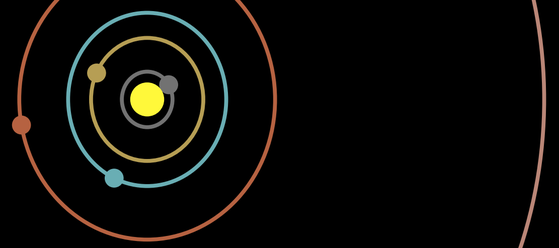


Too Close For Comfort

Solar system stability in the presence of weak stellar flybys

NSERC CRSNG

UNIVERSITY OF TORONTO

Garett Brown
Hanno Rein

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?

Old News

Historical Background

Laplace-Lagrange-Poisson-Poincaré

"Those who are interested… must feel some astonishment at seeing how many times the stability of the Solar System has been demonstrated…"

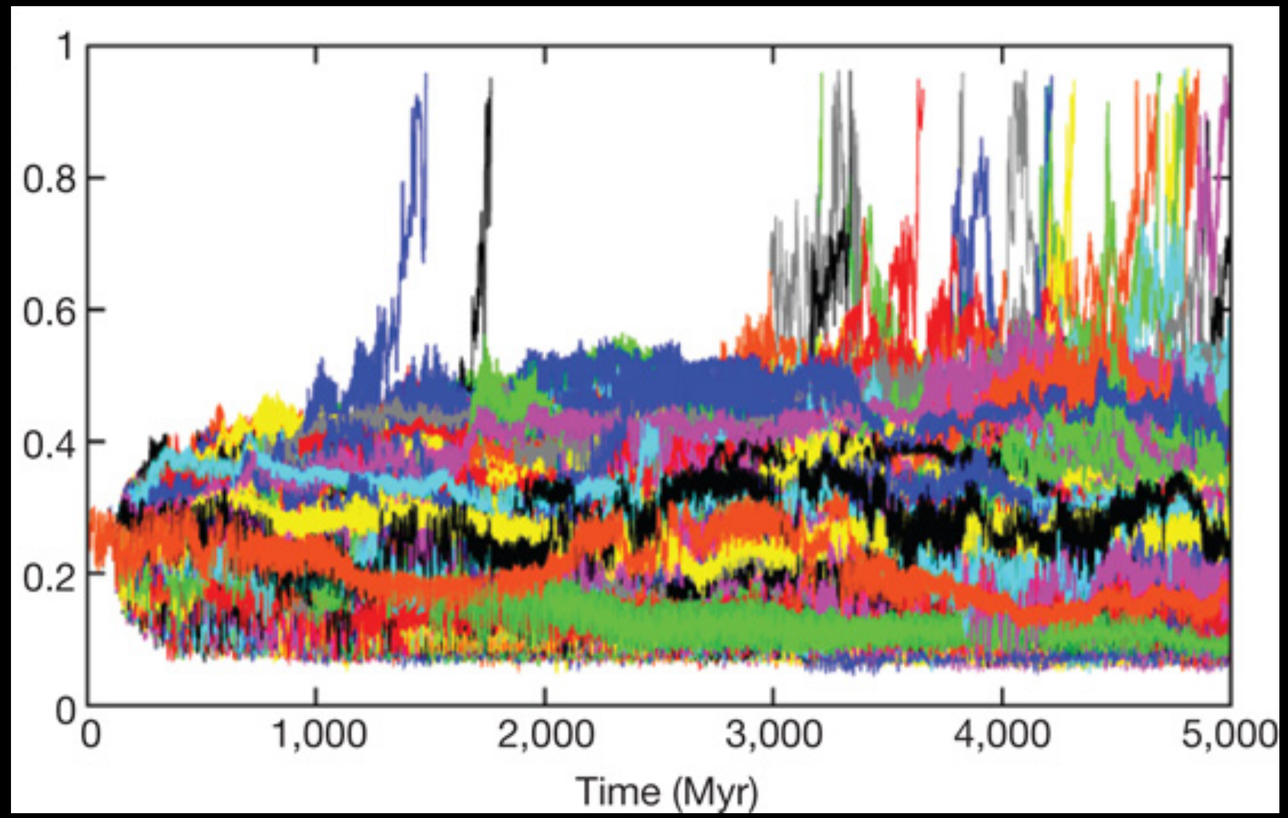
"The astonishment of those people would probably double, if they would be told…, by a rigorous reasoning, that the planetary system is unstable."

Poincaré (1897)

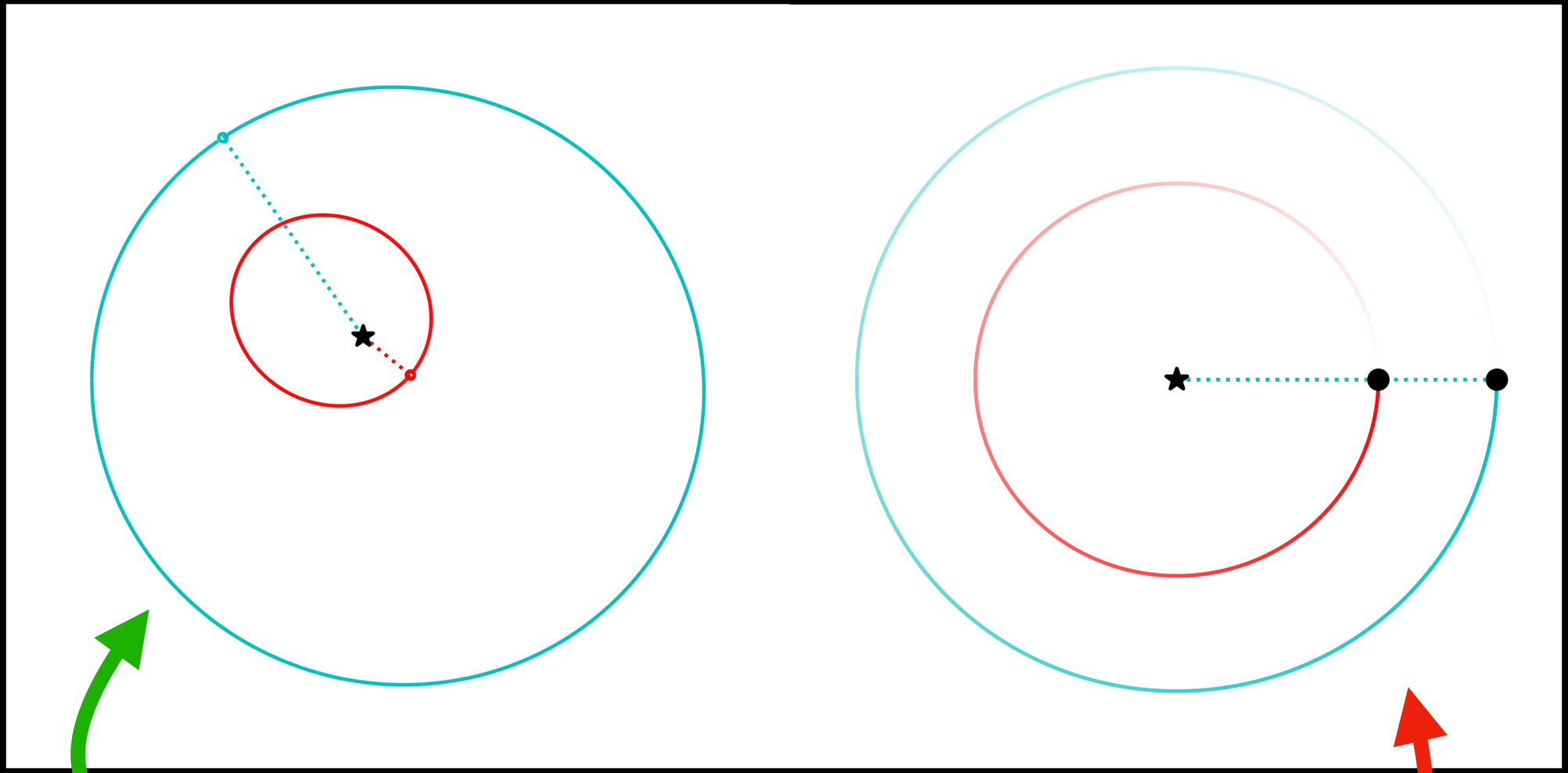
Stability and Chaos

- Laskar & Gastineau (2009)
- 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.



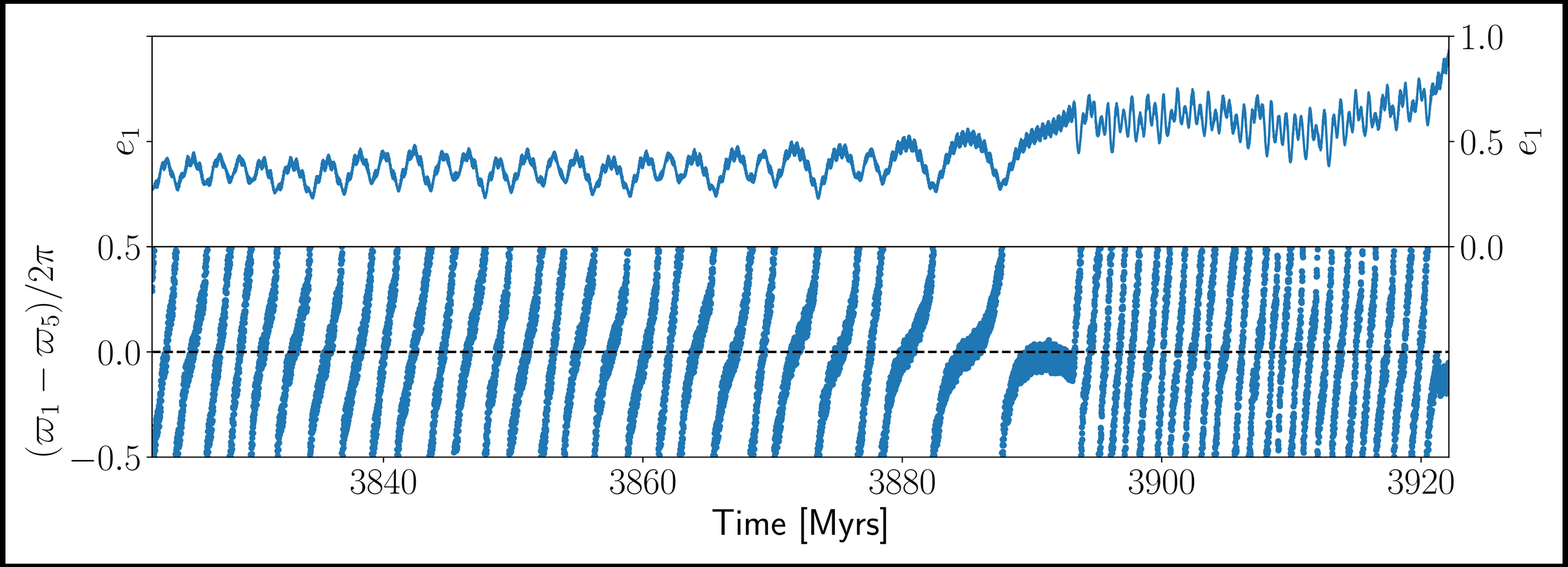
J Laskar & M Gastineau Nature **459**, 817-819 (2009) doi:10.1038/nature08096



Secular Resonances

not mean motion resonances

usually



Secular Resonances

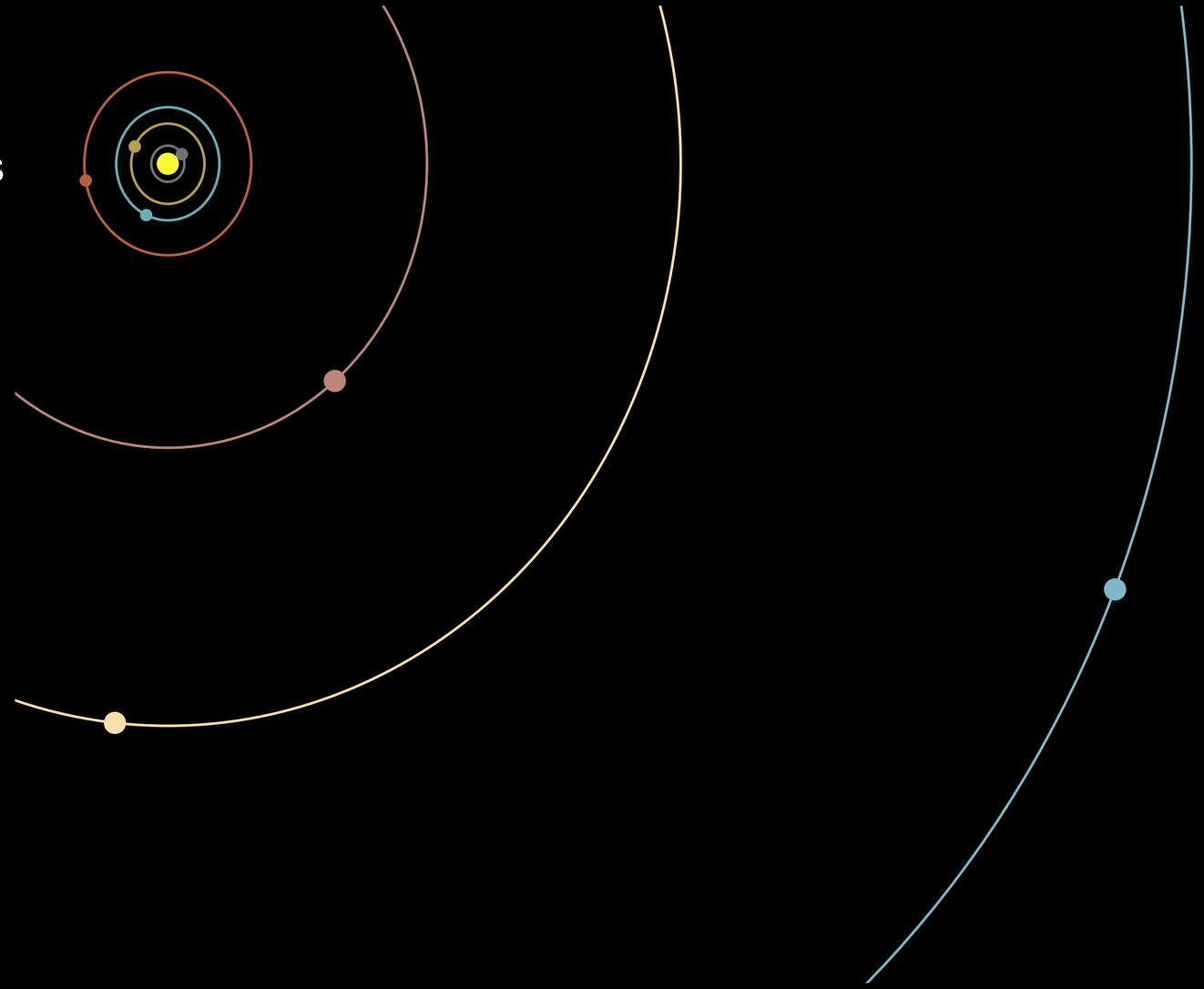
between Mercury and Jupiter

Recent News

The sun isn’t the only star

Experimental Setup

- 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

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

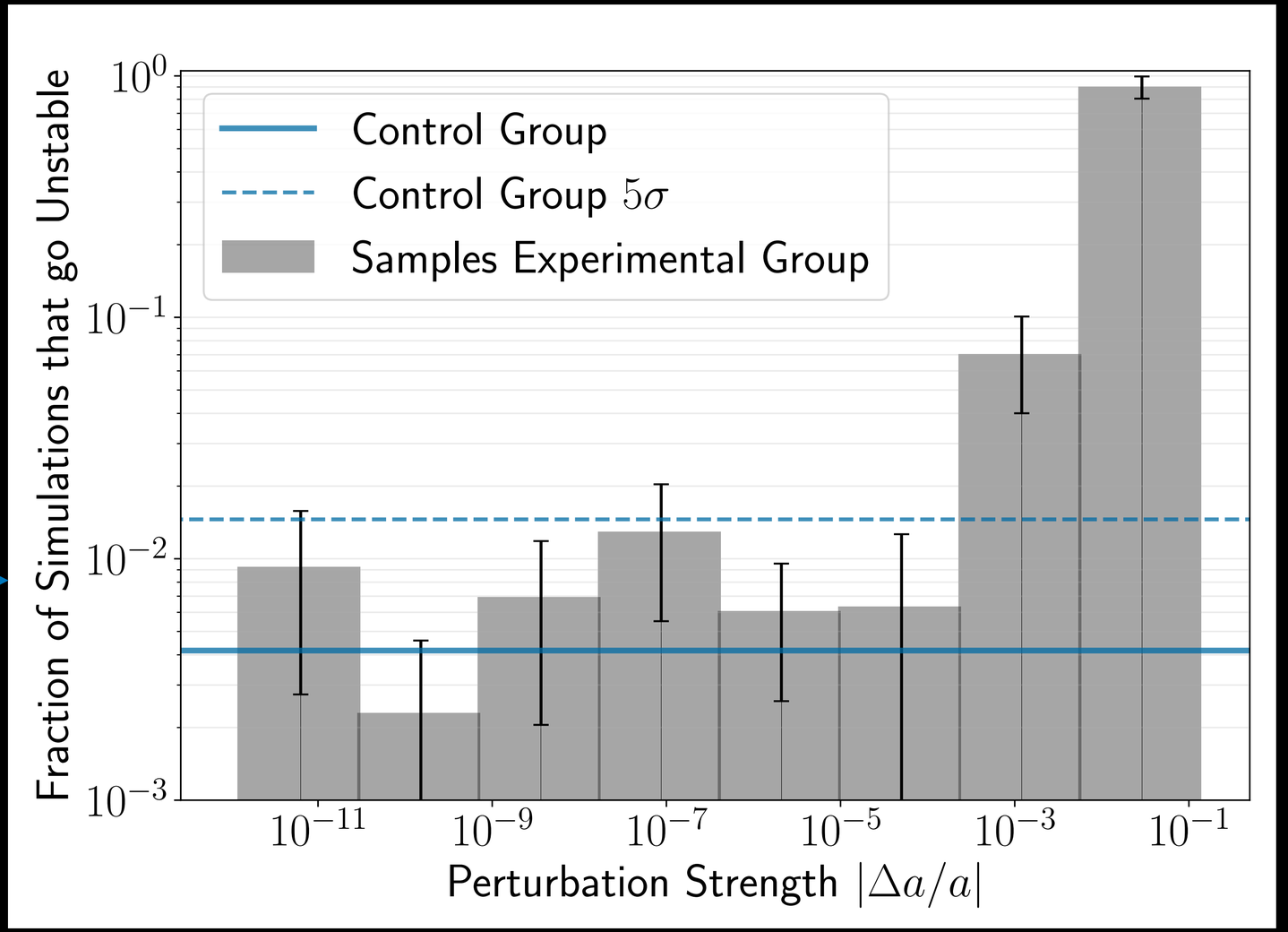
$$\frac{\Delta g}{g} \propto \frac{\Delta a}{a}$$

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

Roy & Haddow 2003
Heggie 2006

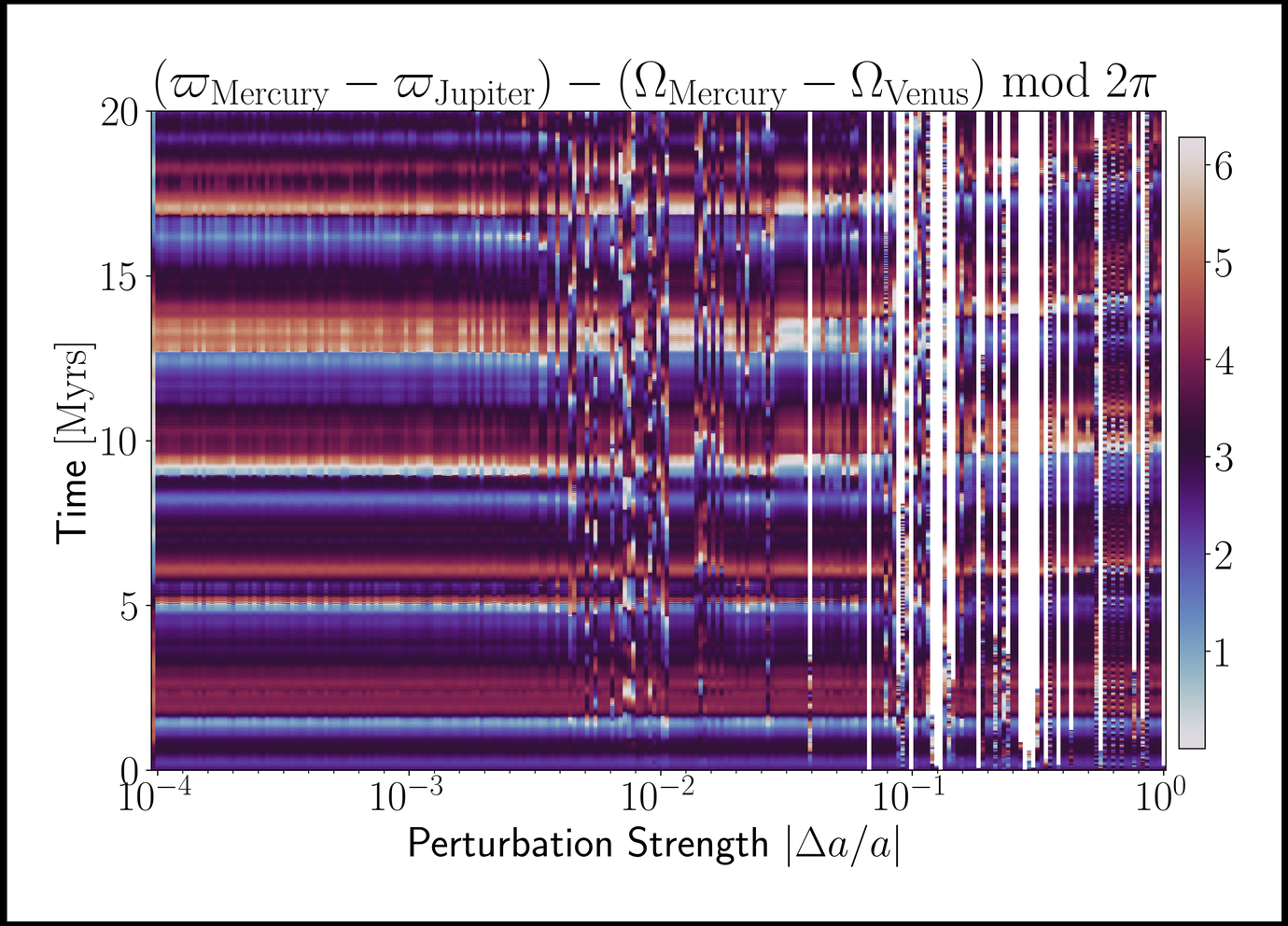
Changes >0.1% are critical

- 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.

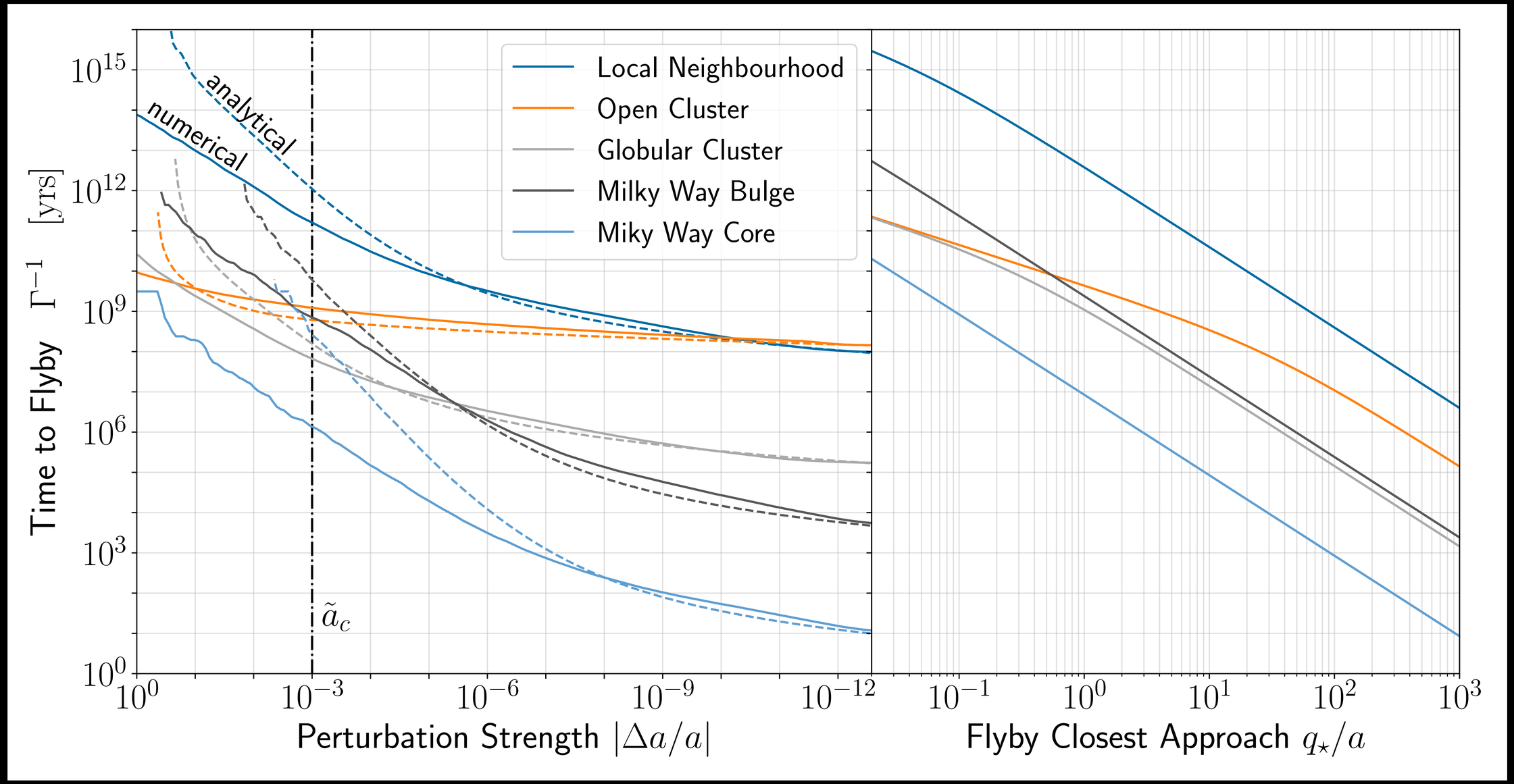


Secular Changes

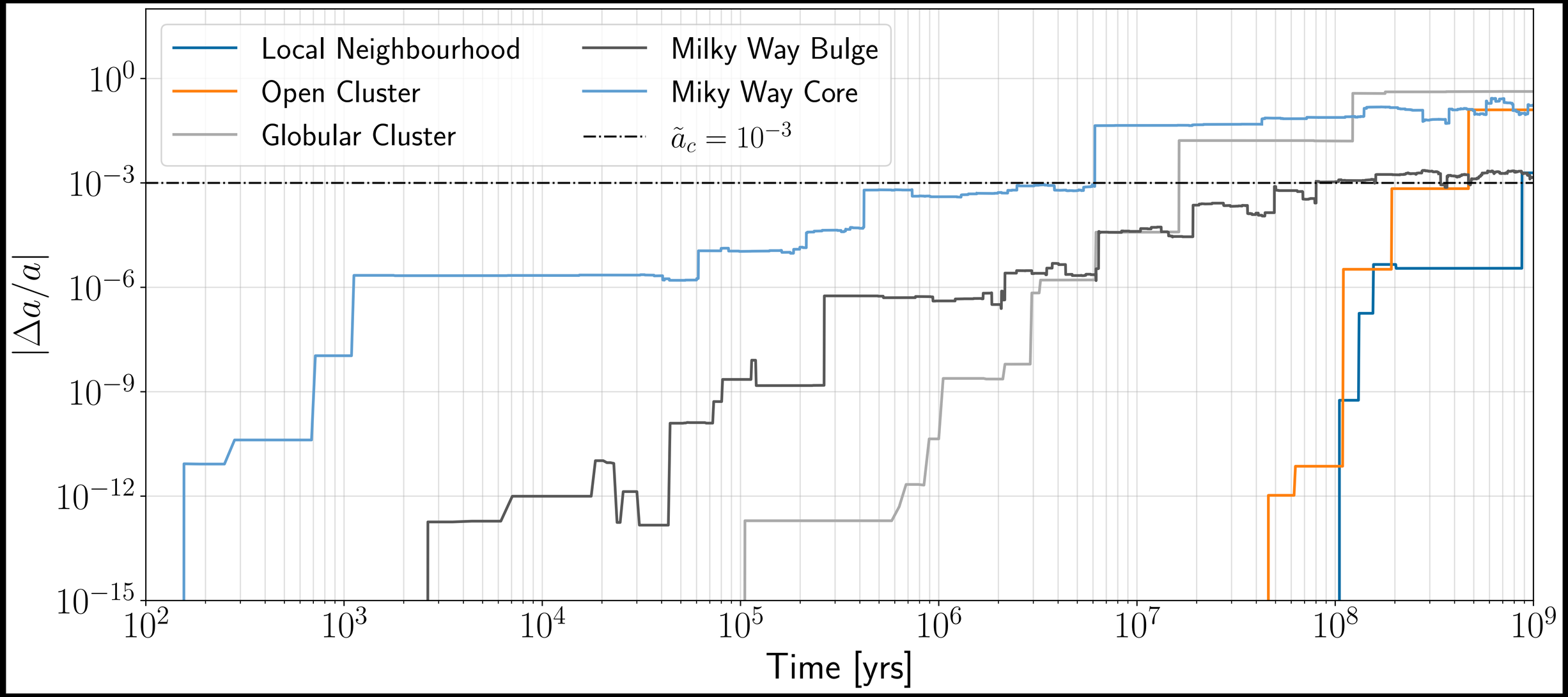
- 240 more solar system simulations
- Artificially move only Neptune
- Changes appear with changes >0.1%
- Major instabilities starting at 10%



How Likely is a Stellar Flyby?



Do Successive Flybys Matter?

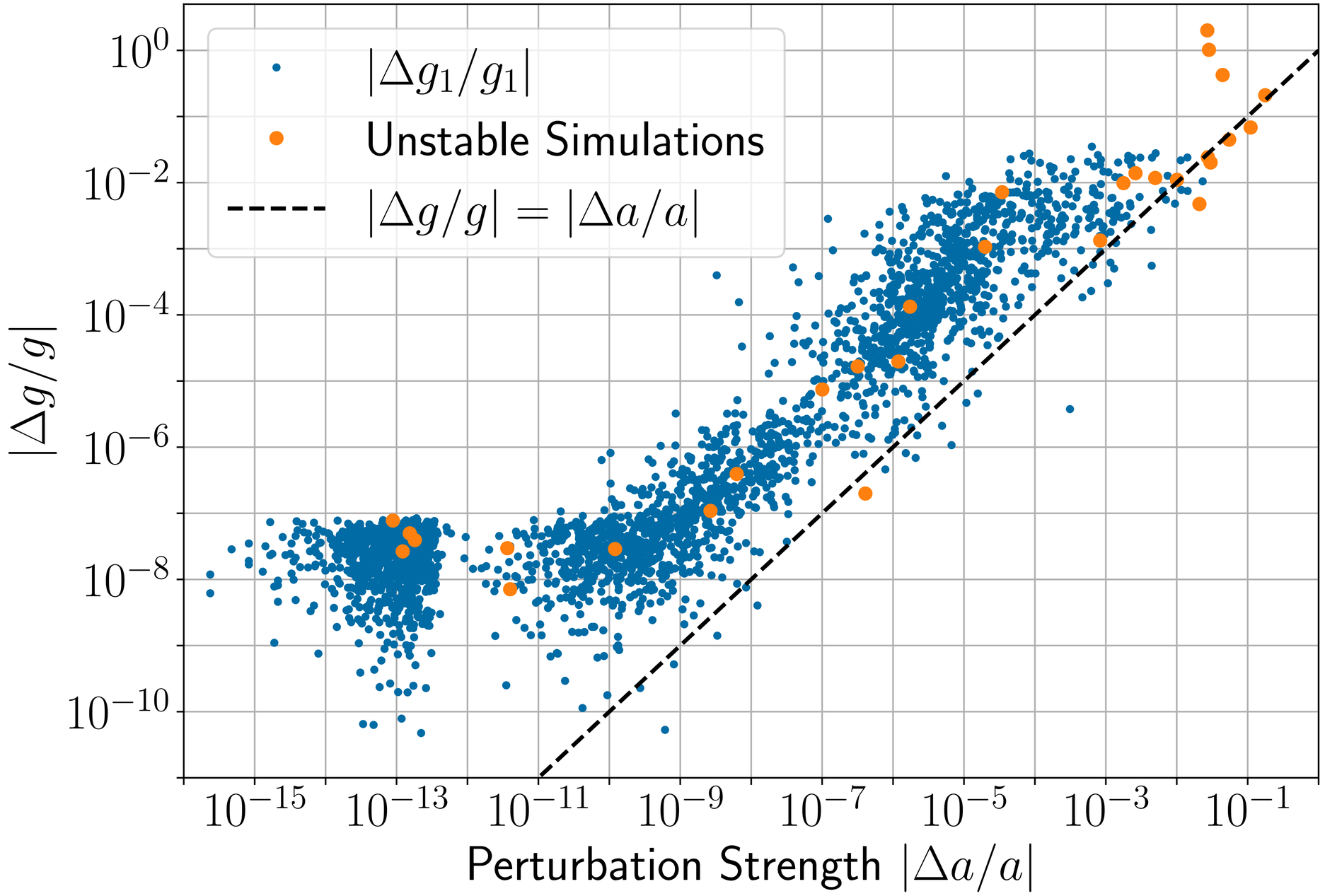


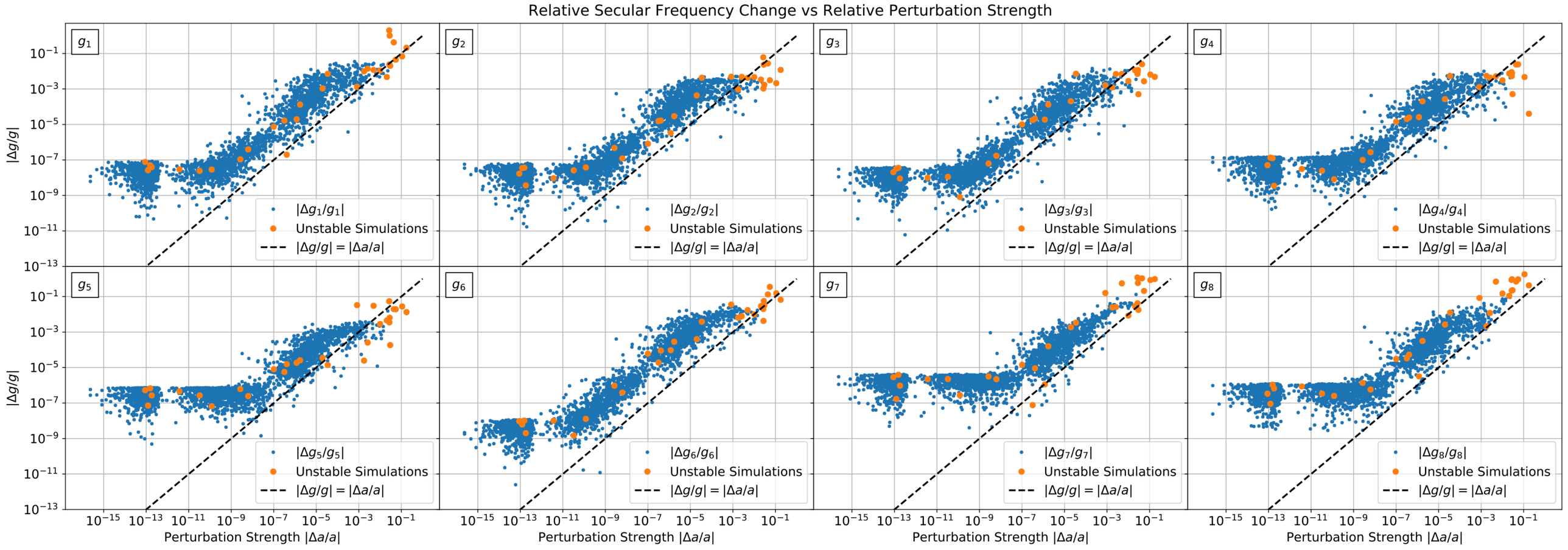
Too Close For Comfort

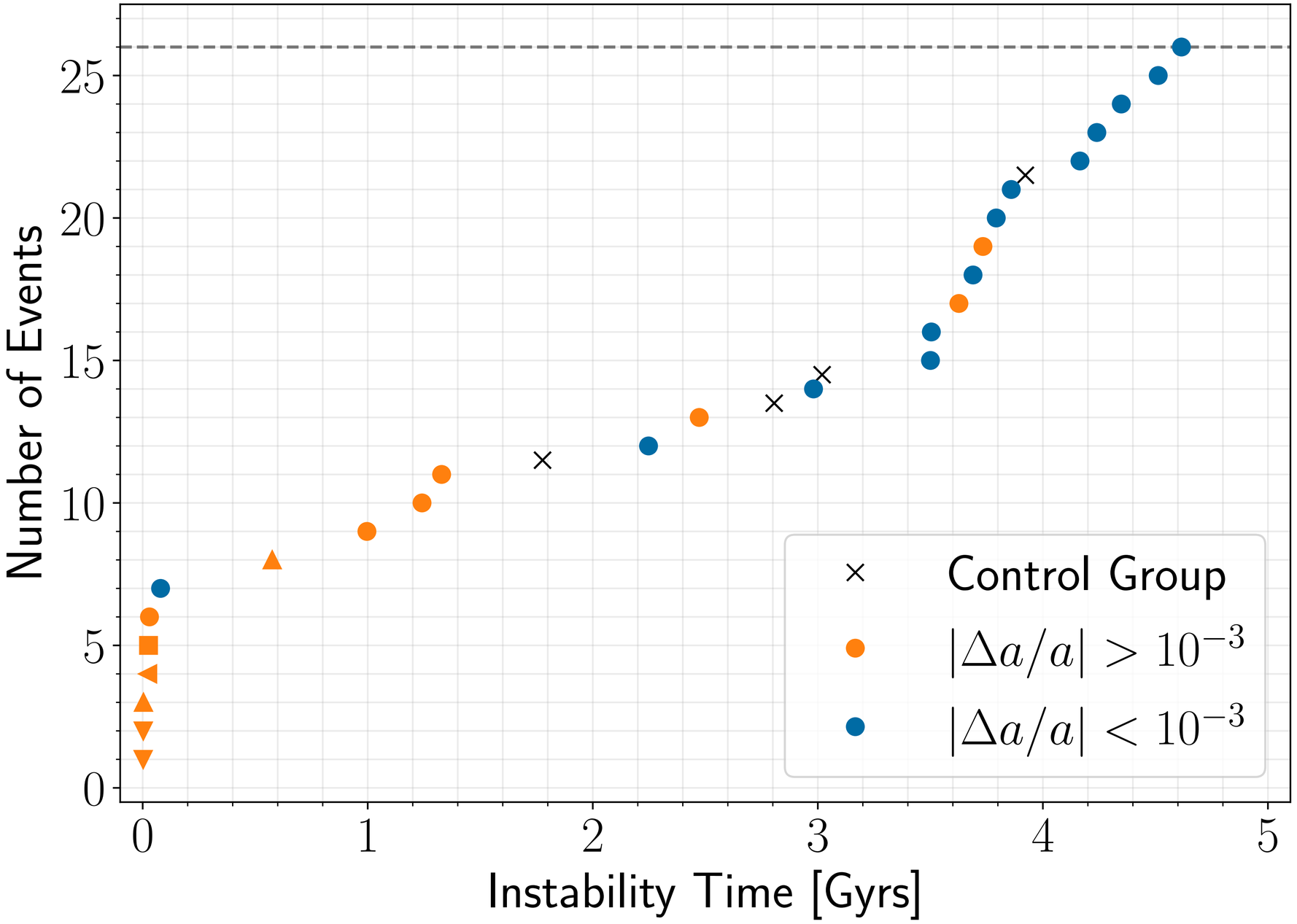
- How stable is the solar system?
  - Reasonably stable, ~99%.
- What is the mechanism for instability?
  - Mercury-Jupiter secular resonance
- How much change causes instability?
  - Change of 0.1% to the secular system
- How likely is a destabilizing stellar flyby?
  - Very unlikely, 1 in 100 billion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

arXiv: 2206.14240
doi: 10.1093/mnras/stac1763

Thank you


$|\Delta g_1/g_1|$
Unstable Simulations
$|\Delta g/g| = |\Delta a/a|$
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$|\Delta g/g|$
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
$|\Delta g/g|$
$|\Delta g_1/g_1|$
$|\Delta g_2/g_2|$
$|\Delta g_3/g_3|$
$|\Delta g_4/g_4|$
$|\Delta g_5/g_5|$
$|\Delta g_6/g_6|$
$|\Delta g_7/g_7|$
$|\Delta g_8/g_8|$
Unstable Simulations
$|\Delta g/g| = |\Delta a/a|$
Perturbation Strength $|\Delta a/a|$
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}


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