

# ASTR 405

## Planetary Systems

### Planet Formation Overview

Fall 2025

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Supplementary Readings: **formation.pdf** on Canvas

*Lecture Notes on the Formation and Early Evolution of Planetary Systems* by Armitage

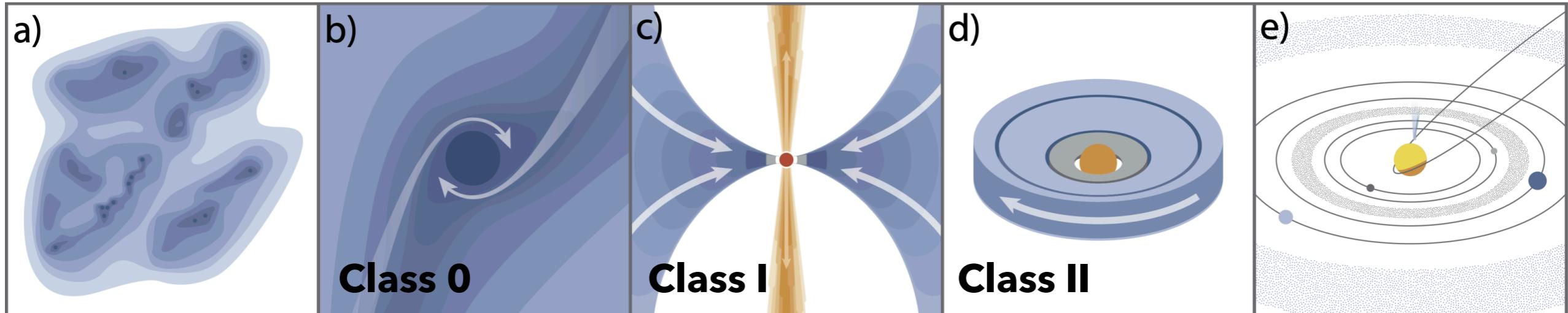
# Modules

- Part I: Exoplanet Detection Methods
  - Explore the techniques astronomers use to discover planets beyond our solar system
- **Part II: Exoplanet Demographics and Planet Formation**
  - **Investigate the statistical properties of exoplanets and theories of how planetary systems form**
- Part III: Exoplanet Atmospheres, Interiors, and Characterization
  - Examine methods for studying the physical properties and compositions of distant worlds

# Module II: Exoplanet Demographics and Planet Formation

- **Protoplanetary Disks:** Gas-dust disks around young stars; evolve on Myr timescales, set the initial conditions for planet formation
- **Dust, Pebbles, and Planetesimals:** Dust grains stick → pebbles (mm-cm); rapid drift & instabilities lead to km-scale planetesimals
- **Planet Formation: Terrestrial and Giant Planets**
  - Terrestrials: runaway/oligarchic growth → embryos → giant impacts
  - Giants:  $\sim 10 M_{\oplus}$  cores accrete gas before disk dispersal or via disk instability
- **Evolution of Planetary Systems:** Migration, resonances, and instabilities sculpt exoplanet architectures

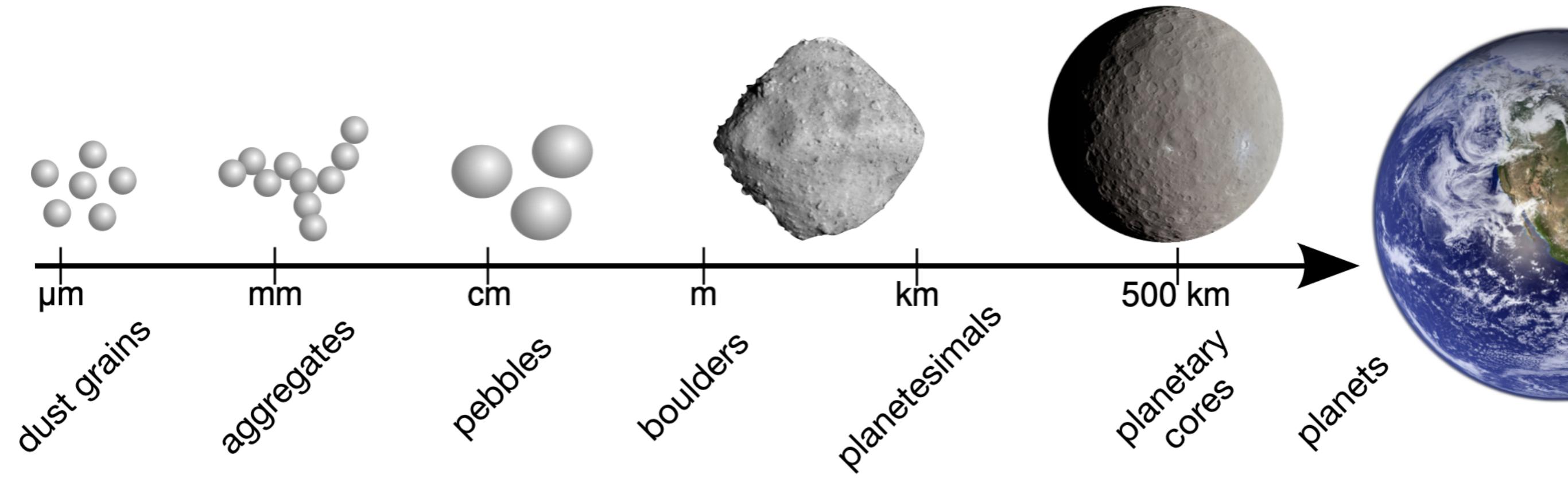
# Formation of the Solar System



Oberg & Bergin 2021, <https://arxiv.org/pdf/2010.03529>

- a) Stars form in dense cores in interstellar molecular clouds.
- b) Star formation begins when such a dense core begins to collapse due to self-gravity.
- c) As the collapse proceeds the center heats up forming a protostar. Accretion of remnant cloud material continues, funneled through a disk, which is formed as a consequence of cloud angular momentum. This stage is also characterized by outflows of material.
- d) Following dispersal of the cloud remnant the now pre-main sequence star is left with a circumstellar disk, which is the formation sites of planets. The disk gas is dispersed through disk winds within ~2-5 Myrs, putting a halt to Gas Giant formation.
- e) Rocky and icy planets can continue to grow for another 100 Myrs at which time a mature planetary system exists.

# Phases of Planet Formation



Credit: J. Drazkowska

- Aerodynamic forces on solid particles orbiting within disk, surface physics
- Aerodynamic and gravitational forces
- Primarily gravitational forces between protoplanets (plus aerodynamically assisted accretion of small particles)
- Accretion of gaseous envelopes
- Post-formation evolution: "migration"

**microns-mm**

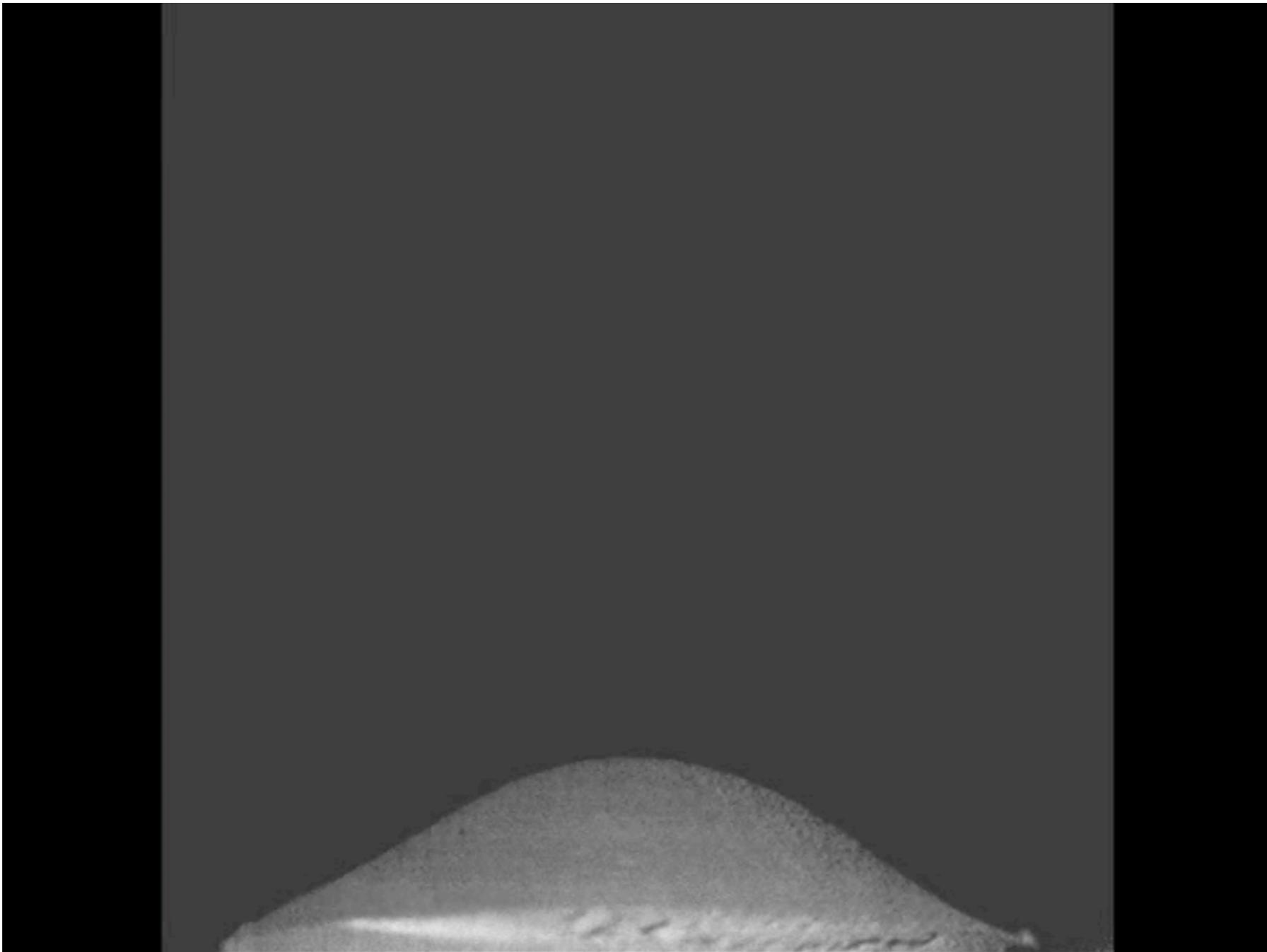
**km-100 km**

**100km – few 1000km**

**5-10 Earth masses**  
**all masses / sizes**

# Dust Coagulation

Credit: Blum & Wurm



Small solid particles colliding at  $\text{cm s}^{-1}$  speeds typically stick on impact

# Planetesimal Formation

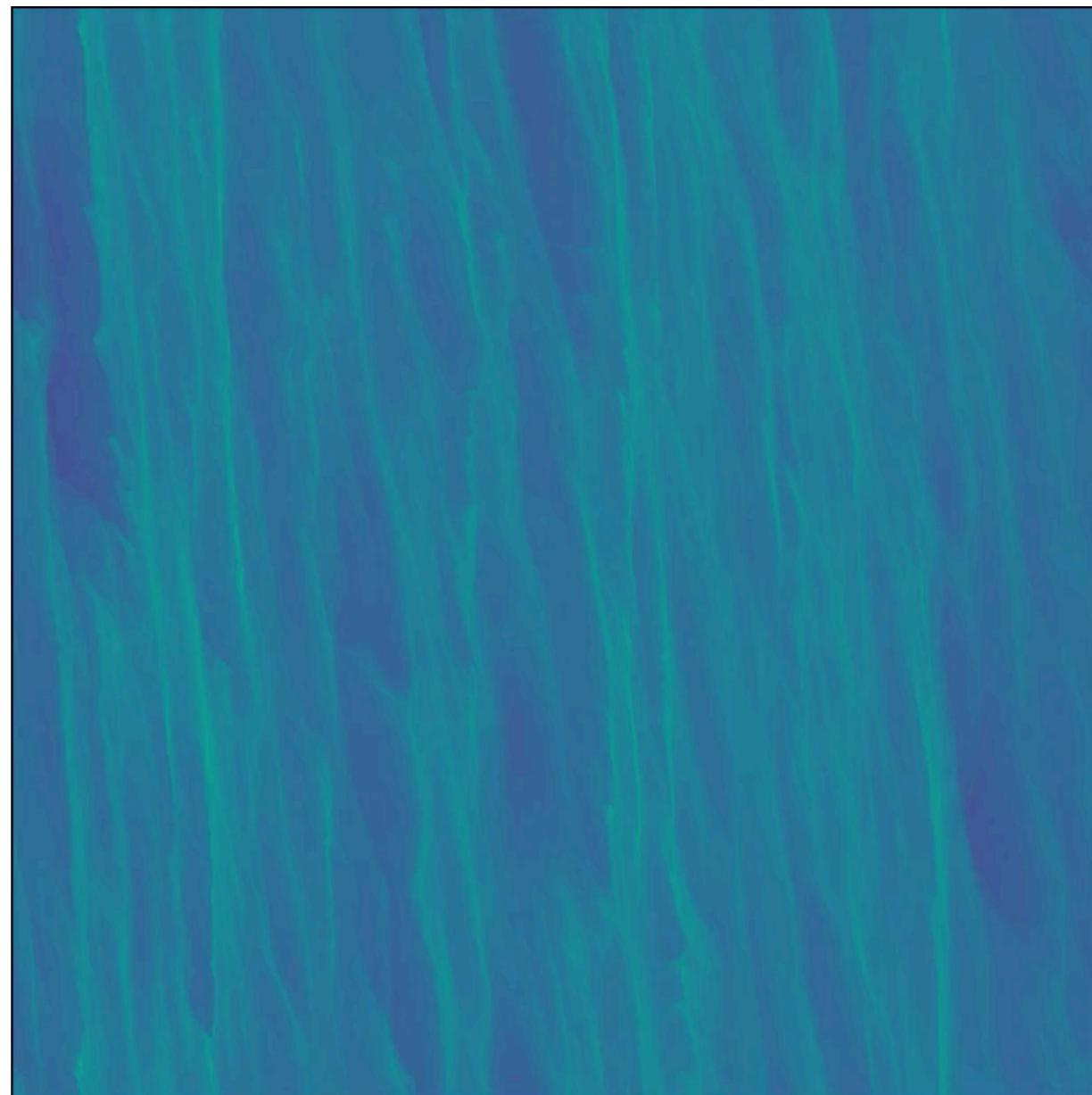
Planetesimals are 1-100 km scale bodies – gravity matters both for their strength and for the evolution of a population



Solar System example: *Arrokoth*  
probably unaltered since the formation of the Kuiper Belt

# Planetesimal Formation

Planetesimals are 1-100 km scale bodies – gravity matters both for their strength and for the evolution of a population

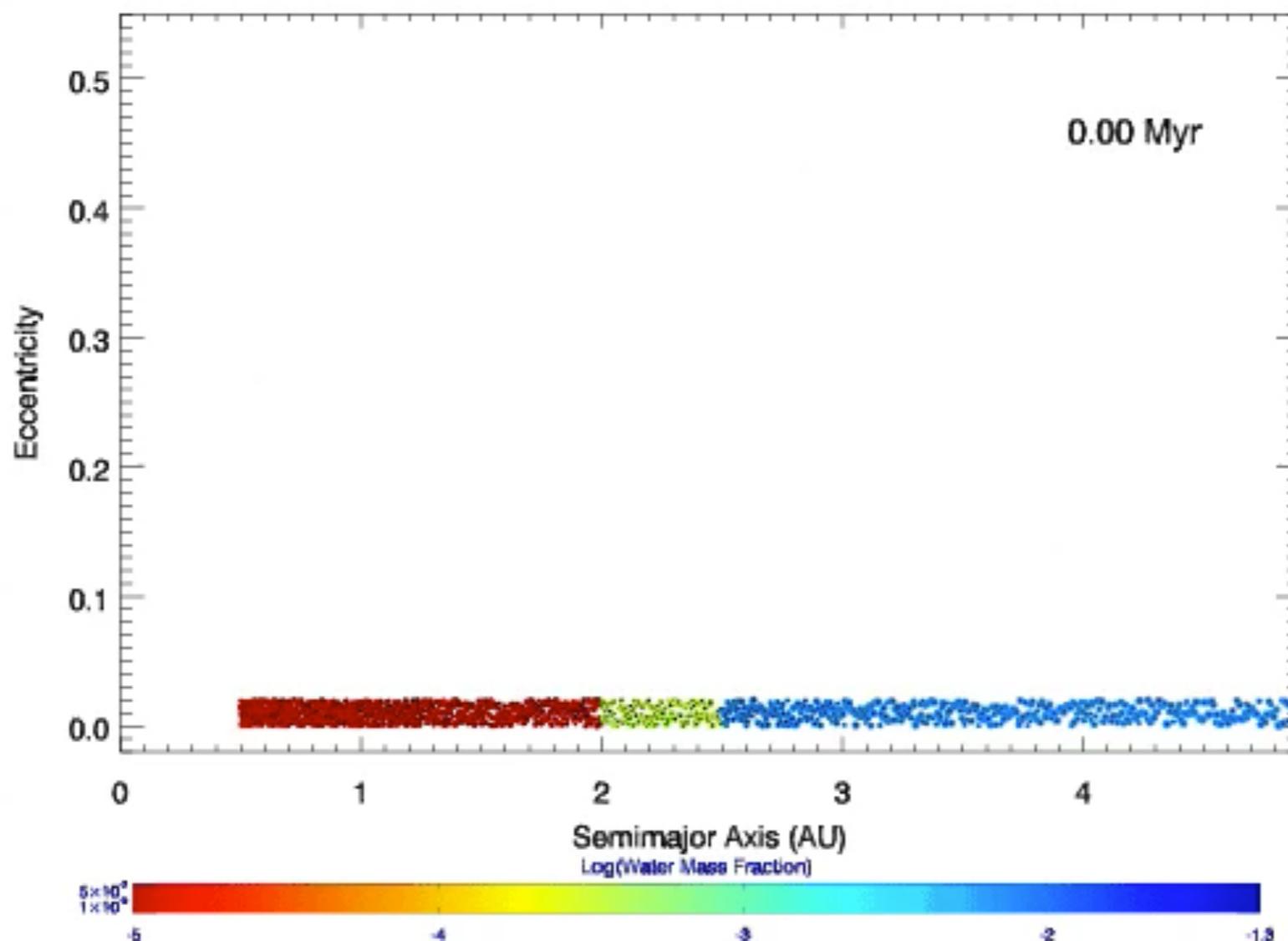


Streaming  
Instability

Credit: Rixin Li

# Terrestrial Planet Formation

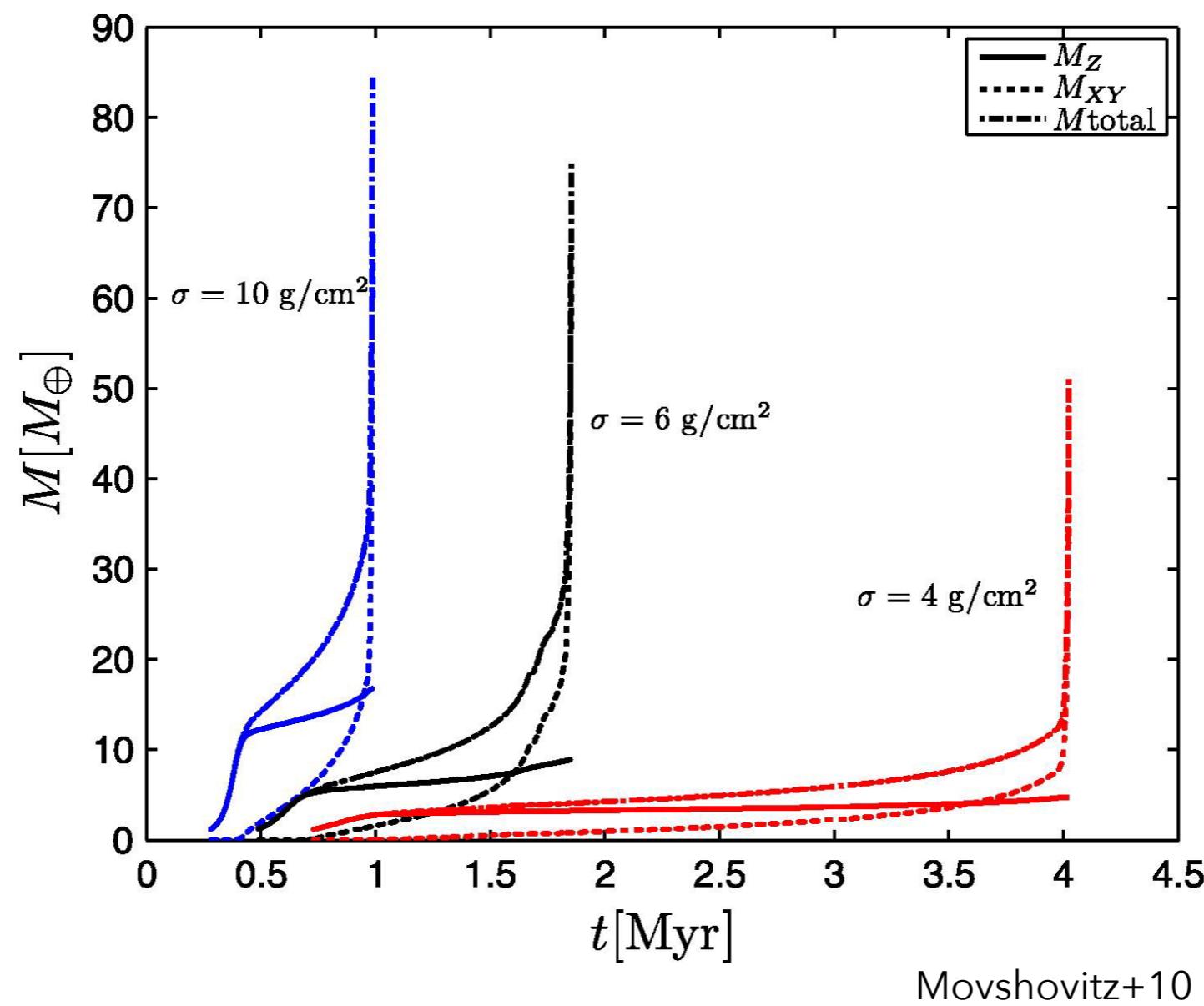
Escape velocity from protoplanets is small compared to orbital velocity → collisional growth



Credit: S. Raymond

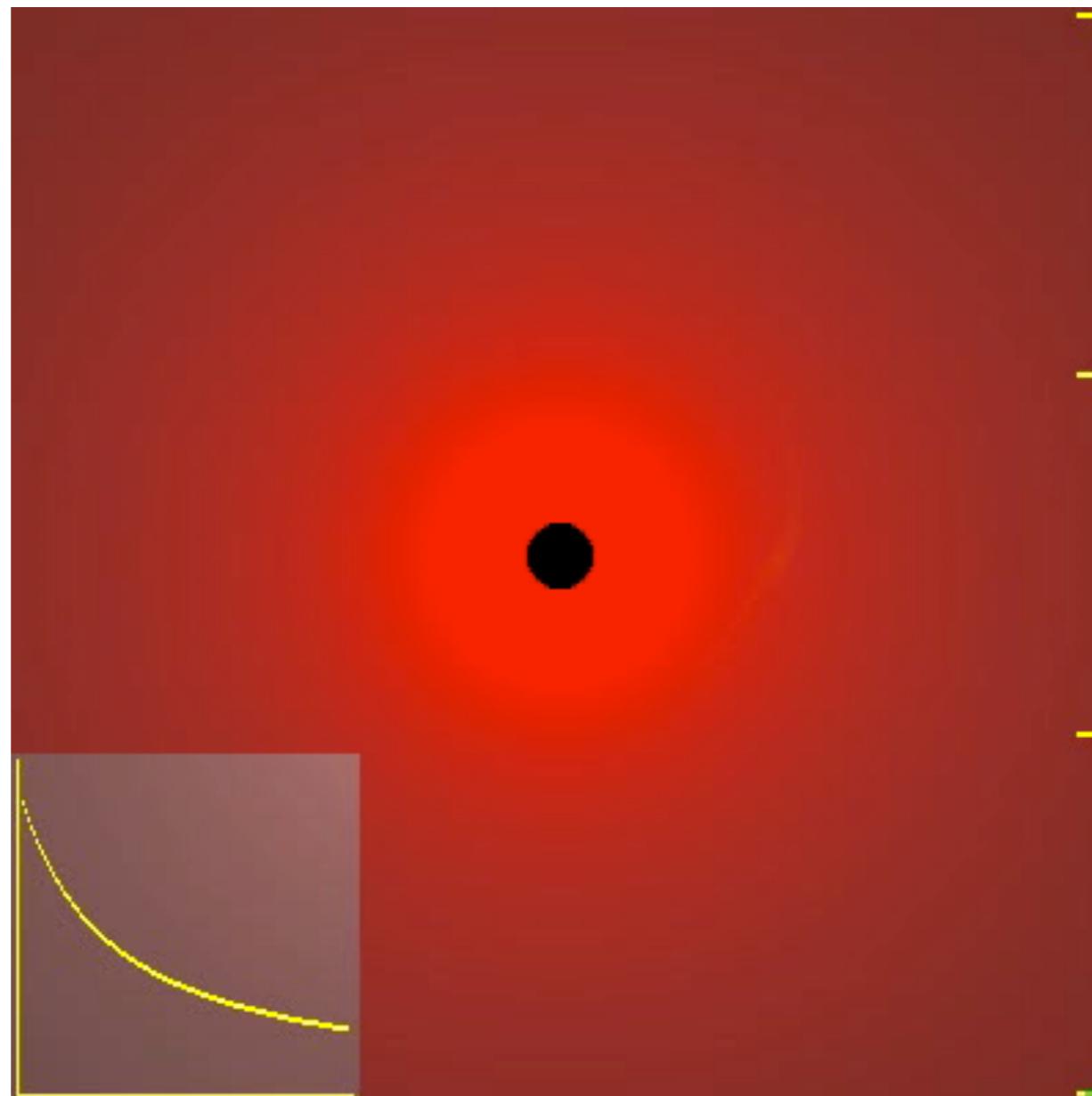
# Giant Planet Formation

- Grow a core of rock and ice in same way as terrestrial planets
- Core of 5-10 Earth masses accretes gas from disk; process must be complete before gas disk dissipates



# Migration

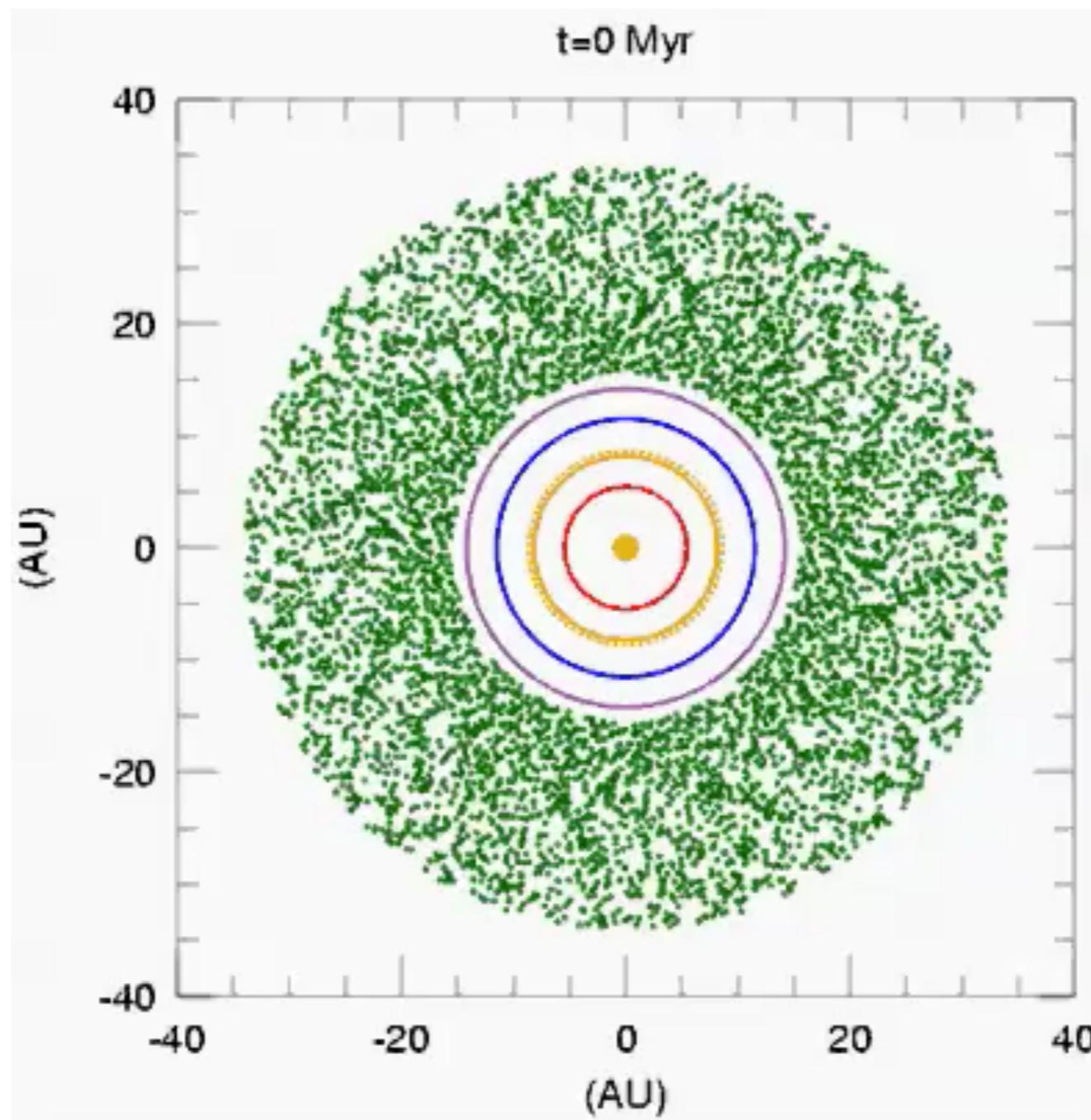
Planet-protoplanetary disk interactions → disk migration



Credit: P. Armitage

# Migration

Solar System “Nice model”



Credit: H. Levison

# Exoplanet Mass–Period Distribution

Planet Mass or Mass $\cdot$ sin(i) vs Orbital Period

exoplanetarchive.ipac.caltech.edu, 2025-08-14

