How Jupiter and Saturn's secular architecture constrains their early orbital evolution

2020 DPS Meeting

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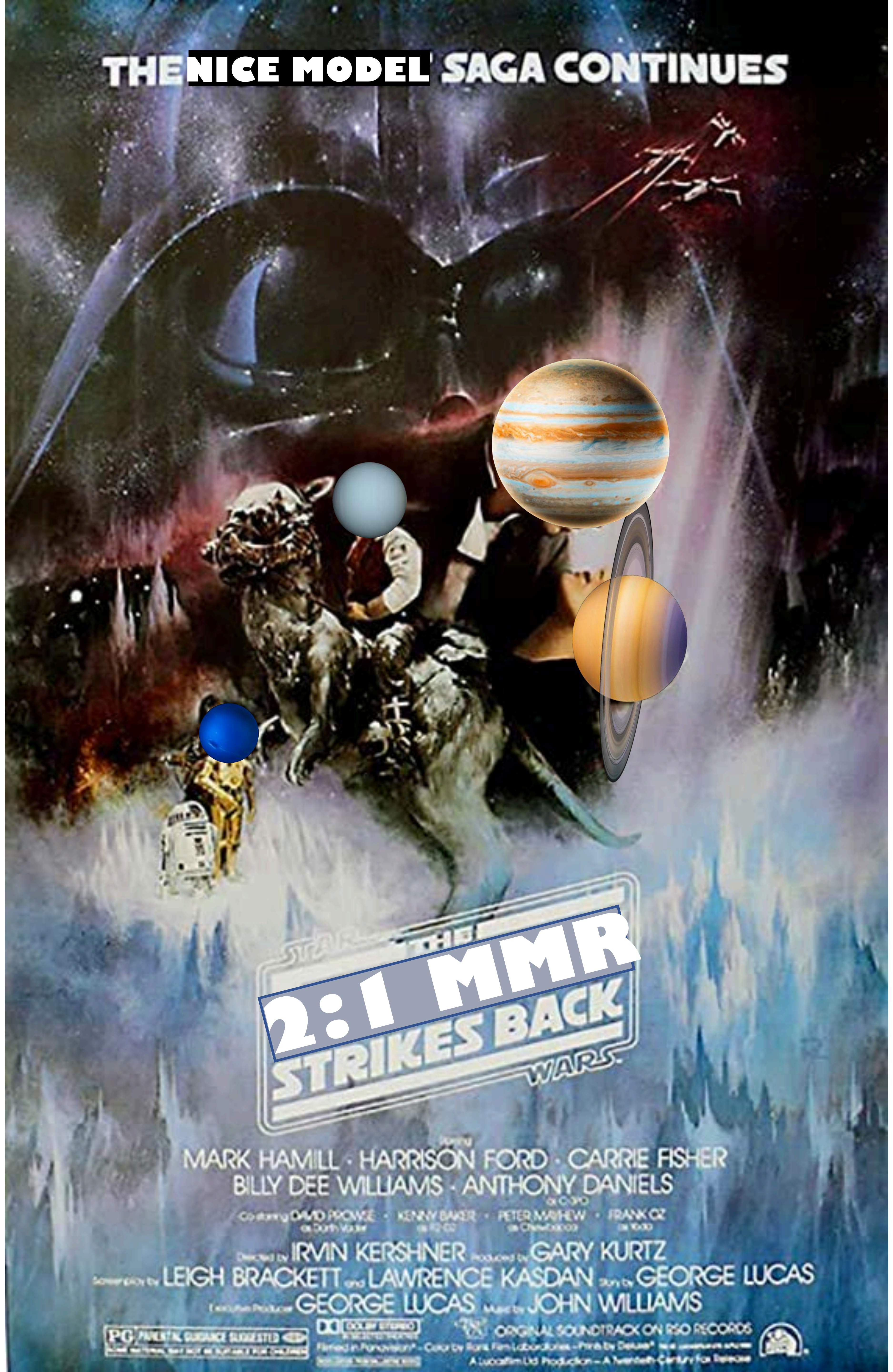

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Constraining the primordial outer solar system's structure:

- **How did we go from this:**

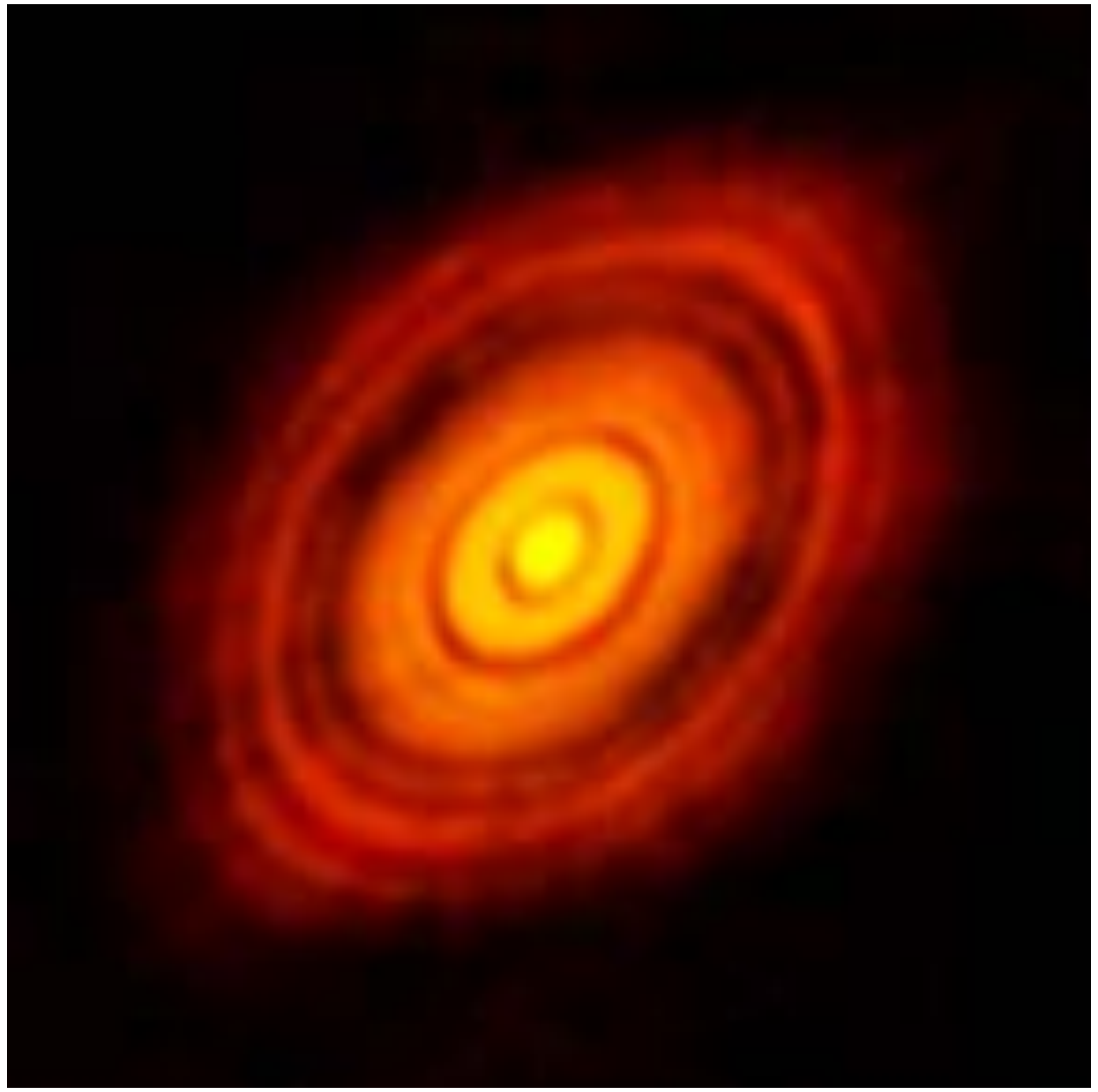
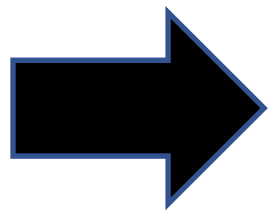
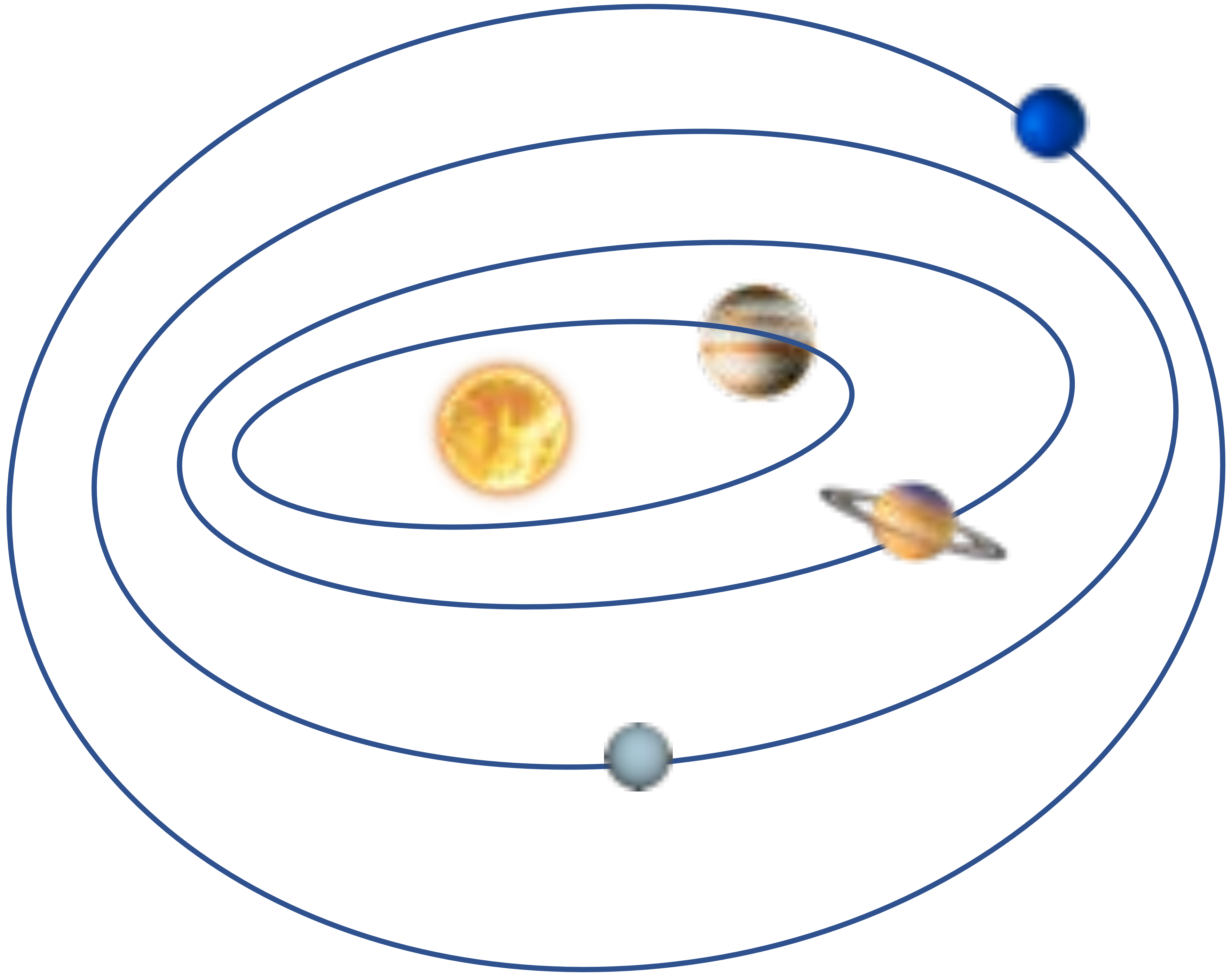


Image Credit: *ALMA (SO/NAOJ/NRAO*



- **To this?**



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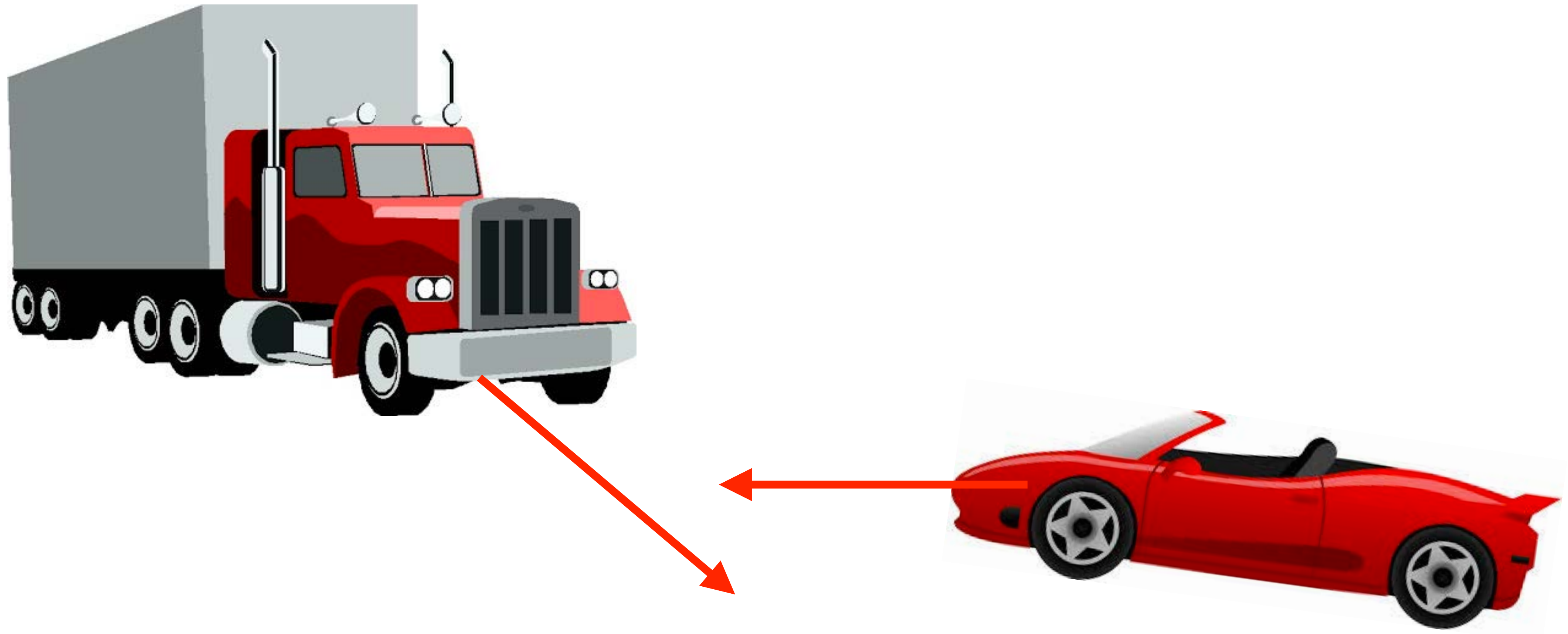
Constraining the primordial outer solar system's structure: Reconstructing a car crash

- **We know the outcome:**

Image Credit: ABC news

- **But what exactly happened?**
  - How fast were the cars going
  - In what directions
  - Who was at fault



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Constraining the primordial outer solar system's structure:

- **Hydrodynamical models can tell us something about the plausible planet birth locations**
  - e.g.: Masset & Snellgrove 2001; Morbidelli et al., 2007; Moridelli & Crida 2007; Pierens & Nelson 2008

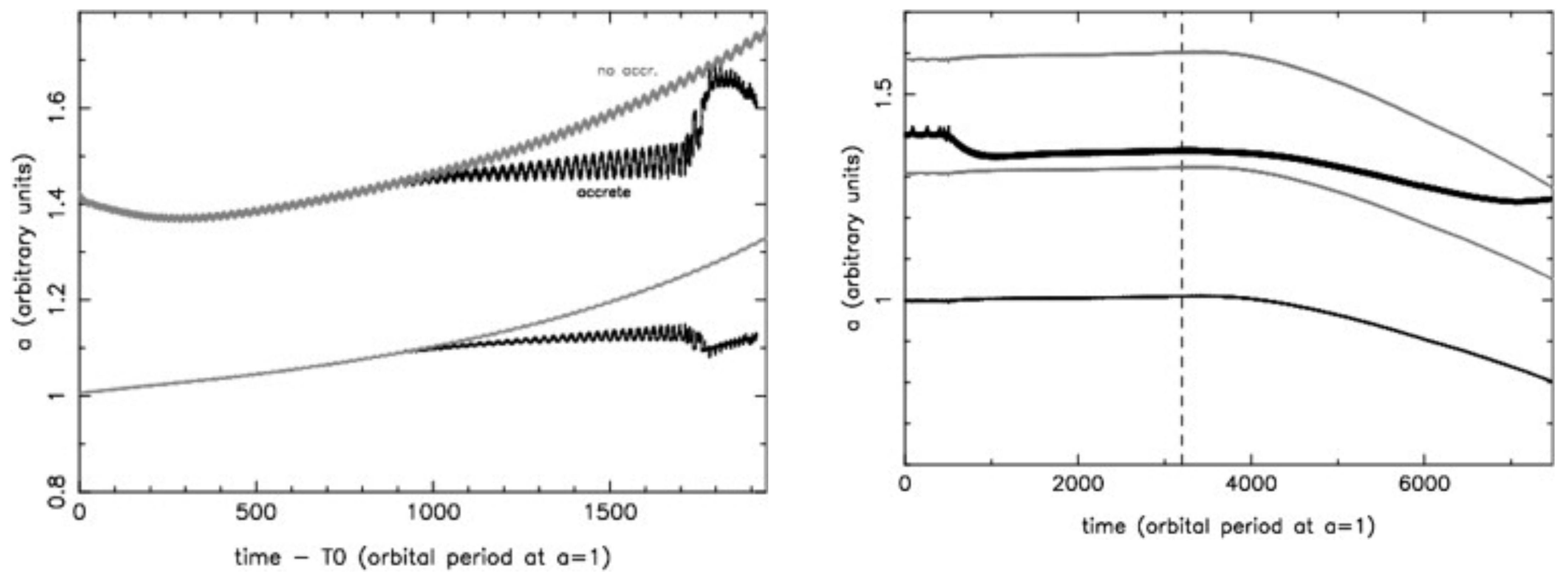

Fig Credit: Morbidelli et al 2007

- **Large statistical studies of dynamical simulations can tell us which ones work best.**
  - e.g.: Batygin & Brown 2010; Nesvorny 2011; Nesvorny & Morbidelli 2012; Deienno et al., 2017

Table 7
The Results of Selected Six-planet Models

M_{disk} (M_{Earth})	Δ (AU)	r_{out} (AU)	$B(j)$	N_{sim}	A (%)	B (%)	C (%)	D (%)
(3:2, 3:2, 3:2, 4:3, 3:2), $a_6 = 20.4$ AU								
20	1.0	30	1	30	23	7	3	7
35	1.0	30	1	30	40	0	0	0
(3:2, 4:3, 3:2, 3:2, 3:2), $a_6 = 20.6$ AU								
20	1.0	30	1	100	30	10	3	3
35	1.0	30	1	30	42	8	0	3
(2:1, 3:2, 4:3, 3:2, 3:2), $a_6 = 24.2$ AU								
10	1.0	30	1	30	69	25	6	6
20	1.0	30	1	30	44	28	3	20
(2:1, 3:2, 4:3, 3:2, 3:2), $a_6 = 24.9$ AU								
20	1.0	30	1	30	31	12	3	7

Table Credit: Nesvorny & Morbidelli 2012

Table 6
The Results of Selected Five-planet Models

M_{disk} (M_{Earth})	Δ (AU)	r_{out} (AU)	$B(j)$	N_{sim}	A (%)	B (%)	C (%)	D (%)
(3:2, 3:2, 4:3, 5:4), $a_5 = 13.9$ AU								
35	1.0	30	1	30	13	3	0	3
50	1.0	30	1	30	37	23	0	0
50	3.5	30	1	30	23	10	0	3
(3:2, 3:2, 3:2, 3:2), $a_5 = 16.1$ AU								
35	1.5	30	0	30	23	3	0	3
35	1.5	30	1	100	33	16	4	8
50	1.5	30	1	100	30	17	0	3
(3:2, 3:2, 4:3, 4:3), $a_5 = 14.5$ AU								
50	1.0	30	1	30	47	23	3	3
(3:2, 3:2, 2:1, 3:2), $a_5 = 22.2$ AU								
20	1.0	30	0	30	33	13	7	3
20	1.0	30	1	30	30	10	7	7
35	1.0	30	1	30	33	17	0	10
(3:2, 3:2, 2:1, 2:1), $a_5 = 24.5$ AU								
35	1.0	30	0	30	43	17	7	7
35	1.0	30	1	30	23	13	3	3
35	2.0	30	1	30	30	23	3	3
35	3.0	30	1	100	44	19	3	3
(2:1, 3:2, 3:2, 3:2), $a_5 = 19.3$ AU								
20	1.0	30	1	30	53	36	3	20
35	1.0	30	1	30	53	43	0	17
(2:1, 4:3, 3:2, 3:2), $a_5 = 17.9$ AU								
20	1.0	30	1	30	67	42	0	17
20	3.5	30	1	30	75	25	0	20

Table 5
The Results of Selected Four-planet Models

M_{disk} (M_{Earth})	Δ (AU)	r_{out} (AU)	$B(j)$	N_{sim}	A (%)	B (%)	C (%)	D (%)
(3:2, 3:2, 4:3), $a_4 = 11.6$ AU								
35	0.5	30	0	30	13	0	0	0
35	1.0	30	1	30	13	0	0	0
50	0.5	30	0	30	37	10	0	0
50	1.0	30	1	100	27	11	1	0
50	3.5	30	1	30	13	3	0	0
50	5.0	30	1	30	10	3	0	0
75	1.0	26	1	30	67	40	0	0
100	1.0	25	1	30	80	27	0	0
(3:2, 3:2, 3:2), $a_4 = 12.3$ AU								
35	1.0	30	1	30	40	0	0	0
50	1.0	30	1	100	39	4	0	0
(3:2, 4:3, 3:2), $a_4 = 11.9$ AU								
35	1.0	30	1	30	7	3	3	0
50	1.0	30	1	30	10	3	0	0
(3:2, 2:1, 2:1), $a_4 = 18.9$ AU								
35	1.0	30	1	100	100	88	0	0
50	1.0	30	1	100	100	89	0	0
(3:2, 2:1, 3:2), $a_4 = 18.9$ AU								
35	1.0	30	1	30	0	0	0	0
50	1.0	30	1	30	0	0	0	0
(2:1, 3:2, 3:2), $a_4 = 14.8$ AU								
35	1.0	30	1	100	100	33	11	0
50	1.0	30	1	100	93	87	0	0
(2:1, 3:2, 4:3), $a_4 = 13.7$ AU								
35	1.0	30	1	100	63	13	0	0
50	1.0	30	1	100	100	50	0	0

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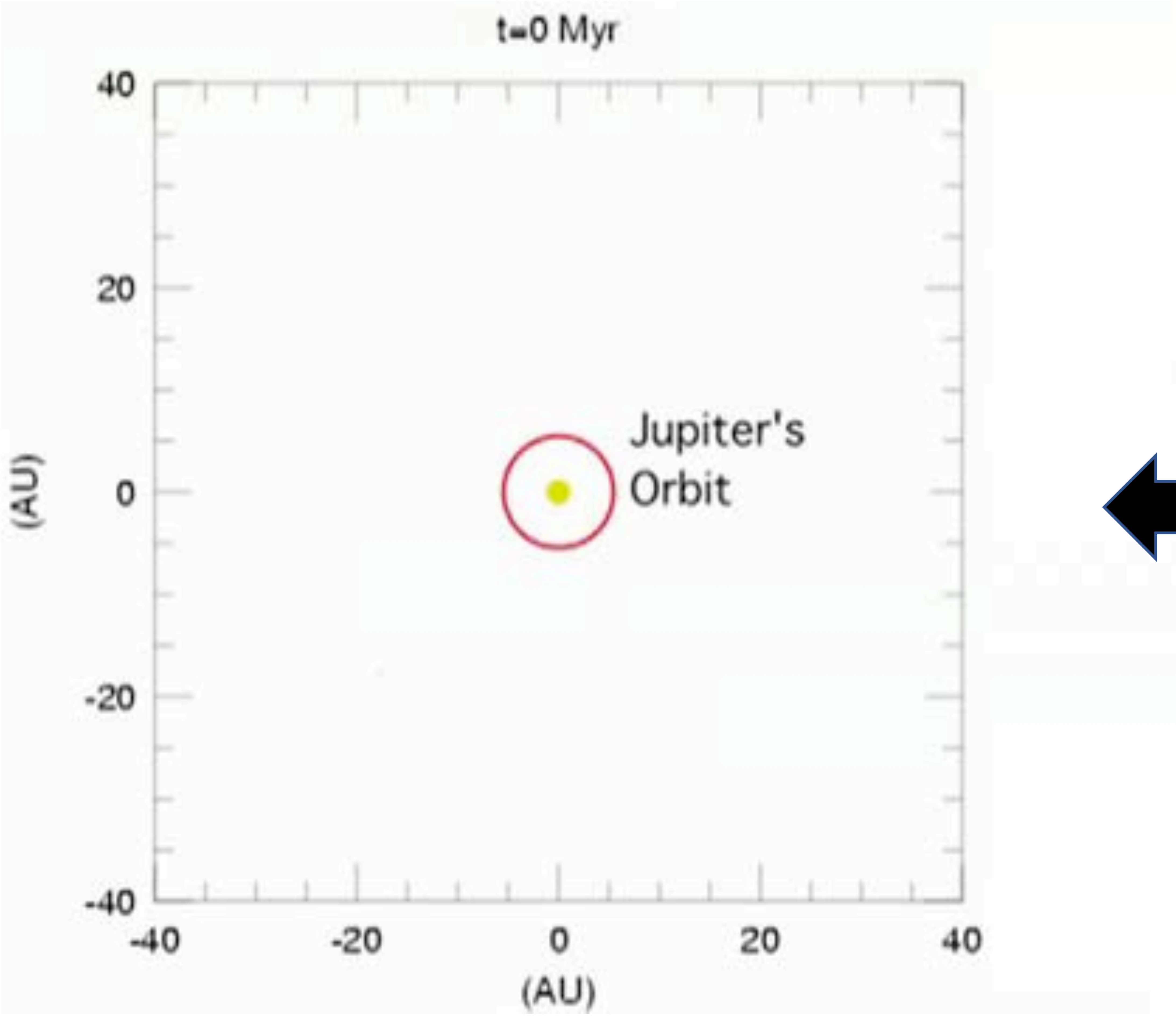
These investigations are important as the Earth was an innocent witness to a multi-car pile-up in the outer solar system



Video Credit: Hal Levison, SWRI

- **Dynamical studies indicate that the giant planets attained their modern architecture through an epoch of instability**
  - The “Nice Model.”
  - It is important that studies use simulations that produce the best matches to the actual solar system:
    - Evolution of the Earth’s young atmosphere (e.g.: Sinclair et al. 2020)
    - The terrestrial planets’ formation (e.g.: Clement et al. 2018)
    - Delivery of volatiles to Earth (e.g.: Meech et al. 2020)

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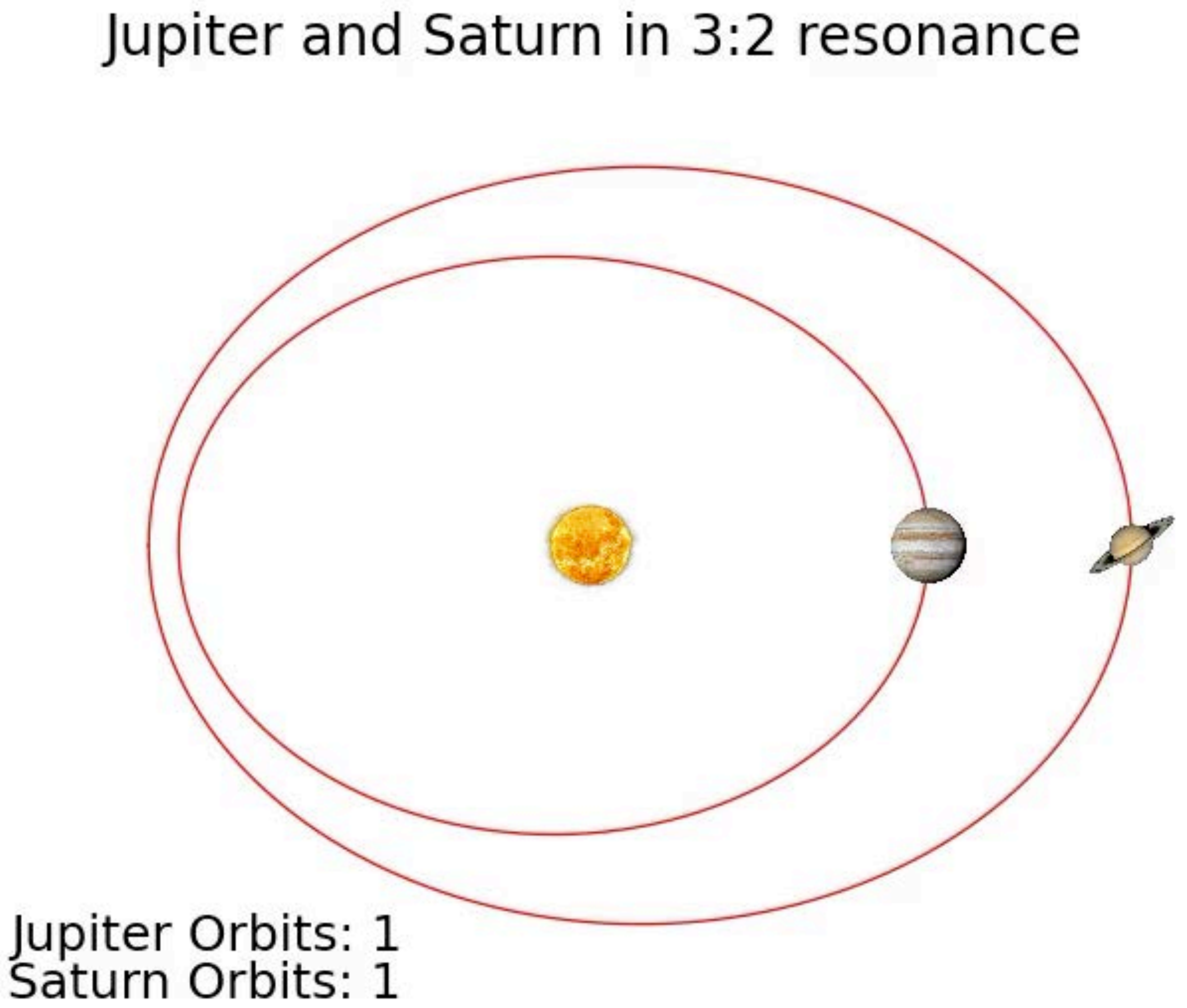
What are the “correct” initial conditions?

- Early disk models indicated rather convincingly that capture in the 3:2 resonance is the only possibility for a Jupiter-Saturn like mass configuration (Morbidelli et al. 2007; Pierens & Nelson 2008)



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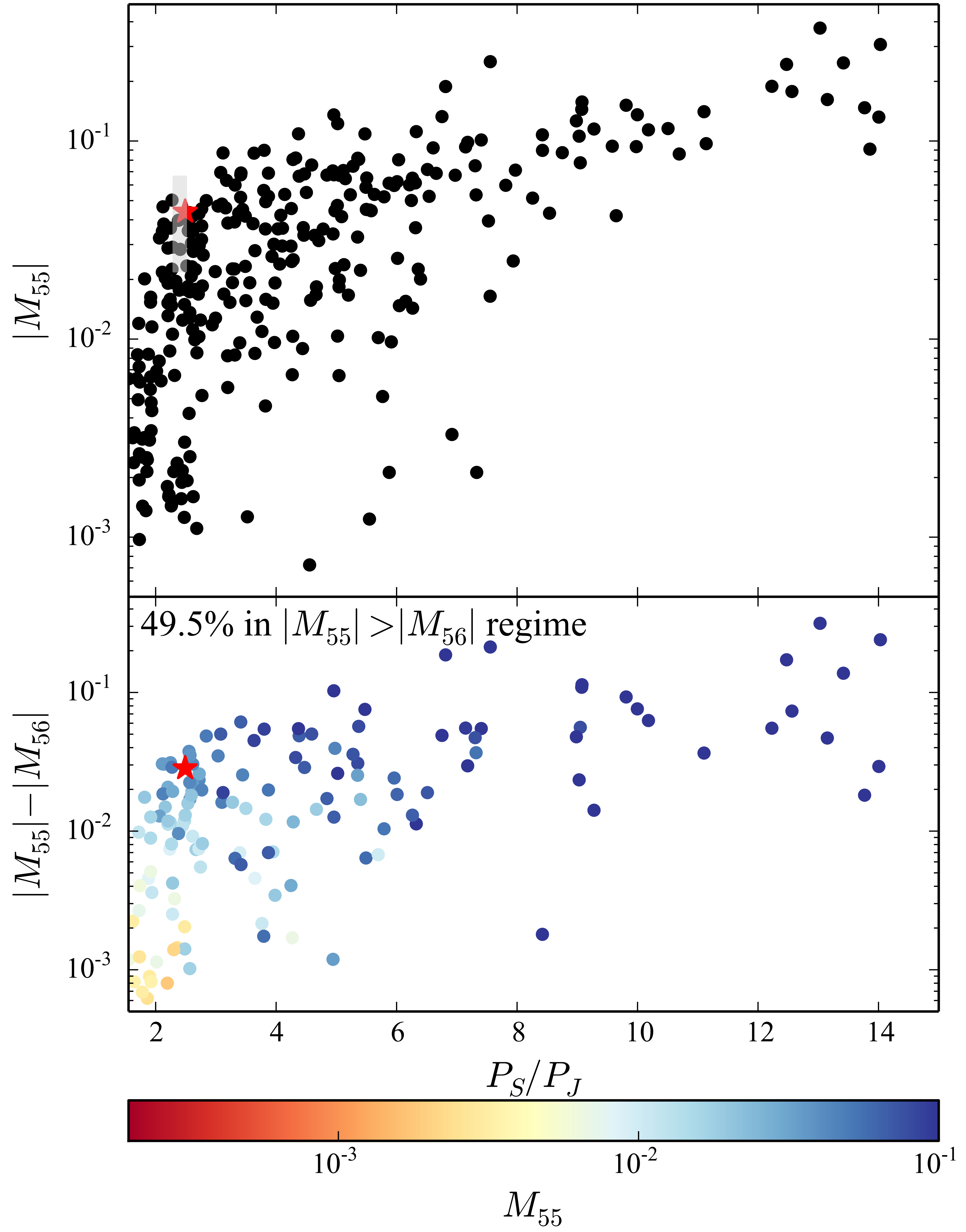
Systematic challenges with the 3:2

- Saturn kicked out past Uranus' orbit.
- Saturn's eccentricity to high relative to Jupiter's.
- Saturn's orbit perturbs Jupiters too strongly

Jupiter eccentricity vs. distance from Saturn

How strongly Jupiter is perturbed by Saturn



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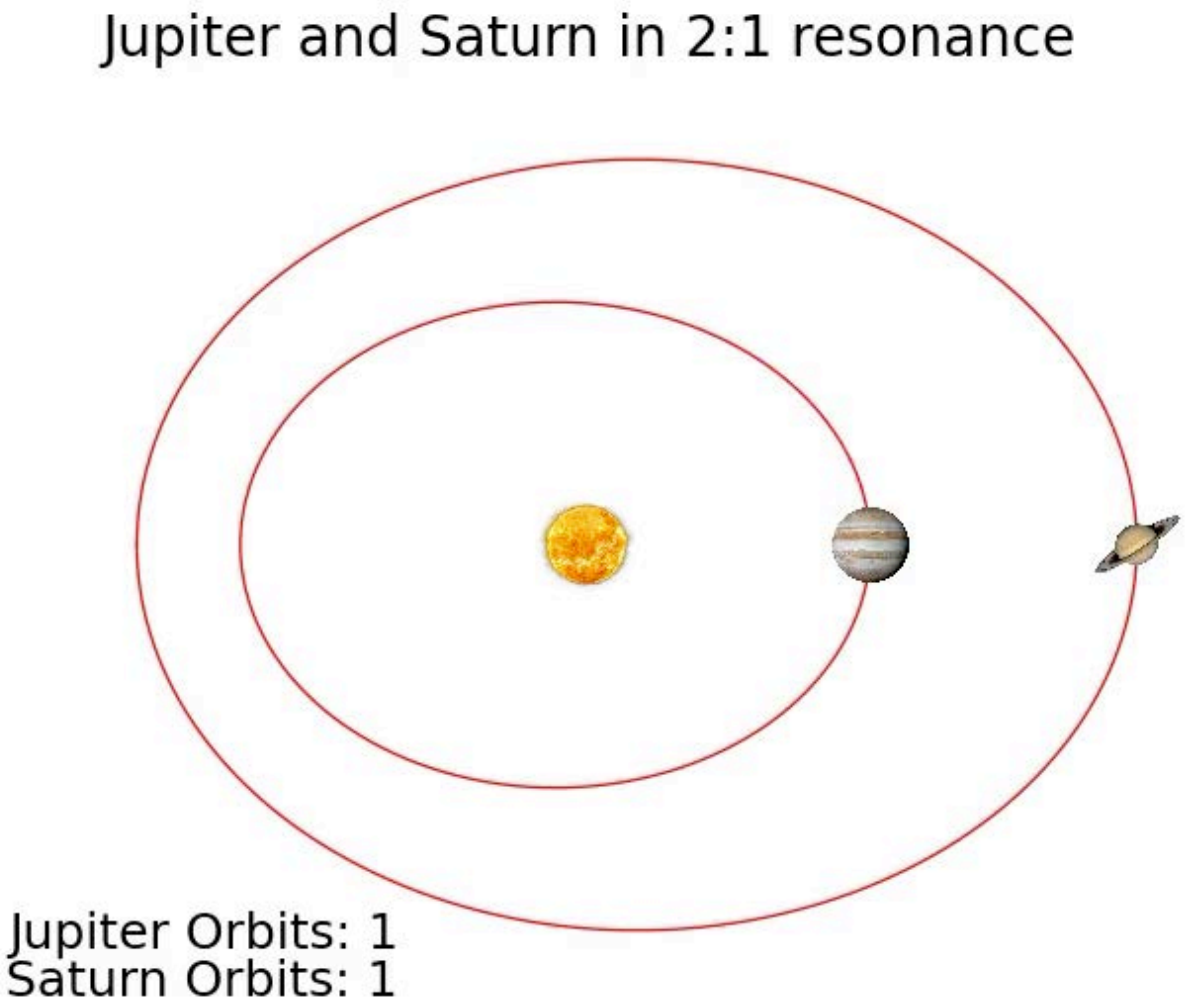
Alternative scenarios: the 2:1

- 3:2 is still a viable option
- Capture in the 2:1 is possible (Pierens et al., 2014)
  - Low mass disks
  - Low disk viscosity
  - Carve larger gaps (attain higher initial eccentricities)



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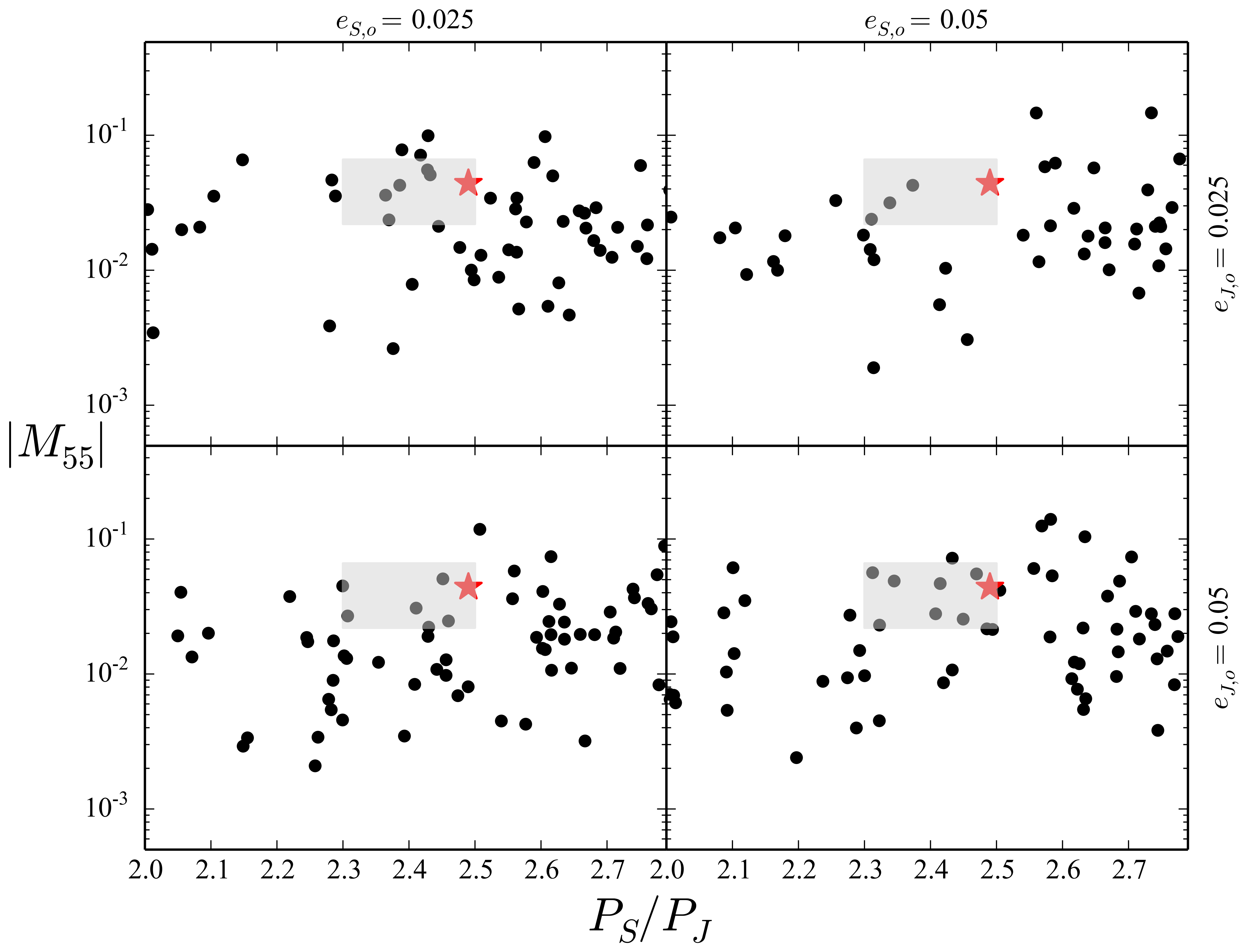
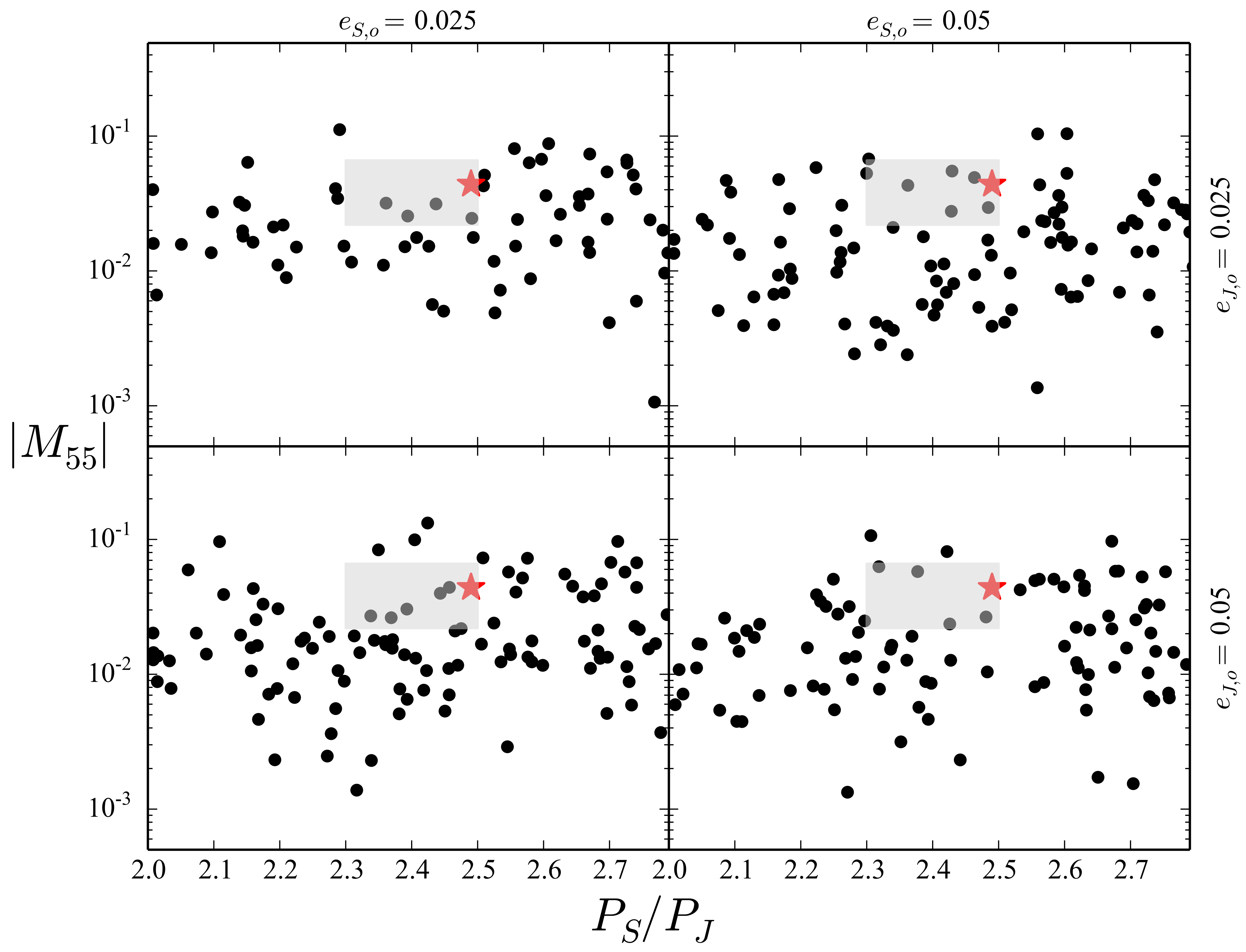
2:1 results: The solar system is a typical outcome

Five initial giant planets



Six initial giant planets



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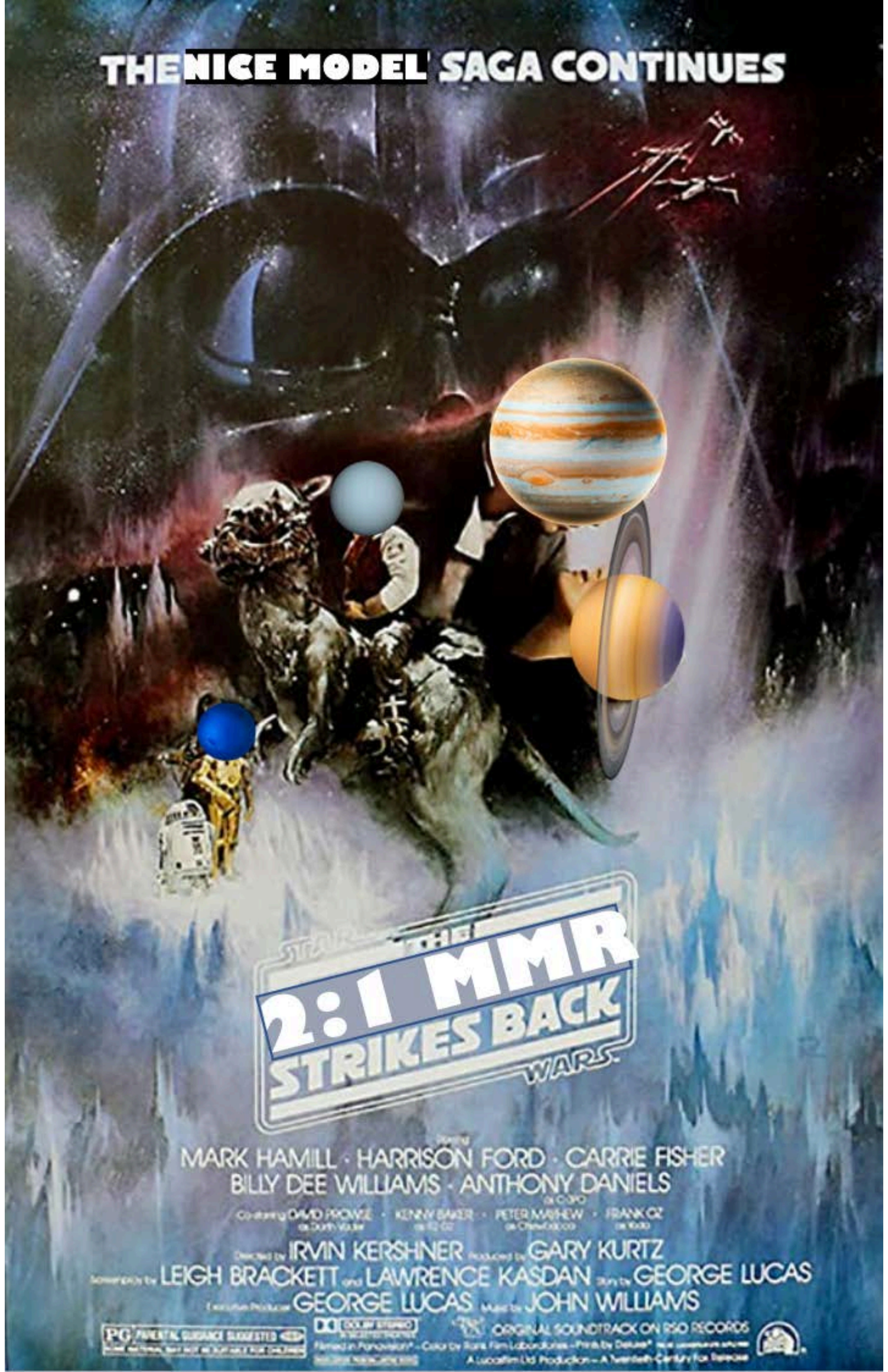
Conclusions

- 2:1 with primordial eccentricity excitation more successful than 3:2 at replicating Jupiter-Saturn system.
- Preferred chains:
  - Five planets: 2:1,4:3,3:2,3:2
  - Six planets: 2:1,4:3,4:3,3:2,3:2
- These new evolutions will have implications for our understanding of:
  - The formation of the terrestrial planets
  - Volatile delivery on Earth
  - The formation of the Moon
  - The dynamical evolution of the Kuiper and Asteroid Belts
- 3:2 still viable



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