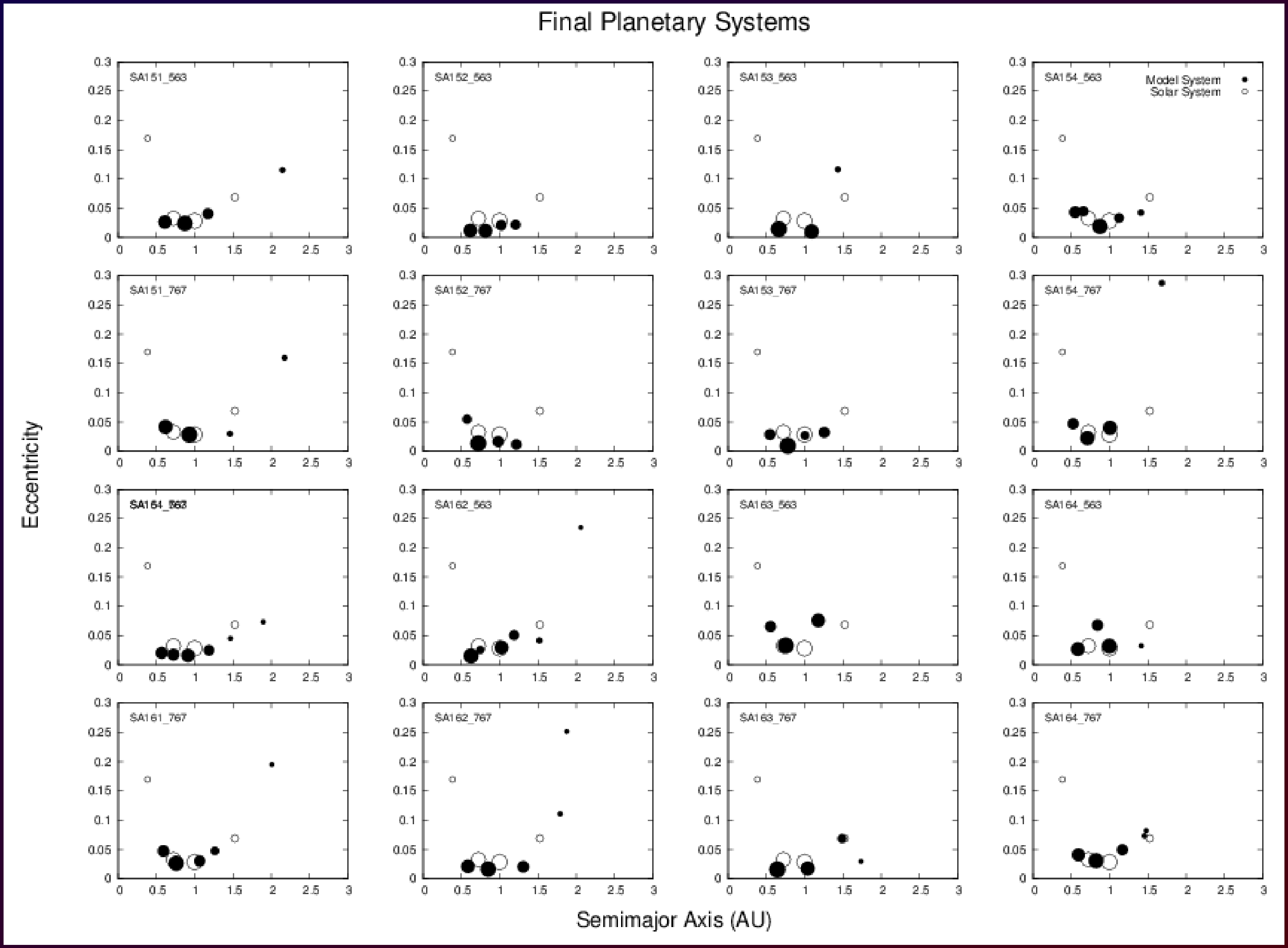


Following jupiter's migration, primitive planetesimals added

Final system

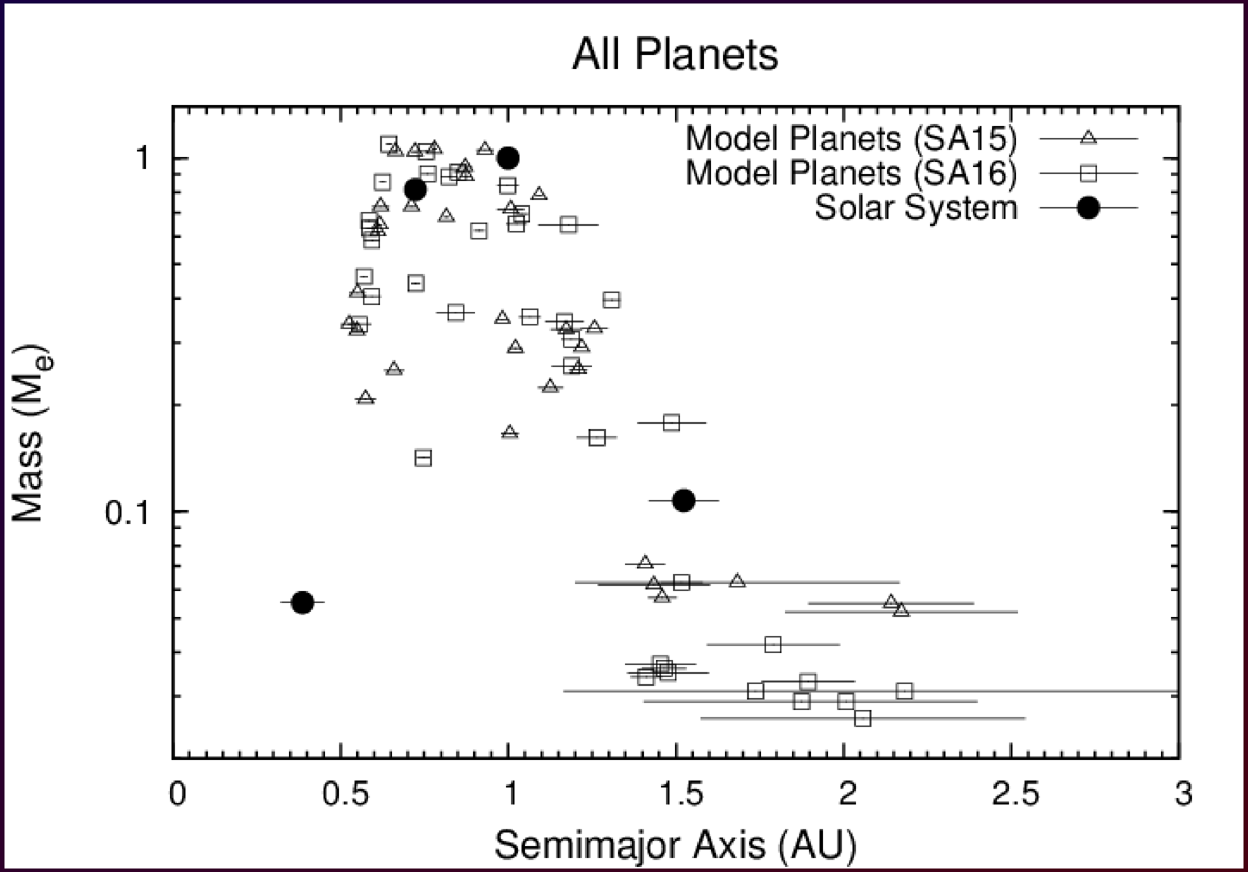
Simulation Analysis

- First step is to look at final system configuration



Simulation Analysis

- Also the general distribution of planet masses and orbits

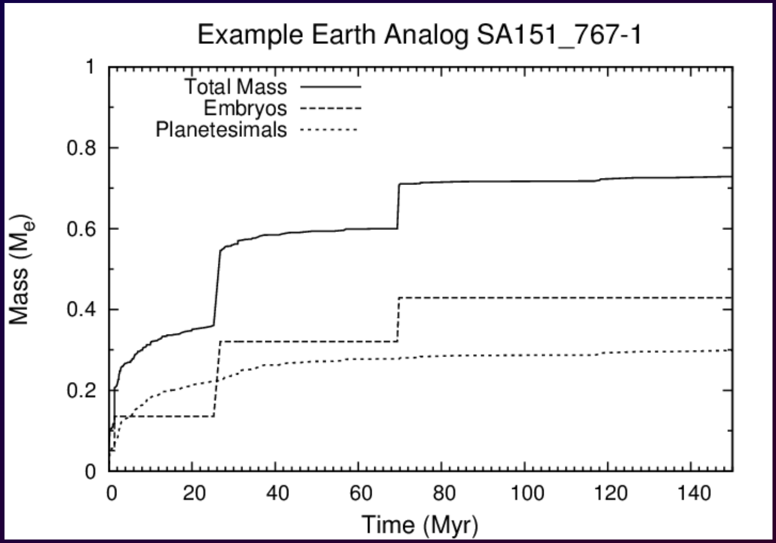


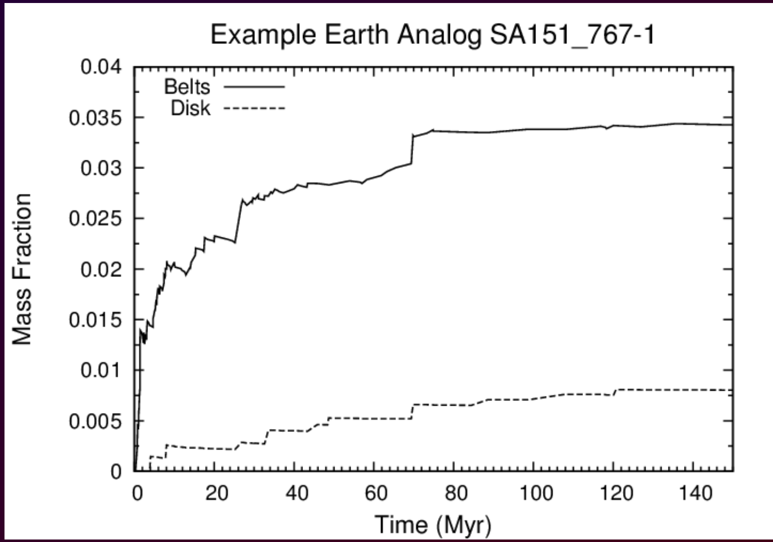
Simulation Analysis

- The good...
  - Roughly reproduces trends of Solar System terrestrial planets
  - Inner- and outer-most terrestrial planets generally less massive than the middle planets
- The not so good...
  - 'Mars' planets that form are generally too small
  - We don't make a good 'Mercury'
  - 'Earth/Venus' planets generally a bit too small

Growth Curves

- Mass vs. time of individual planets can be plotted





- NOTE: 'belts' bodies are from between the giant planets, 'disk' bodies are from beyond the initial position of Neptune

Moon Formation / Late Veneer

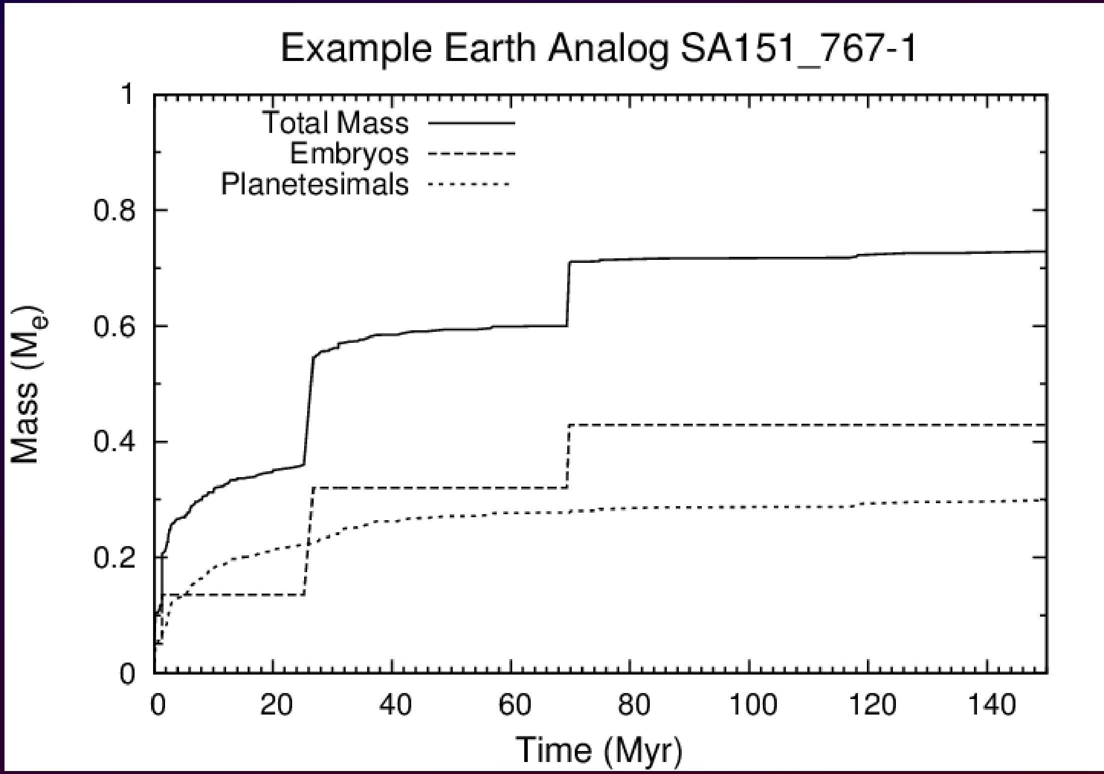
- Earth experienced large collision at ~50 Myr that formed the Moon
  - Probably ~Mars-mass impactor
  - Melting brought some or most siderophiles to core

Moon Formation / Late Veneer

- Mantle siderophile abundance suggests that subsequent mass accretion after Moon formation (the 'late veneer') was minimal
  - Only few x 0.1% of total planet mass
- Forming an 'Earth' requires late giant impact with minimal subsequent accretion

Moon Formation / Late Veneer

- Example: 0.73 Earth mass planet, large impact at ~70 Myr



- Late veneer ~3% of planet mass

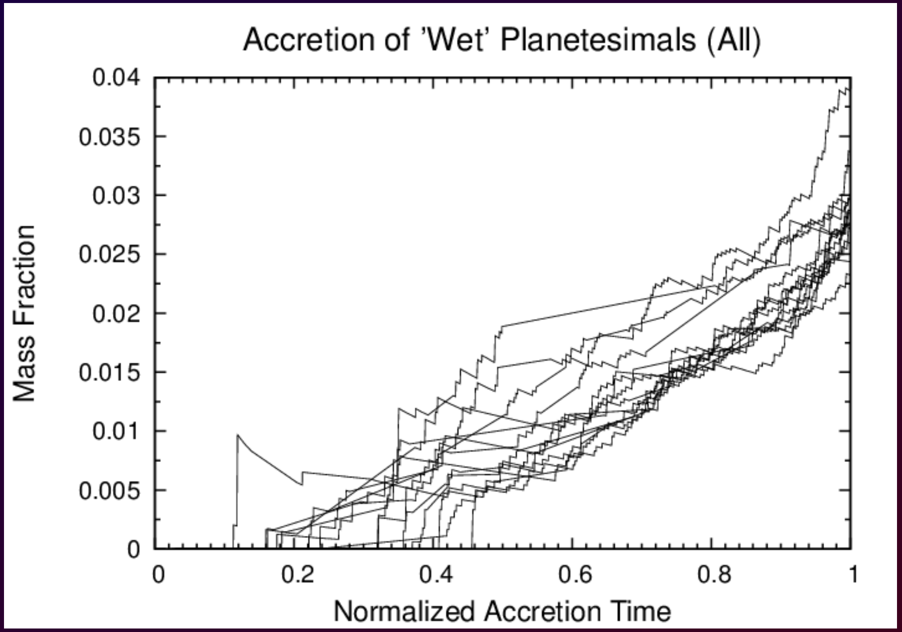
Moon Formation / Late Veneer

- 27 planets have $M>0.5\ M_e$, only 8 experience large impacts after 20 Myr
  - Accretion timescale for 'Earths' is generally too fast
- Median late veneer of those planets is ~3% of total mass
  - This is ~10x too large
  - Possibly reduced if collisional grinding is invoked?

.... Earth-like accretion history is difficult to produce with the initial conditions used here

'Wet' Planetesimal Accretion

- Bodies scattered from outer Solar System can have up to 10% water by mass, and arrive late



- Earth's min water fraction is ~0.0005 by mass
- Model 'Earths' average 0.0025 by mass

Accretion Histories and Composition

- Output of simulations is a big binary file, need to put into a human-readable form

- Generate 'planetgrowth' files for each planet that forms

- Detailed time series of collisions important for geochemical evolution

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.
------------------------------------------------------------------------
0.1731E+08    0.8562  0.00255  17.4363   1.9484   1   0   0
------------------------------------------------------------------------
        89    0.00255   0.804
------------------------------------------------------------------------
0.1762E+08    0.8588  0.00255  20.5717   2.2963   1   0   0
------------------------------------------------------------------------
        53    0.00255   0.726
------------------------------------------------------------------------
0.1764E+08    0.8590  0.00024  12.9448   1.4062   1   0   0
------------------------------------------------------------------------
       920    0.00024   5.288
------------------------------------------------------------------------
0.1796E+08    0.8593  0.00024  15.0937   1.6395   1   0   0
------------------------------------------------------------------------
       923    0.00024   5.303
------------------------------------------------------------------------
0.1799E+08    0.9238  0.06450   9.4804   1.1383   0   1   7
------------------------------------------------------------------------
        32    0.05109   2.335
       217    0.00255   1.111
       268    0.00255   1.248
       357    0.00255   1.505
       526    0.00255   2.059
       583    0.00255   2.266
       890    0.00024   5.098
      1131    0.00039   8.749
------------------------------------------------------------------------
0.1840E+08    0.9240  0.00024  26.7864   2.8374   1   0   0
------------------------------------------------------------------------
       971    0.00024   6.625
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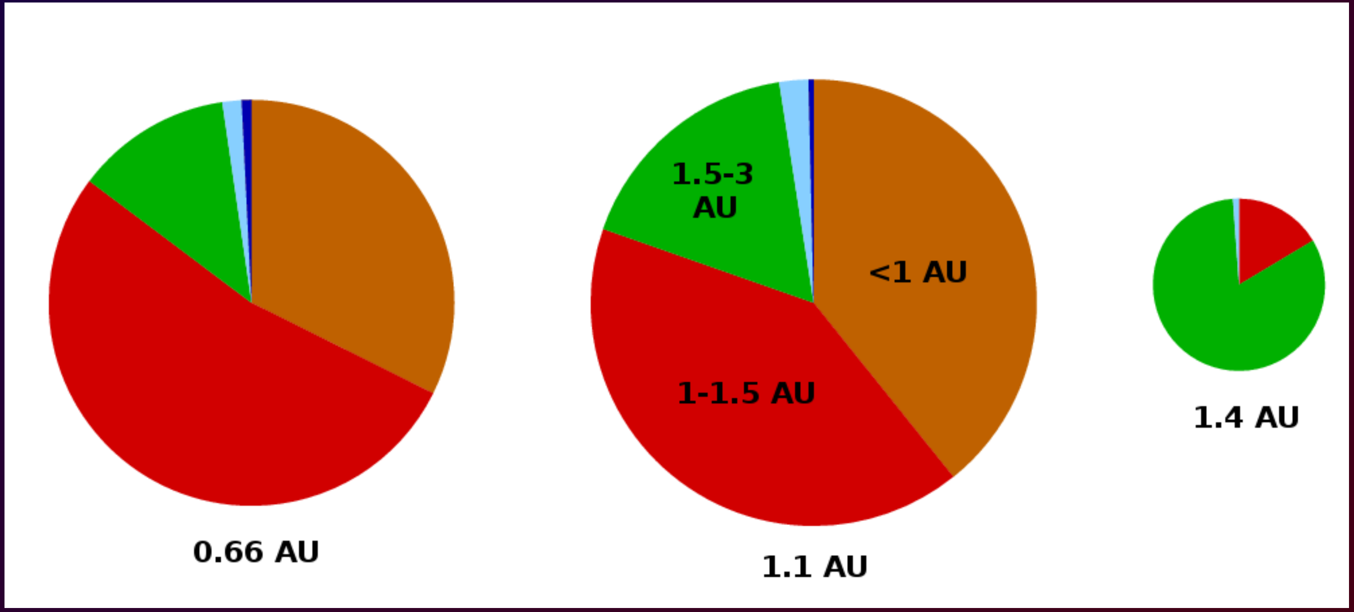
Accretion Histories and Composition

- These planetgrowth files can be analyzed to give the contributions of material from different semimajor axis zones

```
dlt> breakdown 1.0 1.5 3.0 8.0 planetgrowthj05_full.out

 File: planetgrowthj05_full.out

 Planet is 0.78 Earth Mass
 Planet is 0.92 Earth Diameter
 32.7% of planet mass is from embryos
 67.3% of planet mass is from planetesimals

          1.00 AU   1.50 AU   3.00 AU   8.00 AU
              |         |         |         |
 %)    32.35     39.20     26.12      1.54      0.80
 %e)   19.62     13.08      0.00      0.00      0.00
 %p)   12.73     26.12     26.12      1.54      0.80
 Ne)       3         2         0         0         0
 Np)      39        80        80        50        16
```

Accretion Histories and Composition

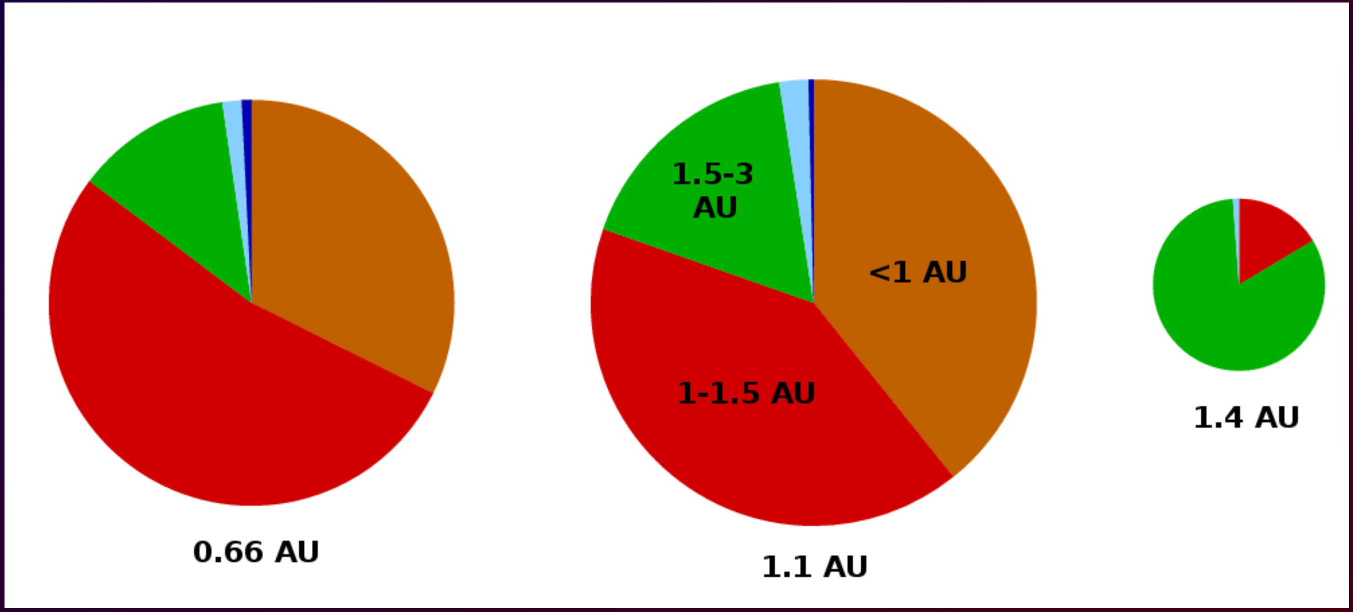
- These planetgrowth files can be analyzed to give the contributions of material from different semimajor axis zones



Final planets formed in one simulation

Accretion Histories and Composition

- Generally a lot of radial mixing, planets form from material spanning a wide semimajor axis range



Final planets formed in one simulation

Accretion Histories and Composition

- More detailed analysis combines accretion history with geochemical and core formation model
  - Dave Rubie's talk tomorrow morning

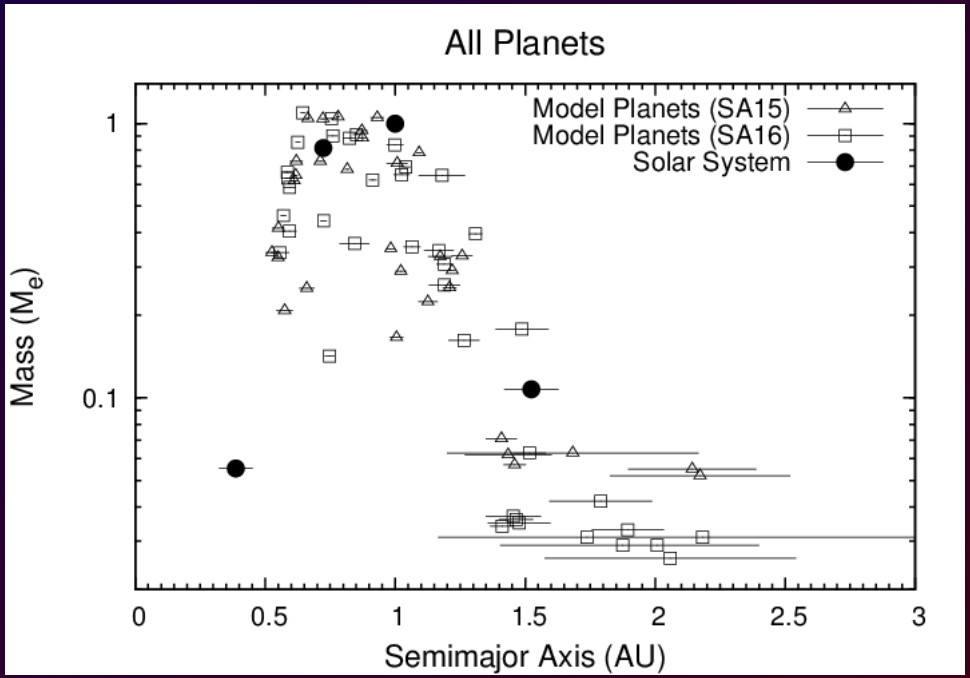
- Dynamical and geochemical modeling will occur in parallel, with the geochemical modeling providing an additional level of constraint on the Grand Tack model

More Simulations!

- Simulations with wider range of initial conditions currently being analyzed
  - Different embryo masses
  - Different embryo/planetesimal mass ratios
  - Different total mass at beginning
- Goal is to identify regions of parameter space that best satisfy wide range of constraints
  - Dynamical configuration of planets
  - Dynamical histories of individual planets
  - Composition and geochemical evolution of individual planets

Summary

- Grand Tack model broadly reproduces the terrestrial planets



- Plenty of water delivered to terrestrial planets during accretion

Summary

- Details still need to be worked out...
  - 'Mars' planets that form are generally too small
  - We don't make a good 'Mercury'
  - 'Earth/Venus' planets generally a bit too small
  - Earth analogues generally accrete too fast, and late Moon-forming impacts are uncommon
- Chemical histories and evolution of planets currently being modeled by Dave Rubie
- More thorough exploration of parameter space underway

Summary

- Future work will incorporate new effects into simulations, eg. collisional grinding and incomplete accretion