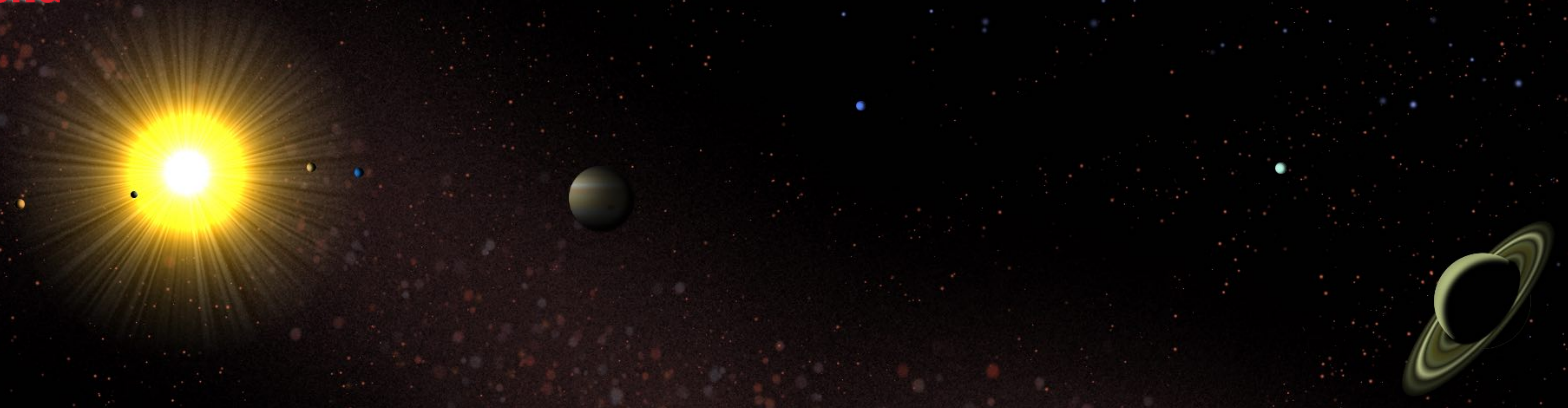
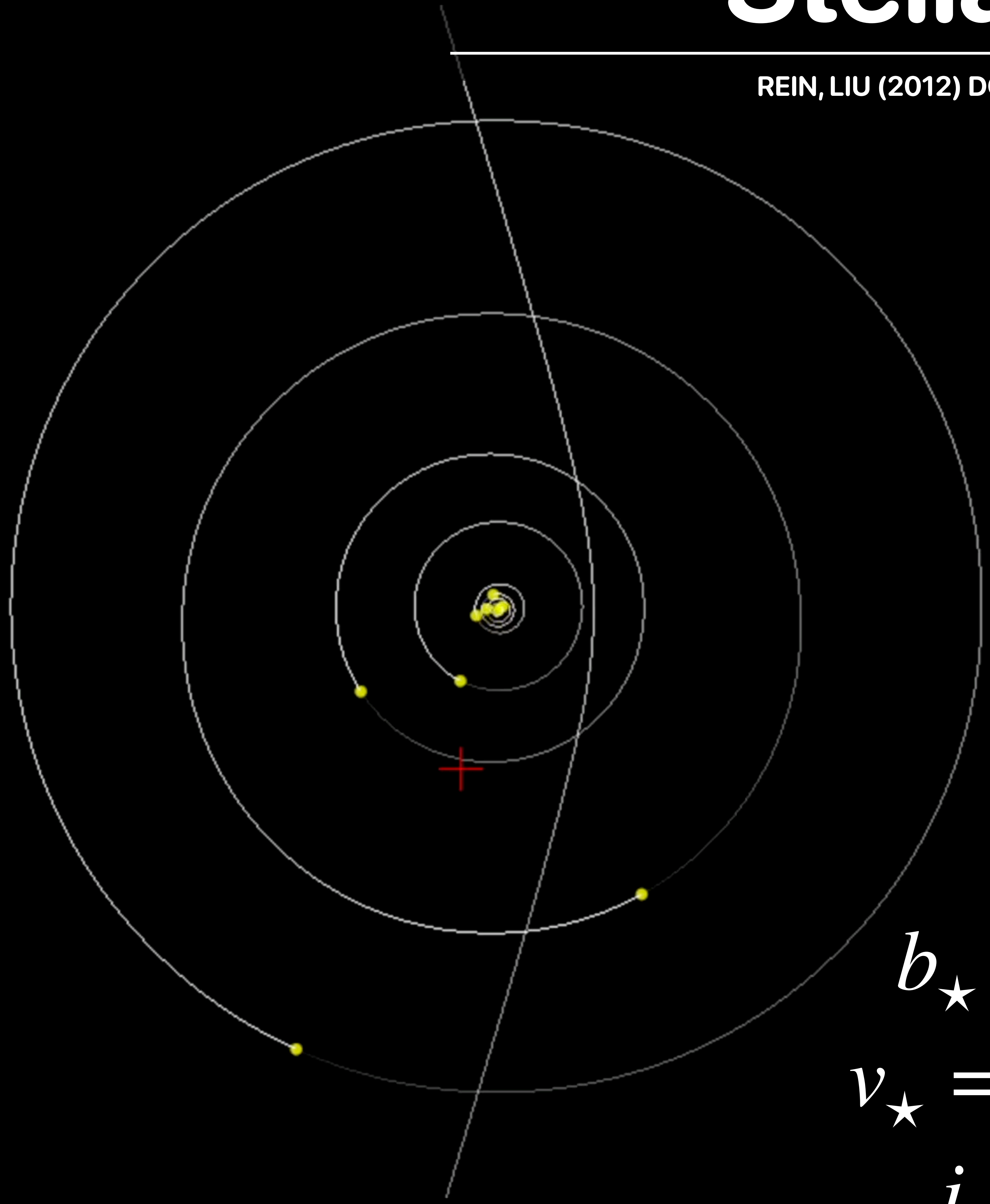


The effects of stellar flybys on the formation and long-term stability of the Solar System

GARETT BROWN, HANNO REIN, RENU MALHOTRA

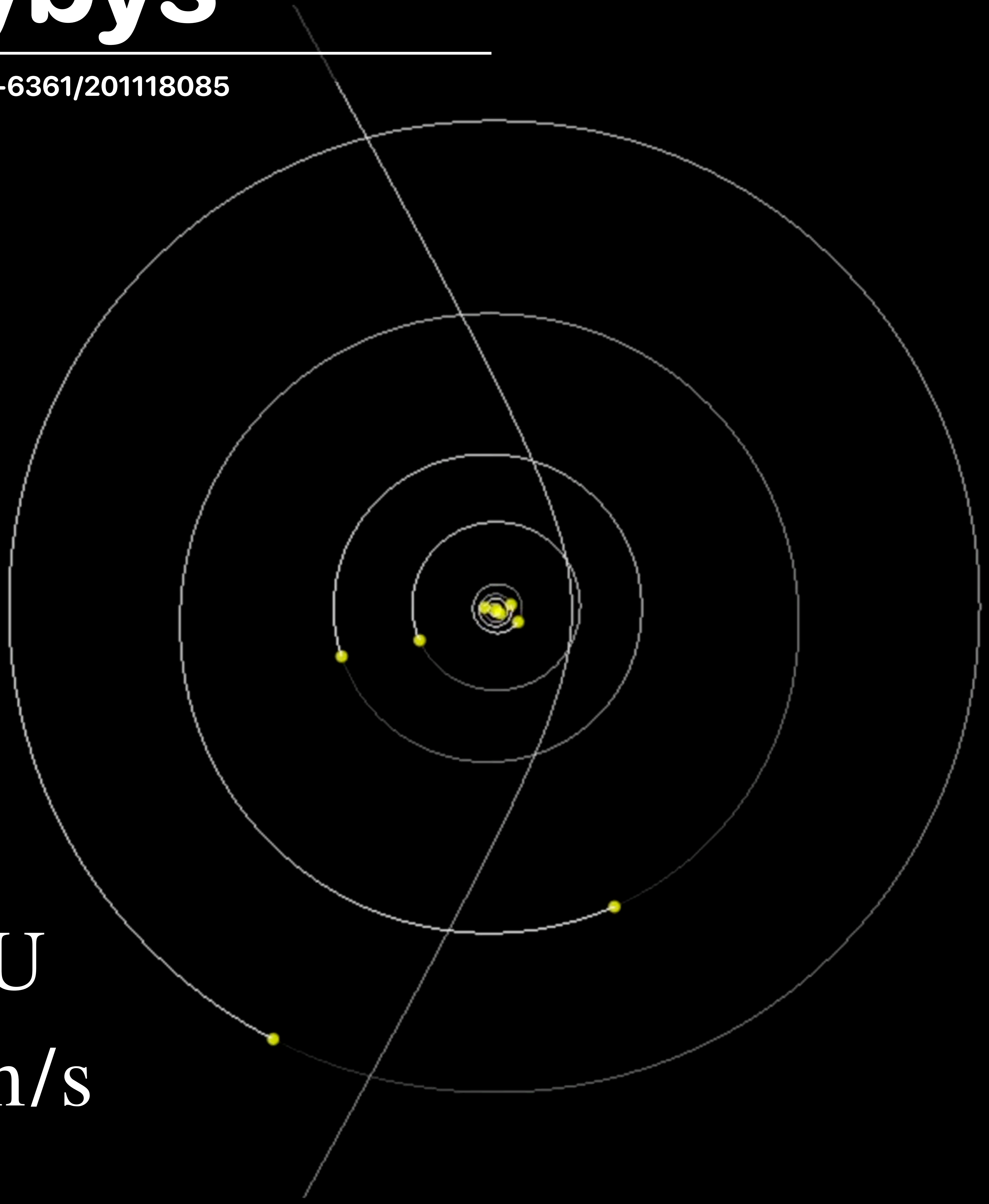
Stellar Flybys

REIN, LIU (2012) DOI: 10.1051/0004-6361/201118085



$$m_\star = 0.1\,M_\odot$$

$$b_\star = 8\,\mathrm{AU}$$
$$v_\star = 20\,\mathrm{km/s}$$
$$i_\star = 12^\circ$$



$$m_\star = 1.0\,M_\odot$$

BROWN ET AL. (IN PREP) AIRBALL.READTHEDOCS.IO

AIRBALL

- A package for running and managing flybys in REBOUND
- Stellar environments for generating flyby stars
- Initial mass functions
- `astropy.units`

BROWN ET AL. (IN PREP)

AIRBALL.READTHEDOCS.IO

AIRBALL

```
> import rebound
> import airball
> sim = rebound.Simulation()
> sim.add('solar system')
> stars = airball.Stars(airball.OpenCluster(),size=10)
> airball.flybys(sim, stars)
```

Origins of the Secular Modes

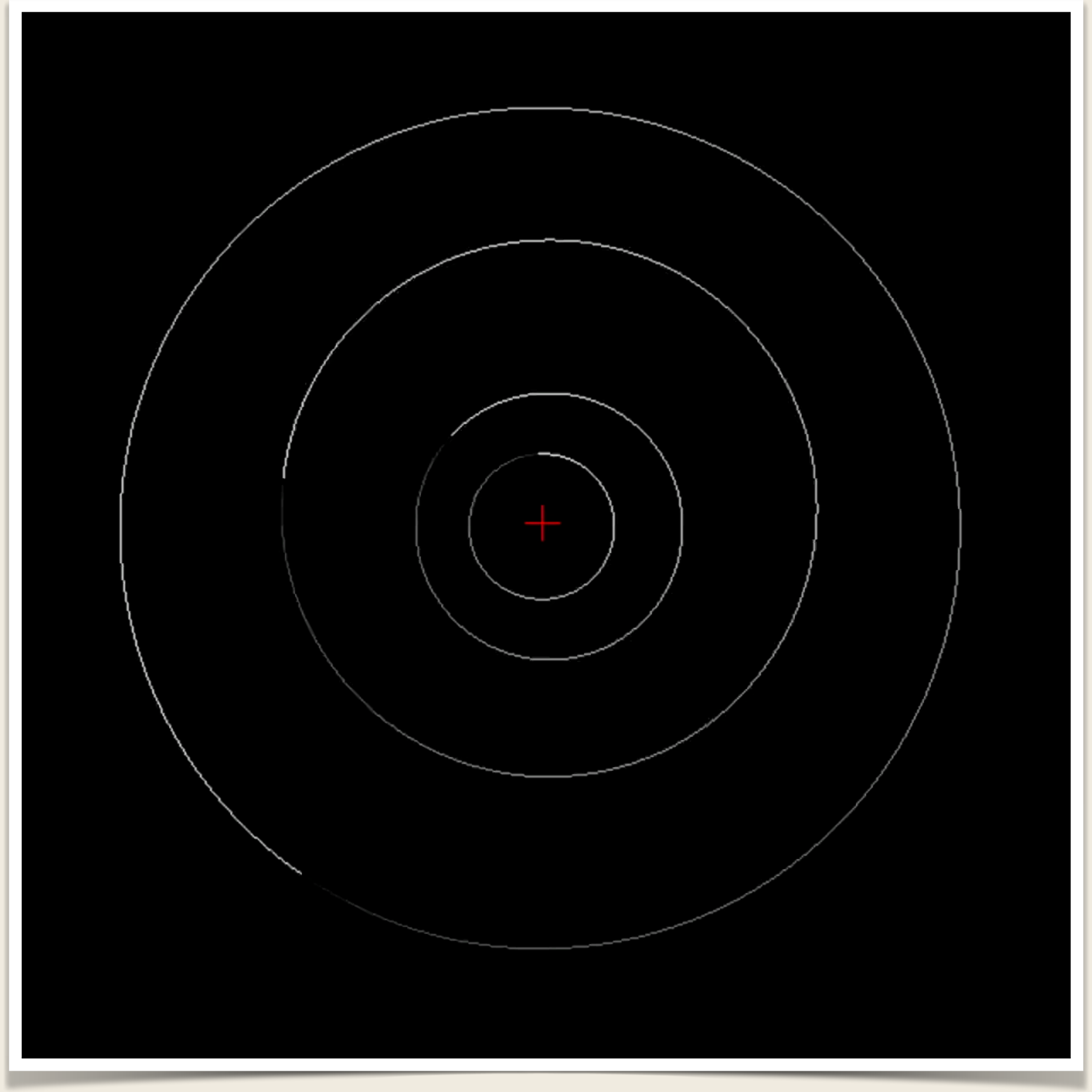
Brown, Rein, & Malhotra (in prep)

LASKAR (1990) DOI: 10.1016/0019-1035(90)90084-M; ŠIDLICHOVSKÝ & NESVORNÝ (1996) DOI: 10.1007/BF00048443

Secular Modes

Integrate over millions of years, then find the modes using Modified Fourier Transform (MFT)

- Assume planets are interacting rings
- Mutual interaction causes the orbits to precess and deform
- Compute the complex eccentricities and inclinations:
  - $z_j(t) = e_j(t)\ \exp[\mathbf{i}\varpi_j(t)]$
  - $\zeta_j(t) = i_j(t)\ \exp[\mathbf{i}\Omega_j(t)]$
- Compute FMFT of $z_j(t)$ and $\zeta_j(t)$.



Origins of the Secular Modes

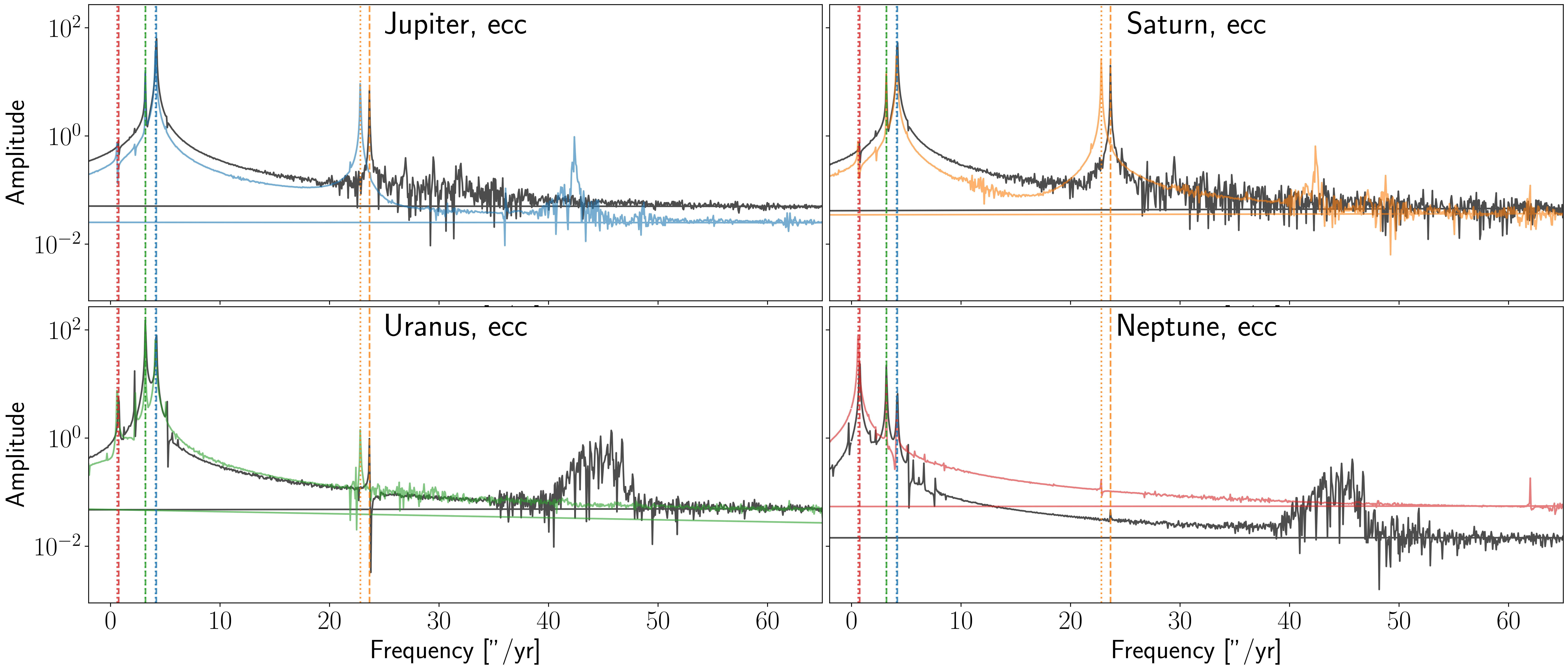
Can a flyby reproduce the solar system architecture we observe today? Yes

- Assume gas giants are:
  - circular, coplanar orbits
  - same semi-major axes as today.
- Simulate one (1) stellar flyby and compare to the solar system today.
- Stellar Flyby:
  - $m_\star = 0.04\,M_\odot$
  - $q_\star = 3.83\ \mathrm{AU}$
  - $v_\star = 59.65\ \mathrm{km/s}$
  - $i_\star = 77.93^\circ$

"/yr	Solar System Today	After Stellar Flyby
g5	4.181	4.113
g6	23.653	22.818
g7	3.194	3.178
g8	0.743	0.613
s5	—	—
s6	-25.952	-25.029
s7	-3.152	-3.349
s8	-0.714	-0.659

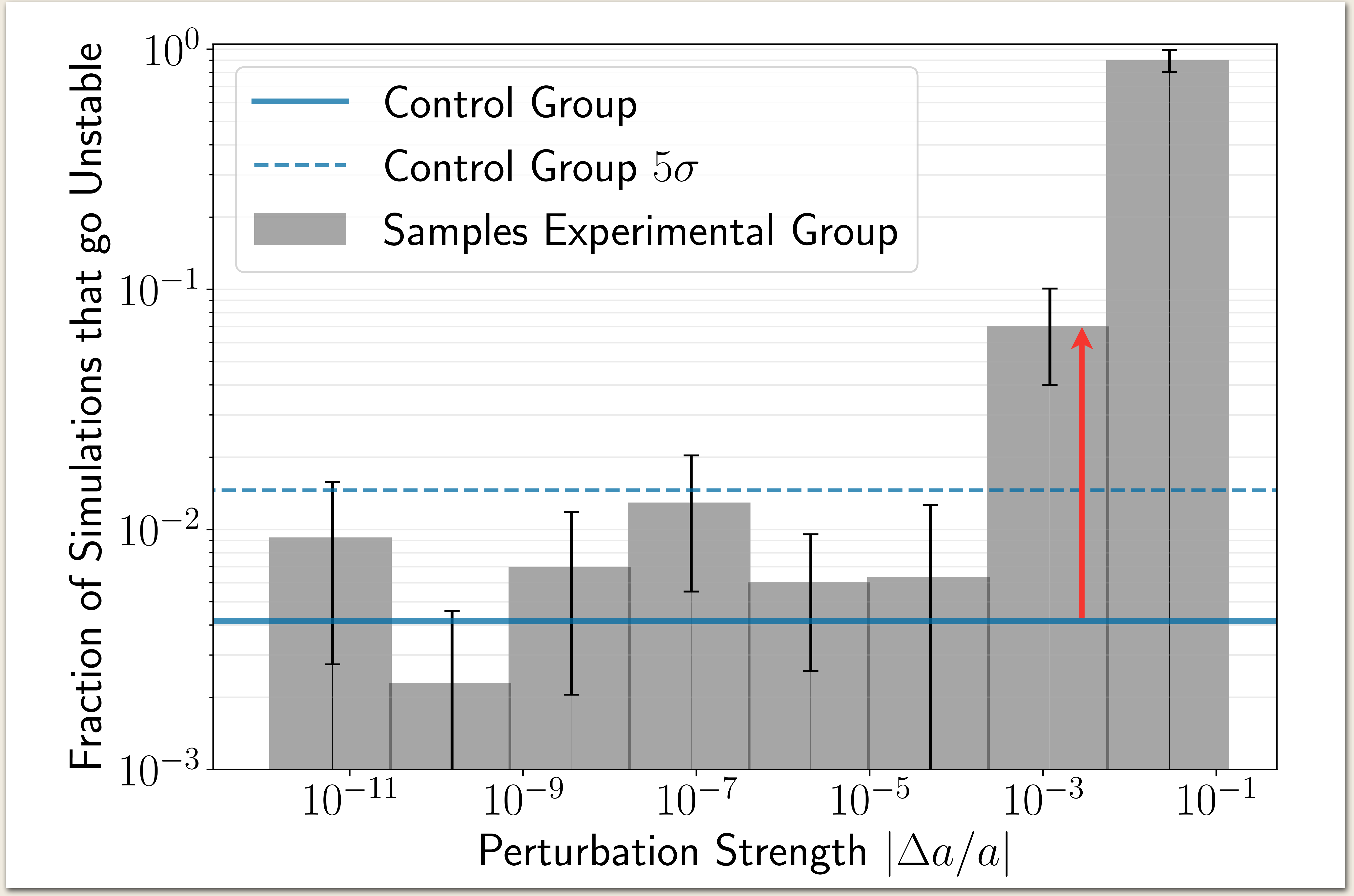
Frequencies match within 8%
Amplitude match within a factor of 2

Origins of the Secular Modes



Stellar Flybys and Long-term Stability

Brown & Rein (2022)



$$N_{\text{Control}} = 960$$
$$N_{\text{Experimental}} = 1920$$

BROWN & REIN (2022) DOI: 10.1093/MNRAS/STAC1763

Stellar Flybys and stability

- 0.1% relative change to Neptune's semi-major axis increases instability within 5 billion years by one order of magnitude.
- A flyby of this magnitude is not likely to pass the solar system for 100 billion years

Summary

- The secular structure of the solar system can be reproduced with a single flyby.
- Weak stellar flybys can increase the chance of solar system instability, over the subsequent 5 billion years.



Stability of the Secular Modes

Integrate over millions of years, then find the modes using Modified Fourier Transform (MFT)

- Solar System fundamental frequencies
- Obtained with modified Fourier transform (MFT)
- 20 Myrs for the inner planets
  50 Myrs for the outer planets

"/yr	Rein & Brown (2019)	Laplace-Lagrange
g1	**5.589**	5.462
g2	7.422	7.347
g3	17.359	17.332
g4	17.914	18.006
g5	**4.258**	3.733
g6	28.246	22.512
g7	3.088	—
g8	0.673	—

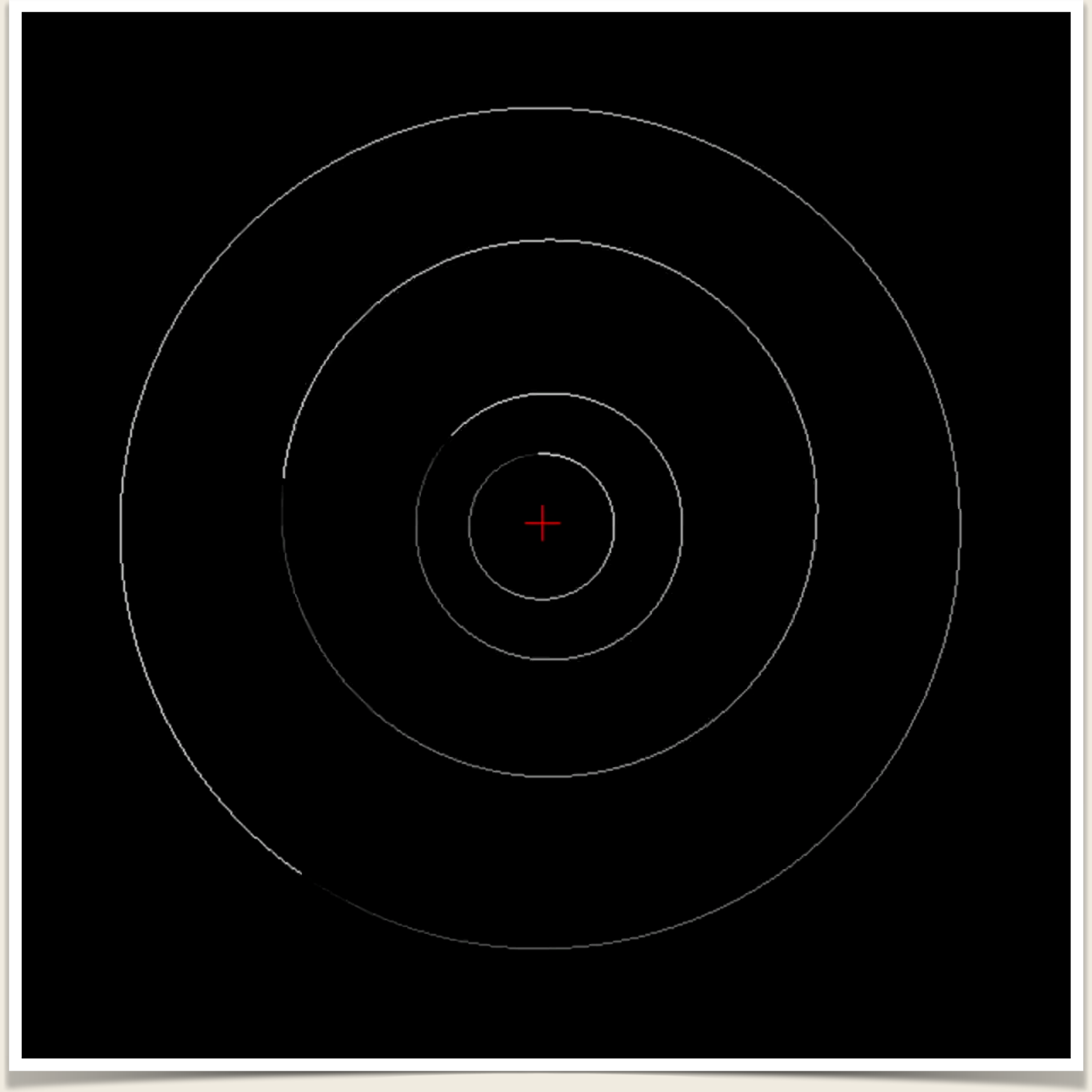
LITHWICK & WU (2011) DOI: 10.1088/0004-637X/739/1/31

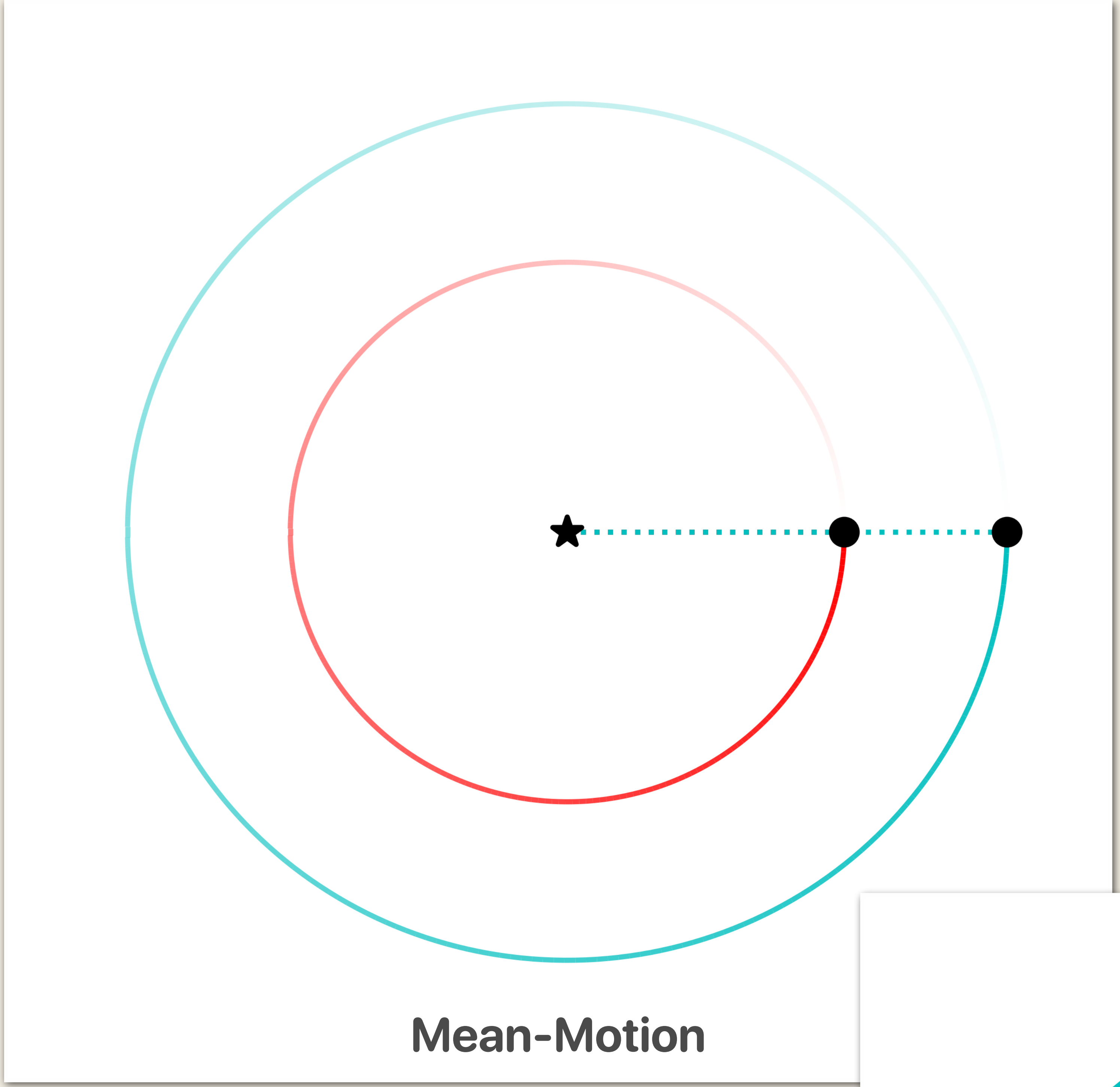
Secular Resonance

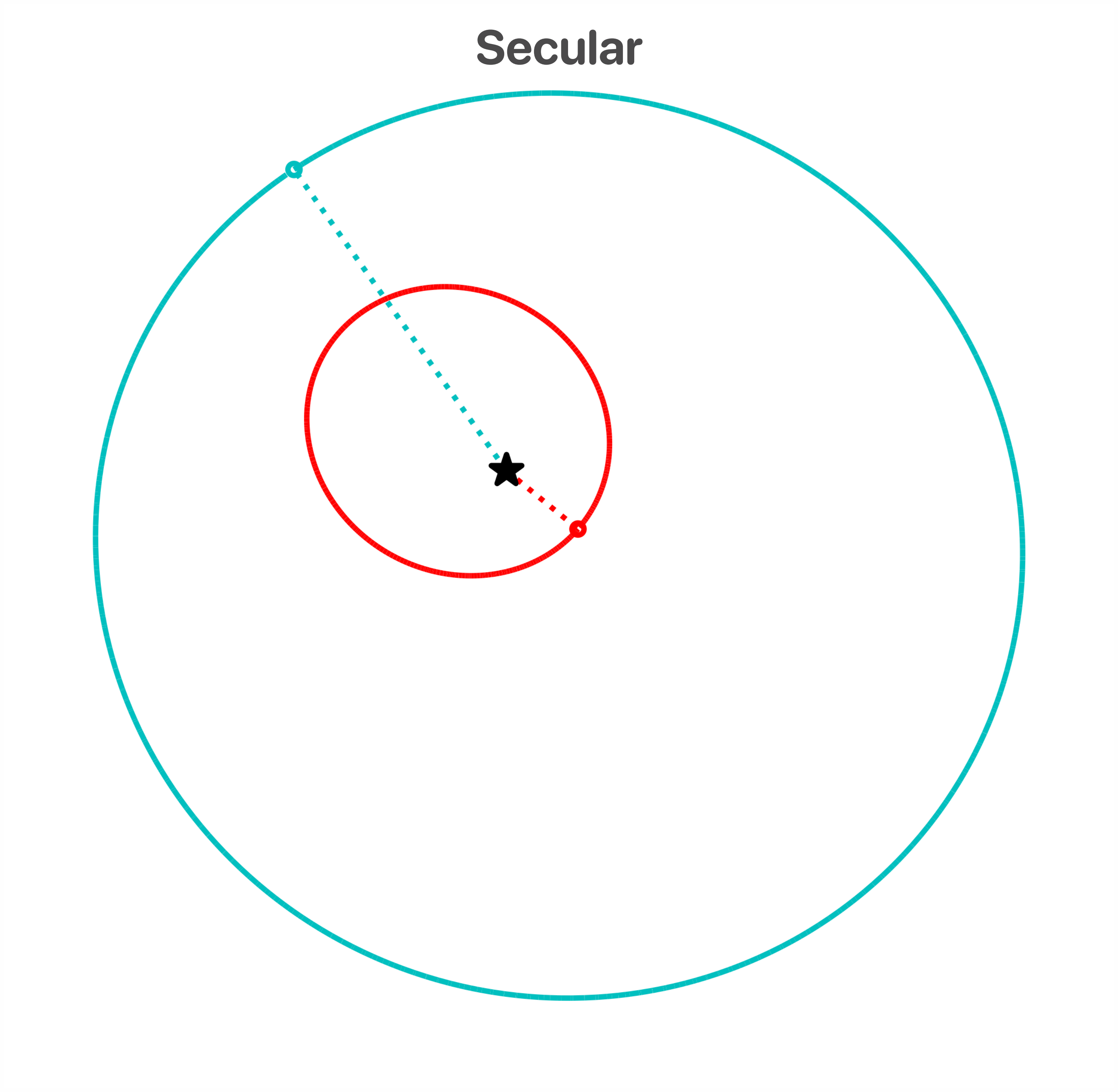
Secular Modes

Average over the fast timescales and expand with perturbation theory...

- Effectively assume the planets are interacting rings of mass
- Mutual interaction causes the orbits to precess and deform
- Linearized equations $\Rightarrow$ eigenvalues (secular frequencies/modes)
- Quasi-periodic functions







MURRAY & DERMOTT (1999); TREMAINE (2023)

Secular Resonance

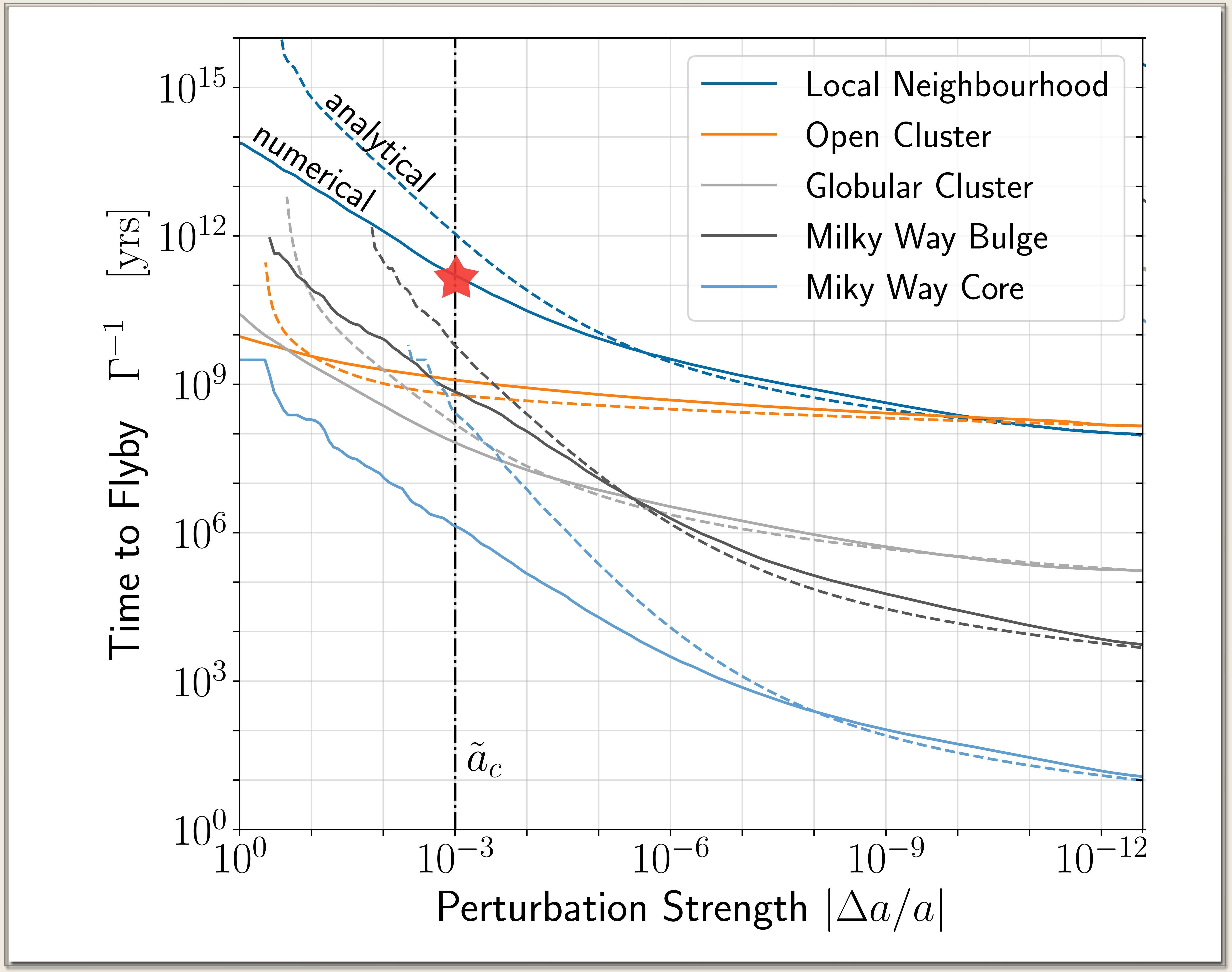
- Secular resonances occur when the precessional frequencies of an orbit are similar to another in the system
- Mean-motion resonances occur when the orbital period of one planet is a small integer ratio of another planet's period

BROWN & REIN (2022) DOI: 10.1093/MNRAS/STAC1763

Experimental Setup: Stellar Flybys

- 2,880, 4.8 Gyrs solar system simulations:
  - 960 control sims, 1920 experimental sims
- NASA JPL Horizons, J2000 epoch
- REBOUND N-body integrator
- REBOUNDx with `gr_potential`
- WHCKL integrator
- `dt` = `8.062` days

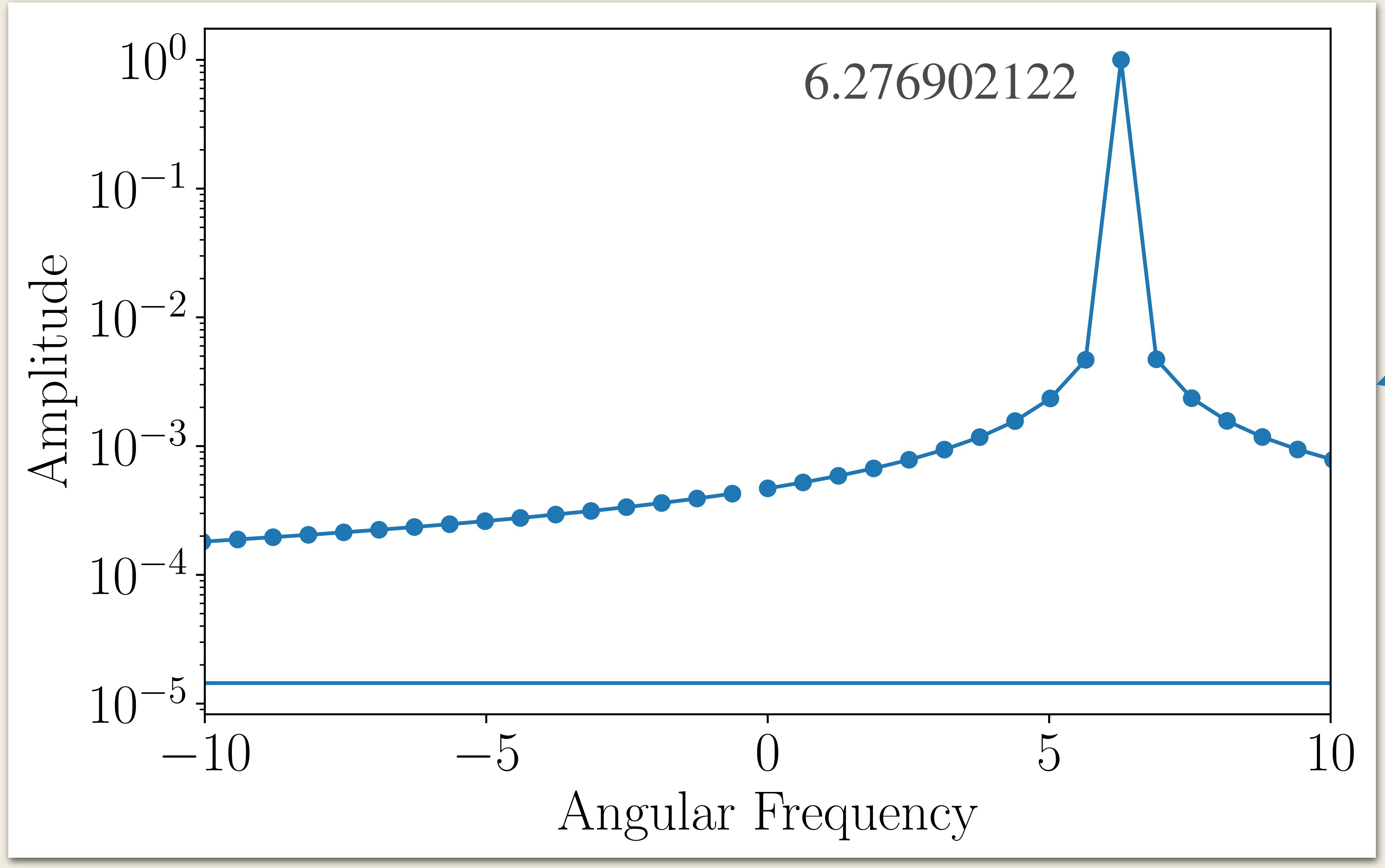
Stellar flybys affect Neptune's orbit more than the other planets



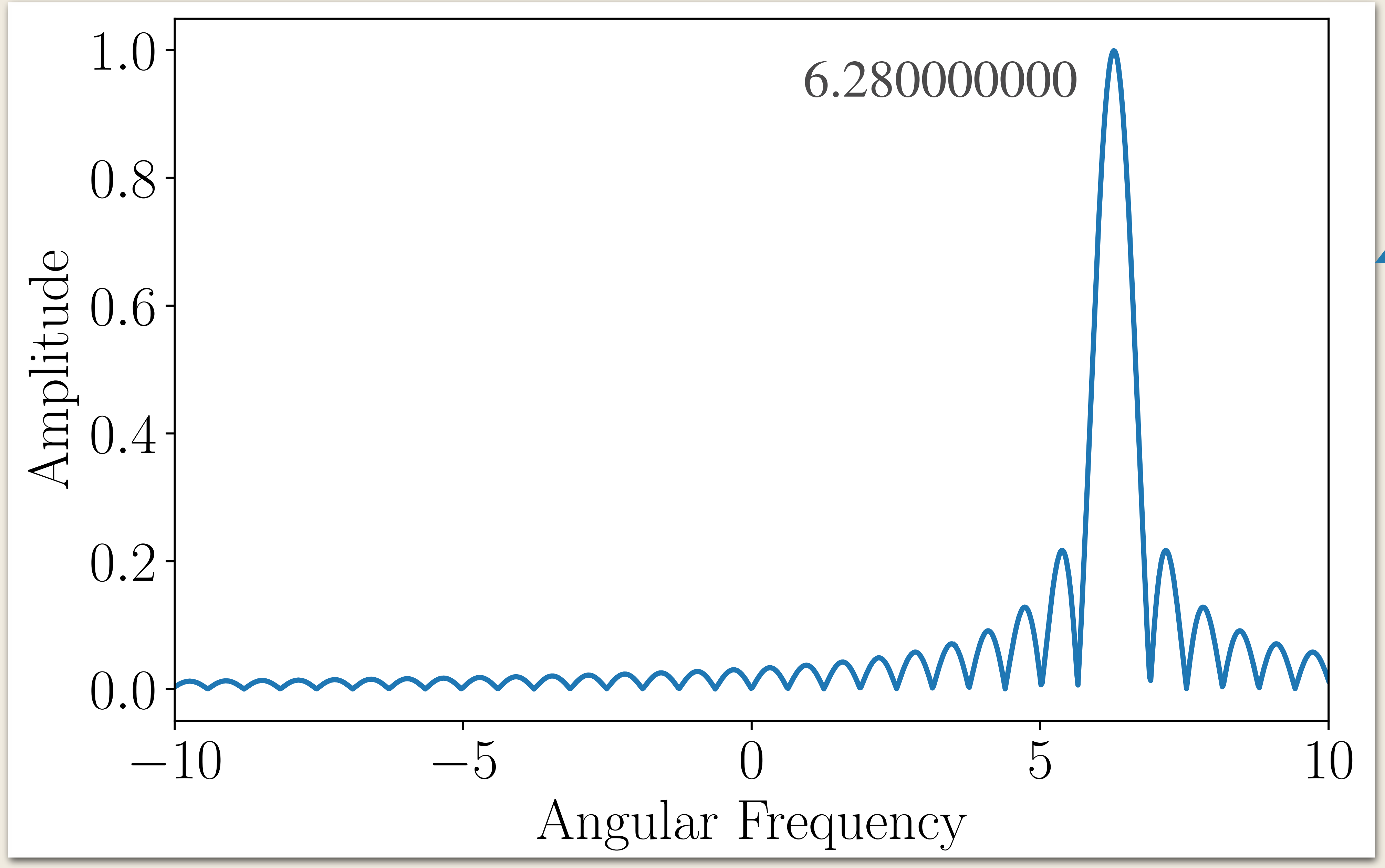
BROWN & REIN (2022) DOI: 10.1093/MNRAS/STAC1763

Stellar Flybys and stability

- A flyby of this magnitude is not likely to pass the solar system for 100 billion years



FFT

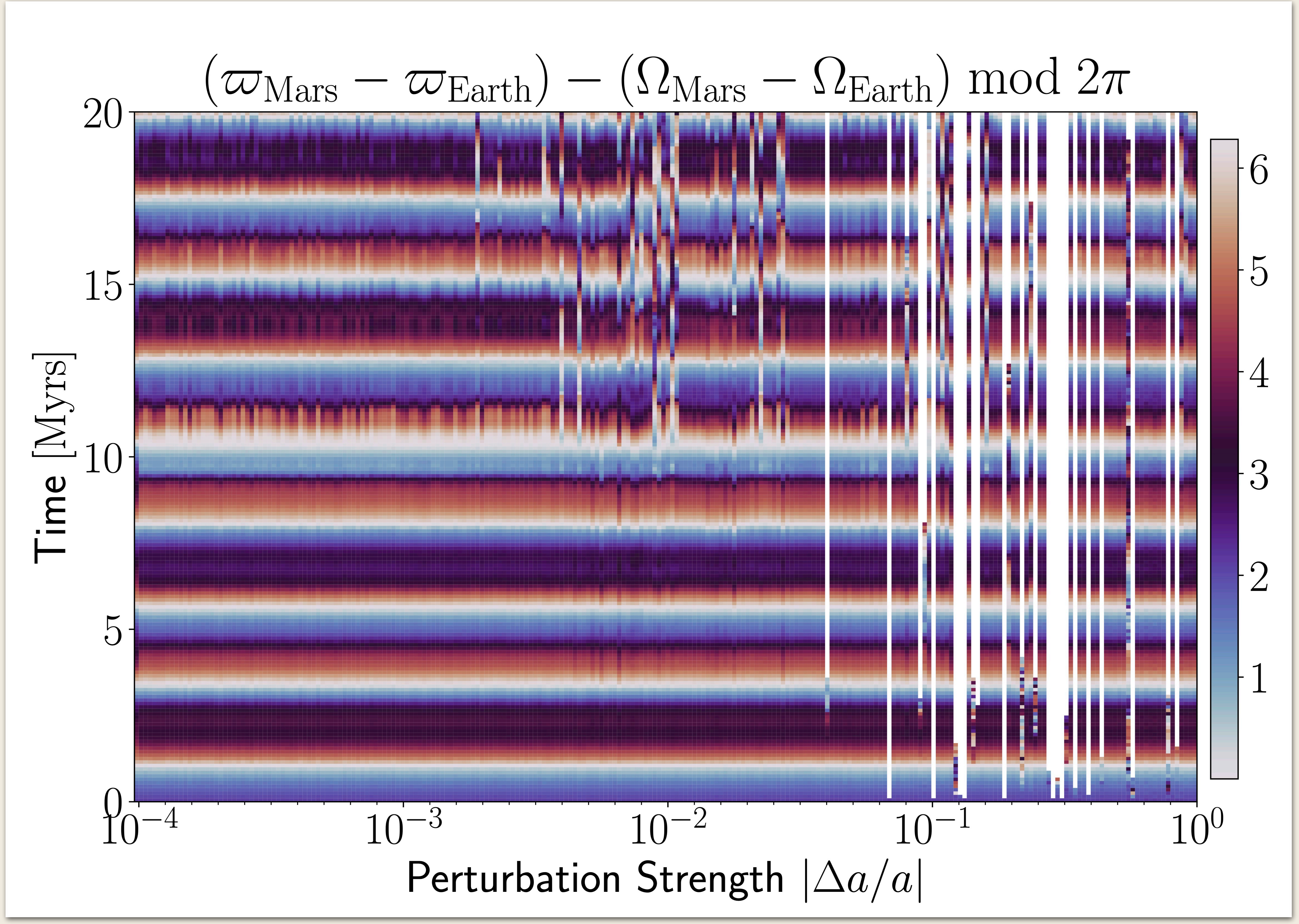


MFT

LASKAR (1990) DOI: 10.1016/0019-1035(90)90084-M
ŠIDLICHOVSKÝ & NESVORNÝ (1996) DOI: 10.1007/BF00048443

Modified Fourier Transform (MFT)

- Contrived Example
- $y(t) = \exp(6.28\mathrm{i}\, t)$
- $t \in [0,10],\ N = 1000$
- $\phi(\nu) = \langle y(t), \exp(\mathrm{i}\nu t)\rangle$
- Maximize $\phi(\nu)$ in the region of ν.



BROWN & REIN (2022) DOI: 10.1093/MNRAS/STAC1763

Stellar Flybys and stability

- Changes to Neptune's orbit effect the inner solar system secular state
- Angular momentum is exchanged between the planets on secular timescales