

Title: Dynamical chaos as a tool for characterizing multi-planet systems

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URL: <http://pirsa.org/17090064>

Abstract: <p>Many of the multi-planet systems discovered around other stars are maximally packed. This implies that simulations with masses or orbital parameters too far from the actual values will destabilize on short timescales; thus, long-term dynamics allows one to constrain the orbital architectures of many closely packed multi-planet systems. I will present a recent such application in the TRAPPIST-1 system, with 7 Earth-sized planets in the longest resonant chain discovered to date. In this case the complicated resonant phase space structure allows for strong constraints. A central challenge in such studies is the large computational cost of N-body simulations, which preclude a full survey of the high-dimensional parameter space of orbital architectures allowed by observations. I will discuss our recent successes in training machine learning models capable of predicting orbital stability a million times faster than N-body simulations, and the discovery space that this opens up for exoplanet characterization and planet formation studies.</p>

# Dynamical chaos as a tool for characterizing multi-planet systems



Dan Tamayo

Hanno Rein, Ari Silburt, Kristen Menou, Naireen Hussain,  
Christopher Simbulan, Alysa Obertas, Diana Valencia,  
Norm Murray, Cristobal Petrovich, Mohamad Ali-Dib

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# Dynamical chaos as a tool for characterizing multi-planet systems



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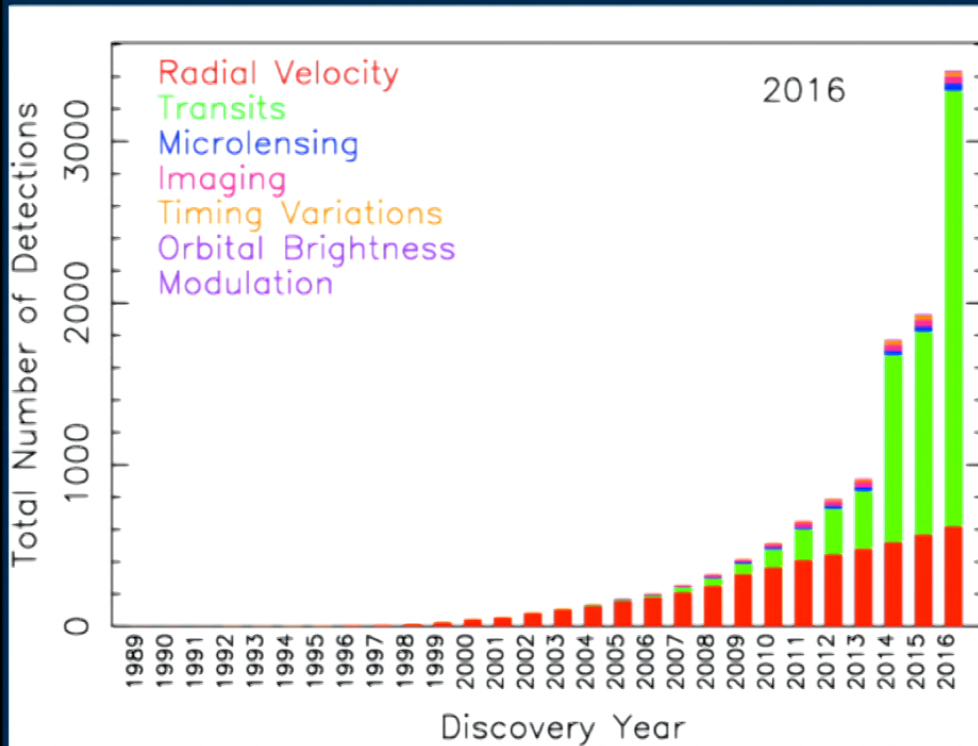
Hanno Rein, Ari Silburt, Kristen Menou, Naireen Hussain,  
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PI 2017

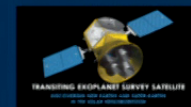
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# Exoplanets in the Era of Big Data



Kepler  
+ K2



TESS  
2018



CHEOPS  
2018



GAIA  
2022



PLATO  
2026

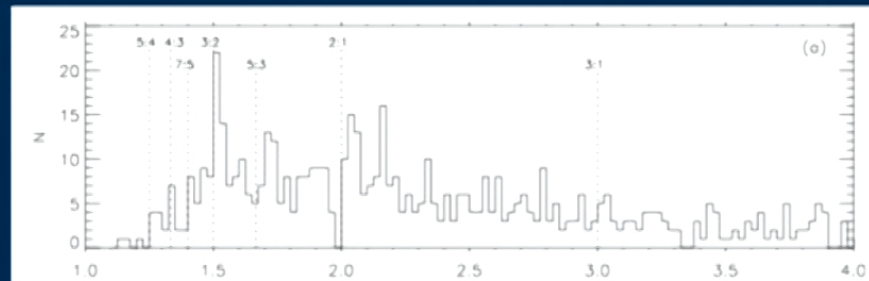
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# A Galactic Context

Period Ratio  
Distributions



Fabrycky+ 2014

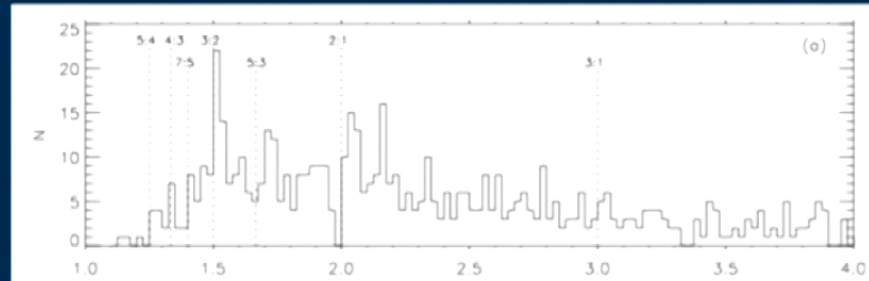
PI 2017

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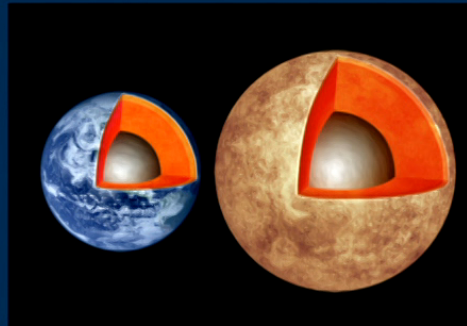
# A Galactic Context

Period Ratio Distributions

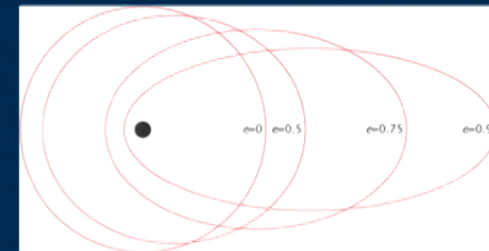


Fabrycky+ 2014

Planet Compositions



Orbital Eccentricities



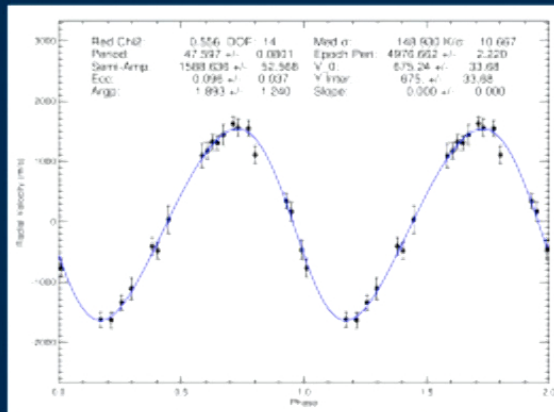
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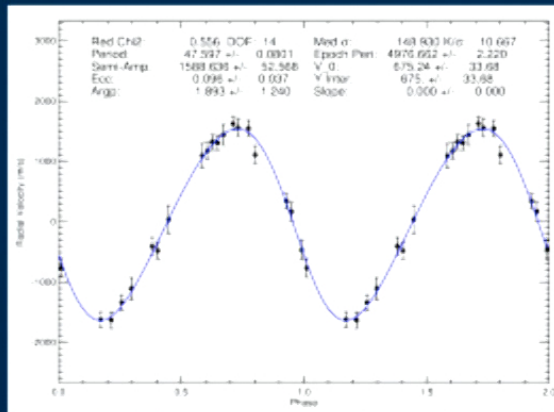
# Exoplanet Characterization

## Radial Velocities

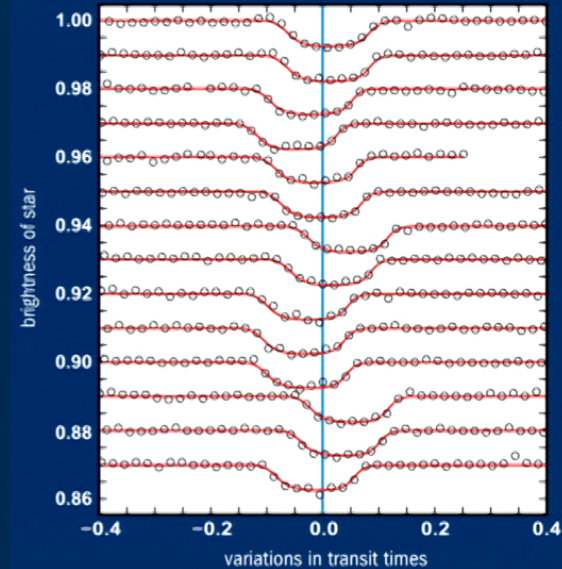


# Exoplanet Characterization

## Radial Velocities

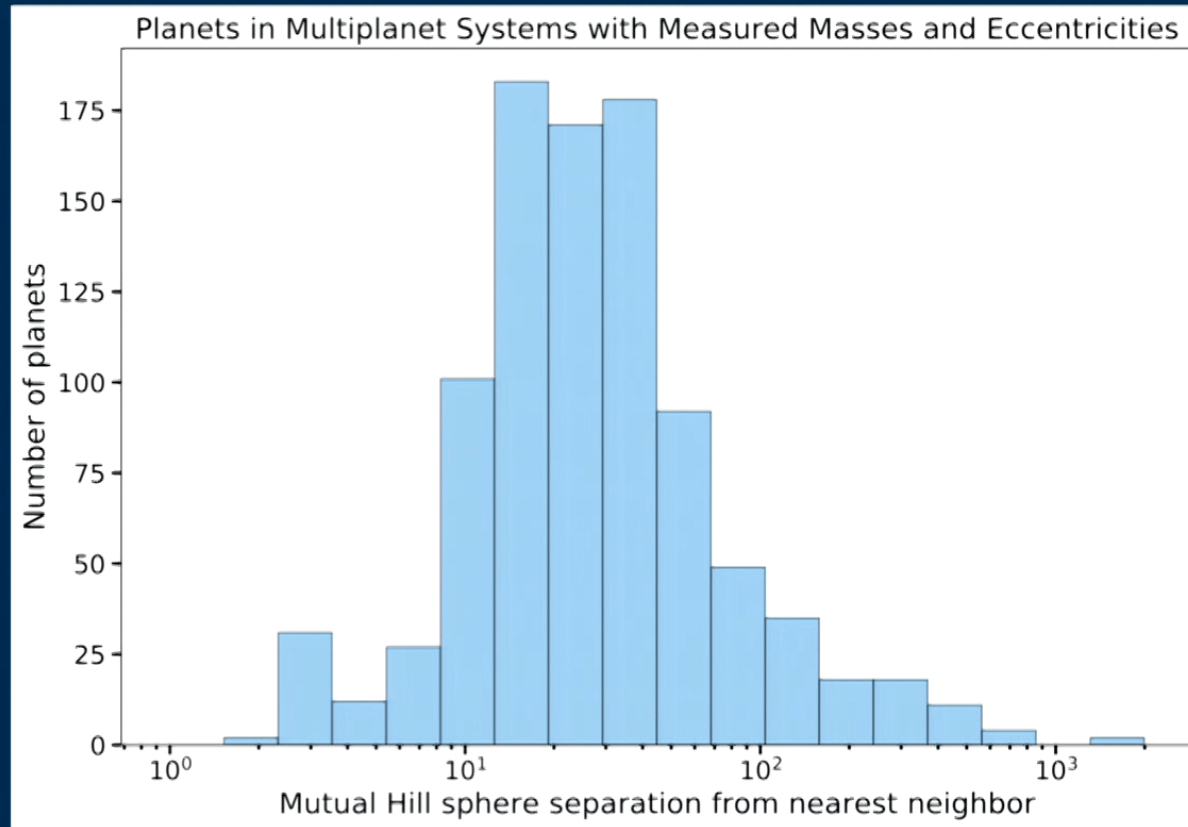


## Transit Timing Variations





# Exoplanets in the Era of Big Data

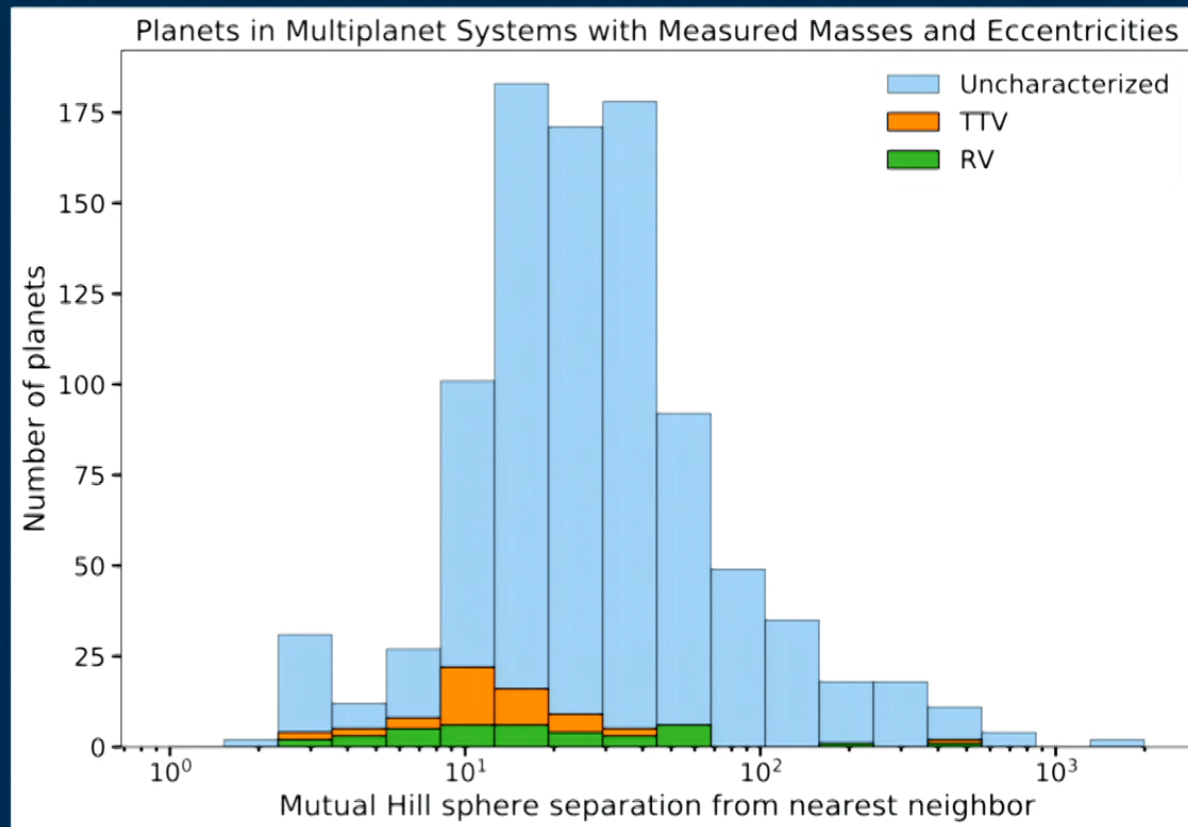


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# Exoplanets in the Era of Big Data

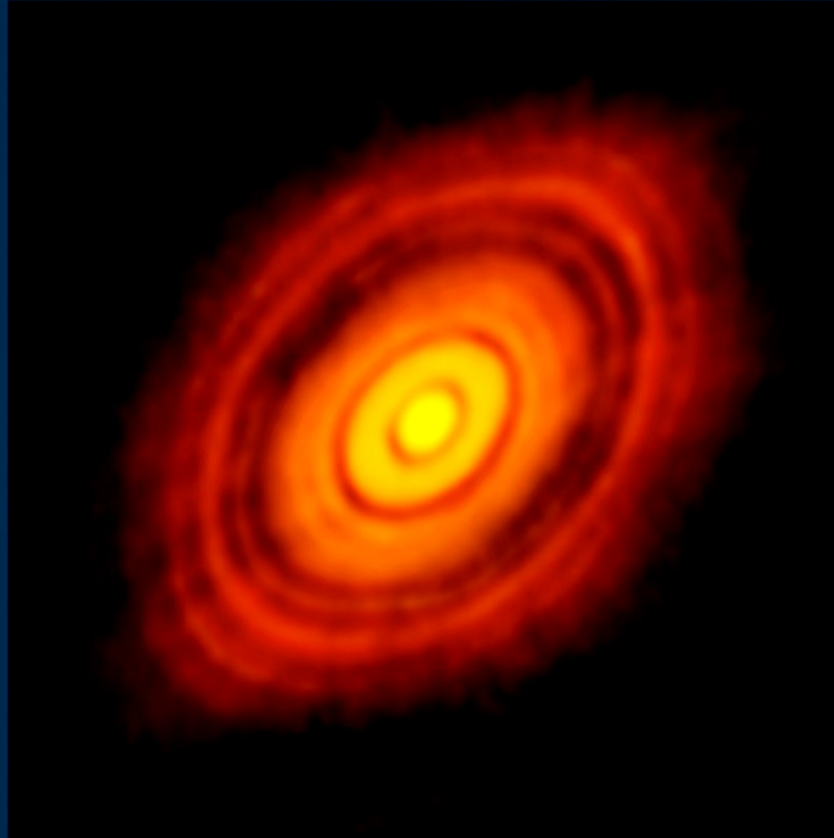


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# Stability Constrained Characterization



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# Stability Constrained Characterization

999936 yrs



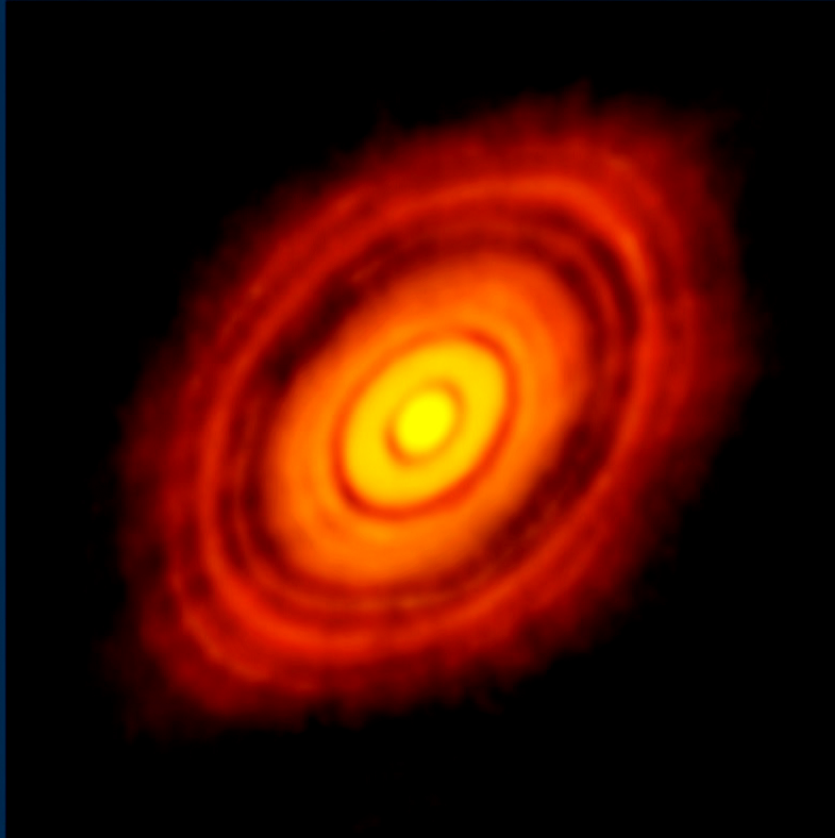
Tamayo et al. 2015

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# Stability Constrained Characterization



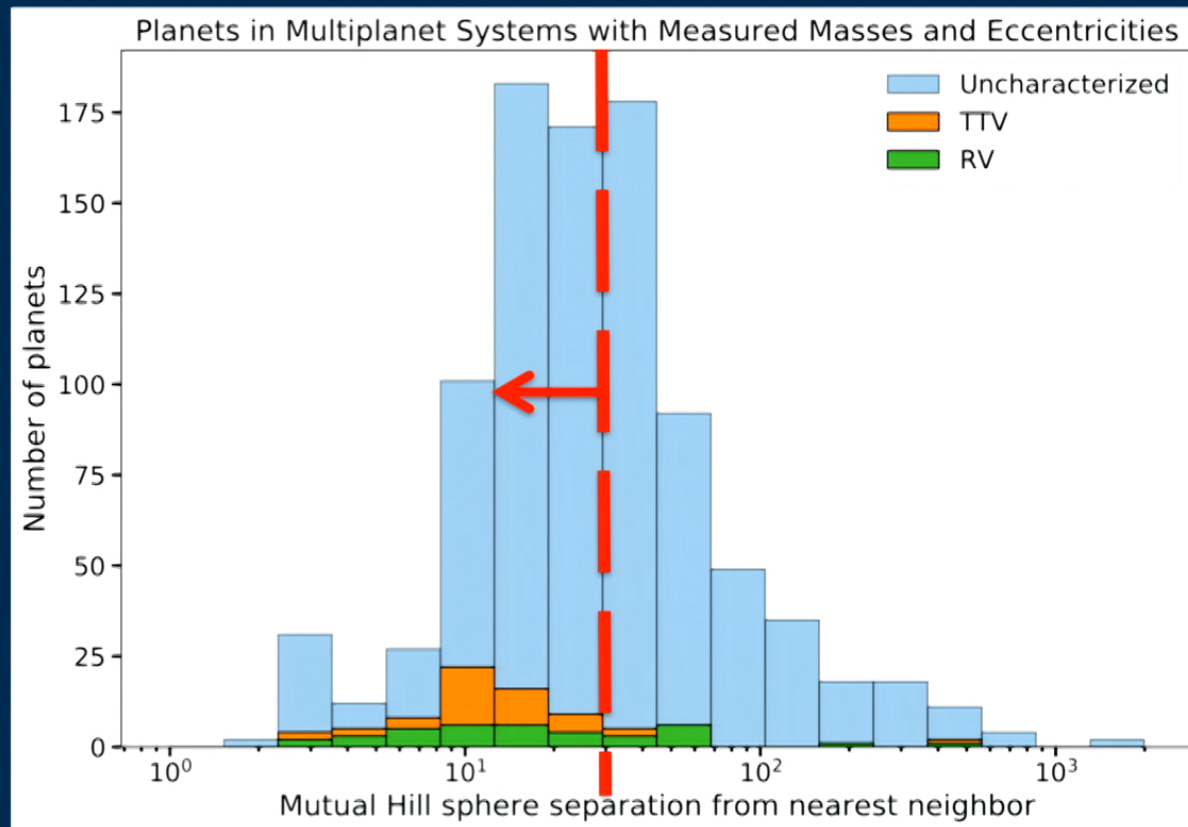
Tamayo et al. 2015

PI 2017

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# Exoplanets in the Era of Big Data



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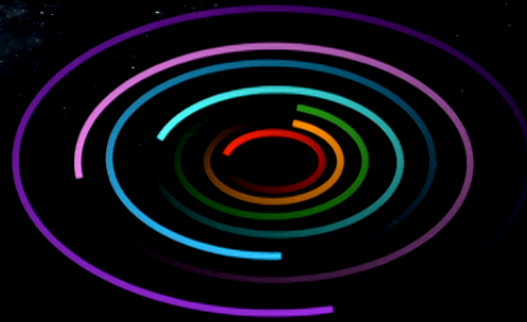
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# Outline

- Predicting long-term stability is challenging
- N-body integrations give important constraints
- A computational wall for N-body integrations
- A new way forward

# The Problem of Planetary Stability



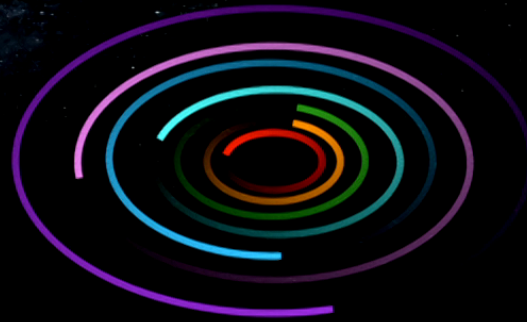
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# A Brief History

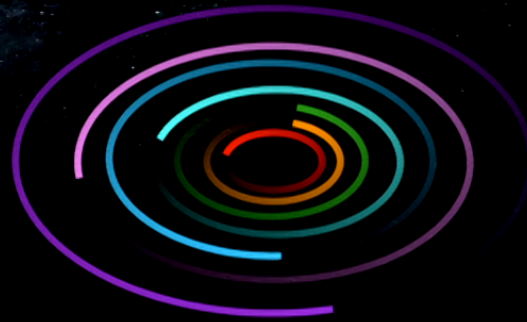


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# A Brief History



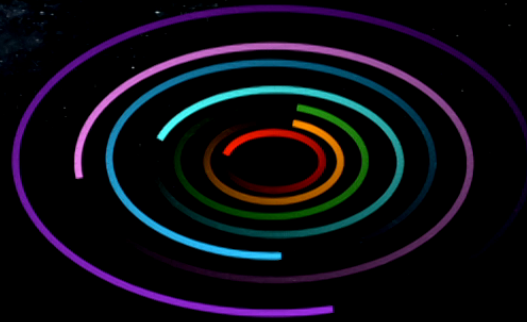
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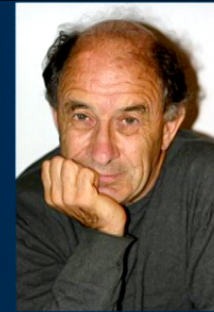
# A Brief History



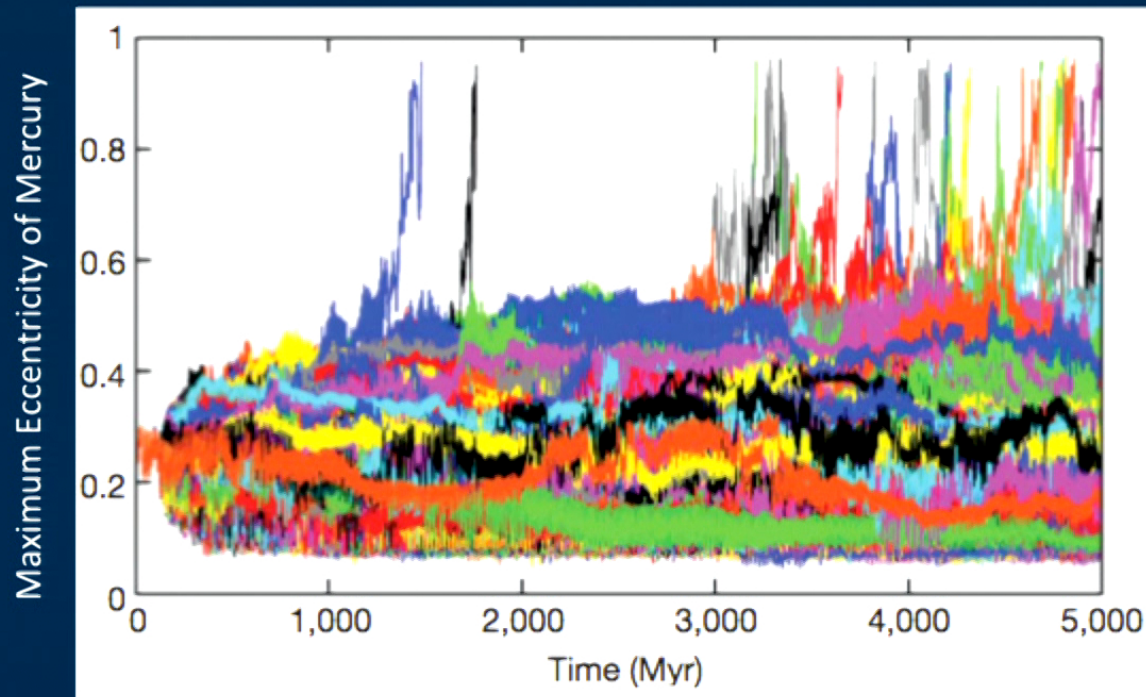
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# Living at the Edge



Laskar & Gastineau 2009

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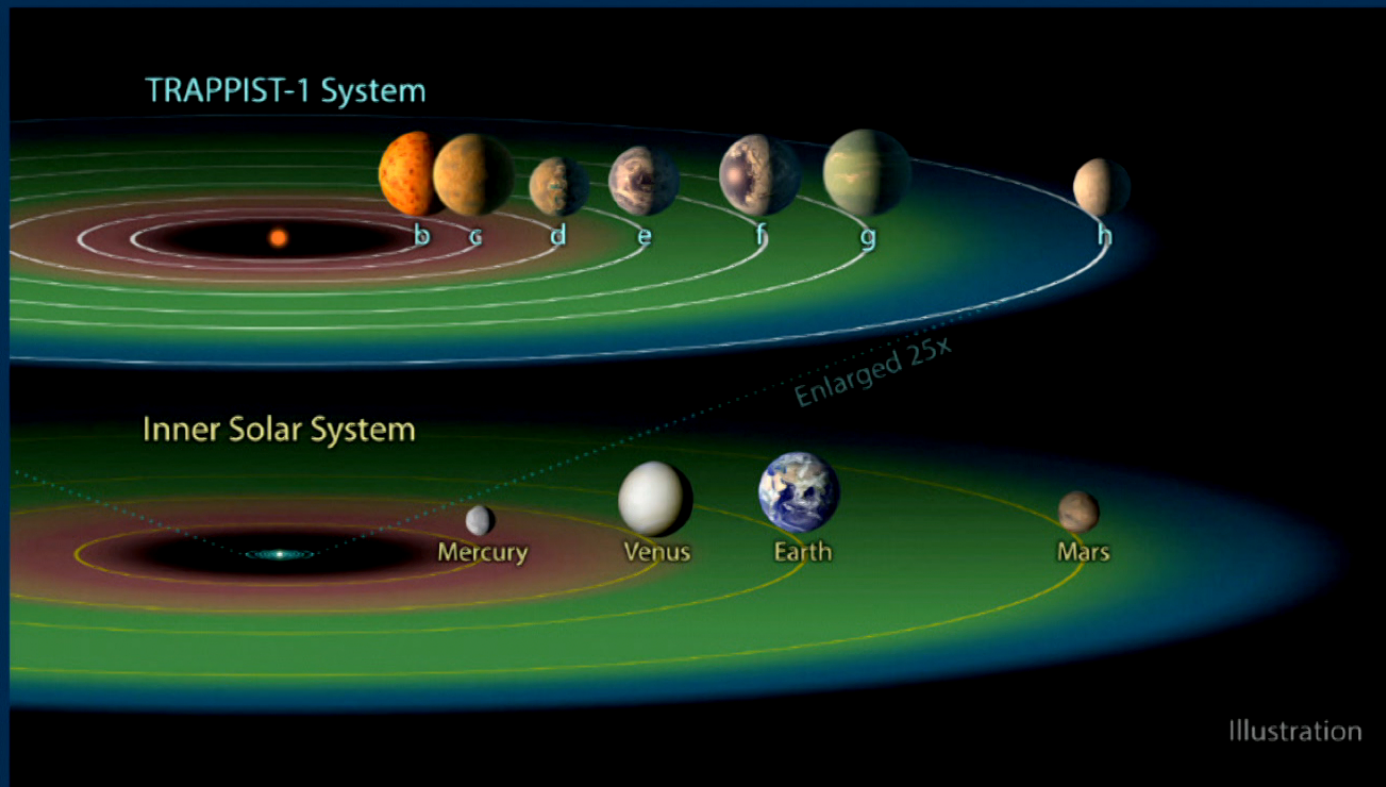


## Outline

# Outline

- Predicting long-term stability is challenging
- **N-body integrations give important constraints**
- A computational wall for N-body integrations
- A new way forward

# TRAPPIST-1

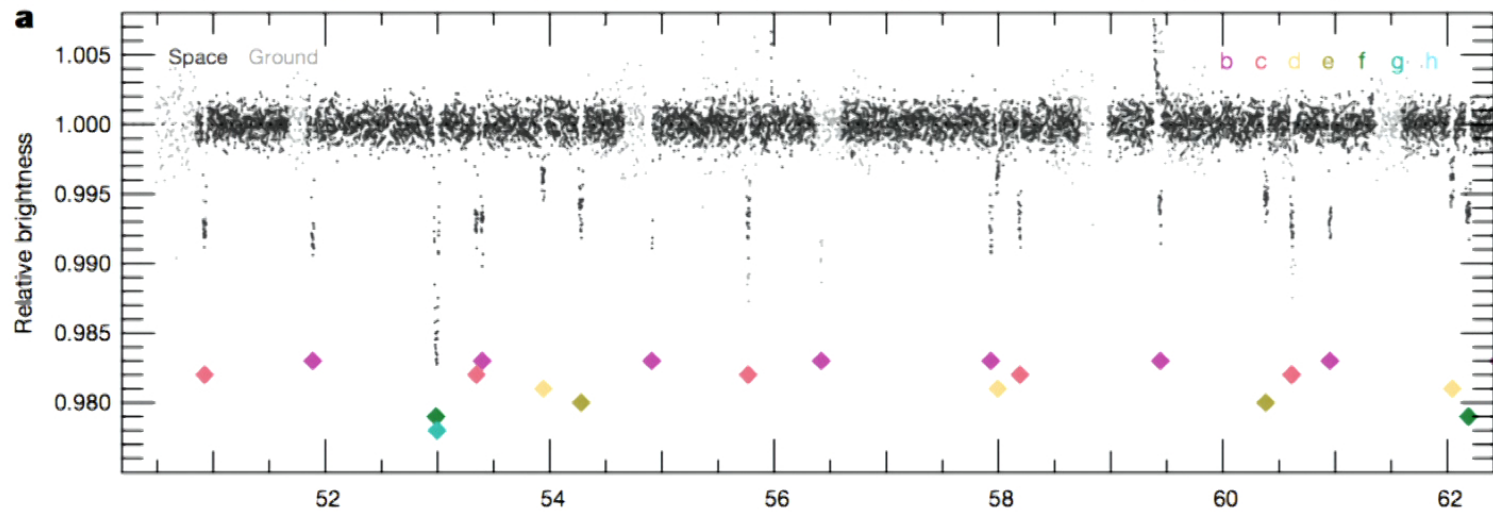


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# TRAPPIST-1

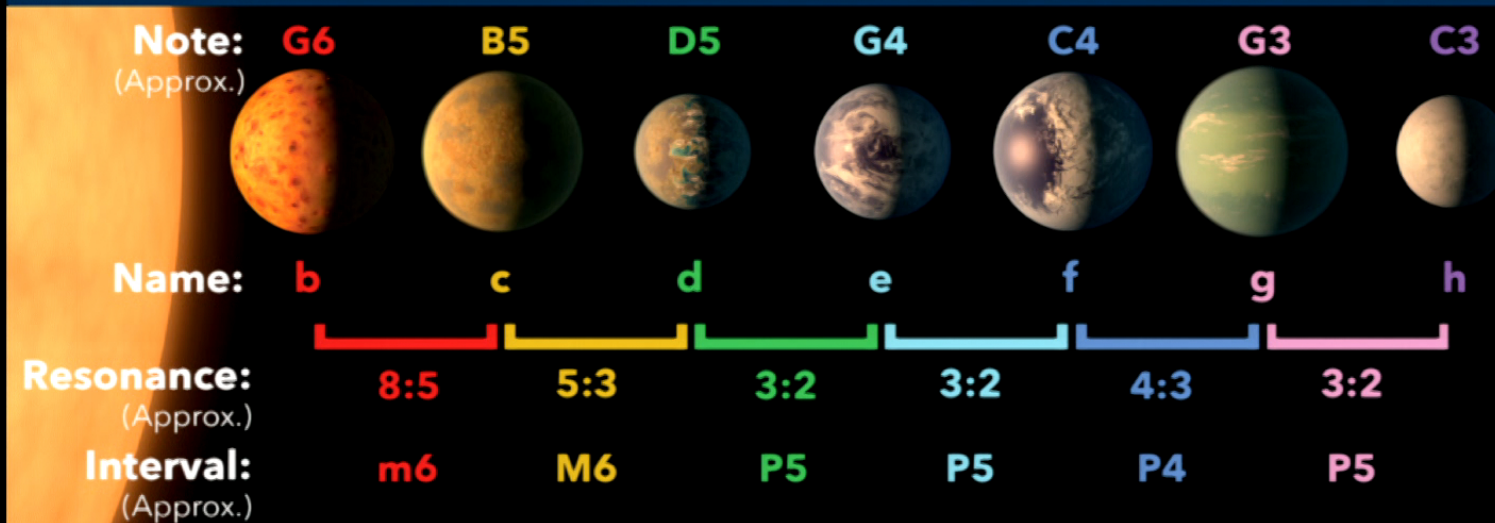


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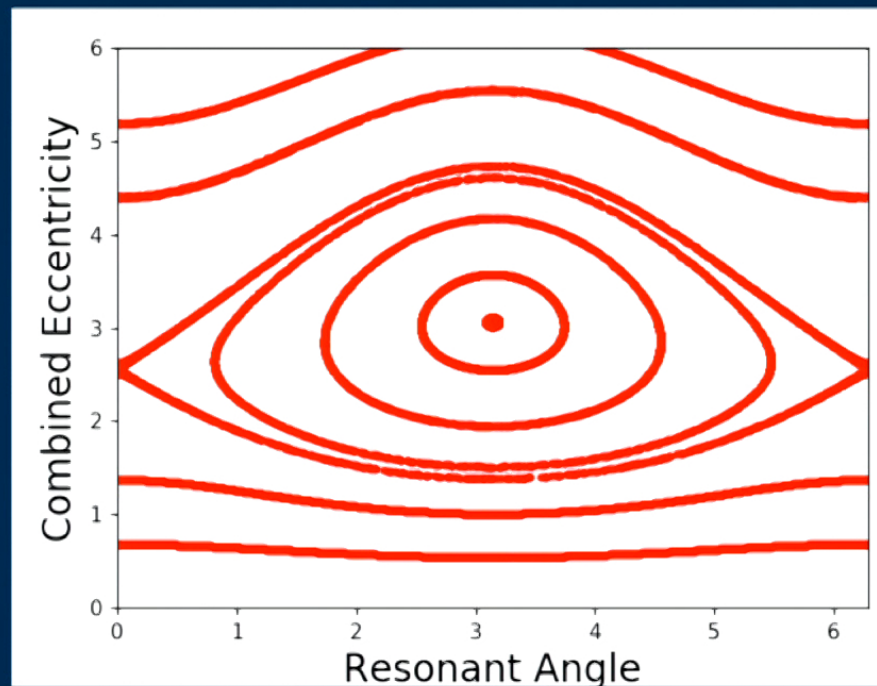
# The Longest Known Resonant Chain



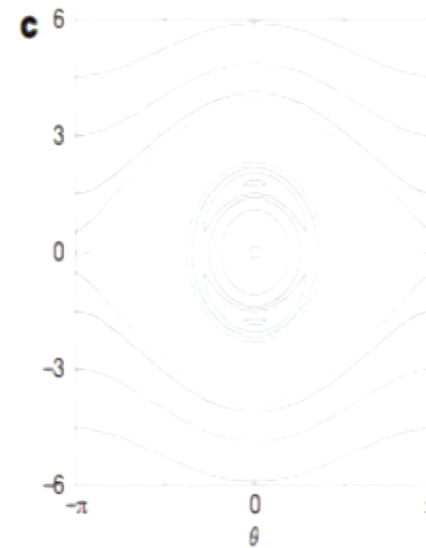
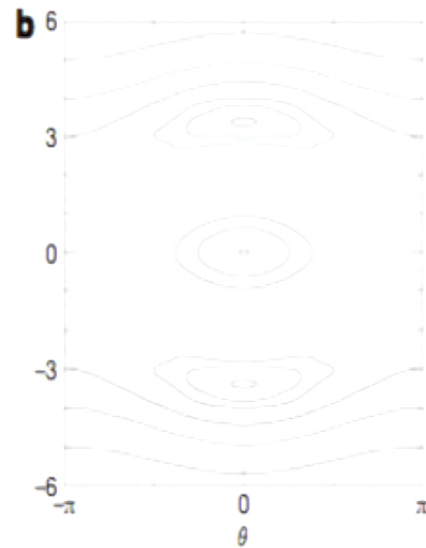
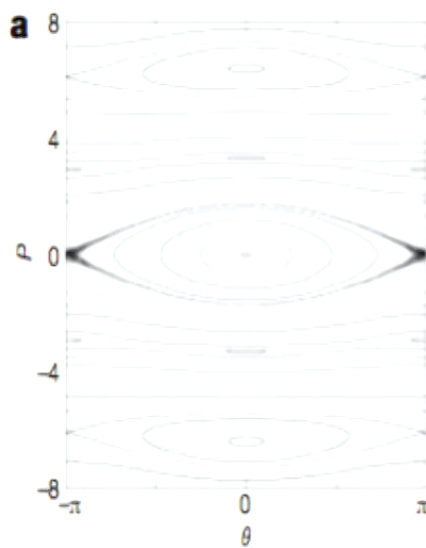


# A Pendulum

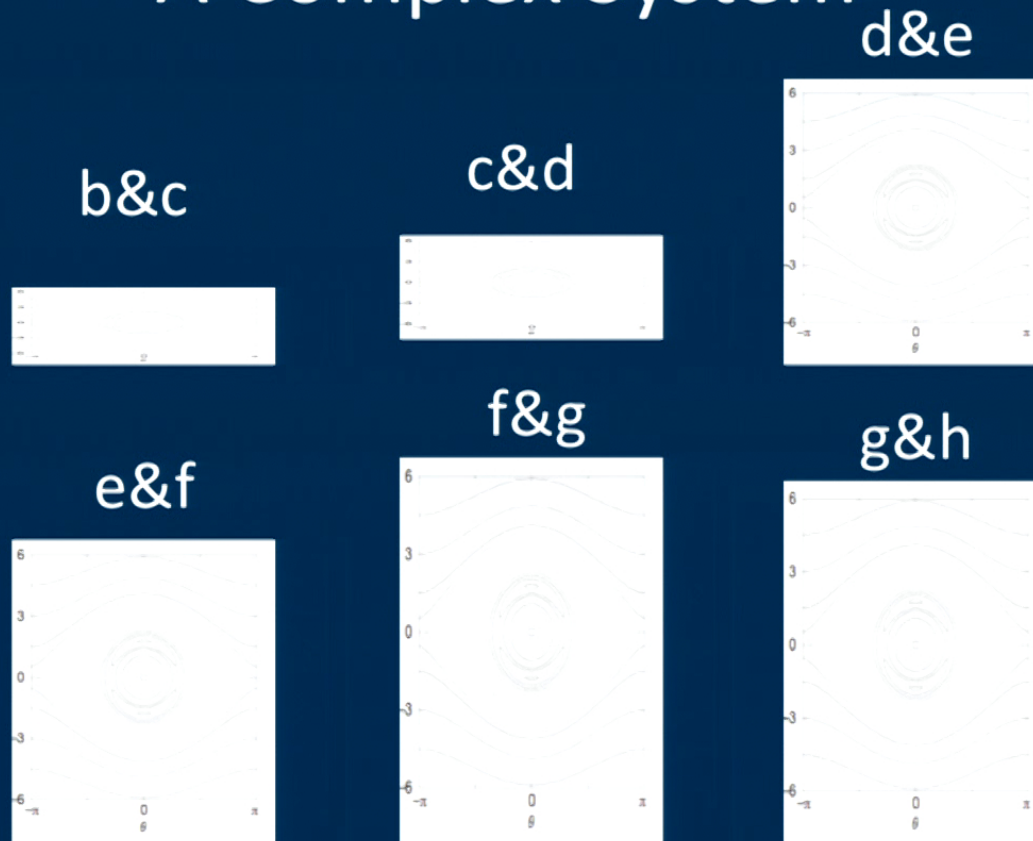
$$\mathcal{H} = p^2 + \epsilon A \cos(\phi)$$



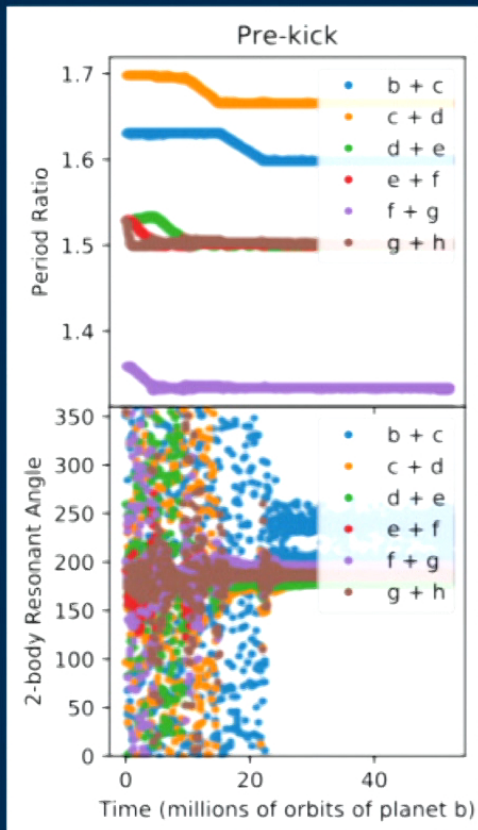
# Where Does Chaos Come From?



# A Complex System



# Forming the TRAPPIST-1 System



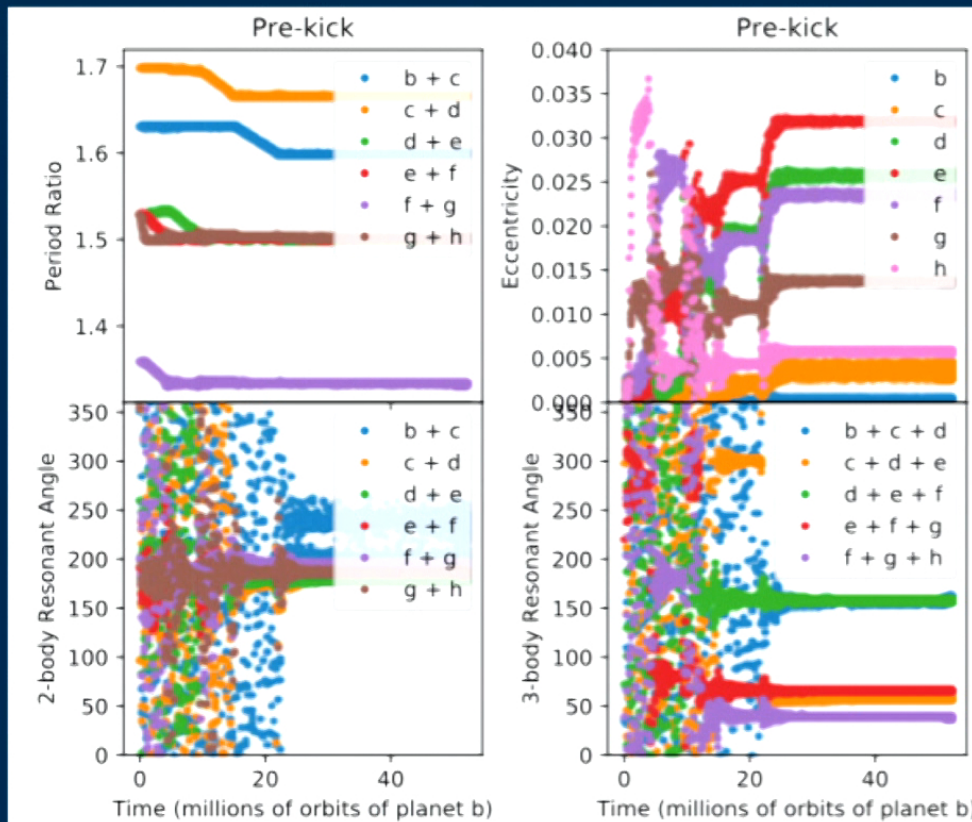
Tamayo et al. 2017

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# Forming the TRAPPIST-1 System



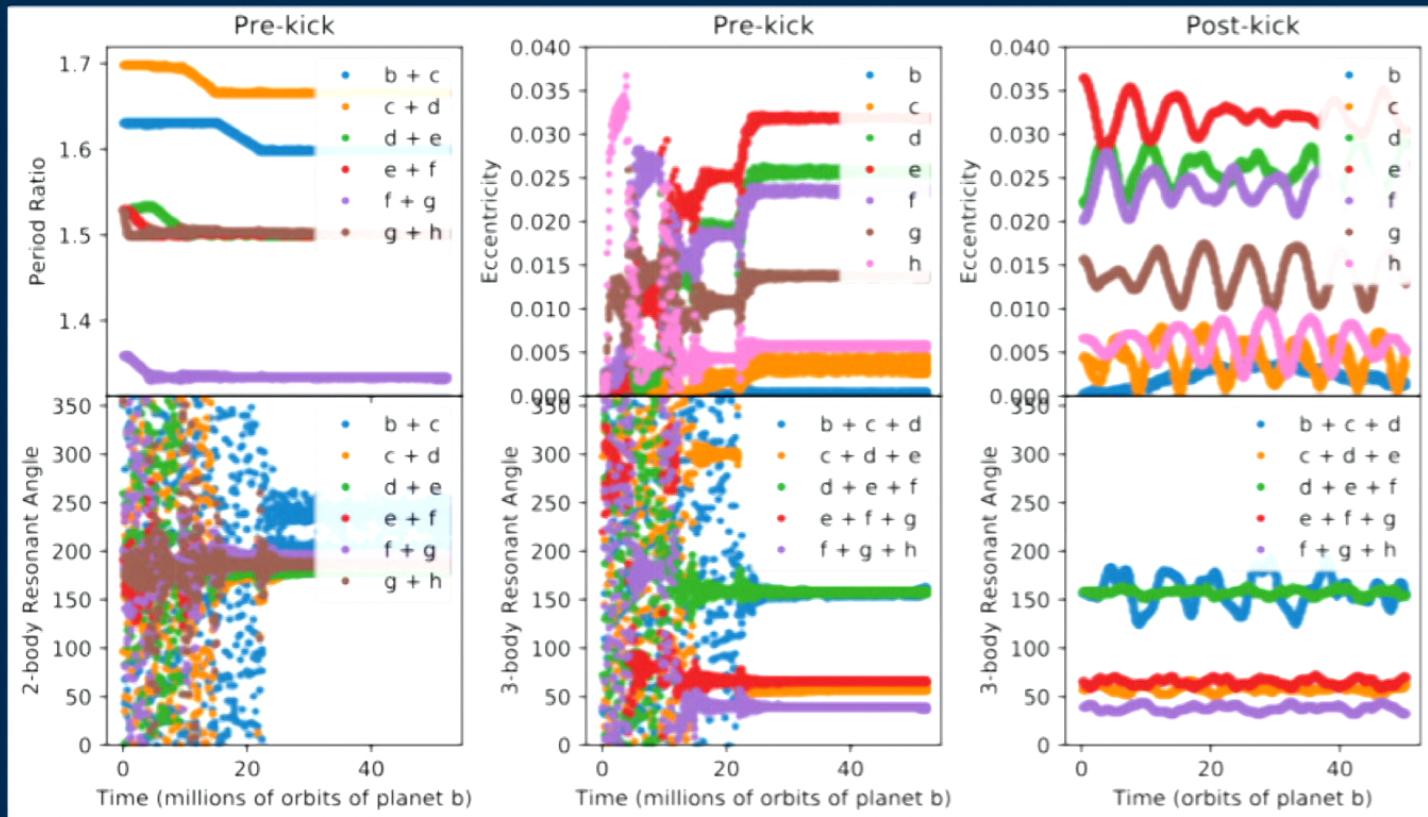
Tamayo et al. 2017

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# Forming the TRAPPIST-1 System

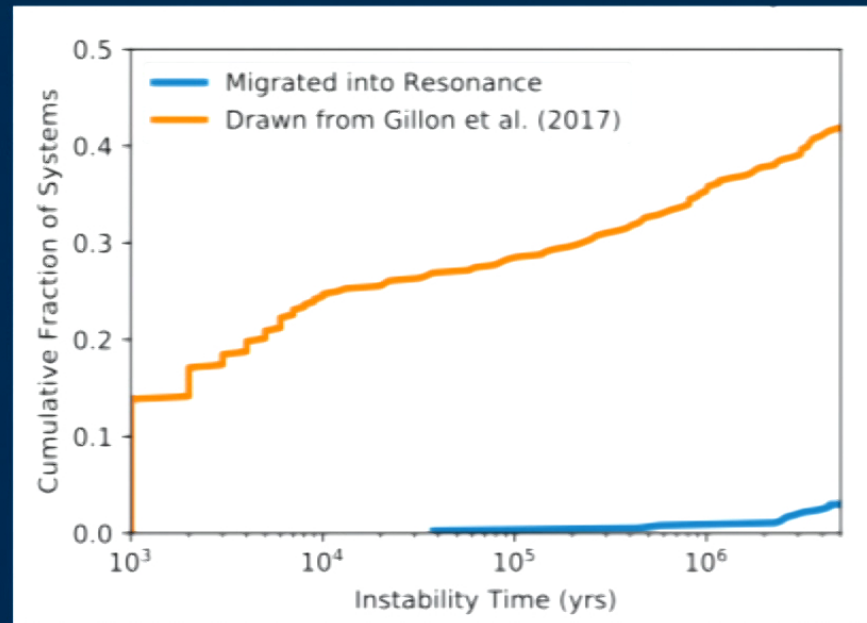


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# Stabilizing TRAPPIST-1



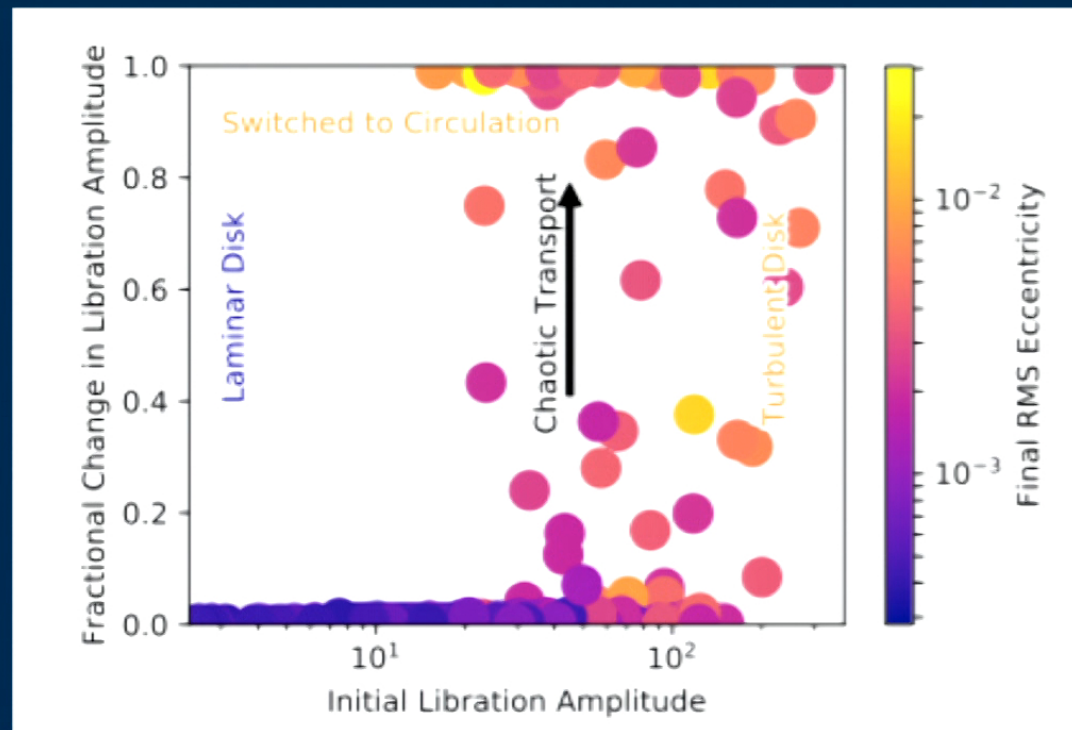
Tamayo et al. 2017

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# Chaotic Transport



Tamayo et al. 2017

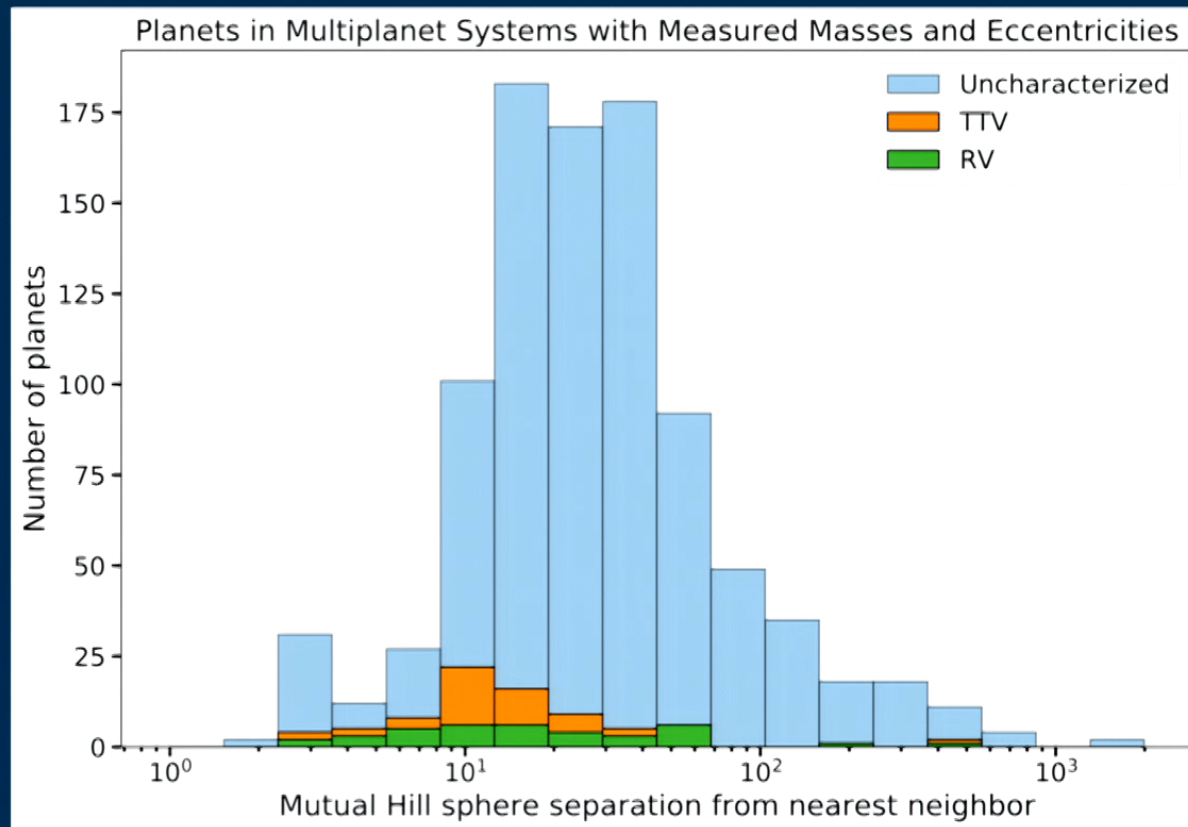
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# Exoplanets in the Era of Big Data



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# A Computational Wall

- TTV Analysis  $\sim 10^7$  samples

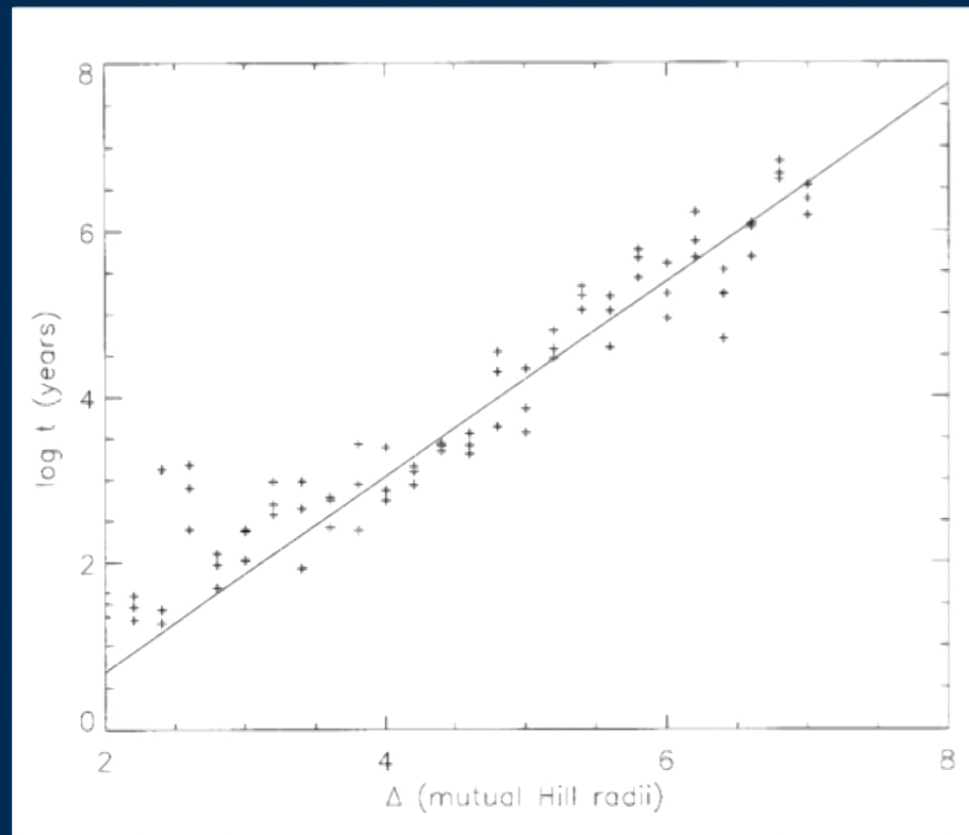
# A Computational Wall

- TTV Analysis  $\sim 10^7$  samples
- $10^{10}$  orbit stability integration  $\sim 1$  week

# Beyond N-body



# An Empirical Fit



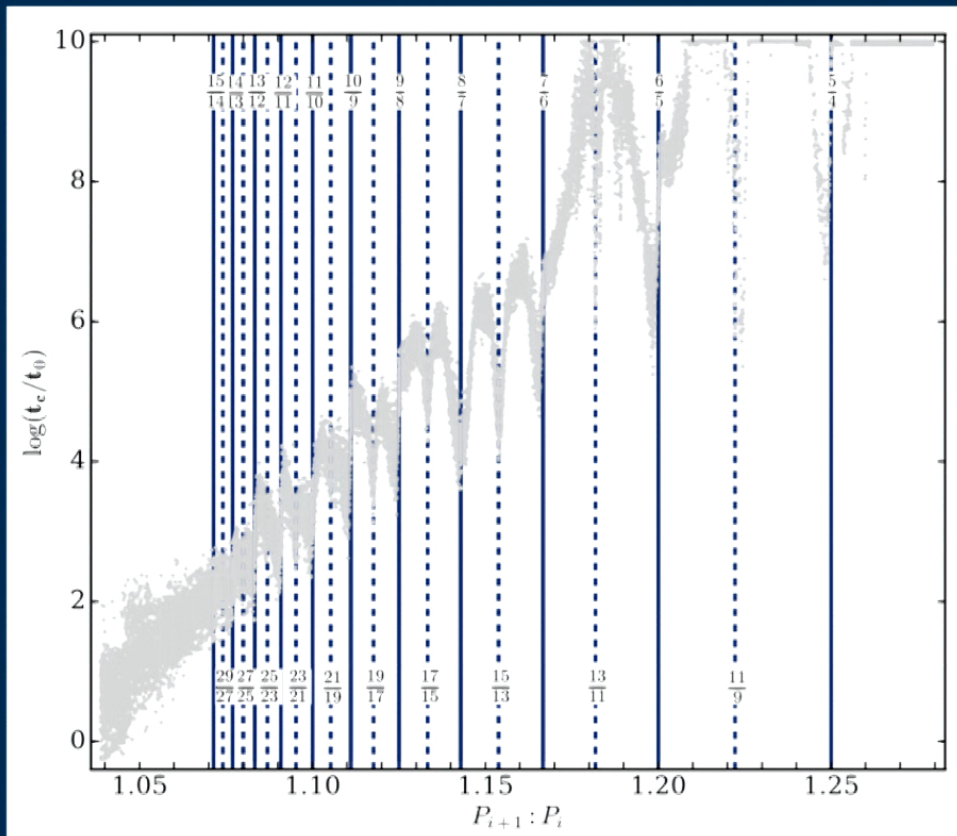
Chambers+ 1996

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# A Controlled Experiment



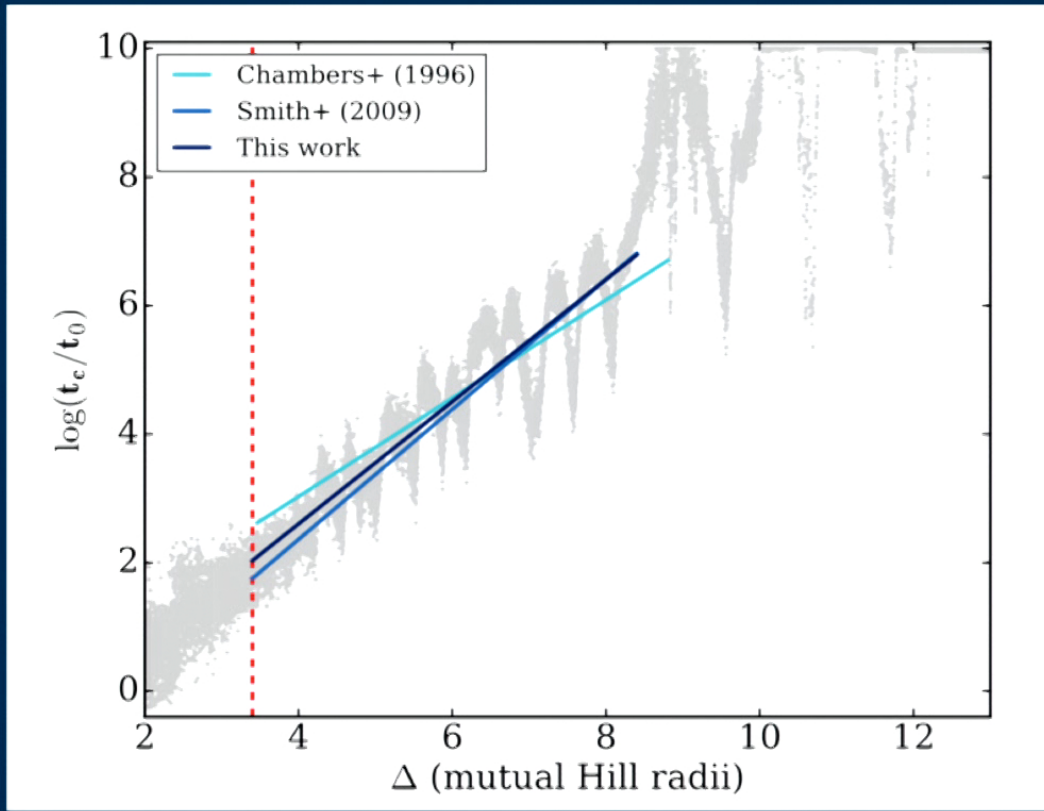
Obertas, van Laerhoven  
& Tamayo, 2017

PI 2017

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# A Controlled Experiment



Obertas, van Laerhoven  
& Tamayo, 2017

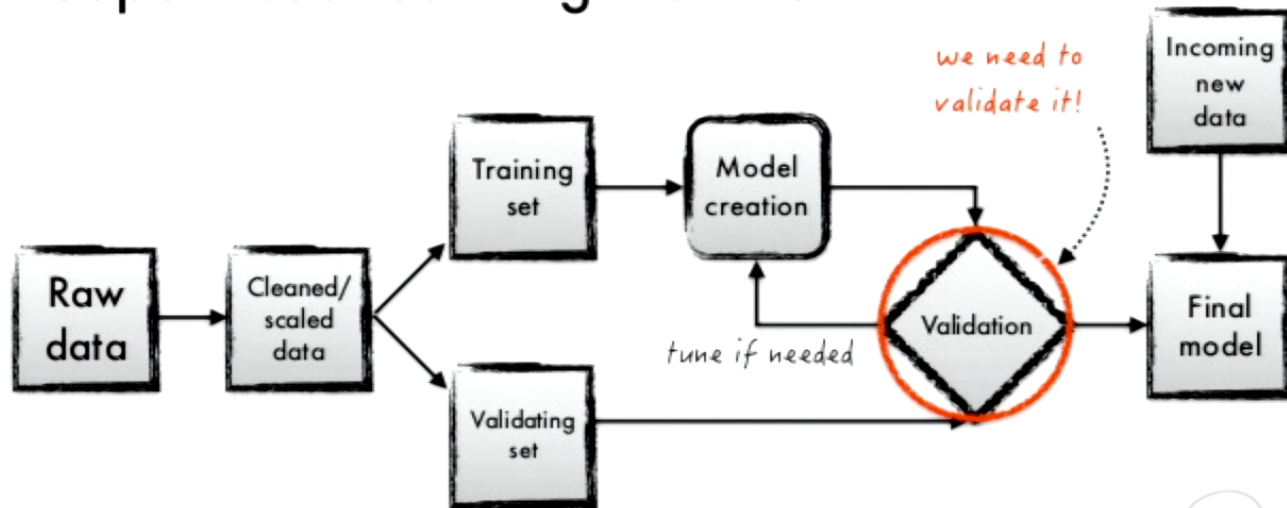
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# Machine Learning

## Supervised learning workflow



Mateusz Dymczyk Prague, 23<sup>rd</sup> October 2015



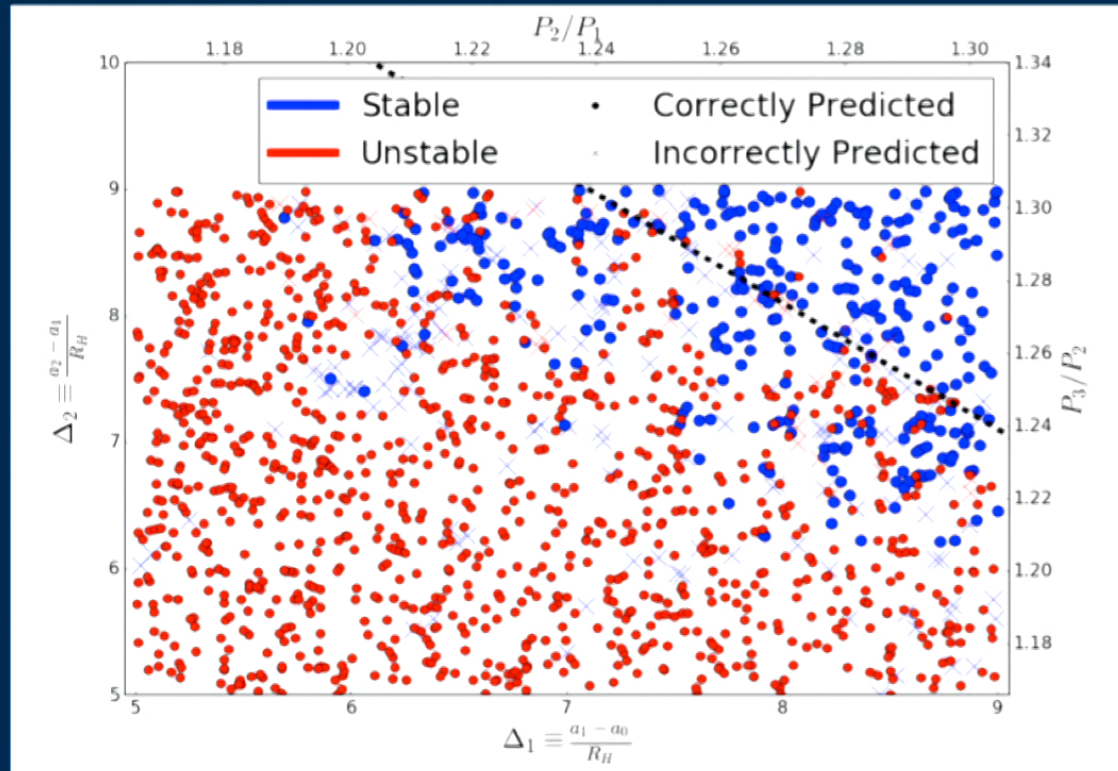


# Dataset



- 5000 systems
- $10^7$  orbits

# From Initial Conditions



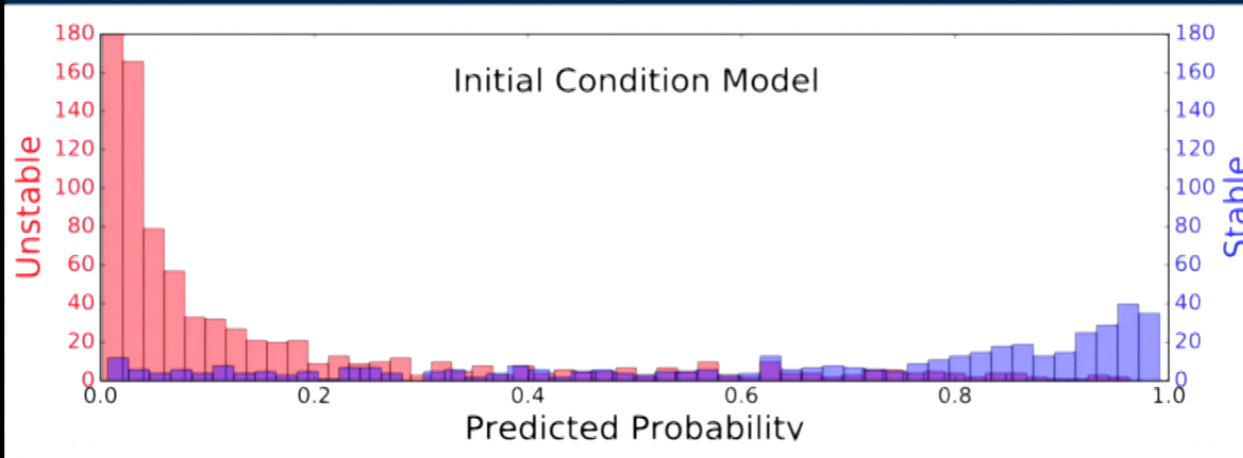
Tamayo+, 2016

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# Performance



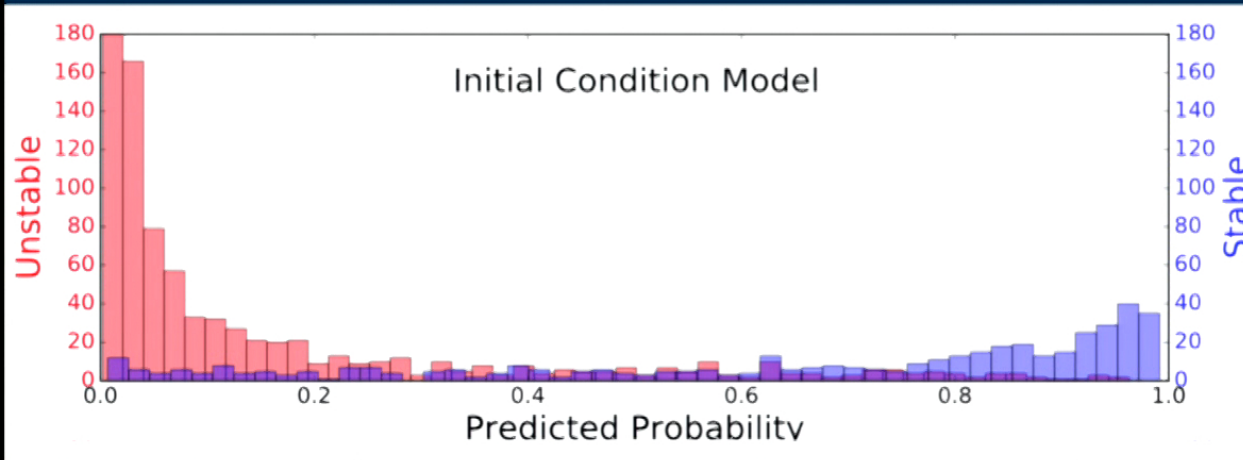
Tamayo+, 2016

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# Performance



Short Integration



10 million orbits

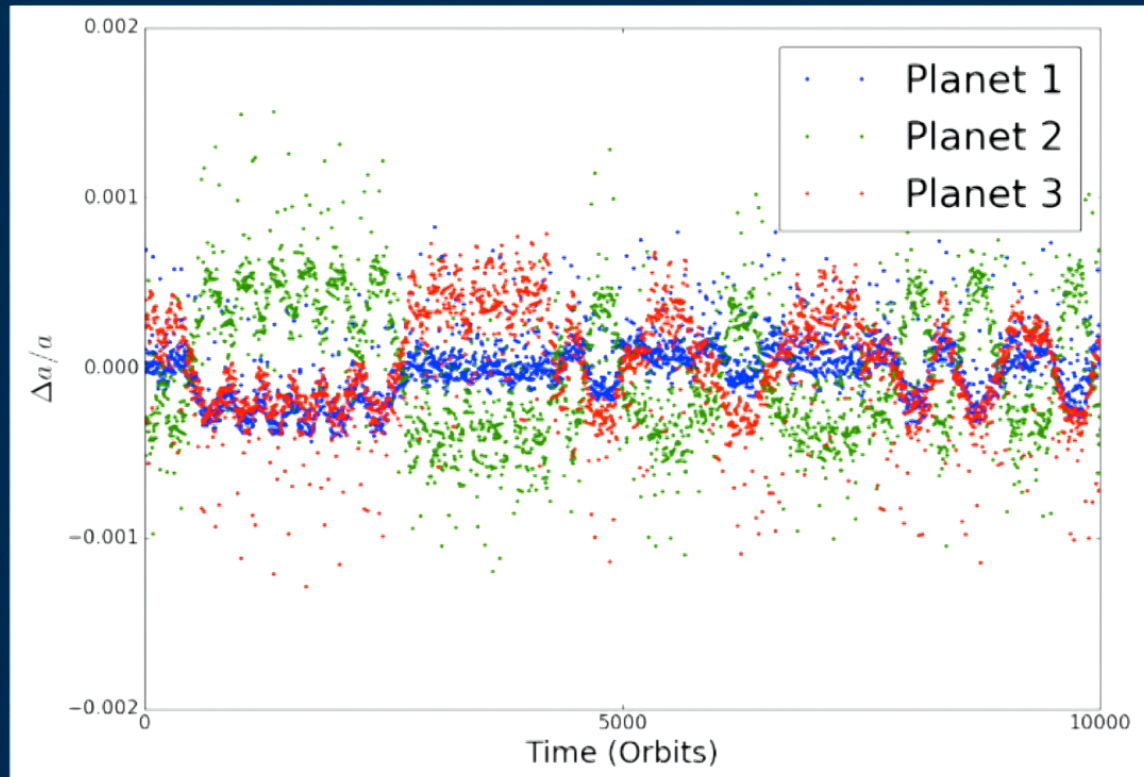
Tamayo+, 2016

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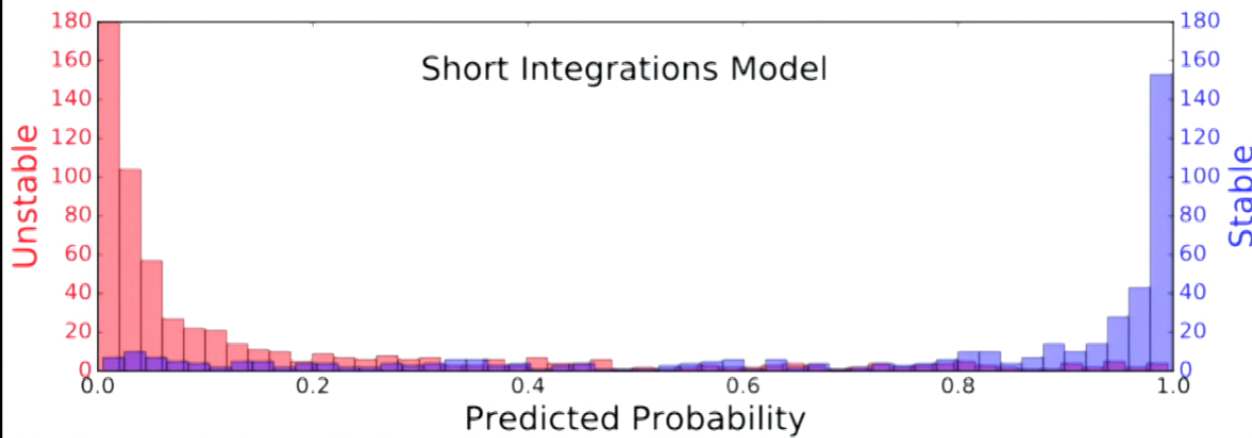
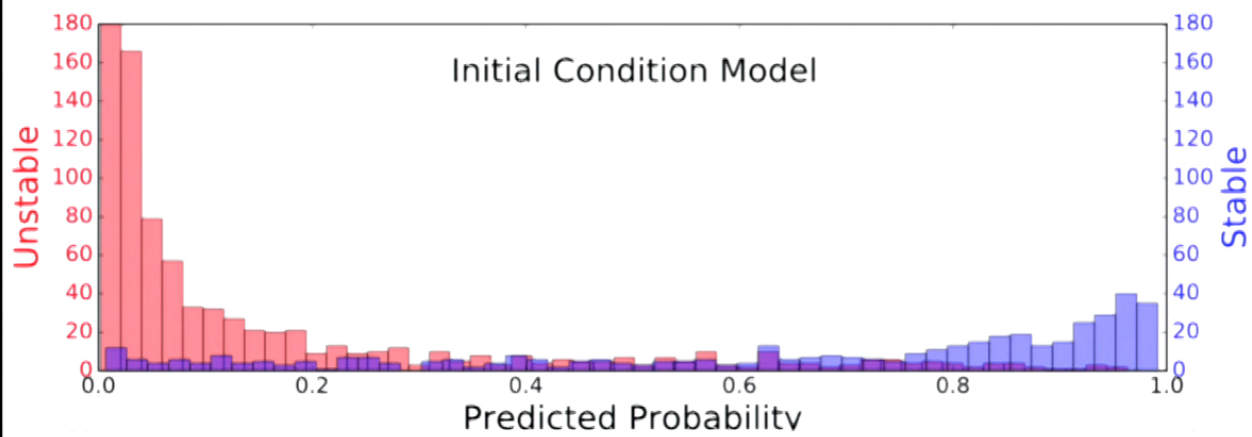
# From Short Integrations



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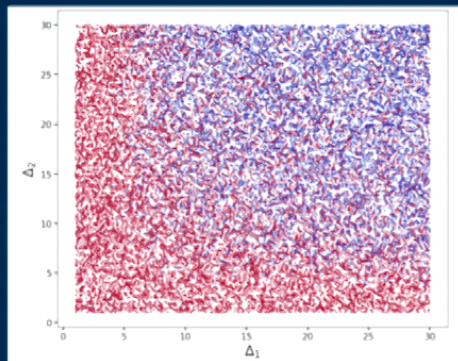
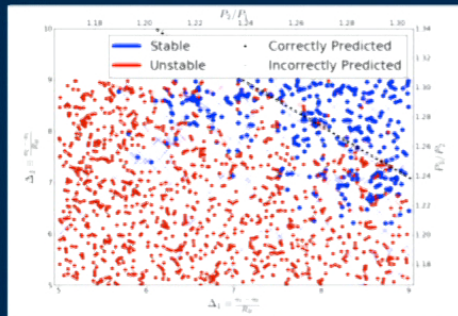
Tamayo+, 2016

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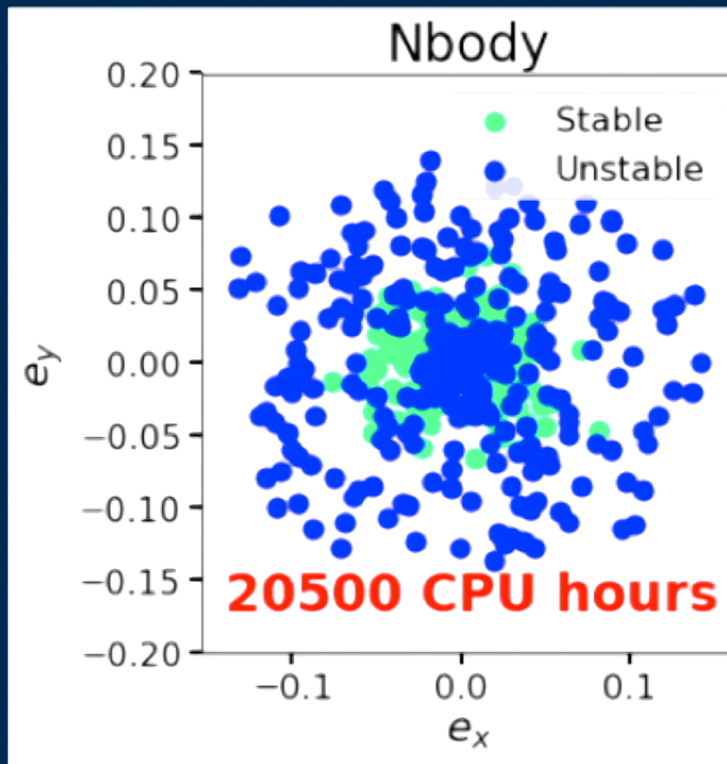


# A Larger Dataset



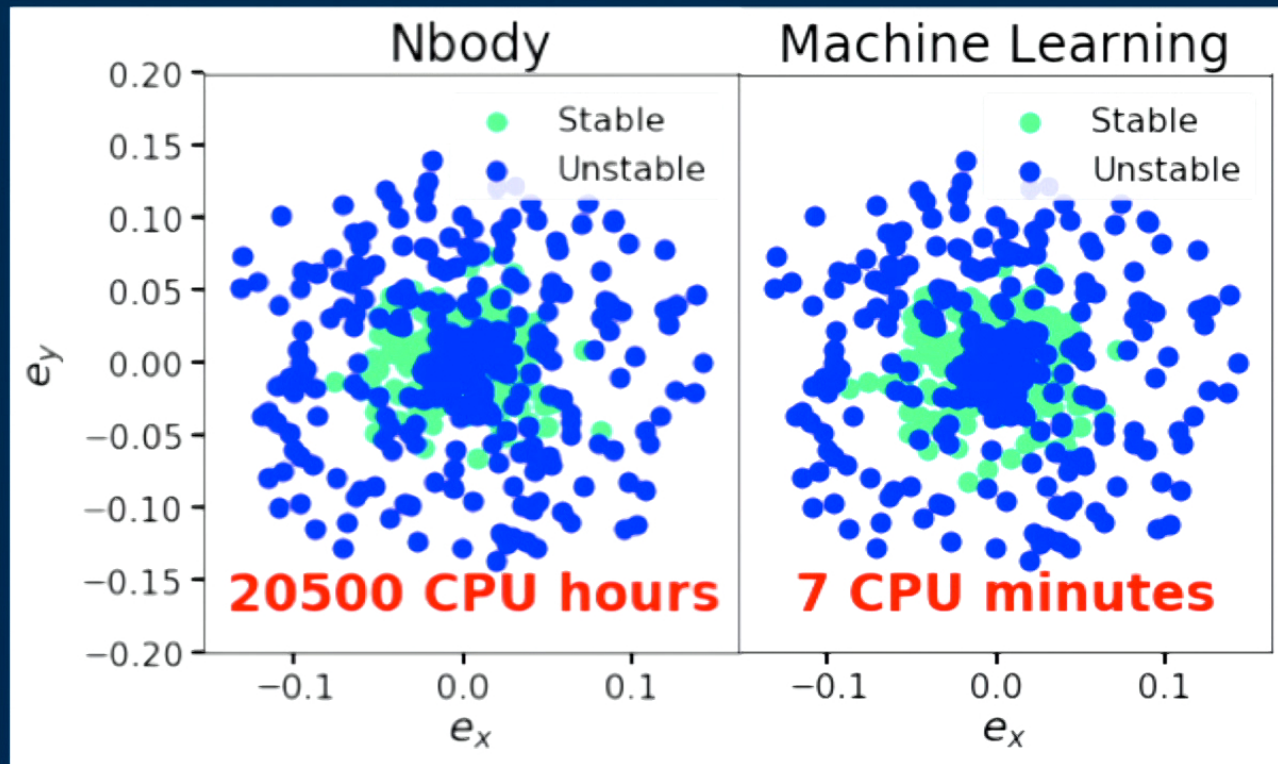
- $10^5$  systems
- 1 billion orbits
- ~1 million CPU hr

# Applying the Model

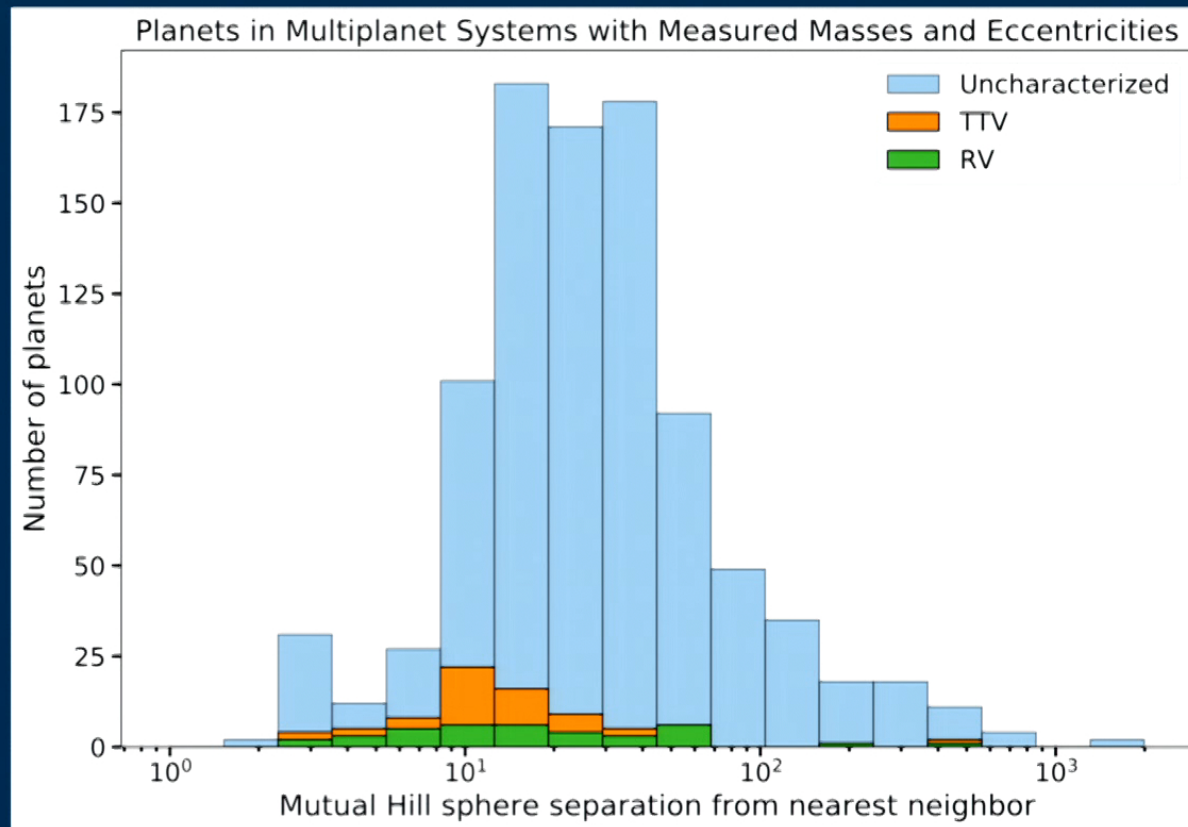




# Applying the Model



# Exoplanets in the Era of Big Data



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# Conclusions

- Predicting long-term stability is challenging
- N-body integrations give important constraints, but are expensive
- Machine learning yields a million-fold speedup that can help us characterize an order of magnitude more systems

