Planet migration and resonances

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Image credit: NASA/SOFIA/Lynette Cook

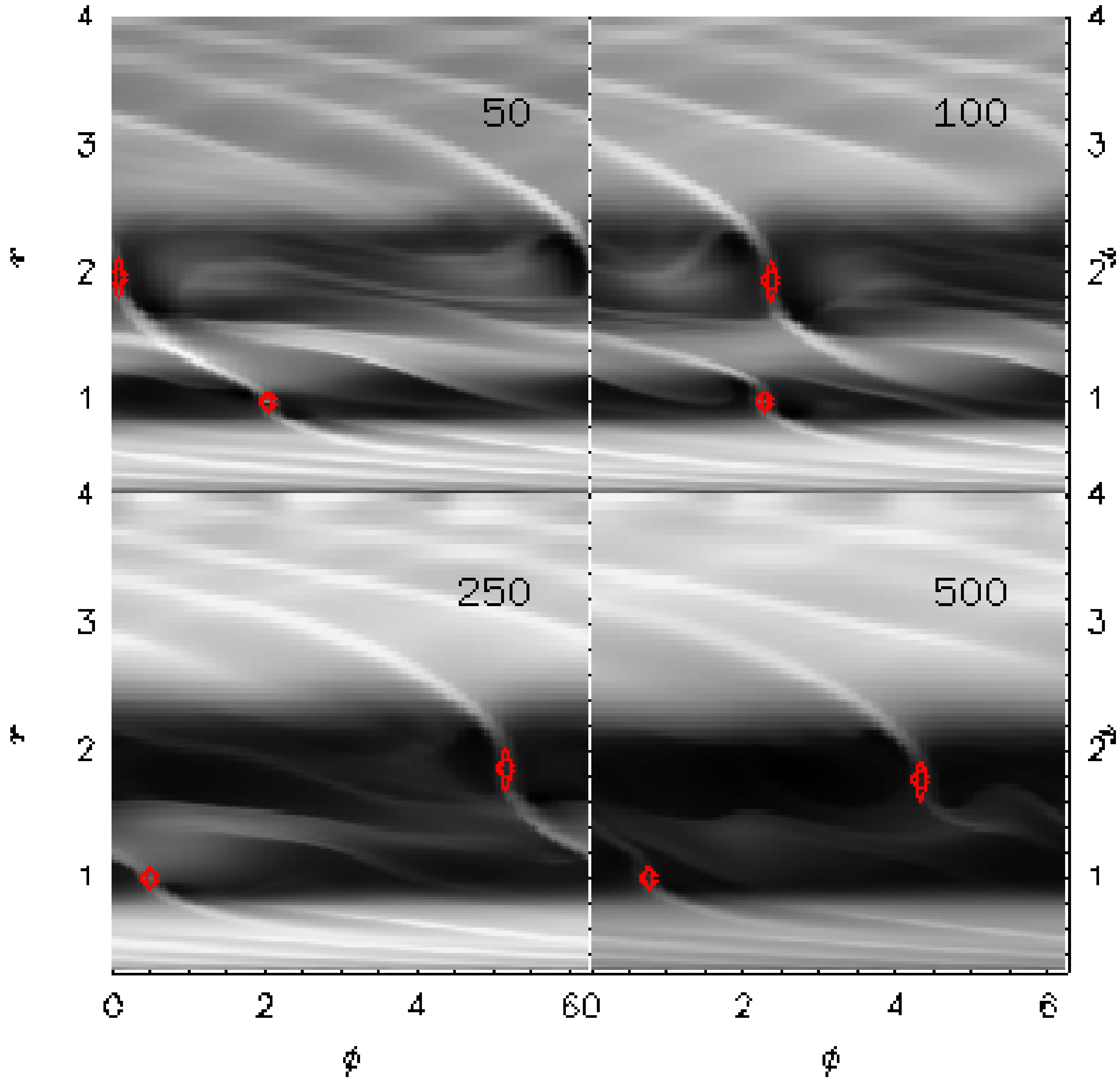
Willy

Following in Willy’s footsteps…

Image credit: NASA/SOFIA/Lynette Cook

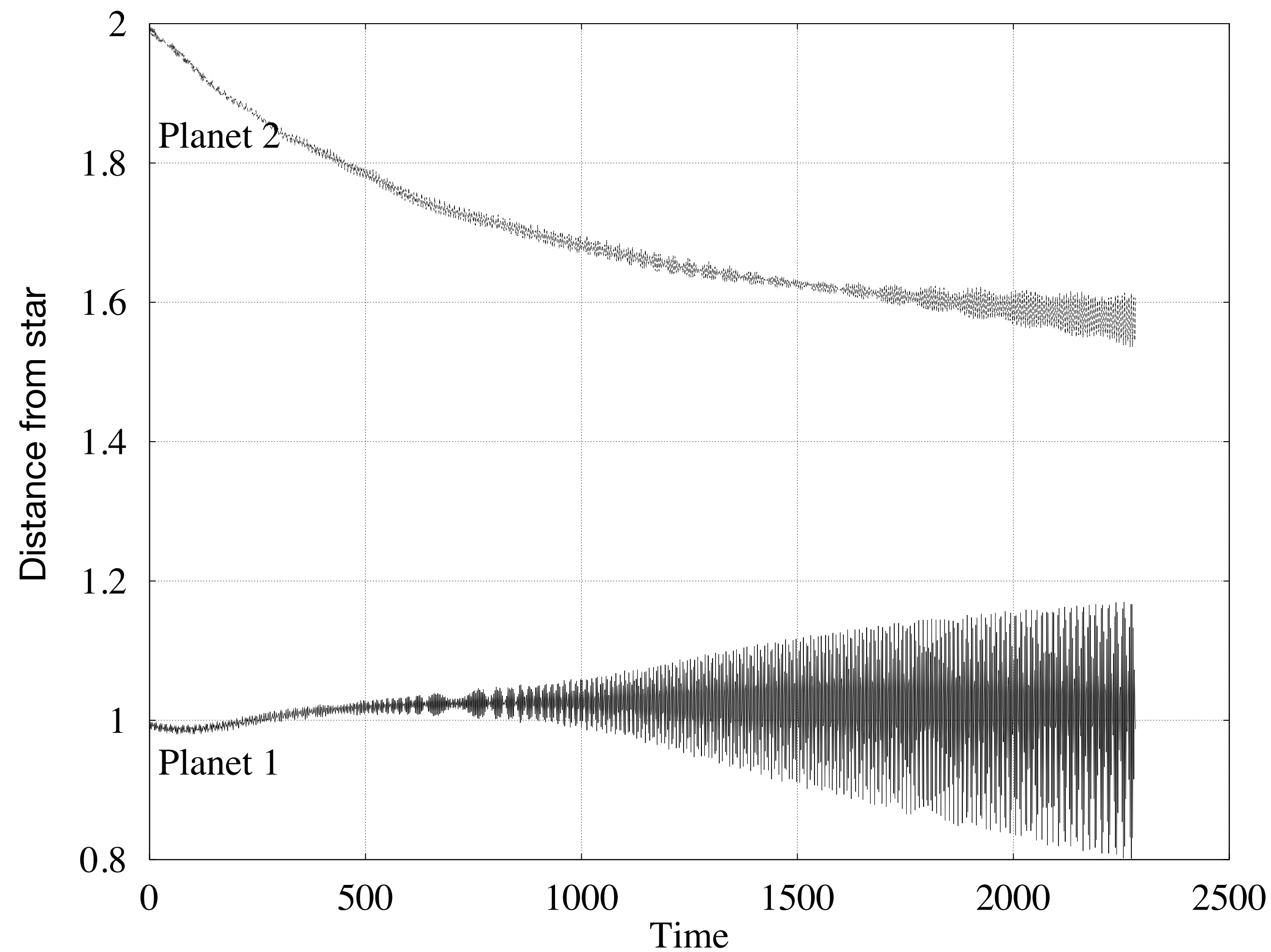
Kley (2000)

- Evolution of two planets in a circumplanetary disk
- hydrodynamic simulation
- 128^2 grid
- 2500 orbit



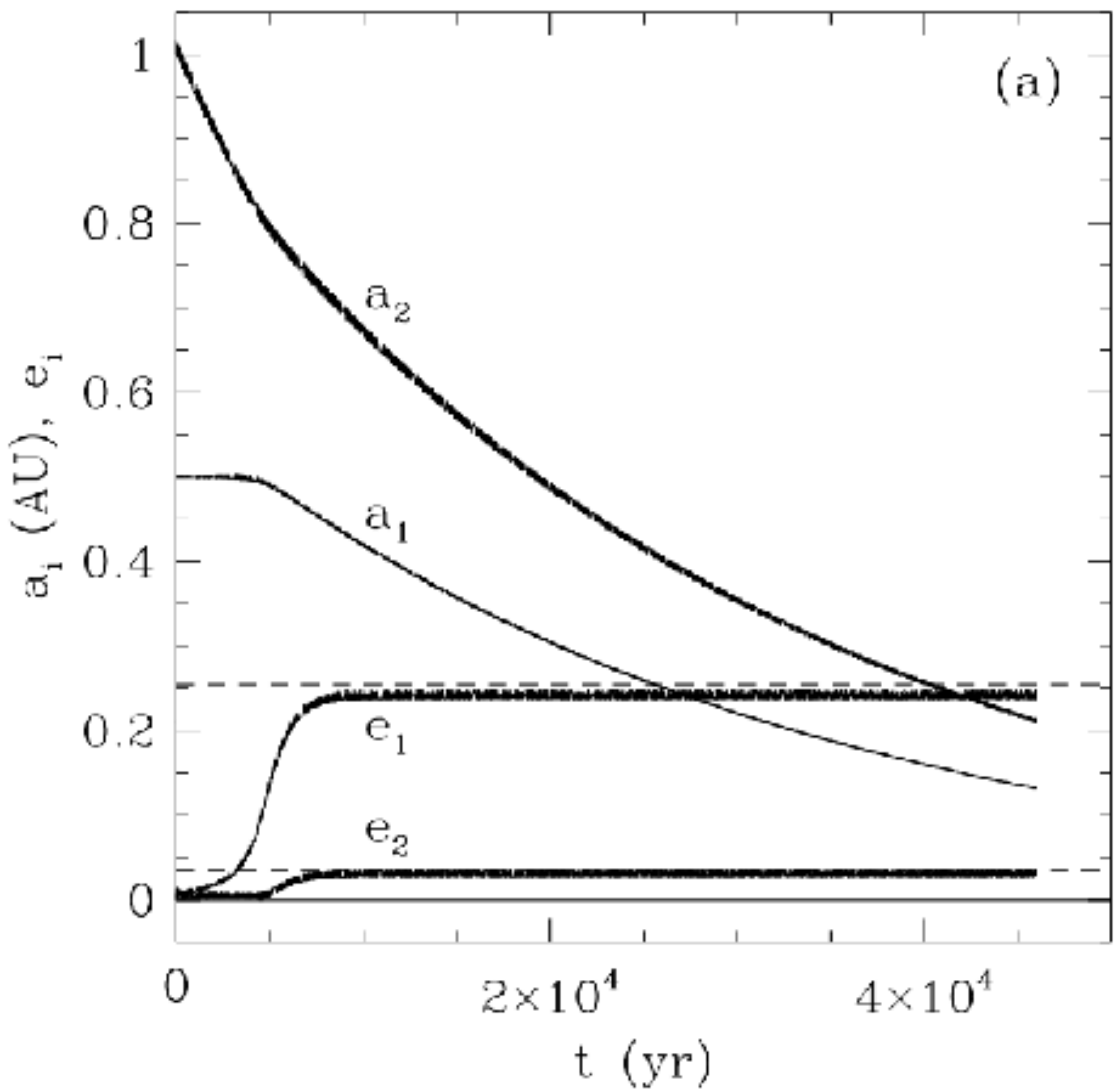
Kley (2000)

- Planets are converging
- Eccentricities increase
- Conclusion: highly eccentric orbits, instabilities, ejected planets
- Fitted the observations at the time: ups Andromedae (e~0.2, 0.3)
- Observationally driven subject



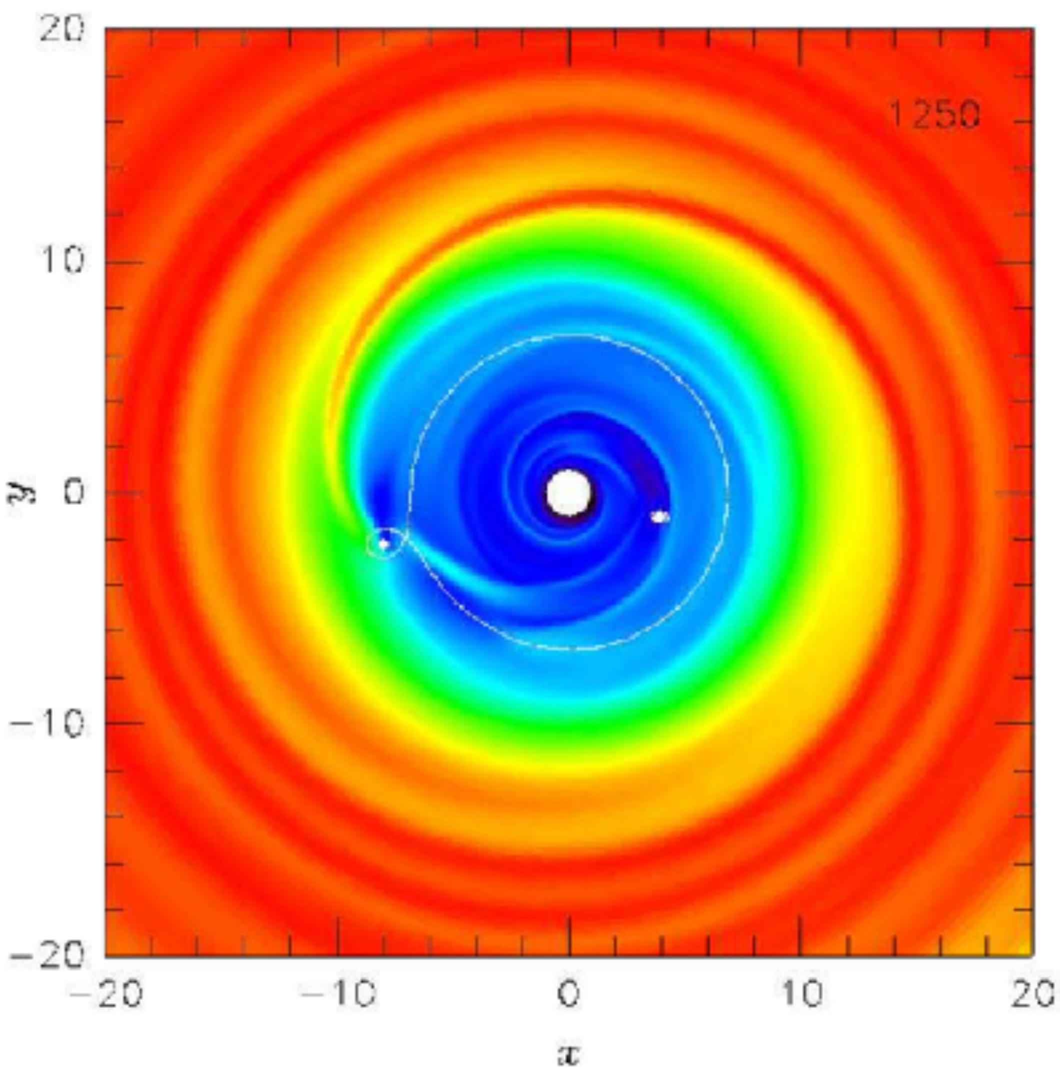
Lee and Peale (2002)

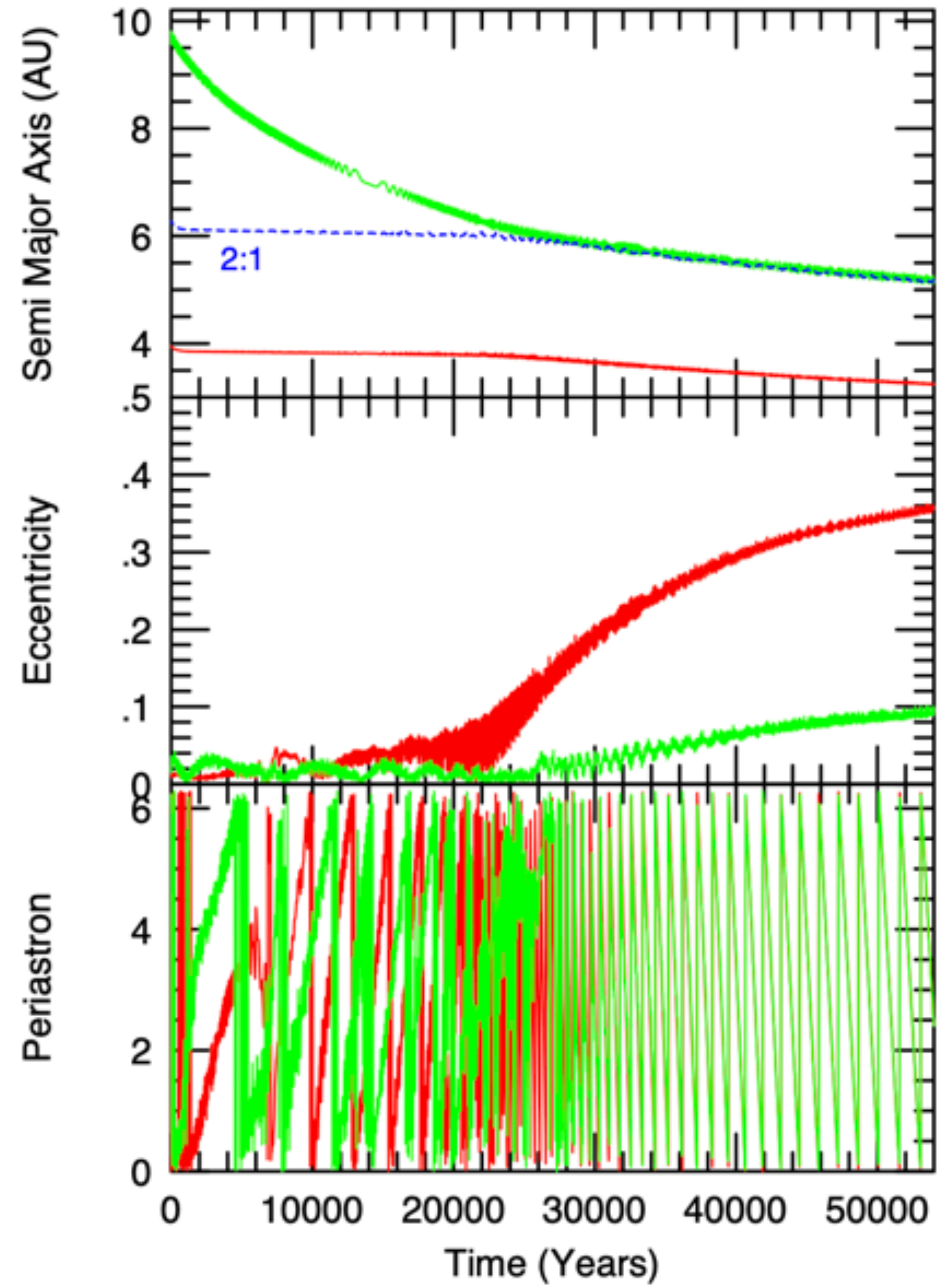
- 11 confirmed multi-planet systems
- 3 systems with confirmed mean motion resonances:
  - GJ 876
  - HD 82943
  - 55 Cnc
- N-body simulation (Ji et al. 2002, Lee & Peale 2002)



Kley, Peitz, and Bryden (2004) + follow-ups

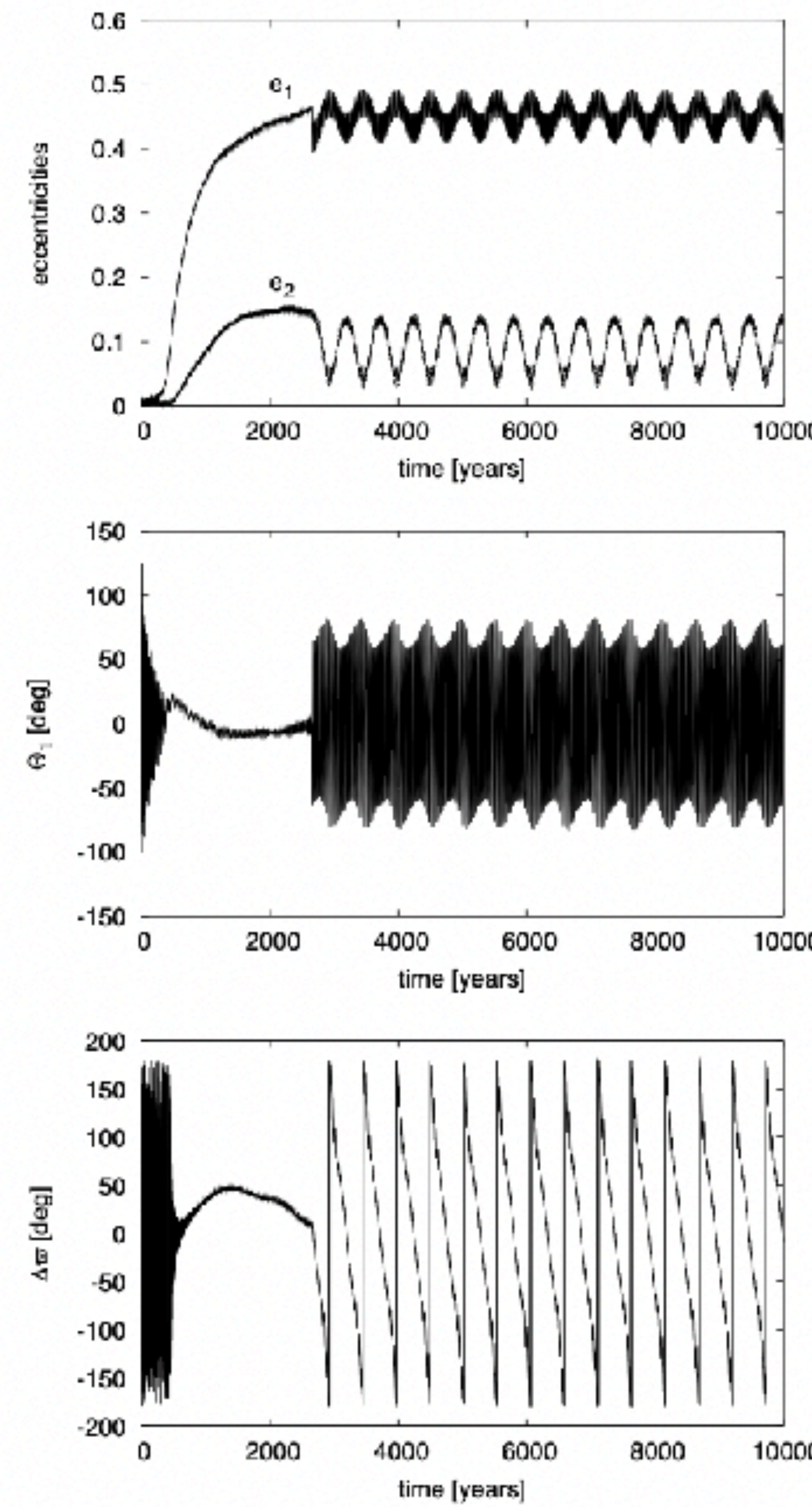
- Hydrodynamics simulations
- Observed resonances can constrain migration phase (e.g. high e-damping, K=100)





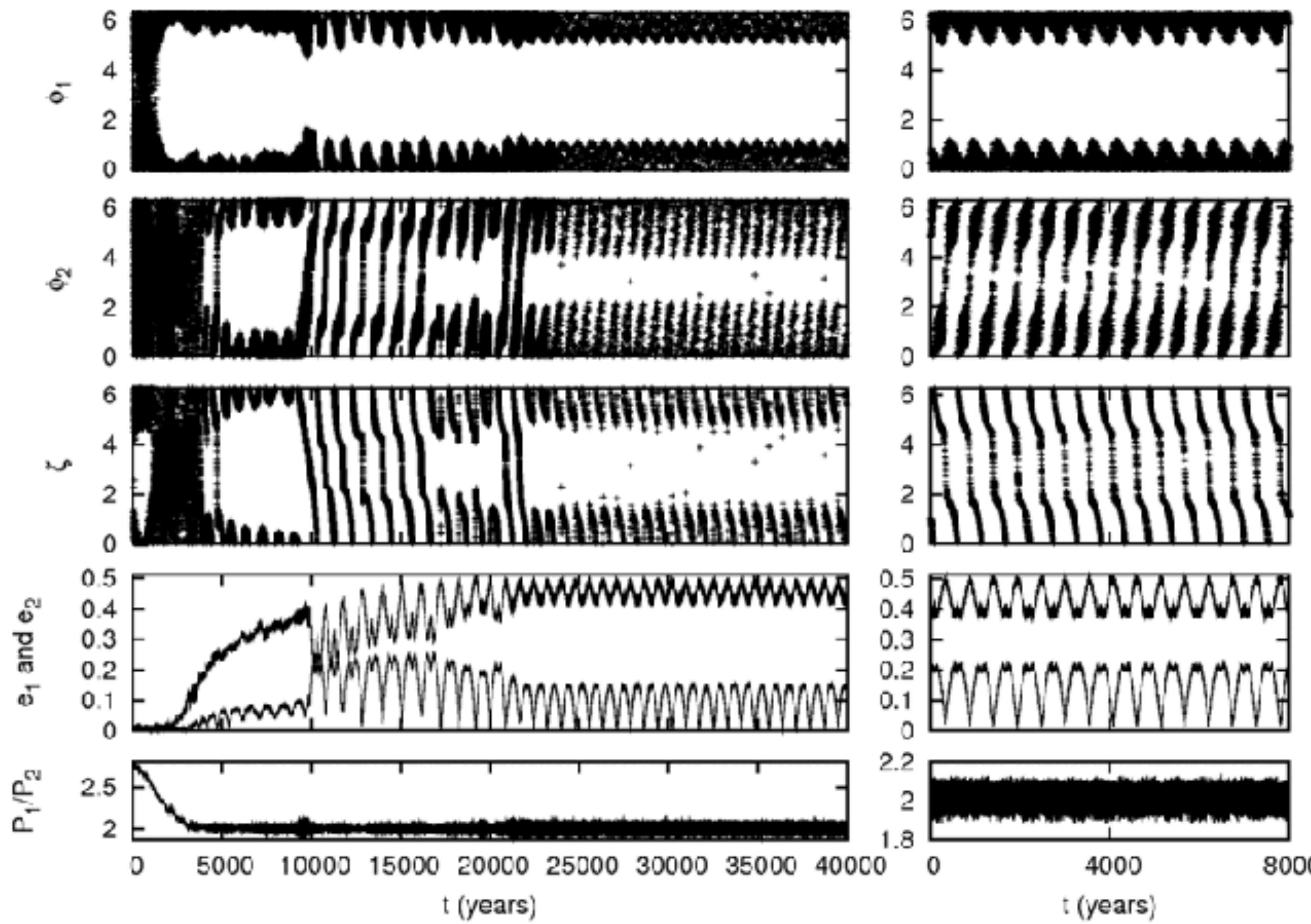
Sandor and Kley (2006)

- HD128311
- Smooth migration:
  apsidal corotation resonance (ACR)
- Migration + perturbations:
  no apsidal corotation
- Perturbation here: sudden disappearance of disk



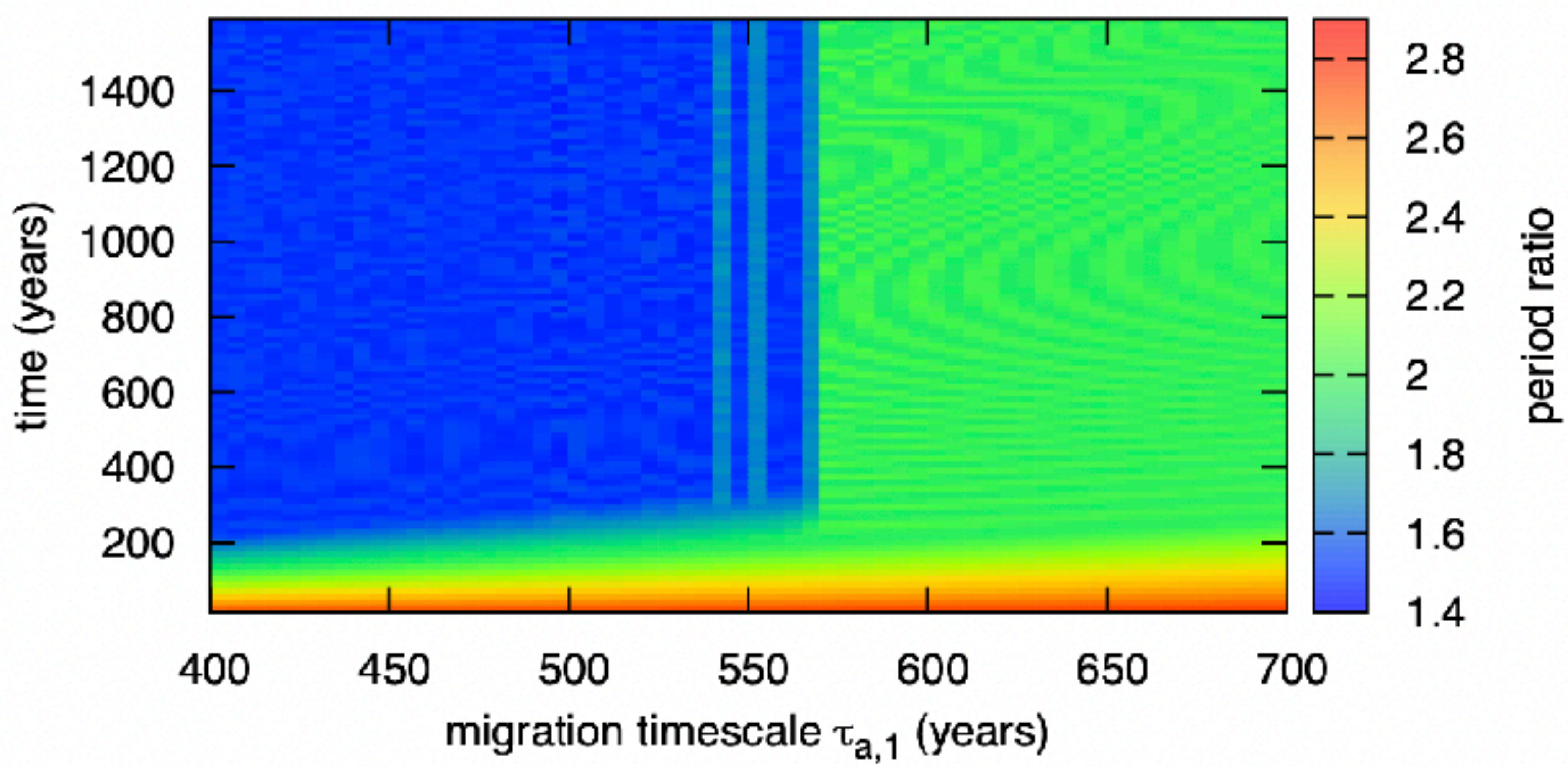
Rein and Papaloizou (2009)

- Perturbations here: Density fluctuation in the disk
- Can get system out of ACR, or get completely out of resonance
- Limits on turbulence in protoplanetary disks

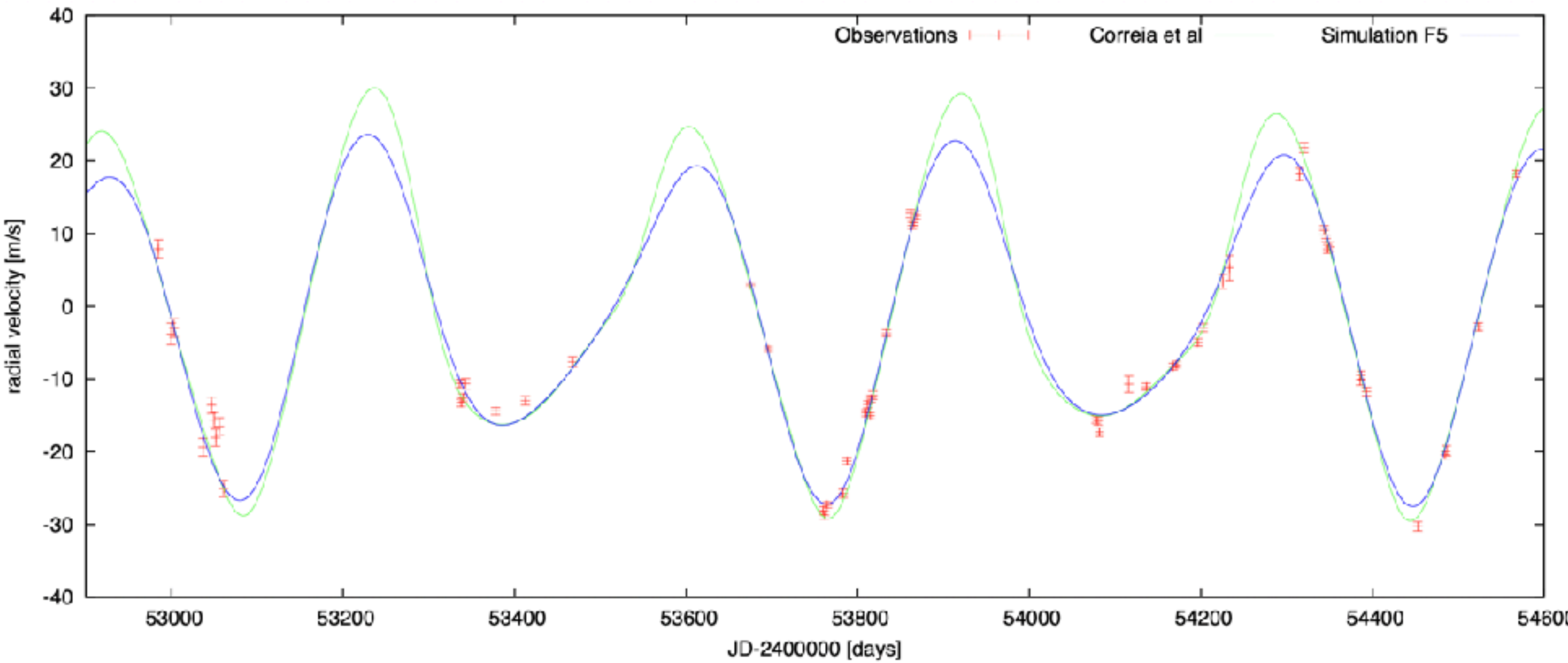


Rein, Papaloizou, and Kley (2010)

- HD45364
- System is in 3:2 resonance
- Migration needs to be very fast to skip over 2:1 resonance



Rein, Papaloizou, and Kley (2010)

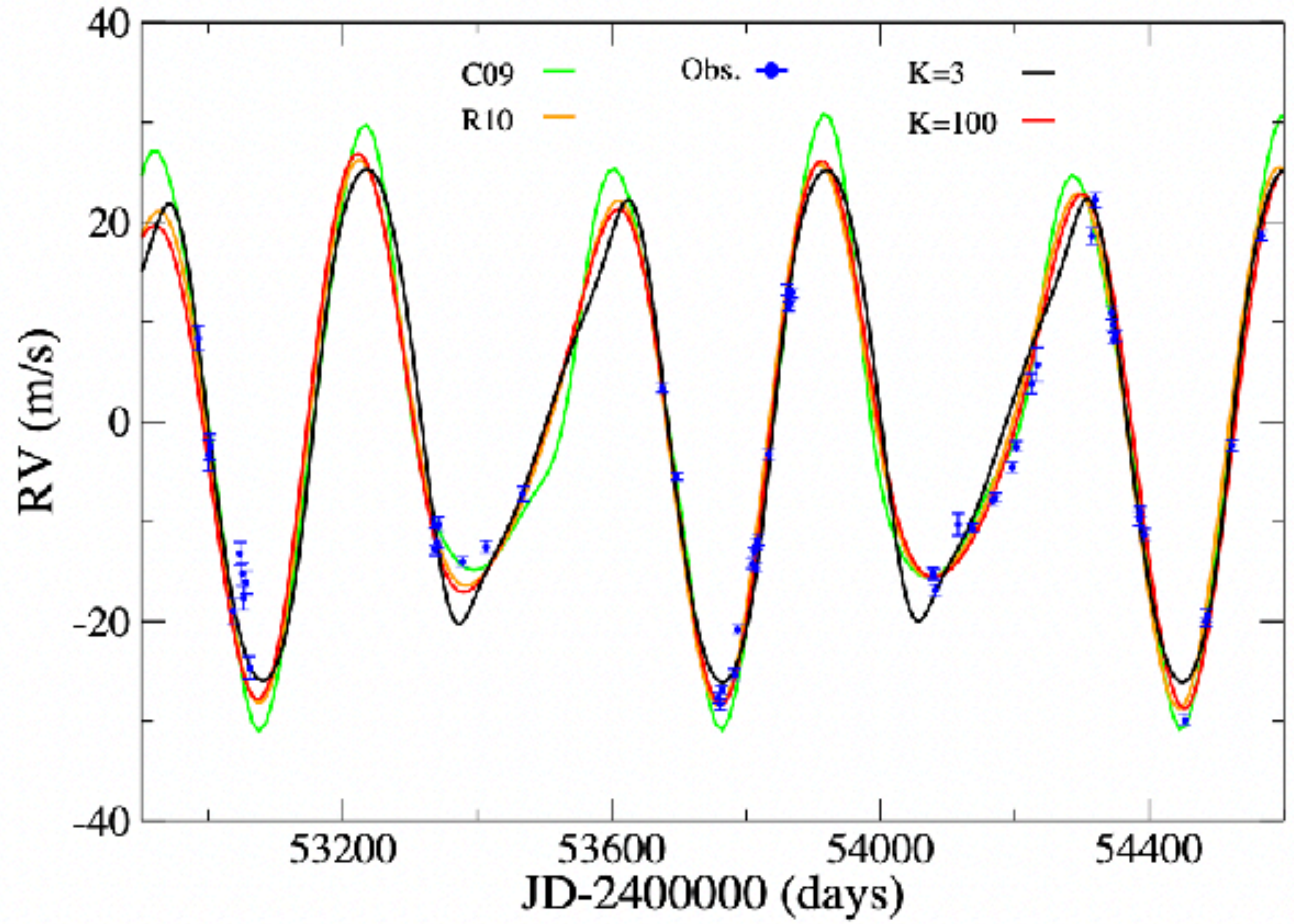


- Simulations fit RV data better than “best fit”
- Eccentricities can be biased

Parameter	Unit	Correia et al. (2009) b	Correia et al. (2009) c	Simulation F5 b	Simulation F5 c
$M \sin i$	$[M_{Jup}]$	0.1872	0.6579	0.1872	0.6579
M_*	$[M_\odot]$	0.82		0.82	
a	[AU]	0.6813	0.8972	0.6804	0.8994
e		0.17 ± 0.02	0.097 ± 0.012	0.036	0.017
λ	[deg]	105.8 ± 1.4	269.5 ± 0.6	352.5	153.9
ϖ	[deg]	162.6 ± 6.3	7.4 ± 4.3	87.9	292.2
$\sqrt{\chi^2}$		2.79		2.76* (3.51)	
Date	[JD]	2453500		2453500	

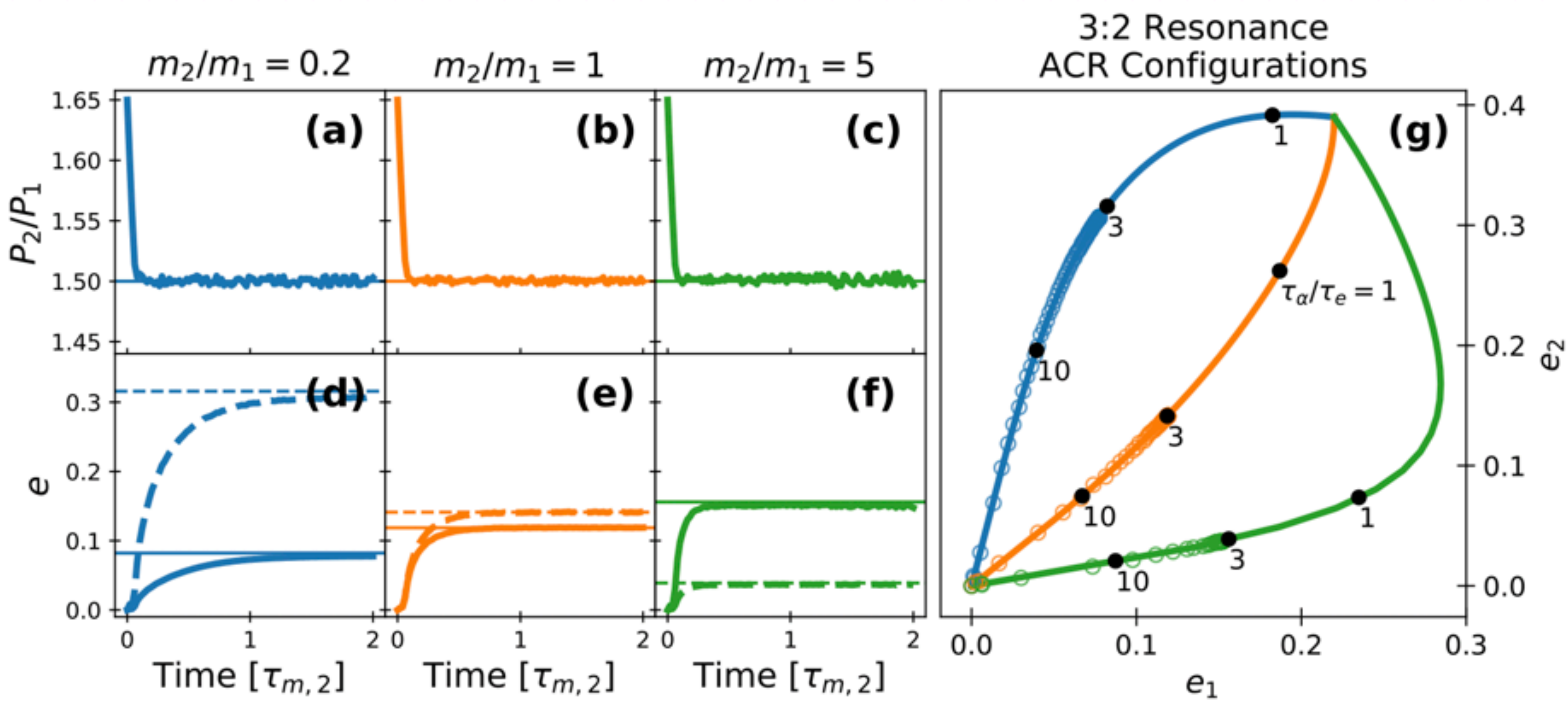
Correa-Otto, Michtchenko, Beaugé (2013)

- Different scenario
- Interaction between different planetary migration types
- Planet growth
- Gap formation



Hadden and Payne (2020)

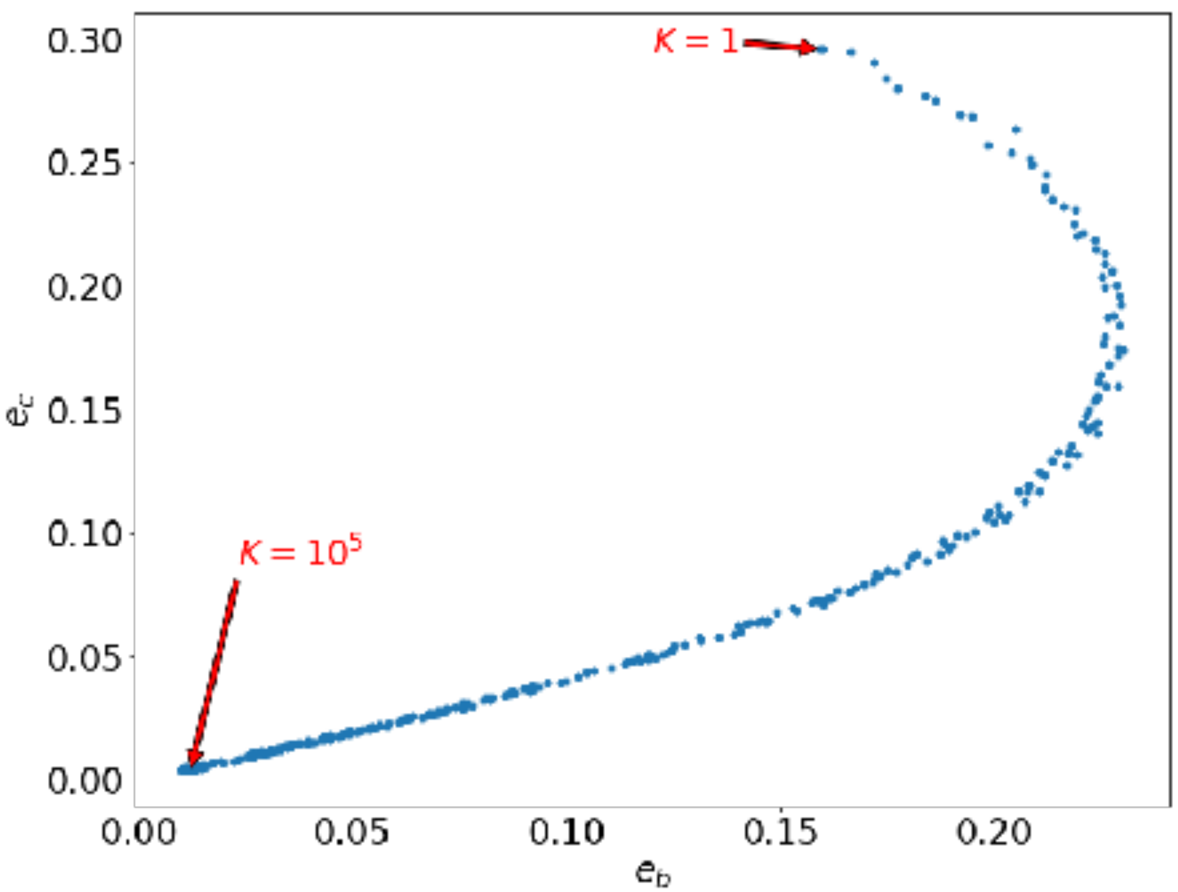
- Very specific dynamical configuration
- Apsidal corotation resonance (ACR)
- Restricts parameter of RV model
- Analytical model

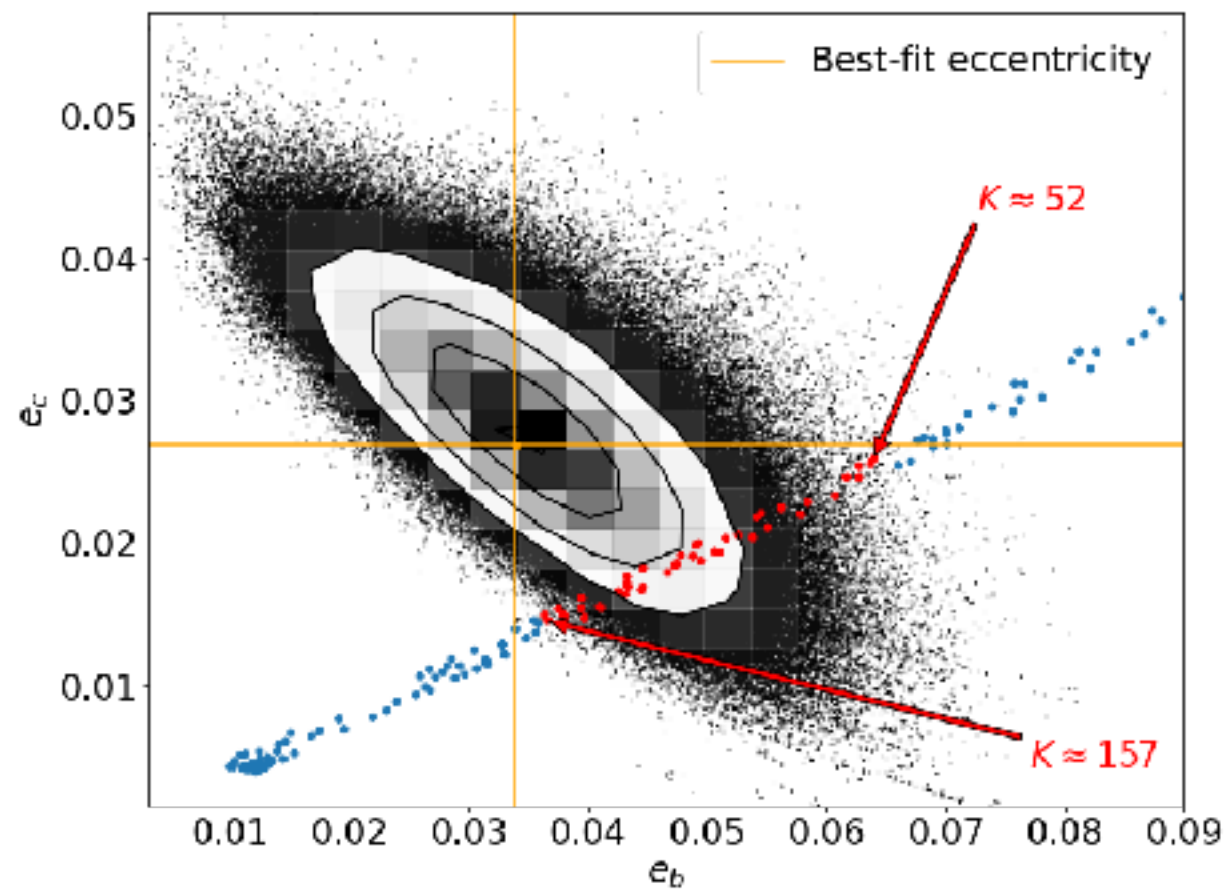


Chow, Hadden, Rein (in prep)

- Analytical model
- Predict eccentricity as a function of migration parameters

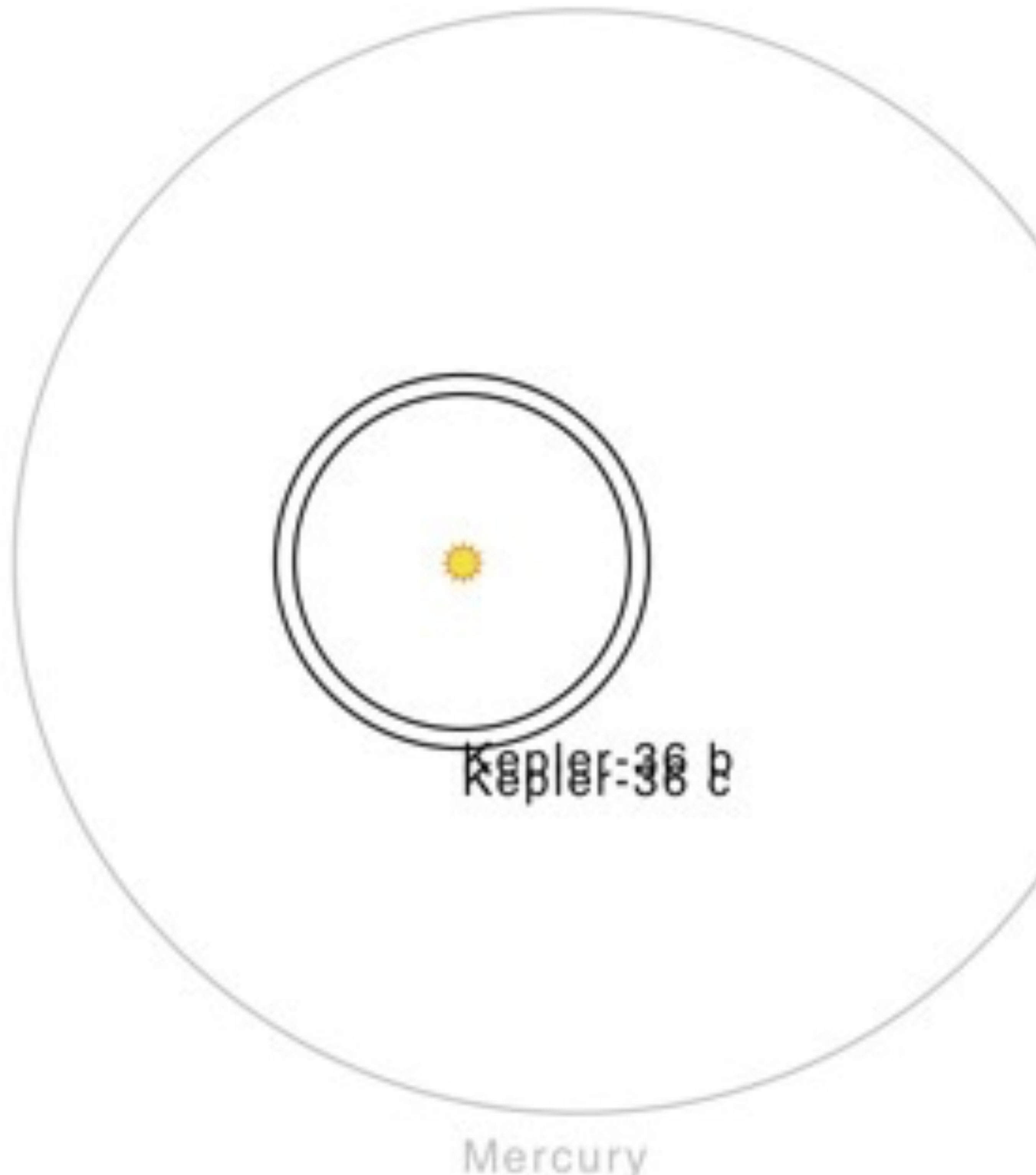
- New data
- Consistent with ACR model
- Can use observations to constrain K





Kepler-36

- Super-Earth and Mini-Neptune
- Close to 7:6 MMR
- Different densities



Kepler-36

Paardekooper, Rein, and Kley (2013)

- Turbulent migration

Quillen et al (2013)

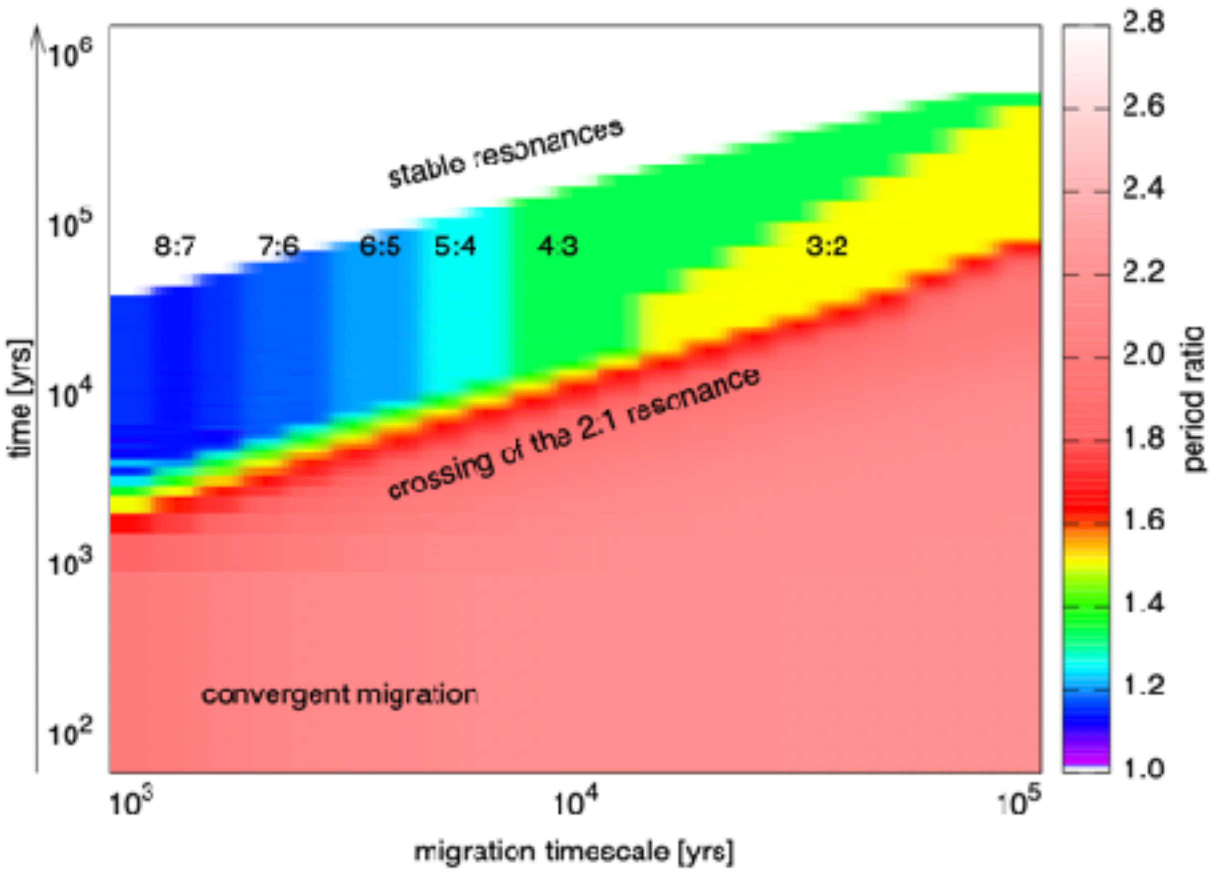
- Impacts by embryos cause migration and stripping of outer layers

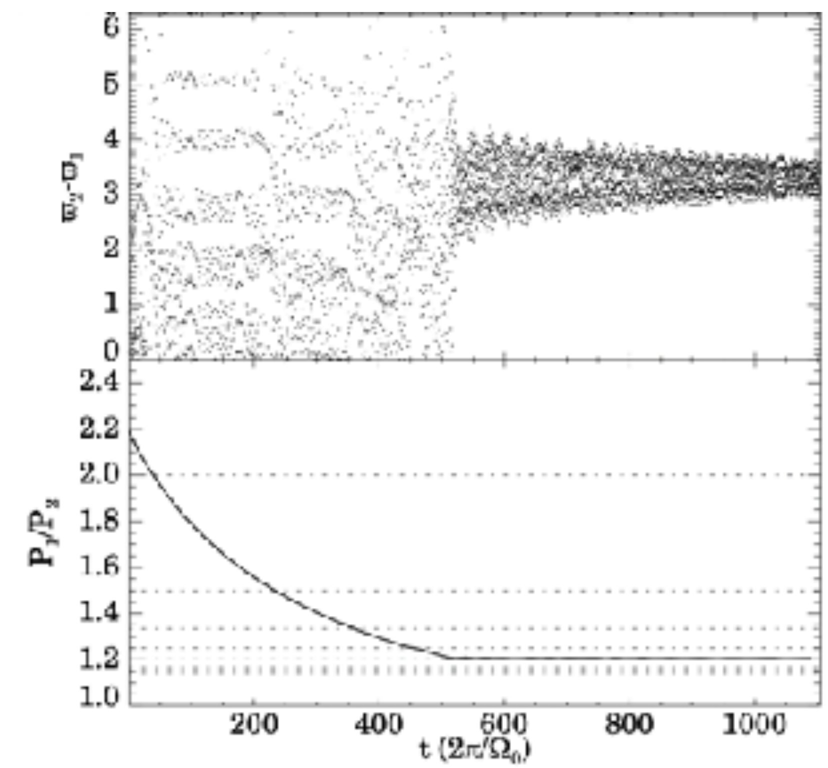
Raymond et al (2018)

- Migration due to embryos + mergers

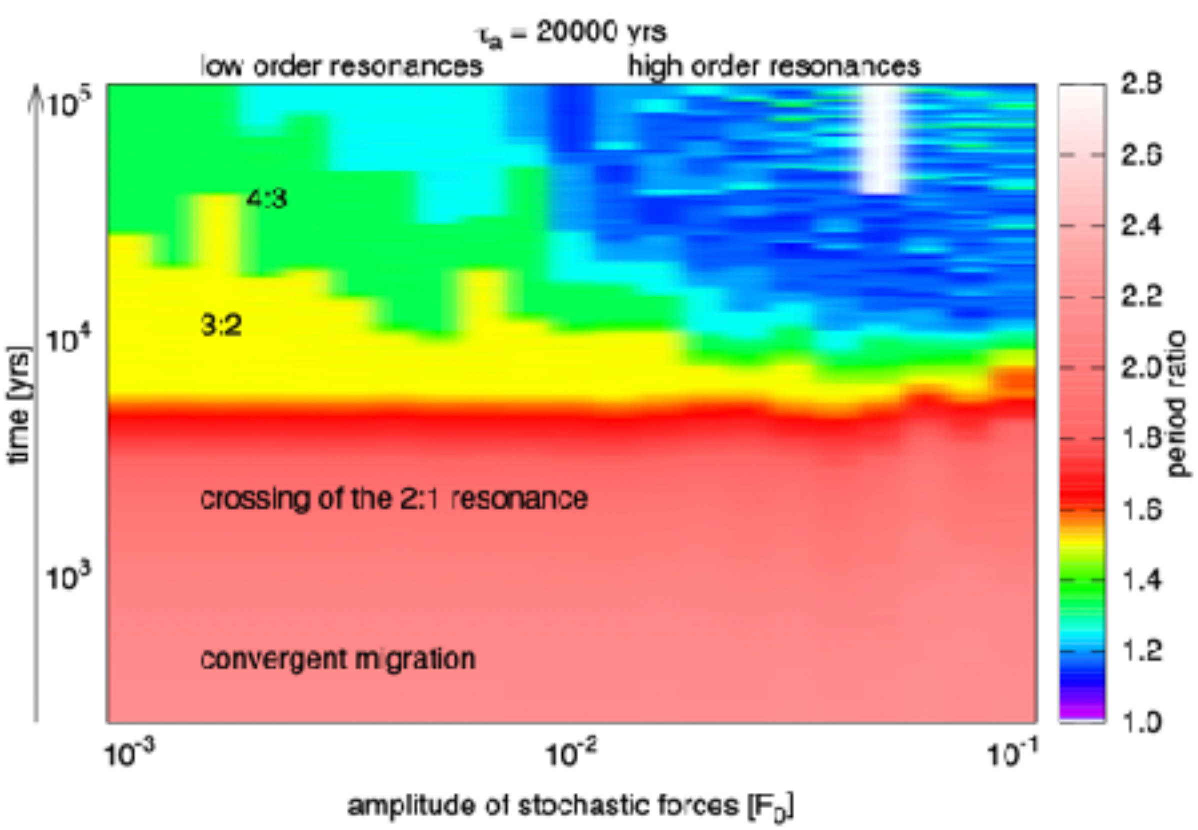
Paardekooper, Rein, and Kley (2013)

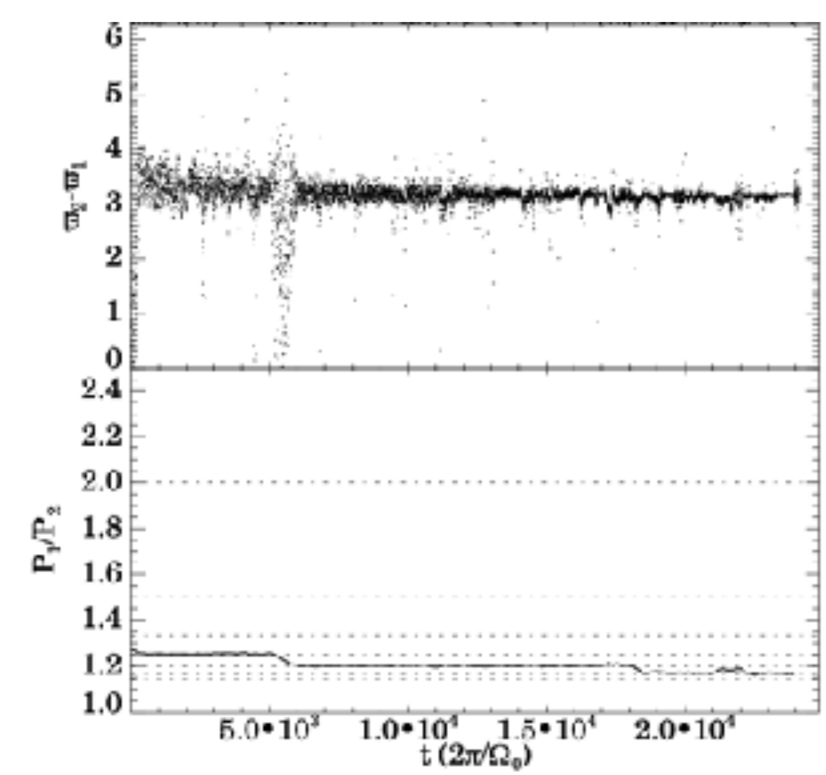
Smooth:





Stochastic:



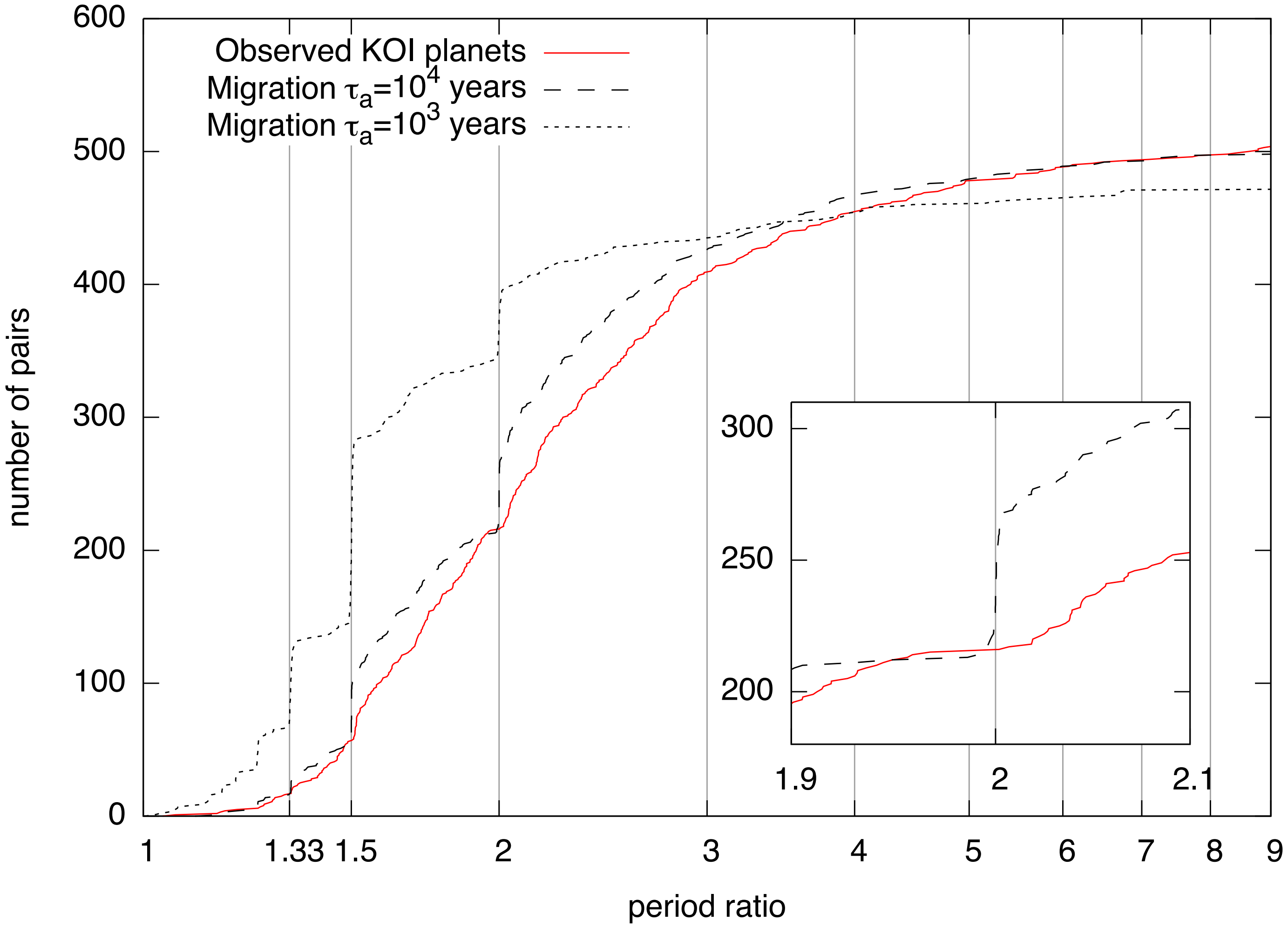


Conclusions

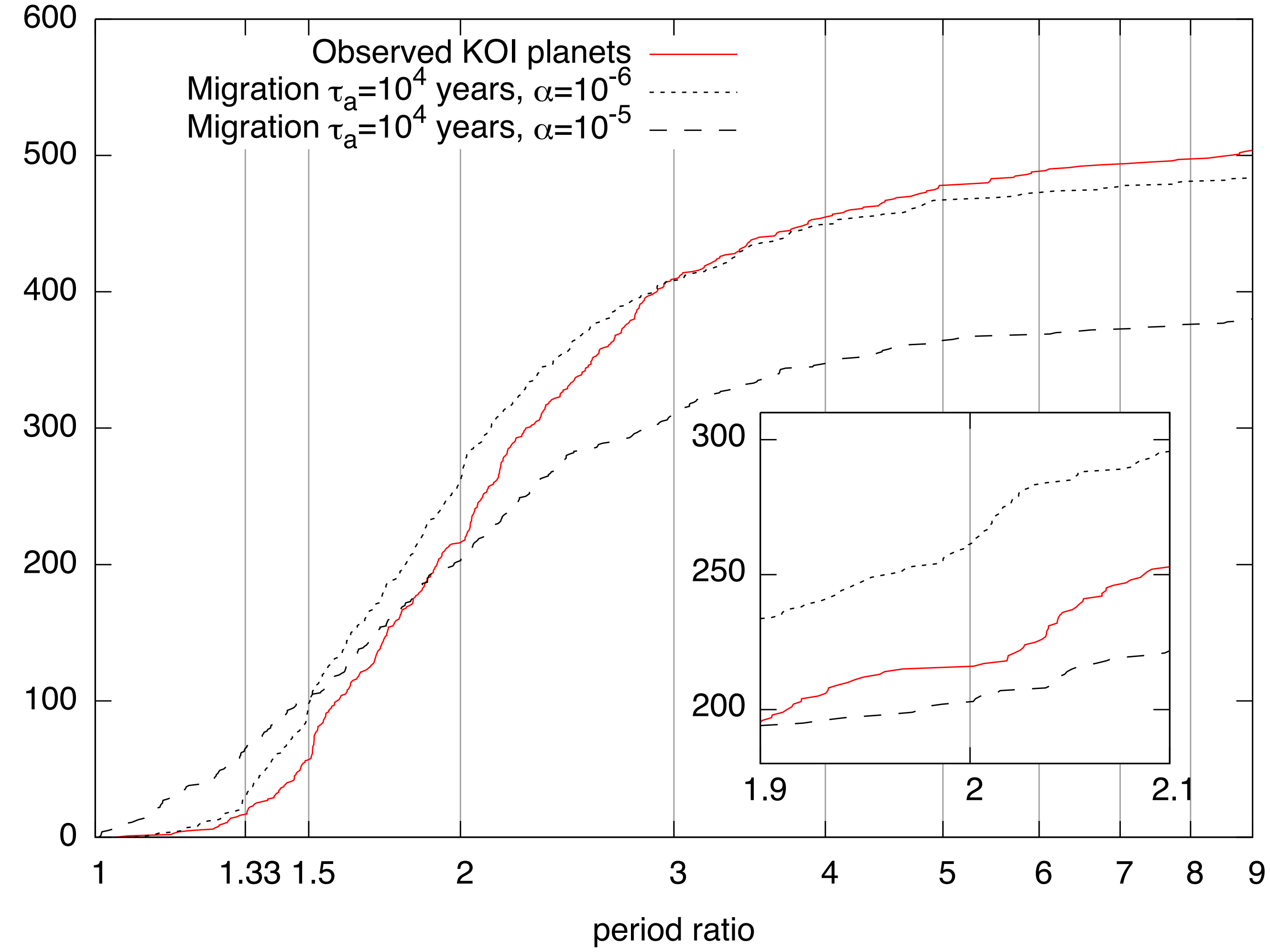
- Observationally driven
- We’re not good at making predictions
- We’re trying to understand why planets are where they are
- Smooth migration works for some systems
- In many cases, something else needs to be added to explain the observed dynamics state
- A (small amount) of random kicks / stochasticity / turbulence is surprisingly good at explaining many systems

Conclusions

Smooth:



Stochastic:



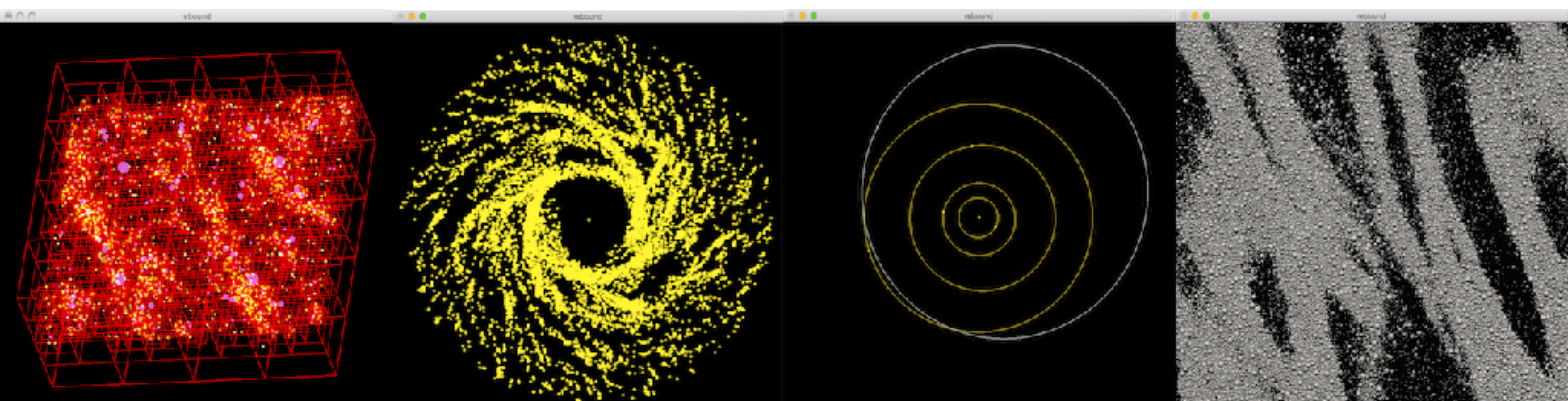
Rein (2012)

REBOUND / REBOUNDx

Image credit: NASA/SOFIA/Lynette Cook

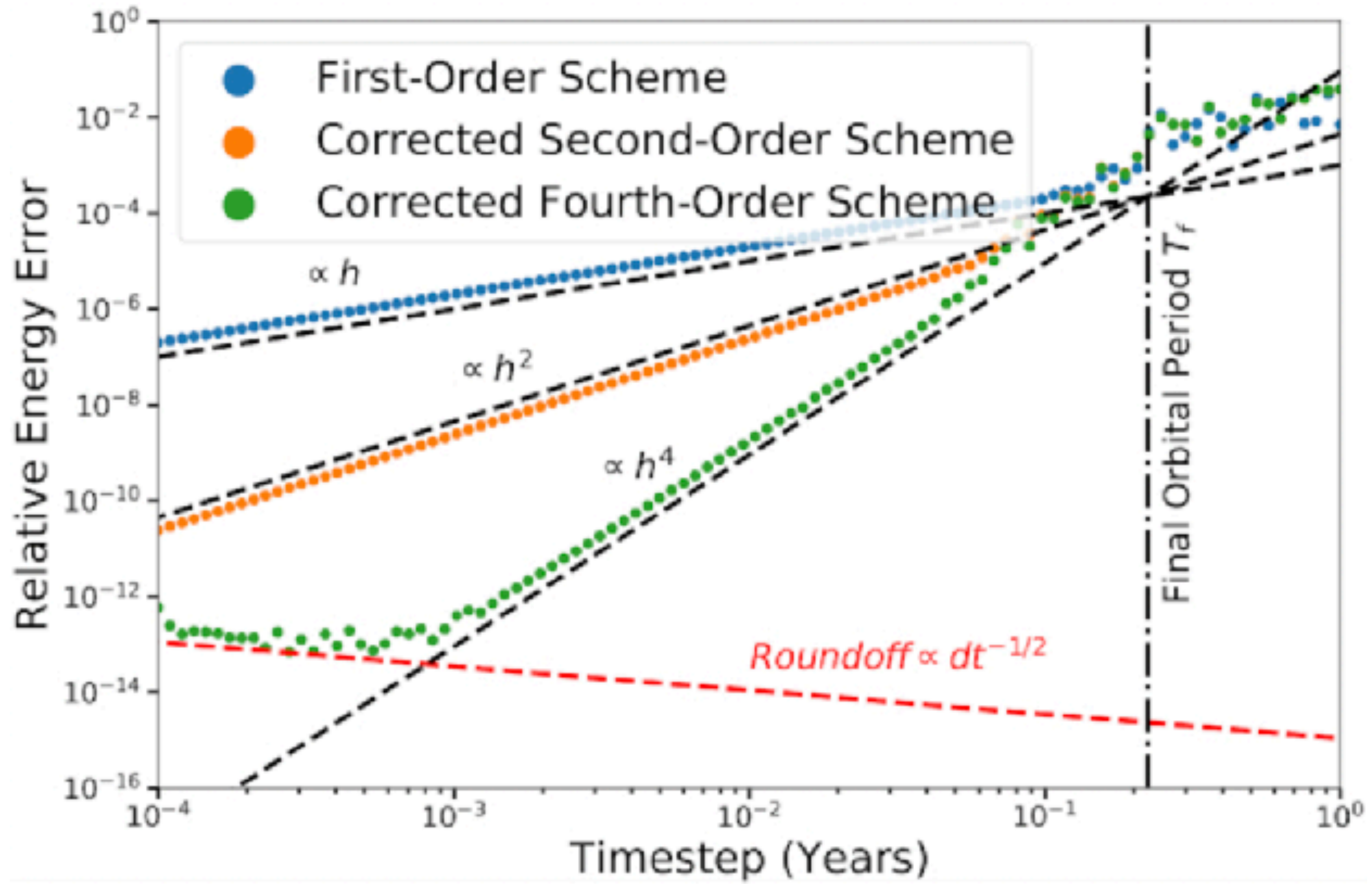
REBOUND

- N-body integrator package
- Many different built-in integrators
- Planetary systems
- Collisional simulations of planetary rings
- Written in C with an easy to use python interface

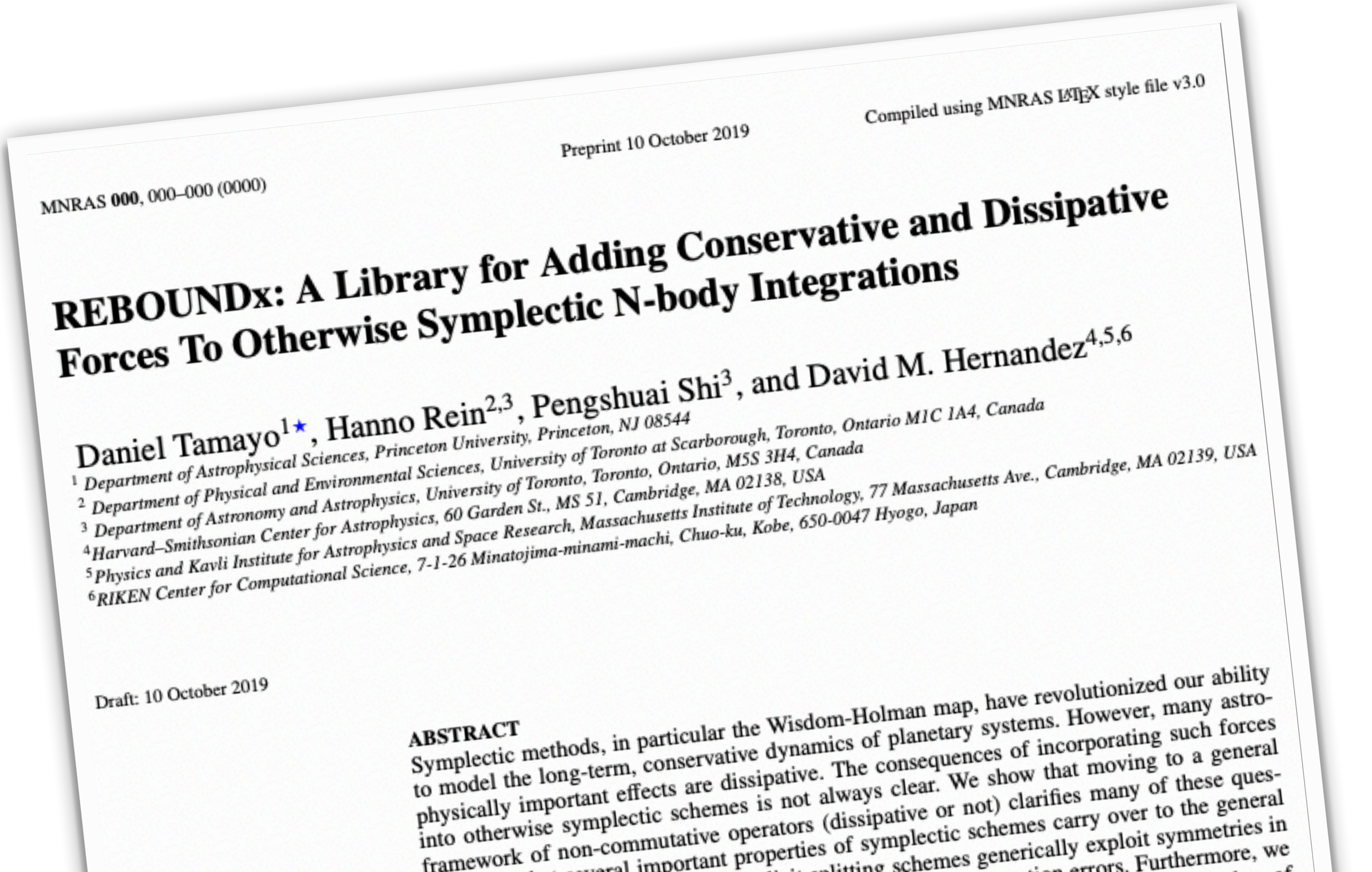


REBOUNDx

- Developed by Dan Tamayo (Princeton -> Harvey Mudd)
- Incorporate additional physics into N-body simulations
- Very easy to use!
- Also very smart behind the scenes!



REBOUNDx



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MNRAS **000**, 000–000 (0000)

REBOUNDx: A Library for Adding Conservative and Dissipative Forces To Otherwise Symplectic N-body Integrations

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ABSTRACT
Symplectic methods, in particular the Wisdom-Holman map, have revolutionized our ability to model the long-term, conservative dynamics of planetary systems. However, many astrophysically important effects are dissipative. The consequences of incorporating such forces into otherwise symplectic schemes is not always clear. We show that moving to a general framework of non-commutative operators (dissipative or not) clarifies many of these questions and that several important properties of symplectic schemes carry over to the general case. Explicit splitting schemes generically exploit symmetries in ... errors. Furthermore, we

REBOUND

Goal: Make REBOUND even easier to use!

- No installation
- No servers / no user management
- Native speed

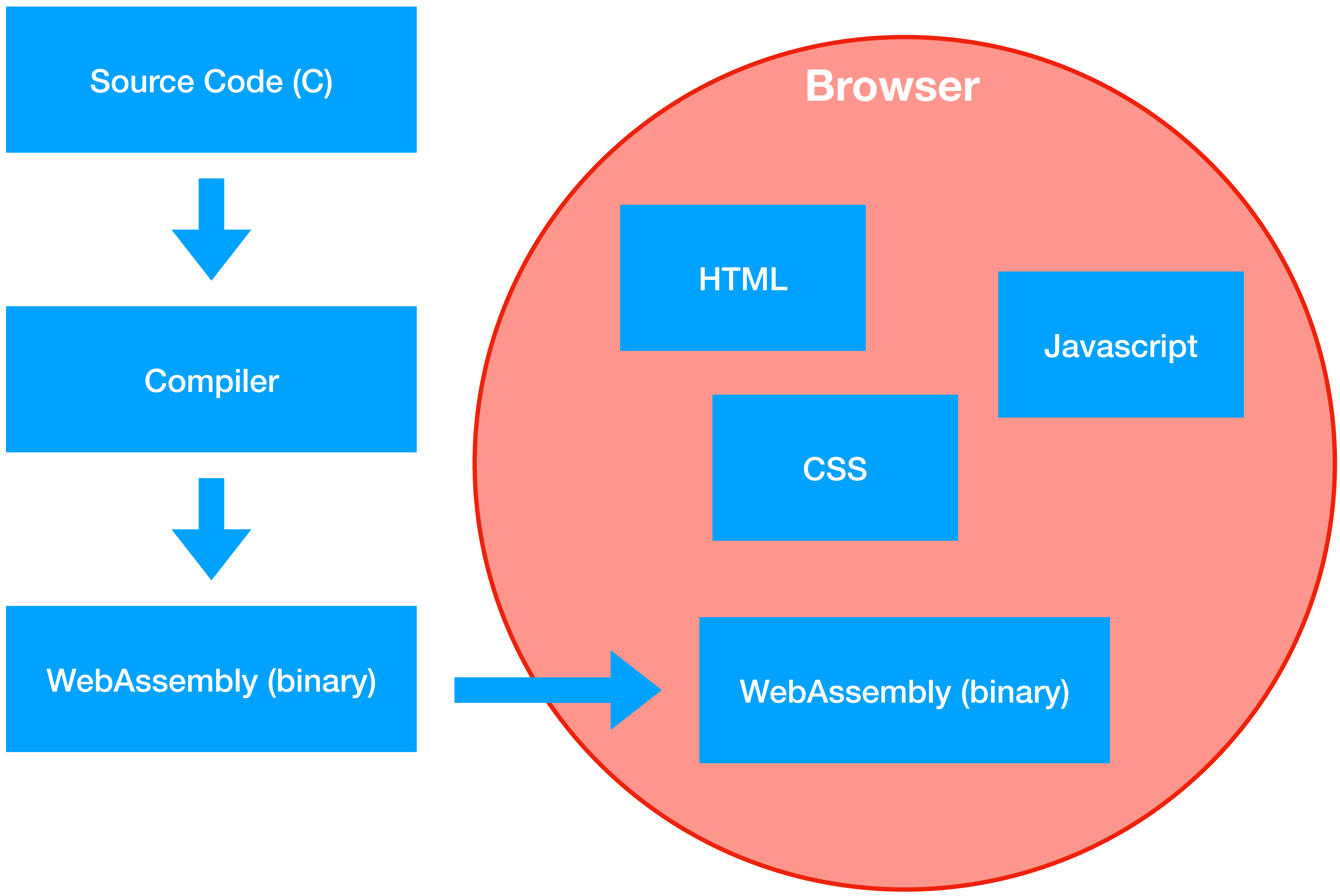
REBOUND

Idea: Embed REBOUND in a static website!

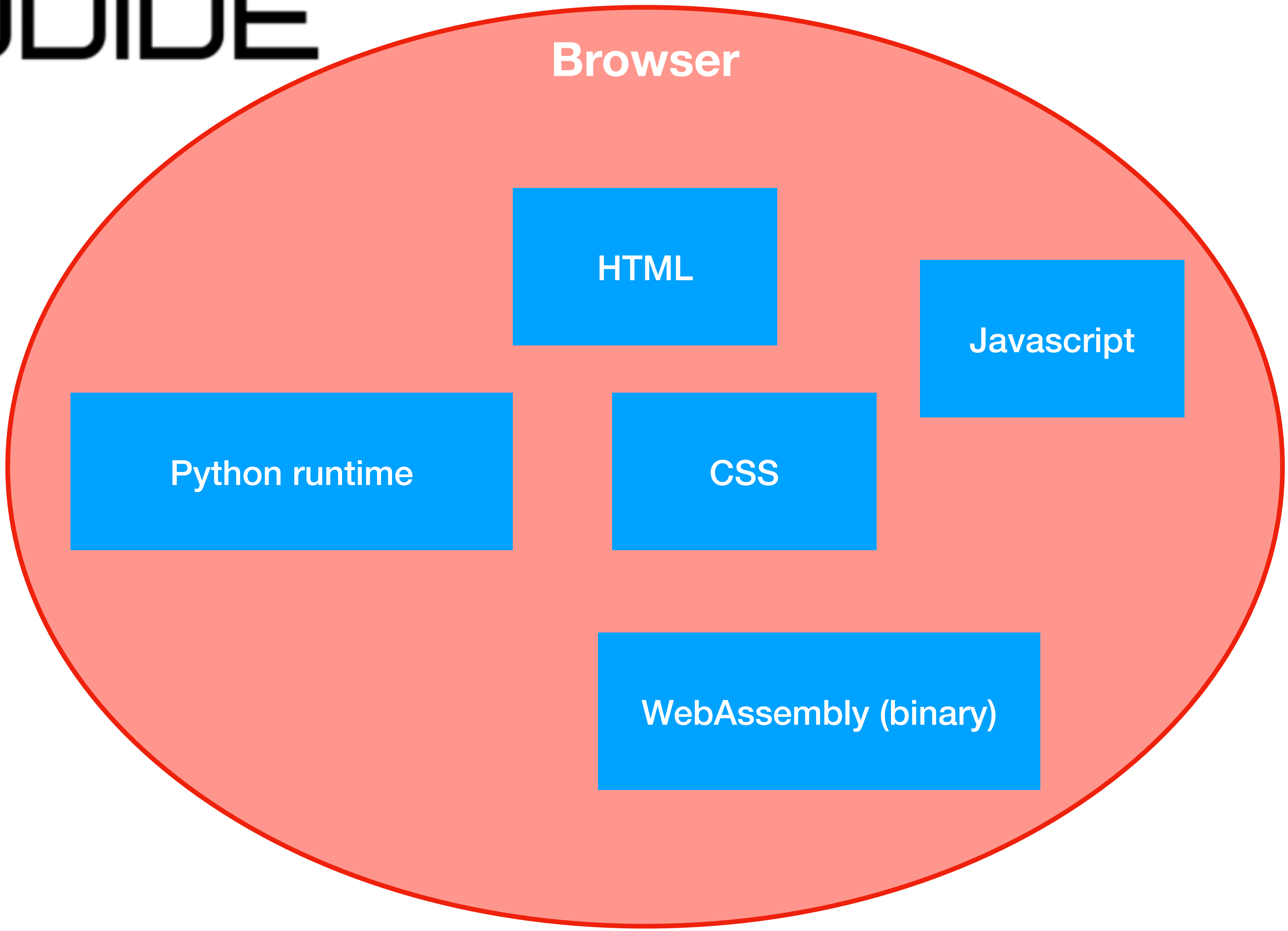
Use cases:

- Tutorials
- Education
- Reproducible publications

WebAssembly



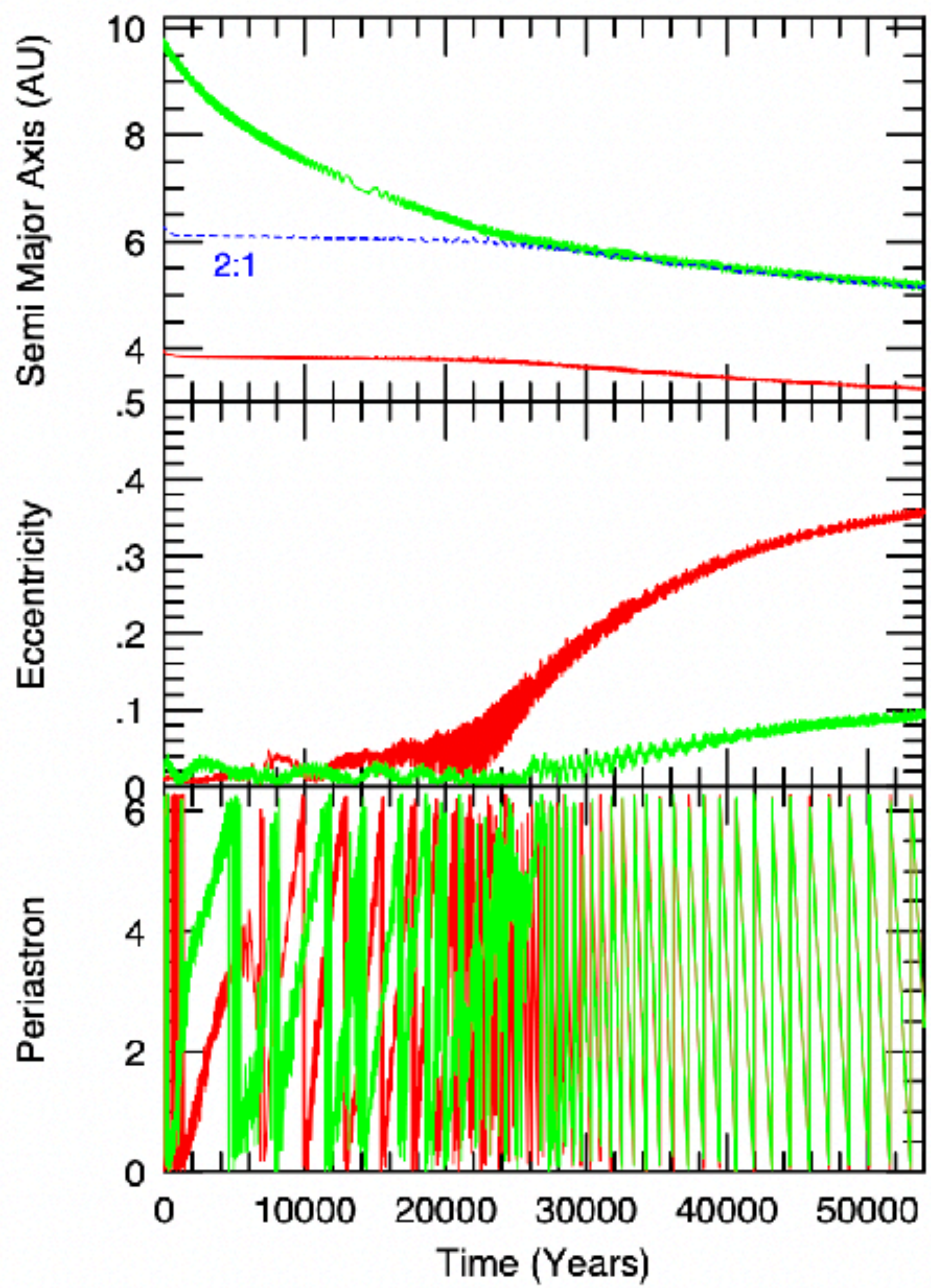
Pyodide



Browser
HTML
Javascript
Python runtime
CSS
WebAssembly (binary)

Demo!

- Let's reproduce some results from Kley, Peitz, and Bryden (2004)!
- Using REBOUND and REBOUNDx
- Running in the web browser using pyodide



rebound.hanno-rein.de

Image credit: NASA/SOFIA/Lynette Cook

Demo

```
import micropip
await micropip.install(“plotext")

import rebound, reboundx
import numpy as np
import plotext as plt
sim = rebound.Simulation()
sim.add(m=1.)
sim.add(m=3e-3,a=4)
sim.add(m=5e-3,a=10)
rebx = reboundx.Extras(sim)
mof = rebx.load_force(“modify_orbits_forces")
rebx.add_force(mof)
sim.particles[2].params["tau_a"] = -200000
sim.particles[2].params["tau_e"] = -400000

N = 1000
a = np.zeros((N,2))
times = np.linspace(0.,2e5,N)
for i in range(N):
    sim.integrate(times[i])
    a[i] = sim.particles[1].a, sim.particles[2].a

plt.plot(times,a[:,0])
plt.plot(times,a[:,1])
plt.show()
```