

*From planetary embryos to planetary systems:  
integrated models of planet formation*

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*Q1 of ELSI: What is the origin of the Earth?*

1- Planet formation

2- Why do we need to consider giant planets

3- Integrated models

1- Planet formation

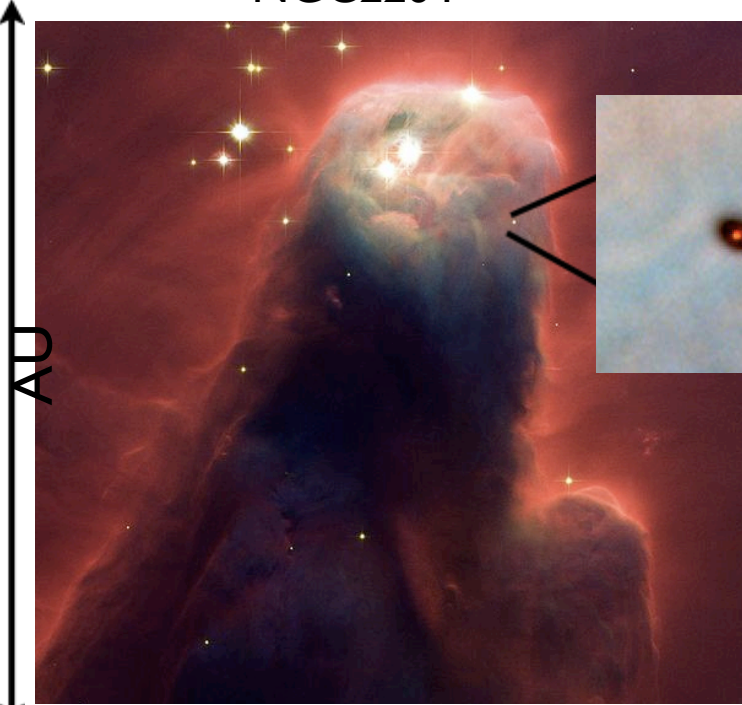
2- Why do we need to consider giant planets

3- Integrated models

# Planet formation

NGC2264

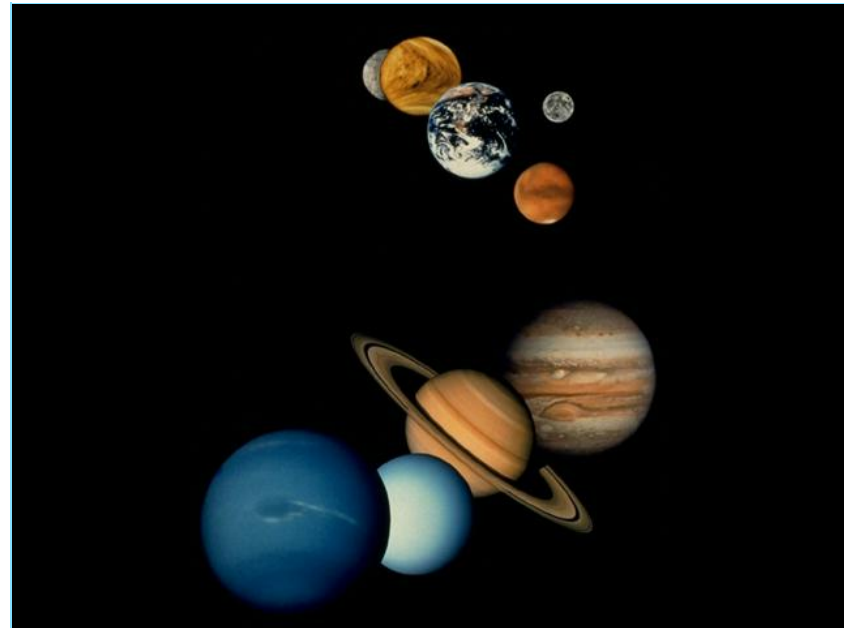
2.5 Light years ~ 160000 AU



~100s AU



Model



# Protoplanetary disks: observations

Giant planets form by accreting gas from protoplanetary disks

⇒ disks lifetime gives maximum formation time

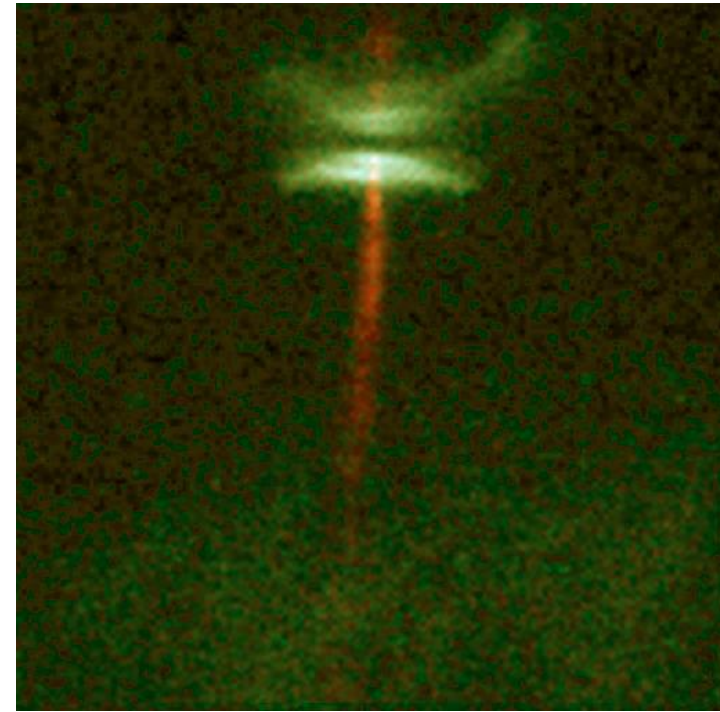
Giant planets must form in  $< 10$  Myr

⇒ disks mass and gas-to-solids ratio give available material

Typical mass from 0.001 to 0.1  
 $M_{\text{sun}}$

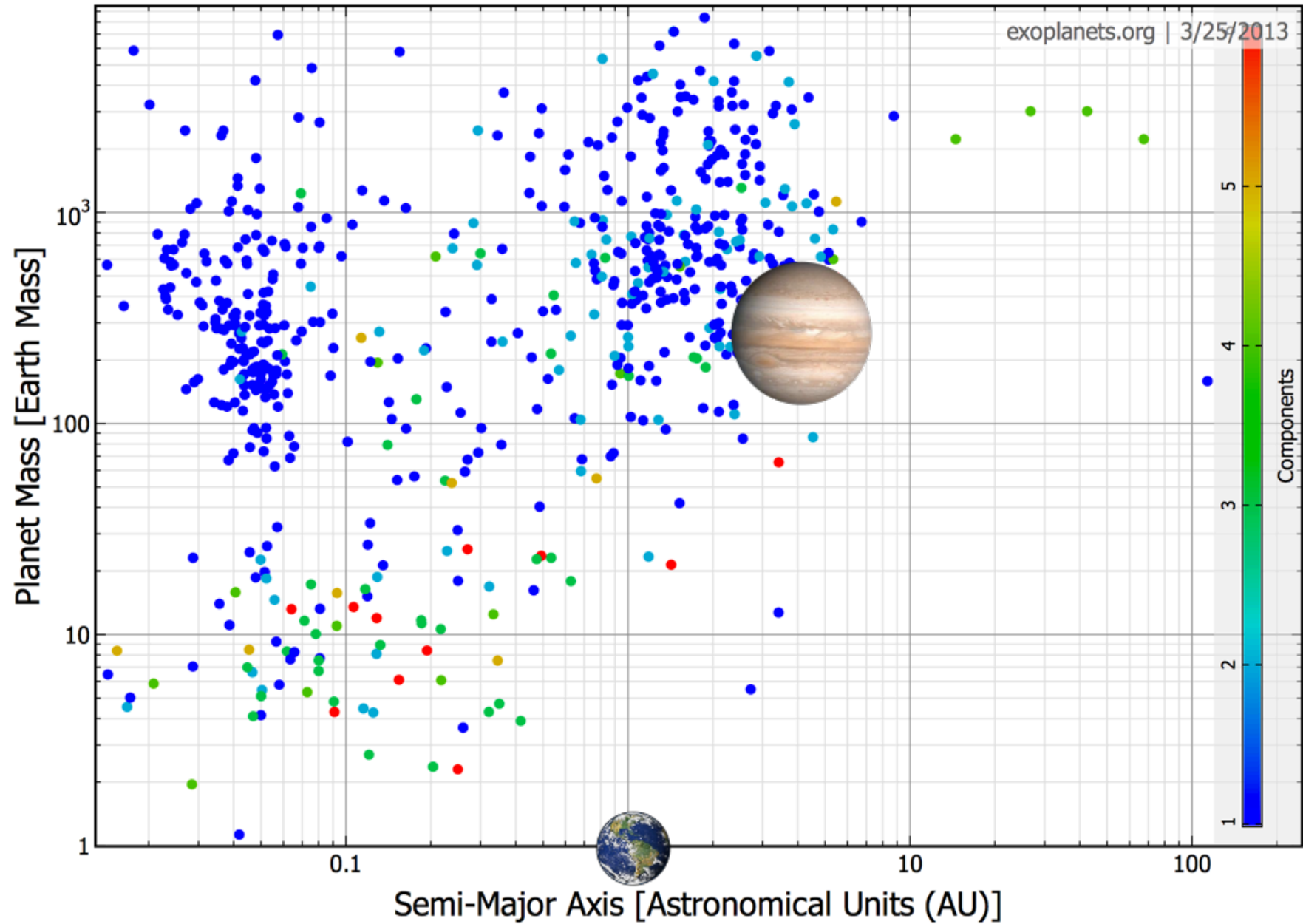


Protoplanetary disks in the Orion Nebula; HST

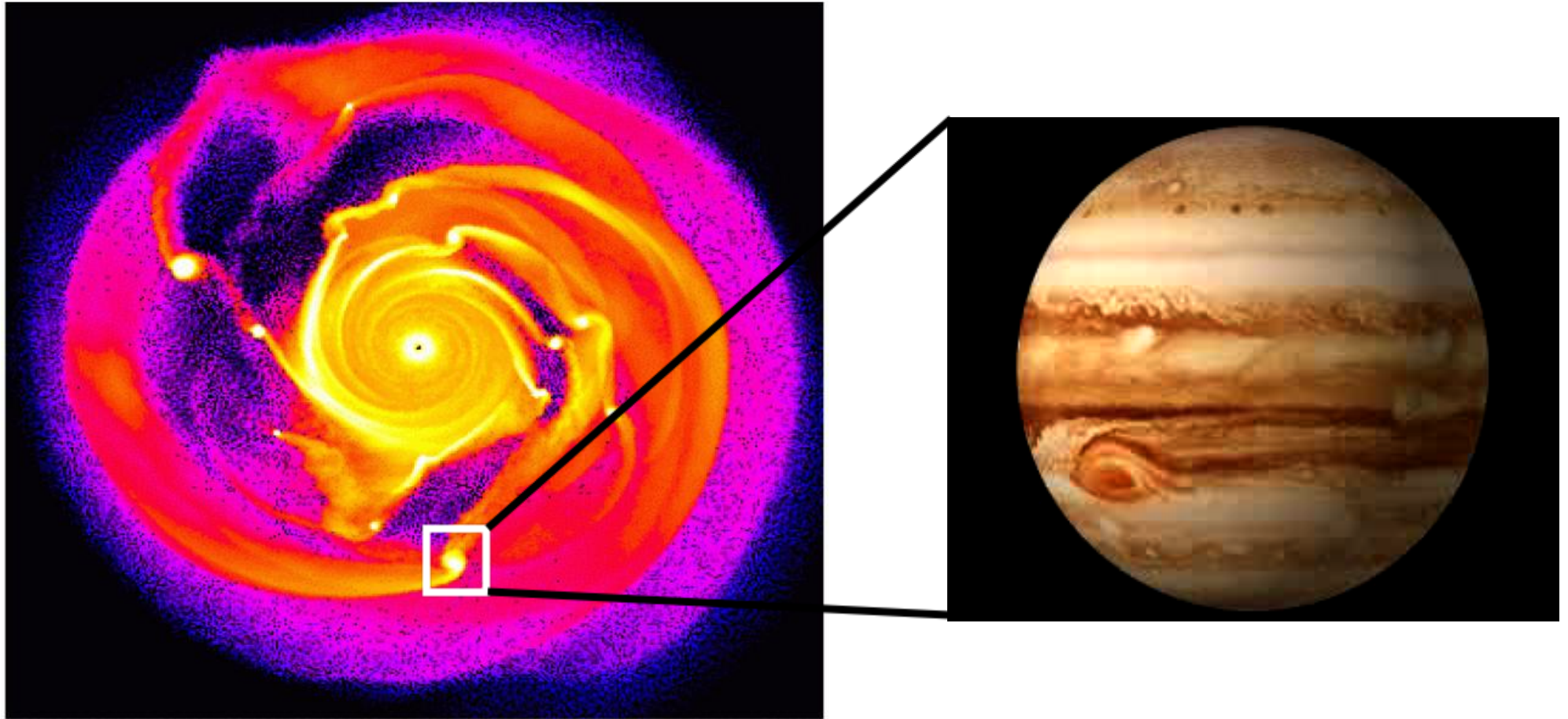


HH-30; Burrows et al.; NASA

# Extrasolar planets: observations



# The disk instability model



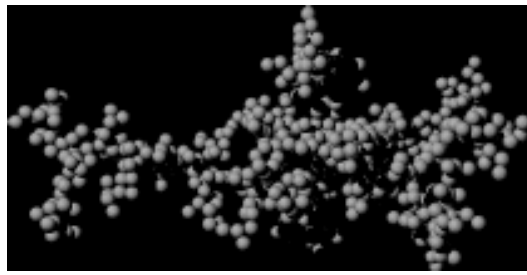
Mayer et al. 2004

Clump formation depends critically on disk cooling

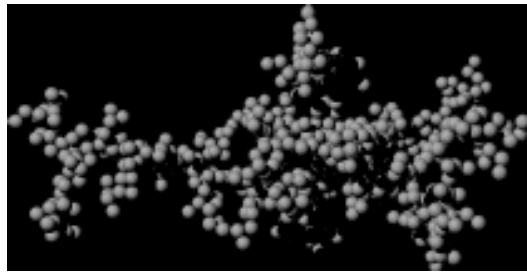
- ⇒ formation of massive planets
- ⇒ formation in outer parts of the disk

Origin of enrichment in heavy elements/formation of low mass (Earth, Neptune) planets?

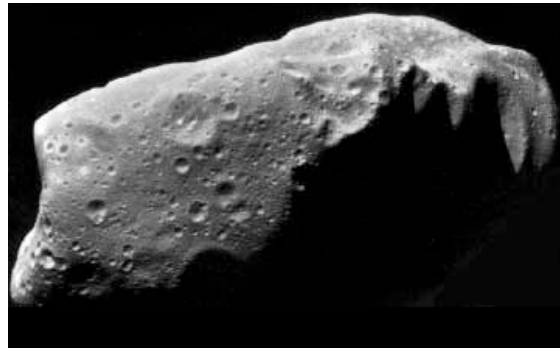
# The nucleated instability model (I)



+



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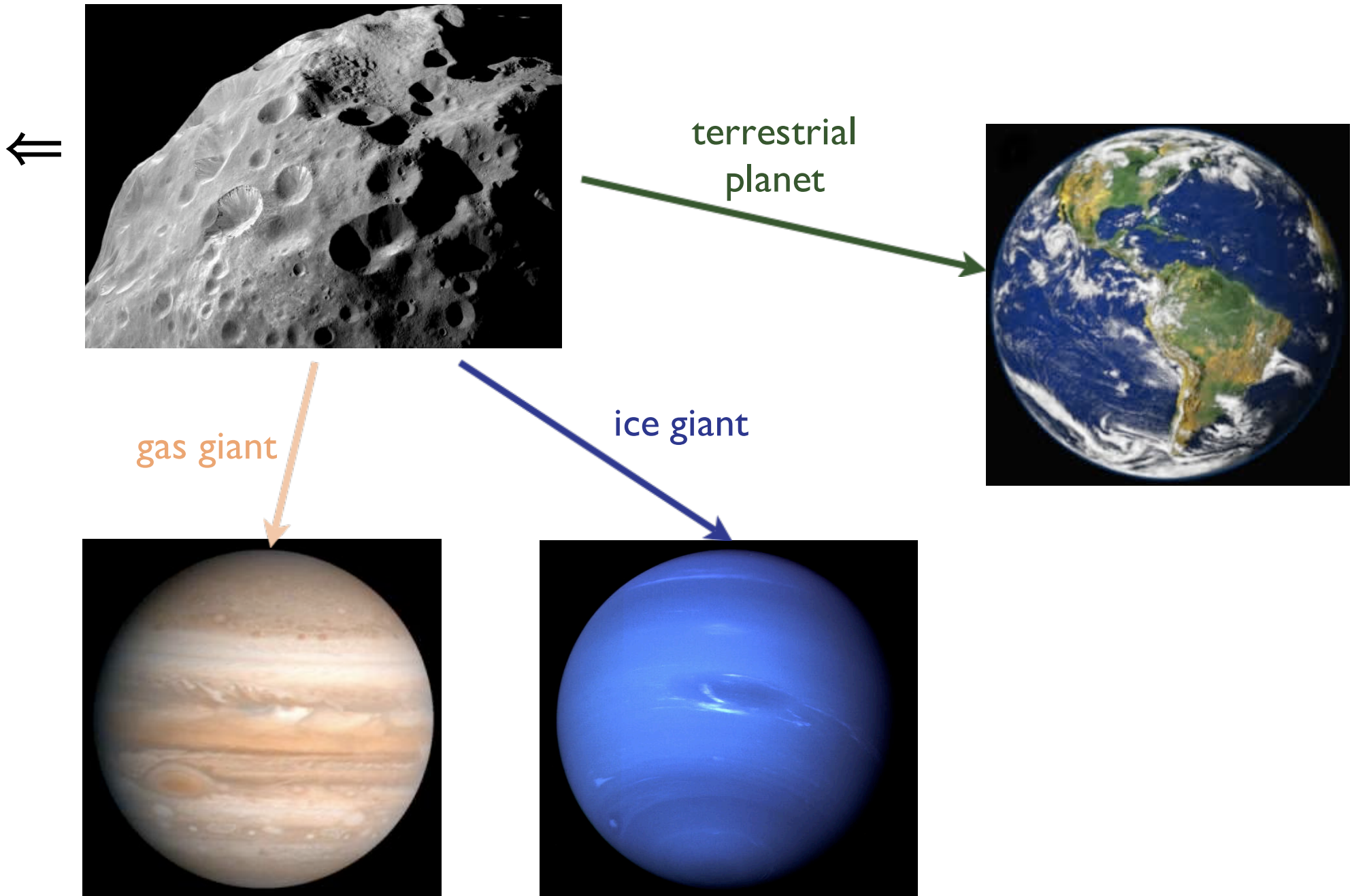
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Planet  
embryo



# The nucleated instability model (2)



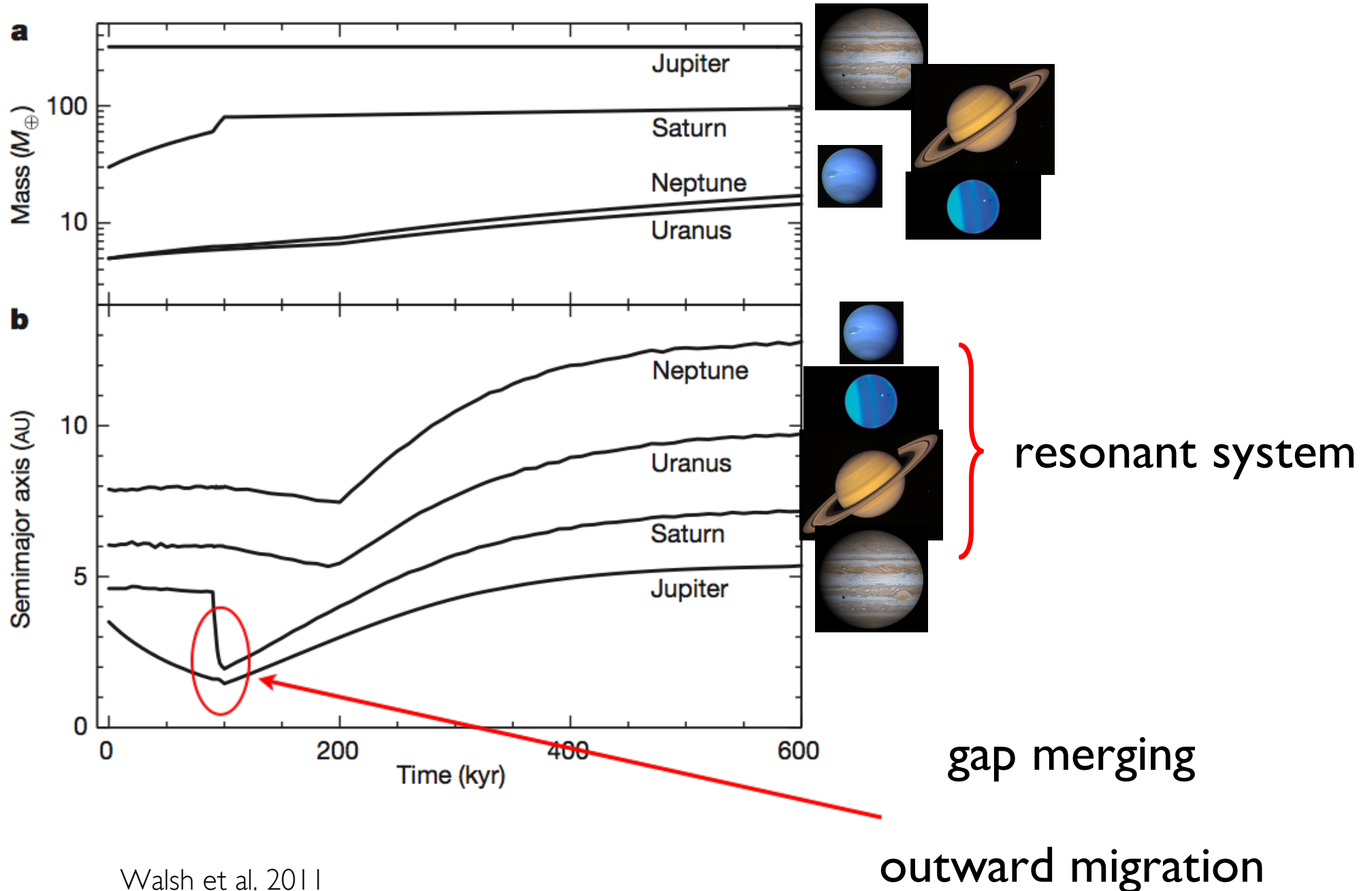
# Giant planets and planetary systems

1- Planet formation

2- Why do we need to consider giant planets

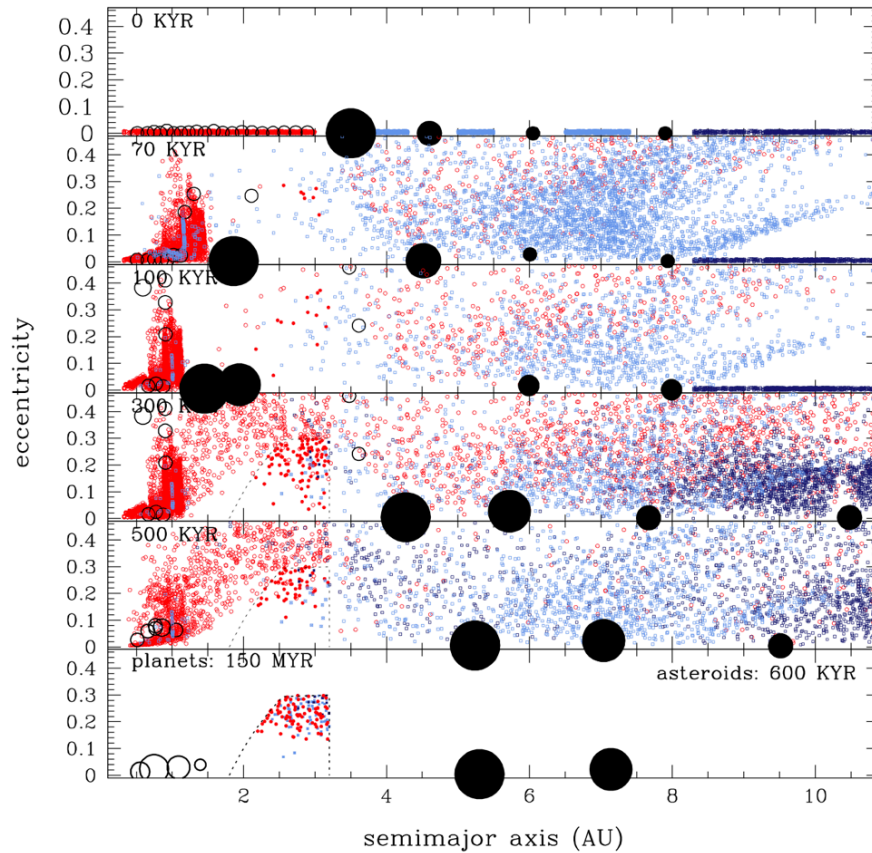
3- Integrated models

# Formation of the Solar System - the Grand Tack model

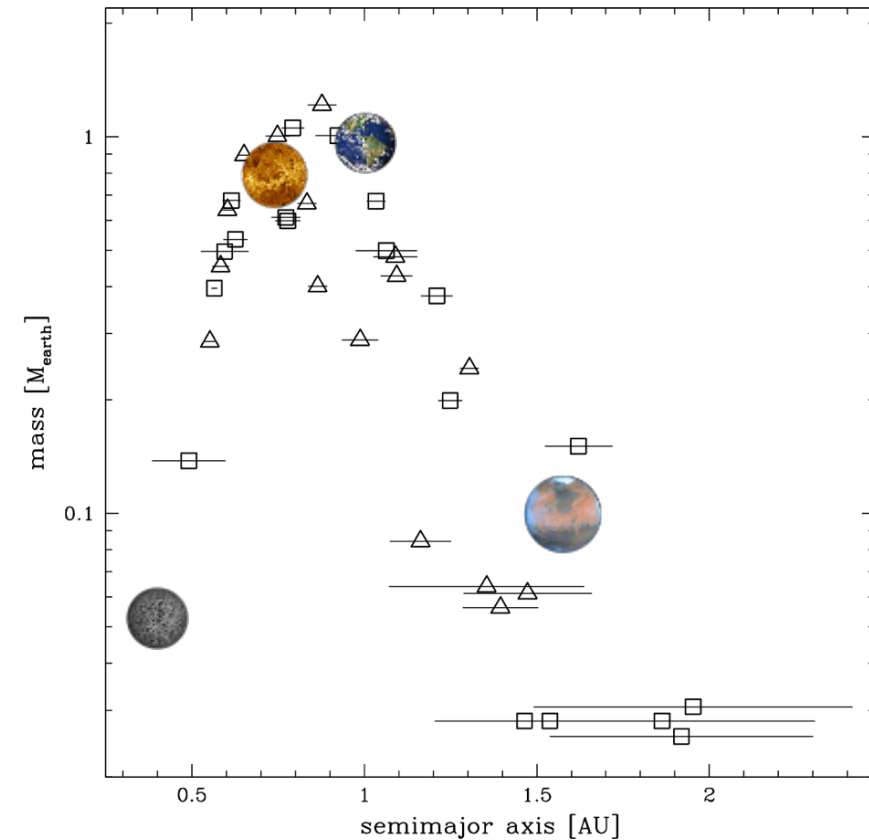


# Formation of the Solar System - the Grand Tack model

Walsh et al. 2011



Mixing of asteroids



Formation of terrestrial planets

*possible source of water on Earth*

# Integrated models

1- Planet formation

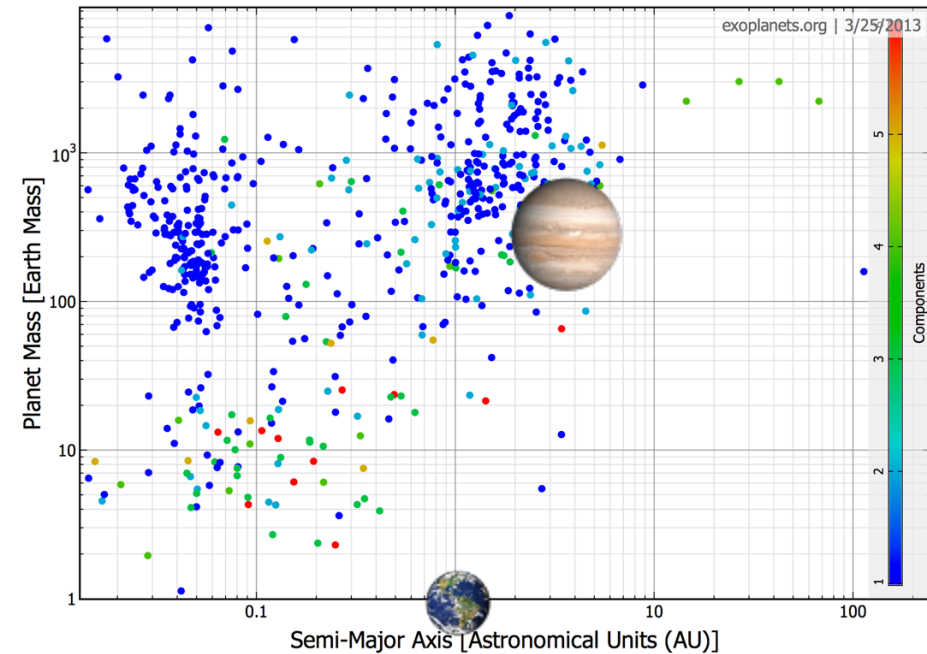
2- Why do we need to consider giant planets

3- Integrated models

# Processes involved during planet formation

- planetesimal-planetesimal interactions
- gas disk structure and evolution
- planetesimal accretion
- planetesimal-gas disk interactions
- planet-disk interactions
- planet internal structure and gas capture
- planet-planet interactions
- many others

# Integrated models



*What is the effect of the combined processes in shaping planetary systems?*

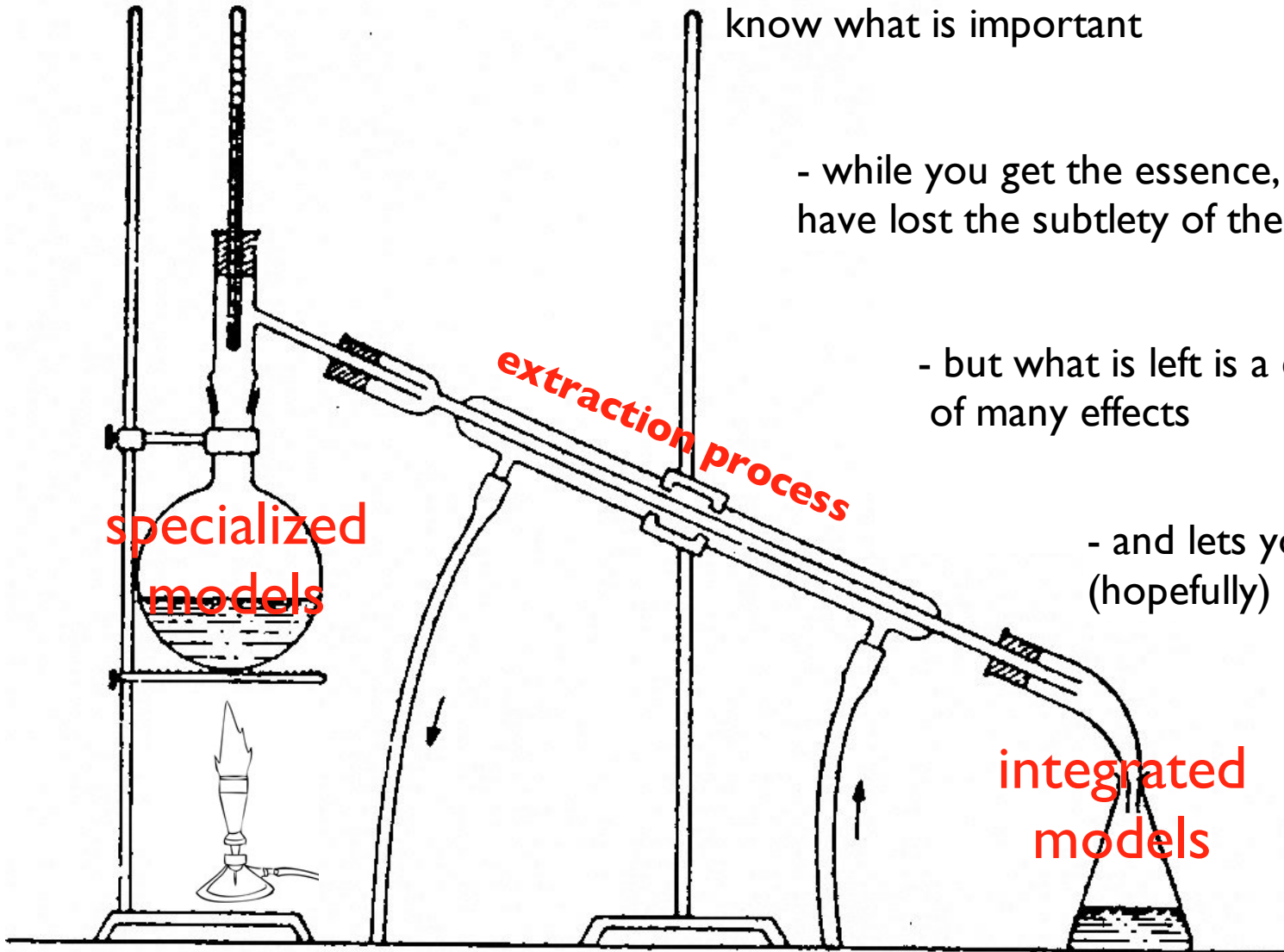
# Integrated models

- you need specialized 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)

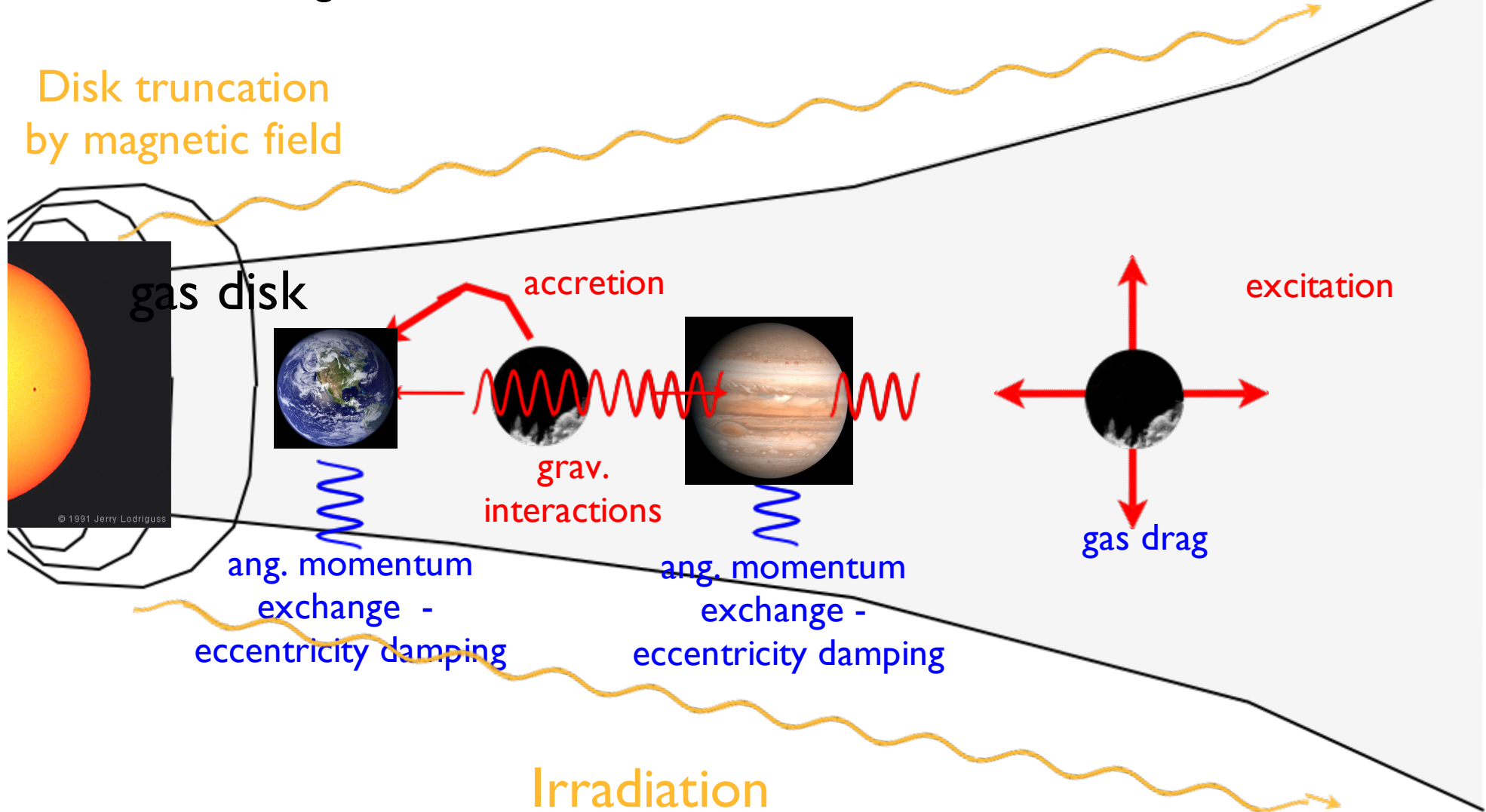




# Bern model

Seen from the edge

protoplanetary disk = gas disk + planetesimals



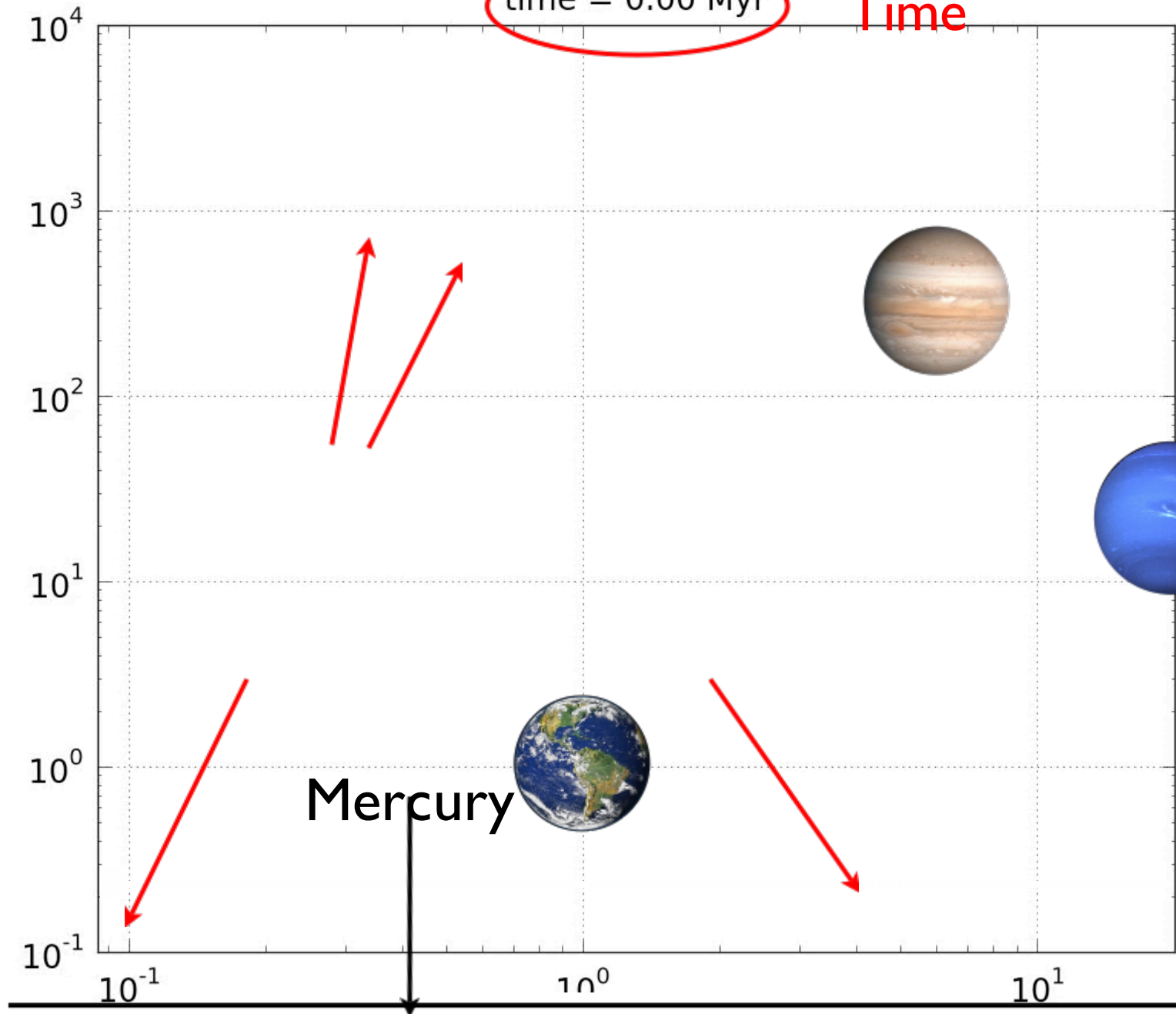
number of growing planets (initially of Moon mass) is a free parameter

I planetary system - 10 planetary seeds/system

time = 0.00 Myr

Time

Mass (Earth masses)



Icy

fraction of icy planetesimals

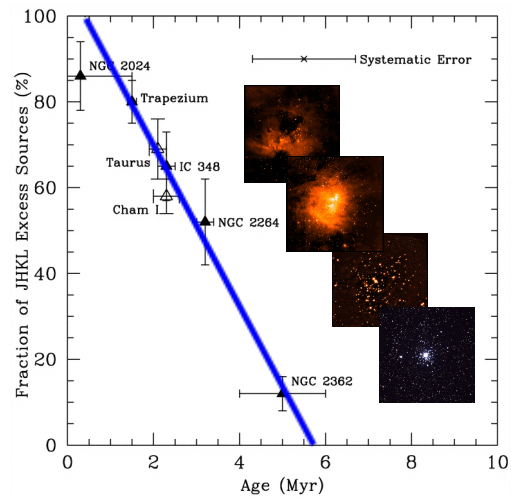
Rocky

Semi-major axis (AU)

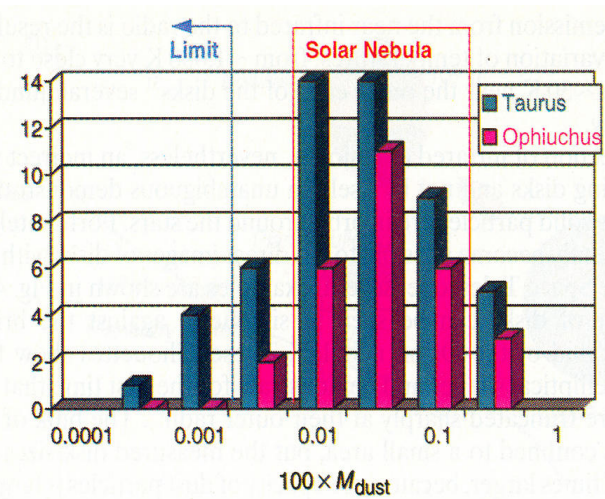
# Population synthesis



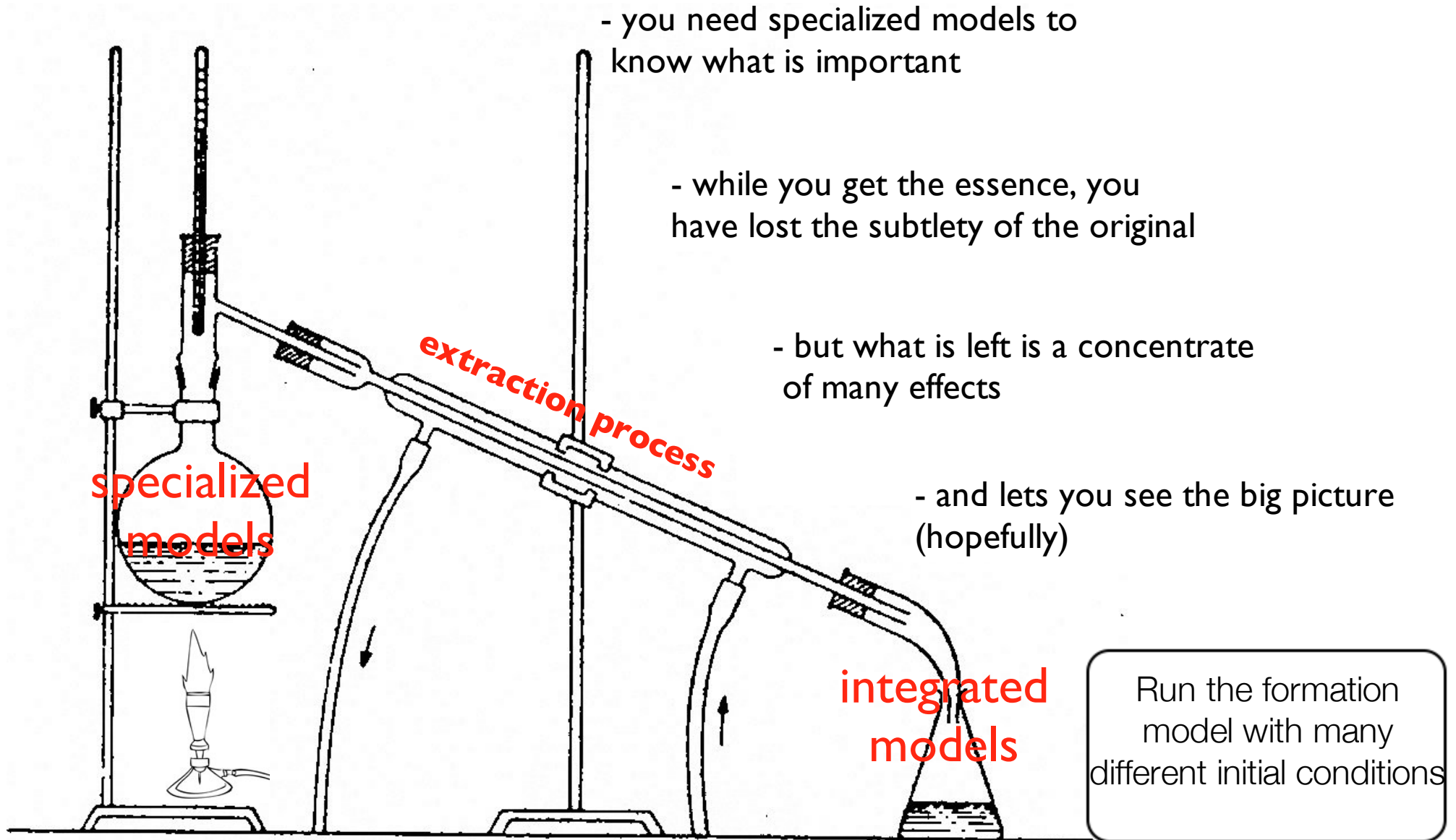
## lifetime



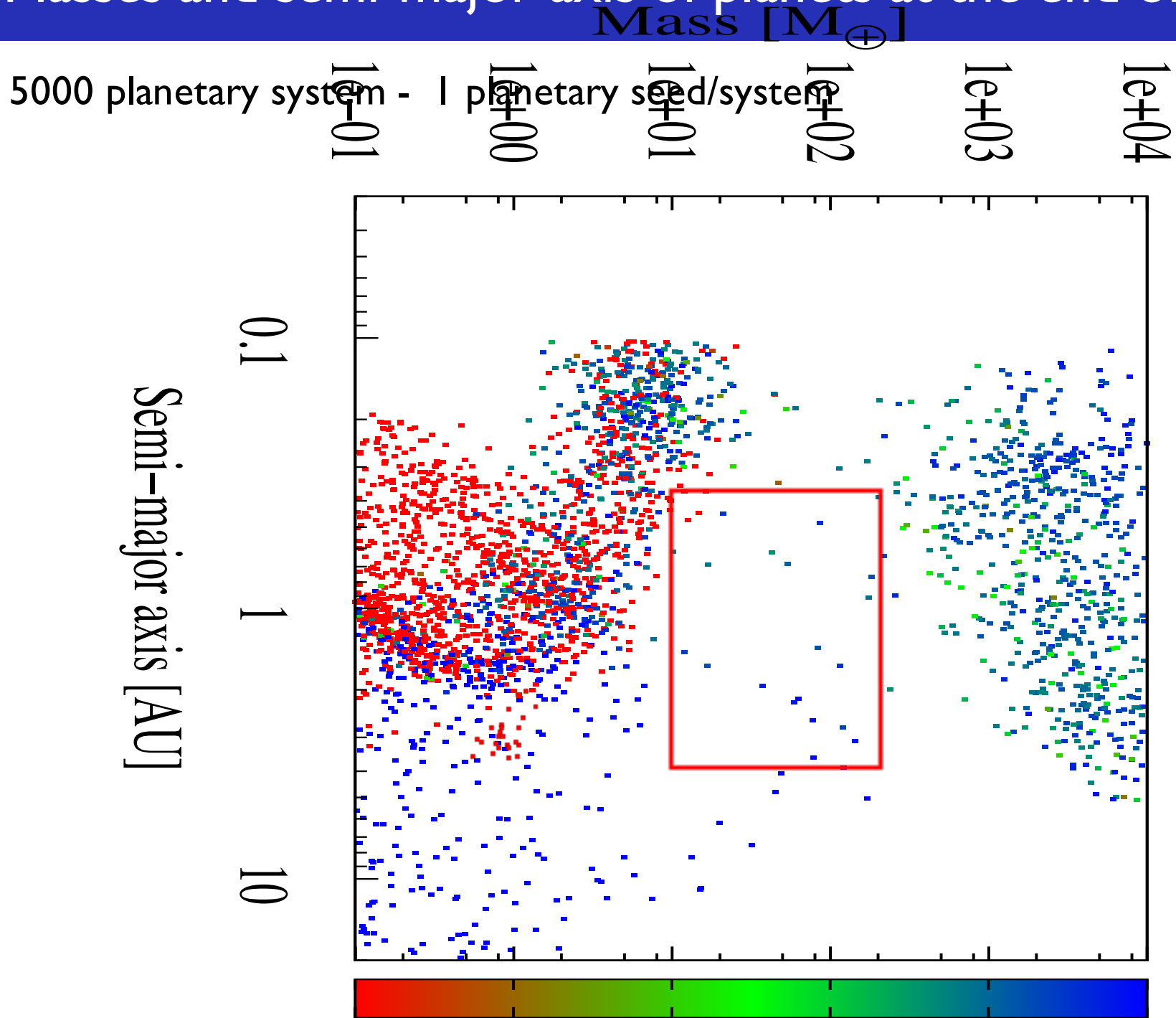
## mass



# Population synthesis

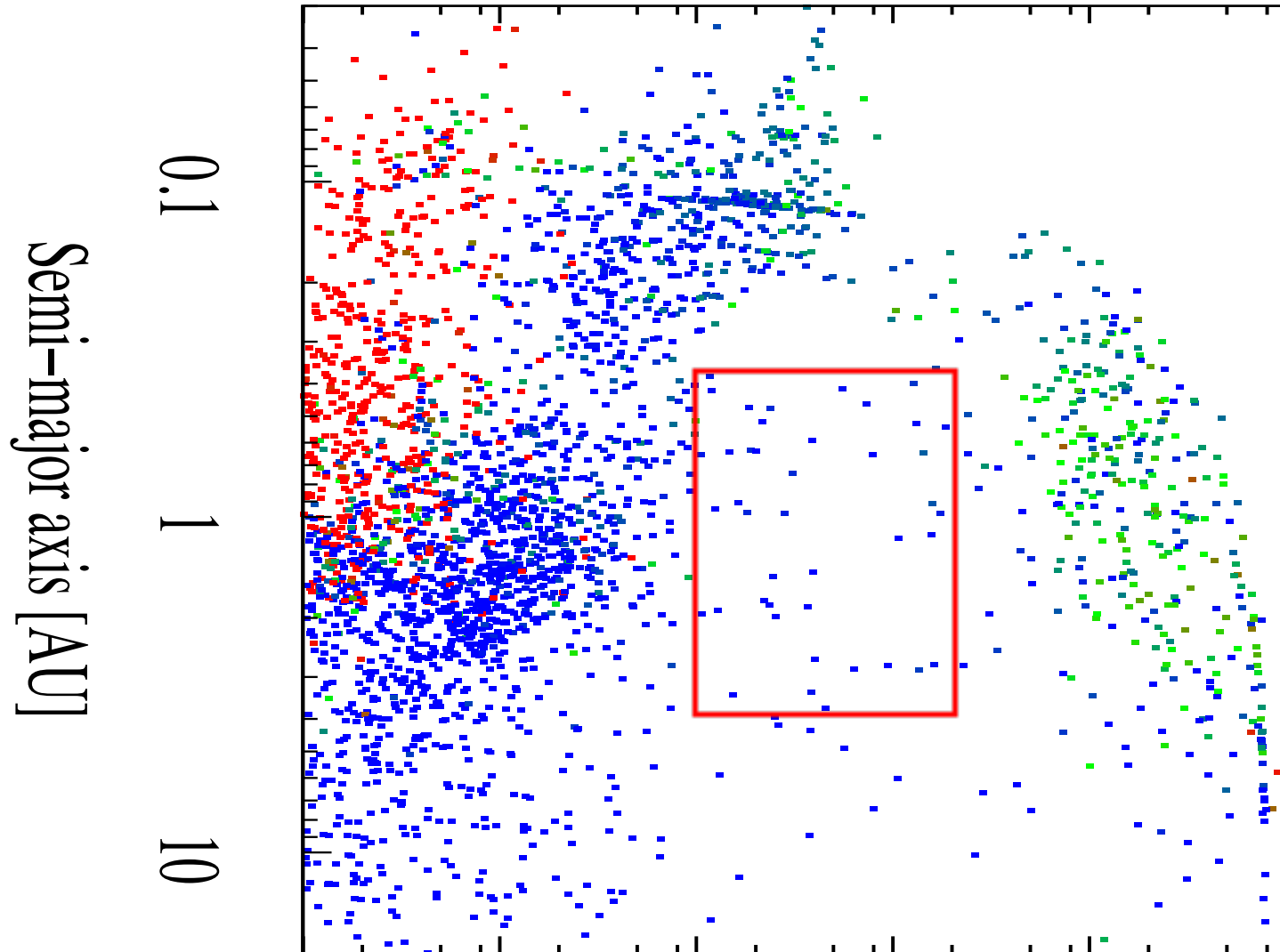


# Masses and semi-major axis of planets at the end of formation



# Masses and semi-major axis of planets at the end of formation

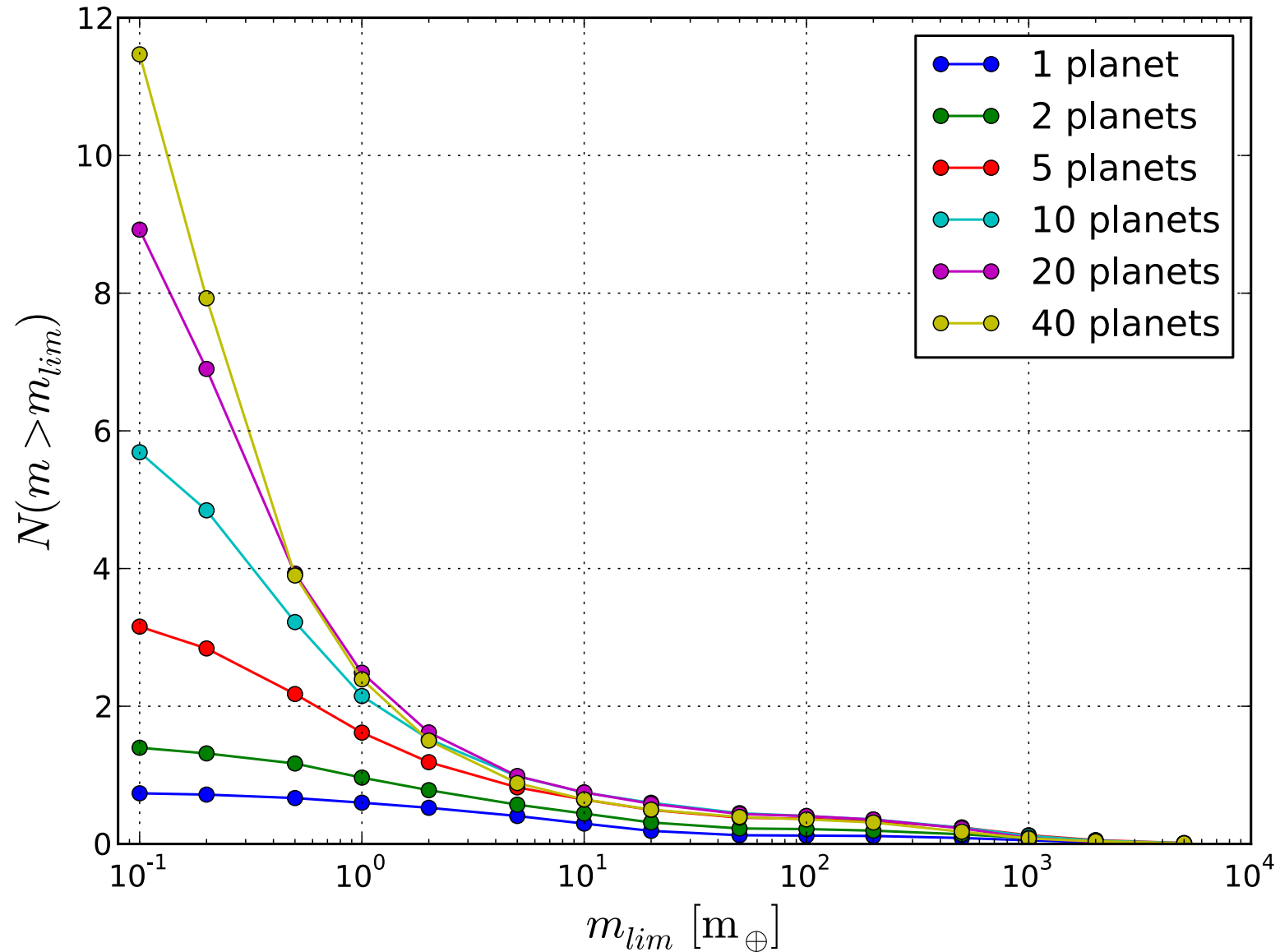
500 planetary systems - 10 planetary seeds/system



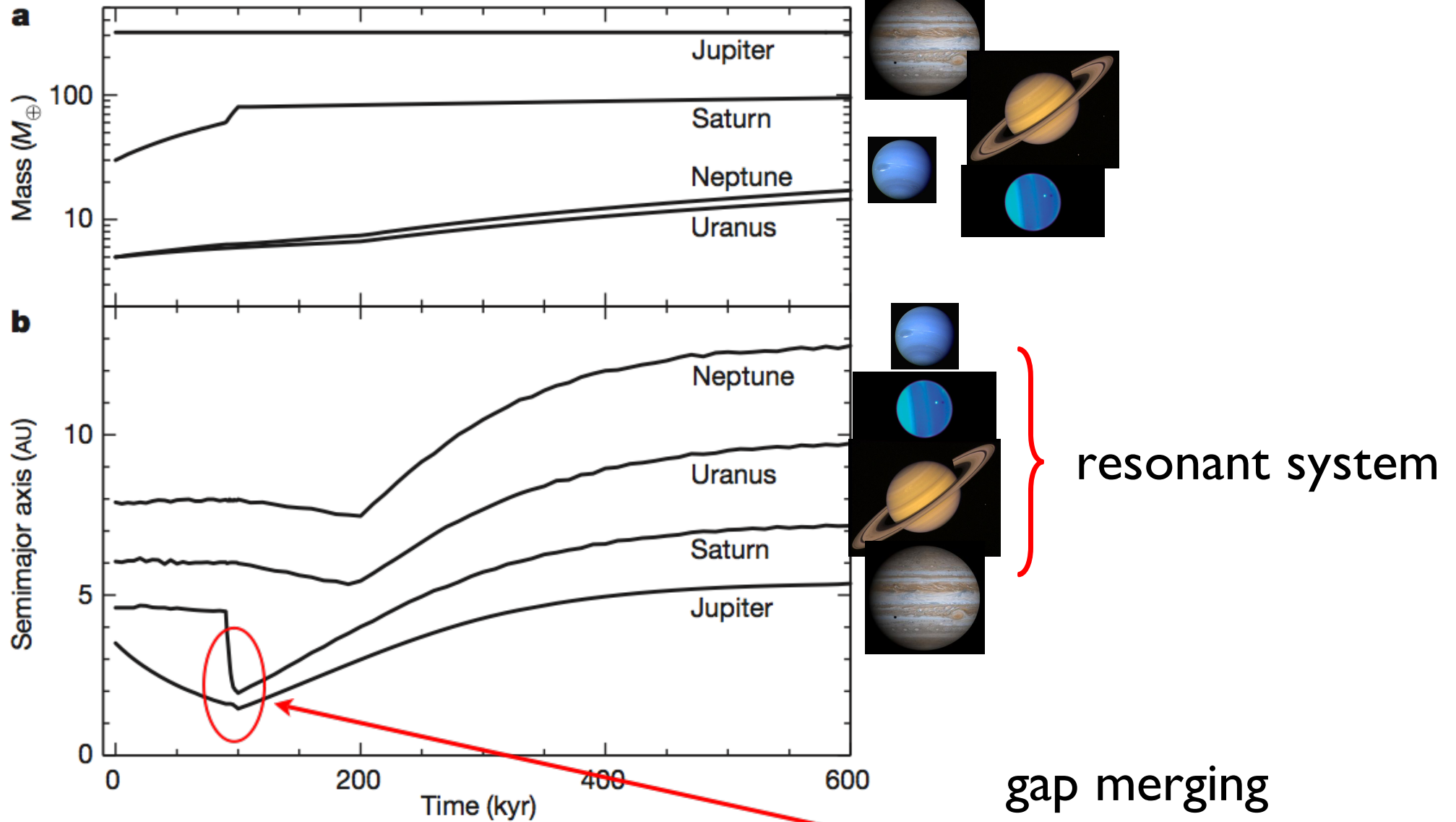
Q2 of ELSI: Why is water on Earth so little?

# Number of planetary embryos

500 planetary system - 1/2/5/10/20/40 planetary seeds/system

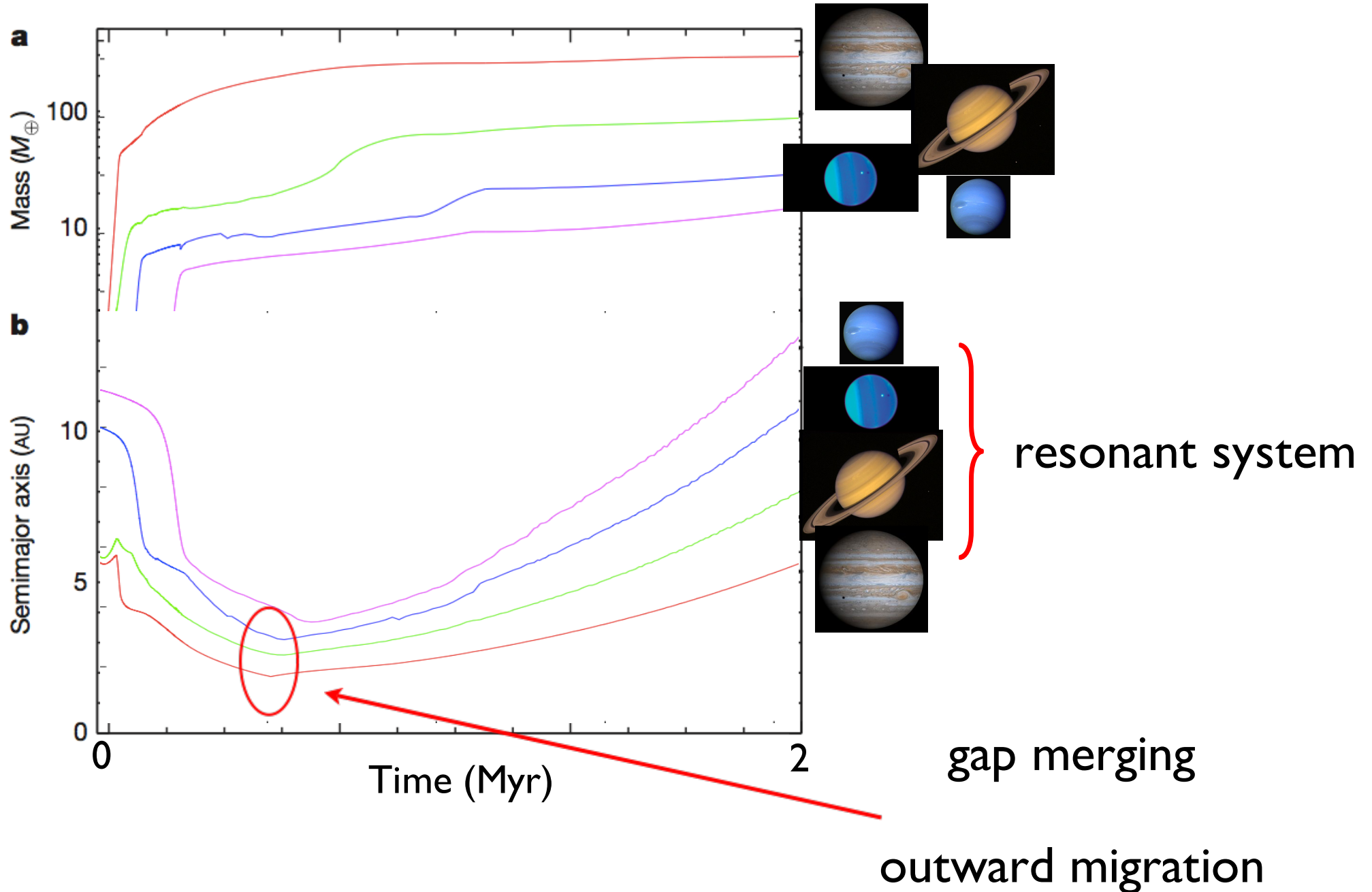


# Back to the Solar System

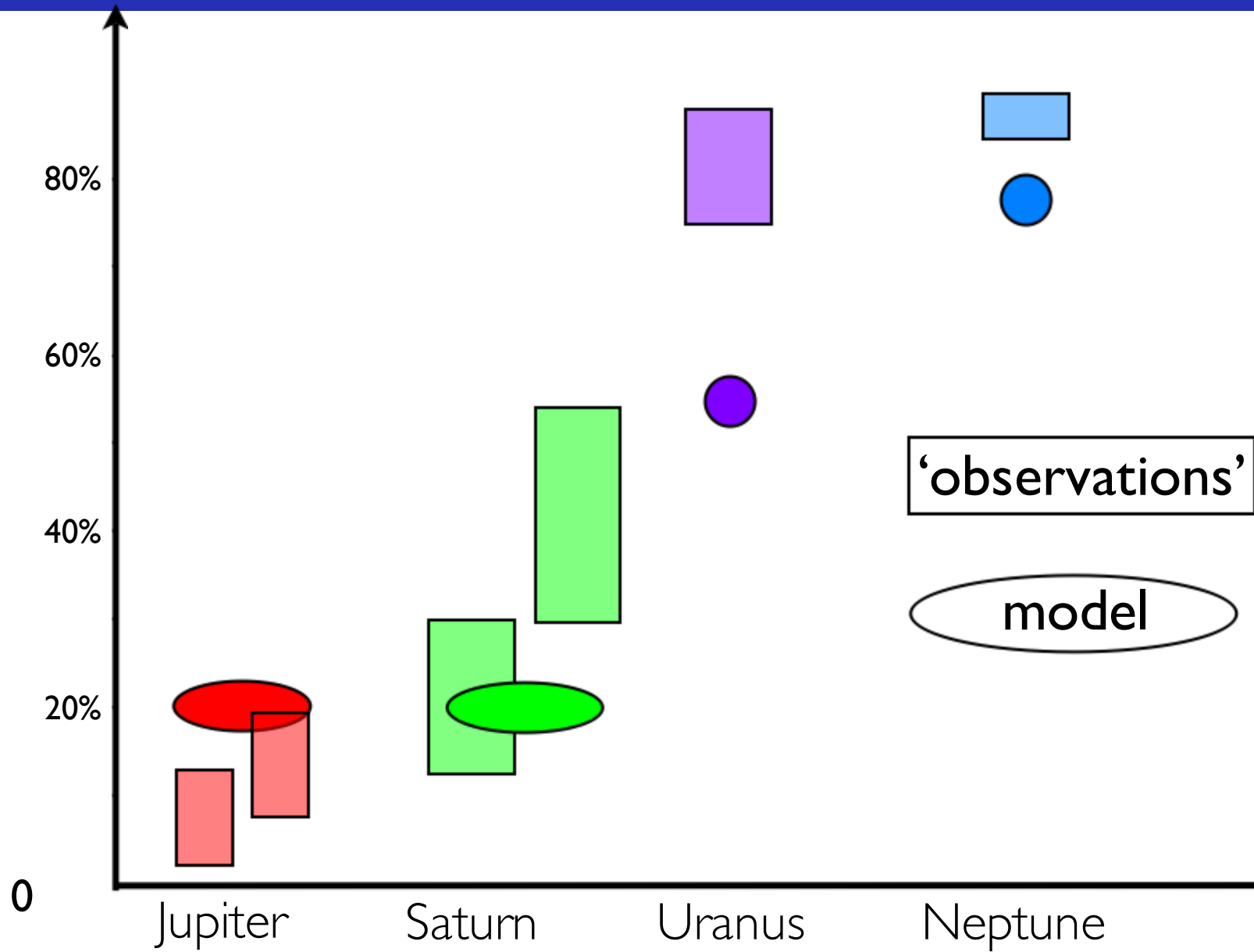




# Back to the Solar System



# Back to the Solar System



# Conclusions

- 1- Considering the system is mandatory to predict/explain terrestrial planet properties
- 2- Testing our understanding requires both specialized and integrated models

ありがとうございました！

Thank you!

100 planetary systems - 10 planetary seeds/system

