Applications of 3D climate system models towards understanding exoplanetary atmospheres.

4th Eddy Cross-Disciplinary Symposium
Thursday November 2nd, 2023

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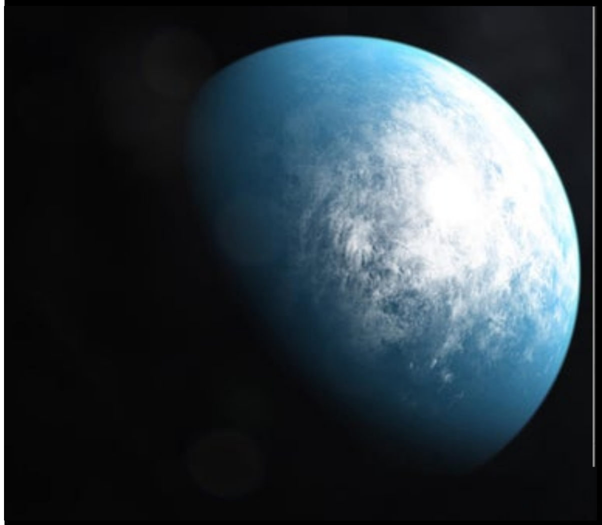
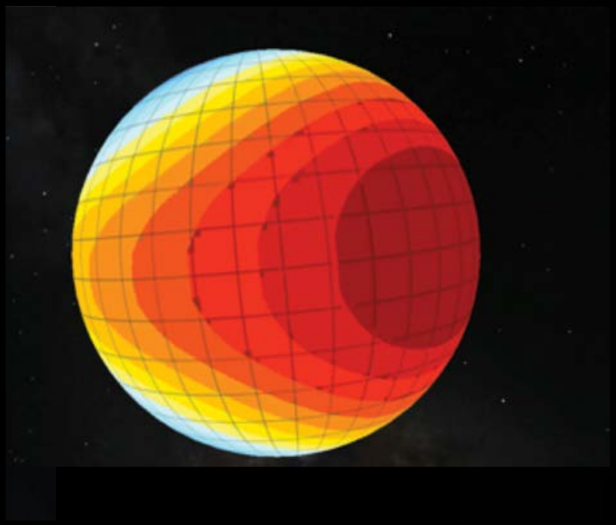
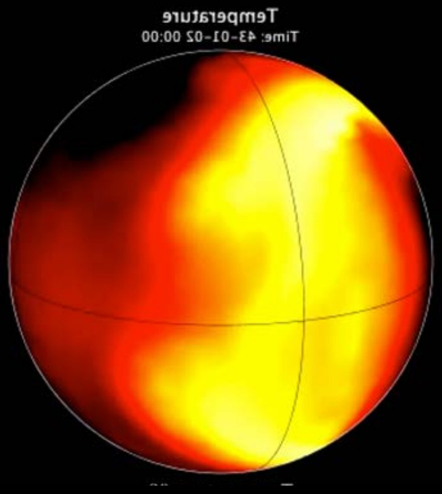
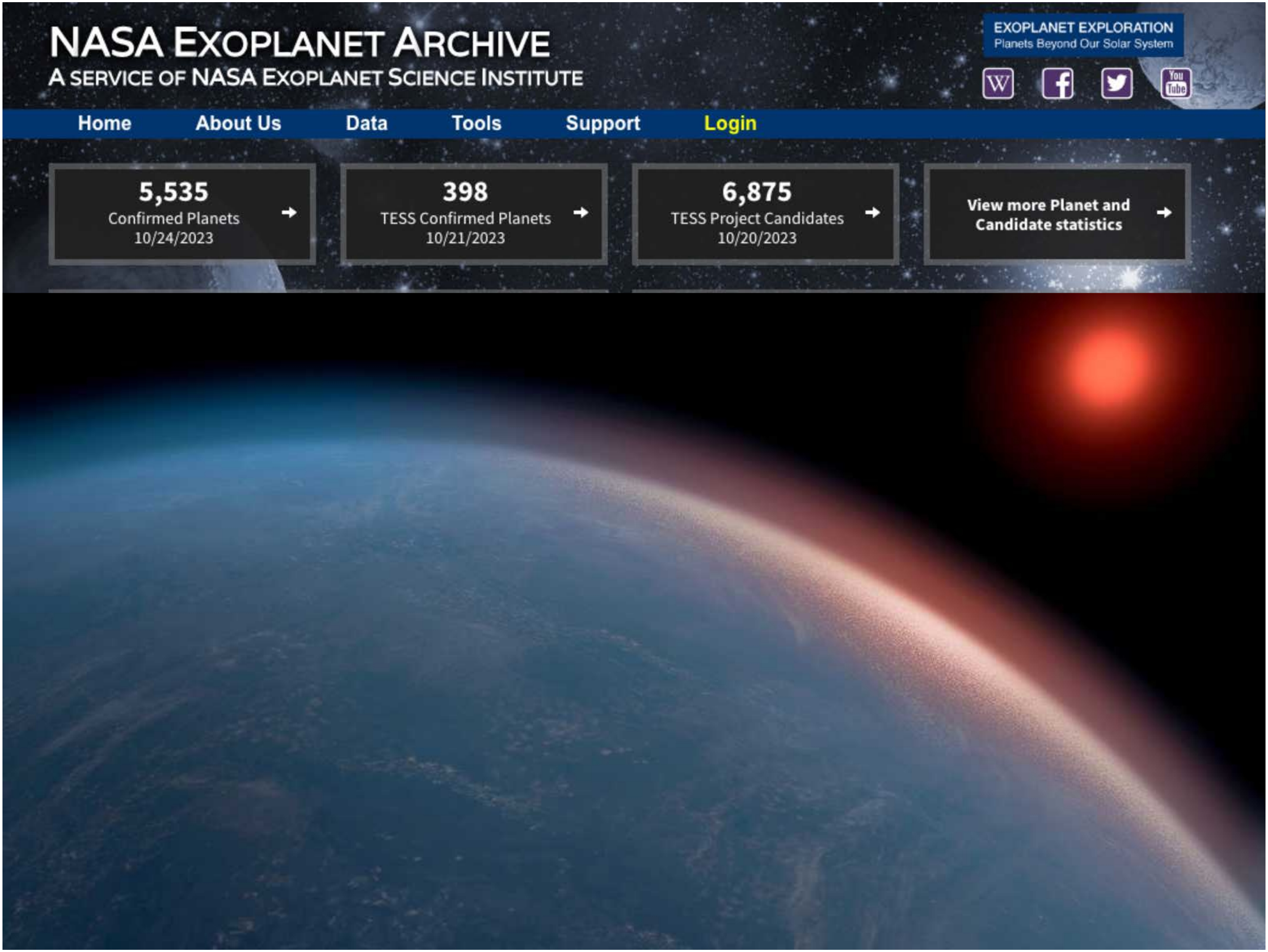








NASA EXOPLANET ARCHIVE

A SERVICE OF NASA EXOPLANET SCIENCE INSTITUTE

5,535
Confirmed Planets
10/24/2023

398
TESS Confirmed Planets
10/21/2023

6,875
TESS Project Candidates
10/20/2023

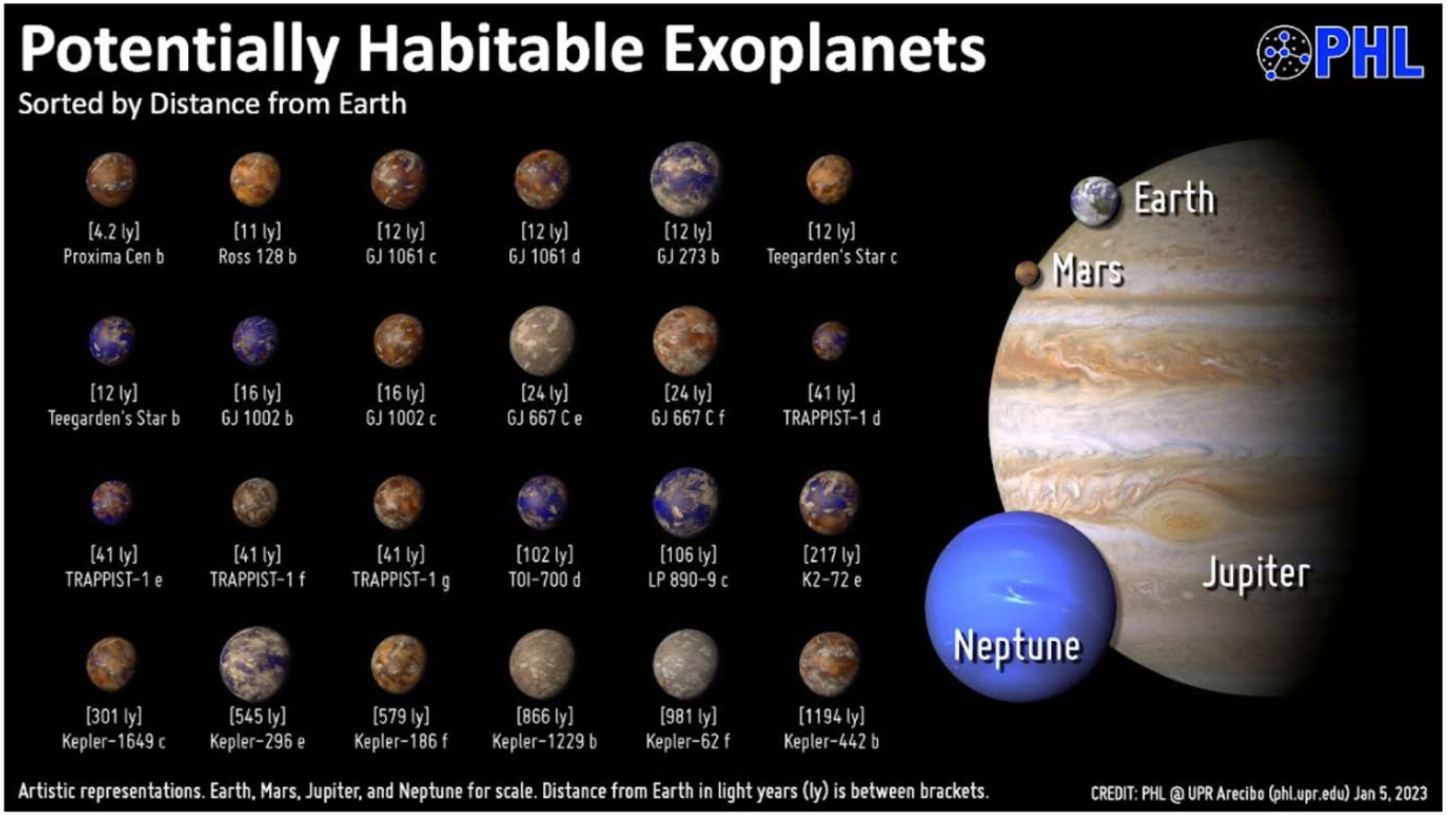
View more Planet and Candidate statistics

Current Numbers of Potentially Habitable Worlds

Subterran	Terran	Superterran	Total
1	23	39	63
(Mars-sized) 0.1 — 0.5 M_E or 0.4 — 0.8 R_E.	(Earth-sized) 0.5 — 3 M_E or 0.8 — 1.6 R_E	(Super-Earth/Mini-Neptunes) 3 — 10 M_E or 1.6 — 2.5 R_E	

24 – conservative

63 – optimistic



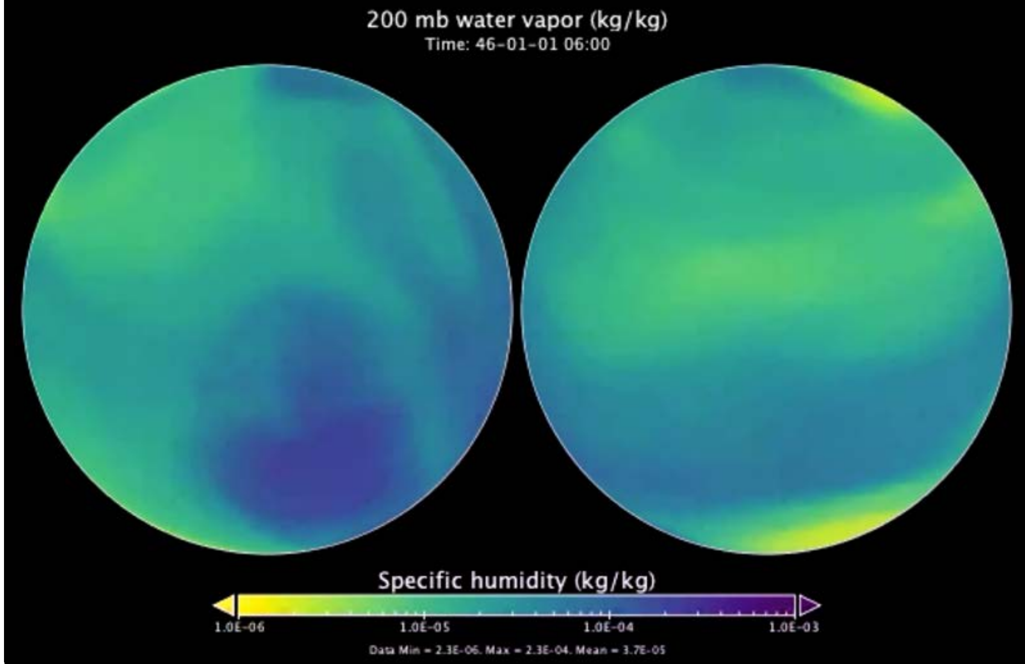
Potentially Habitable Exoplanets

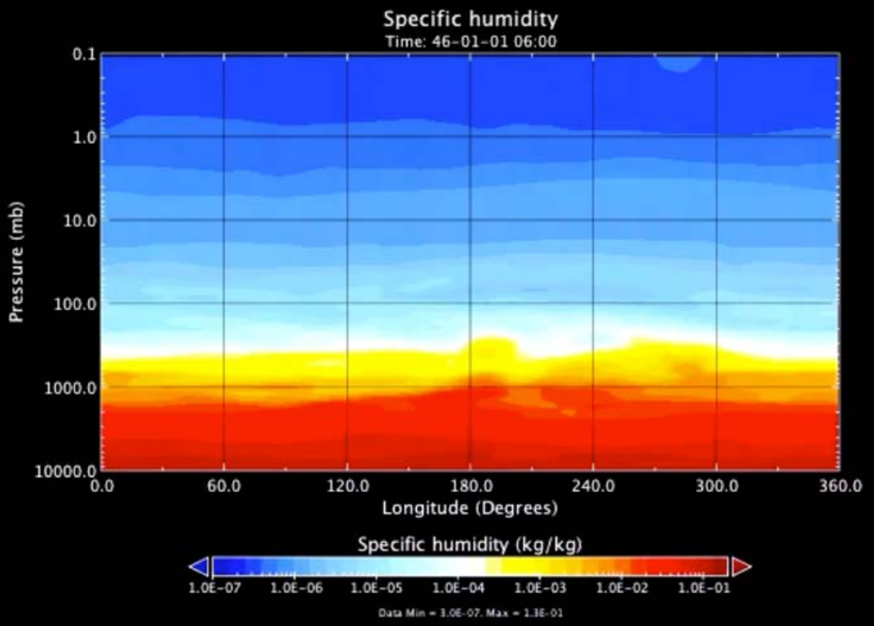
Sorted by Distance from Earth

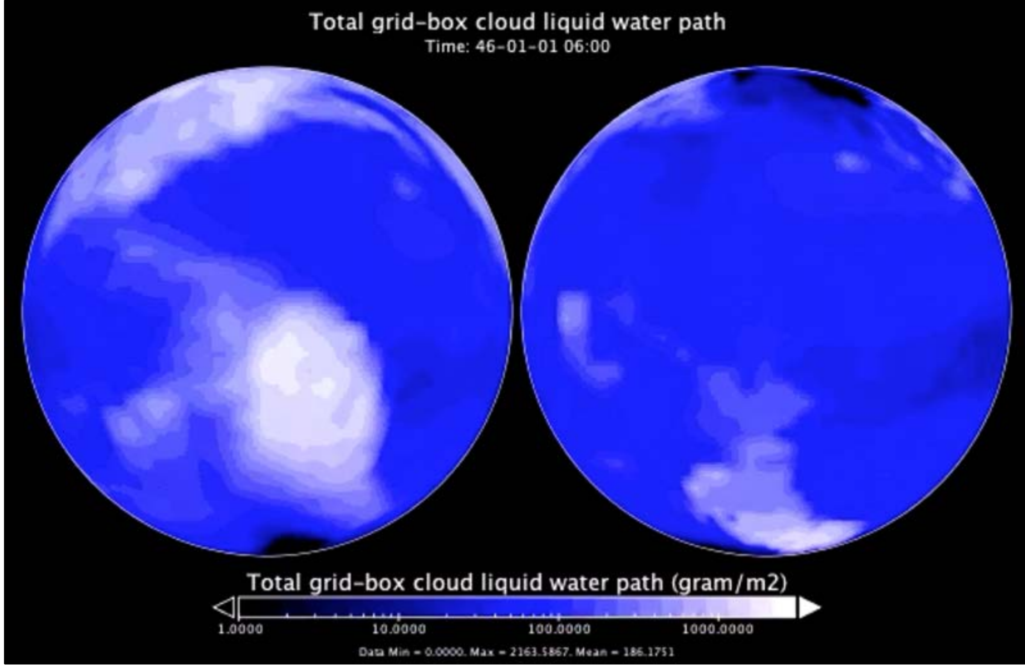
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth in light years (ly) is between brackets.

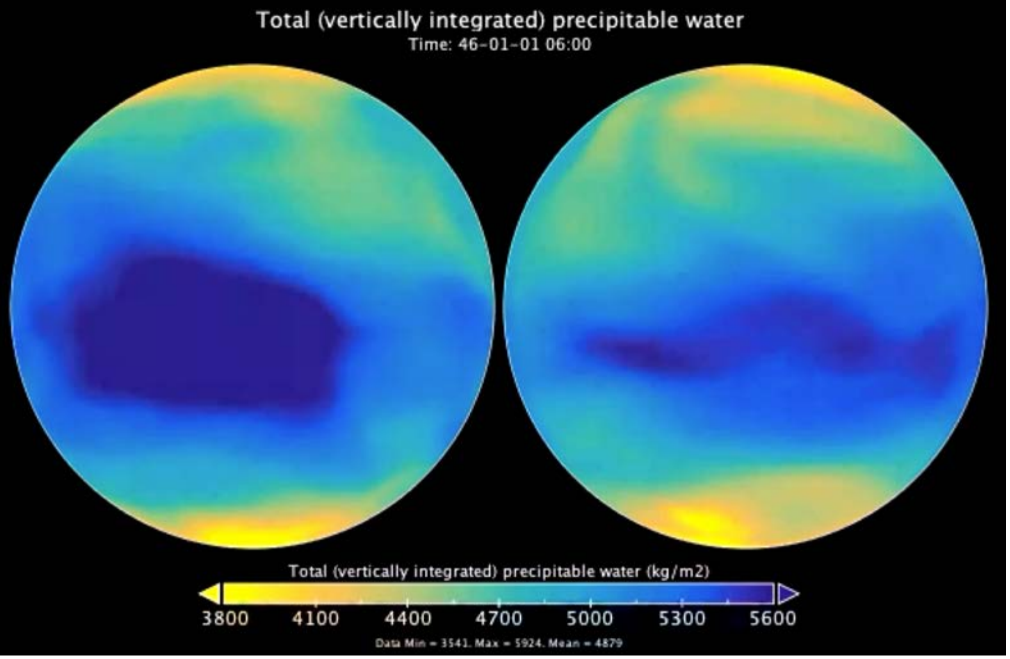
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Jan 5, 2023

The door has been opened to a new frontier of observation and theory of the weird, wild, and infinitely diverse world of exoplanetary atmospheres


200 mb water vapor (kg/kg)
Time: 46-01-01 06:00


Specific humidity
Time: 46-01-01 06:00


Total grid-box cloud liquid water path
Time: 46-01-01 06:00

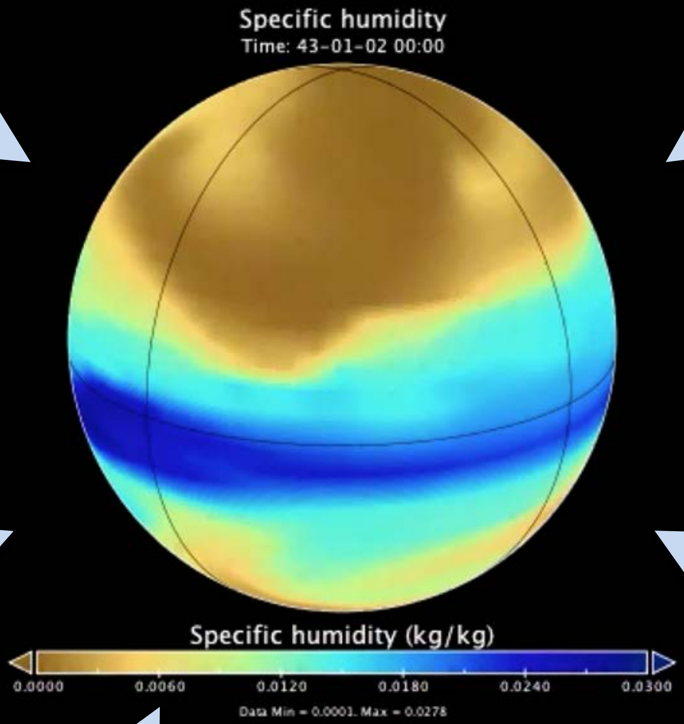

Total (vertically integrated) precipitable water
Time: 46-01-01 06:00

3D climate models can allow us to explore theories of exoplanetary atmospheres

dynamical core

clouds and aerosols

radiative transfer



surface processes

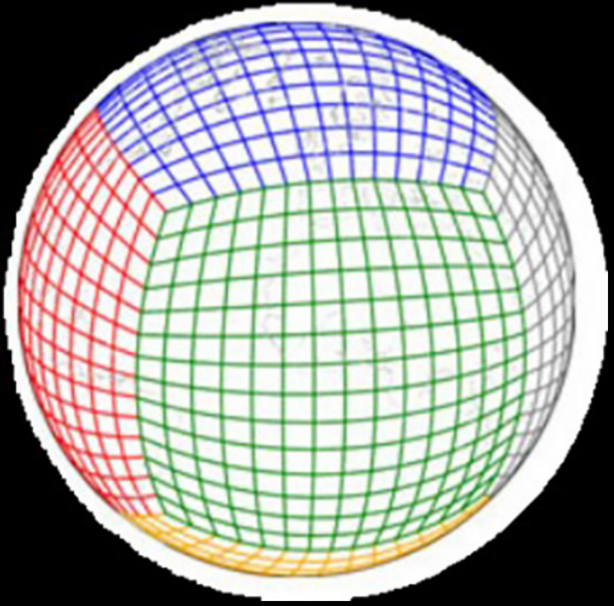
convection/ turbulence

chemistry

dynamic oceans

Two schools of thought for (exo)planet GCMS

1) Start with a dynamical core and iteratively build outward adding physics only as needed



Hot Jupiter models tend to follow this methodology.

Pros:

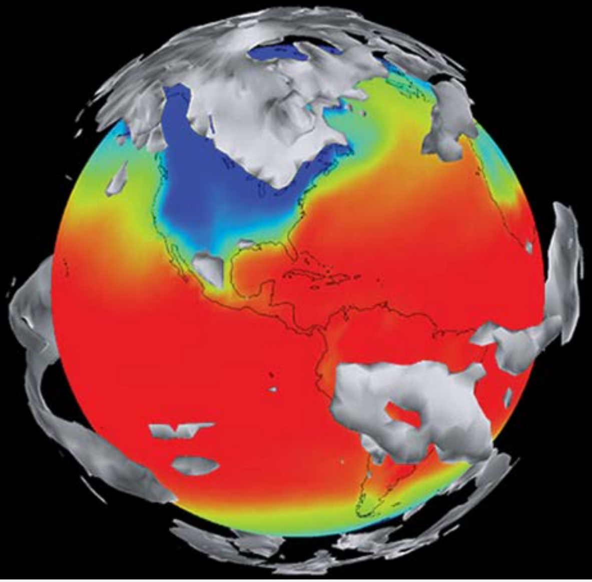
- Full control over model architecture
- Full control over development of model physics with a (exo)planetary perspective
- Avoidance of Earth-centric quirks typical of nationally supported climate system models

Cons:

- ***Very* difficult, time-consuming, and expensive to build a climate system model from scratch.**
- An element to reinventing the wheel, often easier/faster to adapt than create

Two schools of thought for (exo)planet GCMS

2) Start with a nationally supported climate system model and modify to suit your needs



Terrestrial planet models (exoplanet and solar system) tend to follow this methodology.

Pros:

- Leverages a wealth of legacy code developed for Earth-climate, much of which can be repurposed
- Much easier to get started for planetary modeling
- Earth centric models are reasonably suitable to many habitable worlds scenarios

Cons:

- Must adapt to the architecture of the parent model, which can result in messy linkages.
- Earth-centric routines and constants may remain hidden in the code and cause unknown issues
- The radiative transfer almost always needs to be generalized for diverse exoplanets.

Physics implemented in GCMs is reasonably flexible, allowing simulation of terrestrial exoplanets

We can model a generic terrestrial class planet and its evolution, by simply changing a few things…

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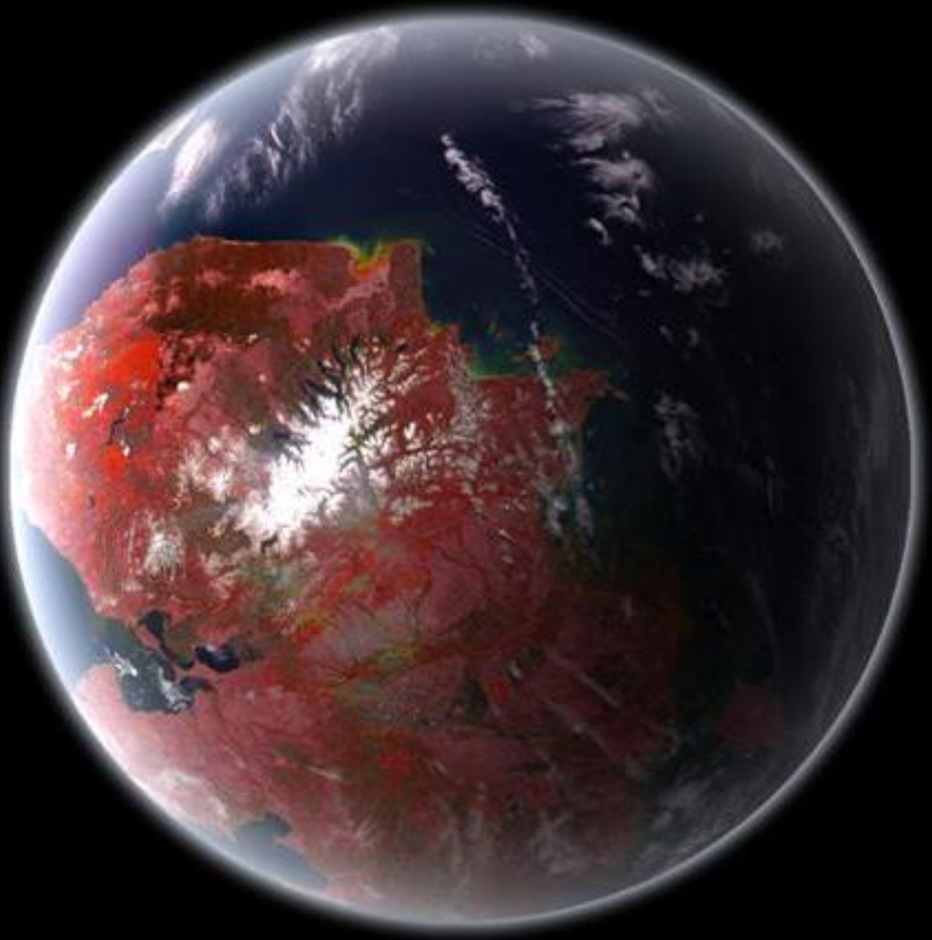
changing surface boundary conditions

continents
ocean
permanent glaciers
albedo properties
soil properties
topography

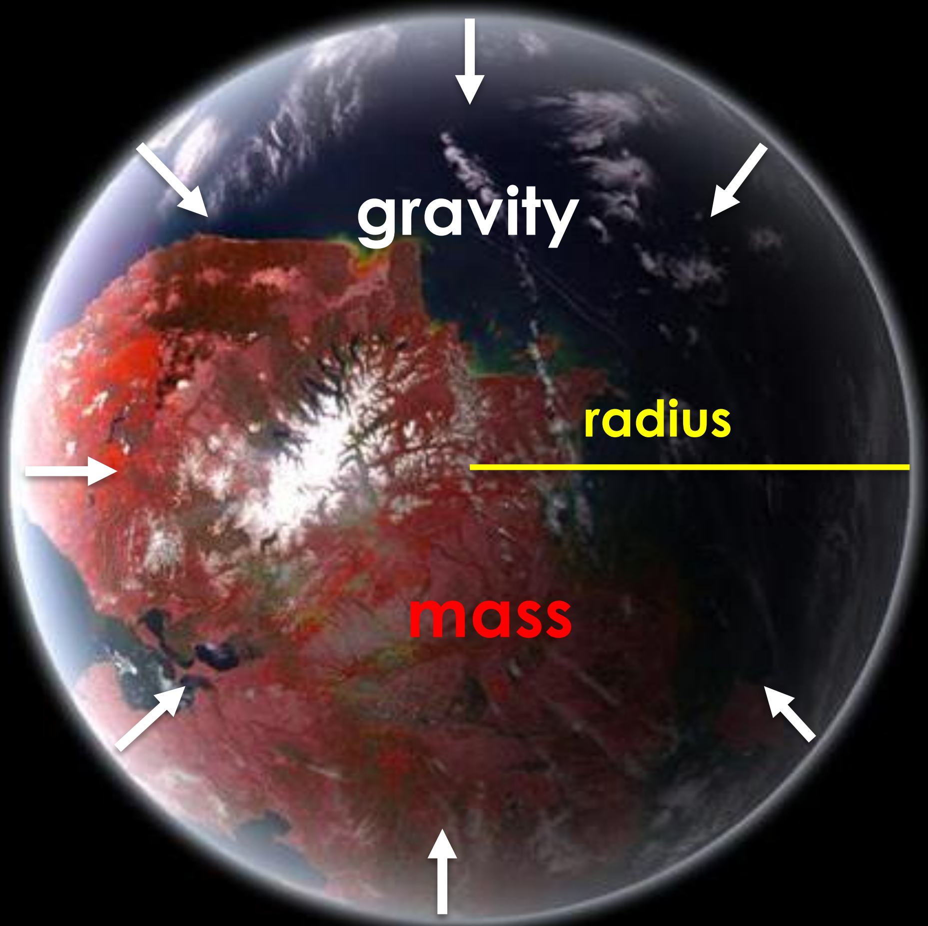


*Generally straight forward, but can be *extremely tedious.*
i.e. see CESM Paleo Climate Took Kit

We can model a generic terrestrial class planet and its evolution, by simply changing a few things…

changing geophysical properties

mass
radius
surface gravity

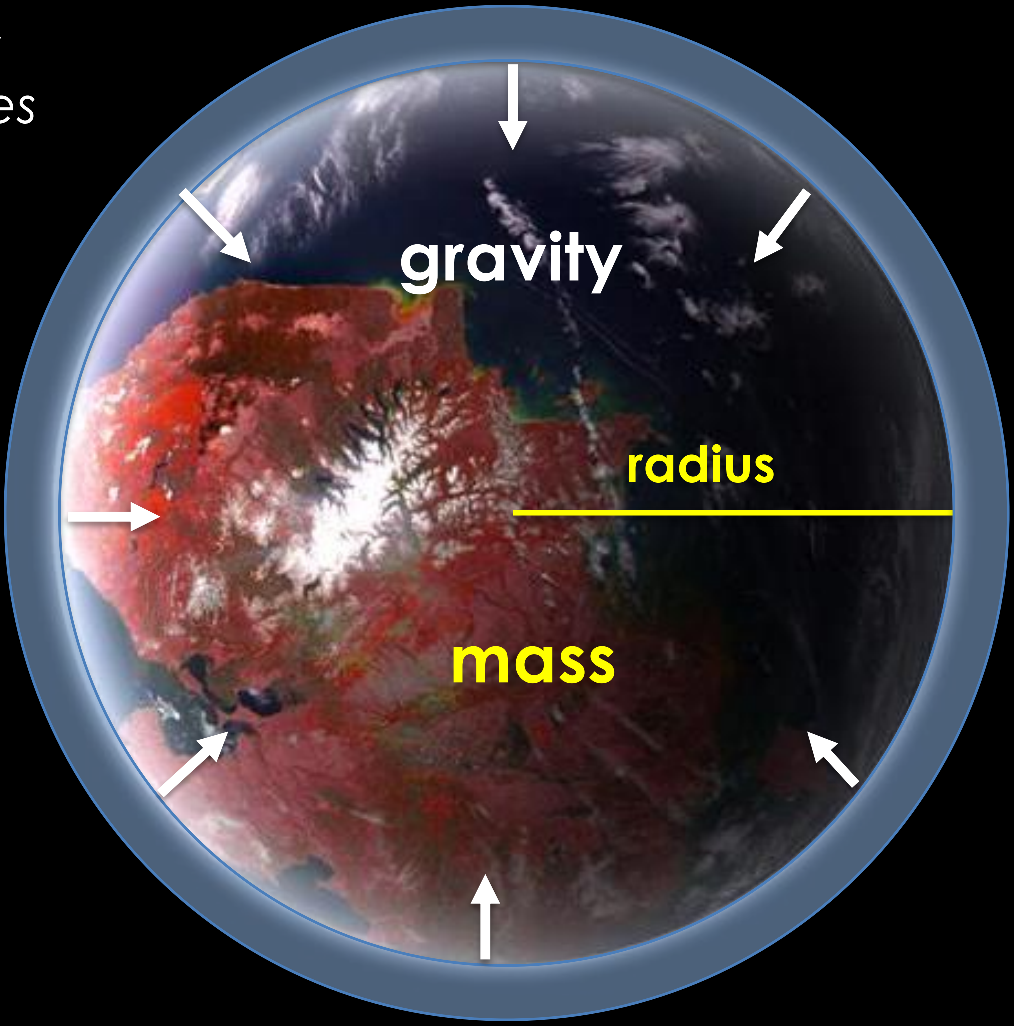


*Straight forward, easy

We can model a generic terrestrial class planet and its evolution, by simply changing a few things…

changing the atmospheric composition

total pressure
greenhouse species
condensable species

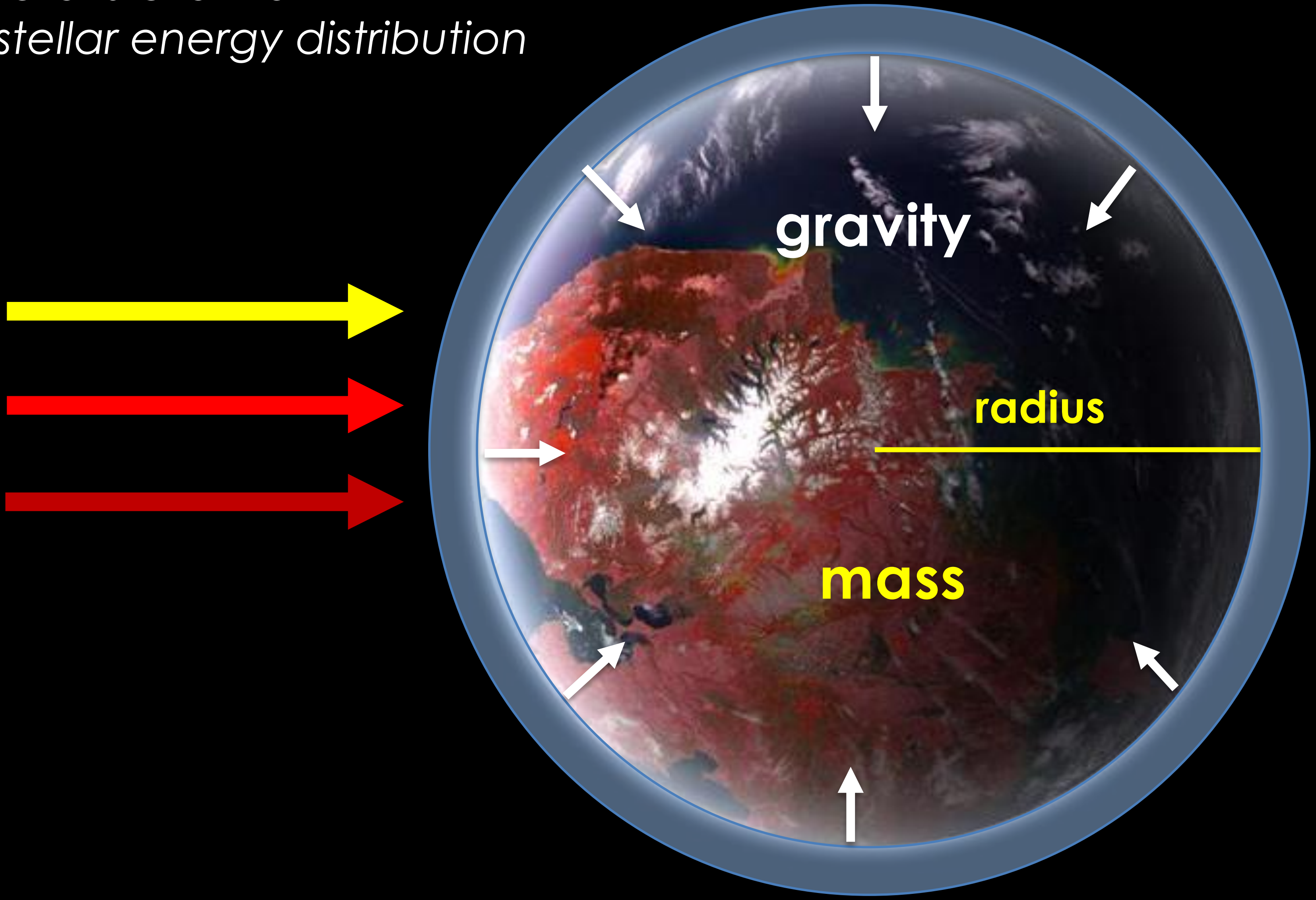


*Typically requires implementation of new flexible radiative transfer schemes to accurately handle compositions other than modern Earth

We can model a generic terrestrial class planet and its evolution, by simply changing a few things…

changing the stellar input

total stellar flux
stellar energy distribution

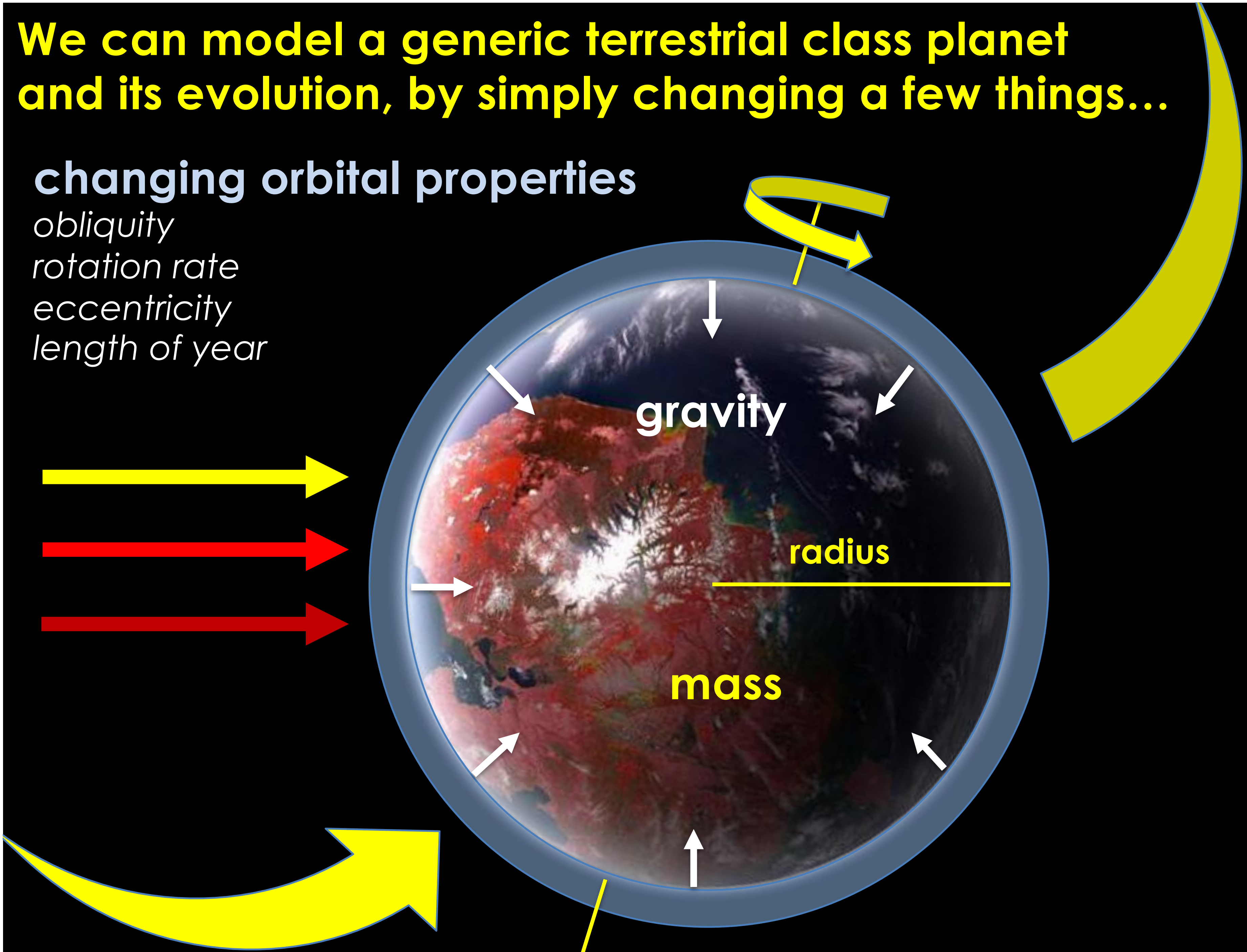


*Straight forward, easy (once new radiation implemented).

We can model a generic terrestrial class planet and its evolution, by simply changing a few things…

changing orbital properties

obliquity
rotation rate
eccentricity
length of year

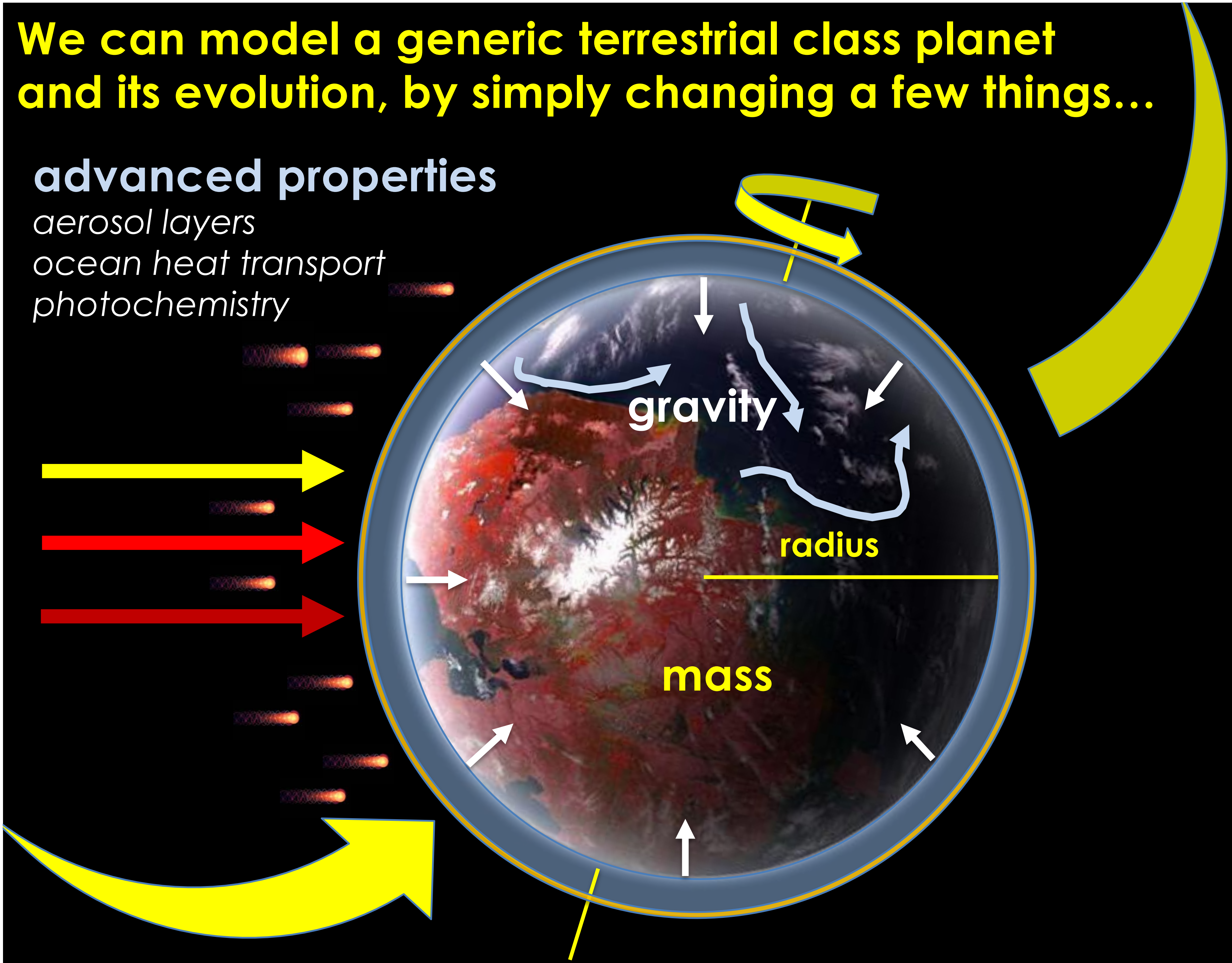


*Not terribly difficult, but time keeping and output systems tend to be tied to Julian or Gregorian calendars, so care must be taken in integrating alien calendars.

We can model a generic terrestrial class planet and its evolution, by simply changing a few things…

advanced properties

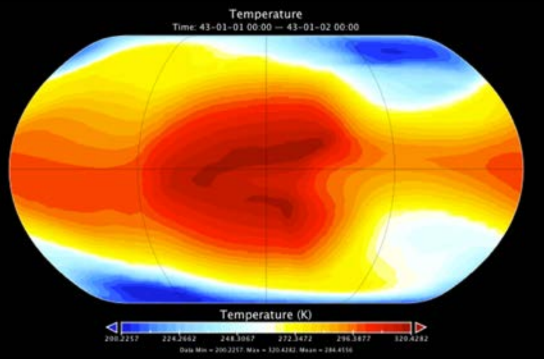
aerosol layers
ocean heat transport
photochemistry



*Hit or miss depending on the model.

3D GCMs used to simulate extrasolar planets

an incomplete list



GFDL FMS (intermediate complexity)

MITGCM – SPARC (idealized, gas giants)

PlaSim (intermediate complexity)

CCSR/NIES AGCM5.4g -> DRAMATIC (terrestrial)

LMD Generic Climate Model -> PGCM (terrestrial)

Met Office United Model -> LFRIC (terrestrial, gas giants)

NASA GISS Model E/ROCKE-3D (terrestrial) **(I work with RT, SOCRATES)**

NCAR CESM, ExoCAM (terrestrial) **(I developed from grad school to now)**

3D climate models have been used for a wide variety of studies - too much to reasonable broach in a 12 minute talk

Including:

defining the habitable zone

inner edge – moist and runaway greenhouse

outer edge – dense CO_2 atmospheres, snowball

tidally locked planets around M-dwarfs

Proxima Cen b, Trappist-1 system, TOI-700 d,

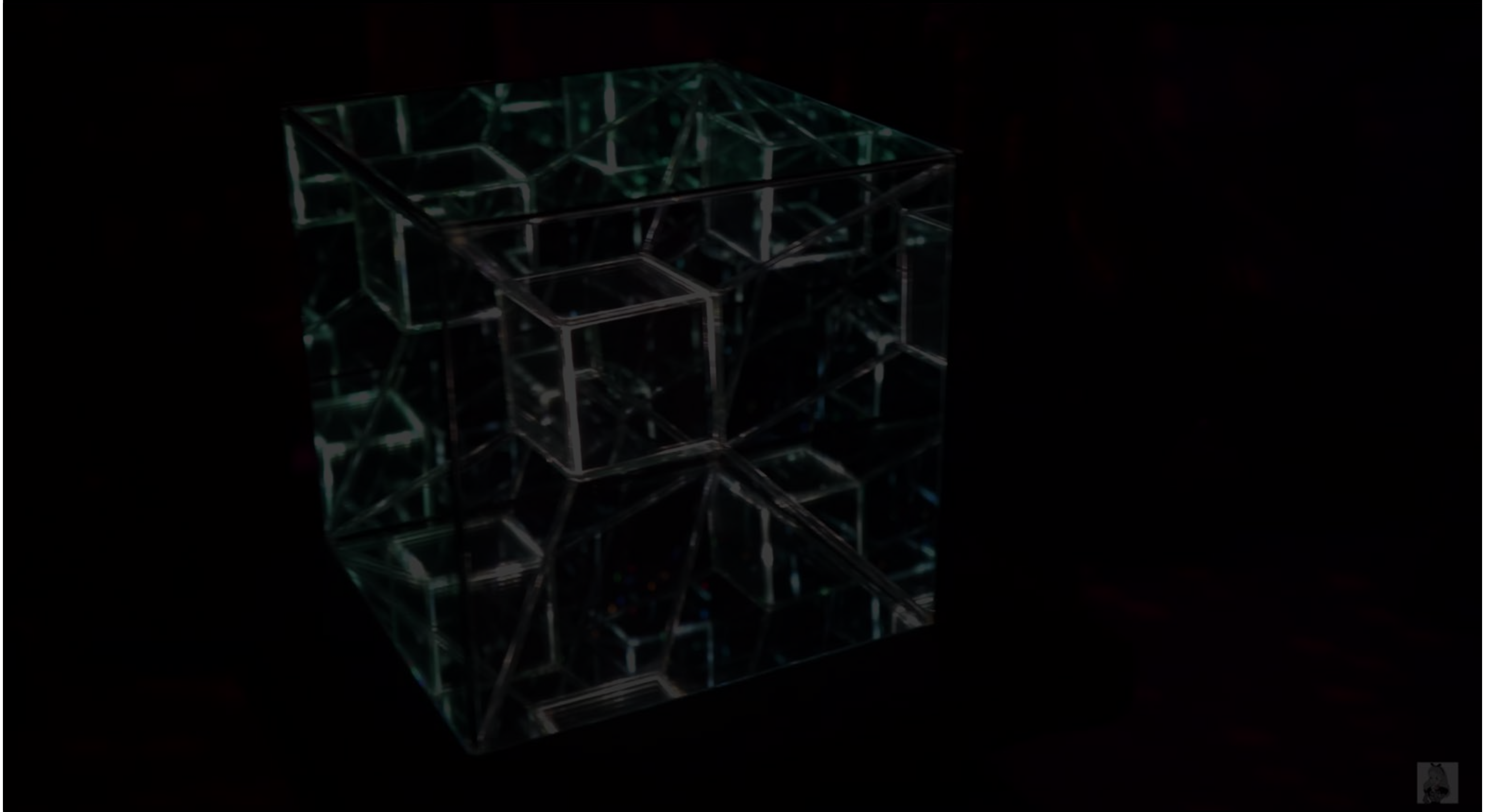
flavors of exoEarths

*S_0, stellar spectra, Mass/Radius/gravity, total pressure, greenhouse gases, H_2O inventory, rotation rate, eccentricity, obliquity, ocean heat transport, continental configuration, surface albedos, haze and dust, photochemistry, flares (**LOTS OF PARAMETERS)***

observability

transmission spectra, reflected spectra, thermal emission phase curves, effects of clouds and hazes

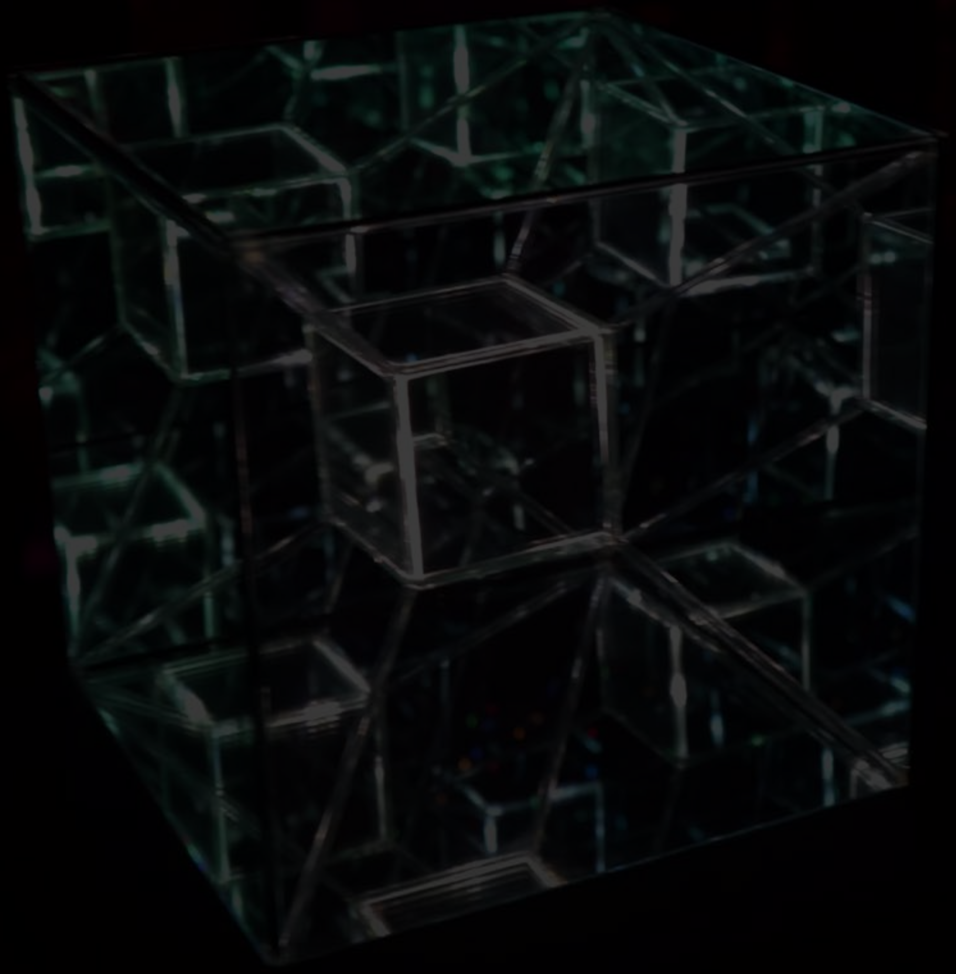
Where is the field going next?



Where is the field going next?

a desire to connect strongly with observations…

to move beyond our theoretical climate sandbox…



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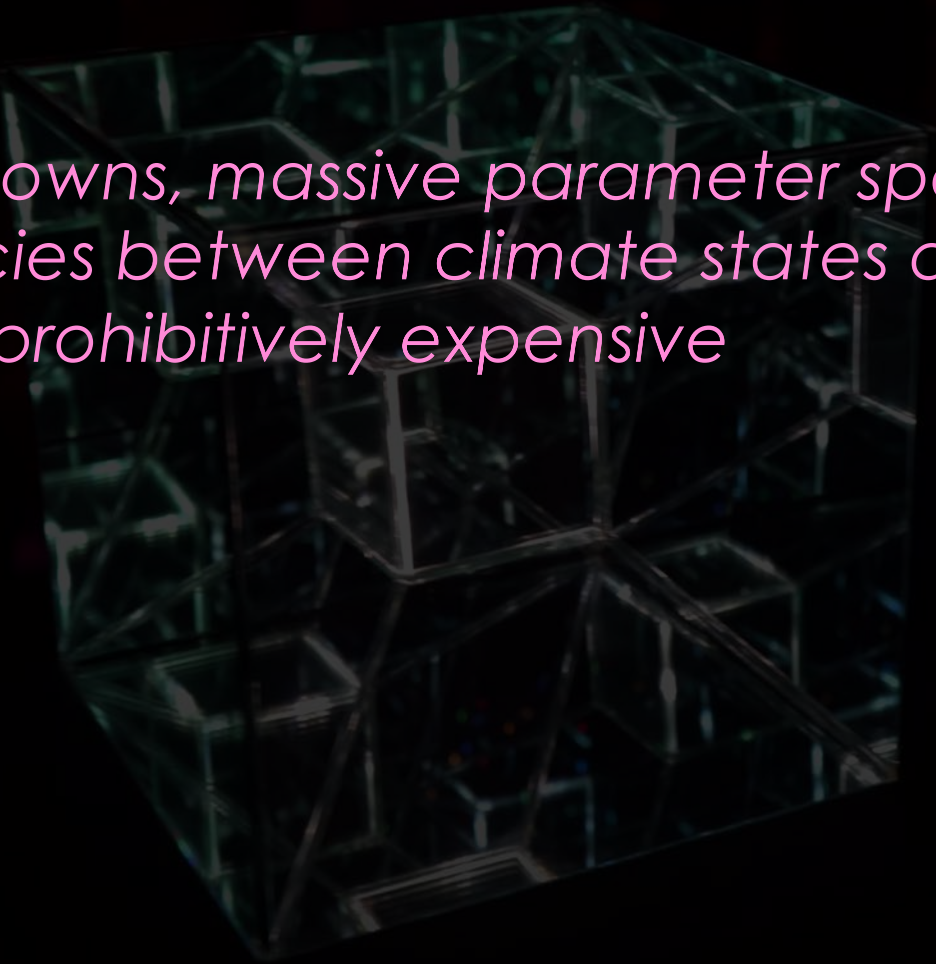
Problems:

many unknowns, massive parameter spaces to explore
degeneracies between climate states and observations
GCMs are prohibitively expensive



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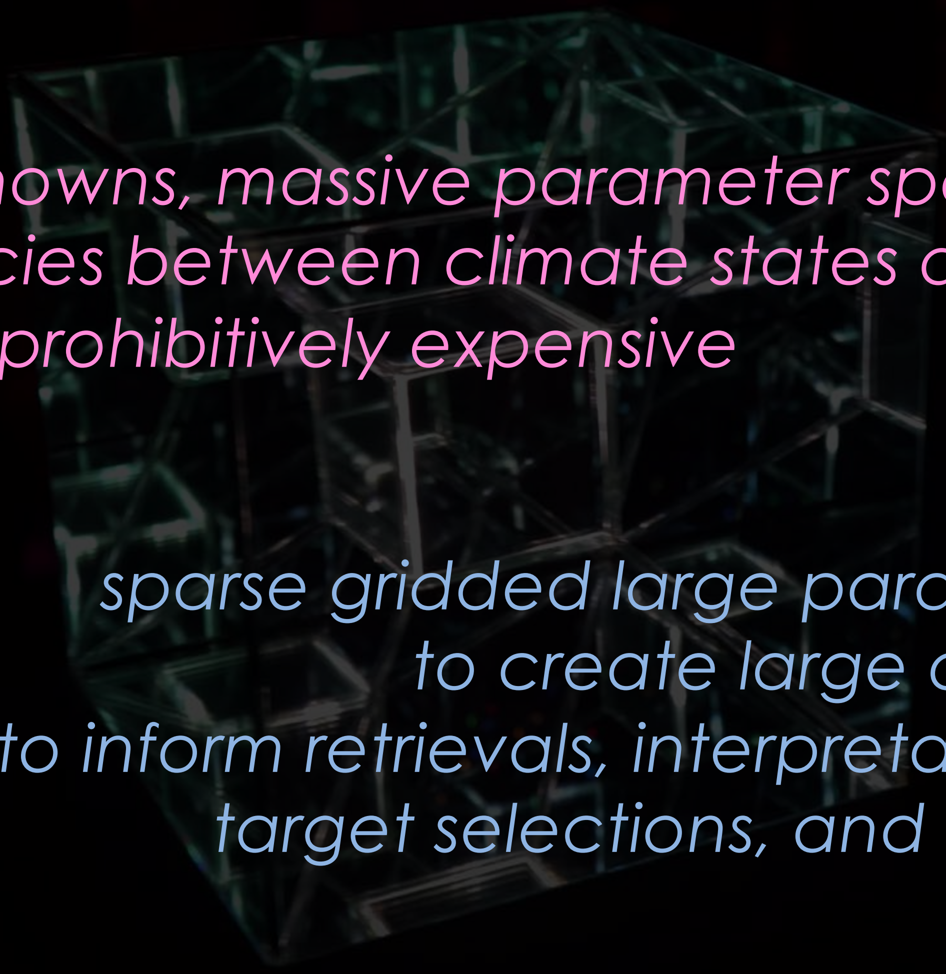

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degeneracies between climate states and observations
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Solution:

sparse gridded large parameter space studies,
to create large databases of models,
to inform retrievals, interpretations of observations,
target selections, and future mission design.

\Talk

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