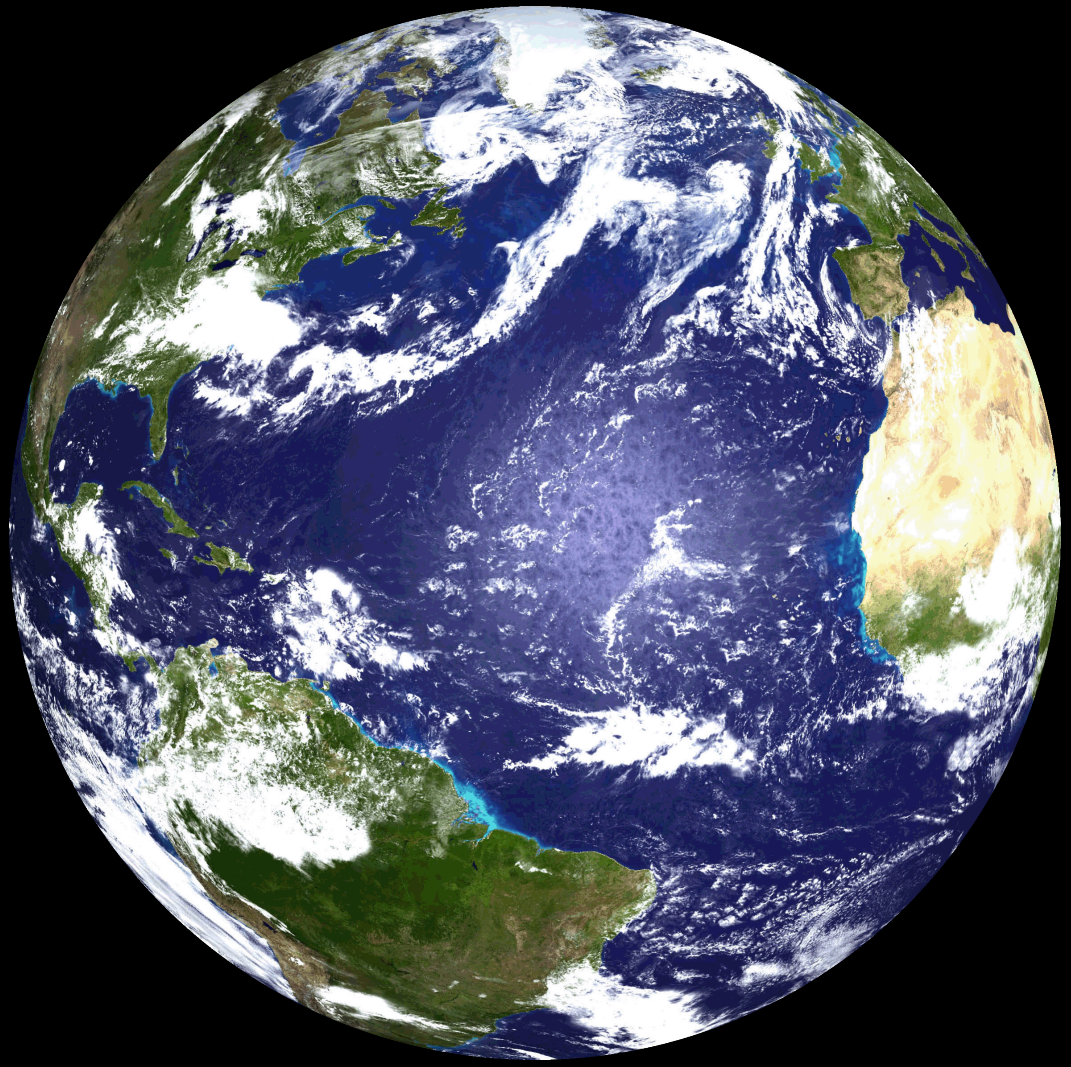
First VPLanet Developers Workshop

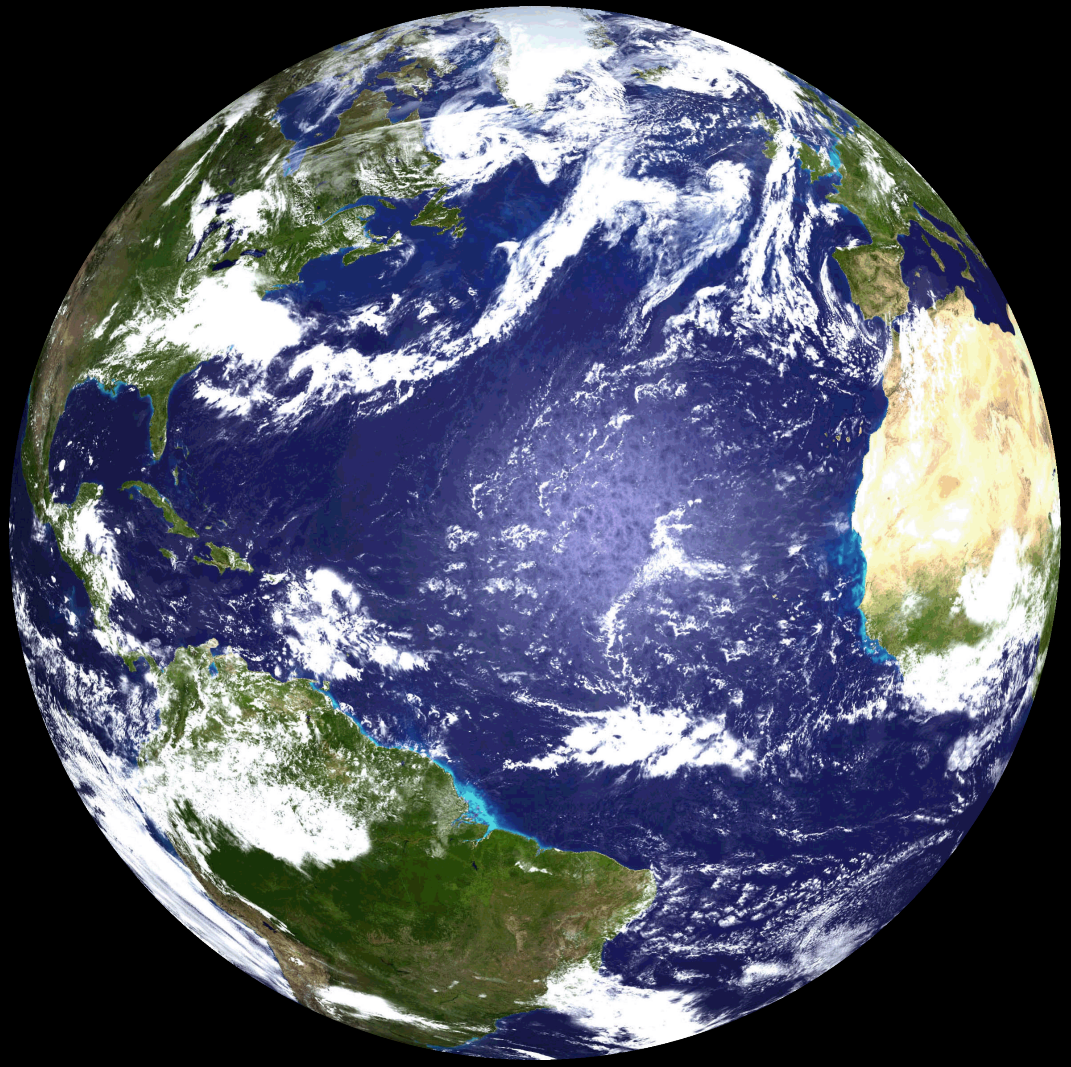
Lesson 1
Motivation and Overview

Our Aspirational Goal:

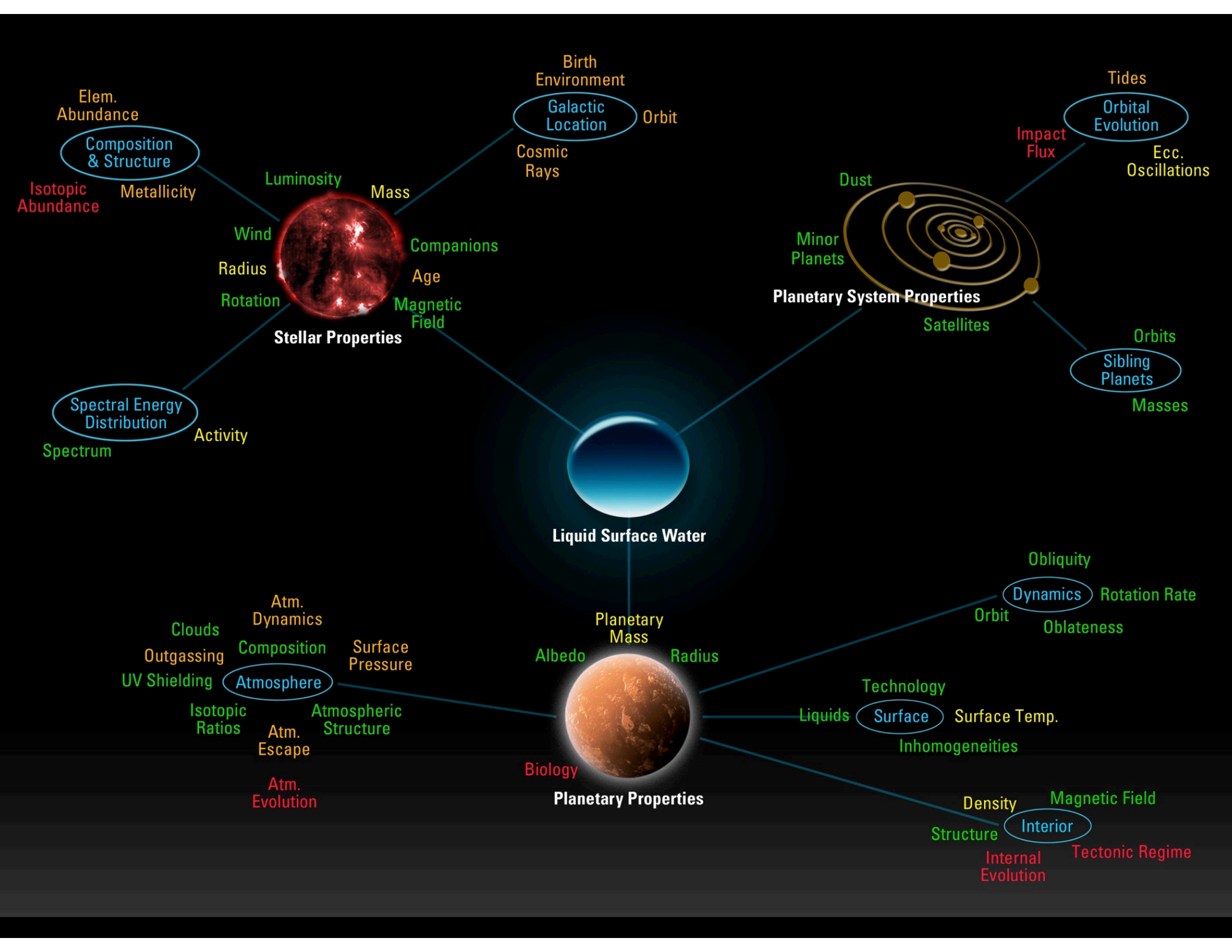


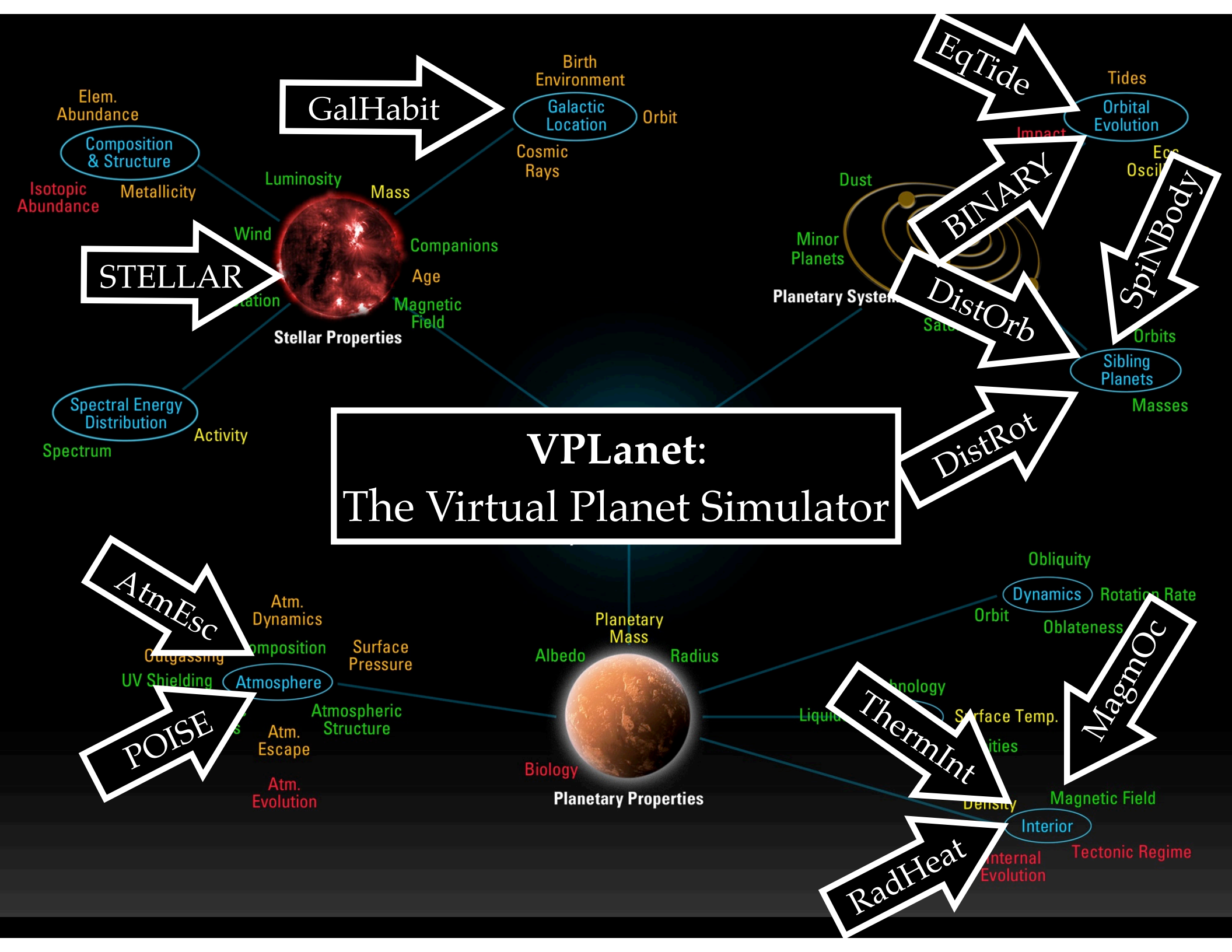
To model planetary habitability as realistically as possible

All life on Earth requires liquid water



But liquid water is rare in the Solar System,
So VPLanet simulates the processes that sustain it


Elem. Abundance
Composition & Structure
Isotopic Abundance
Metallicity
Luminosity
Mass
Wind
Radius
Rotation
Companions
Age
Magnetic Field
Stellar Properties
Birth Environment
Galactic Location
Orbit
Cosmic Rays
Spectral Energy Distribution
Activity
Spectrum
Tides
Orbital Evolution
Impact Flux
Ecc. Oscillations
Dust
Minor Planets
Planetary System Properties
Satellites
Orbits
Sibling Planets
Masses
Liquid Surface Water
Obliquity
Dynamics
Rotation Rate
Orbit
Oblateness
Atm. Dynamics
Clouds
Composition
Surface Pressure
Outgassing
UV Shielding
Atmosphere
Isotopic Ratios
Atm. Escape
Atmospheric Structure
Atm. Evolution
Planetary Mass
Albedo
Radius
Biology
Planetary Properties
Technology
Liquids
Surface
Surface Temp.
Inhomogeneities
Density
Magnetic Field
Interior
Structure
Internal Evolution
Tectonic Regime


VPLanet:
The Virtual Planet Simulator
GalHabit
Birth Environment
Galactic Location
Orbit
Cosmic Rays
Elem. Abundance
Composition & Structure
Isotopic Abundance
Metallicity
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MagmOc
ThermInt
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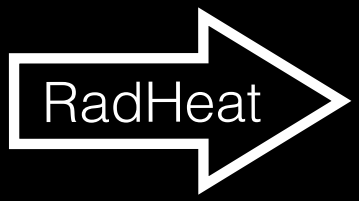
Interior
Tectonic Regime
RadHeat

Module Summary

"Thermal Interior Evolution": Core and mantle evolution, including magnetic dynamo (Driscoll & Bercovici 2013). (*Peter Driscoll)*

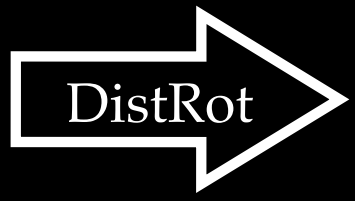


"Radiogenic Heating": Heating of planetary interiors by radioactive decay of aluminum-26, potassium-40, thorium-232, uranium-235, and uranium-238. This module splits the planet into core, mantle and crust. (*Rory Barnes and Peter Driscoll)*

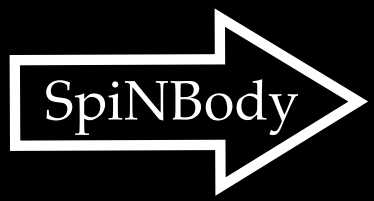
"Magma Oceans": Thermal and geochemical evolution of a magma ocean, including surface fluxes of oxygen and water, as well as iron oxidation in the interior (Elkins-Tanton, 2008; Schaefer+ 2016). (*Patrick Barth and Ludmila Carone)*

Module Summary

"Disturbing Function—Orbits": Semi-analytic models of multi-planet system orbits (Ellis & Murray, 2000). This module includes both the 2nd order eigenvalue solution and the 4th order solution. It can also account for central body oblateness and general relativity. (*Russell Deitrick*)

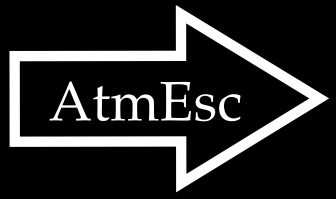


"Disturbing Function—Rotation": Semi-analytic model for the rotational evolution of a planet due to orbital plane evolution and the torque from the central body (Laskar+ 1993). This module can also read in pre-computed orbital evolution. (*Russell Deitrick*)



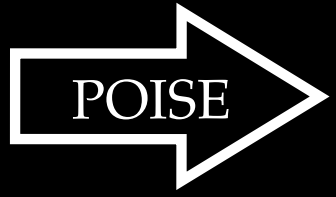
"Spin and N-Body Evolution": Direct calculation of gravitational forces between objects from first principles. Note that torques are not yet implemented. (*Hayden Smotherman*)

Module Summary



"Atmospheric Escape": Atmospheric loss due to Roche lobe overflow, radiation-recombination, and energy-limited escape by XUV radiation (Watson+ 1981; Erkaev+ 2007; Owen+2017). This module includes water photolysis and oxygen escape via hydrodynamic drag. (*Rodrigo Luger and David Fleming)*

"Equilibrium Tides": Deformation by a nearby object affects orbital and rotational properties, as well as internal heating (Ferraz-Mello+ 2008, Leconte+ 2010). This module includes both the "constant-phase-lag" (tidal Q) and "constant-time-lag" models. (*Rory Barnes*)



"Planetary Orbit-Influenced Simple EBM": Energy balance climate model to track surface temperatures and ice sheets of Earth-like planets (North & Coakley 1979; Huybers & Tziperman 2008). (*Russell Deitrick and Cecilia Bitz*)

Module Summary

GalHabit

"Galactic Habitability": For wide binary stars, the galactic tide and passing stars can modify the stellar orbit, which then affects planetary orbits (Rickman+ 2008). This module also accounts for radial migration, the stellar mass function, and the radial density gradient of stars in the Galaxy. (*Russell Deitrick and Tom Quinn*)

BINARY

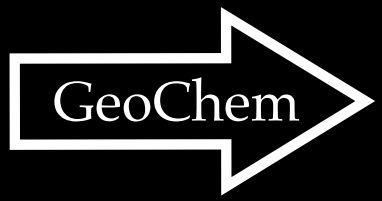
"Circumbinary Planet Orbit": Semi-analytic model for the orbital evolution of a single circumbinary planet (Leung & Lee, 2013). (*David Fleming)*

STELLAR

"Stellar Evolution": Luminosity and structural evolution of stars from birth to the end of the main sequence (Baraffe+ 2016). This module also accounts for magnetic braking (Reiners+ 2014) and XUV evolution (Ribas+ 2005). (*Rodrigo Luger and David Fleming*)

Modules in Preparation

"Stellar Flares": XUV emission from flares following the empirical relationship from Davenport+ (2019) or the model from Lacy+ (1976). (*Laura Amaral*)



"Geochemistry": Surface volatile fluxes for planets in plate tectonics and stagnant lid tectonic modes. Includes evolution of the crust and pressure-dependent outgassing (Foley & Smye, 2019; Wogan+ 2021). (*Rudy Garcia)*

An Interdisciplinary Model for Planetary System Evolution

VPLanet has been developed by an interdisciplinary team, mostly consisting of members of the Virtual Planetary Laboratory

The modules have been validated by reproducing observations or past results

All the modules are run with the same executable, regardless of the physics

While many modules are coupled, many more are not.

- **12 modules => millions of module combinations!**
- **Enough science for the whole community!**

Guiding Principles

VPLanet should be easy to use, regardless of your specialty

- Simple API, single executable for many phenomena

Planets *are* hard — this tool should make them easier to understand!

- Code connects different physics, tracking feedbacks and water

No process is considered "dominant" or even necessary

- Input files allow users to select physics on a per-body basis

Users should trust accuracy on processes for which they are not experts

- Examples demonstrate functionality

- Unit tests ensure updates don't break existing functionality

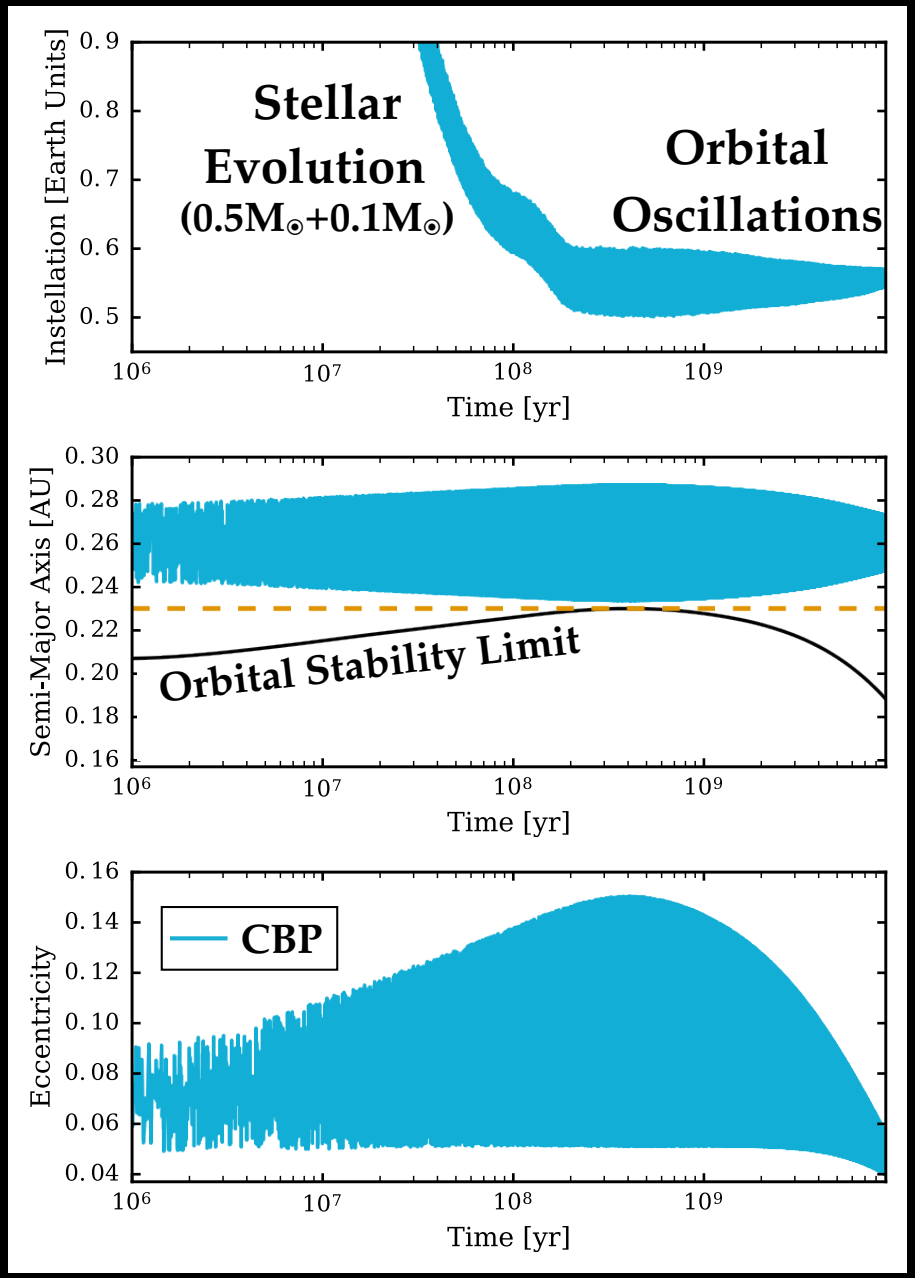
- Memory checks minimize programming errors

Results should be transparent and reproducible

- Open source model, examples, tests, follow software best practices

- Participants follow the Code of Conduct

Recent and Upcoming Results



Graham+ (2021)

Orbital evolution of a circumbinary planet reacting to the tidal interaction of its host stars

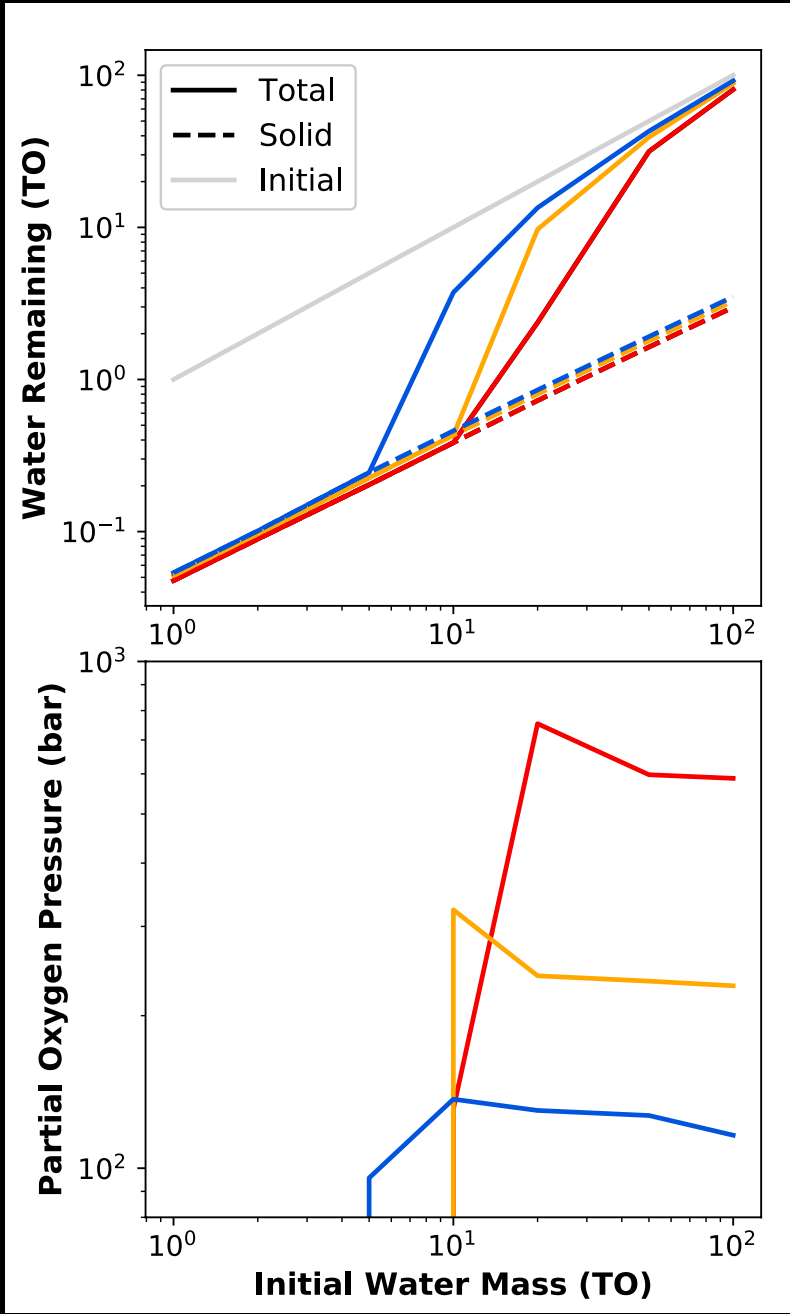
The coupled stellar+tidal evolution drives the binary orbit out, then back in (Fleming+ 2018)

This evolution drives the orbital stability limit outward over millions to billions of years

The CBP's instellation can evolve dramatically due to the host star's stellar and orbital evolution

Modules: STELLAR, BINARY, EqTide

Recent and Upcoming Results



Barth+ (2021)

The magma oceans of the TRAPPIST-1 planets can change the water and oxygen abundances in the atmosphere

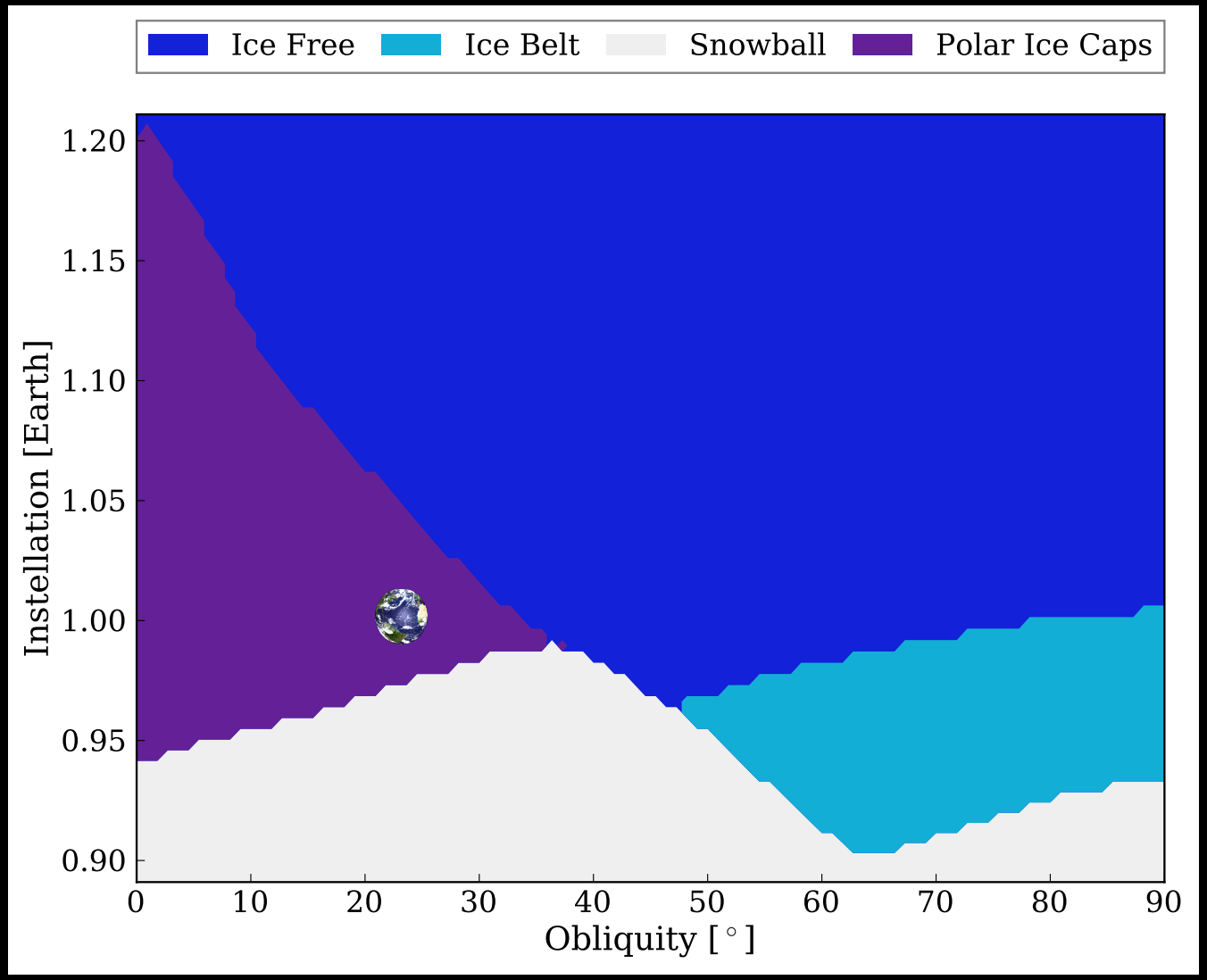
The amounts correlate strongly with initial water content

If the planets formed with >10 Earth oceans of water, they likely retained it through the magma ocean phase

Abiotic oxygen build-up is also likely

Modules: MagmOc, AtmEsc, STELLAR, EqTide, RadHeat

Recent and Upcoming Results



Wilhelm+, submitted

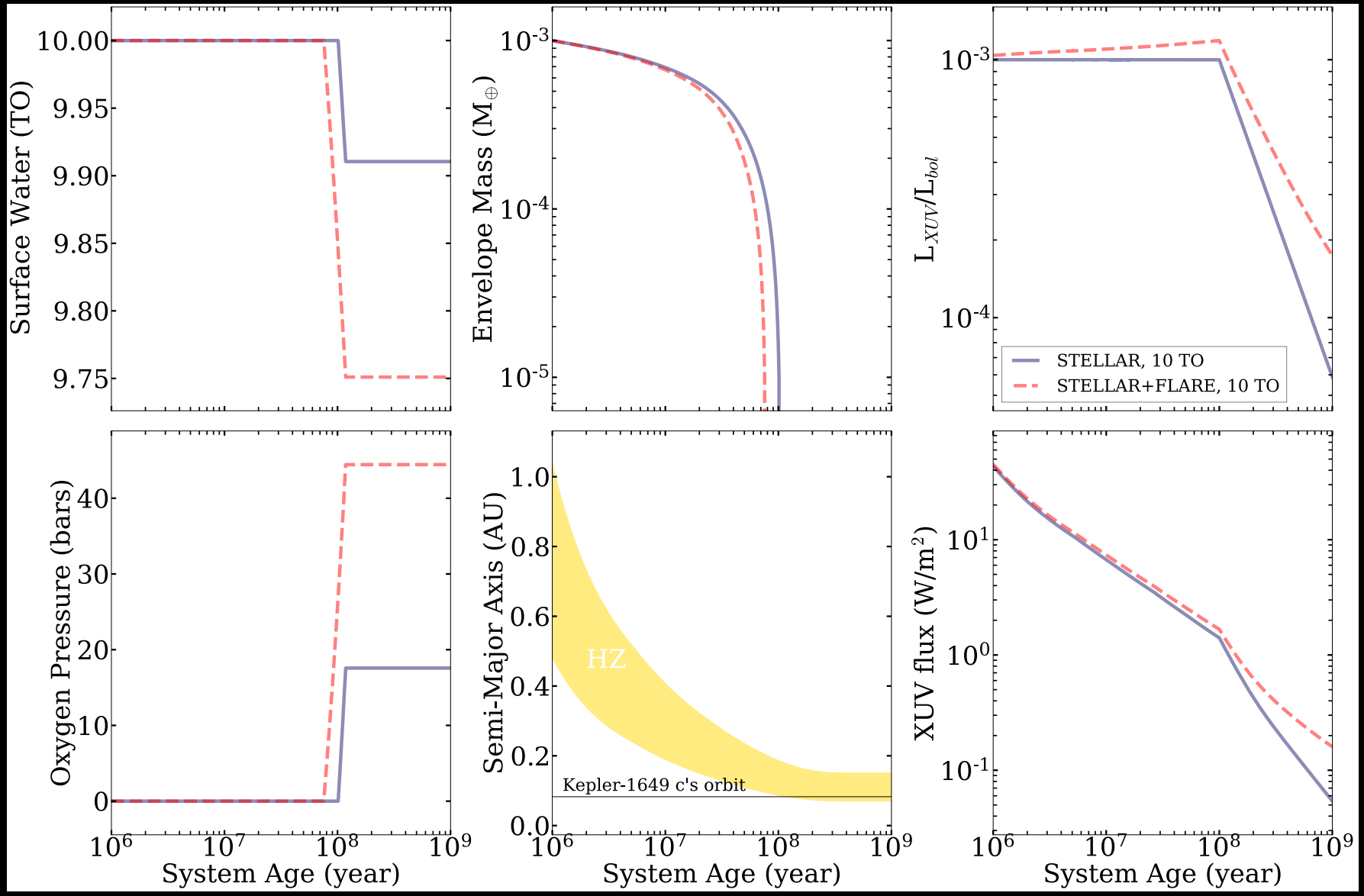
Module: POISE

Mapping of ice sheets on planets as a function of orbit and spectral type

Most Earth-like planets are ice free

Planets tend to form with obliquity ~90 => ice belts are more common than caps

Recent and Upcoming Results

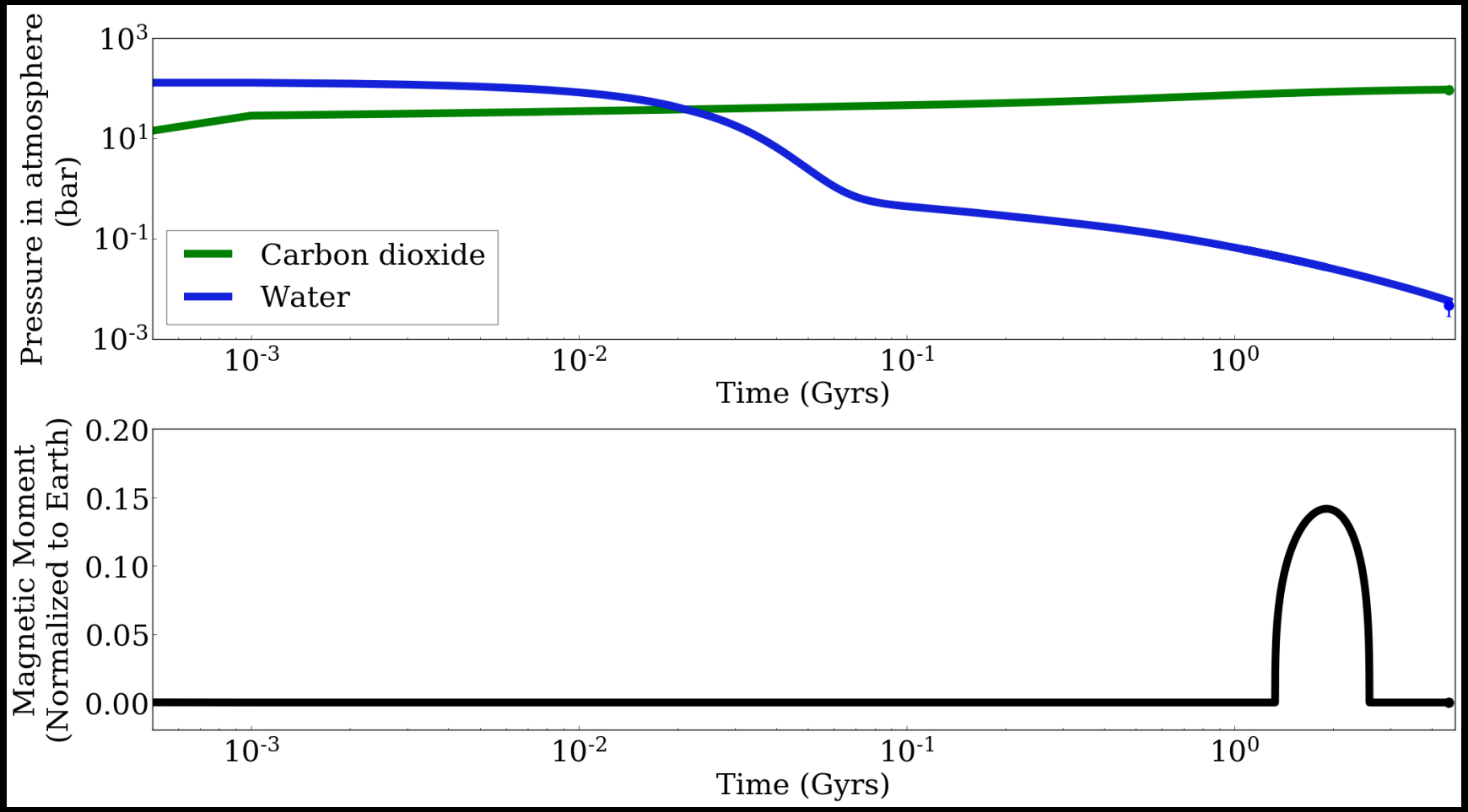


Modules: STELLAR, *FLARE*, AtmEsc

Amaral+, in prep.

Flares remove additional water, and release additional oxygen

Recent and Upcoming Results



Garcia+, in prep.

Modules: STELLAR, AtmEsc, ThermInt, *GeoChem*, RadHeat

Stagnant lid geochemical model

First model to reproduce geodynamo, CO_2, and water of Venus

The Big Picture

VPLanet connects simple models together to enable new insight into planetary and stellar evolution, focusing on habitability

It is best used as a preliminary analysis tool and for parameter sweeps to identify trends and categories

In some cases it can provide predictions and explanations

It is part of the process of discovering habitable and inhabited exoplanets and should connect to formation models and observables

This week's Schedule

Tue. 8 June 2021, 9am PT Using VPLanet	Wed. 9 Jun 2021, 9am PT Basic Development	Thu. 10 Jun 2021, 9am PT Intermediate Development
9:00 Intro and Overview	9:00 VPLanet Architecture	9:00 Primary Variables
10:00 Break	10:00 Break	10:00 Break
10:30 Best Practices	10:30 How to Add an Output	10:30 Coupling Modules
11:30 Break	11:30 Break	11:30 Break
12:00 Support Scripts	12:00 How to Add an Option	12:00 Adding a New Module

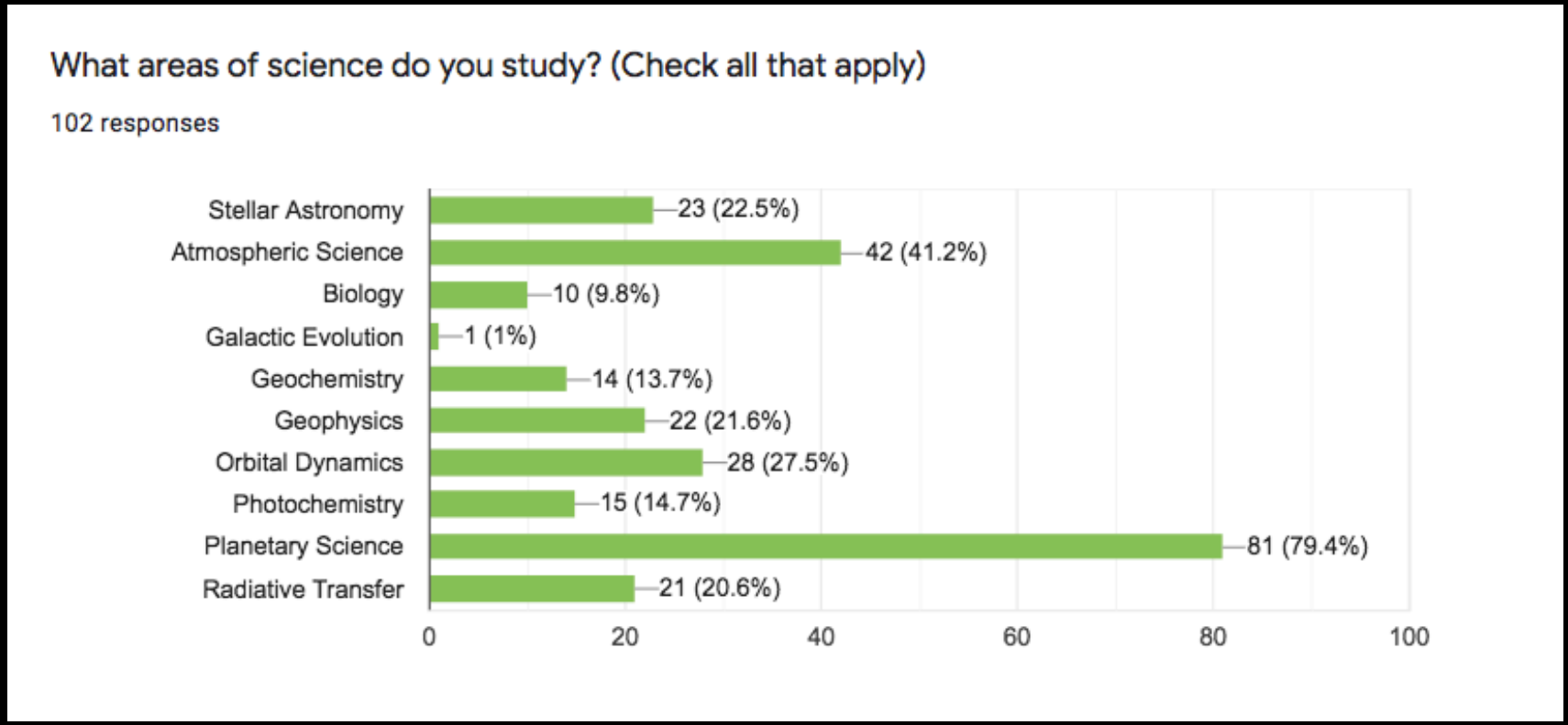
Friday, June 11 is an extended "office hour" to discuss projects with Rory
All are welcome, but sign up here to discuss a specific project

Workshop Participants

102 registrants (thank you!!)

Undergraduates to professors/civil servants

At least 4 continents



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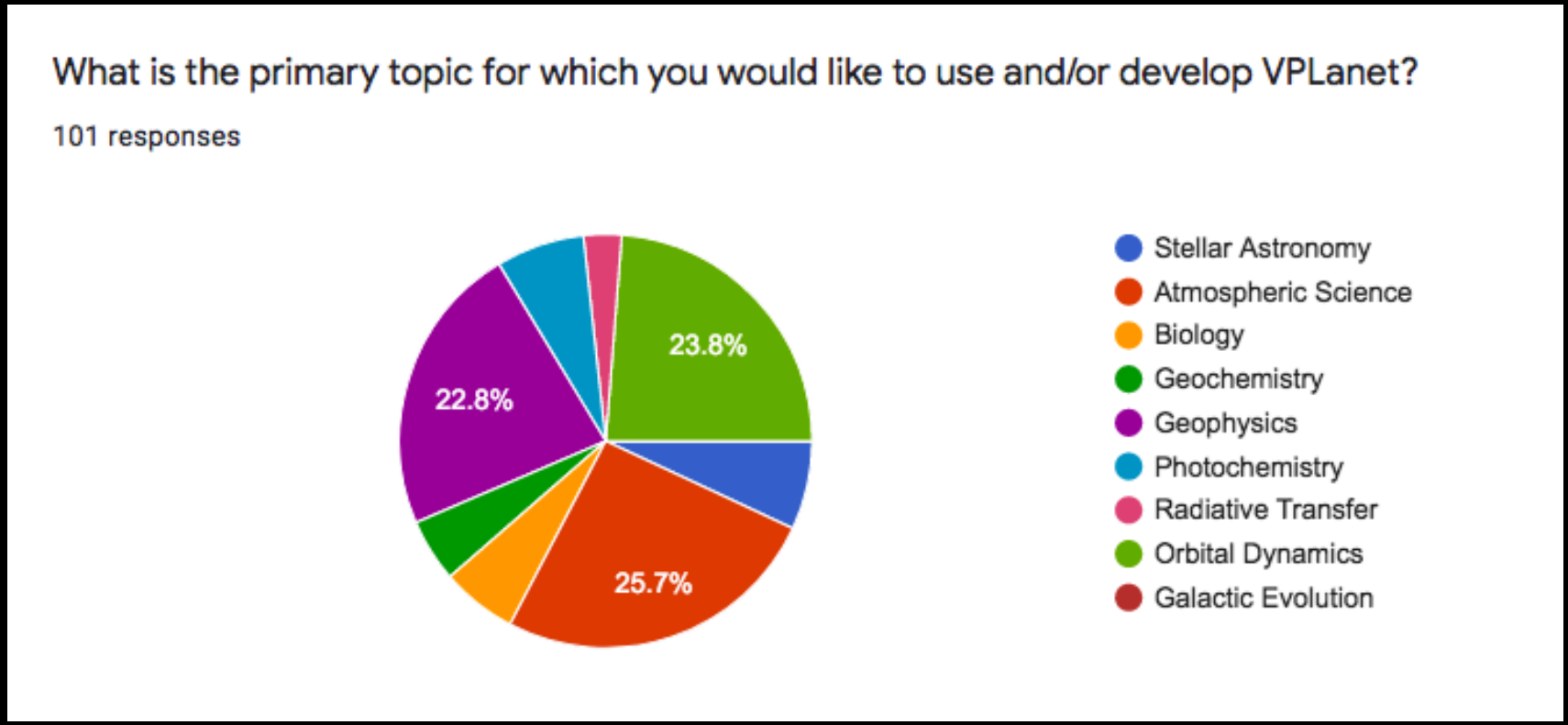

HUGE THANKS!

Primary Developers

Rodrigo Luger (Flatiron Institute)
Russell Deitrick (U. of Bern)
Peter Driscoll (Carnegie)
David Fleming (Beyer)
Caitlyn Wilhelm (UW)
Thomas Quinn (UW)
Rudy Garcia (UW)
Hayden Smotherman (UW)
Laura Amaral (UNAM)
Patrick Barth (St. Andrews)

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Diego McDonald (UW)
Benjamin Guyer (UW)
Pramod Gupta (UW)
Shawn Domagal-Goldman (Goddard)
John Armstrong (Weber St)
Paul Moliere (Heidelberg)
Antigona Segura (UNAM)
Lena Noack (FU Berlin)
Billy Quarles (Georgia St)