dead zones and planet formation

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disk model wish list

- sufficient transport (turbulence, laminar, winds) to yield measured accretion rates *(requires vertical field in Am dominated region; Simon et al. 2013)*
- goldilocks level of turbulence – keep small dust aloft in disk atmosphere, allow significant settling *(but scaling* $h_{dust} / h_{gas} \sim (\alpha / \tau)^{1/2}$*)*
- enough mid-plane stress to desaturate co-orbital resonances and slow / reverse Type I migration *(review Kley & Nelson '12)*
- small enough density fluctuations to keep planetesimals in accretion region *(Okuzumi & Ormel '13)*

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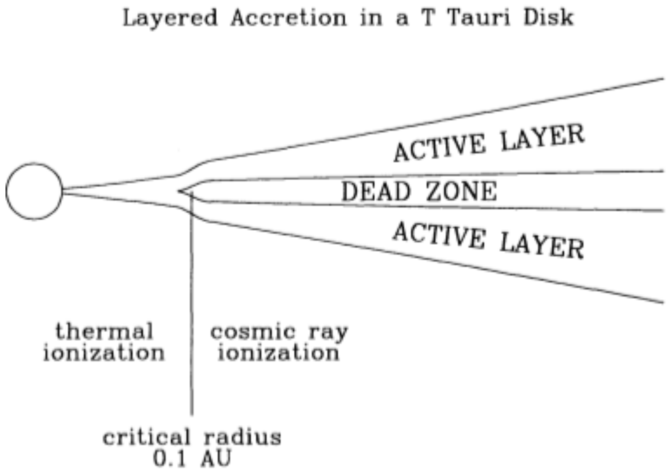
All debatable: BUT $\alpha \sim 10^{-3}$ in Am zone, laminar stress 10^{-2} with turbulence 10^{-4} in Hall zone, broadly consistent

dead zones and planet formation

Does the self-consistent radial structure of the disk require *qualitative* changes to planet formation models?

Caveat 1: No modern analog to Gammie (1996), i.e. $\Sigma(r,t)$ as f(accretion rate, B_z) in steady state, or statement of when steady state is not possible



what follows is wrong

"we're not retreating, we're advancing in another direction…"

dead zones and planet formation

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Caveat 2: Generic ideas of what might be different are not original (*Lyra et al.'09, Dzyurkevich et al.'11, Sandor et al.'11, Hansen '09, Izidoro et al.'14, Drazkowska et al.'13, Ward '09, Zhu et al. '12, Chatterjee & Tan '14, Boley & Ford '13)*

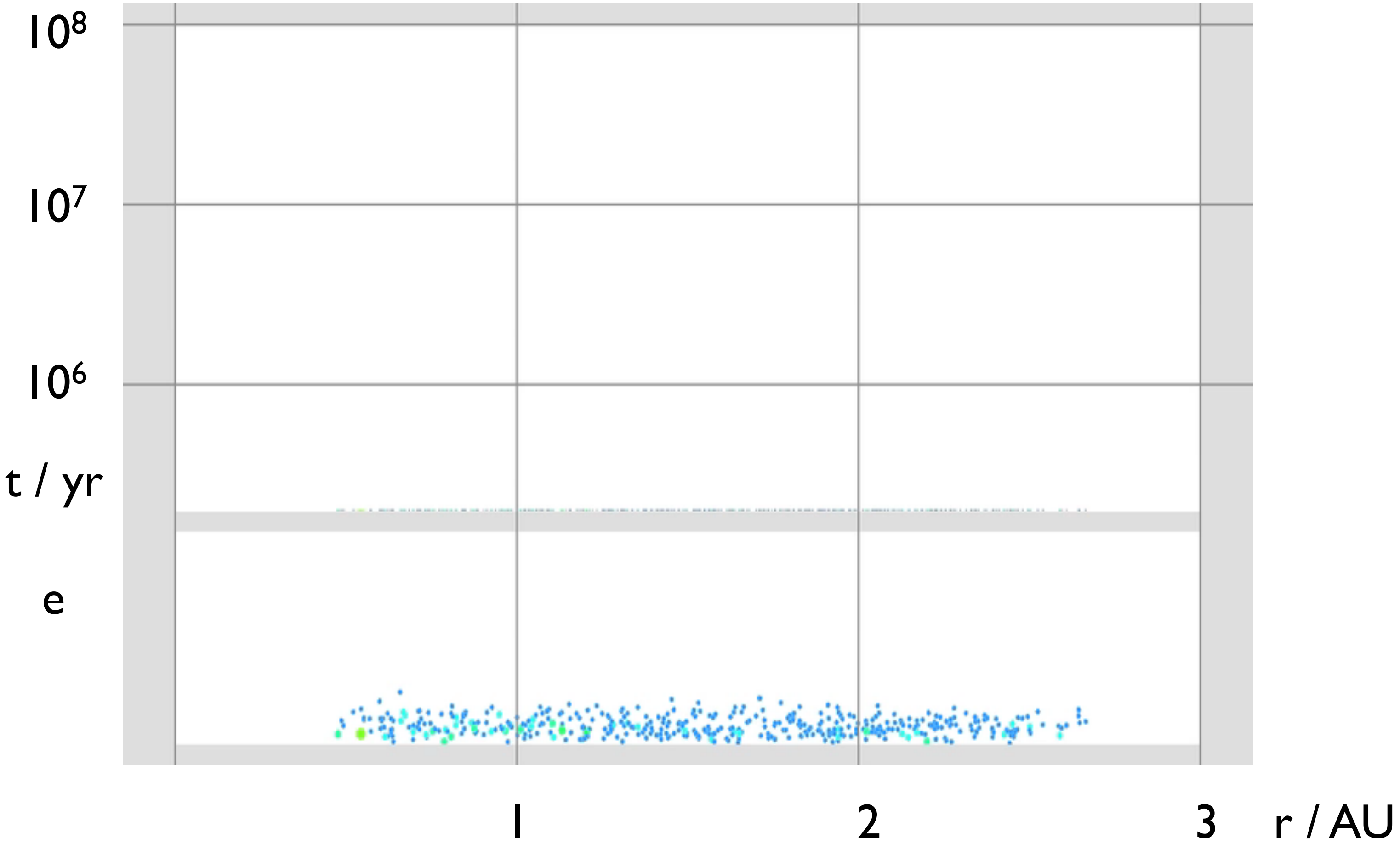
planet formation assumptions 1

- gas disk has smooth radial profile of pressure
  - *MMSN, α model ignoring opacity transitions*
- small solids track gas with condensation sequence

  gas / dust ratio
- planetesimals form ~in situ
  - *original Goldreich-Ward, rapid coagulation*
- subsequent growth to few Earth masses gravitational

smooth radial distribution of planetesimals
(km - 100 km) initial conditions for later growth

6 M_{earth}, $\Sigma_p \sim r^{-1}$, 500 equal mass embryos in $0.5 < a / AU < 2.5$



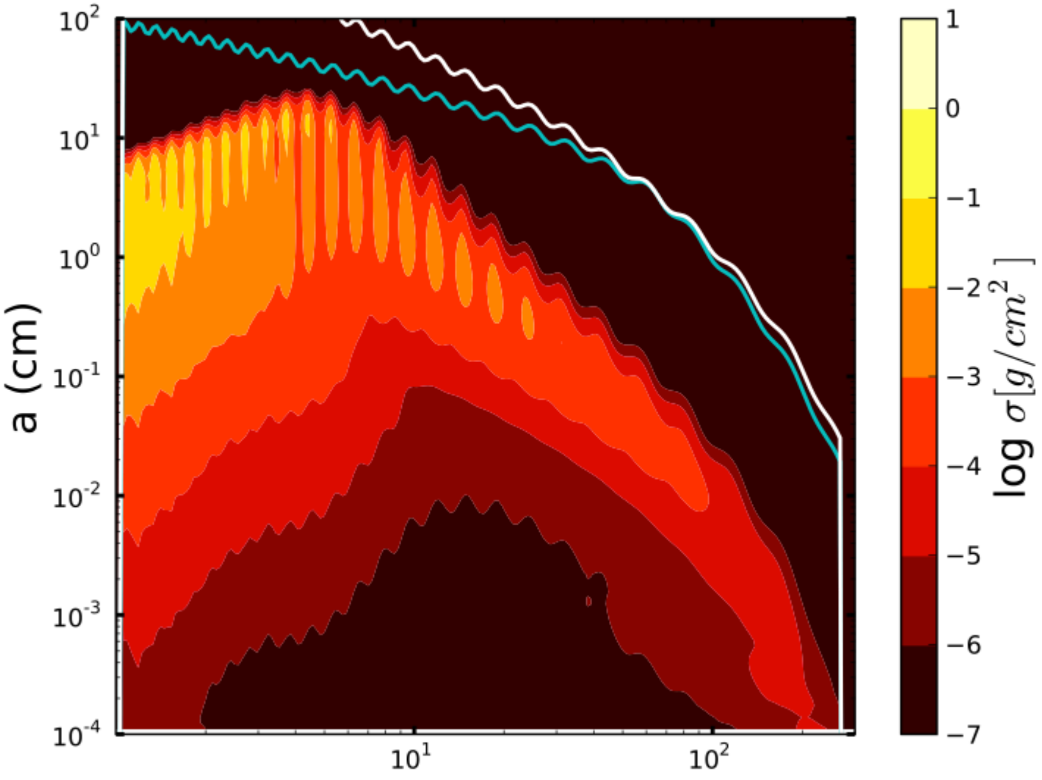
Known problems (Mars…) but at leading order this simple model gives internally consistent Solar System description

Foundations are questionable

planet formation assumptions 1

- planetesimals cannot form from gravitational instability of small dust layer
  - *large amounts of radial drift / redistribution very likely (Weidenschilling '77; Youdin & Chiang '04)*
- most plausible models for planetesimal formation require threshold over-density ($\rho_{solid} \sim \rho_{gas}$) of solids with stopping times $\tau \sim 0.01 - 0.1$
- gas disk probably has non-trivial radial structure, with transient or persistent local pressure maxima

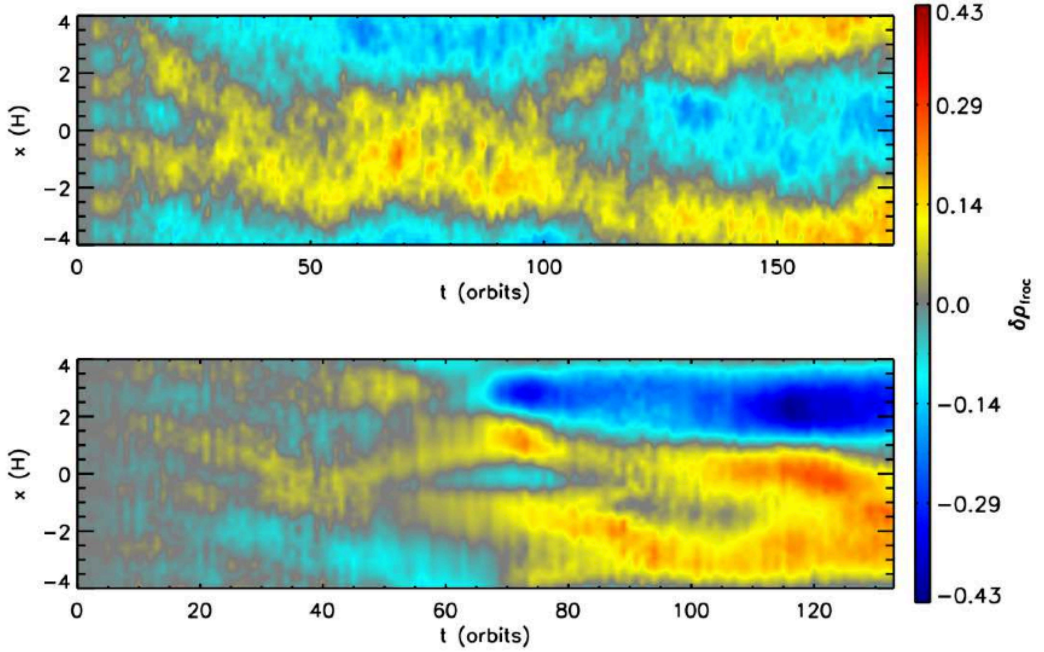
Recover smooth initial distribution of planetesimals if temporary trapping of solids in large-scale turbulent features across disk

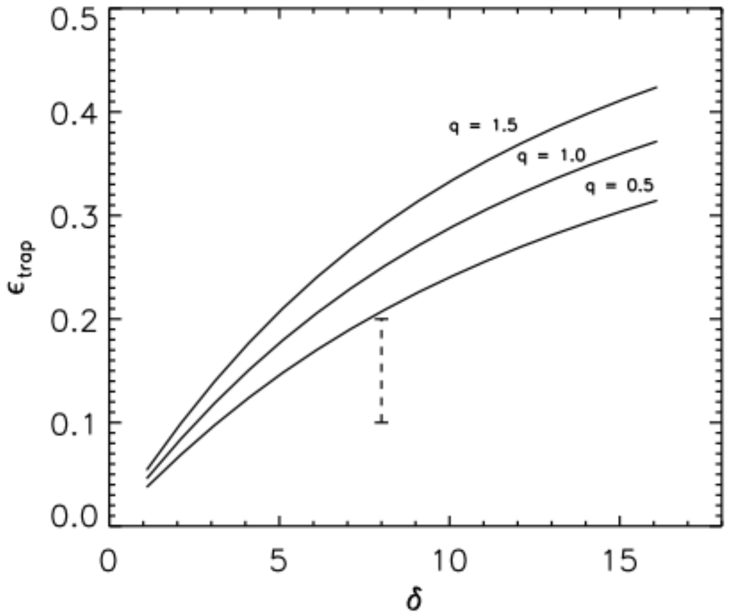


Pinilla et al. (2012)

zonal flows, Johansen et al. ‘09…

Recover smooth initial distribution of planetesimals if temporary trapping of solids in large-scale turbulent features across disk





Simon & Armitage (2014)

In Am zone (30-100 AU), amplitude of zonal flows is at best marginal to trap solids, even with net field…

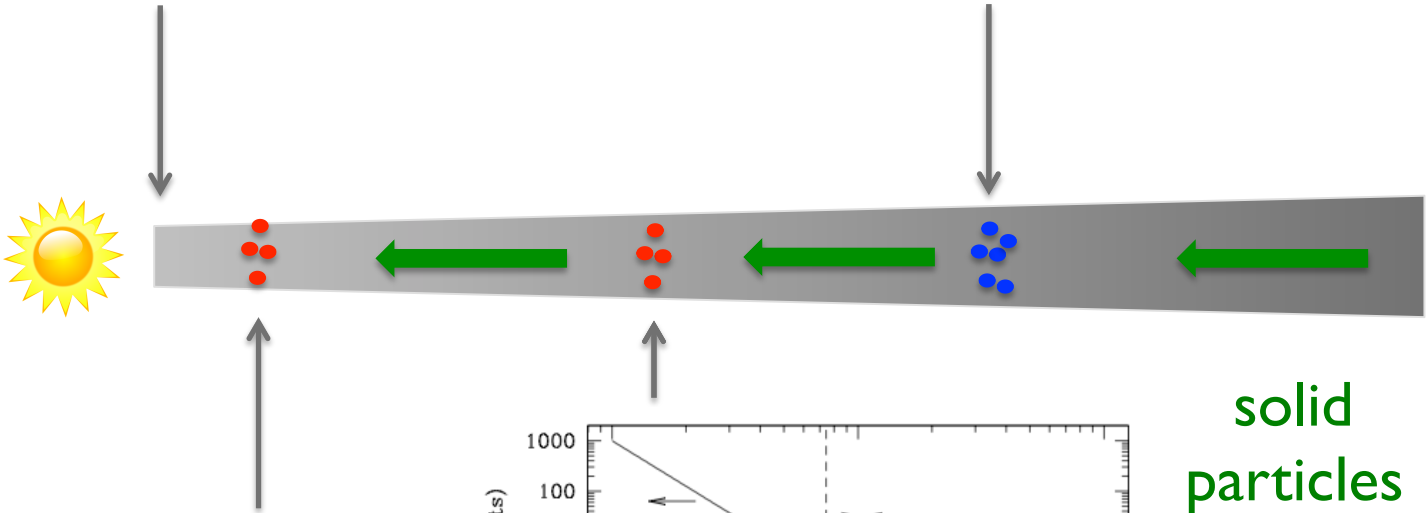
Global calculations would really help *(c.f. Mario Flock's talk)*…

planet formation assumptions II

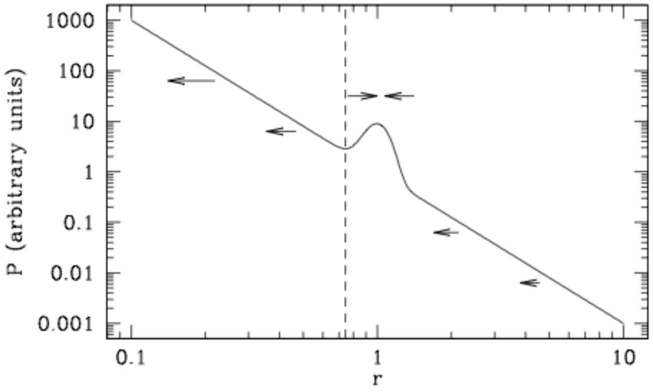
Alternate possibility

magnetosphere
$r \sim 0.05$ AU

snow line
(Kretke & Lin '07)



inner edge
of dead zone
$T \sim 800$ K



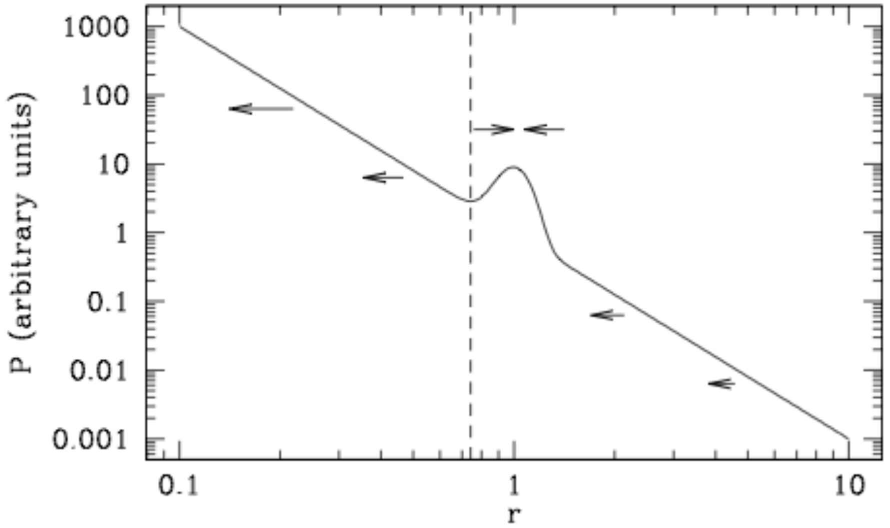
solid
particles
collisionally
grown to
$s \sim 1$ mm

Could most (all?) planetesimal formation occur in radially narrow annuli?

- requirements on disk model
  - *in MRI context, but sublimation fronts also (more?) viable (Stevenson & Lunine '88; Ros & Johansen '13)*
- dynamical considerations

No computers were harmed in the calculations on these slides…

particle “traps” in 1D



$$\frac{\partial \Sigma_p}{\partial t} + \frac{1}{r}\left(r\left[F_{\rm diff} + F_{\rm adv}\right)\right] = 0$$

$$F_{\rm diff} = -D_p \Sigma \frac{\partial}{\partial r}\left(\frac{\Sigma_p}{\Sigma}\right)$$

$$D_p = D/(1+\tau^2)$$

Given gas disk model, with diffusion, can always find steady-state particle distribution

Compute concentration of particles at trap location, compare to value if trap was not there

Morfill & Volk ‘84, Clarke & Pringle ‘88, Youdin & Lithwick ’07, Zhu et al. ‘12

particle “traps” in 1D

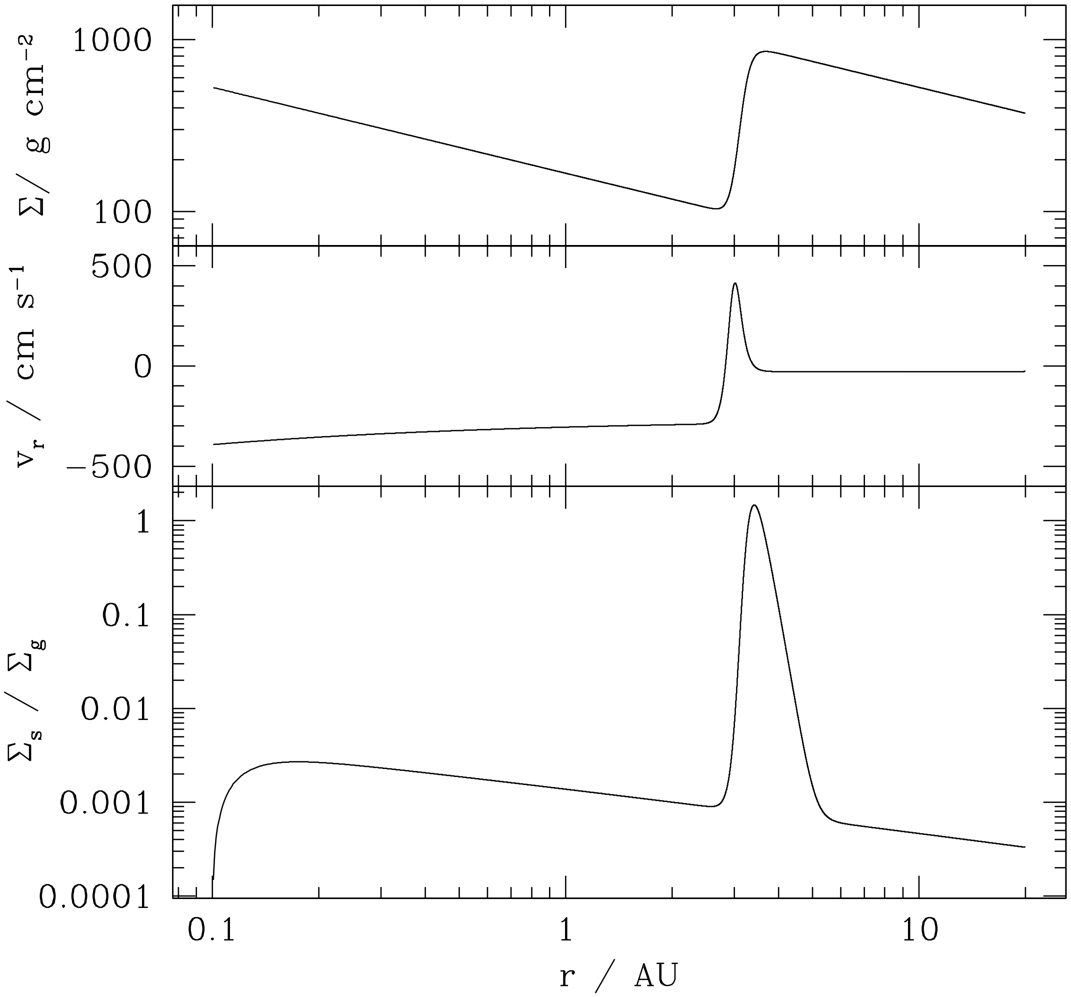
$\alpha_{in} = 10^{-2}, \alpha_{out} = 10^{-3}$

10^{-8} Solar masses / yr

h / r = 0.03 (r / AU)$^{0.25}$

s = 1 mm

trap width w = 2h



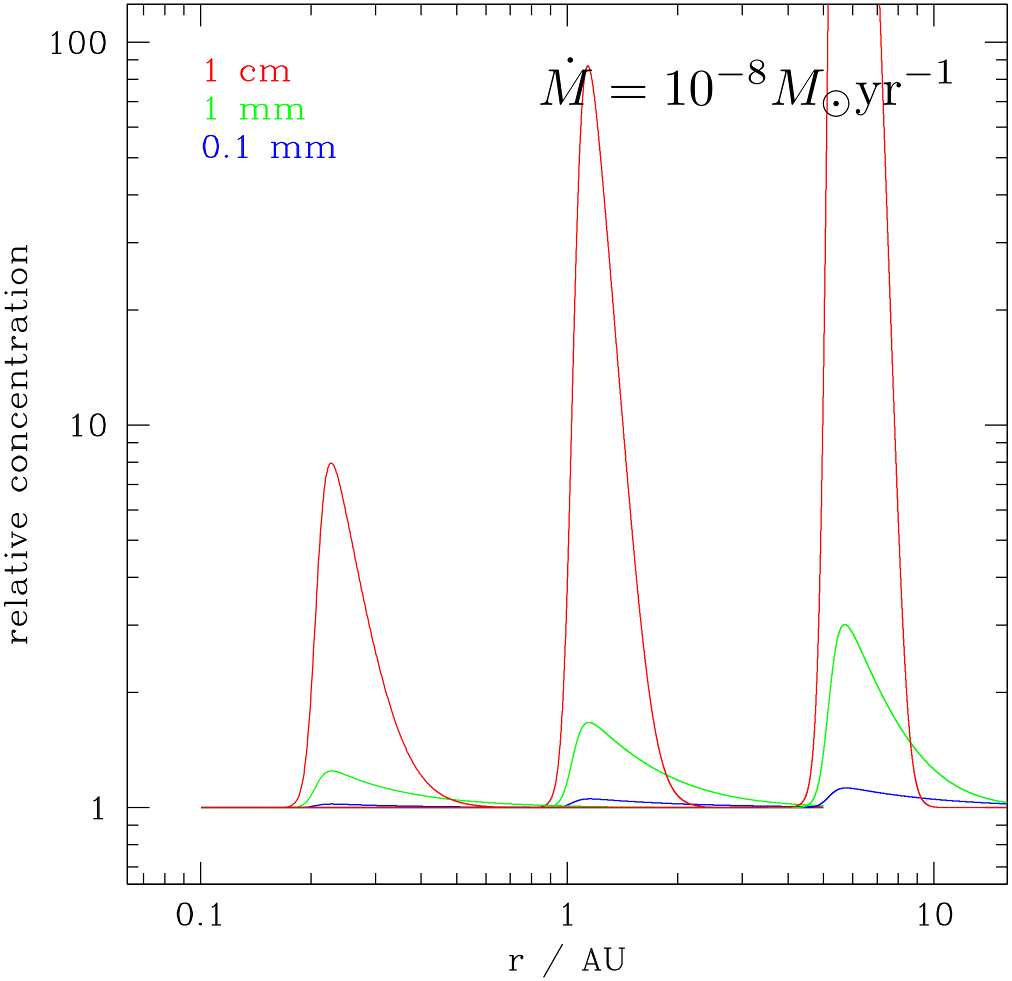
particle “traps” in 1D

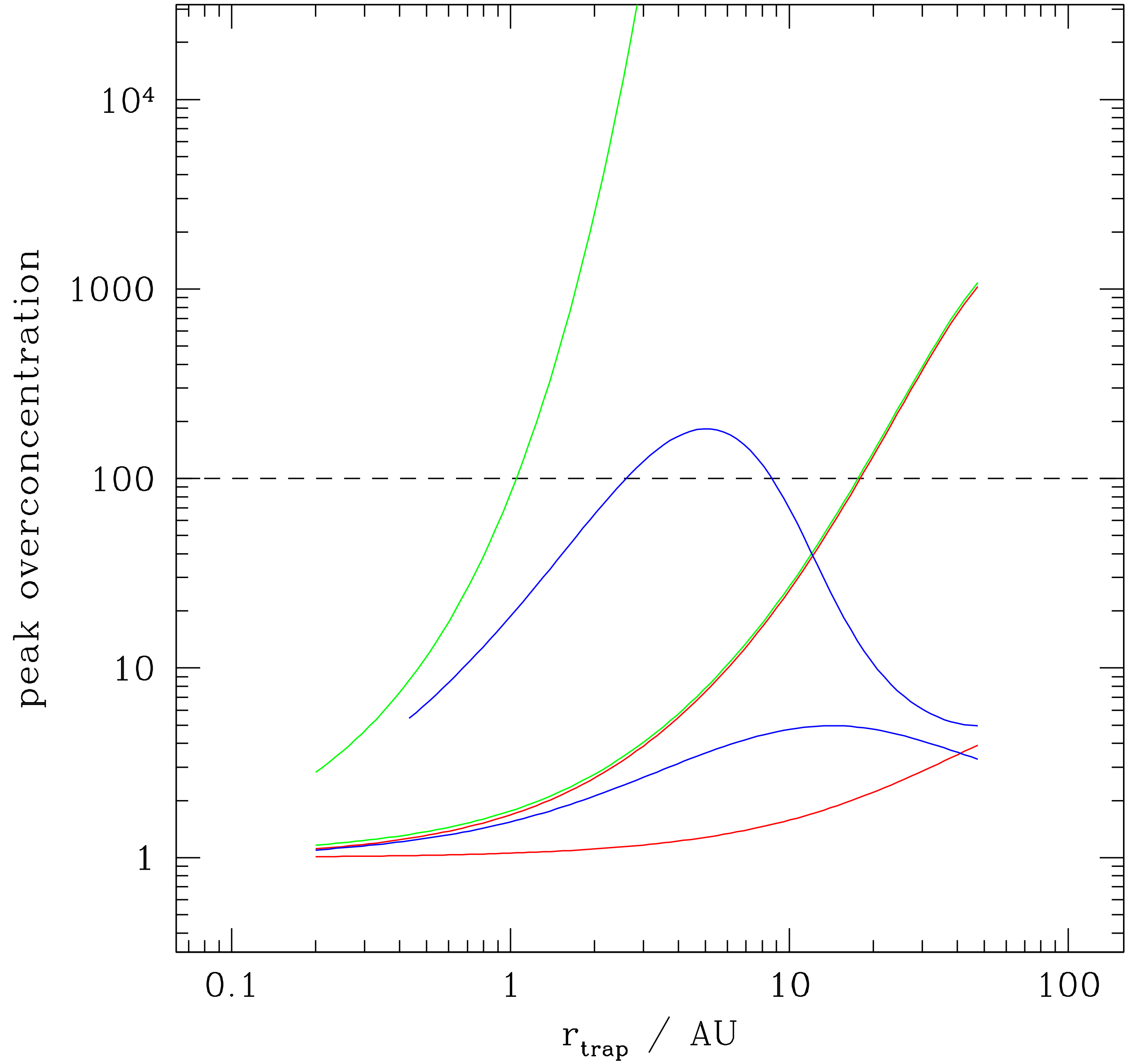
$\alpha_{in} = 10^{-2}$, $\alpha_{out} = 10^{-3}$, width w = 2h

Stopping time

$$\tau = \frac{\pi}{2}\frac{\rho_m}{\Sigma}s$$

If collisional growth yields particles of ~fixed maximum size, trapping is much more efficient in outer disk





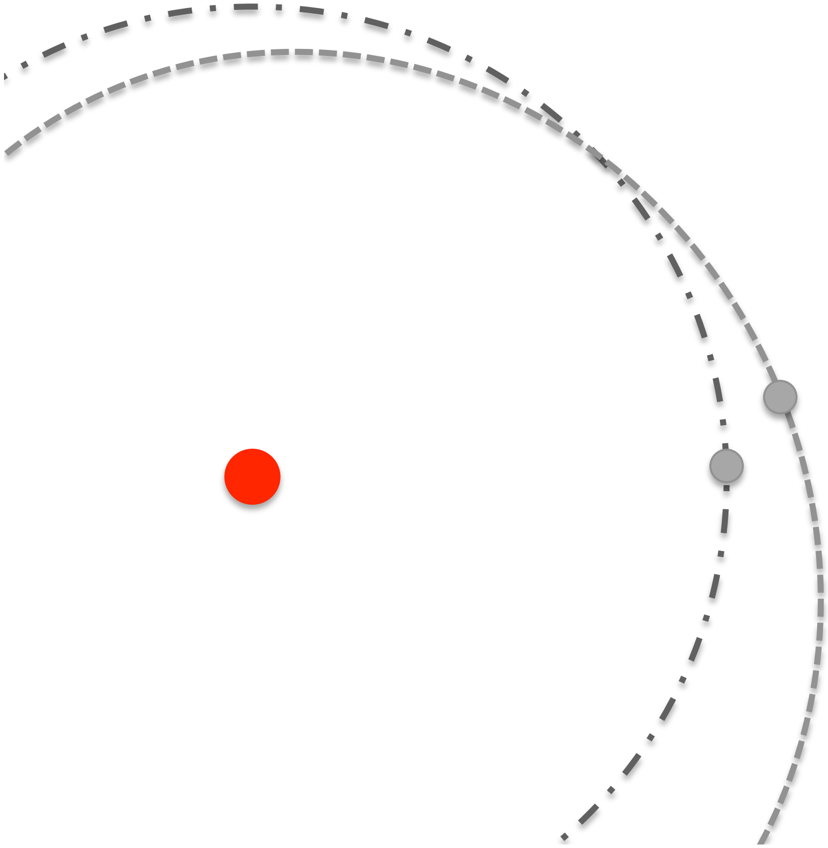
Red: 10^{-7} Solar masses / yr, s = 0.1, 1 cm, w = 2

Green: 10^{-8} Solar masses / yr

Blue: 10^{-8} Solar masses / yr, w = 4

All $\alpha_{out} / \alpha_{in} = 0.1$

dynamics of planet formation at traps



Encounter *outcome* f(v_{esc} / v_{enc})

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM_p}{r_p}} \quad v_{\mathrm{K}} = \sqrt{\frac{GM_*}{a}}$$

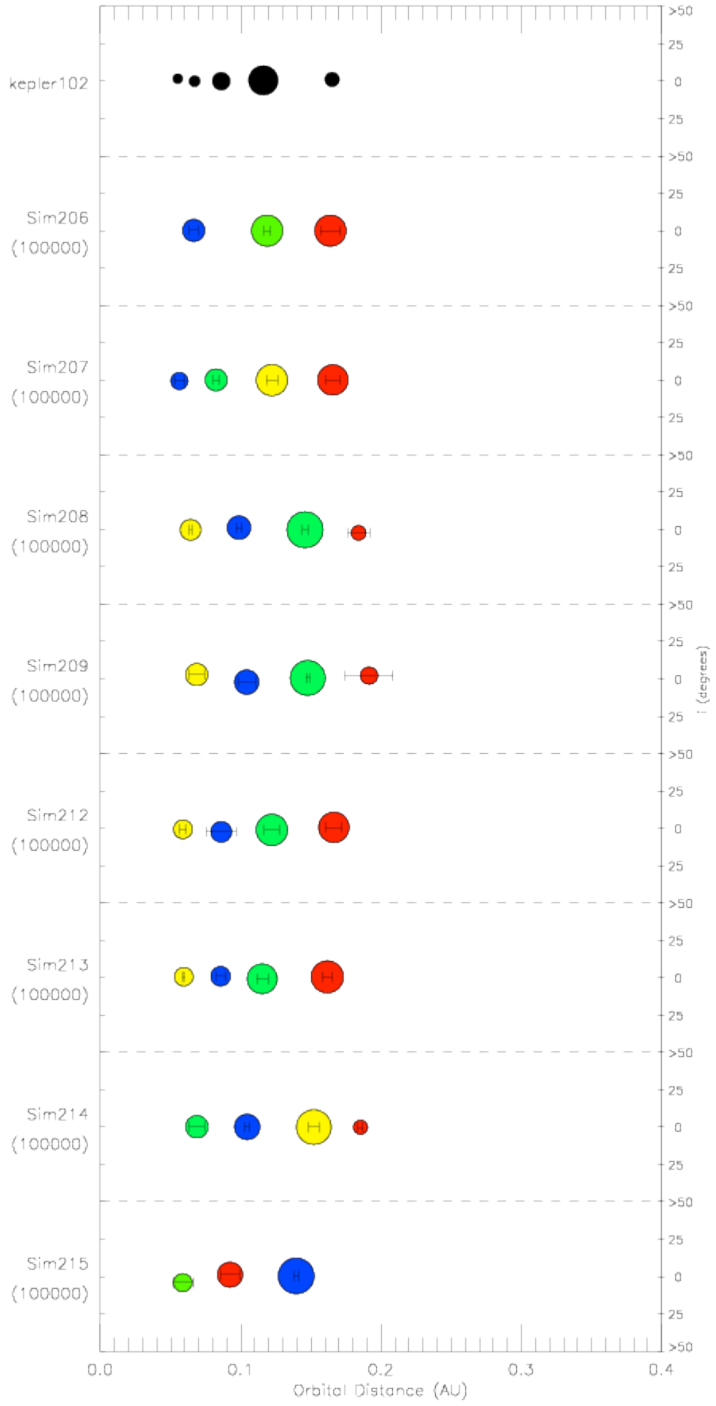
Mass cannot scatter far in terrestrial / Kepler region

Scattering is efficient for > M_{earth} bodies in outer disk

Trap at small radii forms compact planetary systems, very similar to in situ models

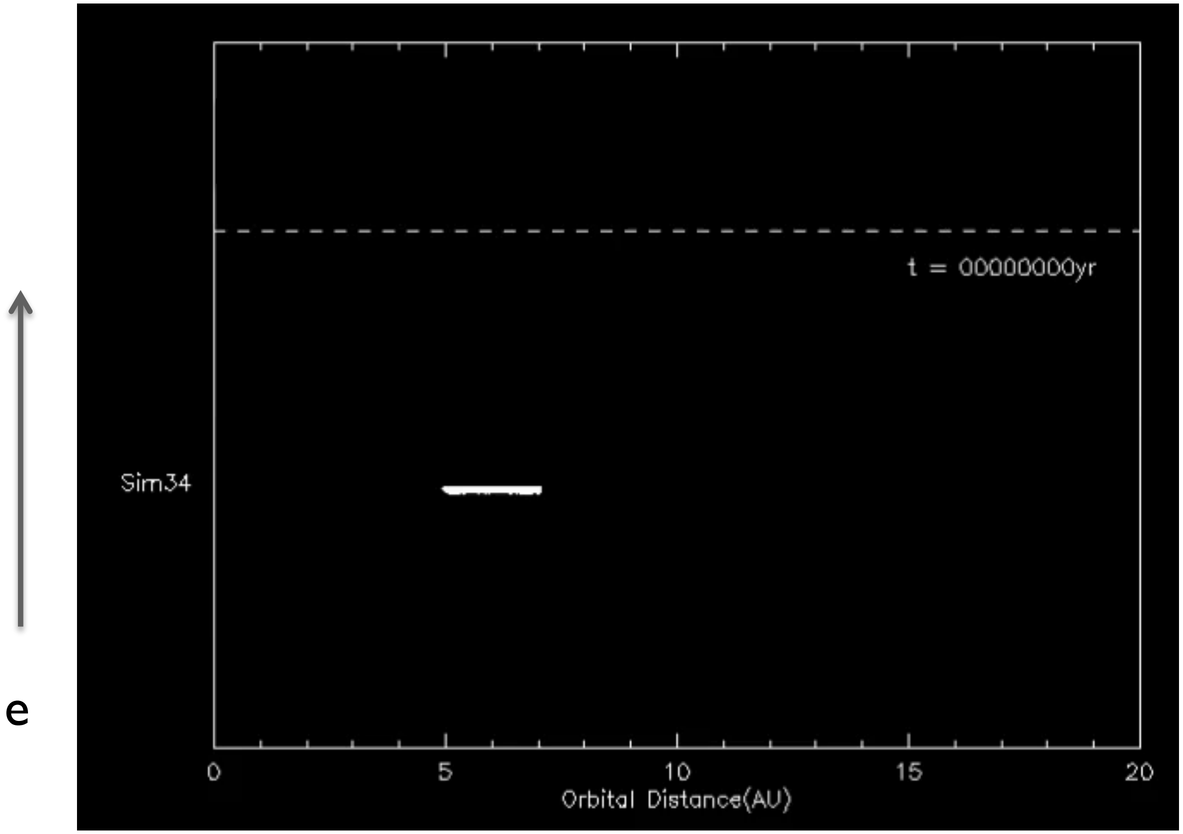
Tendency to form co-orbital systems, not seen in the data

BUT, even if systems form this way, Type I migration must be important



Jacob Bruns, in prep

- outer disk,
  one trap populates
  broad regions
- c.f. Stevenson & Lunine ’88; Ali-Dib et al. ‘14



Particle flux 2.4 M_{Earth} / Myr, trapped at 5 AU *(Jacob Bruns)*

Dynamically, known planetary systems could be formed from planetesimal populations formed at as few as ~3-4 discrete radii

summary

- model for planet formation based on
  - radial aerodynamic drift
  - “trapping” at local P maxima
  - gravitational collapse into planetesimals

- unknown if real disks contain traps, generically much easier to make traps in outer disk

- dynamics of subsequent growth consistent with observations

- hope we will be able to translate local physics into robust evolutionary disk models soon!