From Formation to Destruction: The Life of Planetesimals

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Observing Planetary Systems II

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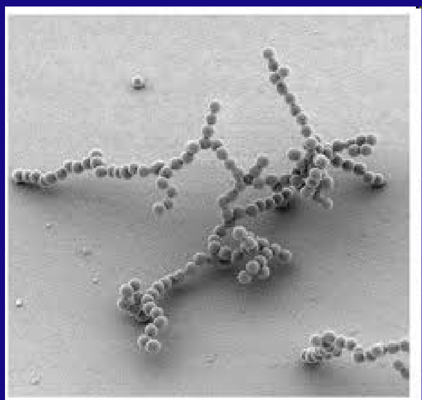
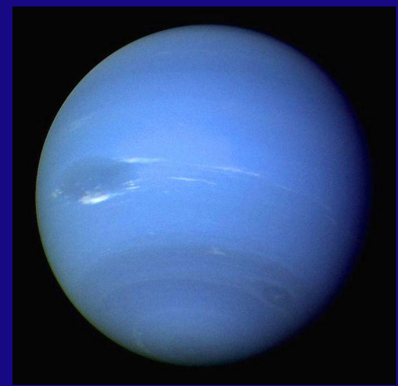
The Life of a Planetesimal

µm-sizd Dust

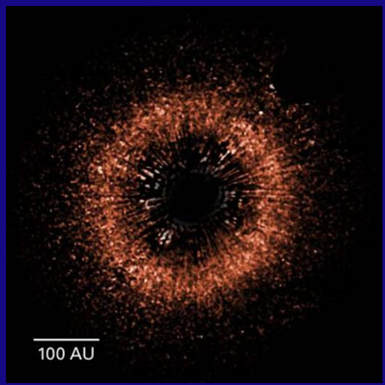


km-sized Boulders

Planets



µm-sizd Dust



Planetesimal
Formation

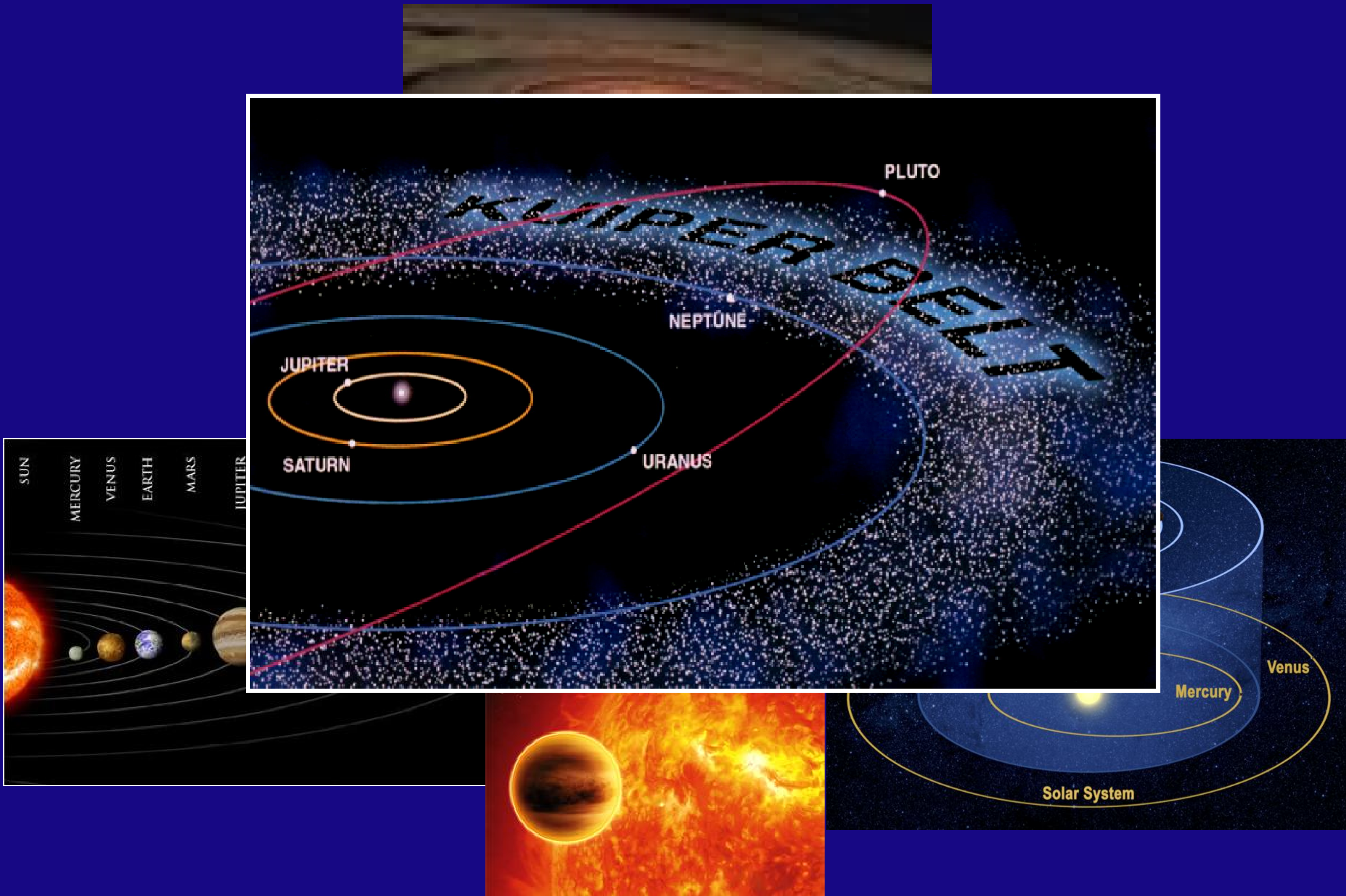
Runaway
Growth

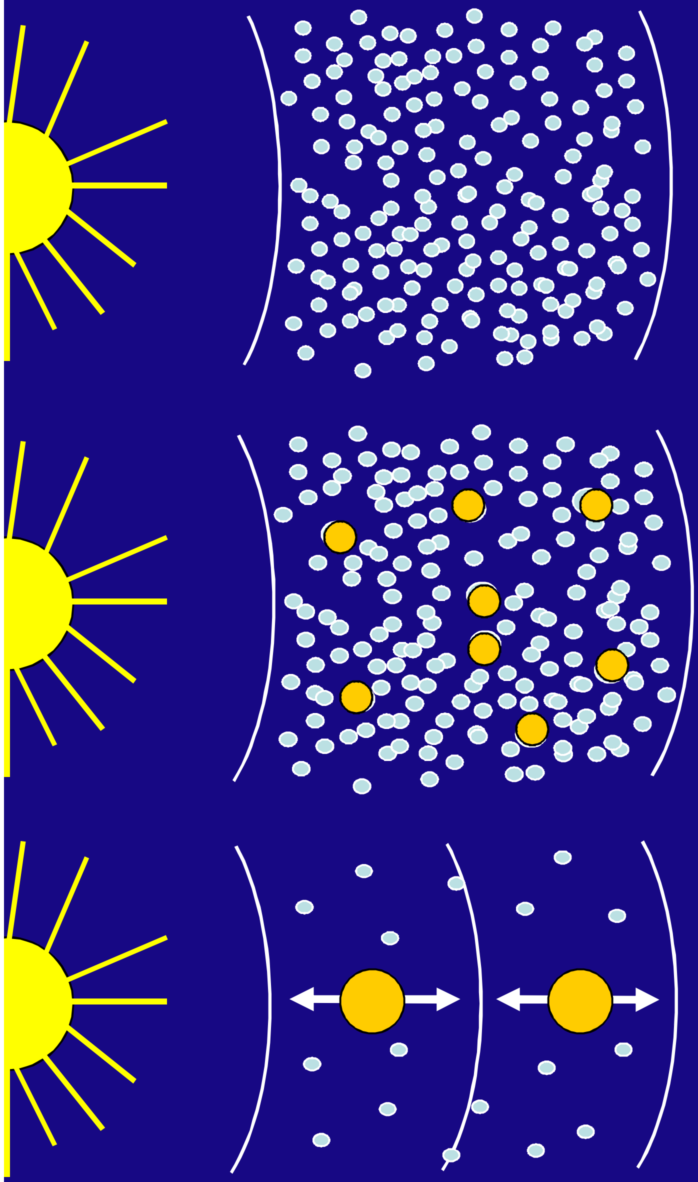
Oligarchic
Growth

Collisional Evolution

Debris Disk Formation

From Gas & Dust to Planets





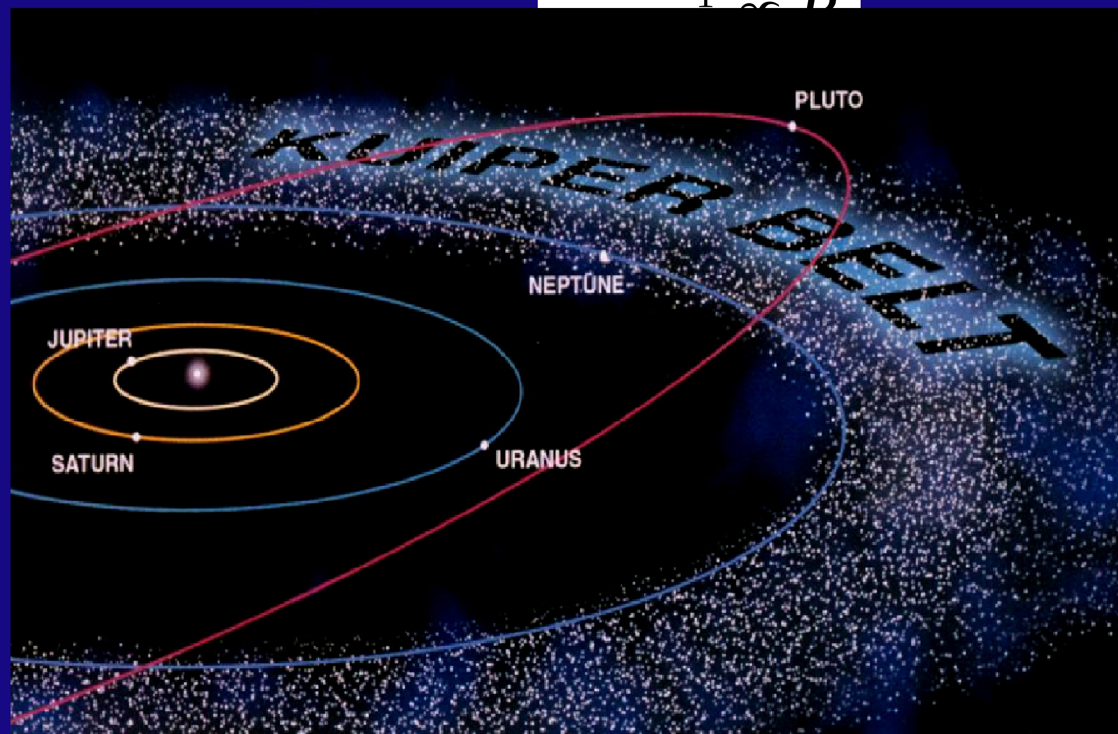
planetesimals protoplanets

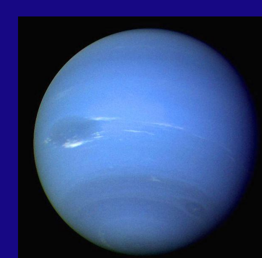
u, σ v, Σ

1. Planetesimal formation:

2. Runaway growth:

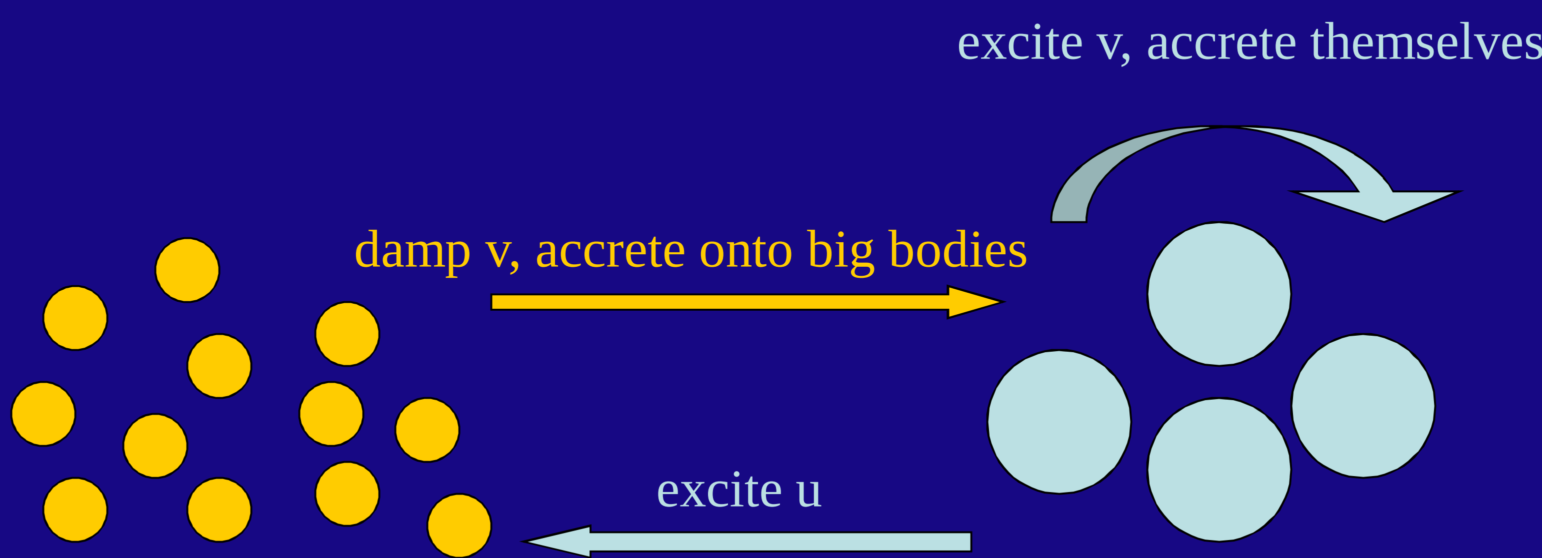
$1 \quad dR_1 \propto R$



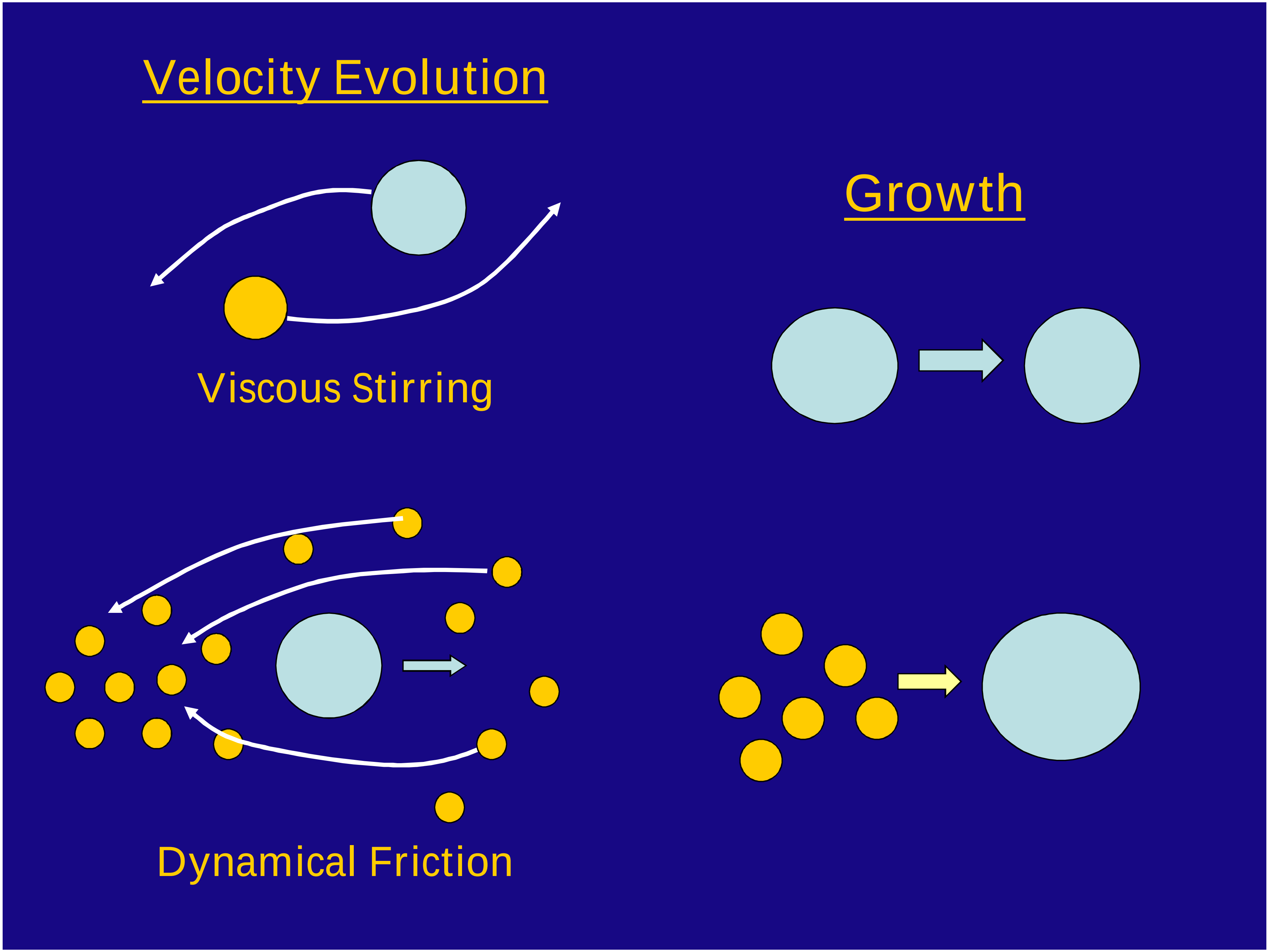


Two-Group-Approximation

Small bodies | Big bodies



Small bodies	Big bodies
Mass surface density = σ	Mass surface density = Σ
mass = m, radius = r	Mass = M, Radius = R
velocity dispersion = u	velocity dispersion = v


Velocity Evolution
Viscous Stirring
Dynamical Friction
Growth

Runaway Growth

$$\frac{1}{R}\frac{dR}{dt} \sim \frac{\sigma\Omega}{\rho R}\left(\frac{u}{v_{esc}}\right)^{-2} + \frac{\Sigma\Omega}{\rho R}\alpha^{-3/2}$$

$$\alpha \sim R_{Sun}/a \sim 10^{-4} \text{ at } 40 \text{ AU}$$

Accretion of small bodies

Accretion of big bodies

When accretion of small and big bodies contribute equally to the growth:

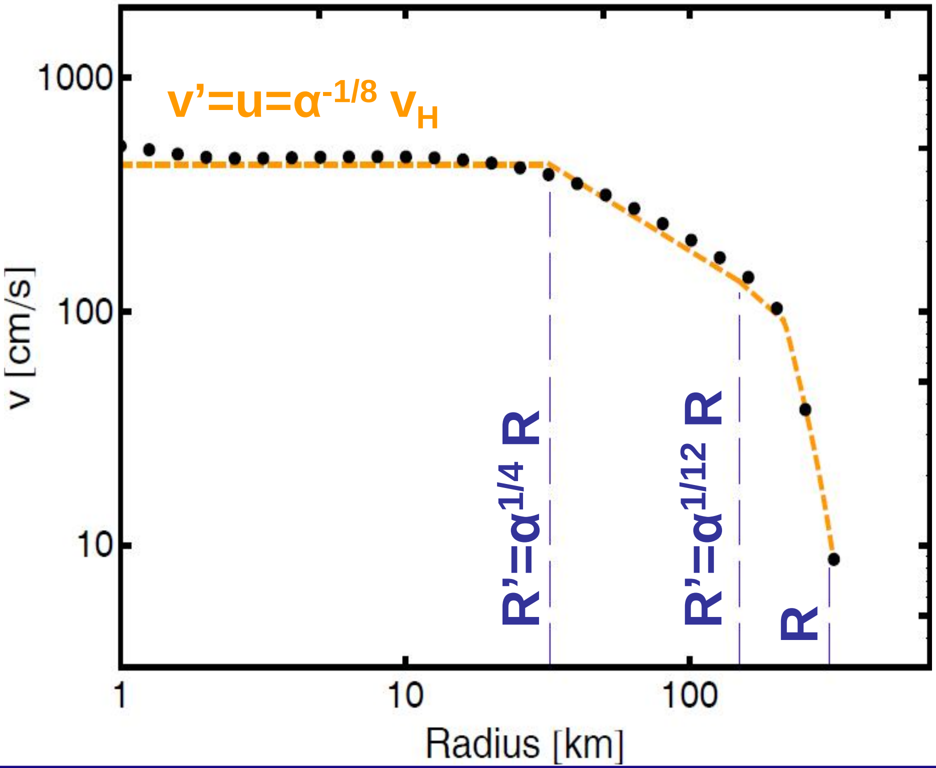
$$\boxed{\Sigma \sim \alpha^{3/4}\sigma \sim 10^{-3}\sigma \sim 3\times 10^{-4} \text{ g/cm}^2}$$

$$\sigma \sim \sigma_{\mathrm{MMSN}} \sim 0.3 \text{ g/cm}^2$$

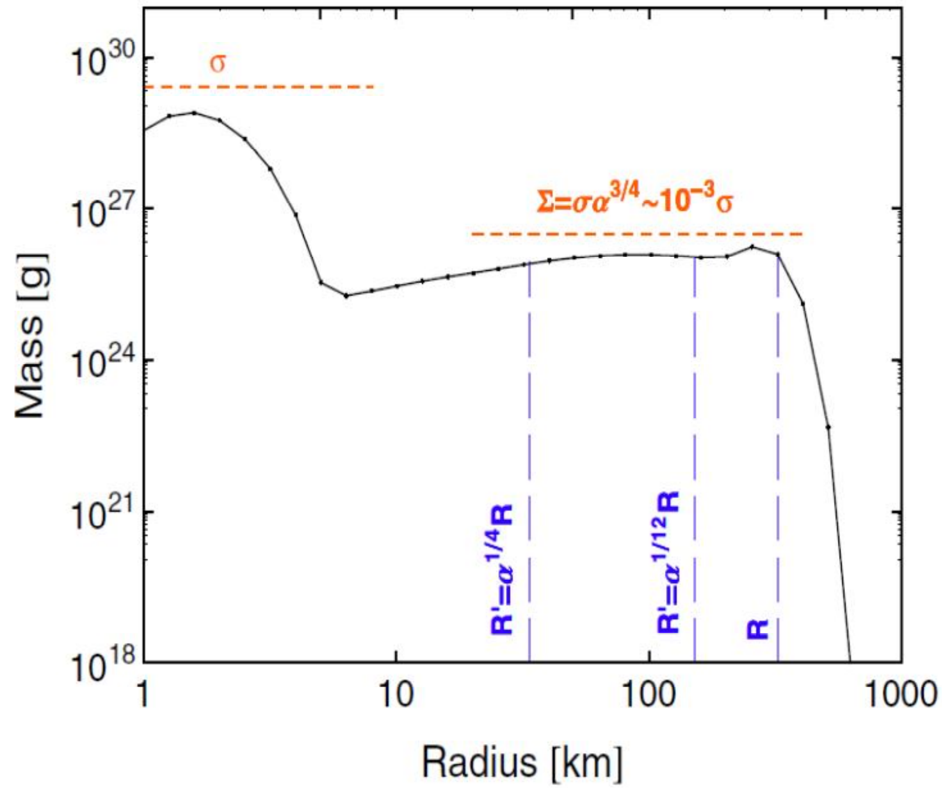
$$\Sigma \propto N(>R)R^3 \sim \text{const} \Rightarrow \mathrm{N}(>\mathrm{R}) \propto \mathrm{R}^{-3} \Rightarrow \boxed{\mathrm{q} = 4}$$

i.e. Equal mass per logarithmic mass bin

Velocity



Mass

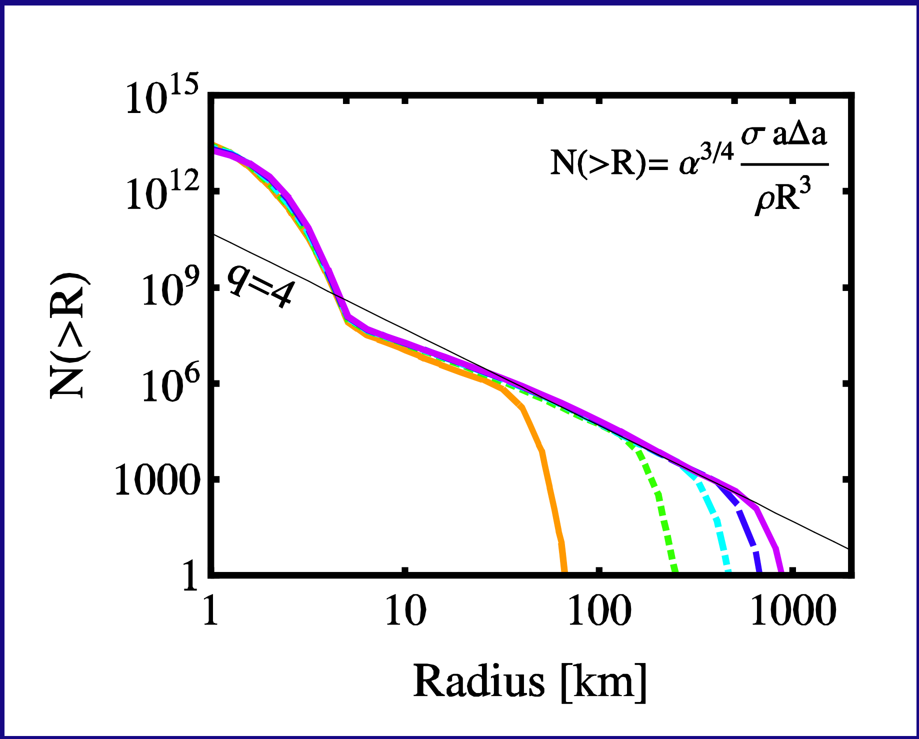


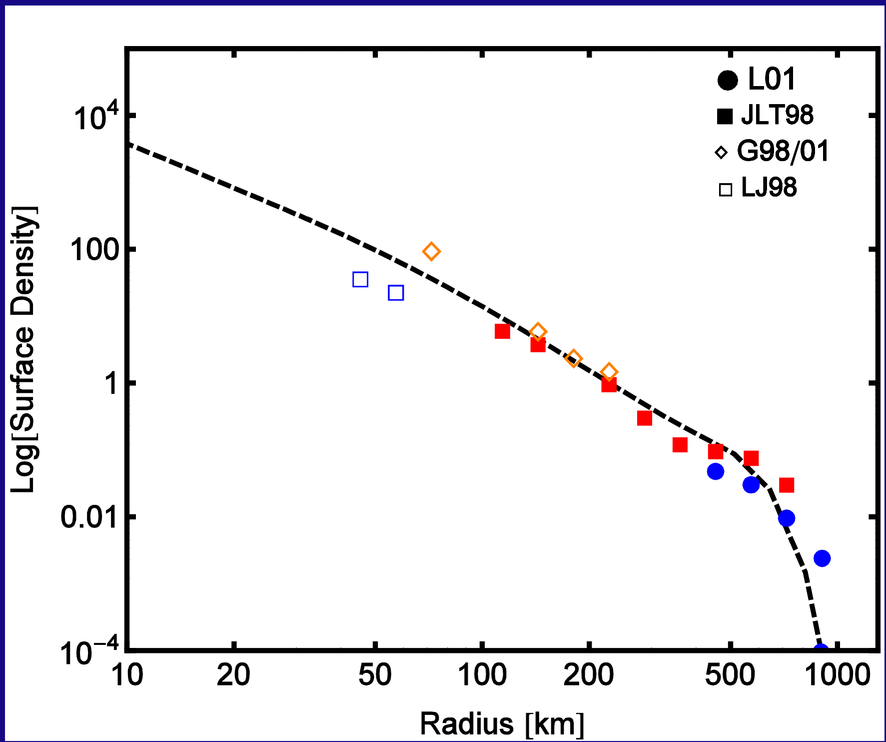
(Schlichting & Sari, 2011)

Time = 10^7 years

Self-similar Growth

Comparison with Kuiper Belt Size Distribution





(Schlichting & Sari, 2011)

$$\frac{dN(R)}{dR} \propto R^{-q}$$

Final size distribution independent of initial conditions, provided r<10km (see also Kenyon & Bromley 2009)

t = 10^6 years, t= 10^7 years, t = 2 x 10^7 years, t = 3 x 10^7 years, t = 5 x 10^7years

Runaway Growth Summary

Runaway growth:

1) Only a small fraction of initial mass in converted into protoplanets during runaway growth: $\Sigma \sim \sigma \alpha^{3/4} \sim 10^{-3} \sigma_{MMSN}$
2) Size distribution of runaway tail: $q \sim 4$, equal mass per logarithmic mass bin
3) Final size distribution independent of initial conditions, provided $r<10$km

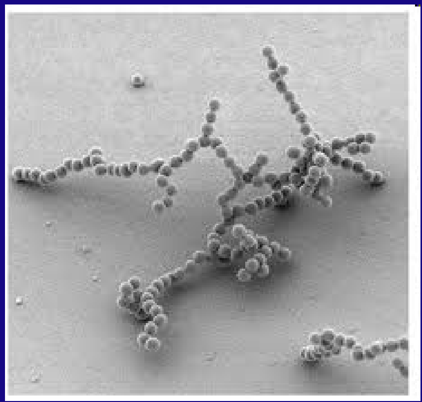
For the Kuiper Belt we can successfully explain:

1) The total mass in large KBOs ($\Sigma \sim \sigma \alpha^{3/4} \sim 10^{-3} \sigma_{MMSN}$)
2) The slope of KBO size distribution ($q \sim 4$)
3) The observed mass ratio of Kuiper Belt binaries ($M/m \sim 8$)

This argues strongly against that there was significantly more mass in large Kuiper Belt objects in the past.

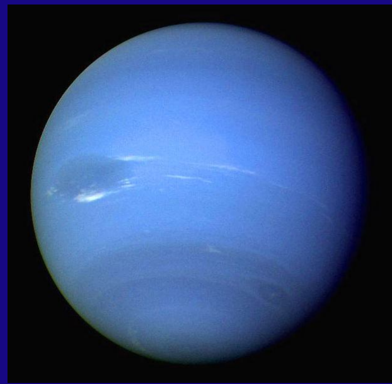
The Life of a Planetesimal

μm-sizd Dust

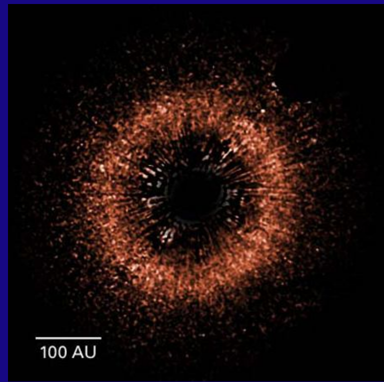


km-sizd Boulders

Planets



μm-sizd Dust



Planetesimal
Formation

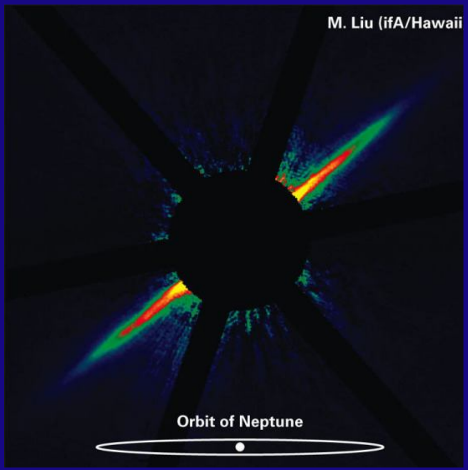
Runaway
Growth

Oligarchic
Growth

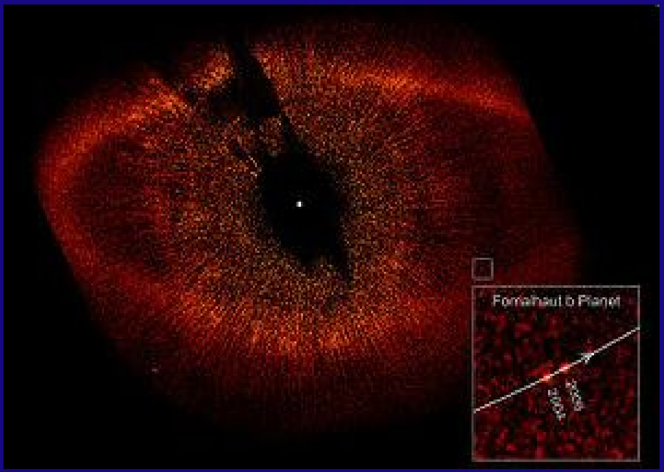
Collisional Evolution

Debris Disk Formation

Collisional Cascades, Debris Disks & the Presence of Planets



AU Mic (M. Liu, Keck)



Fomalhaut (Kalas et al., HST)

Collisional Evolution → Debris Disk Formation → **Infer Presence of Planets (disk scale height) &**

Physical Properties of Debris (e.g. material strength)

Collisional cascades

$N(r) \propto r^{1-q}$

Steady state: → Mass conservation

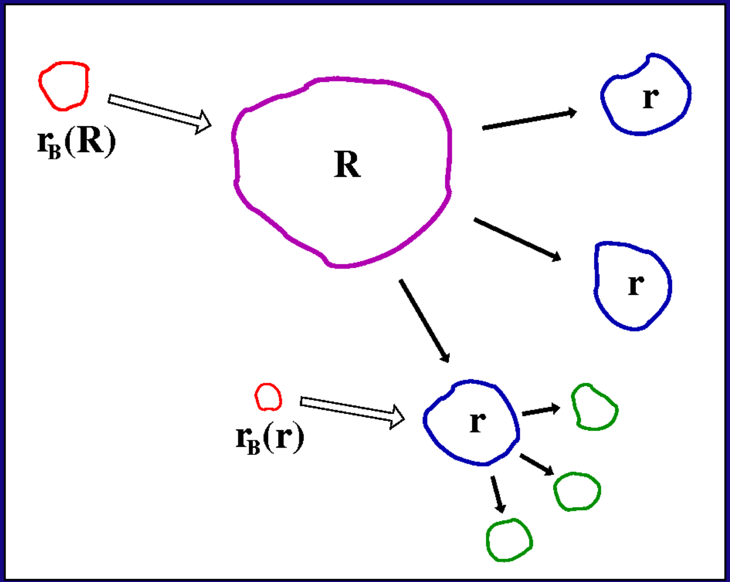
mass rate of destruction

covering fraction of targets

$$\boxed{\text{constant}} = \boxed{\rho r^3} \cdot \boxed{\frac{N(r)\, r^2}{\text{area of disk}}} \cdot \boxed{N(r_B(r))\,\Omega}$$

target mass

rate of disk crossings by bullets



Bullet to Target Ratio:

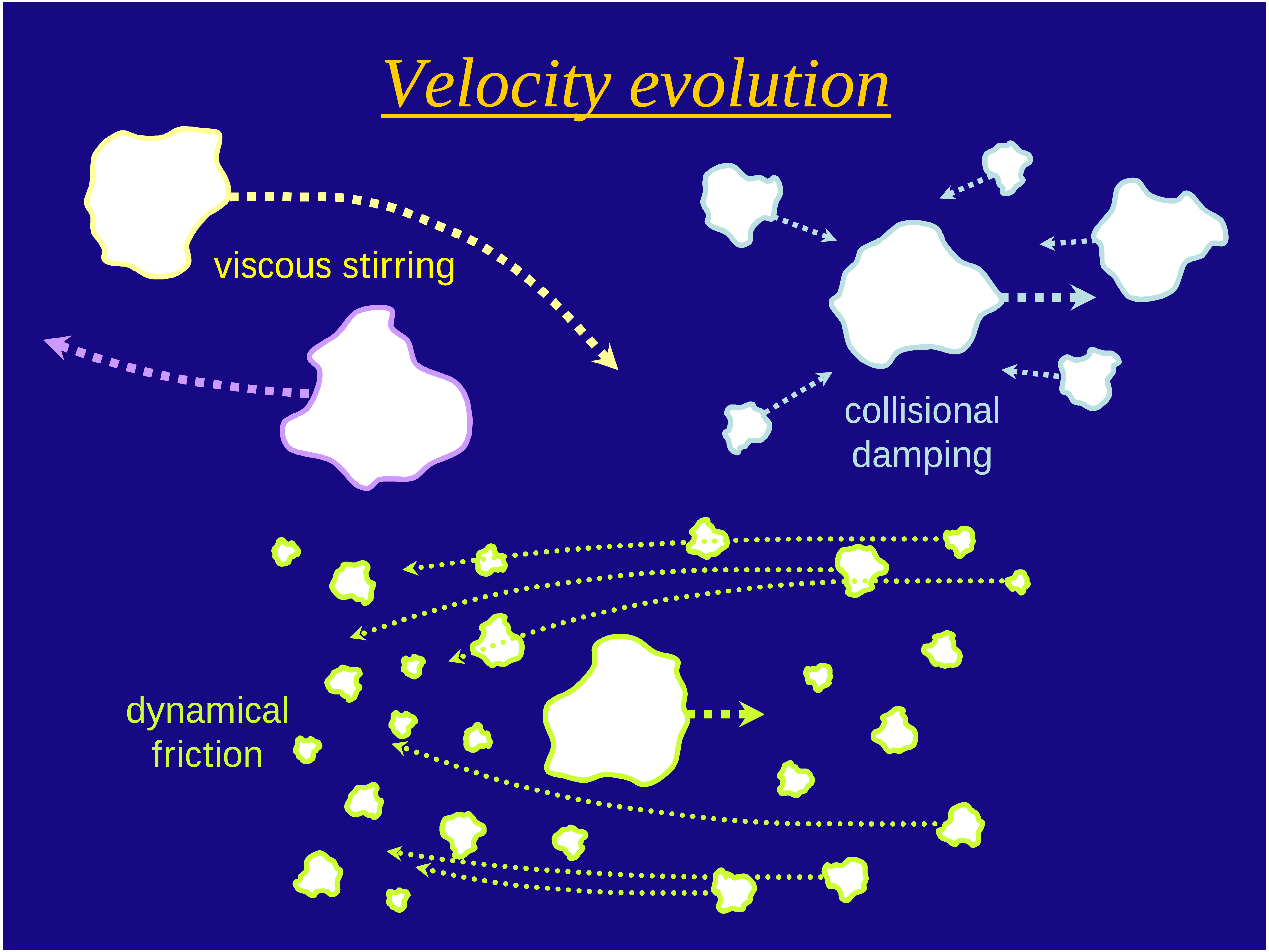
Strength Regime: $\rho r_B^3 v^2 = Q^* \rho r^3$ → $r_B \propto r$ → $q = 7/2$

Dohnanyi (1969)

Gravity Regime: $\rho r_B^3 v^2 = \rho r^3 v(r)_{esc}$ → $r_B \propto r^{5/3}$ → q ~ 3

Pan & Sari (2007)

But in general, r_B is a function of breaking strength and **velocity!**


Velocity evolution
viscous stirring
collisional damping
dynamical friction

Self-consistent sizes and velocities

$$\text{constant} = \rho r^3 \cdot \frac{N(r)\, r^2}{\text{area}} \cdot N(r_B(r))\, \Omega$$

mass conservation

viscous stirring

$$0 = \frac{1}{v(r)} \frac{dv(r)}{dt} \sim + \frac{N(R) R^2 \Omega}{\text{area}} \frac{v_{\text{esc}}^4(R)}{v^2(R) v^2(r)}$$

velocity equilibrium

$$- \frac{N(s) \Omega}{\text{area}} \frac{s^3}{r}$$

collisions

$$\left[- \frac{N(s) \Omega}{\text{area}} \frac{s^3}{r} \frac{v_{\text{esc}}^2(r)}{v^2(r) v^2(s)} \right]$$

dynamical friction

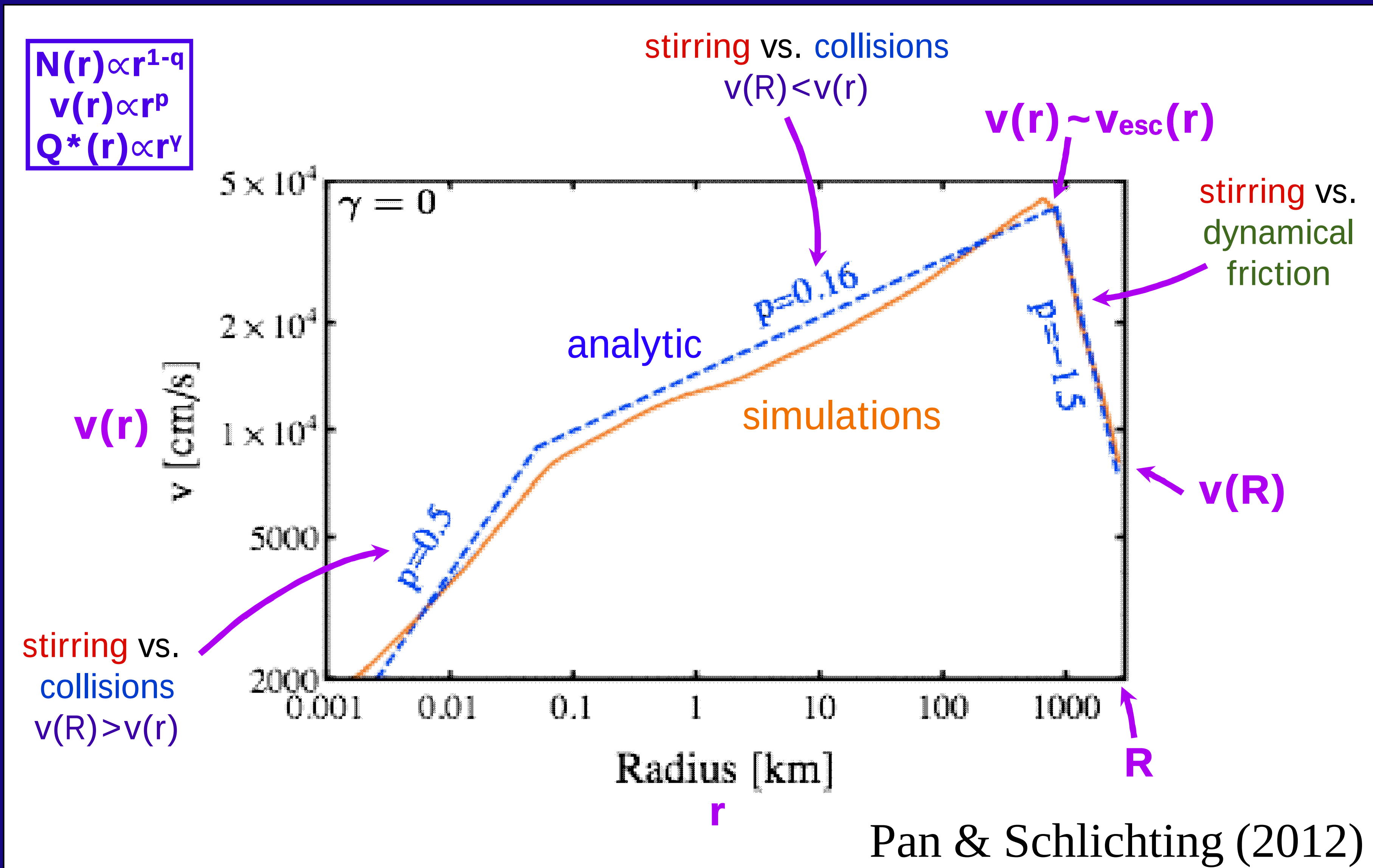
body strength

$$Q^*(r) \propto r^\gamma$$

v(r)

N(r)

Self-consistent sizes and velocities



Self-consistent sizes and velocities

$N(r) \propto r^{1-q}$
$v(r) \propto r^{p}$
$Q^*(r) \propto r^{\gamma}$

$\gamma = 0$

Size distributions steepen:

- Dohnanyi:

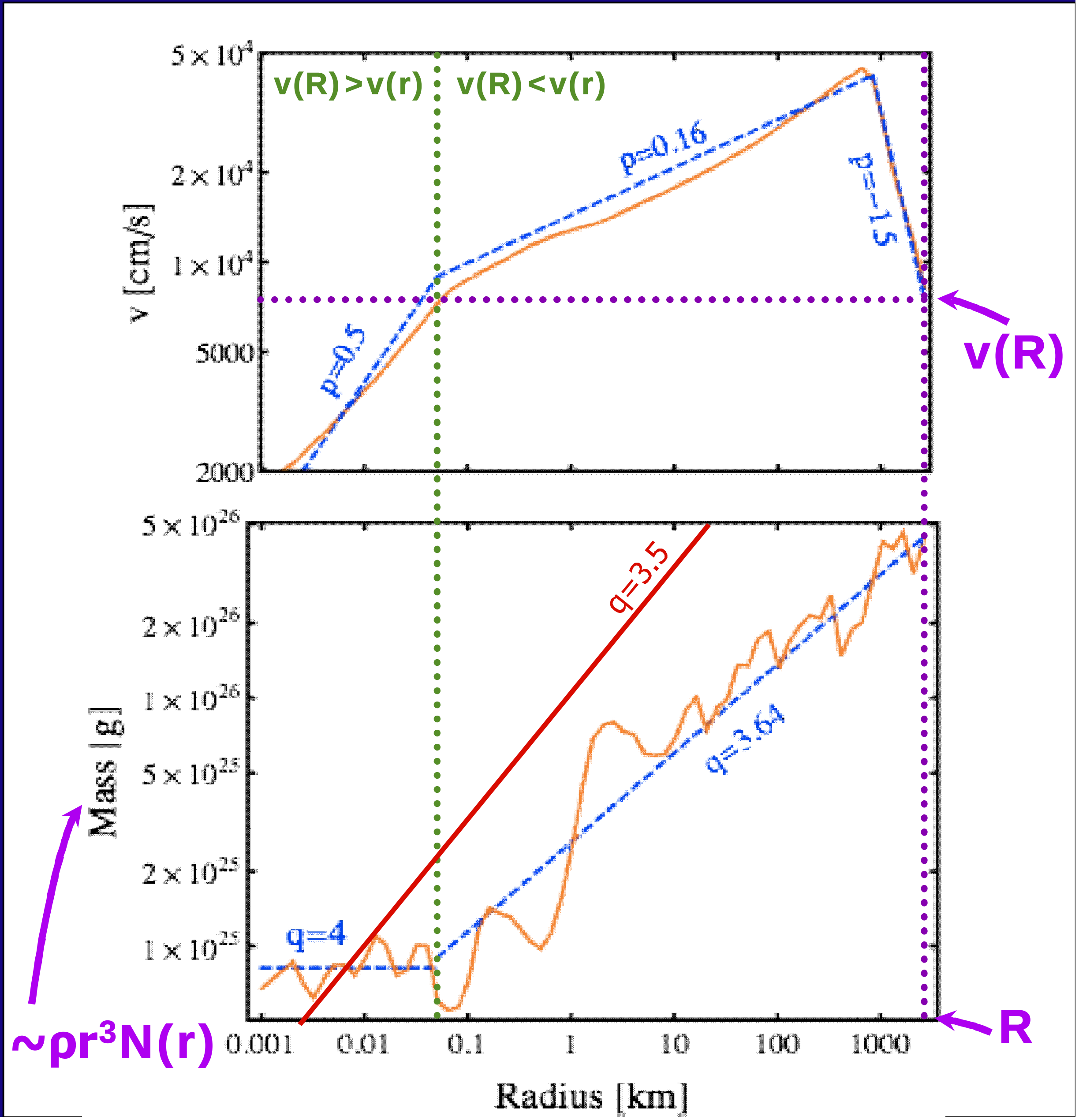
old

$q = 7/2$

new

$$q = \begin{cases} 4 & v(R) > v(r) \\ 3.64 & v(R) < v(r) \end{cases}$$

Pan & Schlichting (2012)



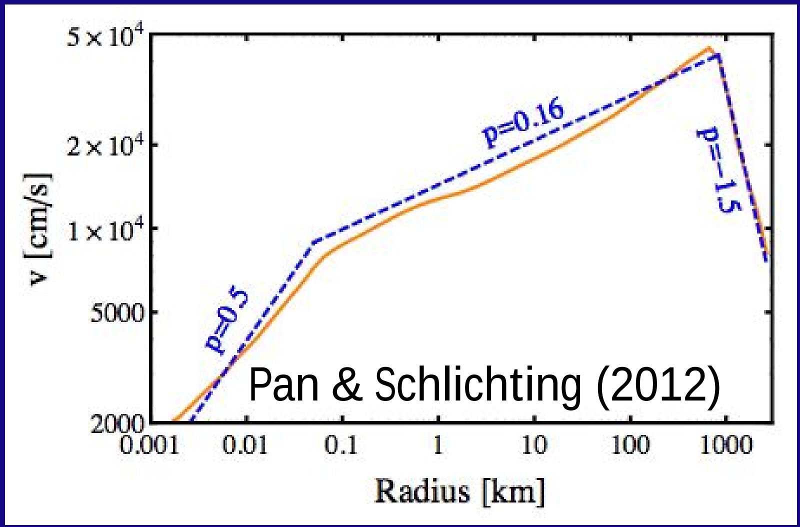
Comparison with Observations

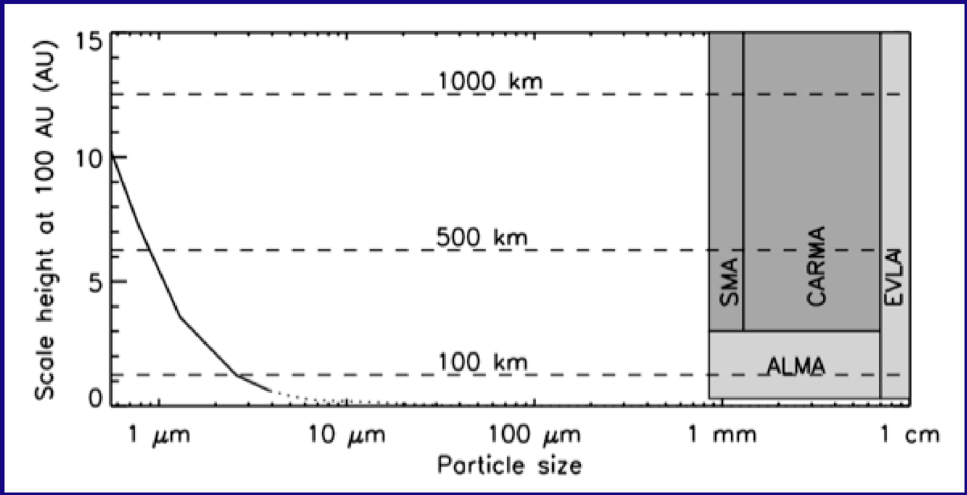
Scale height of disk ~ [random velocity]/[orbit velocity]

We expect scale height = power law of observing wavelength:

e.g $\boxed{v \propto r^{0.5}}$ implies $\boxed{h \propto \lambda^{0.5}}$

Slope depends on bodies' internal strength, which can constrain internal structure and possibly history → Look for this at ~mm sizes





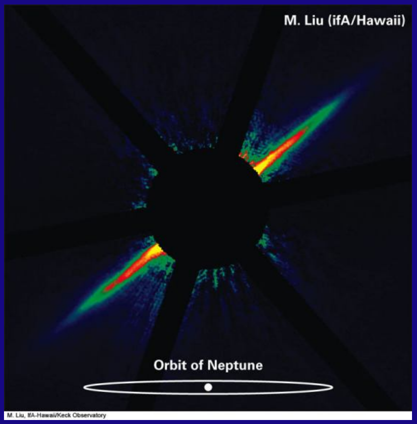
Adapted from Thebault (2009) and Hughes et al. (2012)

The Signature of Planets

- Absolute value of scale height depends on stirring rate: ie, size and number of largest bodies
- Disk scale height as function of wavelength depends on material properties.

For Example: AU Mic-like system ($M^*=0.5M_{sun}$, dust mass $\sim M_{Moon}$, a=40 AU):

–assume observed dust is in 1mm particles
stirring by single $5M_{Earth}$ planet, eccentricity 0.03
damping by collisions with equal-sized bodies



–scale height ~ 1 AU ($M_{planet}/5M_{Earth}$) for 1mm bodies :
angular size ~100 mas (ALMA resolution ~20 mas)

–similarly, scale height ~ 0.5 AU for 0.3mm bodies
~1.5 AU for 10mm bodies

–Compare observed heights with different cascade models for info on gravity vs strength, damping mechanisms

Summary

Collisional Evolution

- Velocities are likely a function of particle size
- Need to solve velocity evolution and collisional evolution together
- Can test collisional evolution models with ALMA

Runaway Growth

- Only a small fraction of initial mass in converted into protoplanets during runaway growth: $\Sigma \sim \sigma \alpha^{3/4} \sim 10^{-3} \sigma_{MMSN}$)
- Size distribution of runaway tail: q ~ 4, equal mass per logarithmic mass bin