Quantifying the Effects of Stellar Flybys on Planetary Systems

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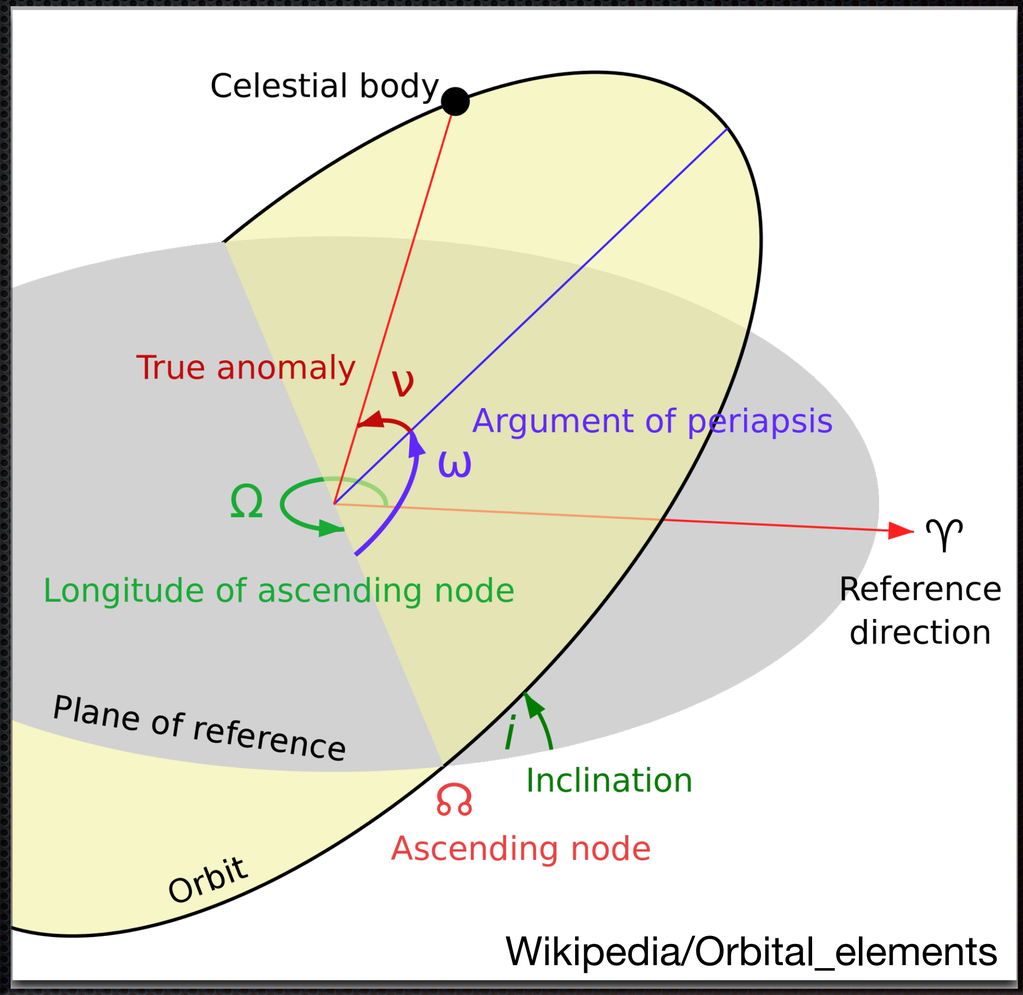
Outline

N-body simulations and Secular Dynamics

- Frequency Modified Fourier Transform (FMFT).
- Numerical checks and optimizations for computing secular frequencies.
- Applications of FMFT to an external body passing the solar system on a hyperbolic orbit.

Secular Frequencies

- Secular precessions of the periapses and the ascending nodes
- Obtained from time series data of the complex eccentricities and inclinations
  - $z_j = e_j \exp(\mathbf{i}\varpi_j)$
  - $\zeta_j = \sin(i_j/2)\ \exp(\mathbf{i}\Omega_j)$



Modified Fourier Transform

(Laskar 1988, 1990)

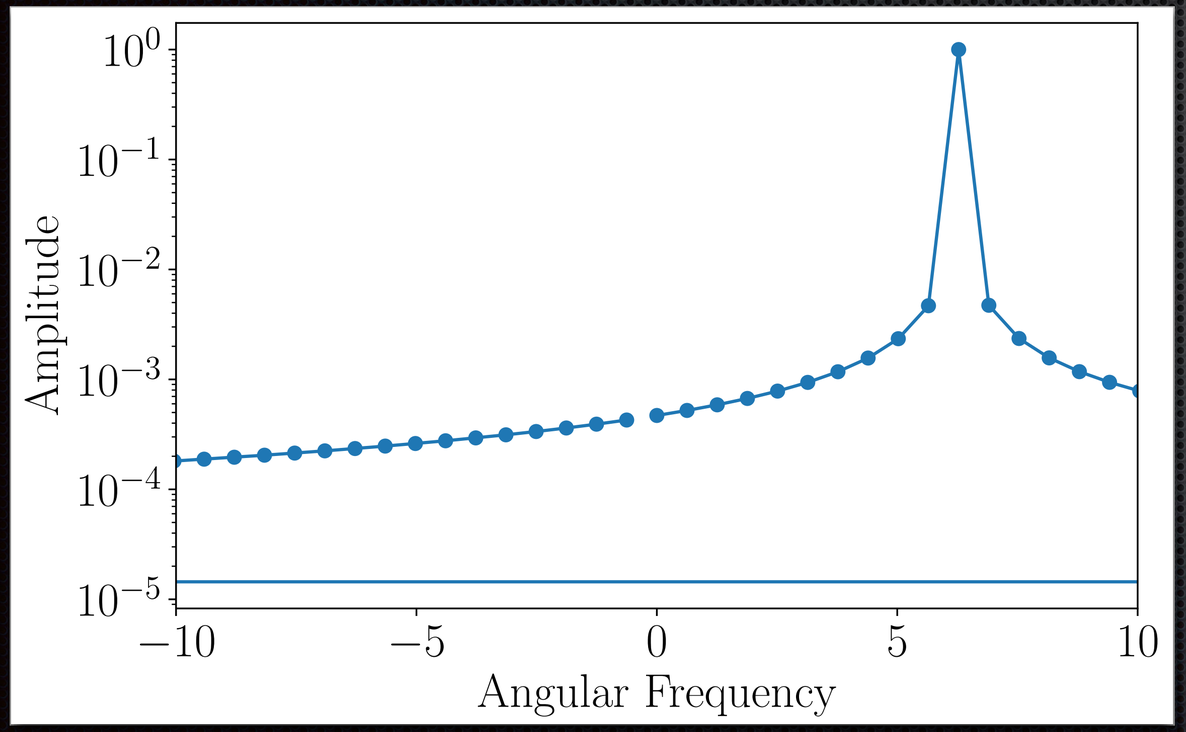
A simple example

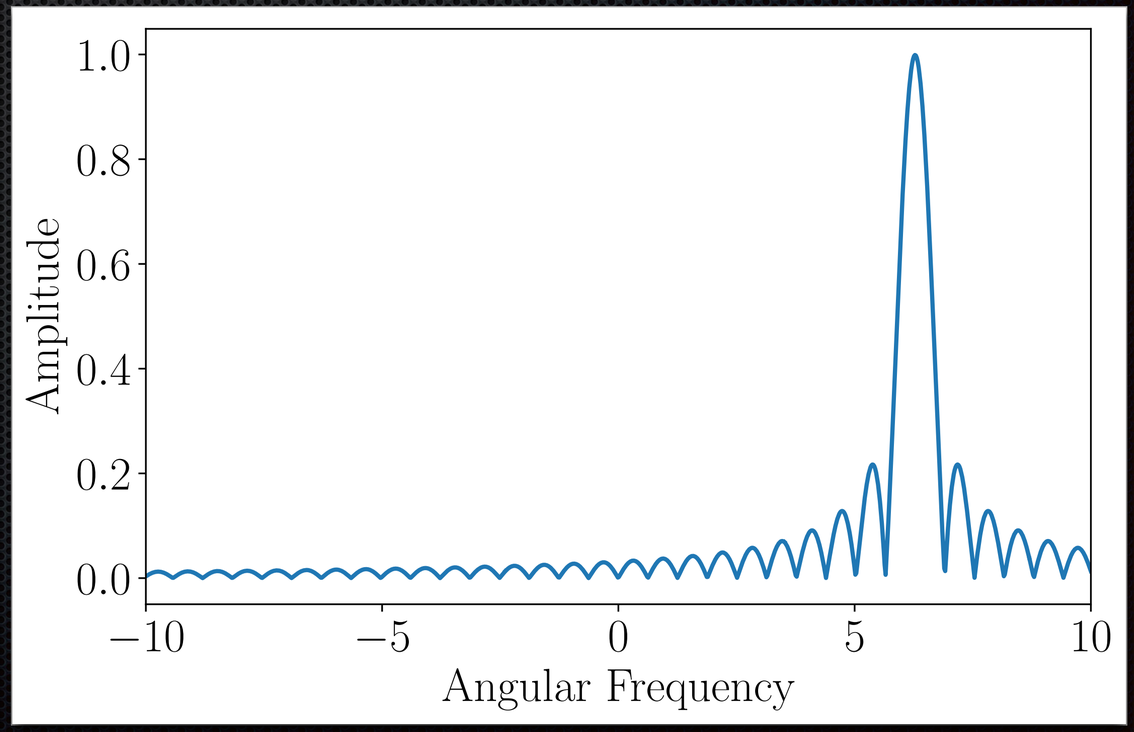
$$y(t) = \exp(6.28\mathbf{i}\,t),\ t \in [0,10],\ N = 1000$$

6.276902122

$$\phi(\nu) = \langle y, \exp(\mathbf{i}\nu t)\rangle$$

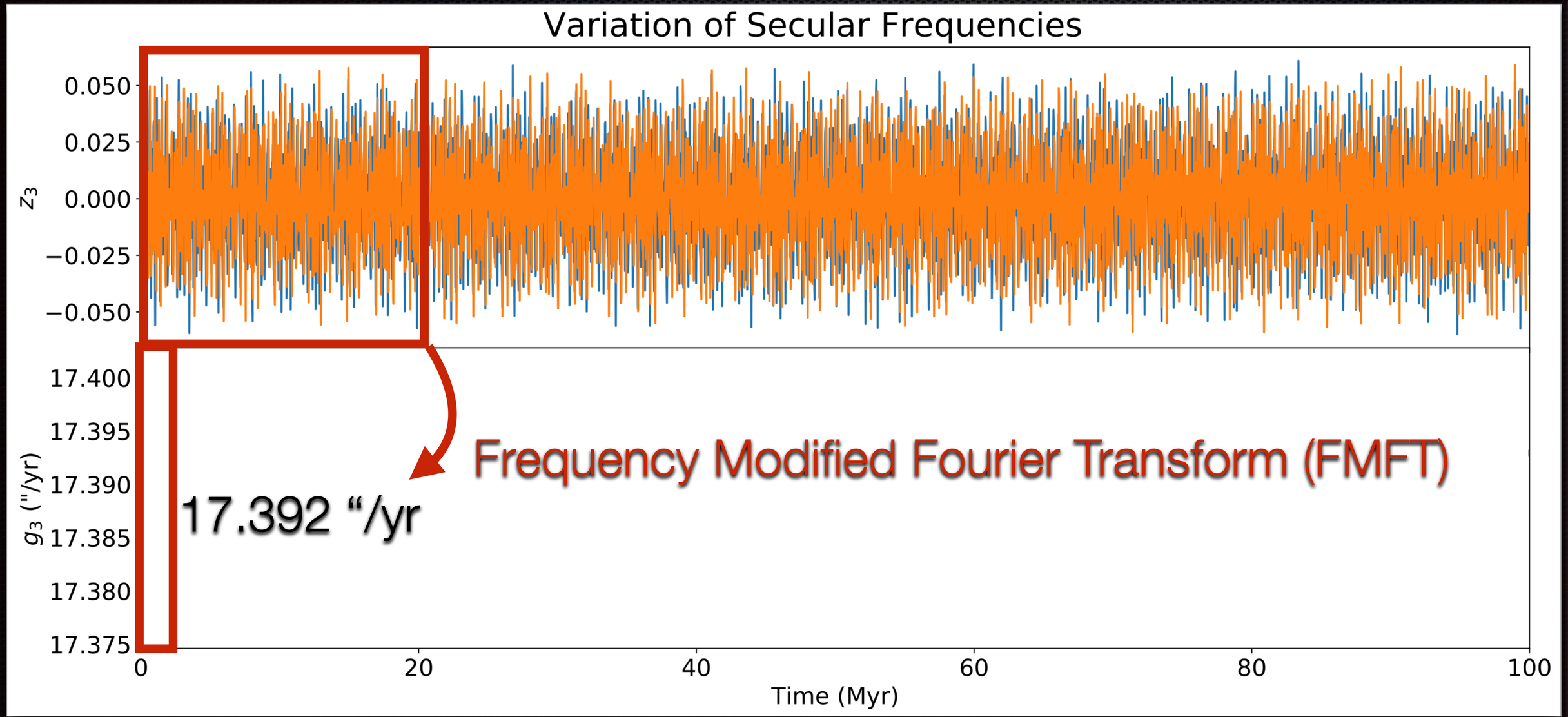
6.280000000





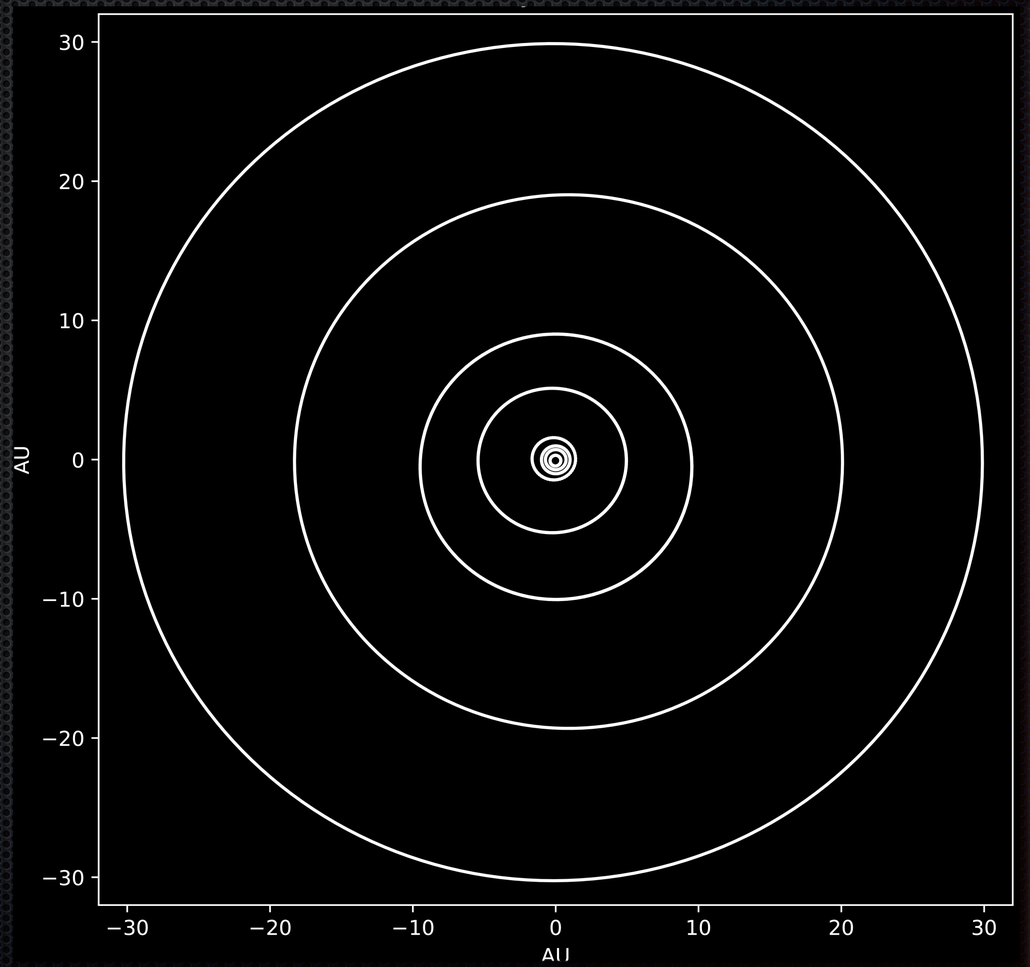
Frequency Analysis

(Laskar 1988, 1990)
(Šidlichovský & Nesvorný 1997)



Rebound

- Solar System (8 planets)
- NASA Horizons Database
- WHFast Symplectic Integrator
- GR scalar potential (Reboundx)



Secular Frequencies

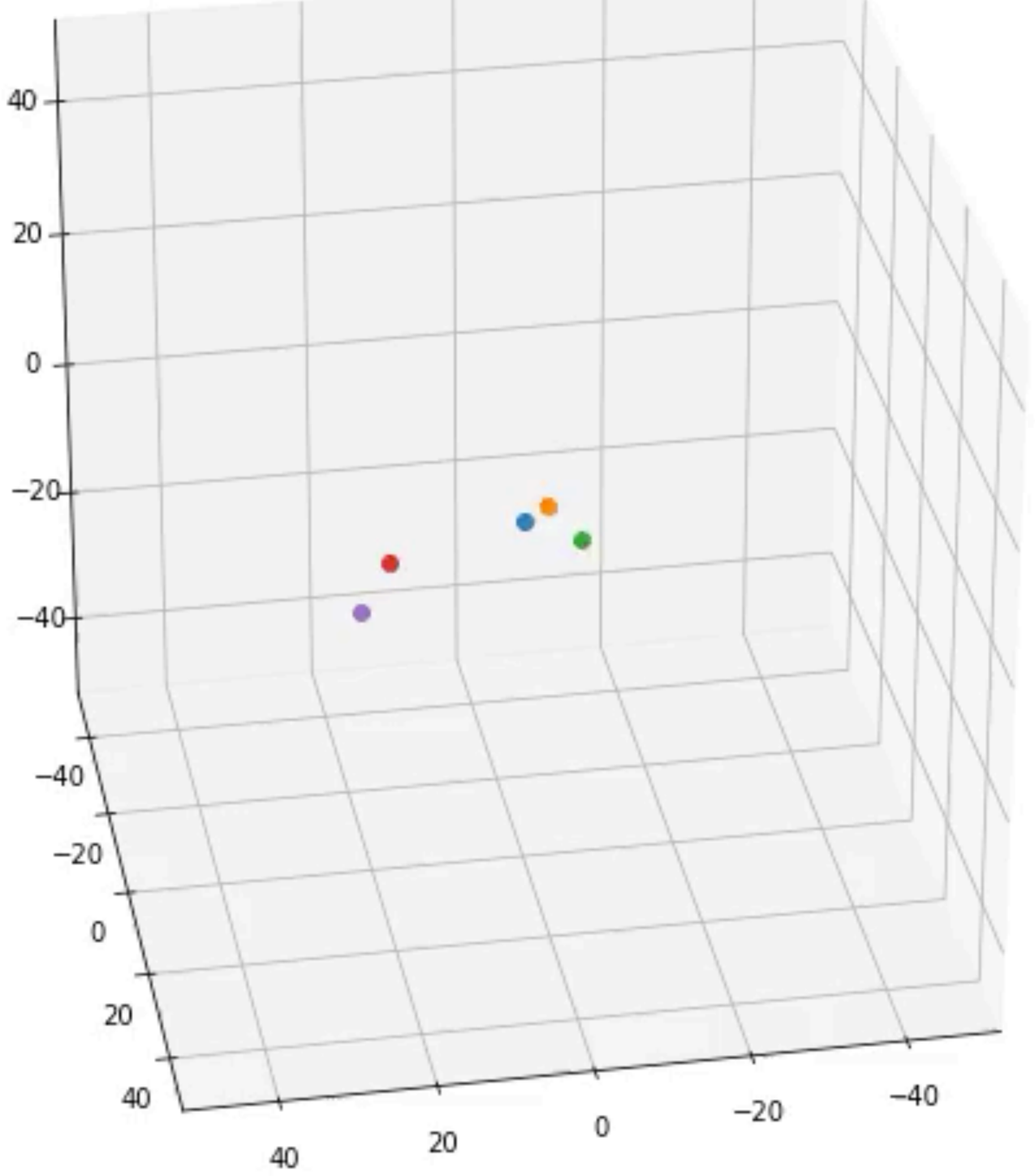
- Solar System fundamental frequencies
- Obtained with FMFT
- 20 Myrs in ~25 minutes
- Inner planets within 0.1%
  Outer planets within 0.001%

“/yr	RB2019	La2010
g_1	5.599	5.59
g_2	7.420	7.453
g_3	17.3582	17.368
g_4	17.9163	17.916
g_5	4.257523	4.257482
g_6	28.24617	28.2449
g_7	3.088024	3.087946
g_8	0.673289	0.673019

(Laskar 2011)

Quantifying Stellar Flybys

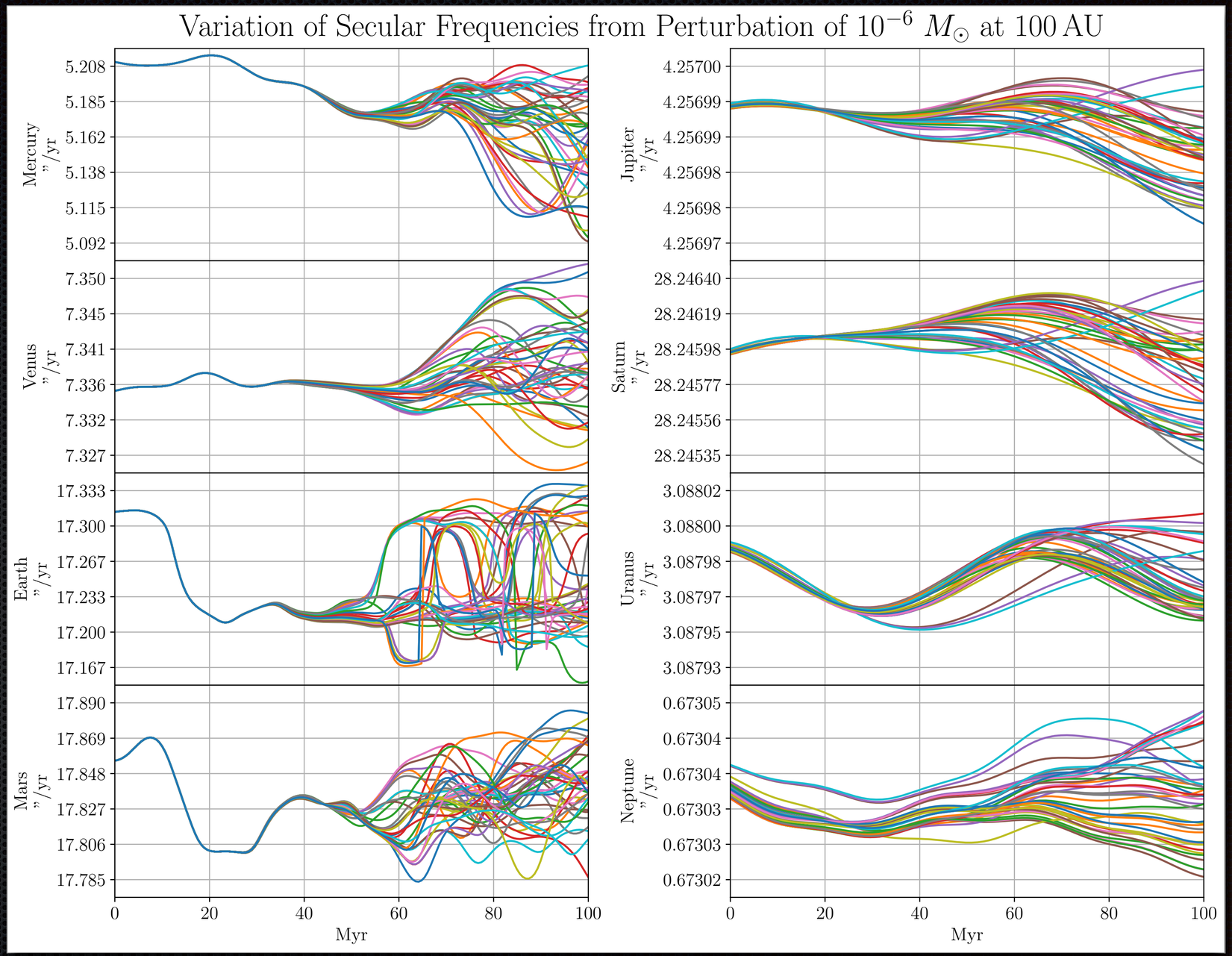
- Quantitative laboratory for the long-term stability of planetary systems.
- Exploration of changes to initial conditions.



Quantifying Stellar Flybys

Perturbation by Earth-mass at 100 AU

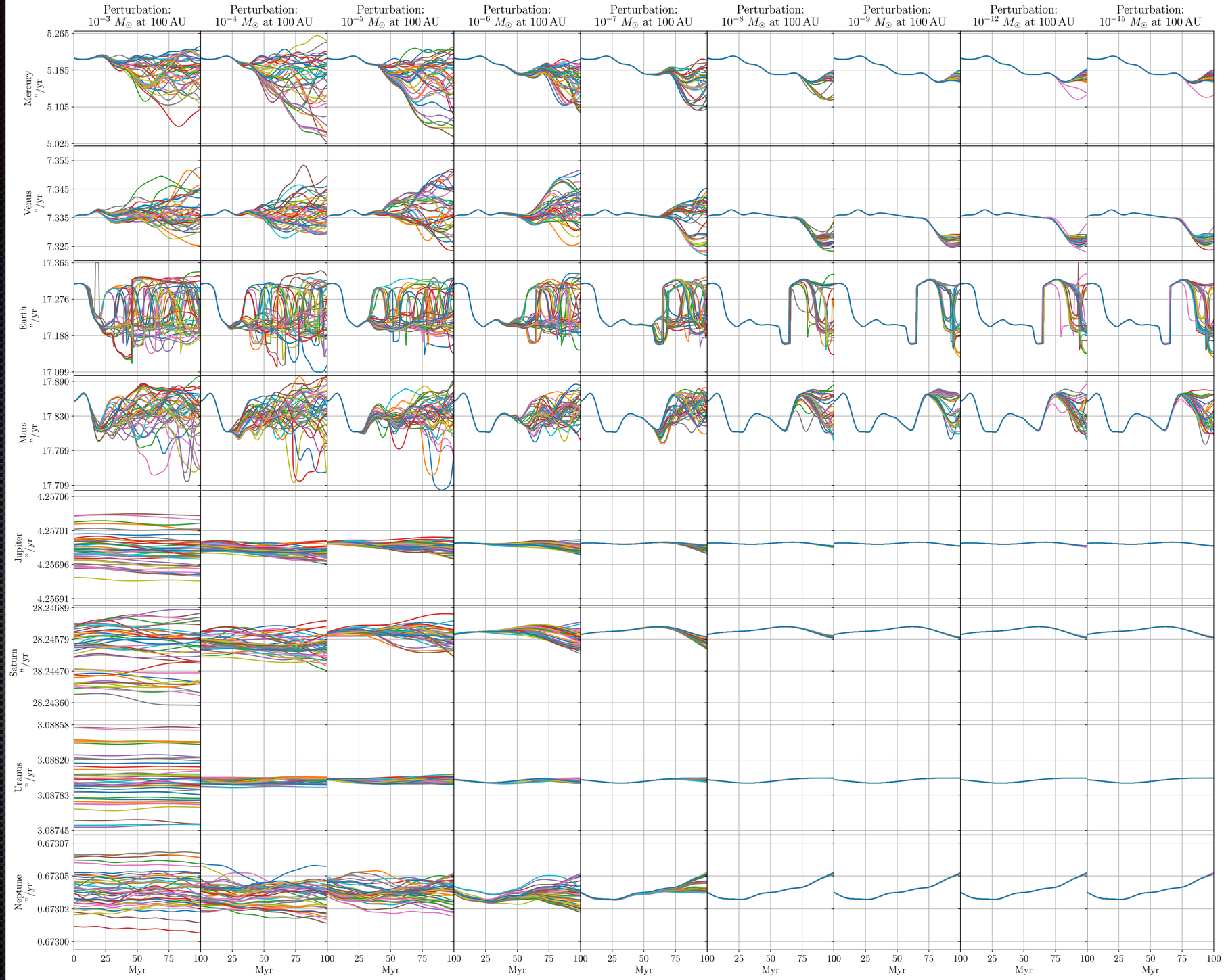
- Variations of secular frequencies over 100 Myrs
- Analyzed with FMFT



Brown and Rein, in prep.

- From Jupiter-mass perturbations to asteroid-mass perturbations.
- FMFT

Brown and Rein, in prep.



Conclusion

- The secular frequencies of the solar system can be computed from N-body integration in ~25 minutes (with GR corrections).
- Using FMFT, very subtle changes made to the solar system can be detected.

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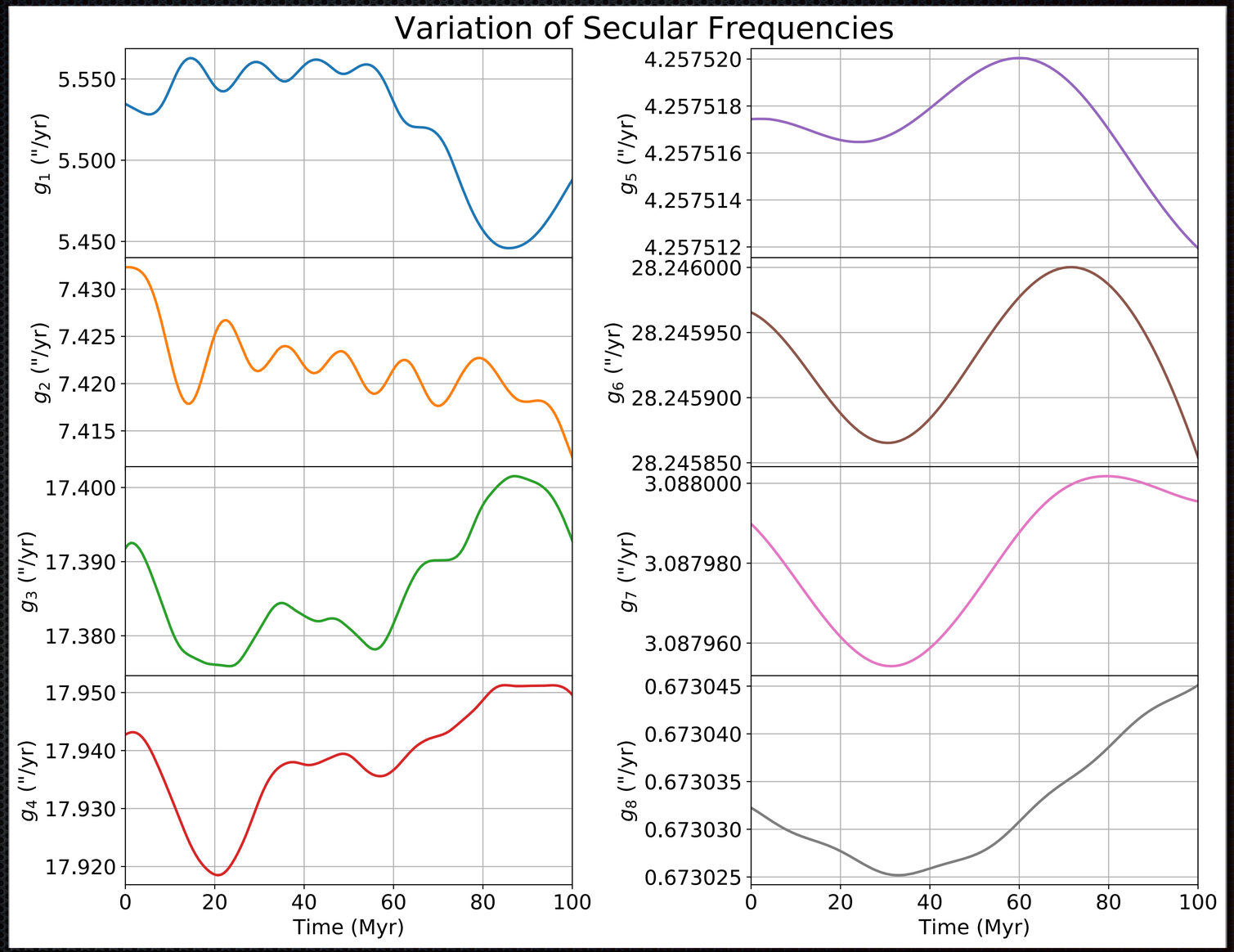
Quantifying Stellar Flybys

No Perturbation

- Variations of secular frequencies over 100 Myrs
- Analyzed with FMFT



Brown and Rein, in prep.

Secular Frequencies

- Explored the effects of:
  - Window Length
  - Timestep
  - Sampling Frequency (Nyquist)
  - Coordinate System
  - Windowing Function

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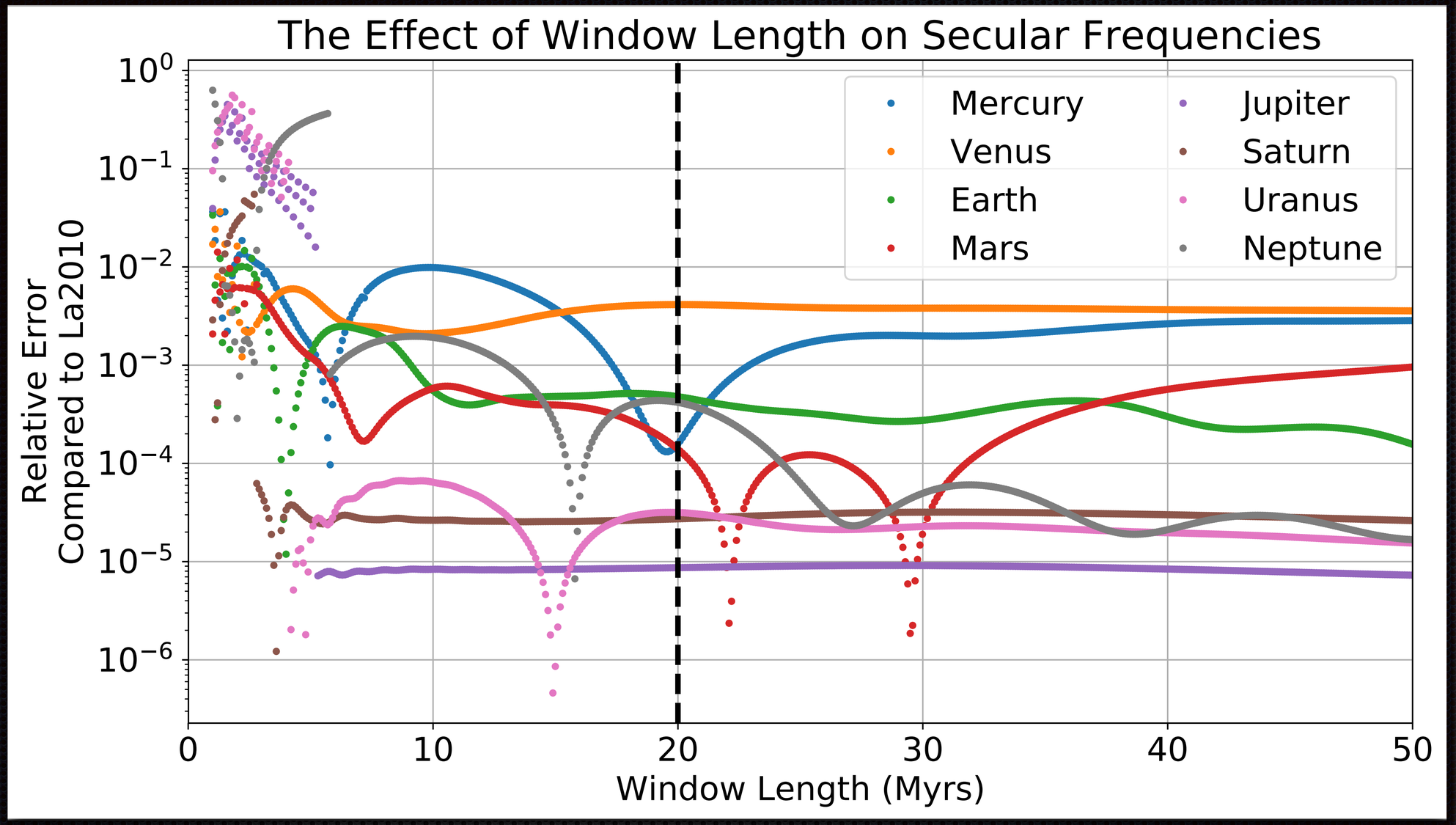
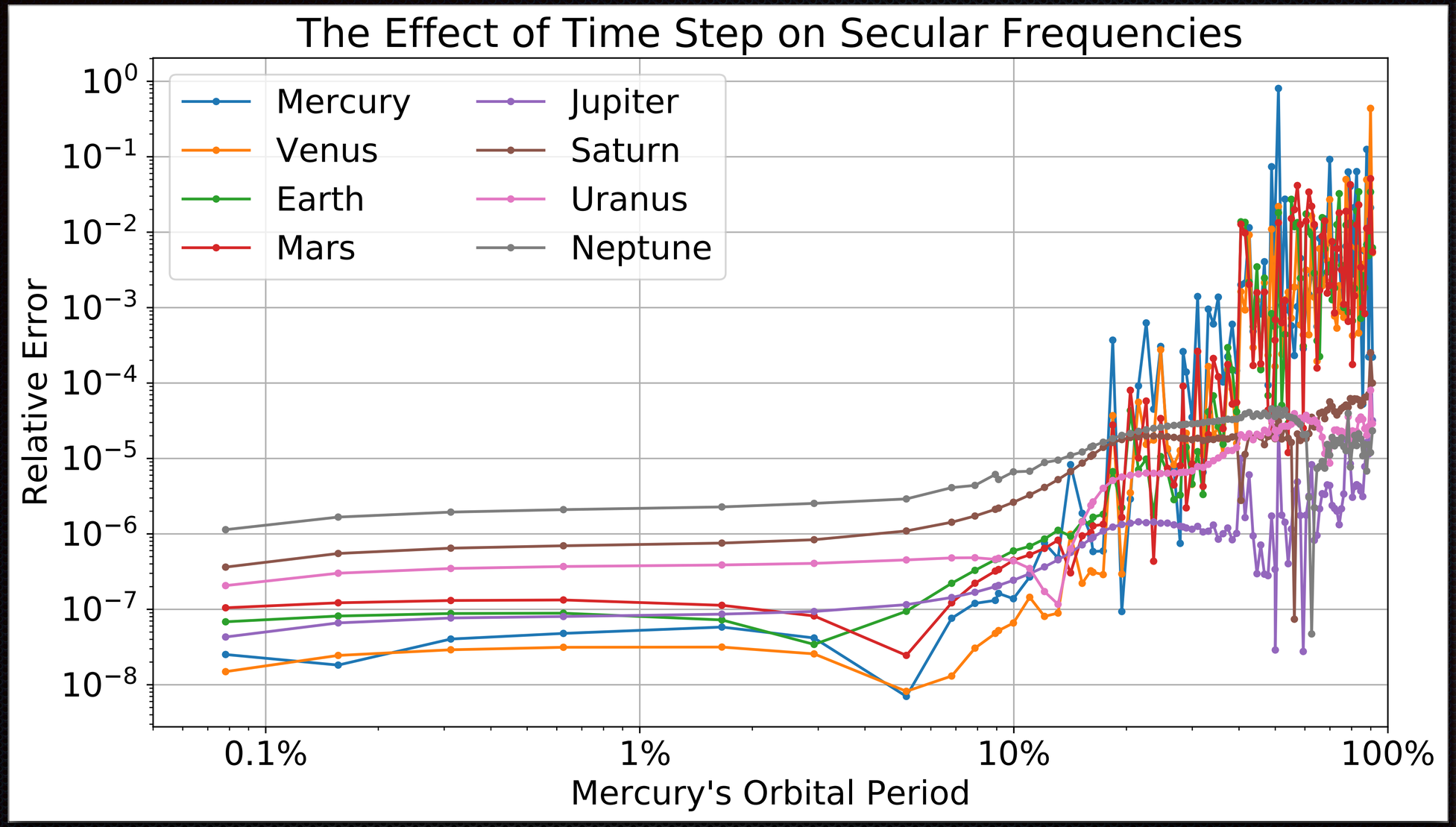


Window Length



Time step

N-body Accuracy

Motivation

What shapes the long-term stability of planetary systems?

- Newtonian Gravity
- General Relativity (GR)
- Gravitational Moments
- Galactic Tides
- Changes in Stellar Mass
- Stellar Wind/Drag
- Small bodies (asteroids)
- Passing bodies (flybys)

Recent Work

Spalding, Fischer, and Laughlin (2018)

- A quantitative test of solar mass loss.
- Linear solar mass loss of 5% over 4.5 Gyrs.
- Low inclinations and eccentricities.
- Tabulated every 450 yrs in Jacobi coordinates; FFT on 450 Myr segments.

The Astrophysical Journal Letters, 869:L19 (6pp), 2018 December 10 https://doi.org/10.3847/2041-8213/aaf219

CrossMark

An Orbital Window into the Ancient Sun's Mass

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[2] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
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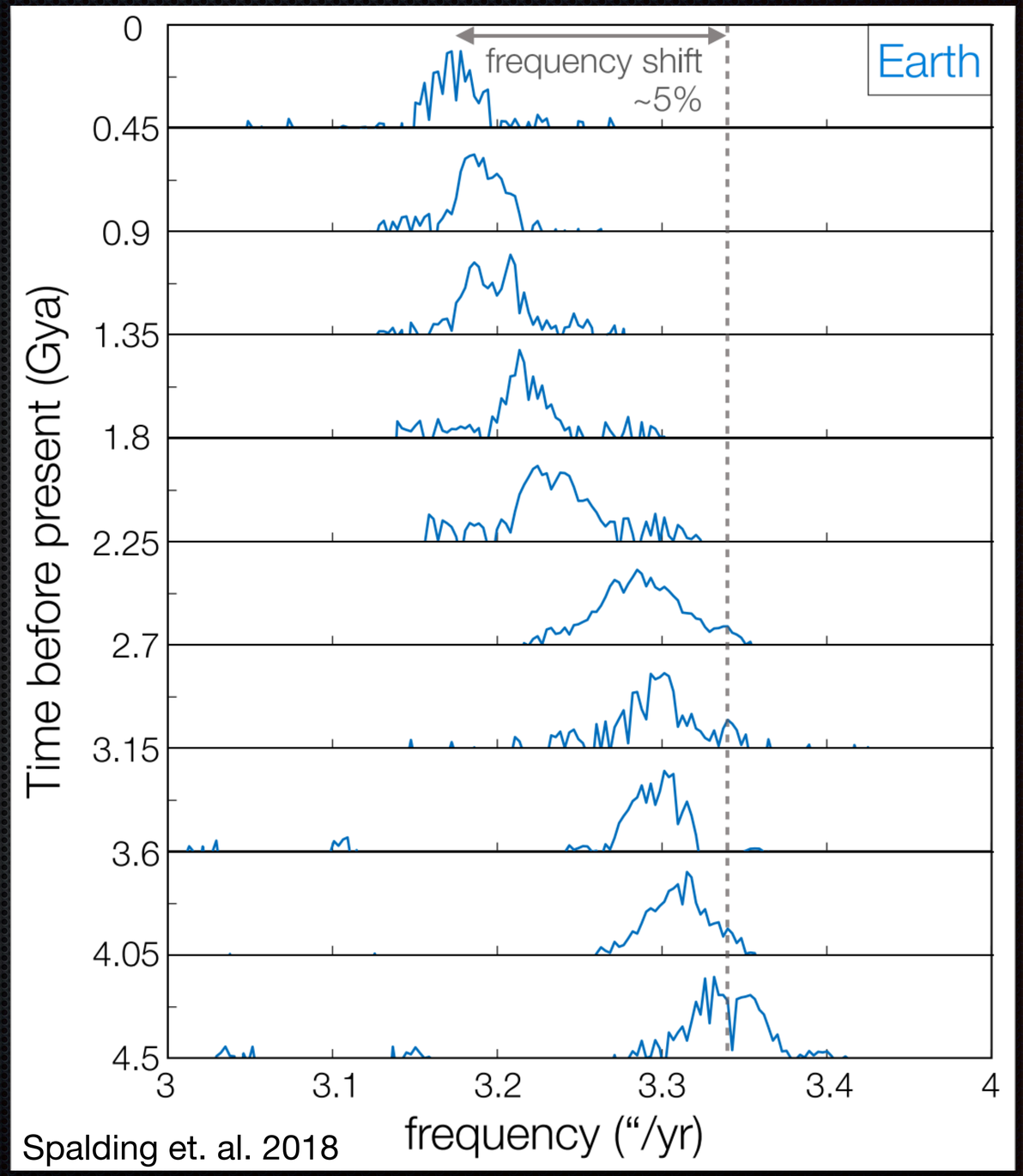
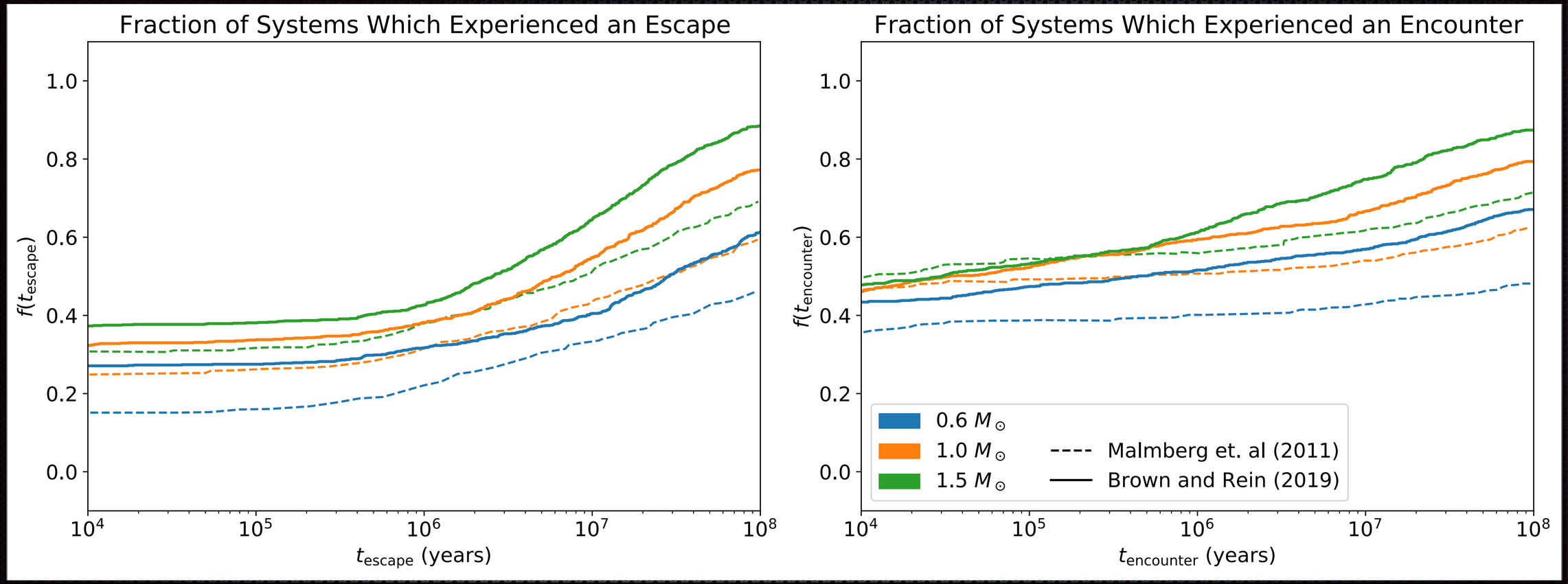
Recent Work

Spalding, Fischer, and Laughlin (2018)

- Frequencies do scale with mass.
- Matched fundamental secular modes of La2010 to within ~1%.
- FFT instead of FMFT



Spalding et. al. 2018



Stellar Fly-by Results

Reproducing the statistical results of Malmberg et al. (2011).