Observational Cosmology Journal Club

Nov 16th, 2020 | Shijie Wang

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1. Shibaike & Alibert. **Planetesimal formation at the gas pressure bump following a migrating planet I. Basic characteristics of the new formation model** arxiv:2010.10594v1
2. Ali-Dib & Petrovich **Constraining protoplanetary disks with exoplanetary dynamics: Kepler-419 as an example** arXiv:2009.06448v1
3. Ronco et al. **How Jupiters Save or Destroy Inner Neptunes around Evolved Stars** 2020 *ApJL* 898 L23

Preview

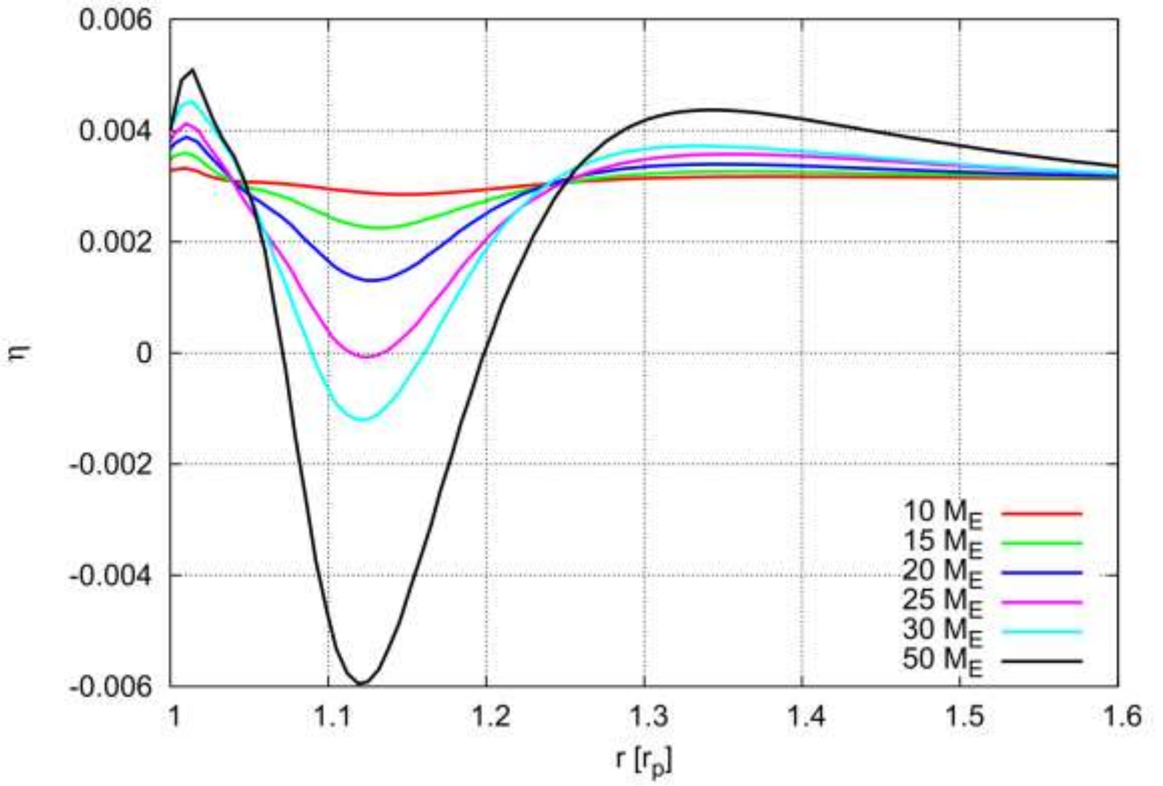
[P1] Planetesimal + planetary migration: a new scenario in which planetesimals can form in broad areas of the discs

[P2] Deducing the properties of the protoplanetary disk from the observed Kepler-419 system

[P3] After the host star turns to become red giant, the final fate of the “inner Neptune” can be very different if there is an “outer Jupiter”.

[P1] Context

- Some planet formation models believe that planets are formed via coalescence of **planetesimals**
- But how planetesimals grows all the way from dust?
  - Difficulty: Drift & fragmentation barriers may stop the growth
  - Previous solution: instabilities, but only occur at certain locations → not compatible with models & observation (arguably)
- This paper: a new scenario
  - Point 1: Planet can create a pressure bump → streaming instability → planetesimals form
  - Point 2: Planet can migrate → planetesimals can form in broad regions



Planet can create a pressure bump that can trap solid particles (Bitsch+18)

Methods: disk and planet

- Gas-disk models

  $$\Sigma_{\text{g, unp}} = \Sigma_{\text{g,0}}(r/\text{au})^{-p}$$
  $$T = T_0(r/\text{au})^{-q}$$

3 Disk Models→

Disc	$\Sigma_{\text{g,0}}$	T_0	p	q
A	500	280	1	0.5
A'	5000	500	1	0.5
B	1700	280	1.5	0.5

- Planet
  - Single planet, $20\ \text{M}_{\oplus}$ @ 30 au (mig only, no mass growth)
  - Undergoes Type I migration, given by Tanaka+02
- Gap structure
  - $\Sigma_{\text{g,local}} = \Sigma_{\text{g,unp}} \max(s_K, s_{\text{min}})$

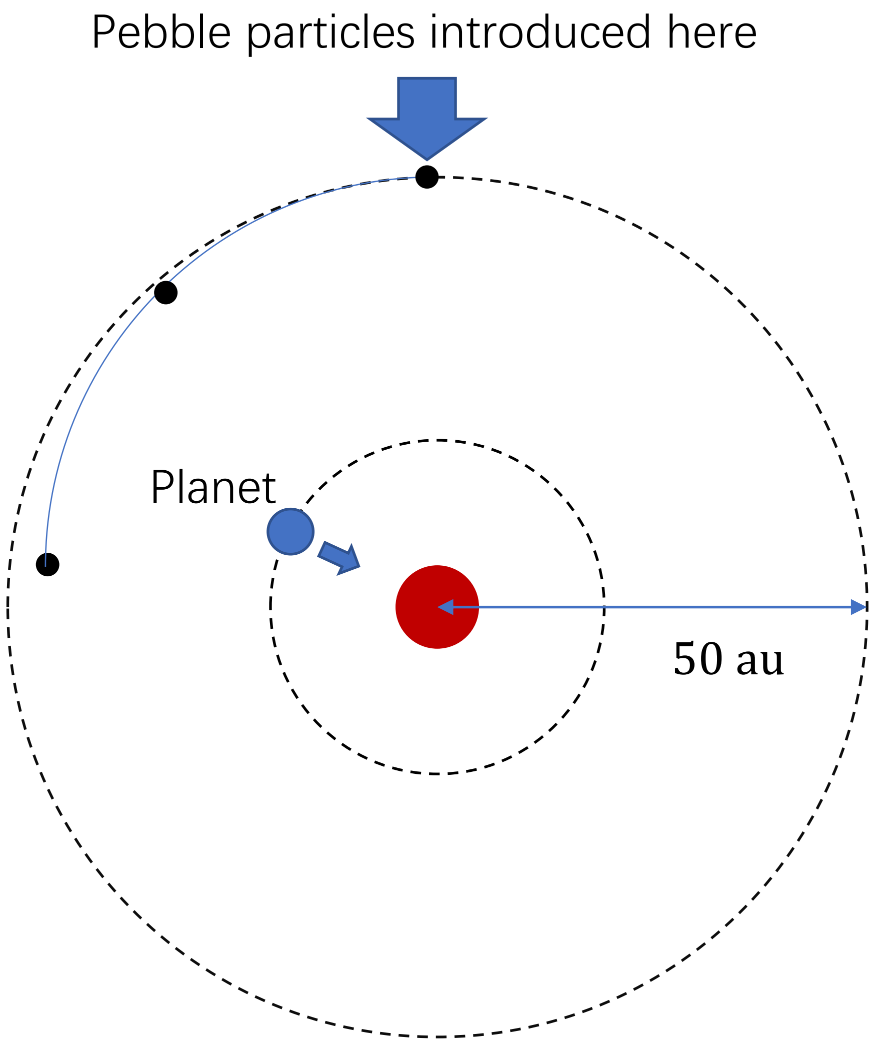
    $s_K = \max(s_{Kepler}, s_{Rayleigh})$

    $s_{\text{min}} = (1 + 0.04\text{K})^{-1}$
  - Pressure gradient / gravity → $\eta = -0.5\left(H_g/R\right)^2 \partial \ln P_g / \partial \ln R$

    $P_g = \rho_g \text{c}_s^2 = \Sigma_{g,local}/\left(\sqrt{2\pi} H_g\right) c_s^2$

Methods: pebbles → planetesimals

- Introduce pebble particles
  - Pebble drift radially $v_r = v_{drift} + v_{diff}$
    $v_{drift} = -2\frac{St}{St^2+1}\eta v_K$(due to head wind), St=0.1
    v_{diff} is the radial diffusion velocity
  - Pebble particles are introduced at $r_{out} = 50$ au
  - At time interval $\Delta t = \Omega_{K,planet}^{-1}$,
    - n particles are introduced to $[r_{out}, r_{out} + v_r\Delta t]$, with total mass $\dot{M}_{peb}\Delta t$. $\dot{M}_{peb}$ surveyed.
    - n is integer and $\mathrm{n} \geq 1$
    - Particles pass the planet's orbit or r_{out} will be removed
  - Calculation stops when $r_{planet} = 0.5\ au$



Methods: pebbles → planetesimals

- Planetesimal formation
  - **Condition**: $\rho_{peb,mid} > \rho_{gas,mid}$

$$\rho_{peb,mid} = \Sigma_{peb}/(\sqrt{2\pi}H_{peb})$$

- Calculation of Σ_{peb} using pebble particles

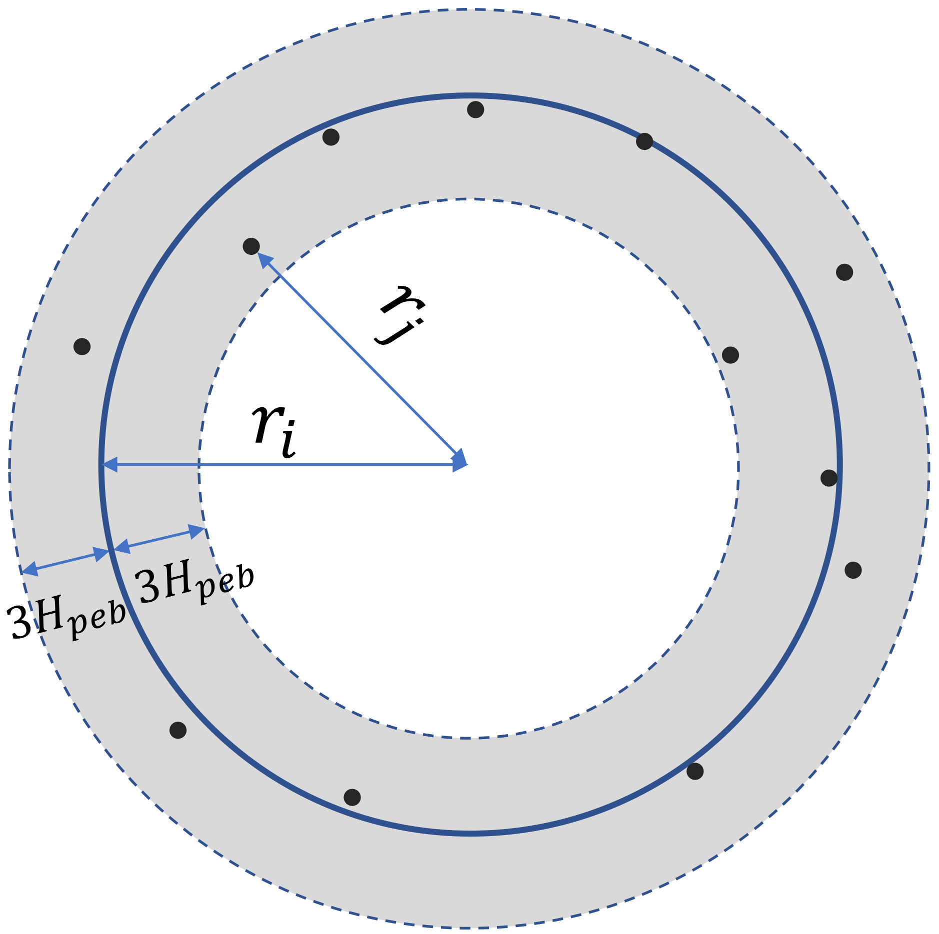
$$\Sigma_{peb}(r_i) \equiv \frac{1}{2\pi r_i}\sum_j m_{peb,j} W(|r_i - r_j|, H_{peb,r_i})$$

$$W(|r_i - r_j|, H_{peb,r_i}) = \frac{1}{\sqrt{\pi}H_{peb,r_i}} \exp\left[-\left(\frac{r_i - r_j}{H_{peb,r_i}}\right)^2\right]$$

  - $j \in$ all particles in grey area
  - H_{peb,r_i} given by Youdin & Lithwick +07
- The pebble particle mass is then replaced by a planetesimal particle mass if condition is satisfied

$$m_{pls} = \chi_{SI} m_{peb},\ \chi_{SI} = \epsilon_{SI}\Delta t/\tau_{SI}$$

- Planetesimals are merged if they are too close

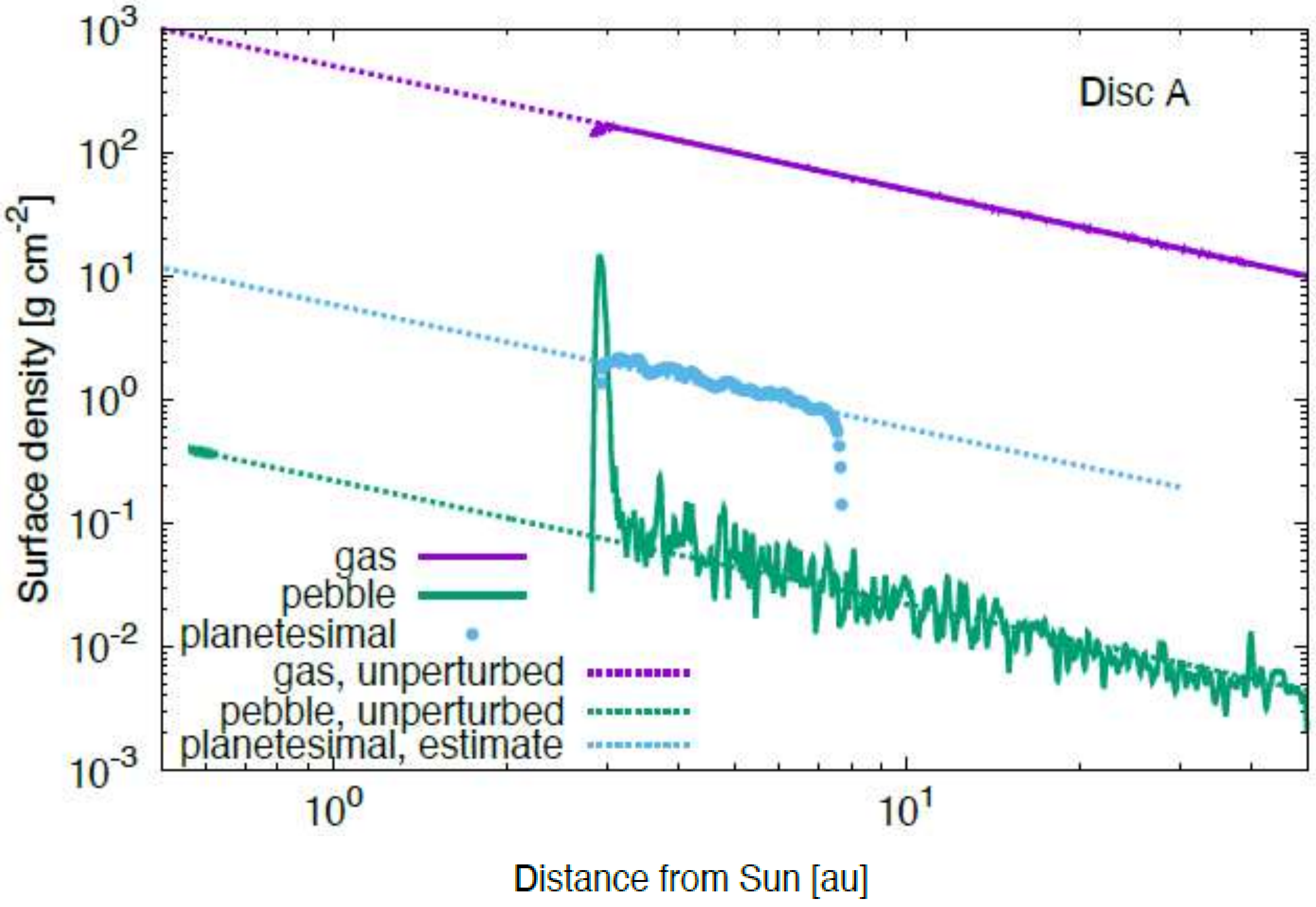


Results

- **A snapshot**: Gas, pebble and planetesimal surface density at 0.38 Myr, $\dot{M}_{peb} = 10^{-4} M_E yr^{-1}$
- Reference profile

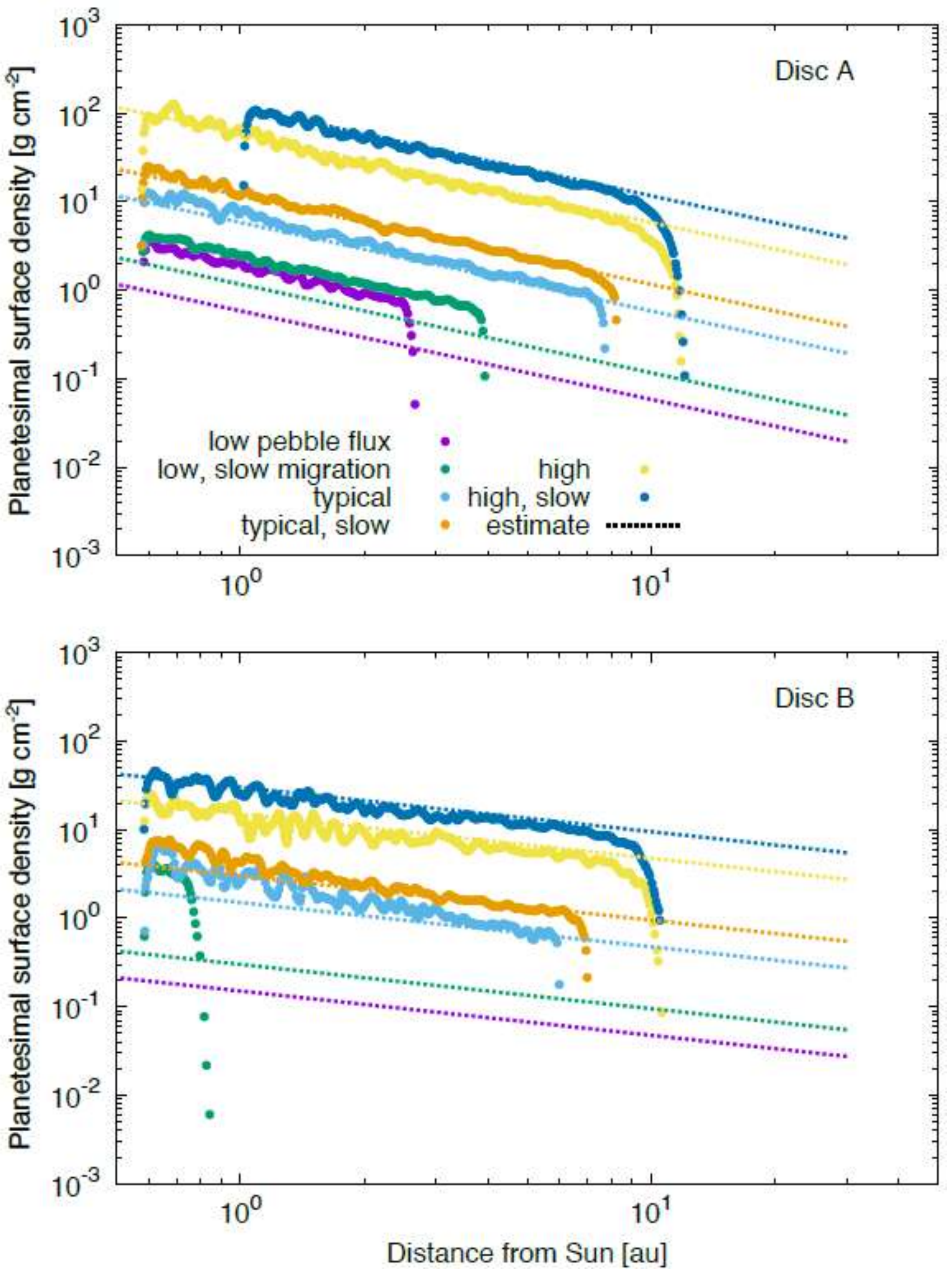
$$\Sigma_{\rm peb,unp} = \frac{\dot{M}_{\rm peb}}{2\pi r v_{\rm drift,unp}}$$

$$\Sigma_{\rm pls,est} \equiv \frac{\dot{M}_{\rm peb}}{2\pi r v_{\rm mig}}$$



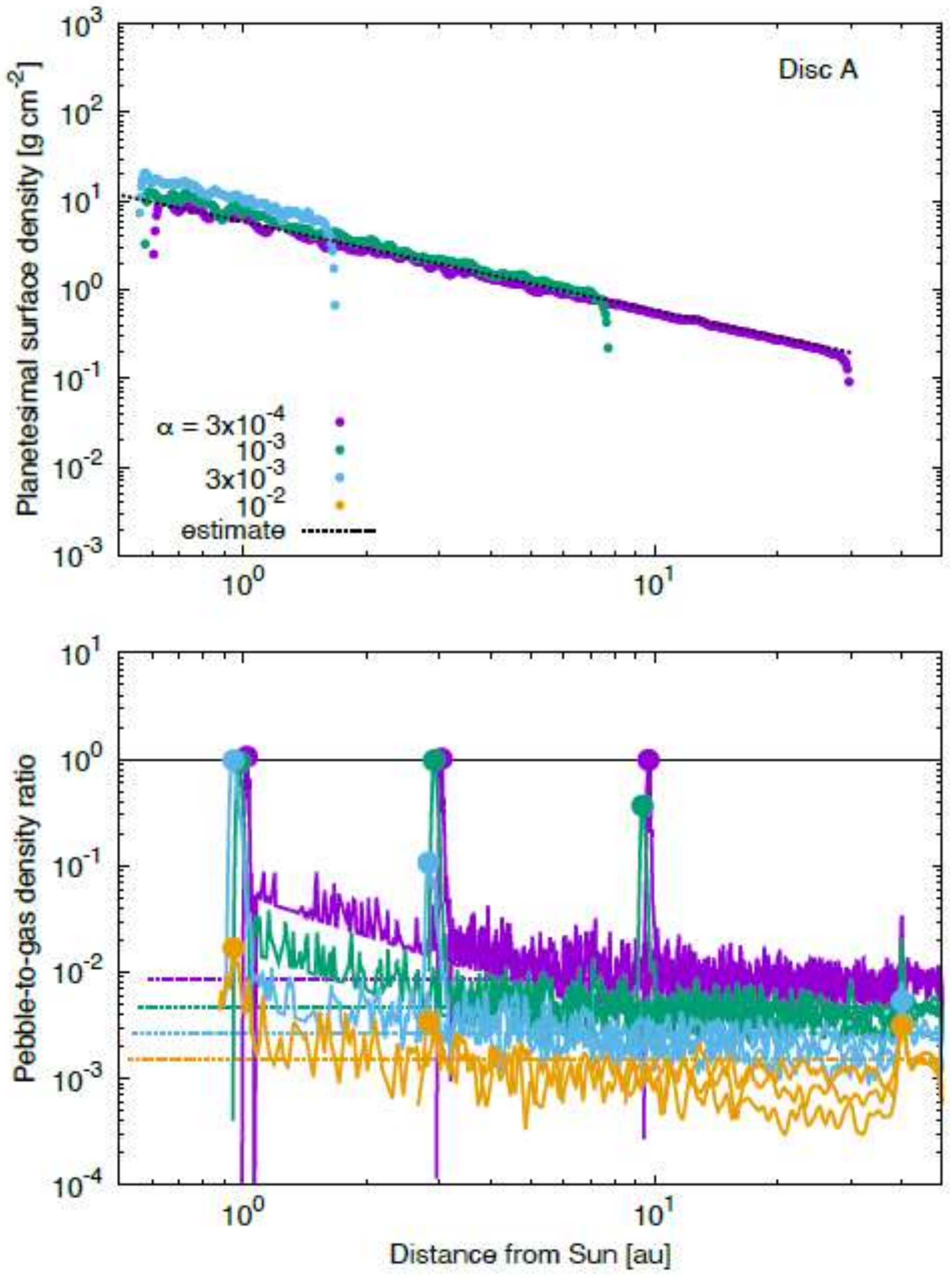
Results

- **Planetesimal surface density**
  - Typical/Low $\dot{M}_{peb} \rightarrow 10^{-4}/10^{-5} M_{\oplus} yr^{-1}$
  - Slow mig→ half speed
- Planetesimals form in wide regions of the discs, except for one case
- Profile well approximated by $\Sigma_{pls,est}$
  → All pebbles near the planet become planetesimal→ quasi-static



Parameter study

- **Three parameters varied:**
  - Strength of turbulence: α viscosity
    - Stronger turbulence → stronger diffusion → harder to achieve high pebble-to-gas ratio → formation condition harder to meet
    - $\alpha = 10^{-2}$ → no planetesimals
  - Mass of protoplanetary disks
    - 10 times heavier gas disk A' → higher $\dot{M}_{peb}$ required to produce planetesimals
  - Timescale of streaming instability(not sensitive)



Dependence on turbulence

Parameter study

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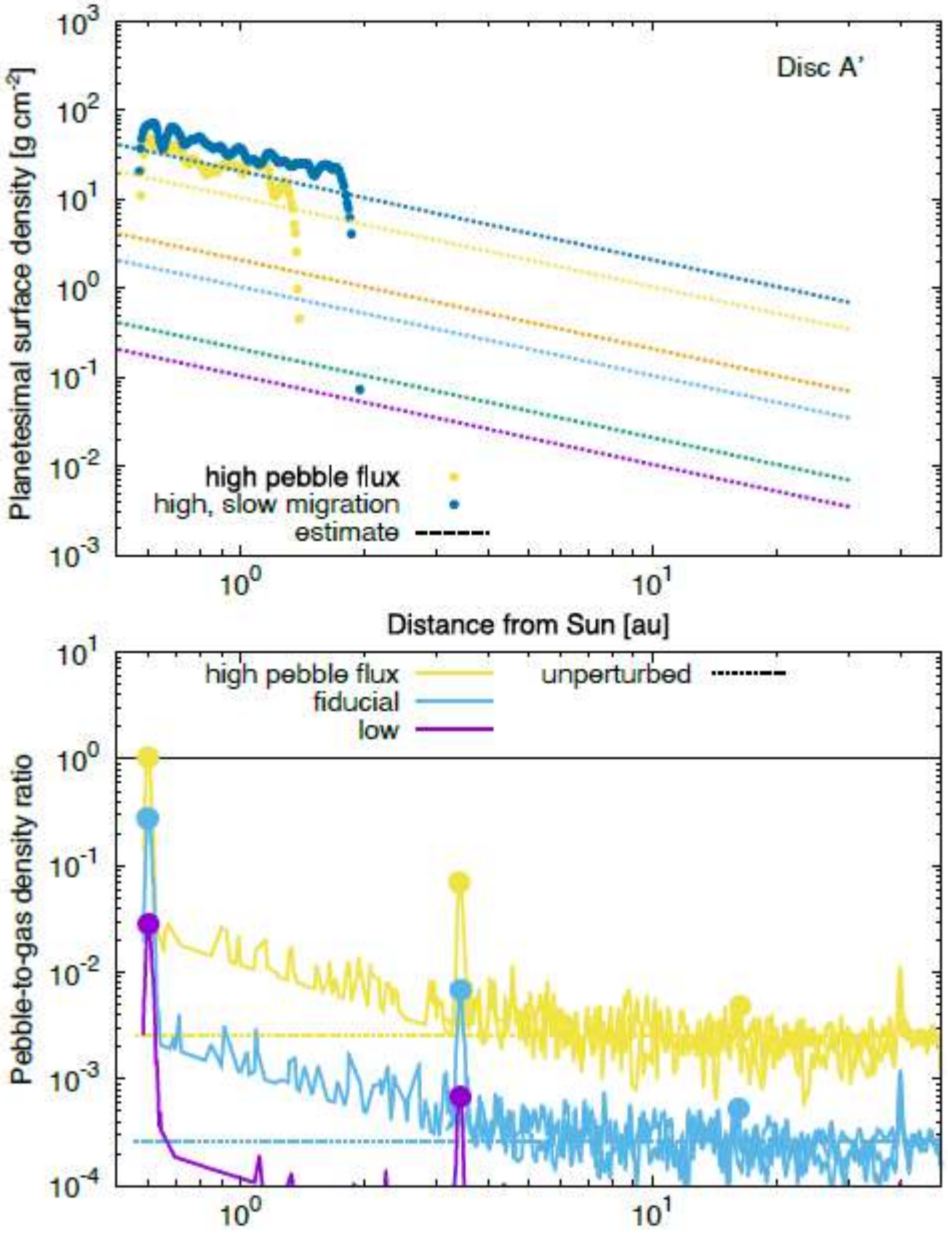


10 times heavier disk

Discussions and future work

- **Compare with population synthesis work**
  - Outer boundary of planetesimals depends on thermal structure of the disk
    → planetesimals do not always spread to outermost region of the disk
    → different from what assumed by population synthesis
  - Total mass of the planetesimals are different from population synthesis model
    → need to address detailed pebble growth scheme & planet accretion → Paper II

- **Planetary mass can significantly change the results**
  - Heavier planet can carve a deeper gap → easier to trap planetesimals
  - Type II migration → slower migration speed → higher surface density of planetesimals

[P2] Kepler-419 system

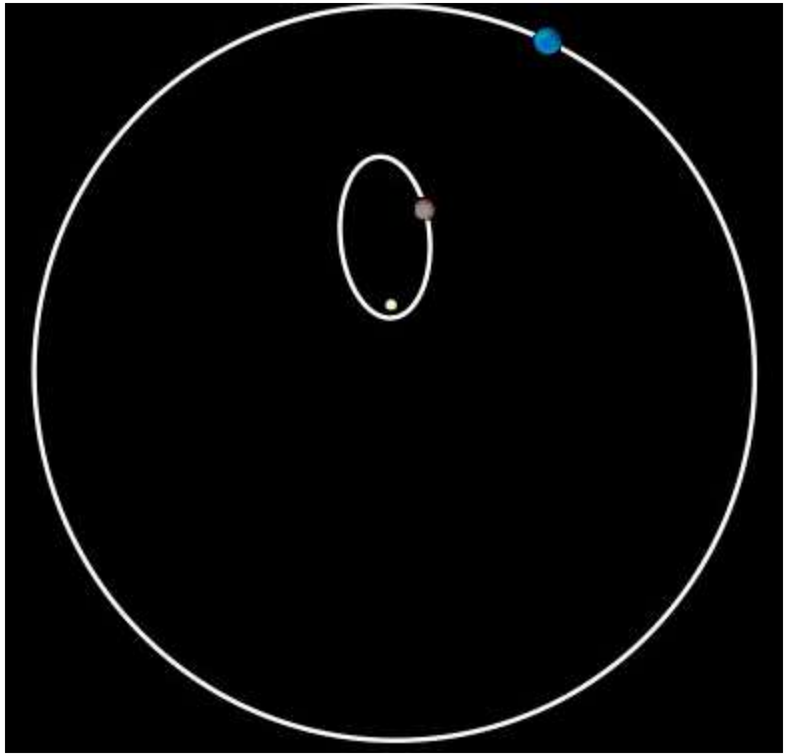
- "A perculiar system hosting two gas gaints"

Table 1
Parameters of Kepler-419 Planets

	Planet b	Planet c
Mass m (M_J)	2.77 ± 0.19	7.65 ± 0.27
Semimajor axis a (au)	0.3745 ± 0.0046	1.697 ± 0.02
Eccentricity e	0.817 ± 0.016	0.1793 ± 0.0017
Inclination i (deg)	87.04 ± 0.72	87 ± 2
Arg. of pericenter ω (deg)	94 ± 2.2	275.7 ± 1.8
Long. asc. node Ω (deg)	180 (fixed)	185.4 ± 7.6

Petrovich+19

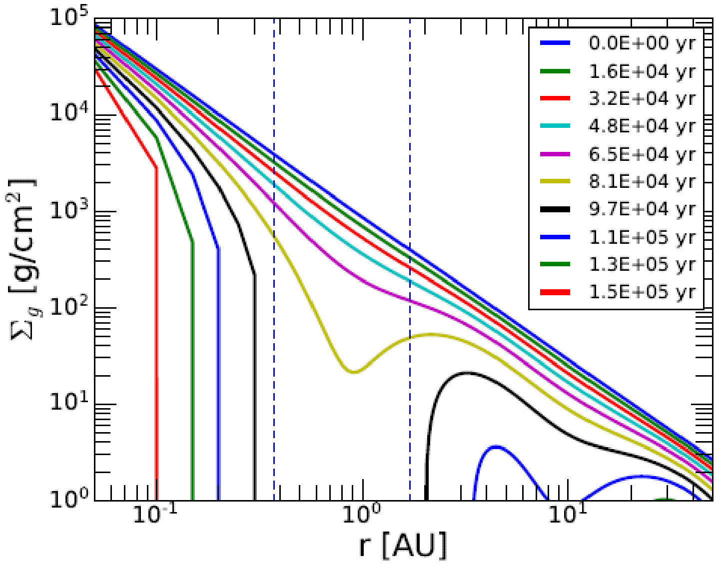
  - $\bar{\omega}_b - \bar{\omega}_c \sim 180^\circ$ → apsidally anti-aligned orbits
- Explanation by Petrovich, Wu & Ali-Dib (2019): planets initially inside the inner gap(hole) of a slowly dissipating massive disk → force the apses to anti-align
  - Initial angular momentum deficit(AMD) of planet c due to **planet-disk interaction** → transfer to planet b
- This paper:
  - Verify the results of PWA+19 as an extension work
  - Constrain & study the disk parameters

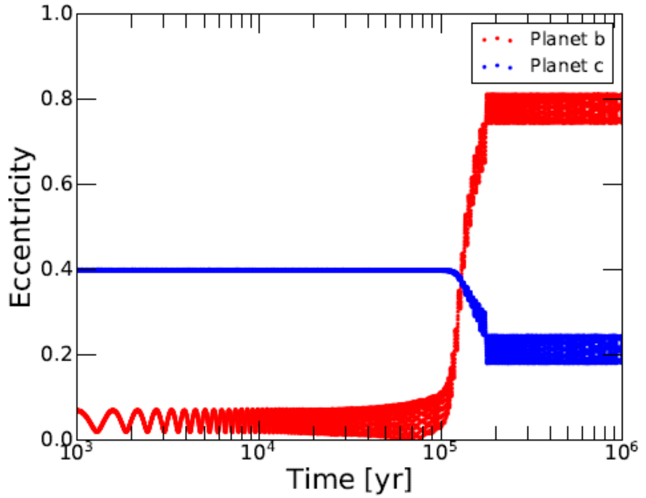


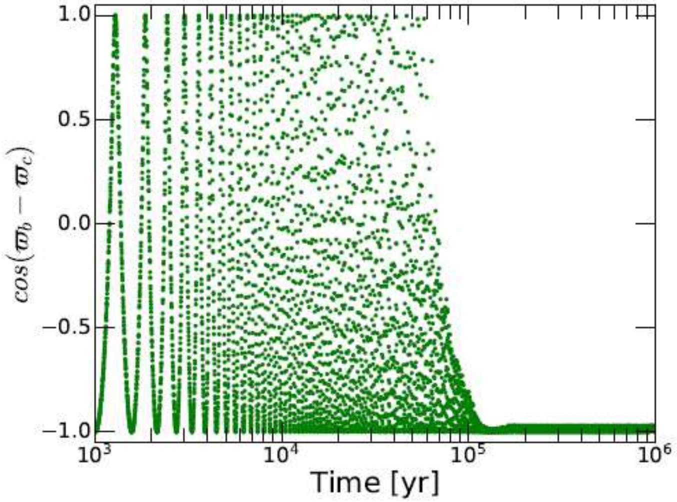
Configuration of Kepler-419 system
Credit: allplanets.ru

Numerical Setup

- Two dimension N-body simulations
  - REBOUND & REBOUNDx
  - Simulation time: 6 Myr
  - Disk potential → radial acceleration
- Initial conditions
  - Stellar mass: $1.39M_\odot$
  - Two planets: SMA $0.374/1.697\ au$, $2.77M_J/7.65M_J$, ini ecc $0.05/0.4$, $\omega_b - \omega_c = 60^\circ$
- Disk profile
  - Initial mass $10M_J$
  - $\Sigma(R) = \Sigma_0 \left(\frac{\mathrm{r}}{\mathrm{r_{in}}}\right)^{-\gamma}$, $r_{in} = 0.05$, $\gamma = -1.5$, outer edge = $50au$
  - Photoevaporation rates adopted from Owen+12; (hydro fitting results)
- Fiducial result

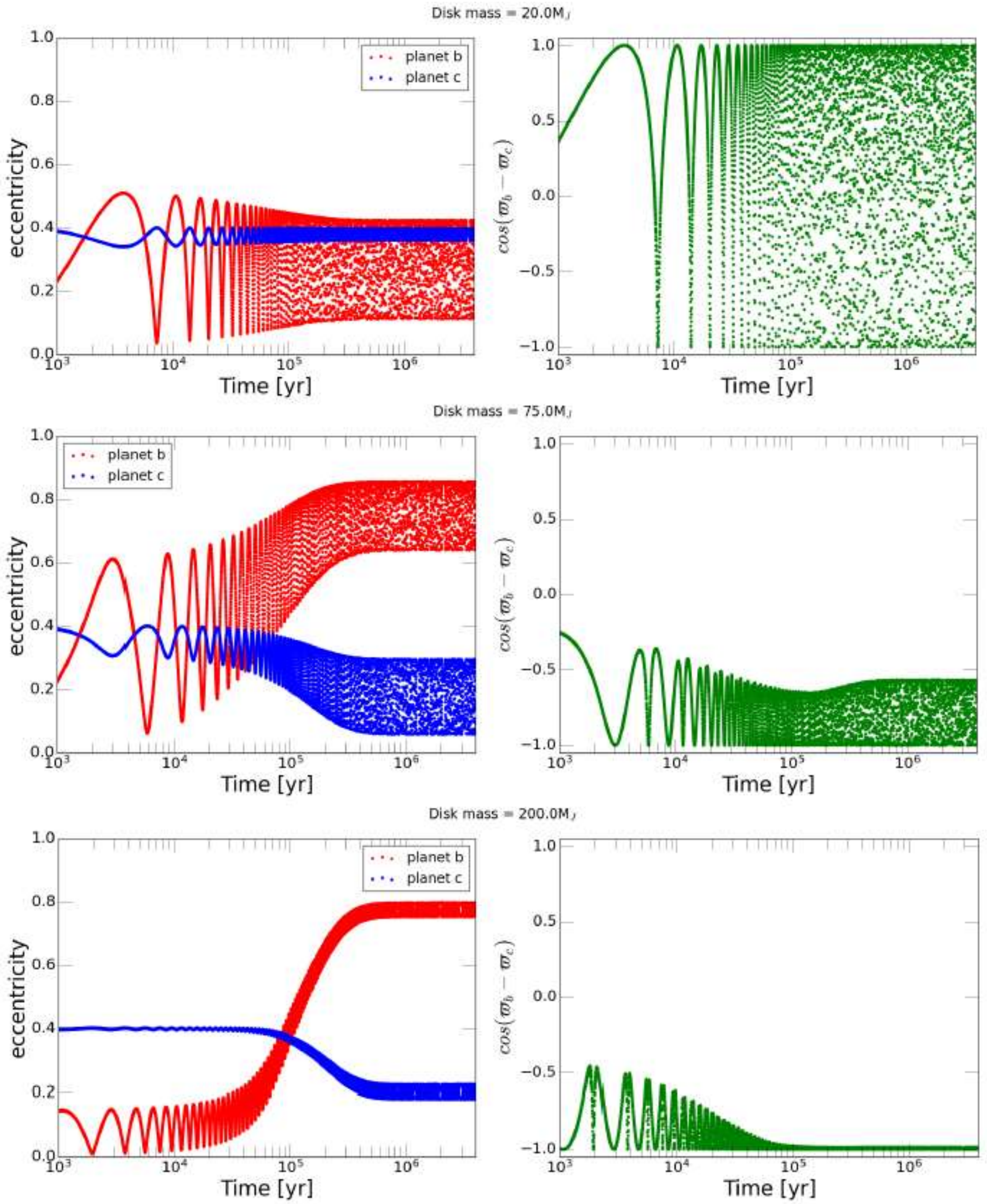






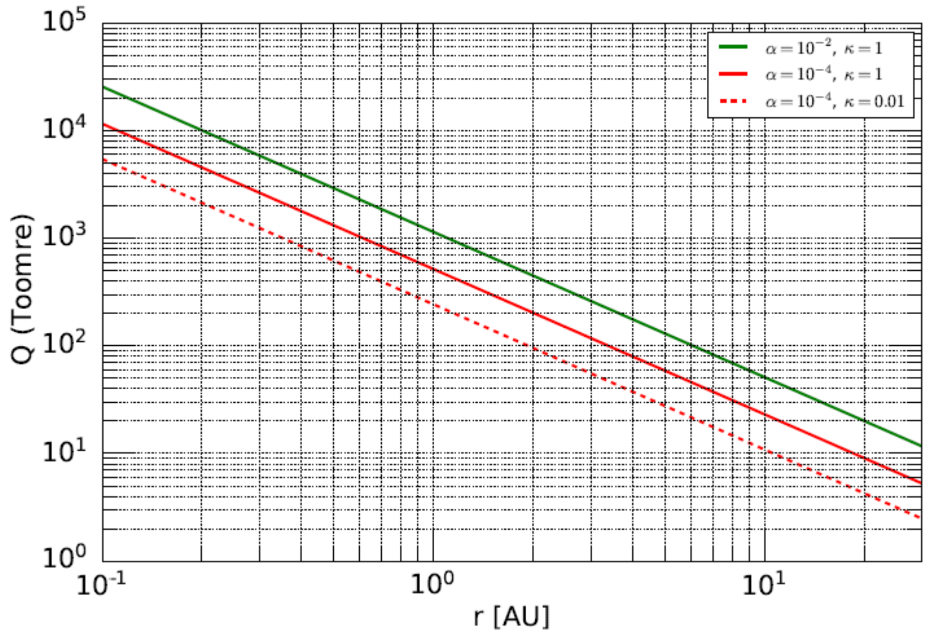
Parameter study

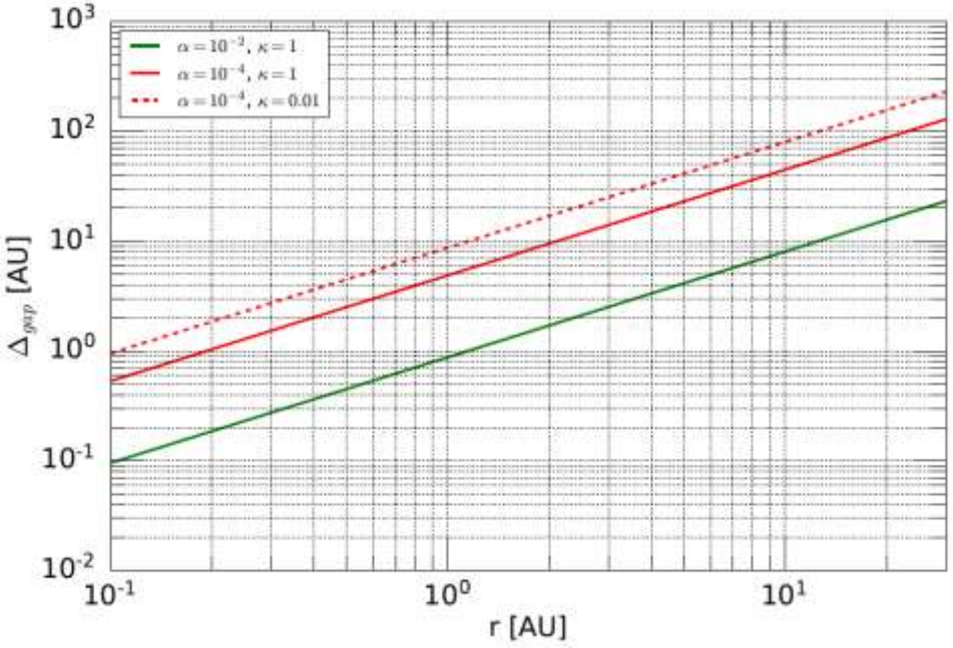
- Now switch to simplified disk decay model:
  $M_{disk} = M_{disk}^{t0} \exp(-t/\tau_d)$
- Varying two parameters: Disk mass and disk's dispersal time scale
  - Mass: 1,20,40,50,75,100,200 M_J
  - τ_d: $10^4, 10^5, 10^6$ year
- Results
  - $M_{Disk} \leq 20\ M_J$(not recover): disk-planet interaction too weak, nearly three body problem
  - $M \sim 40 - 50\ M_J$(not consistent): oscillates with large amplitude
  - Larger mass(recover): libration around anti-alignment, AMD transferred from c to b
  - All disk dispersal time lead to similar results



Is the required disk realistic?

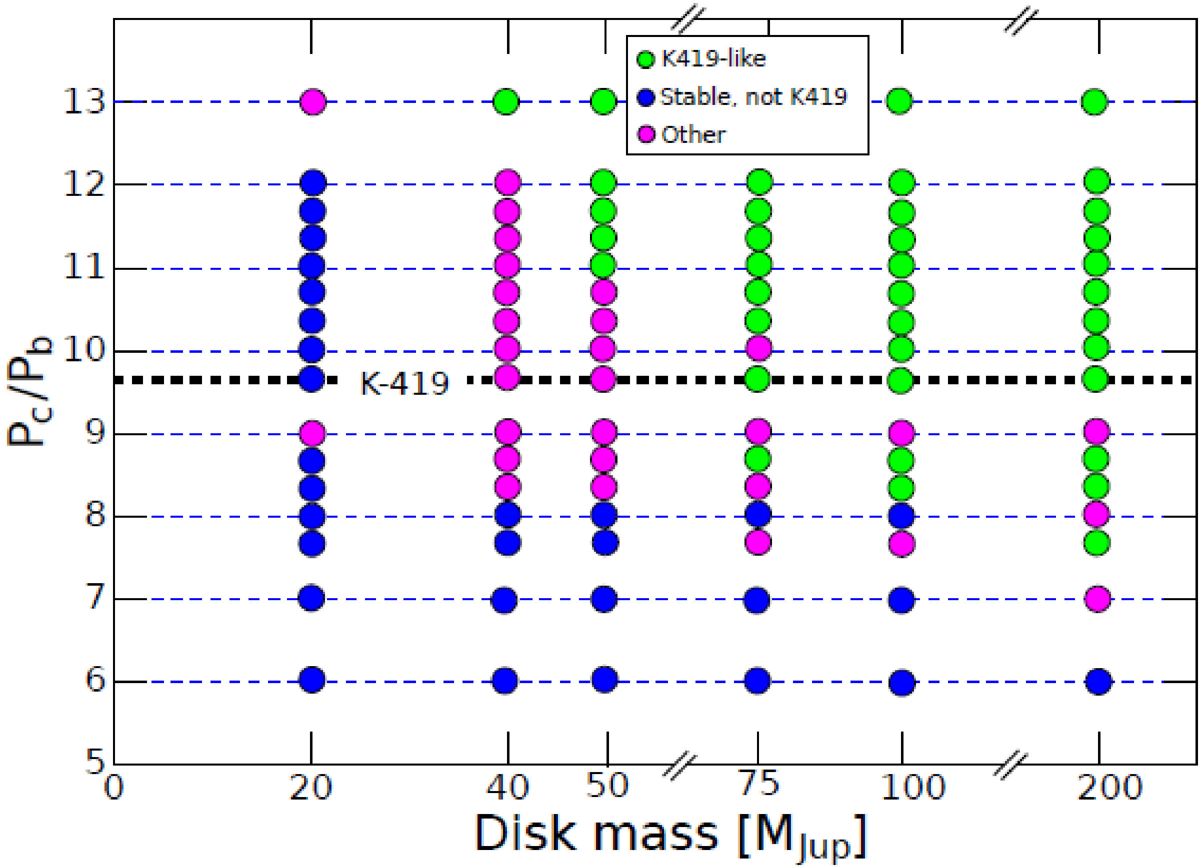
- Disk mass $\geq 75\ M_j$. **Any observational counterparts?**
  - GM Aur and DM Tau, possibly TW Hya($50M_J$)
  - Transition disks: $7\% \geq 100\ M_J$
- **Is the disk gravitationally stable?**
  - Toomre Q value(< 1 means unstable)
  - Everywhere in the planet forming region(<30au) is stable
  - Suggest planets are formed via core acc
- **Can planets open gaps?**
  - Both of the planets can open gaps
  - Gaps will merge to a common gap, even for large α case





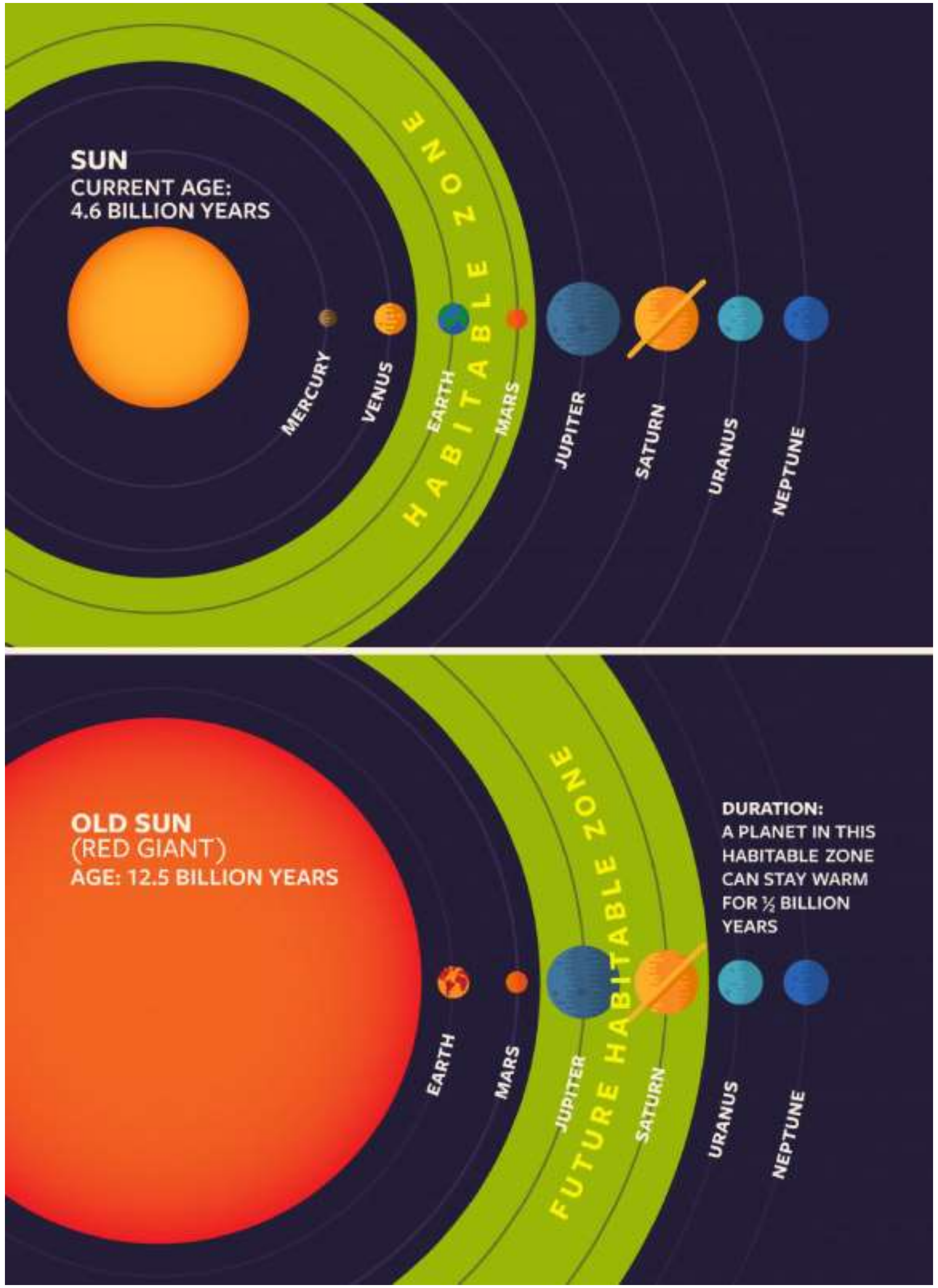
Sensitivity to Planet c

- If Kepler-419 formed by accretion + migration, the assumed architecture is fine-tuned?
  - Need to consider alternative positions of planet c
- Vary the orbits of planet c
  - Fiducial: $P_c = 9.6\ P_b$
  - Survey range $6 - 13\ P_b$
  - $\tau_d = 10^5$yr, and same range of disk mass
- Results
  - **BLUE:** stable, but trapped in other MMR(6:1, 7:1, 8:1)
  - **Pink:** Plethora of behaviours; dynamically noisy
  - **Green:** Kepler-419 like system
  - Conclusion:
    - Higher order MMR does not trap plaents to become K-419-like systems → such system can be more common than expected



[P3] Apocalyptic fate of planets

- The sun will eventually become a red giant with $R \sim$ earth orbit, and then white dwarf.
  - Inner planets < 1au: engulfed and vaporized.
  - But how about outer planets around 1-10 au?
- Observation
  - > 100 gas giants are discovered around red giants
  - Clues show planets(or debris) exist around white dwarfs: metal absorption lines
- Need to model planetary systems beyond main sequence
  - Previous studies: only concern about the surviving condition of a **single planet**
  - **This work:** two planets, one inner Neptune and one outer Jupiter, with stellar mass loss, stellar tides, and mutual gravitational interactions



Credit: Cornell University

Model

- Change of semi-major axis

$$\left(\frac{\dot{a}}{a}\right) = -\left(\frac{\dot{M}_{\star}}{M_{\star}+M_{\mathrm{p}}}\right) - \left(\frac{\dot{a}}{a}\right)_{\mathrm{t}}$$

Typo

Tidal

Mass loss

  - Stellar tides

$$\left(\frac{\dot{a}}{a}\right)_{\mathrm{t}} = -\frac{1}{9\tau_{\mathrm{conv}}}\frac{M_{\star}^{\mathrm{env}}}{M_{\star}}\frac{M_{\mathrm{p}}}{M_{\star}}\left(1+\frac{M_{\mathrm{p}}}{M_{\star}}\right)\left(\frac{R_{\star}}{a}\right)^{8} \times\left[2p_2 + e^2\left(\frac{7}{8}p_1 - 10p_2 + \frac{441}{8}p_3\right)\right]$$

$$p_i \approx \frac{9}{2}\min\left[1, \left(\frac{4\pi^2 a^3}{i^2 G(M_{\star}+M_{\mathrm{p}})\tau_{\mathrm{conv}}^2}\right)\right], i = 1, 2, 3.$$

M_{*}^{env}: envelope mass
τ_{conv}: eddy turnover timescale
P_i: frequency components

- Eccentricity damping

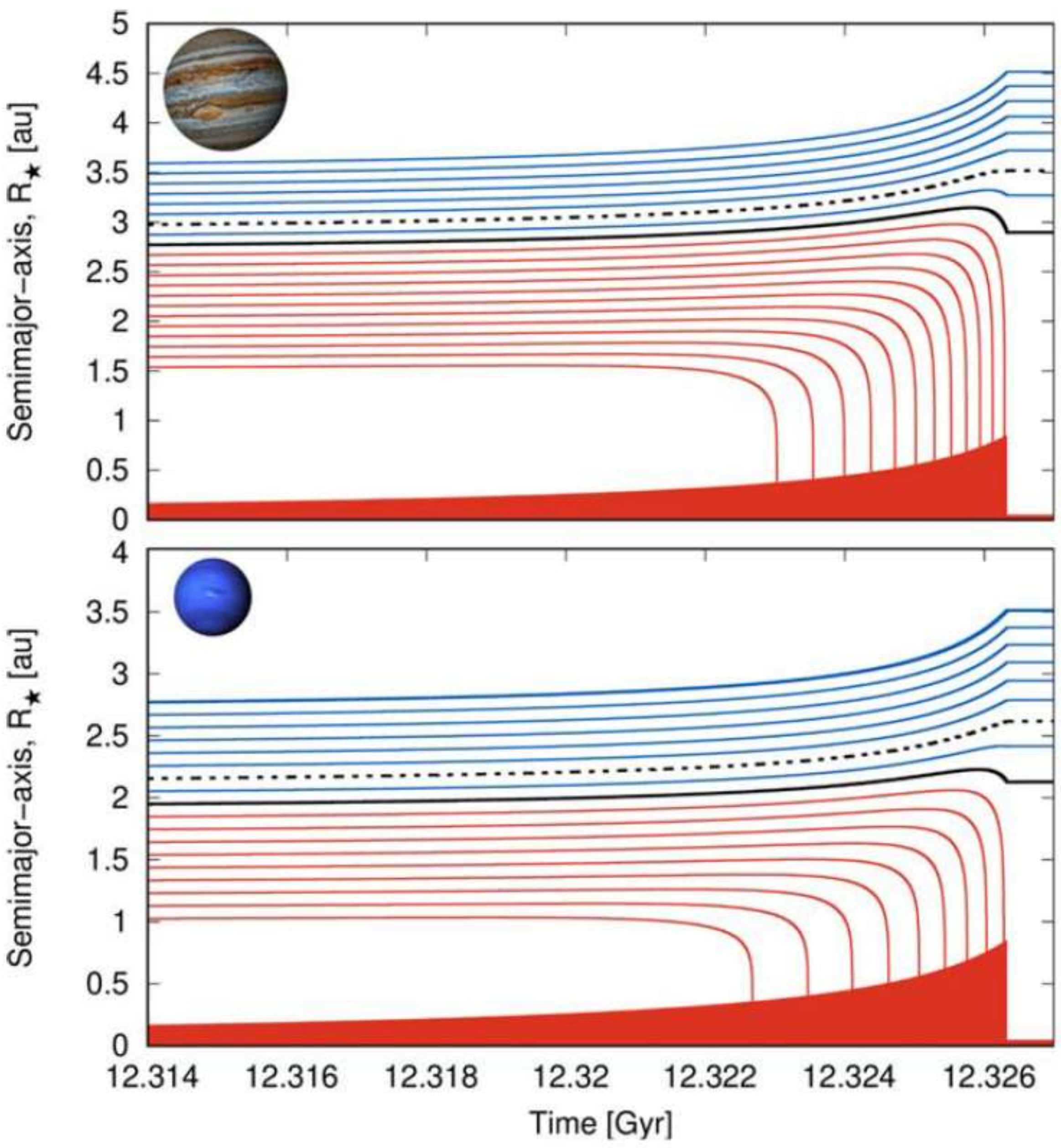
$$\left(\frac{\dot{e}}{e}\right)_{\mathrm{t}} = -\frac{1}{36\tau_{\mathrm{conv}}}\frac{M_{\star}^{\mathrm{env}}}{M_{\star}}\frac{M_{\mathrm{p}}}{M_{\star}}\left(1+\frac{M_{\mathrm{p}}}{M_{\star}}\right)\left(\frac{R_{\star}}{a}\right)^{8} \times\left[\frac{5}{4}p_1 - 2p_2 + \frac{147}{4}p_3\right].$$

- Stellar evolution code SSE
  - Stellar mass = $1M_{\odot}$, $Z = 0.02$
  - Evolution track will give out $M_{*}, R_{*}, M_{*}^{env}, R_{*}^{env}, L_{*}$

Evolution of single planets

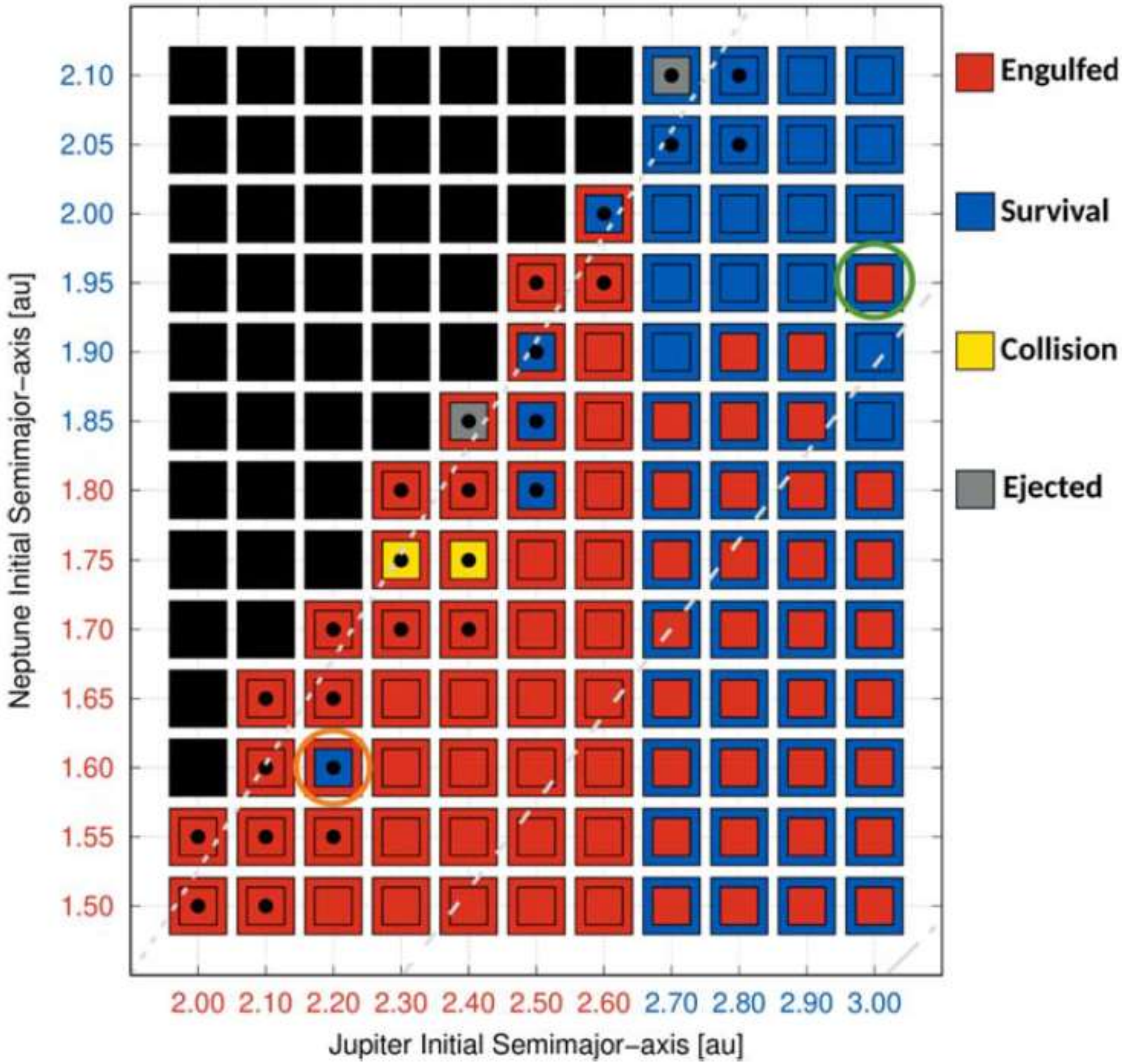
- Initial position
  - Jupiter: $1.5 - 3.5\ au$
  - Neptune: $1.0 \ - 2.7\ au$
- Survival conditions
  - Jupiter $\geq 2.7\ au$
  - Neptune $\geq$ 1.9 au

  → agree with most of the previous studies



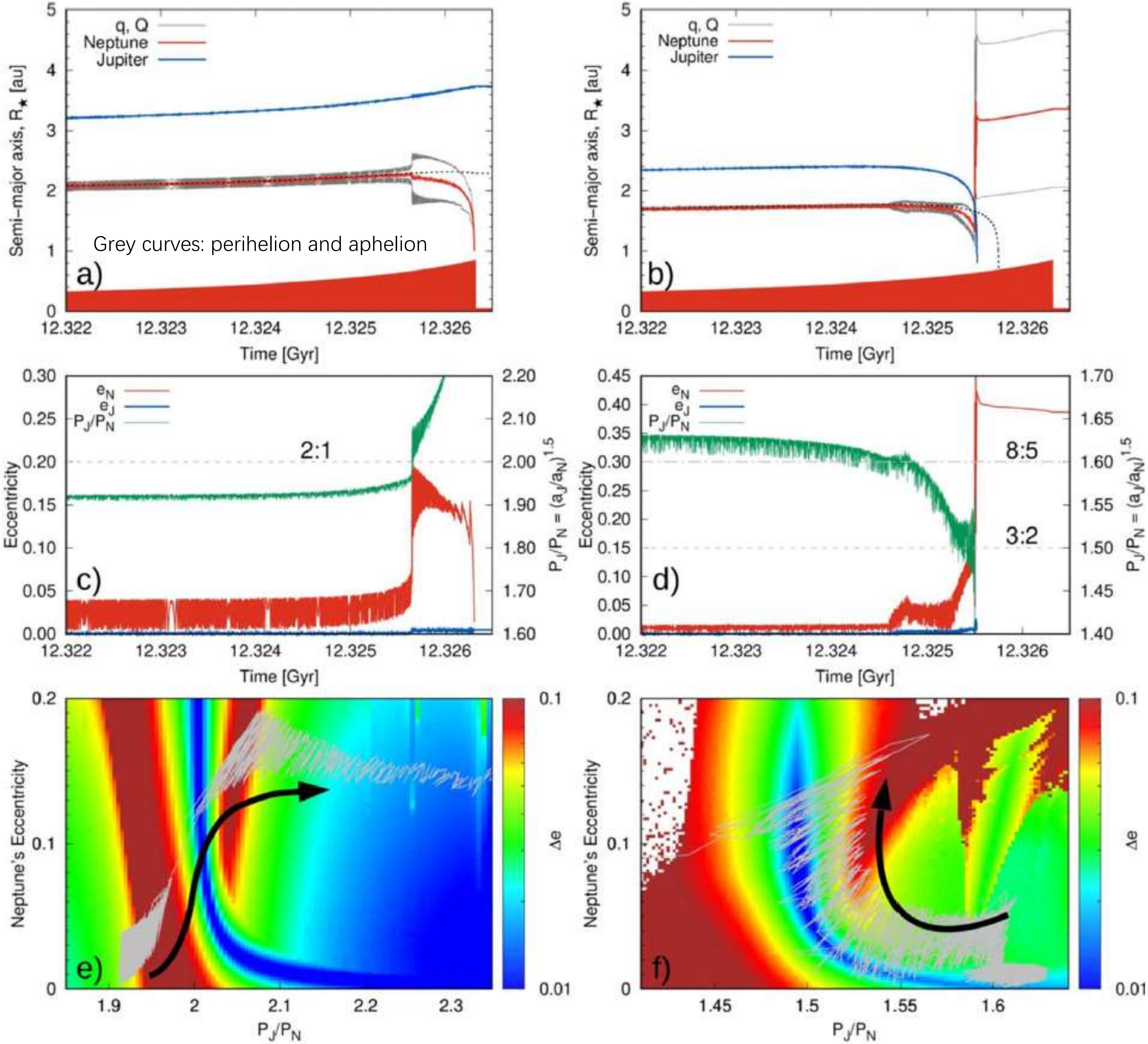
Multi-planetary case

- Integration time: 750 Myr, starting from 11.6 Gyr
- Final fate of the planets
  - Large square: Jupiter
  - Small square: Neptune
  - Black dot: close encounter 3H
  - Yellow: collision
  - Dashed lines: 2:1 & 3:2 MMR
  - Filled black: unstable
- Majority of the Neptunes are engulfec
- Two cases: fates are changed!
  - Orange: although $a_{nep} < 1.9$, the Neptune survives
  - Green: although $a_{nep} > 1.9$, the Neptune is engulfed



Two cases in details

- Left: "Destroyer" case
  - Jup: 3.0 au, Nep:1.95 au
  - Divergent migration: P ratio increases→ instability happens when 2:1 resonance is crossed
  - Sudden increase e_{Nep} → Perihelion distance shrinks → tides more effective
- Right: "Savior" case
  - Jup: 2.2 au, Nep: 1.6 au
  - Convergent: P ratio decreases→ Jupiter falls in, with Neptune scattered out
- Bottom are dynamical maps:
  - 100x100 grid
  - Integrated to 10^4 year



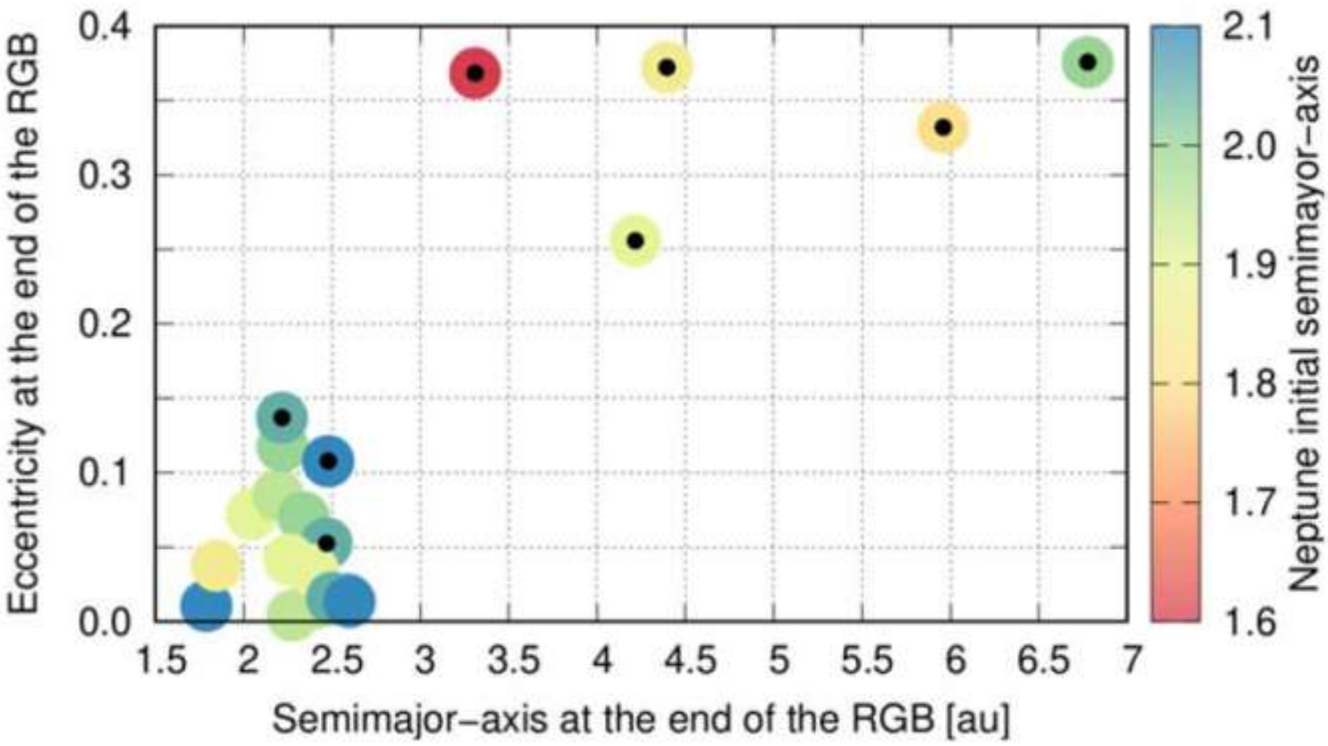
Survivors

- Two groups of the Neptunes can survive:
  - High eccentricity with significant scattering(like the example case)
  - Low eccentricity, relatively large initial SMA

Implications

- A significant fraction of the planetary systems around white dwarfs might be shaped by gravitational interactions, particularly resonance

- Planets in such eccentric orbits can scatter planetesimals/asteroids → metal pollution



*Black dots means the Neptune has undergone significant close encounter with the Jupiter