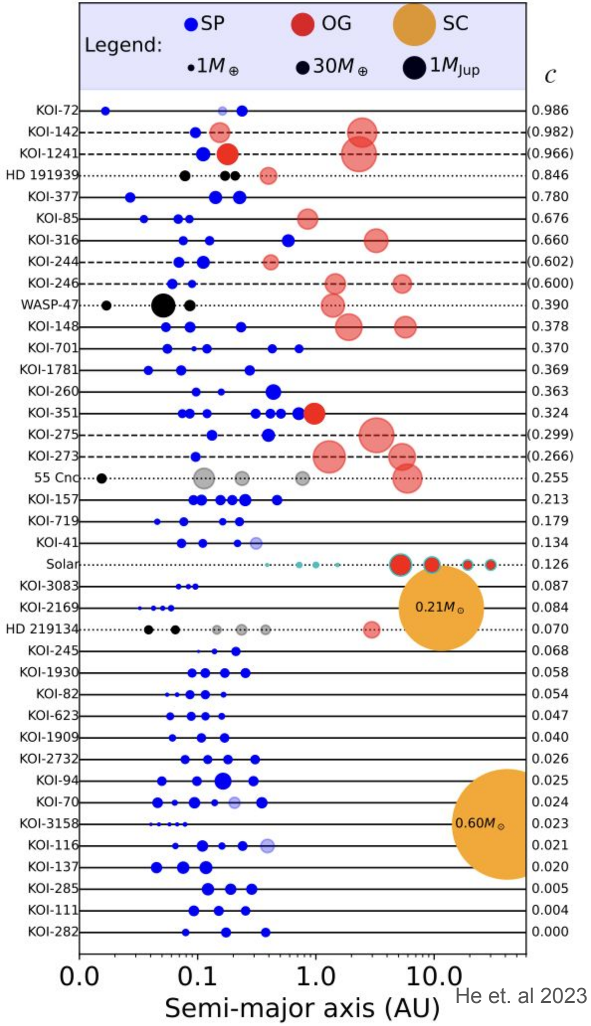
Kepler-139: A test case of Sweeping Secular Resonances Leading to System Non-uniformity

Matthew Doty
(Marcy Best, Cristobal Petrovich, Antranik Sefilian, Carolina Charalambous)

Outer Jupiters & Uneven Spacing

- Systems with Outer Giants → uneven system spacing (KGPS)



He et. al 2023

Outer Jupiters & Uneven Spacing

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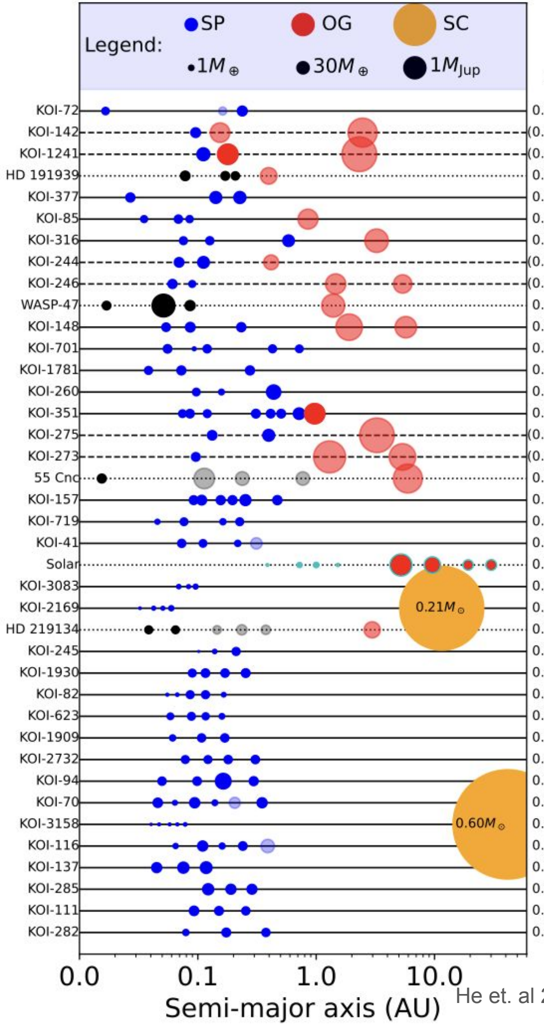
- Formed in-situ or due to post-formation dynamics?

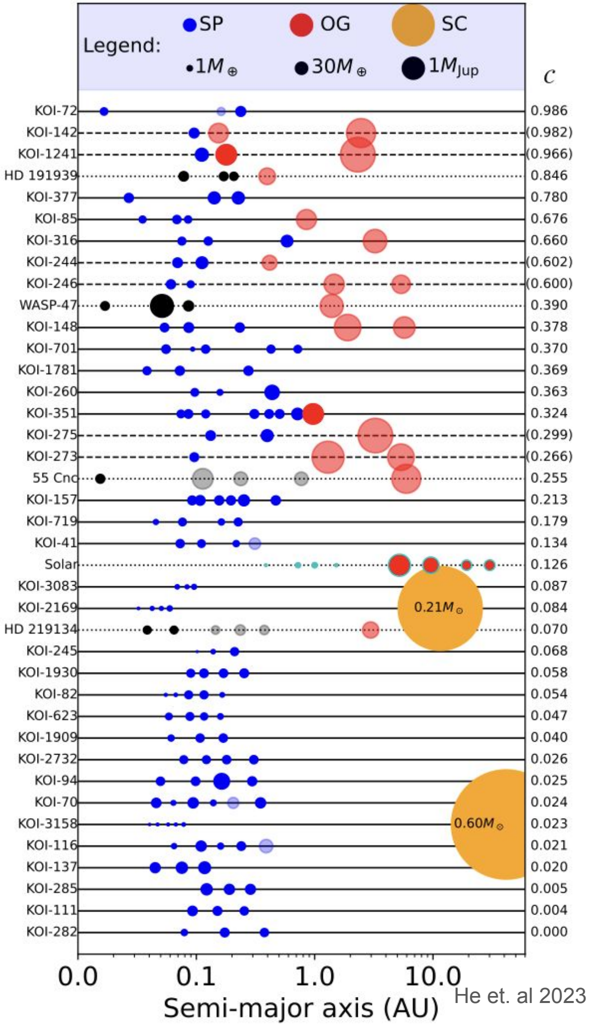


He et. al 2023

Outer Jupiters & Uneven Spacing

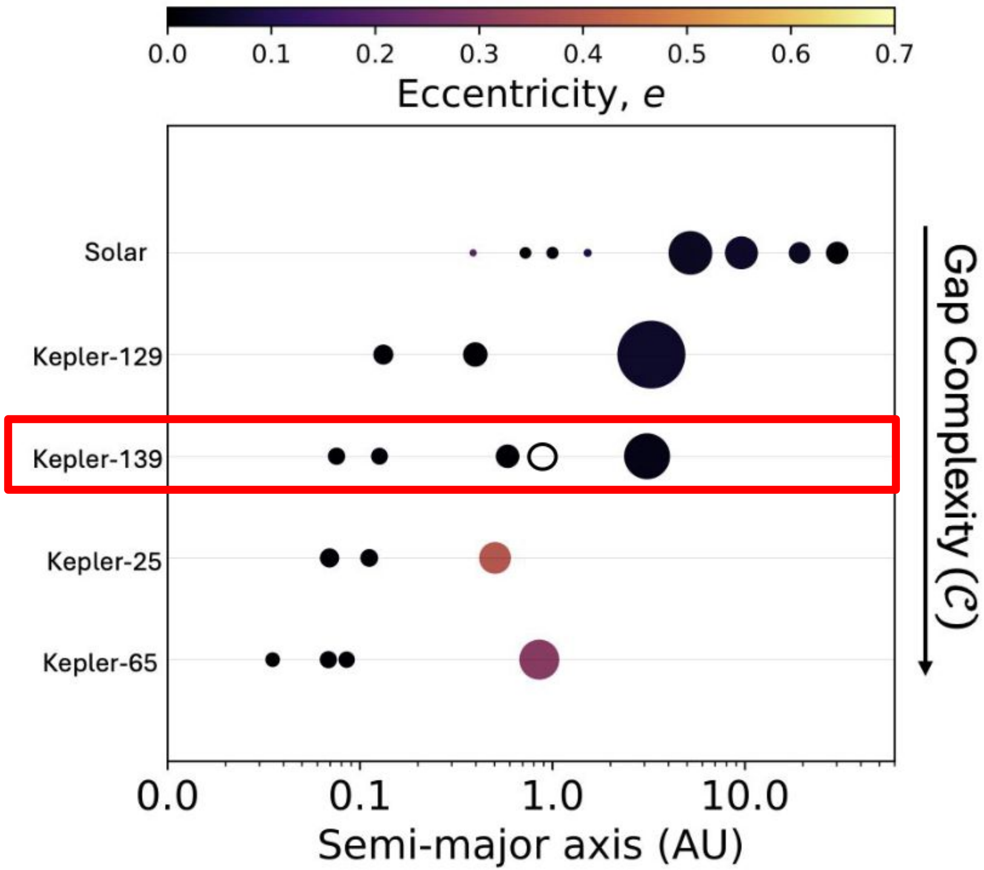
- Systems with Outer Giants → uneven system spacing (KGPS)
- Formed in-situ or due to post-formation dynamics?

Q: Can a dynamical mechanism (SSR) cause a material distribution that could lead to in-situ formation of unevenly spaced systems?



He et. al 2023

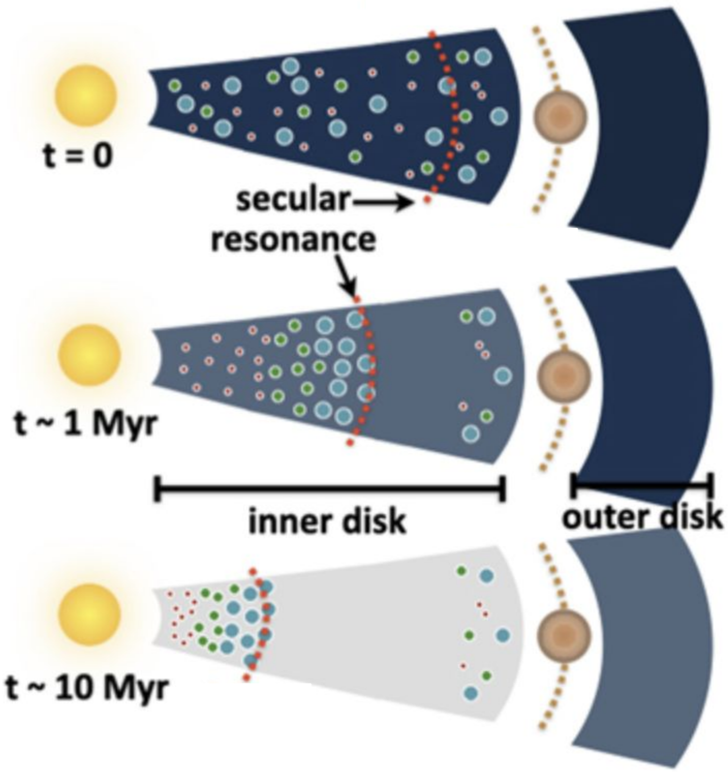
Kepler-139/KOI-85: In-situ formation test case



Sweeping Secular Resonance (SSR): Physical Assumptions

Best et. al (2024)

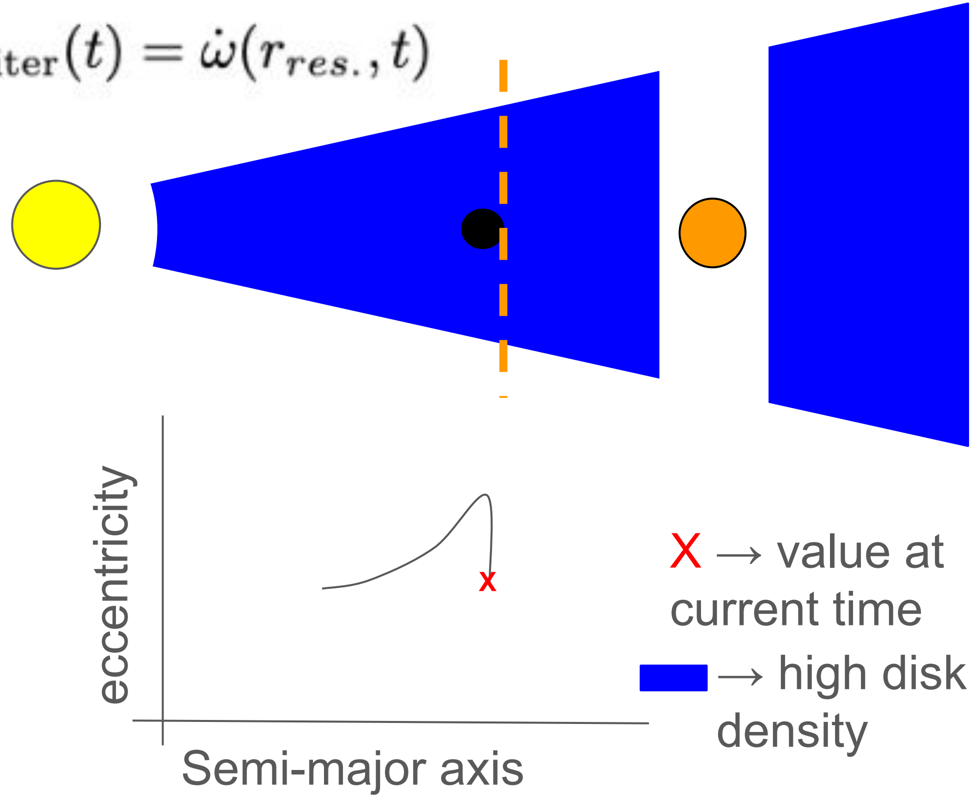
1. Giant Planet (early)
2. Large planetesimals [< 100 km] (early)
3. Post-Migration Formation
4. 1,2,3 + migration → Long Disk Lifetimes



Best et. al 2024

Sweeping Secular Resonance (SSR): Mechanism

$$\dot{\omega}_{\rm jupiter}(t) = \dot{\omega}(r_{res.}, t)$$



Secular Resonance → eccentricity excitation

Sweeping Secular Resonance (SSR): Mechanism

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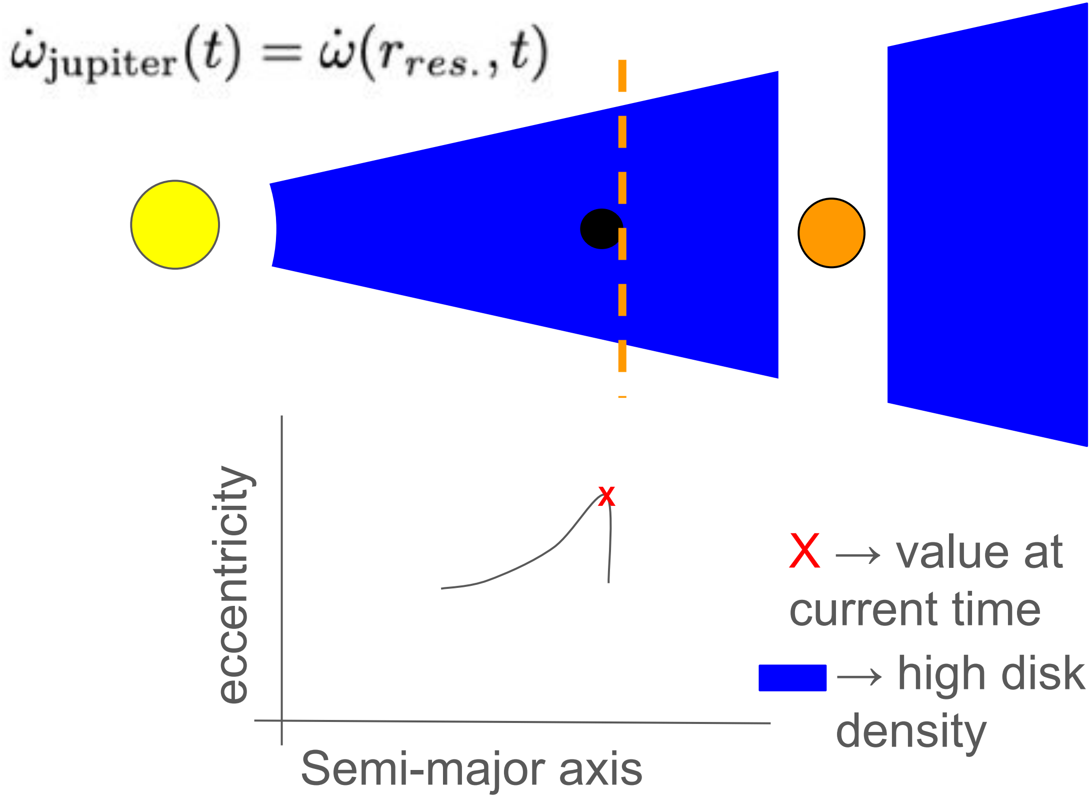

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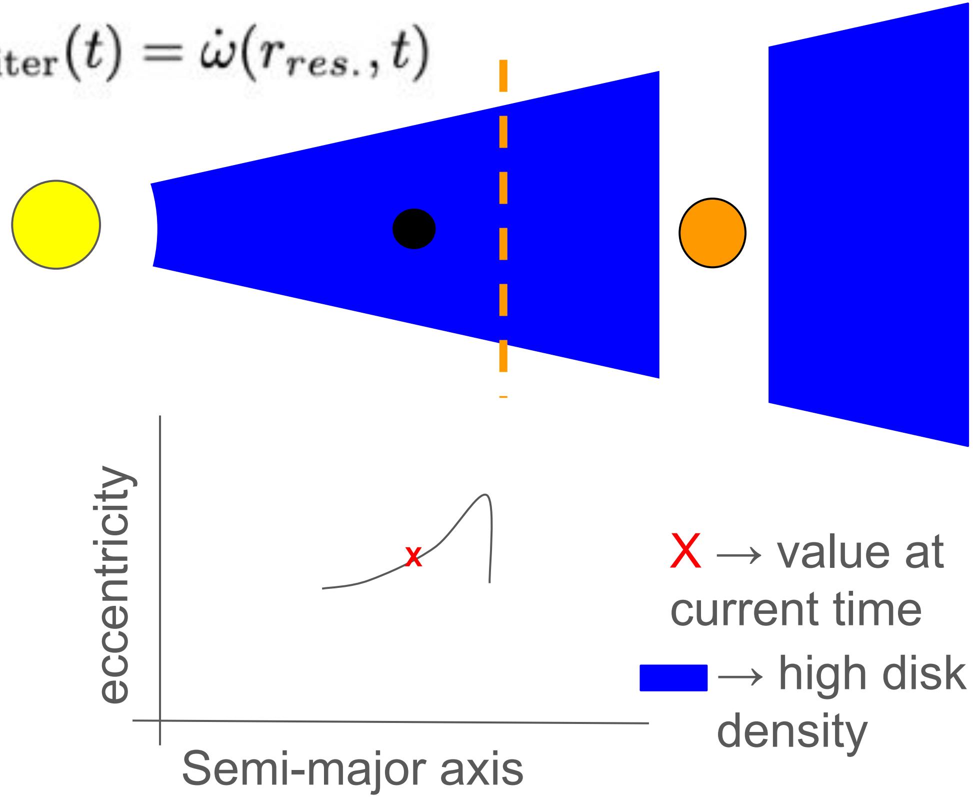

Excited eccentricities → planetesimal migration

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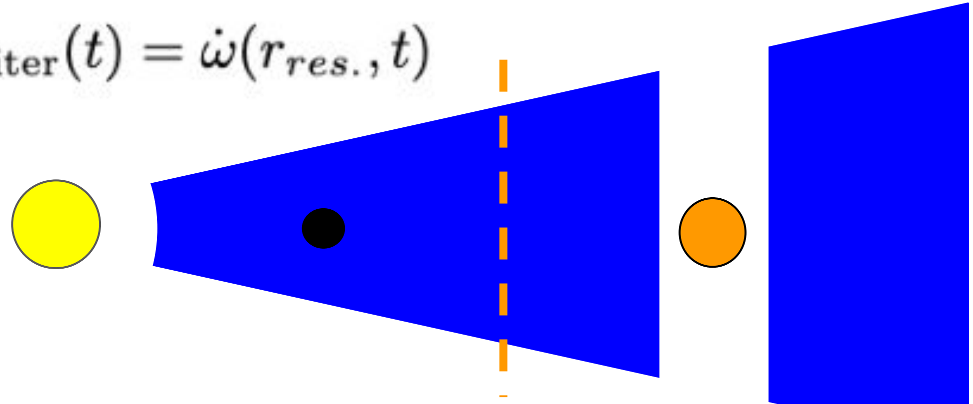

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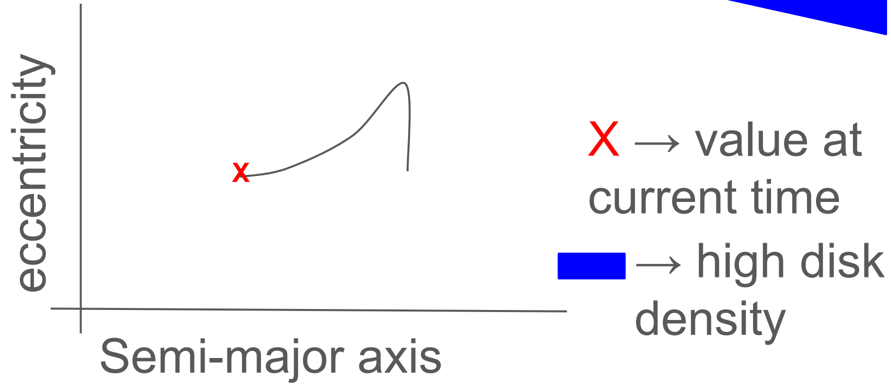
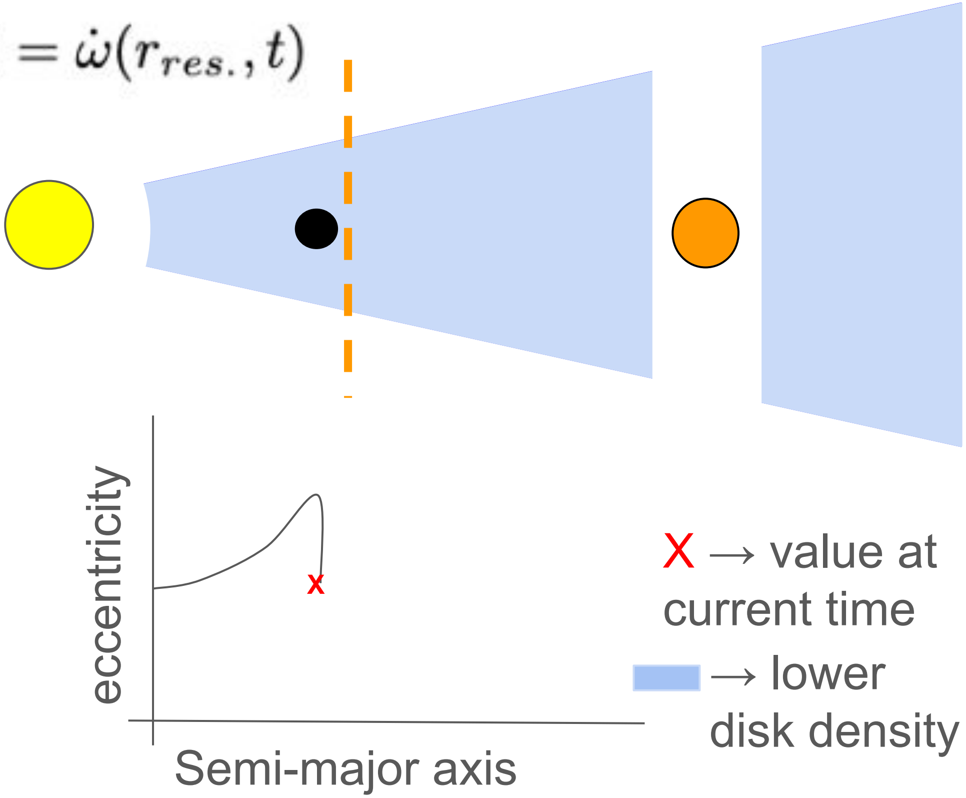


Sweeping Secular Resonance (SSR): Mechanism

$$\dot{\omega}_{\text{jupiter}}(t) = \dot{\omega}(r_{res.}, t)$$

Alpha-viscosity driven dissipation→ Resonance “sweeps” inward



Sweeping Secular Resonance (SSR): Mechanism

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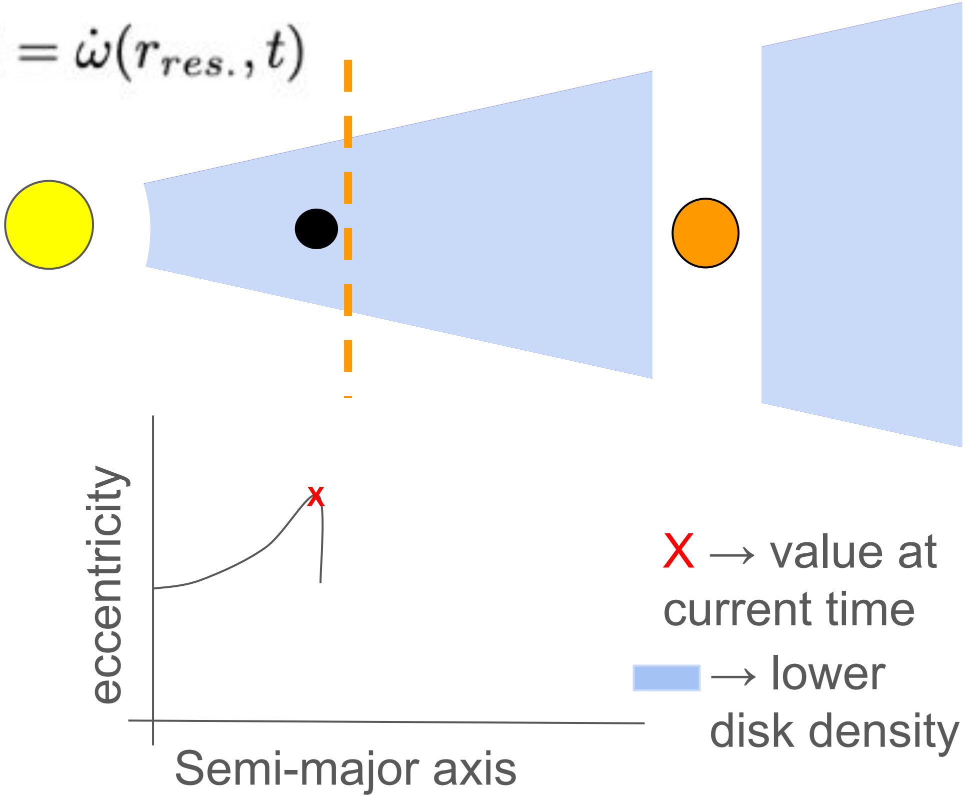
Resonance at new location → eccentricity excitation



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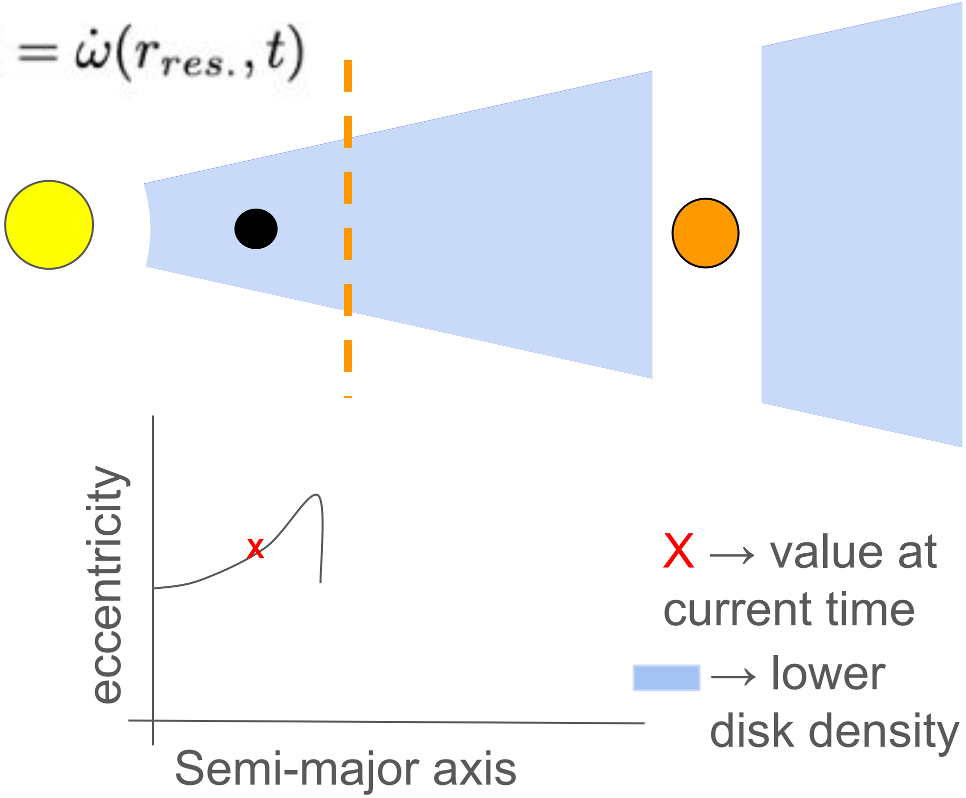

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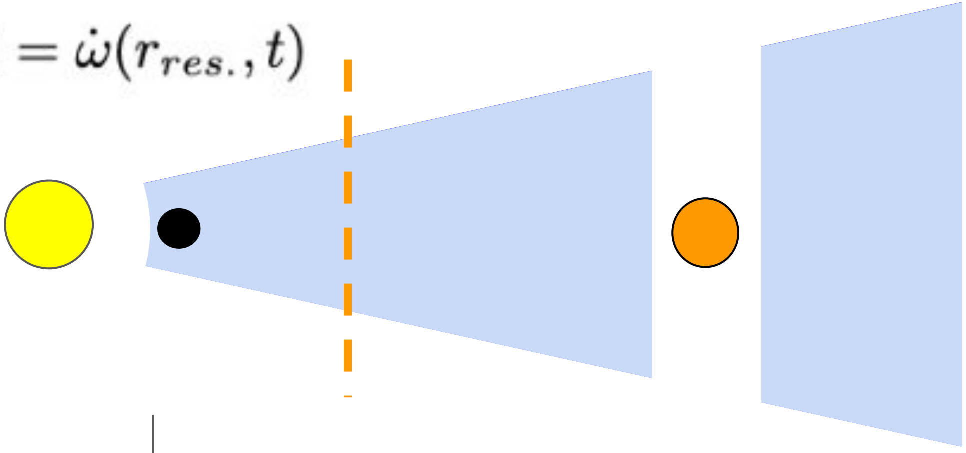
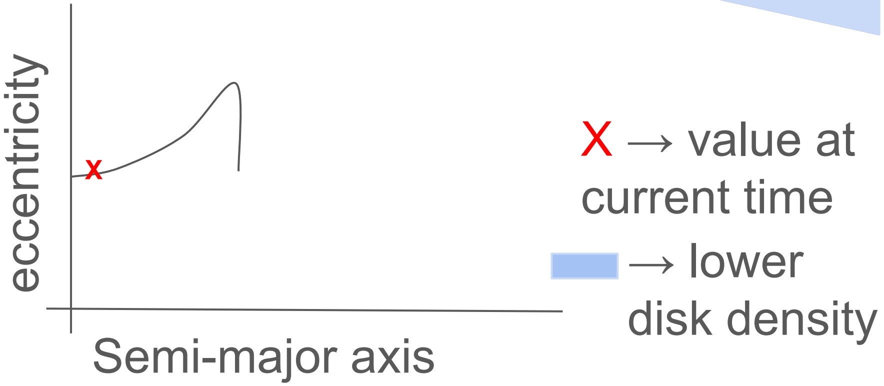
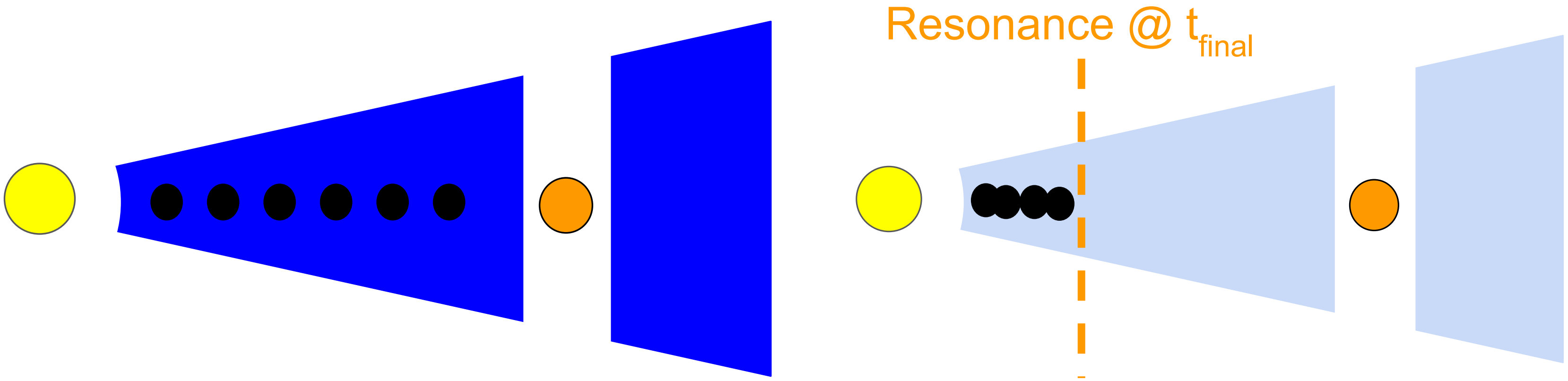




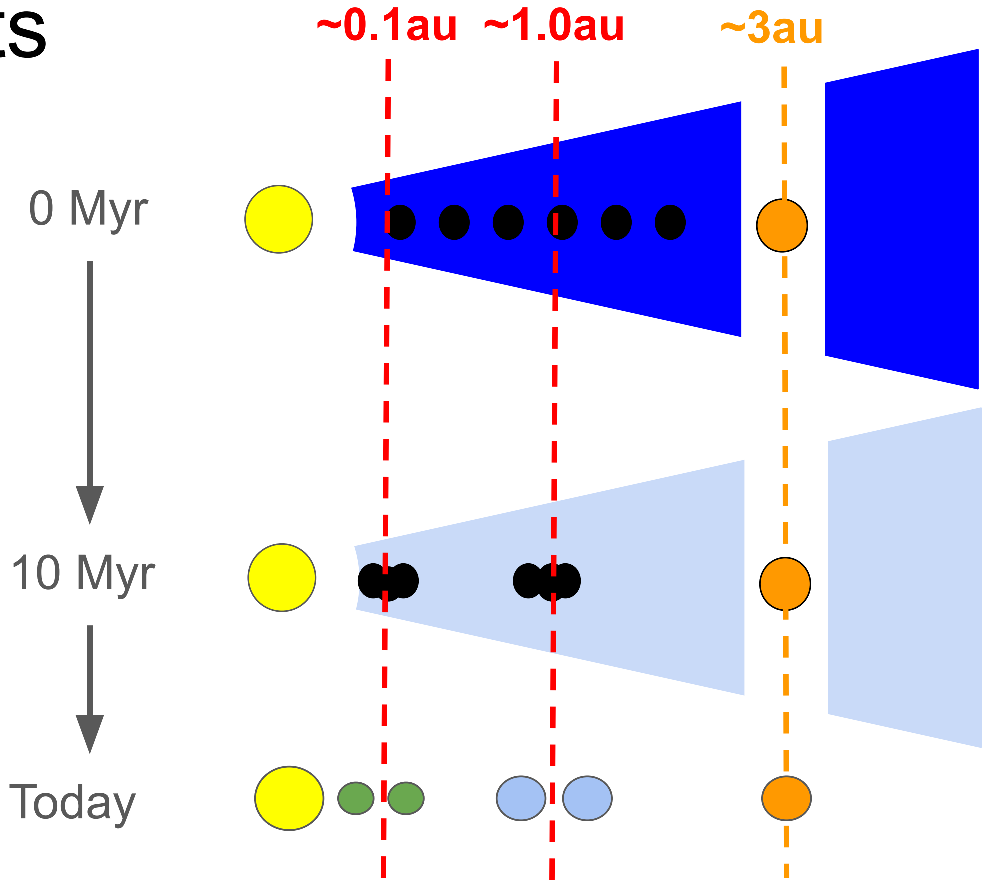
Sweeping Secular Resonance (SSR): Mechanism



Sweeping Secular Resonances can concentrate material in the interior of a disk

Sweeping Secular Resonance: Kepler-139 Constraints

1. Inner ring → 0.1au
2. inner gap → 0.1-1au
3. Outer ring→ 1au



Sweeping Secular Resonance: Kepler-139 Constraints

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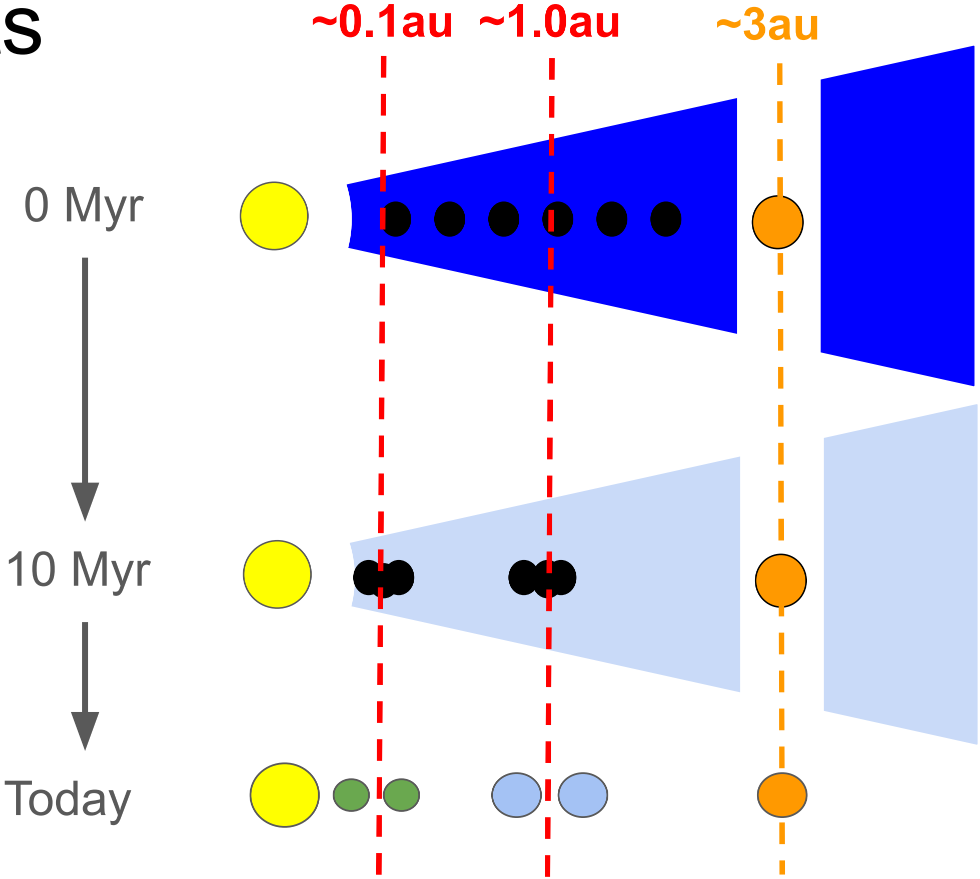
Model must reproduce these features



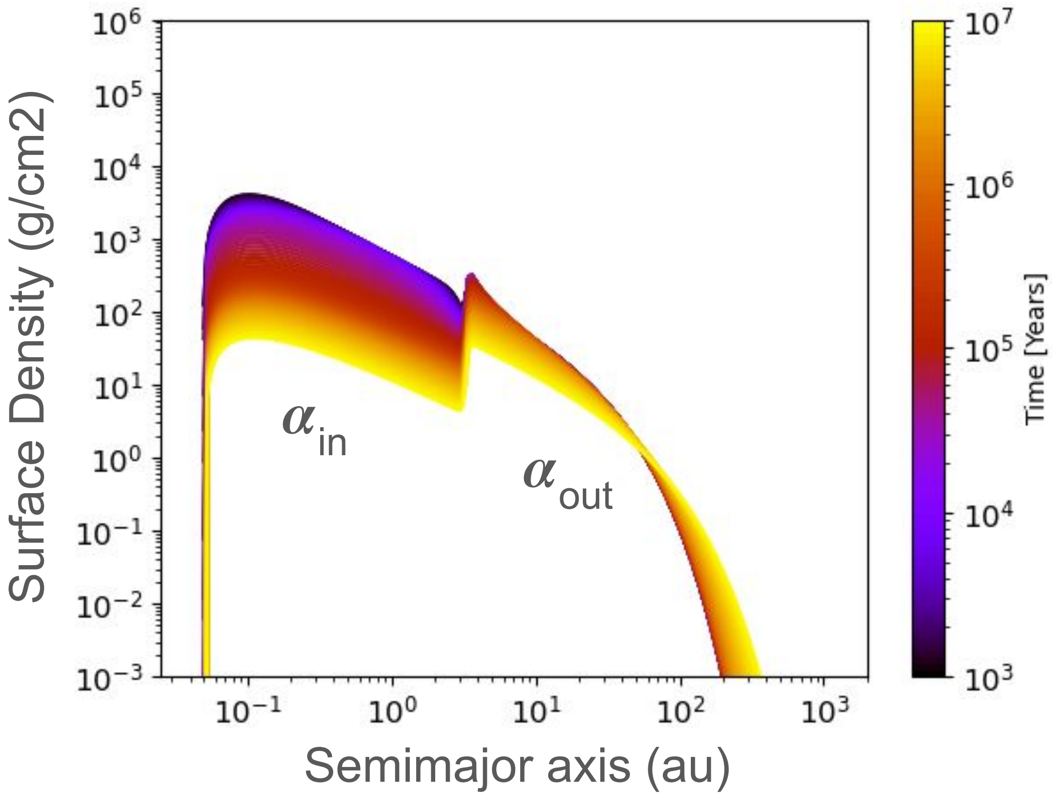
Sweeping Secular Resonance: Disk Dissipation

- "Alpha Disk"
  - alpha → viscosity parameter

$$\nu = c_s \alpha H$$

- Disk dissipation → alpha

$$\partial M_{\mathrm{disk}} / \partial t \sim \alpha$$



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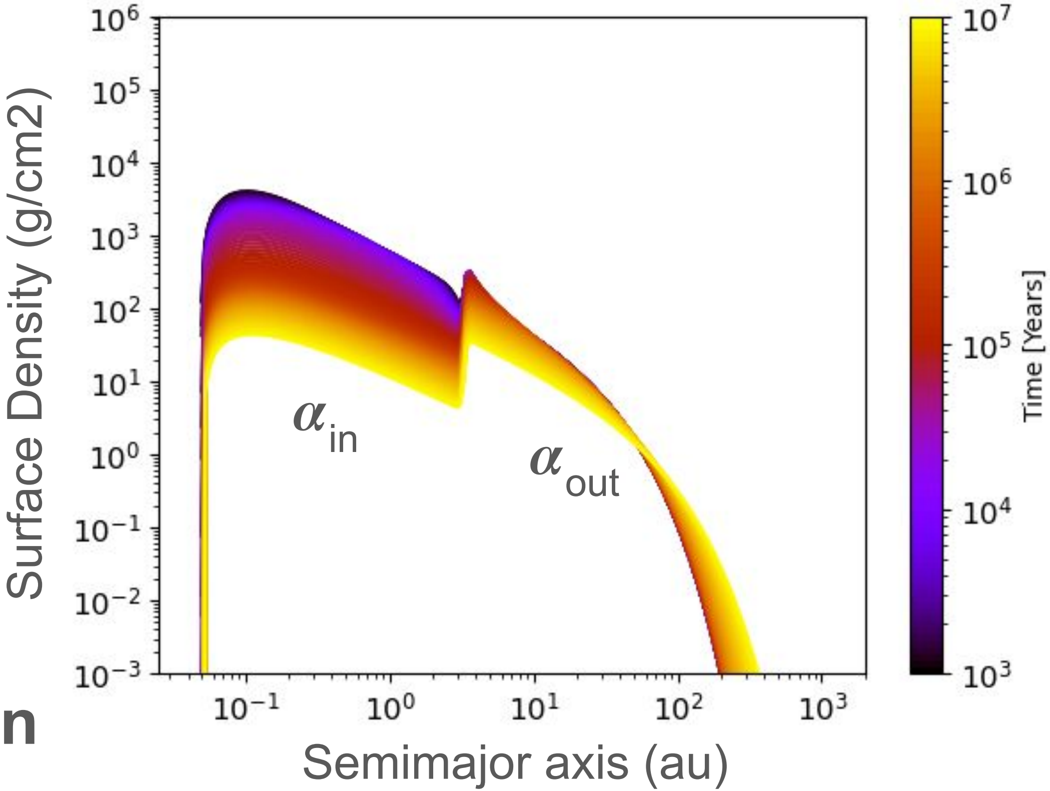
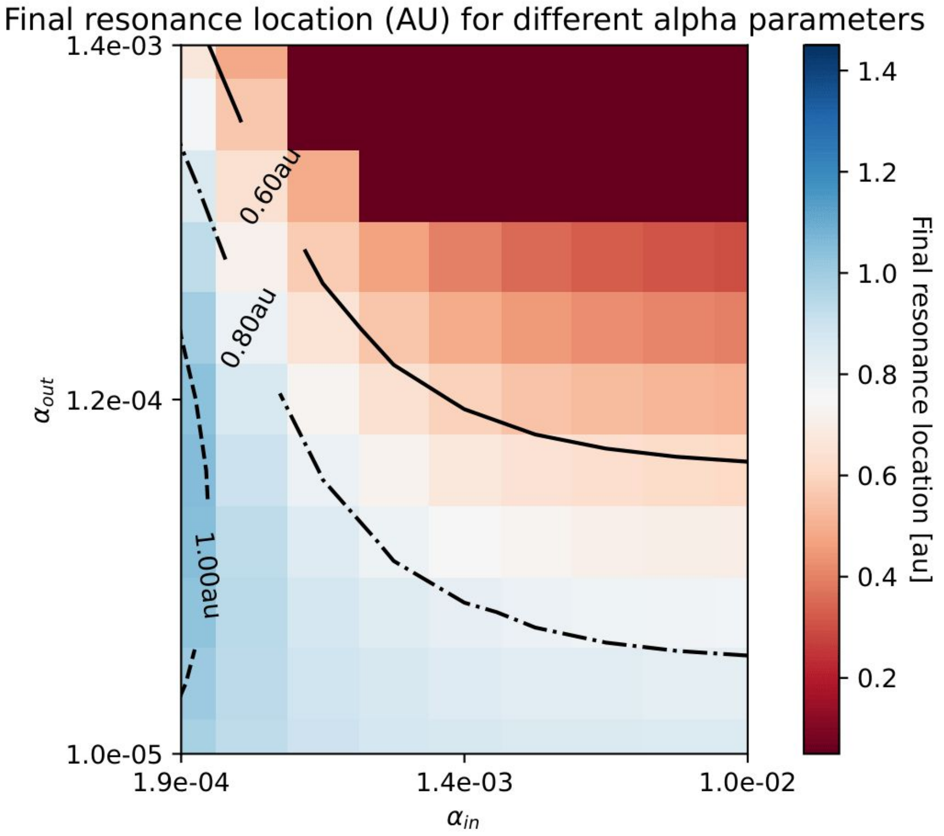
Alpha controls dissipation



Applying the Model: Alpha Parameterization

- Resonance location → disk dissipation (α)
- Wide range of α parameters match outer planets' location.



Applying the Model: Alpha Parameterization

- Resonance location → disk dissipation (α)
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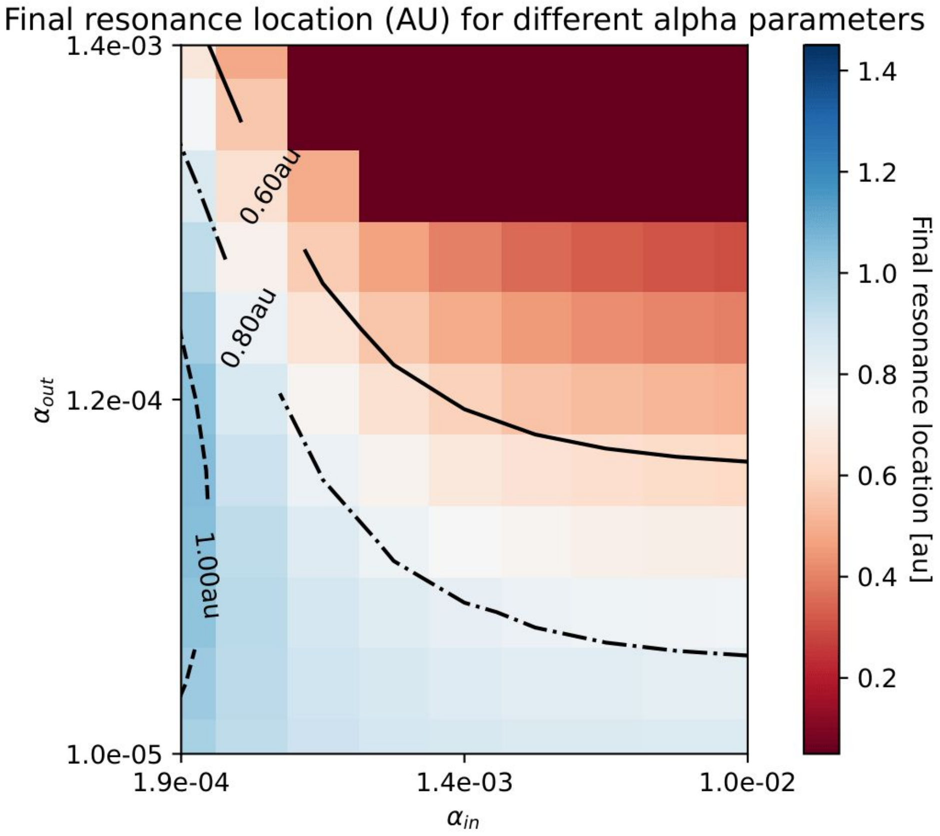
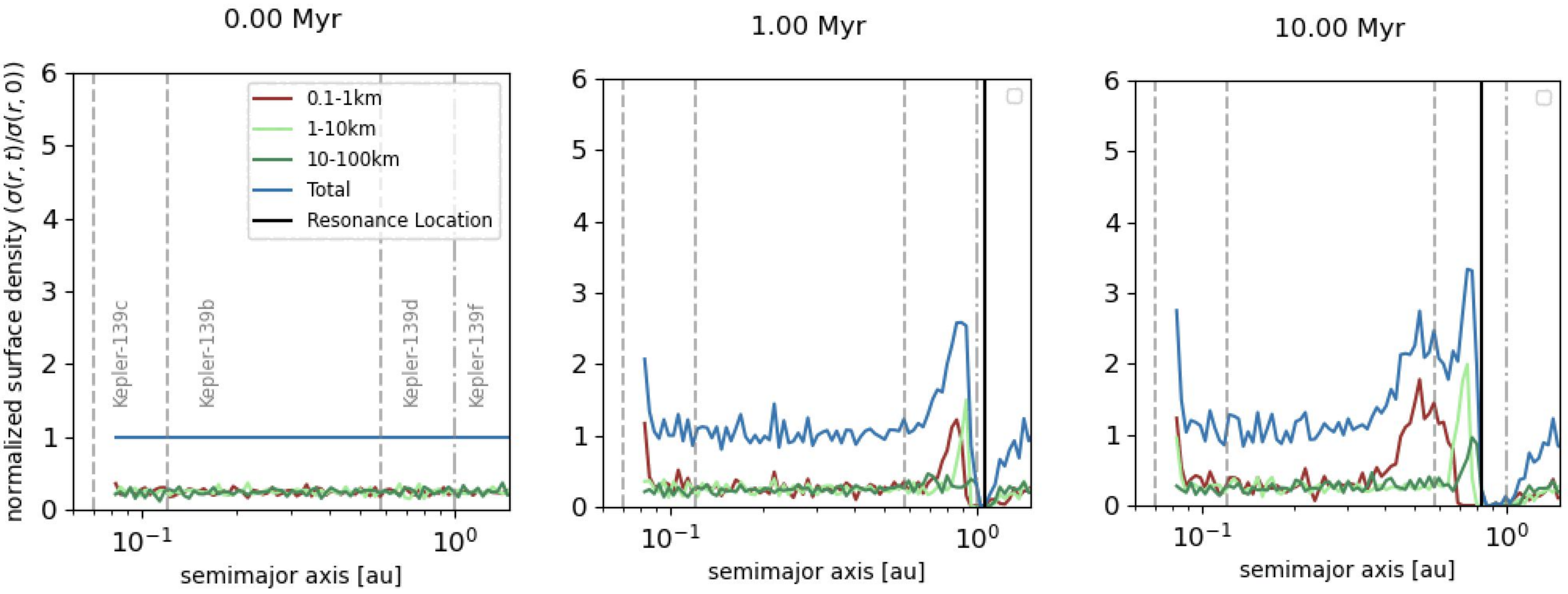
Wide range of α values yield required resonance location ~ 0.6-1AU

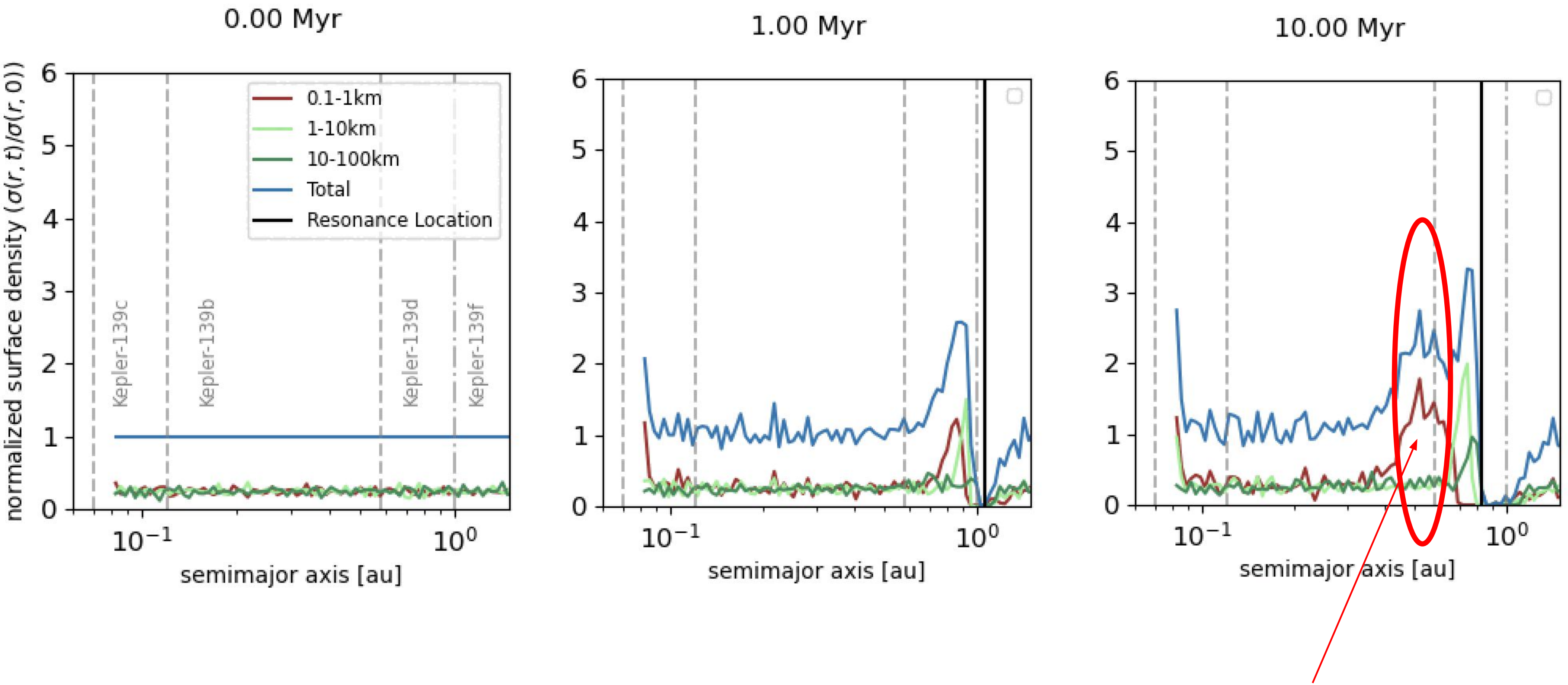


Applying the Model: Outer Ring



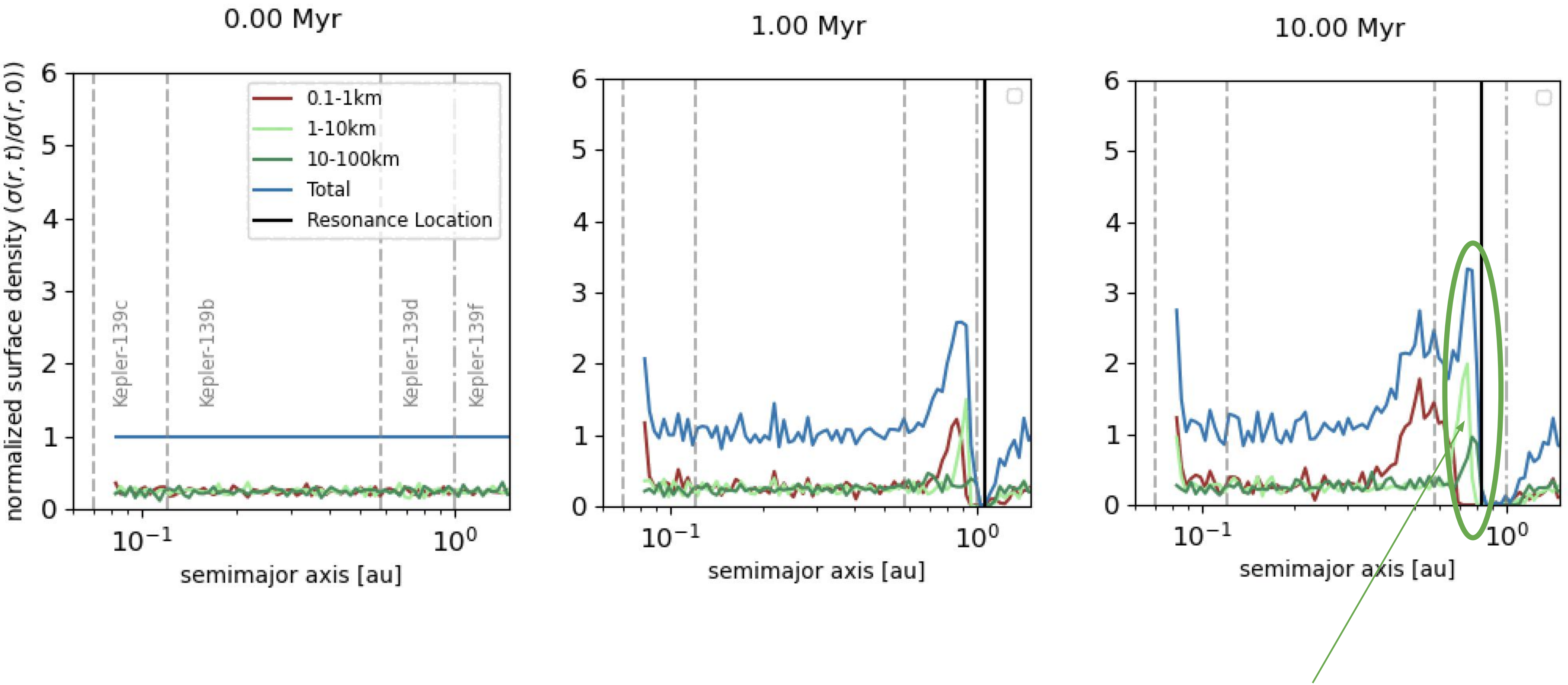
SSR Modeled distribution matches outer planets

Applying the Model: Outer Ring



Interior of peak → faster migrating smaller bodies

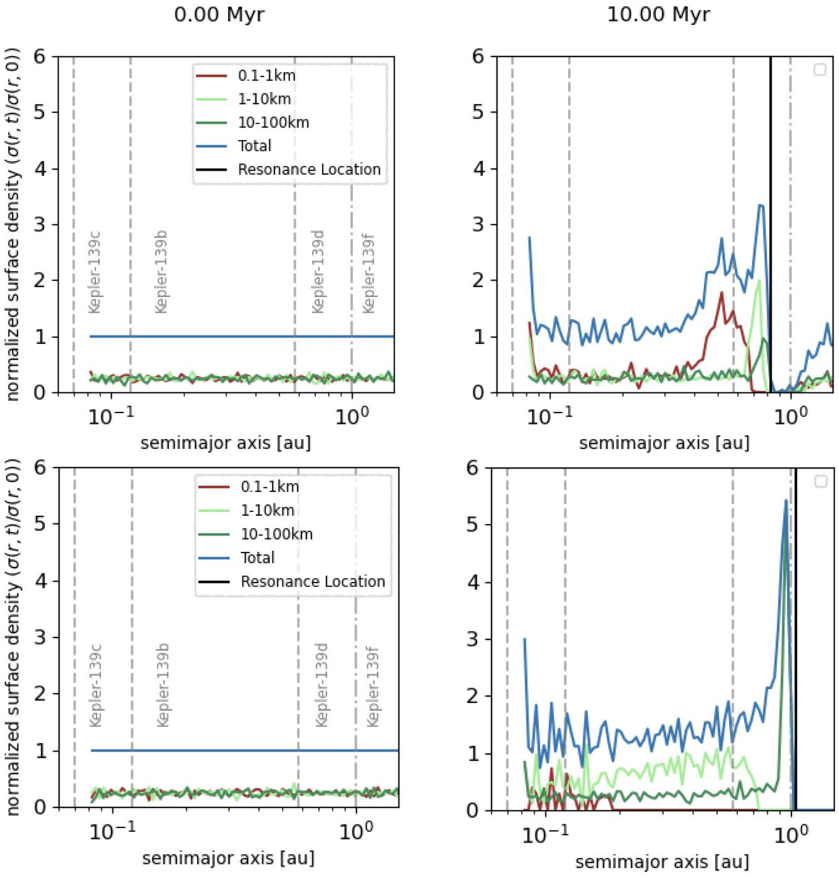
Applying the Model: Outer Ring



Exterior of peak → slower-migrating large bodies

Applying the Model: Alpha (α) Dispersion

- Q: Does final distribution depend on α? (for same outer resonance ~ 0.8 au)
- A:
  - Different α → similar distribution of all sizes
  - Similar α → size segregated distribution



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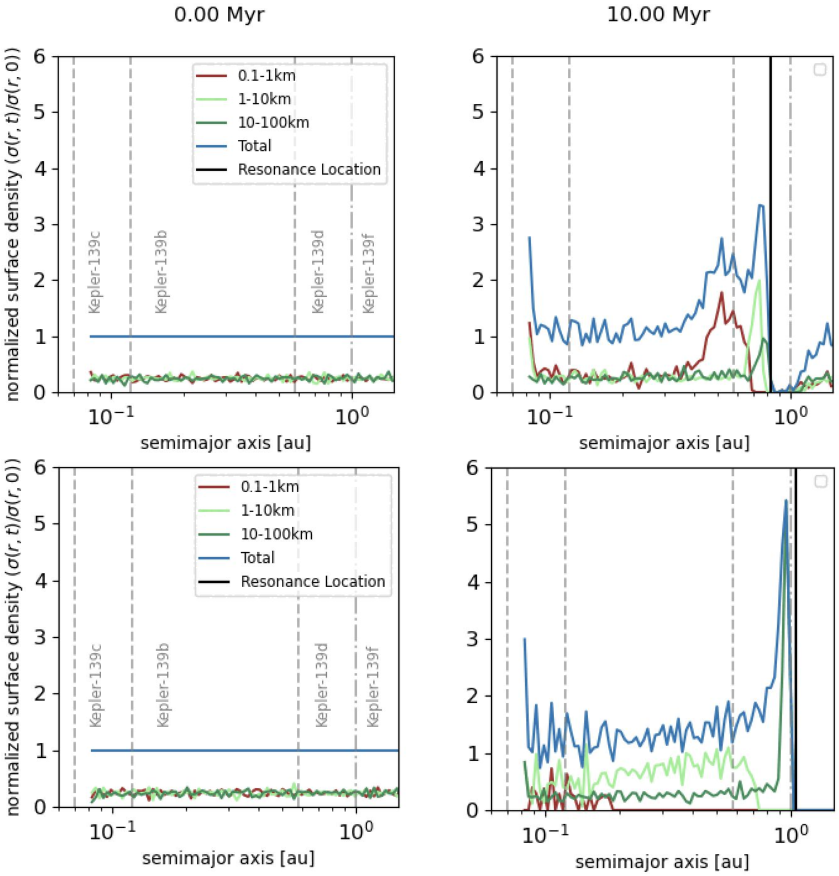
Δα → variations in planetesimal size distribution

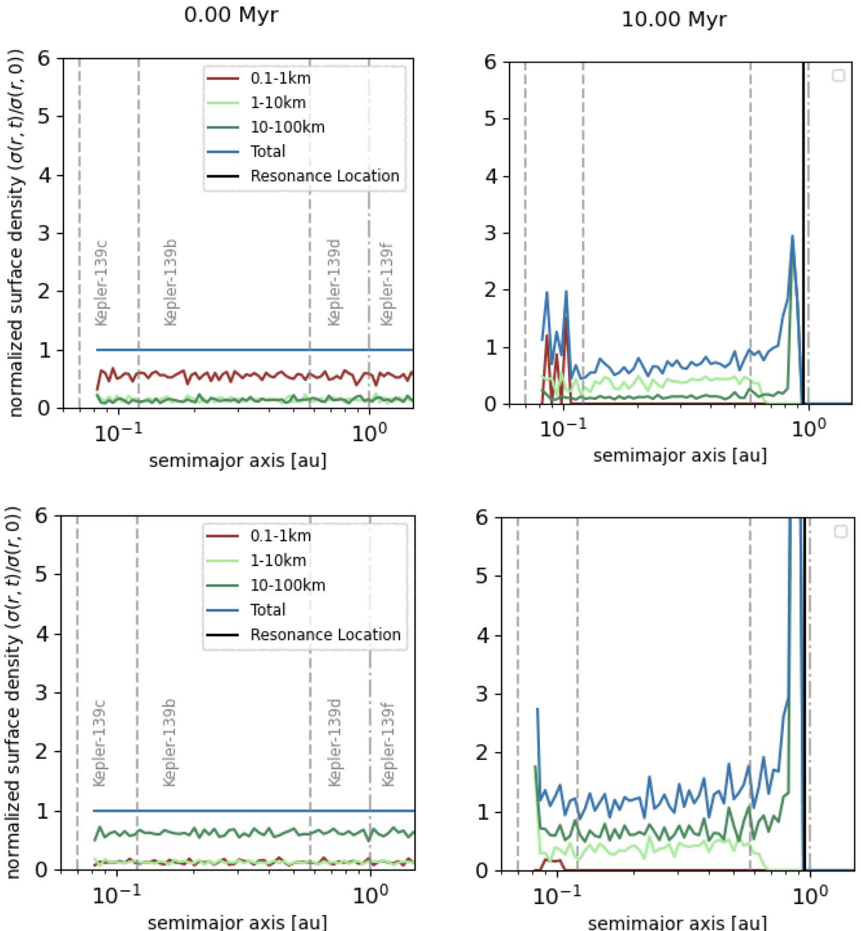


Applying the Model: Effect of Size Distribution

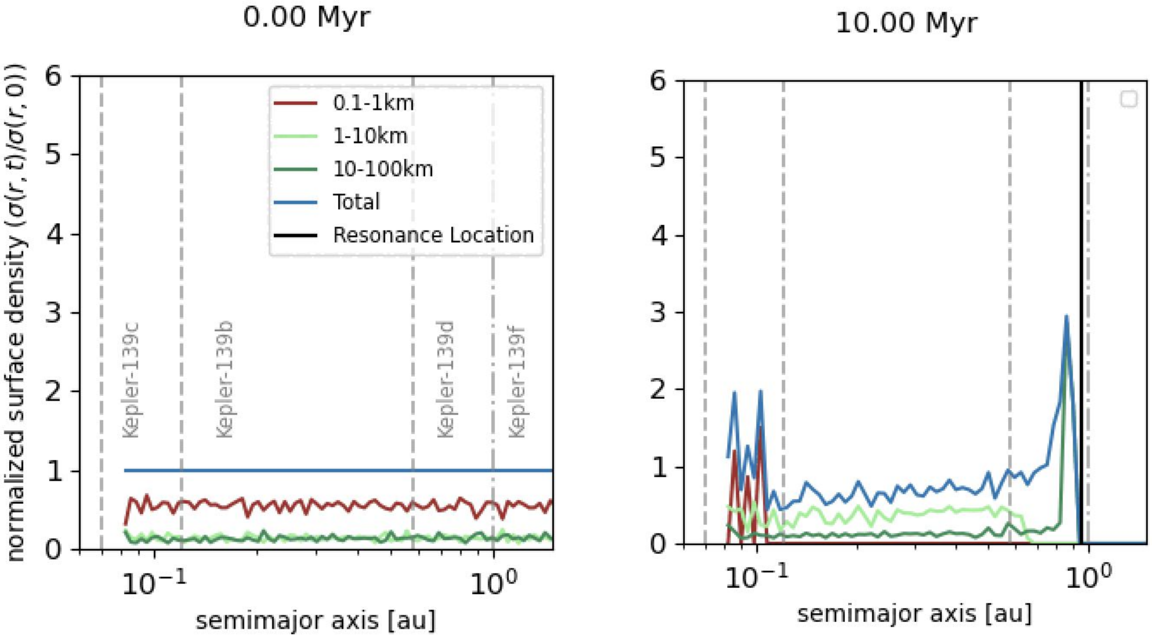
“Knob” re:planetesimal sizes

Effect of Small-planetesimal dominated -vs- Large-planetesimal dominated scenarios?

- Similar general structure
- **Small planetesimals → Denser inner ring**
- **Large planetesimals → Denser outer ring**



Applying the Model: Sweeping & Inner Ring



- **Wide range alpha values + large planetesimals → dense outer ring at ~ 0.6 - 1 AU**
- **Similar alpha values + weighting small planetesimals → inner ring created by migration at ~ 0.1AU**

Conclusions

We have modeled the evolution Kepler-139 using SSR mechanism (Petrovich) in the spirit of Best et. al 2024

In the limit of an early giant planet & purely dynamical evolution, we find that:

1. Wide range of α give planetesimal distributions ~ obs. planet locations
    a. Resonance sweeping to the inner system (<1 AU)
    b. Creation of a massive outer ring near 1AU
    c. Density minima between 0.1 and 1AU
2. Similar α → size segregated distribution
3. Similar α + significant small planetesimals → inner ring driven by small planetesimals ~ 0.1AU

Within the applicable parameter regime, SSRs may provide material distributions that could be consistent with the possibility of in-situ formation

SSR: Resonance Location

$$\dot{\omega}_{\rm jupiter}(t) = \dot{\omega}(r_{res.}, t)$$

$$\dot{\omega}(r,t) = \dot{\omega}_{\rm p,disk}(r,t) + \dot{\omega}_{\rm p,jupiter}(r,t) \sim M_{\rm disk,interior}(t) + M_{\rm jupiter}$$

$$\dot{\omega}_{\rm jupiter}(t) = \dot{\omega}_{\rm j,disk}(t) \sim M_{\rm disk,exterior}(t)$$

$$\left(\frac{a_{\rm res}}{a_{\rm J}}\right)^{3/2} = \frac{0.02 M_{\rm out}\Delta^3 + 3M_{\rm in}\Delta^{-3/2}}{M_{\rm J}}$$

$$\partial M_{\rm disk}/\partial t \sim \alpha$$

$$\nu = c_s \alpha H$$

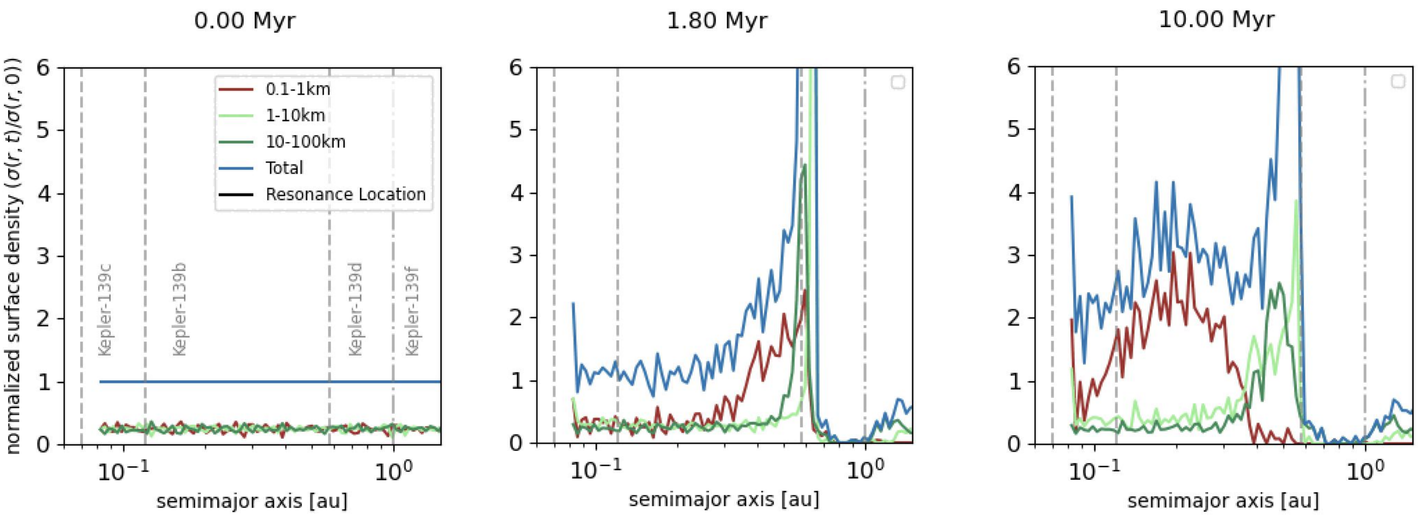
SSR - Disk Dissipation

$$\Sigma_{\mathrm{gas}}(r) = \Sigma_{\mathrm{gas},0}\left(\frac{r}{1\ \mathrm{au}}\right)^{-\gamma} \exp\left[-(r/r_{\mathrm{cut}})^{2-\gamma}\right]. \qquad \gamma = 1$$

$$\frac{\partial \Sigma_{\mathrm{gas}}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[3r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma_{\mathrm{gas}} r^{1/2}\right)\right] \qquad \nu = c_s \alpha H$$

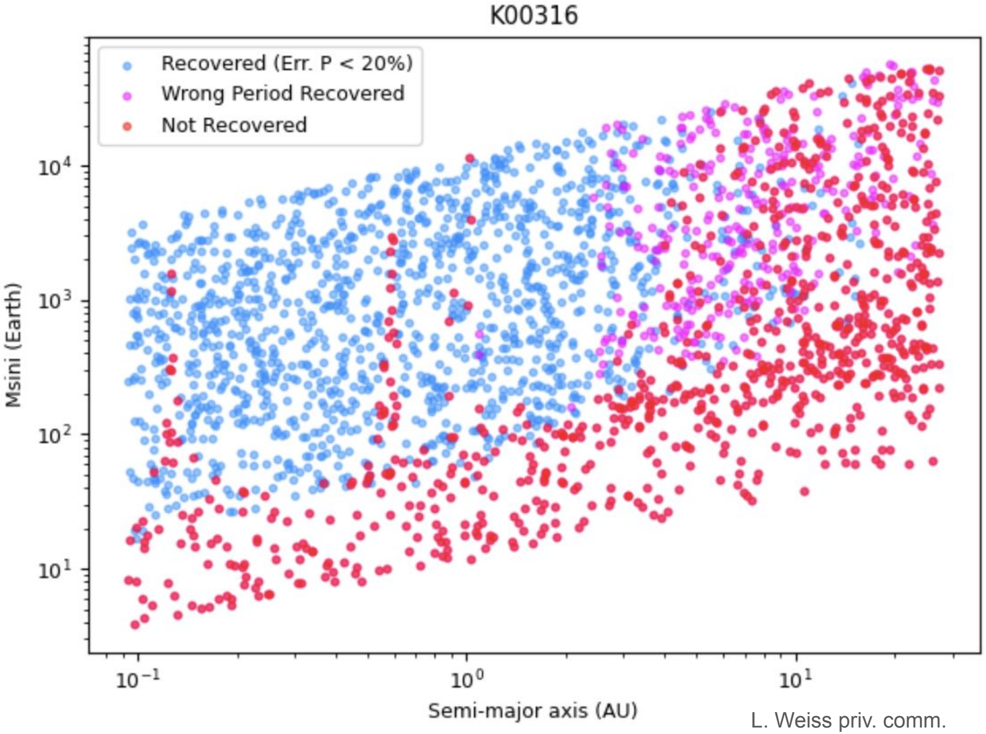
Applying the Model - Oversweeping

- Applying large values of alpha, the resonance can migrate faster than the planetesimals
- This “oversweeping” can leave rings of material behind at the locations the resonance was last “behind” that group of planetesimals



Kepler-139: Working to Constrain the Architecture

- Stability (SPOCK) and Observational (RV) Constraints → mostly unhelpful
- Injection Recovery → <100 Earth Mass planets possible from 0.1-3au
- SPOCK → <100 Earth Mass Planets are stable for most of the regions in the gaps



L. Weiss priv. comm.

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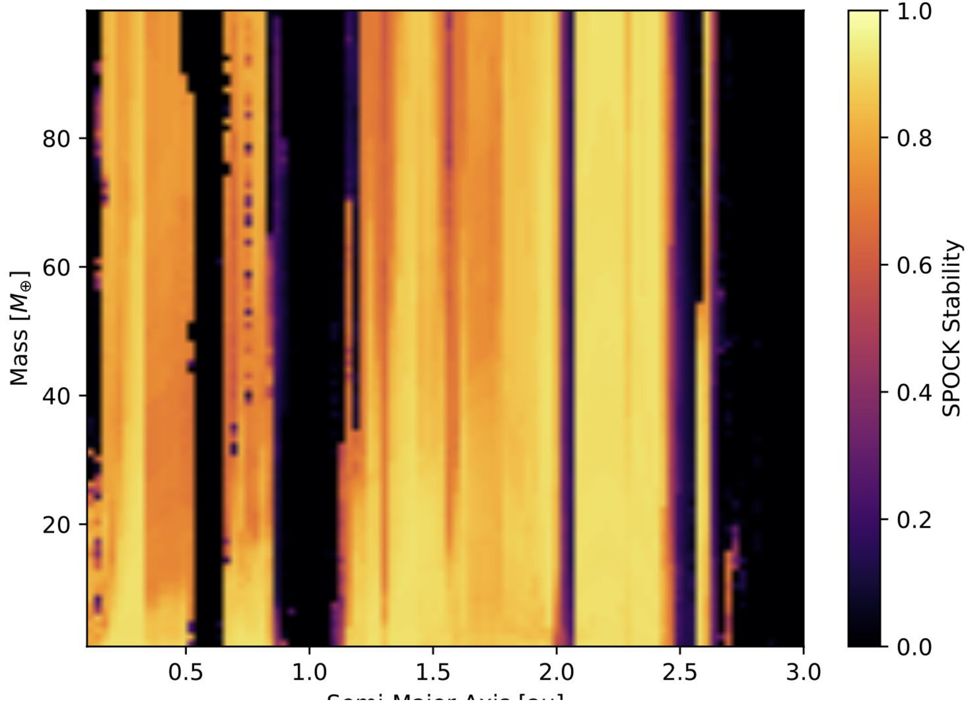
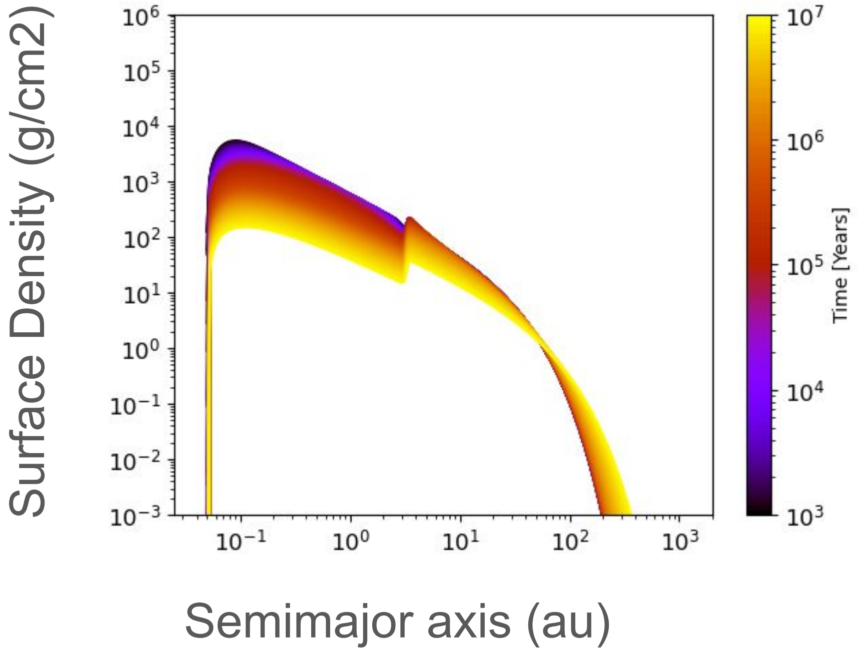


Disk Surface Density Evolution - Plots

Similar Alpha (α_{in}=3e-4, α_{out}=1e-4)



Different Alpha (α_{in}=1e-2, α_{out}=2e-5)