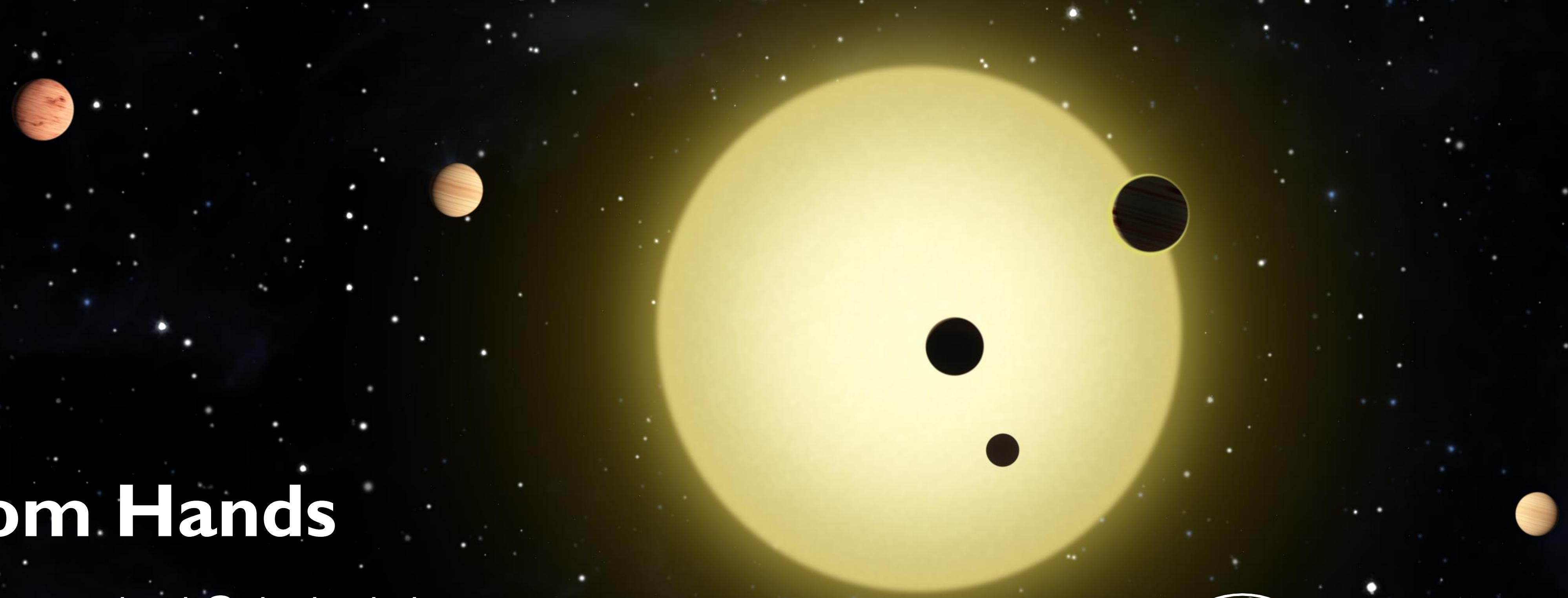
Breaking up is hard to do:

Breaking mean-motion resonances during type I migration



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Kepler-11, artist's impression. Image Credit: NASA/Tim Pyle

Planetary migration caused by angular momentum exchange with a disc

- Type I migration
  - Dominant mode of migration for low mass planets
  - Gas disc largely unperturbed by planet
  - Angular momentum exchanged with gas via resonant torques
  - Migration rate scales linearly with mass of planet
    - Means migration is often **convergent**
  - Eccentricity damped strongly

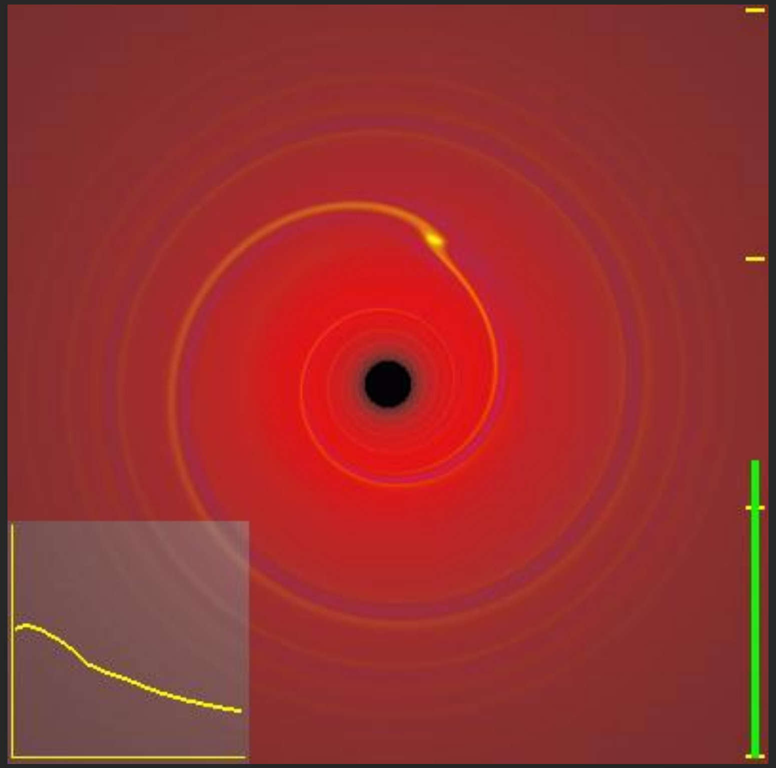


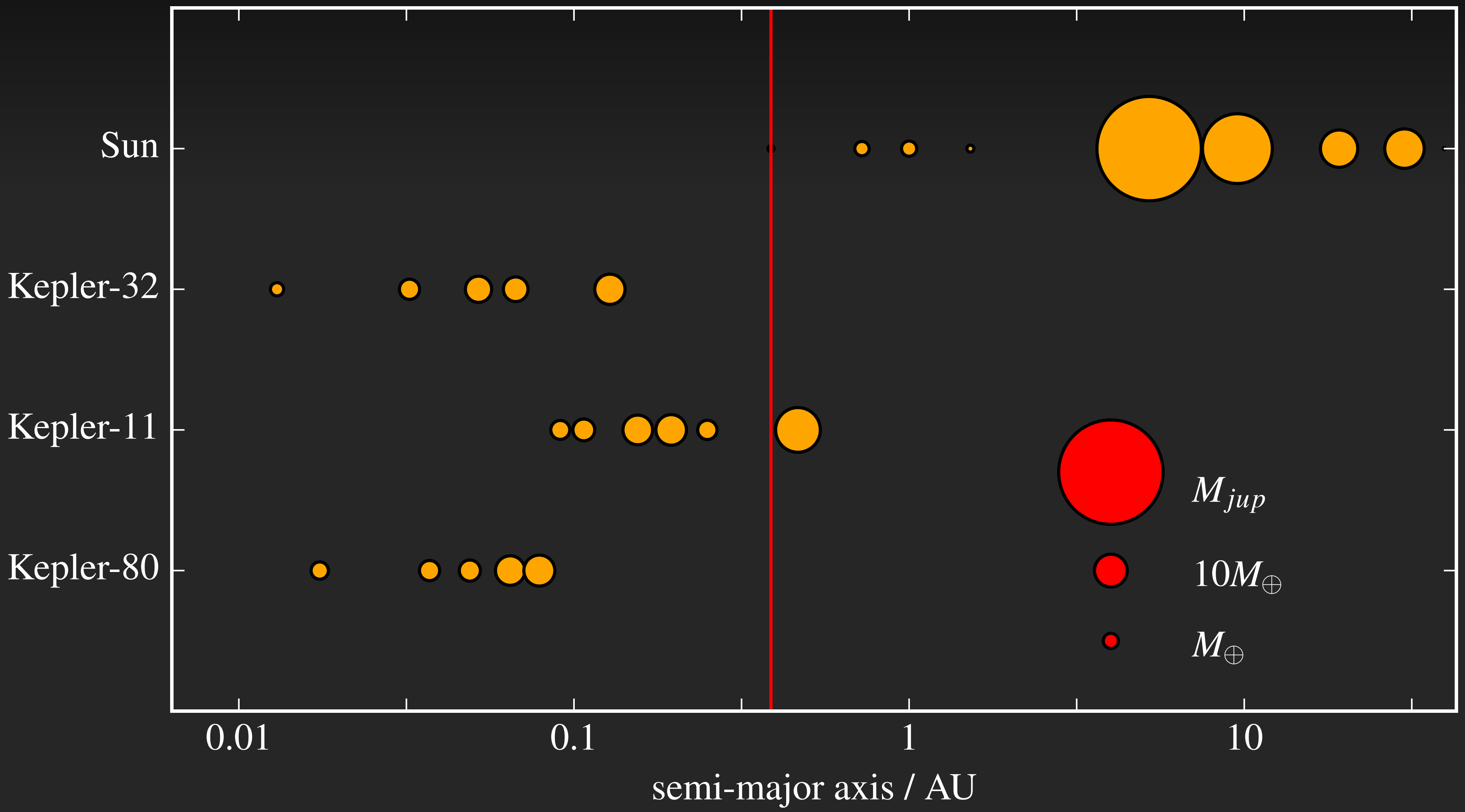
Image Credit: Phil Armitage

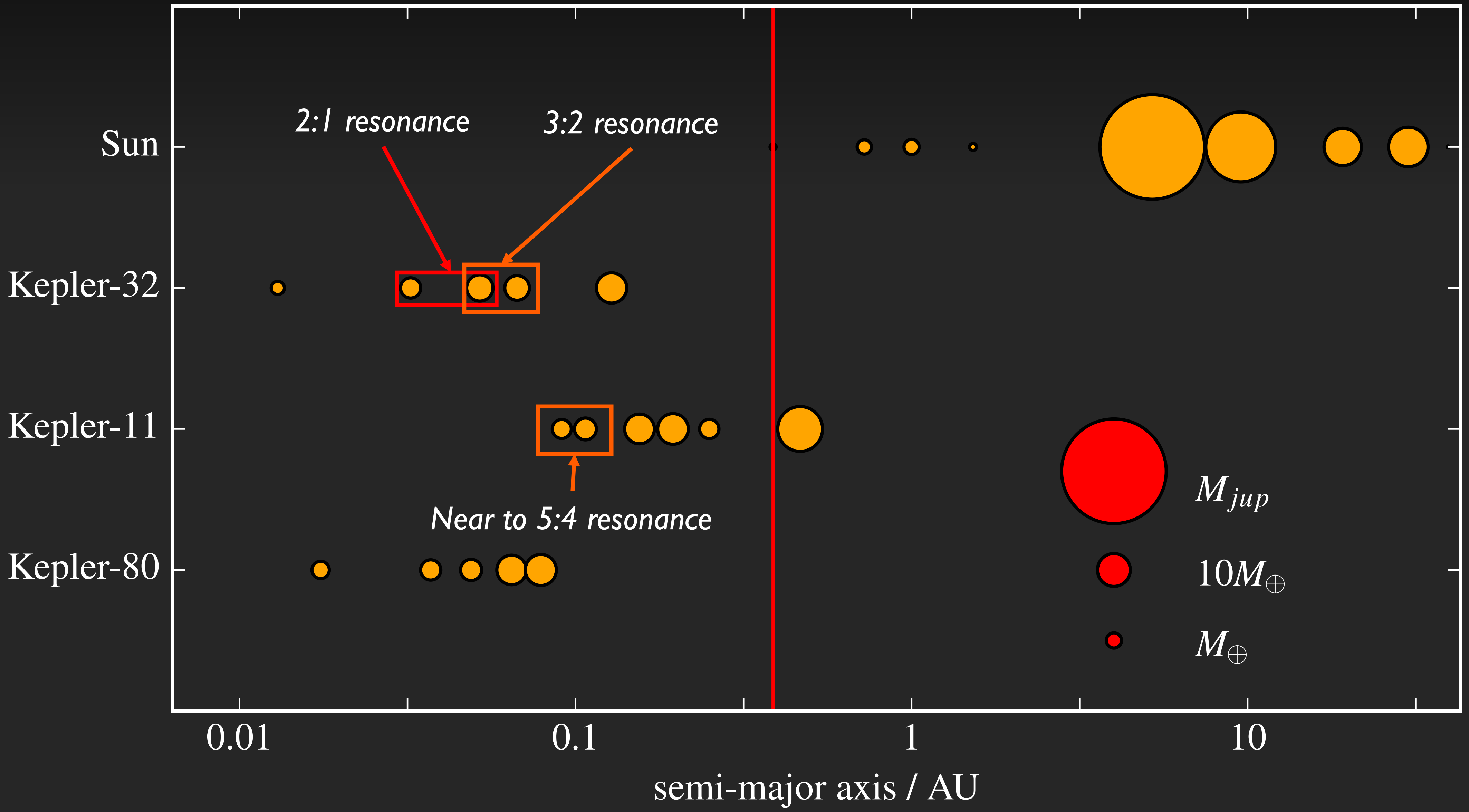
Resonant planet-planet interactions

- Planets interact gravitationally
- When resonant, mean-motions are commensurable and are related as

$$\frac{n}{n'} = \frac{p}{p+q}$$

  - For integer p and q
  - Where $n = 2\pi/T$ is the mean motion
- Resonances are traps that must be broken, excite eccentricity


Sun
Kepler-32
Kepler-11
Kepler-80
M_{jup}
$10M_{\oplus}$
$M_{\oplus}$
0.01
0.1
1
10
semi-major axis / AU



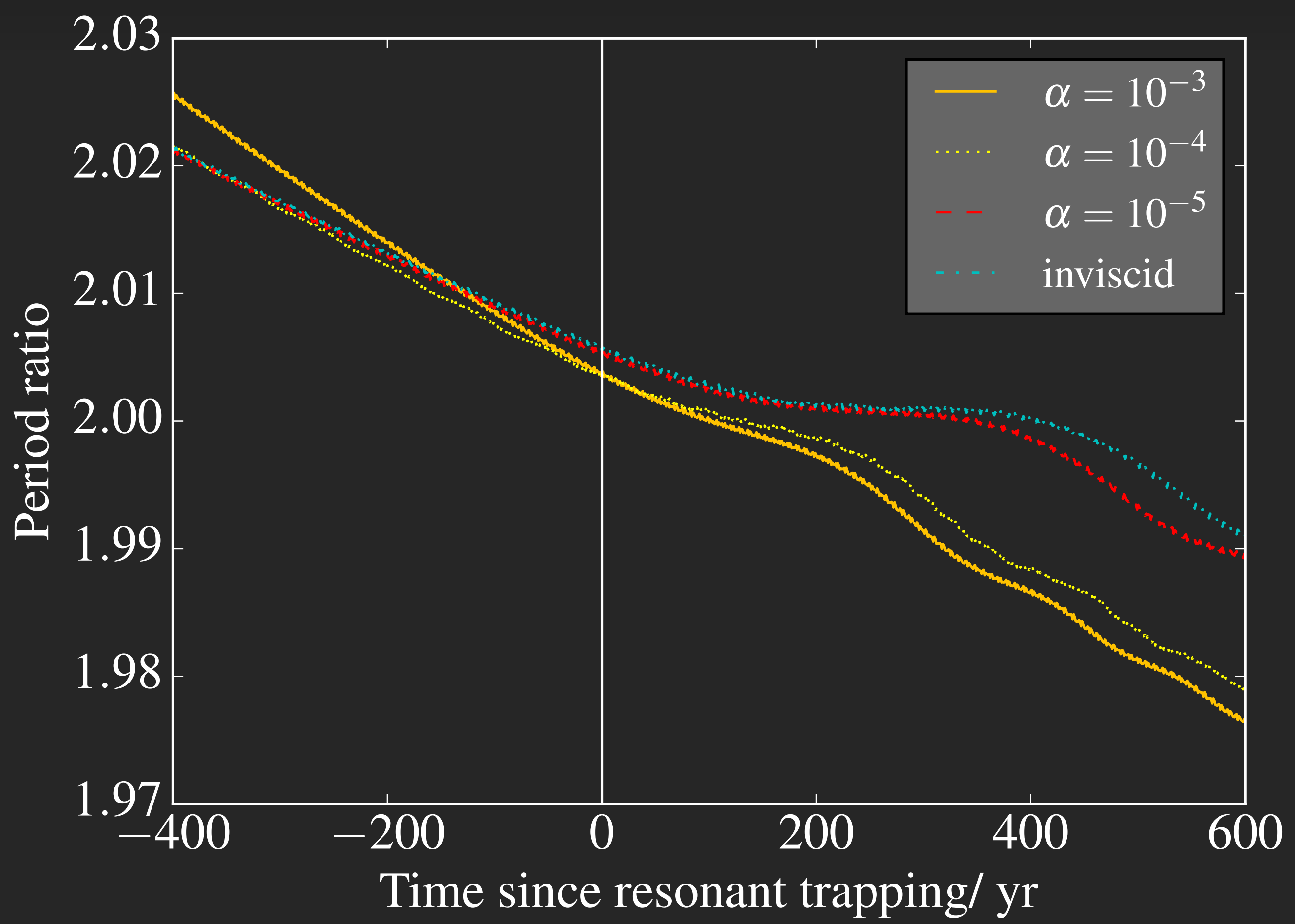
Sun
Kepler-32
Kepler-11
Kepler-80
2:1 resonance
3:2 resonance
Near to 5:4 resonance
M_{jup}
$10M_{\oplus}$
$M_{\oplus}$
0.01
0.1
1
10
semi-major axis / AU

Hydrodynamical simulations of migration

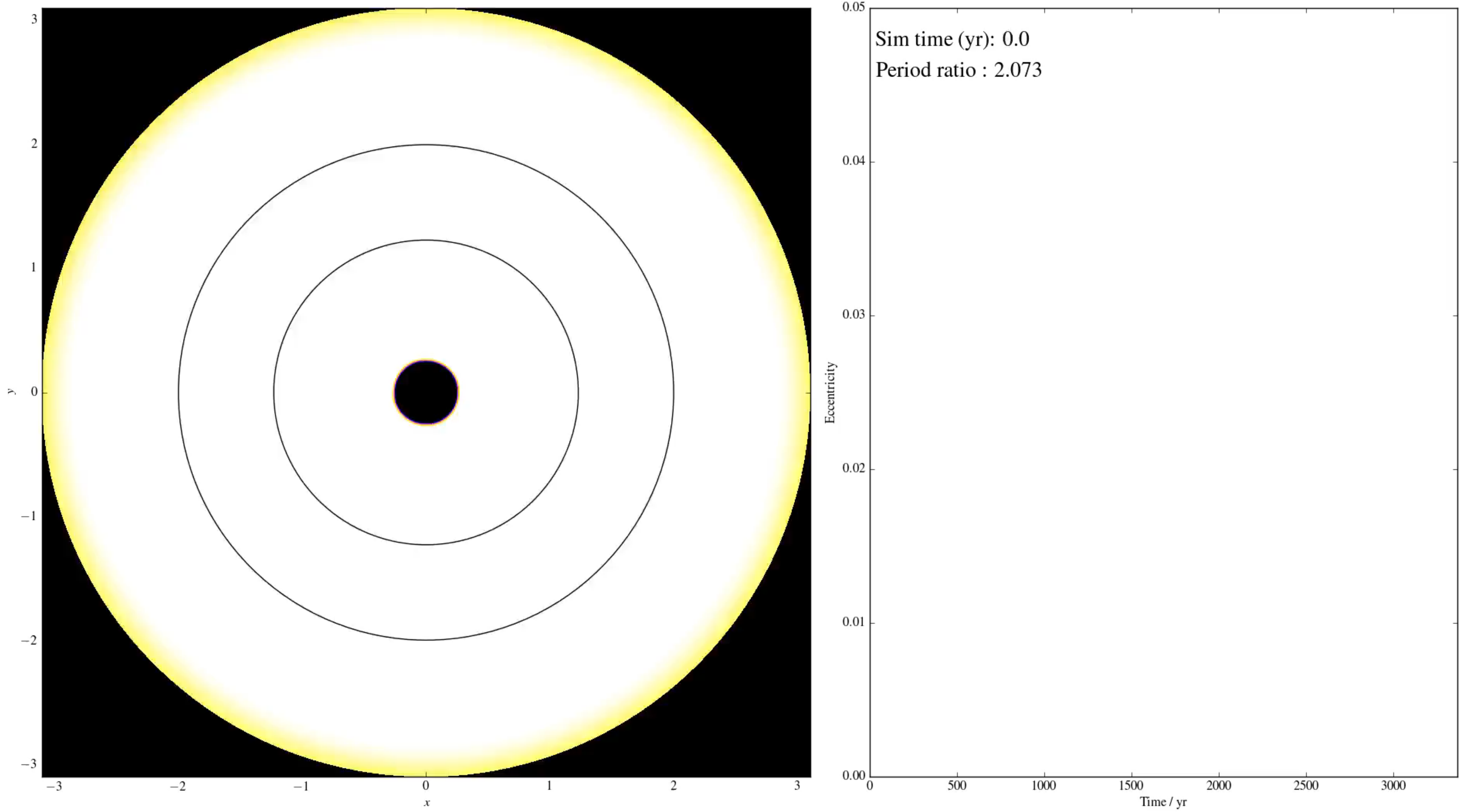
- 2D simulations using the *PLUTO* code (Mignone et al. 2007)
- High resolution model of inner disc: 0.25 – 3AU, 504 x 1256 cells
- Planet masses $5, 10\mathrm{M}_{\oplus}$ - migration is convergent
- Start planets near 2:1 resonance so they converge upon it
- Viscous disc $\alpha = 0, 10^{-5}, 10^{-4}, 10^{-3}$
- Flaring, locally isothermal EOS: $T(R) \propto R^{-1/2}$

Hands & Alexander
Submitted

So what happens?



- All cases capture in 2:1 resonance
- All cases subsequently break from 2:1 resonance…

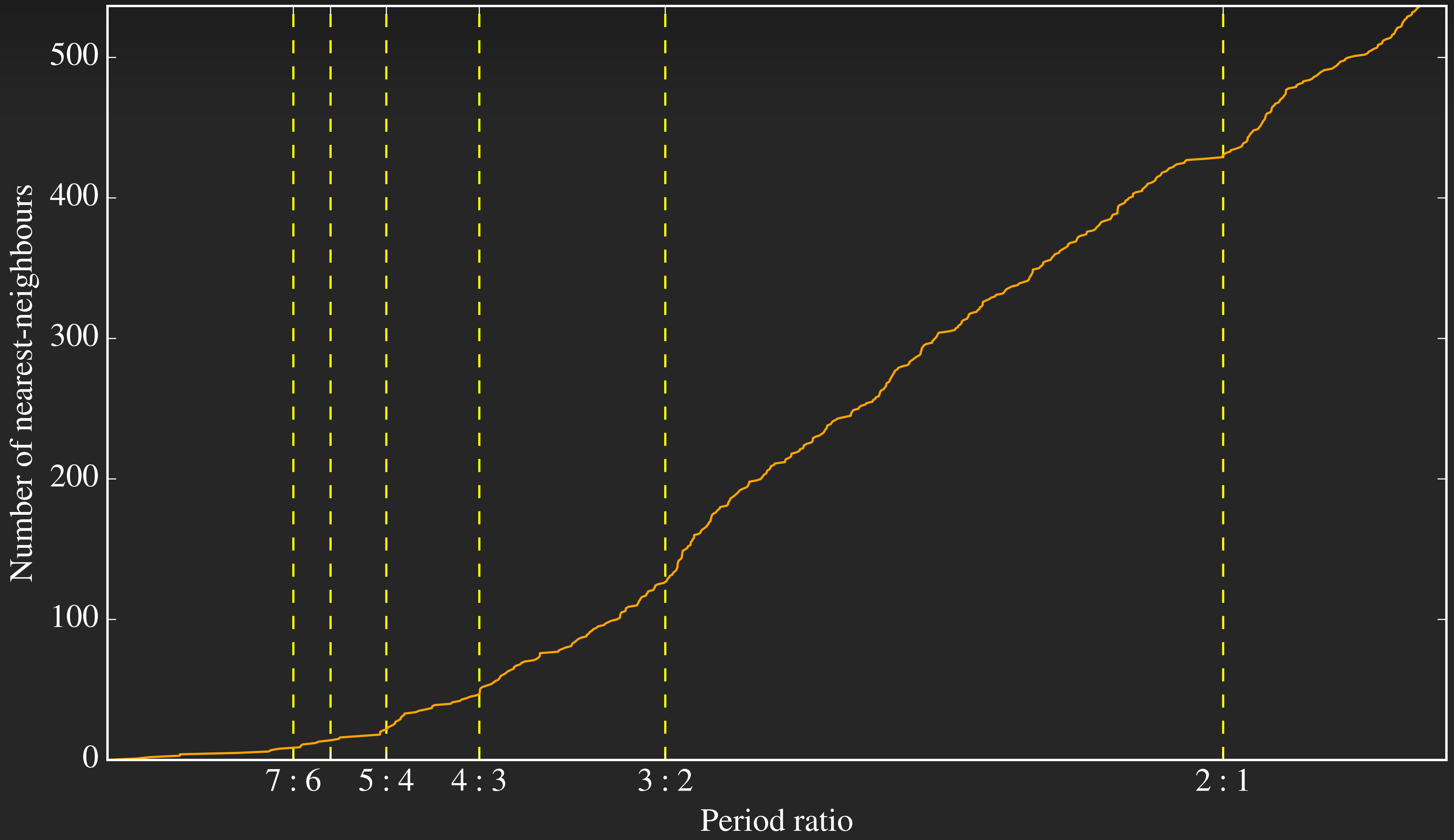


Sim time (yr): 0.0
Period ratio : 2.073
Eccentricity
Time / yr
x
y

Summary

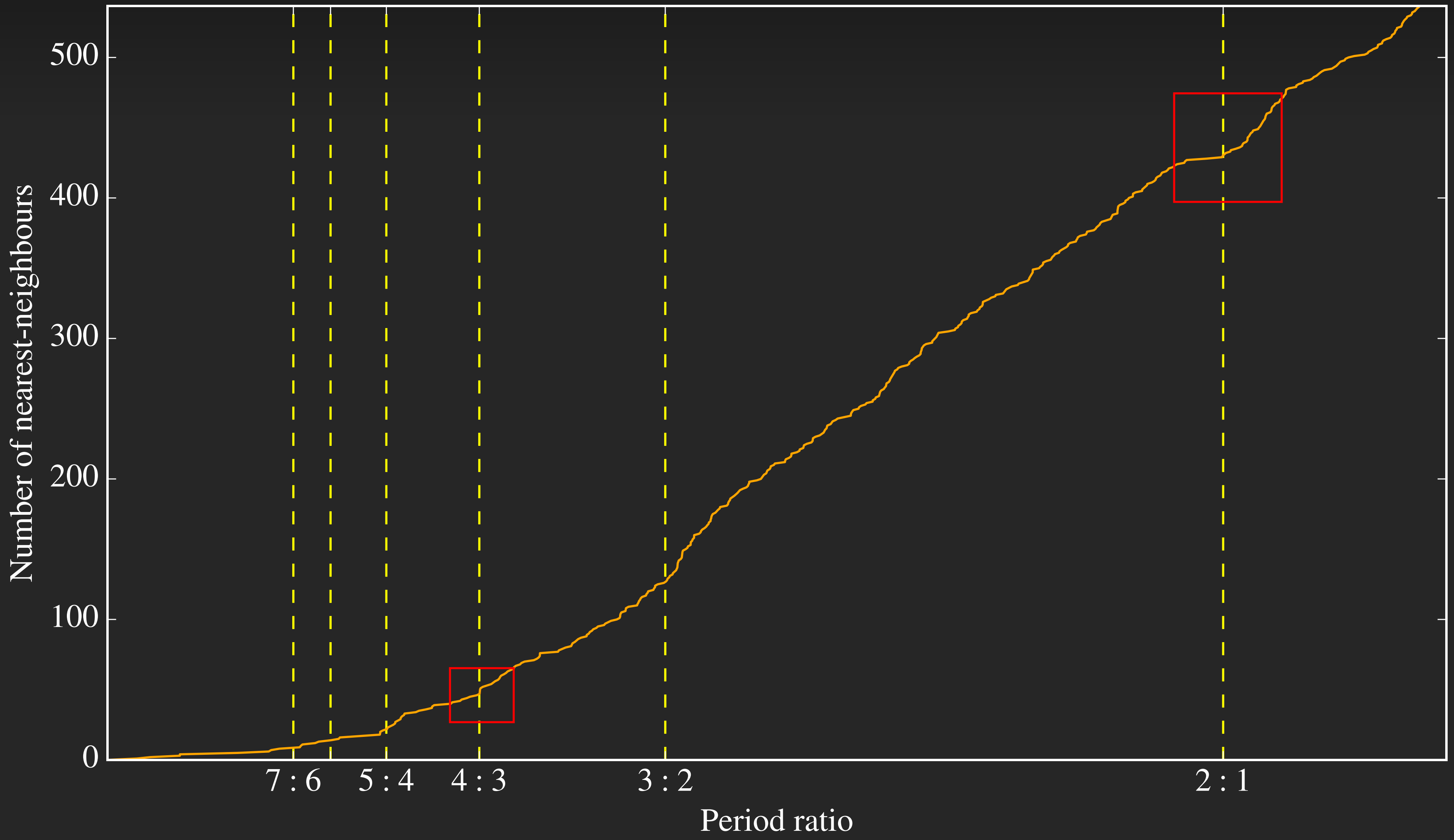
- Type I Migration models over-predict resonances
- HOWEVER, disc-driven migration does not have to result in permanent trapping
- Hydro simulations suggest that discs themselves can break resonances
- Further work required to understand exact mechanism, probably related to Goldreich & Schlichting (2014) mechanism

But not all pairs are resonant…

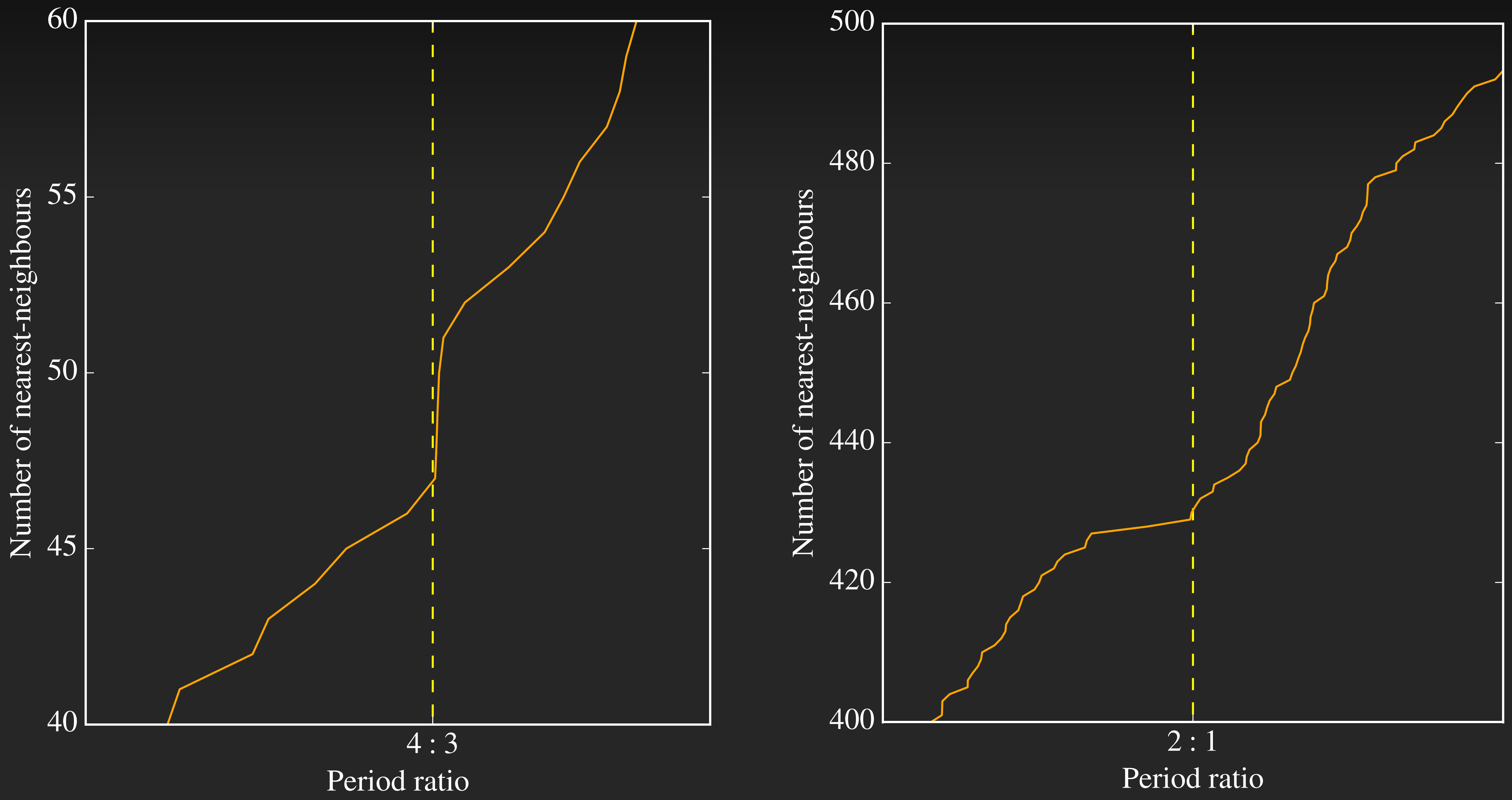


Data: exoplanets.org

But not all pairs are resonant…

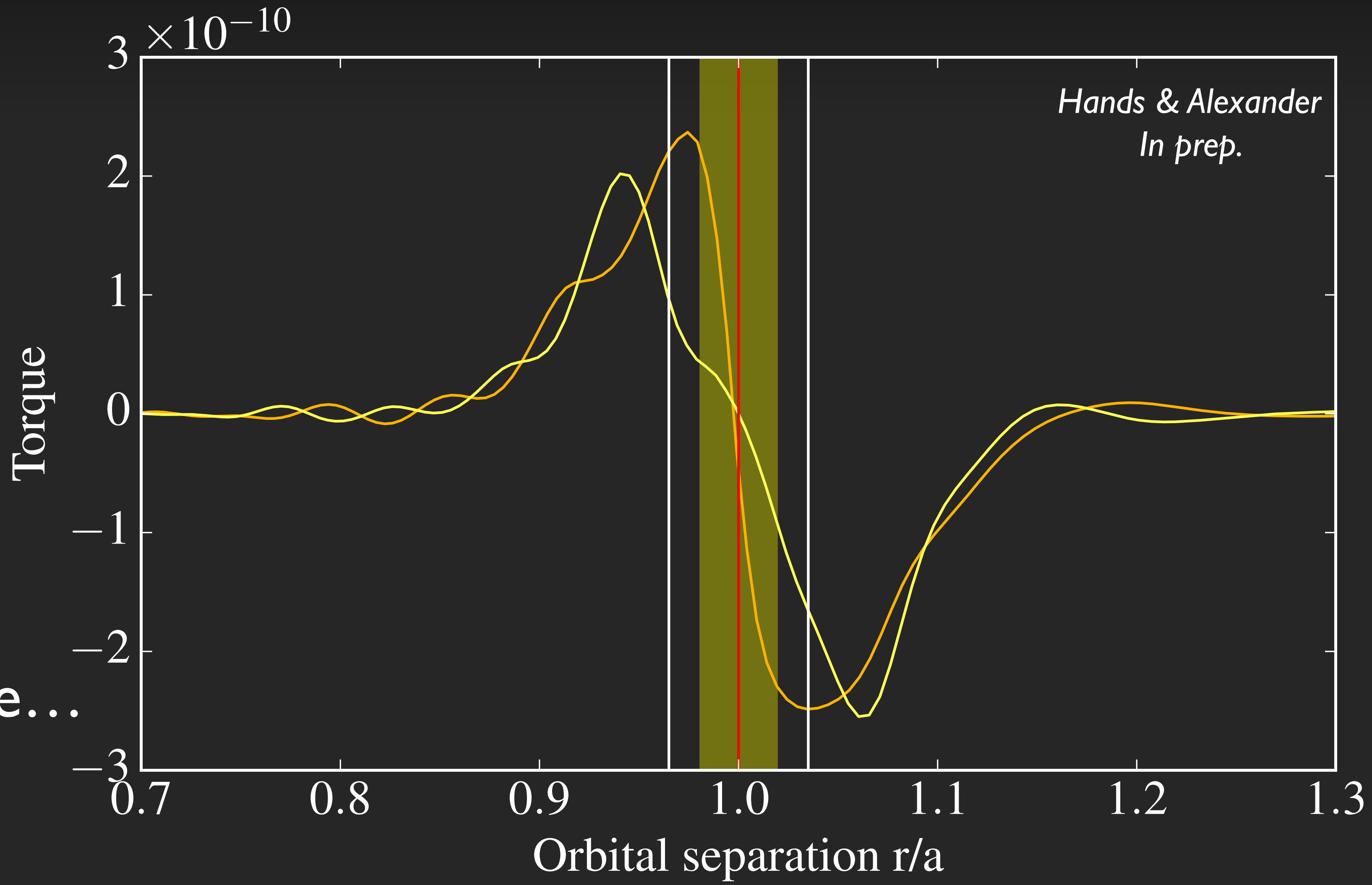


Data: exoplanets.org


60
55
50
45
40
Number of nearest-neighbours
4 : 3
Period ratio
500
480
460
440
420
400
Number of nearest-neighbours
2 : 1
Period ratio

What causes the resonances to break?

- **NOT** *N*-body
- Might be related to Goldreich & Schlichting mechanism
- **But** torques also change…



Eccentric planets feel different torques

- Papaloizou & Larwood (2000)
  - Reversal of Lindblad torques for $e > 1.1(H/R)$
  - Reduction of Lindblad torques for smaller eccentricities
- Fendyke & Nelson (2014)
  - Exponential reduction in corotation talk for small, non-zero eccentricities