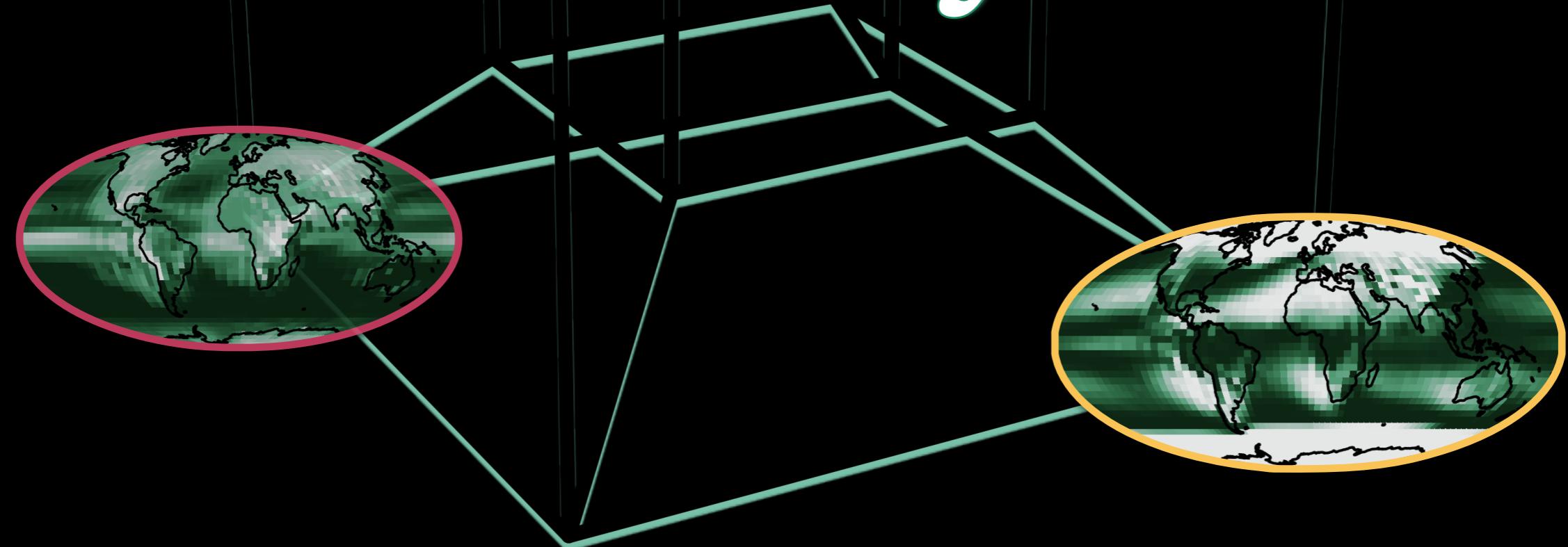


Habitability in 4-D



A. Adams, C. Colose, S. Kane, A. Merelli, M. Turnbull

How does
climate-based habitability
on Earth-like worlds
vary with rotation and orbital state?

Key Points

- Rotation period is the primary influence on habitability
 - ➡ Obliquity influences habitability at “faster” rotations ($\lesssim 20$ days); beyond this there’s a break in habitability where obliquity isn’t as important
 - ➡ Orbital eccentricity has the weakest effect of all (up to our limit of $e = 0.225$)
- A Gaussian process regression does a reasonable job of predicting a global+orbit-averaged climate habitability metric

Defining Habitability

Habitability is a measure of how well a planet or moon can support life. It is often used to describe Earth-like planets, such as Earth, Mars, and Venus. Habitability is determined by a variety of factors, including the planet's size, mass, temperature, and atmosphere.

The first factor to consider is the planet's size. A planet must be large enough to have a strong gravitational pull, which is necessary for holding onto an atmosphere. A planet must also be small enough to have a low density, which is necessary for it to be able to support life.

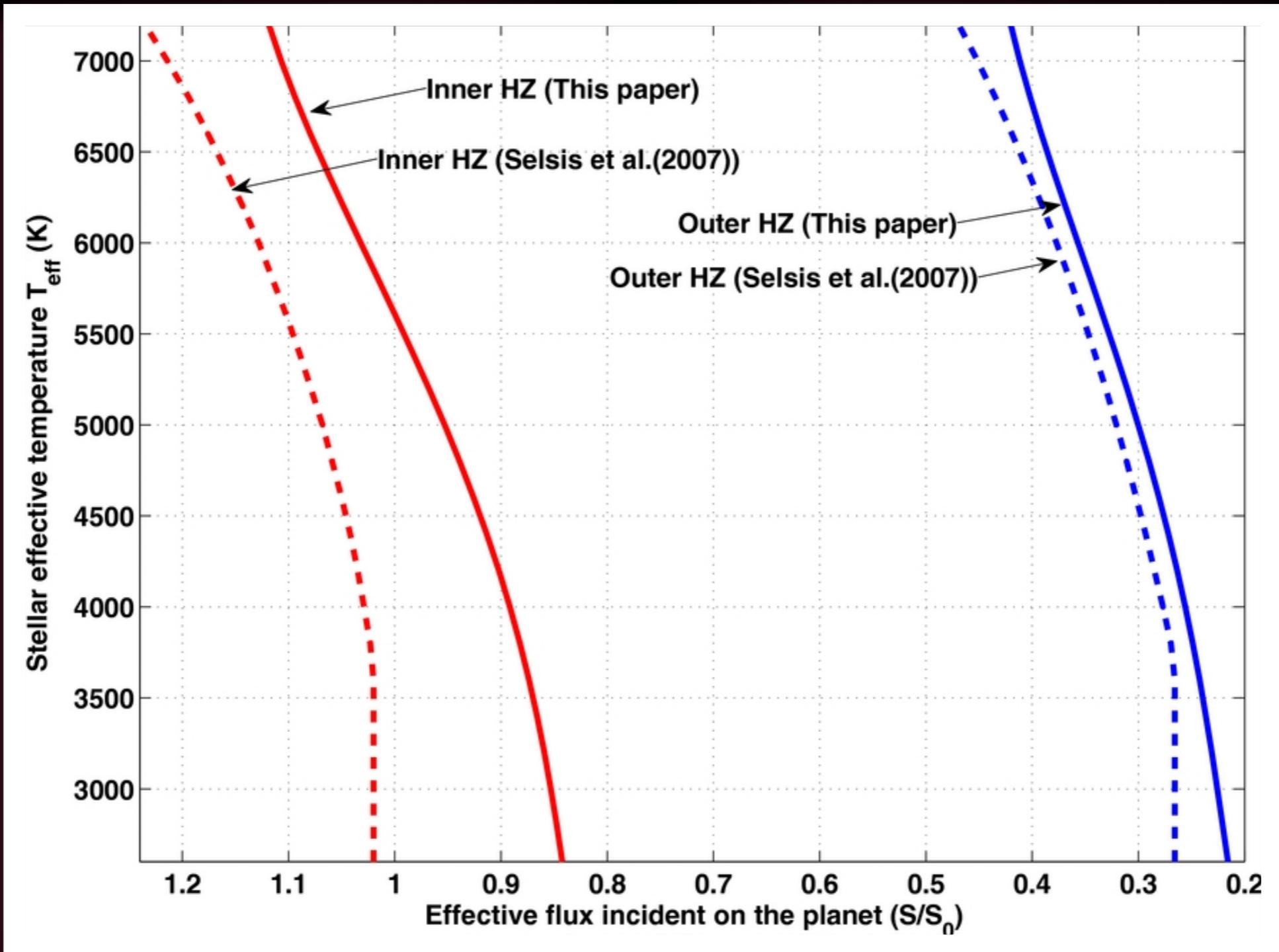
The second factor to consider is the planet's mass. A planet must be massive enough to have a strong gravitational pull, which is necessary for holding onto an atmosphere. A planet must also be massive enough to have a high density, which is necessary for it to be able to support life.

The third factor to consider is the planet's temperature. A planet must be warm enough to have liquid water, which is necessary for life. A planet must also be cool enough to have a stable atmosphere, which is necessary for life.

The fourth factor to consider is the planet's atmosphere. A planet must have a thick atmosphere, which is necessary for life. A planet must also have a thin atmosphere, which is necessary for life.

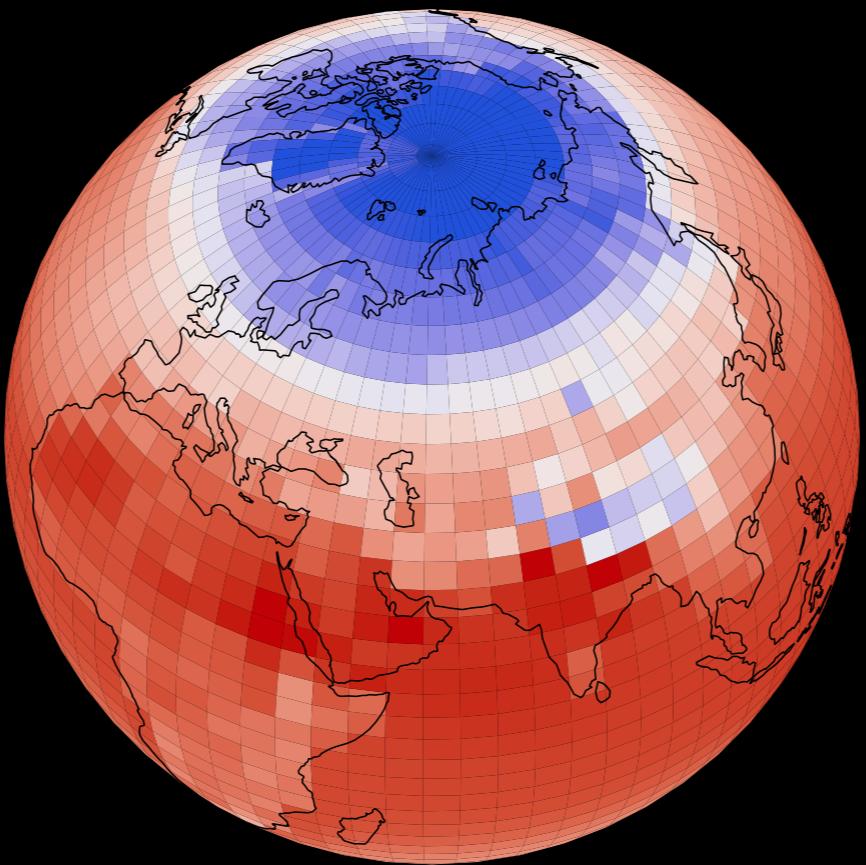
These four factors are the most important when determining habitability. However, there are other factors that can also affect habitability, such as the planet's distance from the sun, its orbital period, and its rotation rate.

Defining Habitability



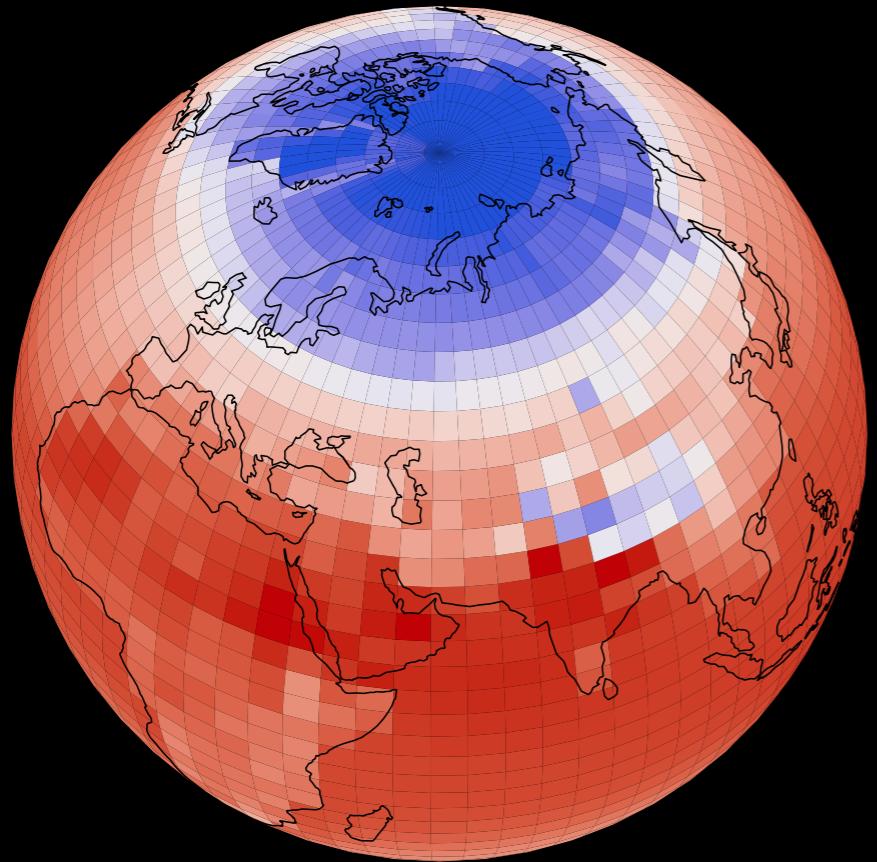
Kopparapu et. al. (2013)

“Climate” Habitability

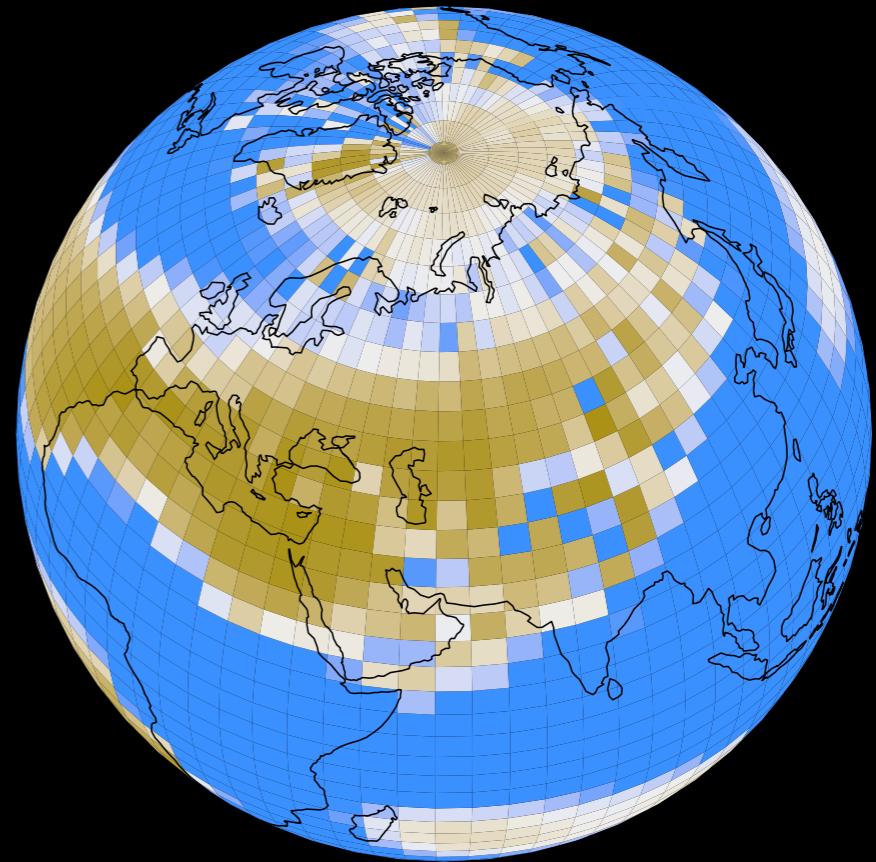


$$0 \leq T_{\text{surf}} \leq 100^\circ \text{ C}$$

“Climate” Habitability

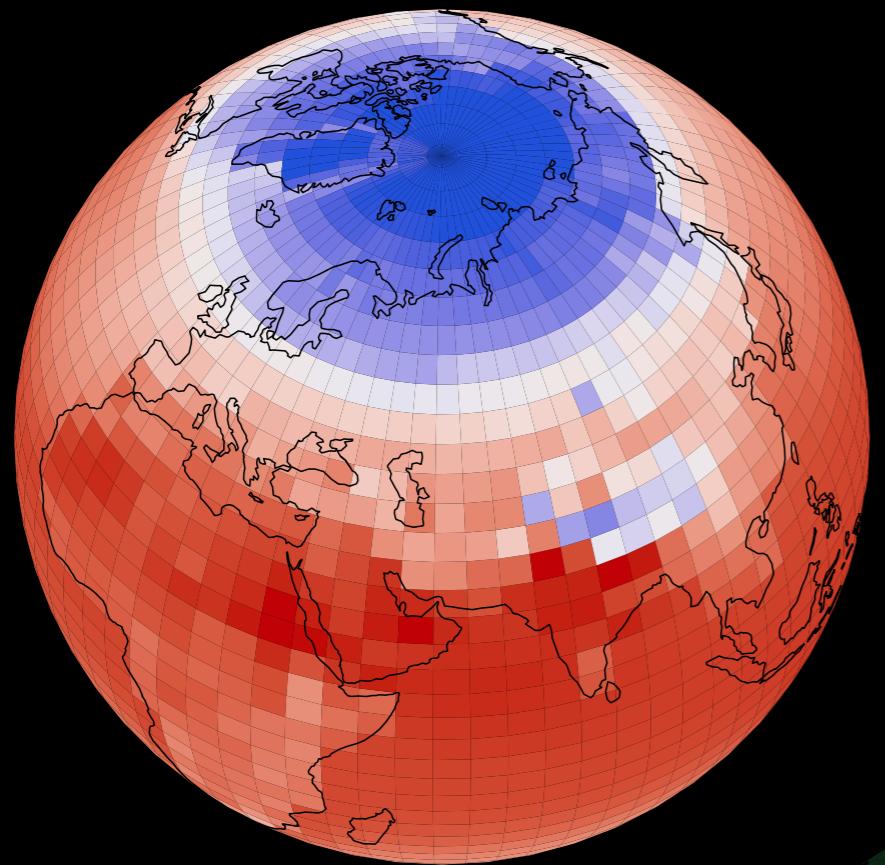


$0 \leq T_{\text{surf}} \leq 100^\circ \text{ C}$

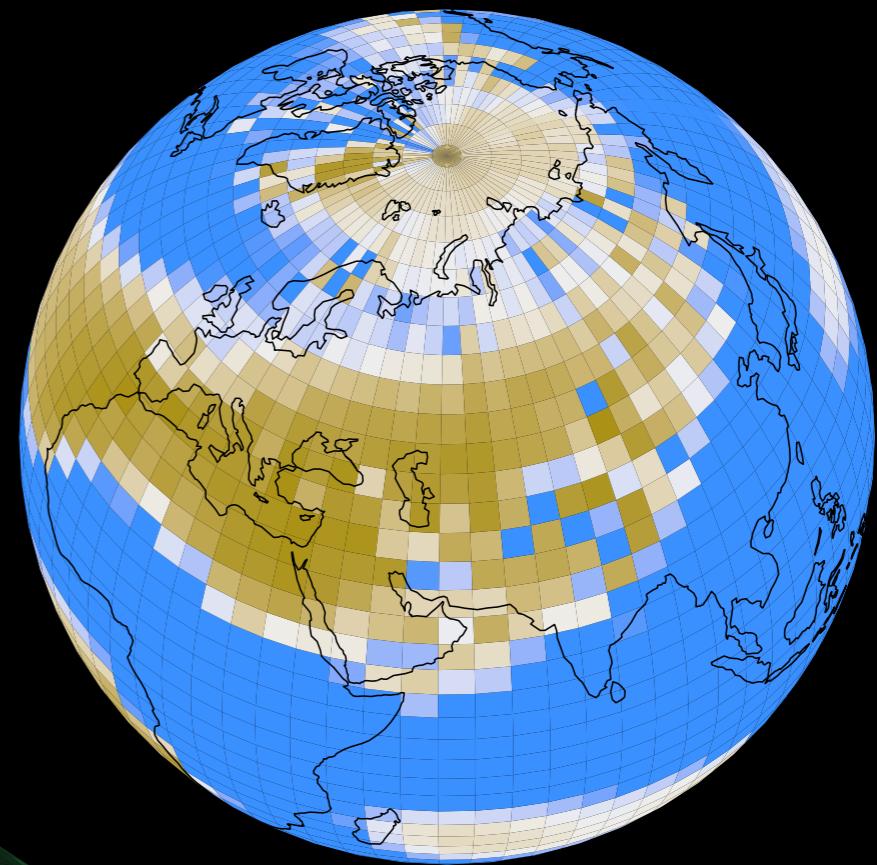


Precipitation $\geq 300 \text{ mm/year}$

“Climate” Habitability



$0 \leq T_{\text{surf}} \leq 100^\circ \text{ C}$



Precipitation $\geq 300 \text{ mm/year}$





$$f_X(P_{\text{rot}}, \psi, e, \phi_{\text{peri}}) \equiv \frac{1}{A_{\text{terr}}} \sum_{i=1}^{n_\lambda} \sum_{j=1}^{n_\phi} \frac{1}{n_{\text{orb}} P_{\text{orb}}} \sum_{k=1}^{12n_{\text{orb}}} I_X(\lambda_i, \phi_j, t_k; P_{\text{rot}}, \psi, e, \phi_{\text{peri}}) f_{\text{terr}} A_{ij} \tau_k(e)$$



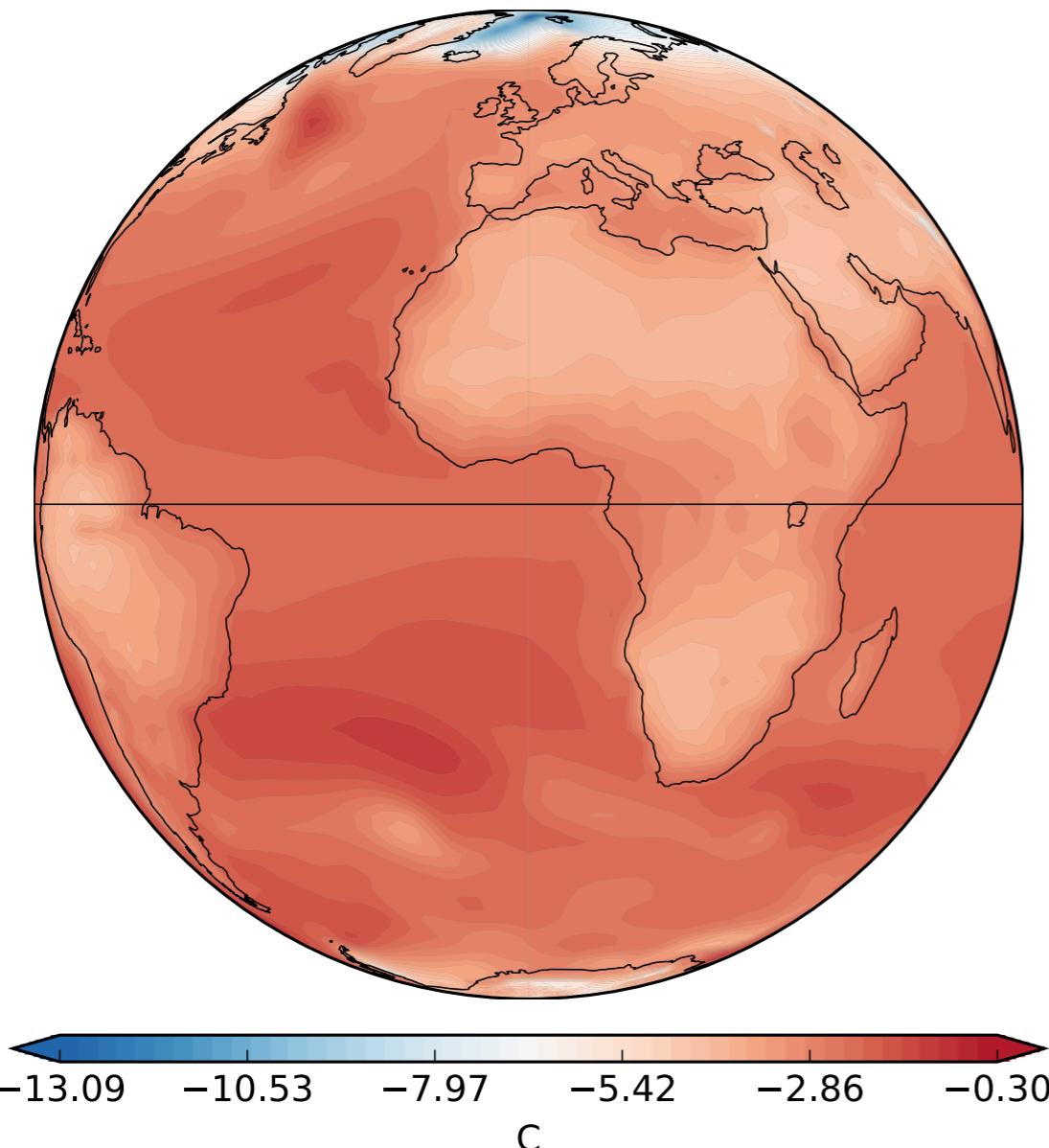
$$f_X(P_{\text{rot}}, \psi, e, \phi_{\text{peri}}) \equiv \frac{1}{A_{\text{terr}}} \sum_{i=1}^{n_\lambda} \sum_{j=1}^{n_\phi} \frac{1}{n_{\text{orb}} P_{\text{orb}}} \sum_{k=1}^{12n_{\text{orb}}} I_X(\lambda_i, \phi_j, t_k; P_{\text{rot}}, \psi, e, \phi_{\text{peri}}) f_{\text{terr}} A_{ij} \tau_k(e)$$

- Each cell gets 0 or 1 per month (**temperate** and **wet**)
- Weight by surface area in land, then take land average
- Weight by month length, then take time average

ROCKE-3D

Way et. al. (2017)

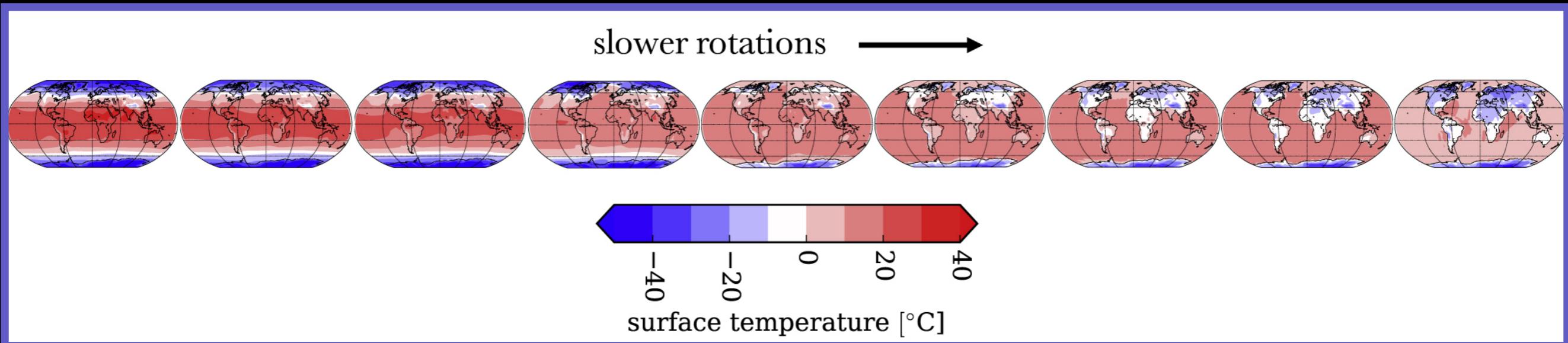
ANN4751-4800.aijE200F40oQ40 - ANN2451-2470.aijE200_2xCO2aF40oQ40
SURFACE AIR TEMPERATURE



- $4^\circ \times 5^\circ$ latitude-longitude resolution
- 40 vertical layers (10^{-4} to 1 bar)
- Dynamic ocean (uniform 1360 m depth)
- Bare soil, ocean, ice (no vegetation)

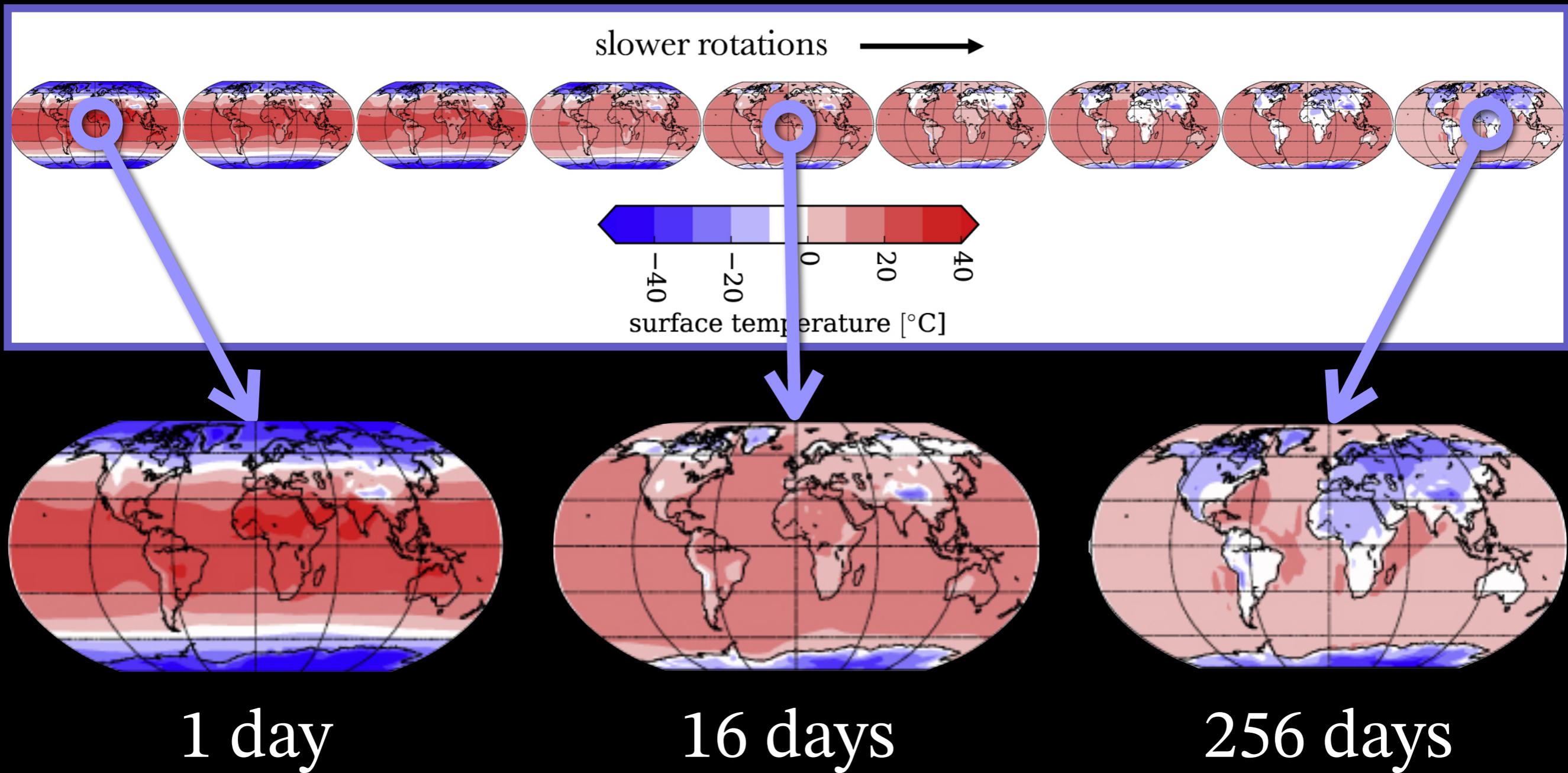


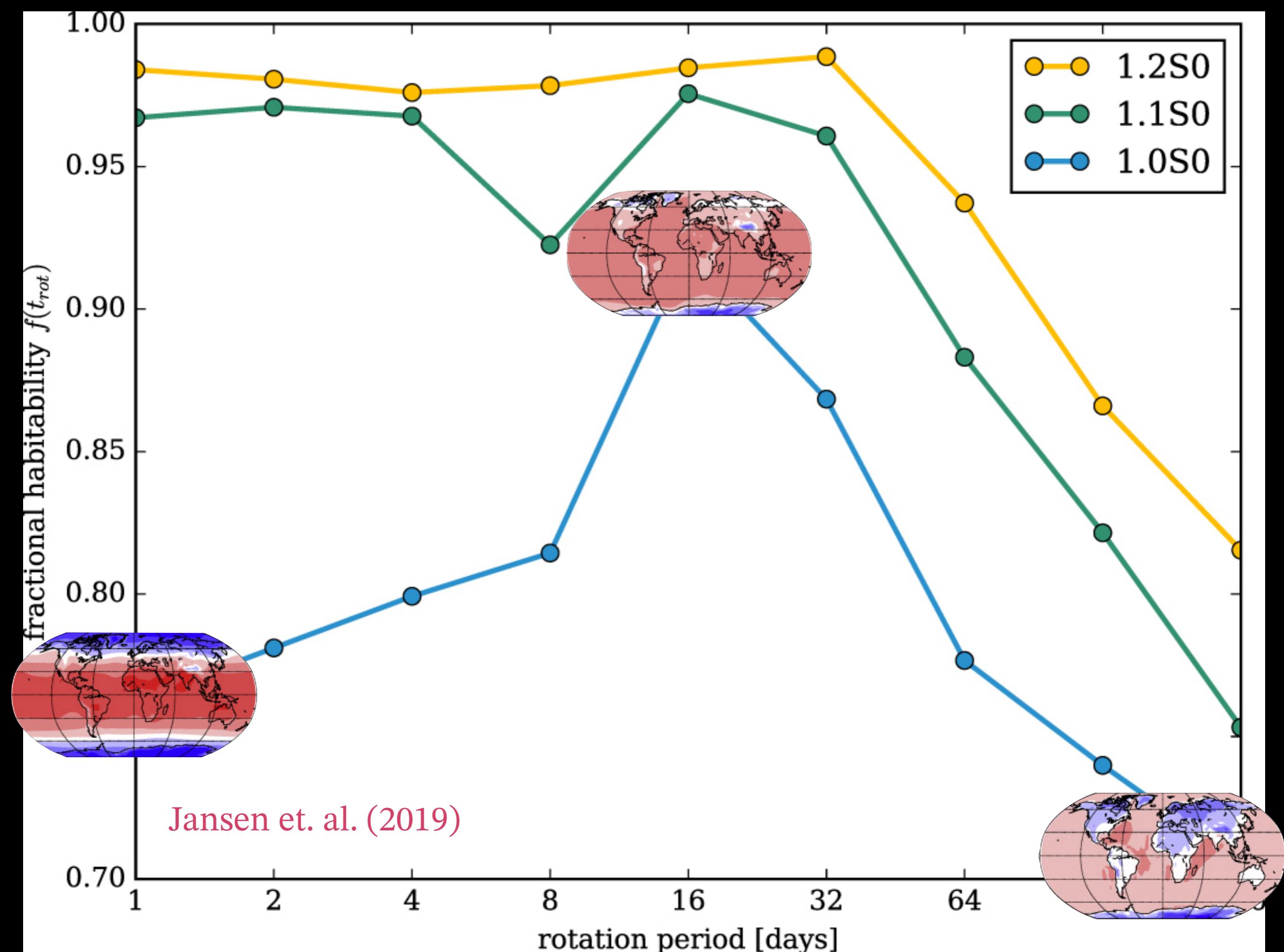
Jansen et. al. (2019): Rotational “Goldilocks” Zone



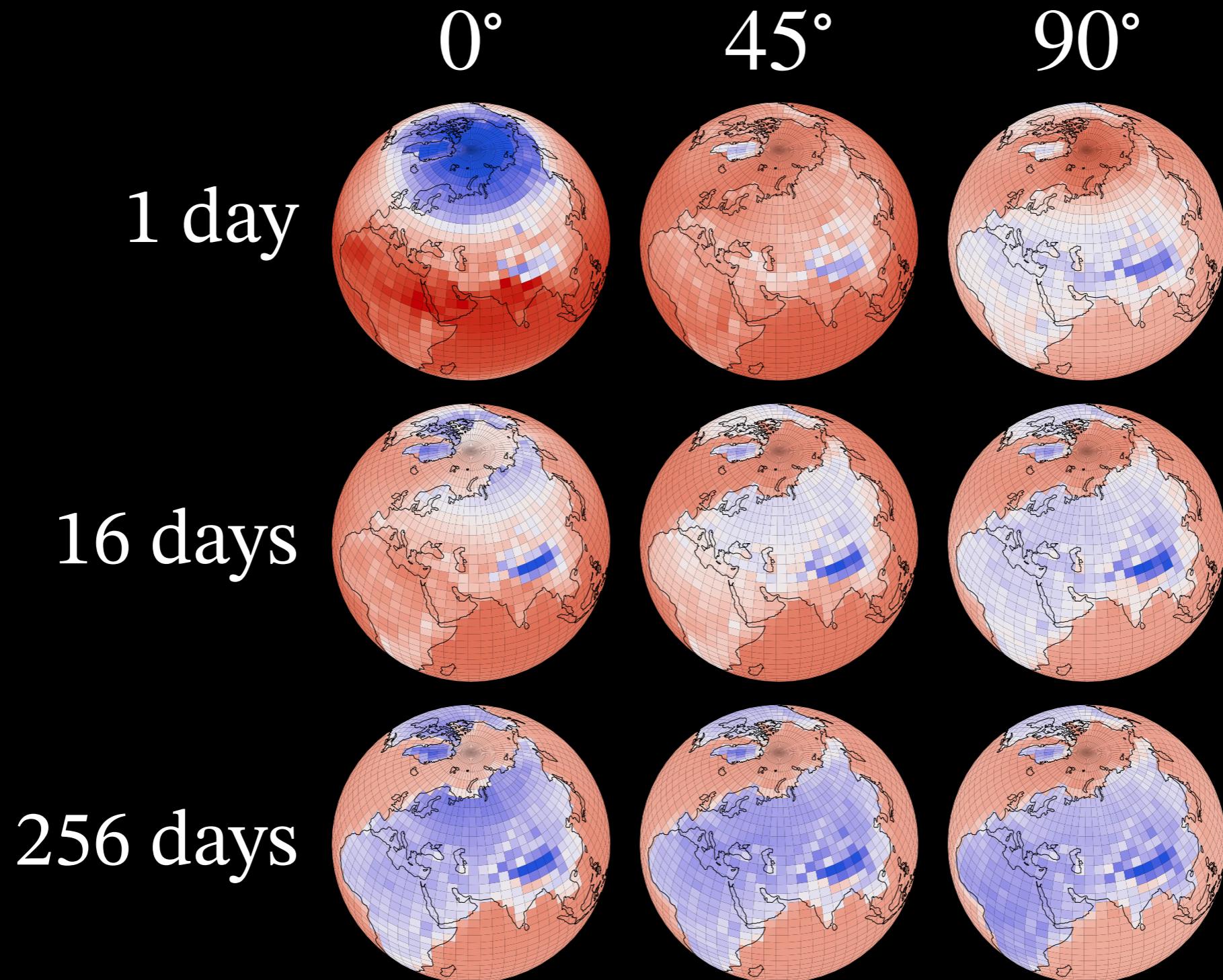
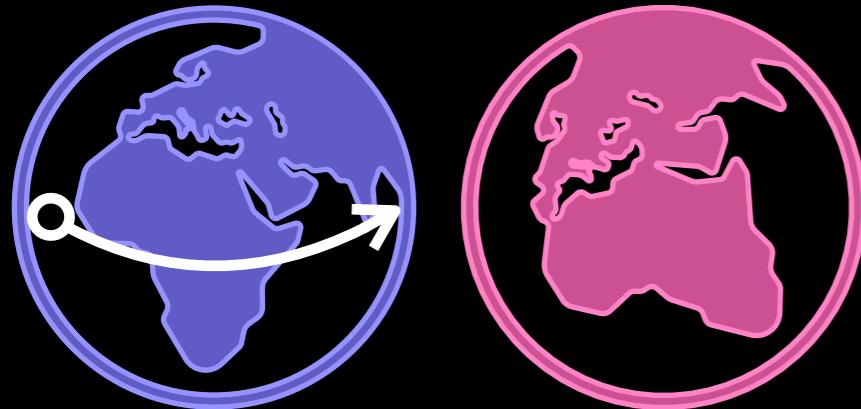


Jansen et. al. (2019): Rotational “Goldilocks” Zone





He et. al. (2022):
Obliquity Matters
at **Fast Rotations**



He et. al. (2022):
Obliquity Matters
at Fast Rotations

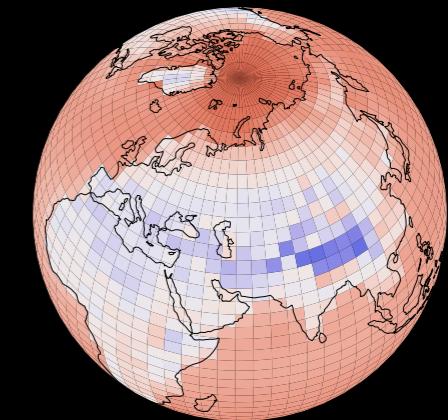
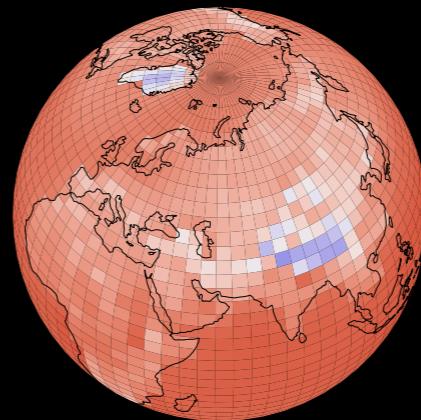
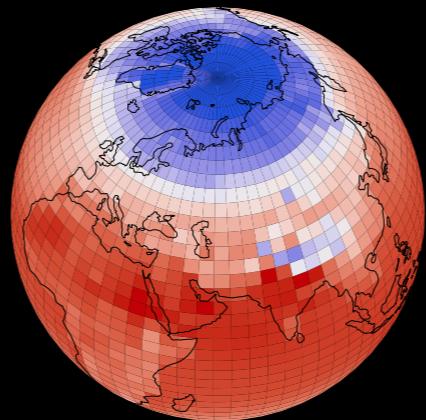


0°

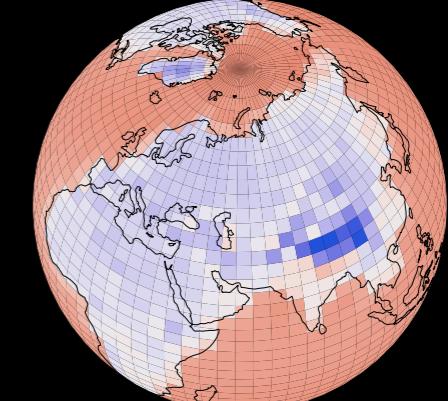
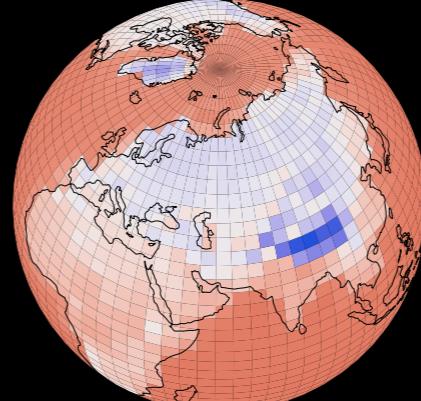
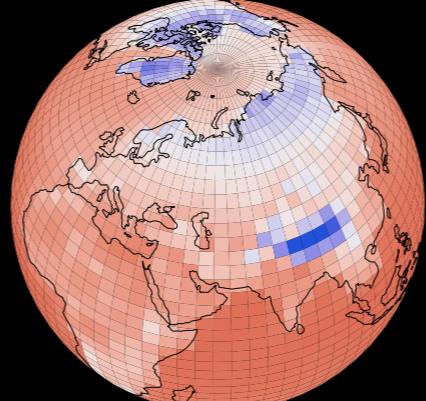
45°

90°

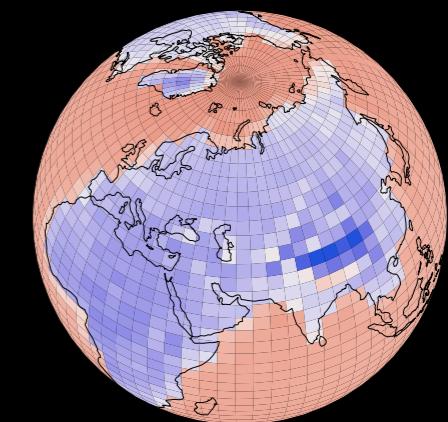
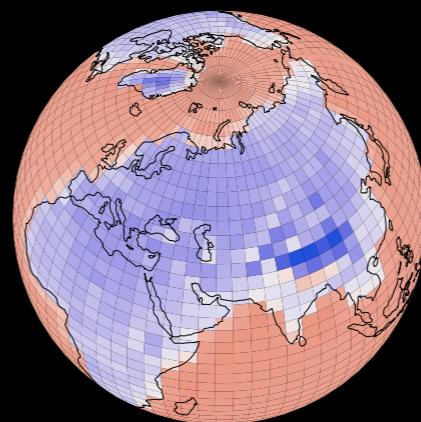
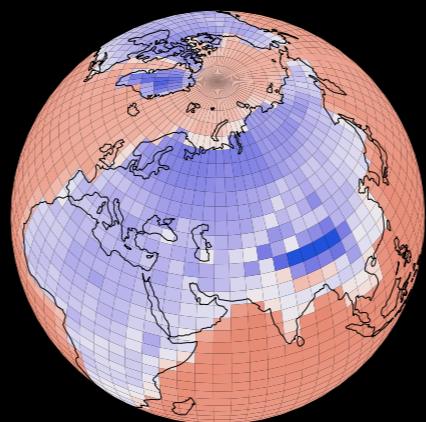
1 day



16 days



256 days



He et. al. (2022):
Obliquity Matters
at Fast Rotations

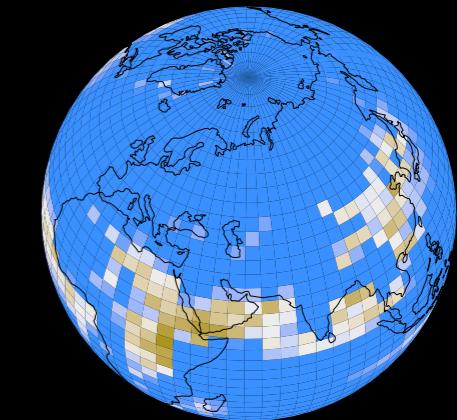
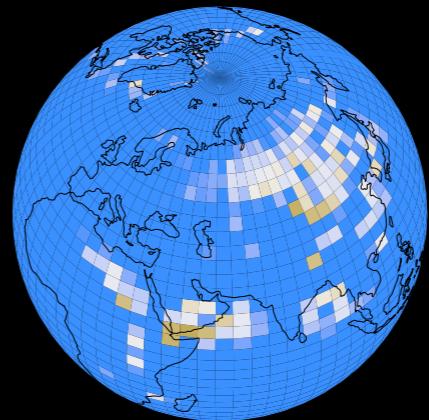
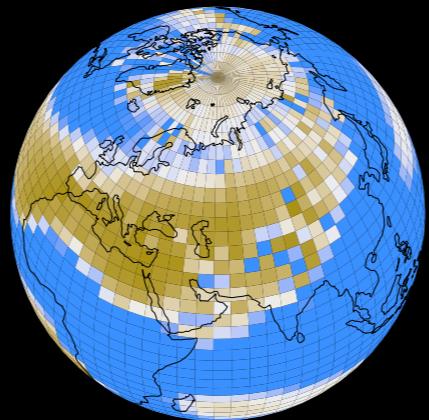


0°

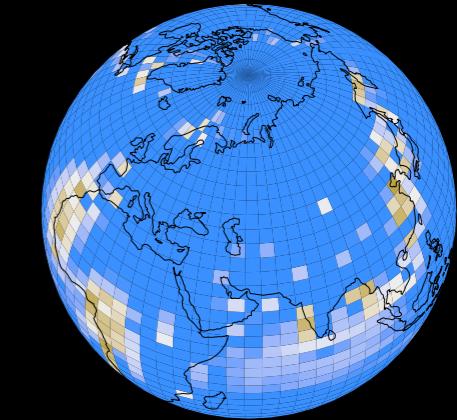
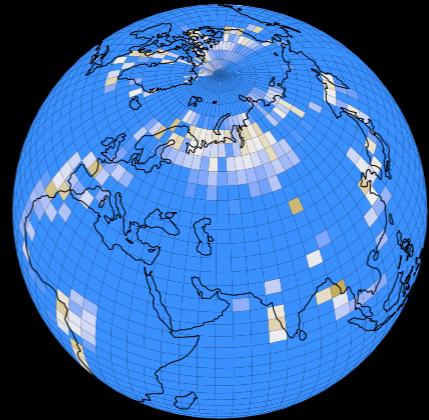
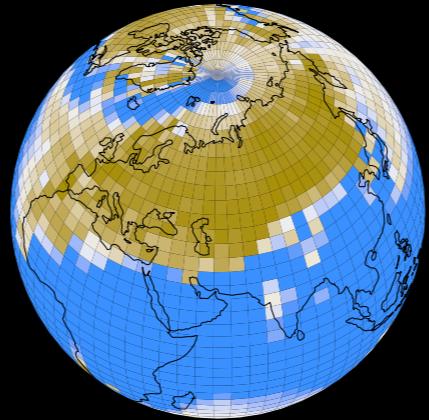
45°

90°

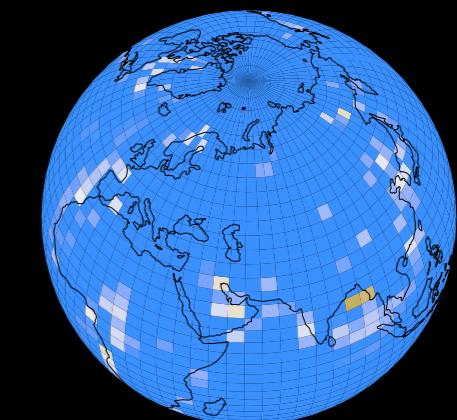
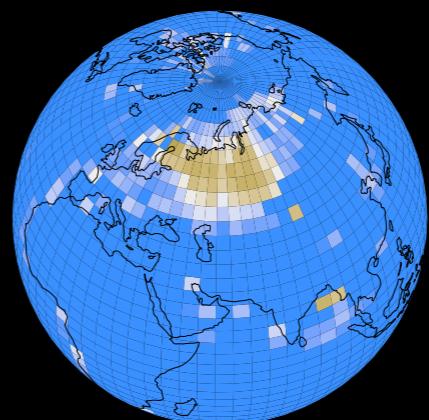
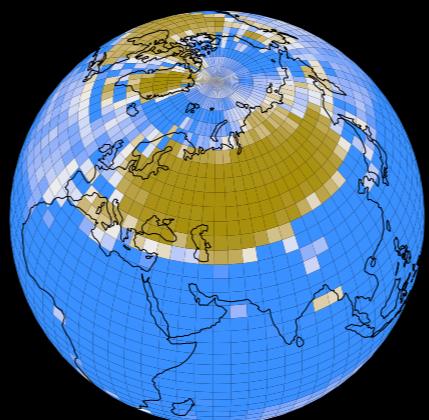
1 day



16 days



256 days



He et. al. (2022):
Obliquity Matters
at Fast Rotations



0°

45°

90°

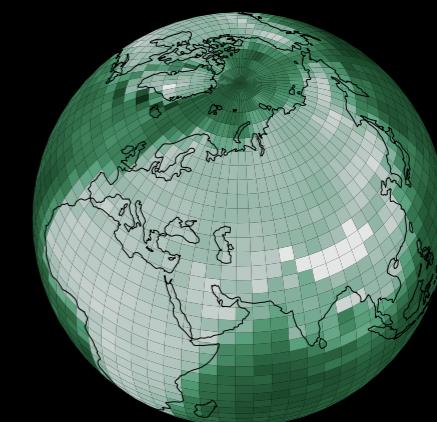
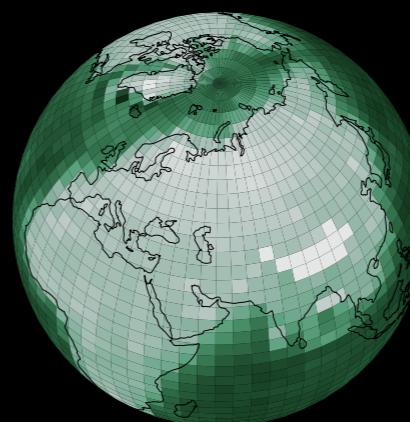
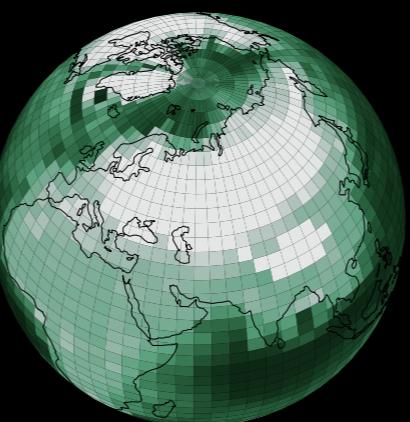
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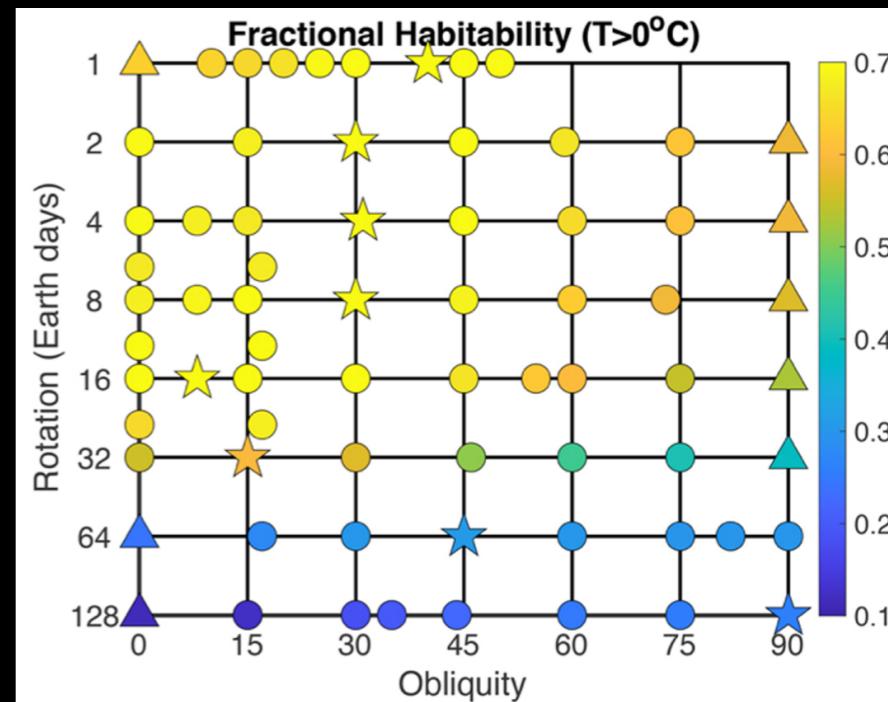
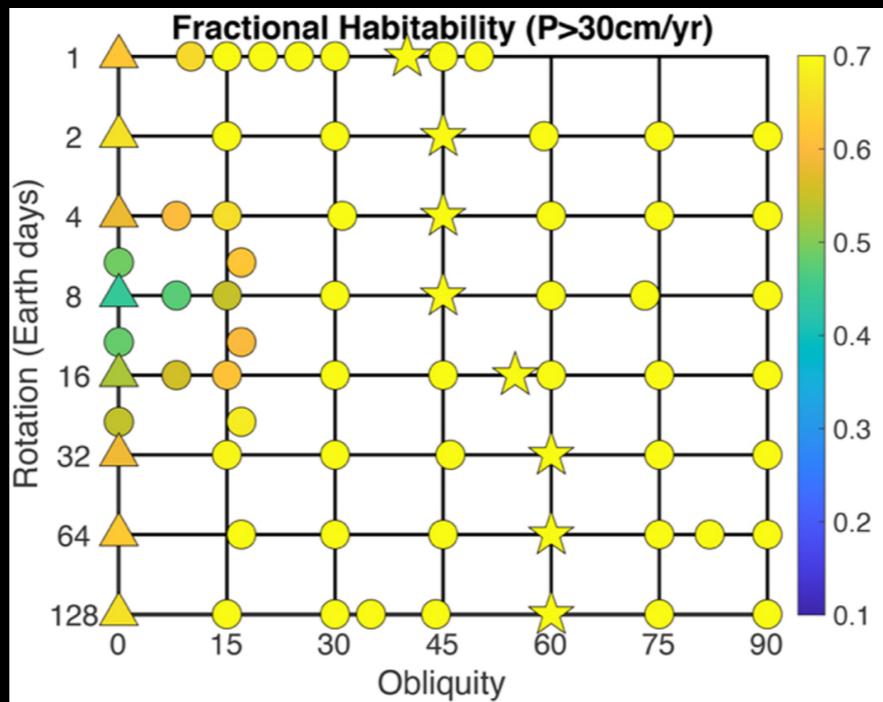
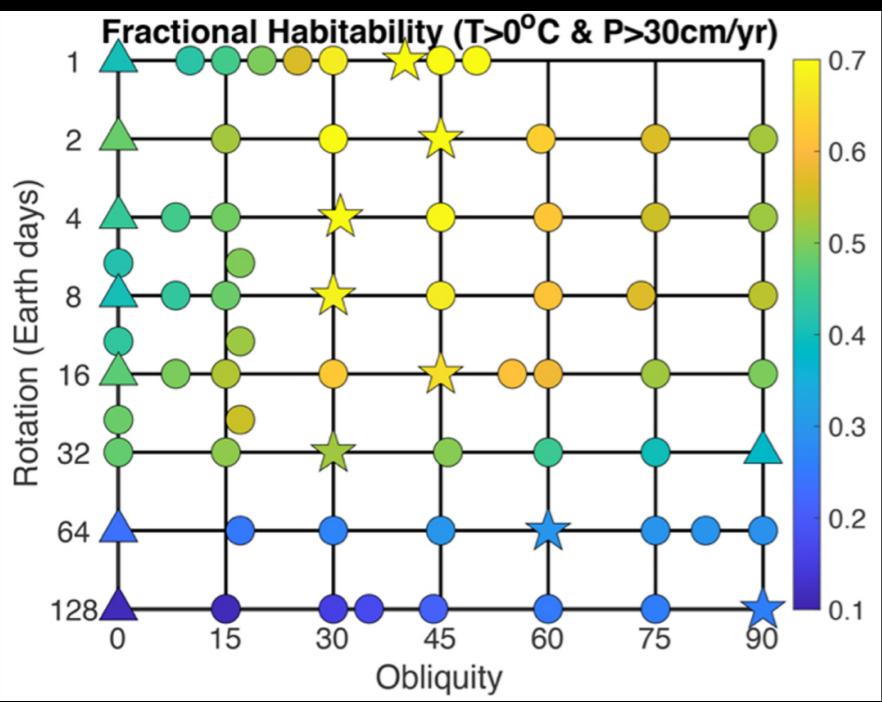


He et. al. (2022): Obliquity Matters at Fast Rotations

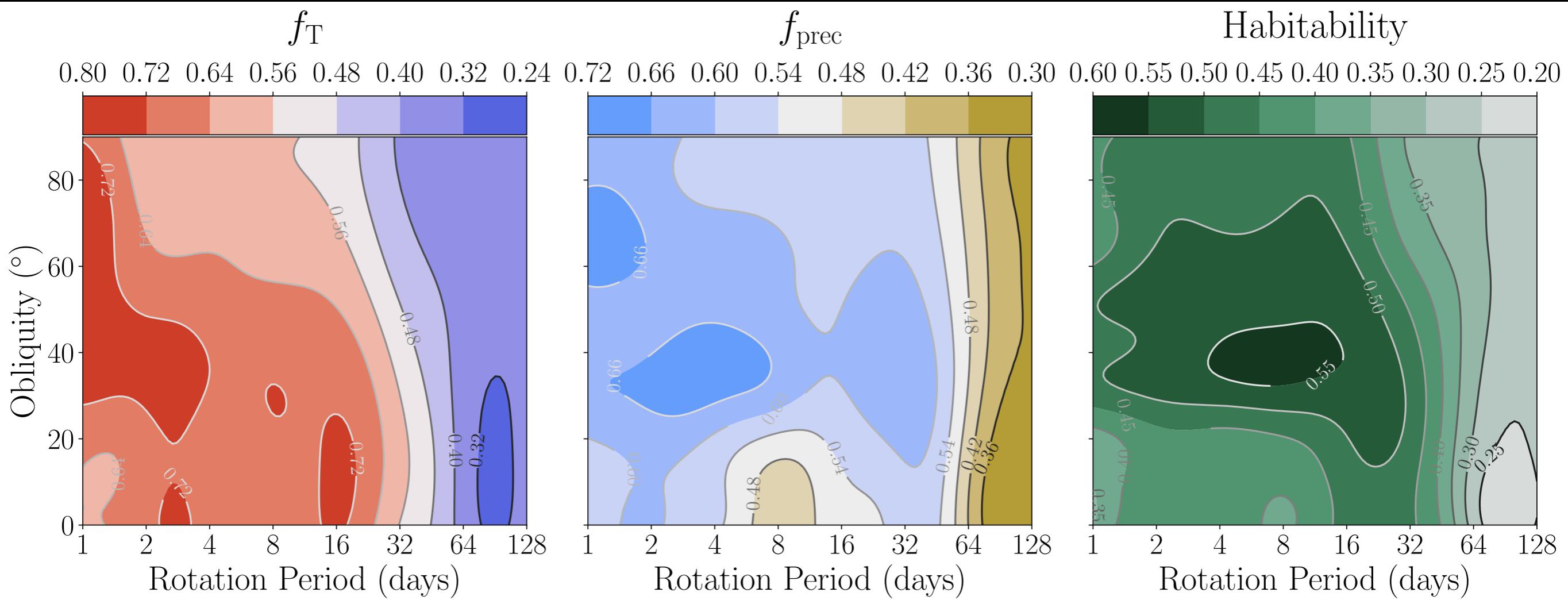
$$0 \leq T_{\text{surf}} \leq 100^\circ \text{ C}$$

Precipitation \geq 300 mm/year

Both



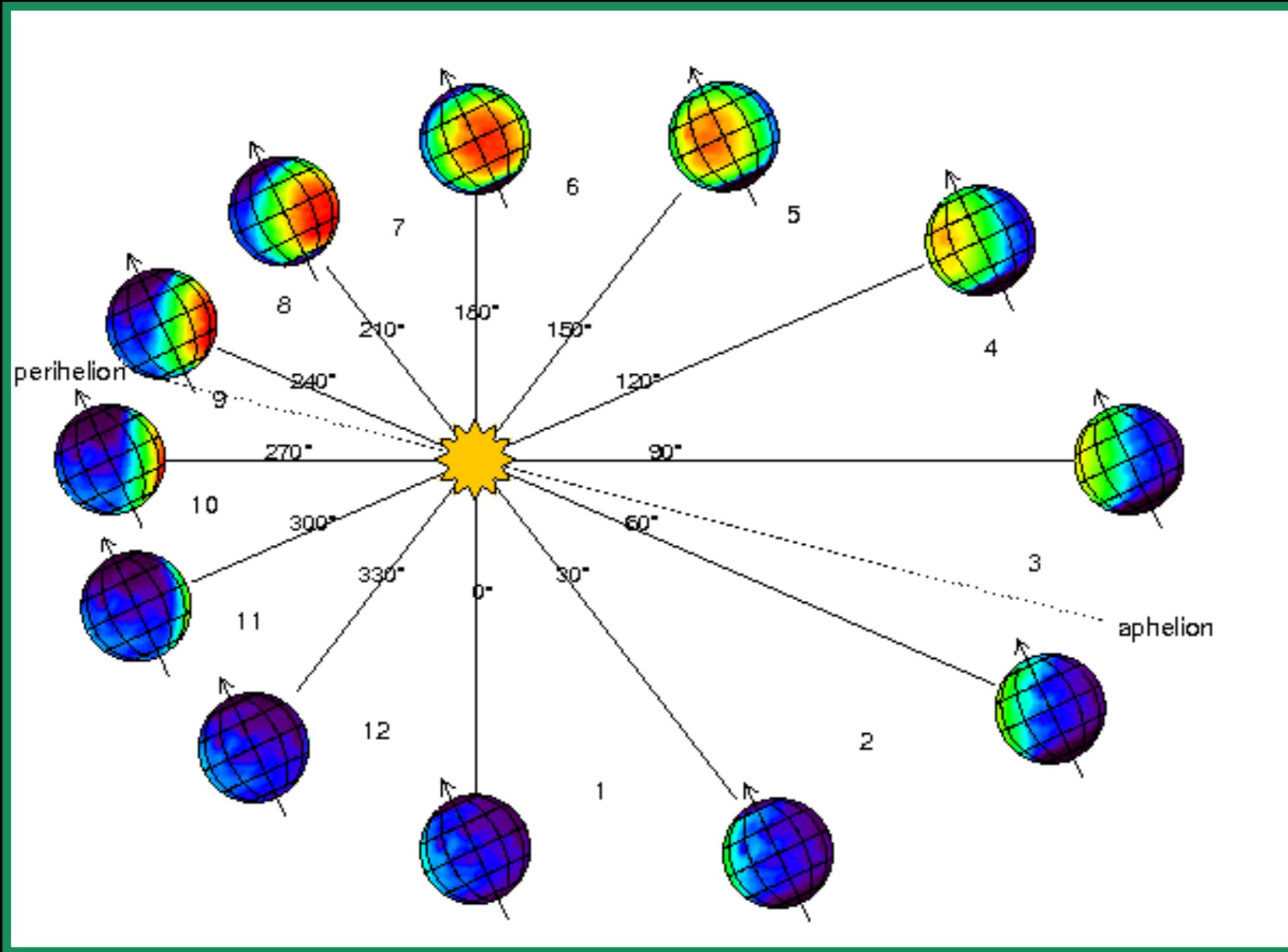
He et. al. (2022): Obliquity Matters at Fast Rotations





Adding Eccentricity

https://www-mars.lmd.jussieu.fr/mars/time/solar_longitude.html



Adding

Eccentricity

$\sin \Phi > 0$: northern summers

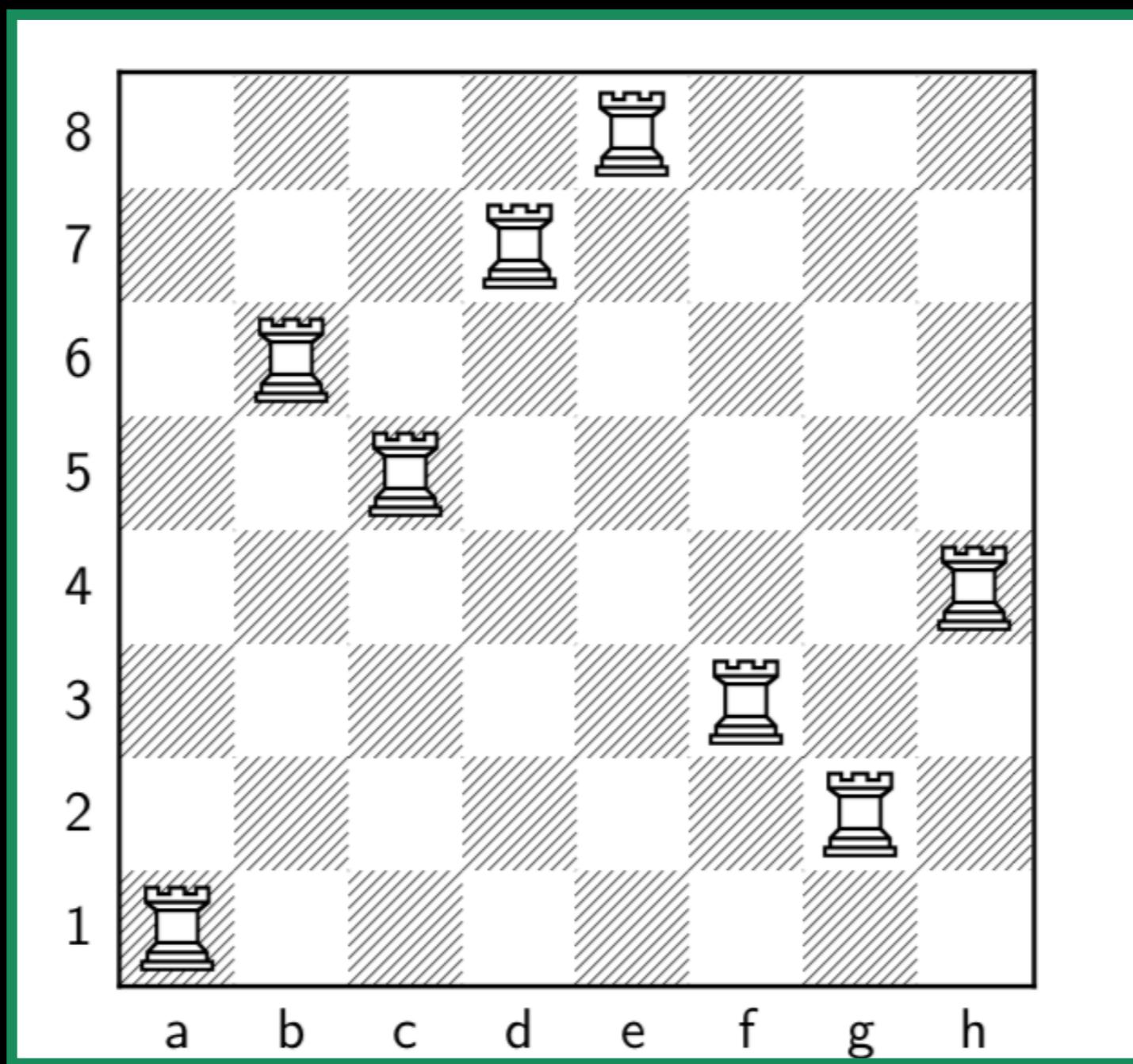
get more intense sunlight

$\sin \Phi < 0$: southern summers
get more intense sunlight

How do we probe a 4-D
parameter space when
computation is limited?

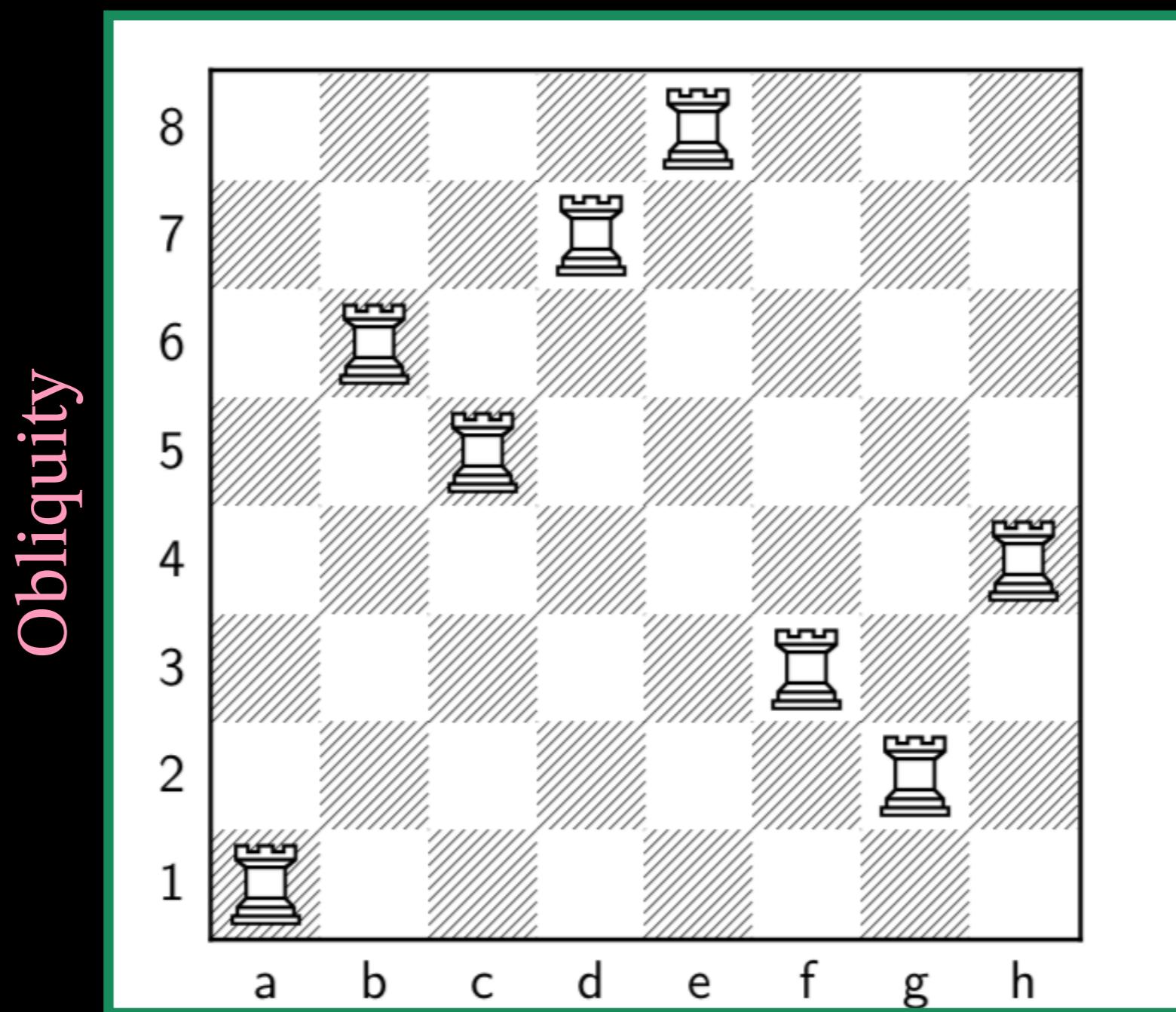


Latin Hypercubes!





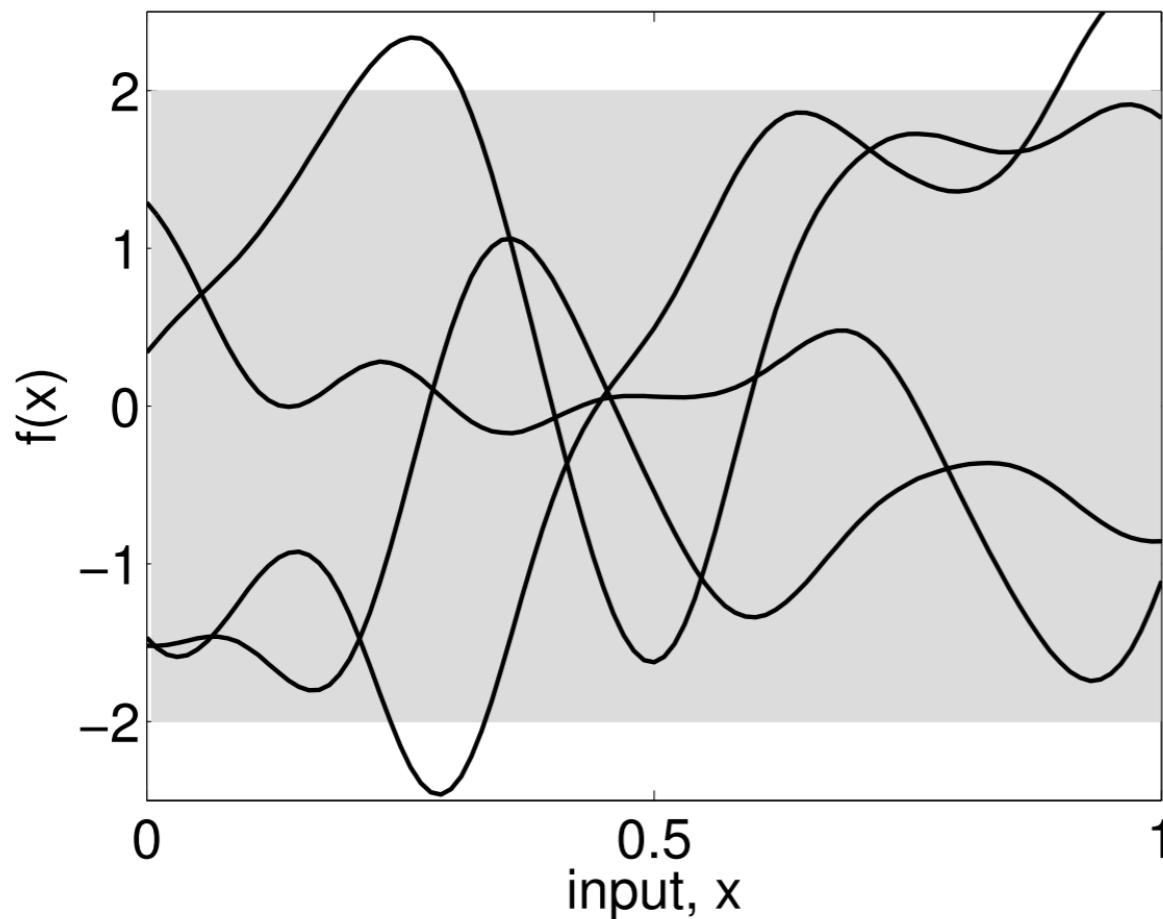
Latin Hypercubes!



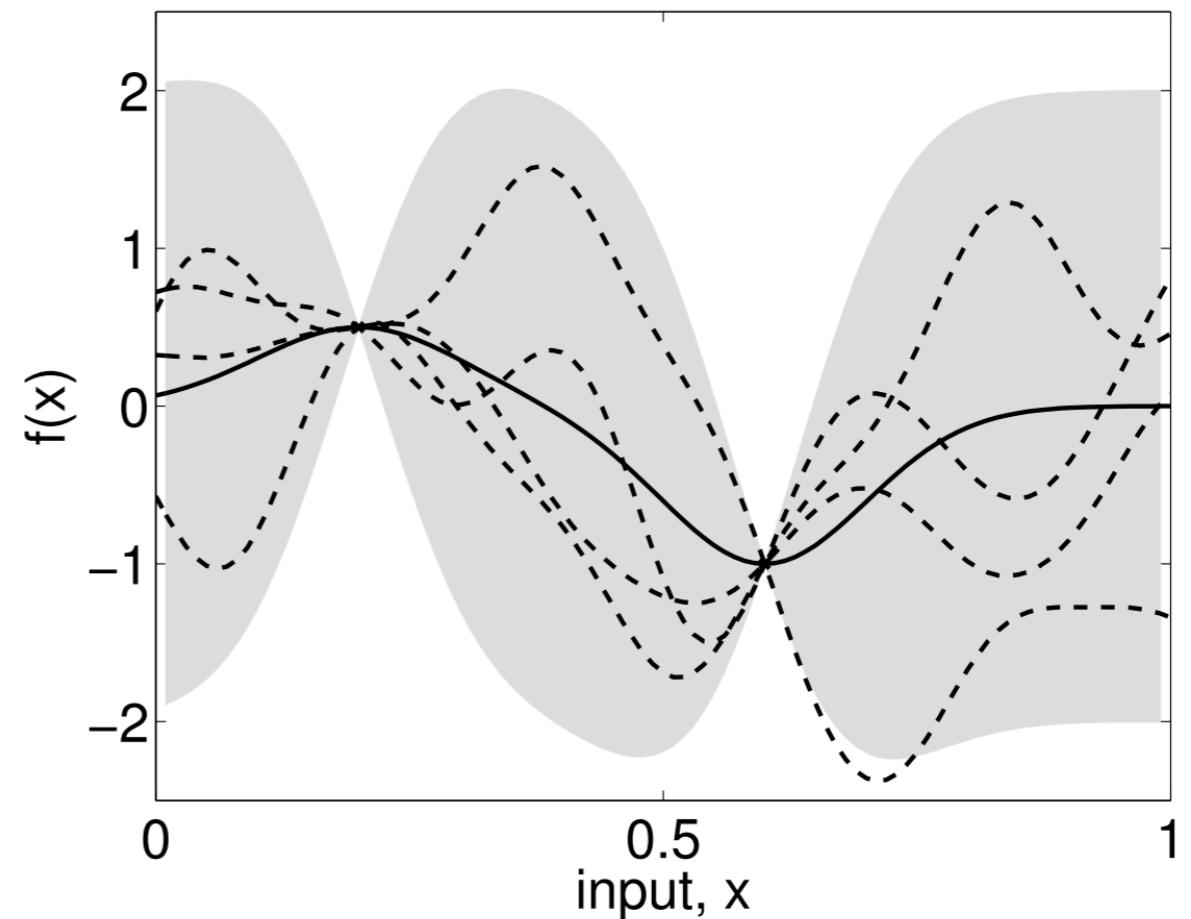
Rotation Period



Emulating Habitability



(a), prior

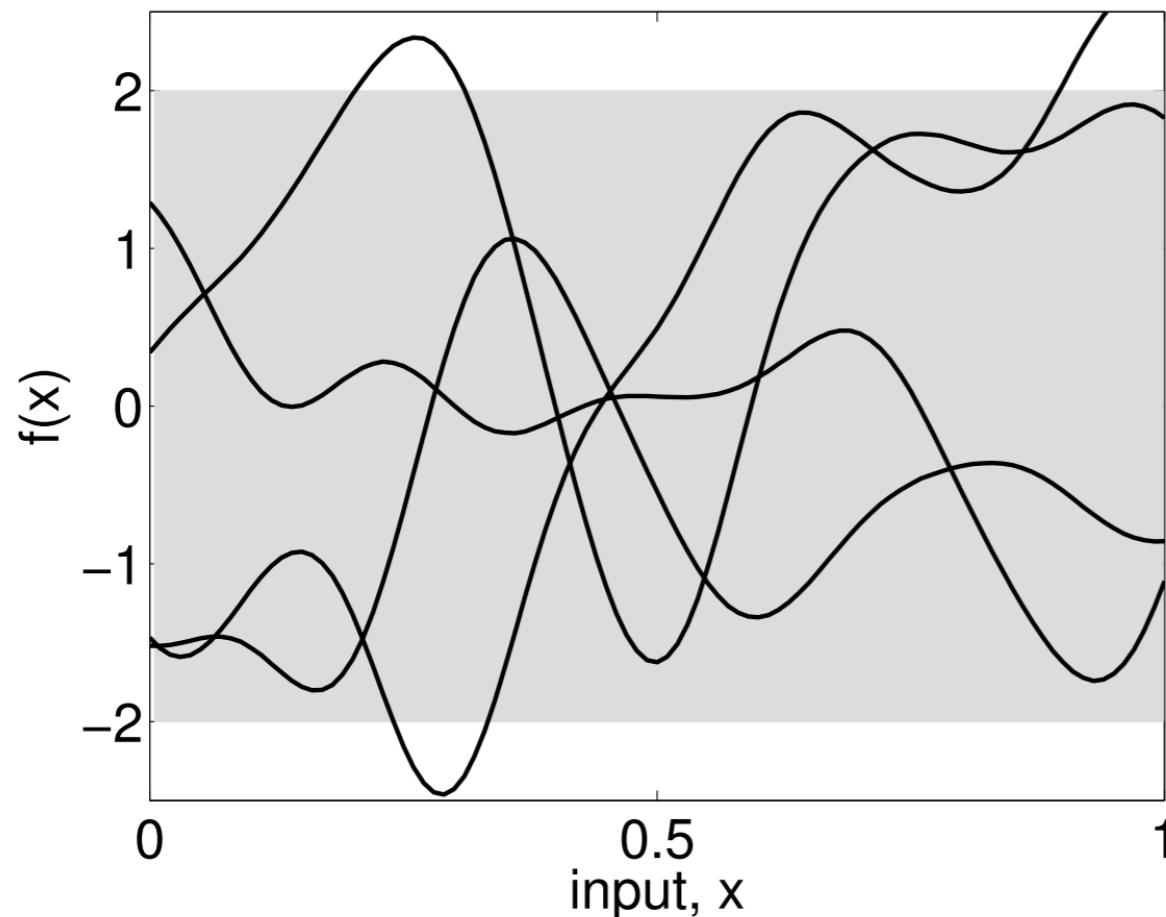


(b), posterior

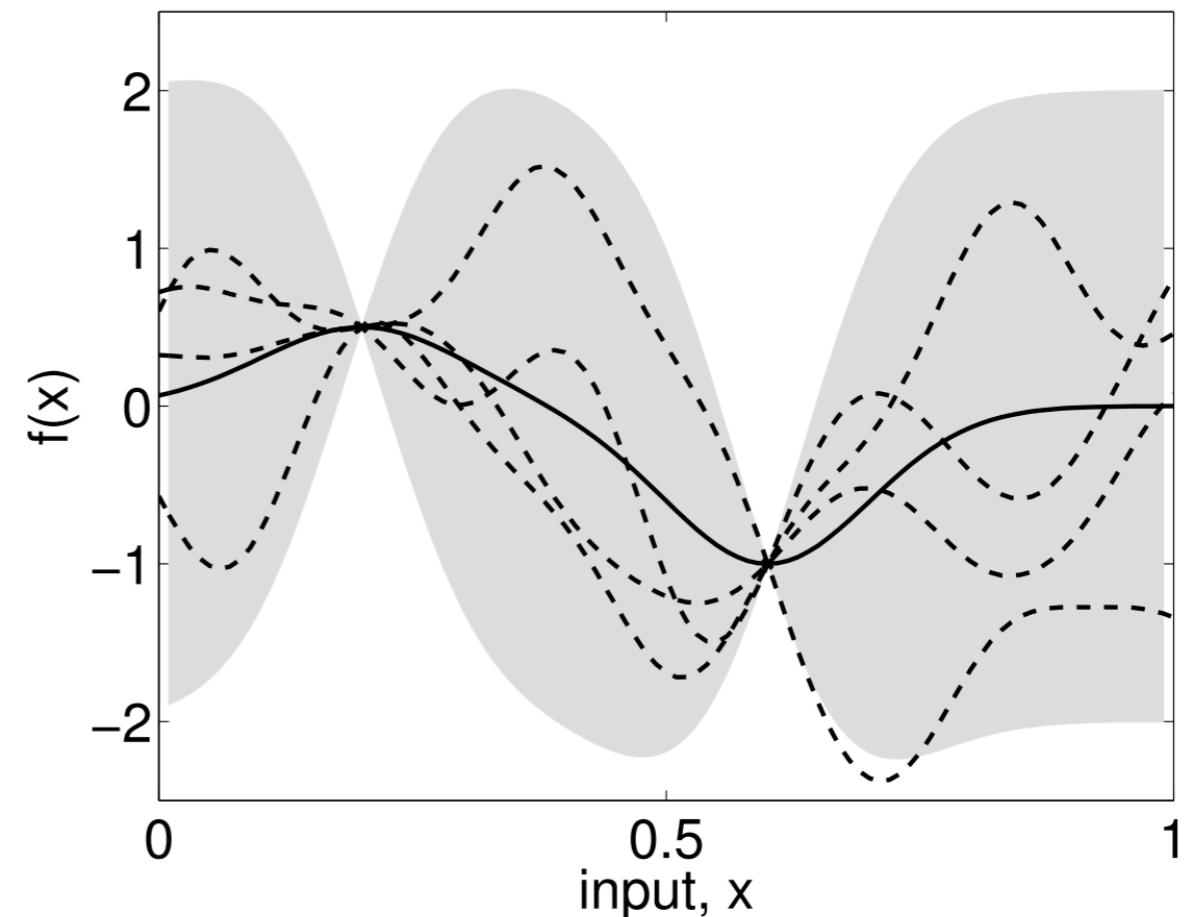


Emulating Habitability

Non-parametric?



(a), prior

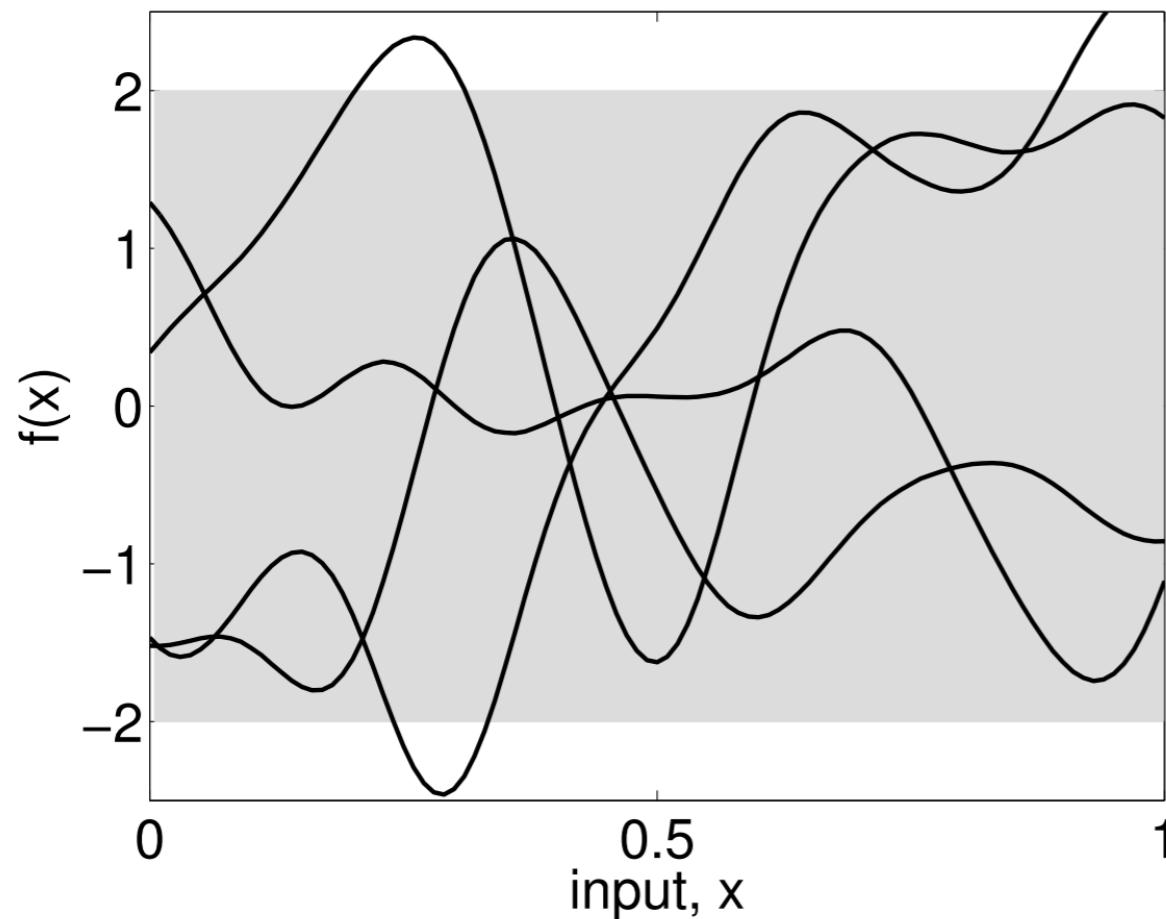


(b), posterior

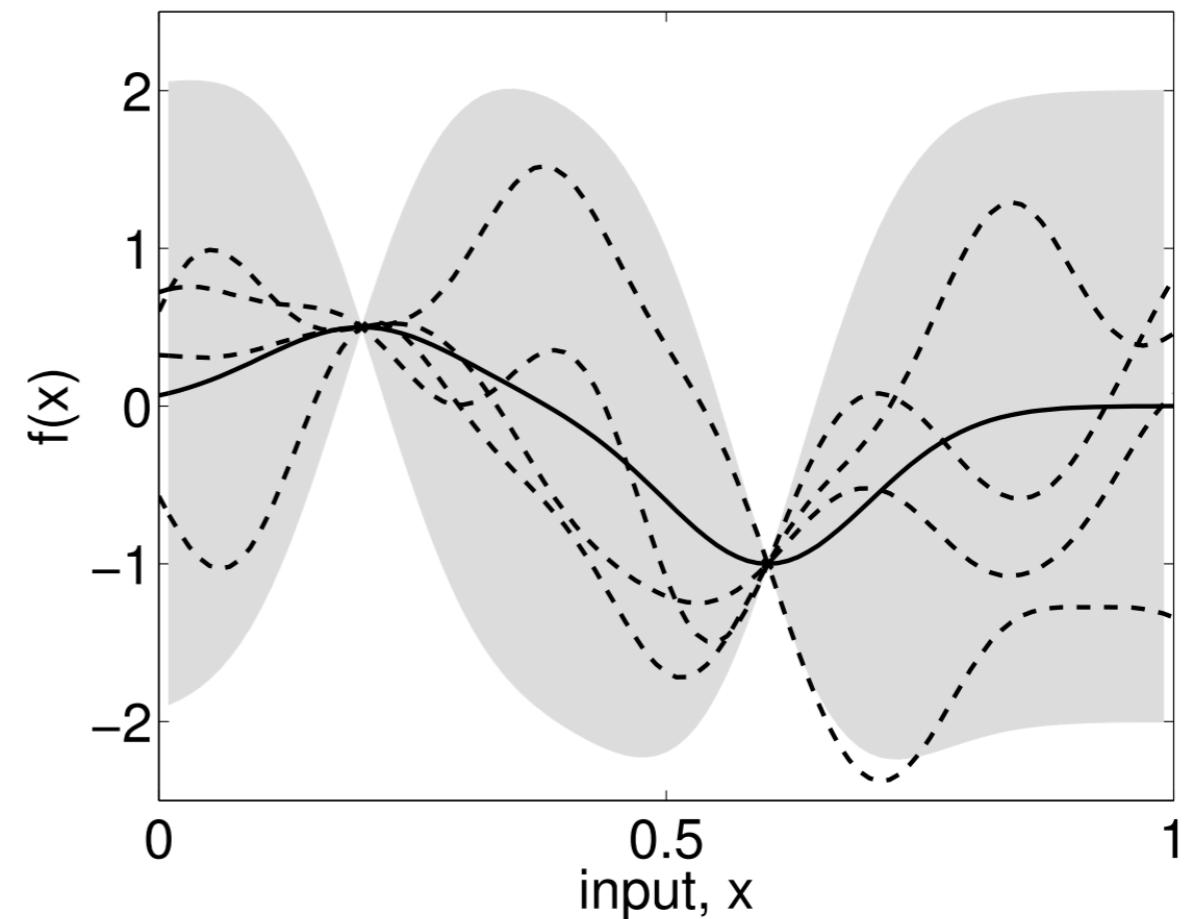


Emulating Habitability

Non-parametric? Bayesian?



(a), prior

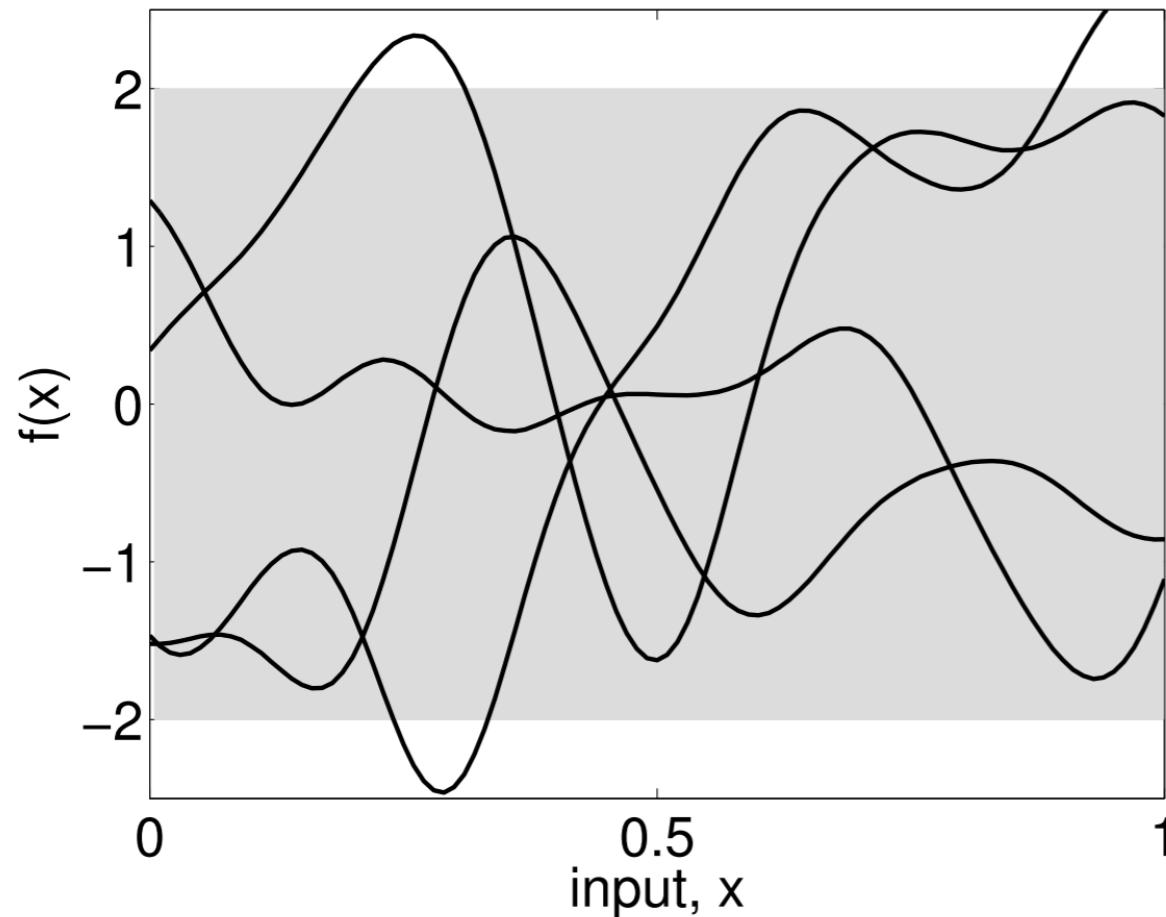


(b), posterior

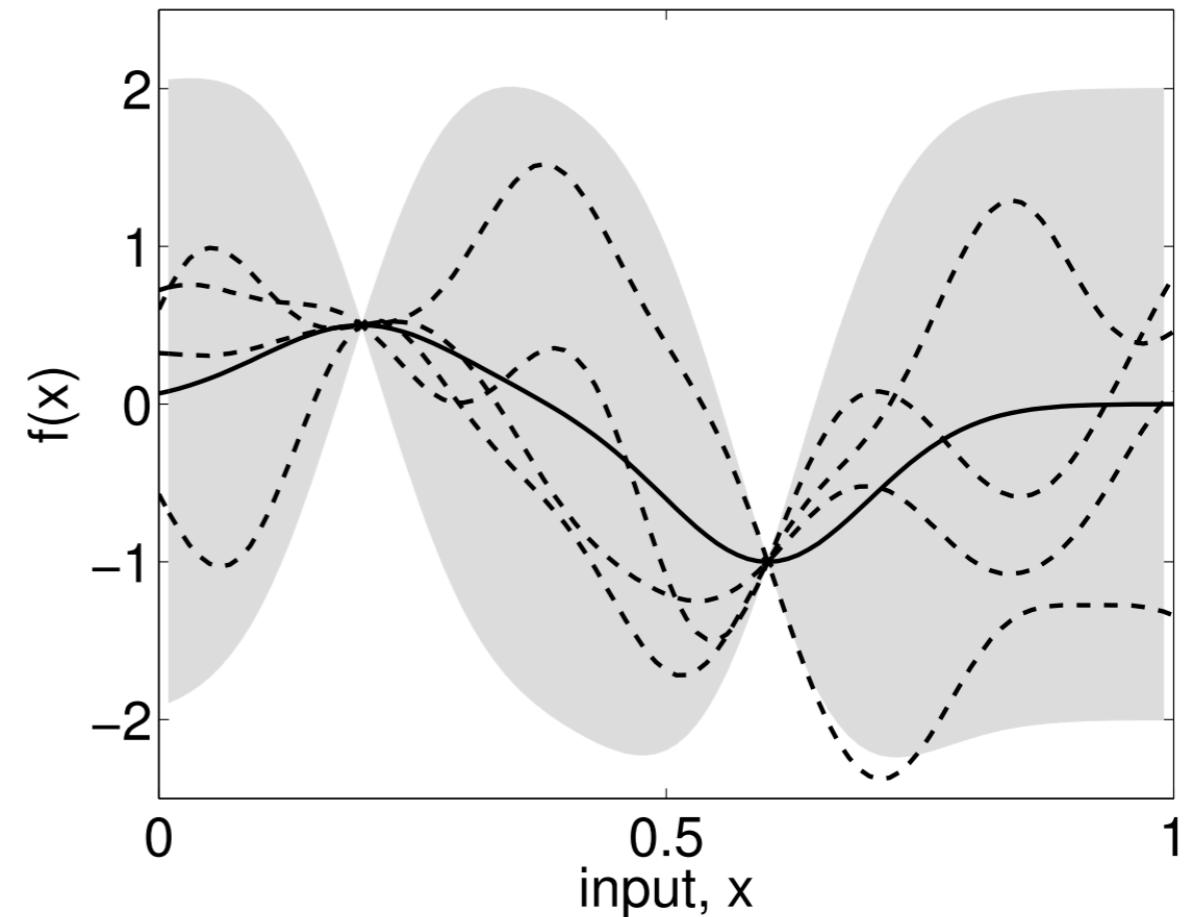


Emulating Habitability

Non-parametric? Bayesian? Gaussian processes!?



(a), prior



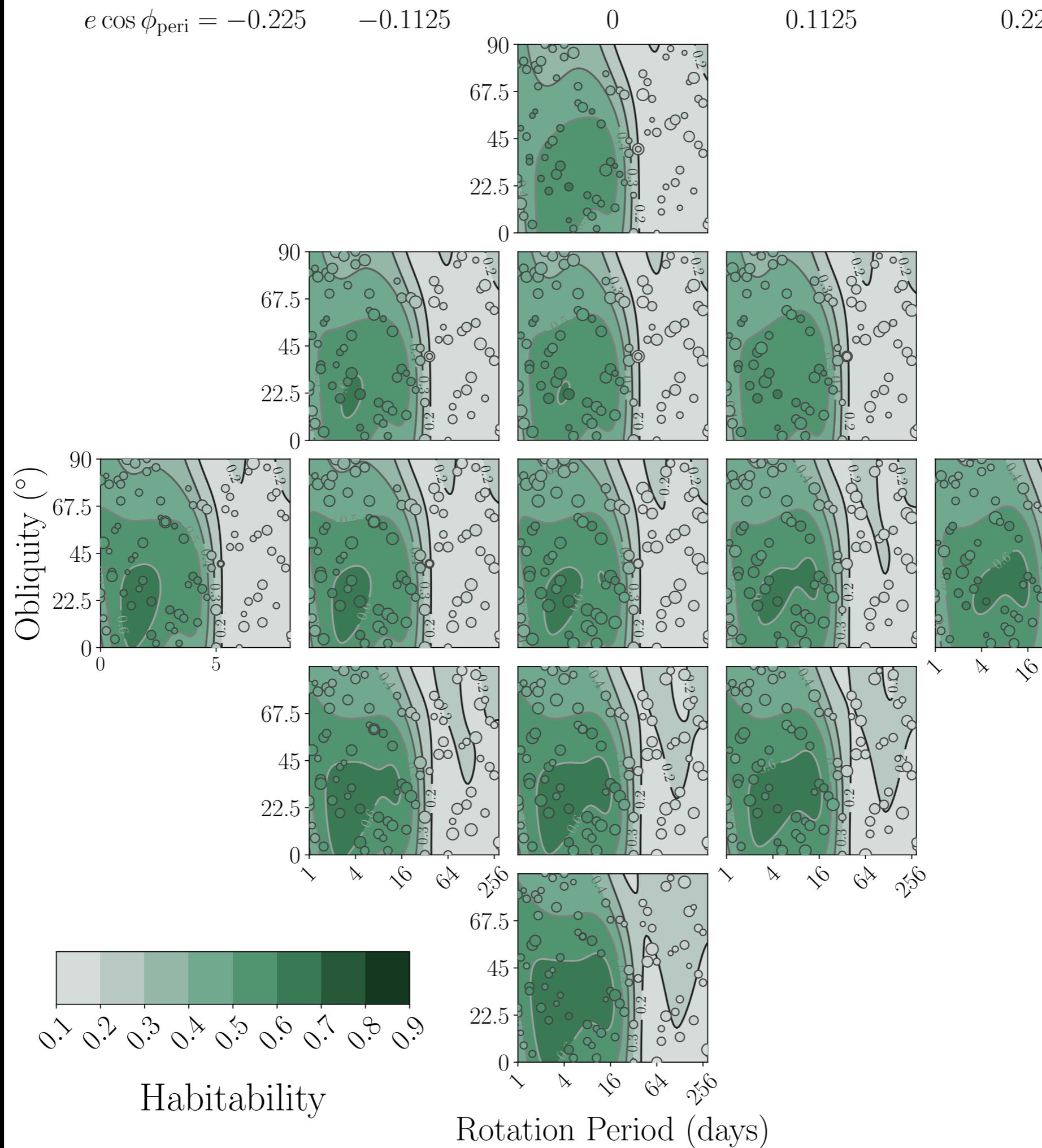
(b), posterior

↑
—

Sin $\dot{\Phi}$

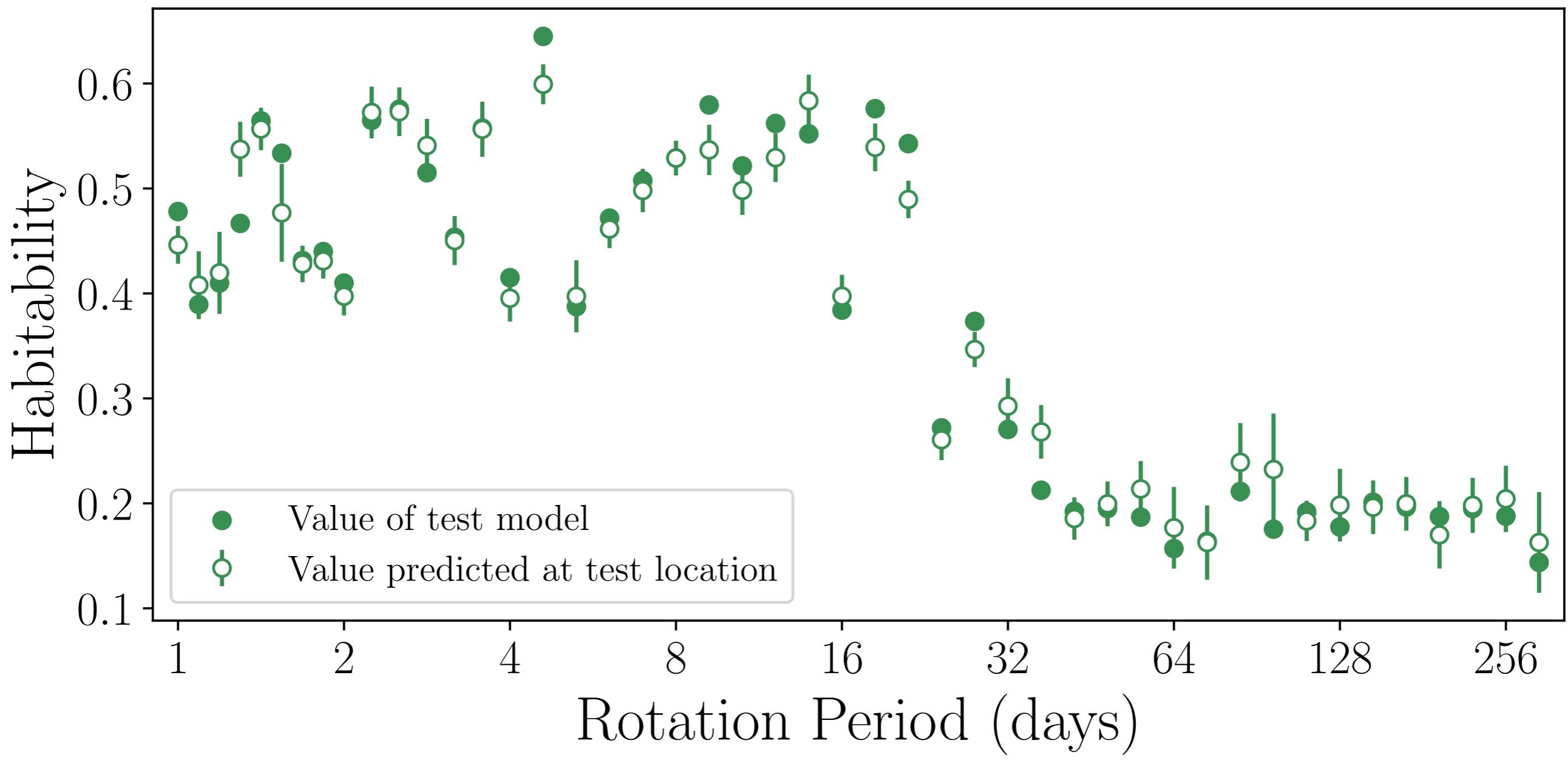
$e \sin \phi_{\text{peri}} = -0.225 \quad -0.1125 \quad 0 \quad 0.1125 \quad 0.225$

$0.225 \quad 0.1125 \quad 0 \quad -0.1125 \quad -0.225$





Emulator does a pretty good job

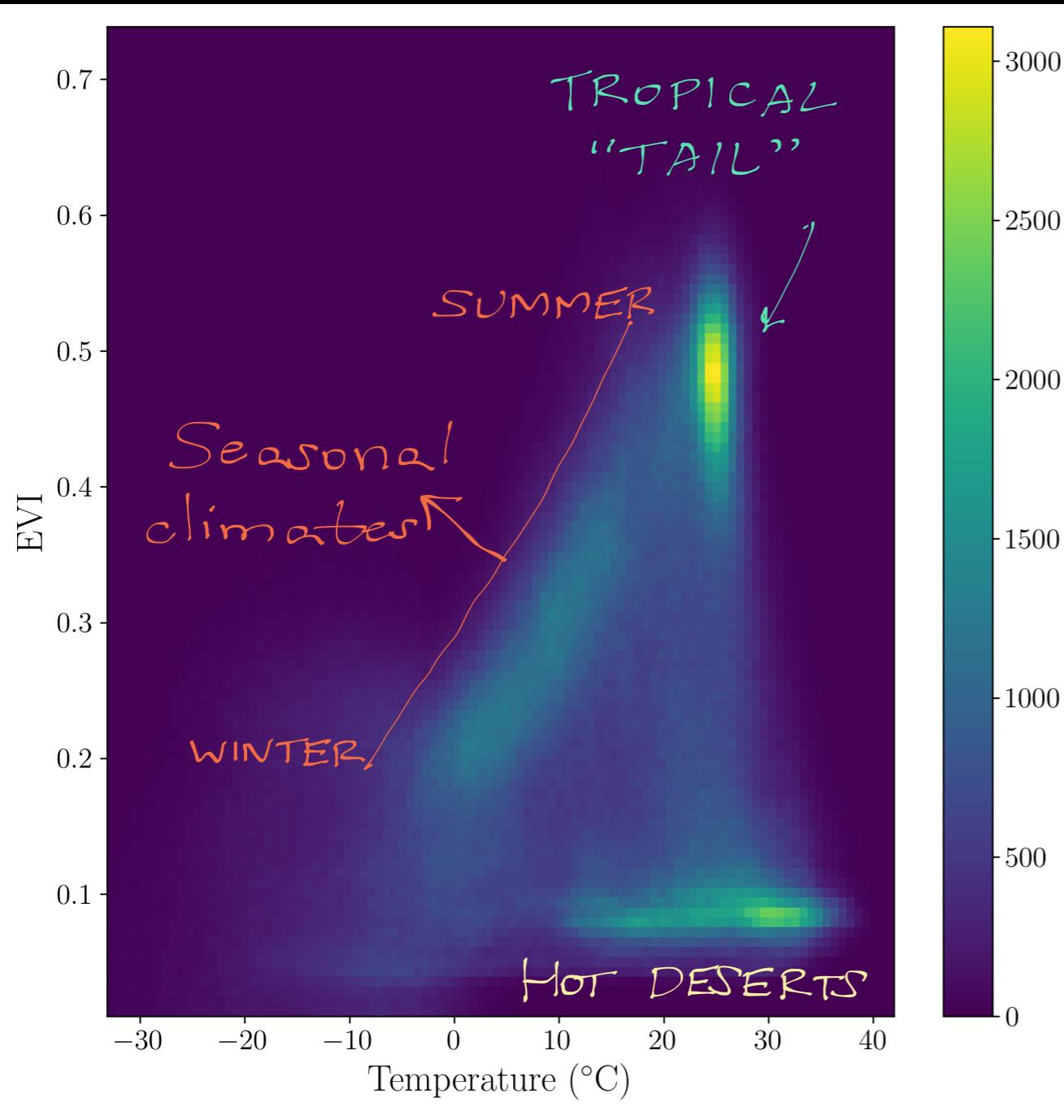


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- A Gaussian process regression does a reasonable job of predicting a global+orbit-averaged climate habitability metric

Future/Parallel Directions:

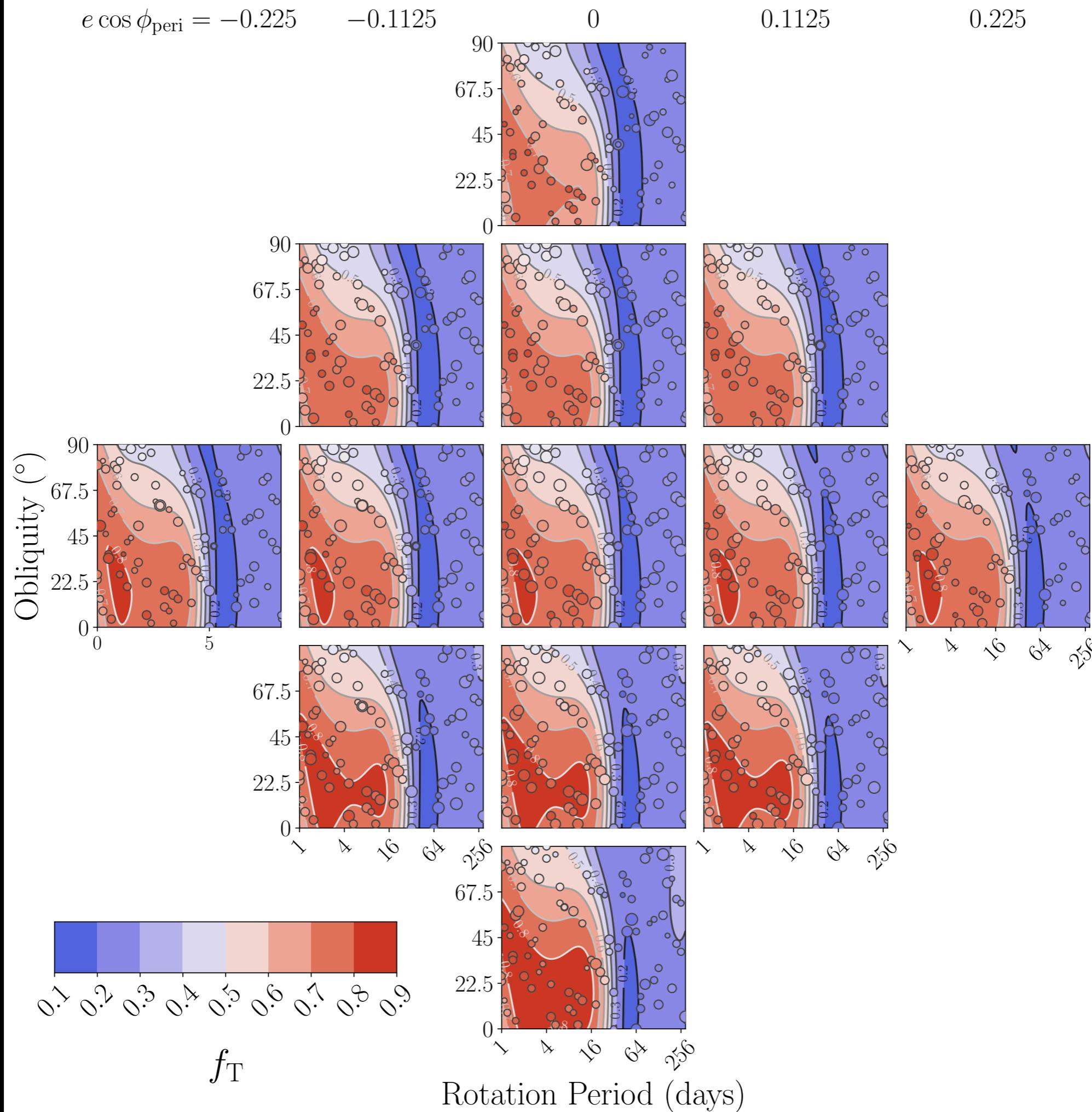
Vegetation index as a habitability metric?



Annie Shelton
(former undergrad at
UCR, now at Cornell)

$\sin \dot{\Phi}$

$e \sin \phi_{\text{peri}} = -0.225 \quad -0.1125 \quad 0 \quad 0.1125 \quad 0.225$



$\sin \dot{\Phi}$

$e \sin \phi_{\text{peri}} = -0.225 \quad -0.1125 \quad 0 \quad 0.1125 \quad 0.225$

$e \sin \phi_{\text{peri}} = -0.225 \quad -0.1125 \quad 0 \quad 0.1125 \quad 0.225$

