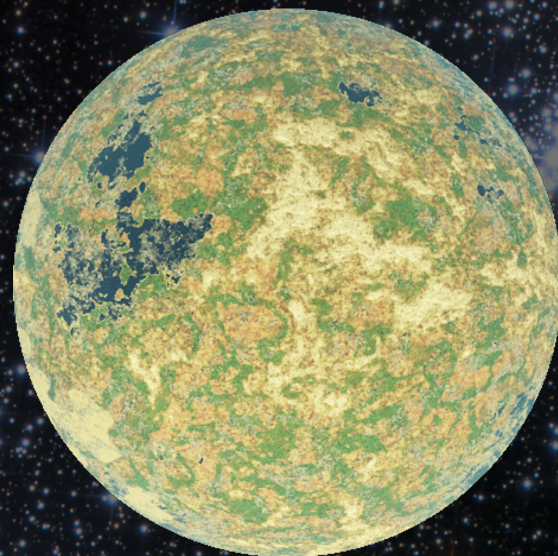
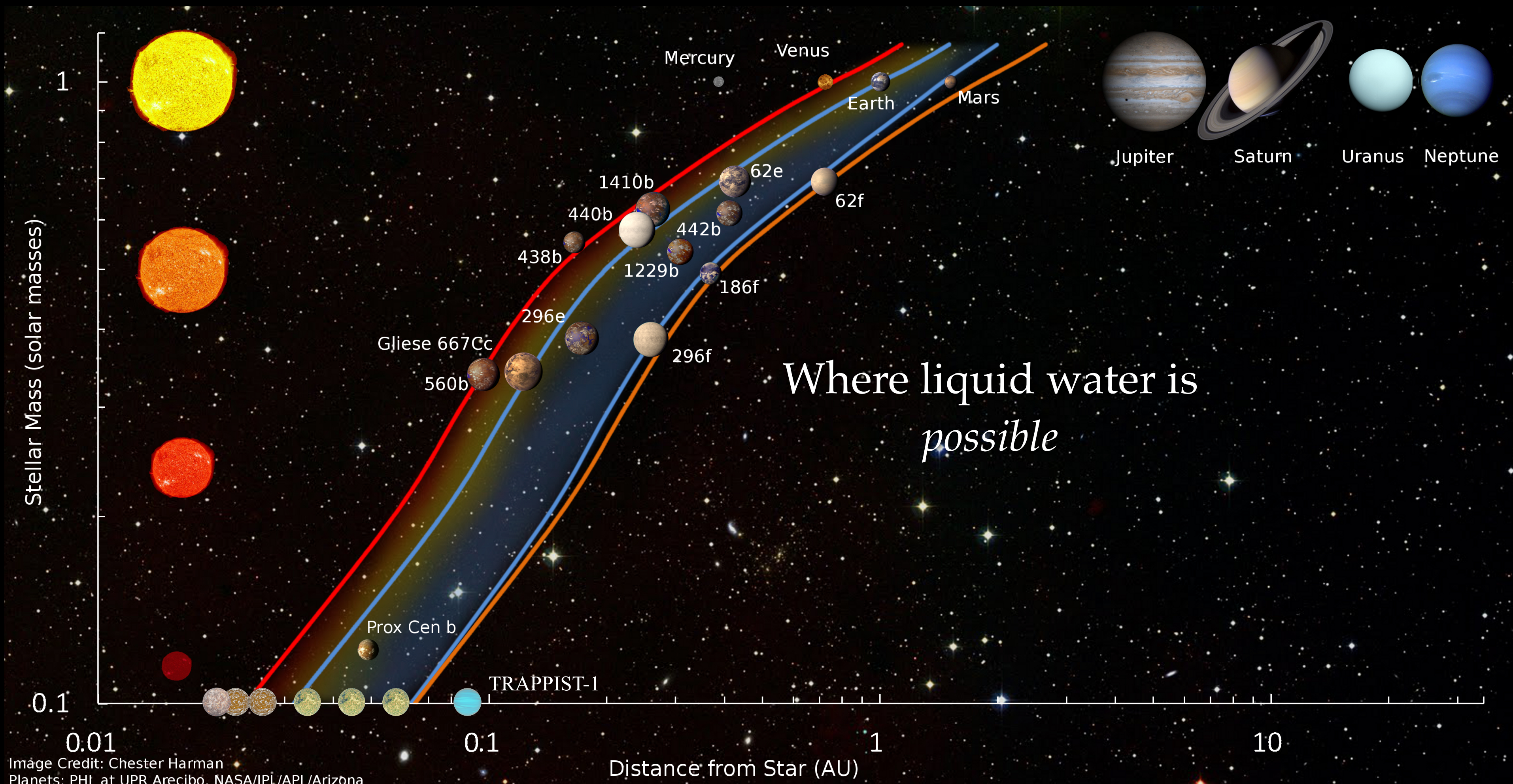
Planetary Evolution and Habitability



Rory Barnes
University of Washington

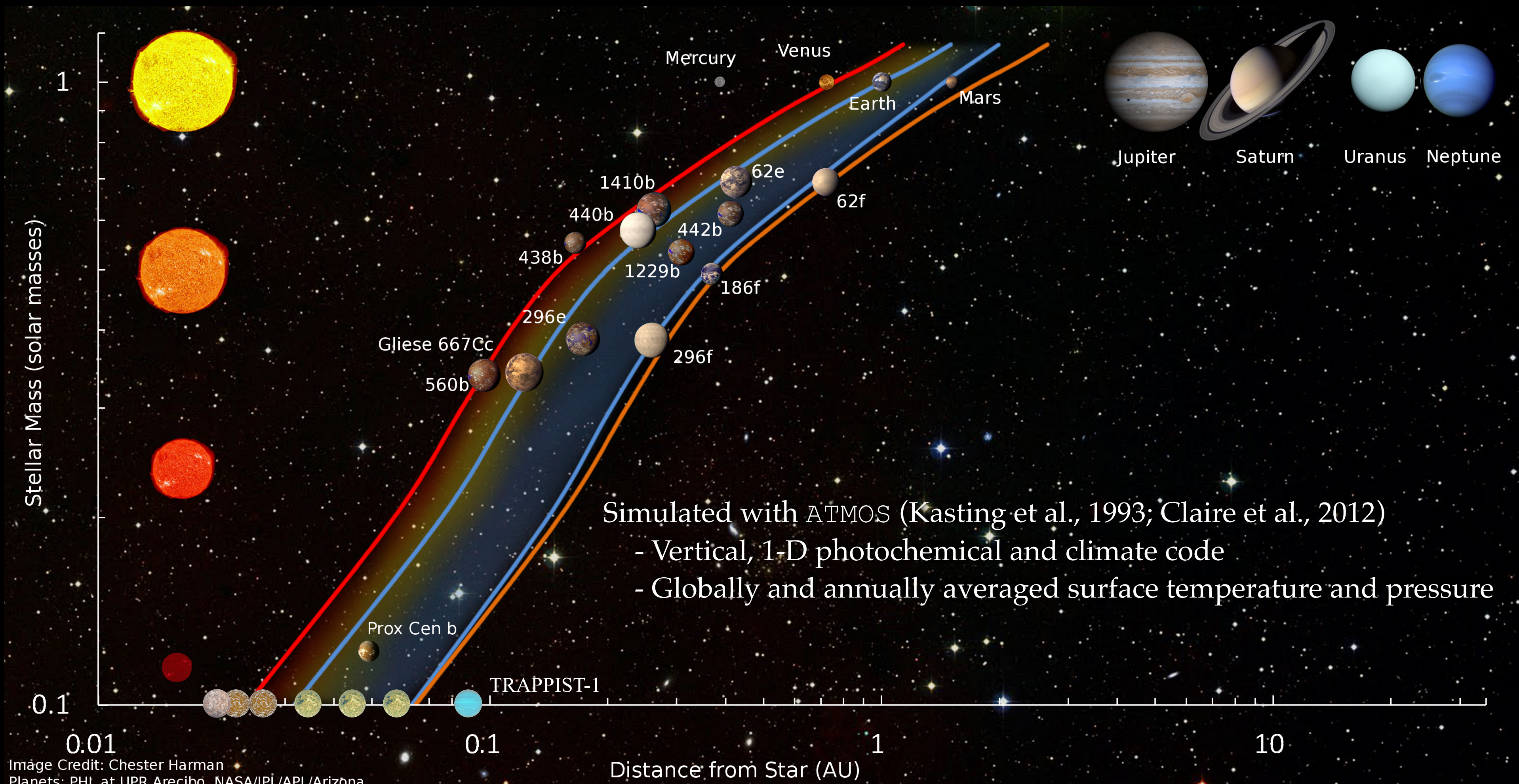
Laura Amaral (UNAM)
Jessica Birky (UW)
Russell Deitrick (UVic)
David Fleming (formerly UW)
Rudy Garcia (UW)
Megan Gialluca (UW)
David Graham (Heidelberg)
Lyan Guez (St. Andrews)
Rodrigo Luger (fomerly UW/CCA)
Caitlyn Wilhelm (formerly UW)

The Circumstellar Habitable Zone



Shields et al. (2016)

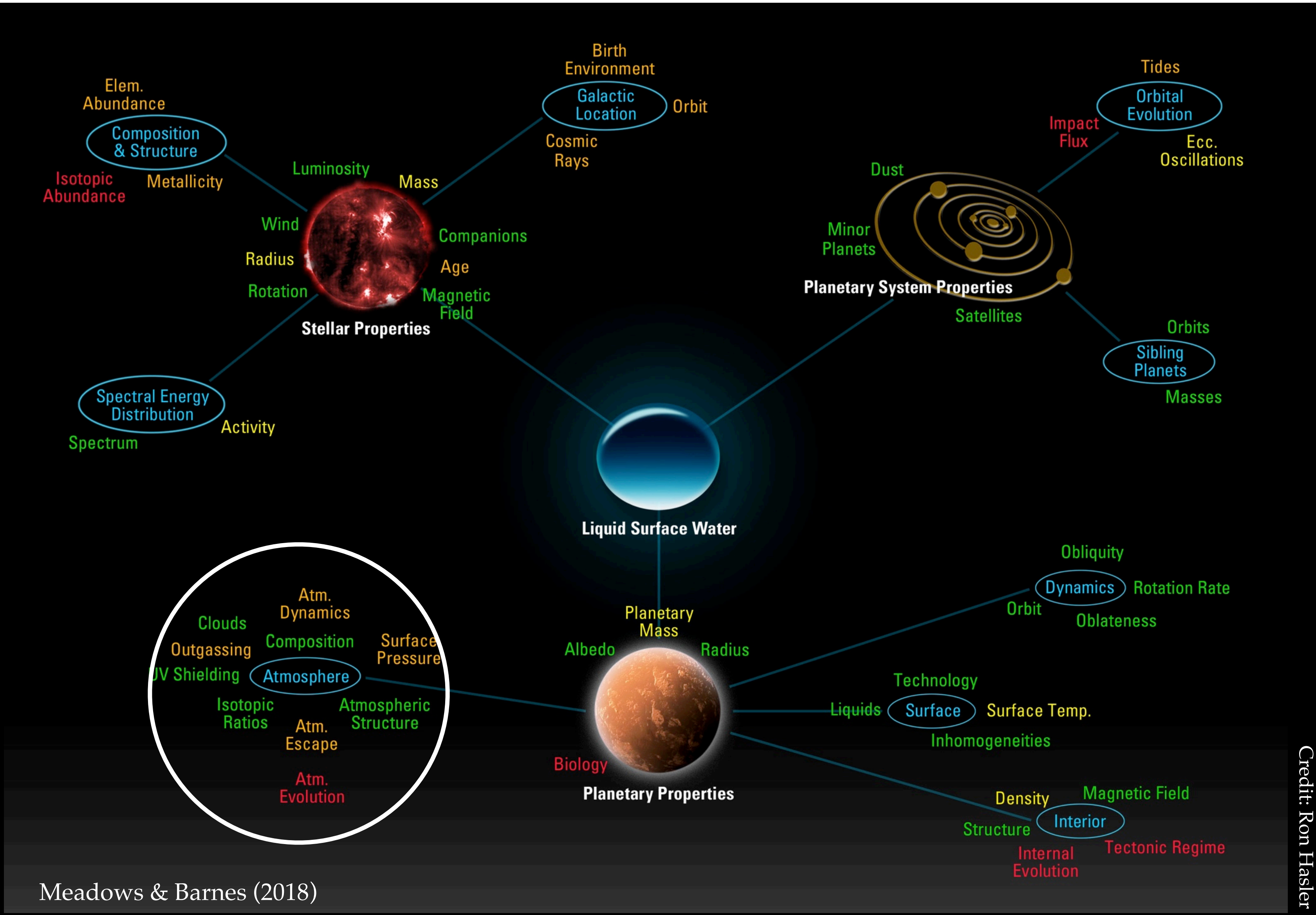
The Circumstellar Habitable Zone



Shields et al. (2016)

Planets Face Many Perils

- Flares
- Tidal Locking
- Orbital Oscillations
- Star’s Early Brightness
- Passing Stars
- Massive Volcanic Eruptions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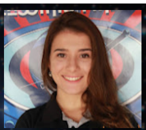
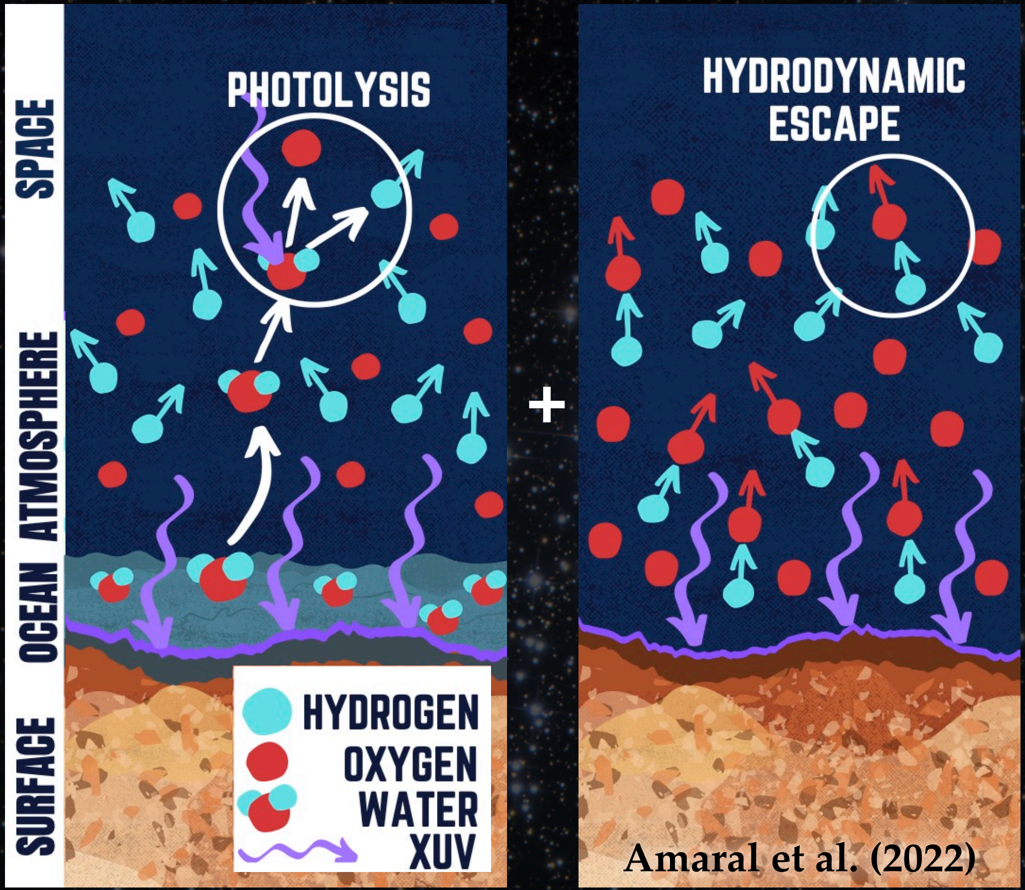
Meadows & Barnes (2018)
Credit: Ron Hasler

The Atmosphere: Water Photolysis and Hydrogen Escape

How much water can high energy radiation from flares remove from planets?



Laura Amaral



Stars emit X-ray+UV light that can remove water

They photolyze (dissociate) water molecules

Hydrogen escapes, permanently removing water

(In future slides:
TO = "Terrestrial Oceans" = Earth's water mass)

The Atmosphere: Water Photolysis and Hydrogen Escape

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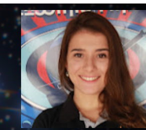
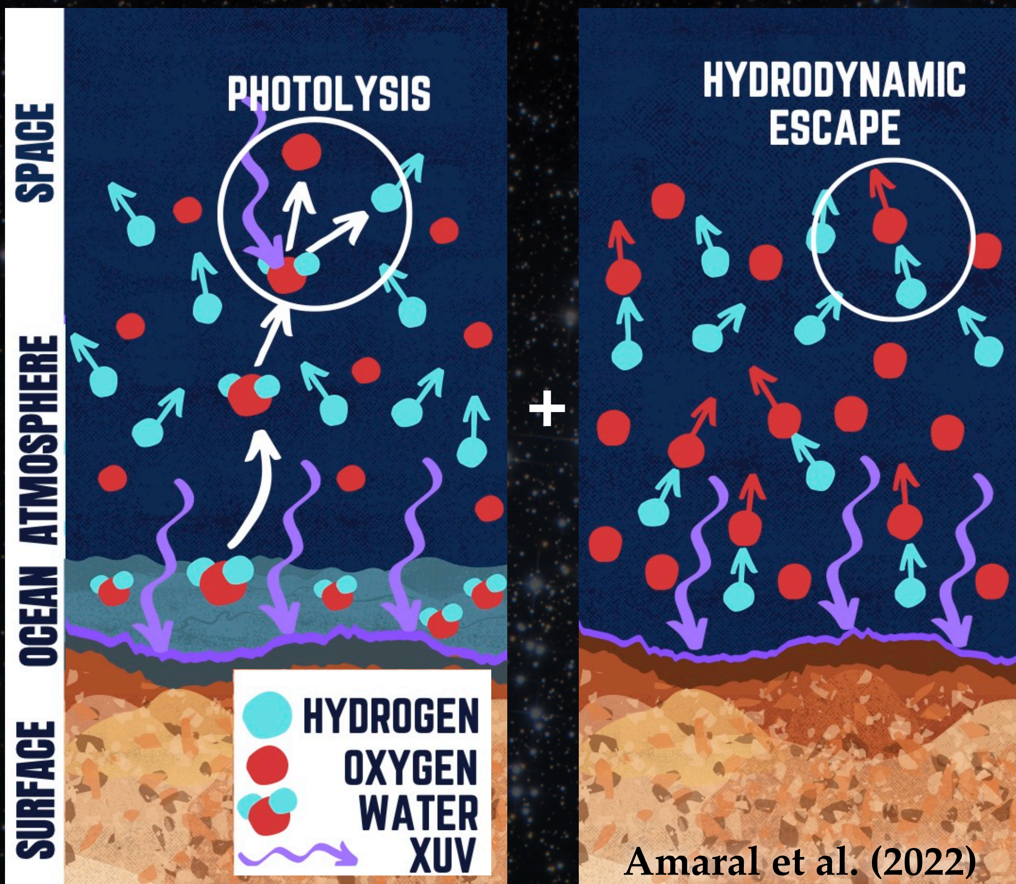
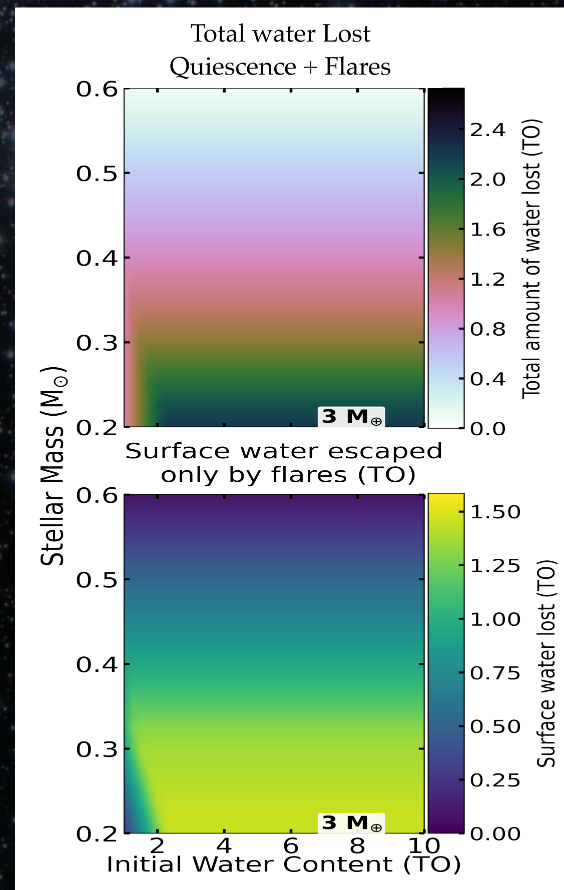
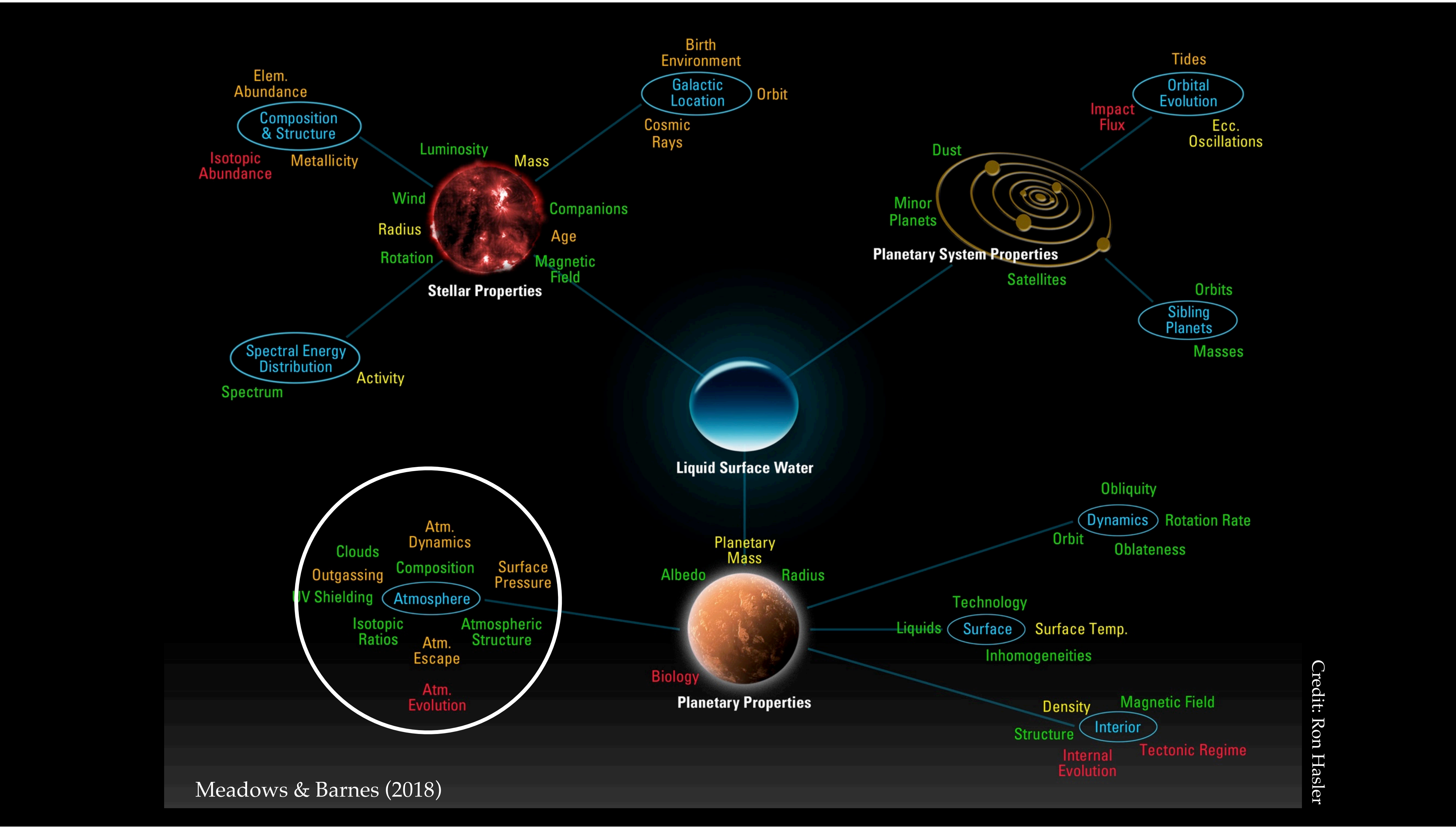


Laura Amaral





In the worst case scenario, flares are responsible for 2 TO (44%) of a planet’s water loss



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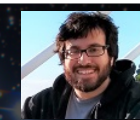
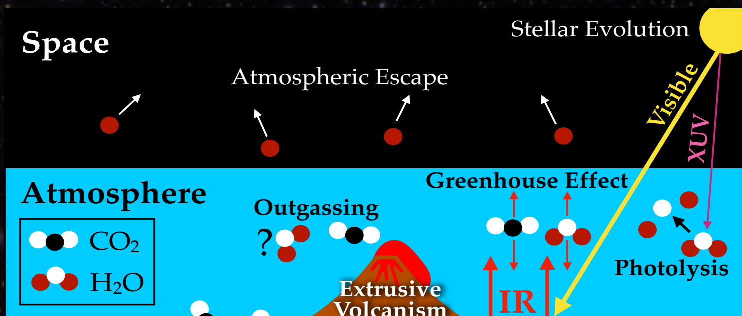
Meadows & Barnes (2018)
Credit: Ron Hasler

The Interior: The Thermal/Magnetic/Volatile Evolution of Venus



Rudy Garcia

How did Venus arrive at its current state if it has always had a stagnant lid?



- Solar X-Ray, UV, visible radiation evolves; XUV destroys water
- Liberated hydrogen can escape to space
- Surface warmed by sunlight and greenhouse radiation
- Grey radiative transfer model for H_2O and CO_2
- Volcanoes outgas H_2O and CO_2; H_2O is pressure-dependent

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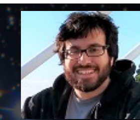
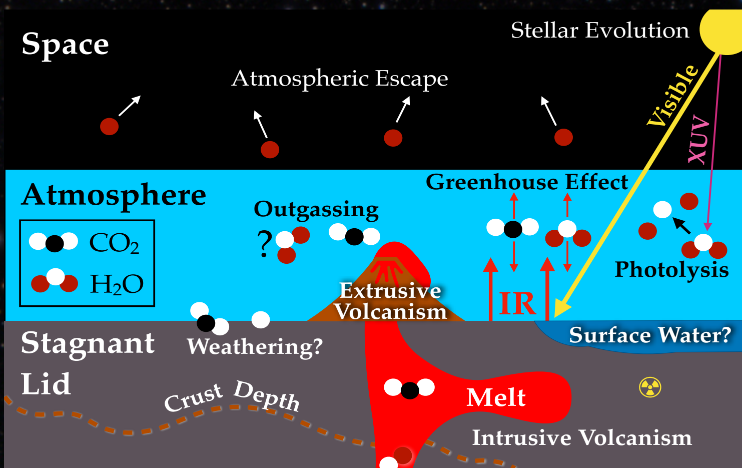


Rudy Garcia



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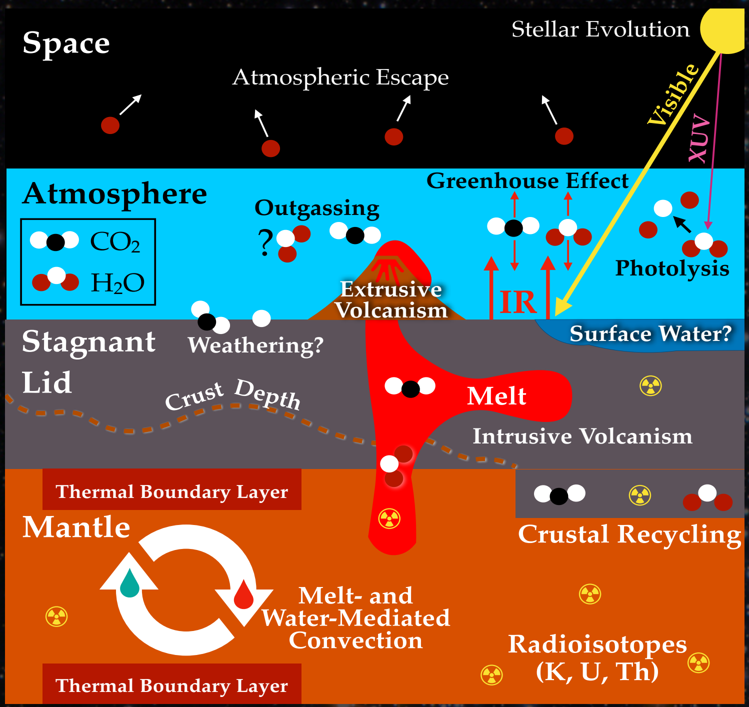

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- New surface pushes lower crust into mantle, including volatiles
- Mantle convects between “boundary layers”
- Melting / freezing affects mantle temp / composition

The Interior: The Thermal/Magnetic/Volatile Evolution of Venus

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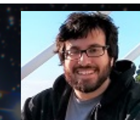
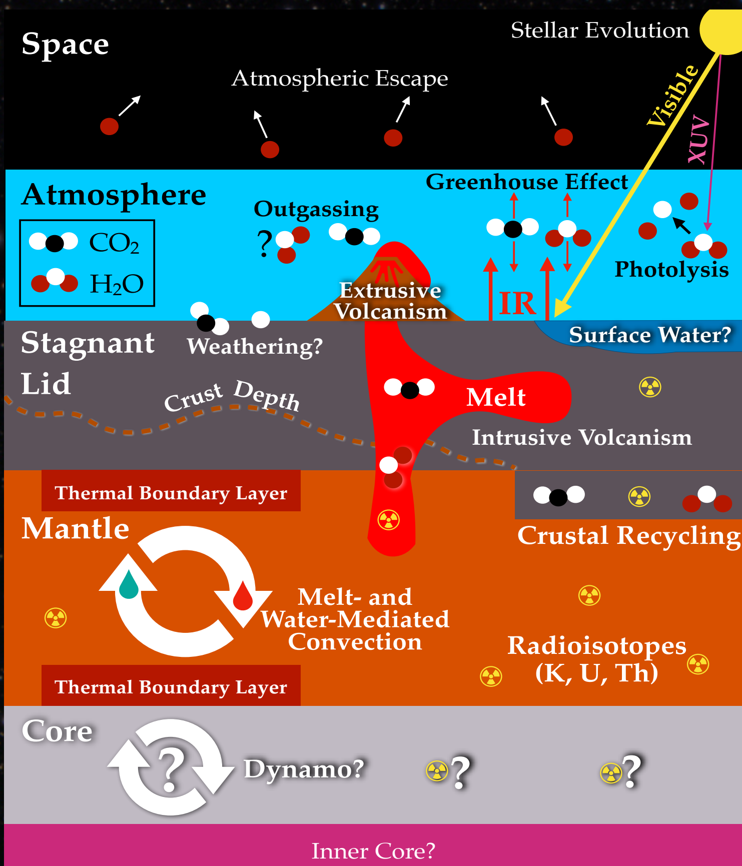


Rudy Garcia



Solar X-Ray, UV, visible radiation evolves; XUV destroys water

Liberated hydrogen can escape to space

Surface warmed by sunlight and greenhouse radiation

Grey radiative transfer model for H_2O and CO_2

Volcanoes outgas H_2O and CO_2; H_2O is pressure-dependent

Surface water allowed if surface temperate is in the right range

O always reacts with surface; CO_2 if surface water present

Crustal thickness evolves with temperature and volatiles

New surface pushes lower crust into mantle, including volatiles

Mantle convects between “boundary layers”

Melting / freezing affects mantle temp / composition

Geodynamo driven by core convection (if occurring)

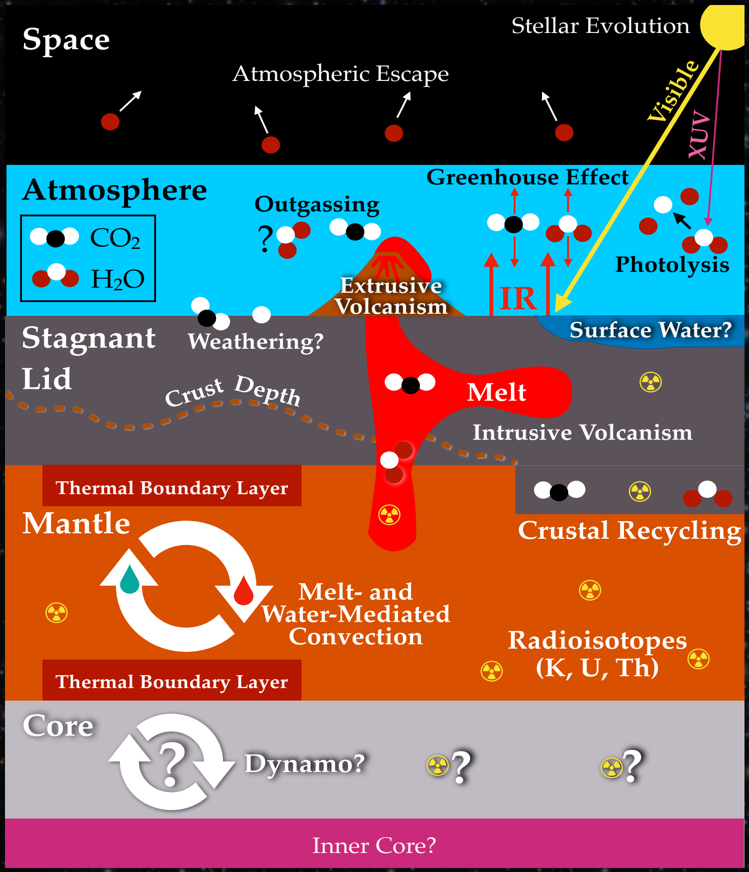
Core can solidify if thermodynamically allowed

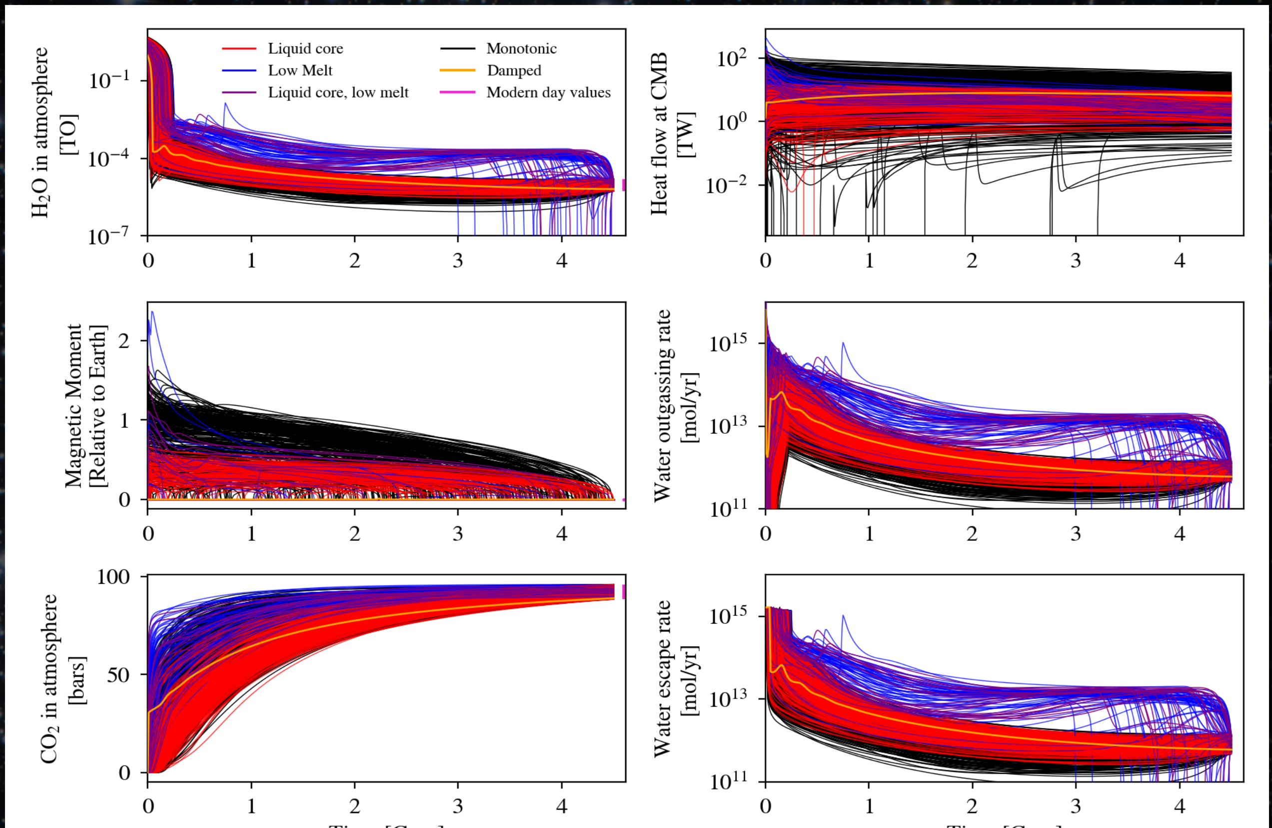
Radioactivity allowed in the core

The Interior: The Thermal/Magnetic/Volatile Evolution of Venus

How did Venus arrive at its current state if it has always had a stagnant lid?

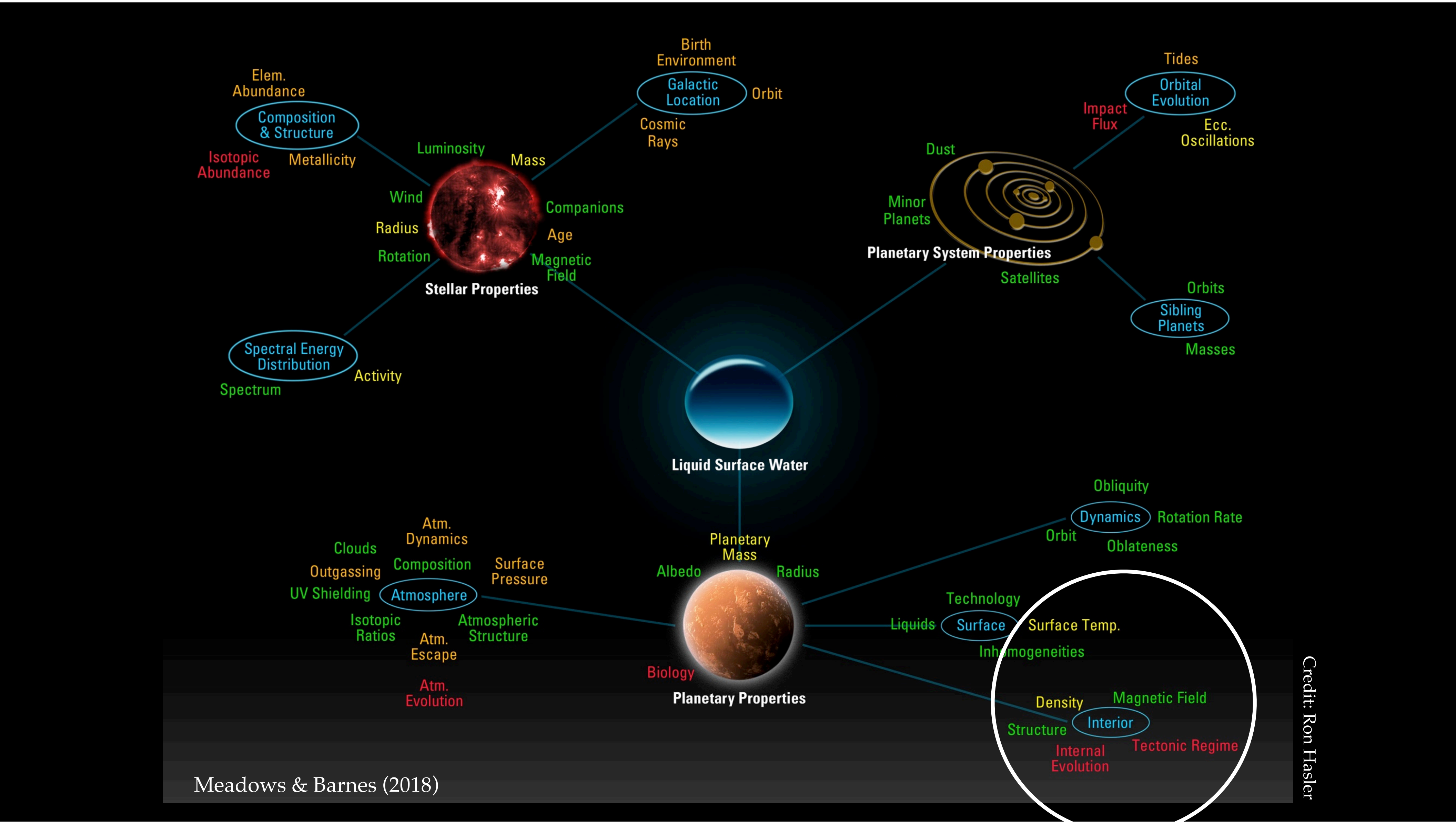
Rudy Garcia





Garcia et al., submitted

Validated model permits many possibilities. We can next apply it to exoplanets.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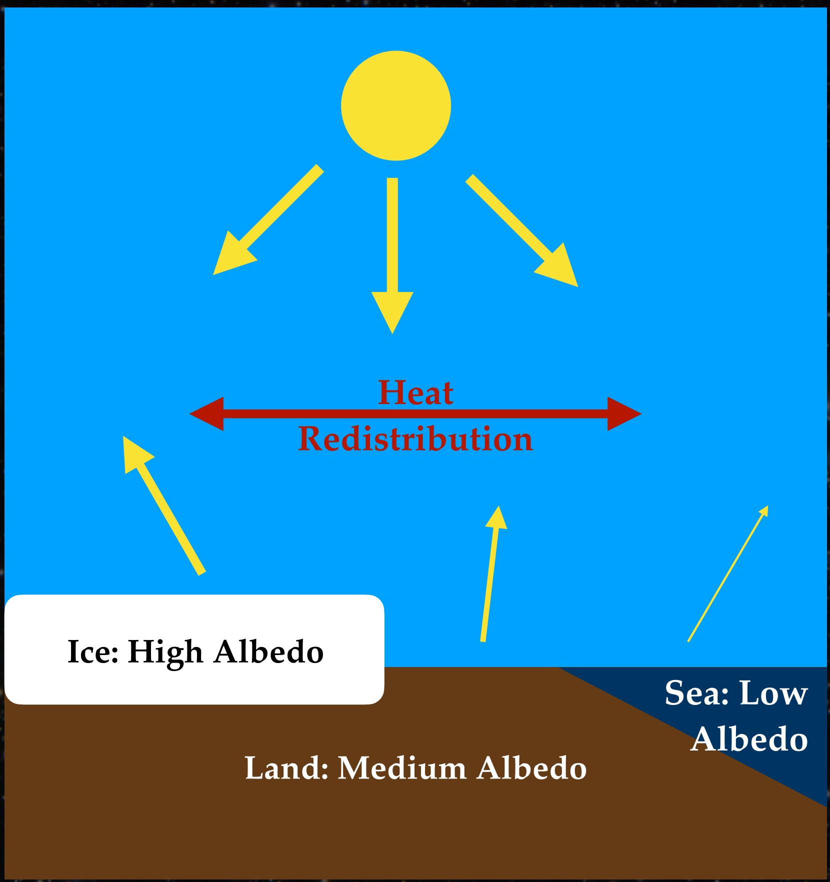
Meadows & Barnes (2018)
Credit: Ron Hasler

The Surface: Ice Coverage of Earth-like Exoplanets

How does ice coverage vary with host star, orbital, and rotational properties?

Caitlyn Wilhelm



One dimensional in latitude energy balance model (EBM)

Divide surface into ice, land, sea. Each with heat capacity

Parameterize heat diffusion by calibrating to Earth

(Wilhelm et al. 2022)

The Surface: Ice Coverage of Earth-like Exoplanets

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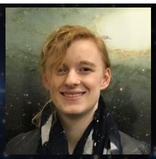

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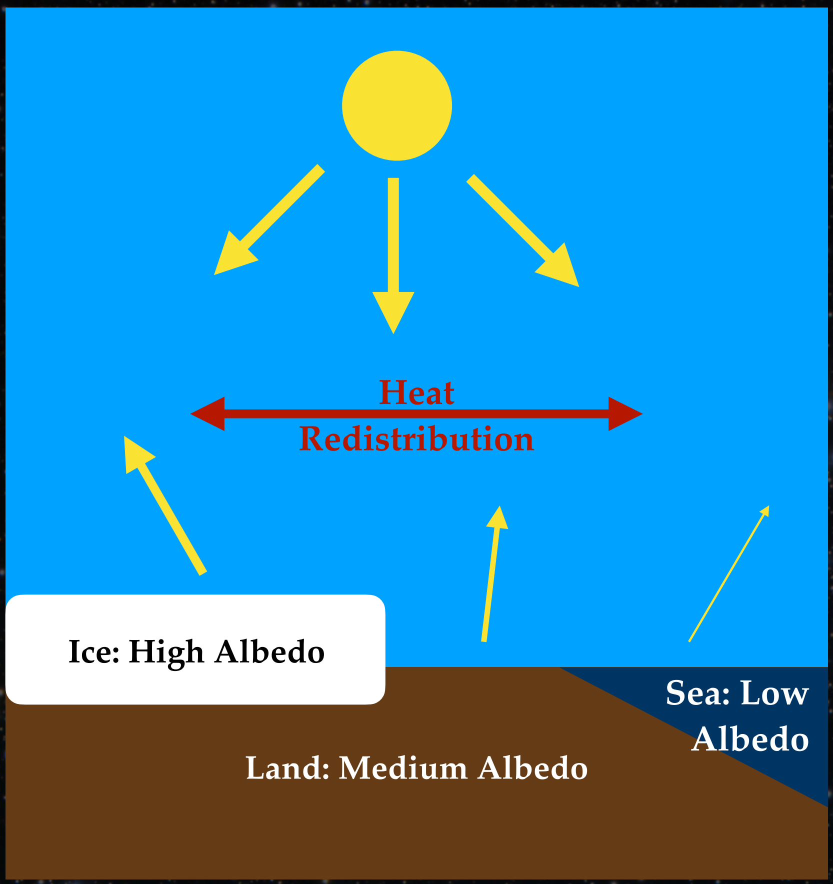
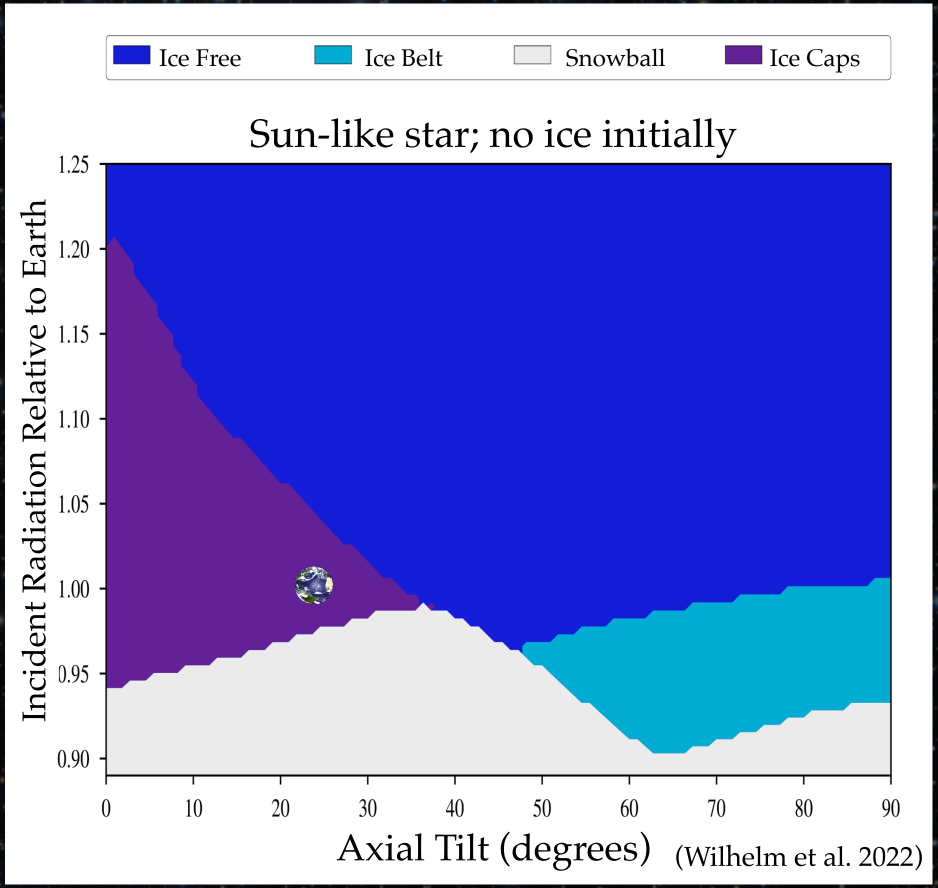
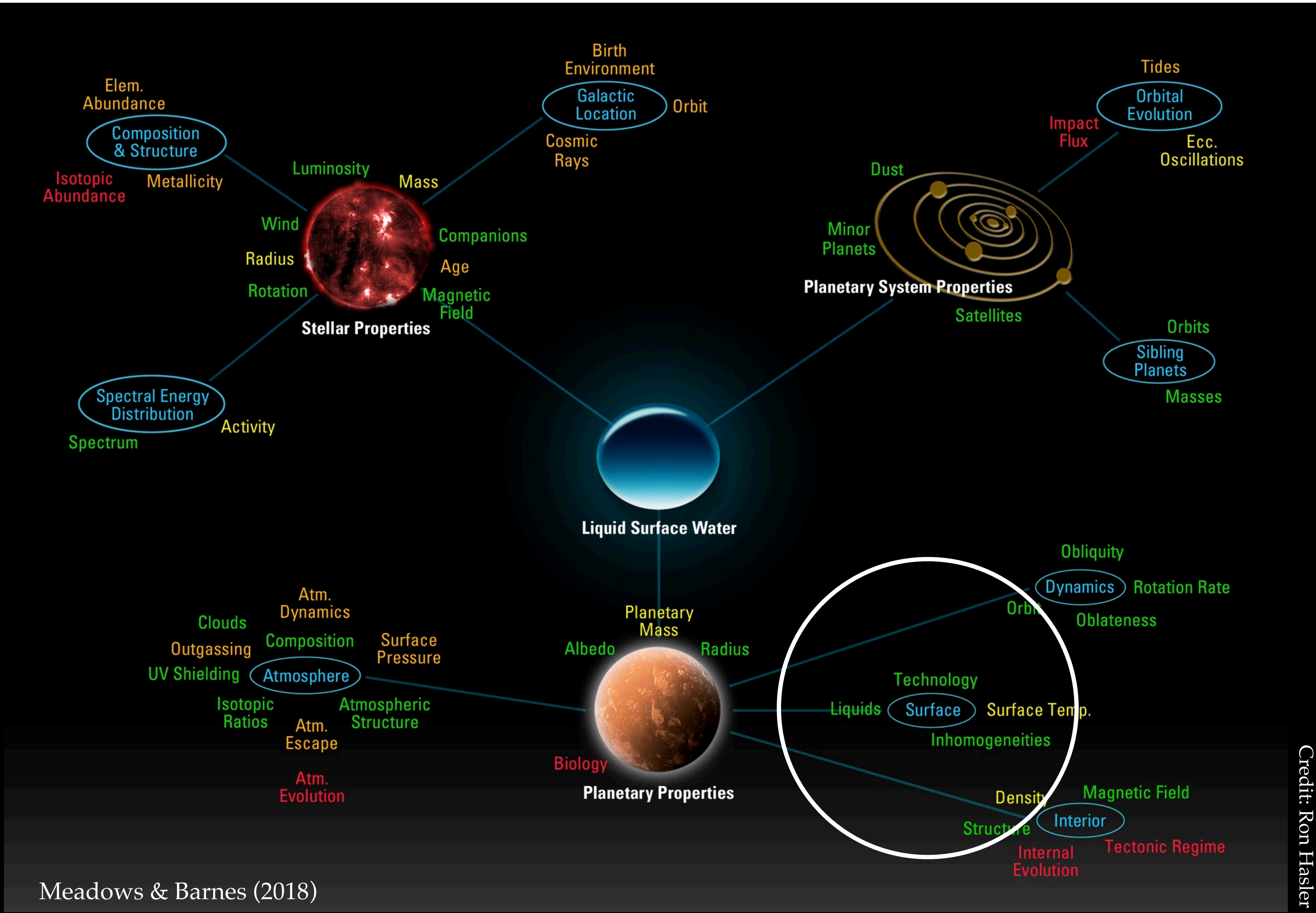




Planet formation favors 90° obliquity → ice belts *twice* as likely as ice caps



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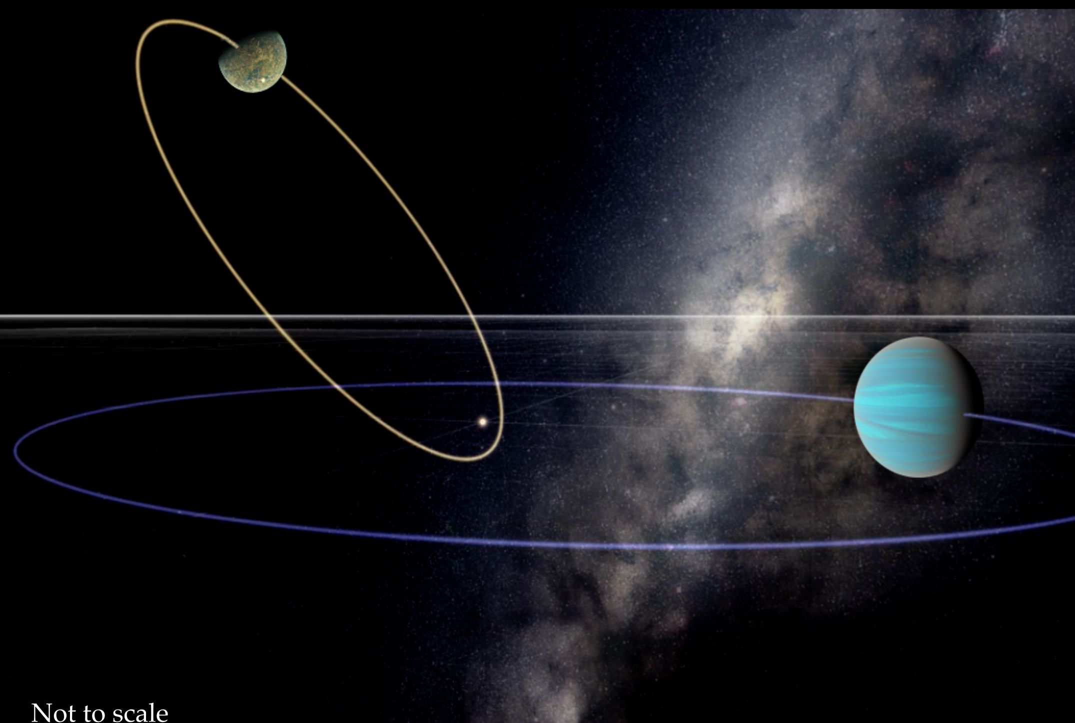
Meadows & Barnes (2018)
Credit: Ron Hasler

The Planetary System: Orbital Evolution in a Resonance

How extreme can the evolution of planetary orbits be?

Me!



Not to scale

Earth-mass + Neptune-mass Planets

Earth orbits a Solar-mass star with 1 year orbit

The Neptune planet's orbit is 3 years

This is a 3:1 mean motion resonance

Assign them some eccentricity and inclinations

Compute the gravitational forces between them

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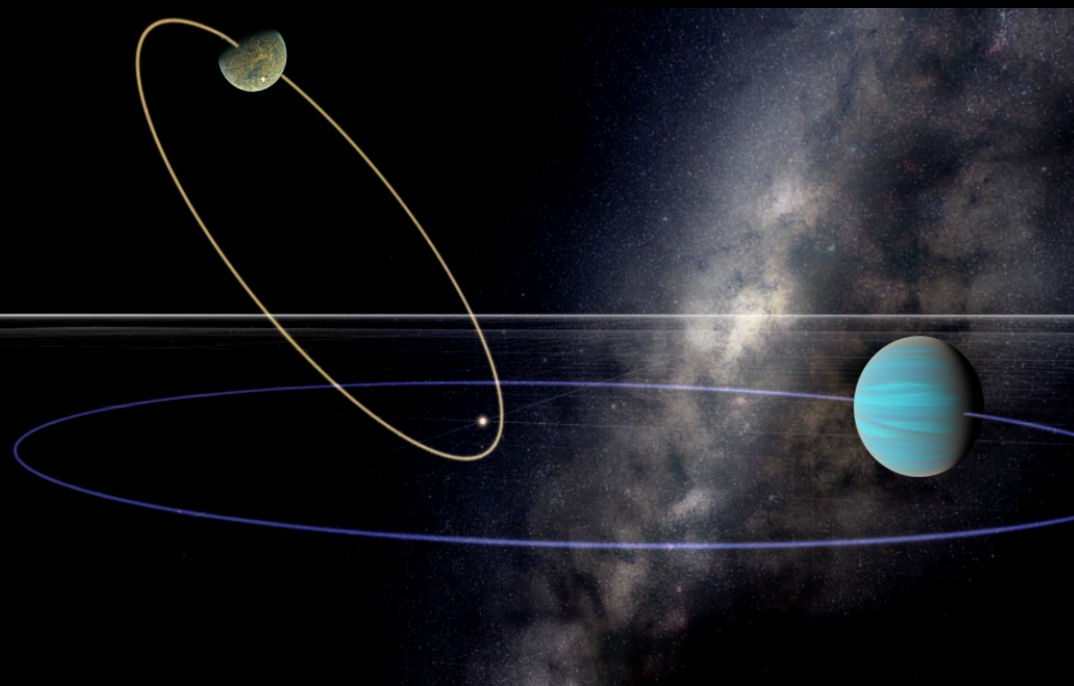

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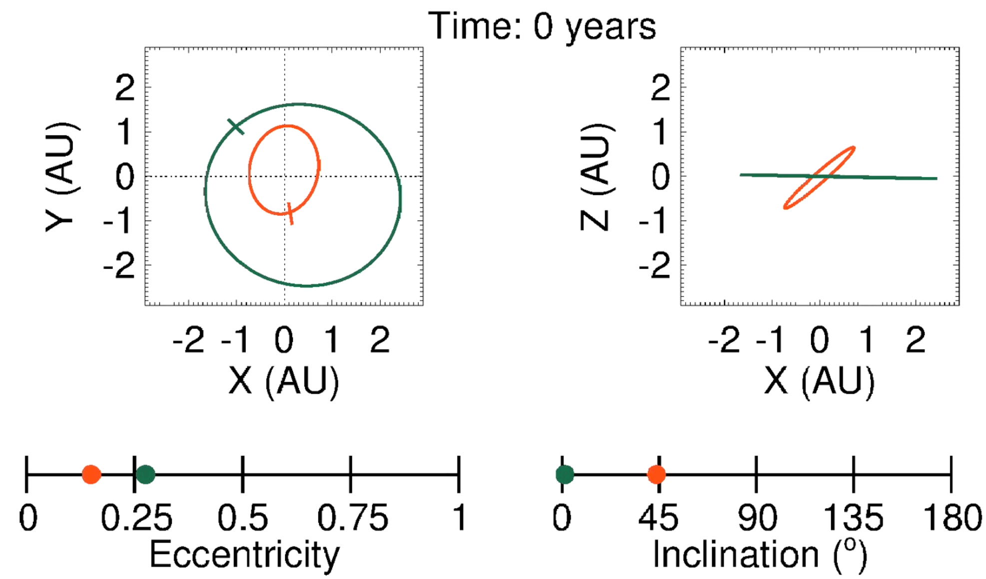
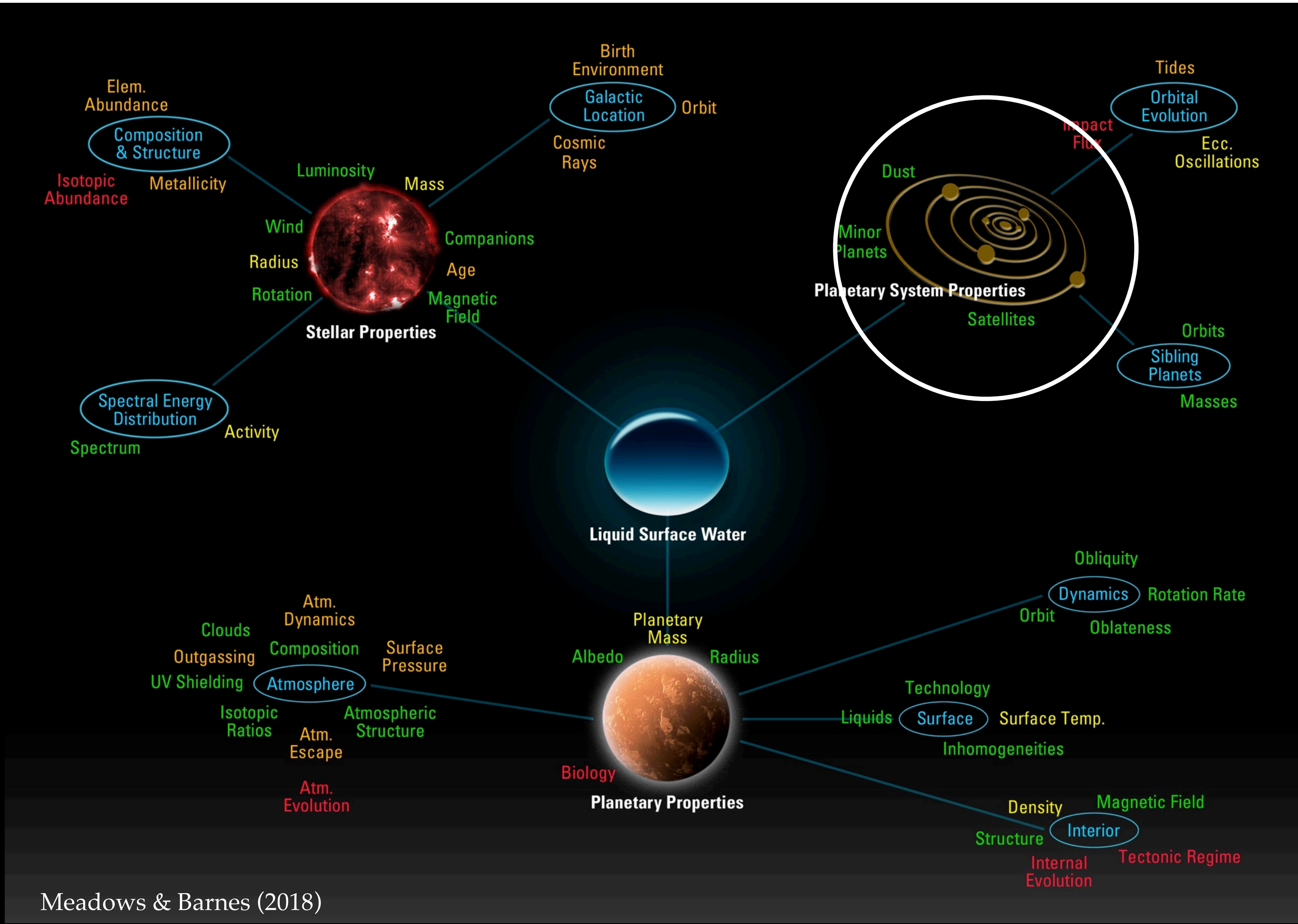


Barnes et al. (2015)

This motion is stable for 10 billion years.

Mean motion resonances in inclined systems can produce the most extreme orbital evolution possible.

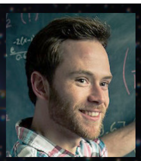


Meadows & Barnes (2018)

Credit: Ron Hasler

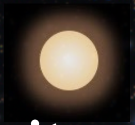
The Star: The Luminosity of TRAPPIST-1

How does the brightness of low mass stars change with time?



Rodrigo Luger

At first, Trappist-1 is big and bright



Slowly it contracts and dims

After 1.5 Byr, it is 100x dimmer

Small stars take a long time to build the central pressure necessary for fusion

Over time, their radii shrink at constant temperature

Smaller surface area -> lower luminosity

The habitable zone moves inwards

The Star: The Luminosity of TRAPPIST-1

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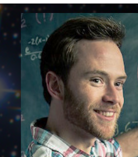

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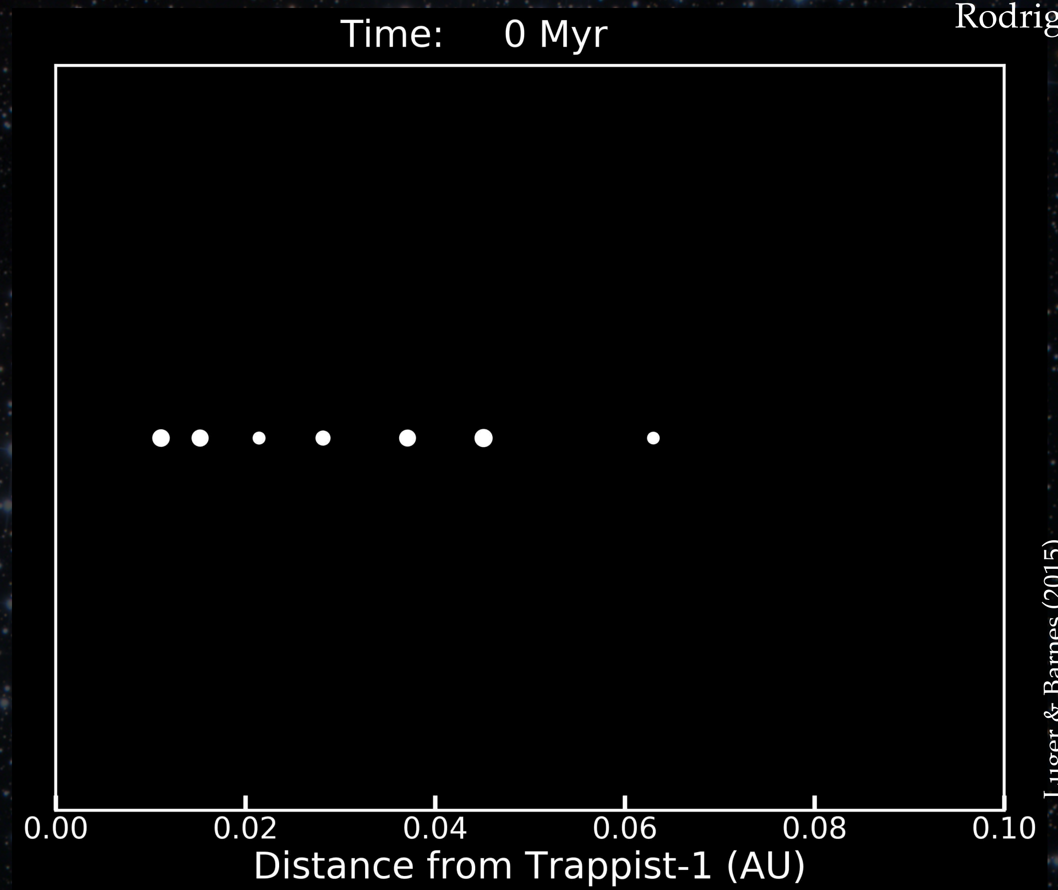
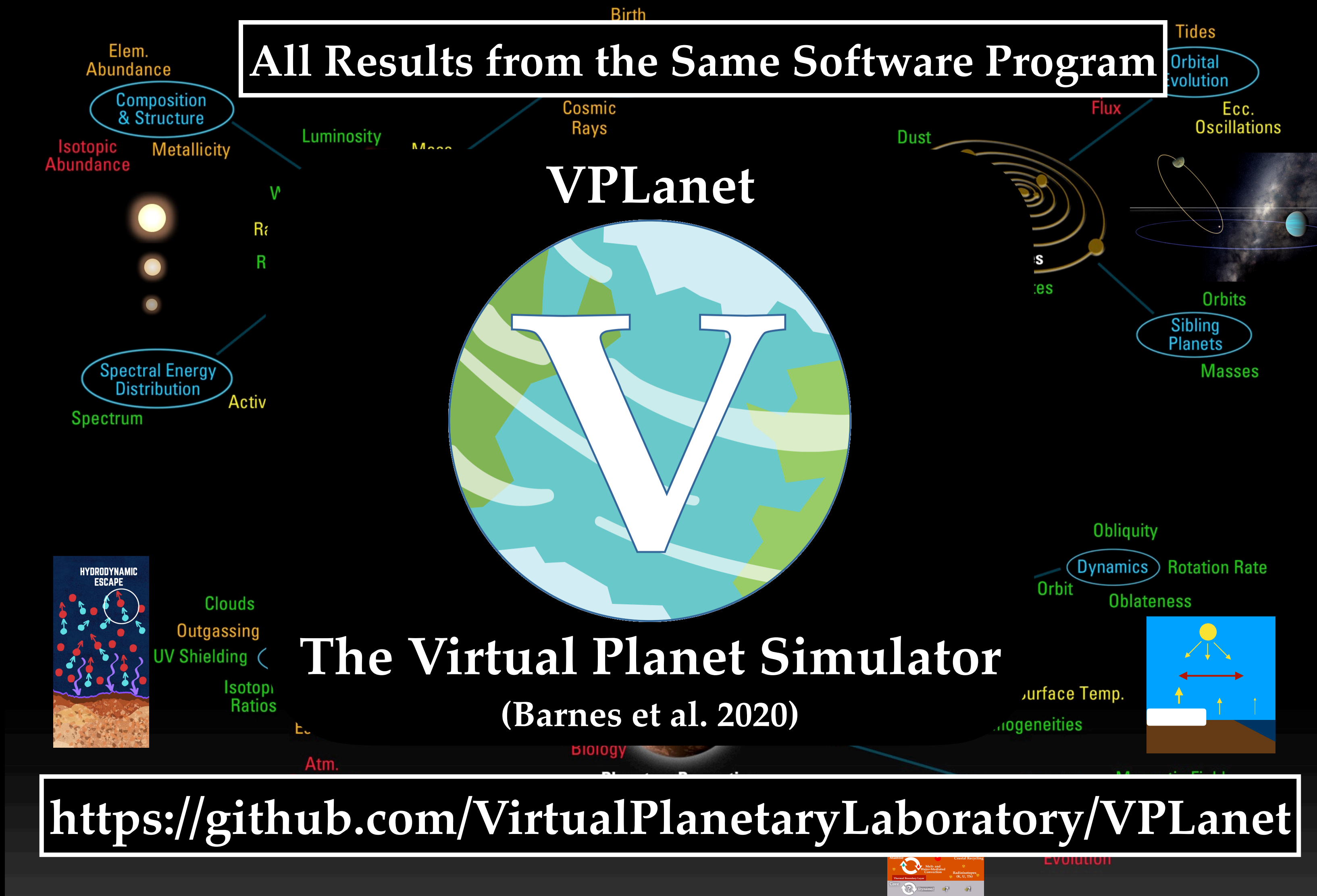


Can planets be habitable after hundreds of millions of years in a runaway greenhouse?

All Results from the Same Software Program

VPLanet



The Virtual Planet Simulator

(Barnes et al. 2020)

https://github.com/VirtualPlanetaryLaboratory/VPLanet

Introducing alabi: Active Learning for Accurate Bayesian Inference

Jessica Birky

A machine learning approach for deriving posteriors

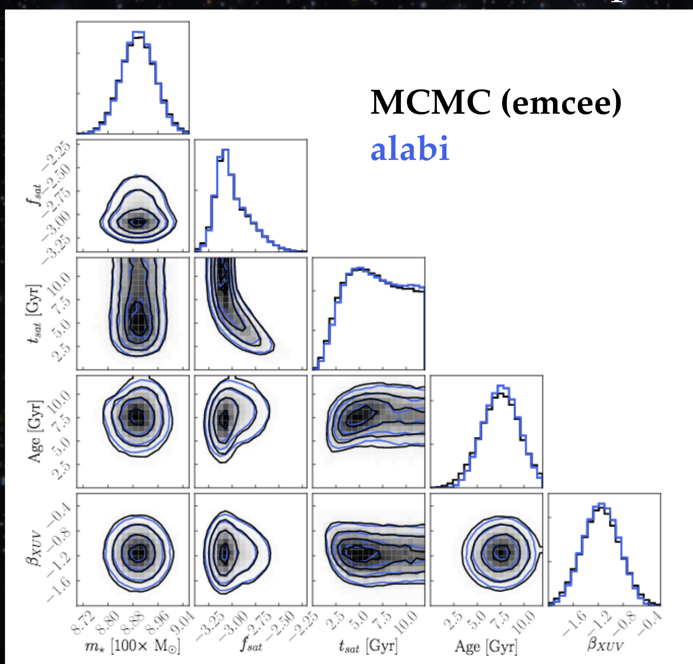
The code derives a “surrogate model” via Gaussian processes

Then uses Markov chain Monte Carlo with this surrogate model to infer posteriors

alabi then identifies where the surrogate model has high likelihood *and* high uncertainty

Then performs a new VPLanet simulation there, rebuilds the surrogate model, recomputes posteriors

Iterates until three consecutive posteriors are the same, i.e. within a tolerance parameter



A 5 parameter model for TRAPPIST-1’s XUV evolution

Posteriors differ by ~3% (within sampling error)

alabi is 1000x more efficient than MCMC (in this case)

Now working to extend to higher dimensional problems

https://github.com/jbirky/alabi

Fleming et al. (2020)

Updated in Birky et al. (2021)

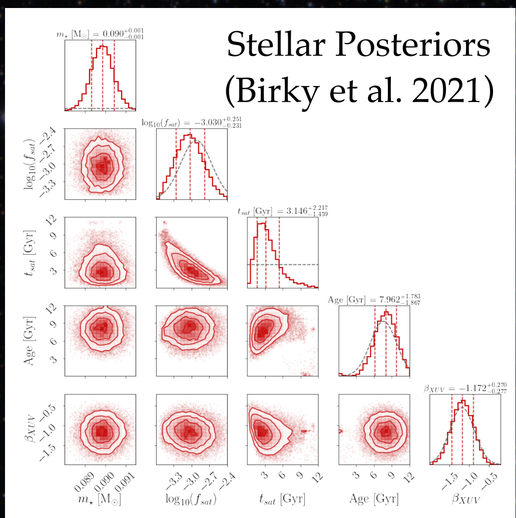
Water Loss + Uncertainties for the TRAPPIST-1 Planets

Megan Gialluca

Combine stellar posteriors with planetary posteriors to model photolysis+escape

Consider the star and planets with a pure water atmosphere

Simulate in batches of 500 until the water content distributions for all planets converge



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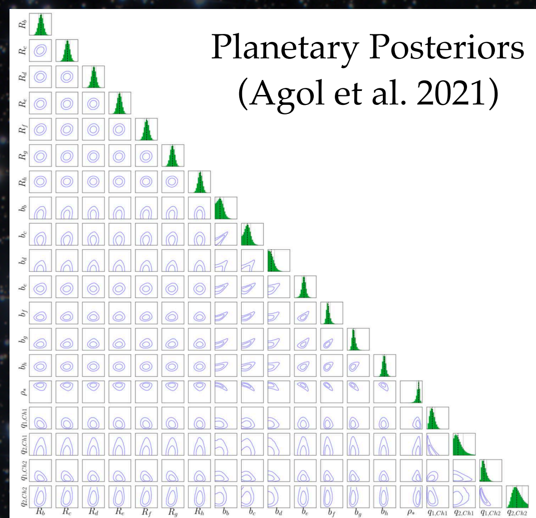

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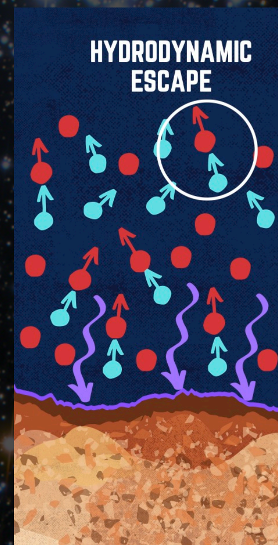

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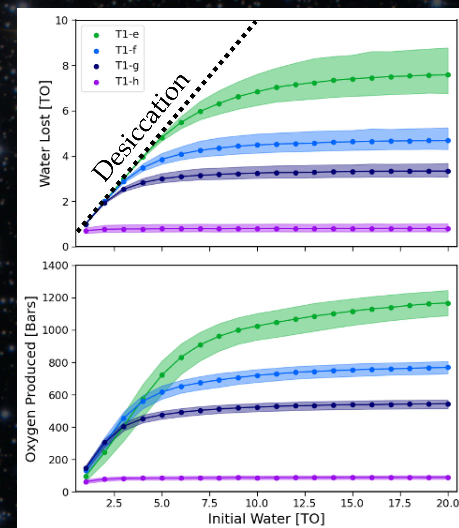

Gialluca et al., in prep.

If the HZ planets formed with <3-5 TO, they are totally desiccated

More likely is that they lost 8.1±0.9 (planet e), 4.9±0.4 (f), 3.4±0.3 (g) and 0.8±0.1 (h) Earth oceans

For this simple model! Future work will include interior, orbits, etc.

Summary

VPLanet is a single code that can simulate many planetary processes

- Flares can removes up to 2 TO of water (Amaral et al., 2022)
- Ice belts are probably twice as common than ice caps (Wilhelm et al., 2022)
- Resonances with high inclination can be chaotic with high amplitude (Barnes et al., 2015)
- Stellar evolution of low mass stars can desiccate terrestrial planets (Luger & Barnes, 2015)
- Whole planet thermal/magnetic/volatile model of Venus (Garcia et al., submitted)

Machine learning enables quantifying uncertainties in the probability of liquid water

- TRAPPIST-1's XUV flux has been constrained with alabi (Birky et al., 2021)
- Can compute likelihood that water survived the pre-main sequences (Gialluca et al., 2024)