$\eta_\oplus$ Estimates Informed by Exoplanet Evolution and Population Models

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$\eta_\oplus$ Is Difficult

Current exoplanet surveys don't cover the habitable zone

Can't observe HZ orbital periods for most G and F stars, and small planets are at/beyond the detection limit

Extrapolation is required

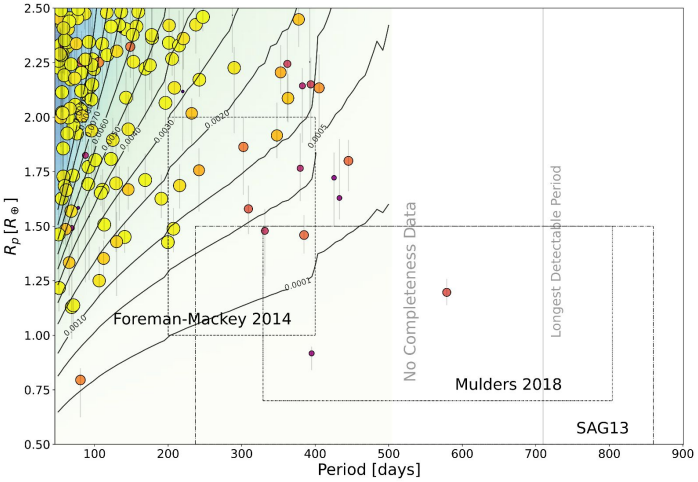
Extrapolating a population model, usually power laws

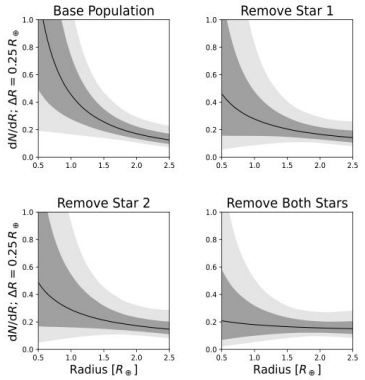
Extrapolation is *dangerous*

Power laws for warmer, larger planets likely do not predict cooler, smaller planets

Extrapolation is *unstable*

Adding or removing a couple planets at the detection limit can change $\eta_\oplus$ by a factor of 3



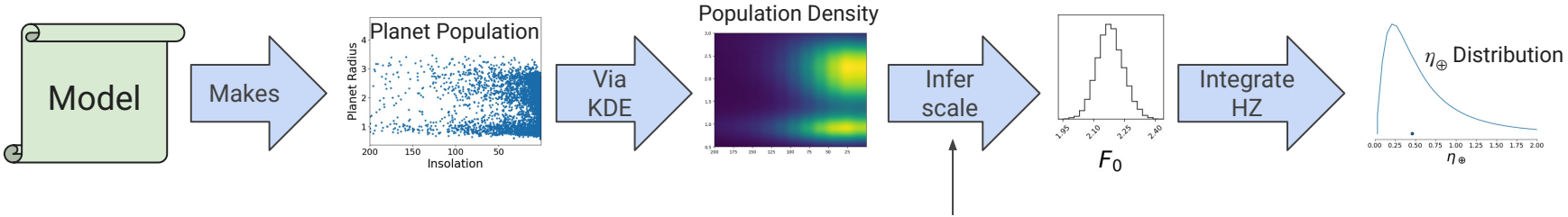


Alternative: Theory-Based Population Models

Explore exoplanet formation/evolution models to infer the population of cooler, smaller planets from observations of warmer, larger planets

Theory-informed extrapolation, much less dependent on planets at the detection limit

From model to $\eta_\oplus$: (in insolation-radius-stellar temperature space (I,r,T))



Poisson inference with rate $= F_0\ \mathrm{KDE}(I, r, T)$

Which theory?

Many theories, Little consensus

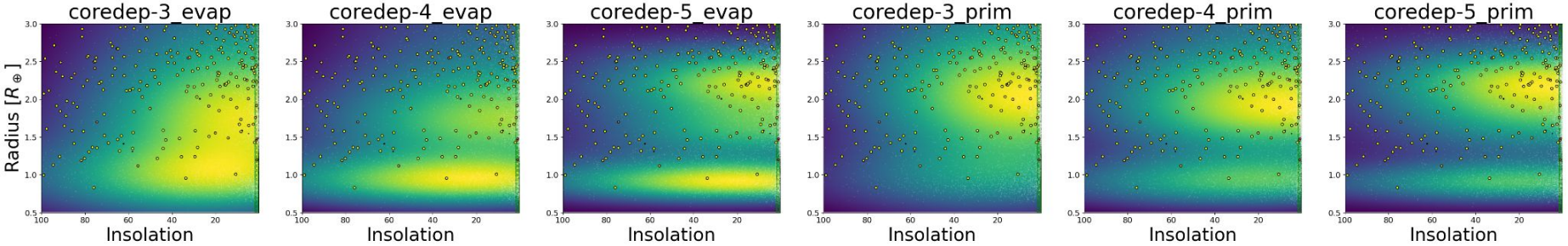
But we'll pick a set of theories to explore this idea for a proof of concept

We prototype using the models of Lee, Karalis and Thorngren (2022)

We consider six models, three with evaporative mass loss ("_evap") and three without ("_prim"), with differing model parameter Coredep

Coredep is the log of the disk gas depletion when the planets accrete gas

Evolved to 3 gigayears



Example with Evaporation, $M_\odot$=1

Example without Evaporation, $M_\odot$=1

Evaluating the Models

Use Bayesian predictive sampling to evaluate how well each scaled model matches the observed population

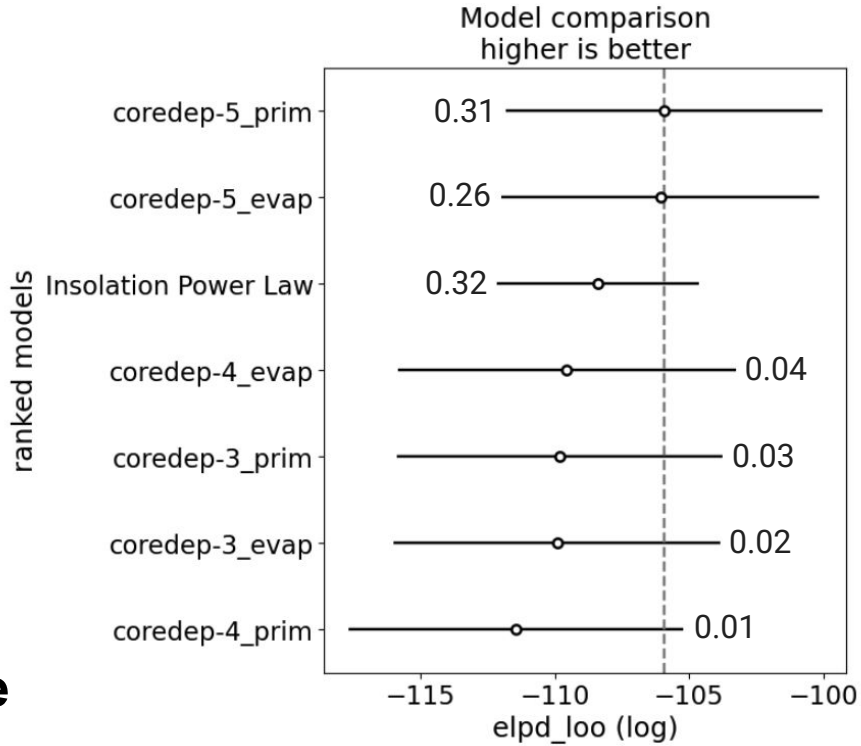
As implemented in arviz.compare()

Include the power law

Each model is assigned a weight so the weighted sum of models best matches the observations

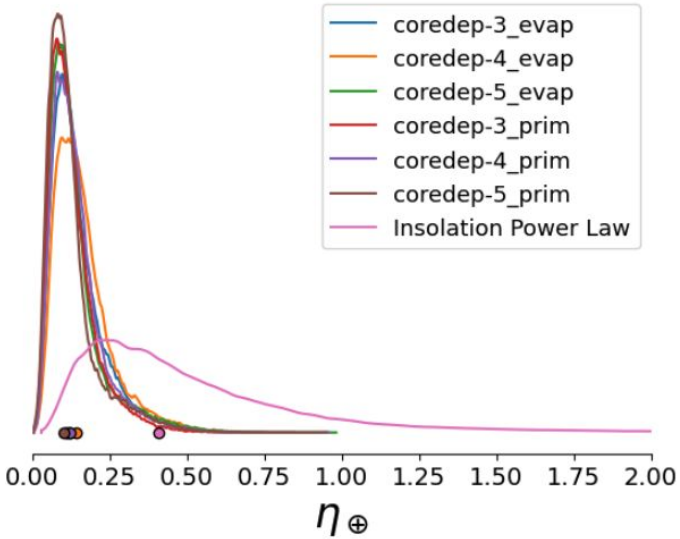
"Bayesian model stacking"

Evaluating in the $\eta_{\oplus}$ regime, two of the models turn out to be competitive with a power law



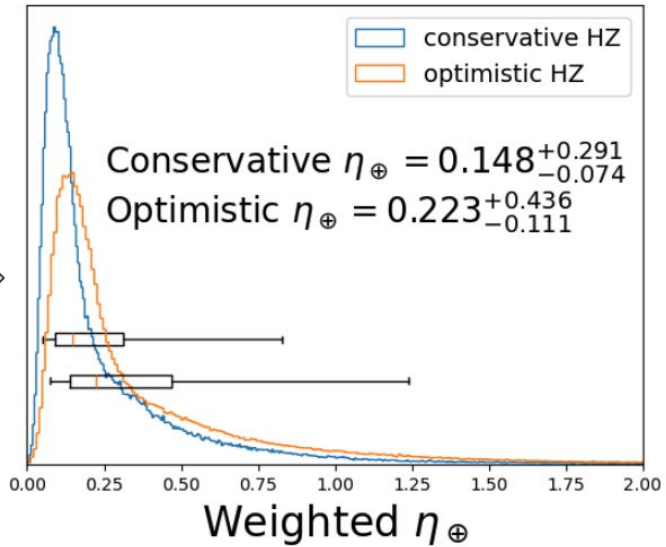
Estimating $\eta_\oplus$

Integrate over the habitable zone to give $\eta_\oplus$ for each model



Via Weights

Combine the model $\eta_\oplus$ distributions using the model weights for the final weighted estimate



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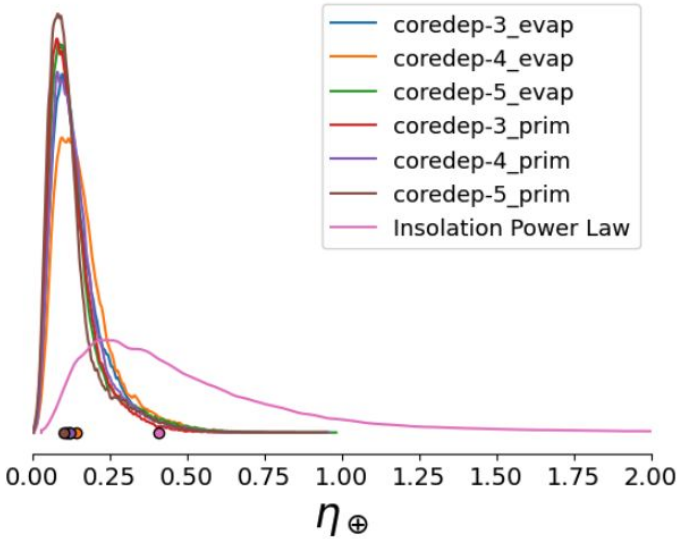

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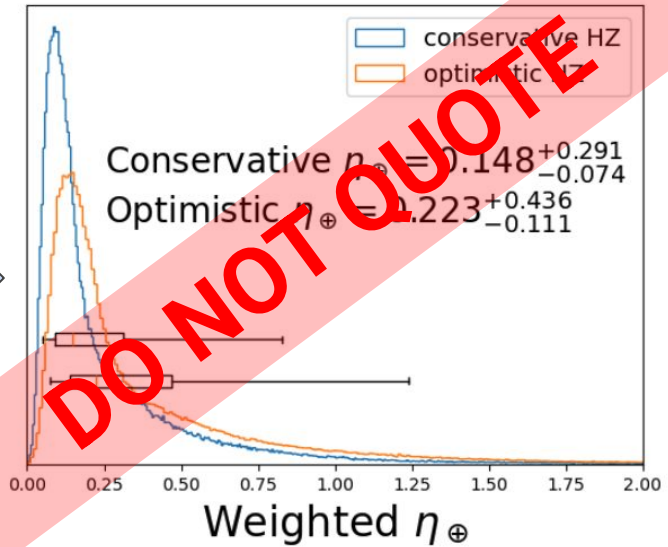


This Is Just a Proof of Concept Prototype!!!

Exoplanet formation and evolution theories need to be better constrained for long-period, small planets before this is a reliable method for estimating $\eta_{\oplus}$

It promises a robust method of extrapolating over the habitable zone

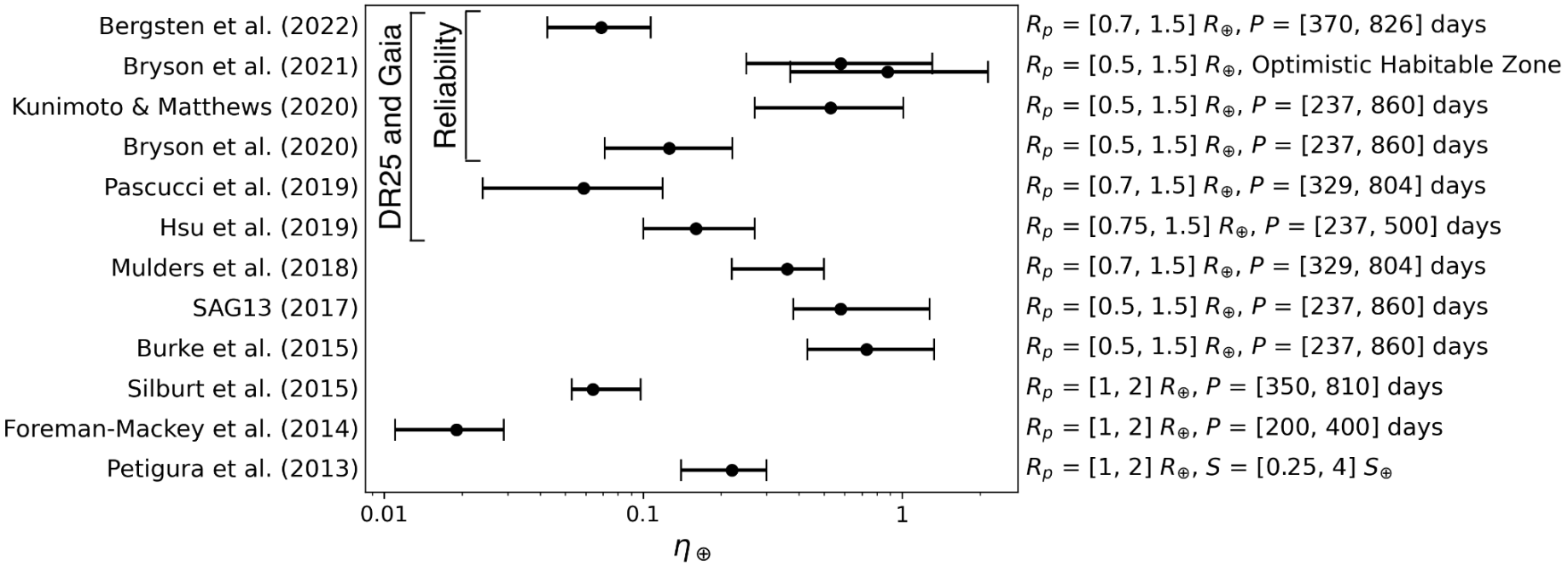
We will extend this approach to include model parameters in the inference for more precise and accurate modeling

Bayesian stacking opens up ways of estimating $\eta_{\oplus}$ that take into account uncertainty of which model to use: several models can be used and combined via their predictive weights.

Previous estimates assumed specific models, neglecting the uncertainty of that assumption

Backup Slides

Large Spread in $\eta_\oplus$ From Kepler Data



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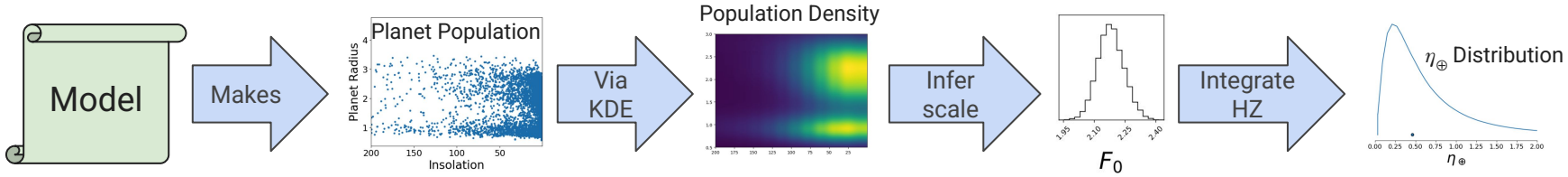
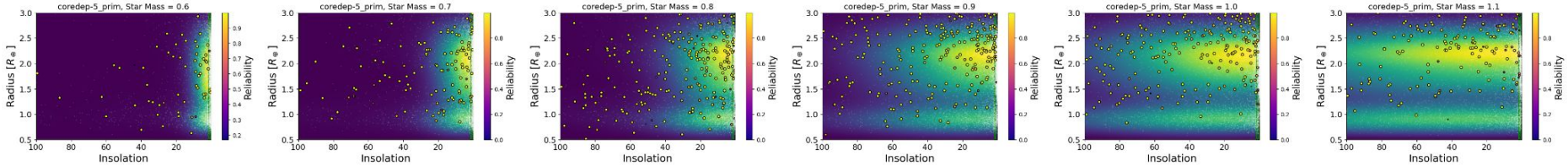


Complication: strong dependence on star mass, so need to jointly fit many populations



0.6 $M_\odot$ ⟷ 1.1 $M_\odot$

Stellar Mass