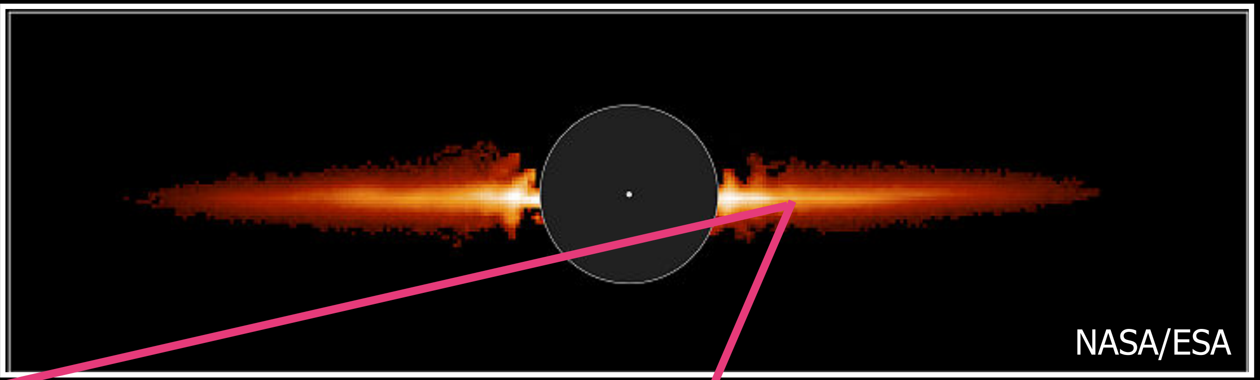
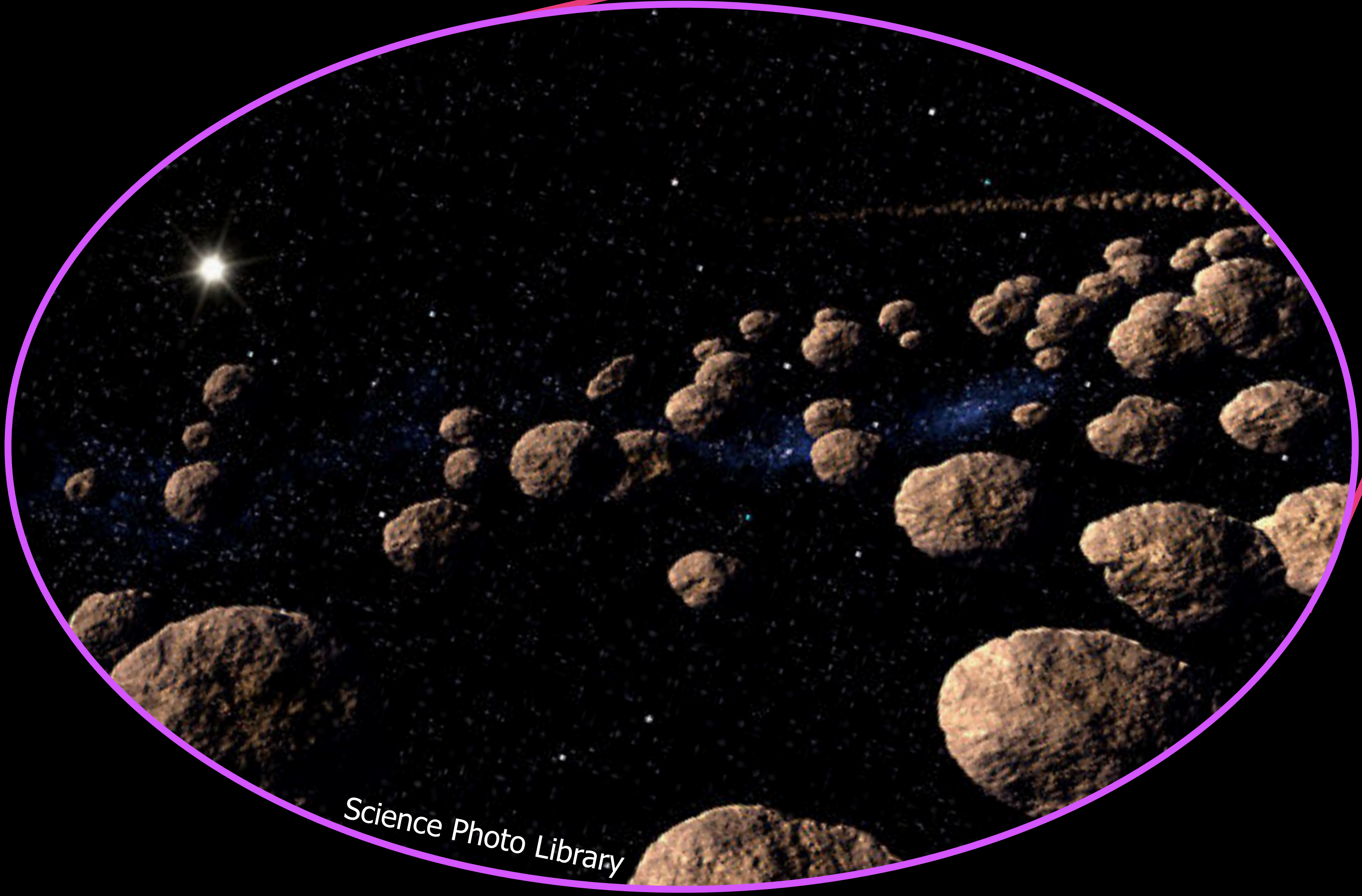
Debris disk scale heights



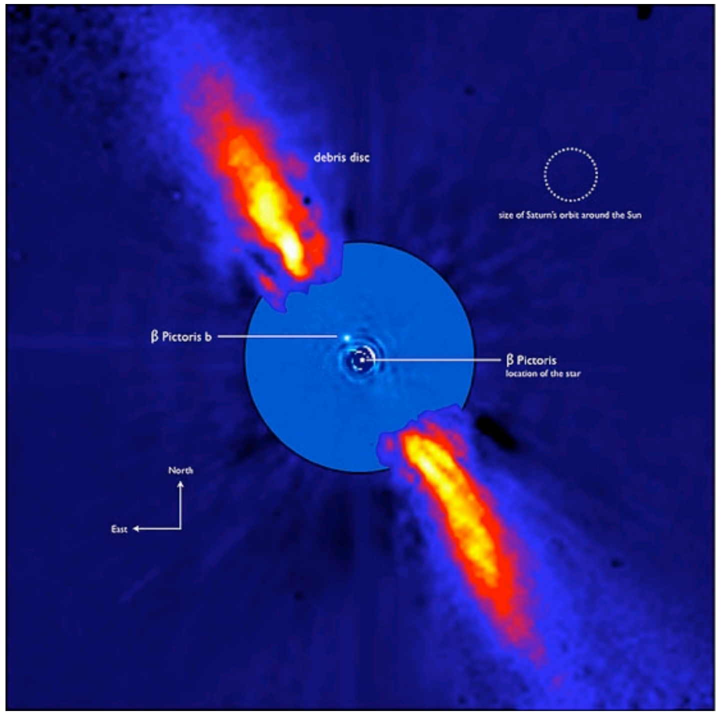


and what they can tell us about planets

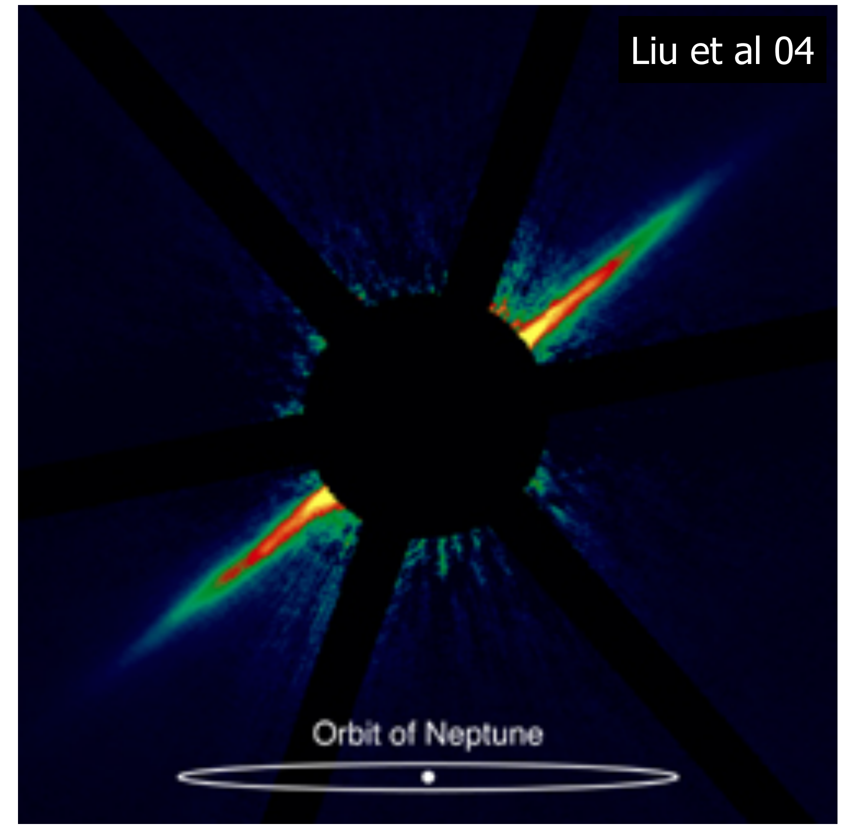
Margaret Pan (GSFC) and Hilke Schlichting (UCLA)

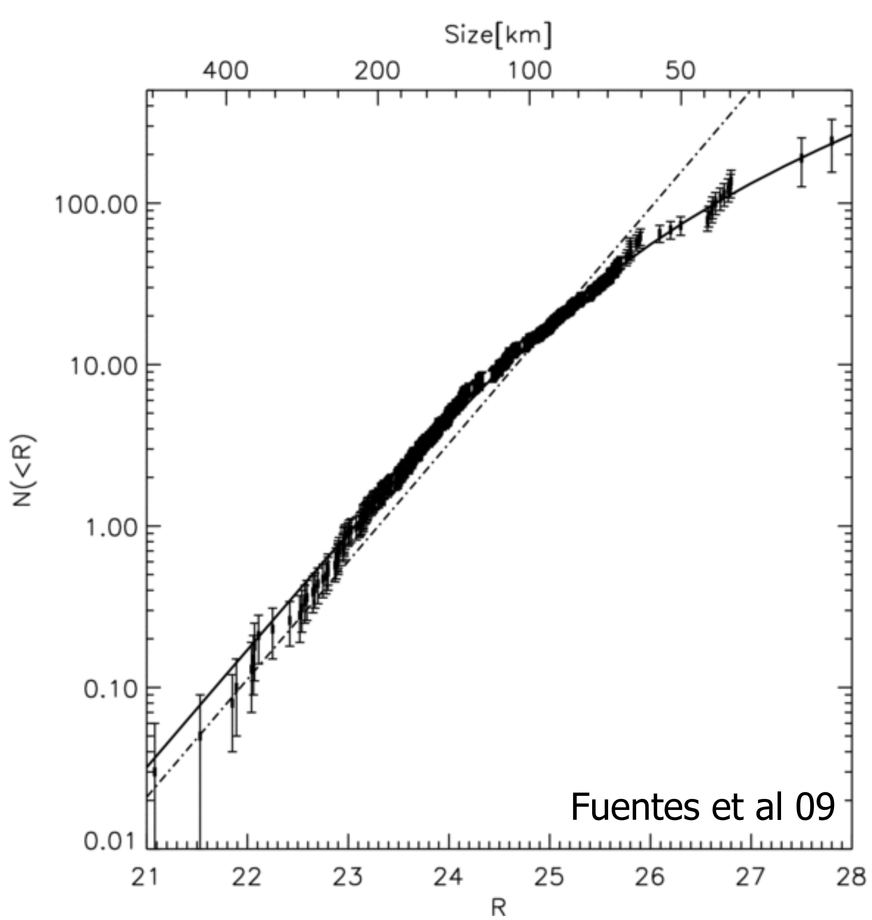
Nearby debris disks

beta Pic



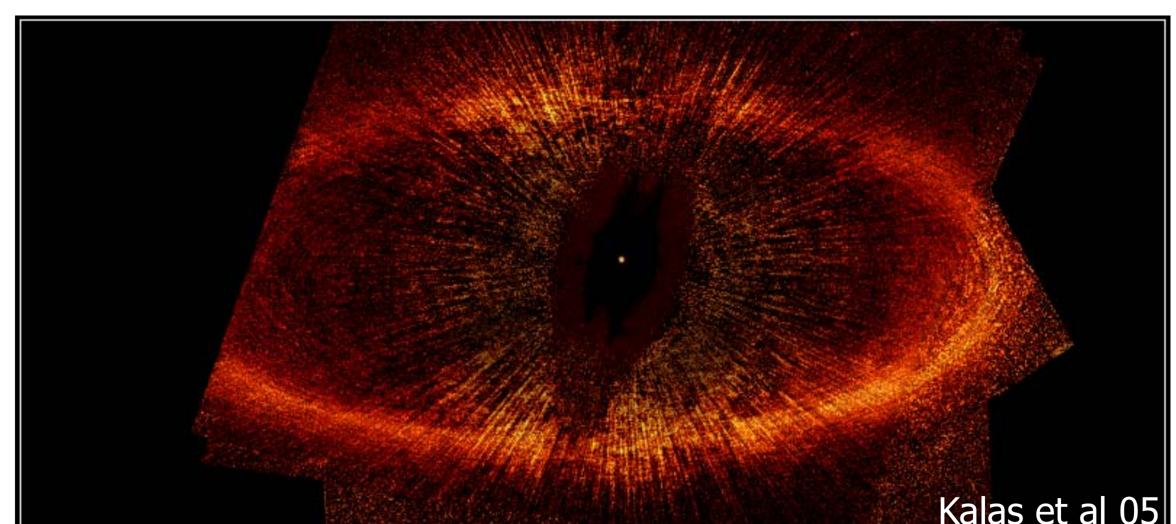
AU Mic





Kuiper belt

Fomalhaut



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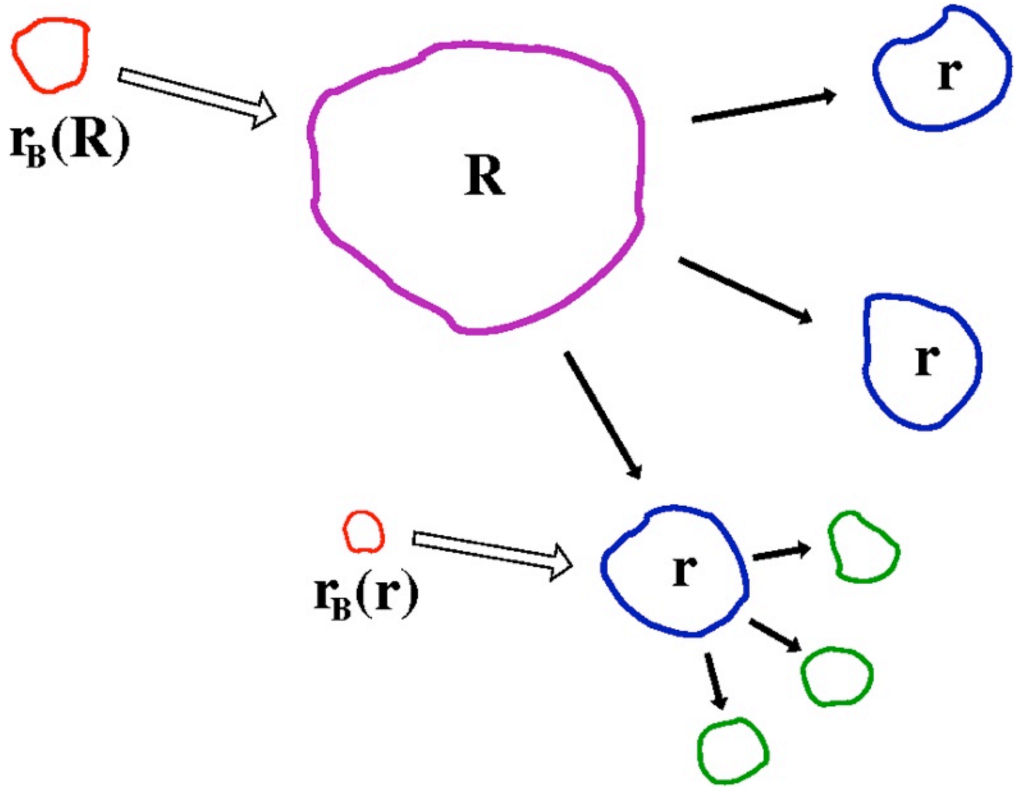
Mass conservation

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



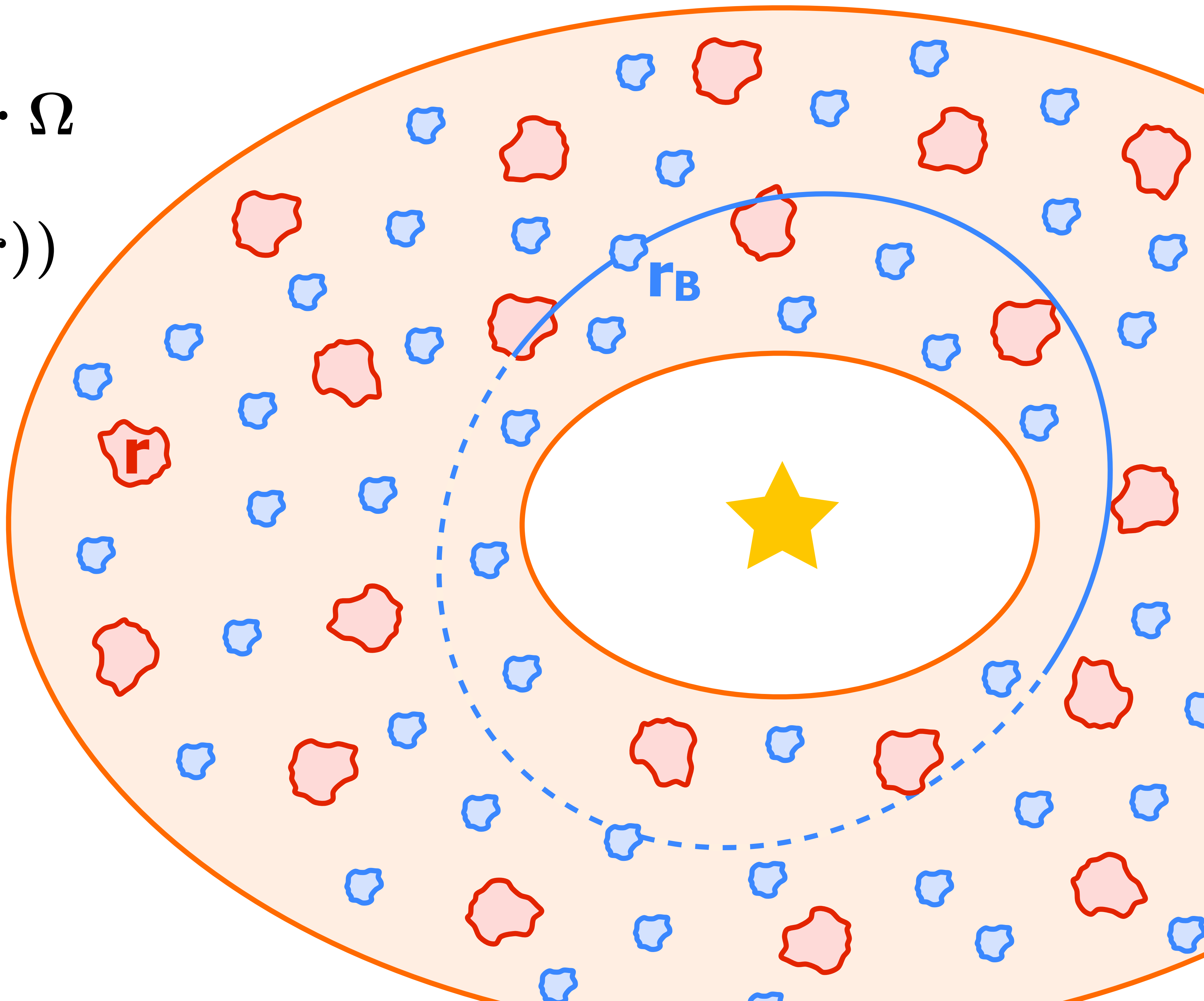
Mass conservation

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

  mass destruction rate of size r:

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

$$\cdot N(r_B(r))$$



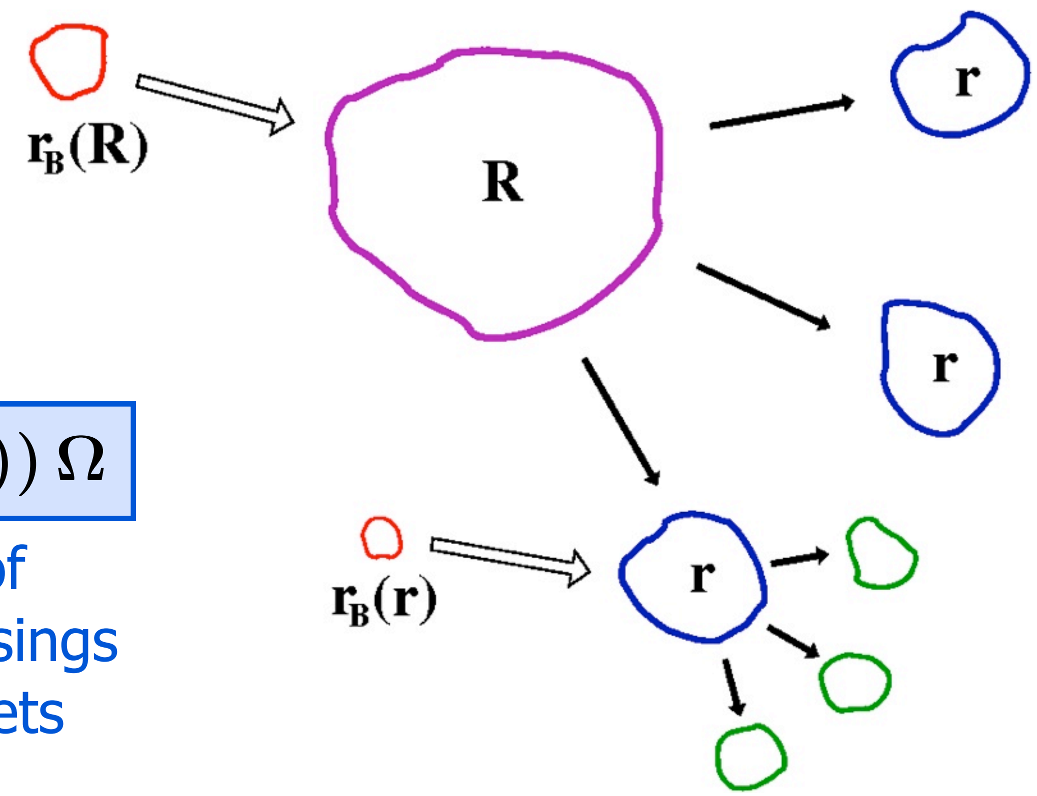
Mass conservation

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

mass rate of destruction · target mass · covering fraction of targets · rate of disk crossings by bullets

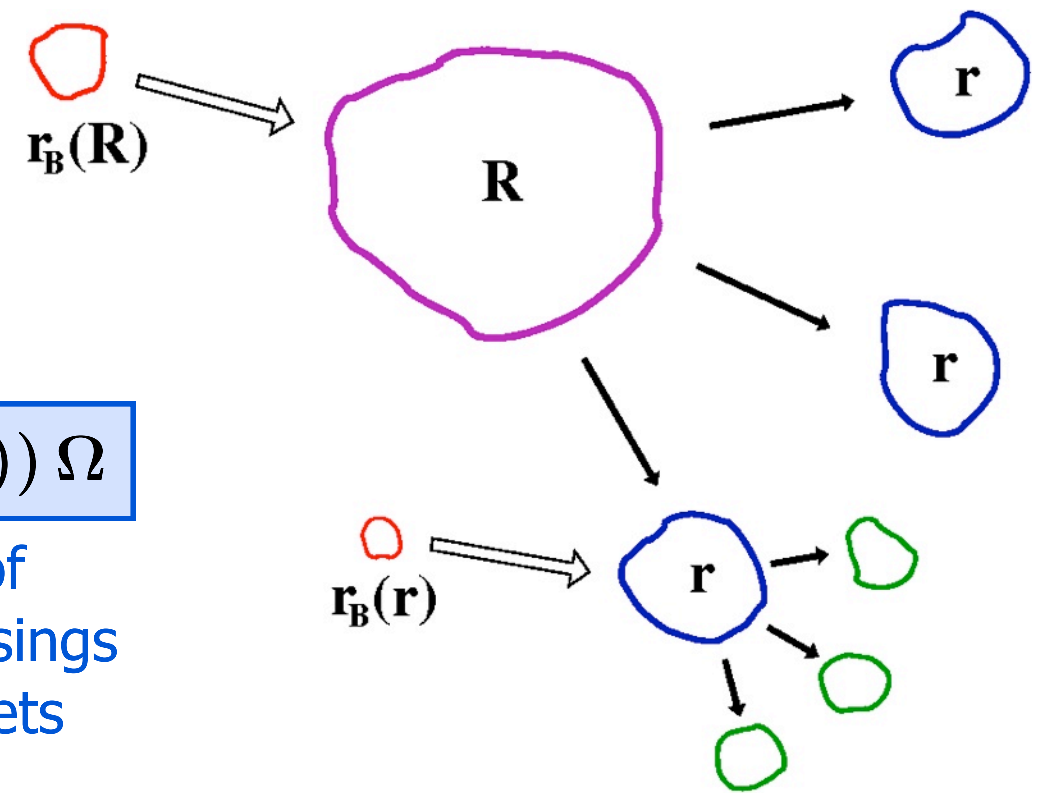
$$\text{constant} = \rho r^3 \cdot \frac{N(r)\, r^2}{\text{area of disk}} \cdot N(r_B(r))\,\Omega$$

$$\text{constant} = r^{6-q} \cdot (r_B(r))^{1-q}$$



Mass conservation

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



mass rate of destruction

covering fraction of targets

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

target mass

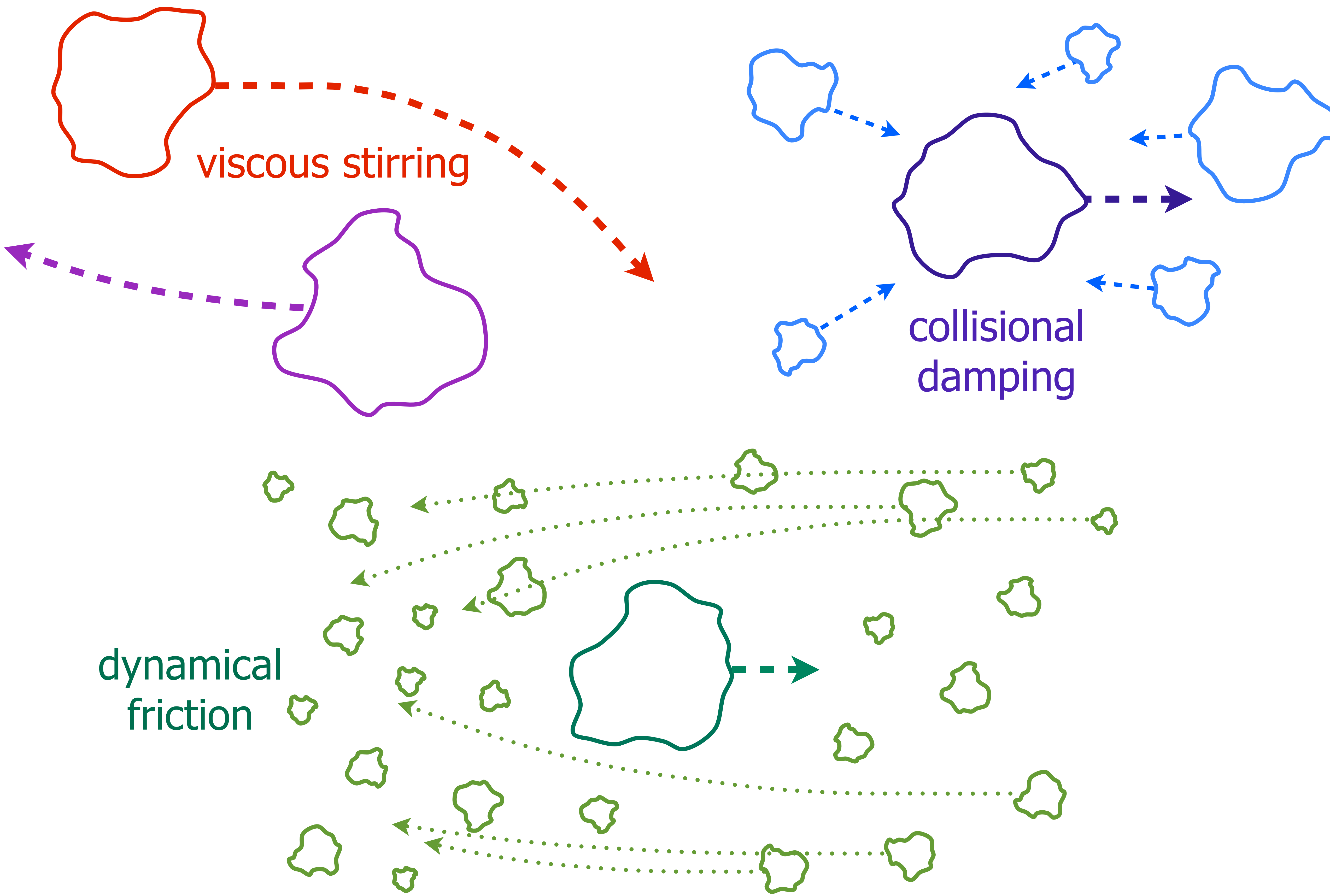
rate of disk crossings by bullets

$$\text{constant} = r^{6-q} \cdot (r_B(r))^{1-q}$$

- $r_B(r)$?
  - In general, r_B is a function of breaking strength and velocity
  - simplest is $r_B \propto r$: $q = 7/2$

- **but why should velocity be constant?**

Velocity evolution



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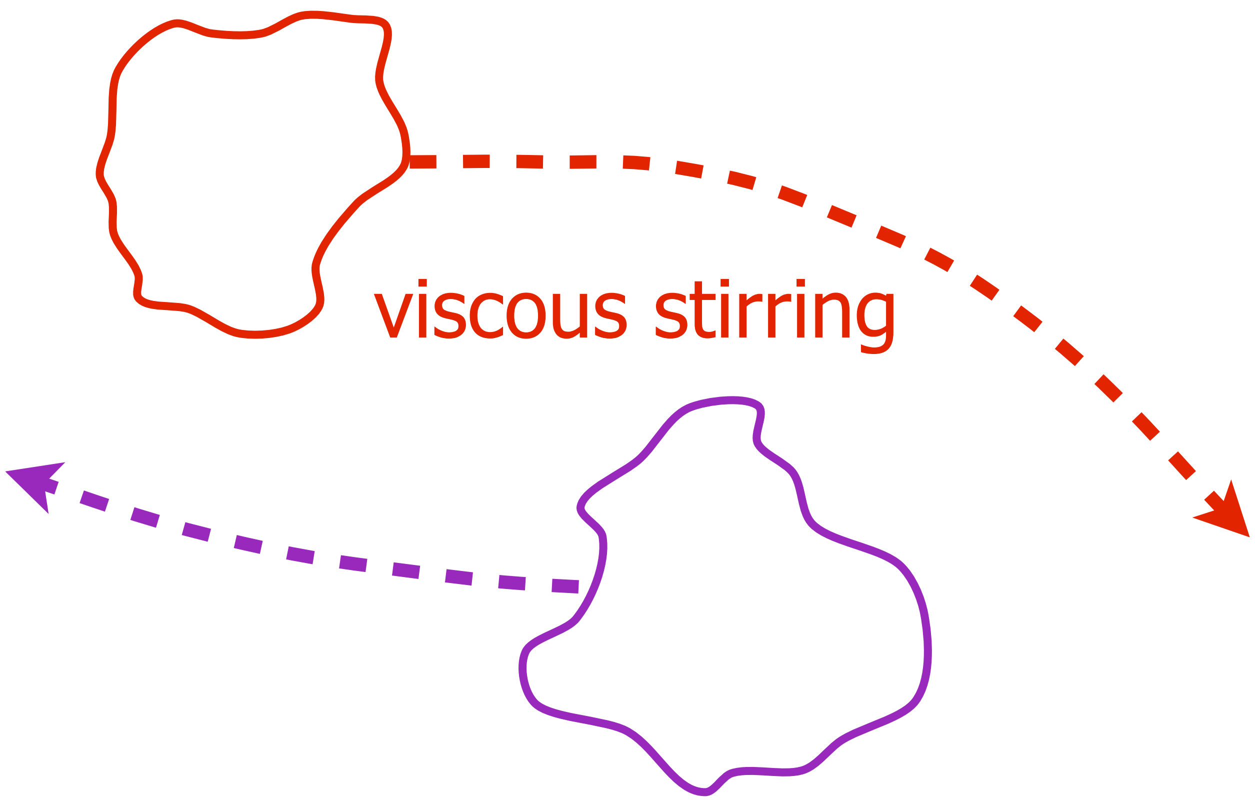
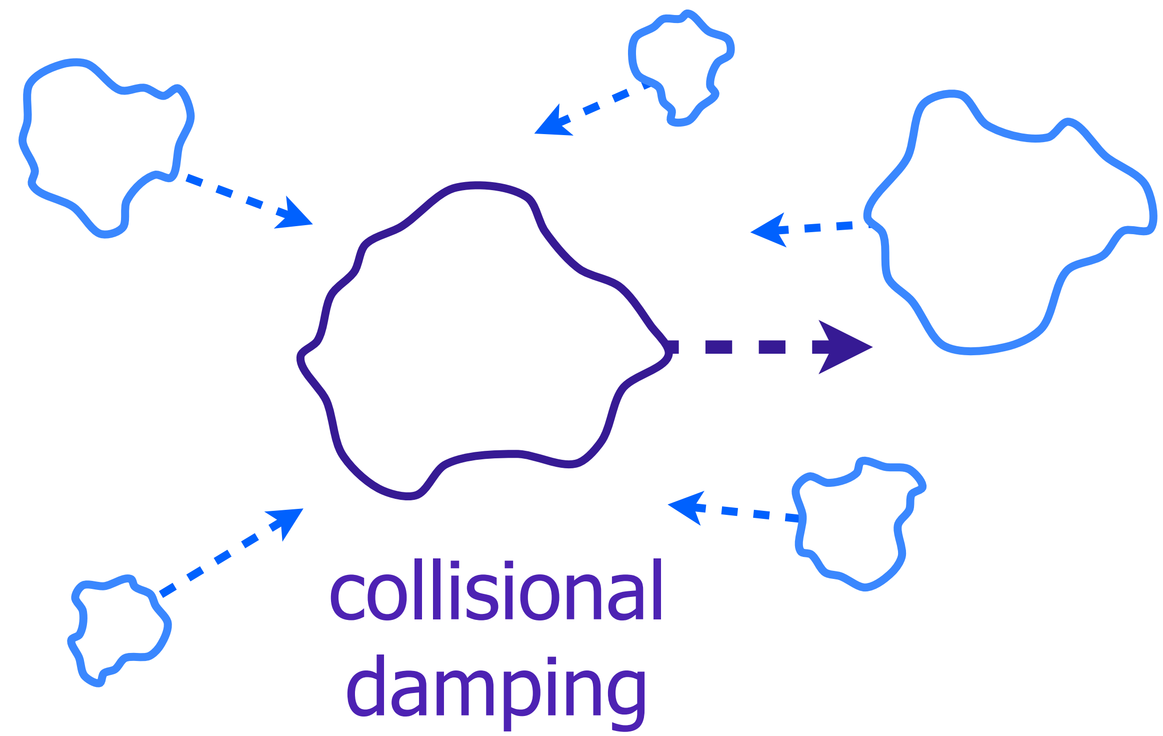
Velocity equilibrium

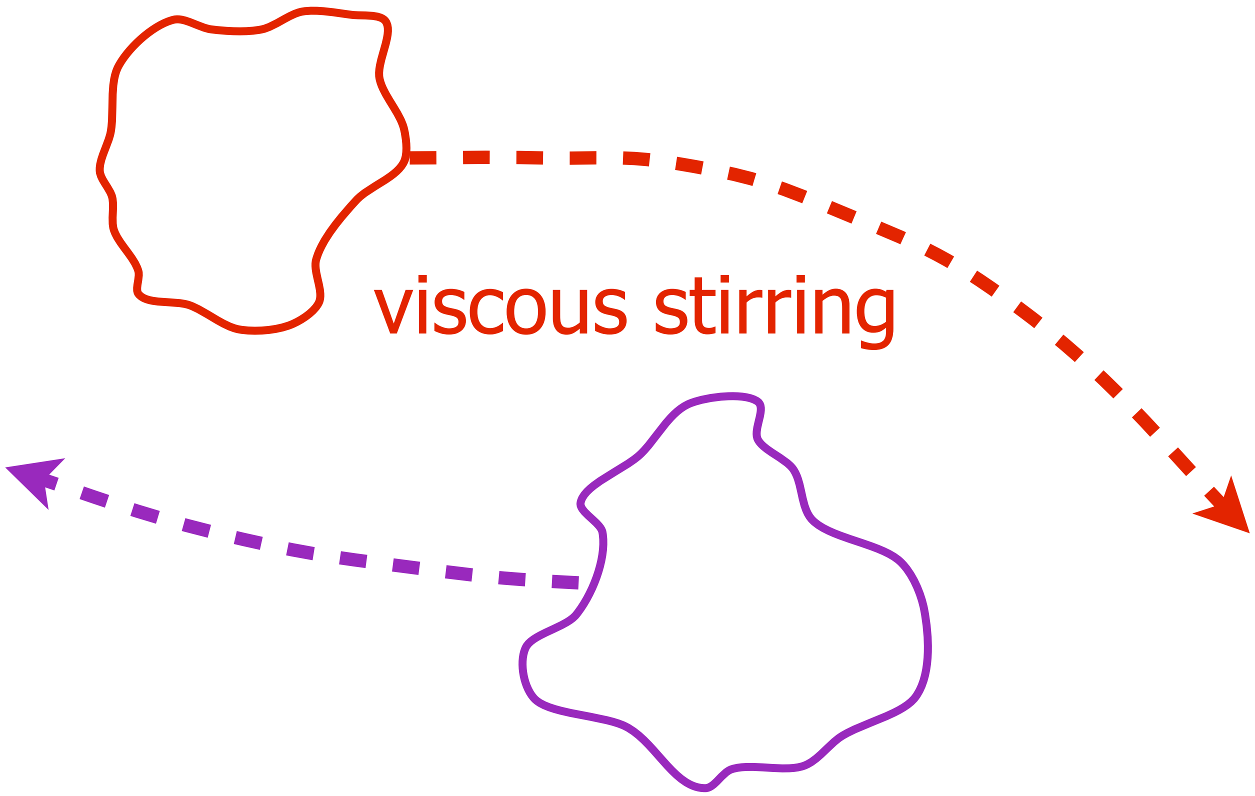




$N(r) \propto r^{1-q}$

$v(r) \propto r^{p}$

Velocity equilibrium



collisional damping of size r by size s

$$\sim -\frac{r^2}{\text{area}} \cdot N(s)\Omega \cdot \frac{s^3}{r^3}$$

covering fraction of target

rate of disk crossings by size s bodies

impactor/ target mass ratio

damping rate $\propto s^{4-q} r^{-1}$

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

$v(r) \propto r^{p}$

Velocity equilibrium

viscous stirring of size r by size R $\sim \frac{N(R)R^2}{\text{area}} \cdot \frac{v_{\text{esc}}^4(R)}{v^4(r)} \cdot \Omega$

- $\frac{N(R)R^2}{\text{area}}$: covering fraction of stirring bodies
- $\frac{v_{\text{esc}}^4(R)}{v^4(r)}$: gravitational focusing
- Ω: rate of disk crossings

stirring rate $\propto R^{5-q} r^{-4p}$

collisional damping of size r by size s $\sim -\frac{r^2}{\text{area}} \cdot N(s)\Omega \cdot \frac{s^3}{r^3}$

- $\frac{r^2}{\text{area}}$: covering fraction of target
- $N(s)\Omega$: rate of disk crossings by size s bodies
- $\frac{s^3}{r^3}$: impactor/target mass ratio

damping rate $\propto s^{4-q} r^{-1}$

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

$v(r) \propto r^p$

Velocity equilibrium

viscous stirring of size r by size R $\sim \frac{N(R)R^2}{\text{area}} \cdot \frac{v_{\text{esc}}^4(R)}{v^4(r)} \cdot \Omega$

covering fraction of stirring bodies

gravitational focusing

rate of disk crossings

collisional damping of size r by size s $\sim -\frac{r^2}{\text{area}} \cdot N(s)\Omega \cdot \frac{s^3}{r^3}$

covering fraction of target

impactor/ target mass ratio

rate of disk crossings by size s bodies

stirring rate $\propto R^{5-q} r^{-4p}$ = damping rate $\propto s^{4-q} r^{-1}$

if q<4 , biggest bodies dominate stirring and damping: R=r_{max} , s=r

steady state means stirring = damping for all r ⟶ $q = 3 + 4p$

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

$v(r) \propto r^{p}$

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Self-consistent sizes and velocities

mass conservation

+

velocity
equilibrium

viscous stirring   collisions   dynamical friction

+

breaking strength

⇒

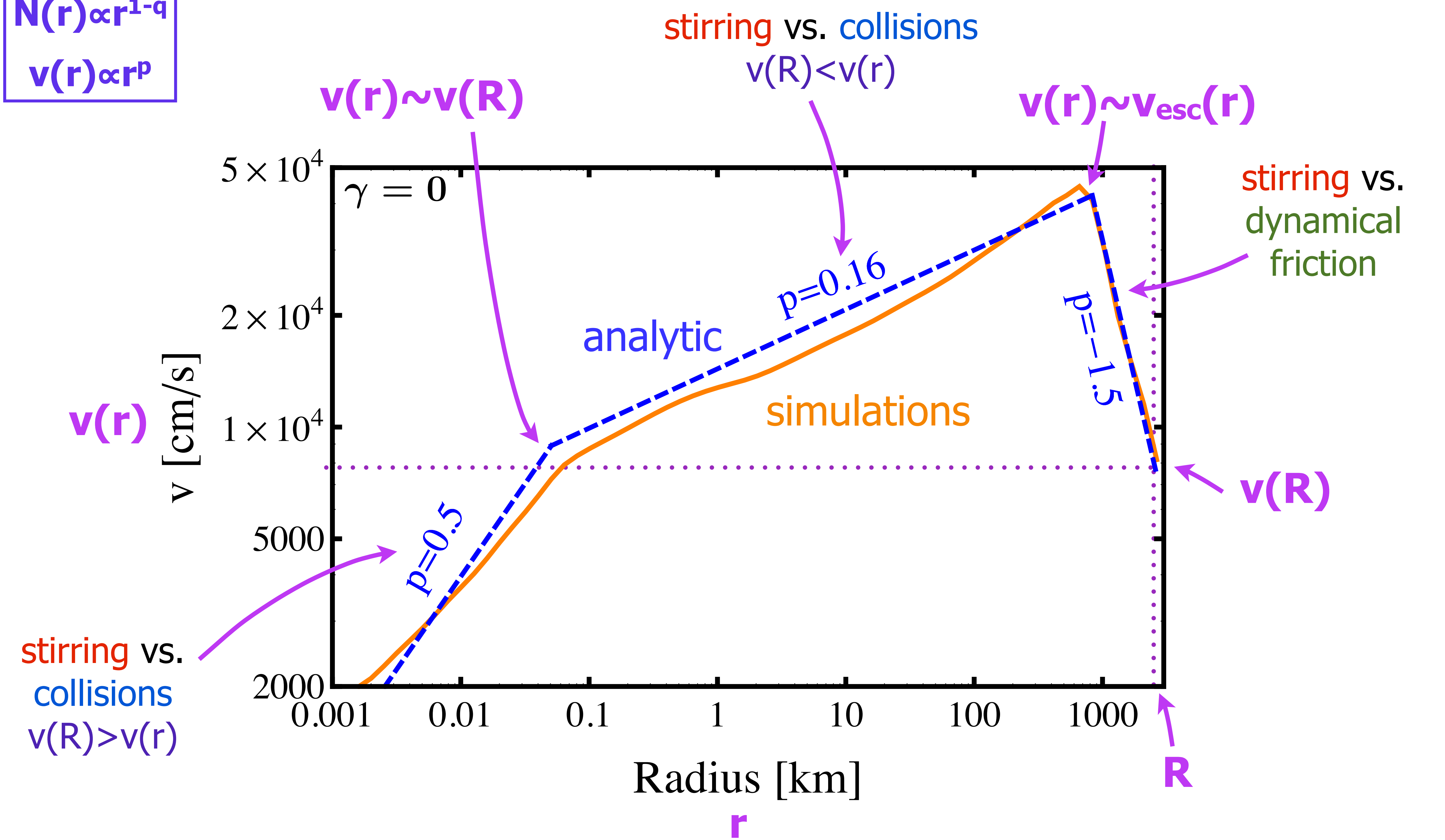
v(r)
N(r)

(power laws)

Self-consistent sizes and velocities

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

$v(r) \propto r^{p}$



Self-consistent sizes and velocities

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

$v(r) \propto r^{p}$

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

Size distributions steepen:

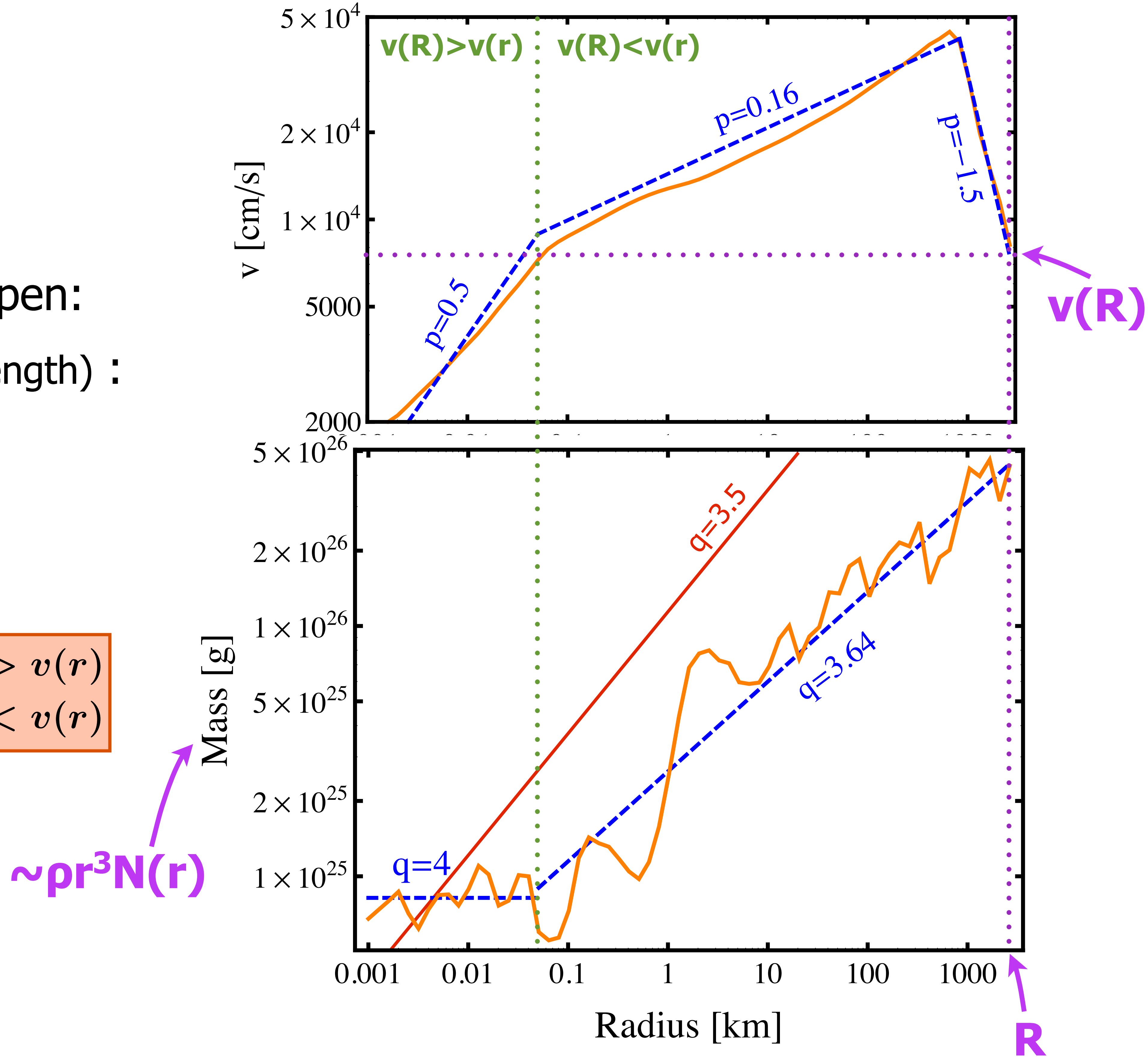
- $\gamma = 0$ (constant strength) :

old (Dohnanyi)

$$q = 7/2$$

new

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



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Steady-state cascades

		damping mechanism	$v(R) > v(r)$	$v(R) < v(r)$
$v(r) > v_{\rm esc}(r)$: includes all bodies in cascade	gravity regime	catastrophic collisions	$0.37 < p < 0.45$ $3.26 > q > 3.11$	$0.20 < p < 1/4$ $3.21 > q > 3$
		collisions with equal-sized bodies	$0 \leq p < 0.085$ $3 \leq q < 3.17$	$0 \leq p < 0.042$ $3 \leq q < 3.17$
	strength regime	catastrophic collisions	$0.090 < p \leq 0.17$ $3.82 > q \geq 3.65$	$0.054 < p \leq 0.10$ $3.78 > q \geq 3.59$
		collisions with equal-sized bodies	$p = 1/2$ $q = 4$	$1/4 > p > 0.16$ $4 > q \geq 3.64$
		collisions with smallest bodies	$p = 1/2$ $13/3 > q > 4$	— —
$v(r) < v_{\rm esc}(r)$: bodies too large for cascade	gravity or strength regime	dynamical friction	$p = -3/2$ $1 < q < 5$	$p = -3/4$ $1 < q < 7$

Dust production and scale height

- Scale height of disk ~ [random velocity]/[orbit velocity]
  - We expect scale height = power law of observing wavelength: ex. $v \propto r^{0.5}$ implies $h \propto \lambda^{0.5}$
  - Slope depends on bodies' internal strength (γ) , which can constrain internal structure and possibly history
  - Look for this at ~mm sizes

Signatures of planets

- Absolute value of scale height depends on stirring rate:
  ie, size and number of largest bodies
  ex. AU Mic-like system ($M_* = 0.5 M_{sun}$, $\sim M_{Moon}$ in dust, a=40 AU, da=10 AU):

  assume observed dust is in 1mm particles
  stirring by single $10 M_{Earth}$ planet, eccentricity 0.03
  damping by collisions with equal-sized bodies

  scale height ~ 2 AU $(M_{planet}/10 M_{Earth})(0.03/ecc)$ for 1mm bodies :
  angular size ~200 mas (ALMA Cycle 1 resolution ~100 mas)

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

- ALMA Cycle 1 time for AU Mic approved
  (PI Meredith Hughes)

Signatures of planets