Southwest Research Institute

Origin of compact exoplanetary systems

Early accretion **during** stellar infall?

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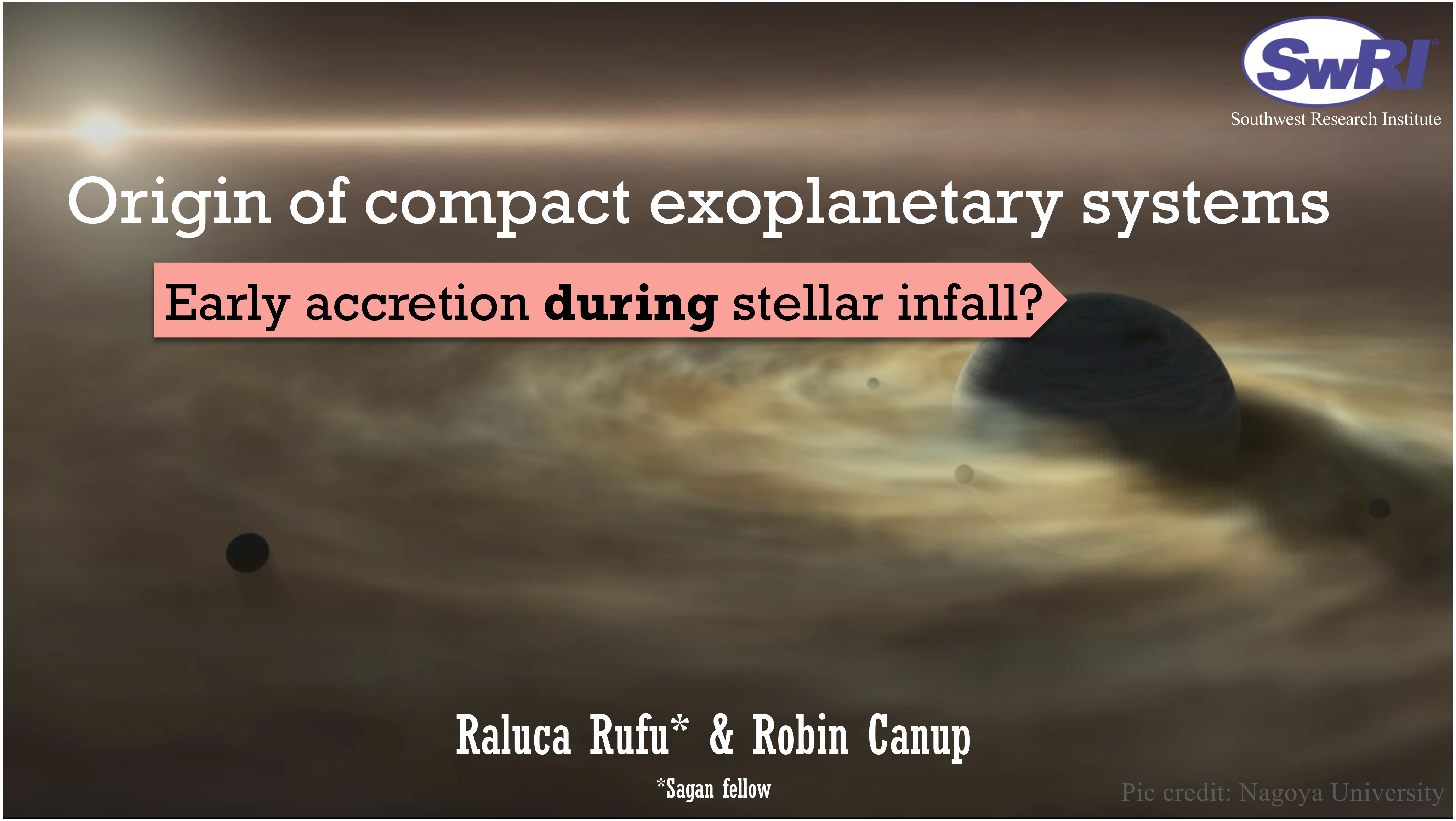
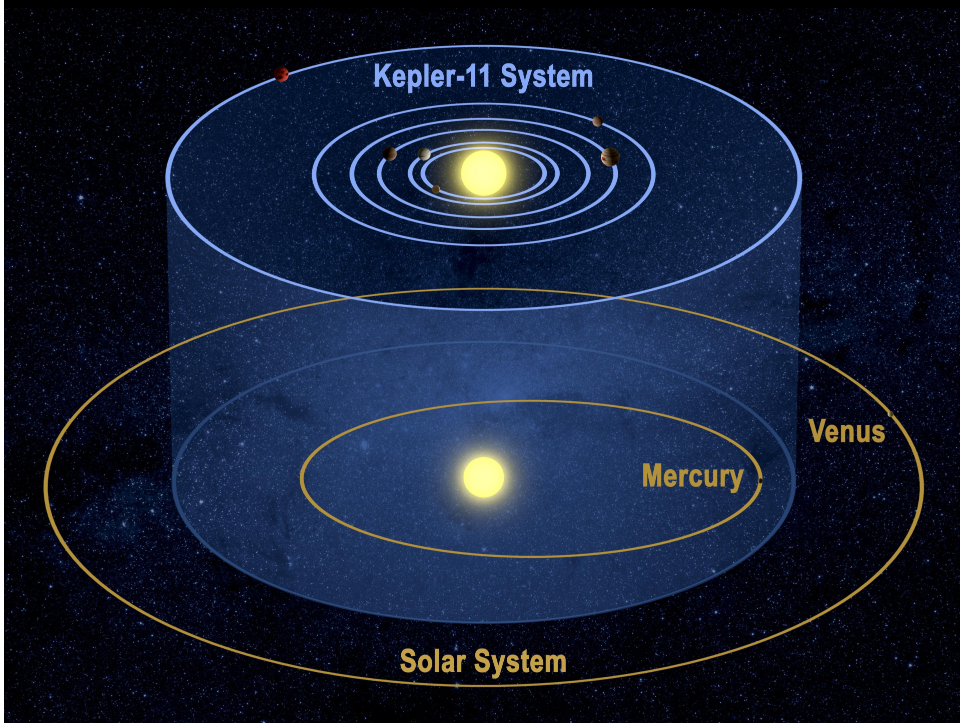
*Sagan fellow



Pic credit: Nagoya University

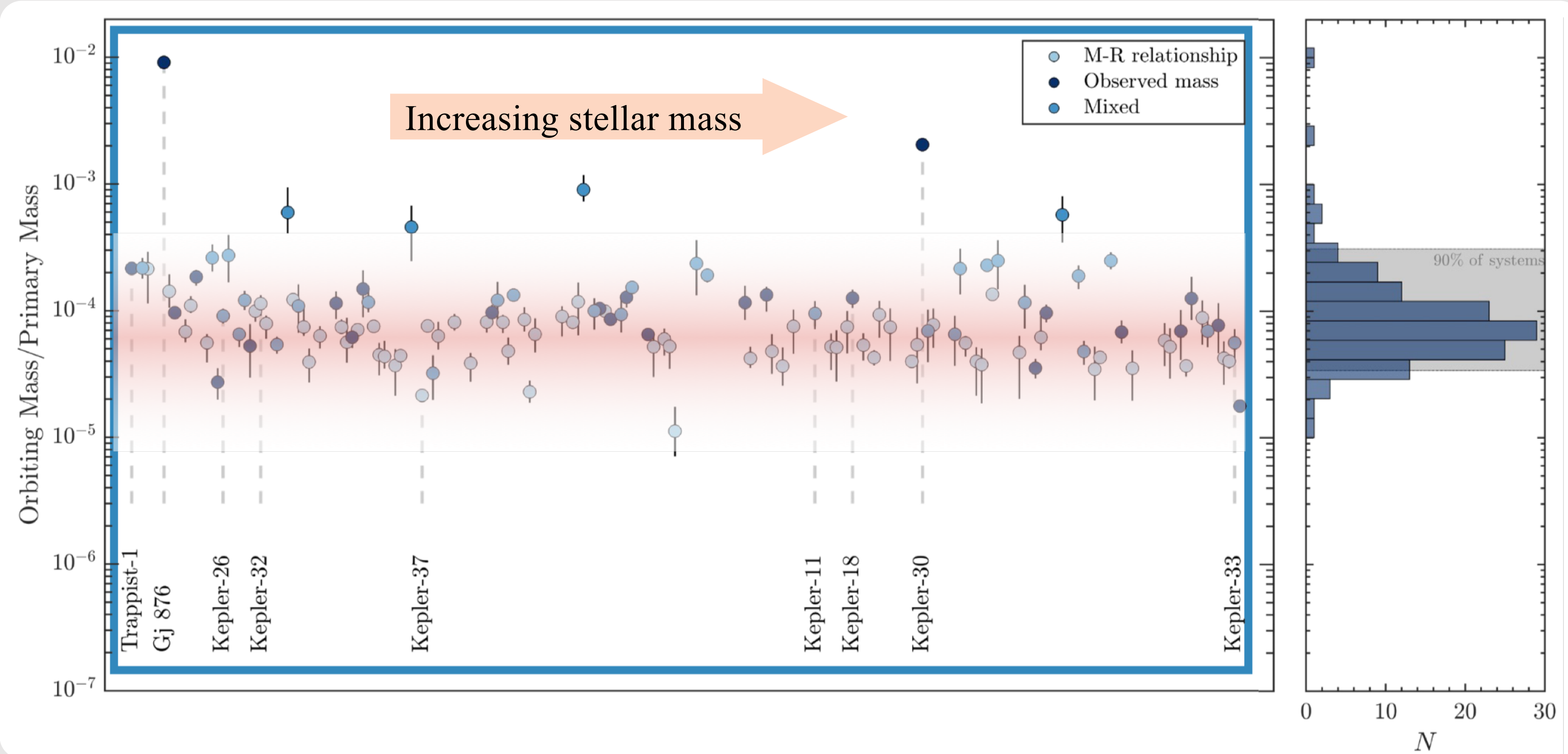
Compact Exoplanetary systems



Multi-planet systems:

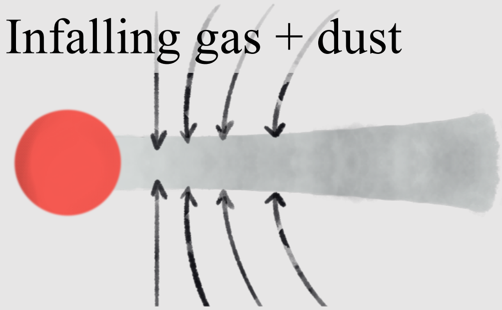
- Similar sized planets ("peas-in-the-pod")
- Earth to sub-Neptune class
- Compact, < 0.5AU
- $10 < a/R_* < 10^2$ and orbit periods of days-to-weeks → similar to gas planet satellites (e.g., Kane et al. 2013, Miguel et al. 2019)

Additionally: similar mass ratios



How do compact exoplanetary systems form?

Some observations



- Infall to stellar disk for $\tau_{in} \sim$ few $\times 10^5$ to 10^6 yr (Evans et al. 2009)
- Standard assumption: planet accretion begins **after** infall ends ($\tau_{acc} \gg \tau_{in}$)
- But in compact systems, fast accretion means $\tau_{acc} \leq \tau_{in}$
- ALMA data: signs that accretion has begun in systems only $\sim 5\times10^5$ to 10^6 yr old

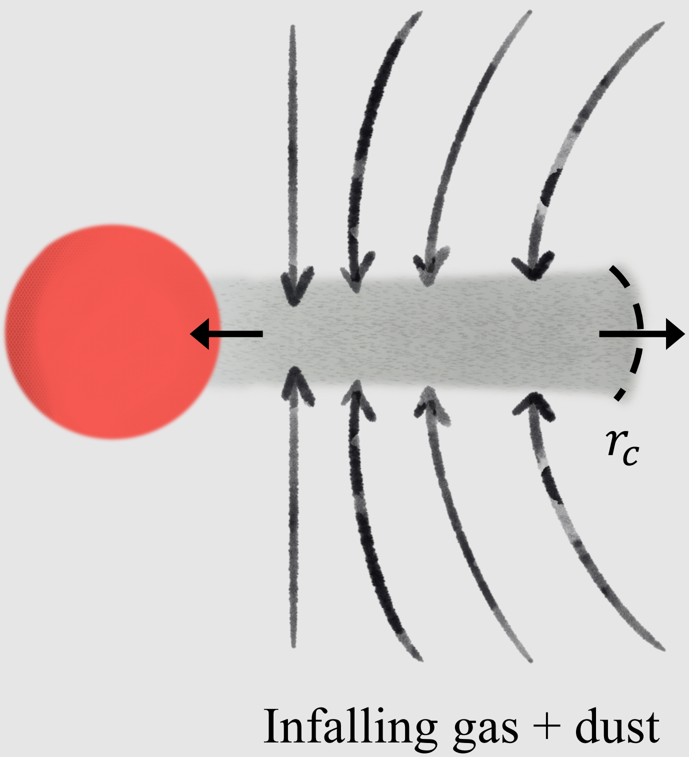
(e.g., Miotello et al. 2014; Harsono et. al 2018, Manara et al. 2018; Alves et al. 2020, Segura-Cox et al. 2020)

If planets accreted **during** infall, would they survive ?

If so, what are the expected properties of such systems?

Our new concept

Planetary accretion **during** stellar infall

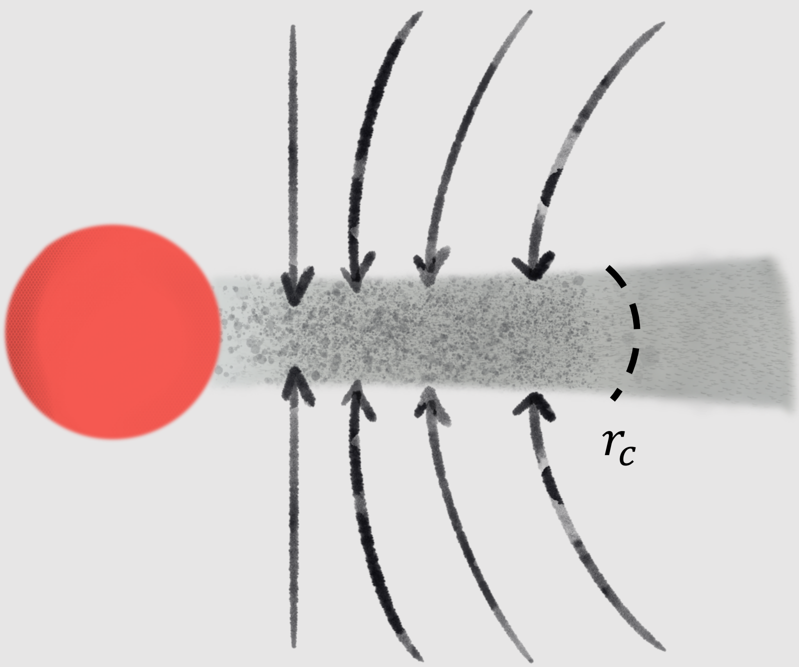


Gas + dust flow into orbits $<$ centrifugal radius, r_c

Gas disk in quasi steady-state between infall and viscous spreading (Canup & Ward 2002)

Our new concept

Planetary accretion **during** stellar infall.



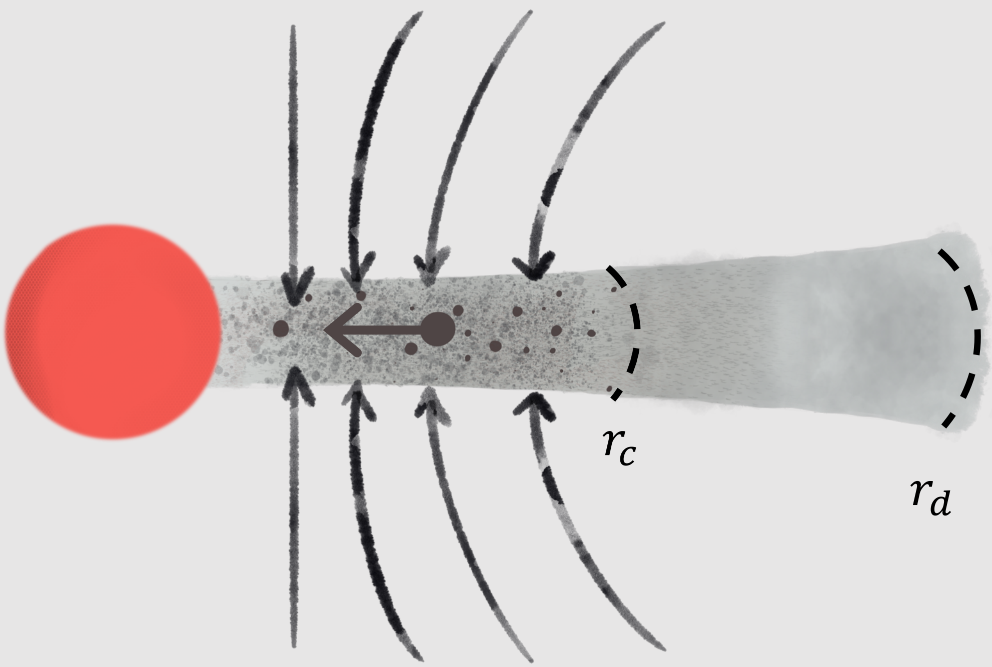
If particle growth begins, large grains/pebbles decouple from the gas and preferentially collect interior to r_c

Disk metallicity interior to r_c increases, producing favorable conditions for planetesimal formation

(e.g., Cridland et al. 2022)

Our new concept

Planetary accretion **during** stellar infall.



Planets accrete in inner disk

As planet grows, its inward Type I migration gets faster

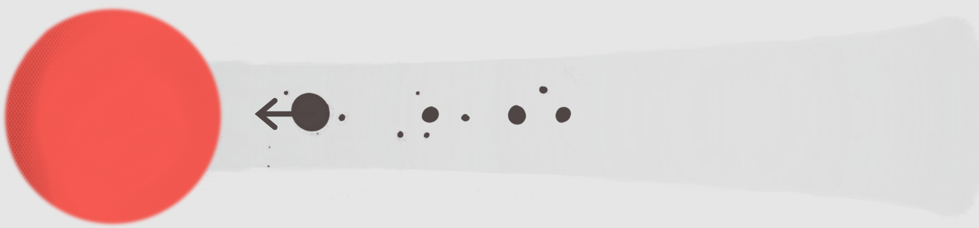
Planets grow to a critical mass ($M_{\rm crit}$) at which growth timescale is comparable to Type I loss timescale, $\boldsymbol{\tau_{\rm acc} \sim \tau_{\rm I}}$

$M \sim M_{\rm crit}$ planets fall inward, *but* while infall supply continues new planets form

$r_d \sim$ tens to 10^2 AU

Our new concept

Planetary accretion **during** stellar infall.



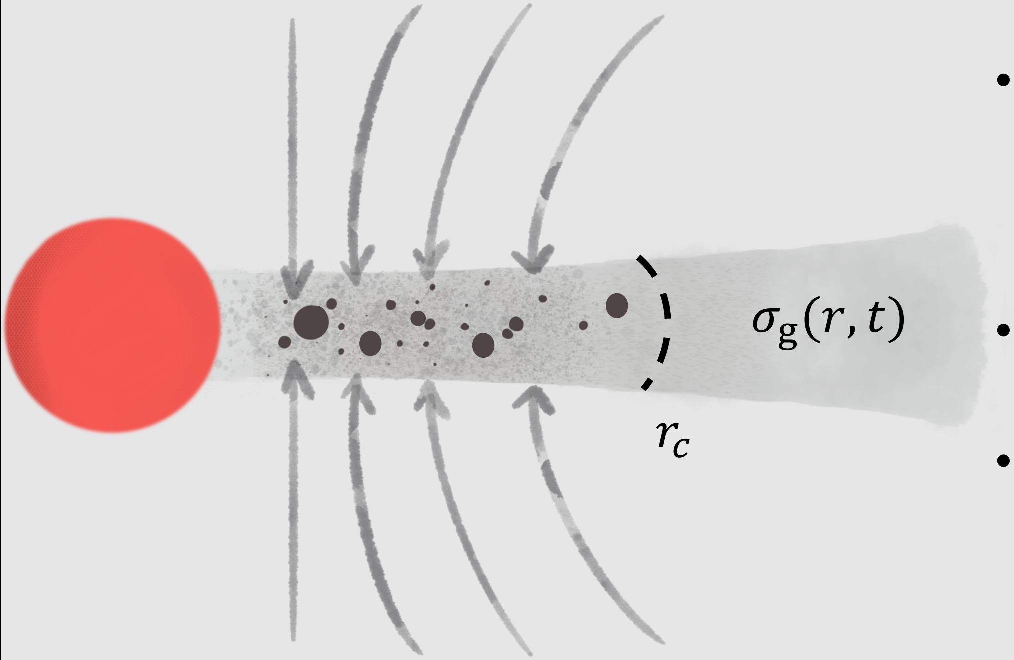
Infall ends over $\tau_{in} \sim$ few $\times 10^5$ to 10^6 yr

(Evans et al. 2009)

Gas disk dissipates (due to viscosity and photoevaporation) over timescale τ_g, causing Type I migration to slow

For range of conditions, planets formed during infall can survive

Simulation setup



Simulate accretion as last few to 10% of stellar mass infalls to stellar disk

N-body accretion model (SyMBA) with infall:

- Solid infall: bodies added to $r < r_c$ with rate

$$F_{\rm in} = (F_0/f)\exp(-t/\tau_{\rm in})$$

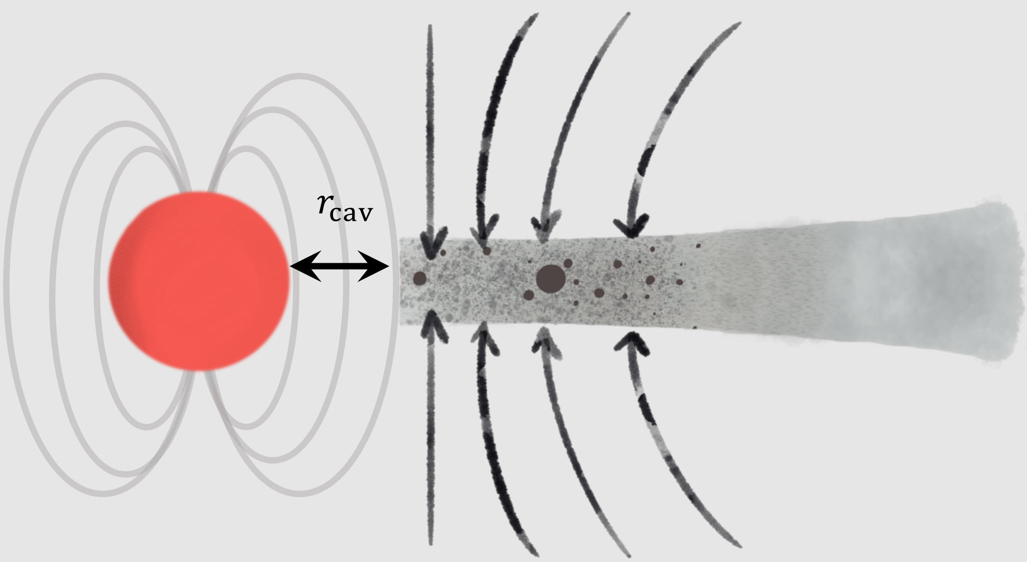
- Inward Type-I migration: $\dot{r} \propto \left(M_p/M_*\right)\sigma_g$

- Initial gas disk in quasi-steady-state (Canup & Ward 2002), and then dissipates on timescale $\tau_{\rm g}$

$$\sigma_g \propto \left(\frac{F_0}{\nu}\right)\exp\left(-t/\tau_{\rm g}\right)$$

$$\nu = \alpha c^2/\Omega$$

Inner disk gap?



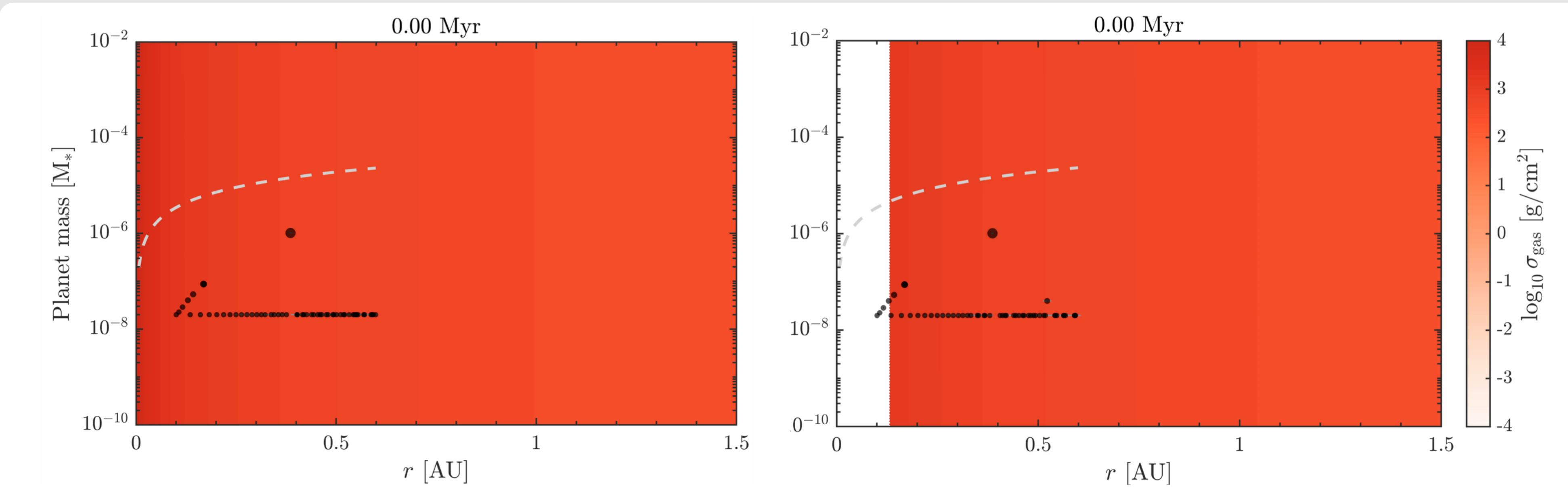
- Surface density close to the star could be depleted due to magnetospheric truncation.
- Such configuration could act as a planetary migration trap.
- Toy model - Type-I migration halts at r_{cav}.

N-body Results

Example with $\tau_g/\tau_{\rm in} = 1.5$

No cavity

$r_{\rm cav} \sim 0.13$ AU



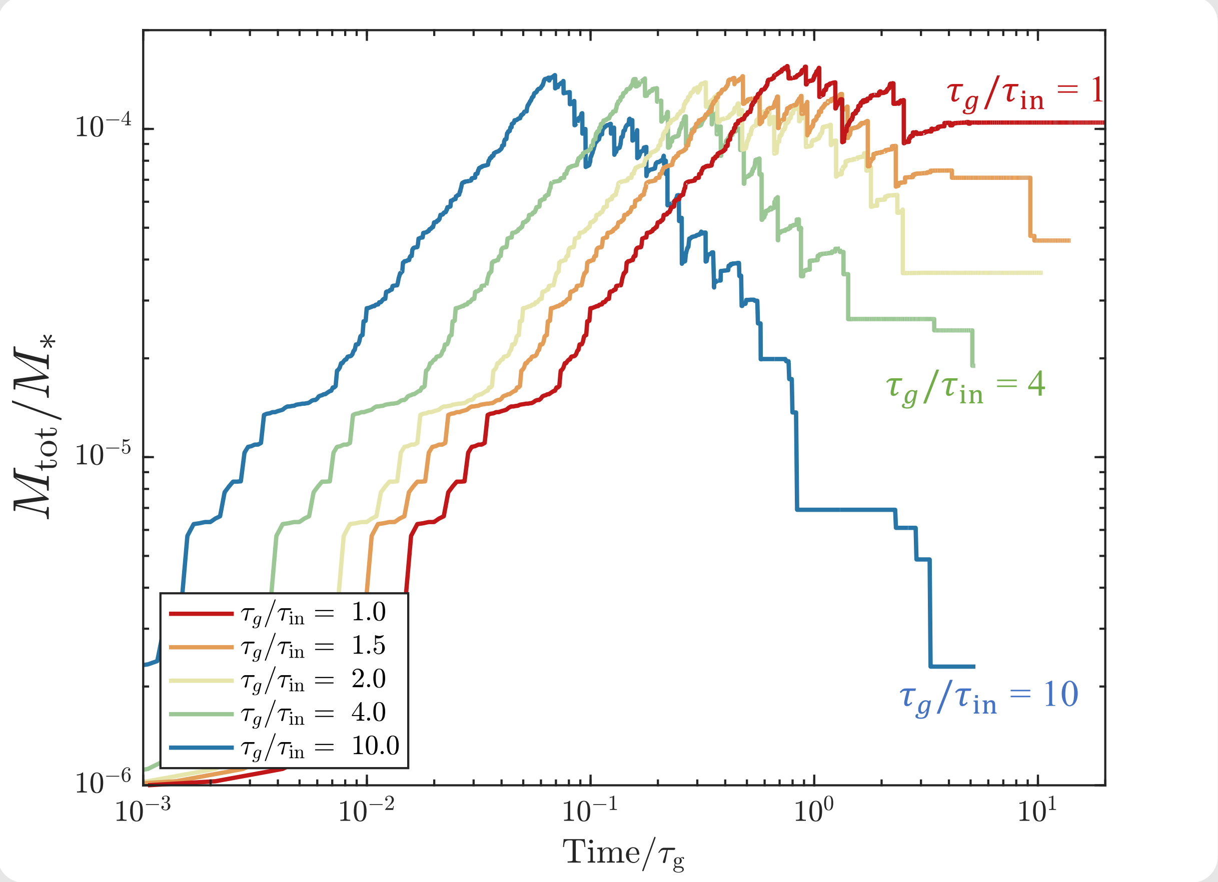
$M_{\rm crit}$ is the mass for which $\tau_I \sim \tau_{\rm acc}$

Infall with $(\alpha/f) = 5\times10^{-5}$

(e.g., $f \equiv f_{\rm gas}/f_{\rm solids} = 10^2$ and $\alpha = 0.005$)

Planet system mass vs. τ_g/τ_{in}

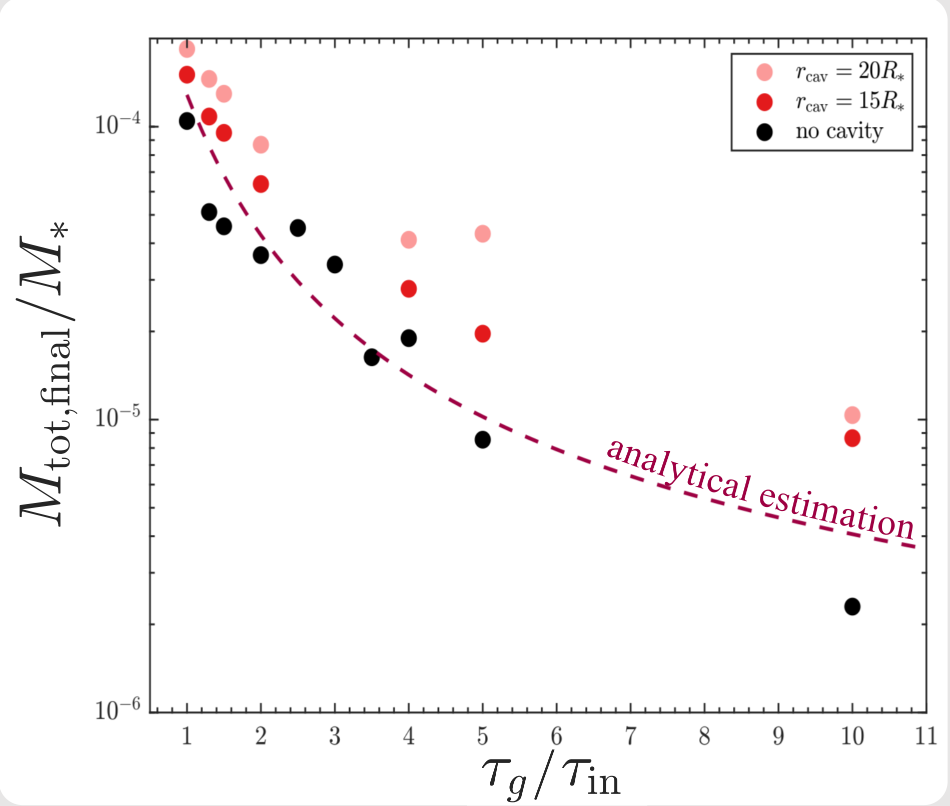
*No cavity



- For fixed disk properties, common *maximum* system mass ratio
- Surviving system mass ratio decreases as τ_g/τ_{in} increases

Final planet system mass vs. $\tau_g/\tau_{\rm in}$

- The final planetary system mass ratio is larger when a cavity is included.

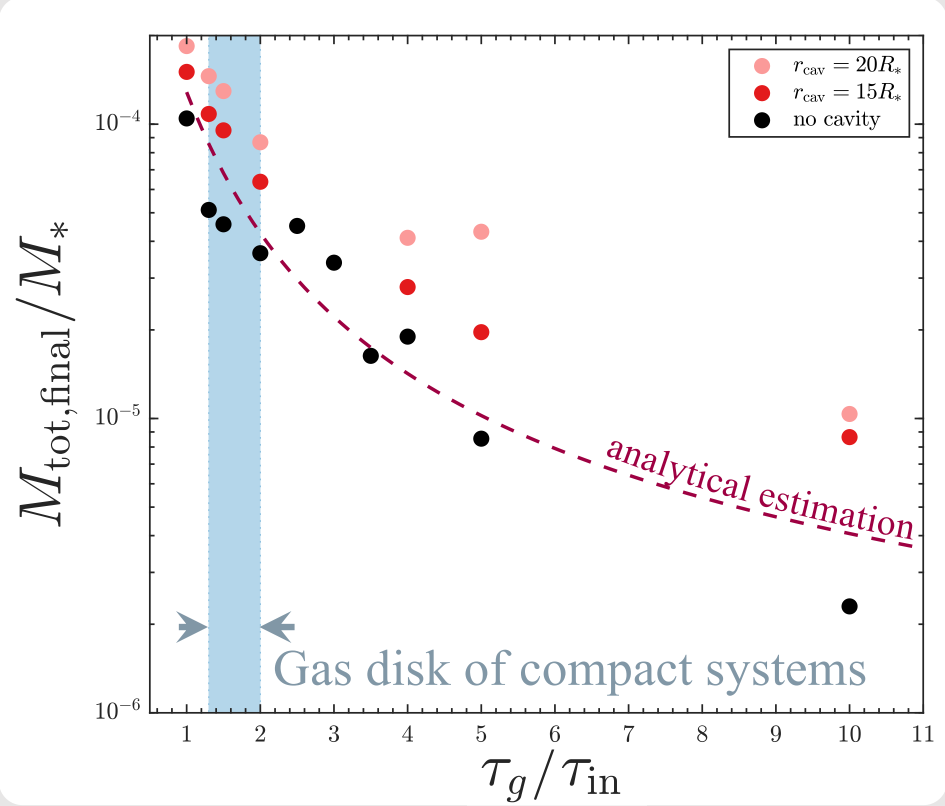


Final planet system mass vs. τ_g/τ_{in}

- The final planetary system mass ratio is larger when a cavity is included.
- Using 1D infall + viscosity + photoevaporation model, we find compact systems have

$$\tau_g/\tau_{in} \sim 1.3 \text{ to } 2$$

- Expect compact systems to retain ~ 20% to 40% of the maximum M_{tot}/M_*



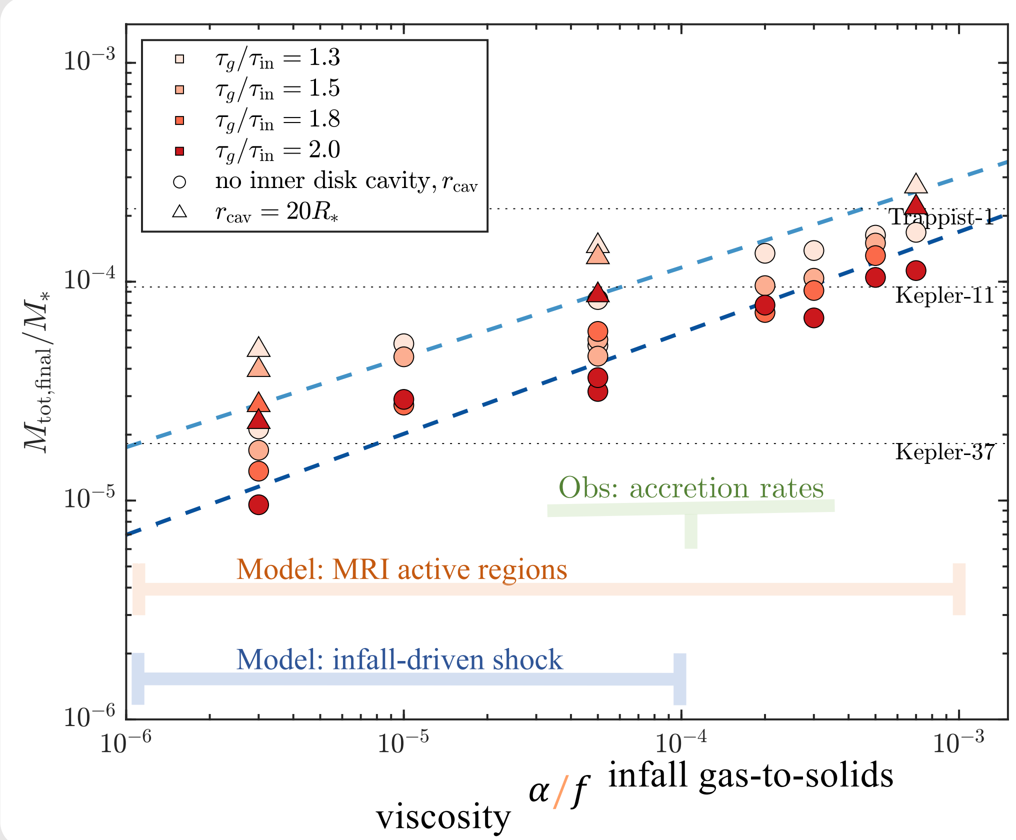
Results

- Relatively weak dependence on disk viscosity and infall properties.

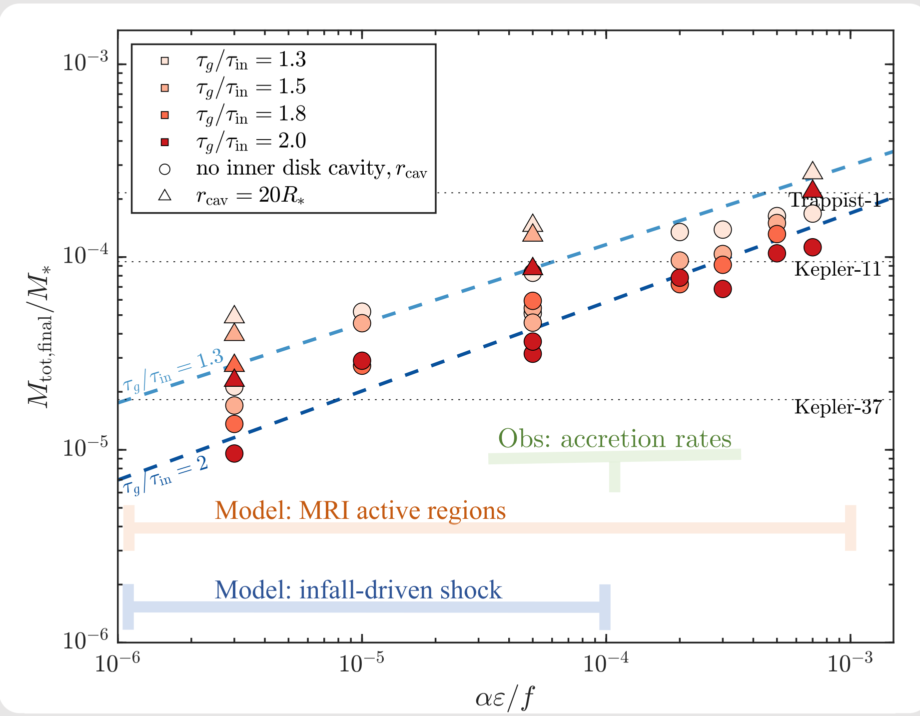
- **For likely compact disk properties, $M_{tot}/M_* =$ few $\times 10^{-5}$ to 10^{-4}**

- Nearly equal occurrence of close super-Earths around stars of wide-ranging metallicities. (Petigura et al. 2018)

Simulations span $10^{-6} < (\alpha/f) < 10^{-3}$
(e.g., with $f \sim 10^2$, $10^{-4} < \alpha < 0.1$)



Conclusions



Rufu & Canup 2024 (*in review*)

- If accretion commences during infall, then planets formed during this period can survive, even with standard Type-I migration.
- α/f and τ_g/τ_{in} control the mass of the surviving planets relative to that of host star.

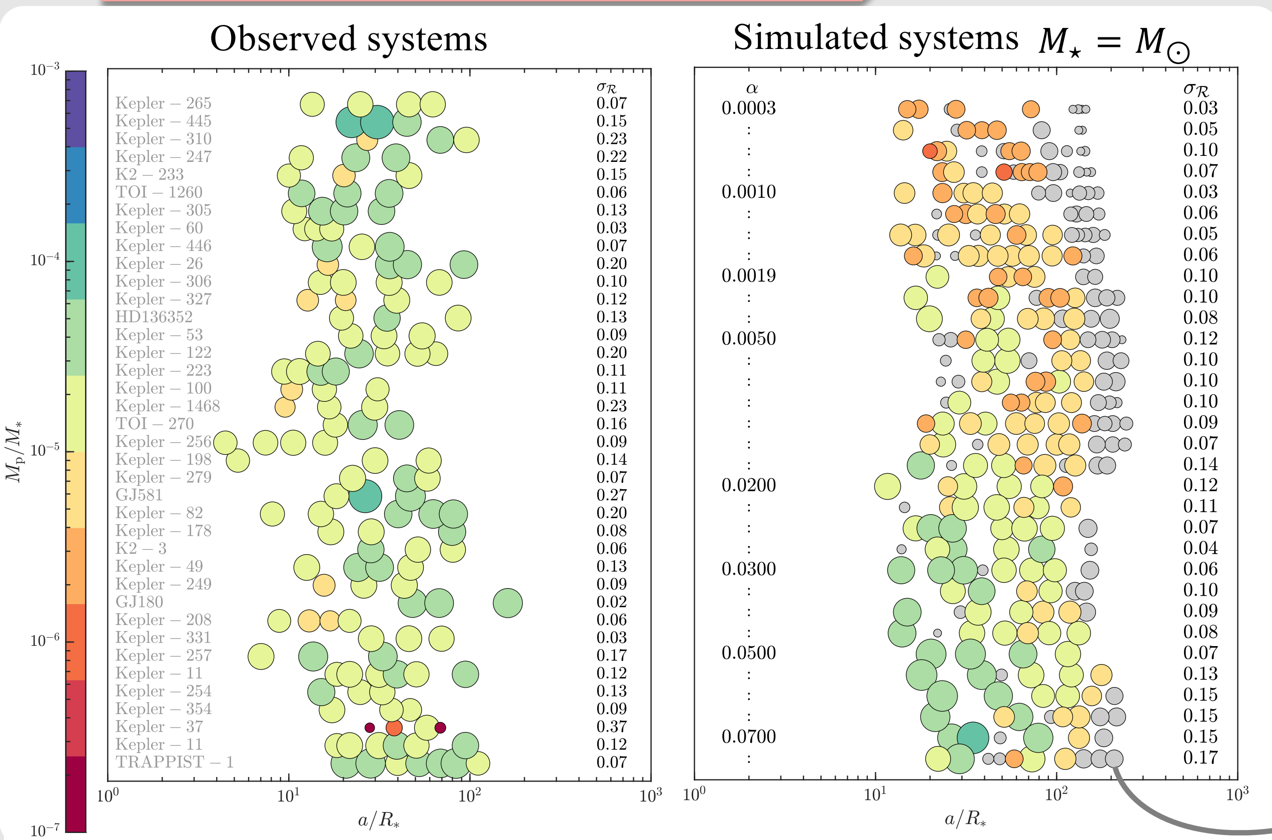
For compact systems, $\tau_g/\tau_{in} \sim 1.3$ to 2.

With $10^{-6} < \alpha/f < 10^{-3}$, simulated systems replicate observed compact system $M_{tot}/M_* \sim$ few $\times 10^{-5}$ to 10^{-4}

Thank you!

Backup slides

Results



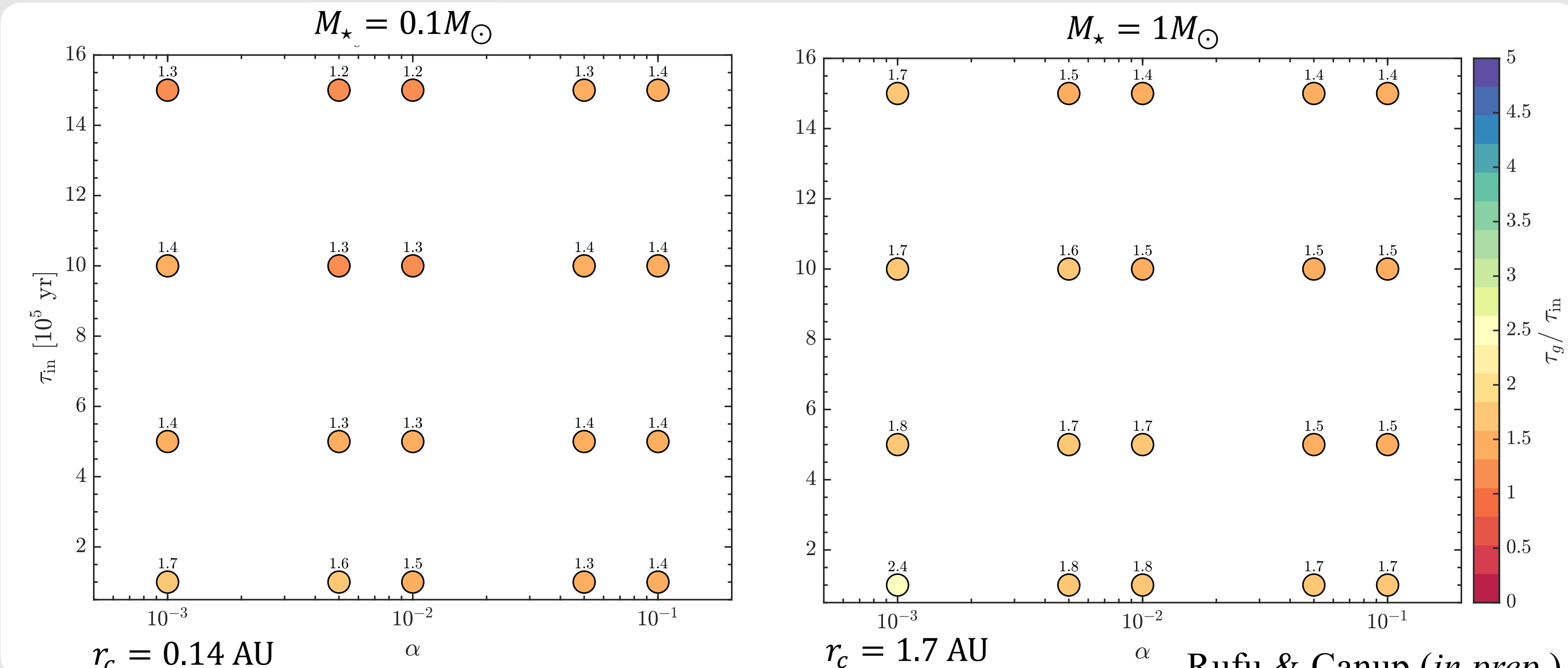
$\sigma_\mathcal{R} = 0.14$ $\sigma_\mathcal{R} = 0.09$

- $\sigma_\mathcal{R}$, size dispersion in a system (Weiss et al. 2022)
- Simulated systems have low $\sigma_\mathcal{R}$
- 5-7 planets with the peas-in-the pod architecture.
- α/f and τ_g/τ_{in} control the final planet size

Gray would be undetectable

Gas disk model

$\sigma_g(r,t)$ and $T(r,t)$: infall + viscosity (alpha-model) + photoevaporation (Owen et al. 2012)



Rufu & Canup (*in prep.*)

Over a wide range of parameters, compact systems have $\tau_g/\tau_{in} \sim 1-2$

Gas disk lifetime ← → Infall timescale