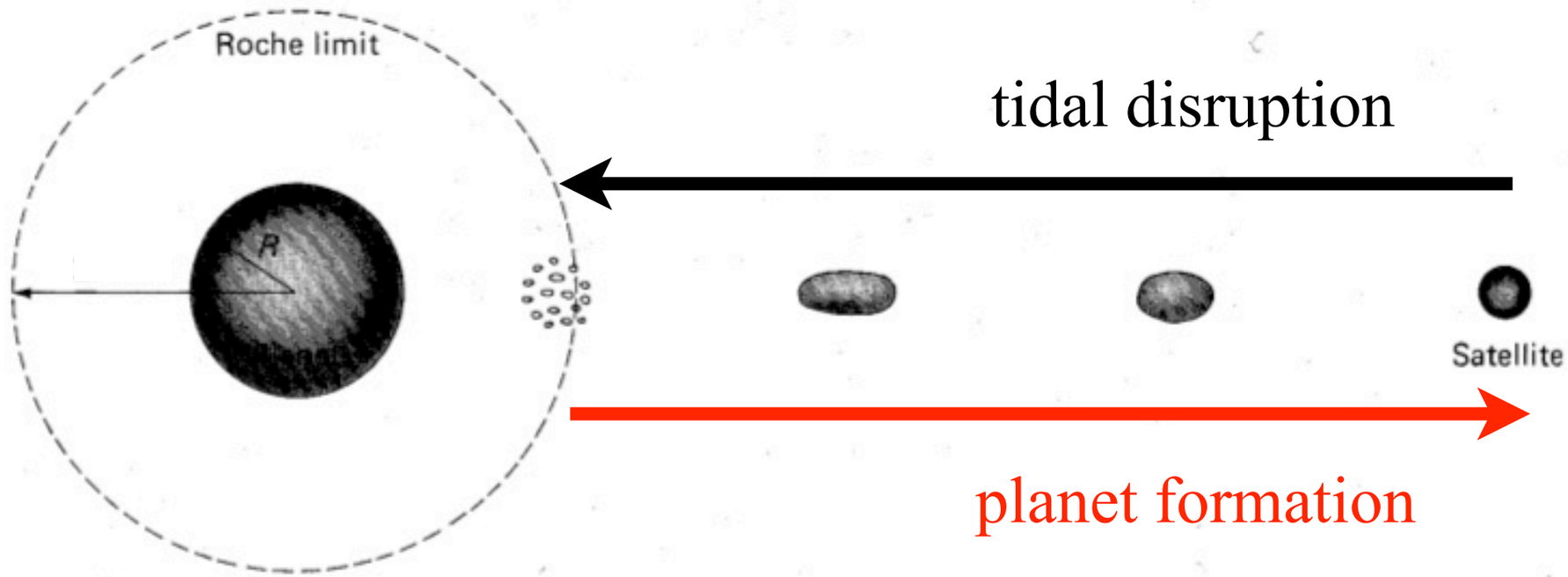
■ **Figure 18.5** The Roche limit. A satellite (far right) in orbit around a planet is slightly deformed by tides. If it moves closer to the planet, it is deformed even more and finally disintegrates when it passes within the Roche limit *(dotted line)*, located 2.44 times the planet's radius from its center.



E. Chiang (UCB)

Planetesimal formation by gravitational instability

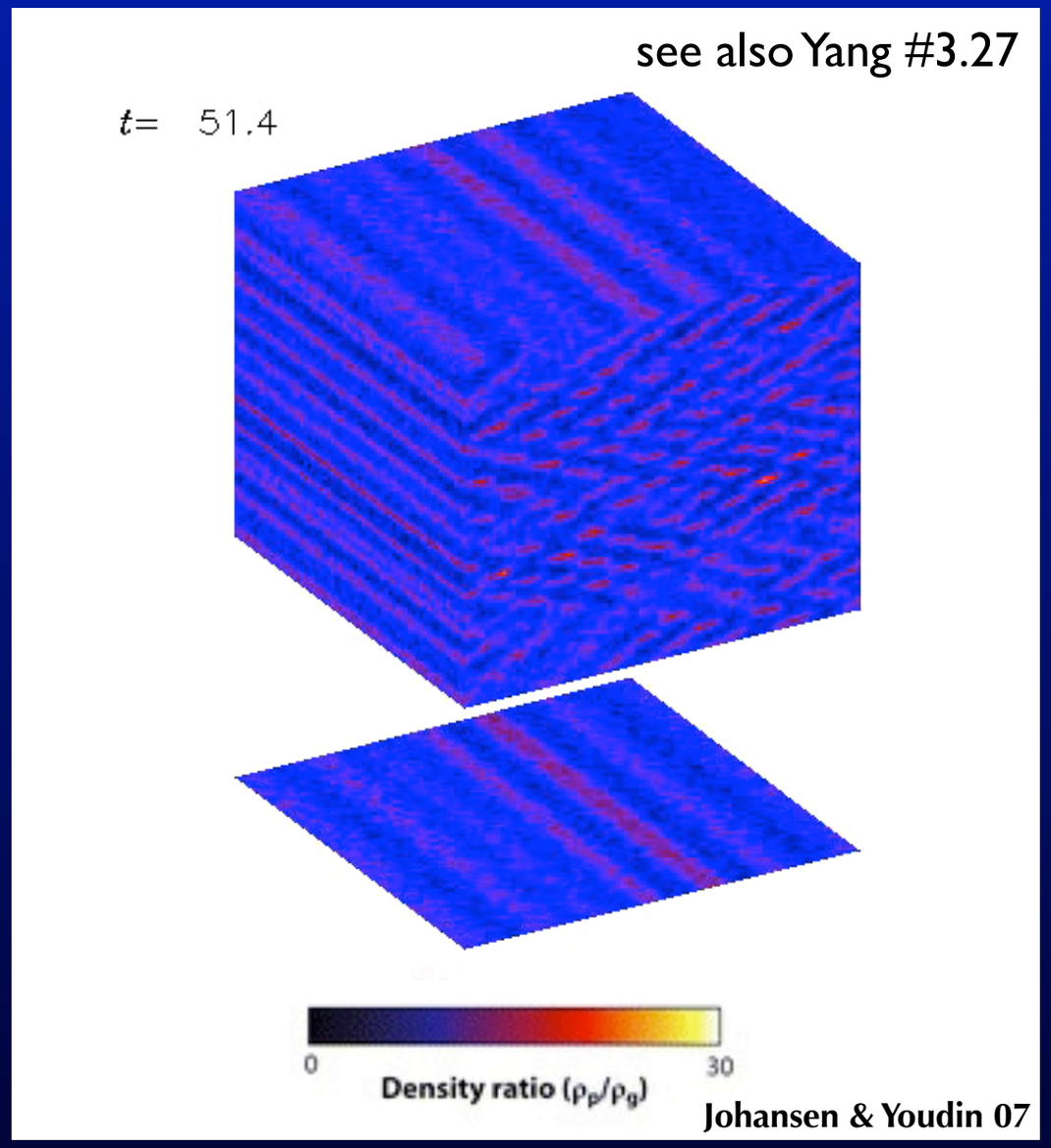
$$\frac{GM_*}{a^2}\frac{R}{a} \sim \frac{G(\rho R^3)}{R^2} \quad \Longrightarrow \quad \text{Roche} \quad \rho \sim M_*/a^3$$

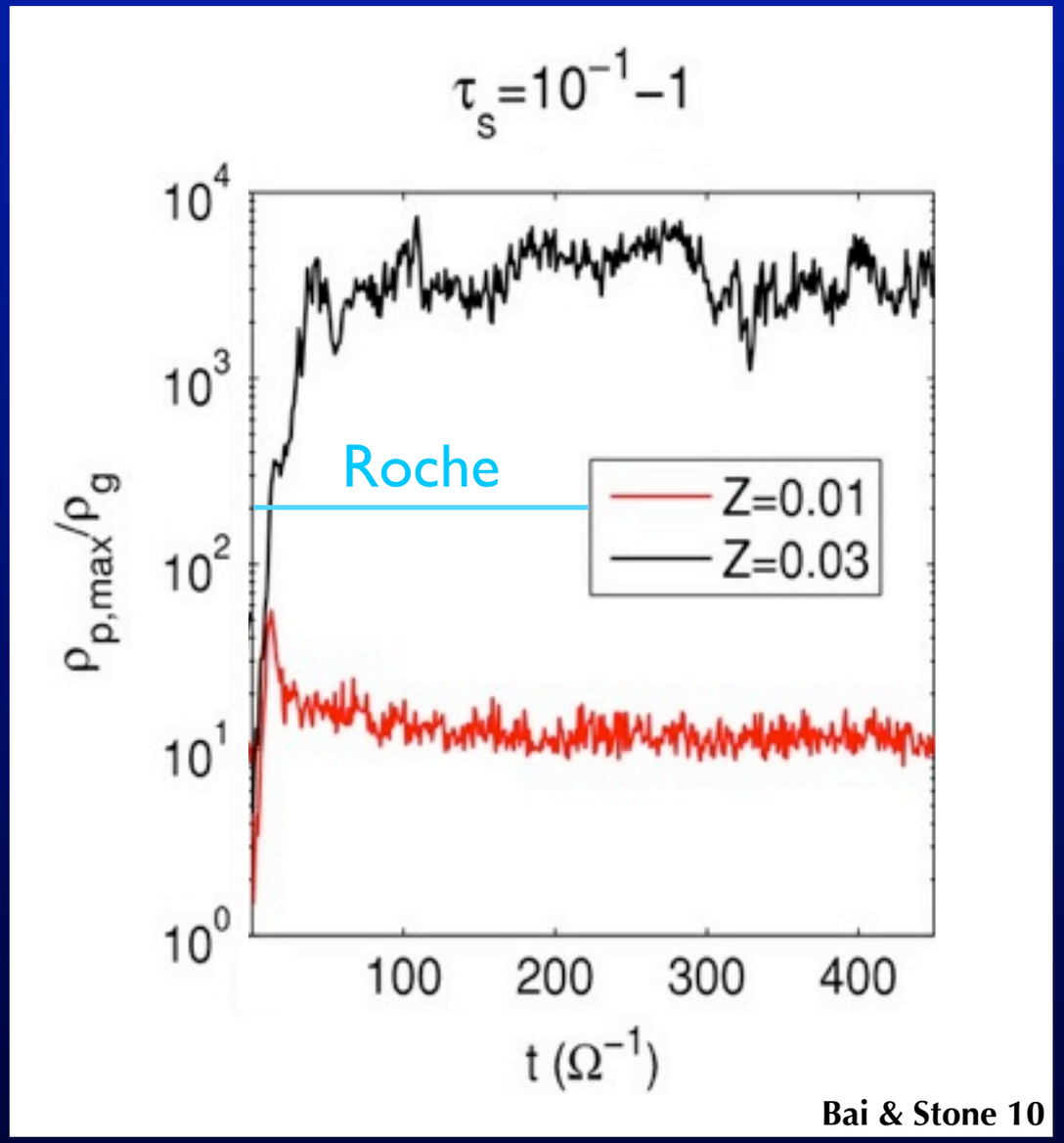
$$\rho_{\rm Roche} \sim 200\,\rho_{\rm MMSN} \quad \Longleftrightarrow \quad \mu \equiv \rho_{\rm dust}/\rho_{\rm gas} \sim 200$$

Assumed starting conditions

- $1 - 10\,\rho_{\rm MMSN}$
- particle size $s < 1\,{\rm cm}$
- bulk metallicity $Z \equiv \Sigma_{\rm dust}/\Sigma_{\rm gas} \sim 0.01 - 0.1$

Streaming Instability
Two-fluid aerodynamic clumping mechanism in disks

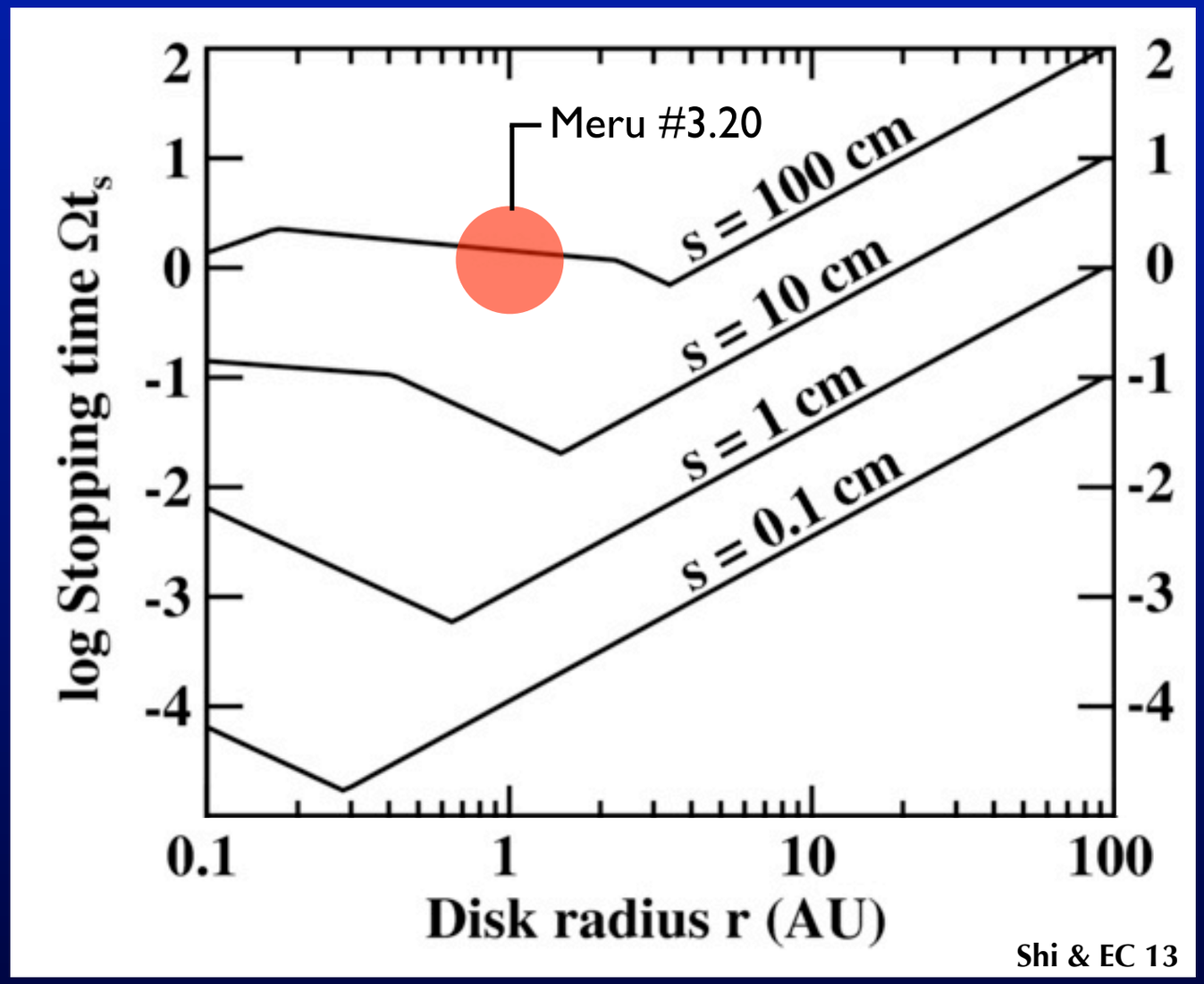


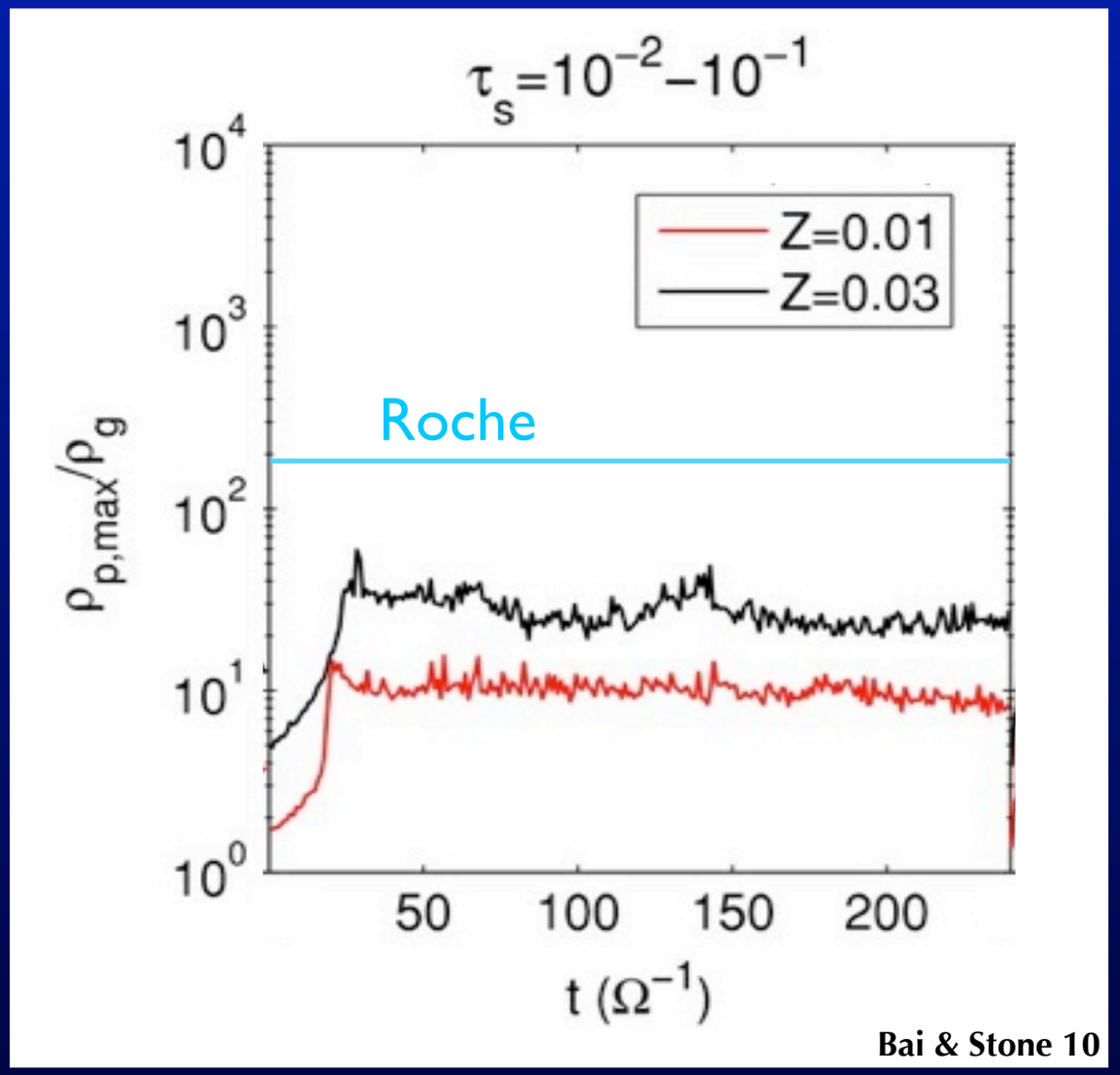


- always present
- most effective when particles are marginally coupled to gas: $t_{\rm stop} \sim \Omega^{-1}$

$$\tau_s \equiv \Omega t_{\rm stop} \sim 1$$

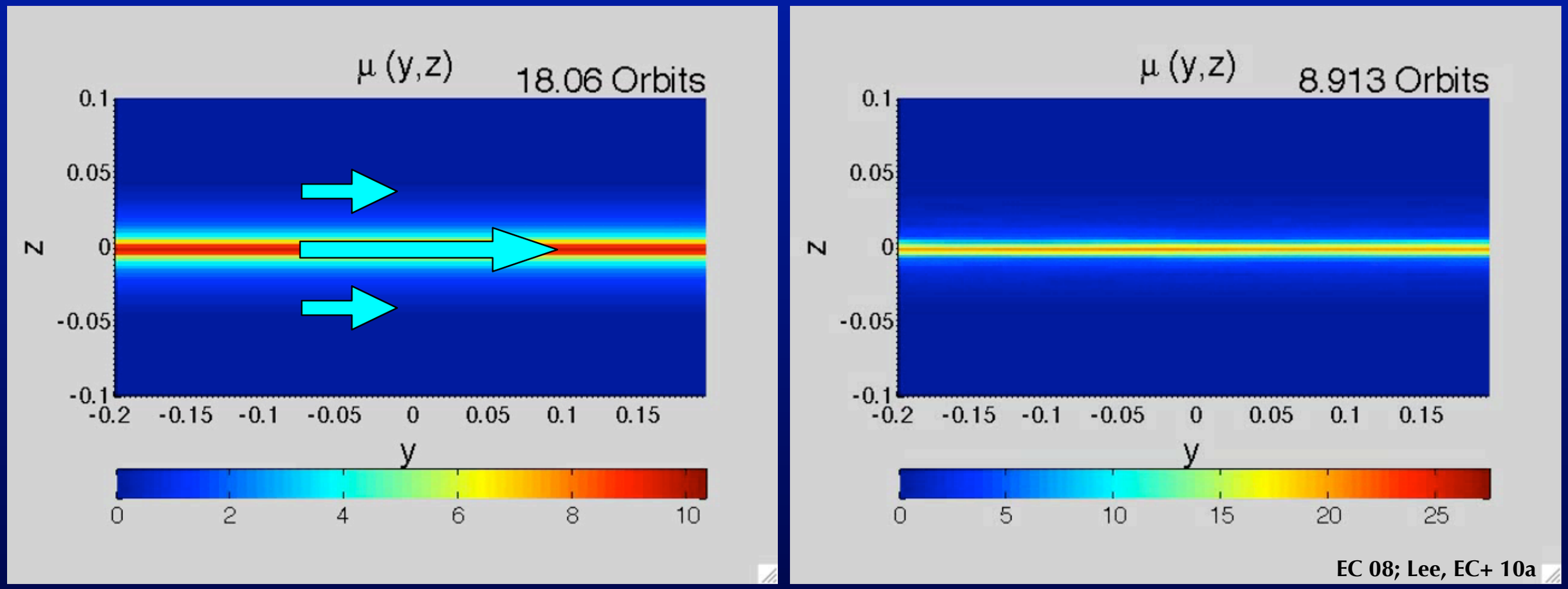
Streaming Instability





- works for outer disk (~100 AU)
- problematic for inner disk: but see Meru #3.20
- but turbulent concentration of particles is general and promising
- also promising is concentration of $\tau_s \sim 1$ in vortices: see Meheut #3.19

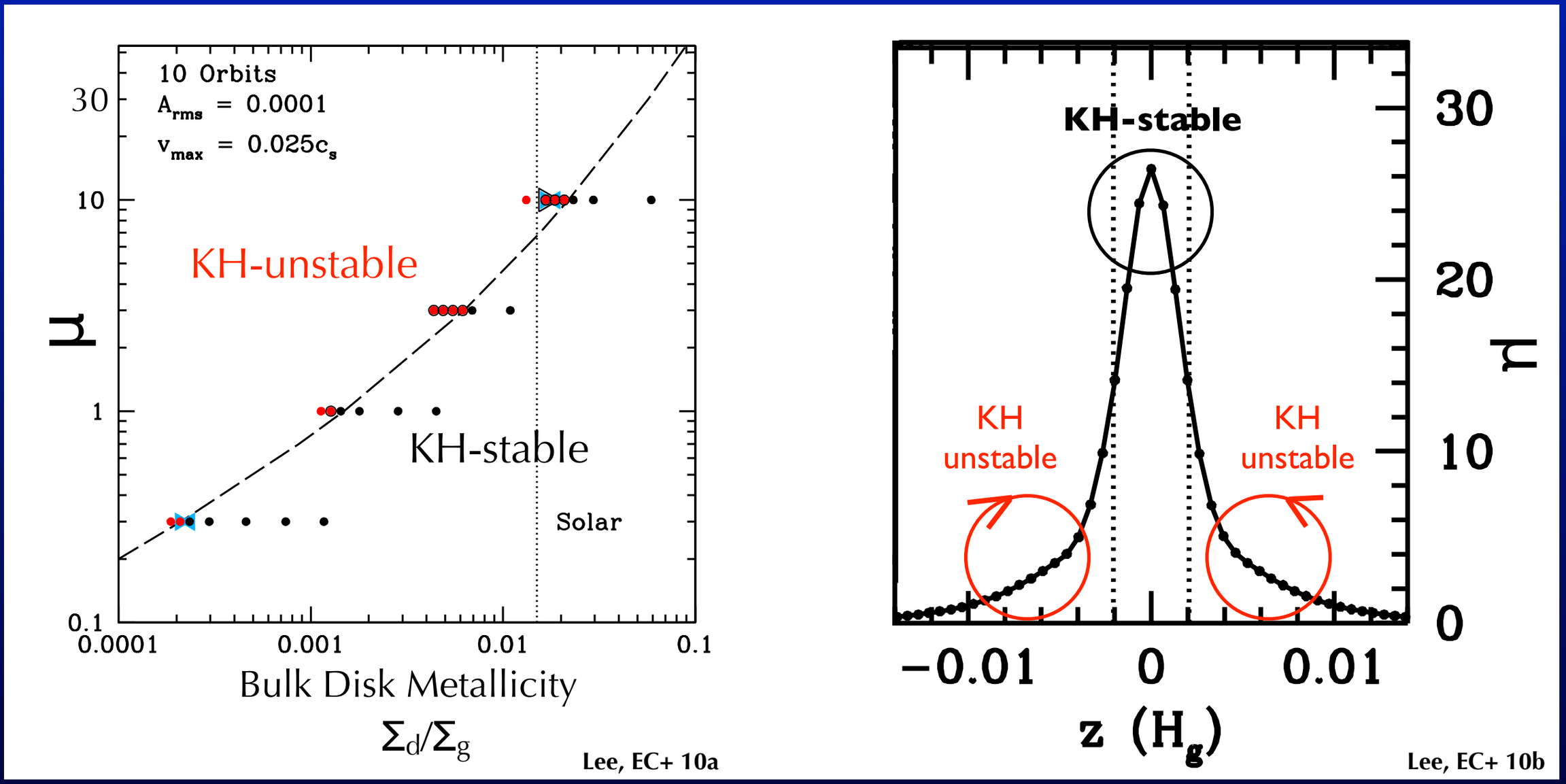
Vertical Settling



EC 08; Lee, EC+ 10a

- dust settles quickly even for $\tau_s << 1$ (10^3 yr for mm grains)
- turbulence (of all forms) is a problem

Vertical Settling

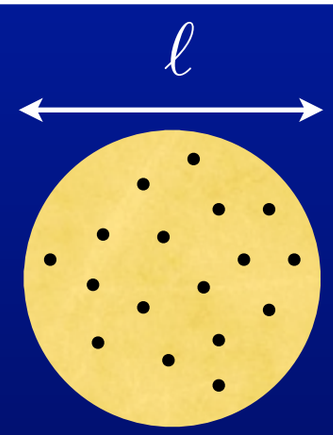


- If Z ~ 0.06 (4 x solar), then max μ ~ 30
- results so far omit self-gravity, whose inclusion should only increase μ
- but streaming instability might prevent vertical settling
- computationally expensive to simulate thin sublayers

Vertical Settling

Only small clumps with big particles can collapse against gas pressure

If $t_{\rm stop} < \ell/c$:

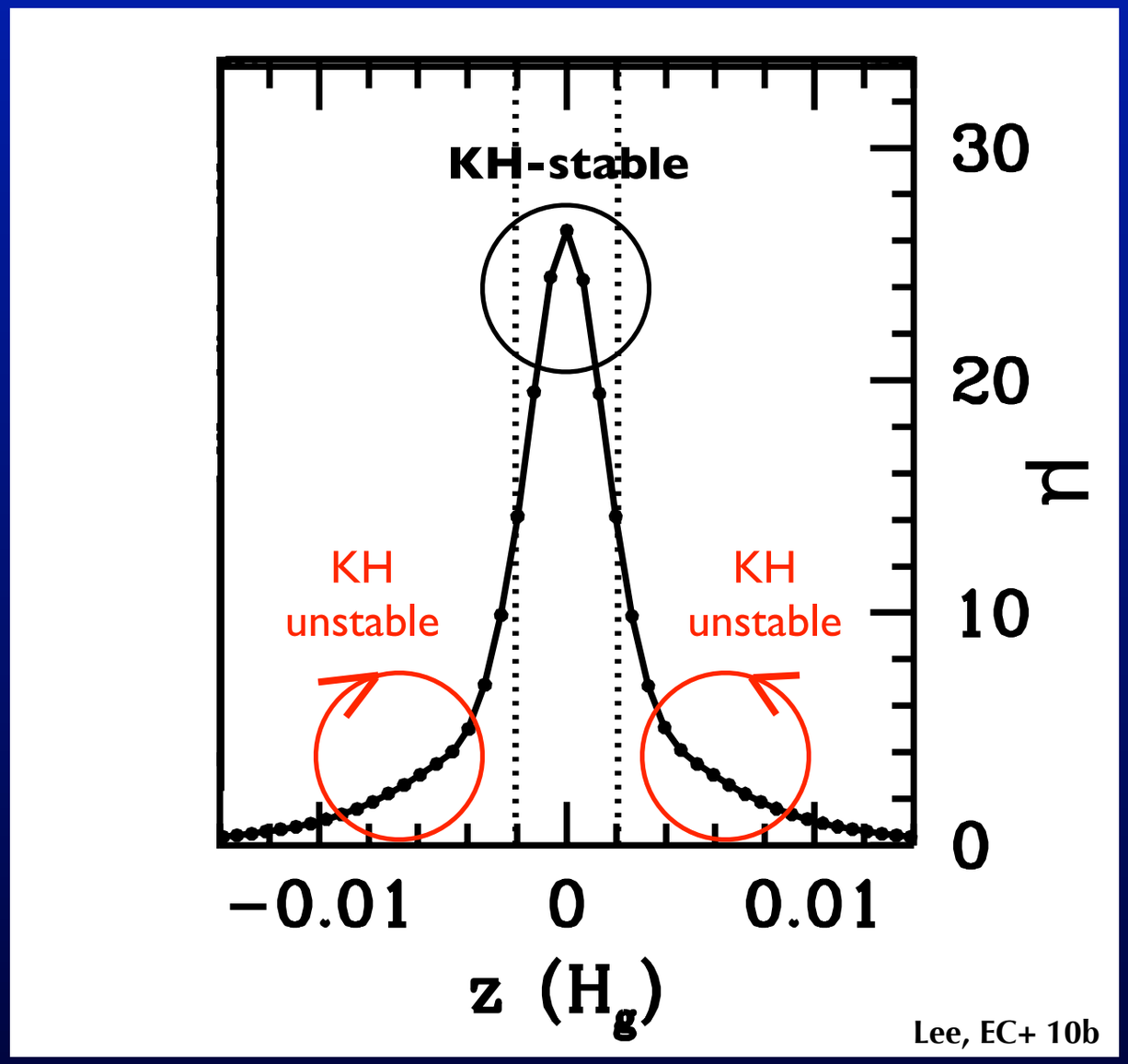


dust-gas mixture acts as a tightly coupled suspension

$$c = \frac{c_{\rm s}}{\sqrt{1+\mu}} \qquad \frac{\ell}{c} \ll \frac{1}{\sqrt{G\rho_{\rm Roche}}}$$

Roche-density suspensions are Jeans-stable

Cuzzi et al. 08
Shi & EC 13



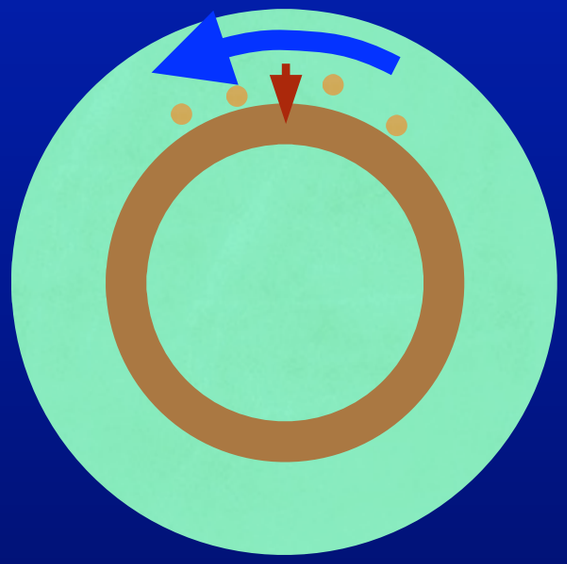
If $t_{\rm stop} > \ell/c$:

dust and gas decouple; loss of pressure support

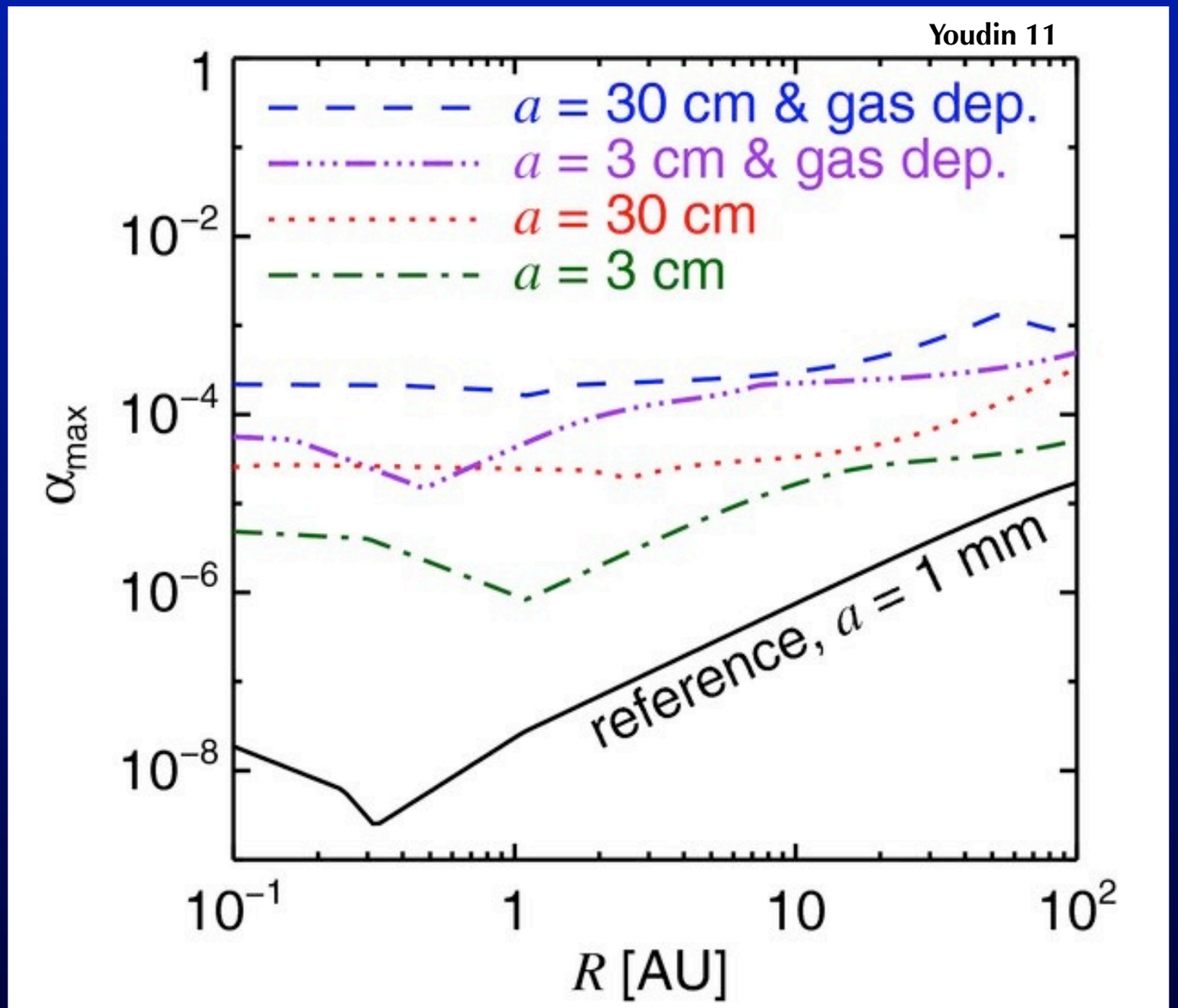
$$t_{\rm collapse} \sim \frac{\ell}{v_{\rm term}} \sim \frac{1}{\Omega\tau_s} \sim 10^3\,\Omega^{-1}$$

collapse is slowed by drag; turbulence could stop it

Secular Gravitational Instability



- overdense rings of dust attract more dust
- modes grow even for $\rho << \rho_{Roche}$!
- accretion rate limited by terminal velocity



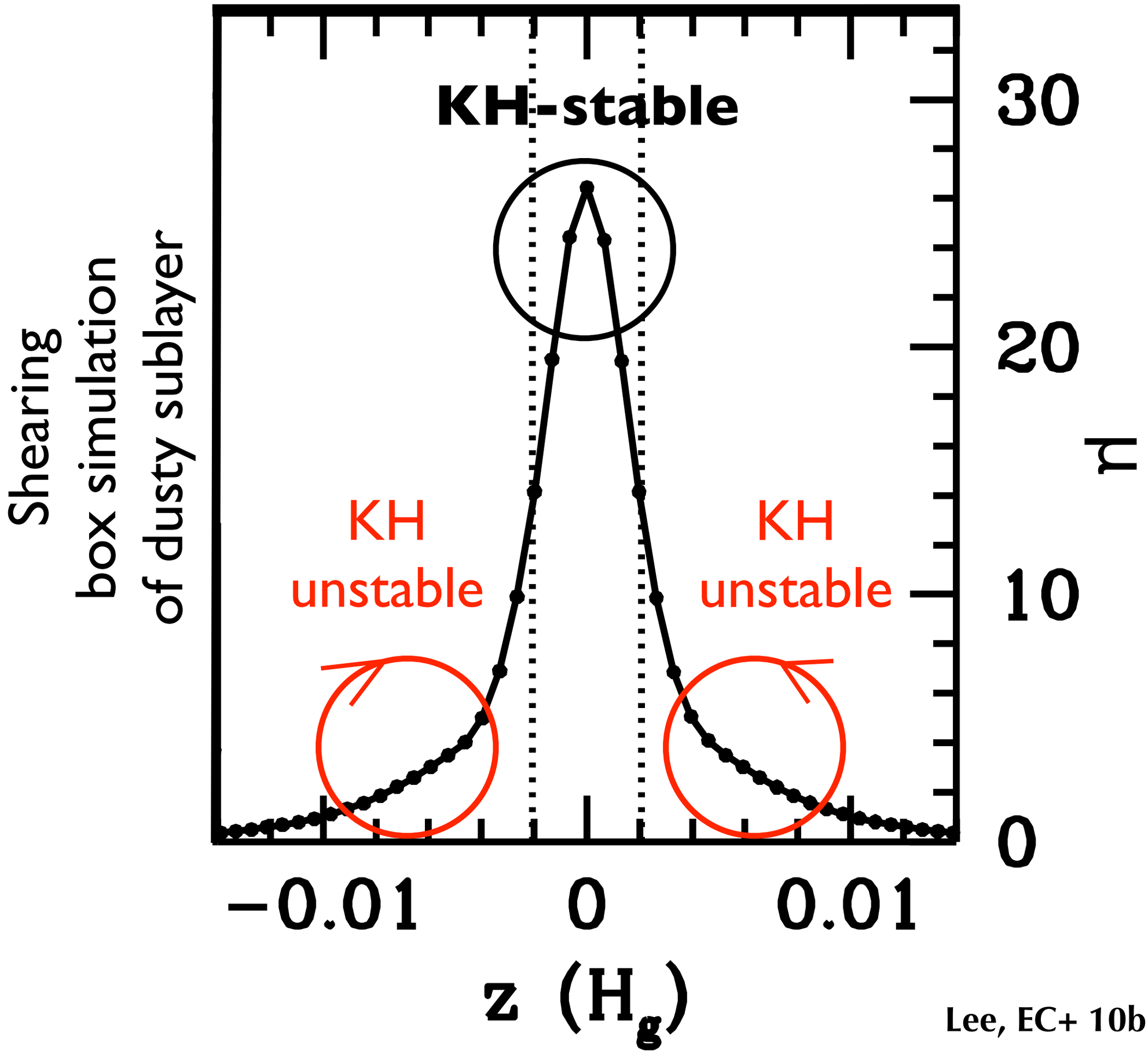
maximal particle diffusivity to keep $t_{collapse} < t_{drift}$

drag-mediated gravitational collapse is slow and sensitive to turbulence

Outlook

Particle concentration in both passive and active disks

- Nonlinear and non-axisymmetric development of secular GI
- Can $\tau_s \sim 10^{-3}$ stick up to $\tau_s \sim 1$? Also need to extend Garaud et al. (2013) to global drift models.
- How thin is thin for $\tau_s \sim 10^{-3}$? How vertically settled can disks be with streaming instability ?
- How dead is dead?


Shearing
box simulation
of dusty sublayer
KH-stable
KH
unstable
KH
unstable
30
20
10
0
η
−0.01
0
0.01
z (H_g)

Lee, EC+ 10b