Too Close For Comfort

Solar system stability in the presence of weak stellar flybys

UNIVERSITY OF TORONTO

Garett Brown
Hanno Rein

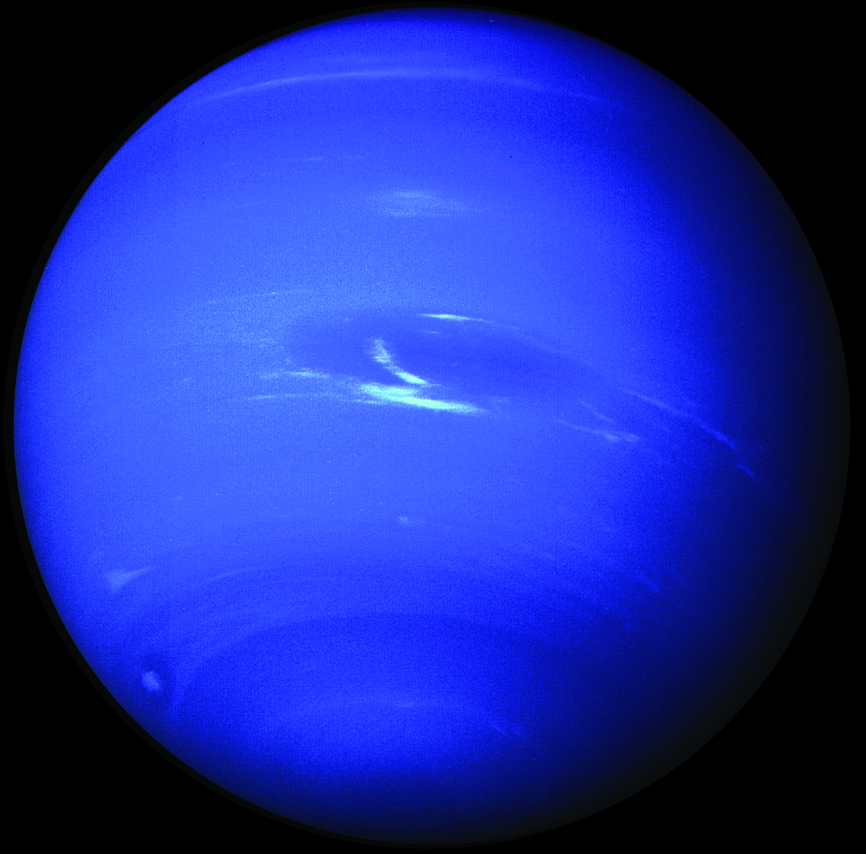
Brown & Rein (2022)
arxiv.org/abs/2206.14240
doi.org/10.1093/mnras/stac1763

NSERC CRSNG

NSERC Discovery Grants
RGPIN-2014-04553
RGPIN-2020-04513

Too Close For Comfort

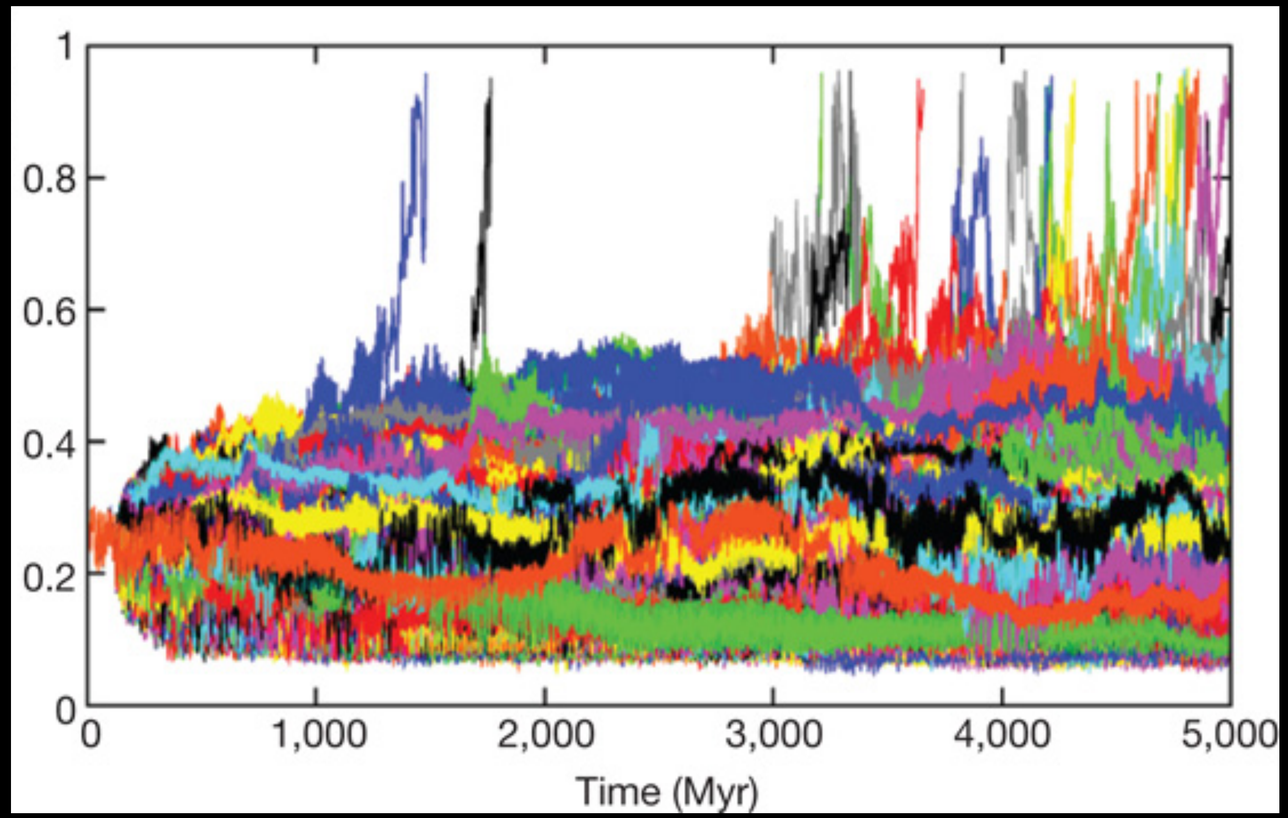
- How stable is the solar system?
- What is the mechanism for instability?
- How much change causes instability?
- How likely is a destabilizing stellar flyby?



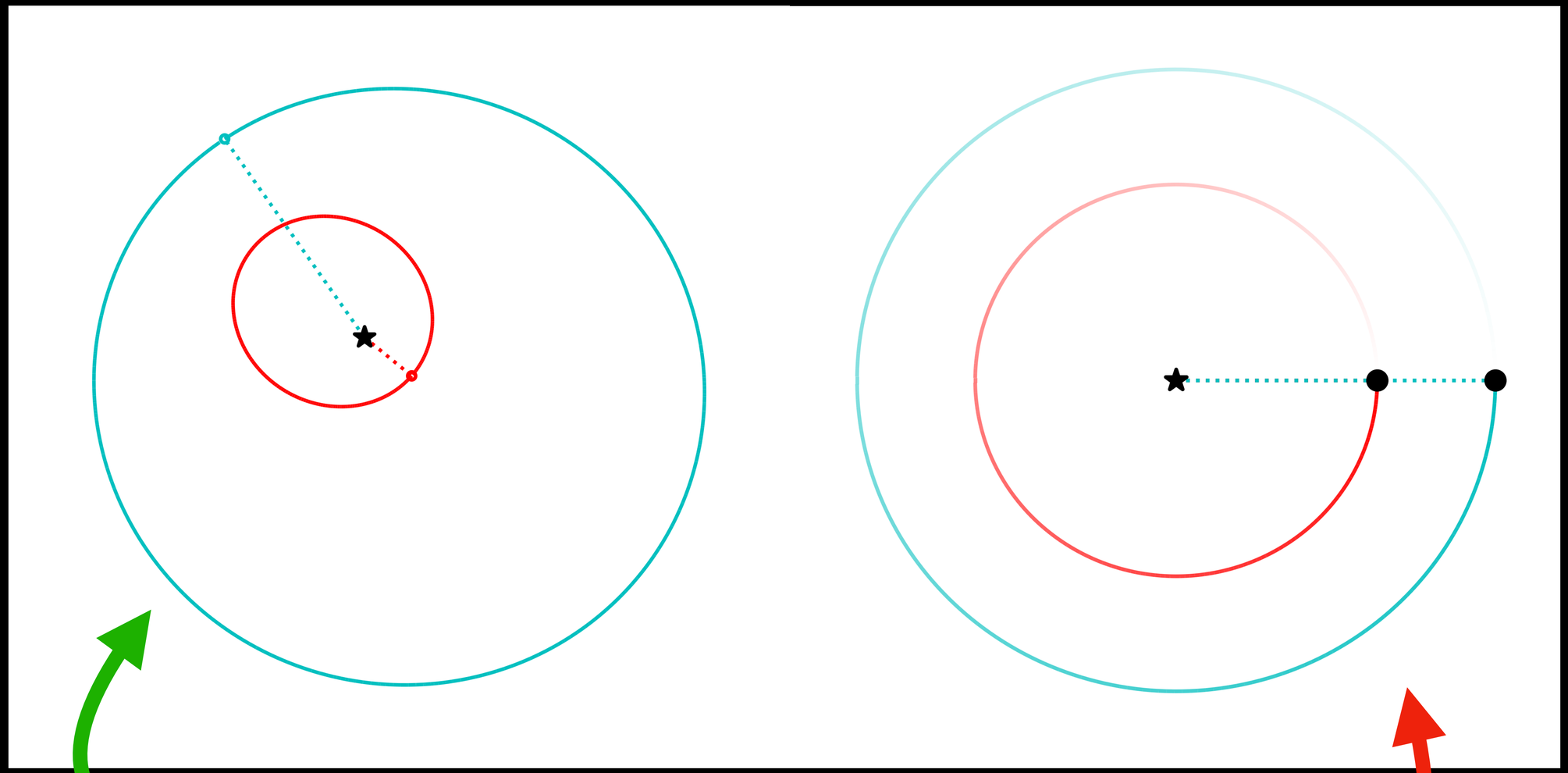
Stability and Chaos

- 2,501 simulations
- Adjusted the initial semi-major axis of Mercury by at most 0.5 meters
- 1% were unstable
  (eccentricity of Mercury > 0.9)

Mercury's Maximum eccentricity over 5 Gyr.



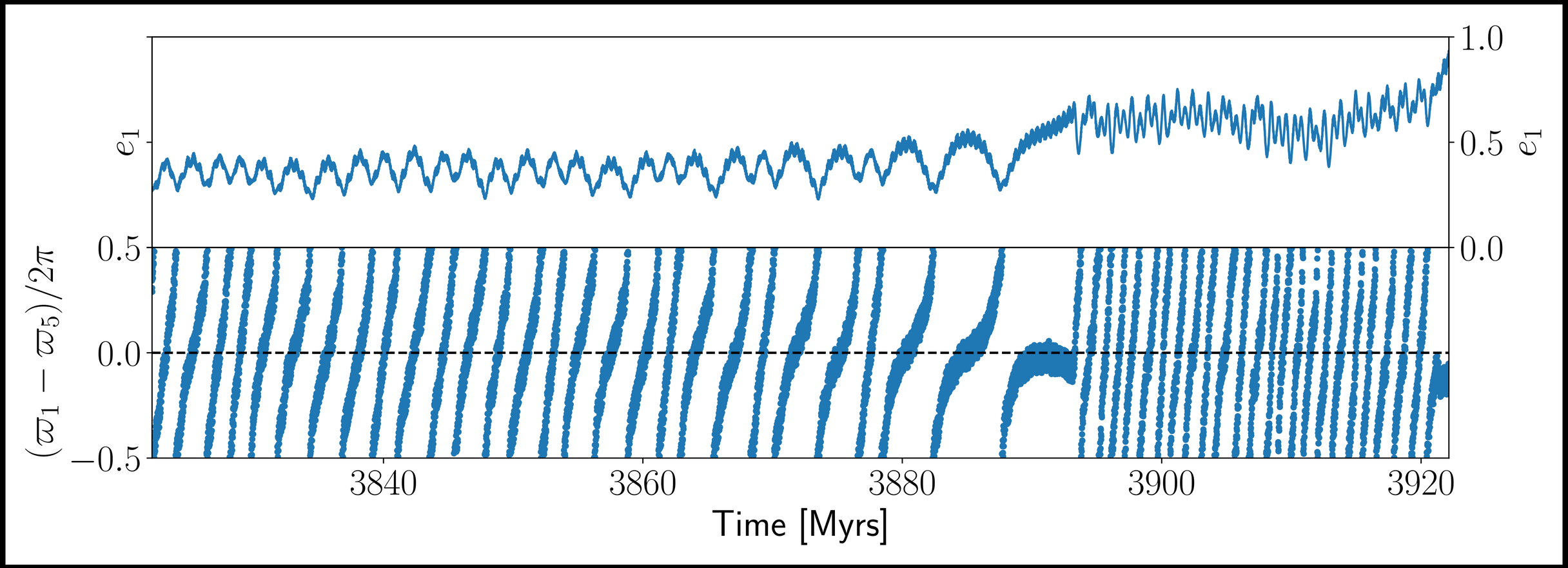
Laskar & Gastineau (2009)



Secular Resonances

not mean motion resonances

(usually)

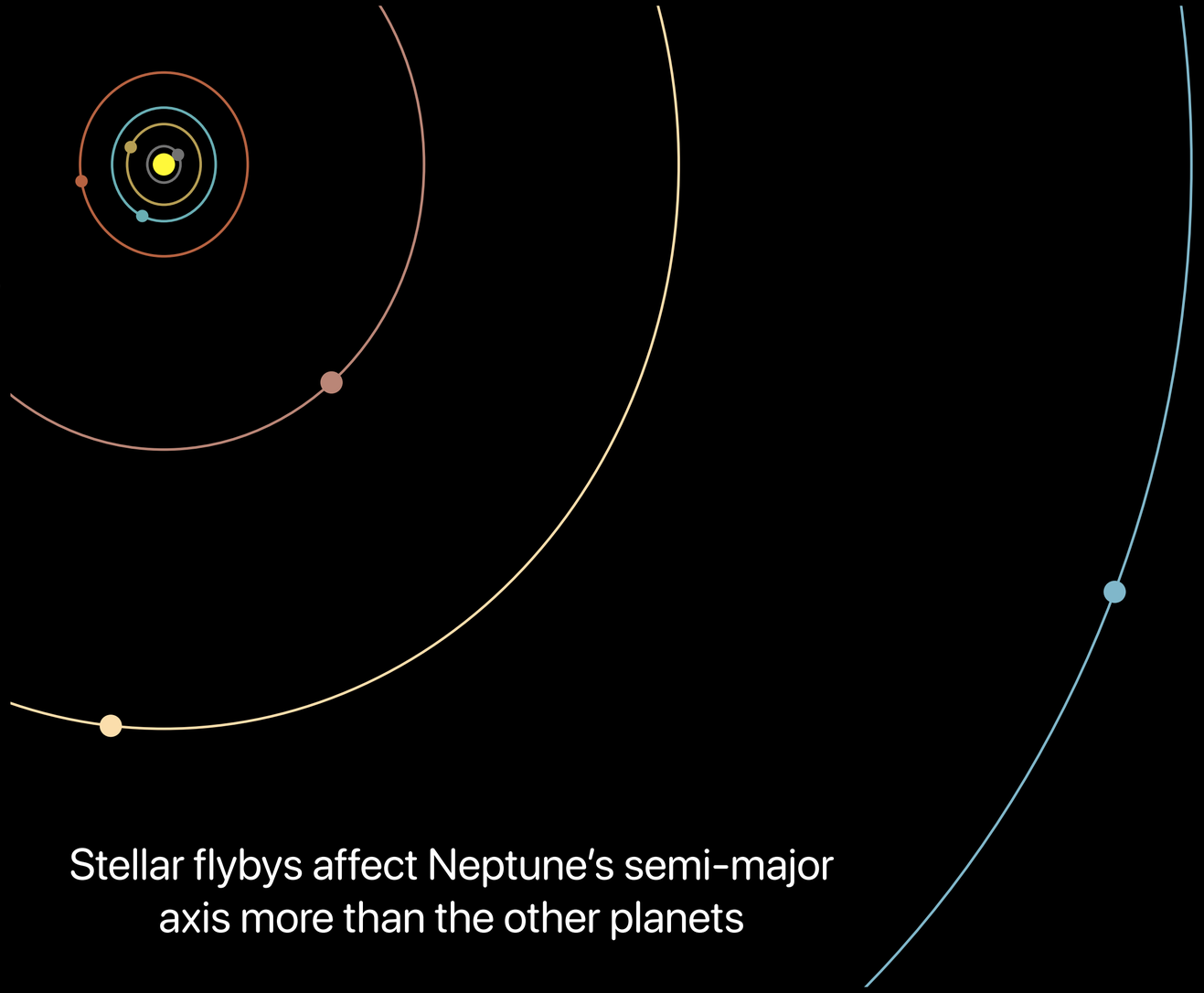


Secular Resonances

between Mercury and Jupiter

Experimental Setup: Stellar Flybys

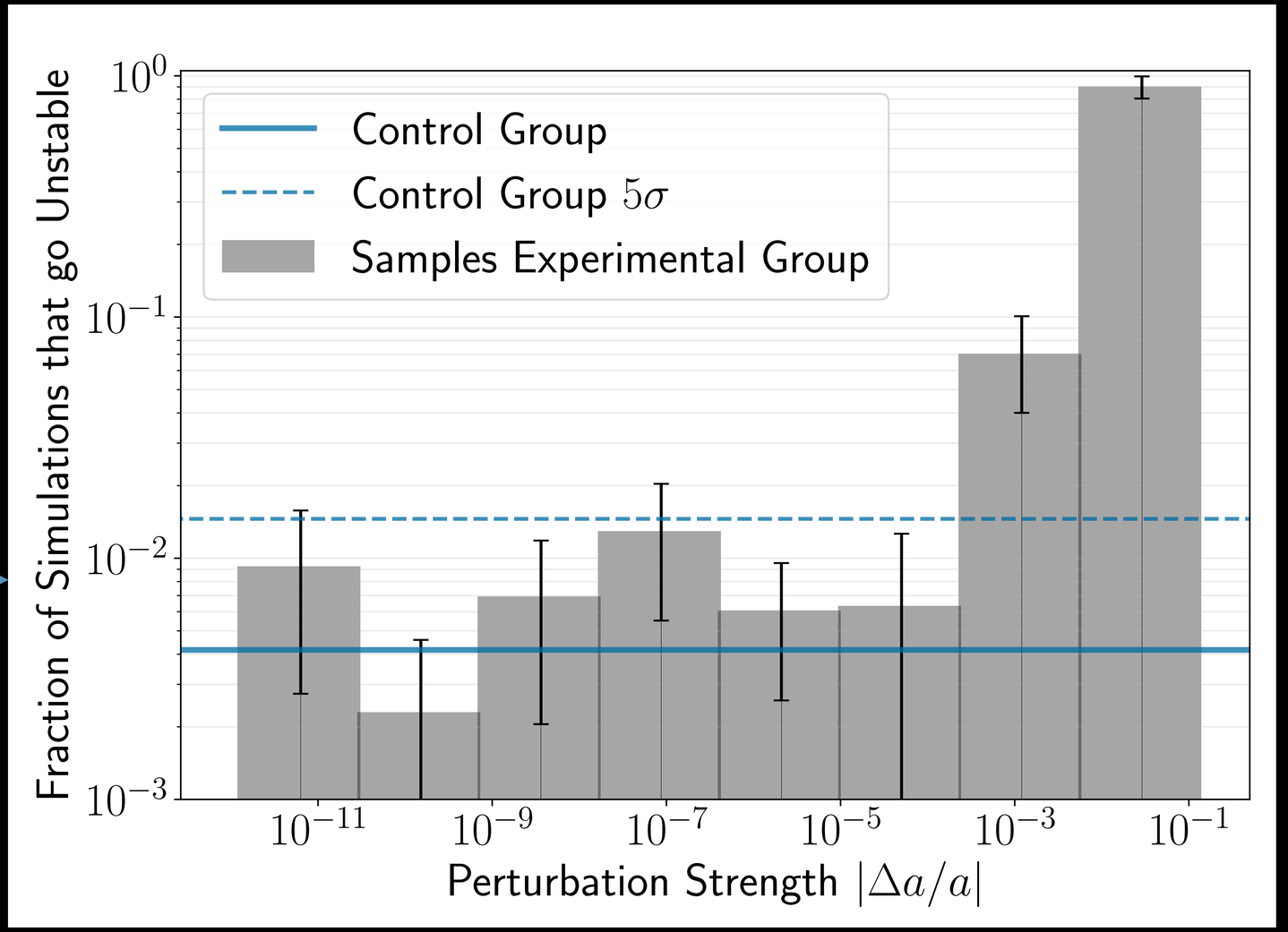
- 2,880, 4.8 Gyrs solar system simulations
  - 960 control sims / 1920 experimental sims
- NASA JPL Horizons, J2000 epoch
- REBOUND N-body integrator
- REBOUNDx with gr_potential
- WHCKL integrator
- dt = 8.062 days



Stellar flybys affect Neptune's semi-major axis more than the other planets

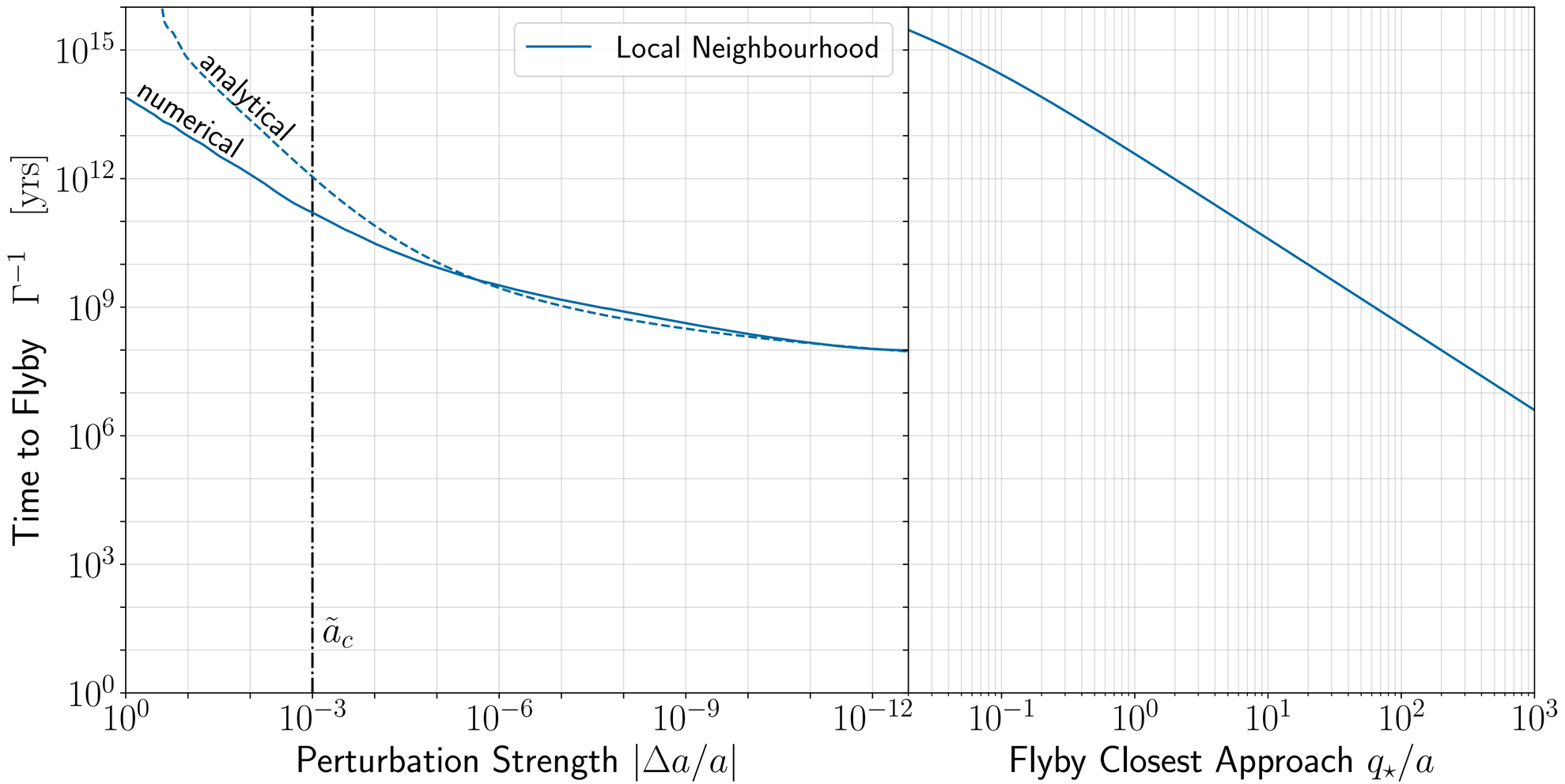
Changes >0.1% are critical

- Control Group
  4 of $960 (\ 0.42\ \%\ )$ are unstable
- Experimental Group
  26 of $1920\ (\ 1.35\ \%\ )$ are unstable
- Bin the instability fraction by perturbation strength
- When $\Delta a/a > 0.1\ \%$, instability fraction is more than 5σ above the baseline.

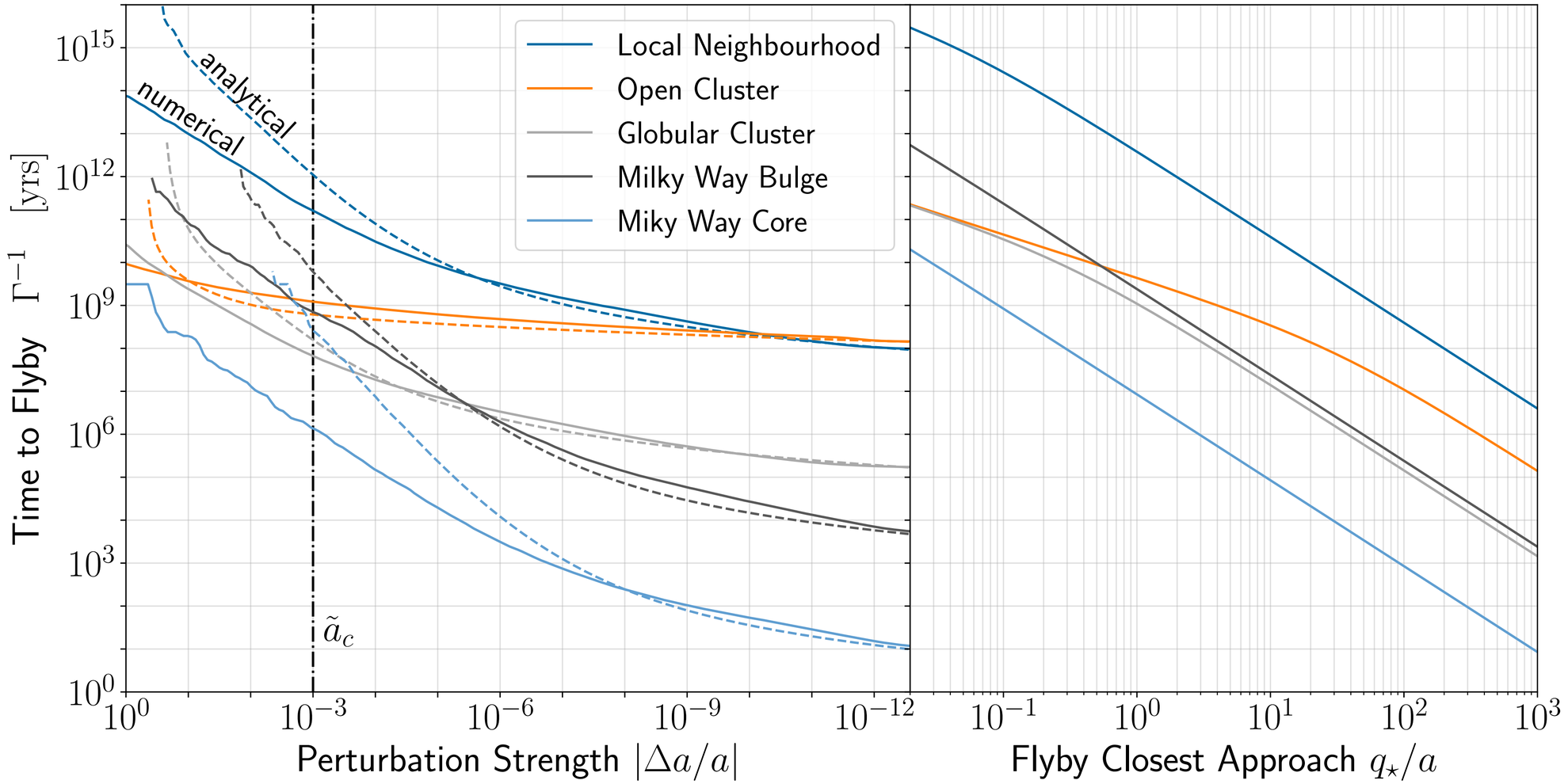


$\Delta a/a :=$ **Relative change to the semi-major axis of Neptune**

How Likely is a Stellar Flyby?

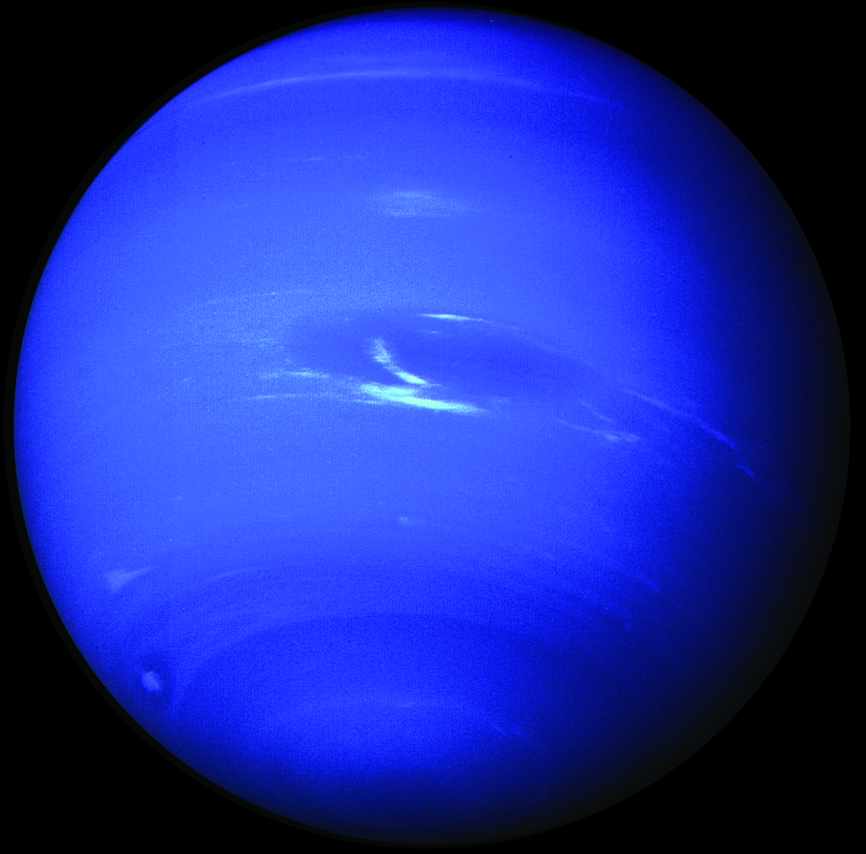


How Likely is a Stellar Flyby?



Too Close For Comfort

- How stable is the solar system?
  - Reasonably stable, ~99%.
- What is the mechanism for instability?
  - Mercury-Jupiter secular resonance.
- How much change causes instability?
  - Change of >0.1% to the secular system.
- How likely is a destabilizing stellar flyby?
  - Very unlikely, 1 in 100 billion years.
    $0.3\ M_\odot$ at ~$200\ \mathrm{AU}$ and $25\ \mathrm{km/s}$



garett.brown@mail.utoronto.ca

Analytic Estimates

- Changes to the semi-major axis of a planet from an adiabatic flyby.

$$\frac{\Delta a}{a} \simeq \frac{\sqrt{\pi}}{2} \frac{m_\star}{m_\odot + m + m_\star} f_1(e_\star) \sqrt{K(q_\star/a)} \exp\left[-K(q_\star/a) f_2(e_\star)\right]$$

- To first order, changes to the secular system

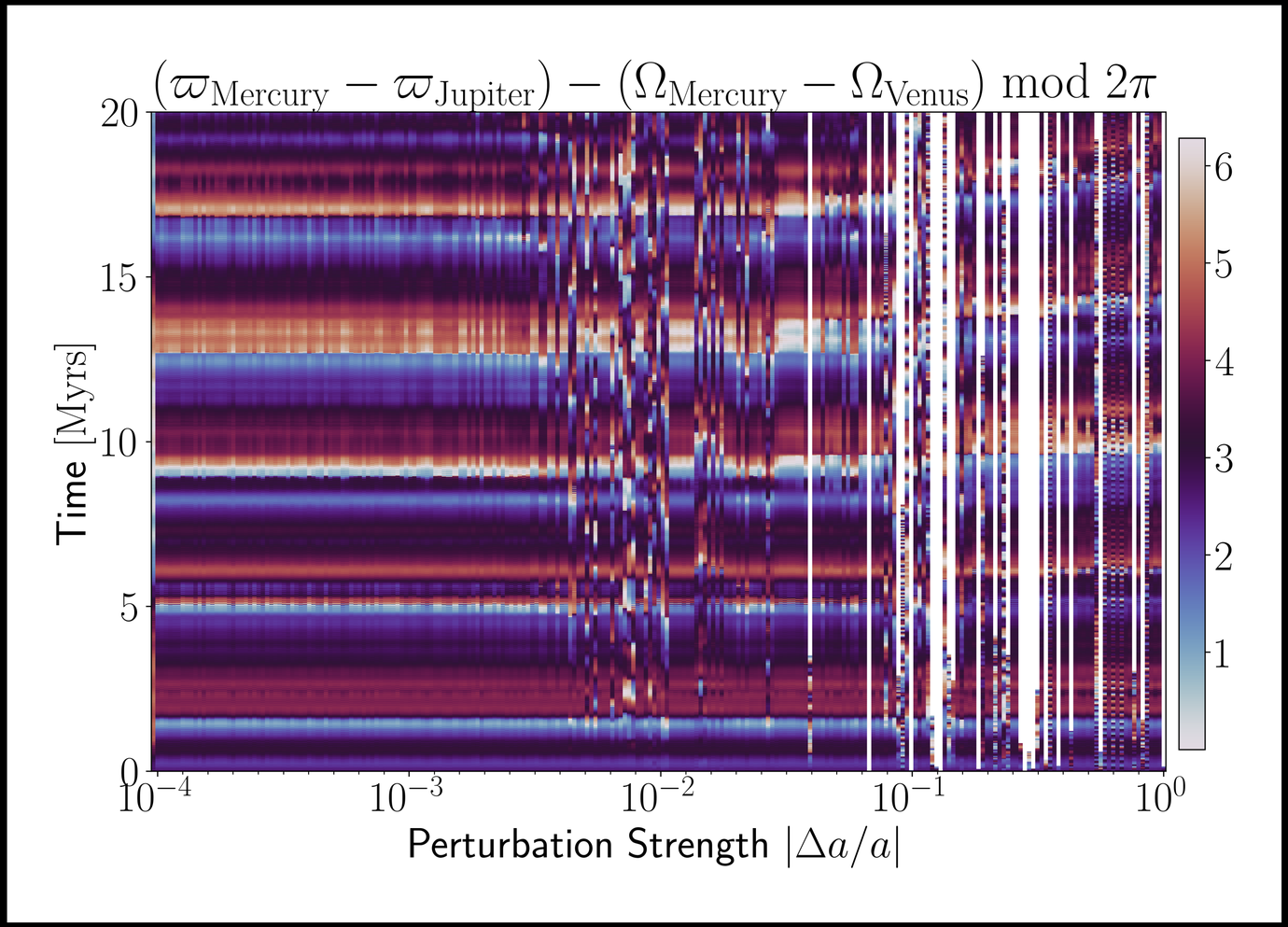
$$\frac{\Delta g}{g} \propto \frac{\Delta a}{a}$$

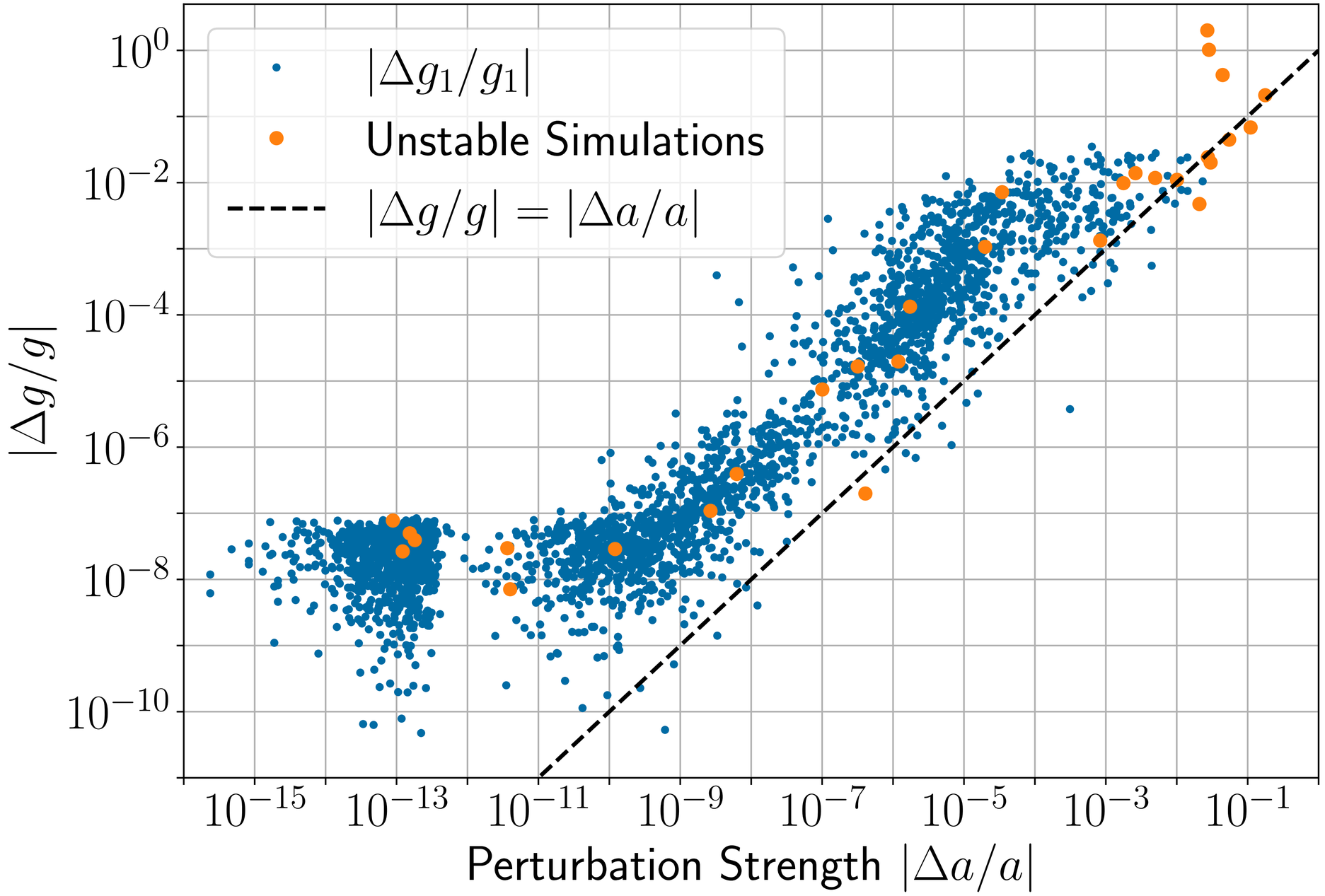
Exponential dependence on the ratio between the closest approach of the star and semi-major axis of the planet

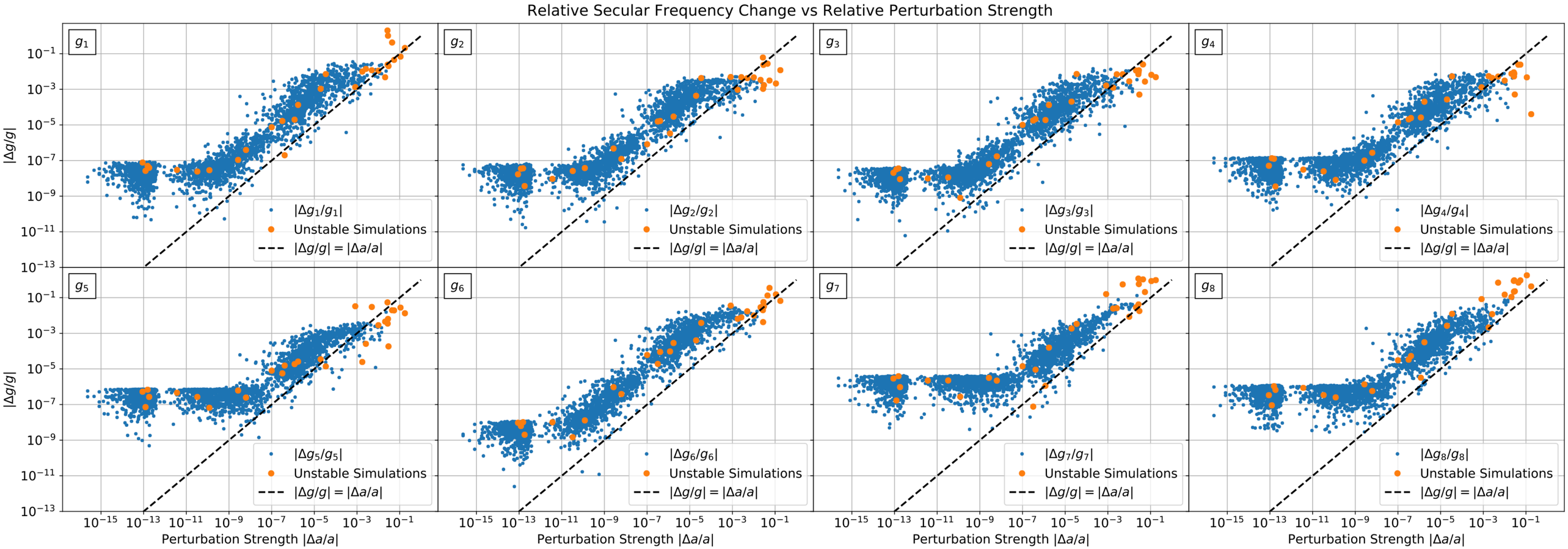
Roy & Haddow 2003
Heggie 2006

Secular Changes

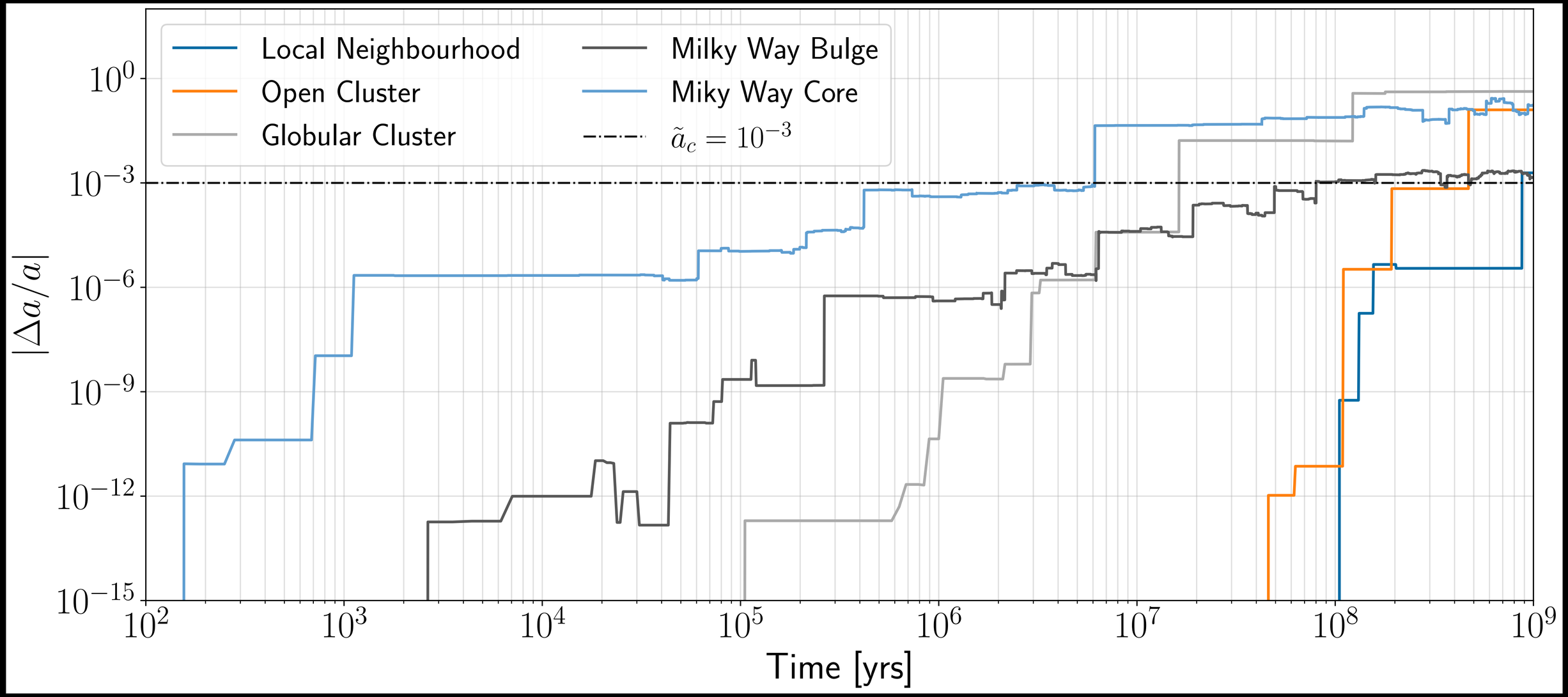
- 240 more solar system simulations
- Artificially move only Neptune
- Changes appear with changes >0.1%
- Major instabilities starting at 10%

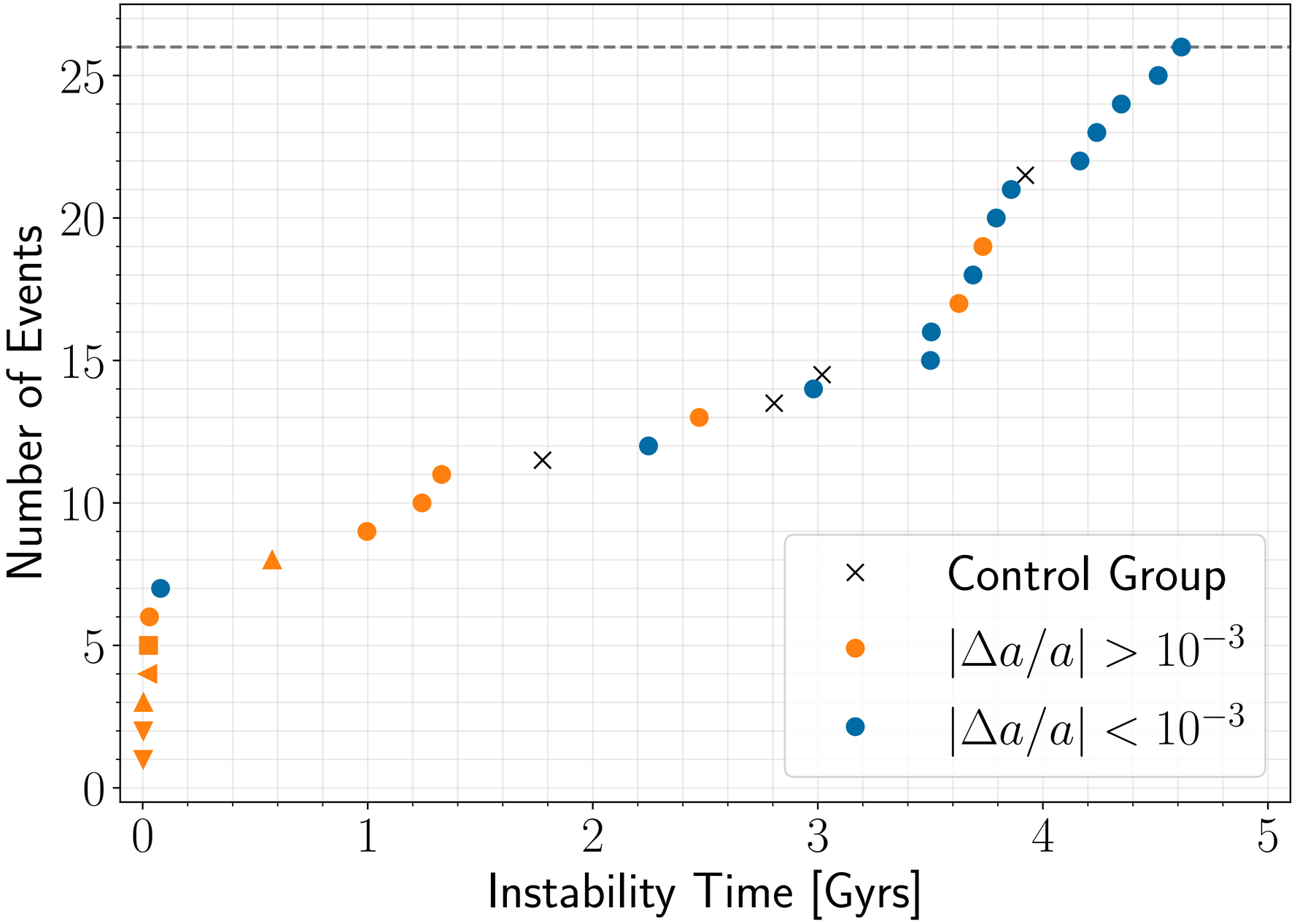



$|\Delta g_1/g_1|$
Unstable Simulations
$|\Delta g/g| = |\Delta a/a|$
$|\Delta g/g|$
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
Perturbation Strength $|\Delta a/a|$


Relative Secular Frequency Change vs Relative Perturbation Strength
g_1
g_2
g_3
g_4
g_5
g_6
g_7
g_8
$|\Delta g/g|$
Perturbation Strength $|\Delta a/a|$
$|\Delta g_1/g_1|$
$|\Delta g_2/g_2|$
$|\Delta g_3/g_3|$
$|\Delta g_4/g_4|$
$|\Delta g_5/g_5|$
$|\Delta g_6/g_6|$
$|\Delta g_7/g_7|$
$|\Delta g_8/g_8|$
Unstable Simulations
$|\Delta g/g| = |\Delta a/a|$

Do Successive Flybys Matter?




Number of Events
Instability Time [Gyrs]
0
5
10
15
20
25
0
1
2
3
4
5
Control Group
$|\Delta a/a| > 10^{-3}$
$|\Delta a/a| < 10^{-3}$