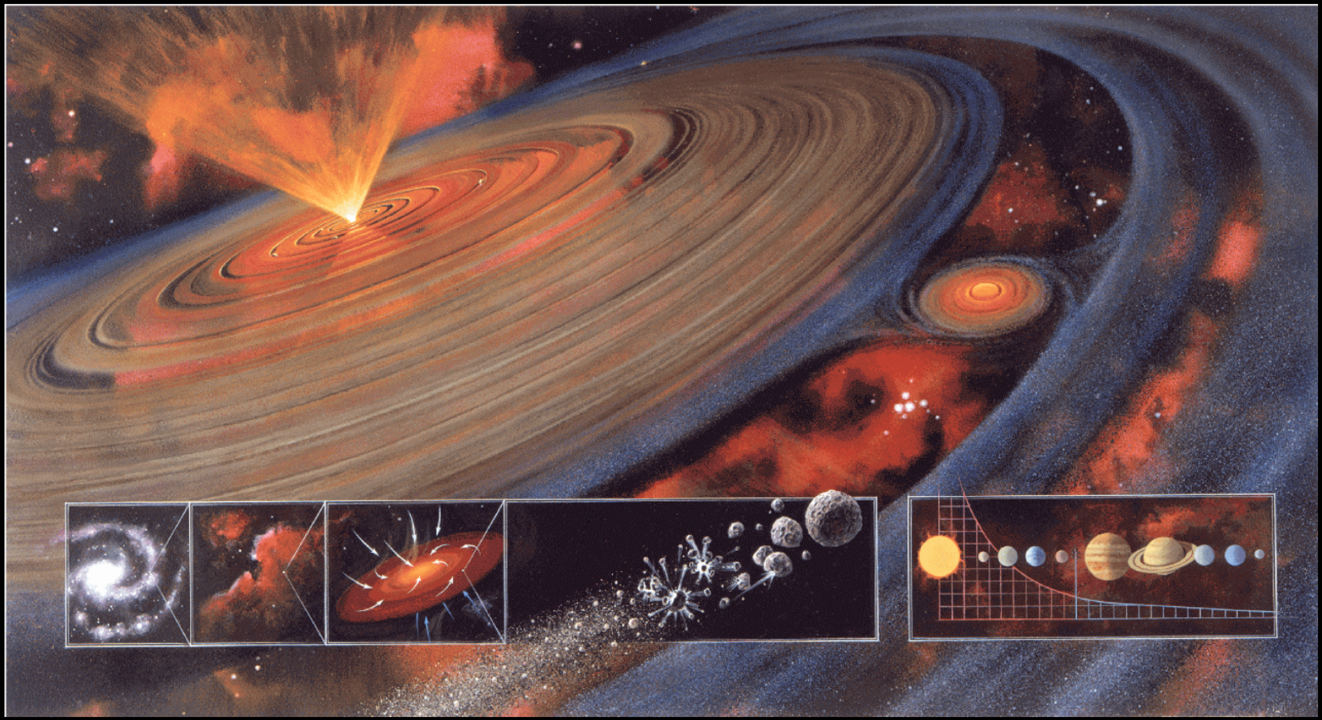
Planet Formation: theory and observations



Sean Raymond
University of Colorado (until Friday)
Observatoire de Bordeaux

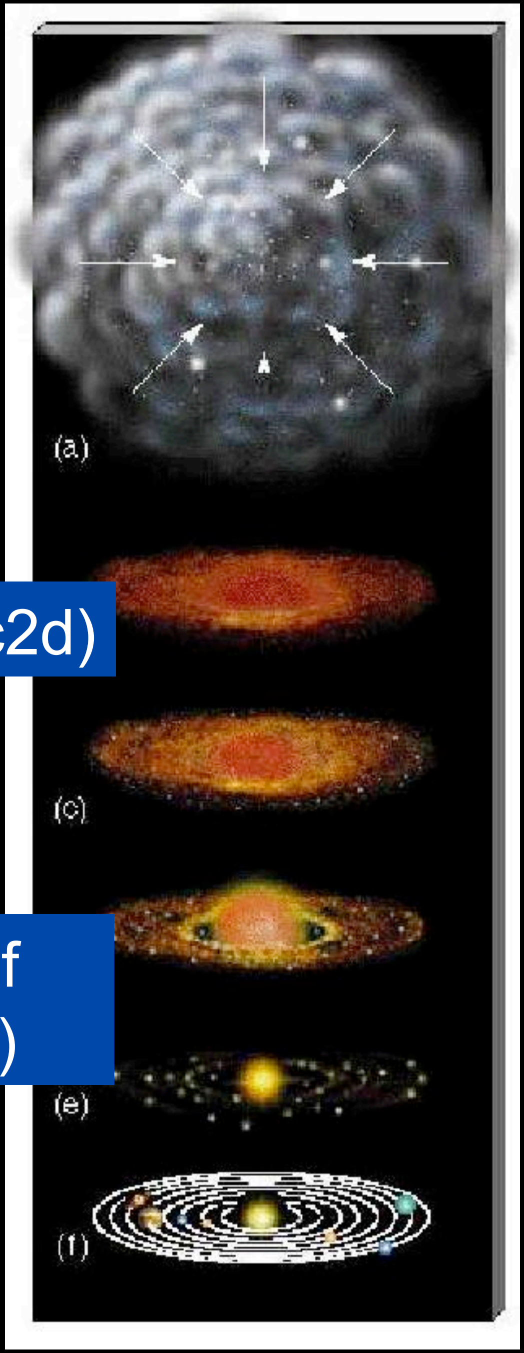
Outline

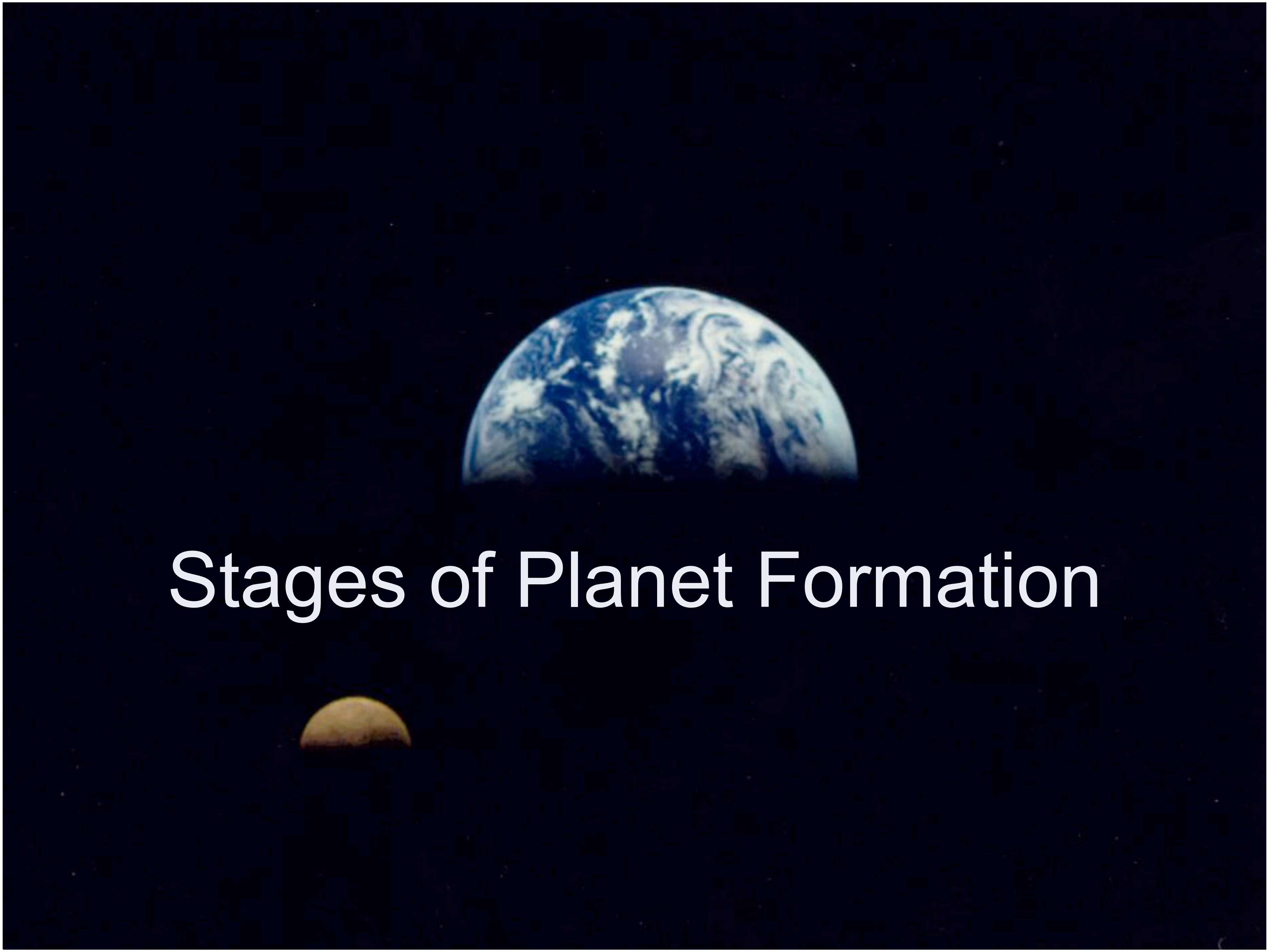
- Stages of Planet Formation

Cores to disks (c2d)

- Solar System Formation
- Observa
  Constraints

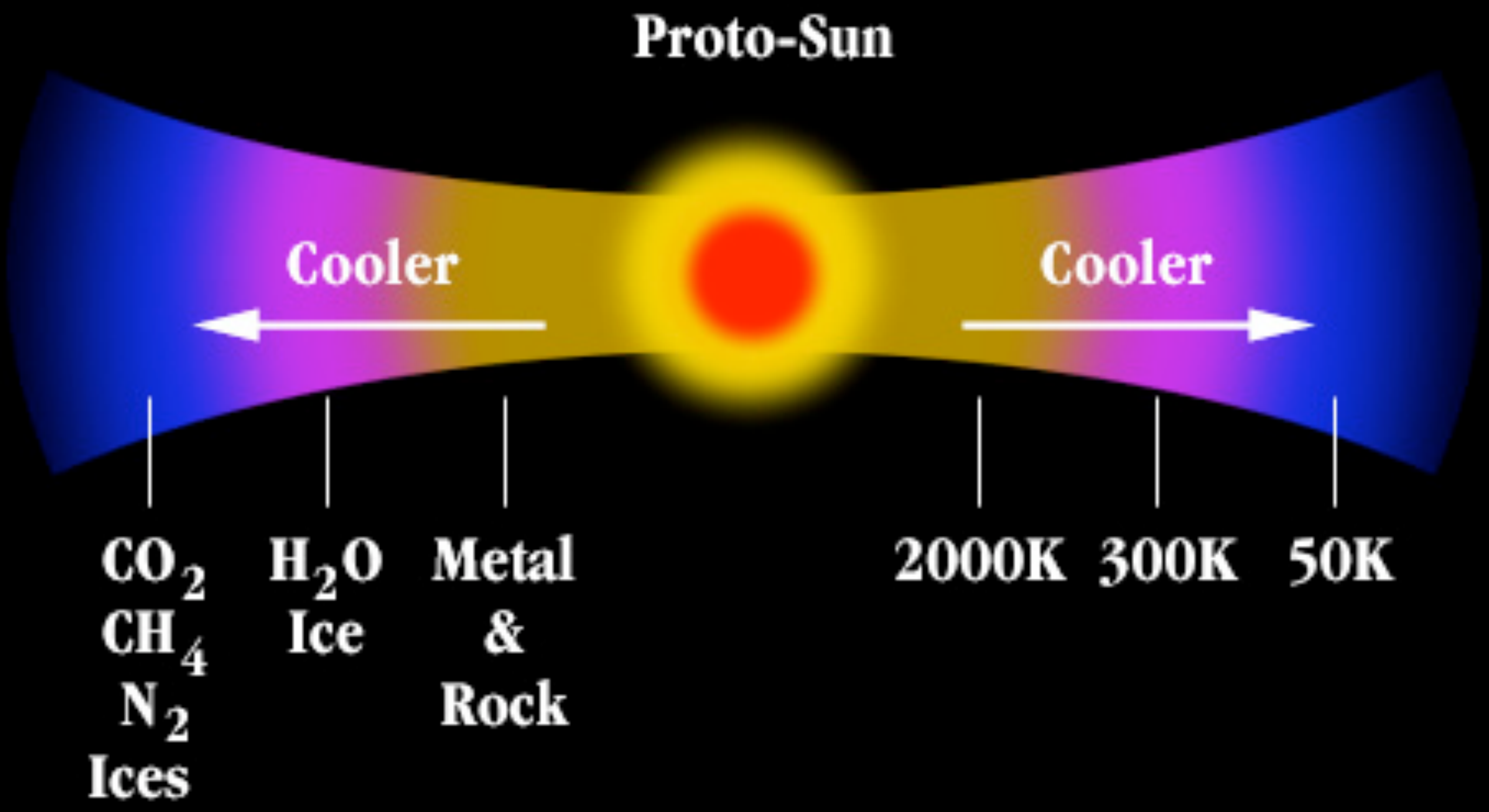
Formation and Evolution of Planetary Systems (FEPS)





Stages of Planet Formation

The Solar Nebula

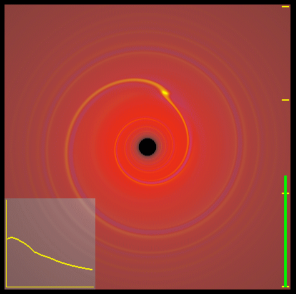


Available solids determined by disk temperature distribution and condensation temperatures

Stages of Planet Formation

Grains

Type 1
migration

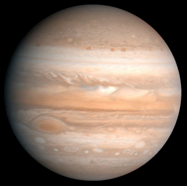


Planetesimals

Planetary Embryos

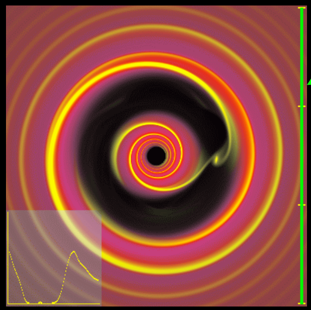
while gas remains

No more gas



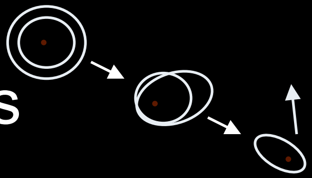
Gaseous Planets

Terrestrial Planets



Type 2
migration

Dynamical
instabilities

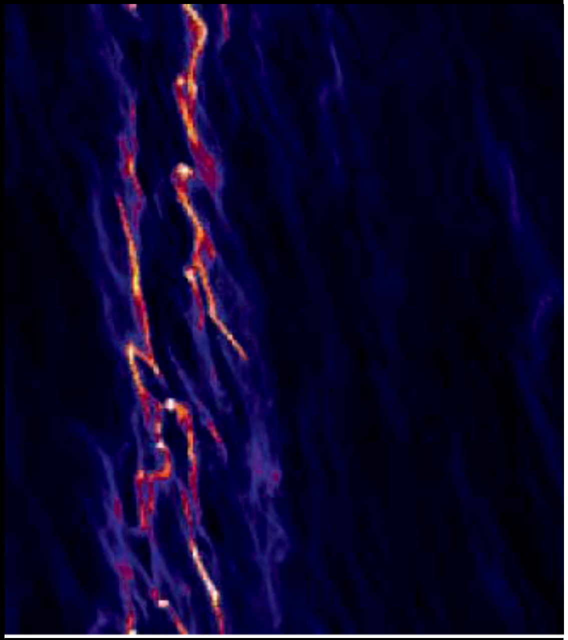


Planetesimal formation (~$10^{3\text{-}5}$ yrs)

- Micron to cm or m sizes: sticking (Dominik & Tielens 1996)

- M to km: sticking vs. gravitational collapse (Goldreich & Ward 1973; Weidenschilling & Cuzzi 1993, Youdin & Shu 2002)

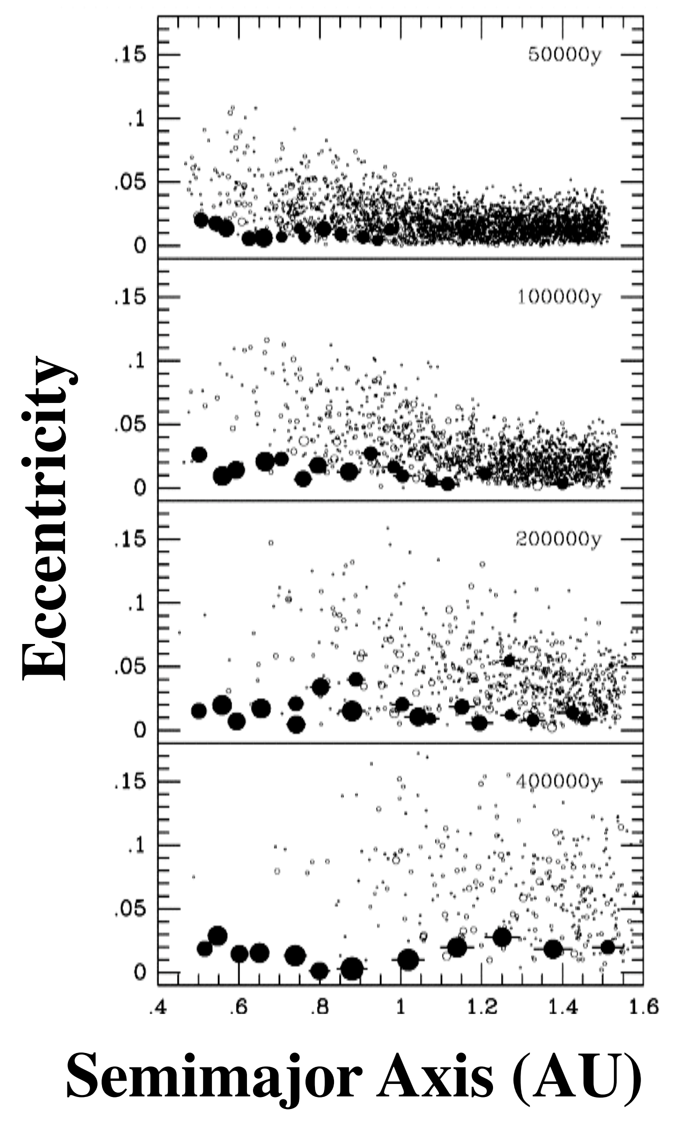
- Gravitational collapse might happen when particles are M-sized: turbulence can concentrate boulders in pressure maxima



Johansen et al (2007)

Planetary Embryos (10^{5-7} yrs)

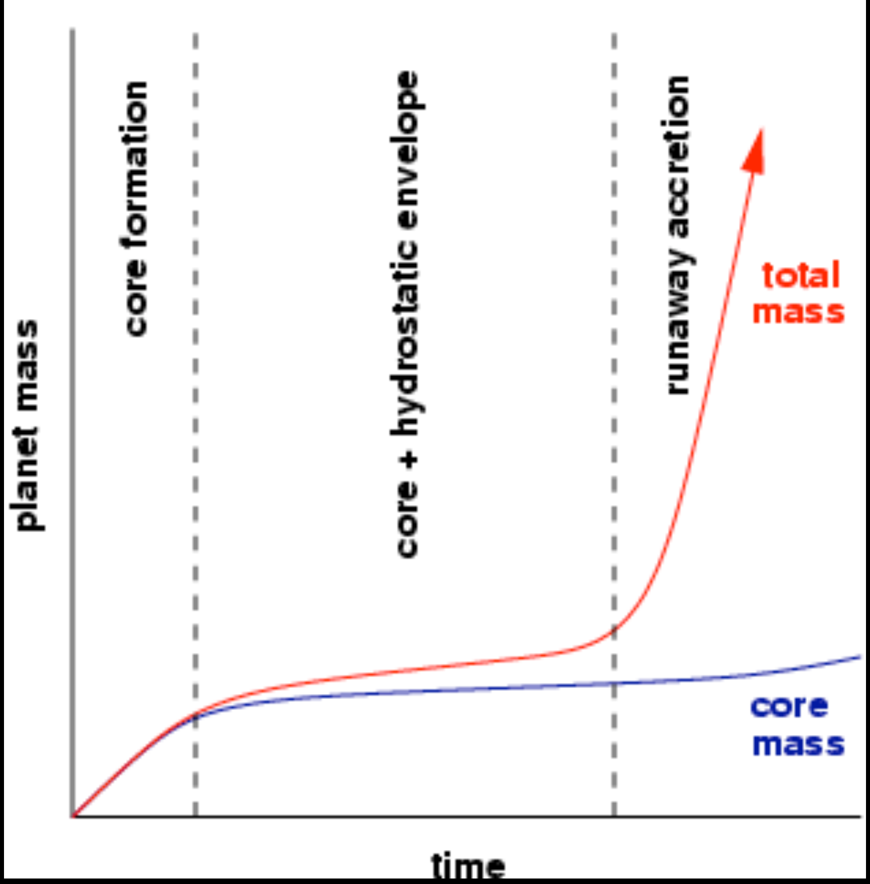
- Gravitational focusing⇒Runaway growth: $dM/dt \sim M^{4/3}$ (Safronov 1969)
- Large bodies excite small bodies: runaway ends when velocity dispersion of small bodies ~ v_{esc}
  - Depends on planetesimal size (Rafikov 2003; Chambers 2006)
- Oligarchic growth: $dM/dt \sim \pi R^2 \sim M^{2/3}$ (Ida & Makino 1993, Kokubo & Ida 1998)
- Late-stage accretion starts when mass in large and small bodies is comparable (Kenyon & Bromley 2006)



Kokubo & Ida 2002

Giant planet formation (“core accretion”)

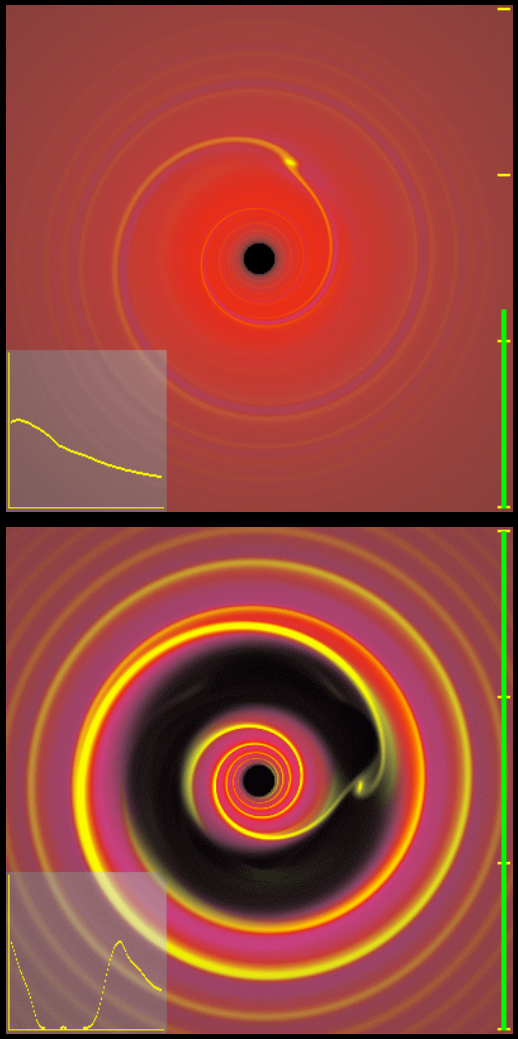
- If embryos reach 5-10 M_{Earth} before gas dissipates, can accrete nebular gas
- Core formation preferred just past “snow line”



Credit: Phil Armitage

Planet migration in gaseous disks

- Type 1: low-mass planets
  - Torques from density waves and co-rotating material
- Type 2: massive planets
  - Carve gaps in disk, linked to disk's viscous evolution
    - $T_{viscous}$ ~ 1 Myr



Credit: Phil Armitage

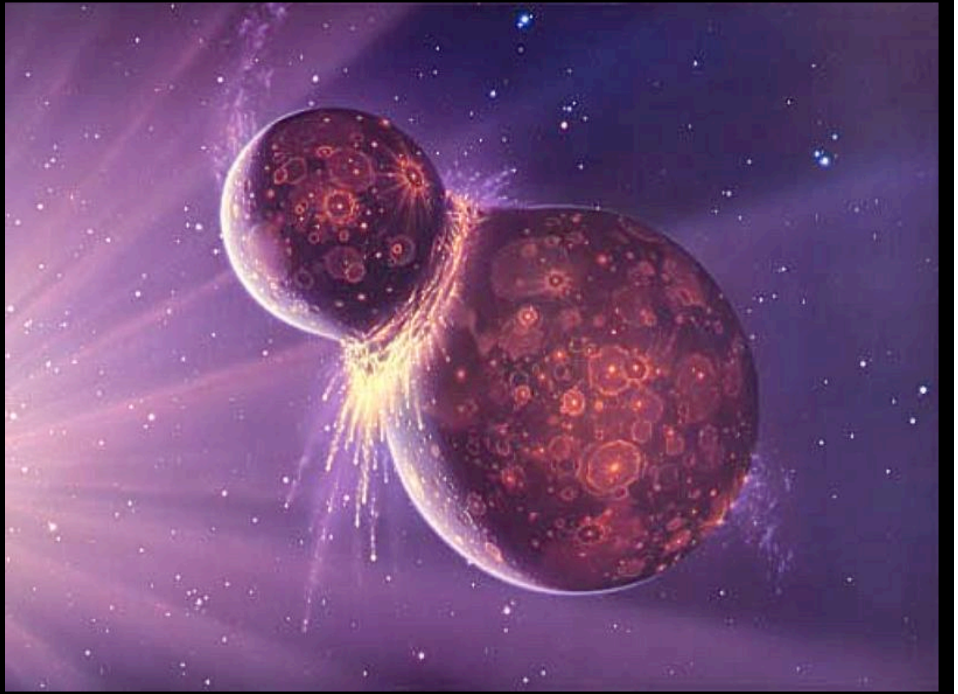
Dynamical instabilities

- Exoplanet eccentricity distribution consistent with all systems going unstable
- Uncertainties: timing of instability (gaseous or gas-free environment?)

Credit: Eric Ford

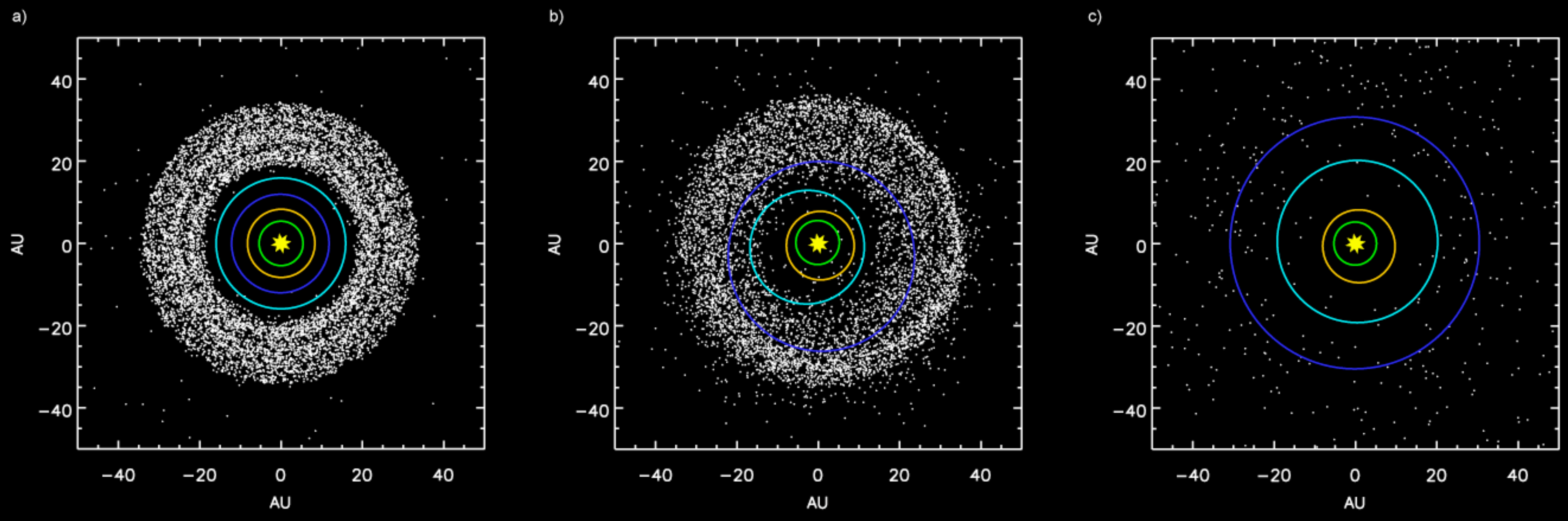
Late-stage terrestrial accretion (10^{7-8} yrs)

- Giant planets already formed (t_{gas} ~ few Myr)
- Impacts from planetesimals and embryos
  - Moon forming impact was last big one on Earth: 50-150 Myr (Touboul et al 2007)
  - 1-10 Myr for last giant impact on Mars (Nimmo & Kleine 2007)

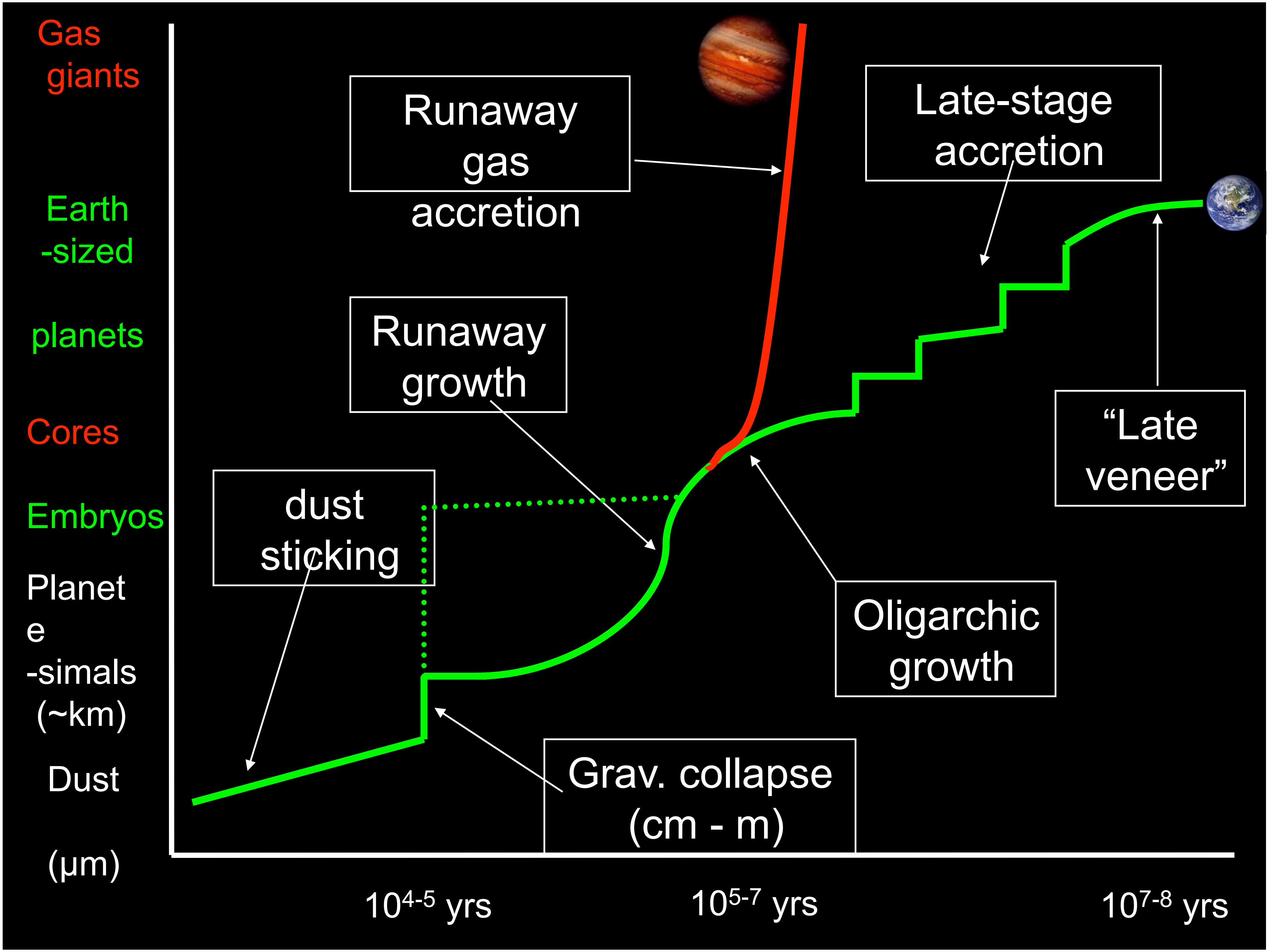


Long-term dynamical evolution (Gyr)

- Small bodies cleared out by planets
- Planetary collision rates decreases rapidly (~power law)
- Late instabilities possible (e.g., “Nice model”)



Tsiganis et al 2005; Gomes et al 2005



Gas giants

Earth-sized planets

Cores

Embryos

Planetesimals (~km)

Dust (μm)

Runaway gas accretion

Late-stage accretion

Runaway growth

dust sticking

"Late veneer"

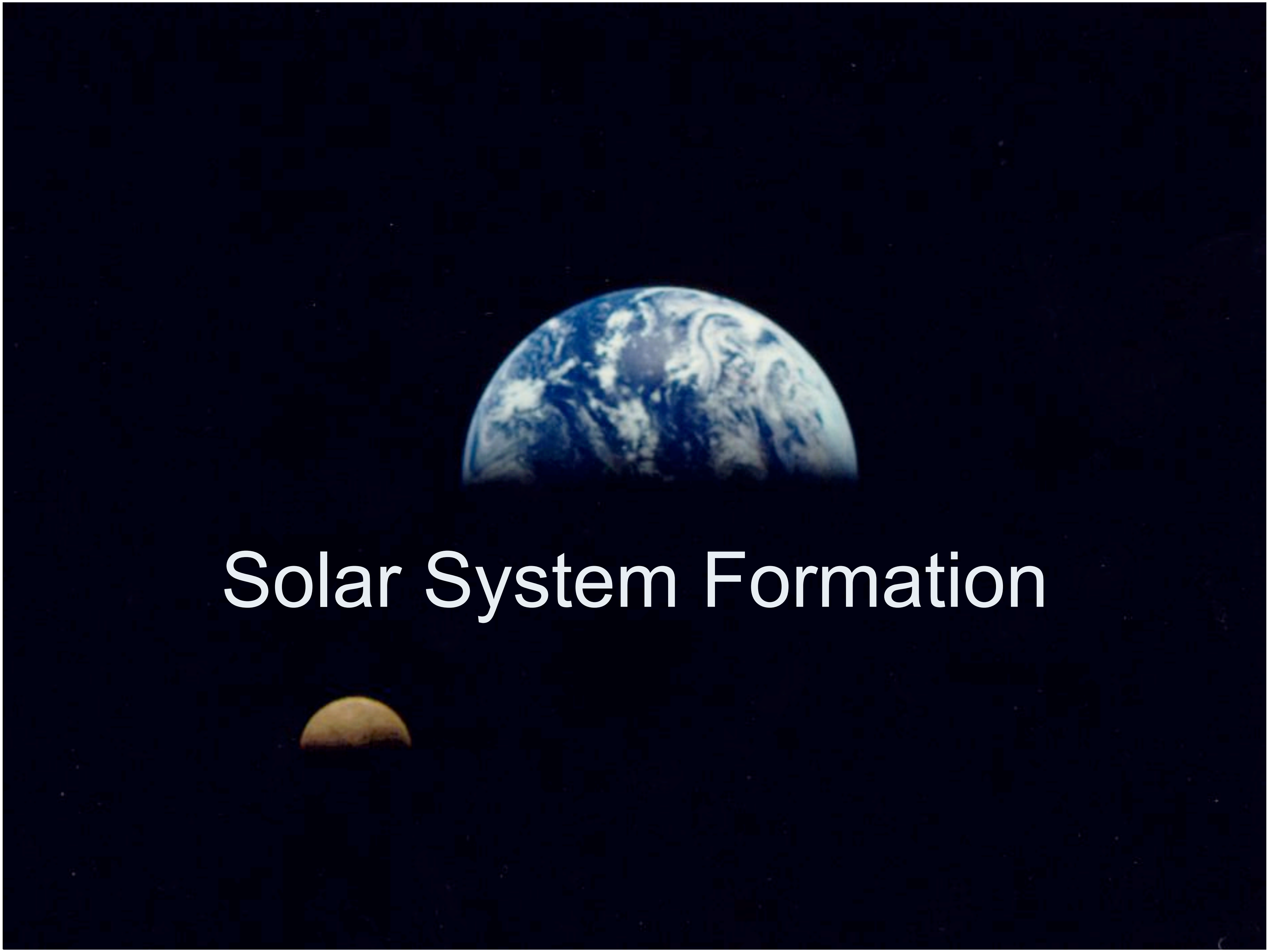
Oligarchic growth

Grav. collapse (cm - m)

$10^{4\text{-}5}$ yrs

$10^{5\text{-}7}$ yrs

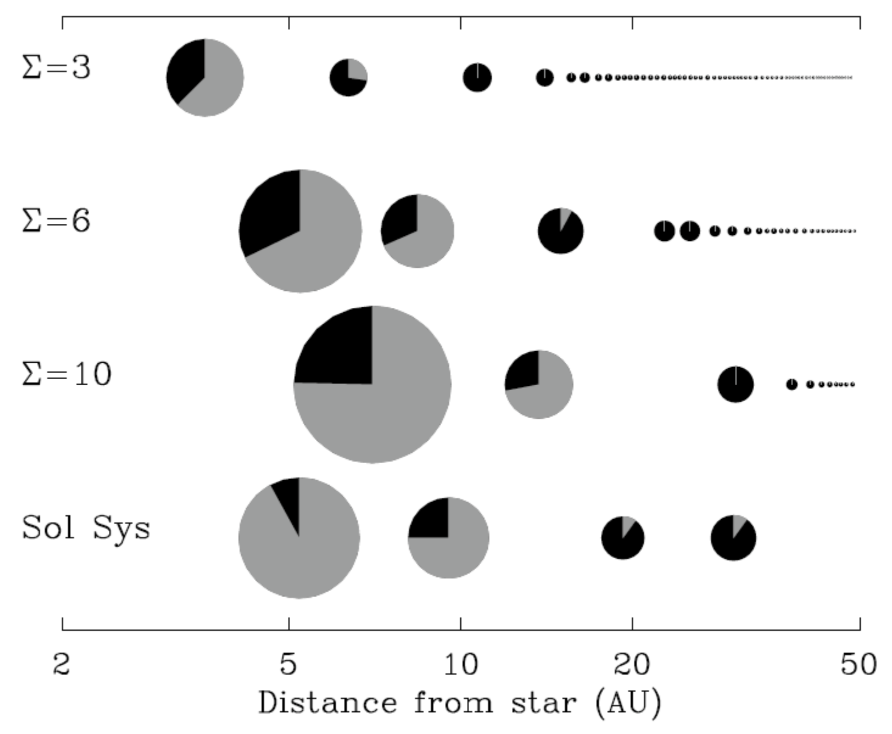
$10^{7\text{-}8}$ yrs



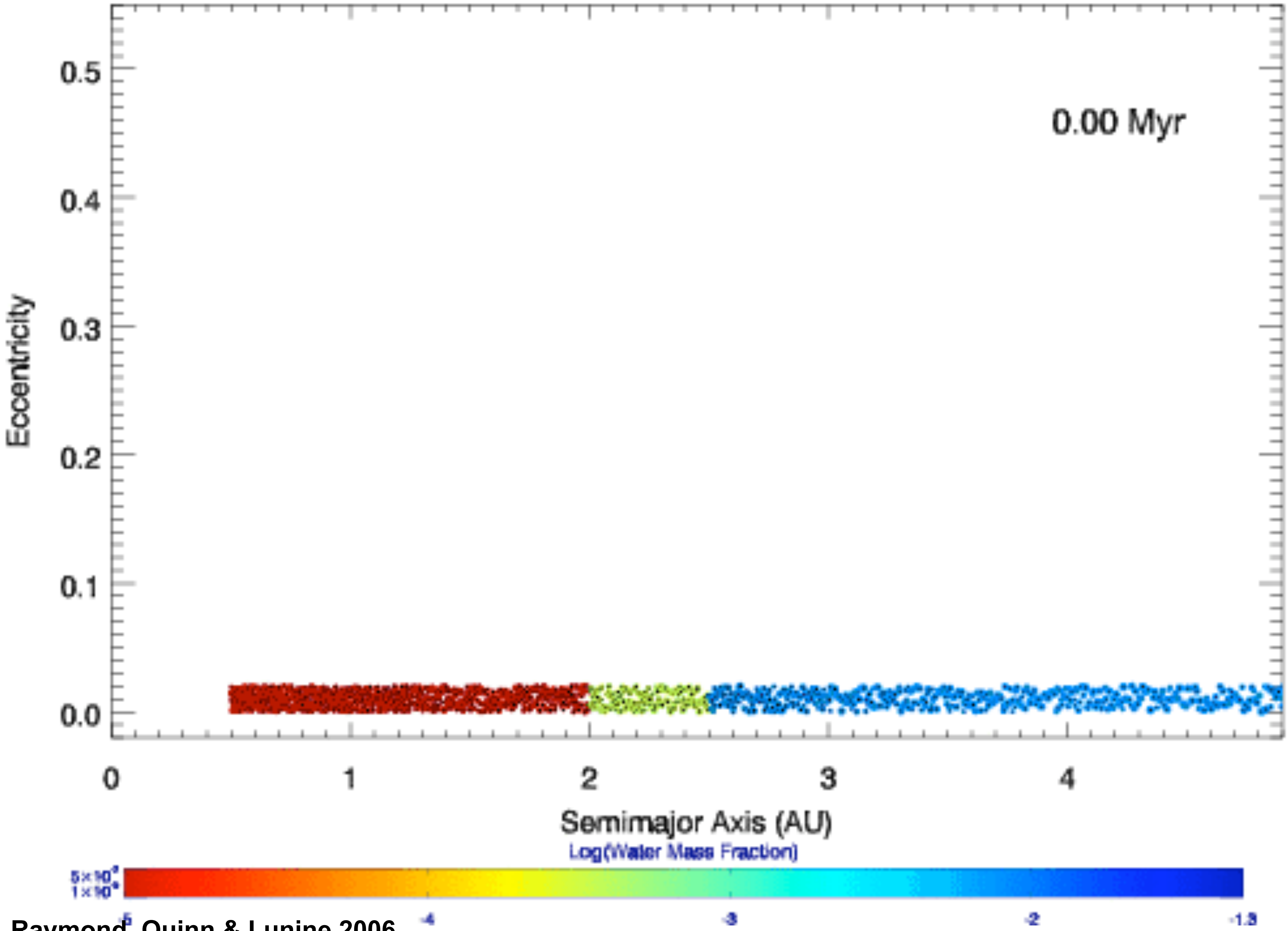
Solar System Formation

Gas giant planets

- Models can sort of reproduce Jupiter and Saturn (Chambers 2006, Thommes et al 2008)
- Uncertainties
  - How to form 10 M_E core in ~1 Myr? (Kenyon & Bromley 2009)
  - Opacity ($t_{form} \sim \kappa^{1/4}$)
  - Gravitational instability?



Chambers 2006



Raymond, Quinn & Lunine 2006

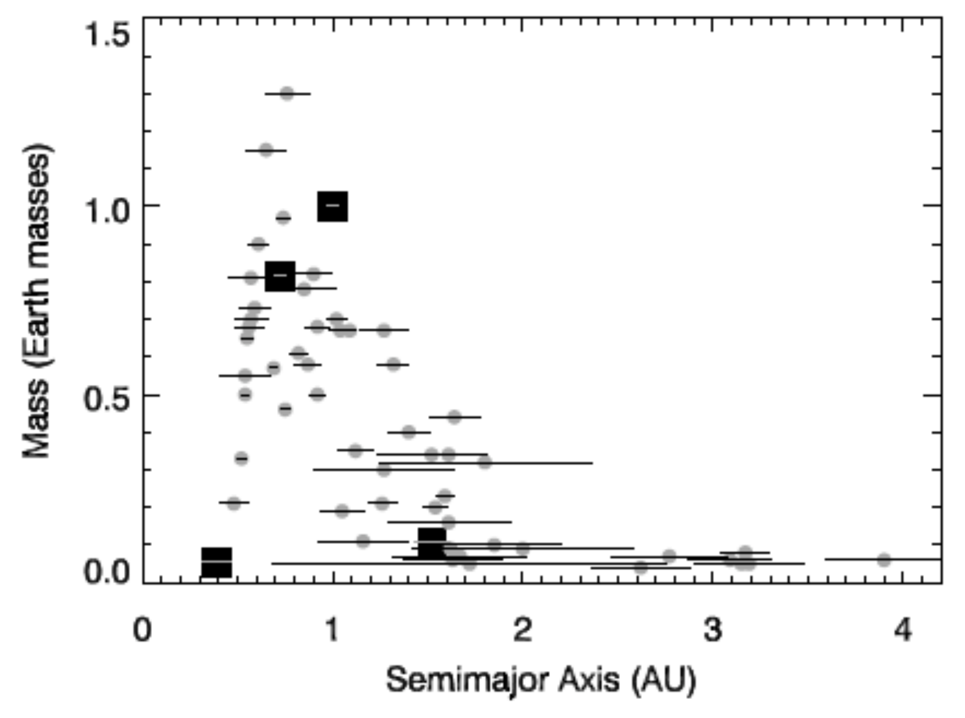
Terrestrial planet formation model

Successes

- Masses and orbits of terrestrial planets (Wetherill; Agnor et al 1999; Chambers 2001; O'Brien et al 2006)
- Earth water from primitive asteroidal bodies (Morbidelli et al 2000; Marty et al 2006)

Shortcomings

- Mars is too small (unexplained – Wetherill 1991)
- Mercury is too small and too iron-rich (giant impact? Benz et al 1988, Wetherill 1988)
- Not included: collisional fragmentation (Asphaug et al 2006), water depletion from impacts and hydrodynamic escape (Matsui & Abe 1986, Canup & Pierazzo 2006, Genda & Abe 2005)



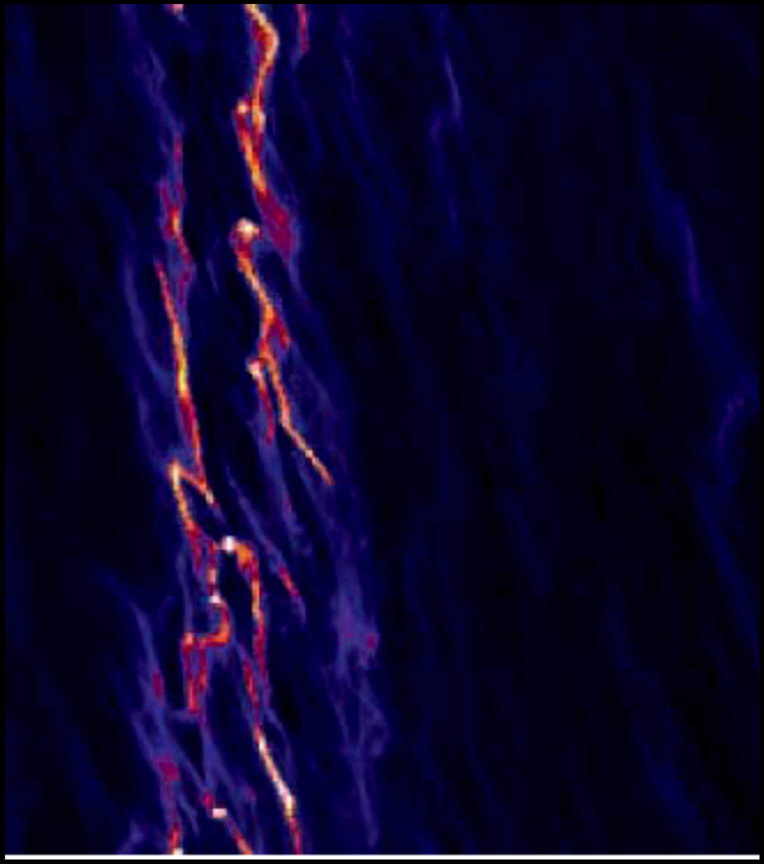
Raymond, O'Brien, Morbidelli, Kaib 2009

Caution: Jup, Sat not consistent with Kuiper Belt in these simulations

Observational Constraints: current and future

Can we constrain planetesimal and embryo formation?

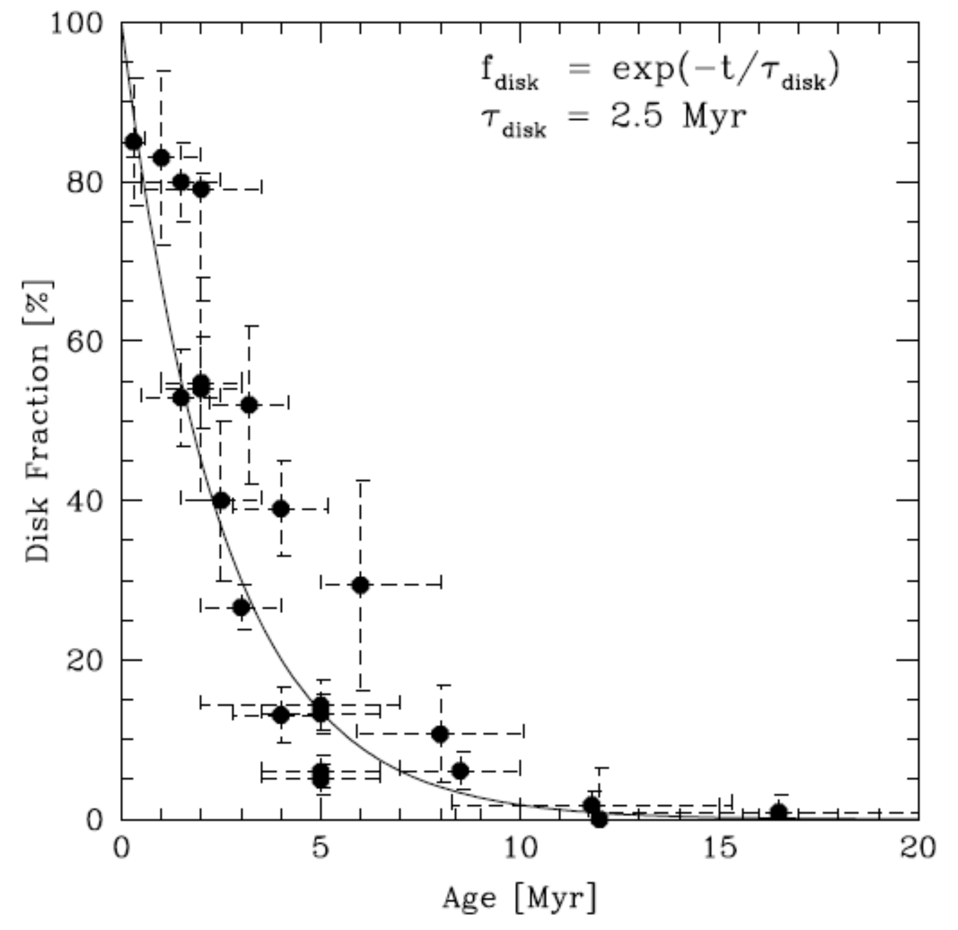
- Need measurements of disk structure:
  - Density
  - Temperature
  - Grain growth
  - Turbulence?



Johansen et al 2007

Protoplanetary Disk Lifetimes

- Disks last few Myr (Haisch et al 2001, others)
- Shorter-lived around binary stars (Cieza et al 2009)
- Last longer for lower-mass stars (e.g., Pascucci et al 2009)
    - BUT fewer gas giants around low-mass stars (Johnson et al 2007)
    - M_{disk}/M_{star} ~ 1% (Andrews & Williams 2007)



Mamajek 2009

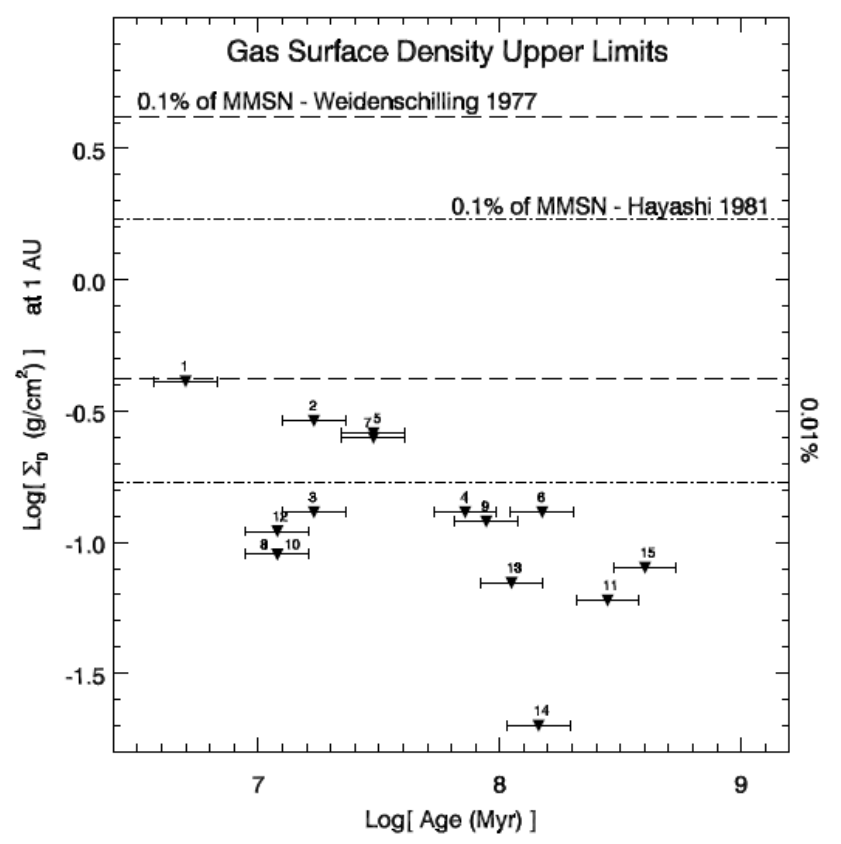
Disk dissipation

- Disks cleared from the inside out or homologously (Currie et al 2009)
  - Longer transition than previously thought (Simon & Prato 1995)
  - Important for planet migration (Armitage 2007)
- Window for giant planet formation is 1-5 Myr (Currie et al 2009)

5 Myr old cluster NGC 2362 from Currie et al 2009

Uncertainties in giant planet formation

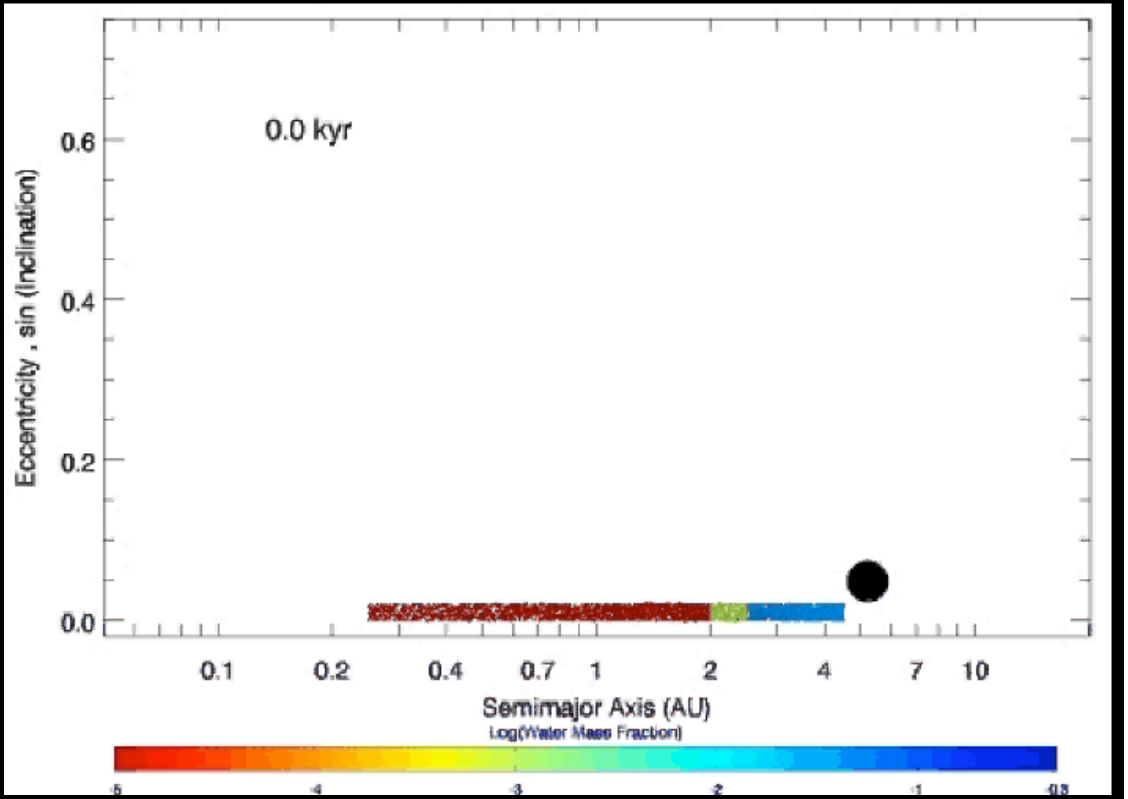
- Key measurements:
  - Disk gas (rather than dust)
  - Inner disk mass
  - Radial Structure (snow line)



Pascucci et al 2006

Planet migration

- Type 1:
  - Turbulence
  - T structure
  - Resonant planets?
- Type 2:
  - Dust from huge collision rates at inner resonances?



Raymond, Mandell & Sigurdsson 2006

Dust (~planet formation timescales) in different radial zones

24 micron (1-10 AU)

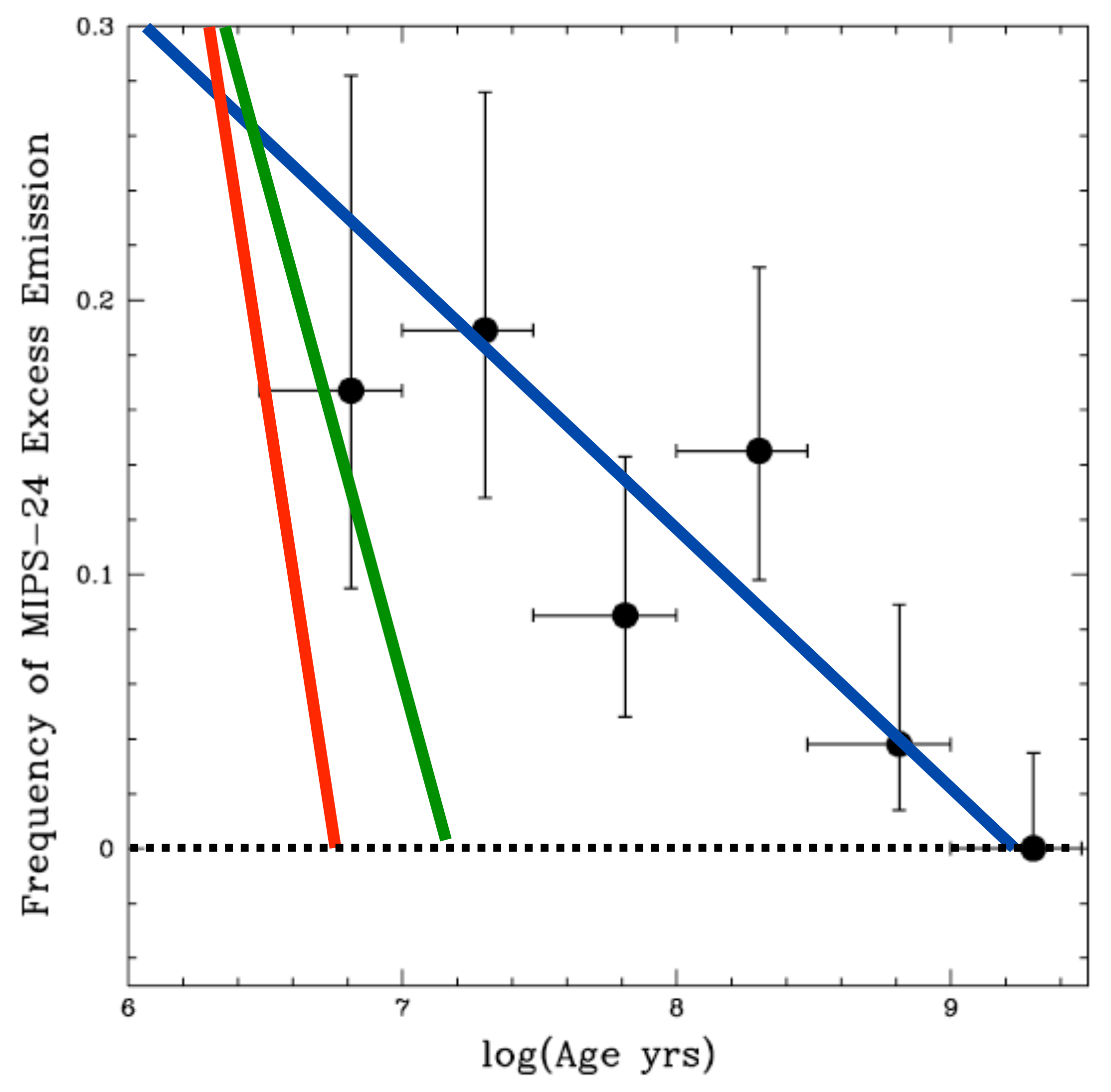
Meyer et al 2008

N Band (0.3-3 AU)

Mamajek et al 2005

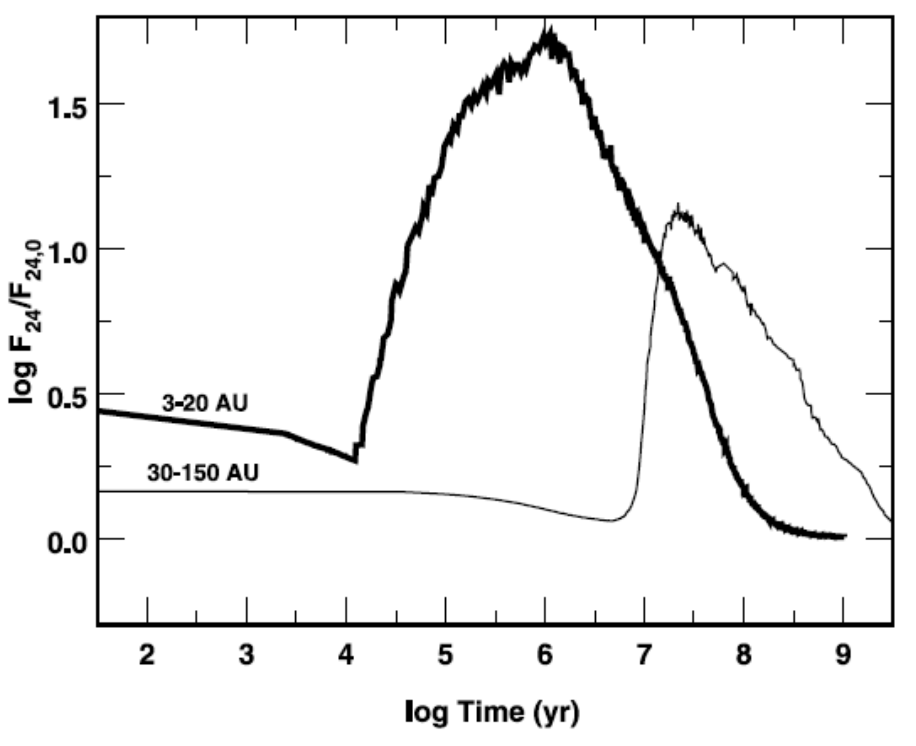
L Band (<0.1 AU)

Haisch et al 2001



Models of dust production from accretion

- Dust in inner system decreases by ~10 Myr
- Colder dust evolves for 100s of Myr
- Reflects accretion and dynamical timescales

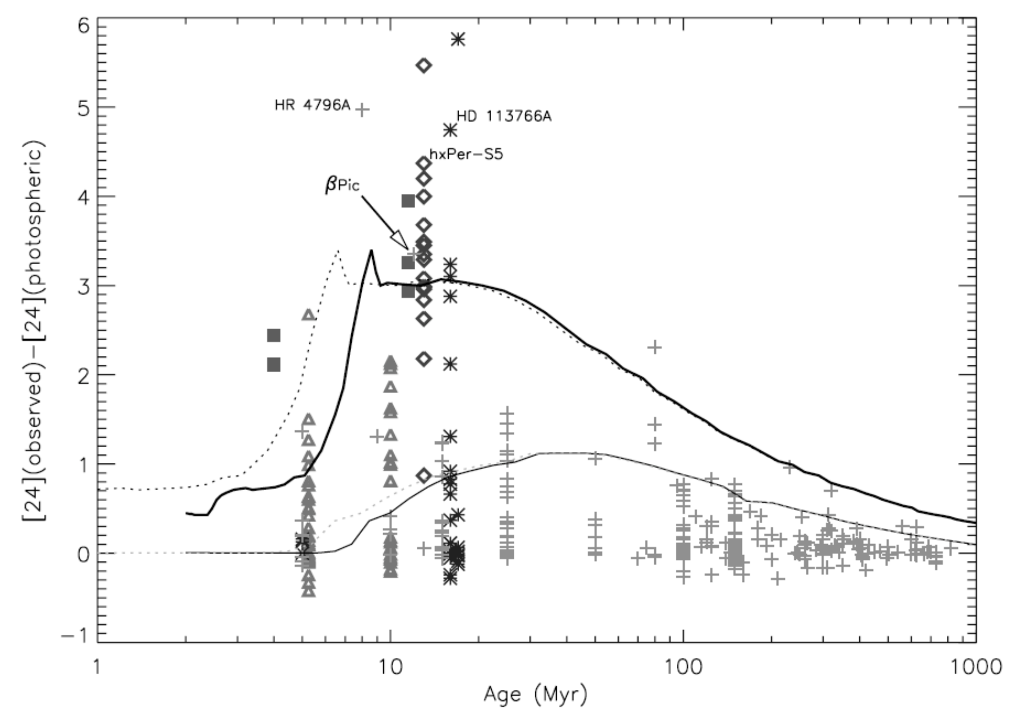


Kenyon & Bromley 2005

24 micron dust brightness vs time

- Ramps up after few Myr
- Peaks at 10-30 Myr
- Slow decline at late times

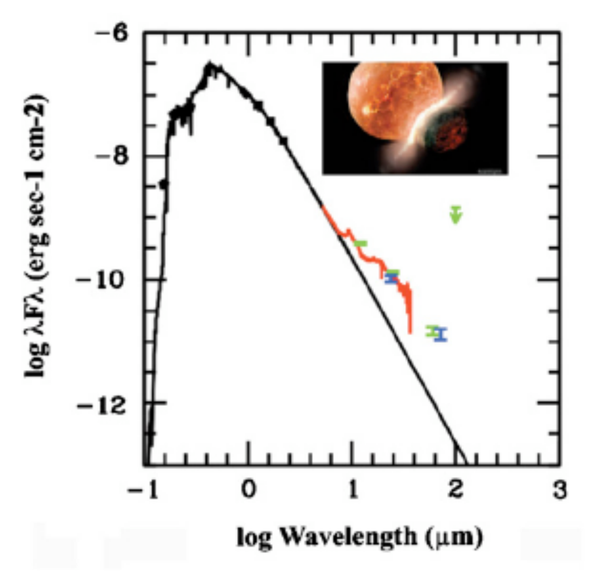
- Broadly consistent with dust production from terrestrial planet formation (Kenyon & Bromley 2004)

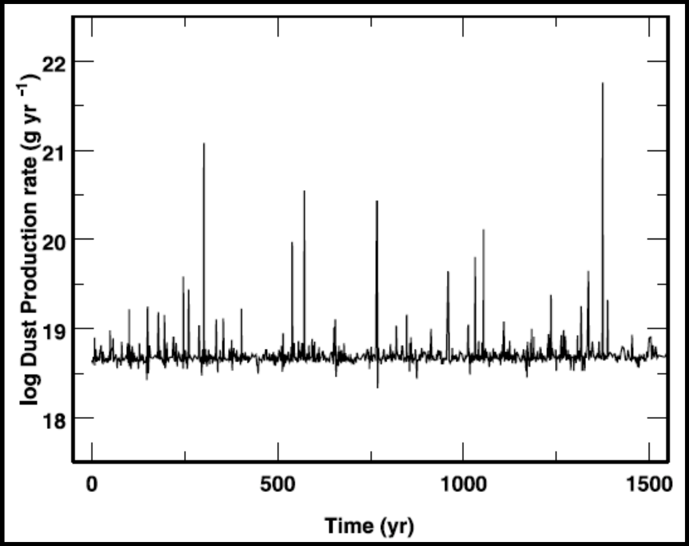


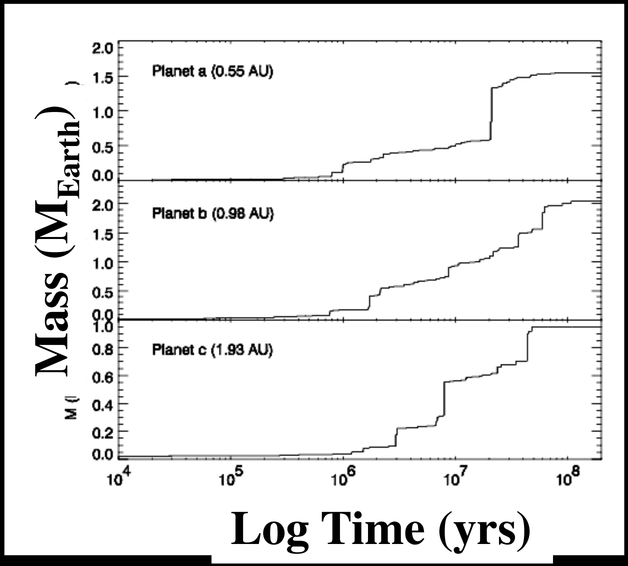
Currie et al 2008

Giant impacts

- Rare
- Increase dust by ~2 orders of magnitude
- Observed in HD 172555 (Lisse et al 2008)



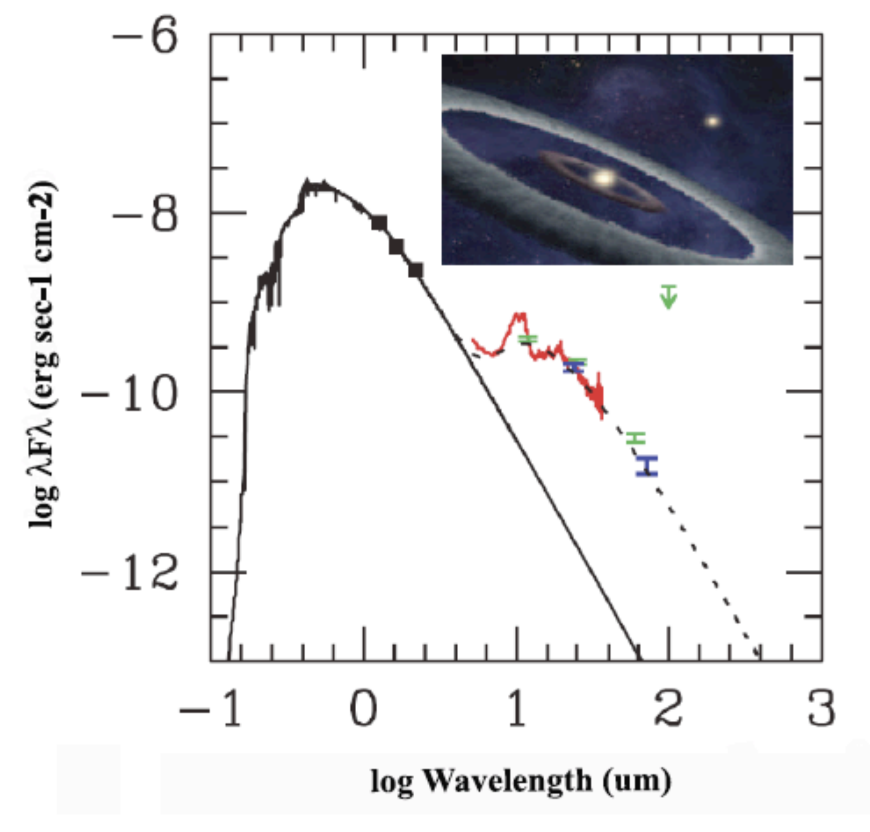




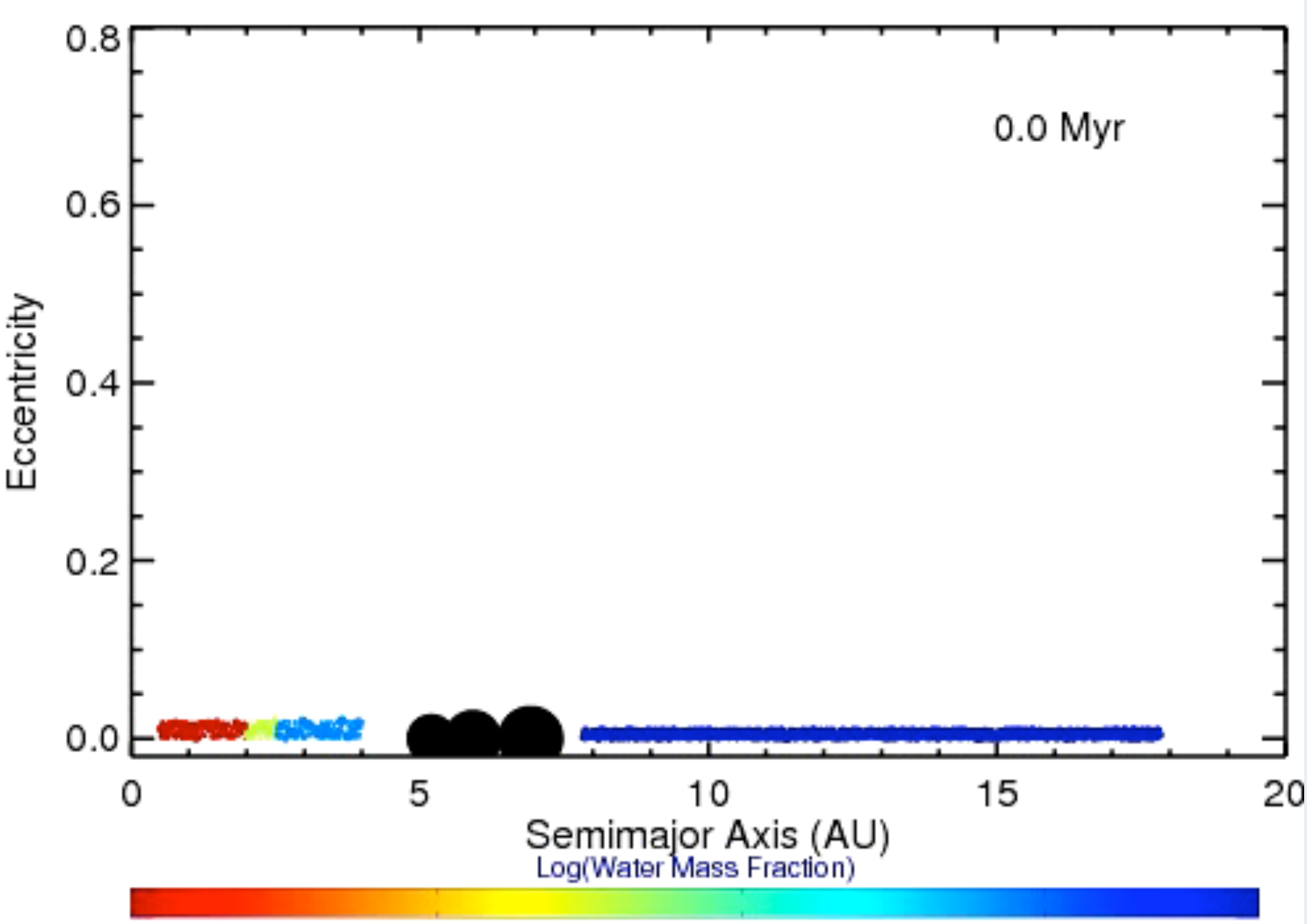
Lisse et al 2008; Raymond et al (2006); Kenyon & Bromley (2005)

Dust belts

- HD 113766: 10-16 Myr F star with 3 dust belts
  - 1.8 AU
  - 4-9 AU
  - 30-80 AU
- 20 year time span: requires dust replenishment from collisions
- Planetary influence on planetesimals?



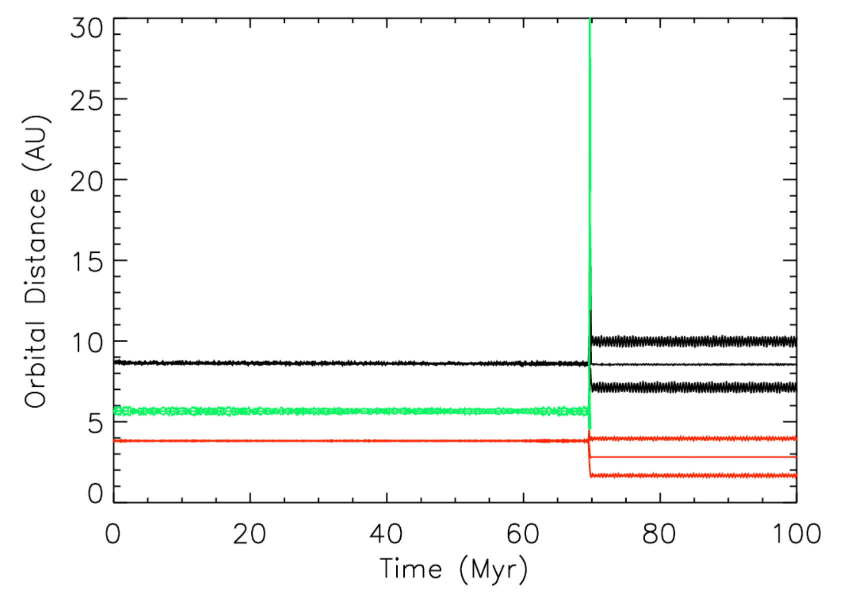
Lisse et al 2008

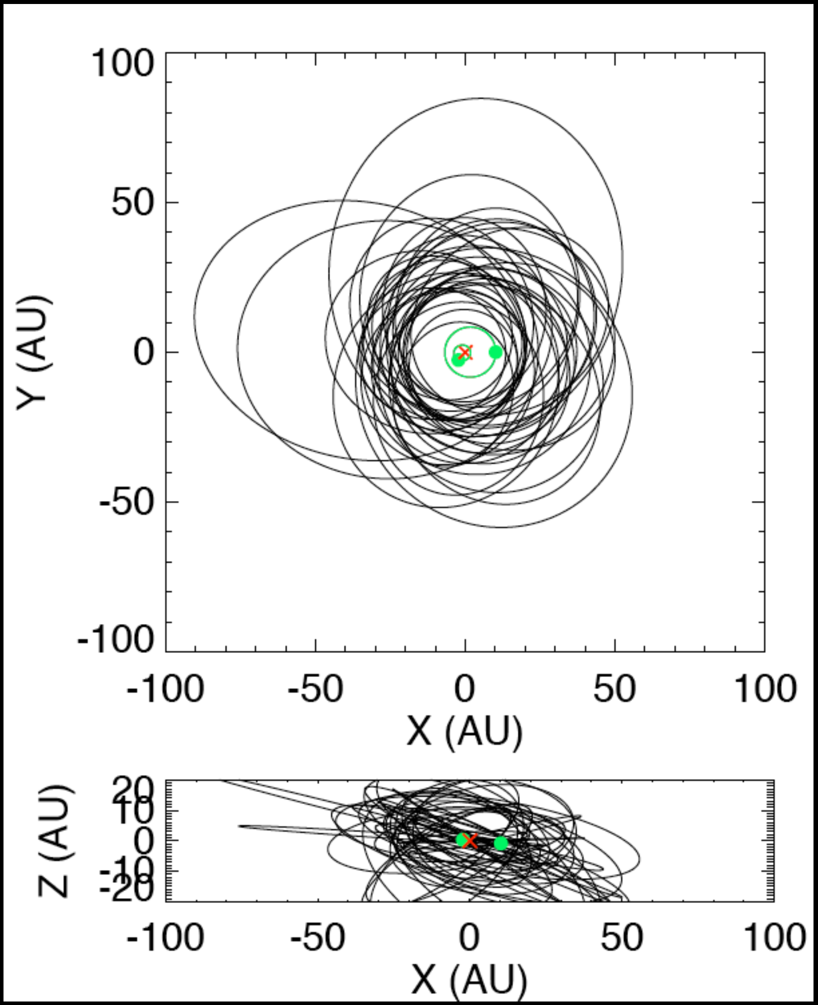


Raymond, Armitage, Mandell, Armstrong 2010

Link between free-floating planets and cold dust disks?

- Spitzer found three ~4 M_J planets in 3 Myr old Sigma Orionis (Bihain et al 2009)



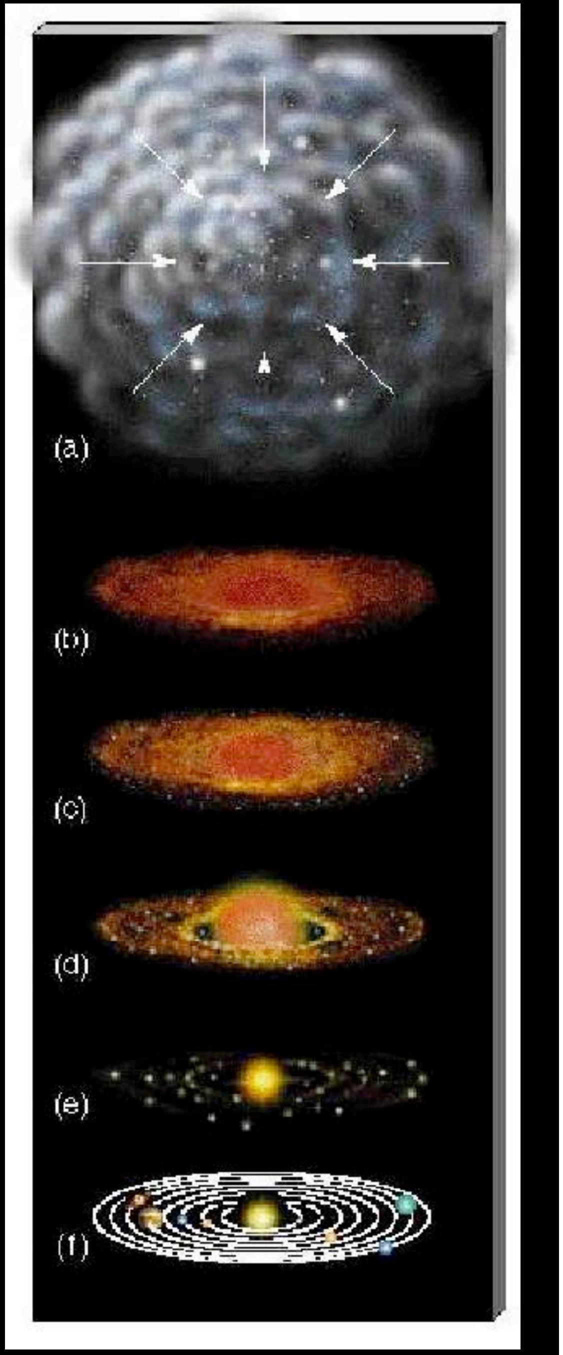


Raymond, Armitage, & Gorelick 2009

Conclusions

- We have a good idea of the stages of planet formation
- Models and observations are mainly in agreement

- Observations that would really help planet formation models:
  - Radial temp., density structure
  - Turbulence



Thank you!