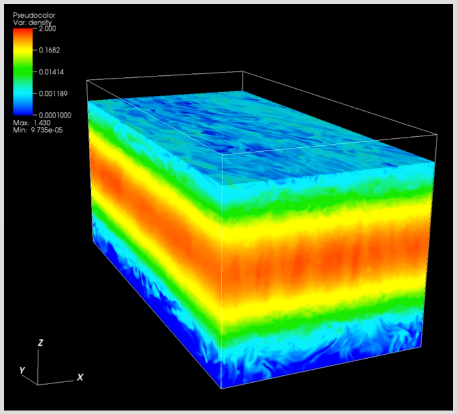
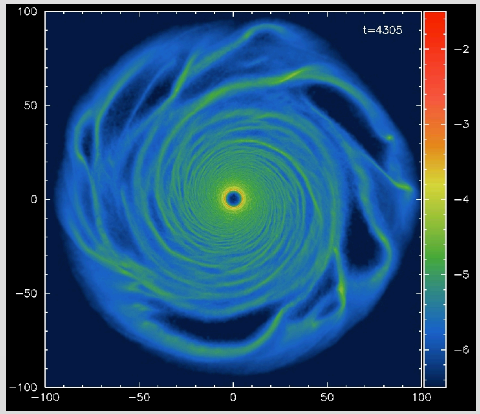
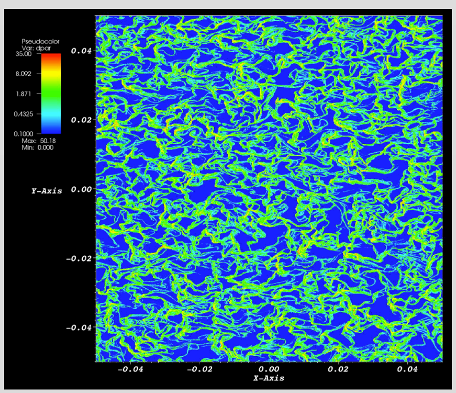
Overview of Planet Formation



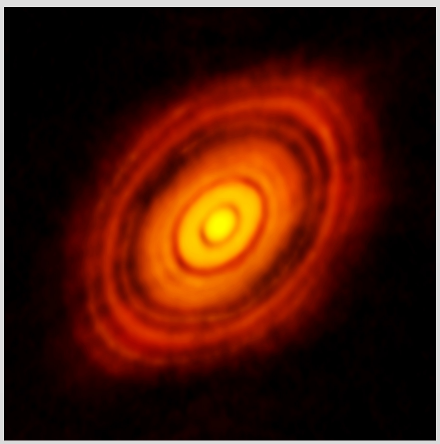




Phil Armitage
Colorado

Overview of Planet Formation

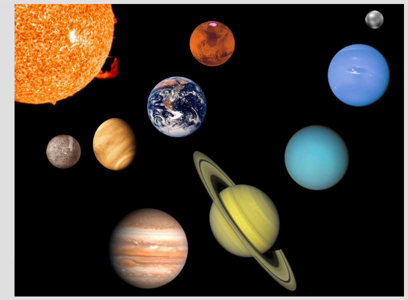
Initial conditions

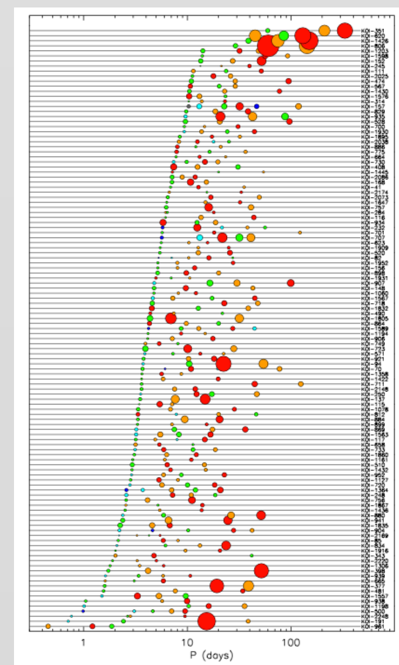


Gas and "dust" in
protoplanetary disks
t ~ Myr

planet
formation
???

Solar
system



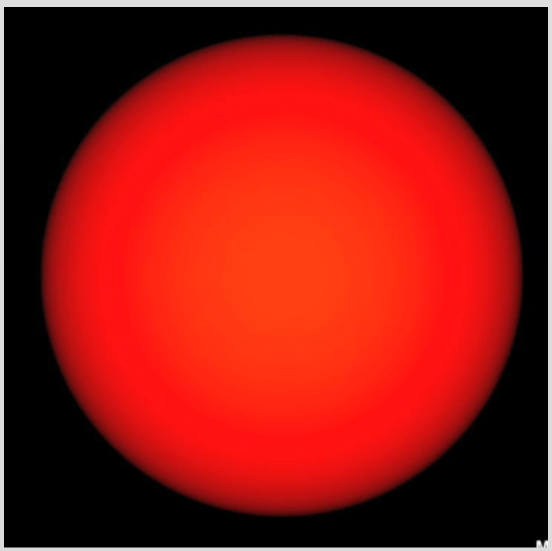


Extrasolar
planetary
systems

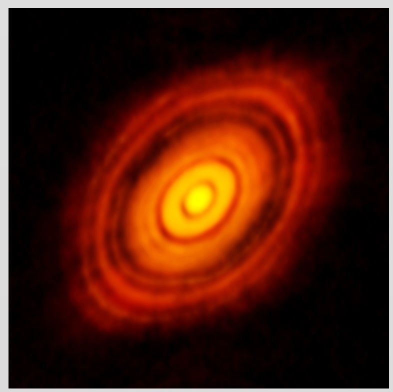
**~stable
final states
t ~ Gyr**

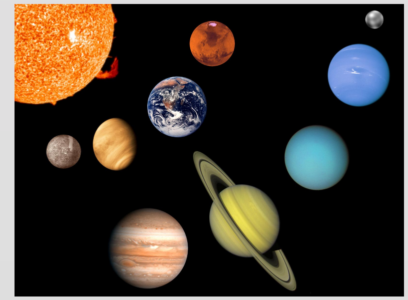
Overview of Planet Formation

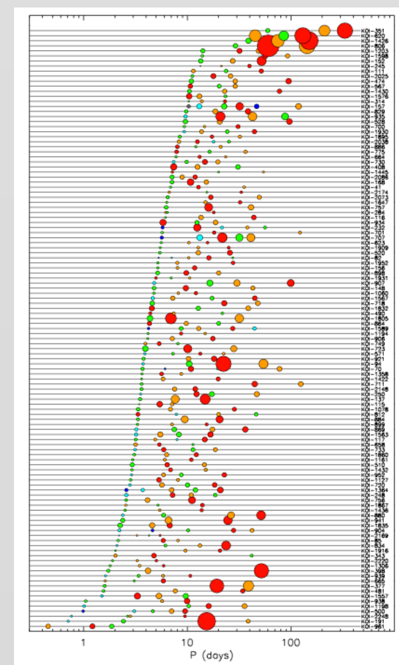
What sets the mass, size, density, magnetic field strength of disks?



Bate (2009)







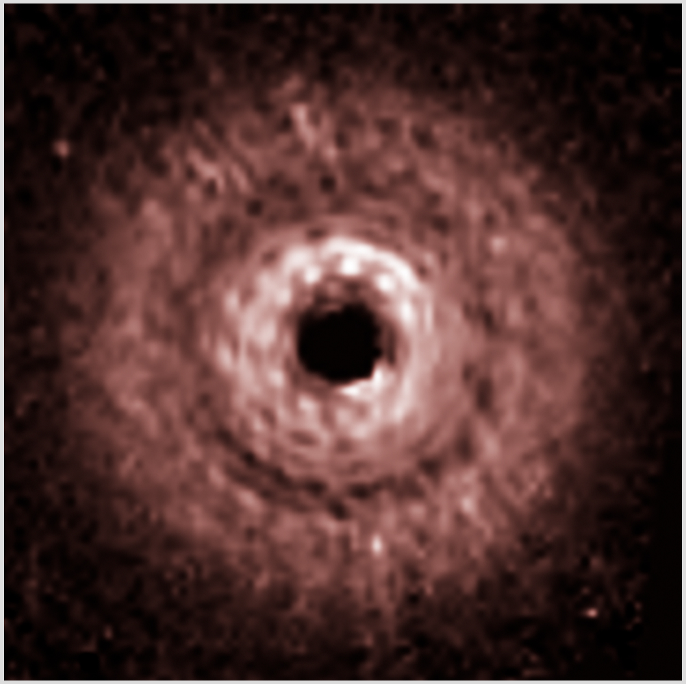
Overview of Planet Formation

- some (simple) physical principles
- a toy understanding of the Solar System
- generating diversity in exoplanet systems
- open questions…

"Planet formation", Lissauer '93, ARA&A
"Lecture notes on the formation…", Armitage, astro-ph/0701485

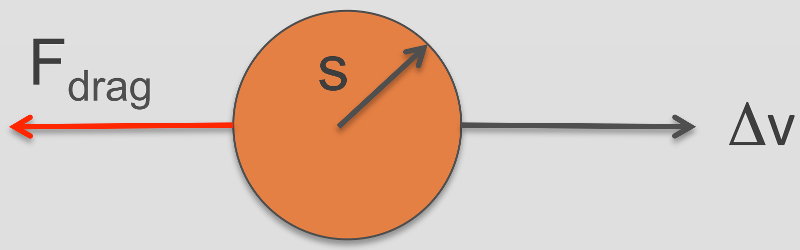
Protoplanetary disks

- scales ~100 AU
- lifetimes ~5-10 Myr
- approximately equilibrium structures in Keplerian rotation
- slow inflow (accretion)
- T ~ 10^3 K – 10 K
- $\rho \sim 10^{-9}$ g cm^{-3} (mid-plane, 1 AU)
- 1% by mass solids, 99% gas (mainly H, He)



Protoplanetary disk of TW Hya imaged with Hubble Space Telescope

Physical regimes



What are the dominant forces?

F_{drag} = const x s^2
m = $(4/3)\pi s^3$

aerodynamics – radial drift, coupling to turbulence, collision velocities… most important for *small* particles

Often particles are *smaller* than mean free path λ (λ ~ cm-m)

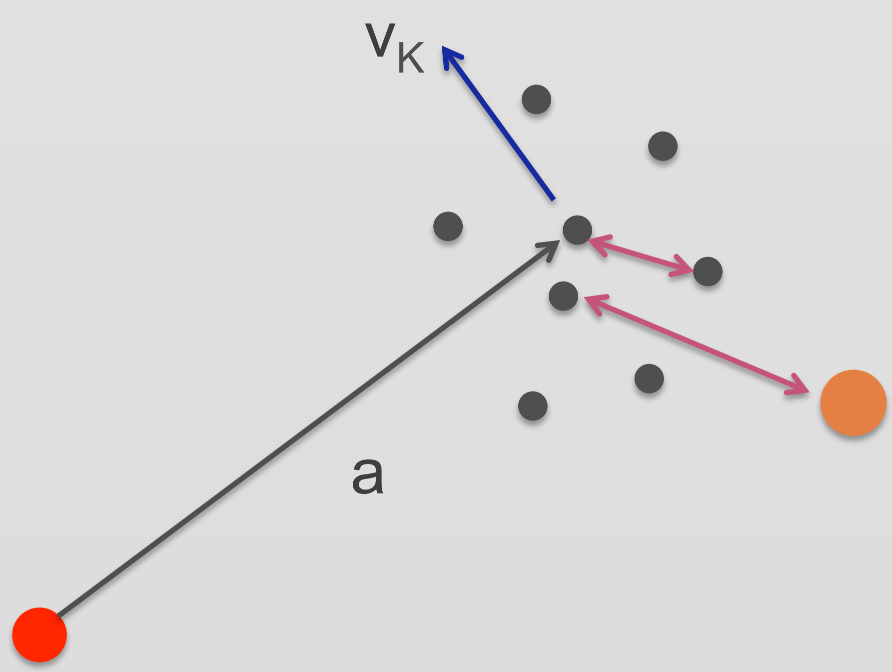
"Epstein drag" – F_{drag} = const x s^2 x Δv

Stopping time

$$t_{\rm s} = \frac{m\Delta v}{|F_{\rm drag}|}$$

$$\tau = t_{\rm s}\Omega$$

Physical regimes



What are the dominant forces?

Keplerian motion + small perturbations σ

$$e \sim i \sim \sigma / v_K$$

↑ velocity dispersion

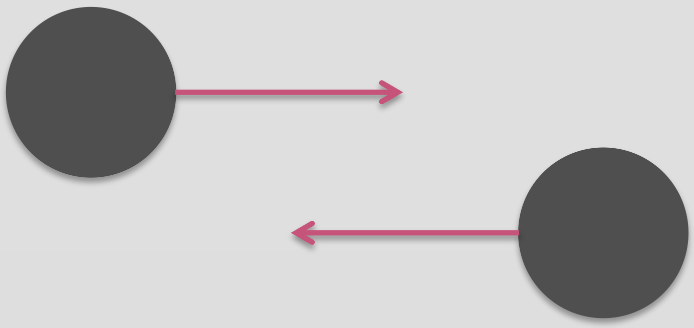
Larger bodies "planetesimals"

- planetesimal-planetesimal gravity ("viscous strirring")
- protoplanet-planetesimal gravity ("dynamical friction")

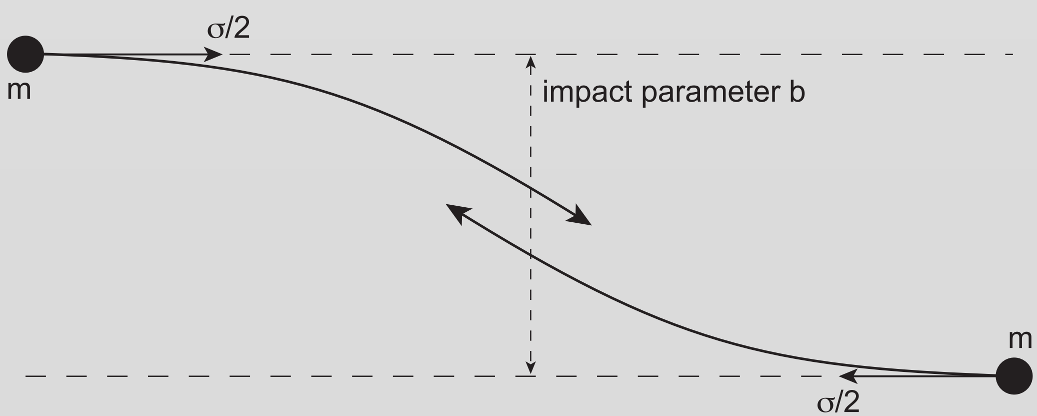
Gravity dominated dynamics for s > km

Collision rates

Physical regimes



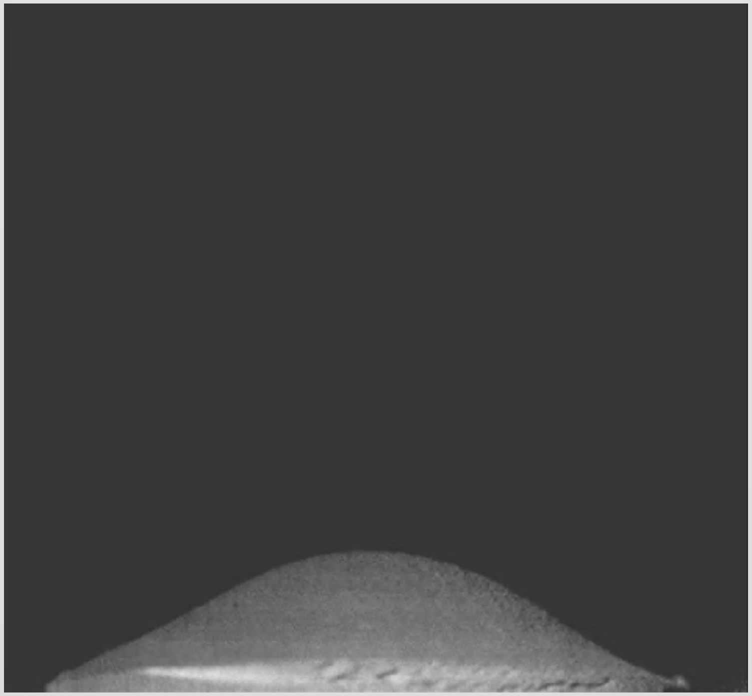
Small particles, bodies with $\sigma > v_{esc}$ – **physical** cross-section



$$\Gamma = \pi s^2 \left(1 + \frac{v_{\rm esc}^2}{\sigma^2}\right)$$

"Cold" disk of bodies, enhancement from gravitational focusing

Physical regimes

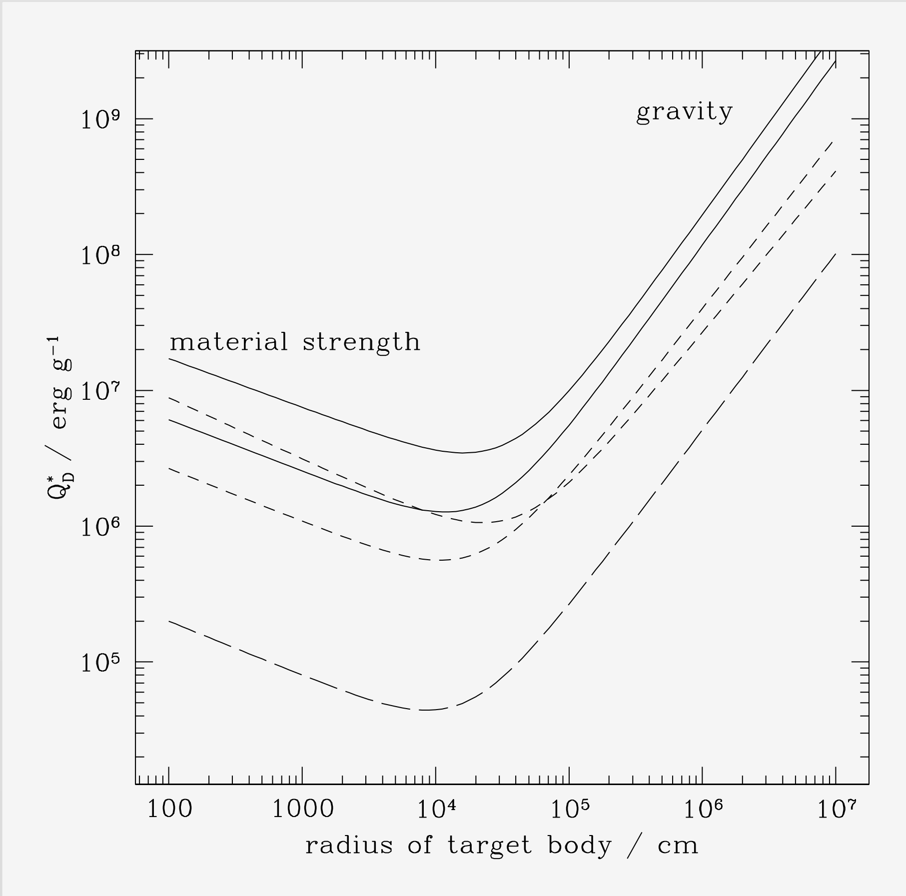


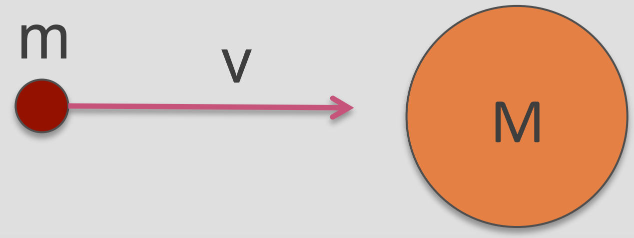
sub-micron – meters… collision outcome determined by collision velocity, **material properties**, ratio of particle sizes

Blum / Wurm group

- collisions at v appropriate to micron-mm sizes generally lead to mass growth
- many / most / almost all collisions at v for > mm sizes lead to erosion ("bouncing barrier")

Physical regimes





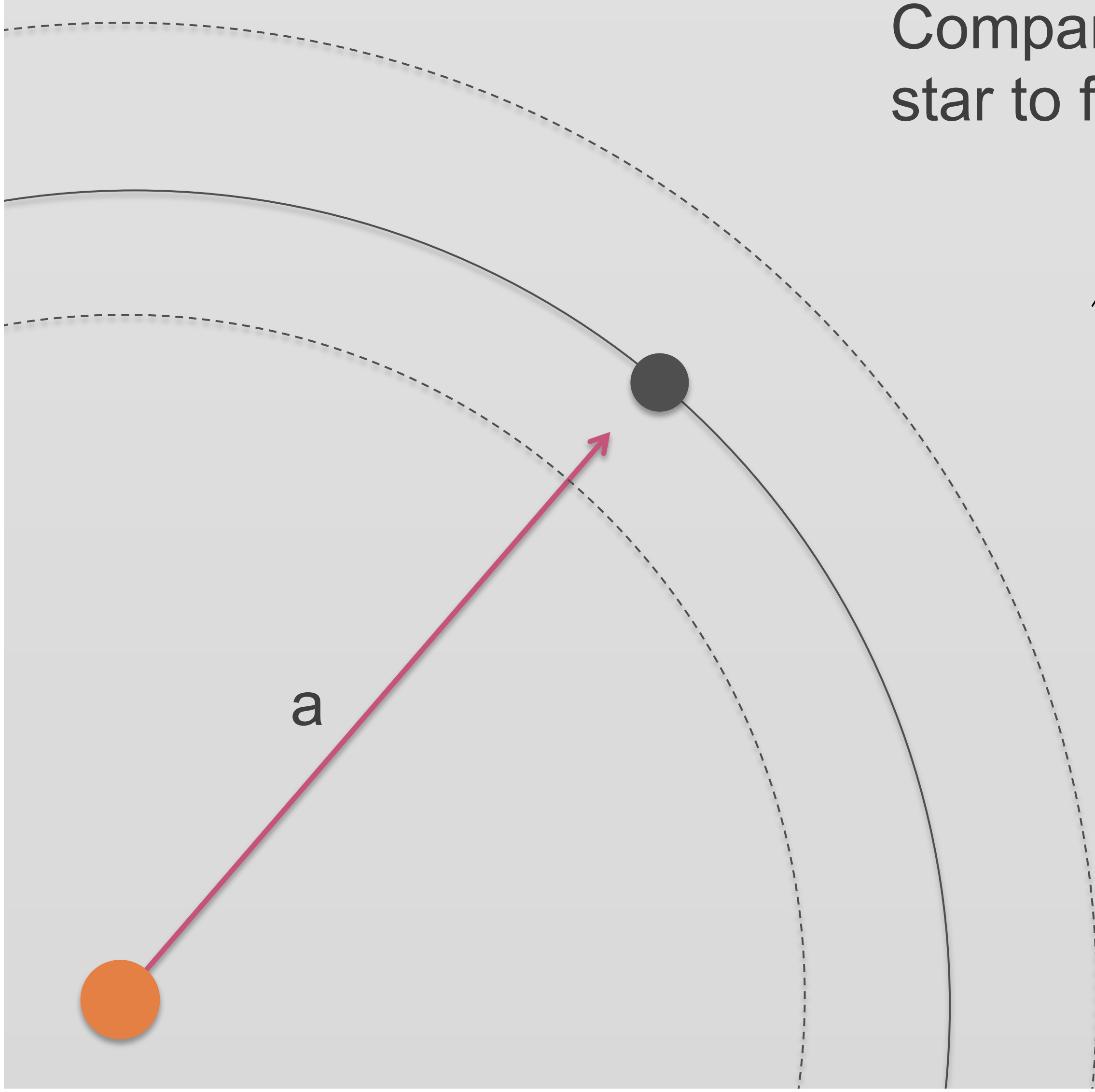
$$Q = \frac{mv^2}{2M}$$

Small bodies (up to ~100m) – material strength
Large bodies – gravity

Gravity dominated: if $\sigma << v_{esc}$ free energy small, even if collision fragments target pieces will (mostly) re-accumulate

Dynamical considerations

Physical regimes



Compare orbital frequency about star to frequency about planet

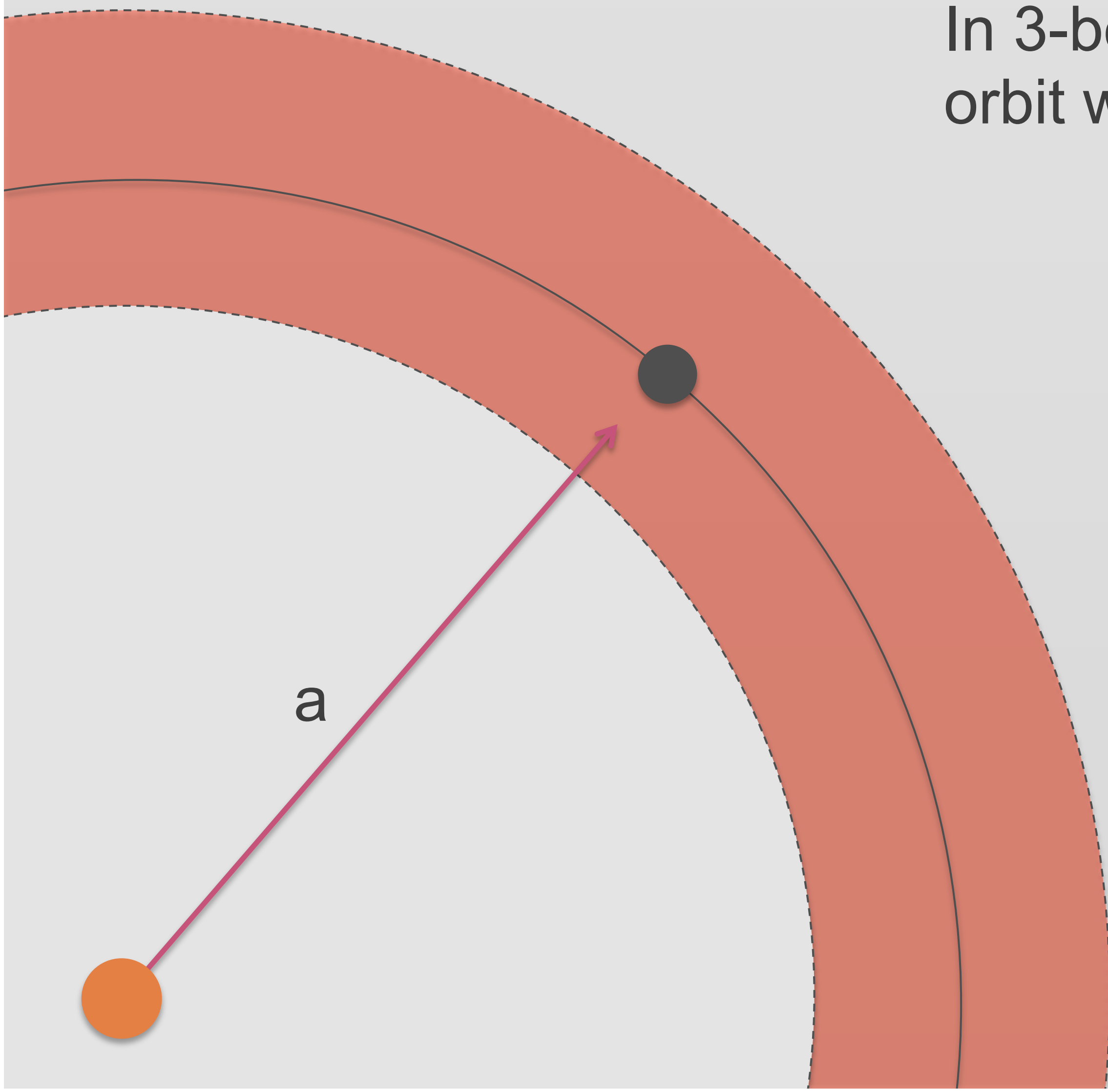
$$\sqrt{\frac{GM_*}{a^3}} = \sqrt{\frac{GM_p}{r^3}}$$

“Hill sphere” – where planet’s influence dominates over star

$$r_{\rm Hill} = \left(\frac{M_p}{3M_*}\right)^{1/3} a$$

Physical regimes

"Feeding zone"



In 3-body problem, bodies that orbit within:

$$\Delta a \simeq C r_{\rm Hill}$$

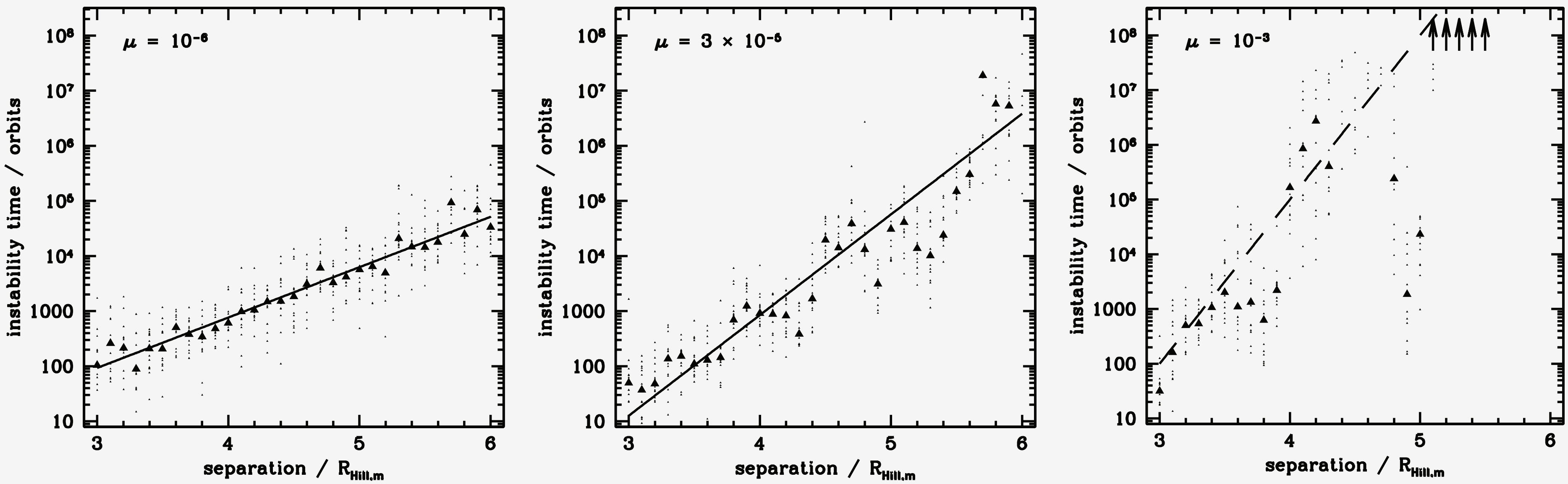
…typically unstable – either collide with the planet or be scattered

Collision probability depends on:

$$\frac{v_K}{v_{\rm esc}}$$

Dynamical considerations

Physical regimes



For systems with more that 3 bodies (Sun + 3 or more planets)

Instability time scale (time till orbits cross) strong function of planetary separation measured in units of Hill radii (with some additional mass dependence)

Solar System

Can we understand aspects of the Solar System based on these simple physical ideas?

Assume that we form a population of planetesimals that are aerodynamically decoupled from gas -

- sizes km – 100 km
- across broad range of orbital radii
- with smooth distribution

$$\Sigma_p \propto r^{-p}$$

e.g. p ~ 1-1.5

Solar System

Inner Solar System – ratio of v_{esc} / v_K relatively small for planets up to ~Earth mass

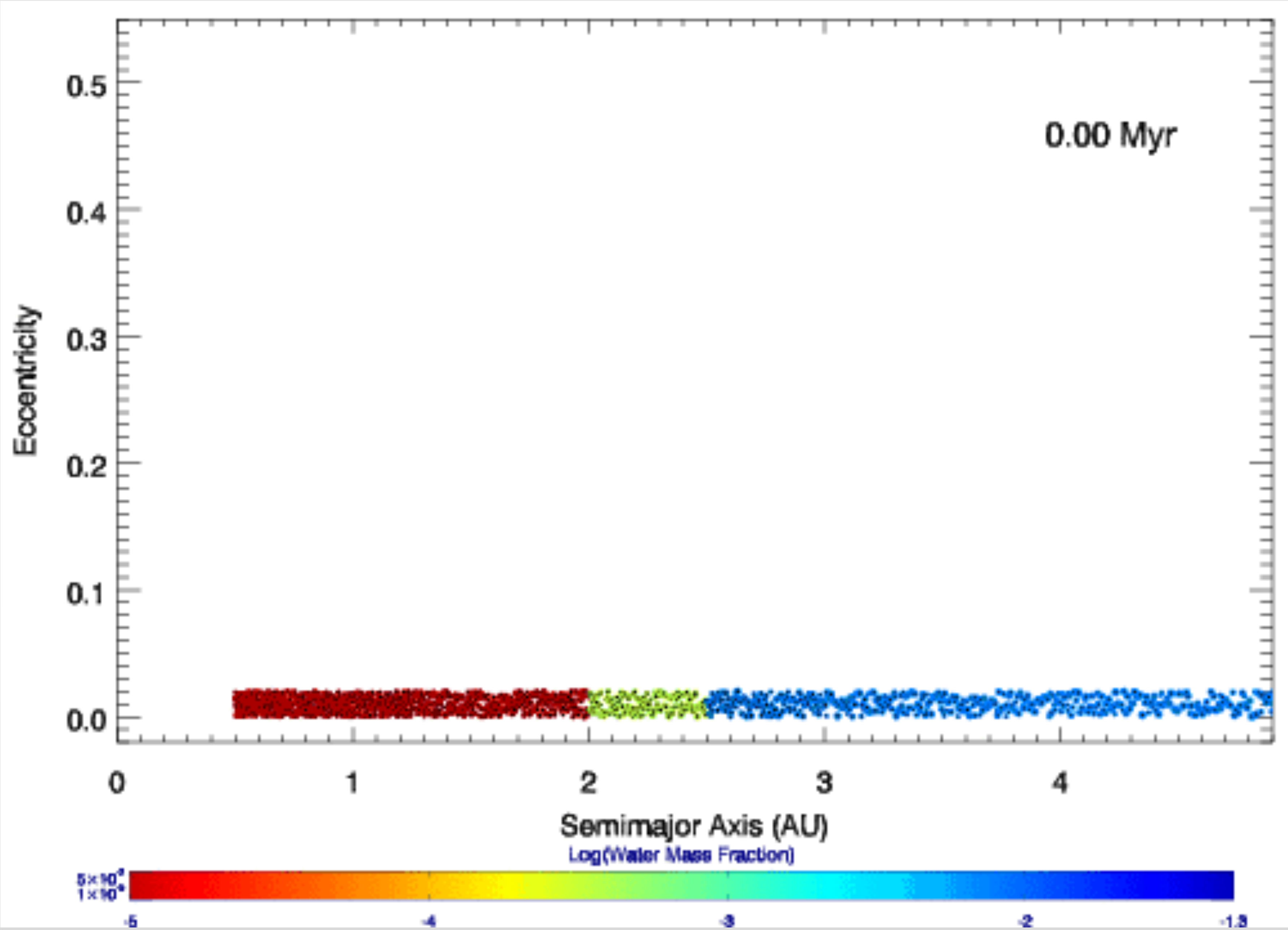
Physical collisions dominate over scattering

→ planets grow "in place" from whatever reservoir of planetesimals is available

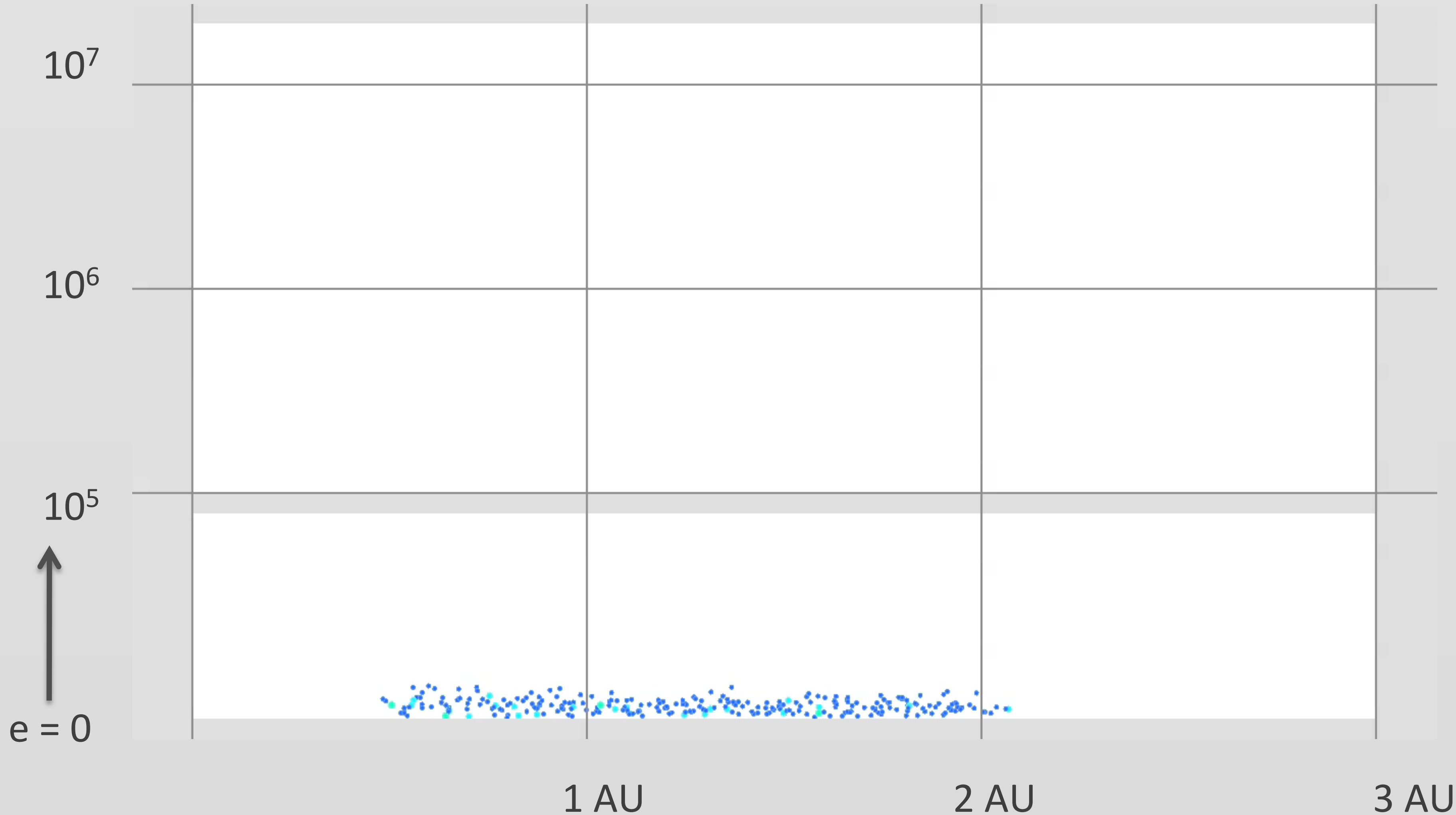
$$r_{\rm Hill} = \left(\frac{M_p}{3M_*} \right)^{1/3} a$$

Hill sphere is **weak** f(M_p) – system becomes more stable as protoplanets collide (separation in units of r_{Hill} increases)

Expect final planet masses ~set by requirement that system is "effectively" stable



Simulation: Sean Raymond



3 M_{earth} of protoplanets between 0.5 – 2 AU, gravity only, for Solar System – not bad at leading order!

Solar System

Jupiter & Saturn – mass within "feeding" zone increases with radius:

- because $\Delta a \sim a$ and $\Sigma_p \sim r^{-1.5}$ or r^{-1}
- because outside the snow line (~2.7 AU) ice + rocky materials vs. rocky only inside

→ growth to ~5 M_{earth} *within lifetime of gas disk* (few Myr), massive enough to maintain gas envelope

Core + envelope – hydrostatic equilibrium possible only while $M_{env} < M_{core}$, once exceeded get rapid accretion

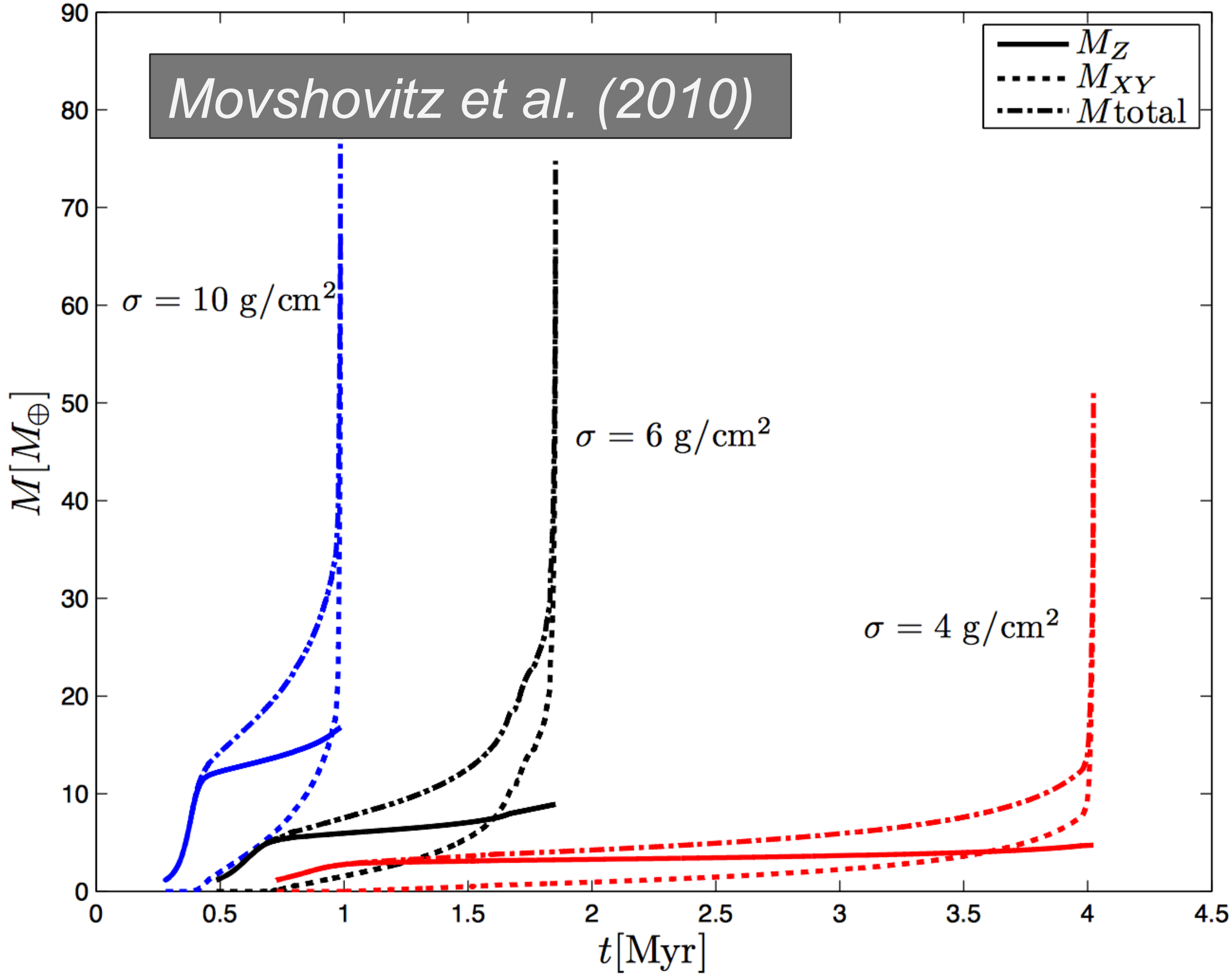


Figure 1: Mass of the protoplanet as a function of time for three cases that include grain settling and coagulation. The solid lines denote the mass of the core, the dotted lines the mass of the H/He envelope, and the dot-dashed lines the total mass. All cases plotted include convection in the grain calculations. The assumed solid surface density σ is indicated for each set of curves.

Solar System

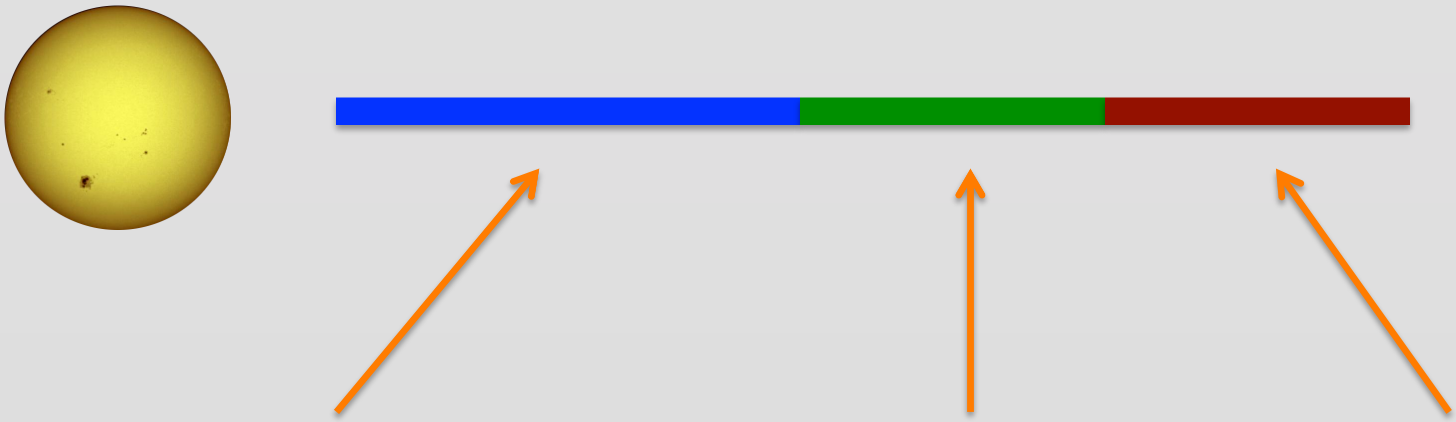
At still large radii… v_{esc} / v_K for a ~Earth mass core is relatively larger

→ **scattering dominates over accretion**

+ long dynamical times

Cannot grow large planets that would accrete envelopes
Incomplete planet formation – disk of smaller bodies persists (Kuiper Belt)

Planet formation expectations



- small feeding zone
- mass stays in place
- fast growth to ~Mars
- slow growth to Earth
- no gas capture
  - terrestrial planets

- large mass in feeding zone
- fast growth to ~5-10 Earth mass
- capture gas
  - giant planets

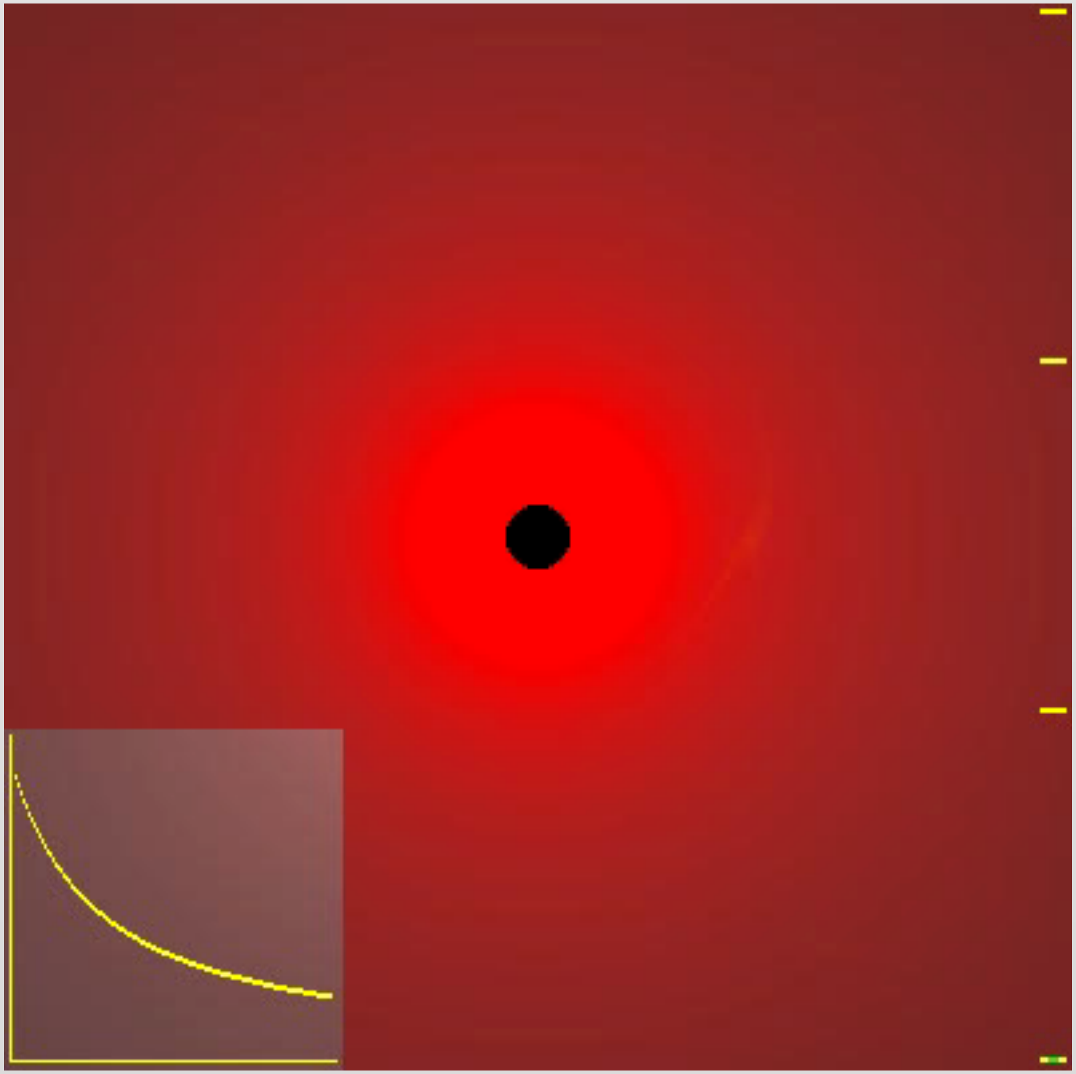
- can't grow large
- debris disks

Exoplanets

Many qualitative differences w.r.t. Solar System

- eccentric orbits (giant planets, RV)
- hot Jupiters (giant planets, RV)
- inclined w.r.t. stellar spin axis
- “super-Earths” / “mini-Neptunes”
- close-in *Kepler* systems
- ….

No fully agreed explanation for the origin of these differences

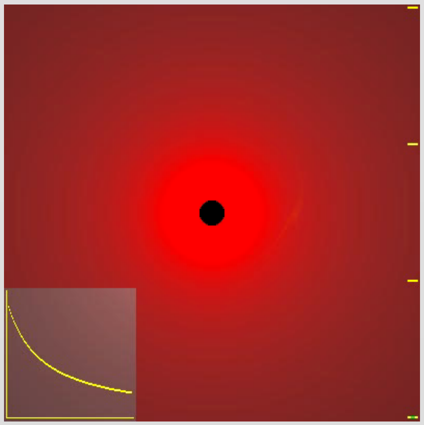


Exoplanets

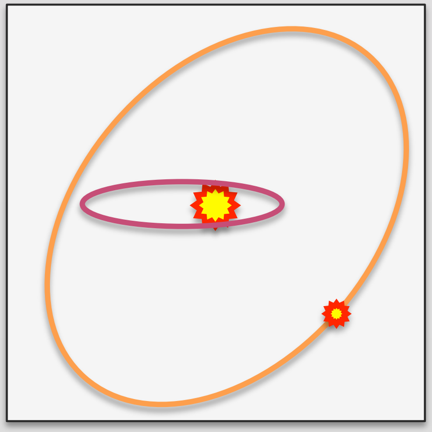
Exchange of energy / angular momentum with gas disk via gravitational torques

Predicted to lead to **orbital migration** of any > Earth mass planet orbiting within a gas disk

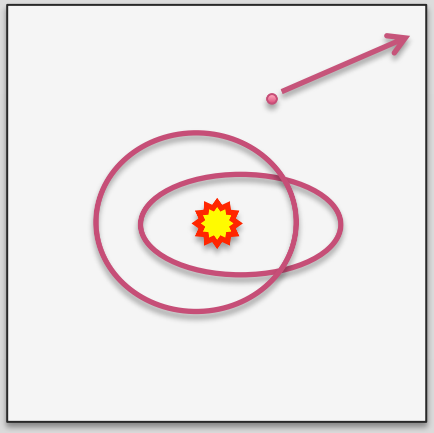
Gas disk interaction: shrink a at (probably) low e
Dynamical interactions: alter a, e and i



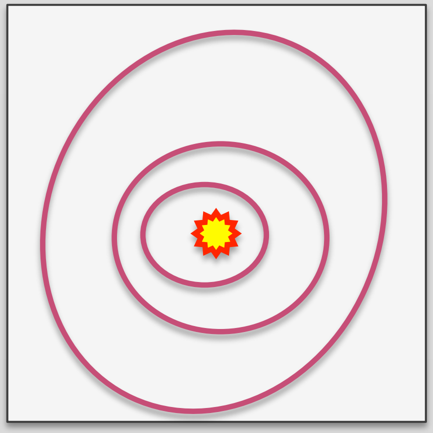
Planet-gas disk interaction



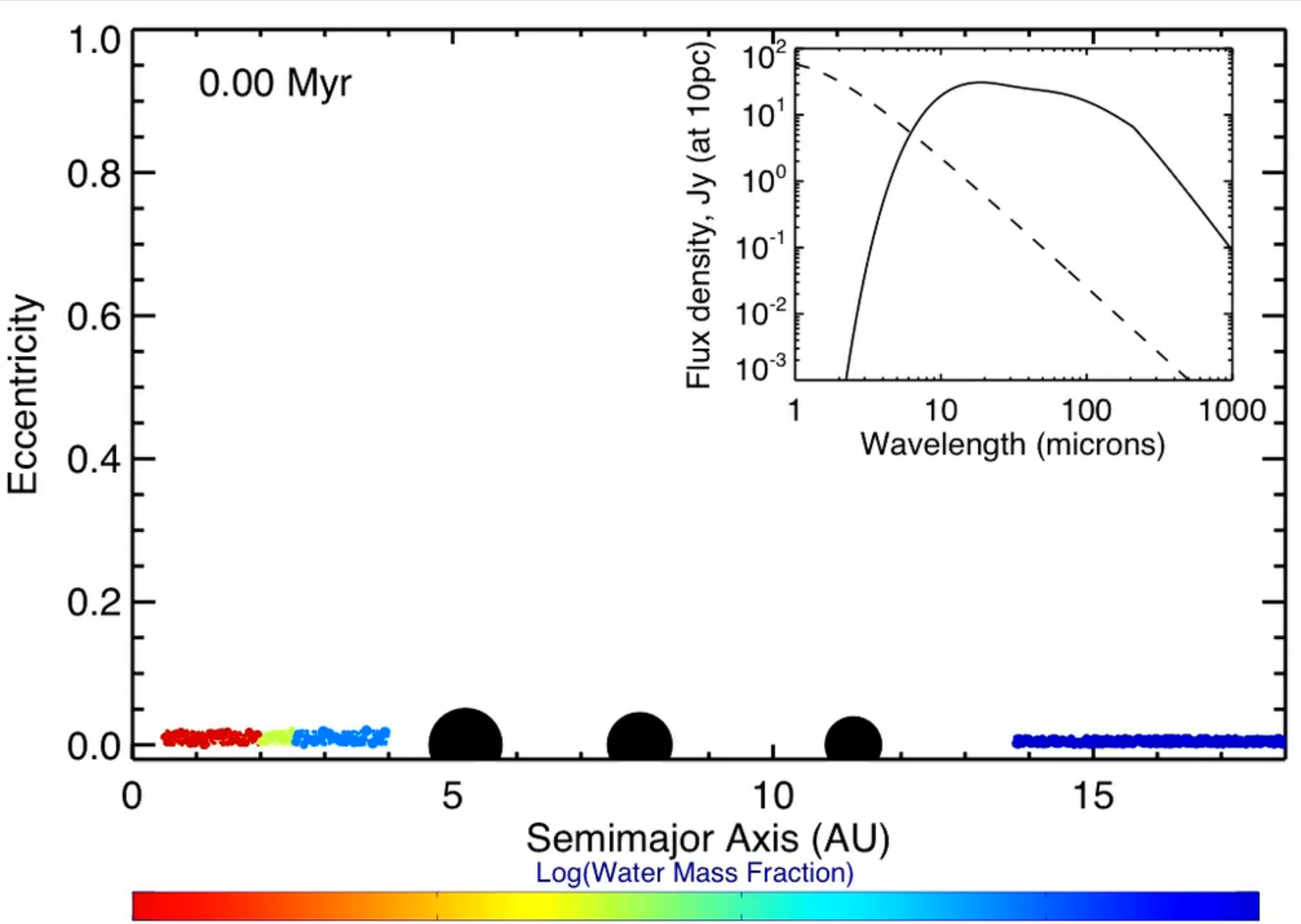
Kozai-Lidov interaction (planet + misaligned binary)



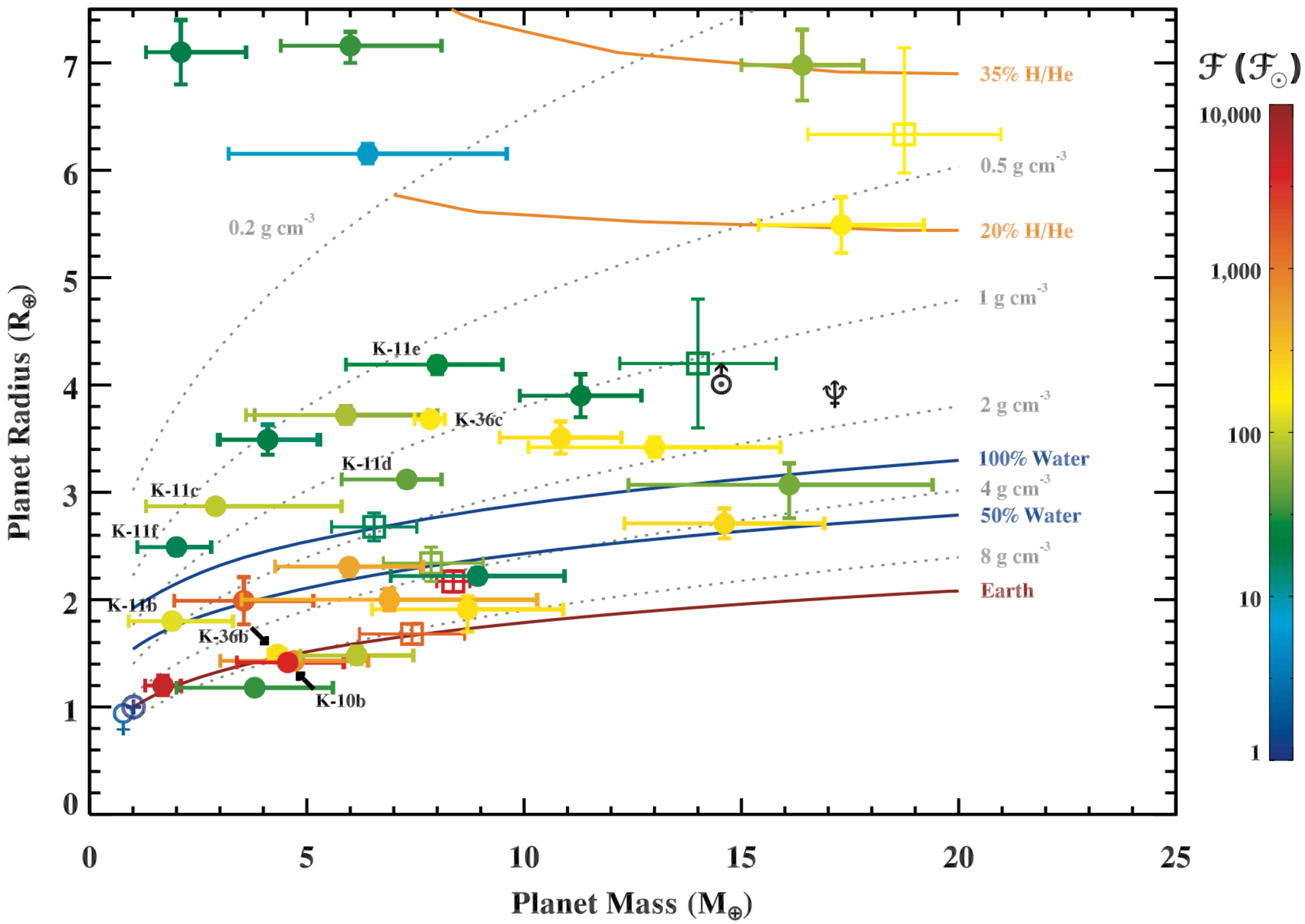
Planet-planet scattering



Secular chaos



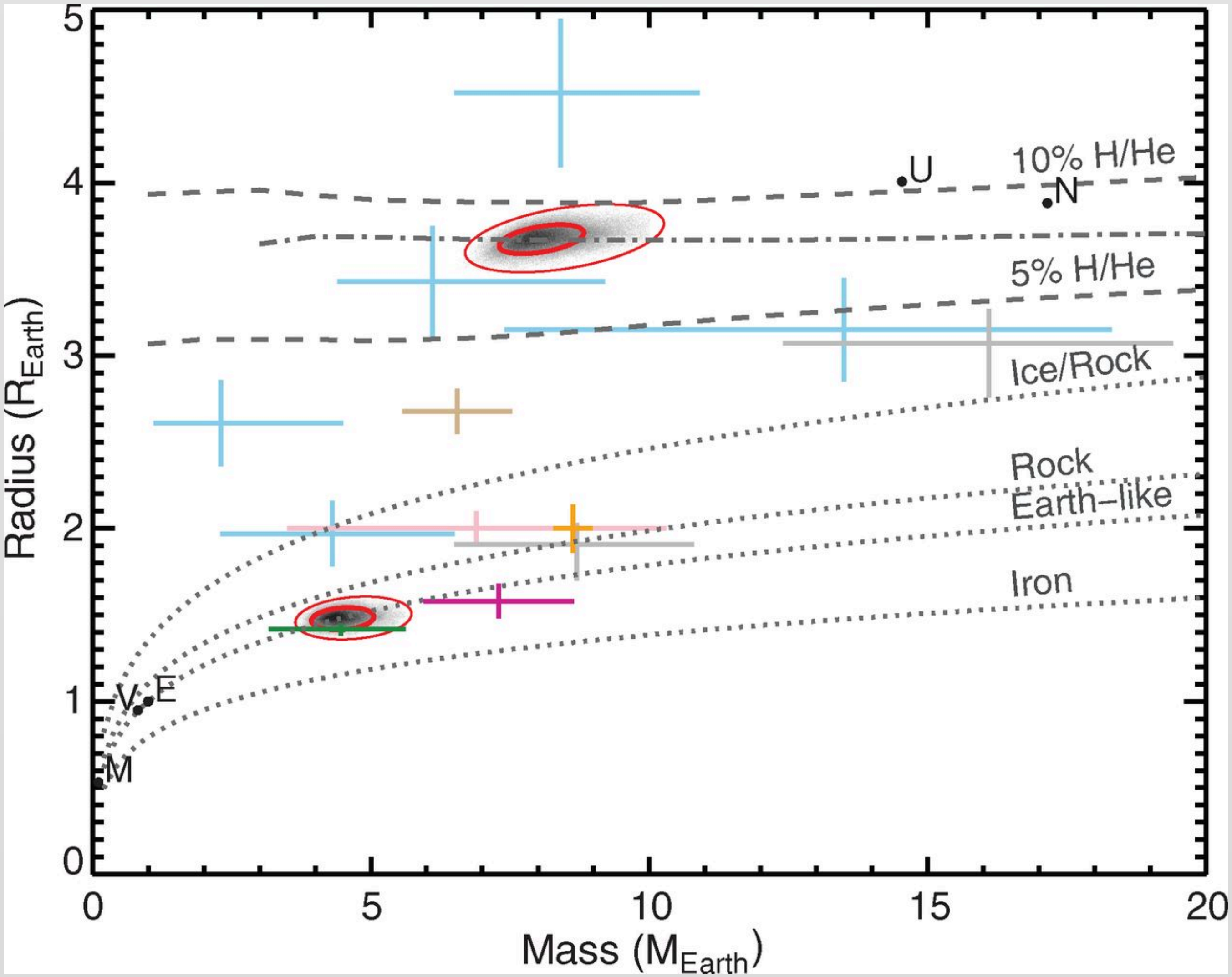
Raymond, Armitage et al. ‘11, ‘12



Lower masses…

Lissauer et al. '14

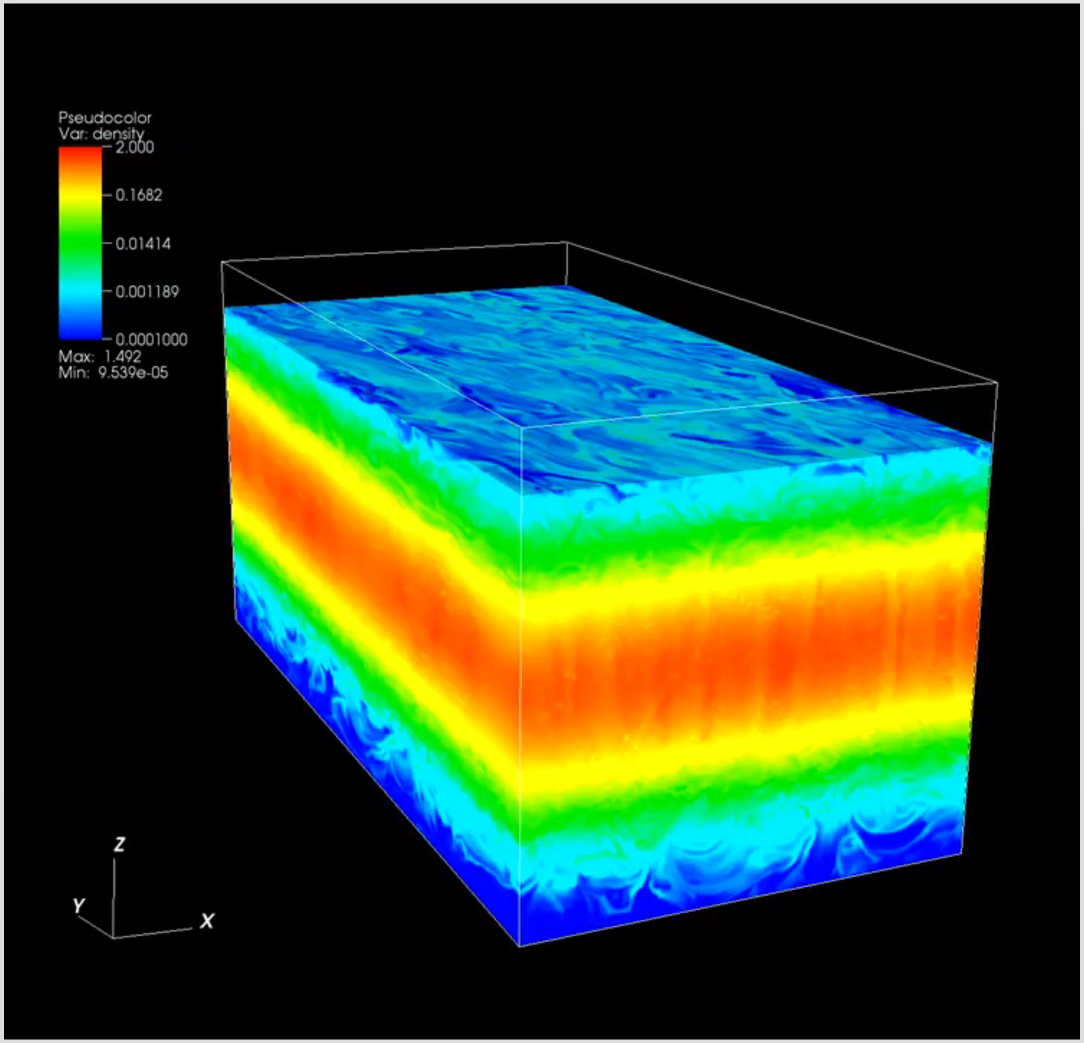
- diverse range of densities (compositions)
- high abundance of planets with no Solar System analogs
- both dynamical and compositional puzzles…



Predicted mass-radius relation and Kepler 36 data *(Carter et al. 2012)*

Open questions

What is the origin and nature of turbulence and angular momentum transport in the gas phase?



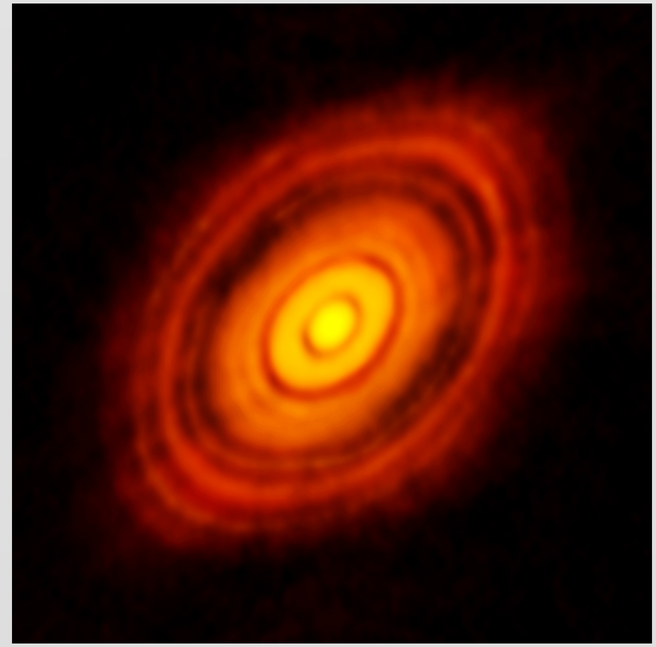
- role of low ionization on MHD processes
- hydrodynamic instabilities and winds
- impact on particle growth, planet migration…

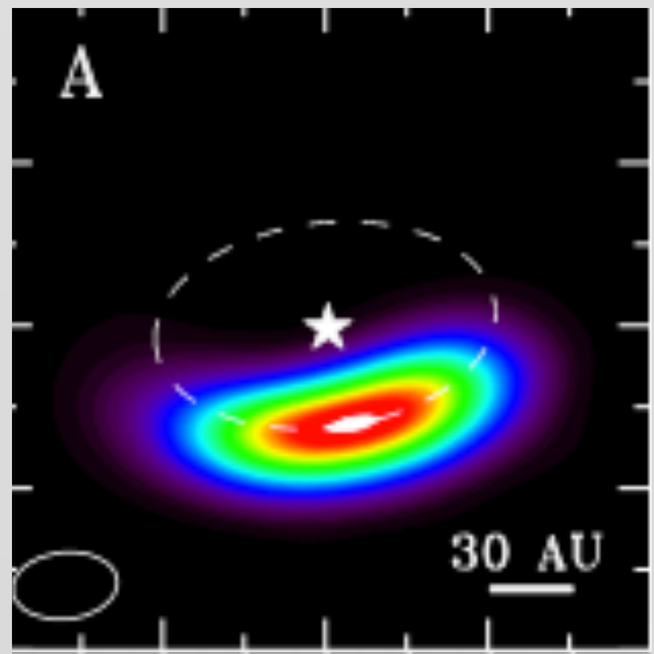
Open questions

Origin of large-scale structure in protoplanetary disks

- rings (HL Tau)
- "vortex-like" structures (IRS 48; *van der Marel et al. '13*)
- scattered light structures…

Particles in aerodynamic regime; **causes** or **consequences** of planet formation

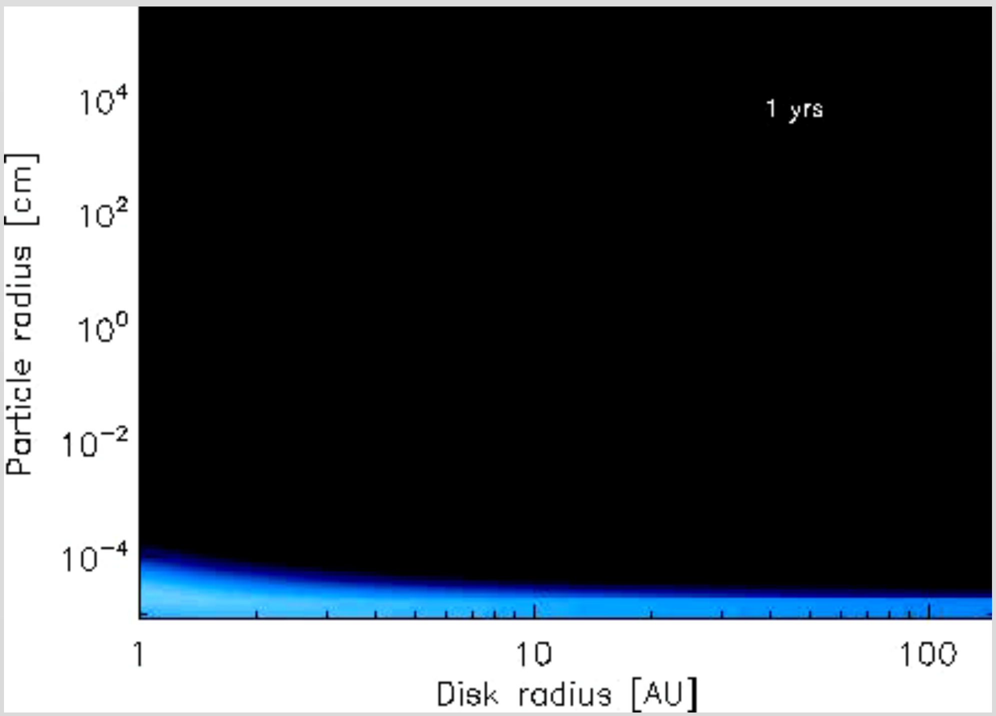




Open questions

How do we form planetesimals from aerodynamically well-coupled small solids?

What is the resulting distribution of planetesimals?

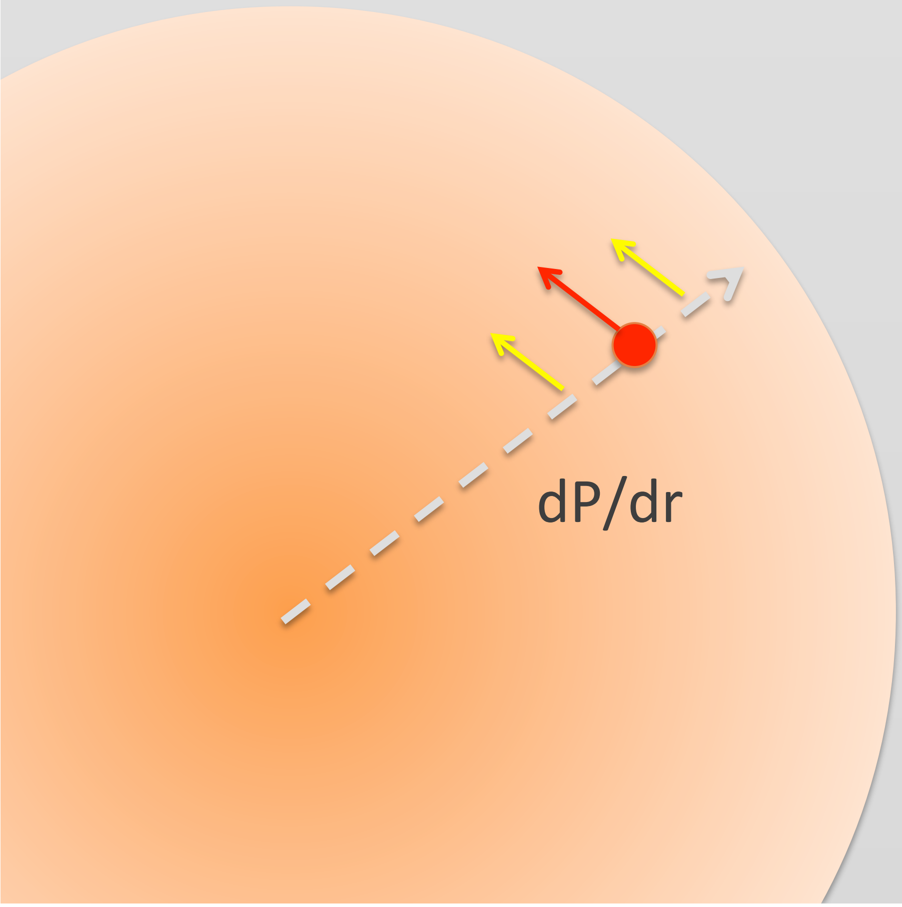


1) Do **material properties** admit growth past mm or cm scales? (Always, never, near ice lines?)

Brauer et al. '08

Open questions

2) Particles with significant aerodynamic coupling to gas disk are predicted to spiral inward, rapidly for s ~ 10cm-m at 1 AU

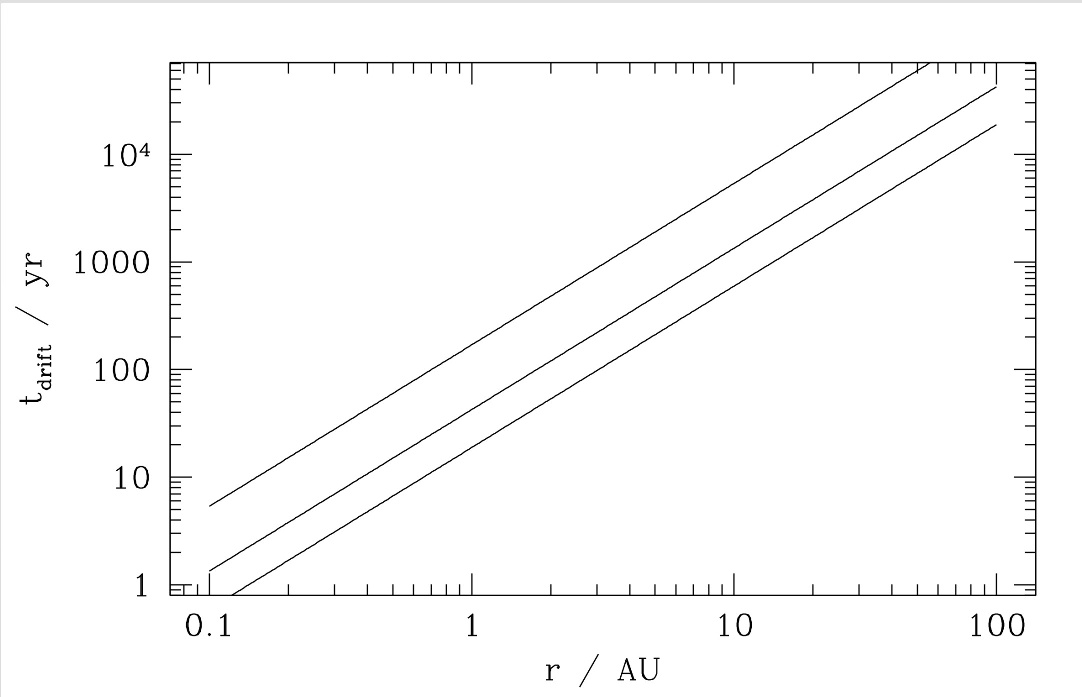


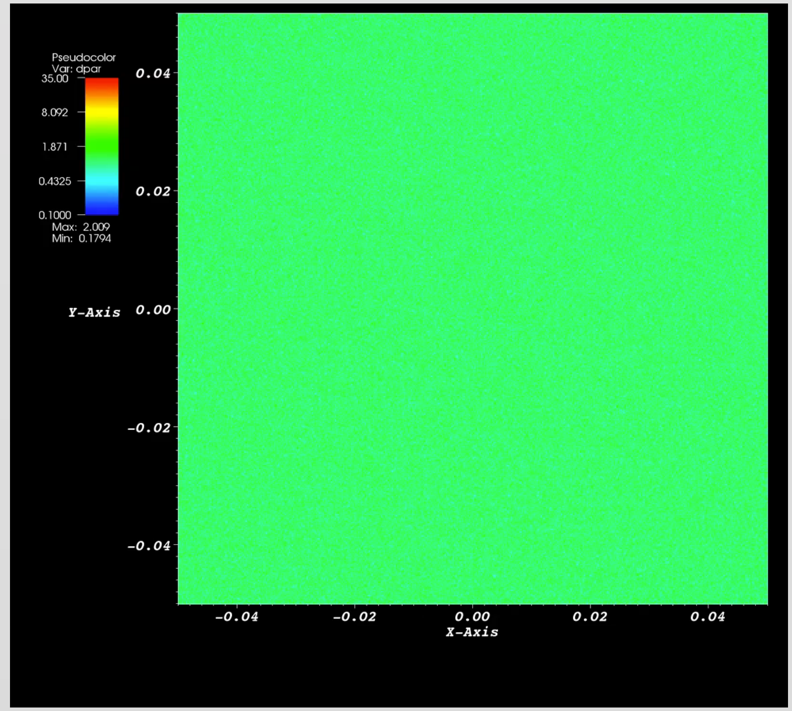
Large solid body orbits at the Keplerian orbital speed:

$$v_K = \sqrt{GM_*/a}$$

Gas at same distance is partially supported against gravity by radial pressure gradient, orbits slightly slower – $O(h/r)^2$

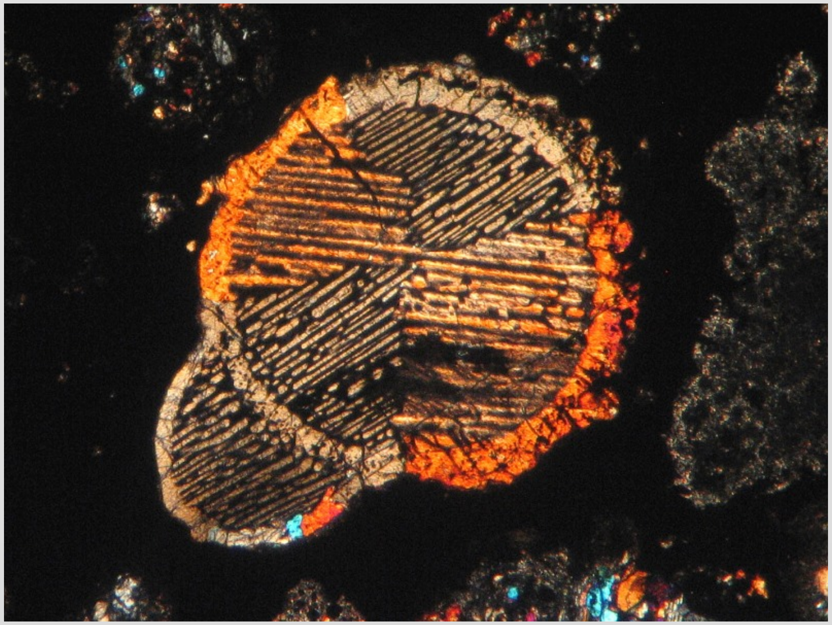
Open questions





Is the solution to these problems *streaming instability* (linear instability of coupled gas and dust mixtures), and if so what are the consequences? *(Youdin & Goodman '05; Johansen et al. '11)*

Open questions



Essentially none of the direct evidence from the Solar System (chondrules, CAIs, Stardust samples…) matches simplest expectations from disk models

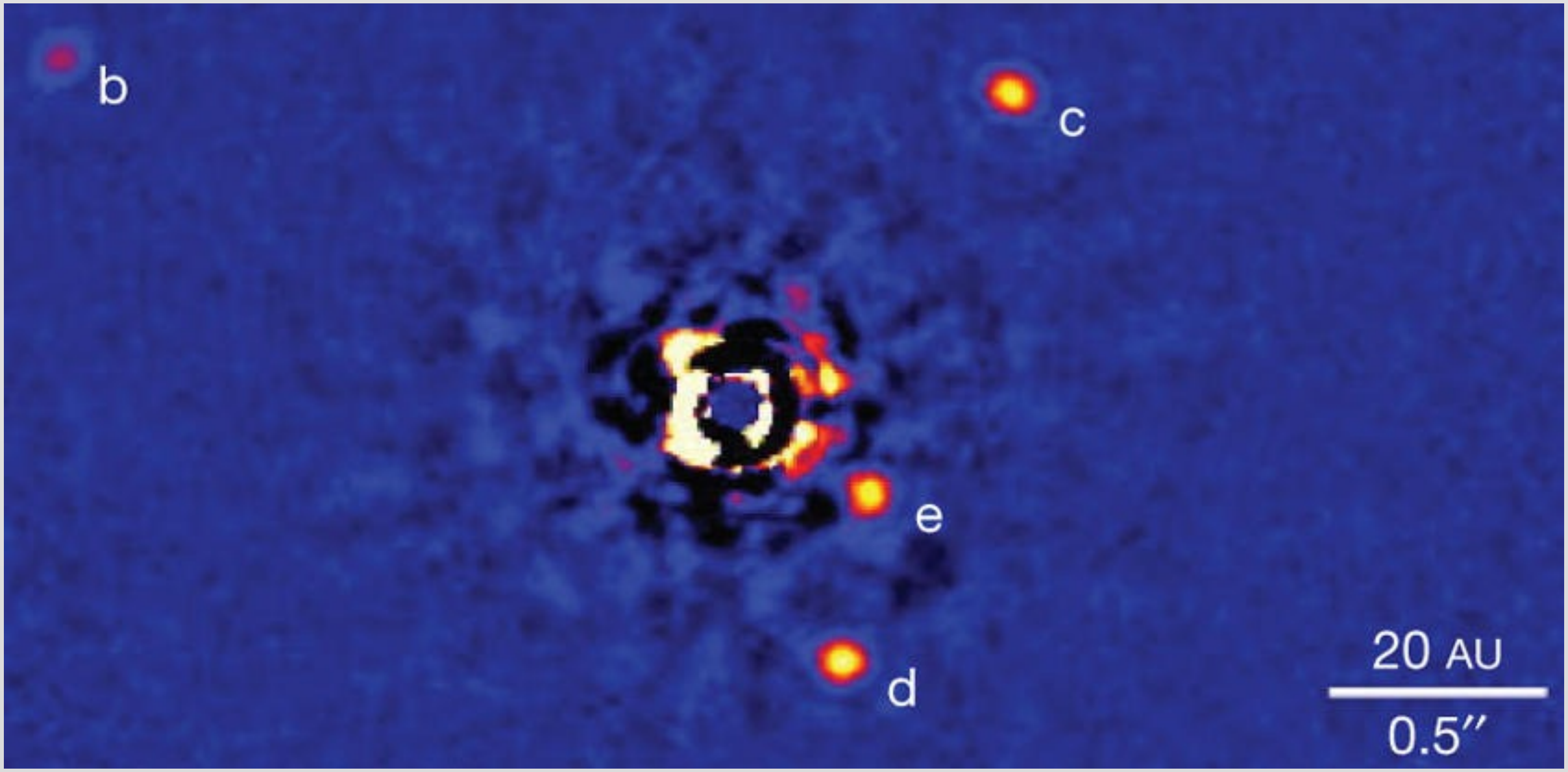
…what is going on?

Open questions

What is the size distribution during later phases of planetary growth?

- traditional idea: mostly planetesimals (10^2 m – 100 km) and larger protoplanets
- growth is different if substantial mass remains in aerodynamically coupled sizes (cm-m) – “pebbles”

Open questions



Almost all known massive planets could form via core accretion, but a few at very large radii (HR 8799) pose major challenges (different mechanisms, unlikely events?)