AMLD EPFL

Data-driven emulation of planetary-scale collisions

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Image credit: Lynette Cook for Gemini Observatory/AURA

Mercury’s large core

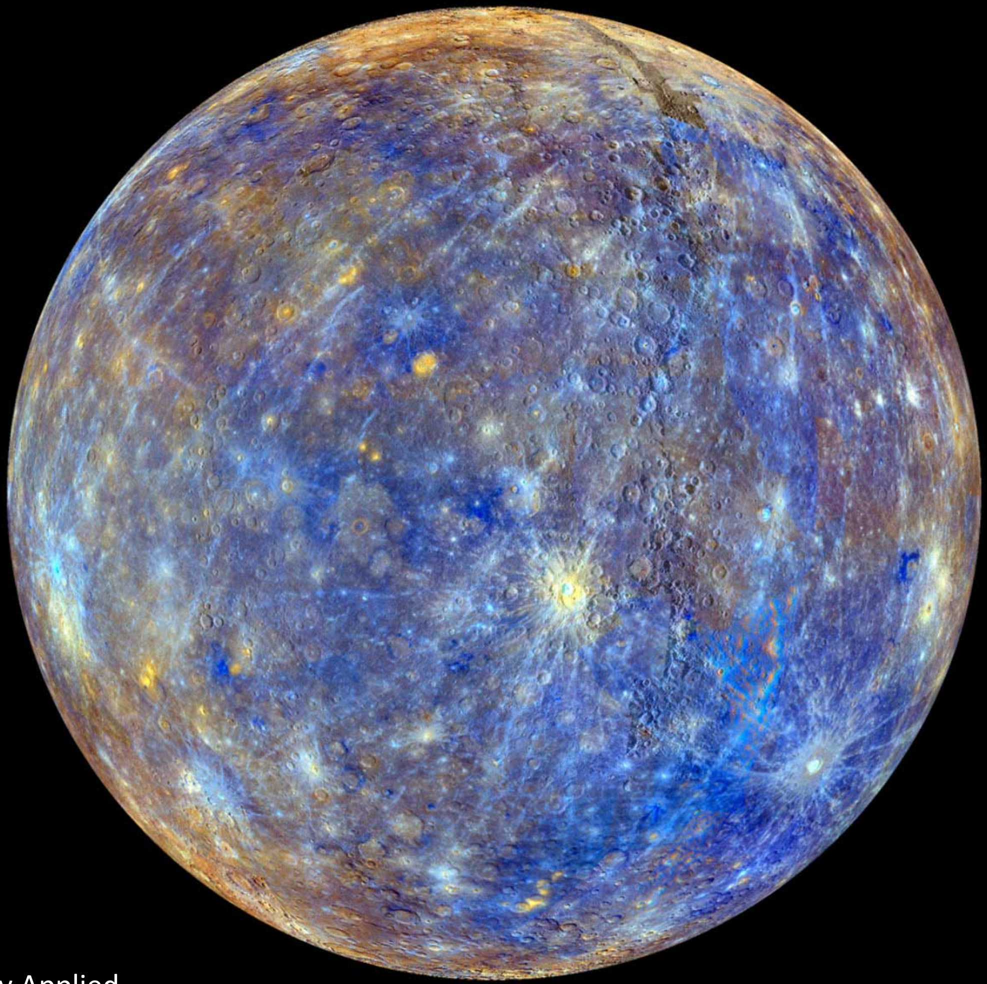


Image credit: NASA / Johns Hopkins University Applied
Physics Laboratory / Carnegie Institution of Washington

Reference: Chau et al. (2018)

Origin of the Moon

Image credit: W. Anders / NASA

Reference: Benz et al. (1986)

Origin of the Moon

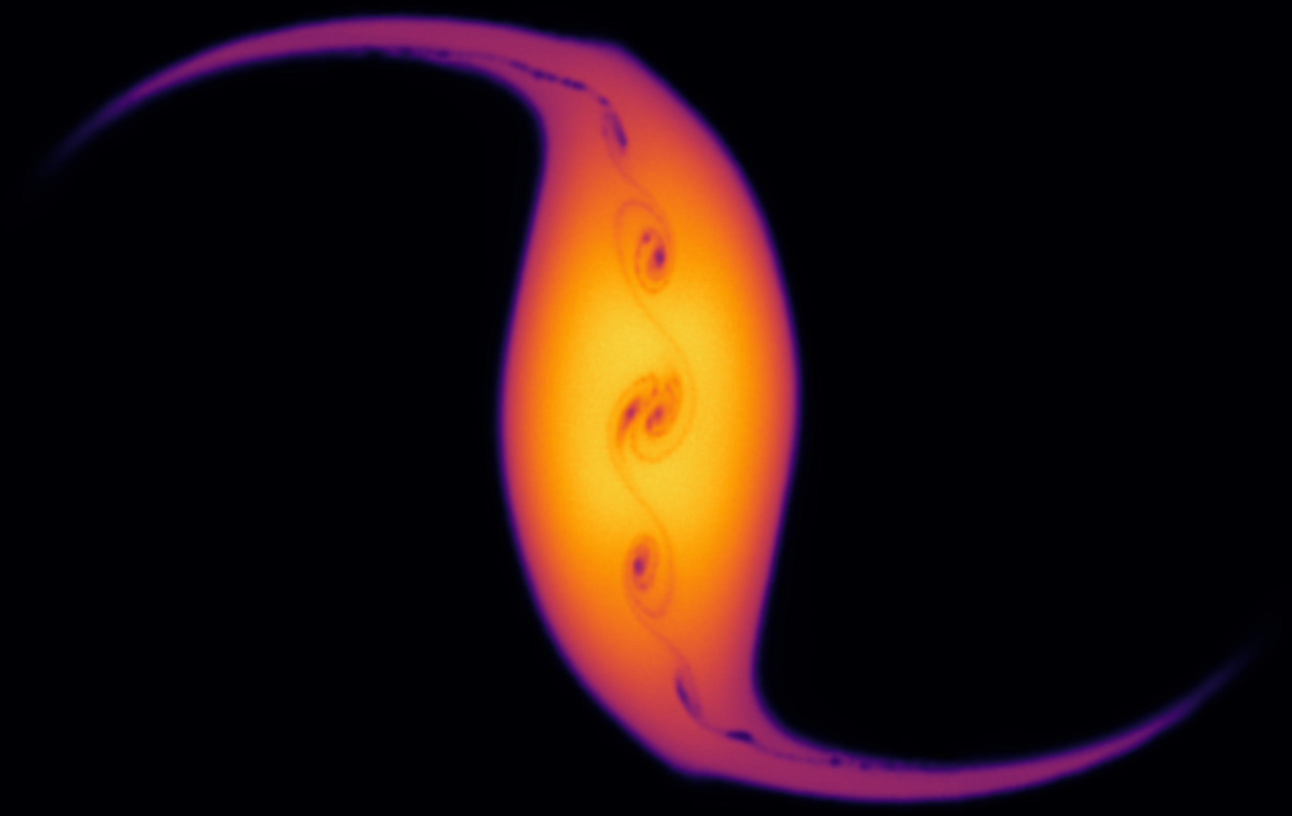


Image credit: M. Timpe / University of Zurich

Reference: Timpe et al. (in prep.)

Martian hemispheric dichotomy

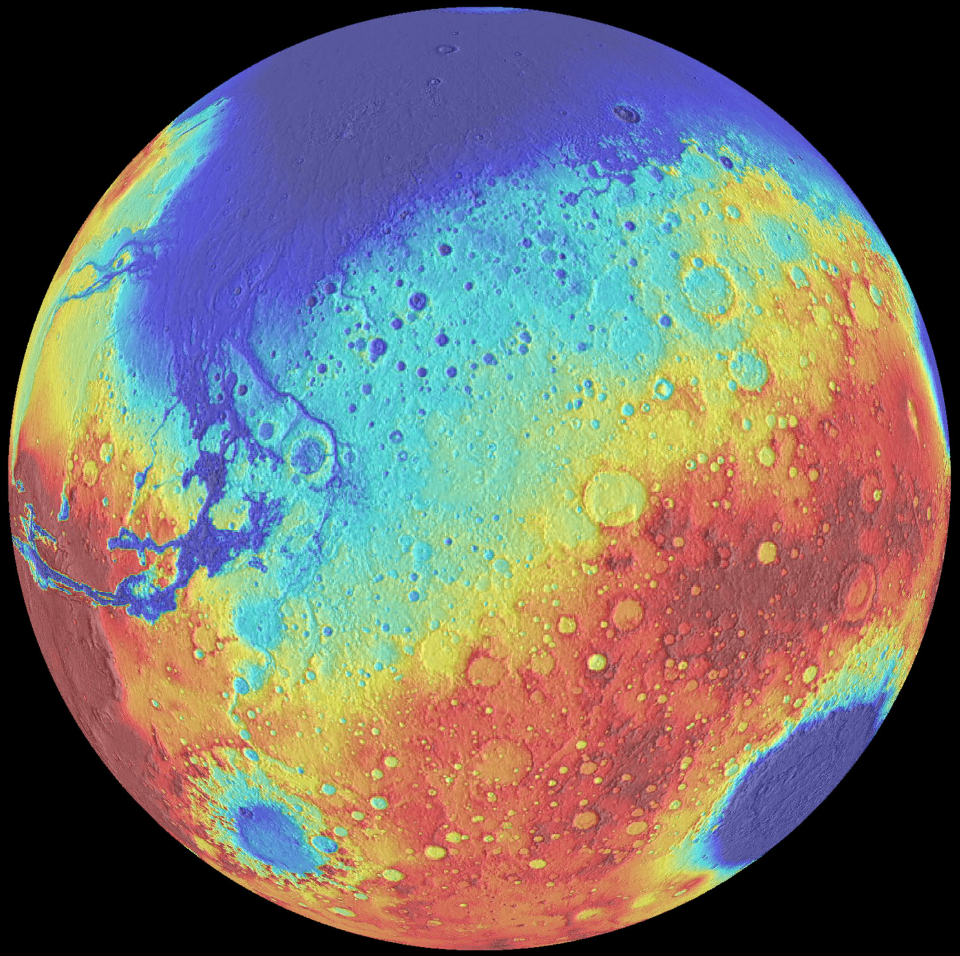


Image credit: University of Arizona/LPL/SwRI

Reference: Wilhelms et al. (1984)

Jupiter’s fuzzy core

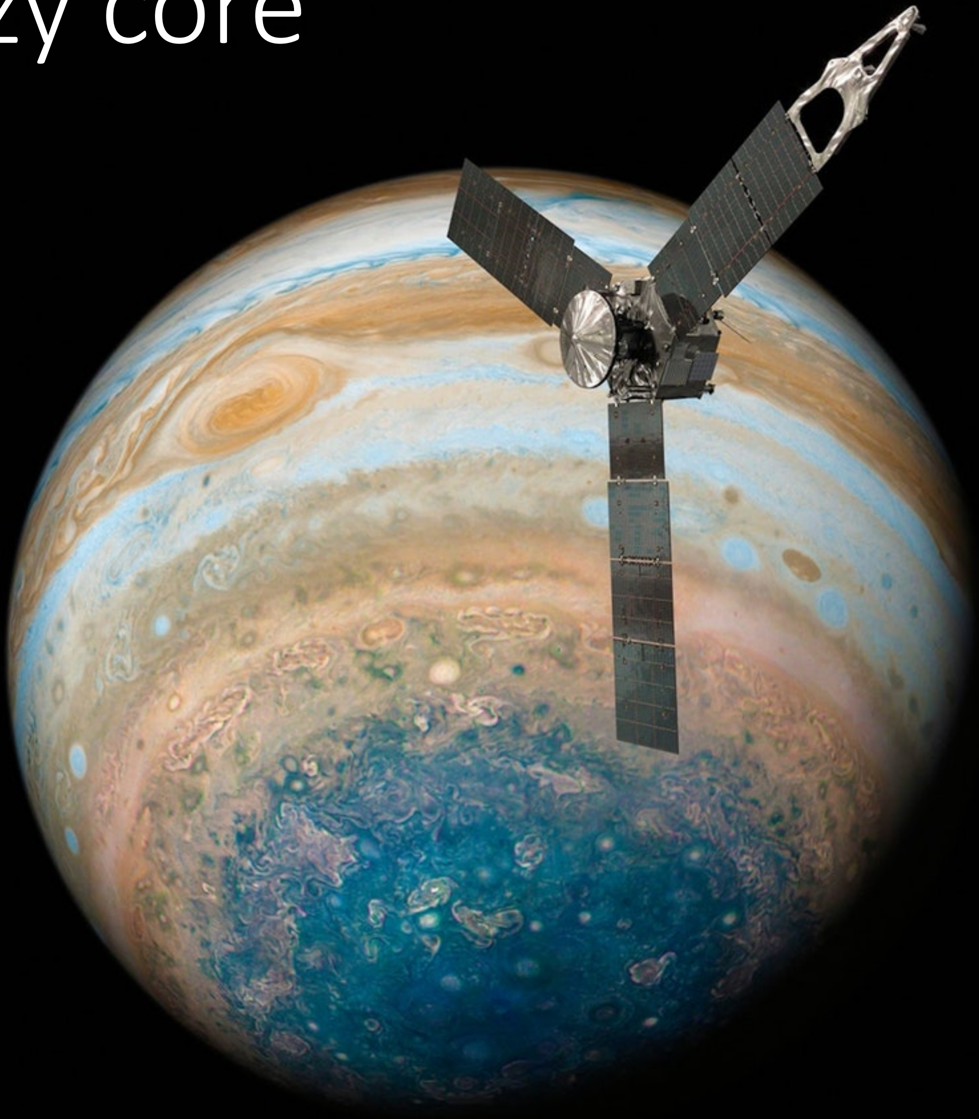


Image credit: NASA/JPL

Reference: Liu et al. (2019)

Uranus’ tilted axis

“Something big crashed into Uranus and changed it forever.”

“We’re finally figuring out how Uranus ended up its side.”

“Uranus was slammed by an object twice the size of Earth.”

Image credit: ESA/Hubble & NASA, L. Lamy / Observatoire de Paris

Uranus’ tilted axis

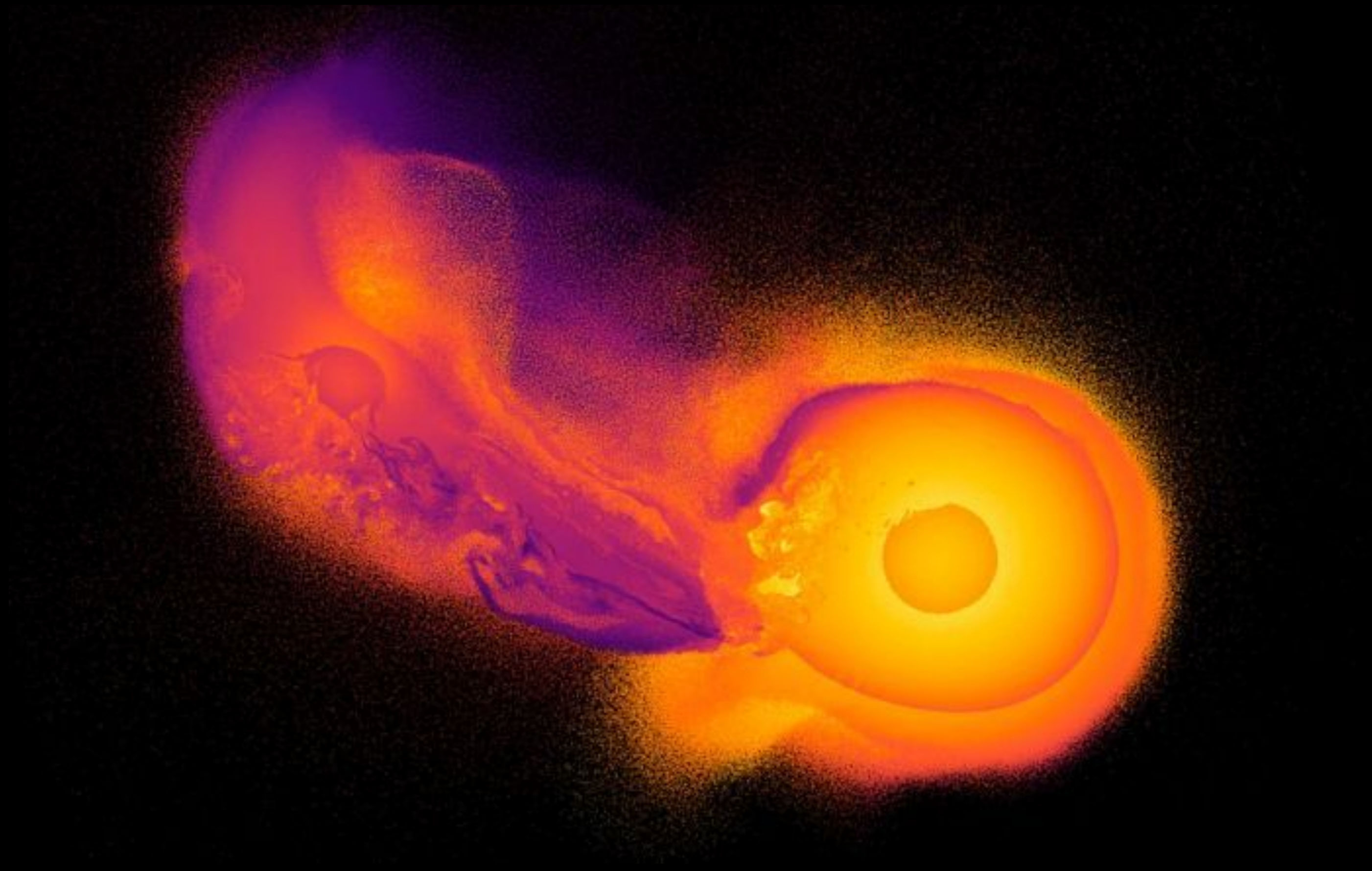


Image credit: J. Kegerreis / Durham University

Reference: Kegerreis et al. (2019)

Ice giant dichotomy

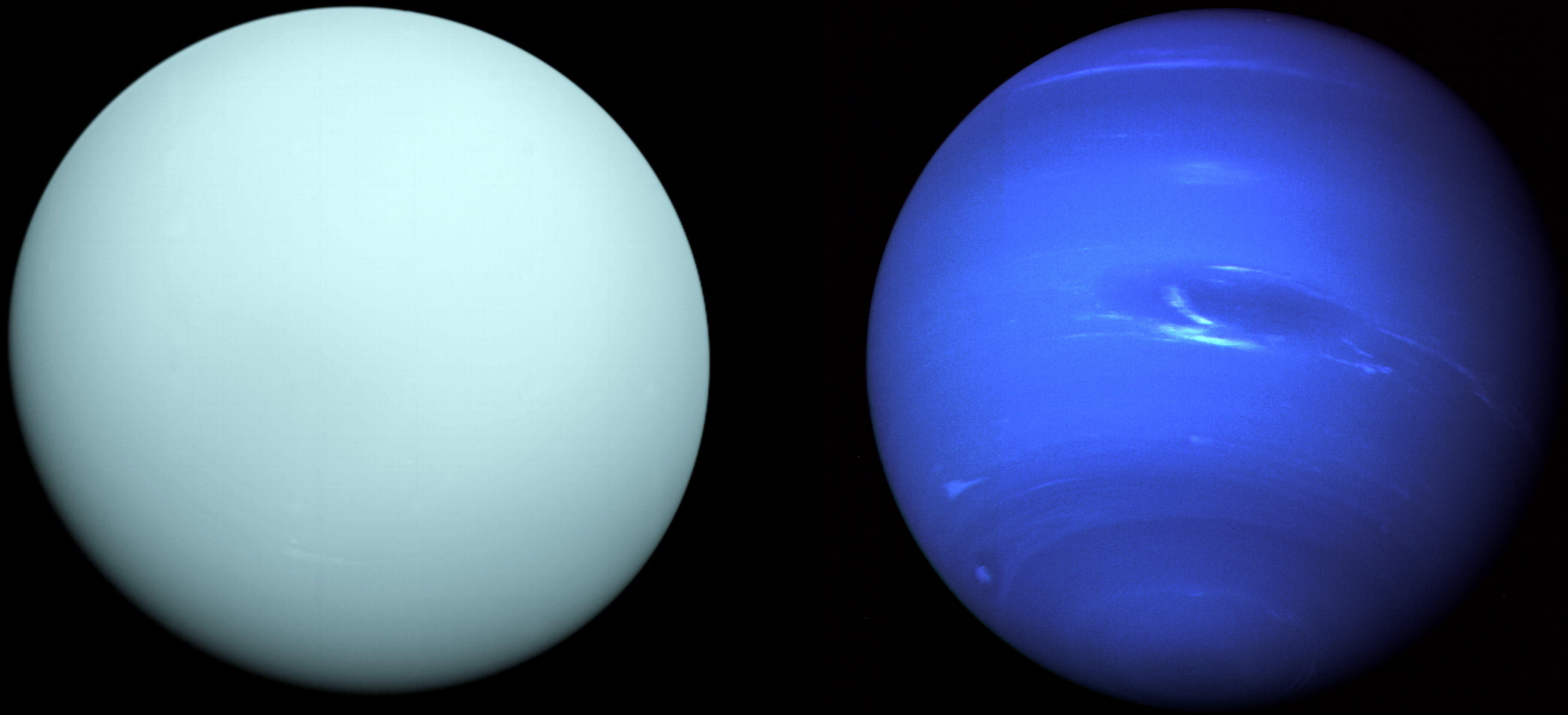


Image credit: NASA/JPL, Voyager 2

Reference: Reinhardt et al. (2019)

Origin of Pluto-Charon

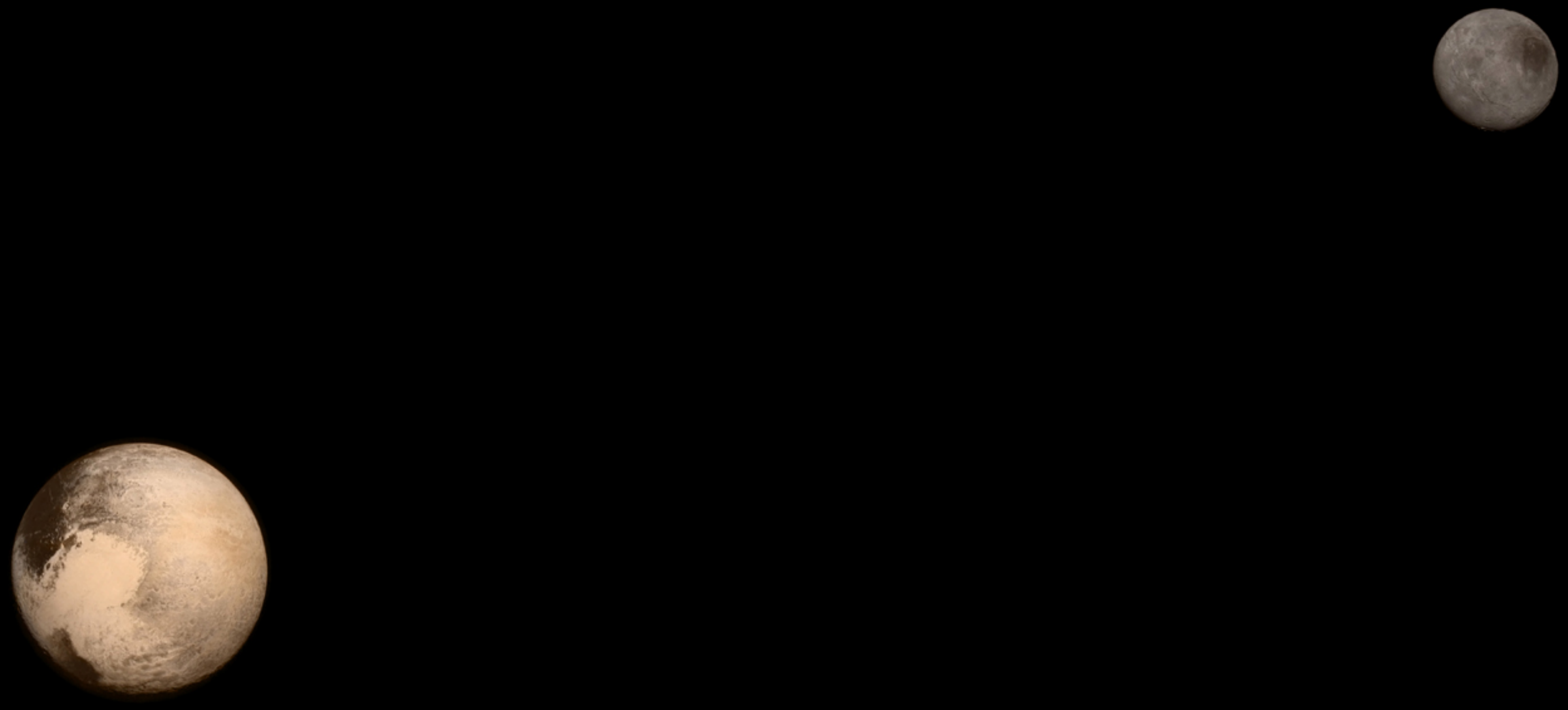


Image credit: NASA / Johns Hopkins University Applied
Physics Laboratory / Southwest Research Institute

Reference: Kegerreis et al. (2019)

Planet Formation

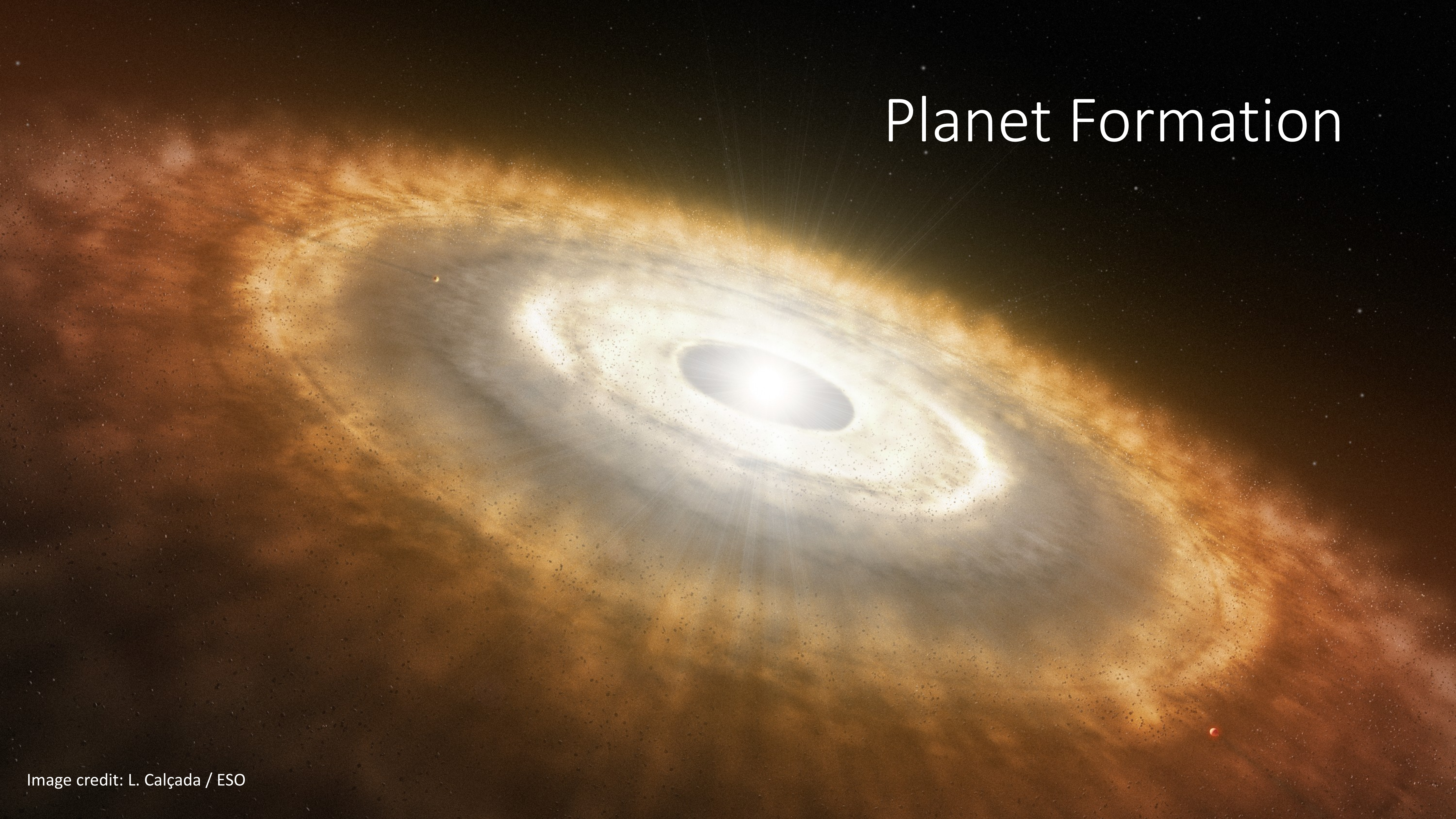
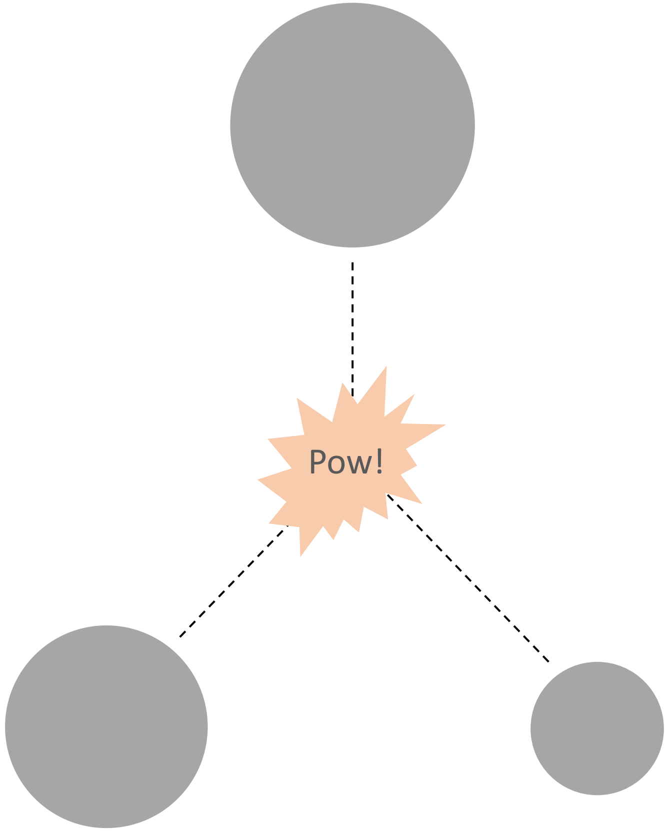


Image credit: L. Calçada / ESO

Planet Formation



Source: Timpe et al. (in review)

Why machine learning?

- Collisions are important for planet formation
- Simulations are expensive, parameter space is high dimensional
- Analytic and semi-analytic approaches aren’t getting the job done
- Needs to generalize to any quantifiable property
- Must be usable “on-the-fly” (i.e., in N-body simulations)
- Should provide us with physical insights
- Would be nice if models obey physics

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Data | Collision Dataset

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- 10,700 simulations of collisions
- Smoothed-particle hydrodynamics run on Piz Daint supercomputer
- Latin hypercube sample (LHS) with adaptive response surface method
- LHS10K, LHS500, LHS200
- Available on Dryad repository: https://doi.org/10.5061/dryad.j6q573n94

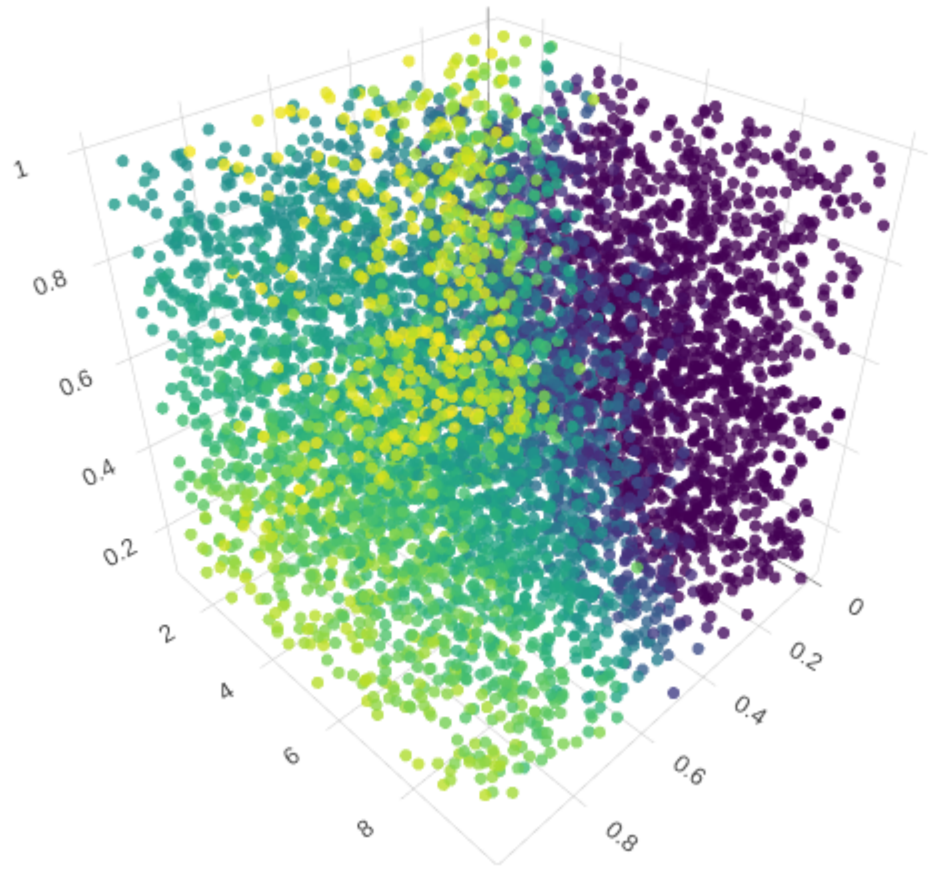

Image credit: M. Timpe / University of Zurich

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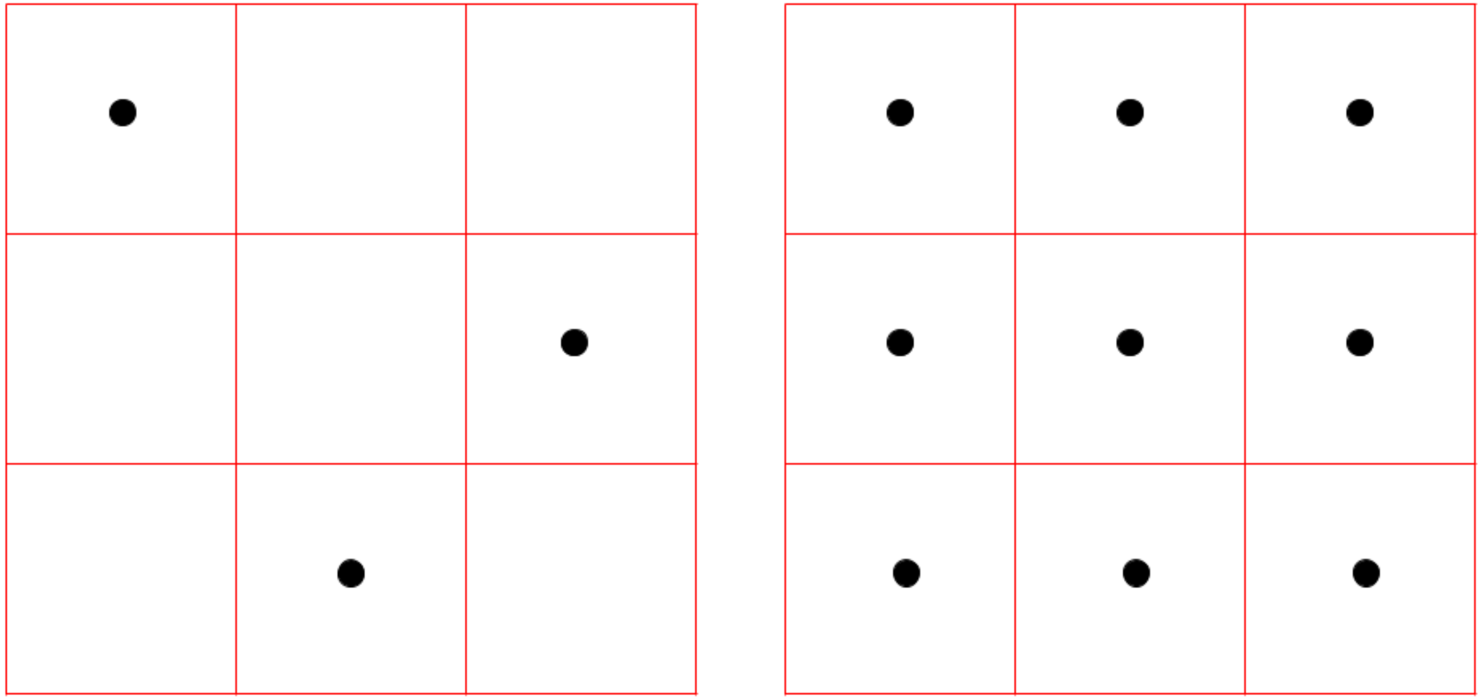
Data | Latin Hypercube Sampling

University of Zurich[UZH]



Latin Hypercube Sampling Standard Stratified Sampling

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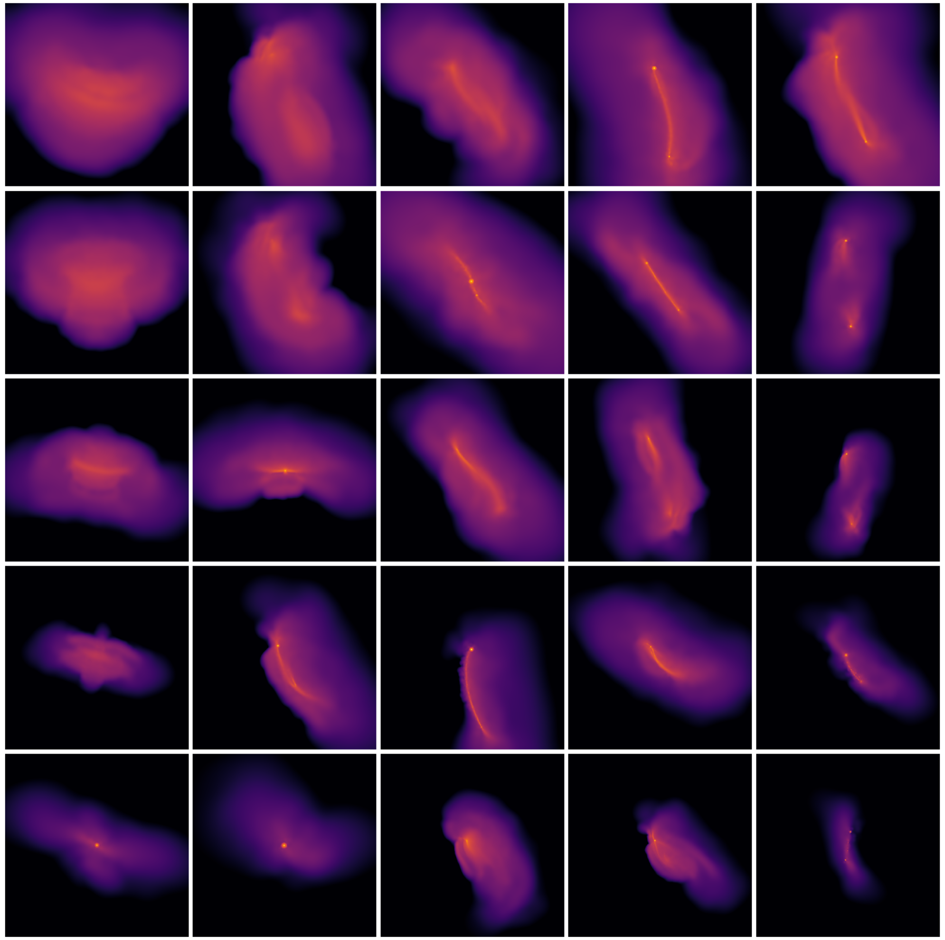
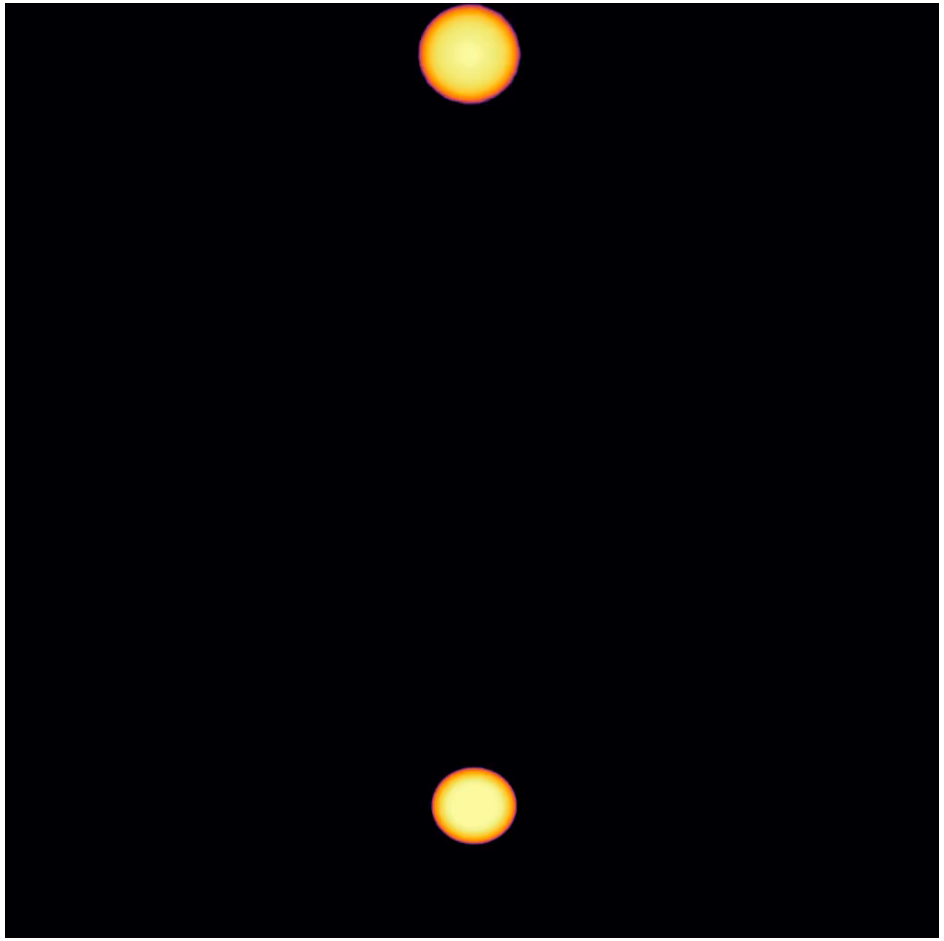
Image credit: Andro Sabaschvili / Medium

Data | Simulations

University of Zurich[UZH]





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Source: Timpe et al. (in review)

Data | Post-Impact Analysis

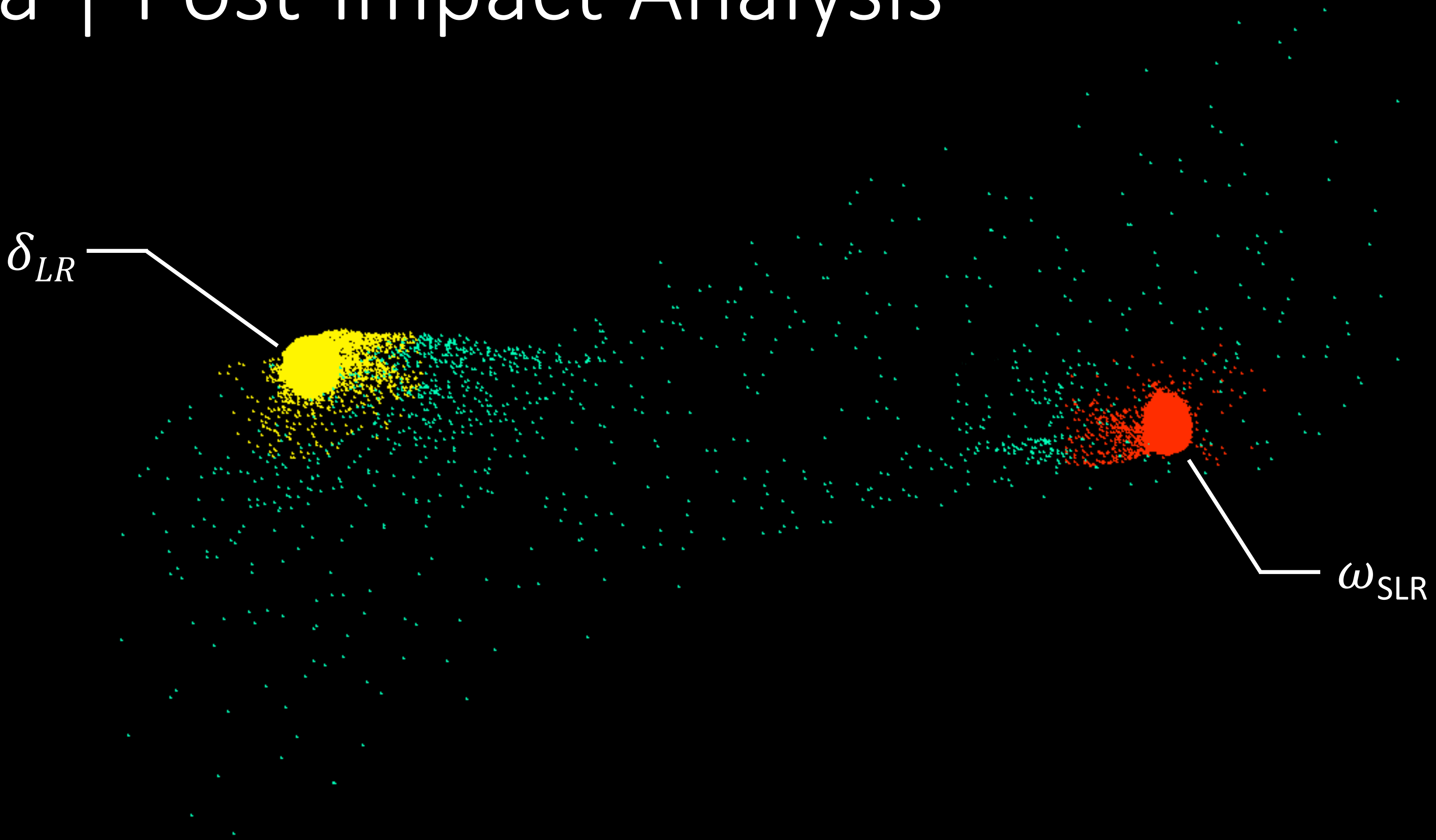
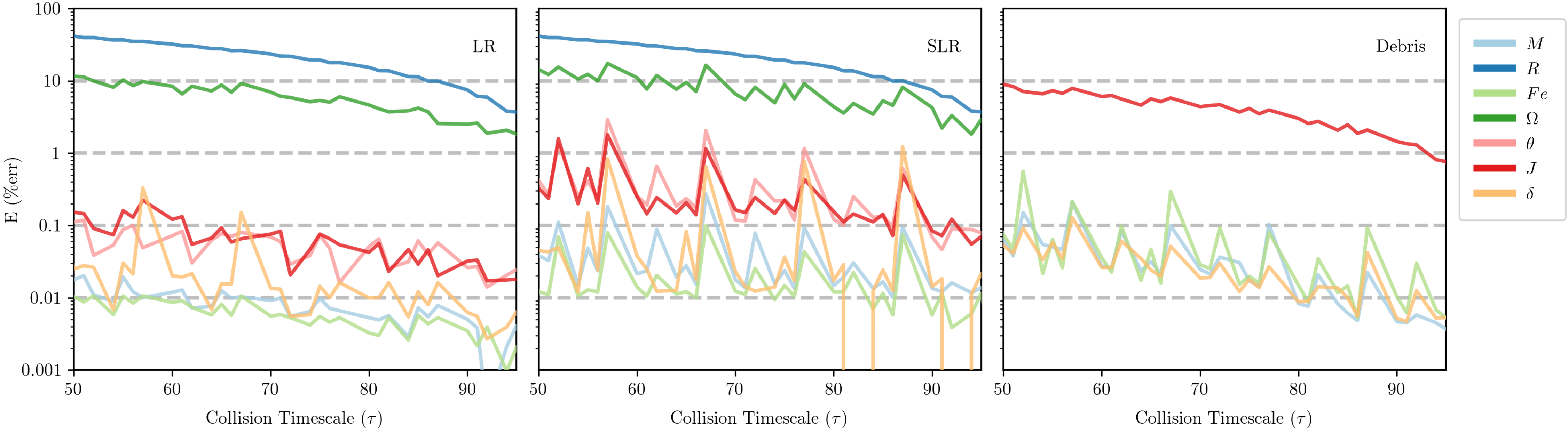


Image credit: M. Timpe / University of Zurich

Data | Post-Impact Convergence



Source: Timpe et al. (in review)

Methods | Collision models

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- Perfectly inelastic merger (PIM)
- Impact-erosion model (IEM)
- Fragmentation model (EDACM)

Analytic & semi-analytic

- Polynomial chaos expansion (PCE)
- Gaussian processes (GP)
- Multi-layer perceptrons (MLP)
- XGBoost (XGB)

Data-driven (ML and UQ)

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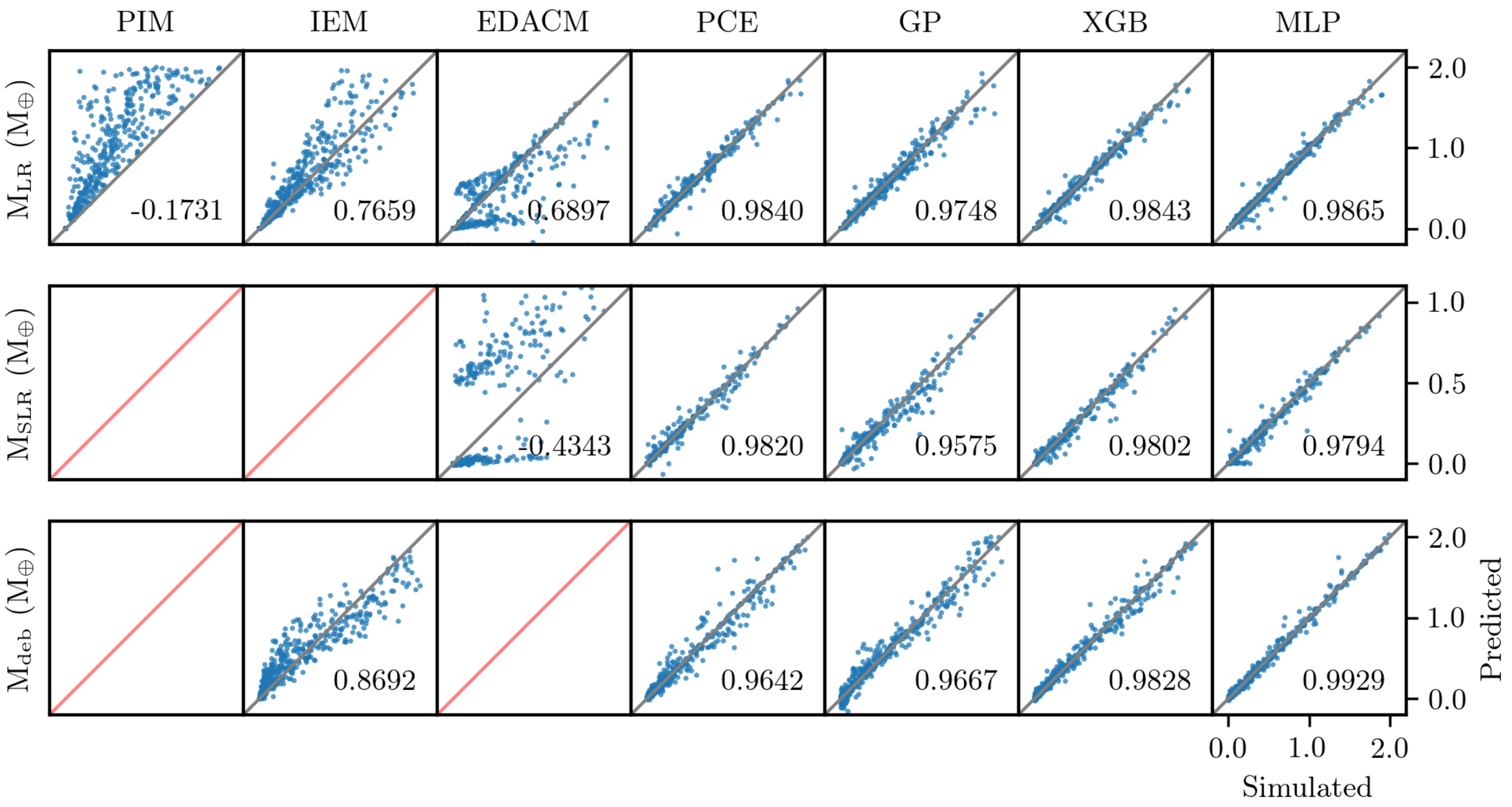
Methods | Training Pipeline

- One emulator per post-impact property (single-target regression)
- GP, MLP, PCE, and XGB
- Train on LHS10K
- Hyperparameter optimization with hyperopt / UQLab
  - 80/20 train/test split
  - 5-fold cross-validation
- Validate on LHS500
- Sensitivity analysis (Sobol' index)

Results | Predictions



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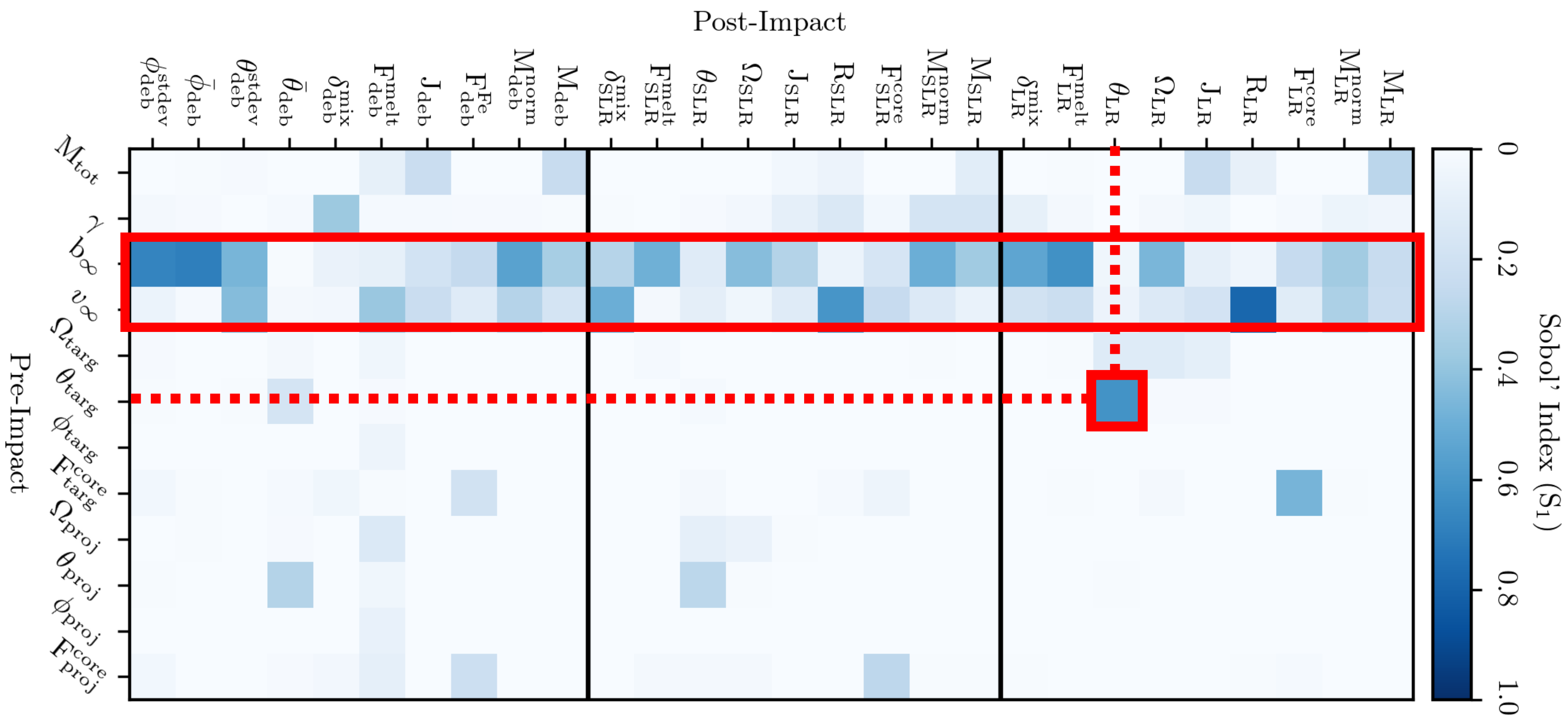
Source: Timpe et al. (in review)

Results | Sensitivity Analysis



Source: Timpe et al. (in review)

Results | Dataset Requirements

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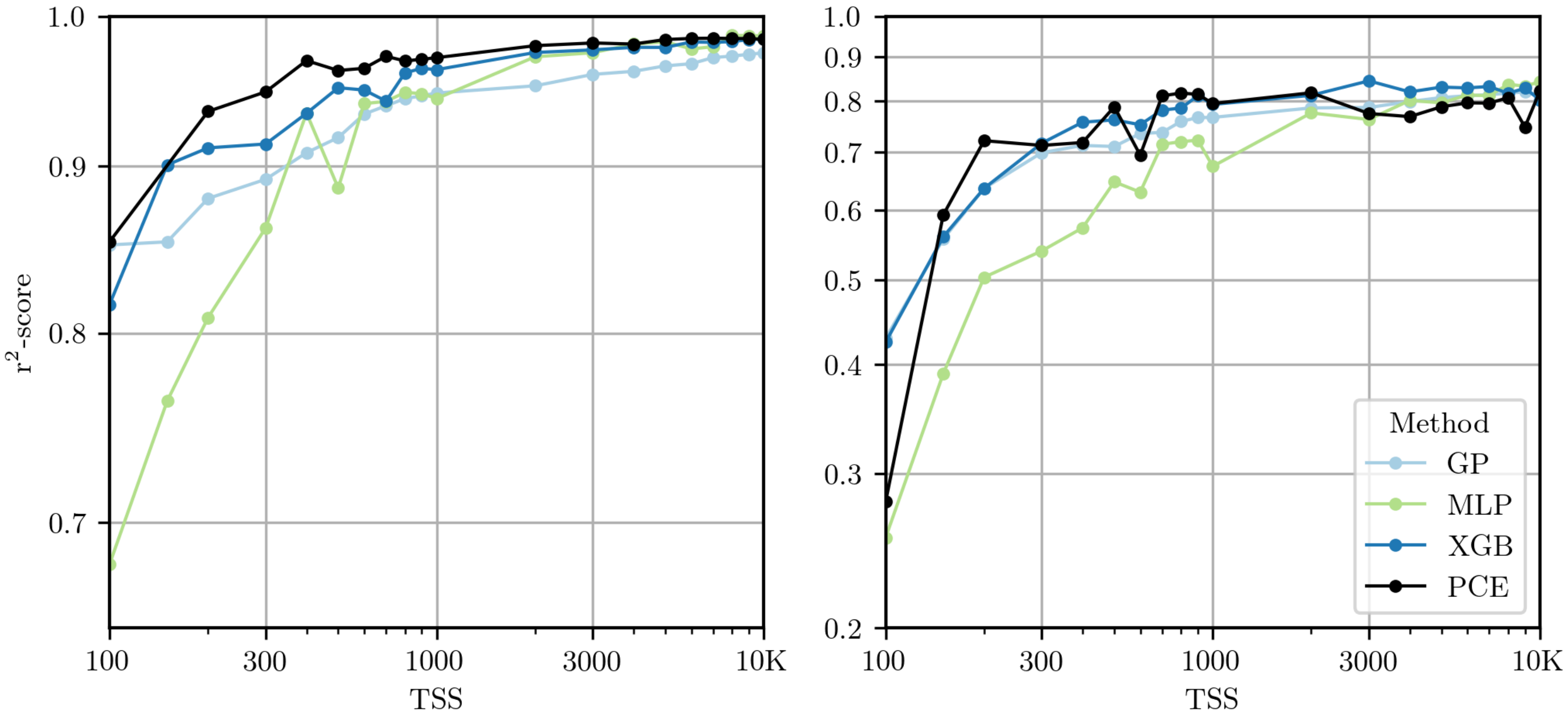

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Source: Timpe et al. (in review)

Results | Dataset Requirements

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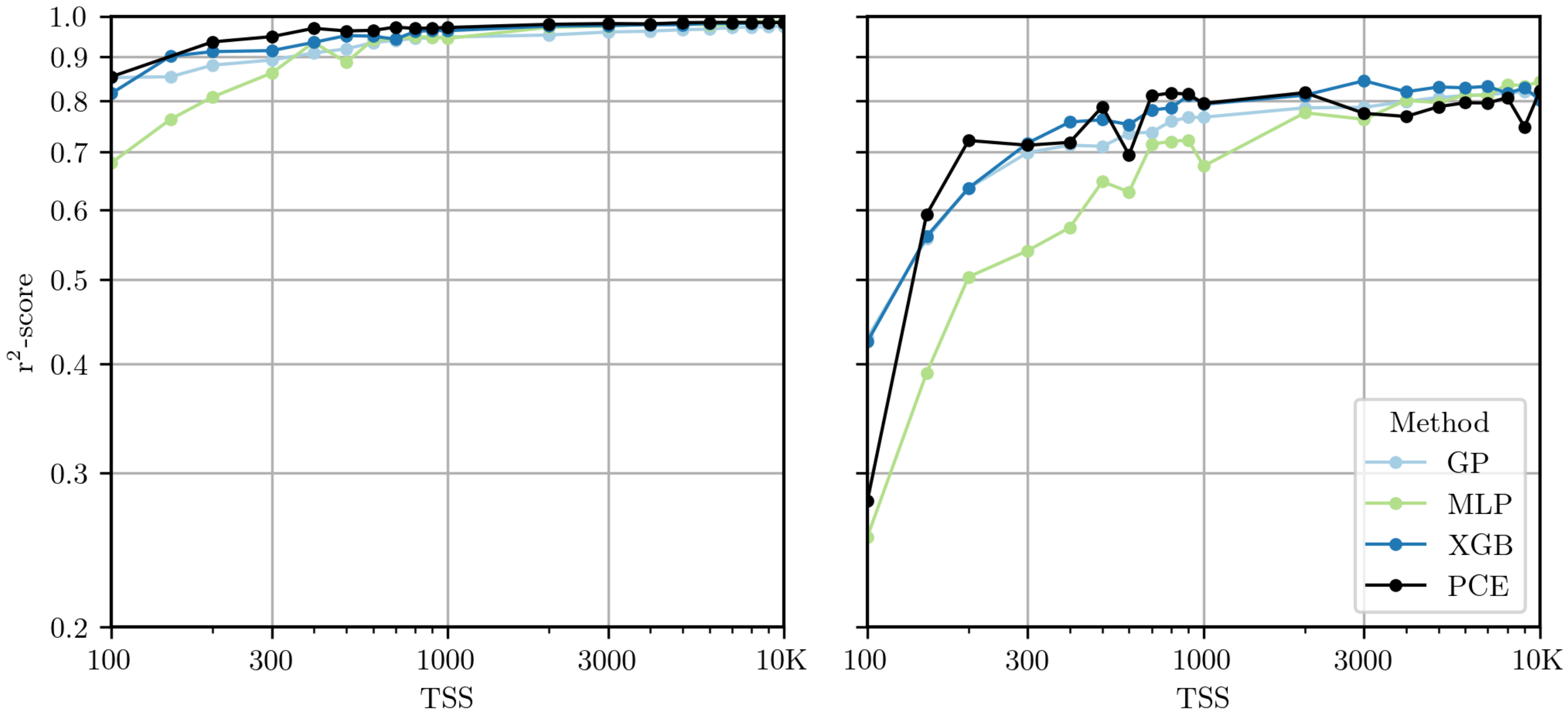

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Source: Timpe et al. (in review)

Work to be done...

- Training Data
  - Expand the collision parameter space
  - Higher-resolution simulations
  - New equations of state
- Models
  - Physical self-consistency
  - Multi-target regression for conserved quantities
  - Advanced techniques (e.g., ensemble methods)
  - Implement into N-body integrators

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Thanks!

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- Pre-print on arXiv from tomorrow!
- Simulations available on Dryad: https://doi.org/10.5061/dryad.j6q573n94
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  - Mischa Knabenhans (UZH)
  - Joachim Stadel (UZH)
  - Stefano Marelli (ETH Zurich)