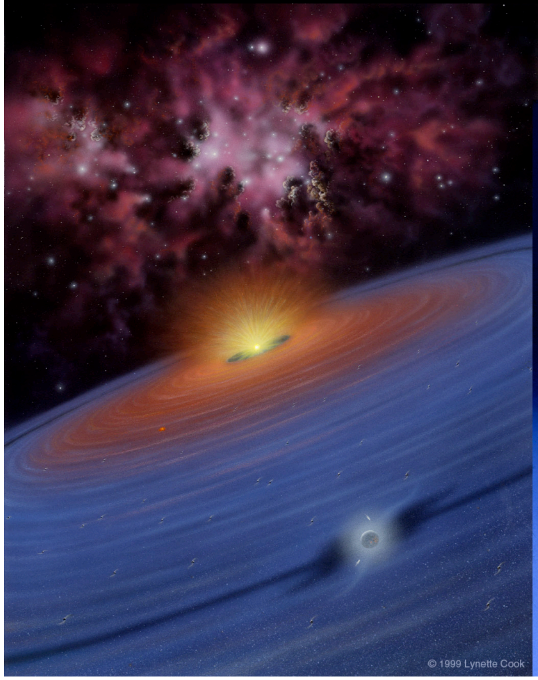
Planetary Formation & Migration

Jack Lissauer - NASA Ames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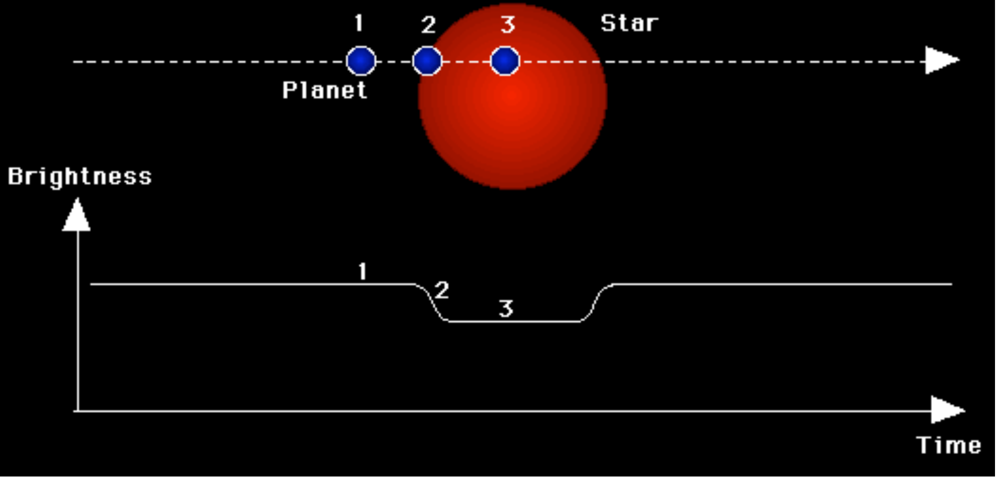
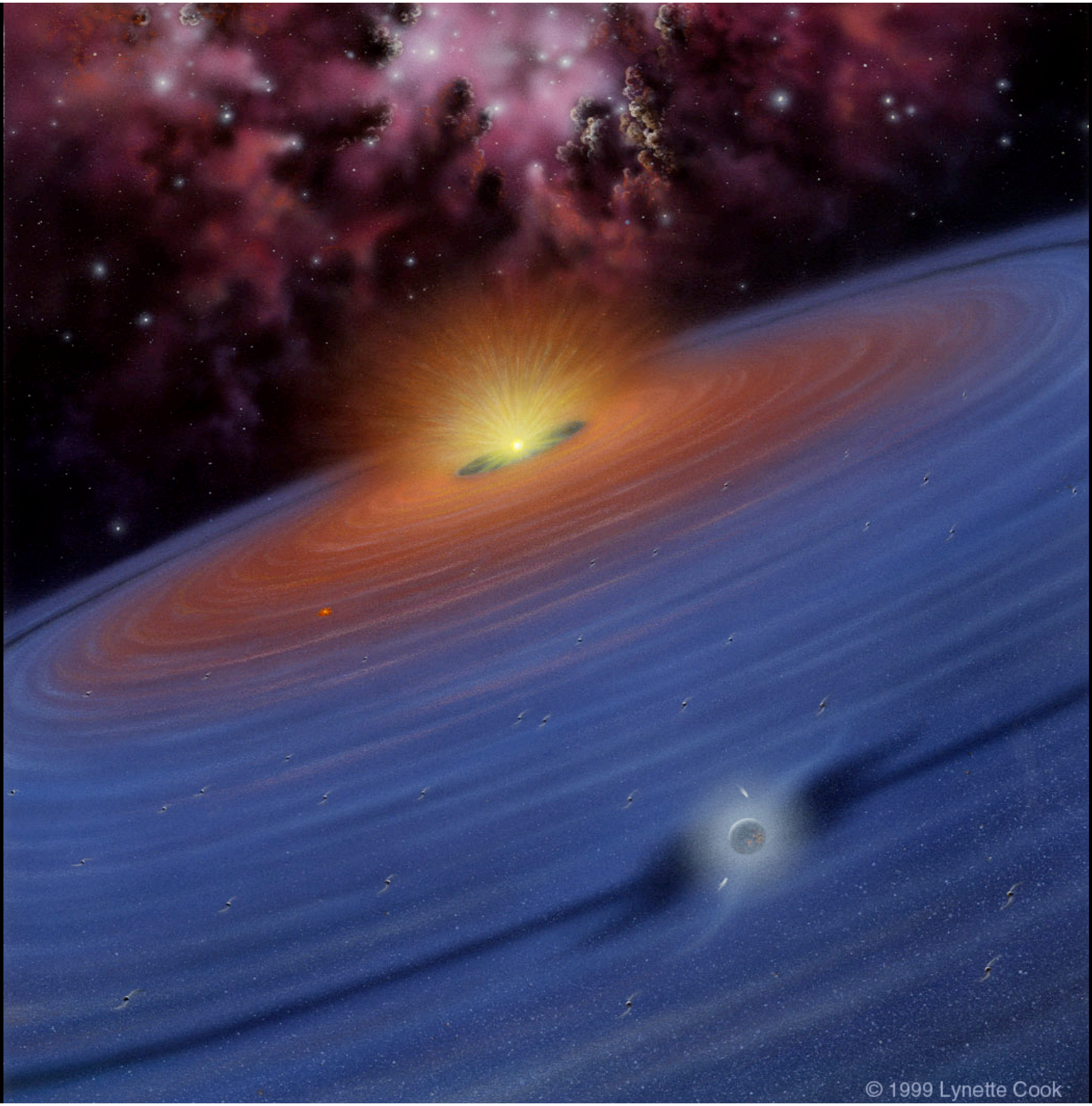


- **Observations: Meteorites to Extrasolar Planets**
  - Our Solar System
    - Dynamics
    - Meteorites
    - Geology
    - Planetary composition & structure
  - Other Stars
    - Circumstellar disks
    - Extrasolar planets
- **Models: Solar Nebula & Planetesimals**
  - Protoplanetary Disks
  - Solid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



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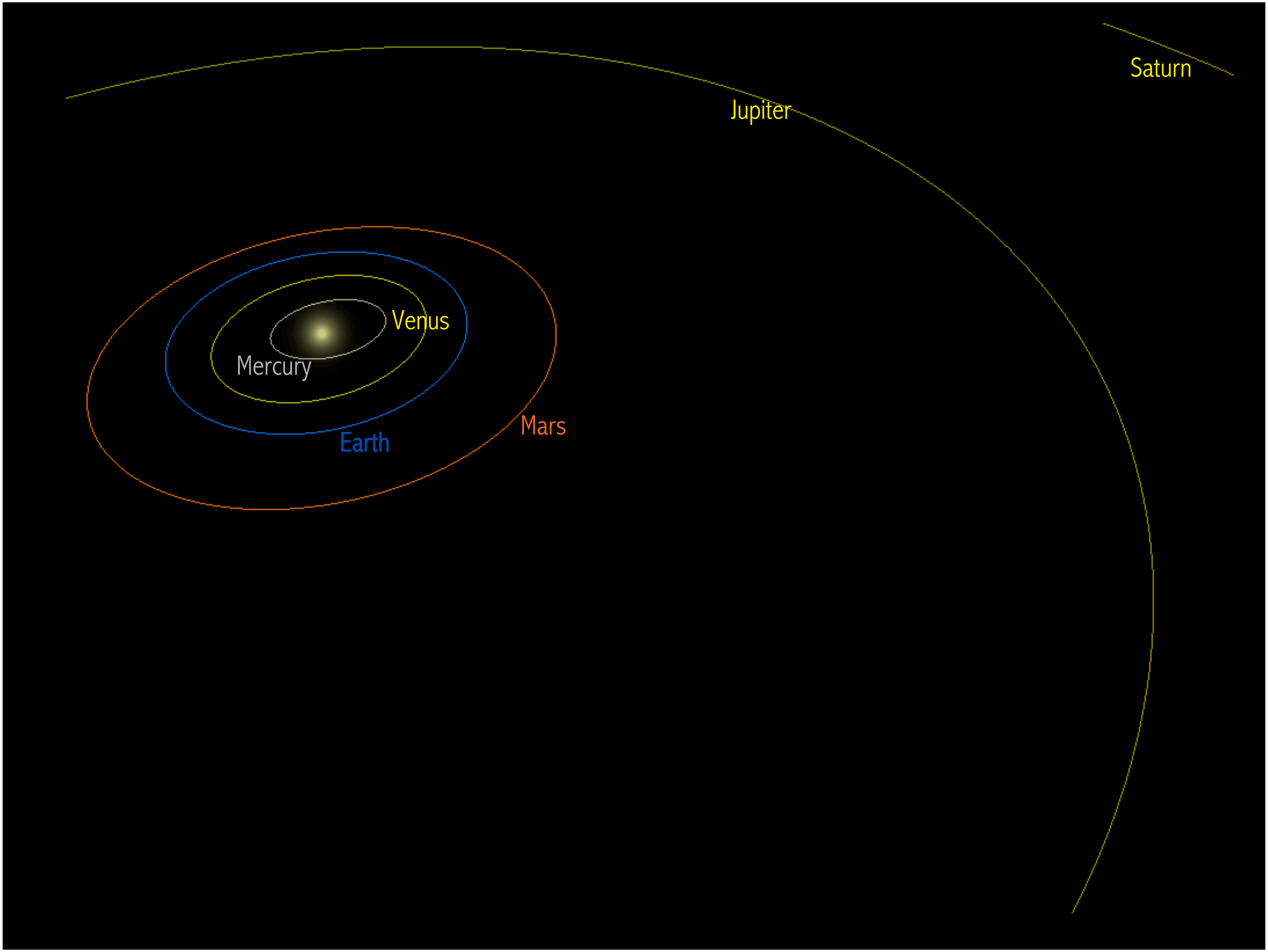
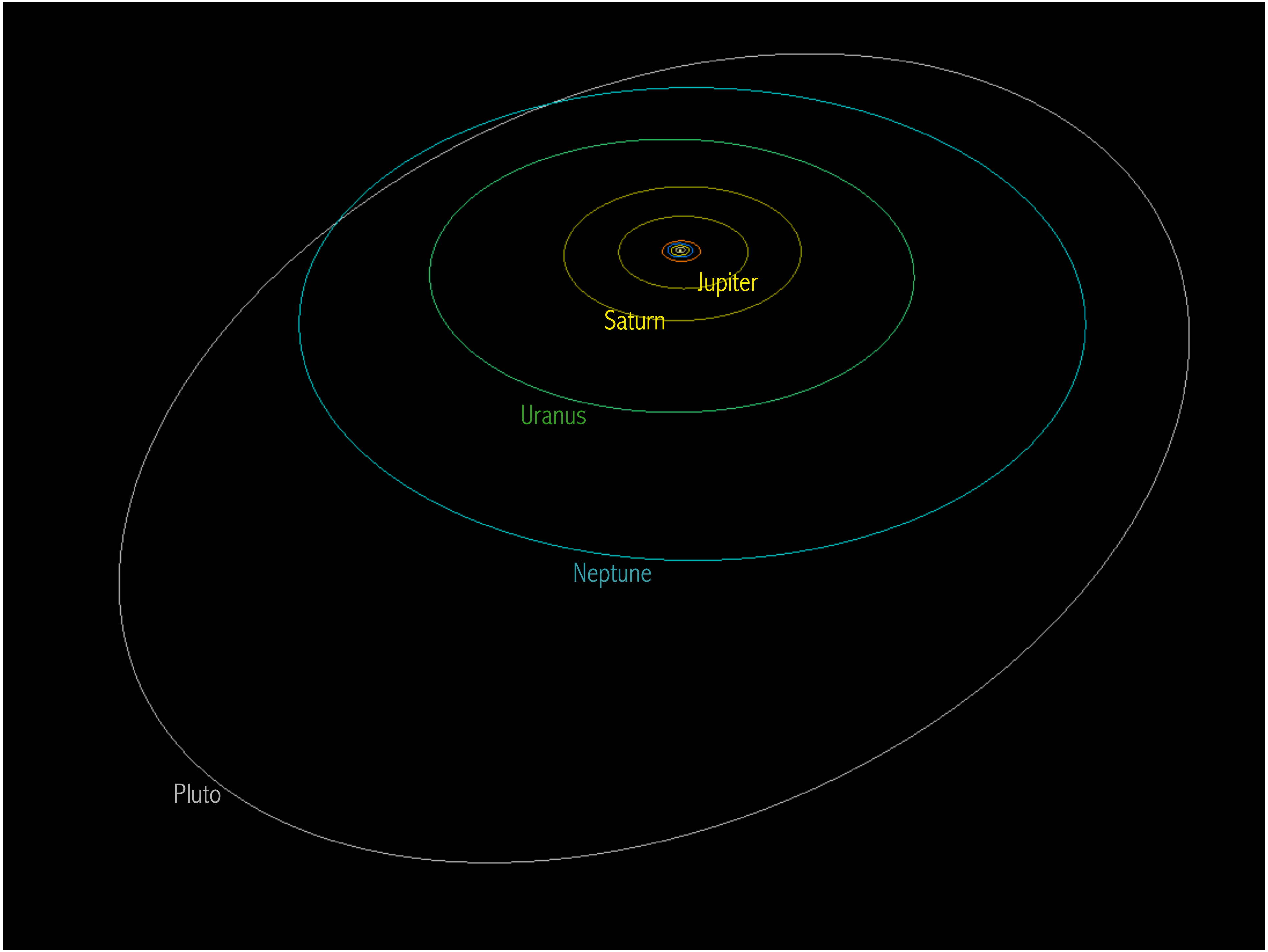
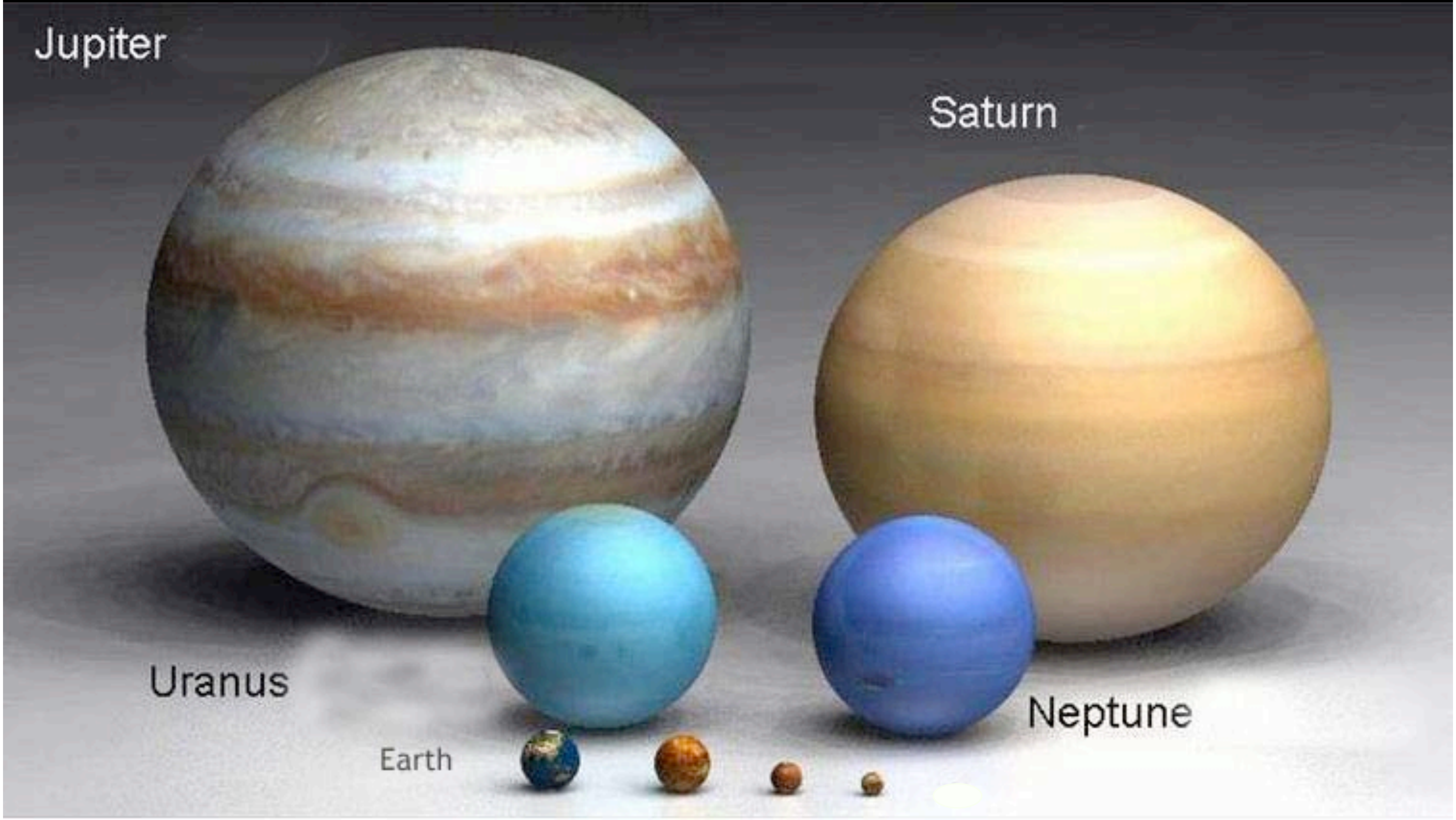
Our Solar System

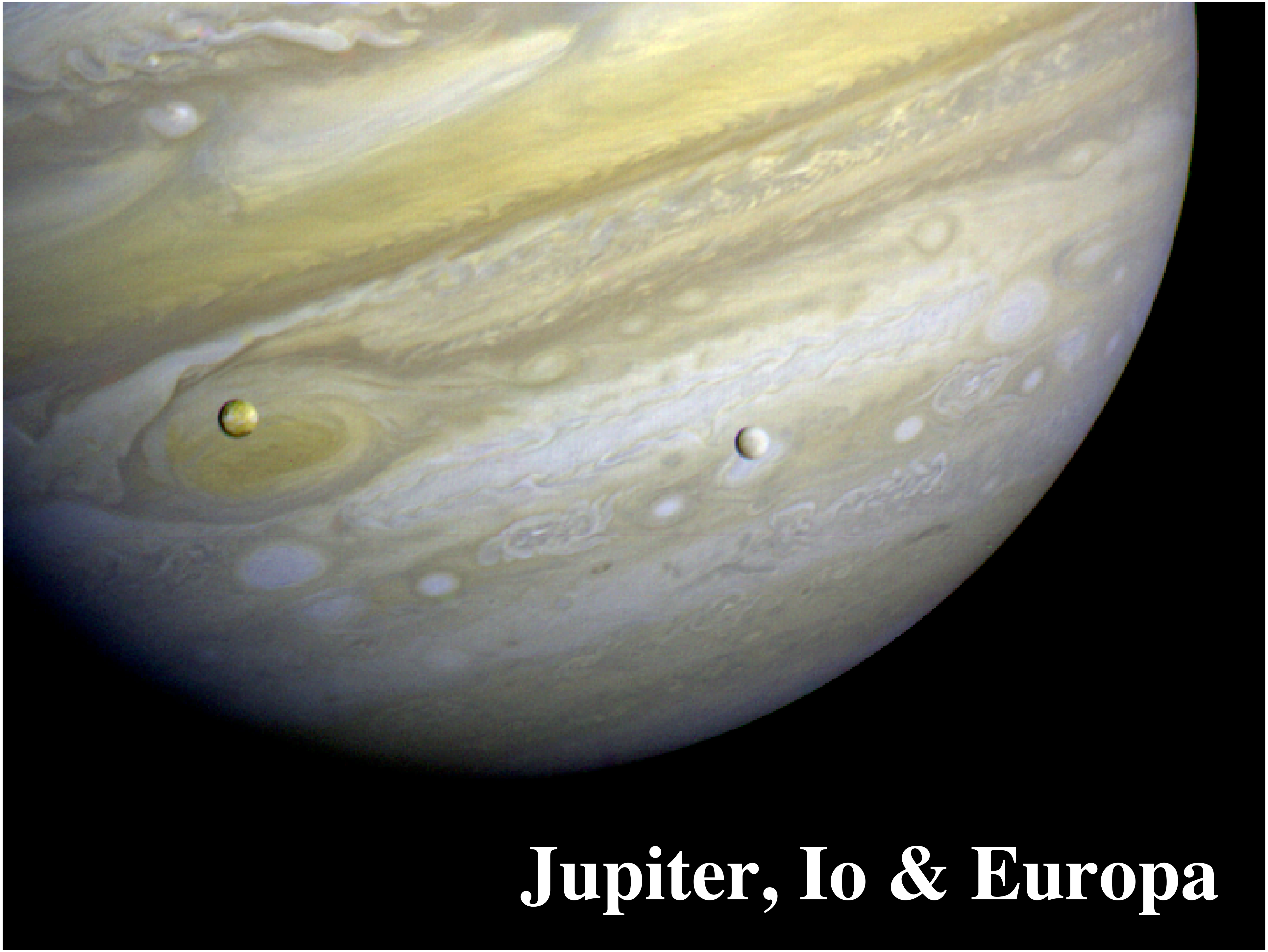
- Dynamics
  - Planetary orbits nearly circular & coplanar
  - Spacing increases with distance from Sun
  - All giant planets have satellite systems
  - Moons far from planets; rings close to planets
- Compositions
  - Largest bodies most gas-rich
  - Rocky bodies near Sun, icy bodies farther out
  -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


Saturn
Jupiter
Venus
Mercury
Mars
Earth


Jupiter
Saturn
Uranus
Neptune
Pluto

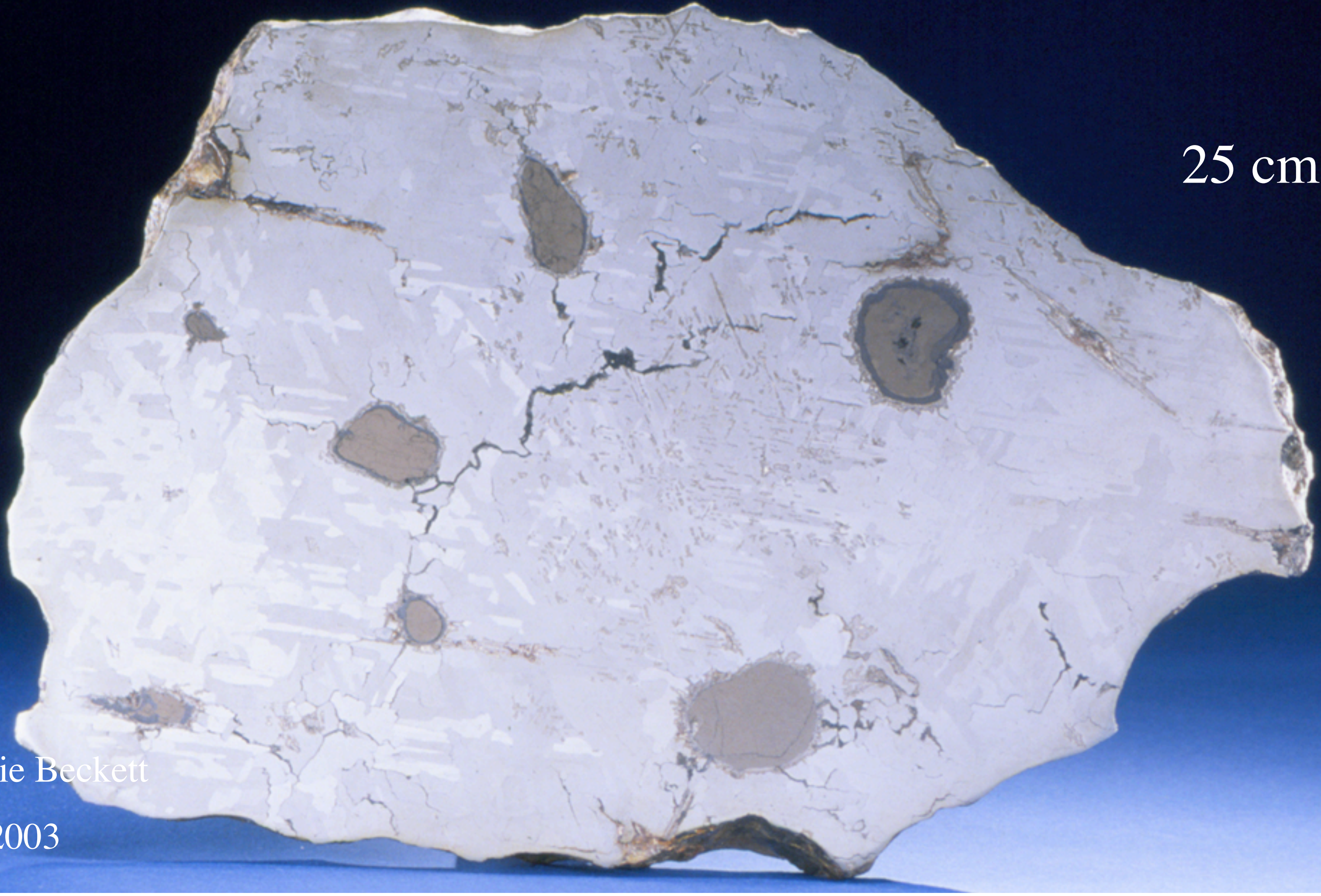
Our Solar System





Jupiter, Io & Europa

Canyon Diablo (Meteor Crater, AZ) **Iron IA** Find



25 cm long

Photo: Jackie Beckett

Meteor Crater

Arizona, USA Smithsonian 1938

Ibitira (Brazil) **Eucrite (4 Vesta, vesicular basalt from crust)**

Fall 1957 Jun 30

Photo: Jackie Beckett

Modoc (KS) **L6 Ordinary Chondrite** Fall 1905 Sep 2

Photo: Jackie Beckett

Peekskill (NY) **H6 Ordinary Chondrite** Fall 1992 Oct 9

12 cm

Photo: Jackie Beckett

Peekskill (NY) Falling on 1992 Oct 9

Photo: S. Eichmiller,
Altoona PA

Orbit

$a = 1.49$ AU

$e = 0.\ 41$

$i = 4.9^{o}$

Peekskill (NY) Meteorite + car it impacted

& Ray Meyer, meteorite dealer

Murchison (Australia) **CM2 Carbonaceous Chondrite** Fall 1969 Sep 28

Photo: Jackie Beckett

Allende (Mexico) **CV3 Carbonaceous Chondrite** Fall 1969 Feb 8

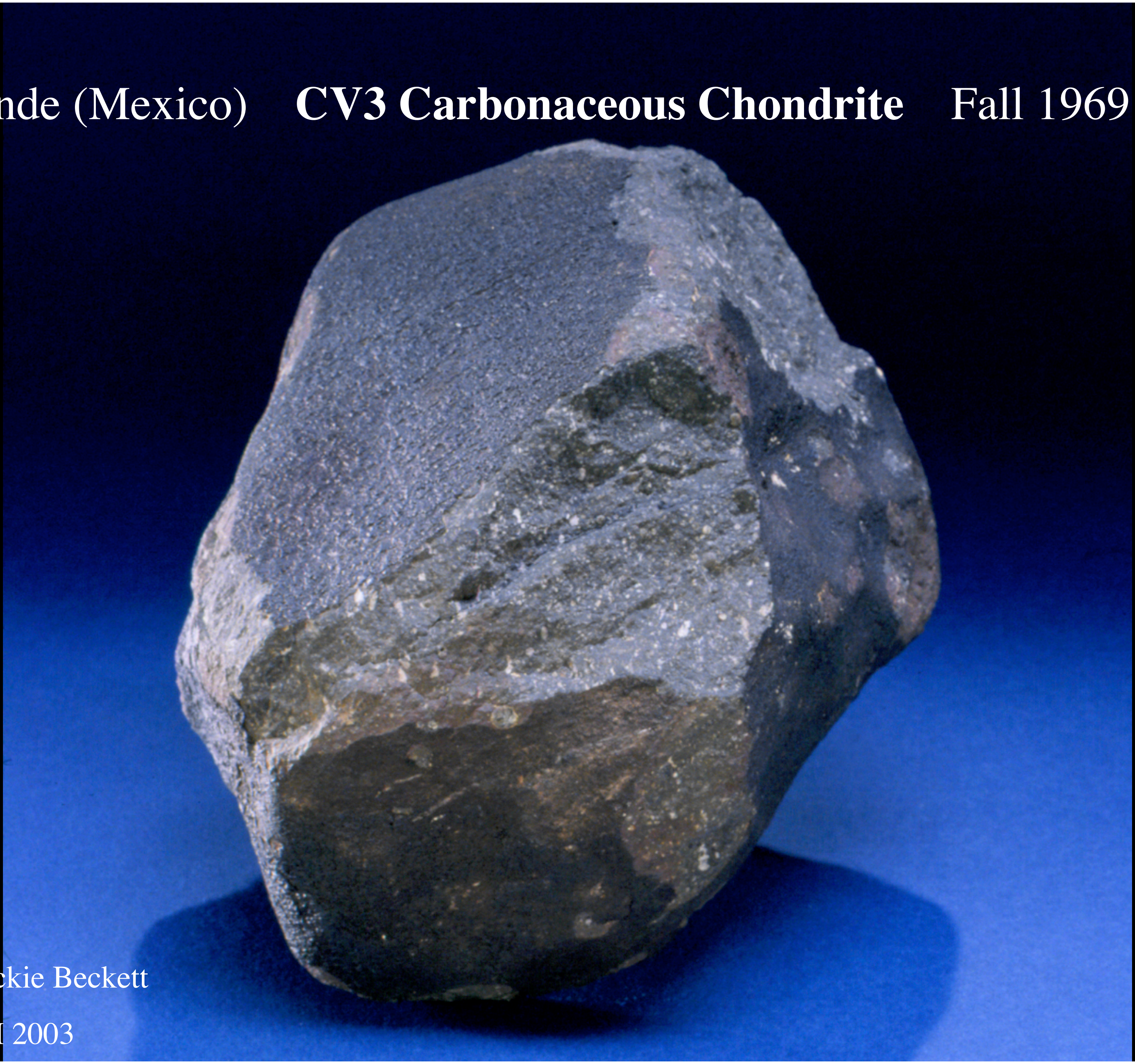


Photo: Jackie Beckett

15 cm

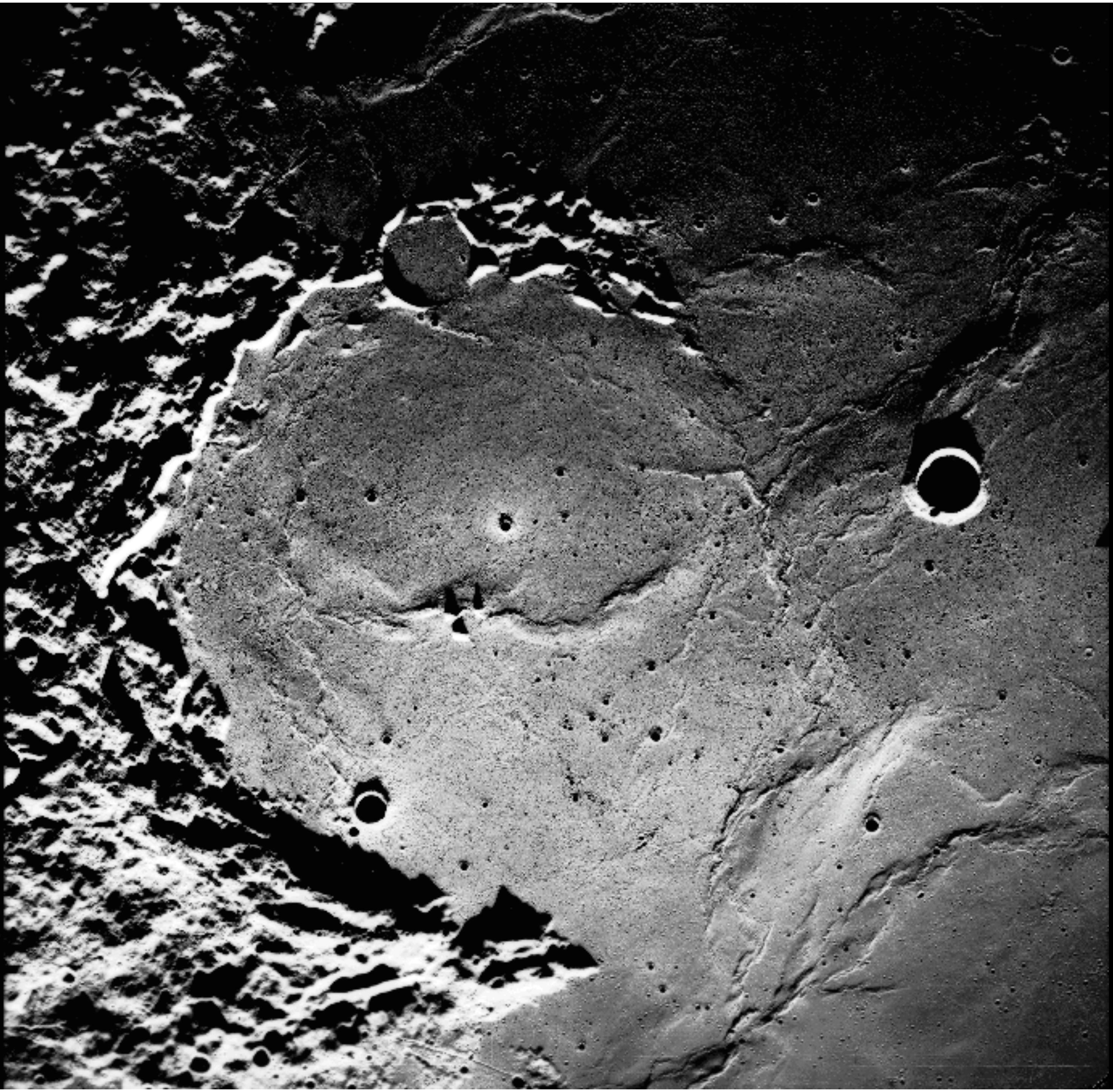
Allende CV3 Carbonaceous Chondrite Meteorite

Close-up view.
This piece is 39 mm long.

Note CAIs & chondrules.

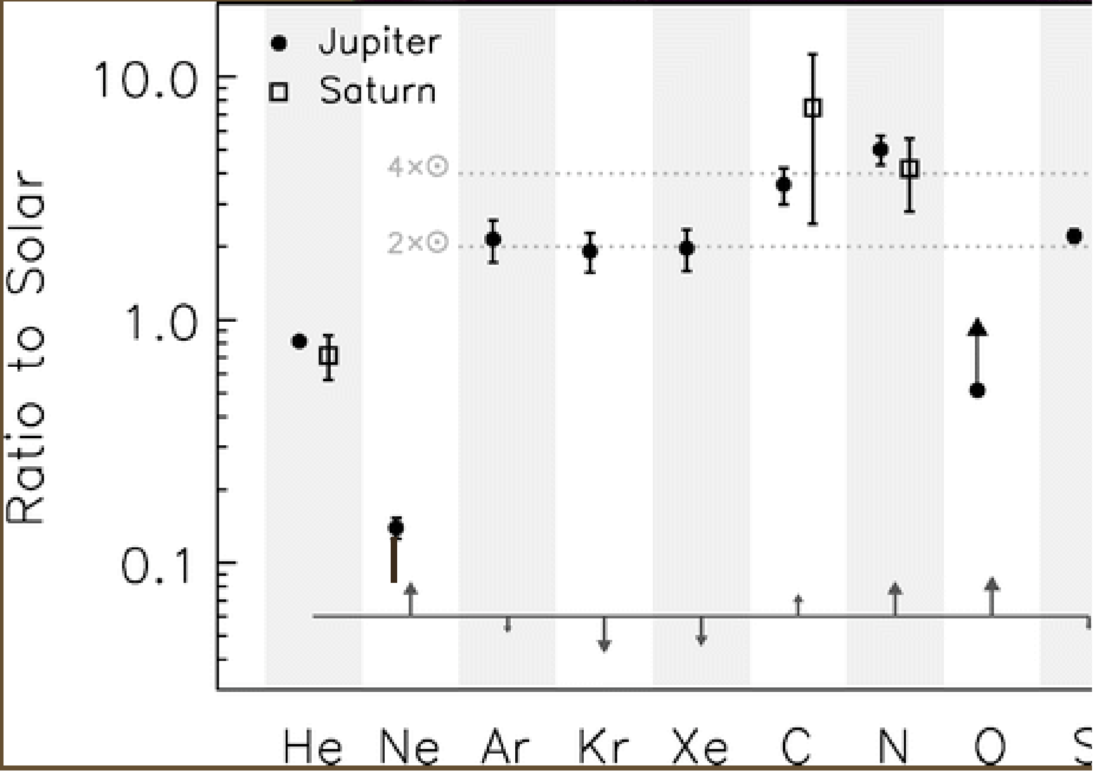
Constraints from Meteorites

- Solar System formed 4,567 ± 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



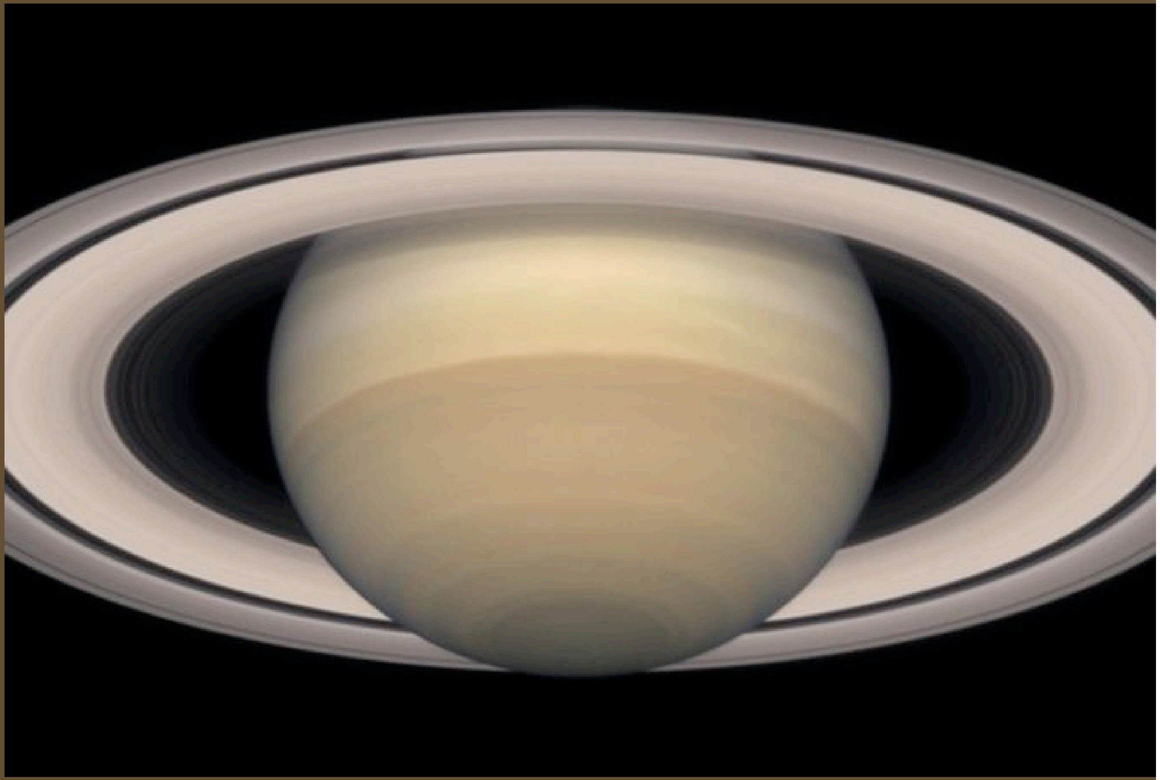
Jupiter

- Metallic hydrogen interior to 0.85 Jupiter radii.
- Factor of **3** enrichment of heavy elements in atmosphere
- Factor of 3 - 10 bulk enrichment in high-*Z* elements
- Presence of core not certain, but up to ~ 10 M_{Earth}



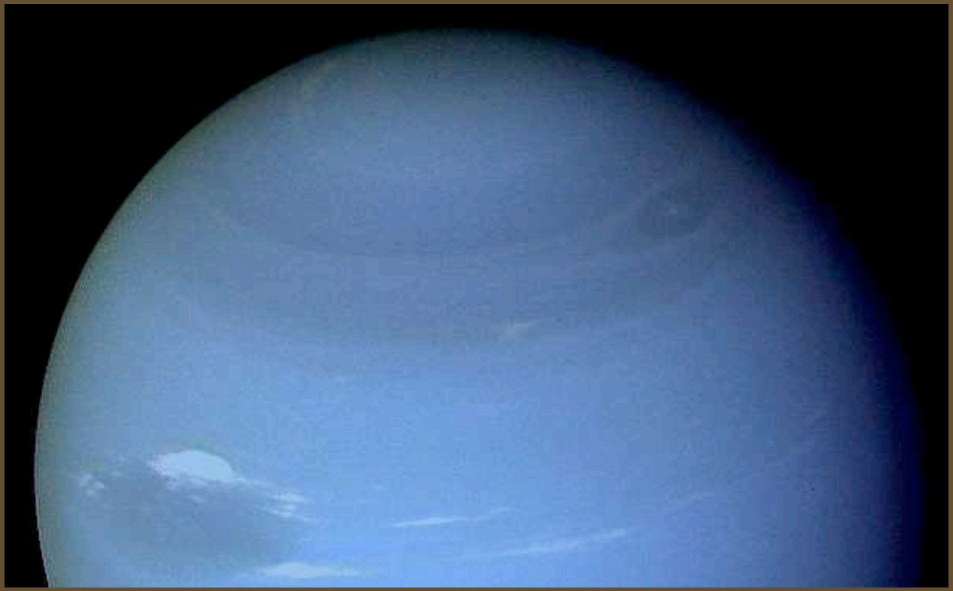
Saturn

- Very similar to Jupiter except less metallic H
- Heavy element enrichment
- Presence of core almost certain; ~ 10 M_{Earth}

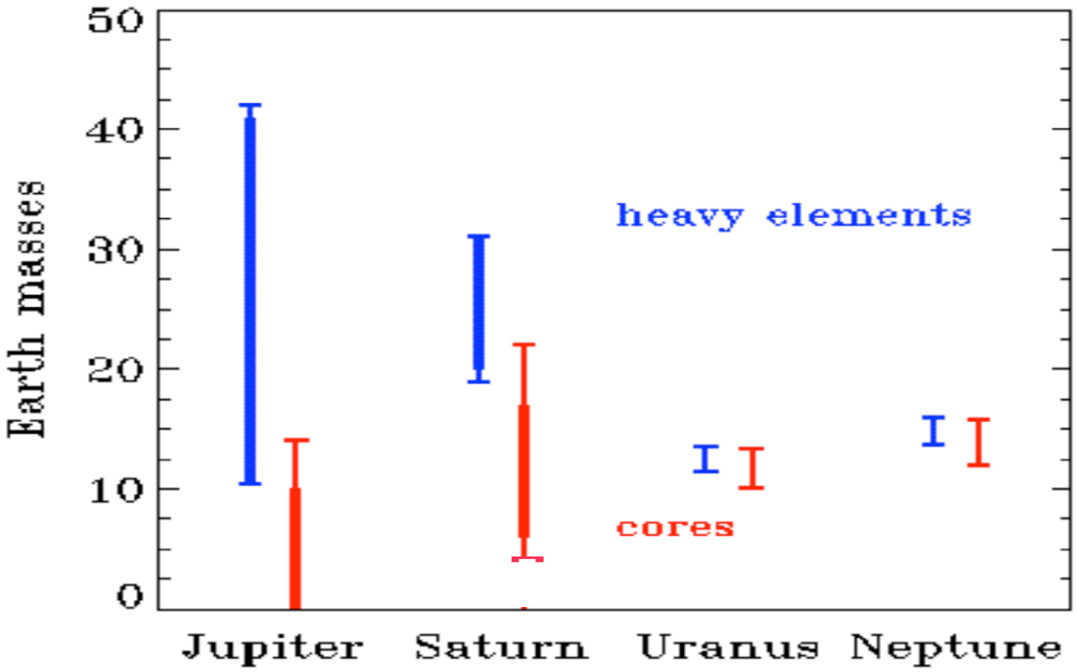


Uranus & Neptune

- 10 - 15 M_{Earth} of ice and rock; a few M_{Earth} of gas.



Neptune

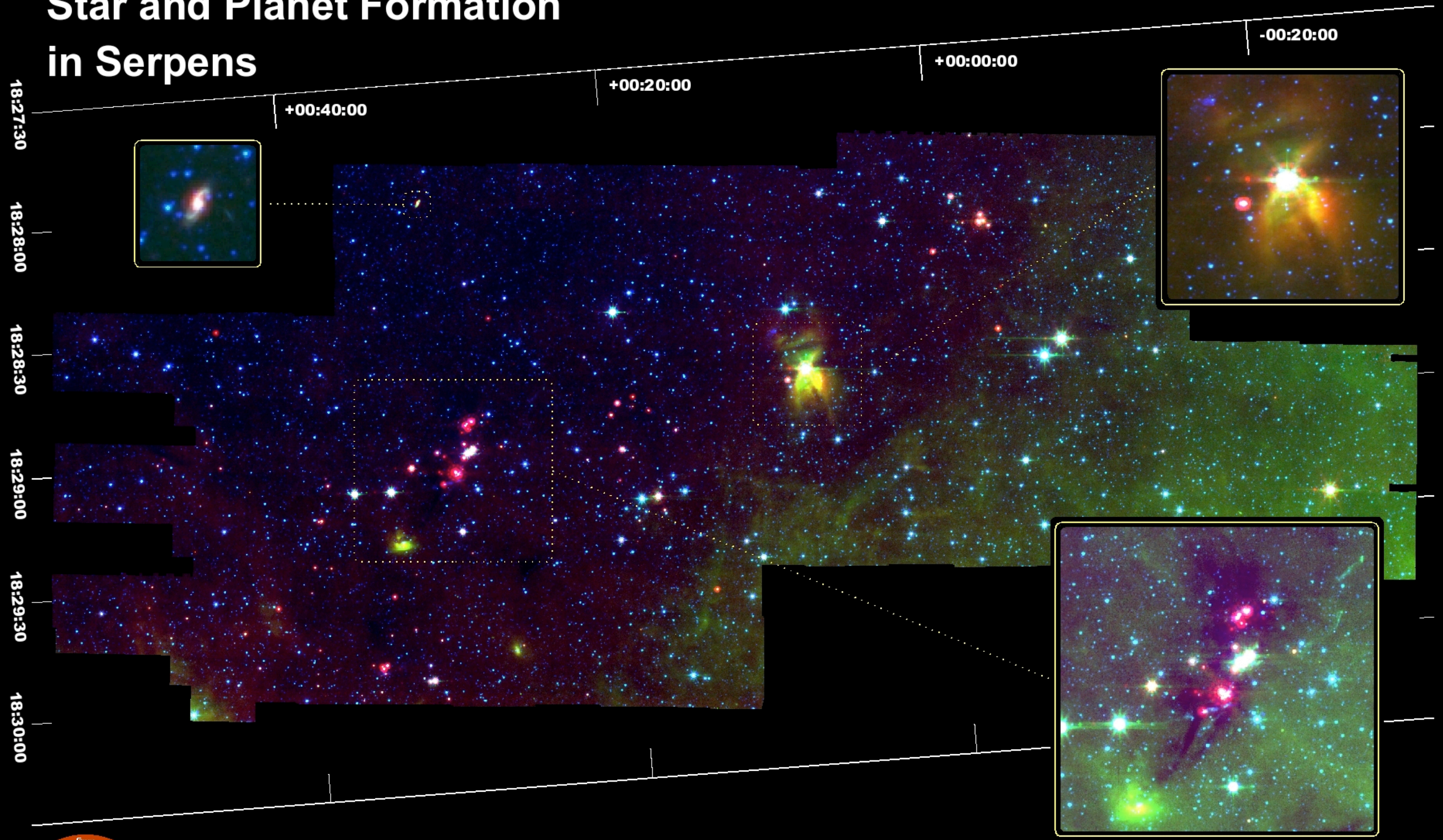


(Modified from Guillot)

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

Infrared Observations of Star Forming Region

Star and Planet Formation in Serpens



"Cores to Disks"
Legacy Team

Spitzer Space Telescope • IRAC • MIPS

24.0, 8.0, 4.5 μm composite image

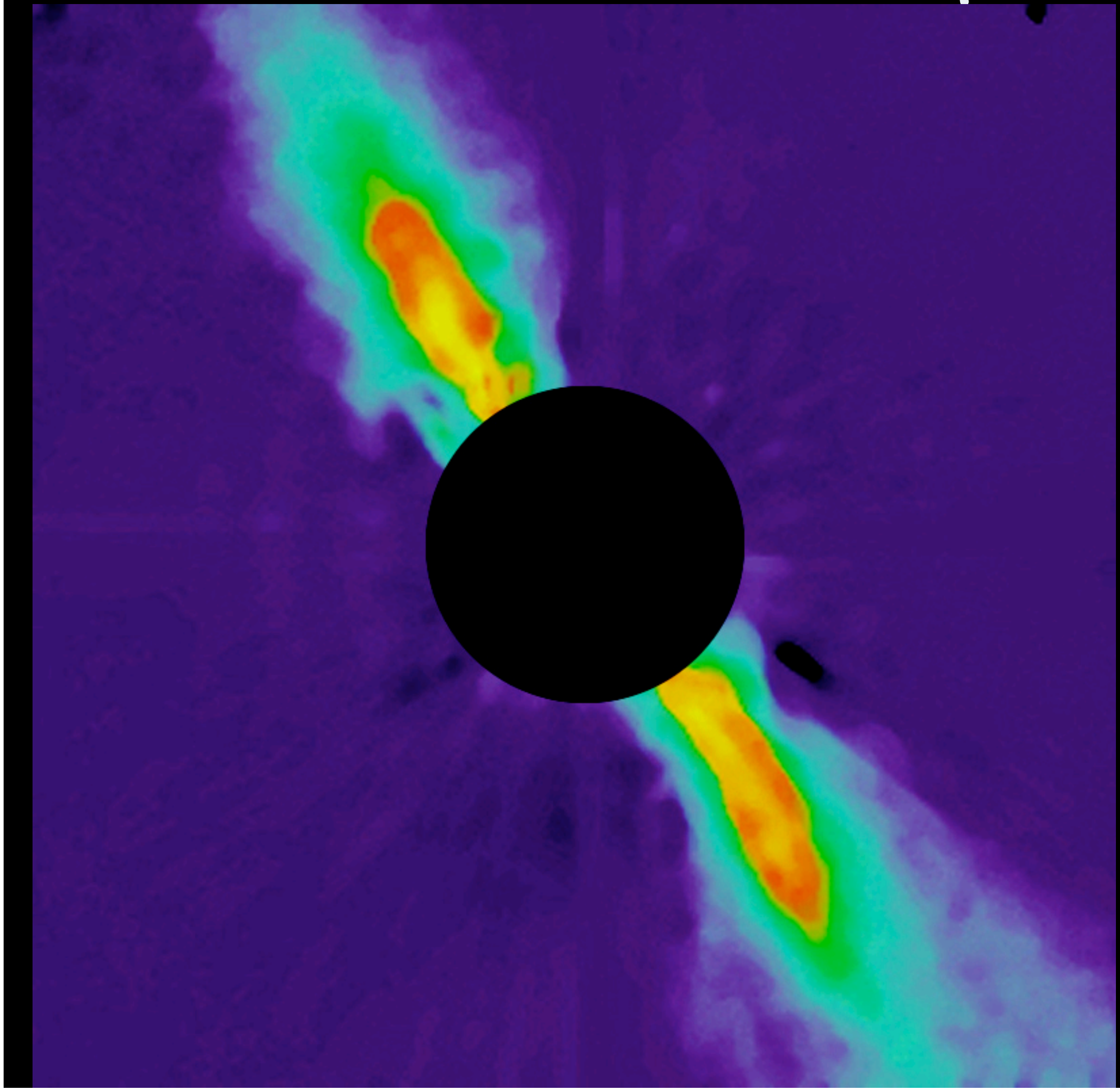
Circumstellar Disks

- Young Stars
  - Evidence: IR excesses, rotation curves, proplyd images
  - Radii tens to hundreds of AU (even larger for massive stars)
  - Typical mass ~ 0.01 - 0.1 M_{Sun}
  - Lifetime (dust) < 10 Myr
  - Some show evidence for gaps, inner holes
- Main Sequence Stars
  - Second generation debris disks - unseen parent bodies
  - Low mass, gas poor
  - More prominent around younger stars
  - Some show evidence for gaps, inner holes

Proplyds in Orion

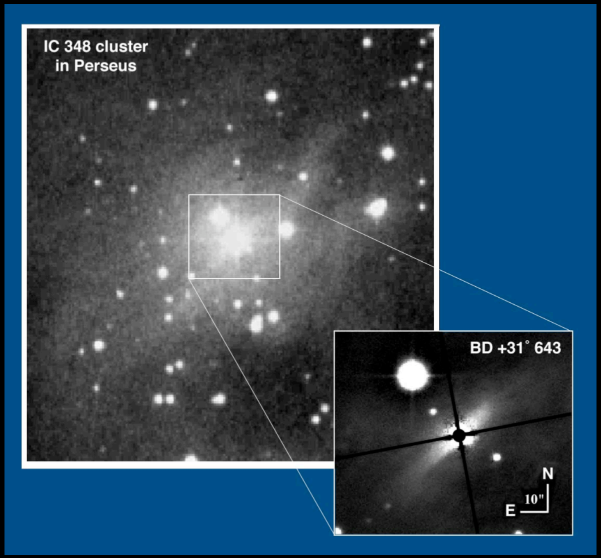
Young Proto-planetary Disk viewed edge-on

β Pictoris Circumstellar Dust Disk at 1.2 μm



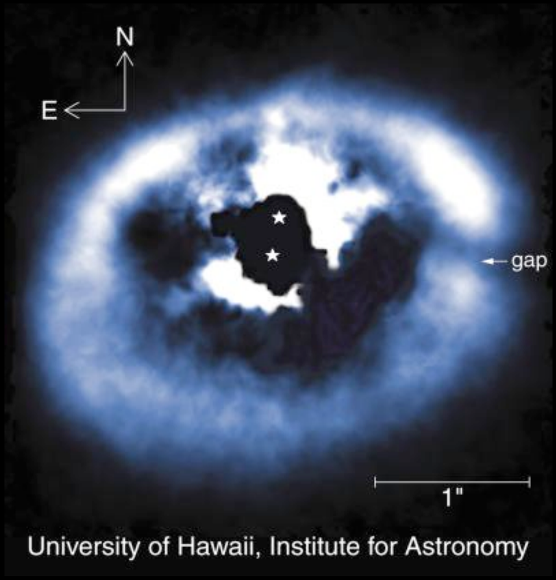
Mouillet et al. 1997,
MNRAS **292,** 896.

Dust Disks Around Young Binaries



← BD +31 643

a_B (stellar semimajor axis) ~ 40 AU



University of Hawaii, Institute for Astronomy

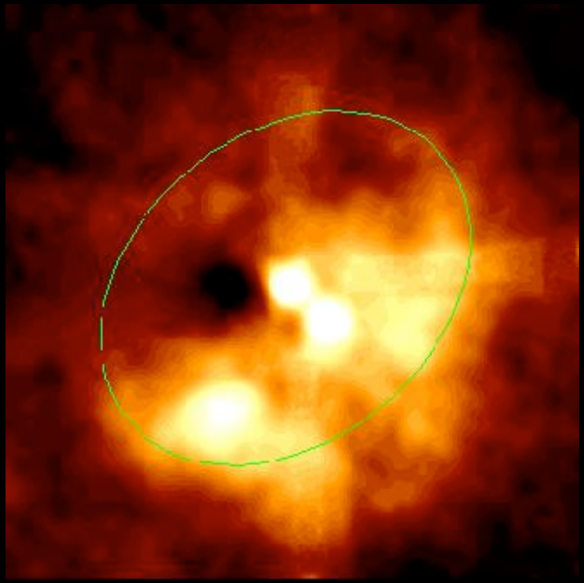
GG Tauri →

$a_B \sim 35$ AU

180 AU < r_{disk} < 260 AU

UY Aur

↓ $a_B \sim 130$ AU



a_B < 1AU

GW Ori	(disk mass $m_D \sim 0.3\ M_{sun}$)
DQ τ	($m_D = 0.02\ M_{sun}$)
UZ τ E	($m_D = 0.06\ M_{sun}$)

Extrasolar Planets: Key Findings

- ~ 1% of sunlike stars have planets more massive than Saturn within 0.1 AU
  - Most if not all are gas giants
  - Models suggest these planets migrated inwards

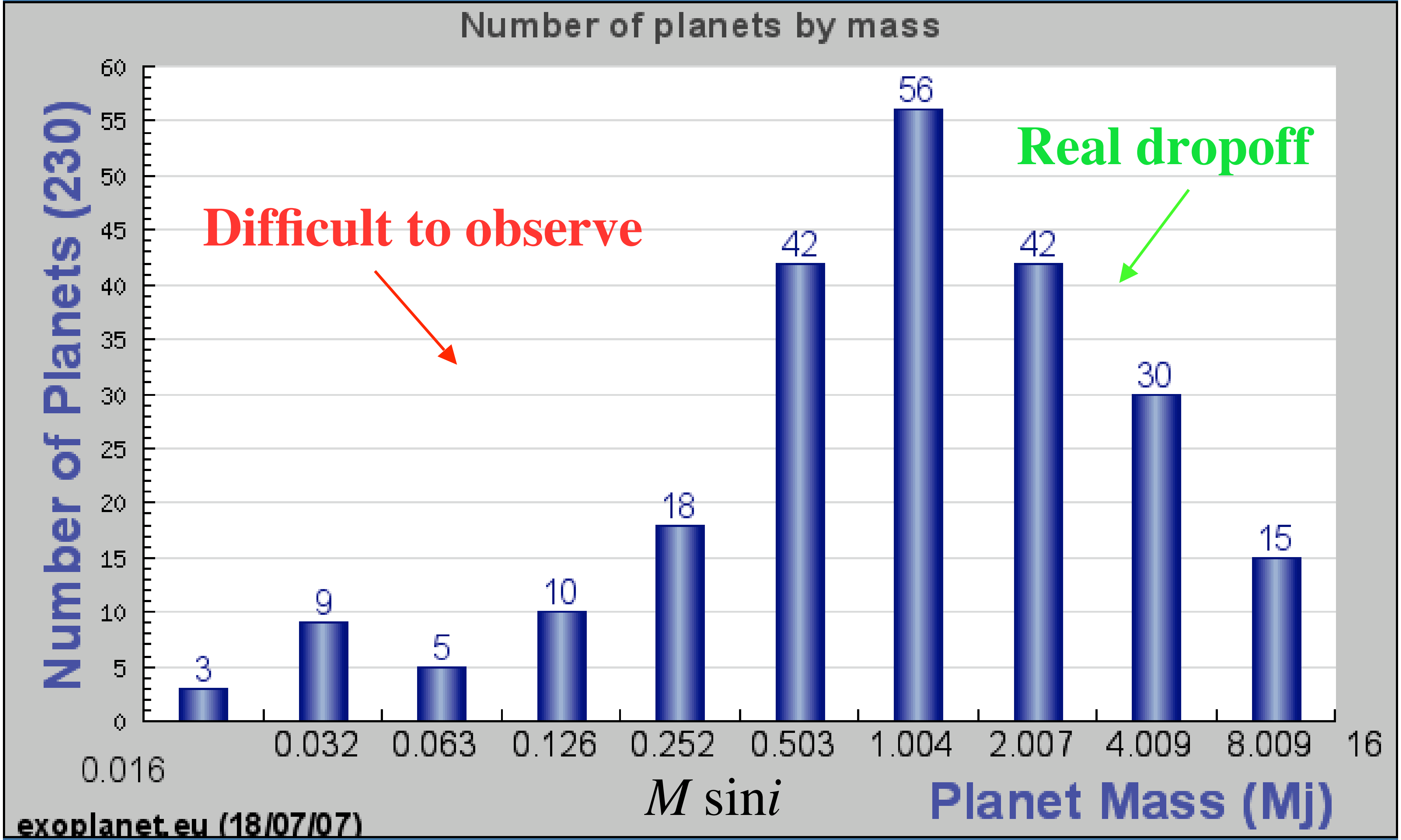
- ~ 7% of sunlike stars have planets more massive than Jupiter within 2 AU
  - Some of these planets have very eccentric orbits

- At least a few % of sunlike stars have Jupiter-like (0.5 - 2 M_J, 4 AU < a < 10 AU) companions, but > 20% do not

- Planets significantly more massive than Jupiter are uncommon

- More (giant) planets around stars with more metals
  - Giant planets more common near more massive stars

Mass Distribution of Planets Detected by Doppler Method

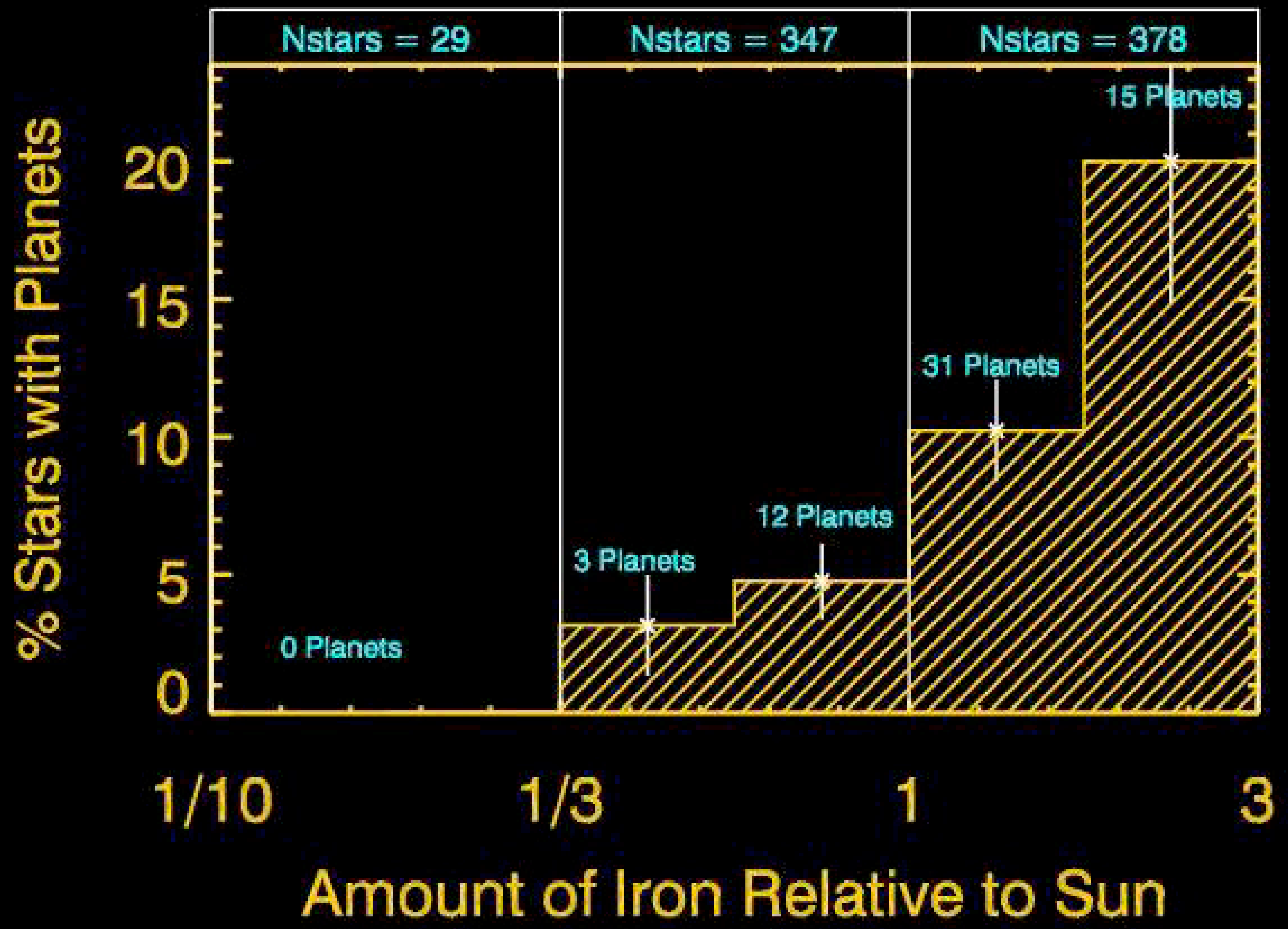


Difficult to observe

Real dropoff

$M \sin i$

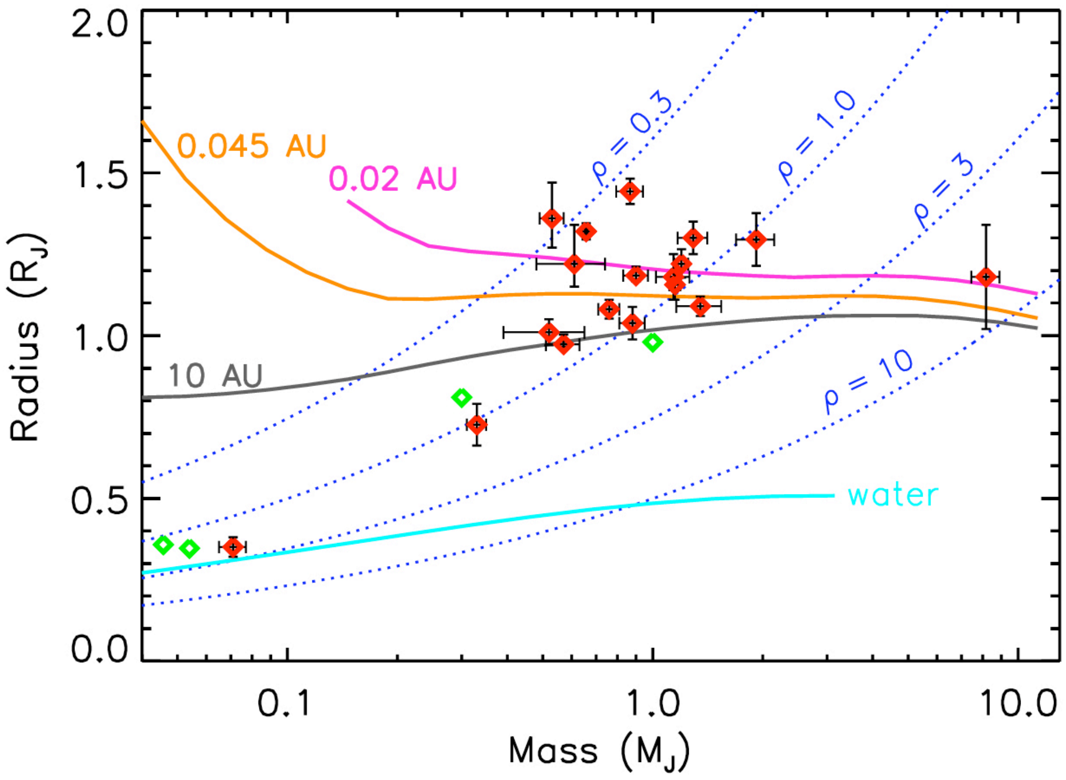
Planet Occurrence Depends on Iron in Stars

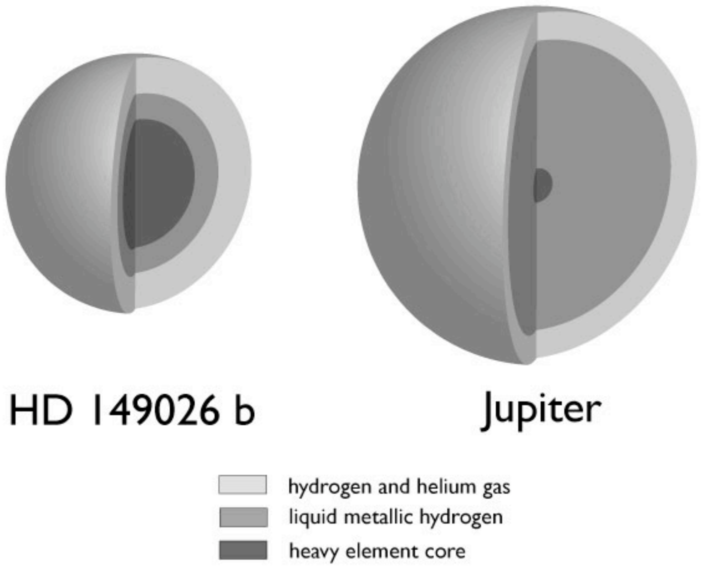


Includes all planets found by California/Carnegie team (7/03).

Giant Planets: Radius *vs.* Mass

All Solar System planets denser than solar composition (>98% H + He), as is HD 149026 b





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 believed to form around most young stars

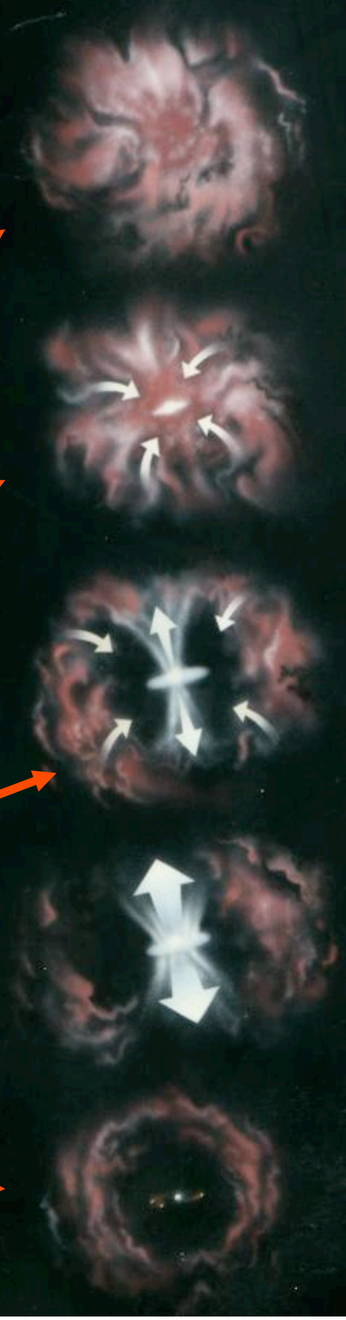
- Theory: Collapse of rotating molecular cloud cores
- Observations: Proplyds, β Pic, IR spectra of young stars

Predicts planets to be common, at least about single stars

Star Formation

Shrink size by 10^7; increase density by x 10^{21} !

Where planets also form



- **Giant Molecular Cloud Core**

  Raw material for star birth

- **Gravitational Collapse & Fragmentation**

  Proto-stars, proto-binaries, proto-clusters

- **Rotation & Magnetic Fields**

  Accretion disks, jets, & outflows

- **Planets**

C. Lada

Protoplanetary Disk Formation & Evolution

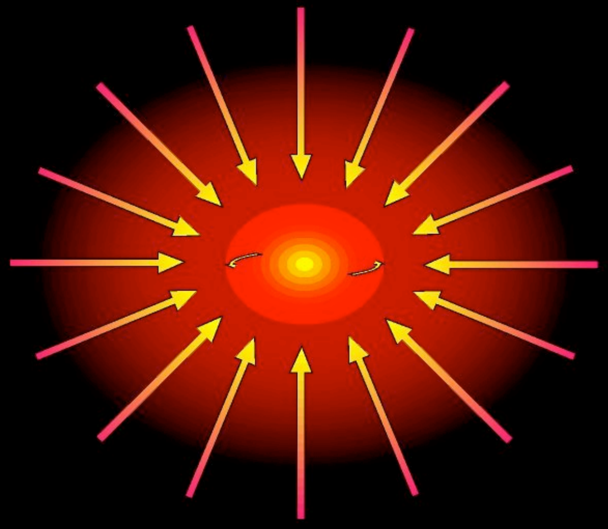
Material falls into gravitational well - it gets heated

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

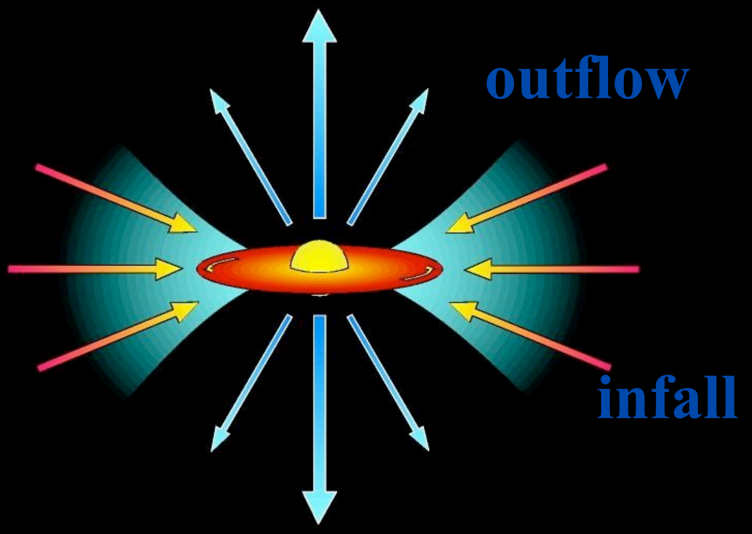
Disks spread: viscosity, gravitational & magnetic forces

- Disk profile flattens
- Star accretes from disk

Scenario for star- and planet formation

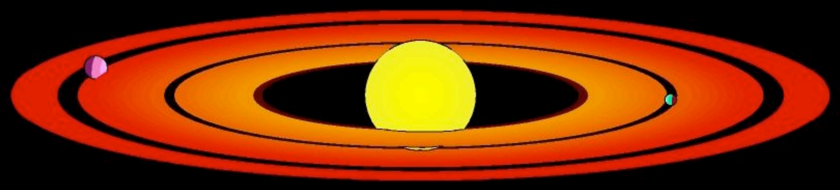


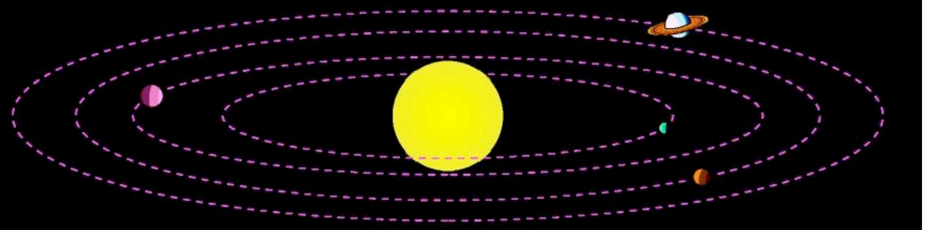
Factor 1000 smaller



Cloud collapse

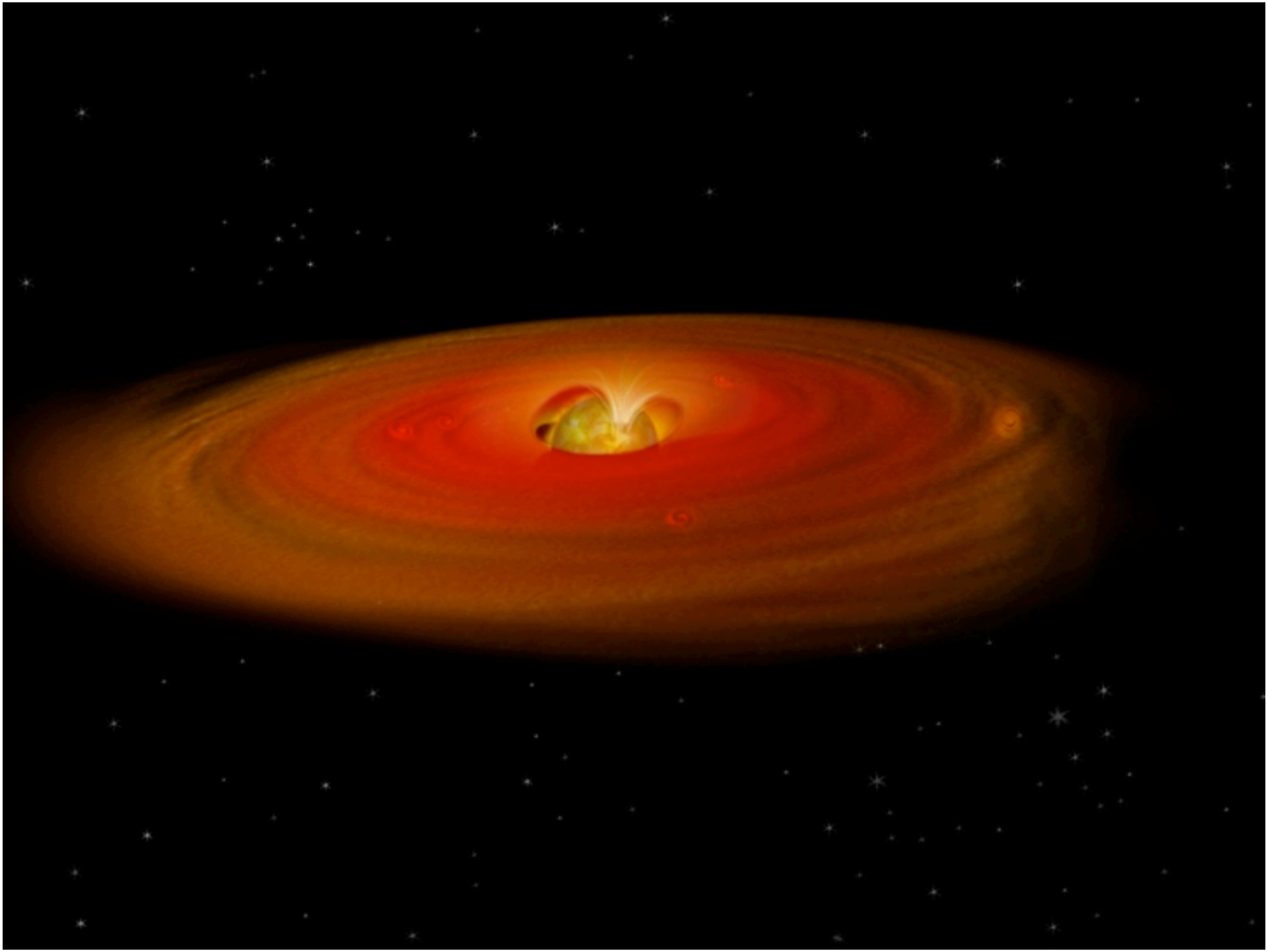
Protostar with disk $t=10^5$ yr





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

Planetary system $t>10^8$ yr



Condensation Sequence

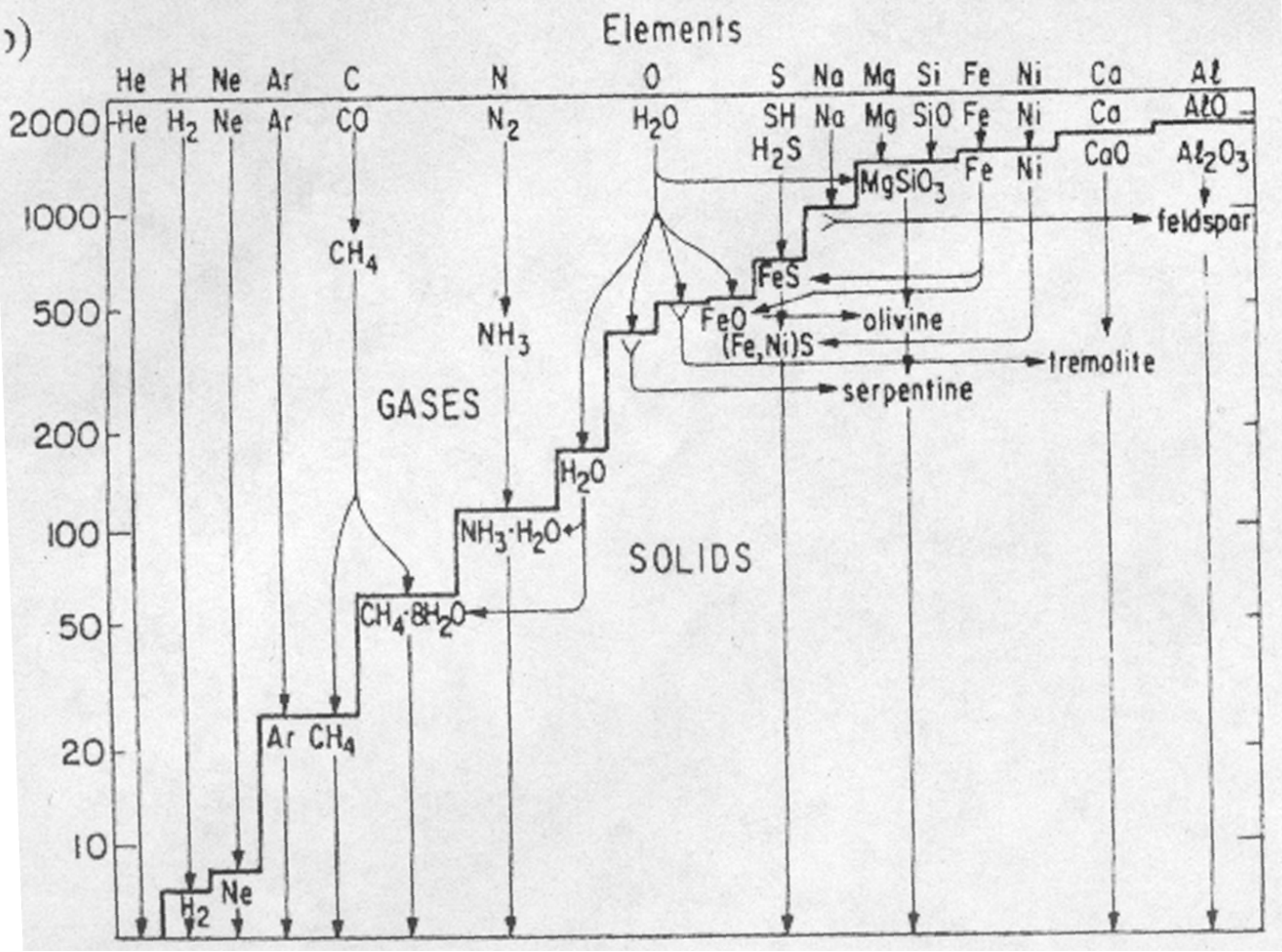
As a gaseous mixture cools, grains condense

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

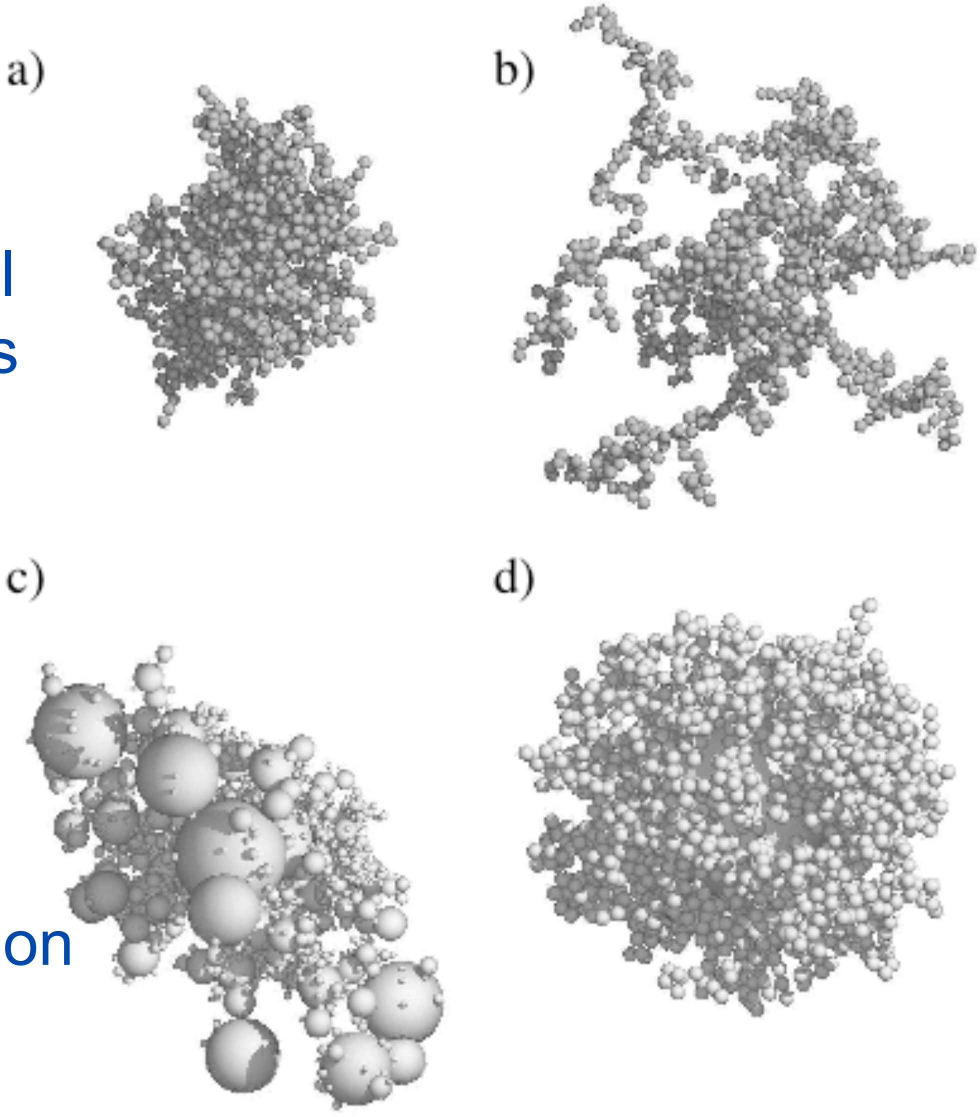
Equilibrium vs. kinetic inhibition

- 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
  - ~ 0.02 M_o
- 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

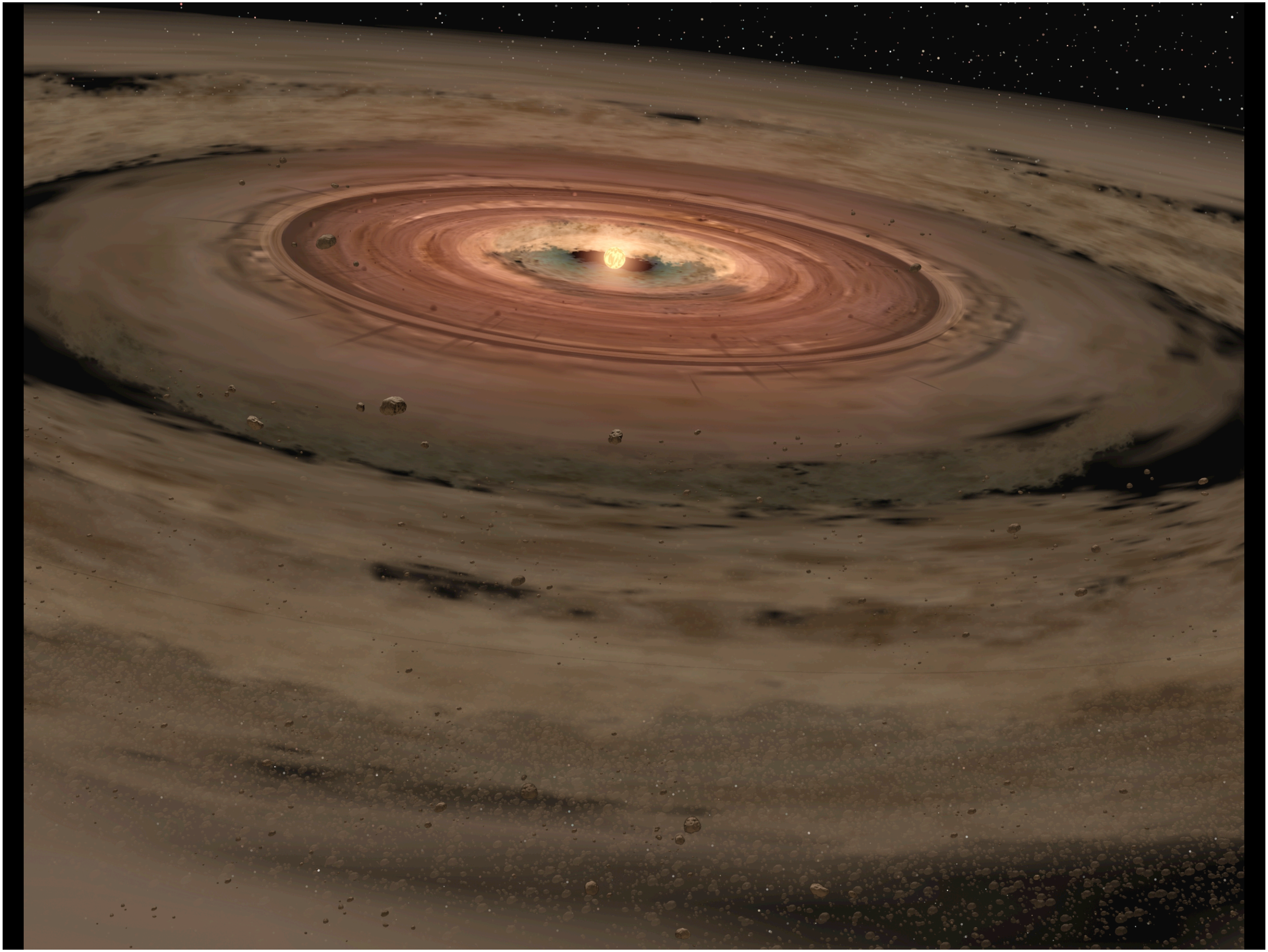
Can account for Solar System; predicts diversity

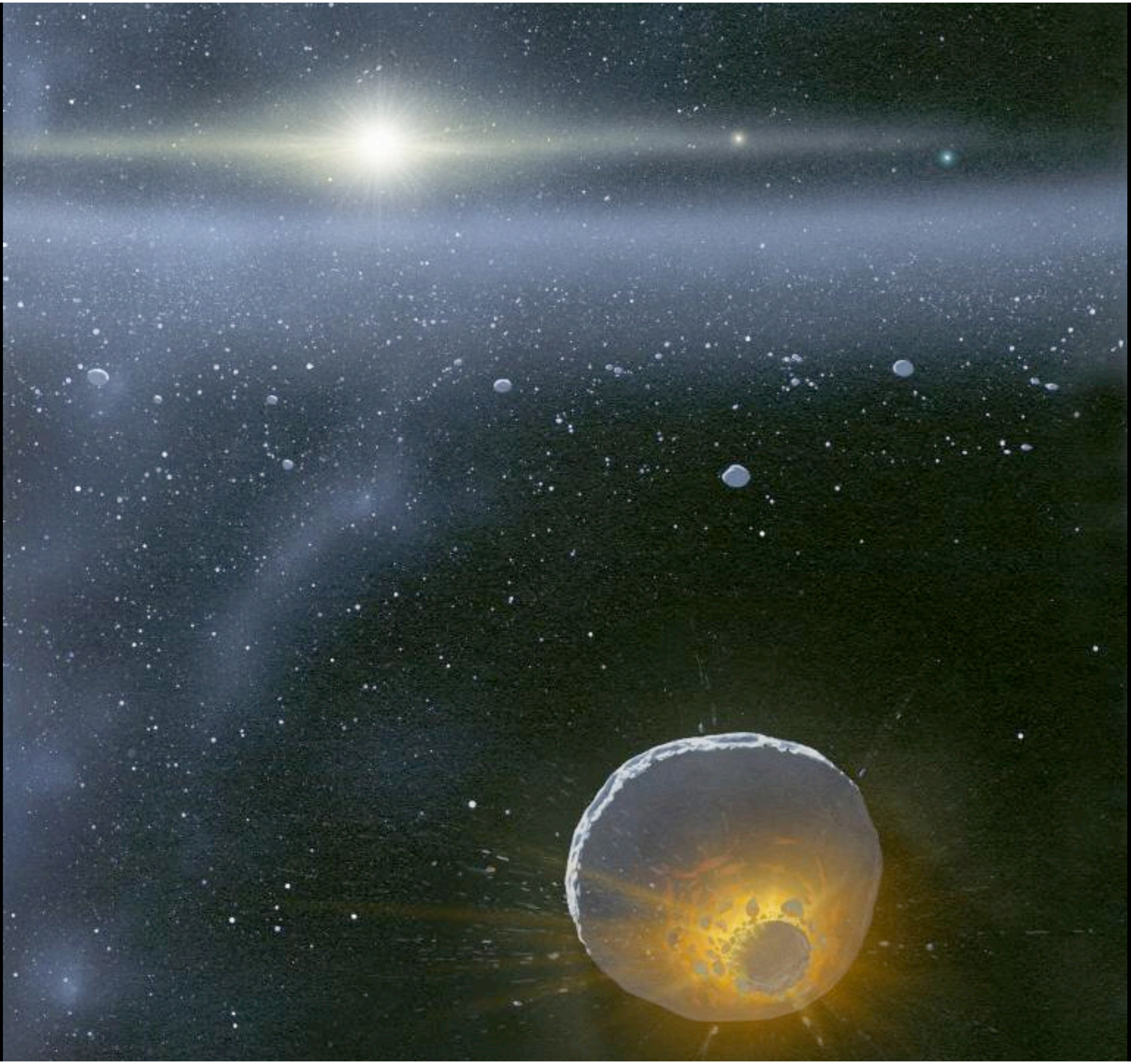
Dust -> Terrestrial Planets

μm - cm: Dust settles towards midplane of disk; sticks, grows. Chondrule & CAI formation??

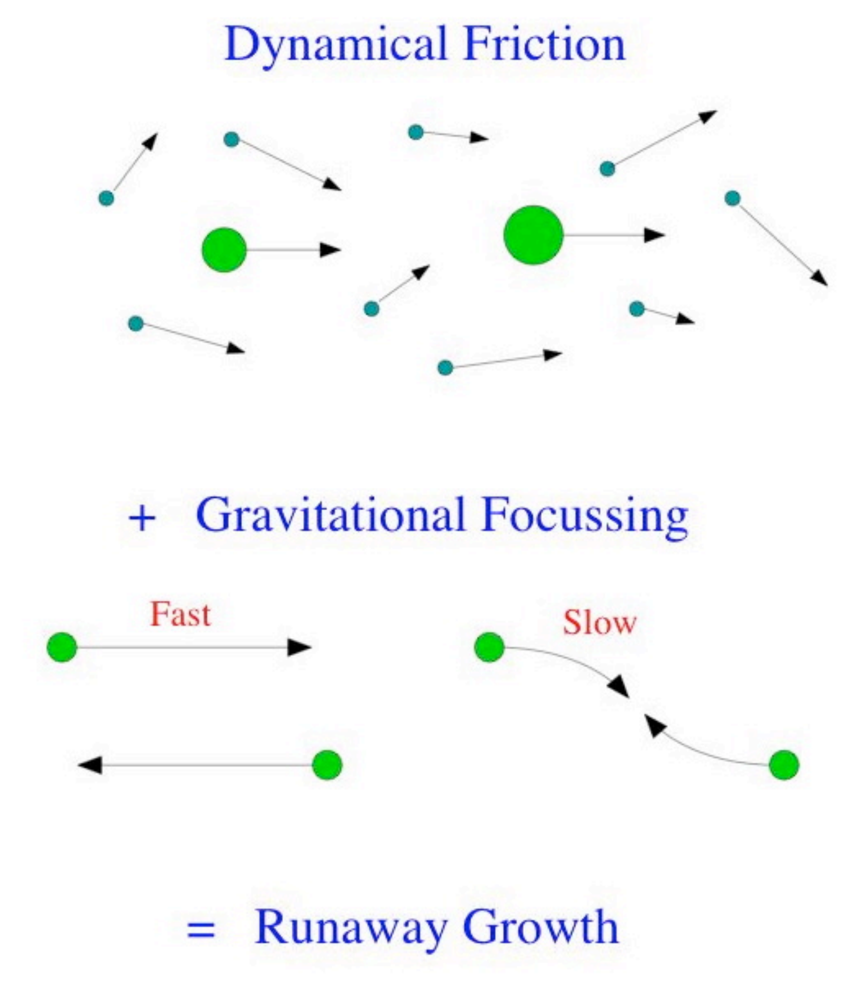
cm - km: Two possibilities:
continued sticking or gravitational instabilities

km - 10,000 km: Binary collisions -
runaway growth; isolation; giant impacts



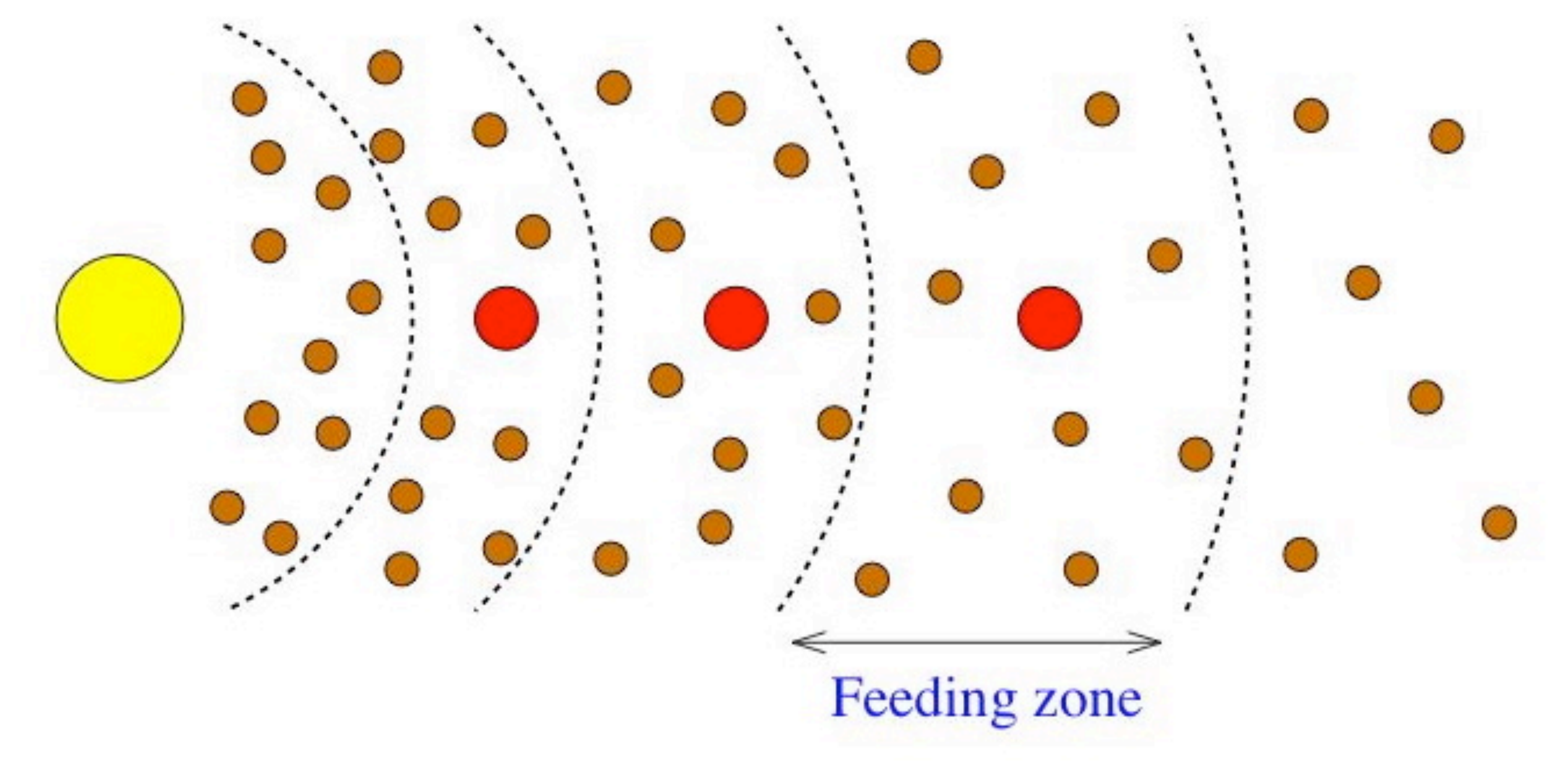


Runaway Growth

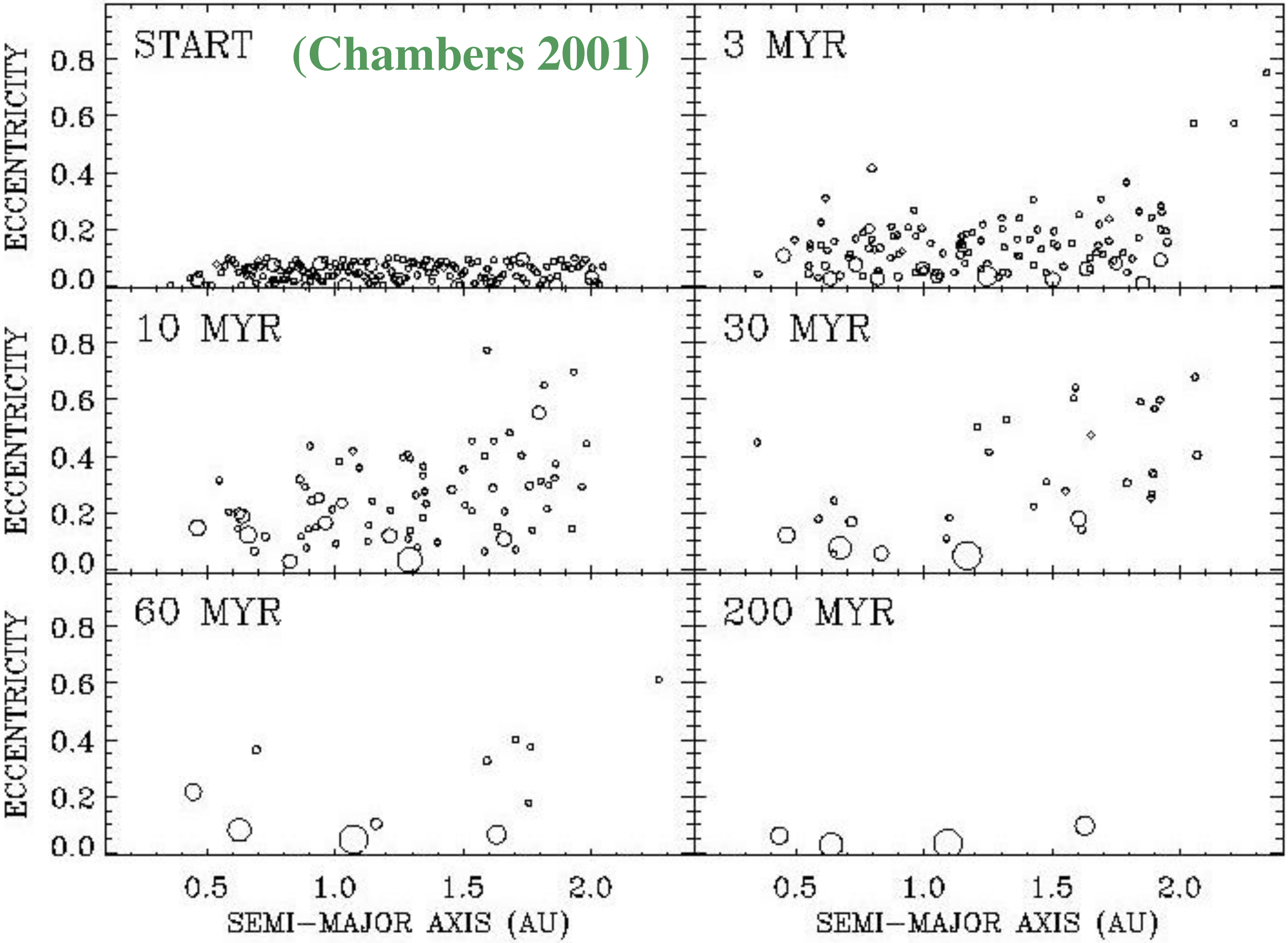


- Gravitational encounters important for bodies > 1 km.
- Close encounters alter trajectories.
- Equipartition of energy determines random velocities.
- Random velocities determine growth rate.
- *Rapid*

Oligarchic Growth

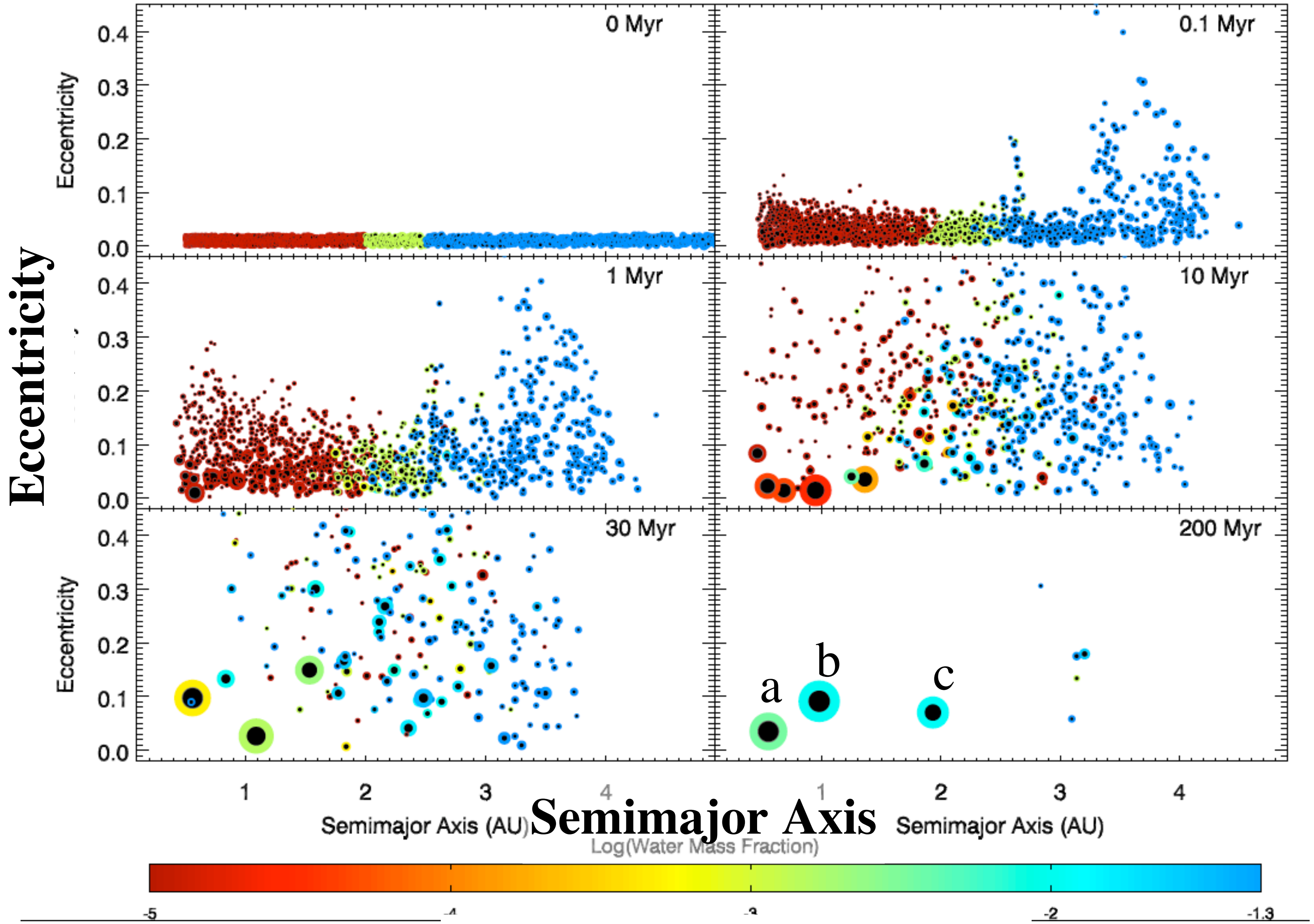


Terrestrial Planet Growth Sun-Jupiter-Saturn



Simulation of planet growth and H_2O accretion

(Jupiter at 5.5 AU, $e_J = 0$)



Raymond, Quinn & Lunine 2006

Planetesimals to **Rocky Planets**

- **Planetesimal velocities**
  - **Gravity vs. collisions**
  - **Energy equipartition/dynamical friction**
- **Runaway growth**
  - **Oligarchic growth**
- **Isolation mass**
  - **3-body effects**
  - **Can produce high velocity collisions between particles**
- **Slow growth at high velocity**
  - **Distant perturbations/chaos**
  - **Giant impacts**
- **Accretion energy/Differentiation**
- **Atmospheric accretion & erosion**

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

Gravitational instability in disk: Giant gaseous protoplanets

Theories of Giant Planet Formation

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Fragmentation during collapse: Planets form like stars

Rapid

Binary stars are common

Mass gap

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

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

Gravitational instability in disk: Giant gaseous protoplanets

Theories of Giant Planet Formation

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

Gravitational instability in disk: Giant gaseous protoplanets

Rapid growth, but cooling rate limits contraction

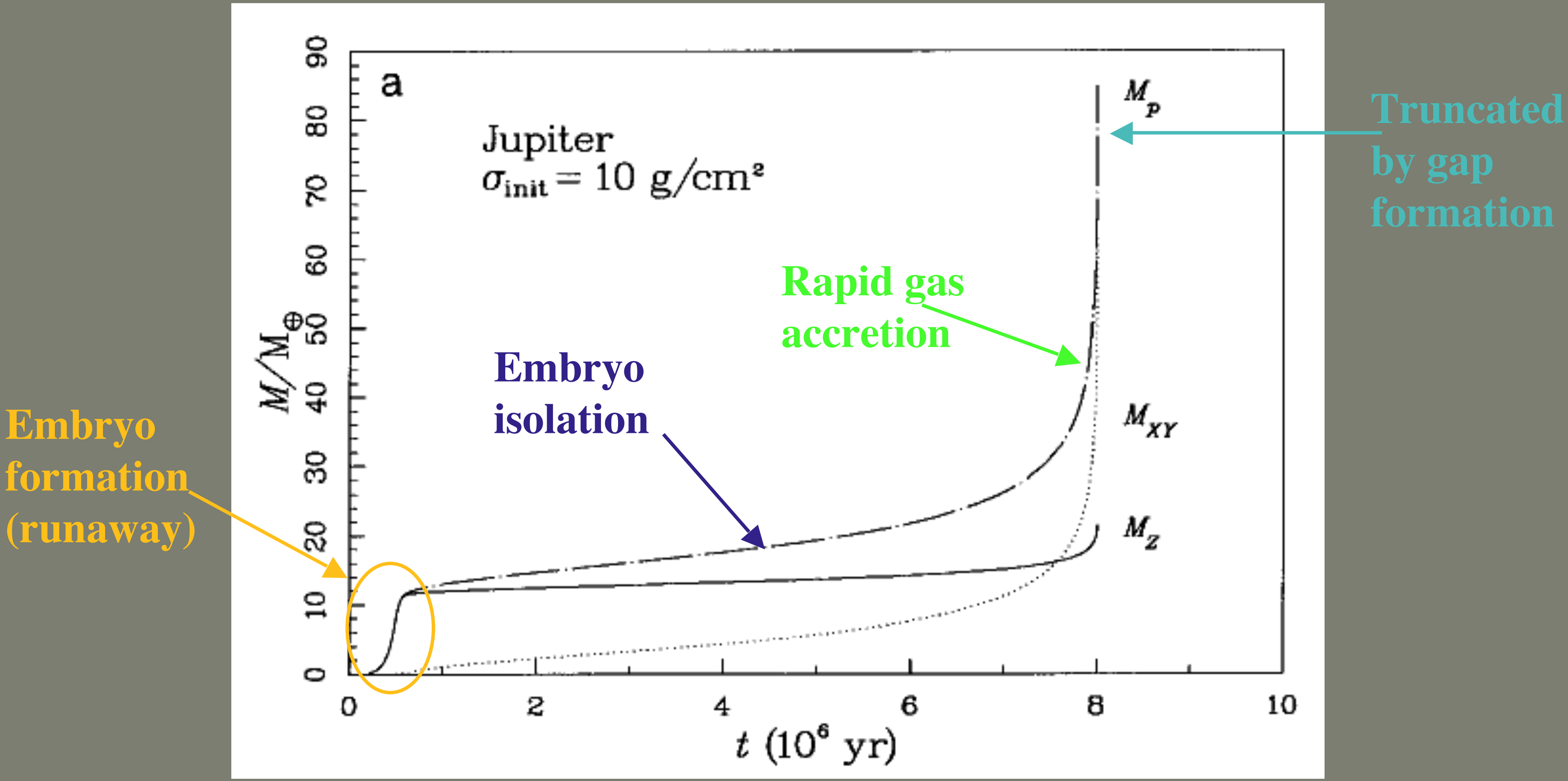
Requires unphysical initial conditions (density waves stabilize)

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

CORE ACCRETION MODEL

- ❍ **planetesimals accrete into a solid core**
- ↓ **growing core attracts gas envelope**
- ↓ **runaway gas accretion with a** little **more solids**
- ↓ **no gas ⇒ accretion ends**
  - nearby gas accreted ?
  - tidal truncation ?
  - protoplanetary nebula removal ?
- **planet contracts and cools**

Nucleated Instability model ("Standard" Case)



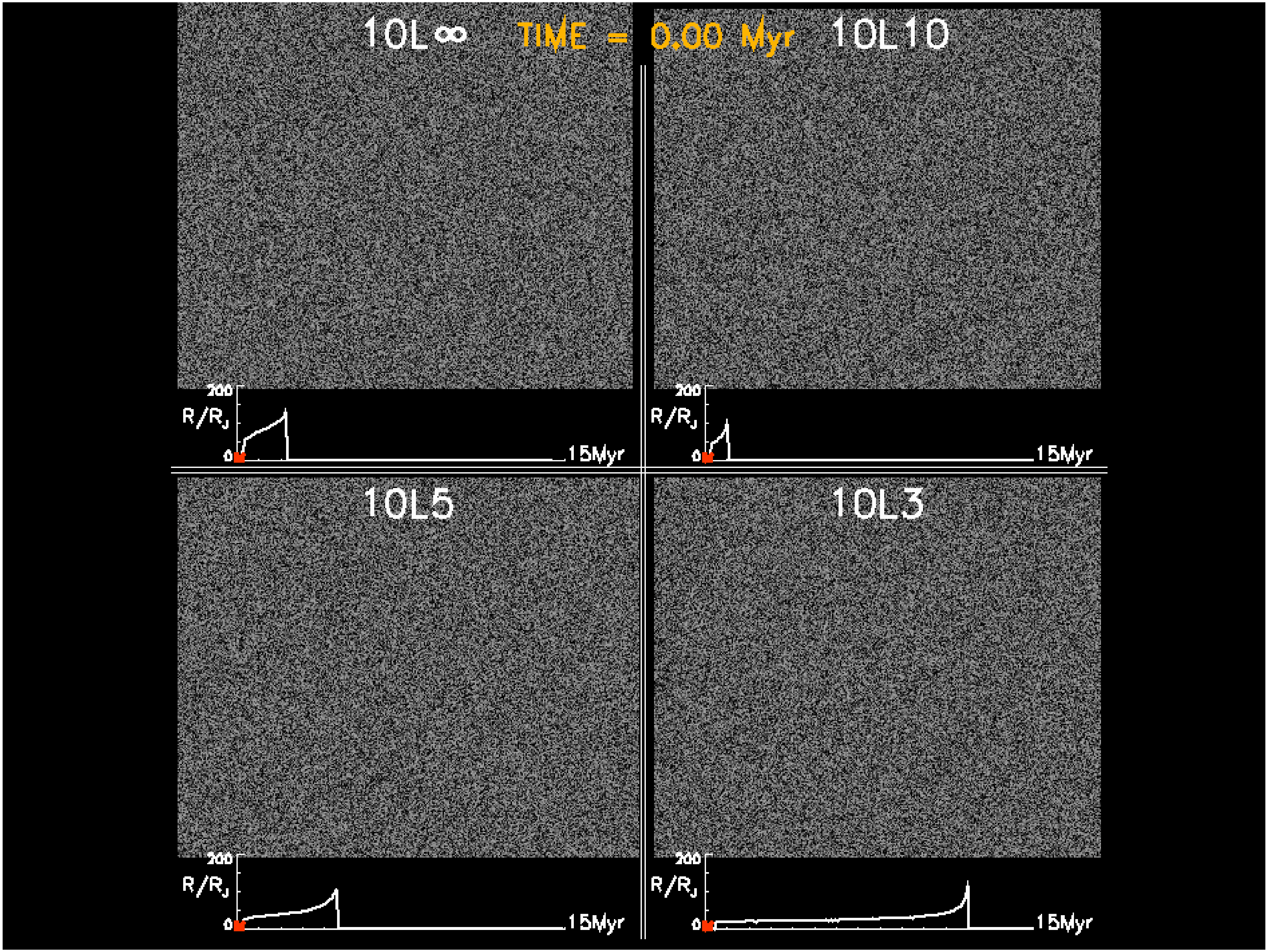
Embryo formation (runaway)

Embryo isolation

Rapid gas accretion

Truncated by gap formation

Pollack *et al*, 1996

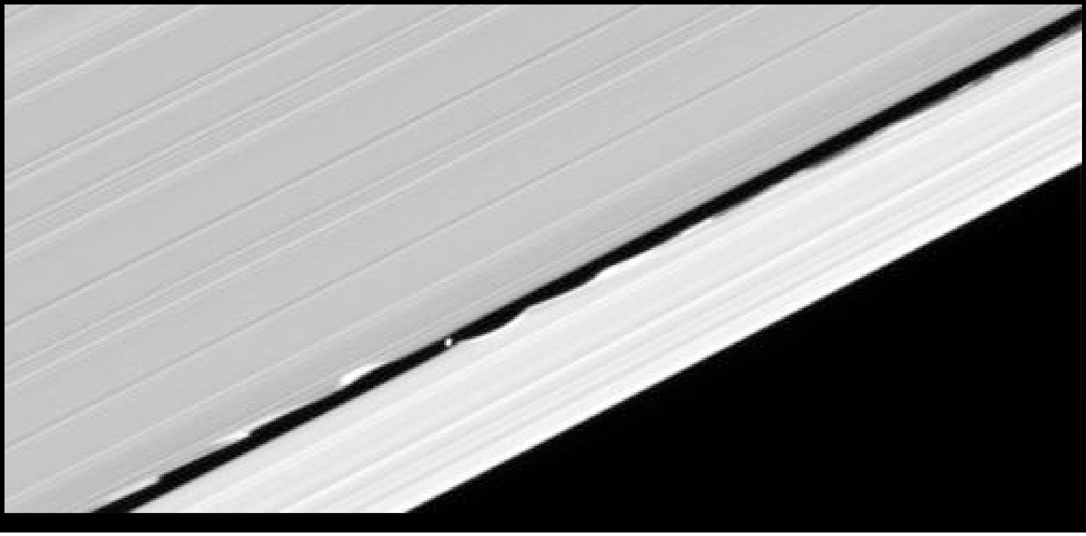

10L∞
TIME = 0.00 Myr
10L10
200
R/R_J
0
15Myr
200
R/R_J
0
15Myr
10L5
10L3
200
R/R_J
0
15Myr
200
R/R_J
0
15Myr

Disk-Satellite Interactions

- Dissipative processes cause disks to spread (e.g., viscous accretion disks, Lynden-Bell & Pringle 1974).
- Satellites can excite density waves in disks - resulting net force is repulsive.
- Satellites repelled by disk on both sides - move if torque is asymmetric.
- Massive satellites clear gaps in disks.

Disk-Satellite Interactions in Saturn's Rings

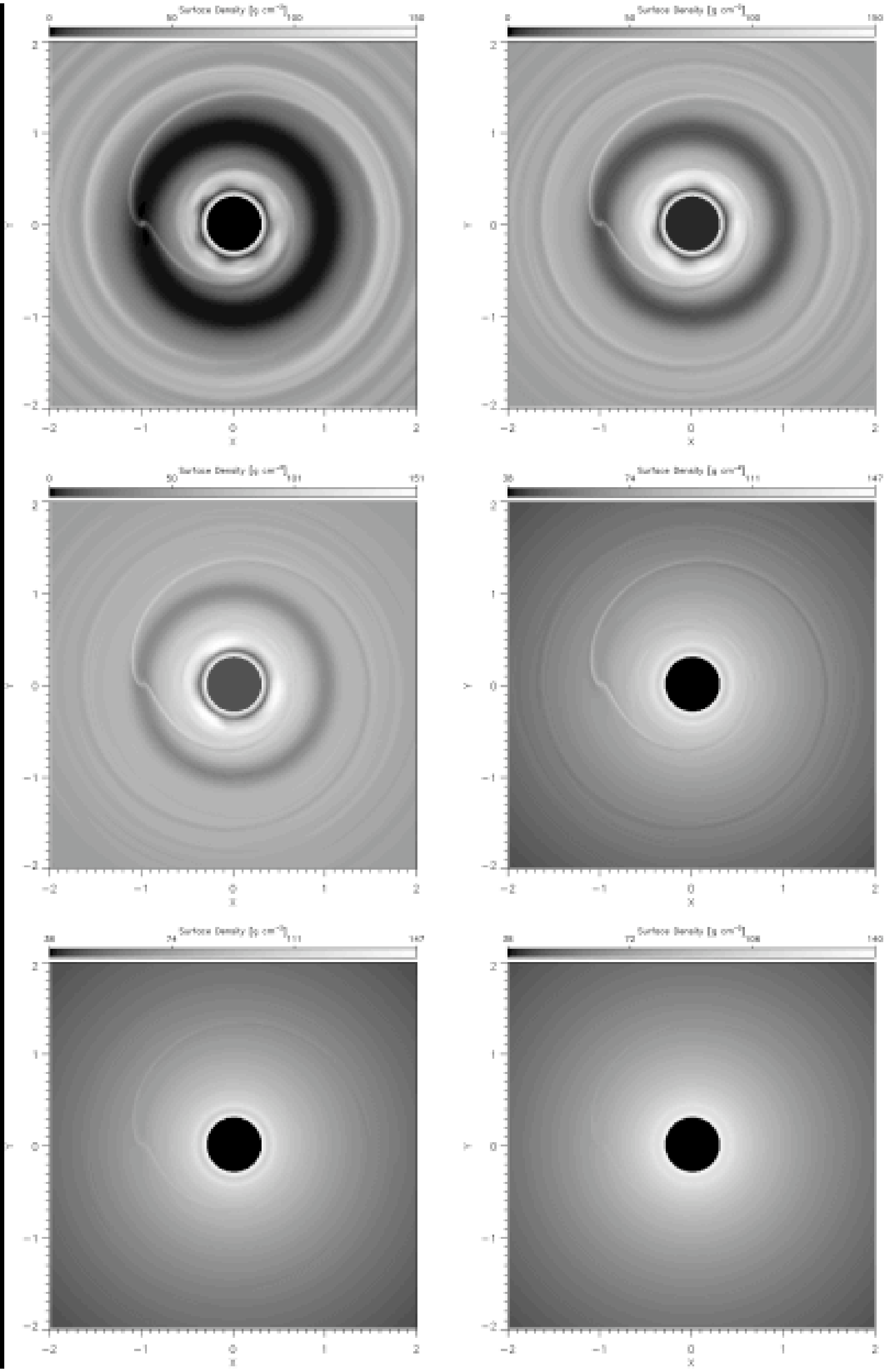
- Moons excite spiral density waves at resonant locations.
- Gaps are produced at strong resonances and close to moons where resonances overlap



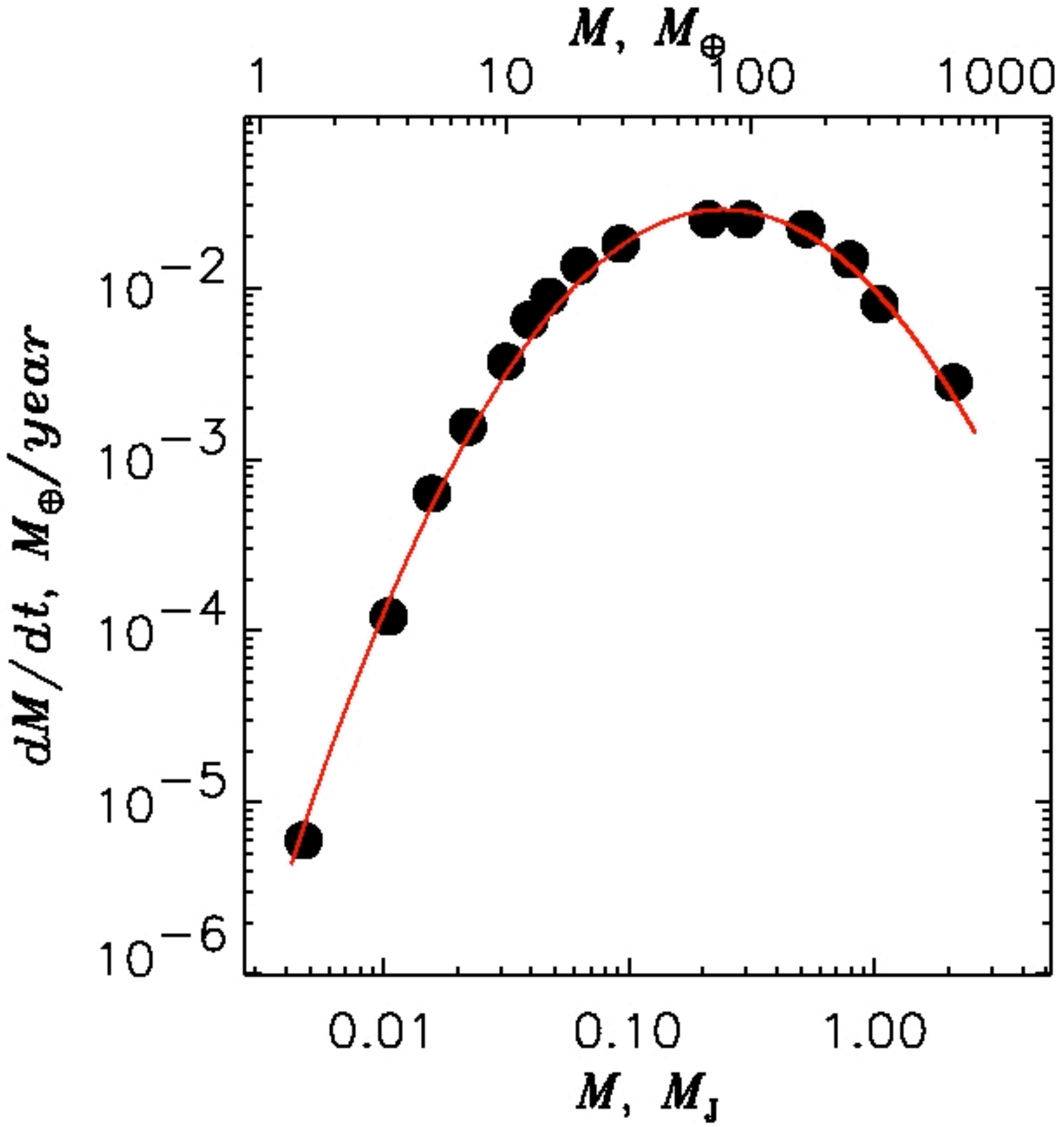
Gas Flow Near Planet

(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)

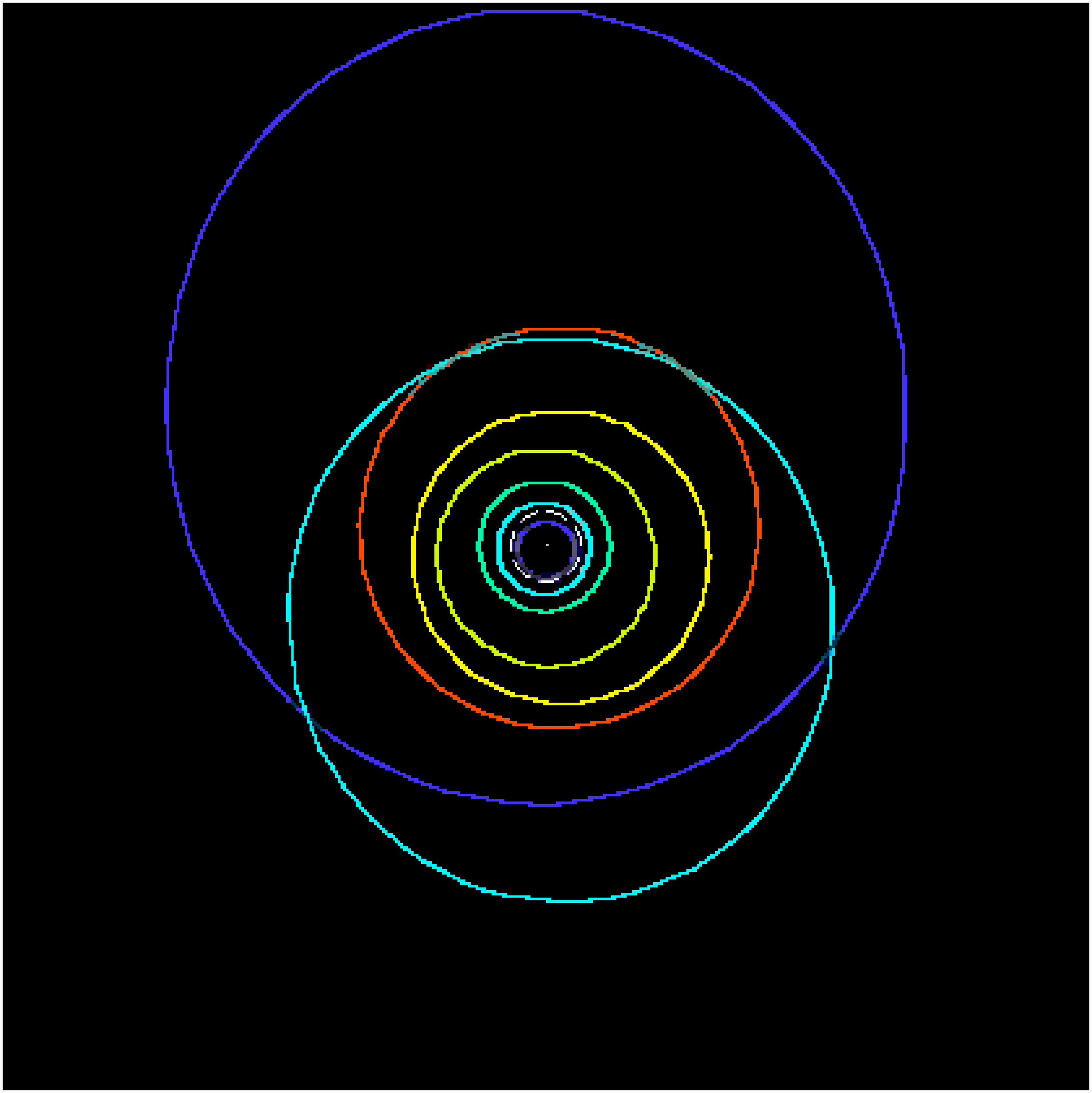


Note flow peaks ~ M_{saturn}; drops sharply > $M_{Jupiter}$.

Orbital Evolution

- **Planet-planet scattering**
  - Produces eccentric orbits
  - Planets well-separated
  - Some planets ejected
- **Planet-planetesimal scattering**
  - Produces circular orbits
  - Kuiper belt provides strong evidence in Solar System
- **Disk-planet interactions**
  - No gap: Migration relative to disk
  - Gap: Moves with disk
  - Faster near star - need stopping mechanism

Planet-Planet Scattering

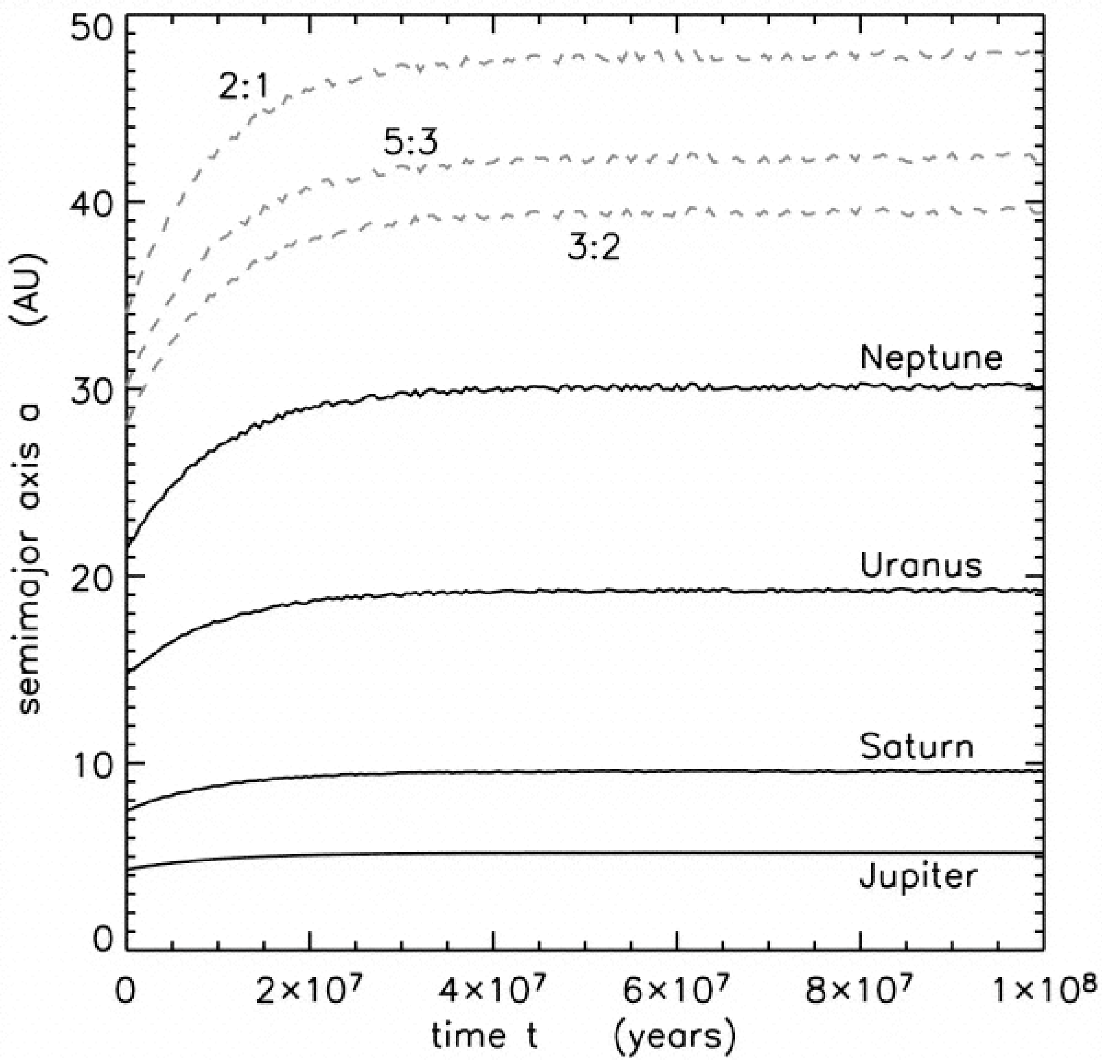


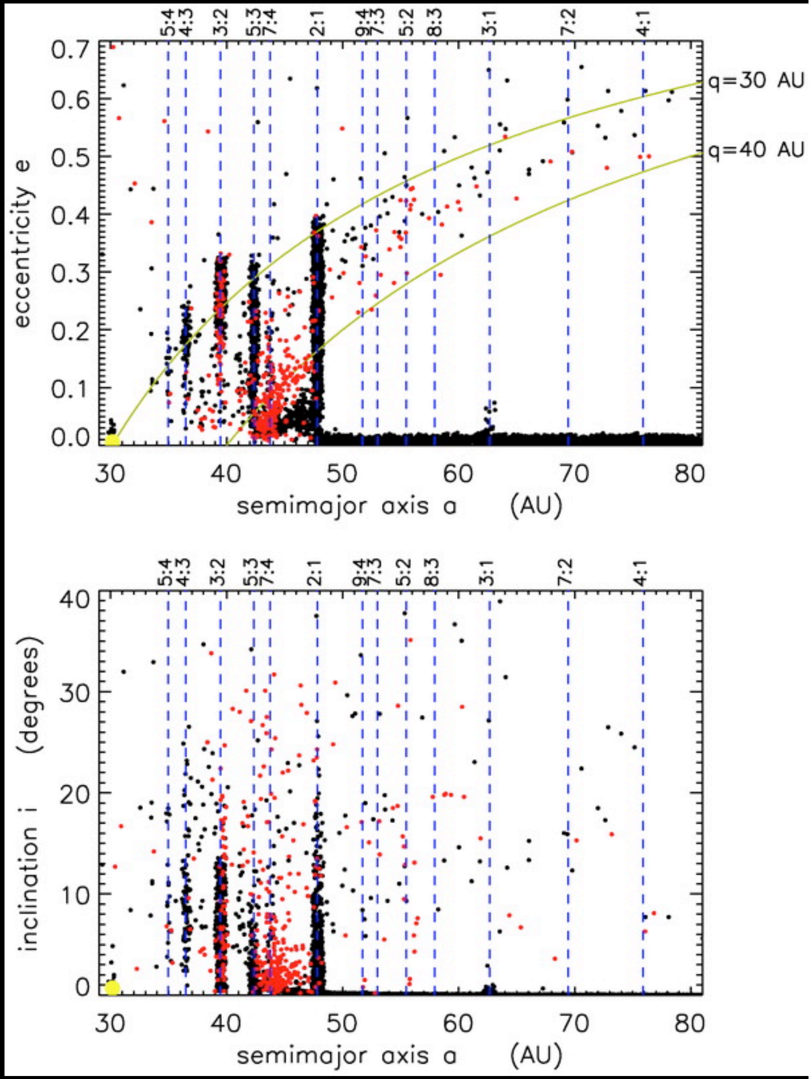
Ellipses display planetary orbits. Dashed circle is 5.2 AU.

Levison, Lissauer & Duncan 1998

Planet-Planetesimal Scattering

(Hahn & Malhotra 2005)





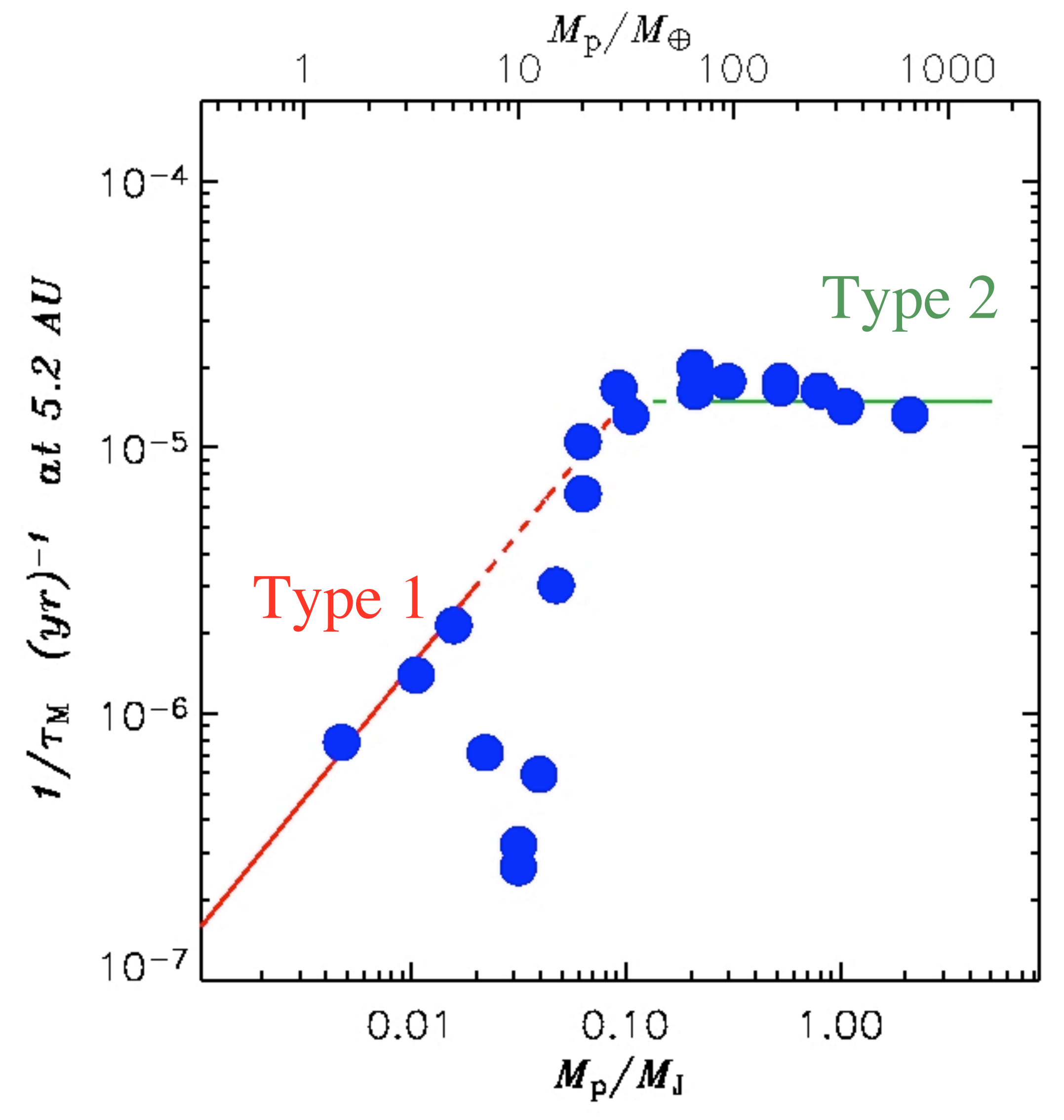
Migration of Extrasolar Planets

- Goldreich & Tremaine (1980) pointed out that disk torques could move planets large distances in ~ 10^5 years.
- Research by Ward, Lin, Papaloizou, etc. has shown that migration is almost always inwards.
- Timescale decreases near star, suggesting planets lost, so “giant vulcans” not predicted.
- Lin et al (1996): tides or gap may halt migration.

Types of Planetary Migration

- Type 1: Small planet, no gap, asymmetric torque from wave excitation. Torque $\propto M^2$, so $v \propto M$.
- Type 2: Planet clears gap, dragged along by massive disk. $v \propto M^0$.
- Type 2a: Planet clears gap in low mass disk, planet's inertia slows disk's evolution, so $v \propto M^{-1}$.

Migration Timescales



D'Angelo
et al. (2003)

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
- Gravitational torques from protoplanetary disks can cause planets to migrate inwards substantial distances
- Planets are common, and planetary systems are diverse
  - New technologies allow observations of many types of extrasolar planets