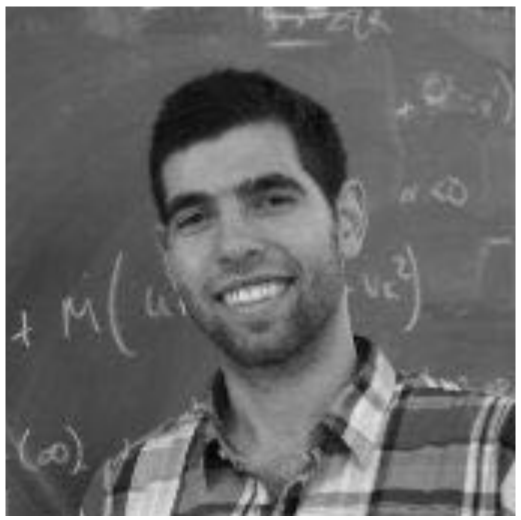
UNIVERSITY OF TORONTO

CPS | CENTRE FOR PLANETARY SCIENCES UNIVERSITY OF TORONTO

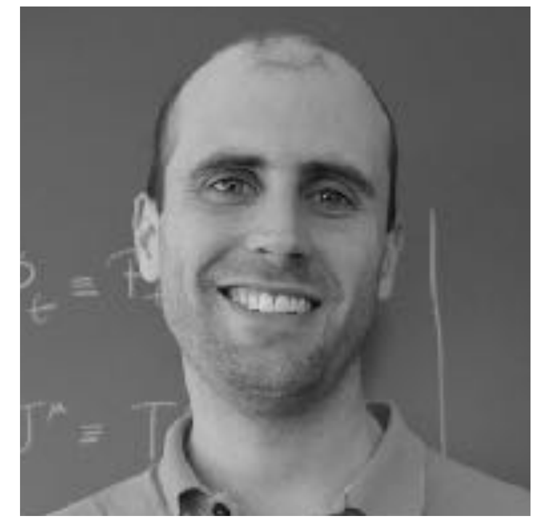
Formation and stability of planetary systems

Hanno Rein

Collaborators

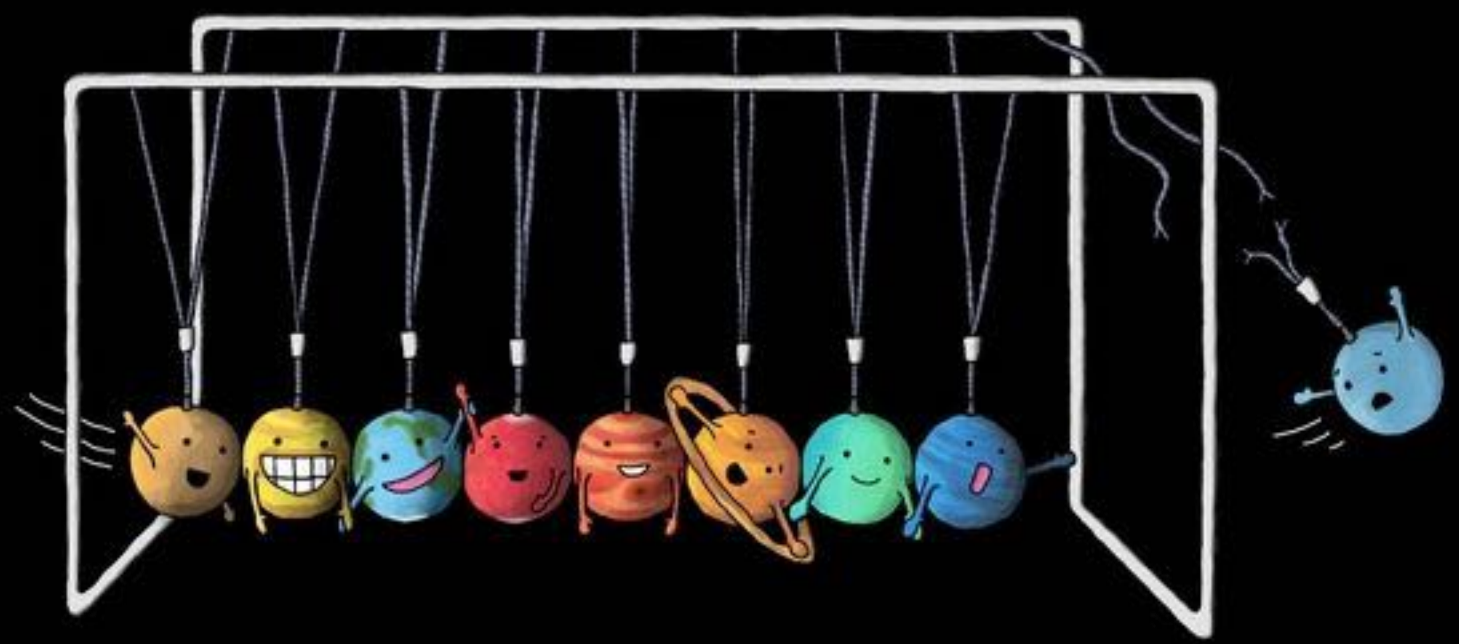


Ari Silburt
My first PhD student!
Now a postdoc at Penn State



Dan Tamayo
Postdoc
Centre for Planetary Sciences
University of Toronto

1. Solar System
2. WHFast
3. Reproducibility
4. JANUS
5. Machine Learning



1. The Solar System

Gravity

$$\ddot{\mathbf{r}}_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} m_j \frac{\mathbf{r}_j - \mathbf{r}_i}{\left|\mathbf{r}_j - \mathbf{r}_i\right|^3}$$

Newton (1687)

History of secular perturbation theory

k	Lagrange (1774)	Laskar *et al.*, 2004
s_1	5.980	5.59
s_2	6.311	7.05
s_3	19.798	18.850
s_4	18.308	17.755
s_5	0	0
s_6	25.337	26.347

Laskar 2012

Previous direct numerical simulations

LONGSTOP (1982)

- Outer planets only
- No instability

Digital Orrery (1988)

- Outer planets only, 800 Myr
- Pluto is chaotic

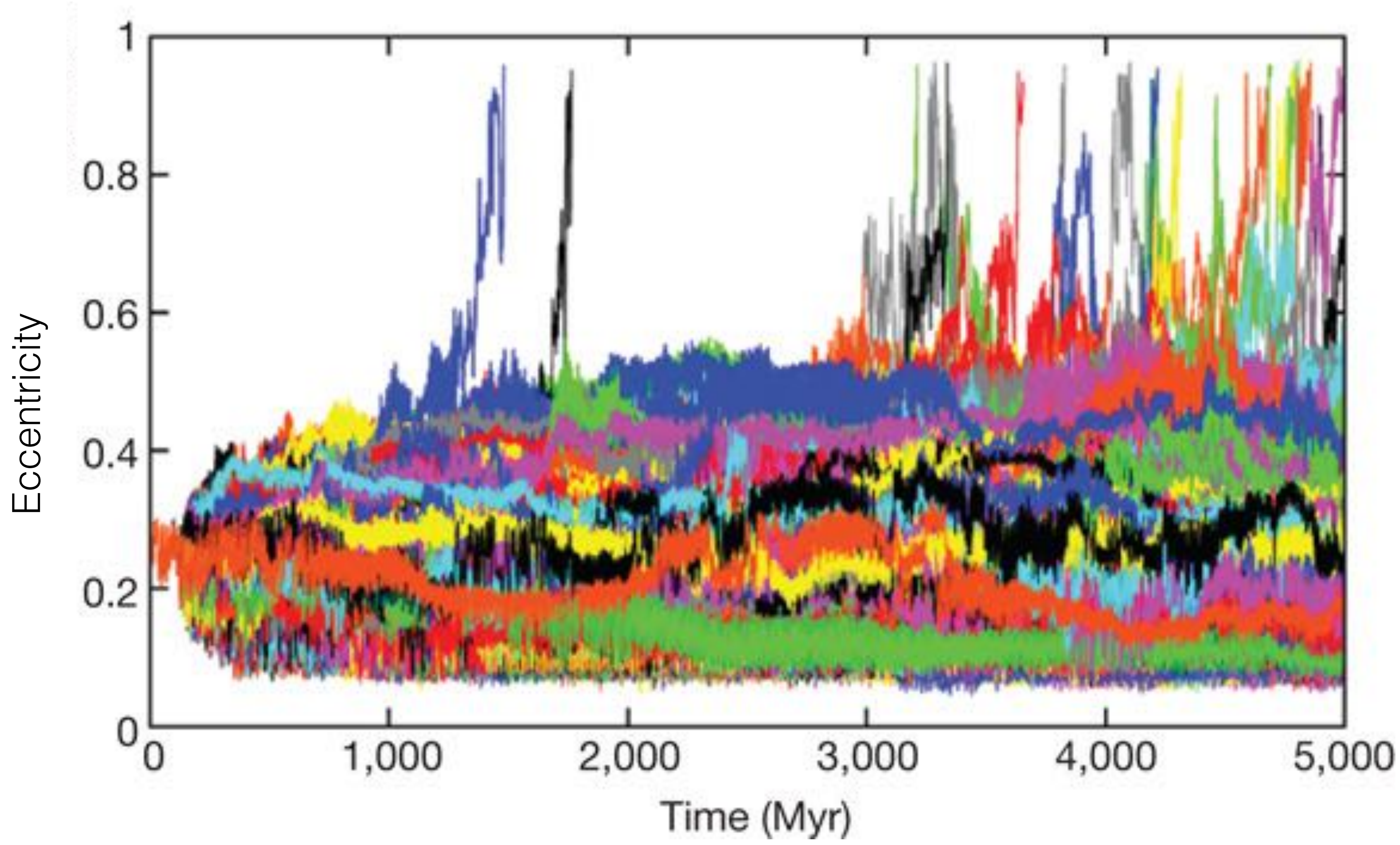
Laskar (1989)

- All planets, averaged equations
- Earth is chaotic on a 100 Myr timescale

Laskar (2009)

- All planets, full equations
- Collisions between terrestrial planets possible

Stability of the Solar System



Laskar & Gastineau 2009

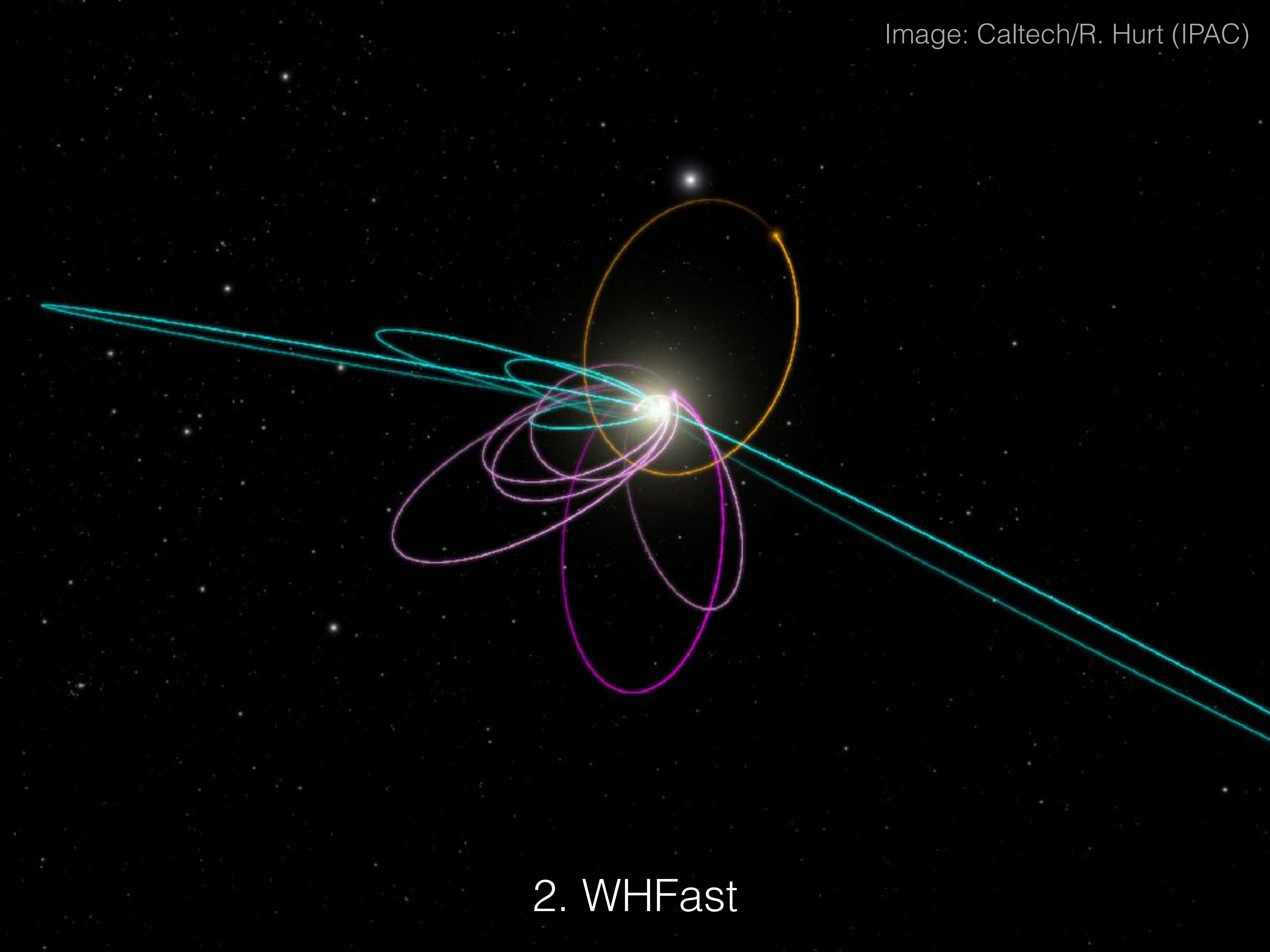


Image: Caltech/R. Hurt (IPAC)

2. WHFast

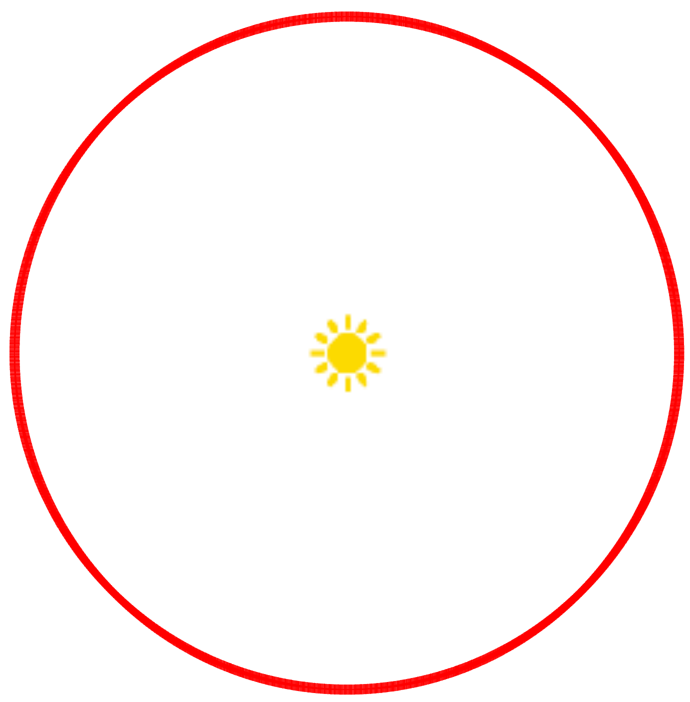
Mixed Variable Symplectic Integrator

$$H = \underbrace{\frac{1}{2}p^2 + \Phi_{\mathrm{Sun}}(q)}_{\text{Drift}} + \underbrace{\Phi_{\mathrm{Other}}(q)}_{\text{Kick}}$$

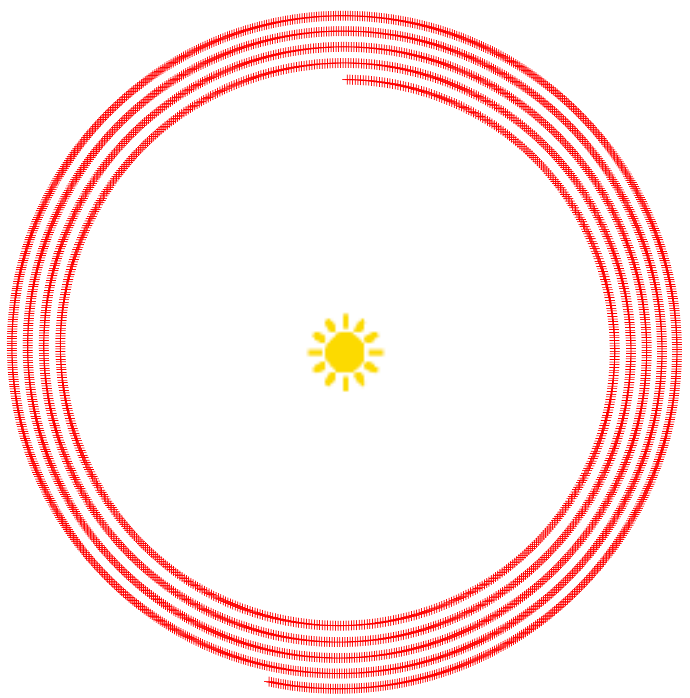
Particularly good if

$$\frac{1}{2}p^2 + \Phi_{\mathrm{Sun}}(q) \gg \Phi_{\mathrm{Other}}(q)$$

Symplectic integrators



Symplectic integrator



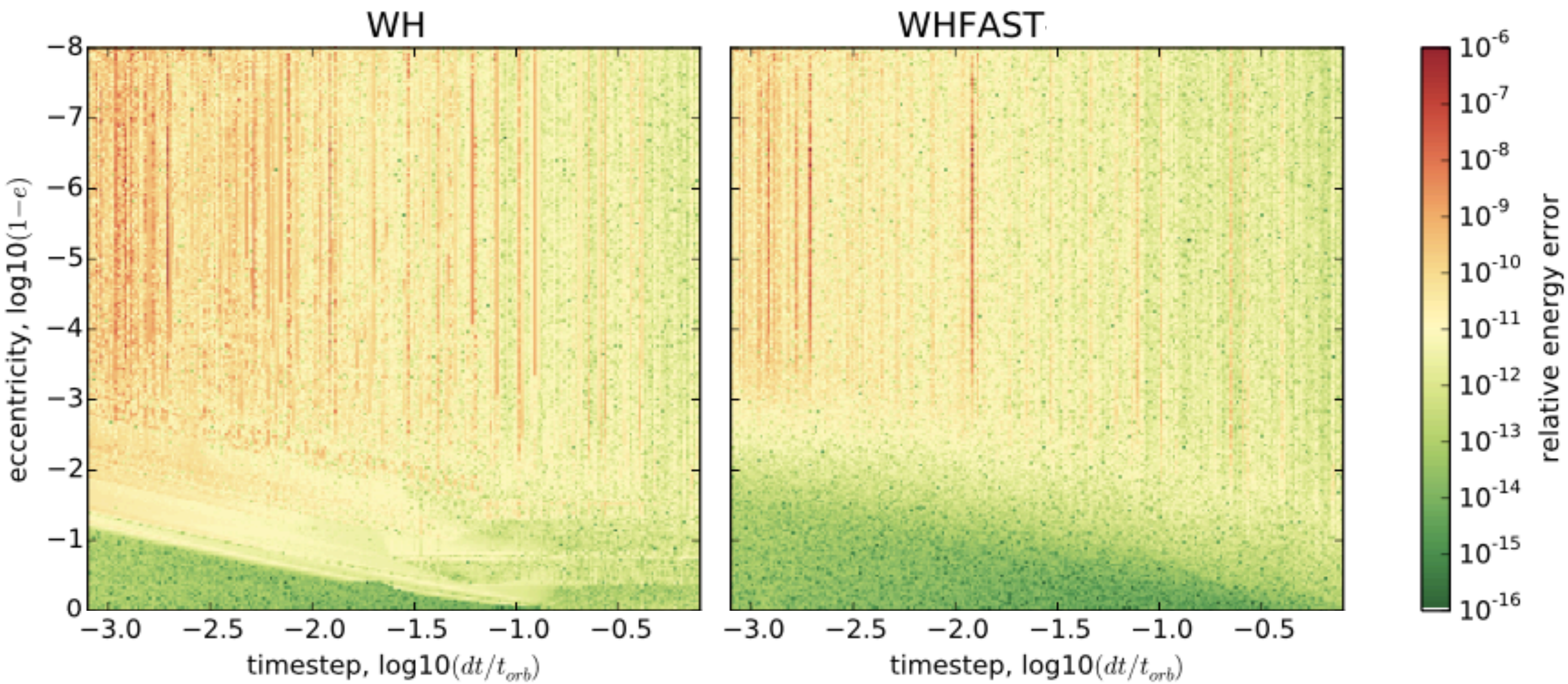
Non-symplectic integrator

WHFast

- 2nd order symplectic integrator with up to 11th order symplectic correctors
- Extremely efficient implementation of a Wisdom-Holman Map (WHM)
- WHFast can integrate variational equations
- Bias free implementation

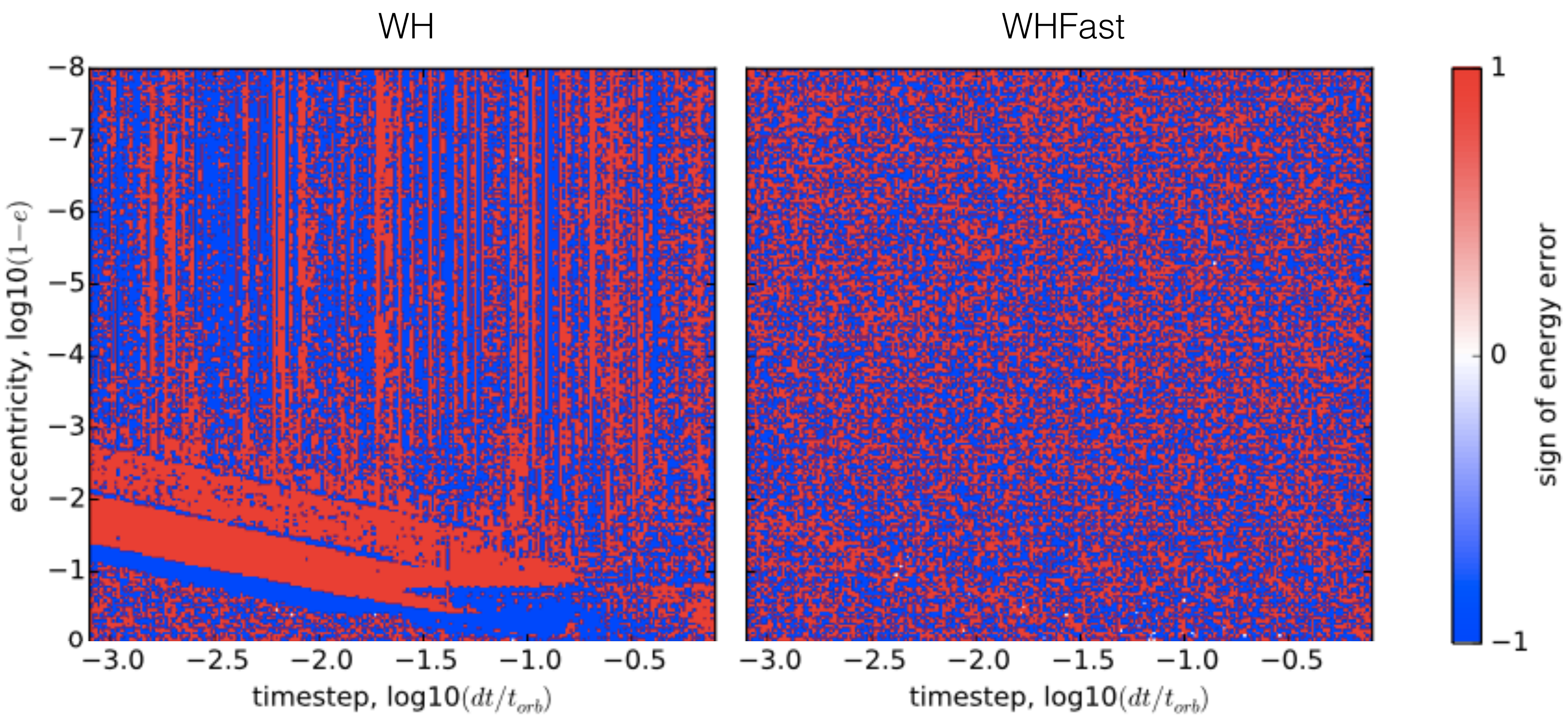
Rein & Tamayo 2015

2-body results



Rein & Tamayo 2015

2-body results



Rein & Tamayo 2015

3. Exact Reproducibility

Reproducible Experiments

Exact reproducibility

- N-body simulations are experiments on a computer
- They do not represent the real physical system
- Simplifications lead to a controllable experiment
- Yet none of the published results are reproducible

Why does it matter?

- Reproducibility is the hallmark of good science
- Non-reproducibility raises bar for follow-up investigations
- Wasted resources, e.g. 6.2 million CPU hours by Laskar 2009

Reproducible Experiments

Reasons for non-reproducible results

- Source code not available
- Initial conditions not available
- Machine dependent software

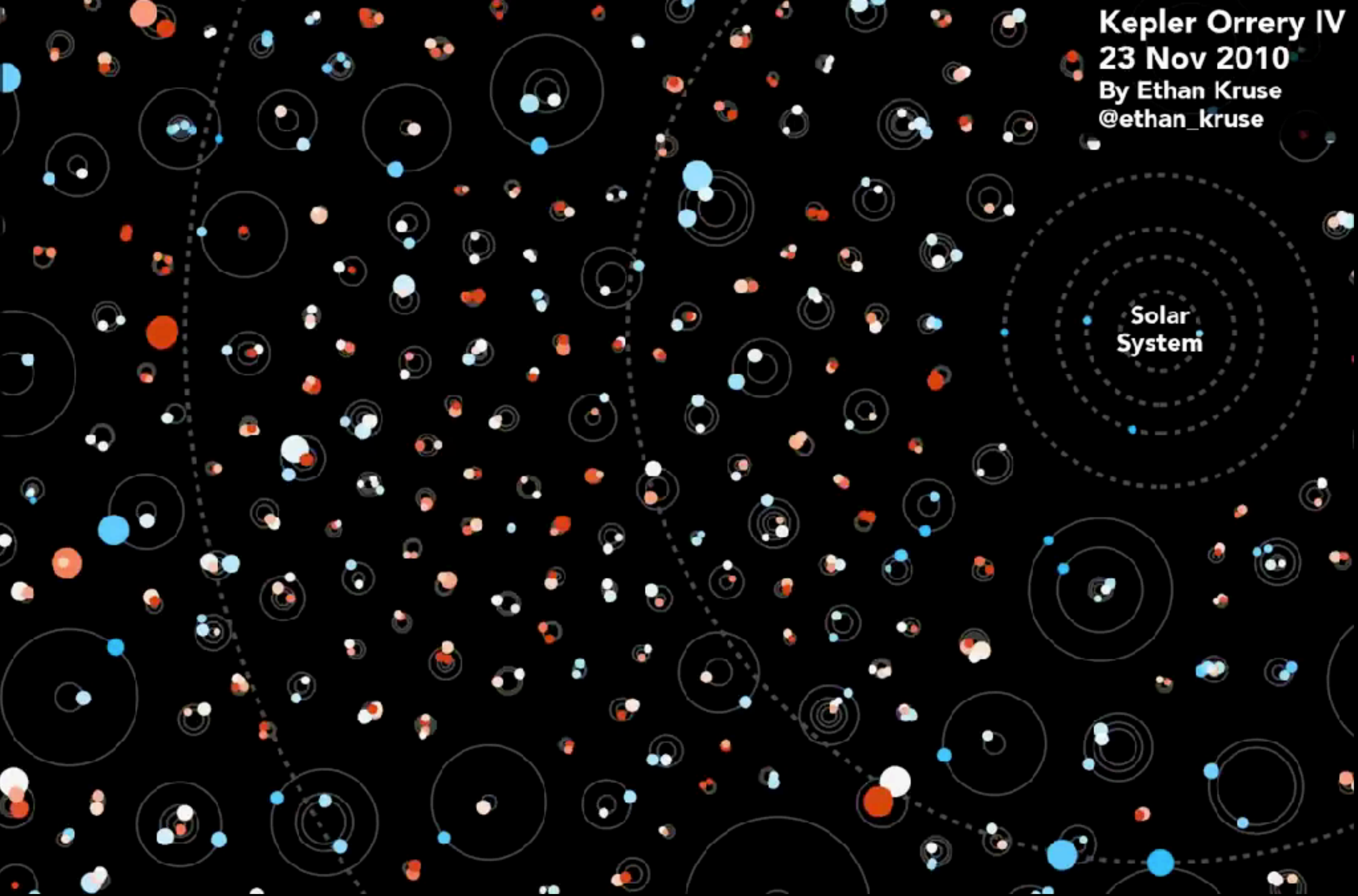
REBOUND + Simulation Archive

- Open Source
- Machine independent
- Exactly reproducible
- Easy to share simulations with the SimulationArchive

demo / rebound

rein010.utsc.utoronto.ca

4. Janus



5. Machine Learning

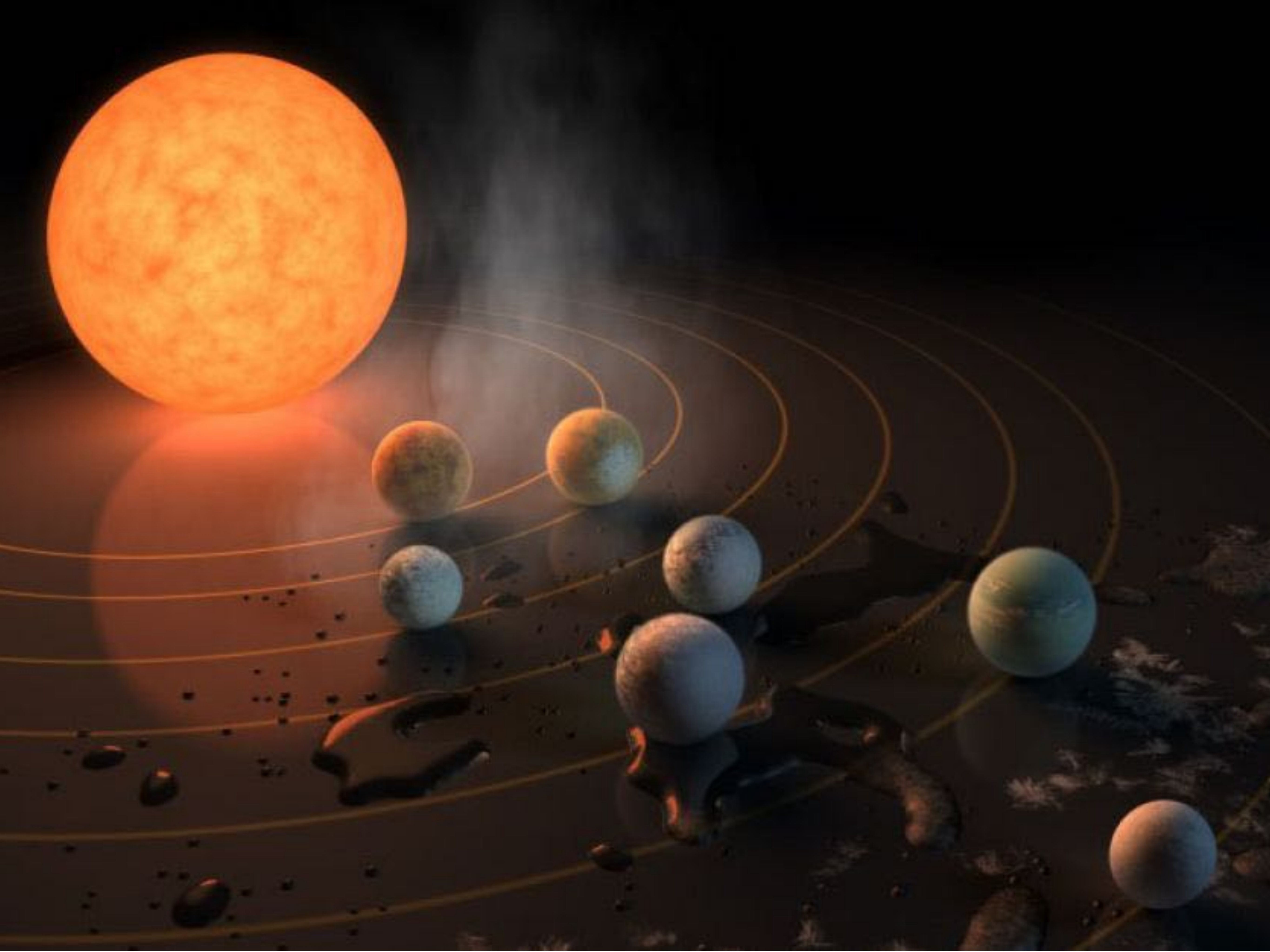
3668

x

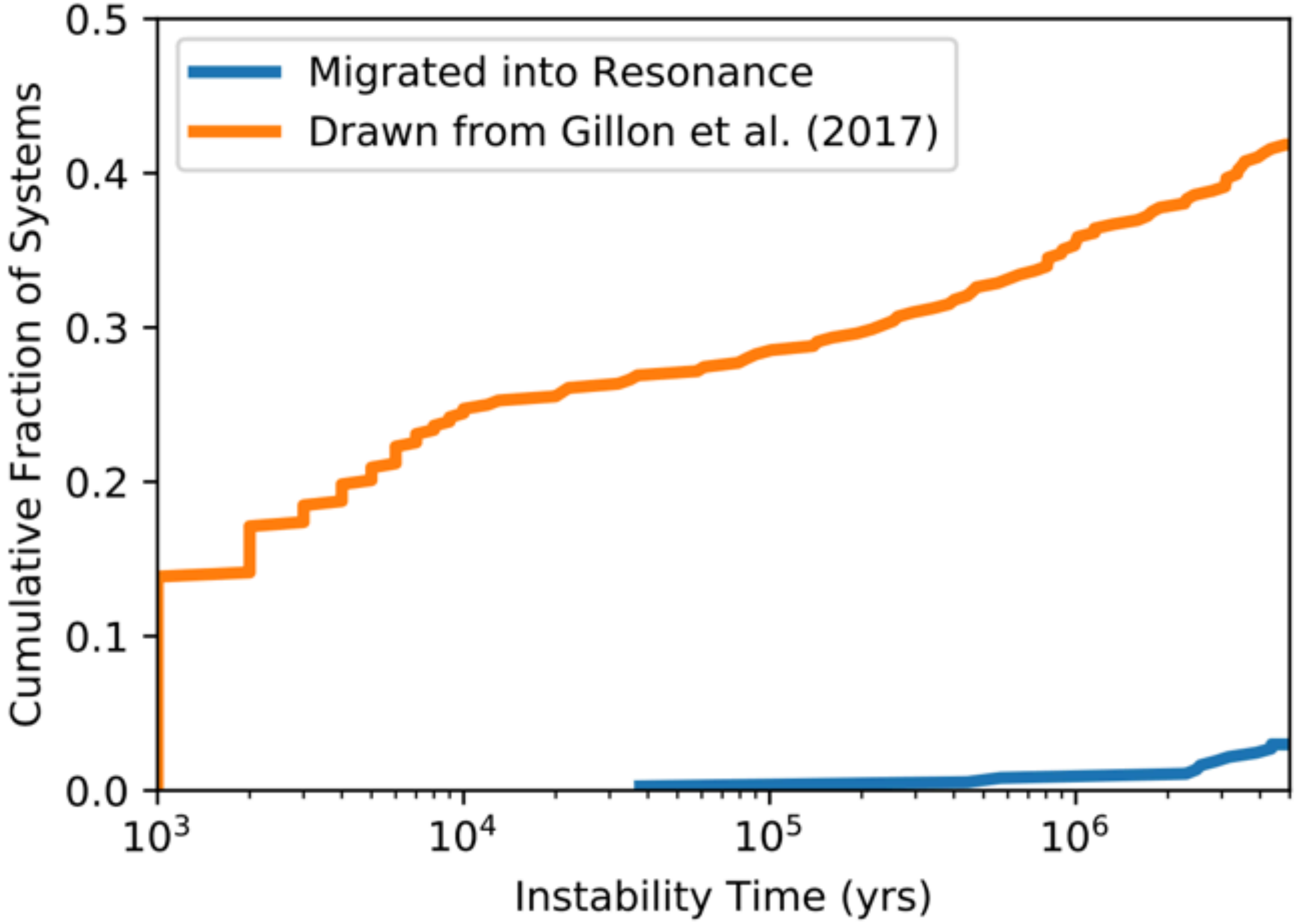
1 000 000 000 000 000

x

10 000

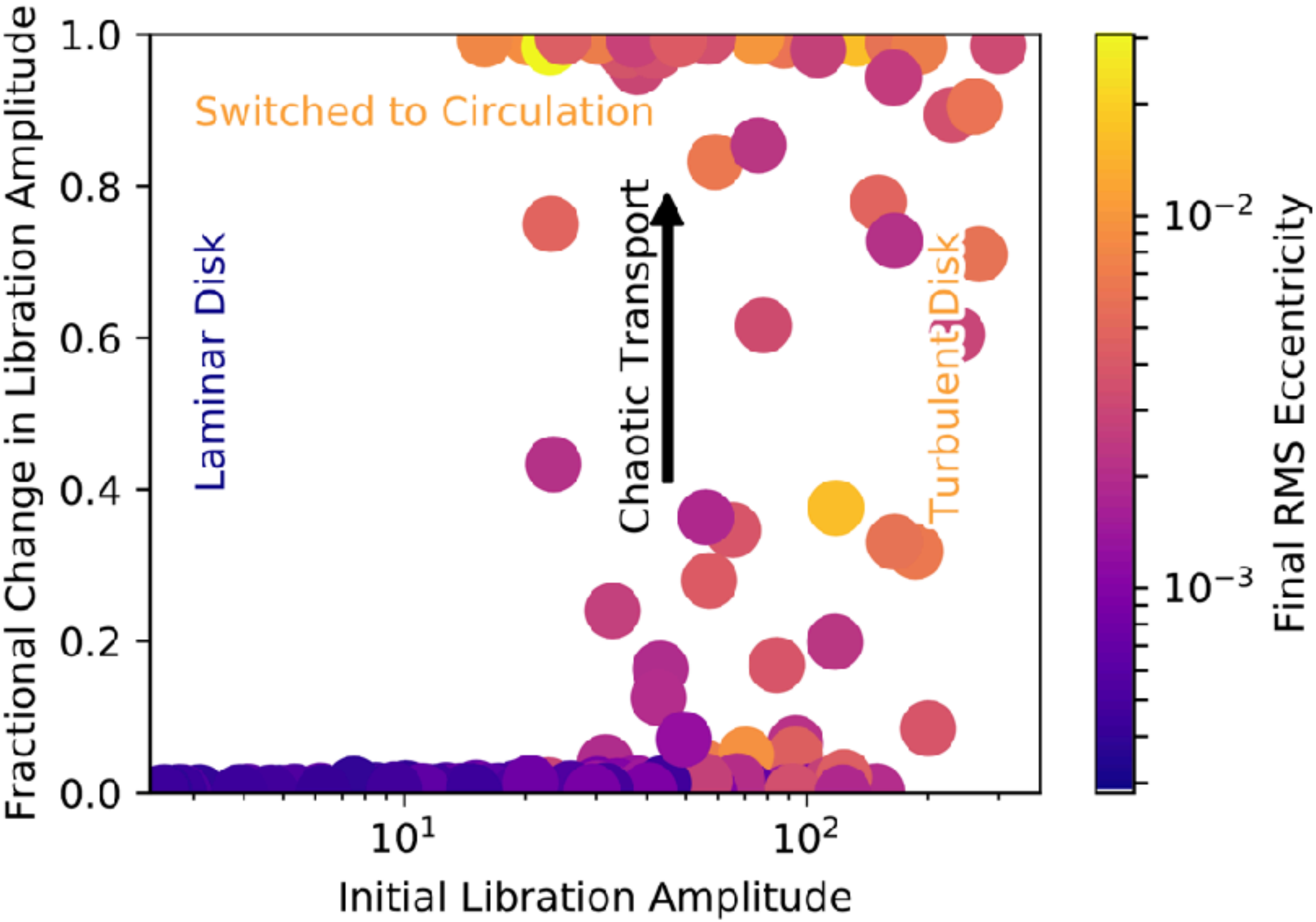


Migration saves Trappist-1



Tamayo, Rein, Petrovich & Murray 2017

Stability implies small amount of turbulence



Tamayo, Rein, Petrovich & Murray 2017

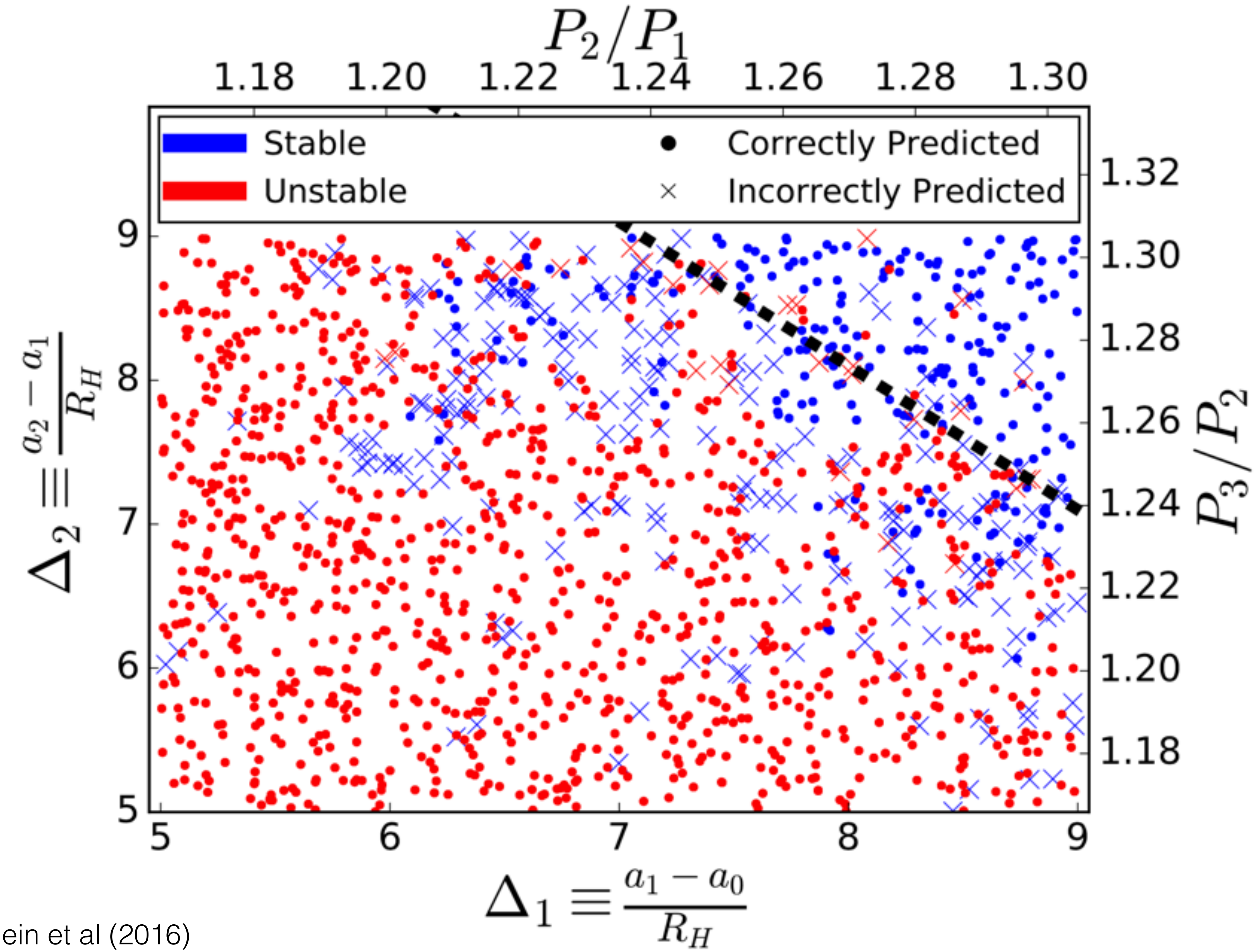
Machine Learning

Idea

- Long term integrations of many systems still hard to do or even impossible
- Train a ML algorithm on short integrations to predict long term outcome

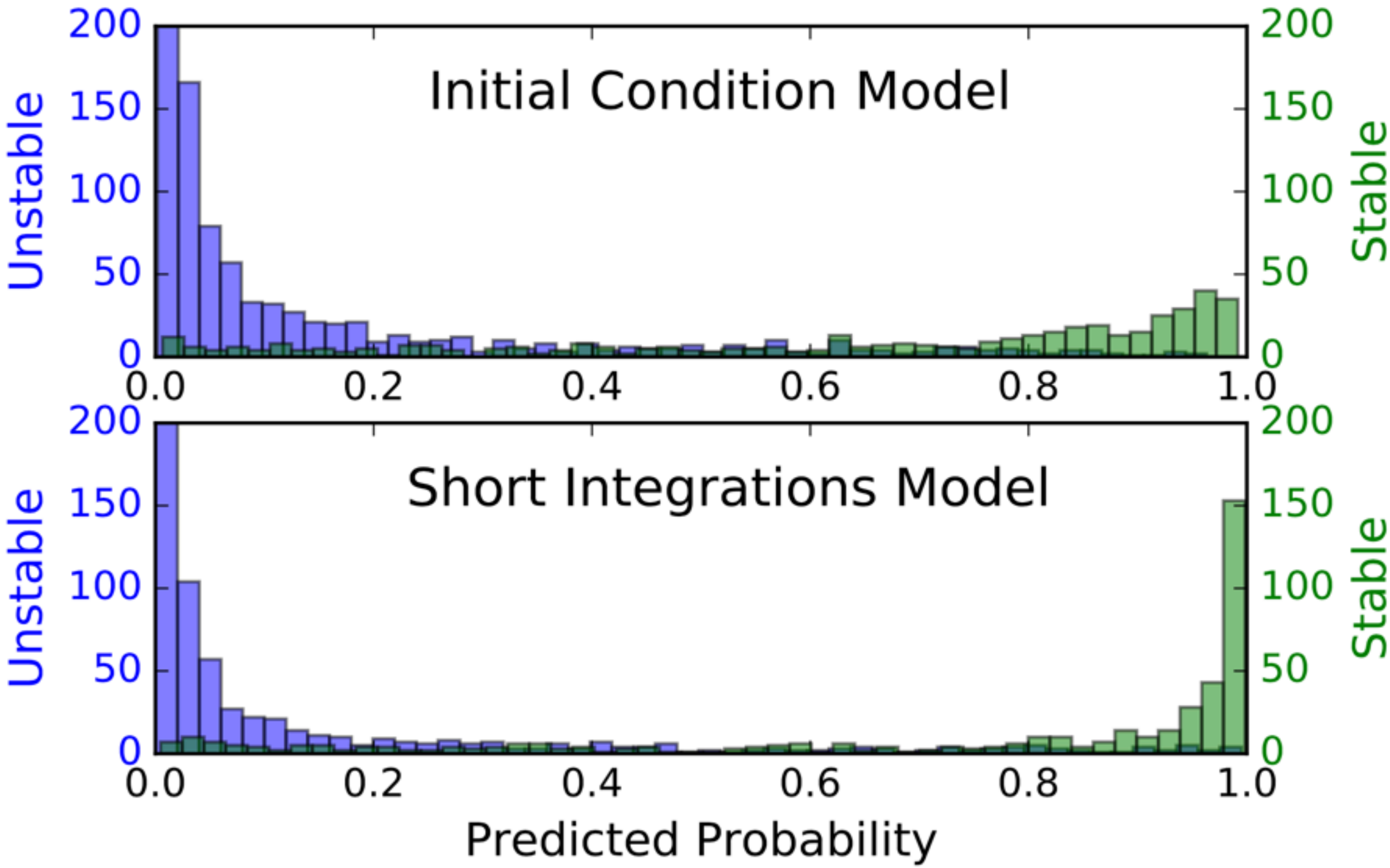
Tamayo, Rein et al (2016)

Machine Learning to Predict Stability



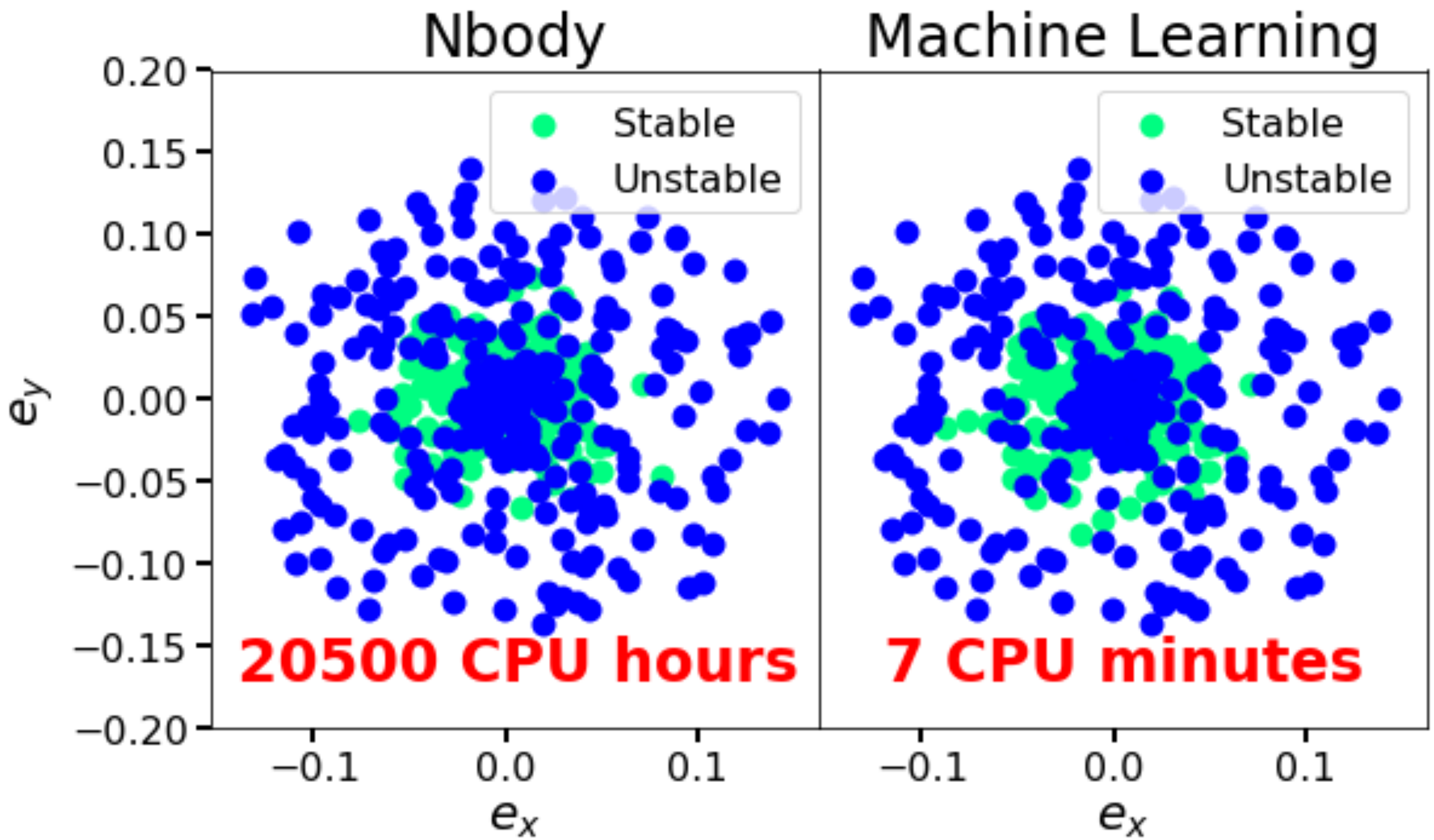
Tamayo, Rein et al (2016)

Accuracy of Machine Learning Algorithm



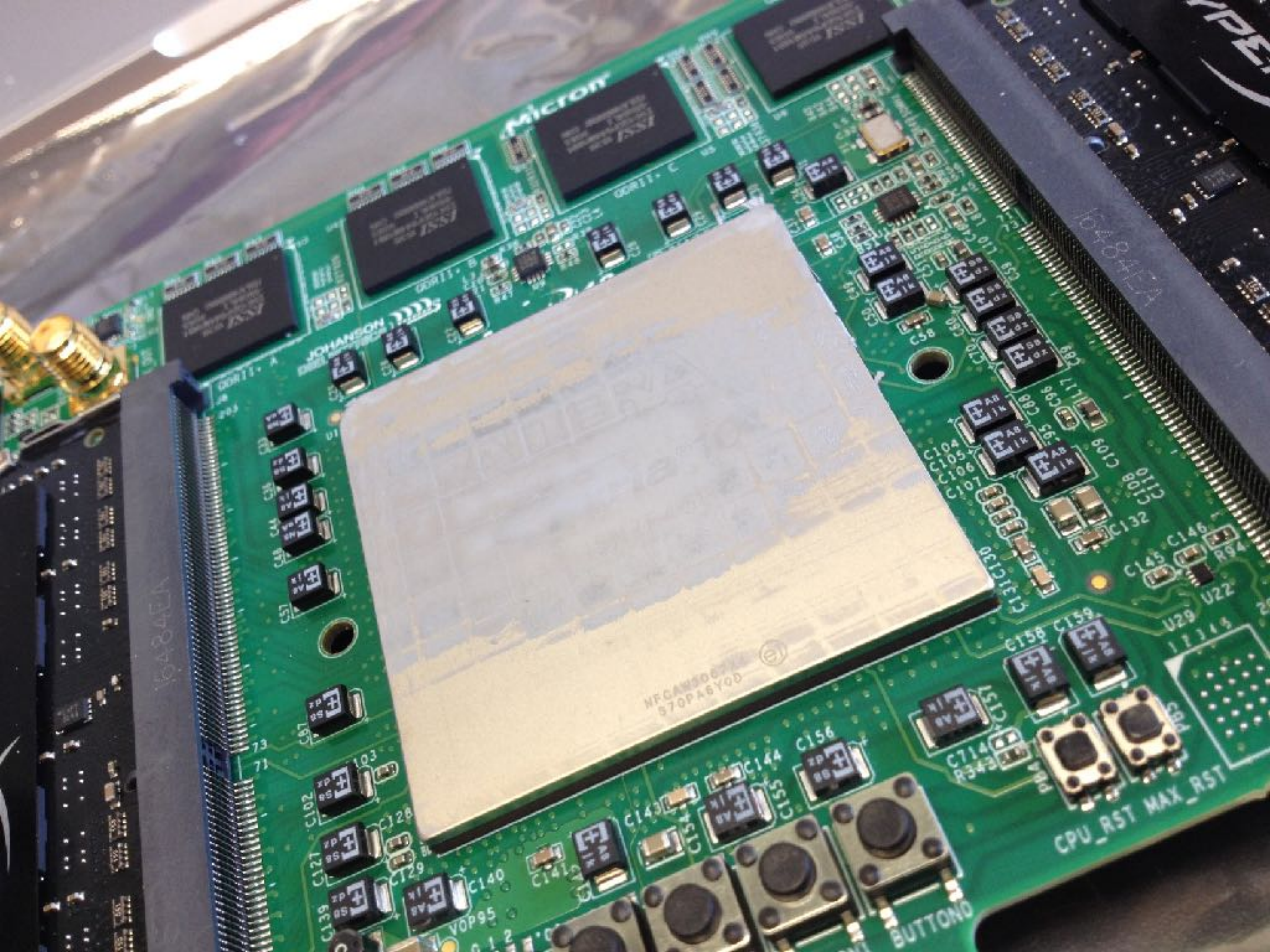
Tamayo, Rein et al (2016)

Kepler-431



Work by Dan Tamayo. Watch out for a new paper!

How to generate training data


Micron
JOHANSON
QDRII- A
QDRII- B
QDRII- C
CPU_RST MAX_RST
BUTTON0
C58
C104
C105
C106
C107
C132
C145
C146
R94
U22
U29
C158
C159
C156
C144
C143
C140
C141
VOP95

Thank you!

Try out REBOUND!

github.com/
hannorein/rebound