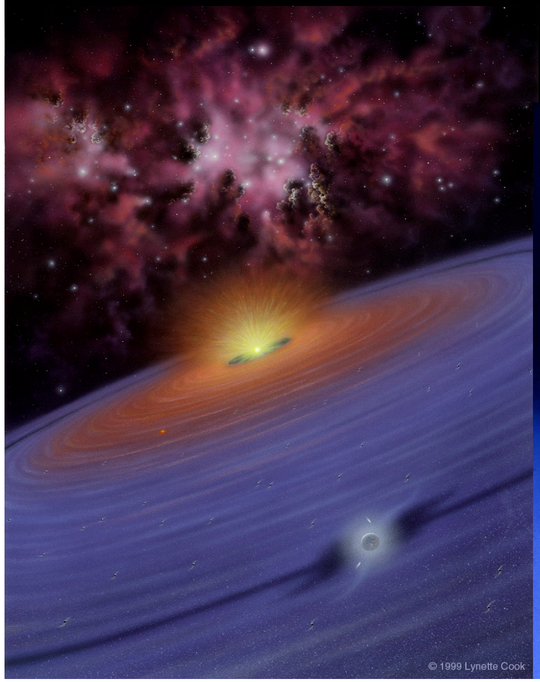
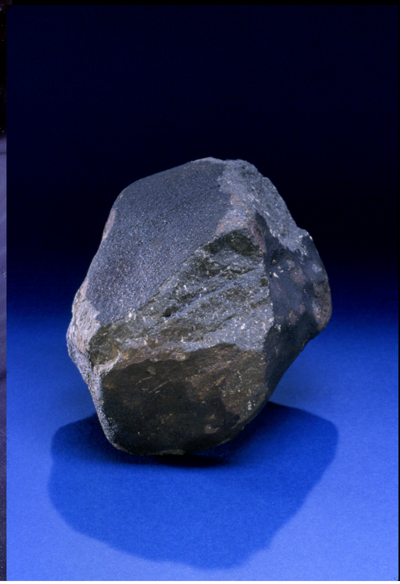
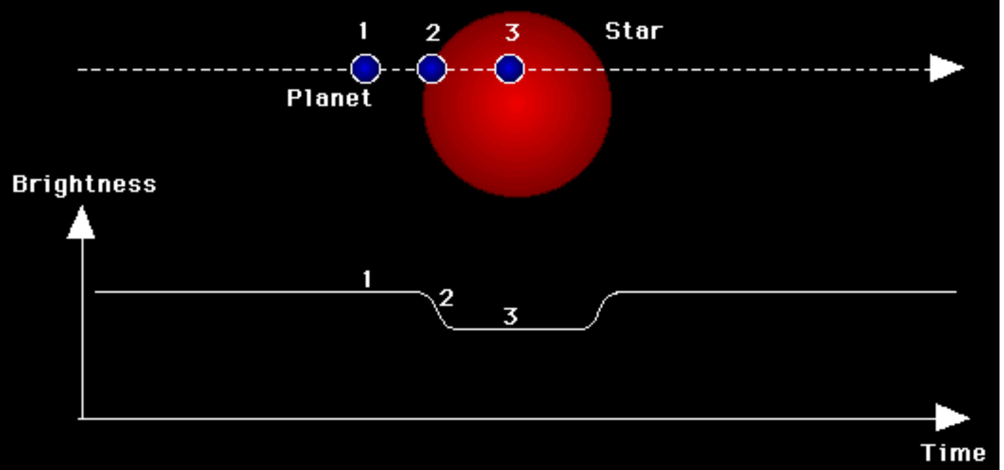
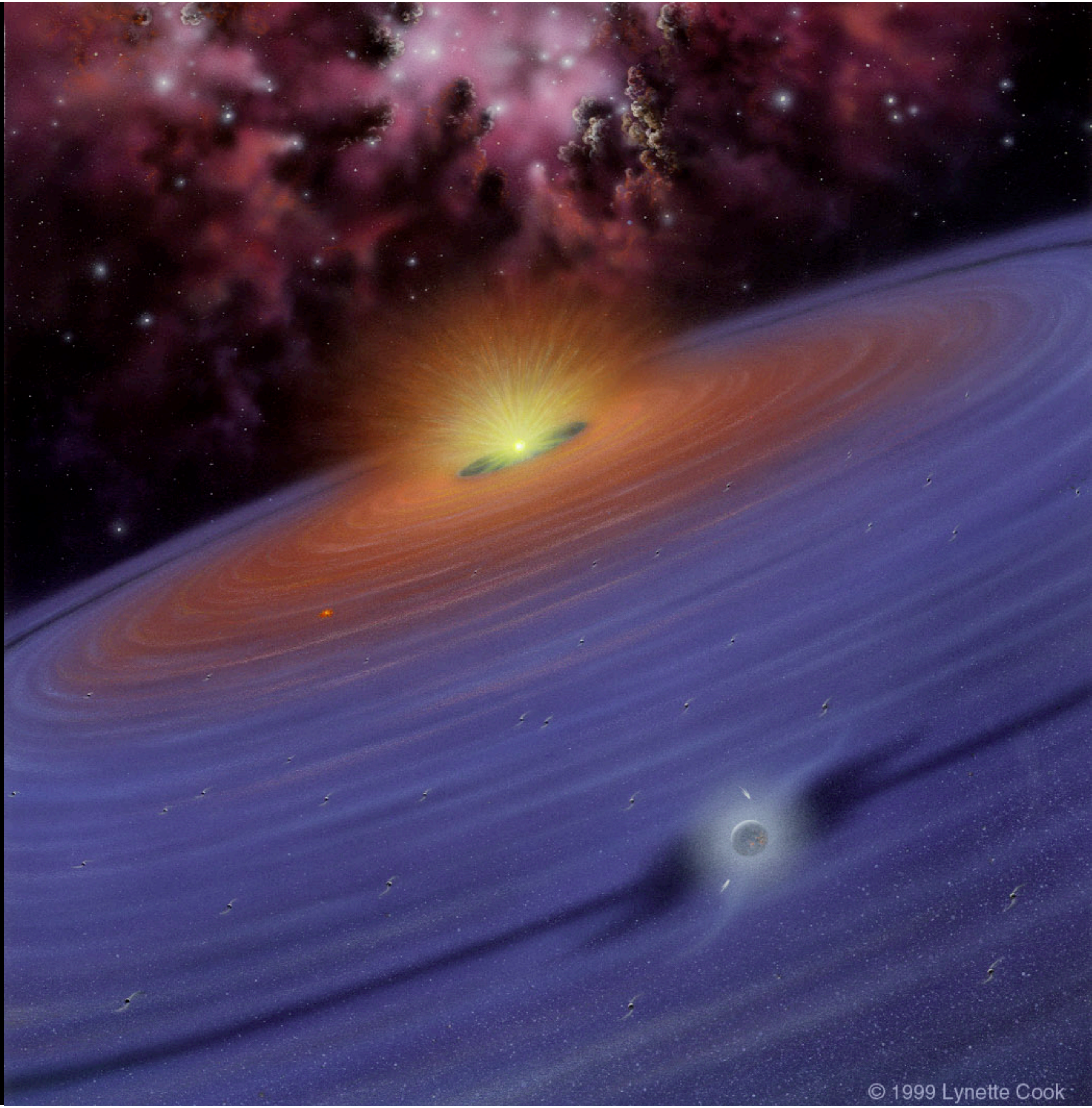
Giant Planet Formation







- Overview
- **Observations: Meteorites to Extrasolar Planets**
  - Our Solar System
    - Dynamics
    - Meteorites
    - Geology
    - Planetary composition & structure
  - Other Stars
    - Circumstellar disks
    - Extrasolar planets
- **Models: Solar Nebula & Planetesimals**
  - Protoplanetary Disks
  - Solid body growth
  - **Accumulation of giant planet gaseous envelopes**
- **Conclusions**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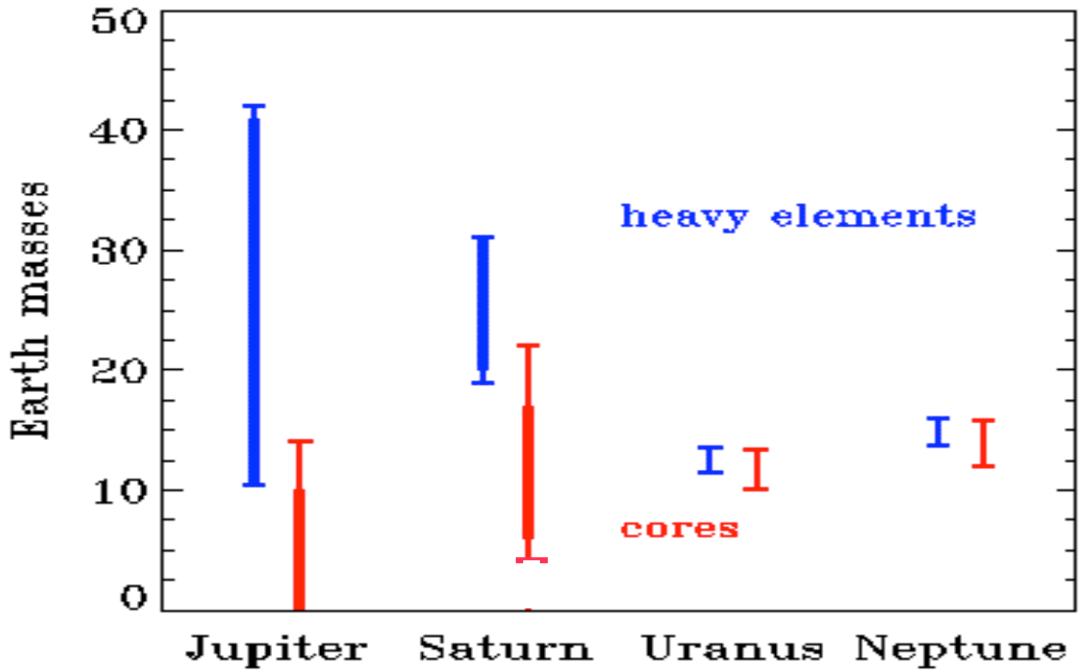
Our Solar System

- Dynamics
  - Planetary orbits nearly circular & coplanar
  - Spacing increases with distance from Sun
  - All giant planets have satellite systems
  - Planetary rings close to planets
  - Many rotations per orbit unless tidally slowed
- Compositions
  - Largest bodies most gas-rich
  - Rocky bodies near Sun, icy bodies farther out
  - Elemental/isotopic abundances similar (except volatiles)
  - Meteorites - active heterogeneous environment
- Planetary Geology: Cratering Record
  - Far more small bodies in 1st 800 Myr than today

Constraints from Meteorites

- Solar System formed 4,568 ± 1 Myr ago
- Accretion occurred rapidly
  - Ages of primitive meteorites span < 5 Myr
  - Some differentiated meteorites < 1 Myr younger than oldest primitive meteorites
- Material well-mixed, but not perfectly
- Some pre-solar grains & molecules survived
- Active processing - chondrules & CAI’s



- **Core** & **total heavy element** abundances in the four major planets and estimated uncertainties
- A major source of uncertainty is in the equations of state.

Planet Formation: Solar System Constraints

- Orbital motions
  - Flat, prograde, low eccentricity
  - Spins mostly prograde, low obliquity
- Age
  - Primitive meteorites 4.568 Gyr
  - Moon rocks 3 - 4.45 Gyr
  - Earth rocks < 4 Gyr
- Sizes & densities of planets
  - Largest planets most gas-rich
- Asteroid & Comets
  - Asteroid belt: Small objects, low total mass
  - Kuiper belt: Larger version of asteroid belt (?)
  - Oort cloud

Planet Formation: Solar System Constraints II

- Satellite systems
  - Regular systems: Rings, small moons, larger moons
  - Irregular satellites: Outer orbits, many retrograde
- Metrorites
  - Very rapid cooling of chondrules and CAIs
  - Isotopic uniformity of meteorites, but exceptions
  - Interstellar grains
  - Differentiation of some small bodies
- Planetary atmospheres
  - Giant planets dominated by accreted gasses
  - Terrestrial planets dominated by volatilized solids
- Planetary surfaces: variation in cratering rates
- Angular momentum distribution

Extrasolar Giant Planets

- ~ 0.5% of Sun-like (late F, G & early K dwarf) stars have planets more massive than Saturn within 0.1 AU
  - Giant planets made primarily of H/He; HD 149026b and a few others are relatively metal-rich
  - Models suggest these planets formed farther from their stars
- ~ 7% of Sun-like stars have planets more massive than Jupiter within 2 AU
  - Many of these planets have very eccentric orbits
- < 2% of M dwarf stars have planets more massive than Jupiter within 1 AU
- Stars with higher metallicity are more likely to host detectable giant planets
- Stars with one detectable giant planet are more likely to host more detectable planets
- > a few % of stars have Jupiter-like companions ($0.5 - 2\ M_{Jup}$, $4\ AU < a < 7\ AU$), but > 25% do not
- Brown dwarf desert; Jupiter-mass planets most common giants

Smaller Extrasolar Planets

- Planets smaller than Neptune are far more common than giants
  - Abundance of planets increases as size decreases at least down to 1.5 R_{Earth}
- ~ 20% of Sun-like stars have one or more planets larger than 1.5 R_{Earth} with orbital periods < 100 days
  - Many of these stars have 2 or more such planets orbiting near the same plane
- The abundance of smaller planets does not depend strongly on stellar mass
- The abundance of smaller planets does not depend strongly on stellar metallicity

- We do not know how common earthlike planets are

Planet Synthesis

- Solar System: metallicity decreases with planet size
  - Gas giants, ice giants, rocks
- Small exoplanets more common than large ones
  - Continuum of masses for planets
  - Brown dwarf desert
- All exoplanets larger than 3 R_{Earth} (plus many smaller ones) with known densities contain substantial hydrogen; exoplanets smaller than 8 R_{Earth} also must contain substantial 'metals'
- Observable planets are more common around higher metallicity stars
- Diverse range of exoplanets; systems like our own may be common

Solar Nebula Theory

(Kant 1755, LaPlace 1796)

The Planets Formed in a Disk in Orbit About the Sun

Explains near coplanarity and circularity of planetary orbits

Disks are thought to form around most young stars

- Theory: Collapse of rotating molecular cloud cores
- Observations: Proplyds, β Pic, IR spectra of young stars

Predicts planets to be common, at least about single stars

Protoplanetary Disk Formation & Evolution

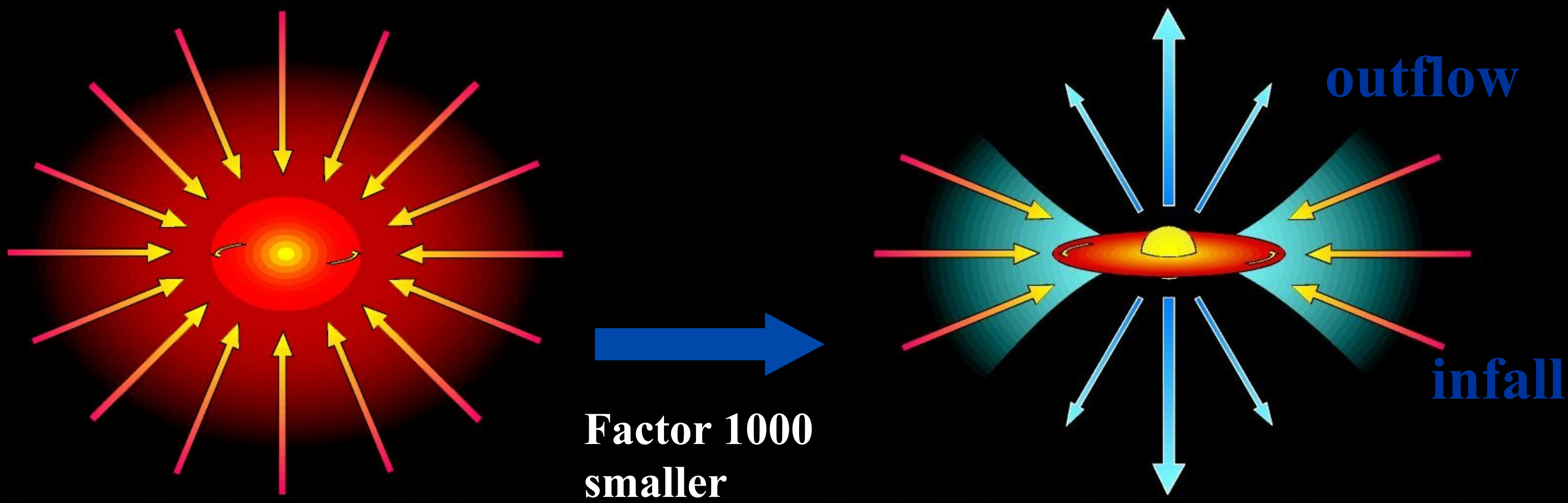
Material falls into gravitational well - it gets heated

- Some heat radiated
- Material near star gets hottest - melting/vaporization

Disks spread: viscosity, gravitational & magnetic forces

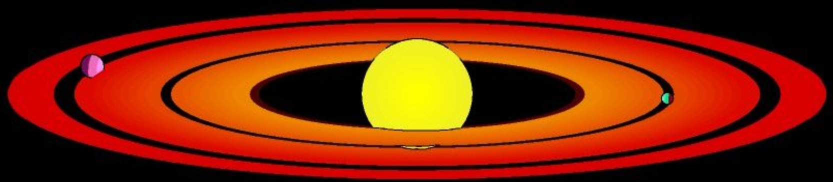
- Disk profile flattens
- Star accretes from disk

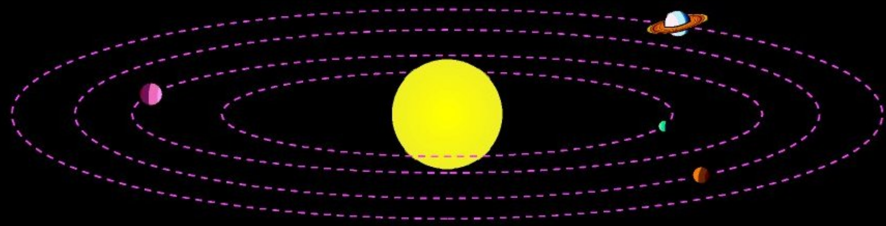
Scenario for star- and planet formation



Cloud collapse

Protostar with disk $t=10^5$ yr





Formation planets $t=10^6$-10^7 yr

Planetary system $t>10^8$ yr

Condensation Sequence

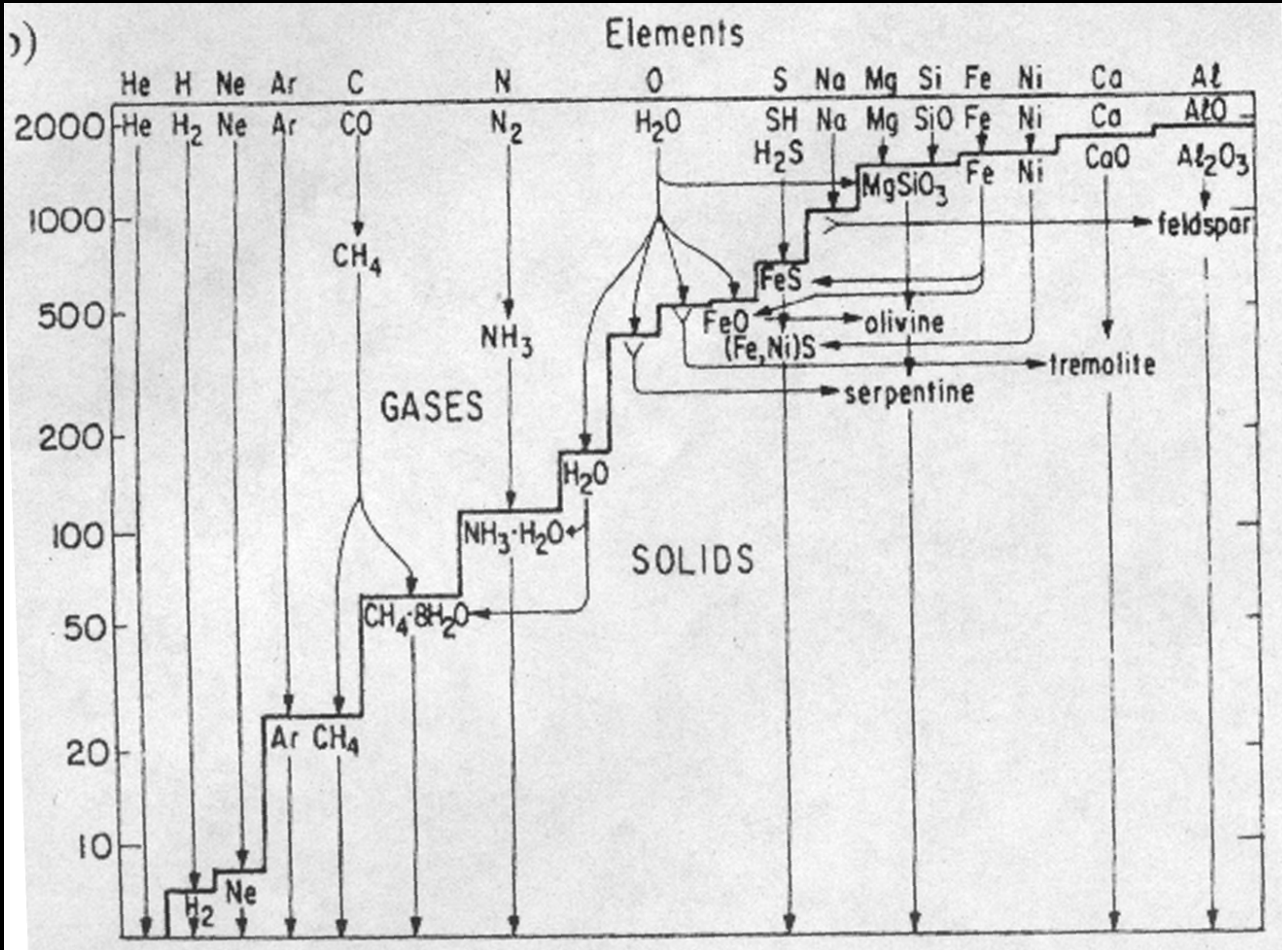
As a gaseous mixture cools, grains condense

- Refractory compounds: TiO, Al_2O_3
- Silicates (e.g., $MgSiO_3$) & iron
- Water ice
- Other ices
- H_2, noble gases don't condense

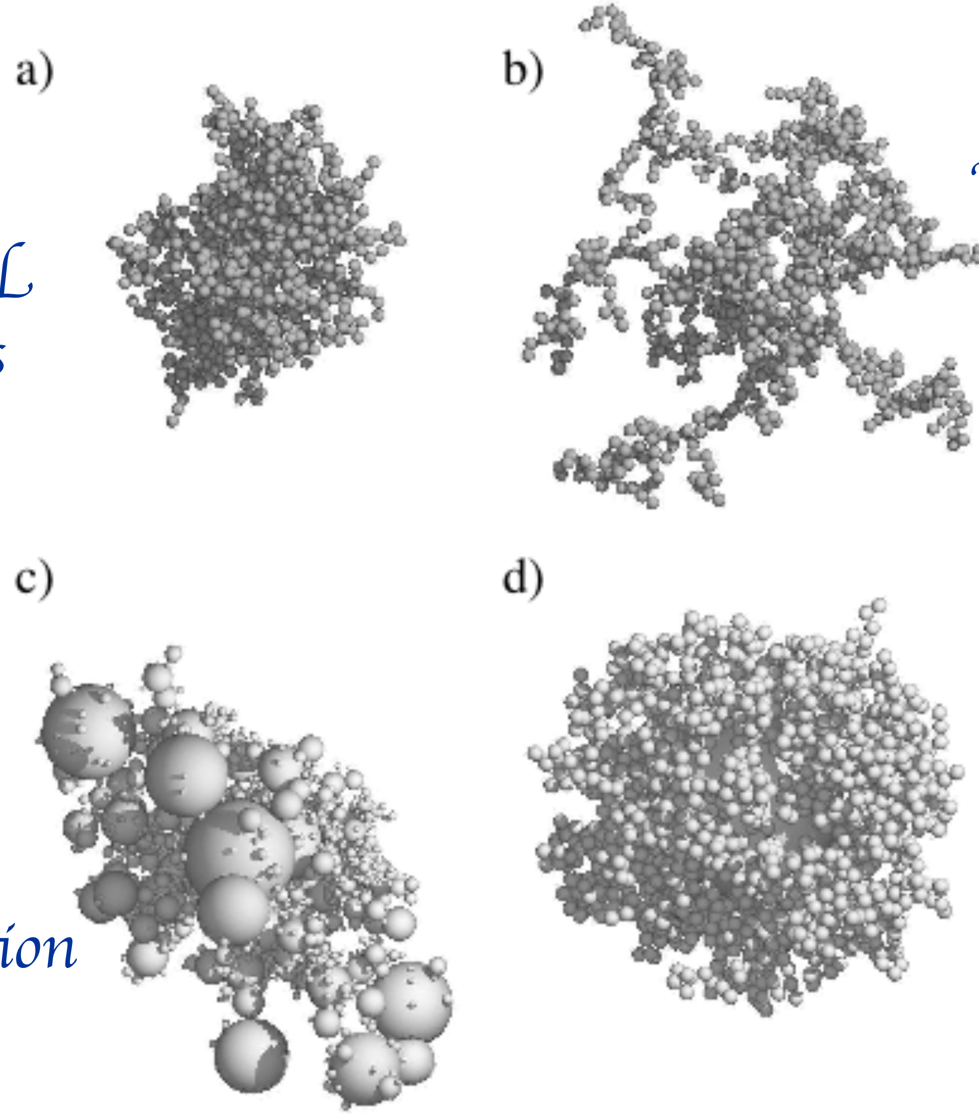
Equilibrium vs. kinetic inhibition

- N_2, CO stable at high T; NH_3, CH_4 at low T
- Equilibrium achieved rapidly at high T, ρ; slowly at low T, ρ

Equilibrium Condensation



Small Particle Coagulation



single identical particles

merging clusters

particle size distribution

large core

Solar Nebula/Protoplanetary Disk

- Minimum mass solar nebula
  - Planets masses, augmented to solar composition
  - $\sim 0.02\ M_{\odot}$
- Infall
  - Shock front
- Disk dynamics
  - Magnetic torques
  - Gravitational torques
  - Viscous torques
- Disk chemistry
  - Equilibrium condensation
  - Kinetic inhibition
- Clearing

Planetesimal Hypothesis

(Chamberlain 1895, Safronov 1969)

Planets Grow via Binary Accretion of Solid Bodies

Massive Giant Planets Gravitationally Trap
H_2 + He Atmospheres

Planetesimals and condensation sequence explain planetary composition vs. mass

General; for planets, asteroids, comets, moons

Can account for Solar System; predicts diversity

Planet Formation

Early stage

dust grains → planetesimals

Middle stage

planetesimals → planetary embryos

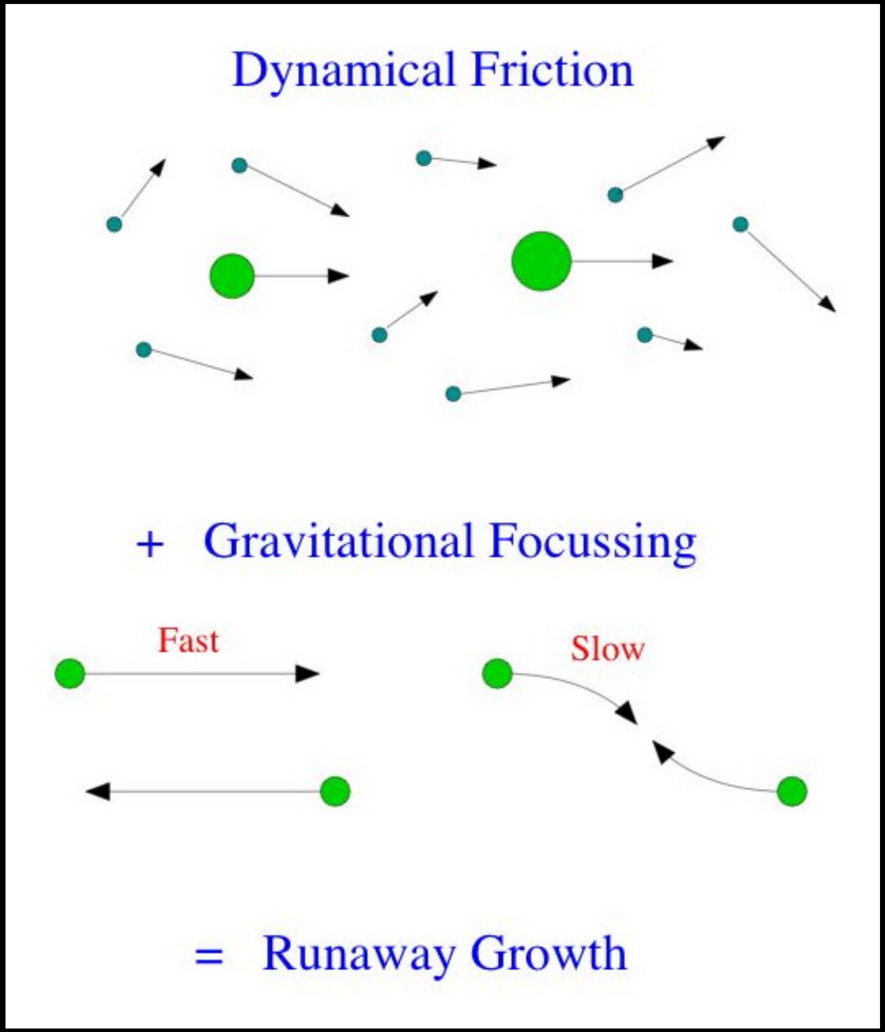
Late stage (terrestrial planets)

embryos → planets

Planetesimal Formation

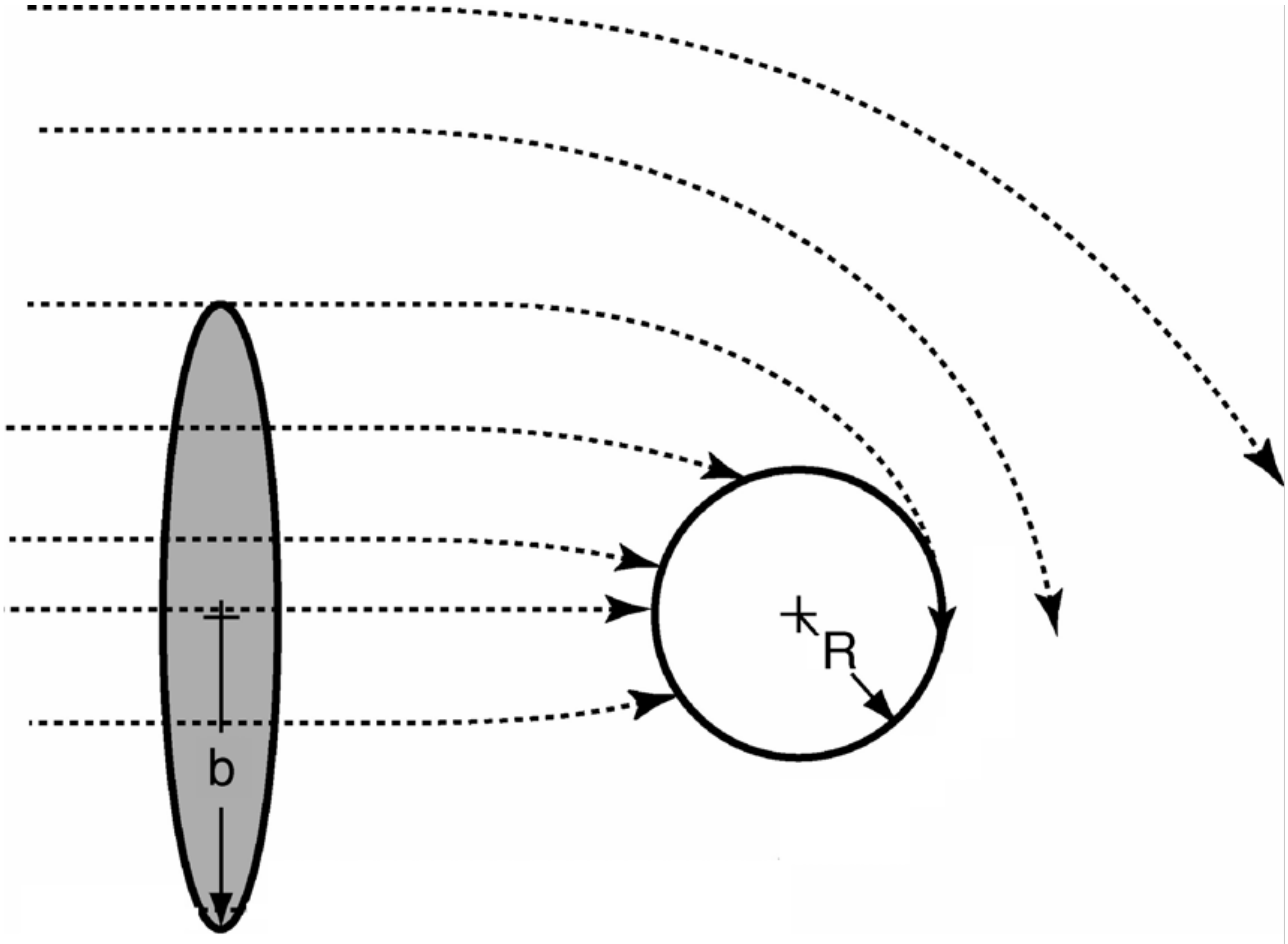
- Observational constraints
  - Timescales from short-lived isotopes
  - Disk chemistry; interstellar grains
- Growth of grains
  - Sticking, falling towards midplane
- Gas drag
  - Strongest when particles collide with own mass each orbit
  - Can produce high velocity collisions between particles
- Clumping & gravitational collapse
- Kilometer bodies dominated by mutual interactions

Runaway Growth

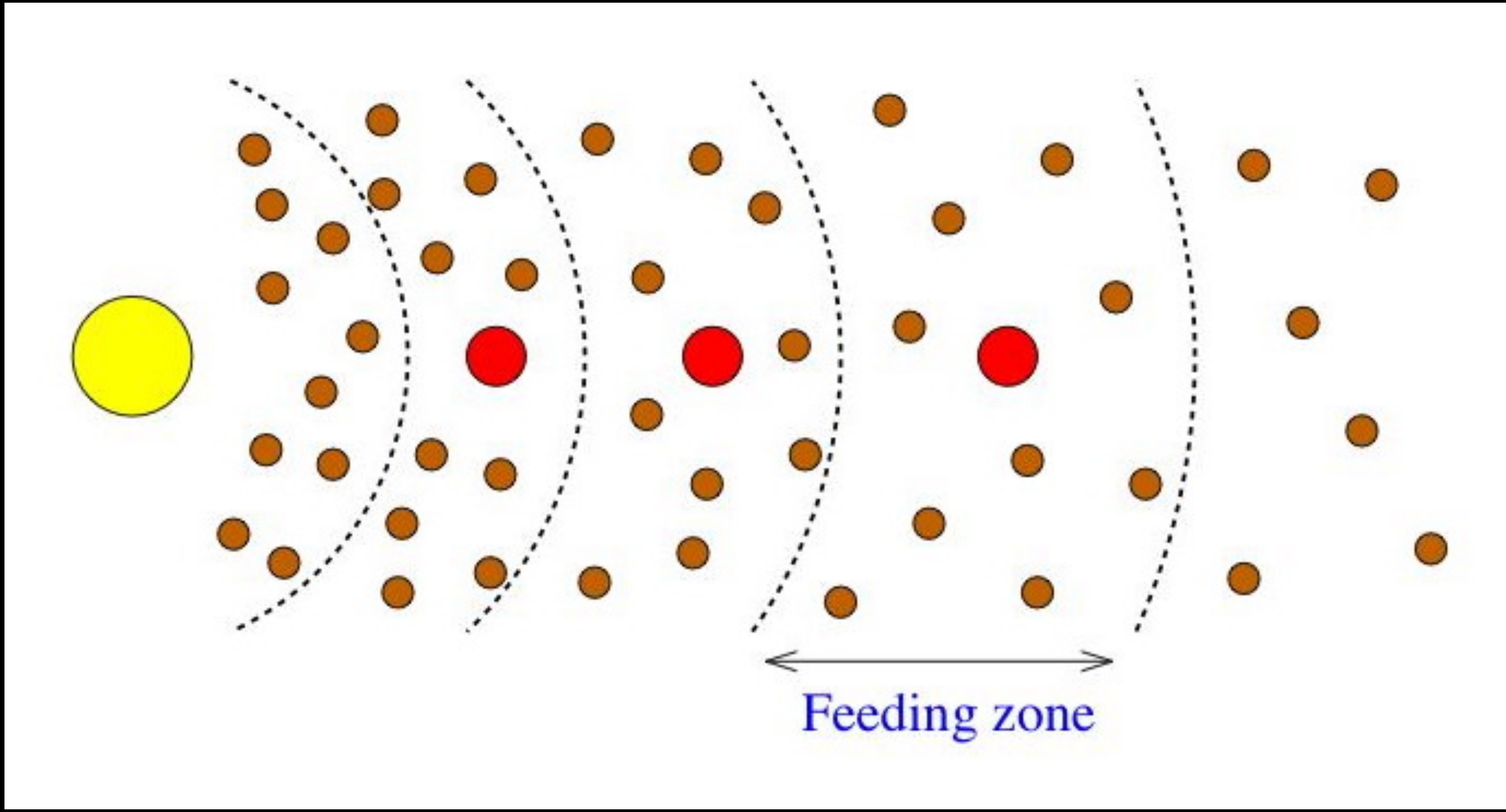


- Gravitational encounters important for bodies > 1 km.
- Close encounters alter trajectories.
- Equipartition of energy determines random velocities.
- Random velocities determine growth rate.
- *Rapid*

Gravitational Focussing



Oligarchic Growth



Terrestrial Planets: Masses & Orbits

Mergers continue until stable configuration reached

Fewer planets usually more stable, even though planets are larger

Resonances (commensurabilities in orbital periods) destabilize system

Stable configurations need to last billions of years

Giant impacts & chaos imply diversity

Terrestrial Planet Growth

Mergers continue until stable configuration reached

Runaway/oligarchic stages ~ 10^5 years

High velocity stage ~ 10^8 years

These processes take longer at greater distances from star

Theories of Giant Planet Formation

Core-nucleated accretion: Big rocks accumulated gas

Fragmentation during collapse: Planets form like stars

Gravitational instability in disk: Giant gaseous protoplanets

Theories of Giant Planet Formation

Core-nucleated accretion: Big rocks accumulated gas

One model for rocky planets, jovian planets, moons, comets…

Explains composition vs. mass

Detailed models exist

Takes millions of years

Fragmentation during collapse: Planets form like stars

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Rapid

Binary stars are common

Mass gap (brown dwarf desert)

Requires $M > 7\ \mathrm{M_J}$

Separate model for solid bodies; no model for Uranus/Neptune

Gravitational instability in disk: Giant gaseous protoplanets

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Mass gap (brown dwarf desert)

Requires $M > 7\ M_J$

Separate model for solid bodies; no model for Uranus/Neptune

Gravitational instability in disk: Giant gaseous protoplanets

Rapid growth, but cooling rate limits contraction

Requires unphysical initial conditions (density waves stabilize)

Separate model for solid bodies; no good model for Uranus/Neptune

CORE ACCRETION MODEL FOR FORMATION OF GIANT PLANETS

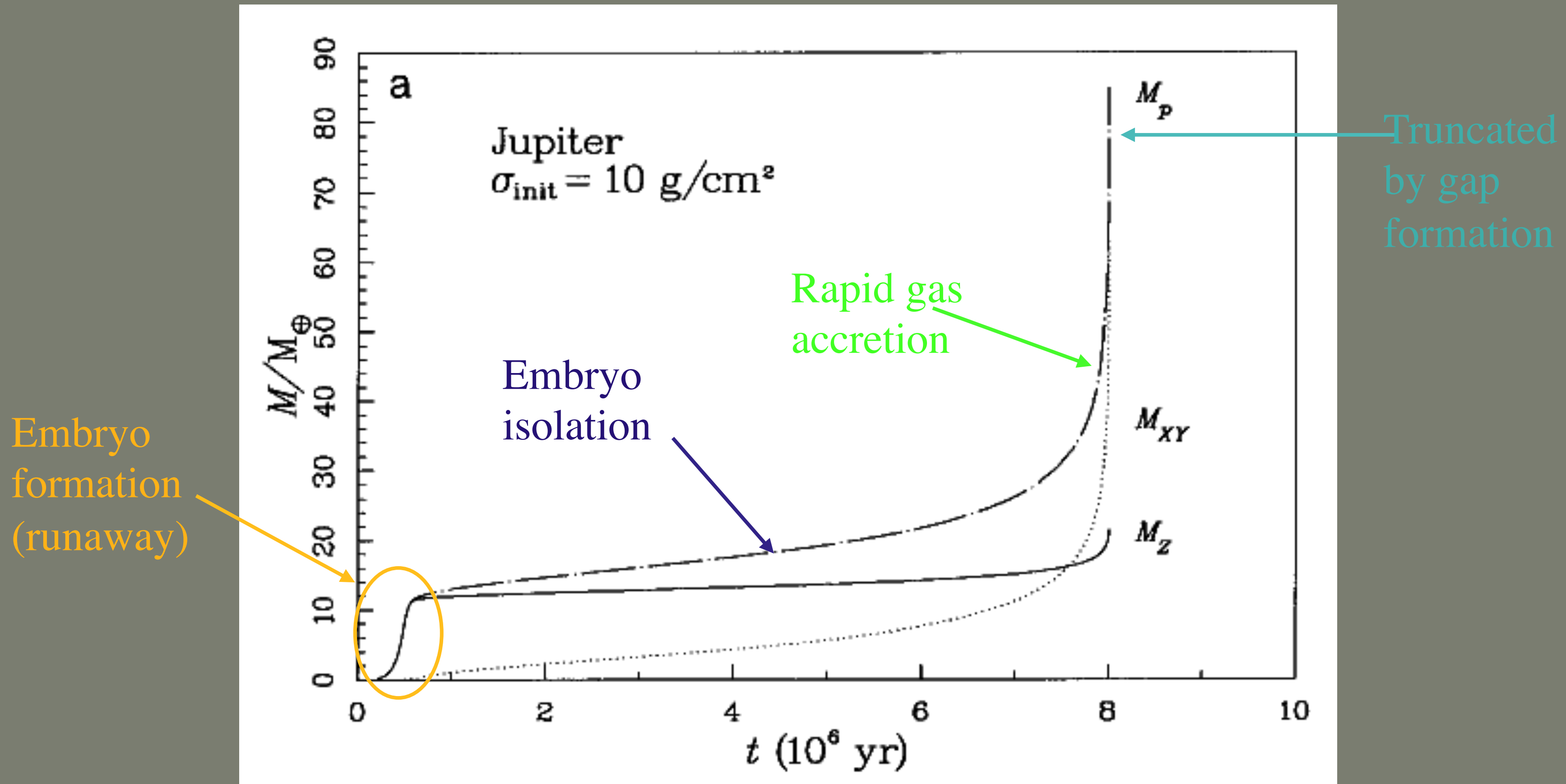
Planetesimals accrete to form a solid core

Growing core attracts gas from nebula

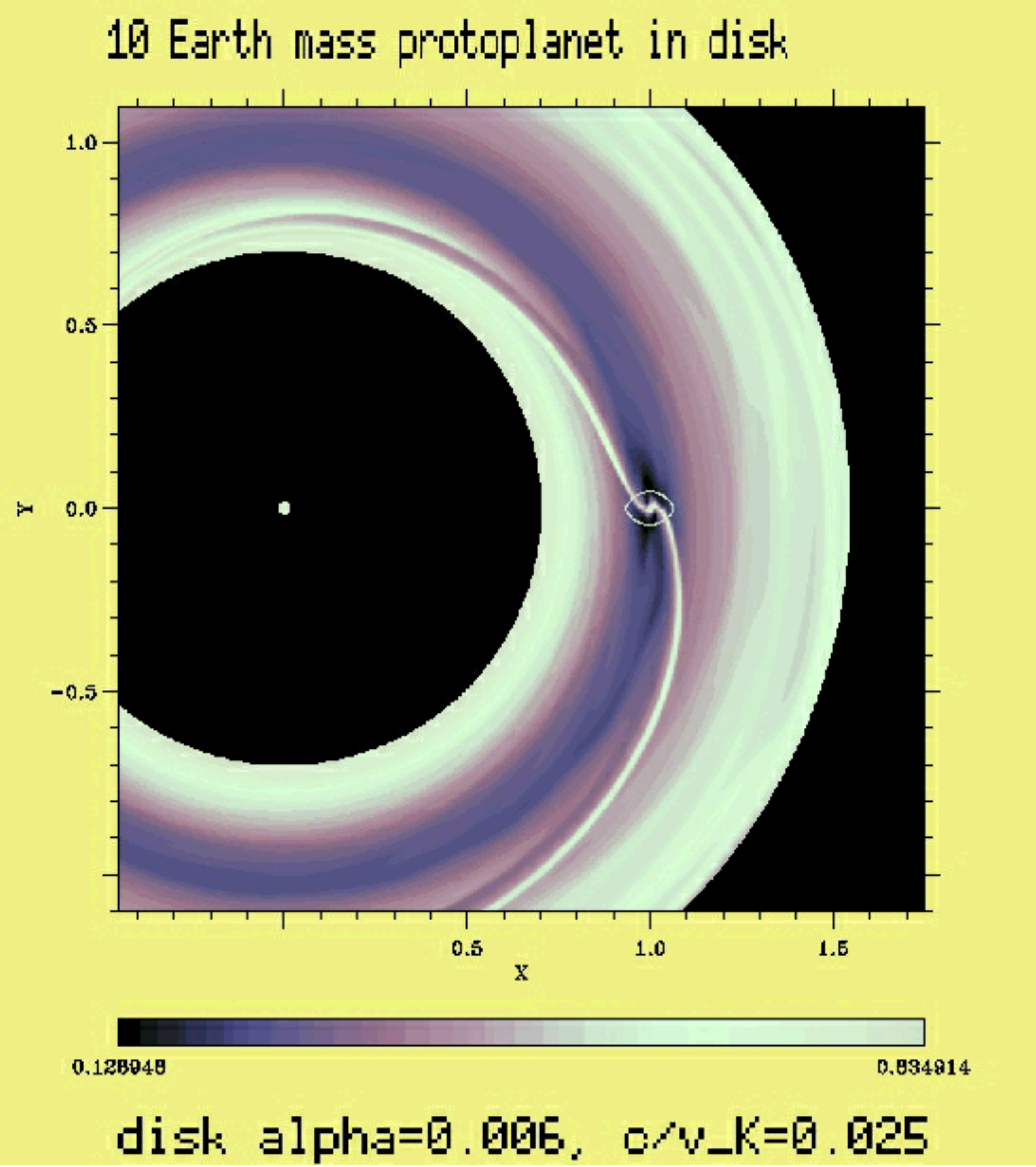
At critical core mass, runaway gas accretion begins; rapid (but NOT hydrodynamic) collapse to form a gas giant

Can core reach critical mass (~ 10 M_{Earth}) before the nebula dissipates (~ 3-10 Myr)?

Core Nucleated Accretion ("Classic" model)



Pollack *et al*, 1996



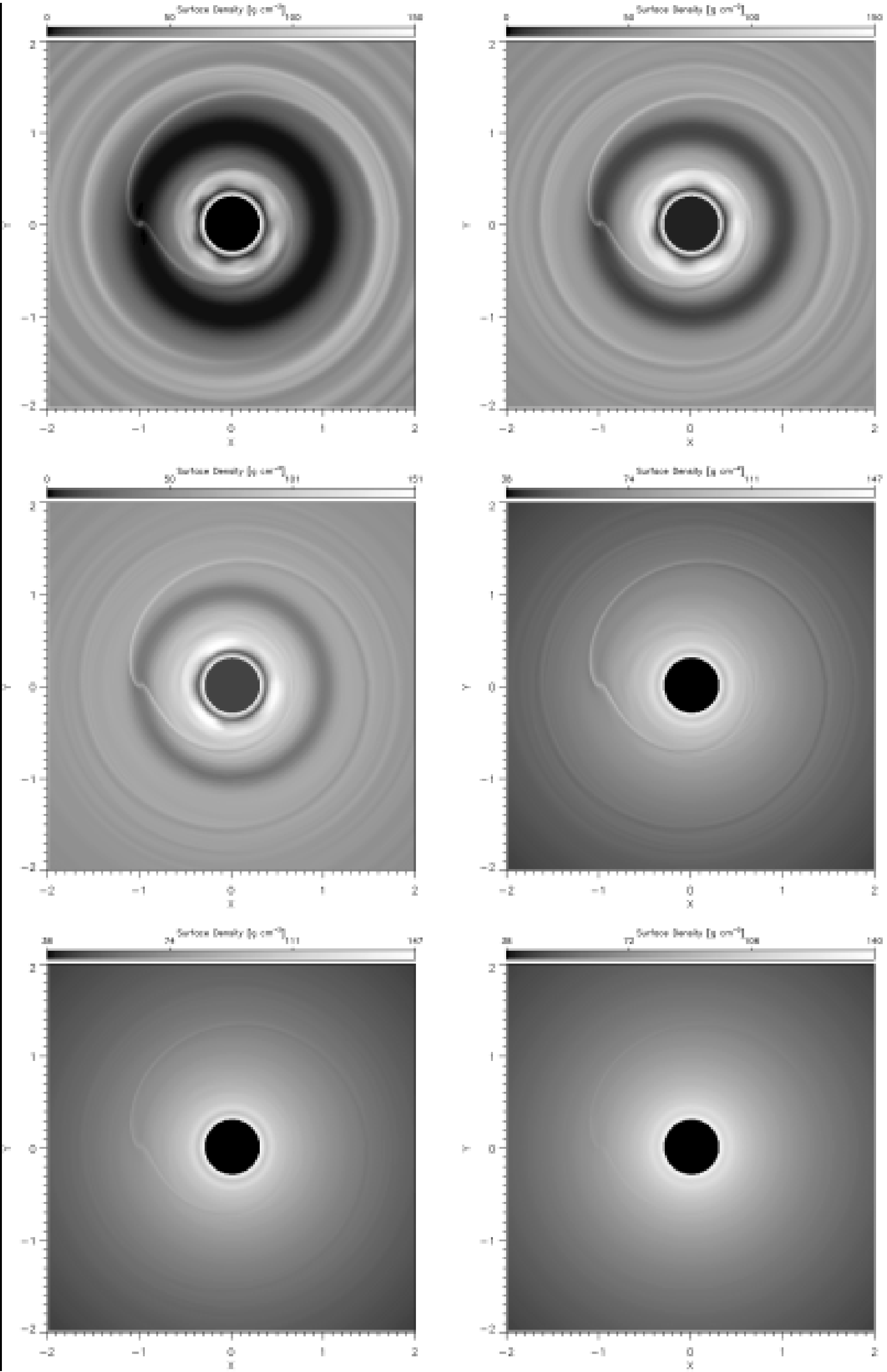
Planet's gravity affects disk.

Computer simulation by P. Artymowicz

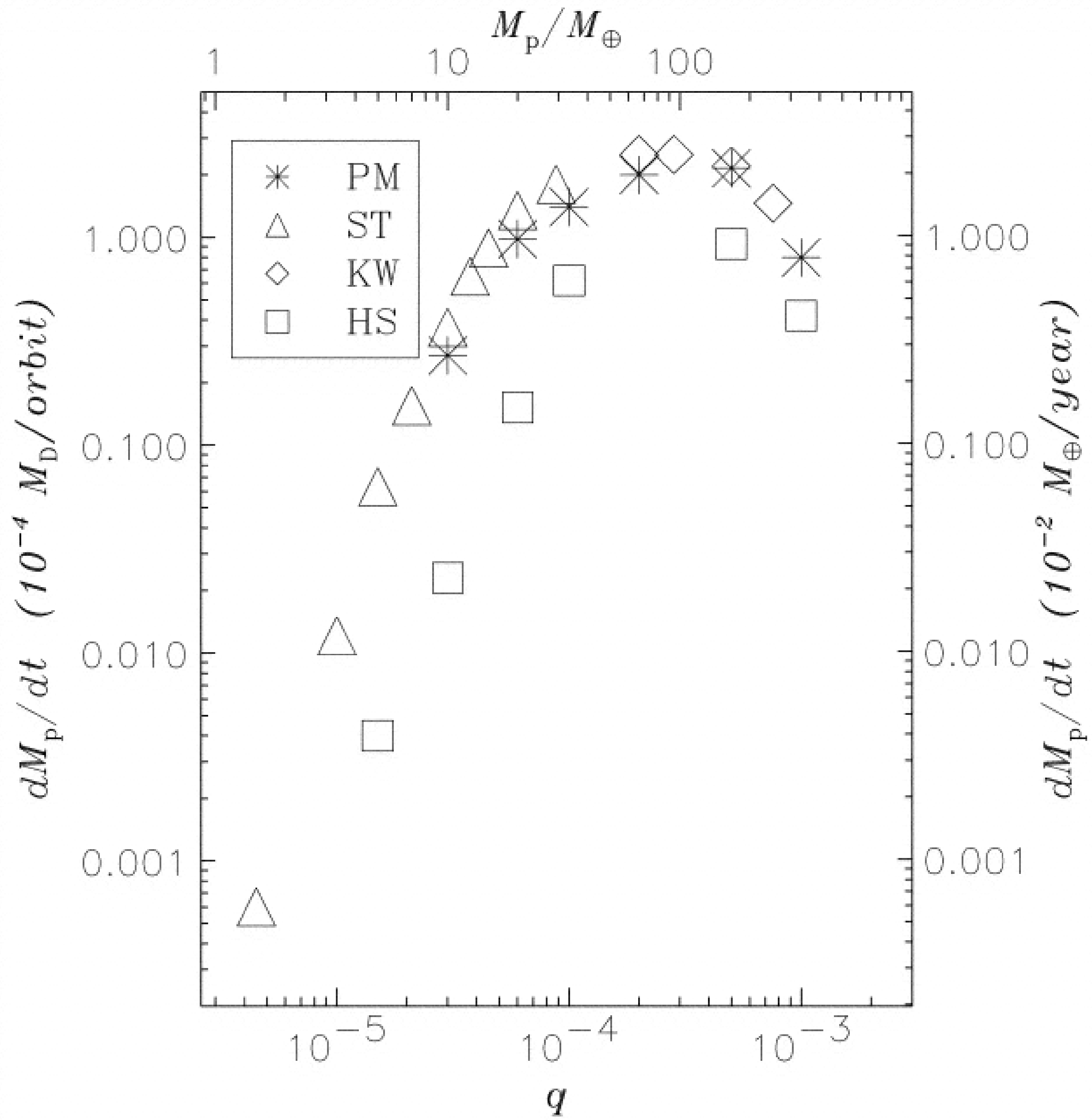
Gas Flow Near Planet

(Bate et al. 2003)

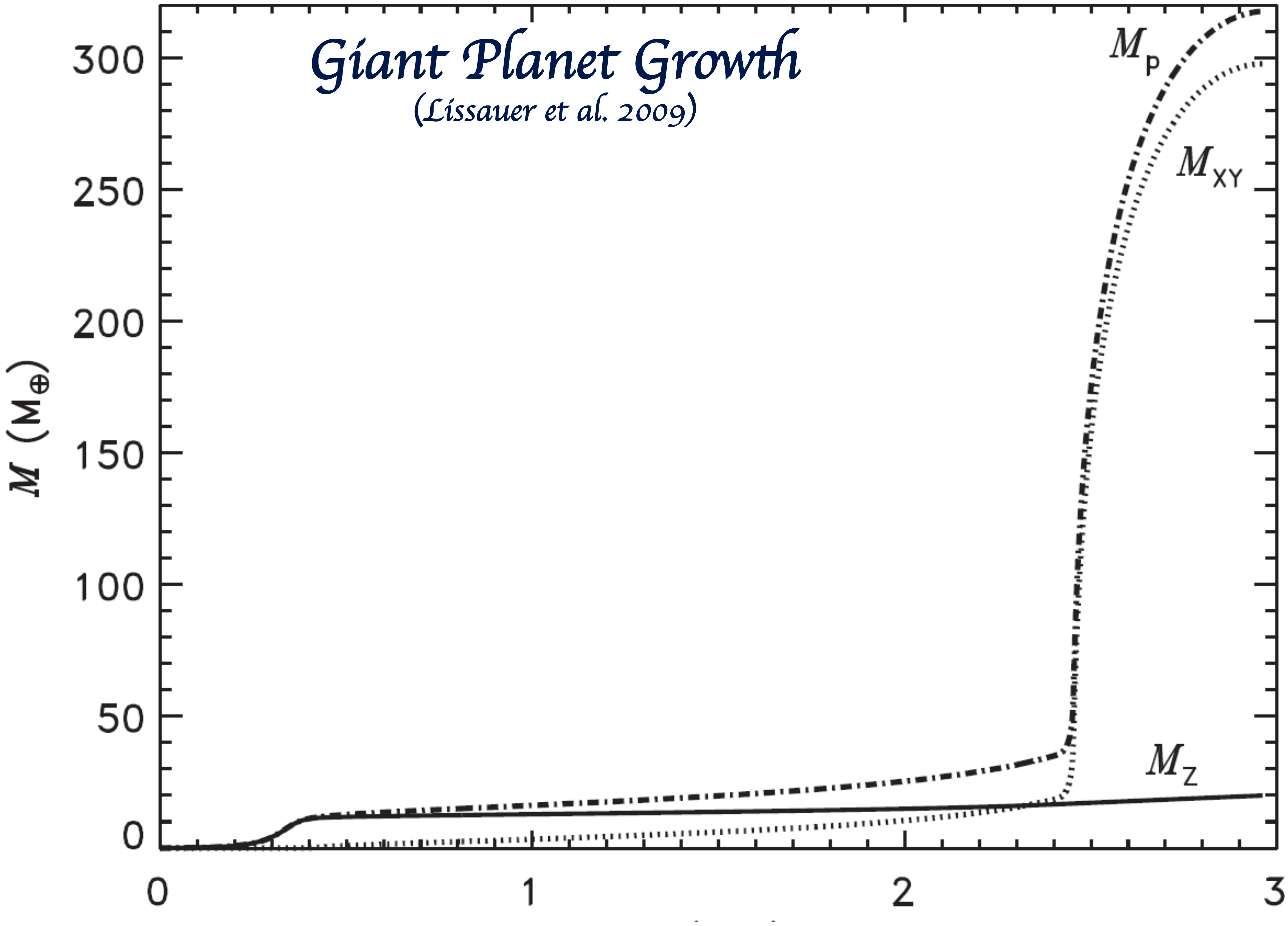
- Planet masses are 1, 0.3, 0.1, 0.03, 0.01, 0.003 M_J



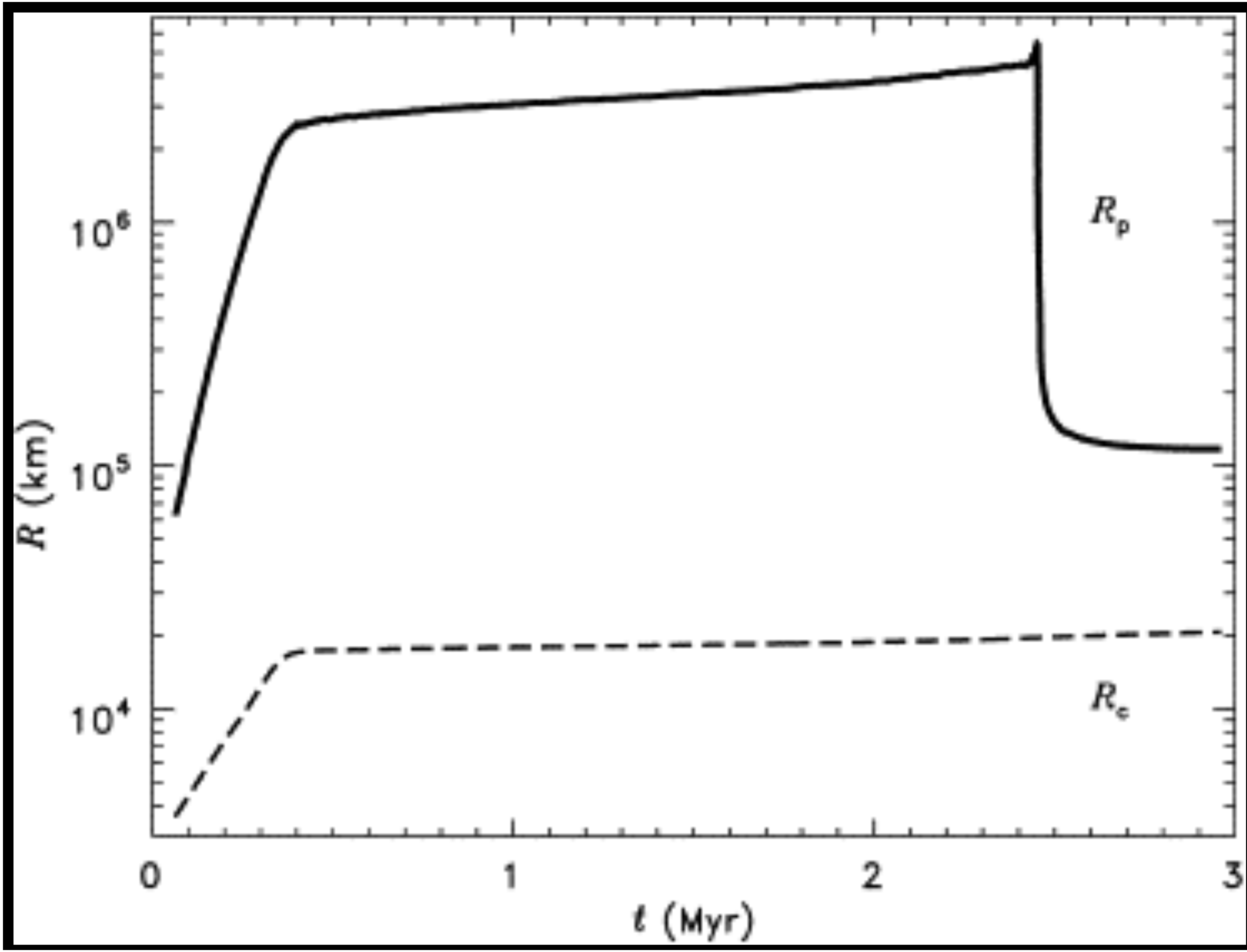
Gas Flow to Planets (D' Angelo et al. 2003)



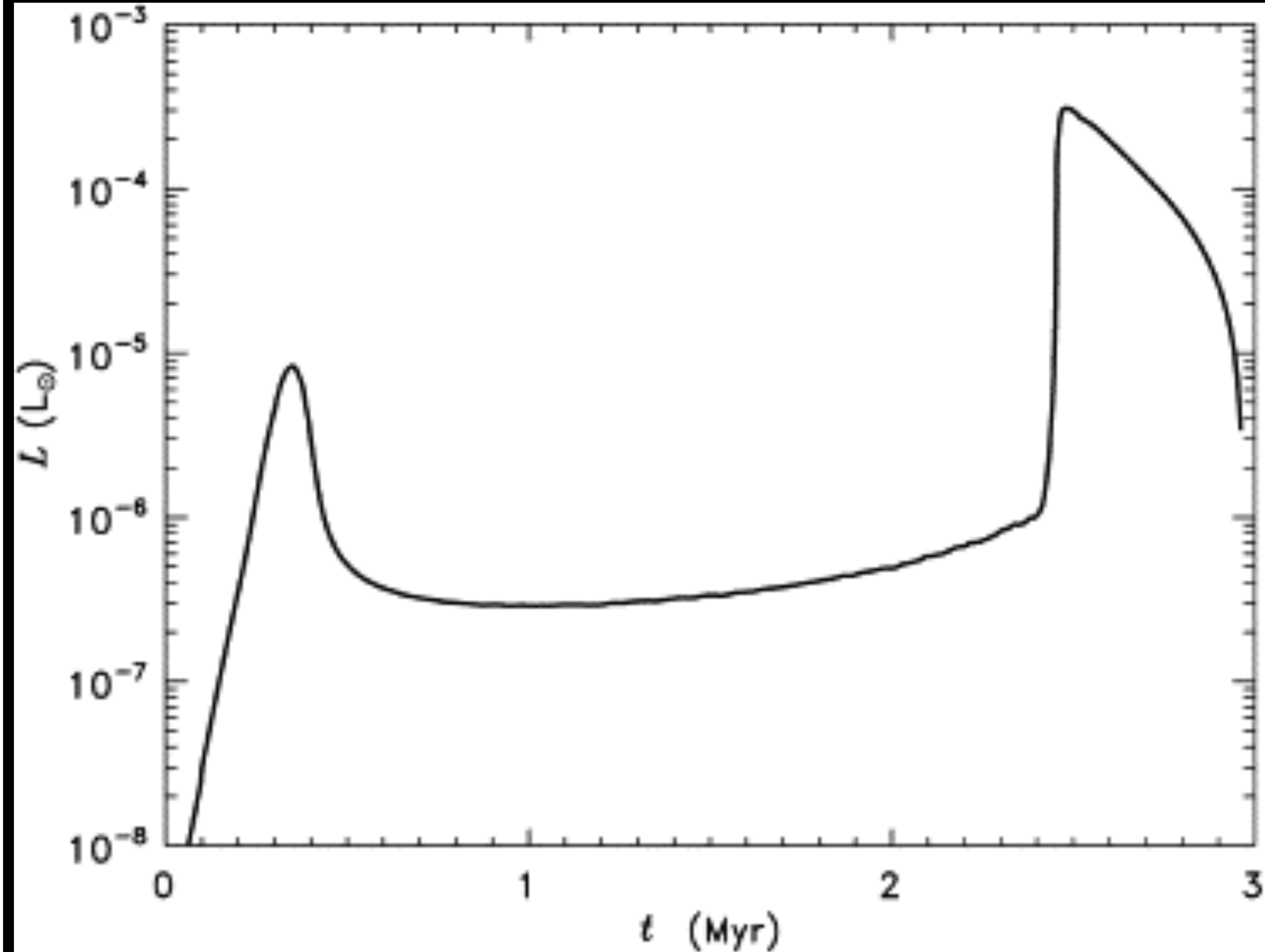
Note flow peaks ~ M_{saturn}; drops sharply > $M_{Jupiter}$.



Giant Planet Growth
(Lissauer et al. 2009)
M_p
M_{XY}
M_Z
M ($M_\oplus$)
300
250
200
150
100
50
0
0
1
2
3



R_p
R_c
10^6
10^5
10^4
R (km)
0
1
2
3
t (Myr)



10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
L ($L_\odot$)
0
1
2
3
t (Myr)

For Small M_p: Envelope Mass and Structure Controlled by

Background pressure of the nebula at outer boundary

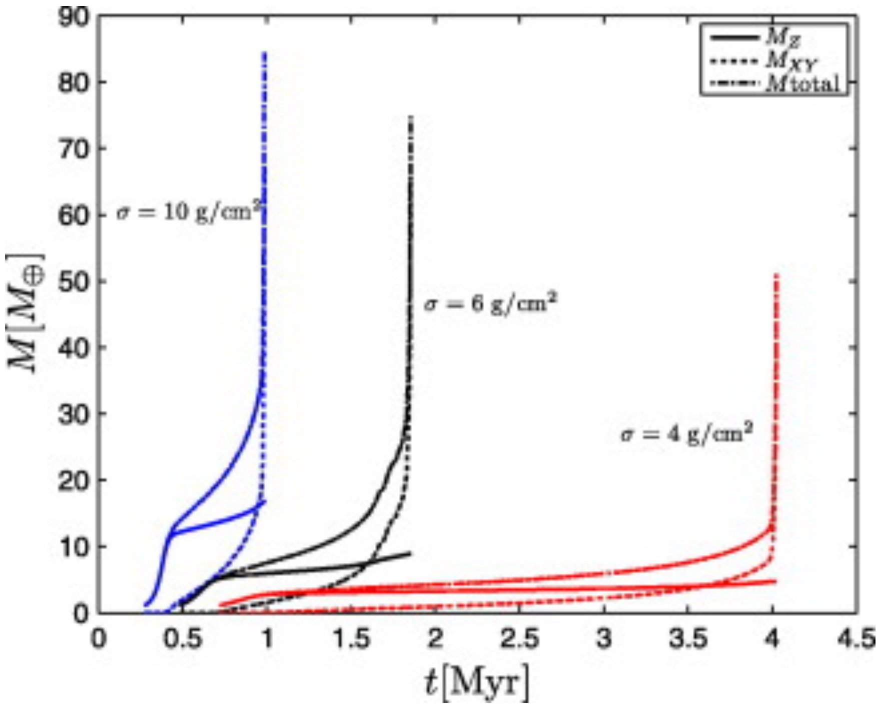
Energy input from infalling planetesimals

Opacity due to dust from nebula and ablating planetesimals

Accretion rate and size distribution of planetesimals

Growth Rate vs. Initial Surface Density of Solids

(Movshovitz et al. 2010)



1996-2013: Simplified Runaway Model

Single size of planetesimals

Feeding zone with width proportional to Hill radius; core limited by "isolation mass"

Surface density of planetesimals assumed uniform across feeding zone at all times, decreasing as core grows

Neglected interactions between planetesimals (collisions, accretion, gravitational scattering)

Current simulations: D’Angelo et al. (2014, 2016)

Treatment of Planetesimals with Multi-Zone Accretion Code

- Interactions: collisions, fragmentation, accretion, mutual gravitational stirring
- Size distribution and surface density vary with semimajor axis and time
- Planetesimals migrate by scattering and gas drag (core fixed in place)
- Gap formation around core’s orbit due to accretion and shepherding

Envelope Calculation

Gas density at boundary matched to nebula conditions

Structure set by energy input from infalling bodies, loss from radiation

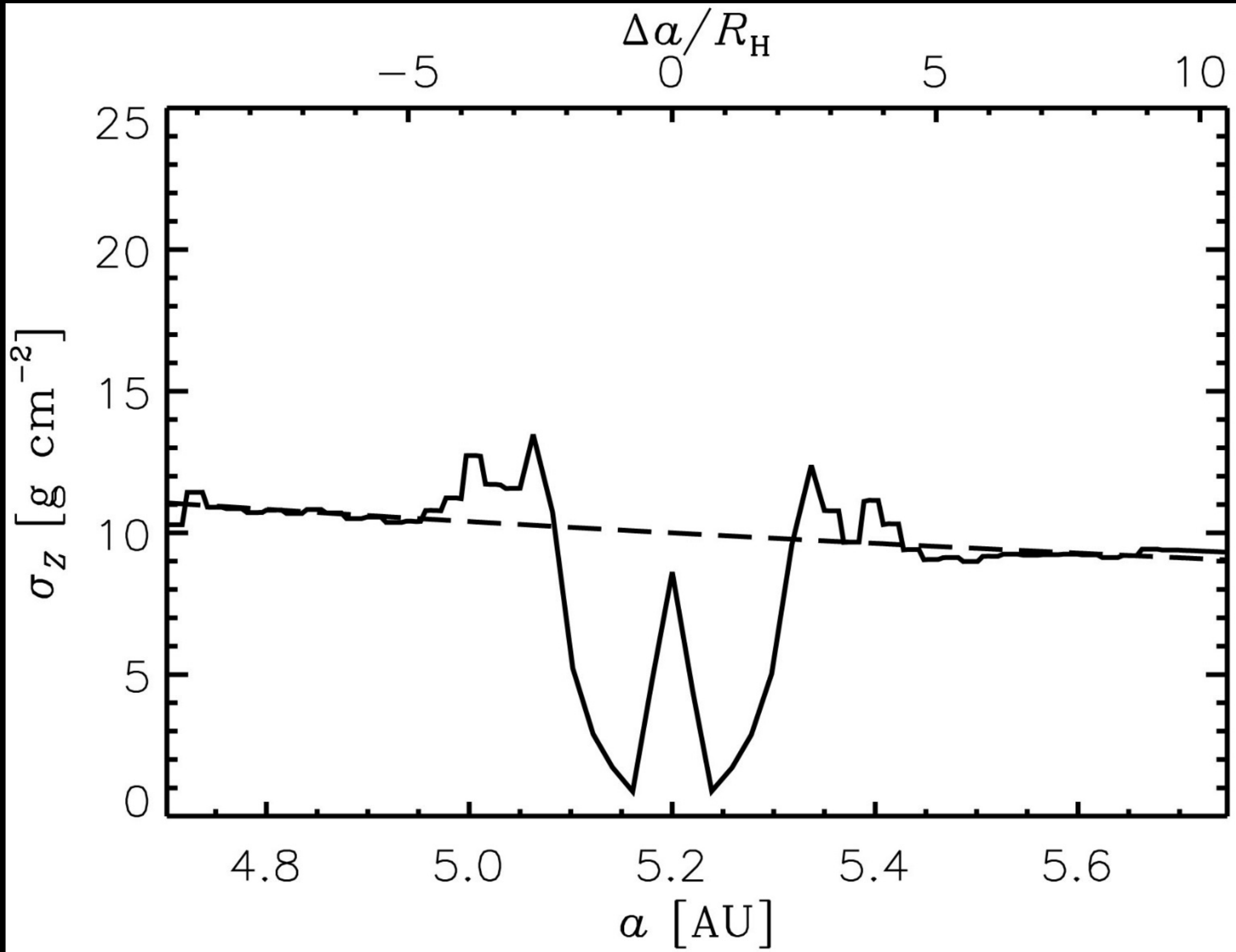
Trajectory integrations yield accretion cross-sections and ablation rates vs. planetesimal size

Opacity due to grains, with coagulation and sedimentation

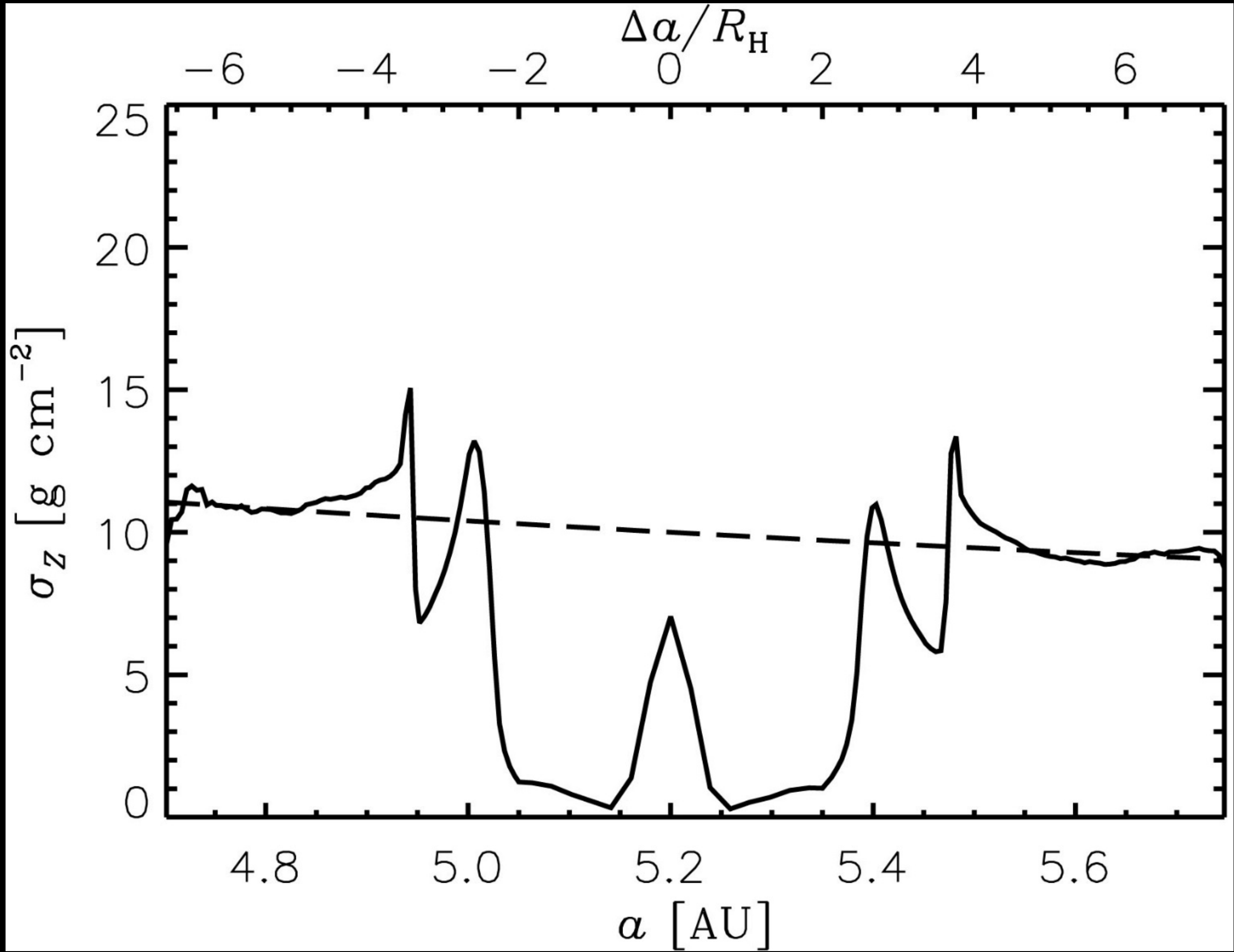
Initial Conditions

- Nebular surface density varies as 1/r
- At 5.2 AU, Σ_{gas} = 1000 g/cm^2 σ_{solids} = 10 g/cm
- Gas density 3.3 x 10^{-9} g/cm^3
- Planetesimal size distribution: power law, radii 15 m – 50 km
- Seed body, M = 10^{-4} M_{Earth} (R~ 350 km)

Surface Density of Planetesimal Swarm vs. Semimajor Axis

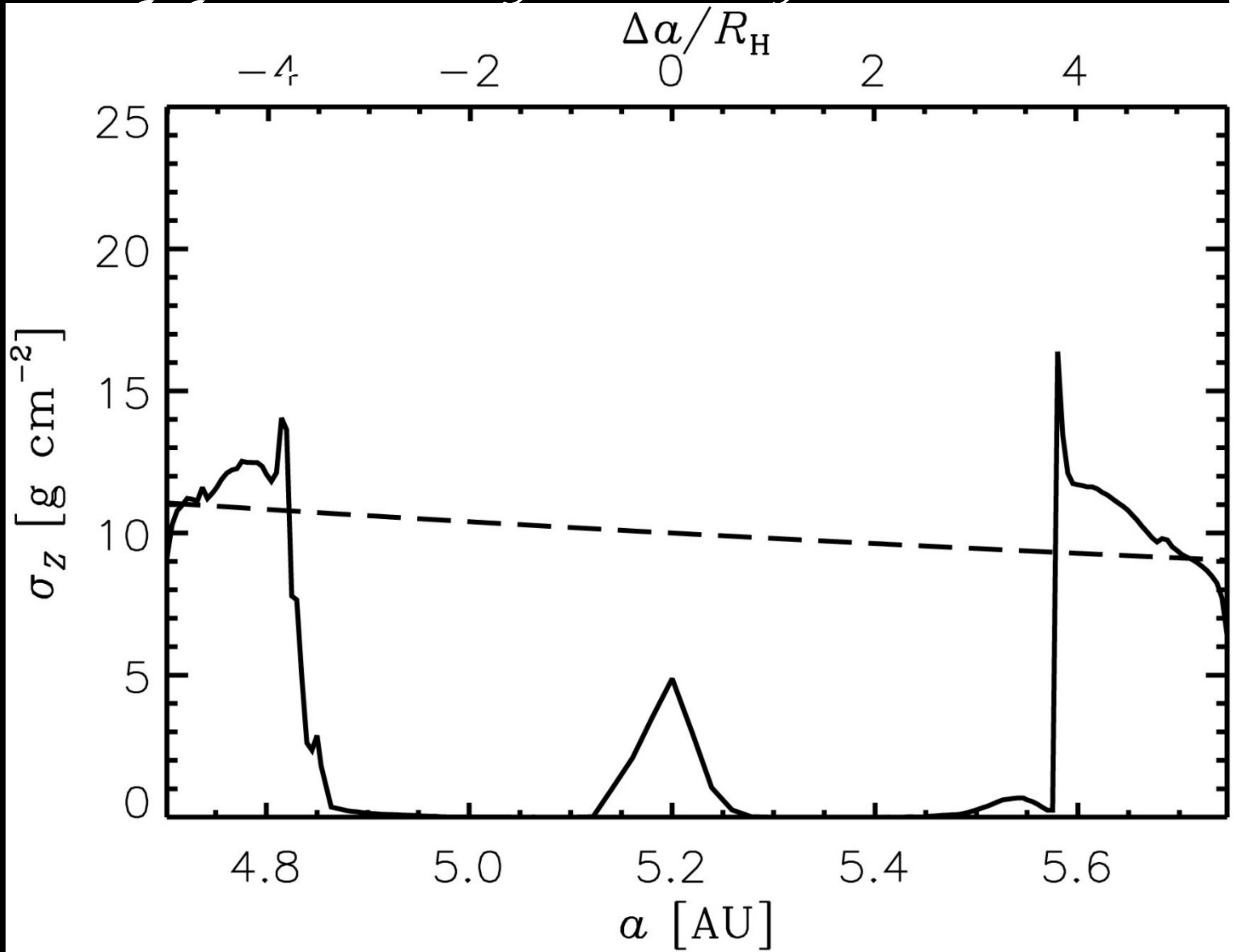


$M_{core} = 1\ M_E \quad M_{env} = 2 \times 10^{-5}\ M_E \quad t = 7.4 \times 10^{4}$ yr

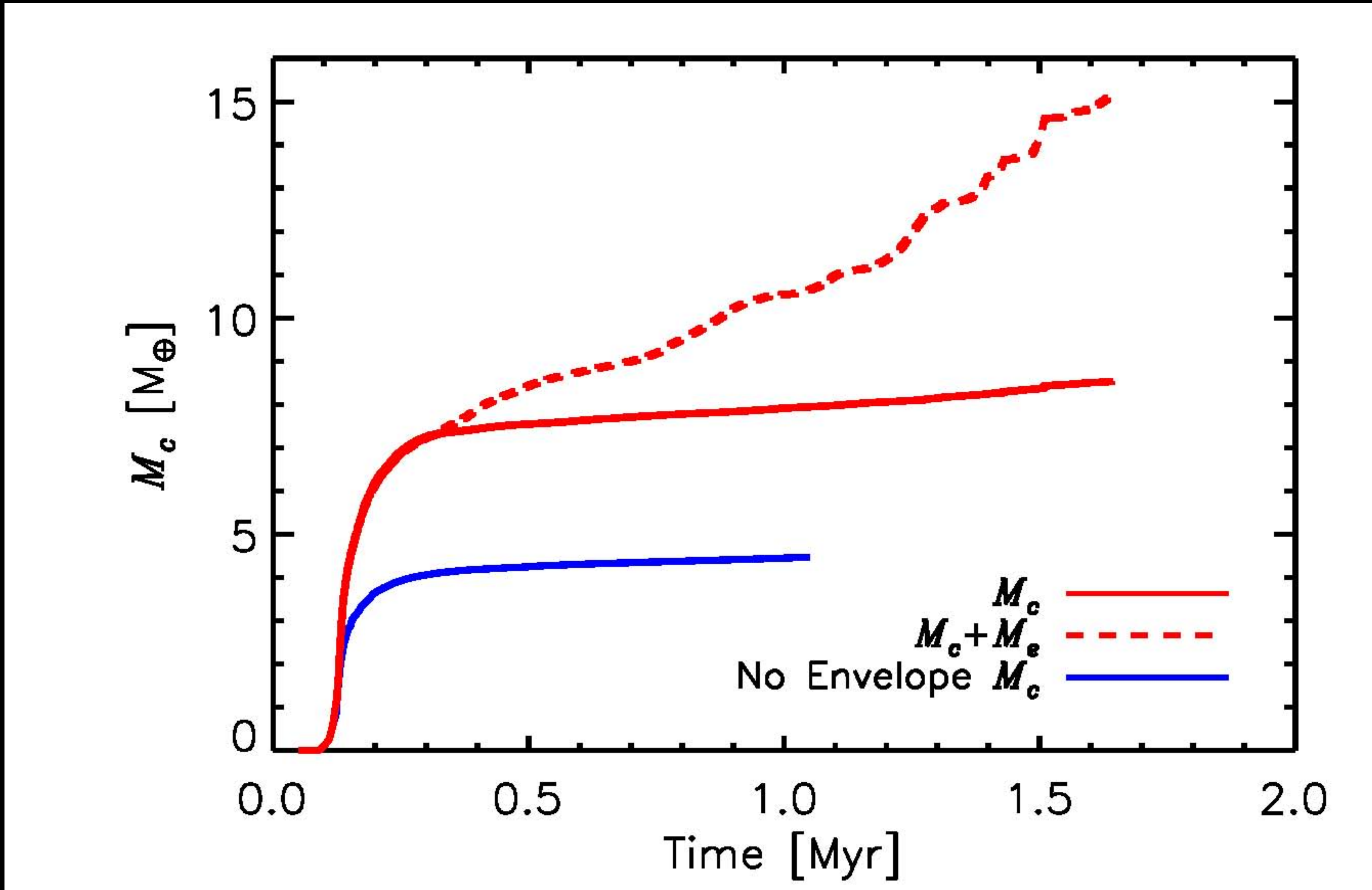


M_{core}= 3 M_E M_{env}= 3x10^{-4} M_E t = 8.4x10^4 yr

Later Growth is by Erosion of the Swarm at Edges



M_{core}= 7 M_E M_{env}= 2x10^{-2} M_E t = 2.3x10^5 yr



Envelope Mass Approaches Core Mass at about 1.5 Myr

- *Core ~ 10 M_{Earth} takes too long to accrete unless surface density of planetesimals is >> Minimum Mass Solar Nebula.*
- *However, core begins to capture a static envelope of nebular gas before it attains critical mass. This envelope significantly increases efficiency of planetesimal capture and allows the core to grow larger, faster*.

Mutual collisions and gas drag produce shepherding and gap formation. This limits core mass to ~ 1/2 of the isolation mass, if interactions of planetesimals with the core's gaseous envelope are neglected

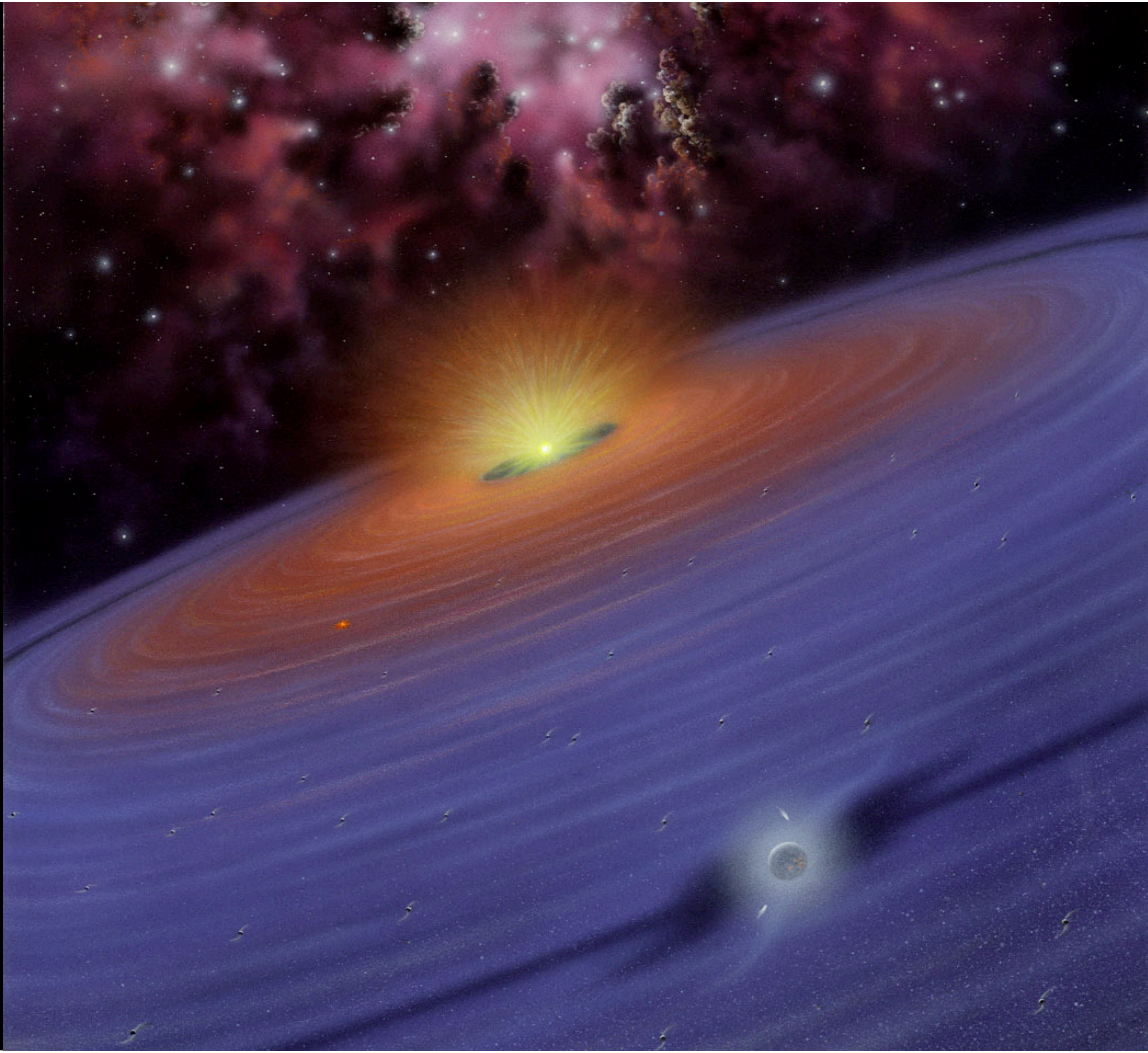
A gaseous envelope from the nebula substantially enhances the accretion rate of solids and allows the core to approach critical mass

Captured envelope becomes significant component of total mass of the planet

Gaseous envelope significantly affects core growth long before the envelope collapse phase

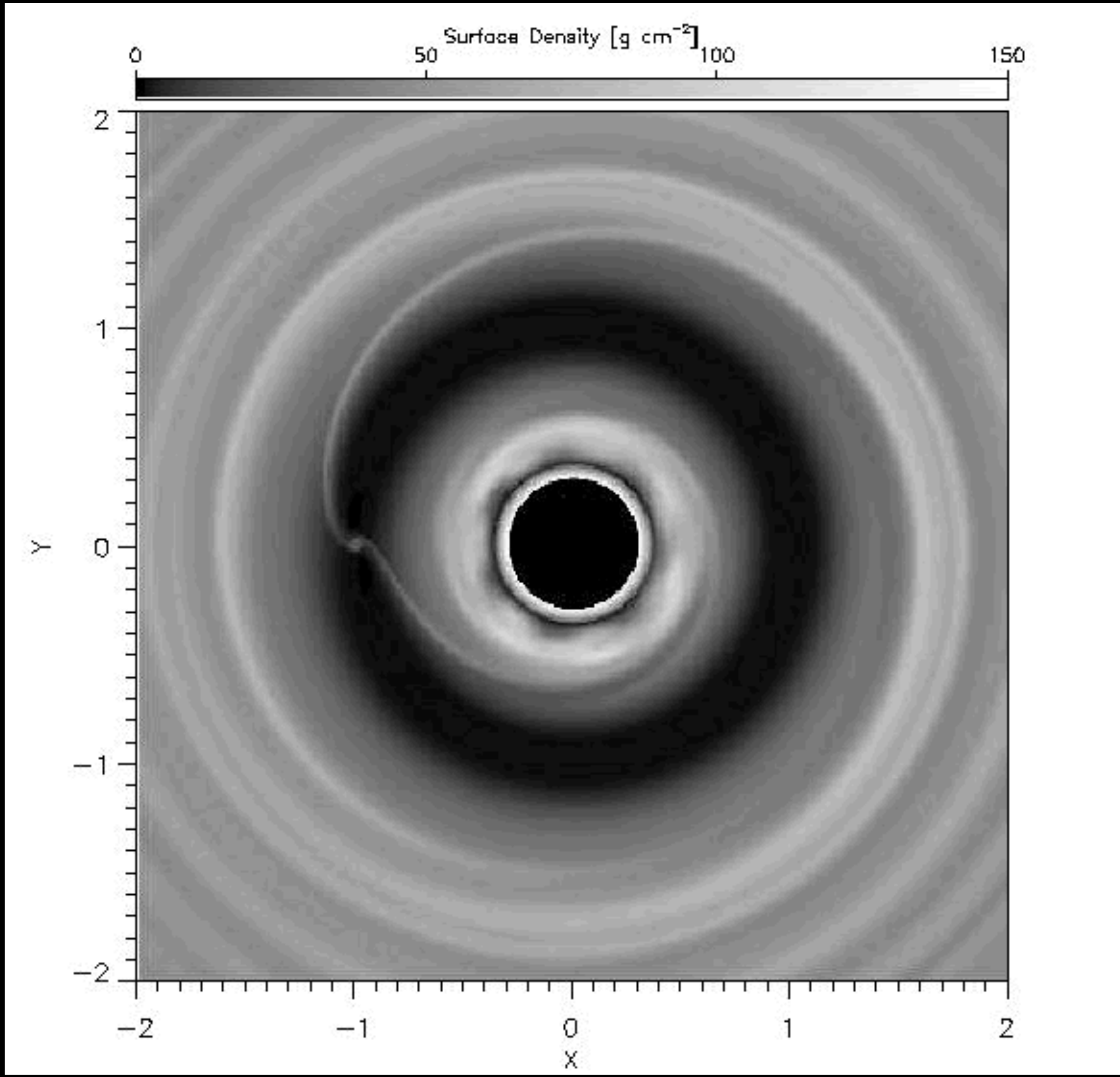
A seed body with mass ~ 10^{-4} M_{Earth} embedded in a swarm of smaller planetesimals is sufficient to initiate "monarchical" runaway growth

A solids surface density of σ = 10 g/cm^2 allows Jupiter to form within the lifetime of a typical protoplanetary disk



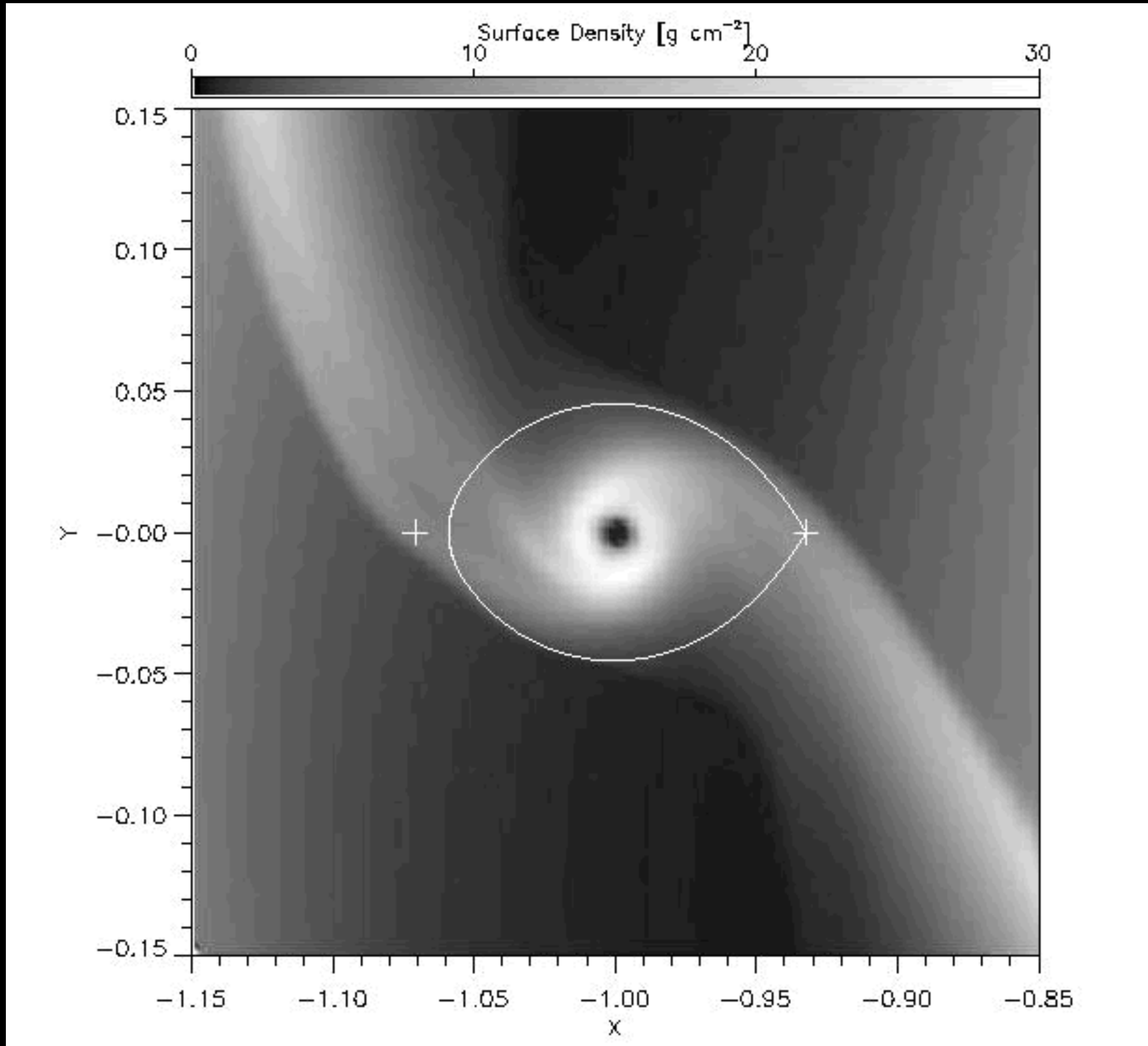
Very Massive Planets Clear Gaps

Bate et al. (2003) *MNRAS*



3-D Close-up of Planet Clearing a Gap

Bate et al. (2003) *MNRAS*



Orbital Evolution

- **Disk-planet interactions**
  - No gap: Migration relative to disk
  - Gap: Moves with disk
  - Faster near star - need stopping mechanism
- **Planet-planet scattering**
  - Produces eccentric orbits
  - Planets well-separated
  - Some planets ejected

Conclusions

- Planet formation models are developed to fit a very diverse range of data
  - Meteorites, planetary orbits, composition, circumstellar disks, extrasolar planets
- Planets form in gas/dust disks orbiting young stars
  - Most stars form together with such a disk
- Solid planets grow by pairwise accumulation of small bodies
  - Massive planets gravitatationally trap H_2, He
- Planets are common, and planetary systems are diverse
  - New technologies allow observations of many types of extrasolar planets