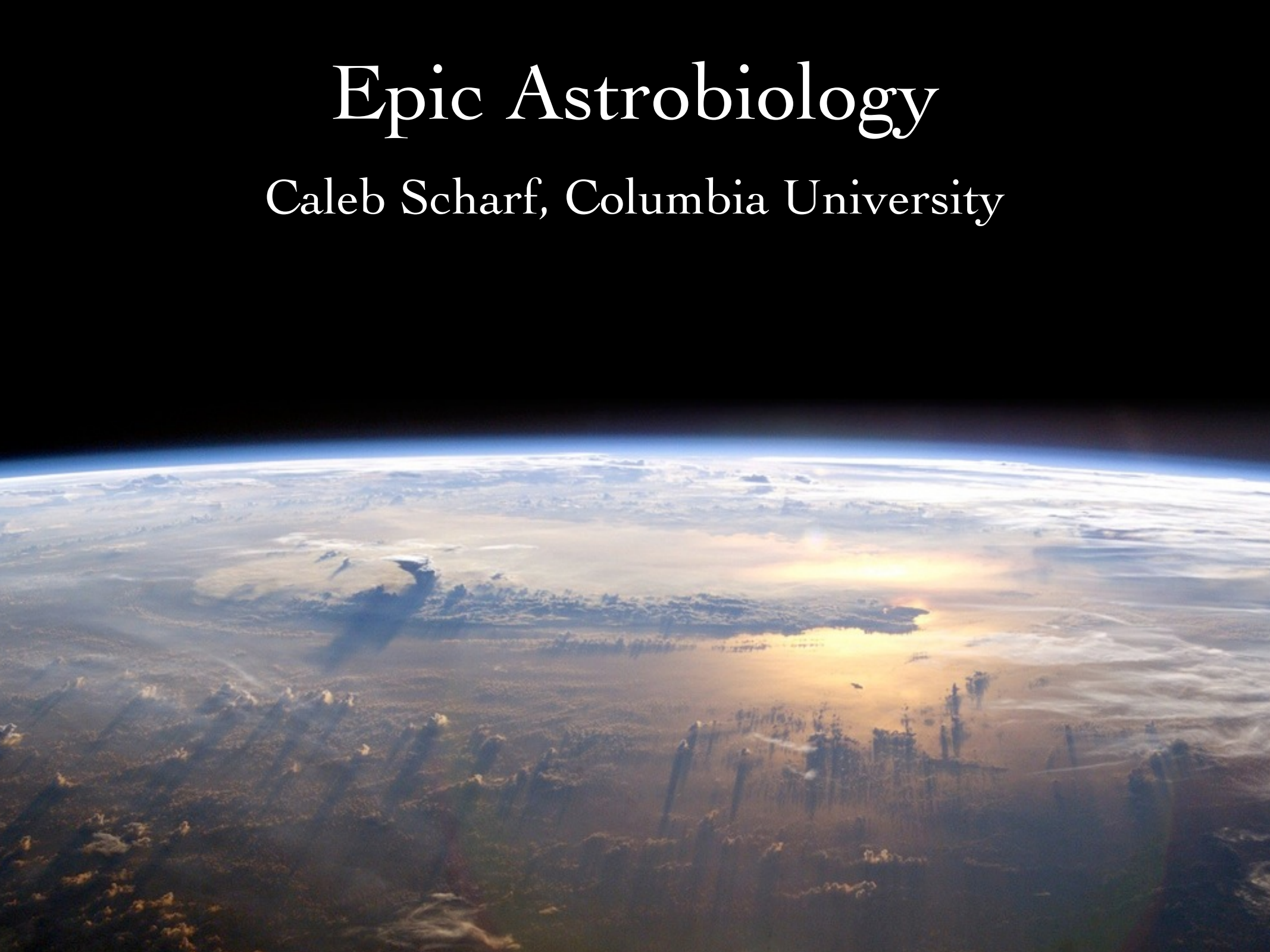
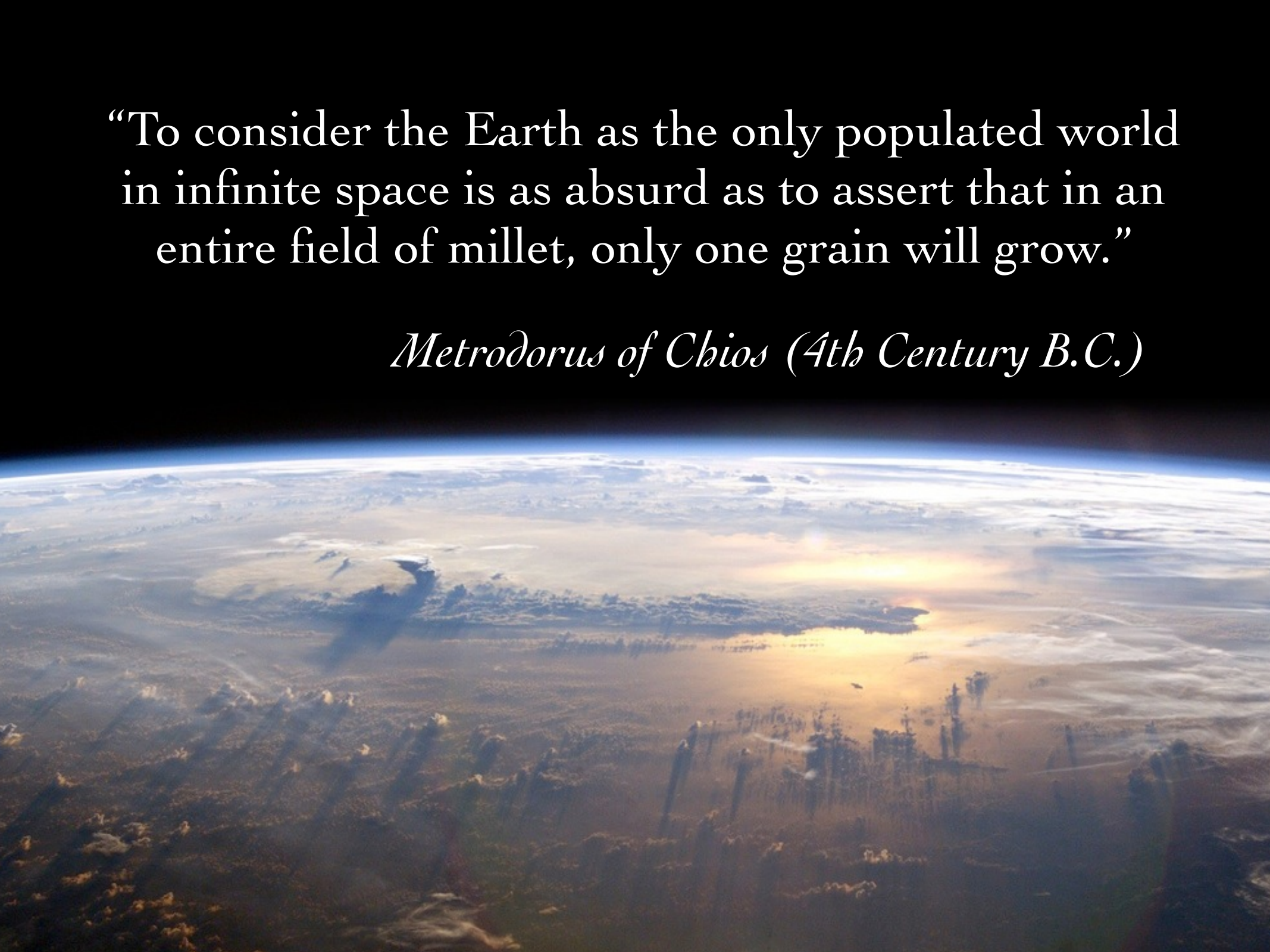
Epic Astrobiology

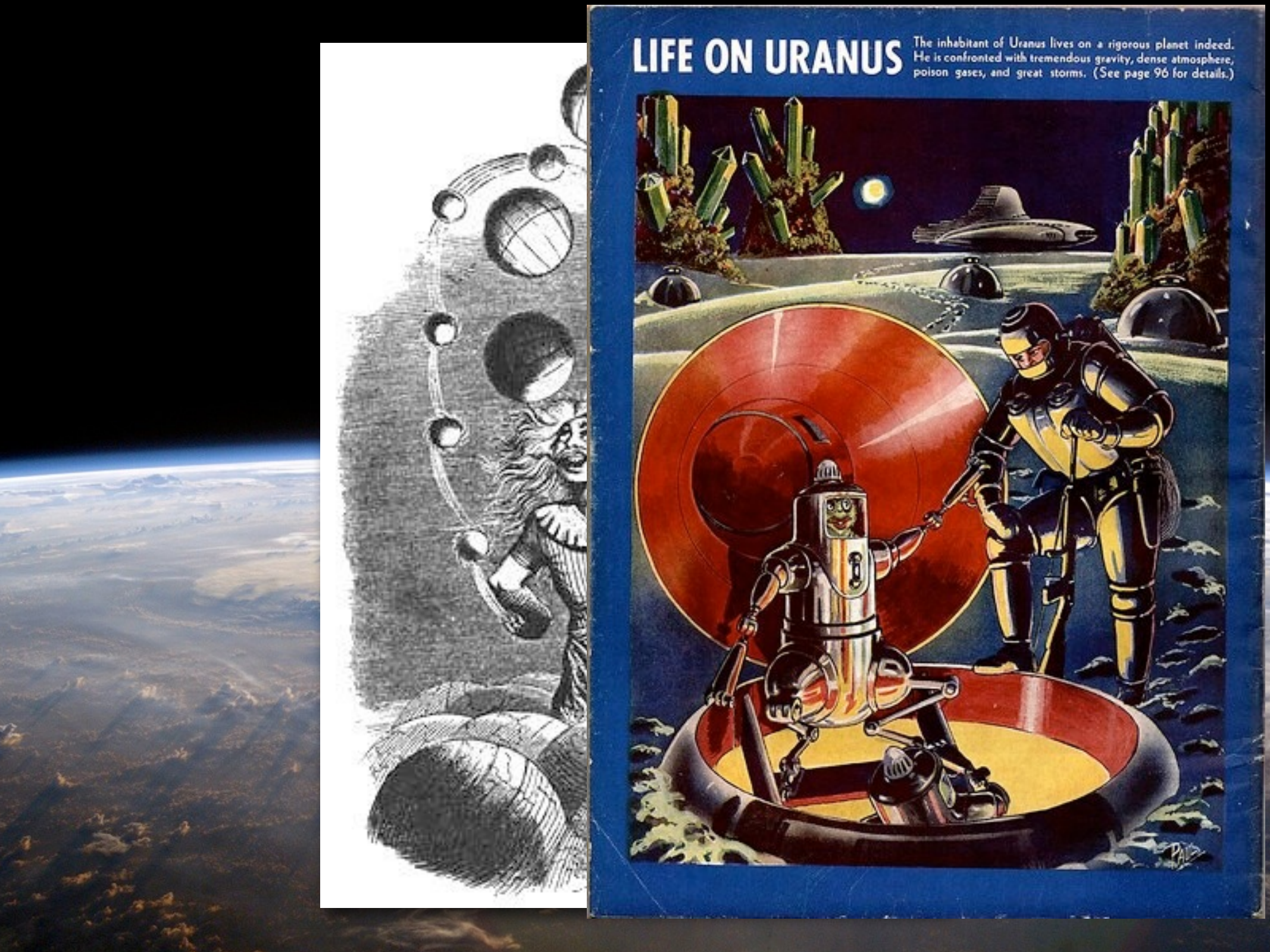
Caleb Scharf, Columbia University



"To consider the Earth as the only populated world in infinite space is as absurd as to assert that in an entire field of millet, only one grain will grow."

Metrodorus of Chios (4th Century B.C.)




LIFE ON URANUS
The inhabitant of Uranus lives on a rigorous planet indeed. He is confronted with tremendous gravity, dense atmosphere, poison gases, and great storms. (See page 96 for details.)

LIFE ON SATURN

Life on Saturn would evolve along insect line
light body, capable of walking spider-like ac
swampy, unstable surface. See page 97 for

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LIFE on TITAN

In this imaginative painting, artist Frank R. Paul has pictured his conception of the possible life forms that may inhabit Titan, the largest of the satellites of Saturn. Titan is larger than our moon, but how much larger is not definitely known. Some scientists believe that Saturn itself, a huge world, still retains enough heat of its own to radiate to its satellites, and thus make it possible that they support life forms. Mr. Paul imagines Titan as a primitive world, inhabited by monster lizards and dinosaurs. A world of swamps and of ferocious beasts and giant plants. For complete details see page 144.

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The MAN from MARS

by PAUL

We take our readers across space to meet the man from Mars. Alighting from our space ship, wearing a space suit, we greet the Martian who approaches. He is a strange looking individual. He has been evolved much differently than we because Mars is a smaller planet, has less gravity, a thin atmosphere, and extremes of heat and cold. He has large ears to catch sounds wasted by rarefied air. He communicates with his fellows by telepathy, using natural antenna. He is tall, walking with the aid of natural suction-type feet. He has magnificent lung development, and narrow, light body. He has retractable eyes and nose, to protect against freezing. His body, besides being protected by scientific garments, is covered with warm fur. Being the most advanced creature in the solar system, he carries an atomic rifle, the result of greater science knowledge. See Page 97.

LIFE ON URANUS

The inhabitant of Uranus lives on a rigorous planet indeed. He is confronted with tremendous gravity, dense atmosphere, poison gases, and great storms. (See page 96 for details.)

Modern Bayesian analysis

Life arose ‘quickly’ in first few 100 Myrs on Earth…

Evidence for high abiogenesis probability?

Spiegel & Turner 2011

Modern Bayesian analysis

Life arose 'quickly' in first few 100 Myrs on Earth

Evidence for high abiogenesis probability?

Not necessarily, choice of prior dominates posterior probability...life on Earth could be 1st in universe

However, *one independent* example of abiogenesis would push posterior rate to >1 per Gyr on suitable planets

Spiegel & Turner 2011

Where do we look?

What do we look for?

How will we know if we see it?

What is life on Earth - really?

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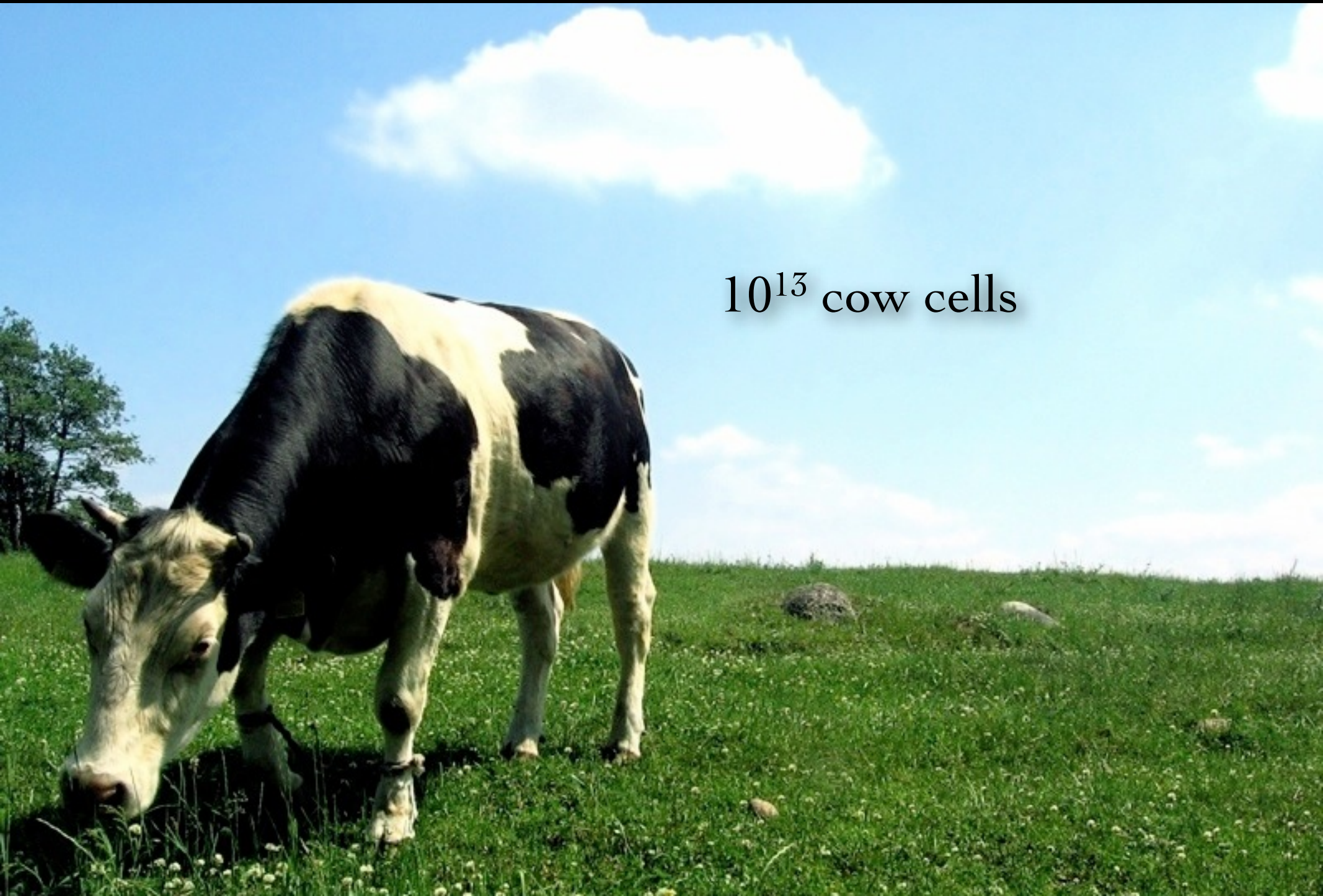
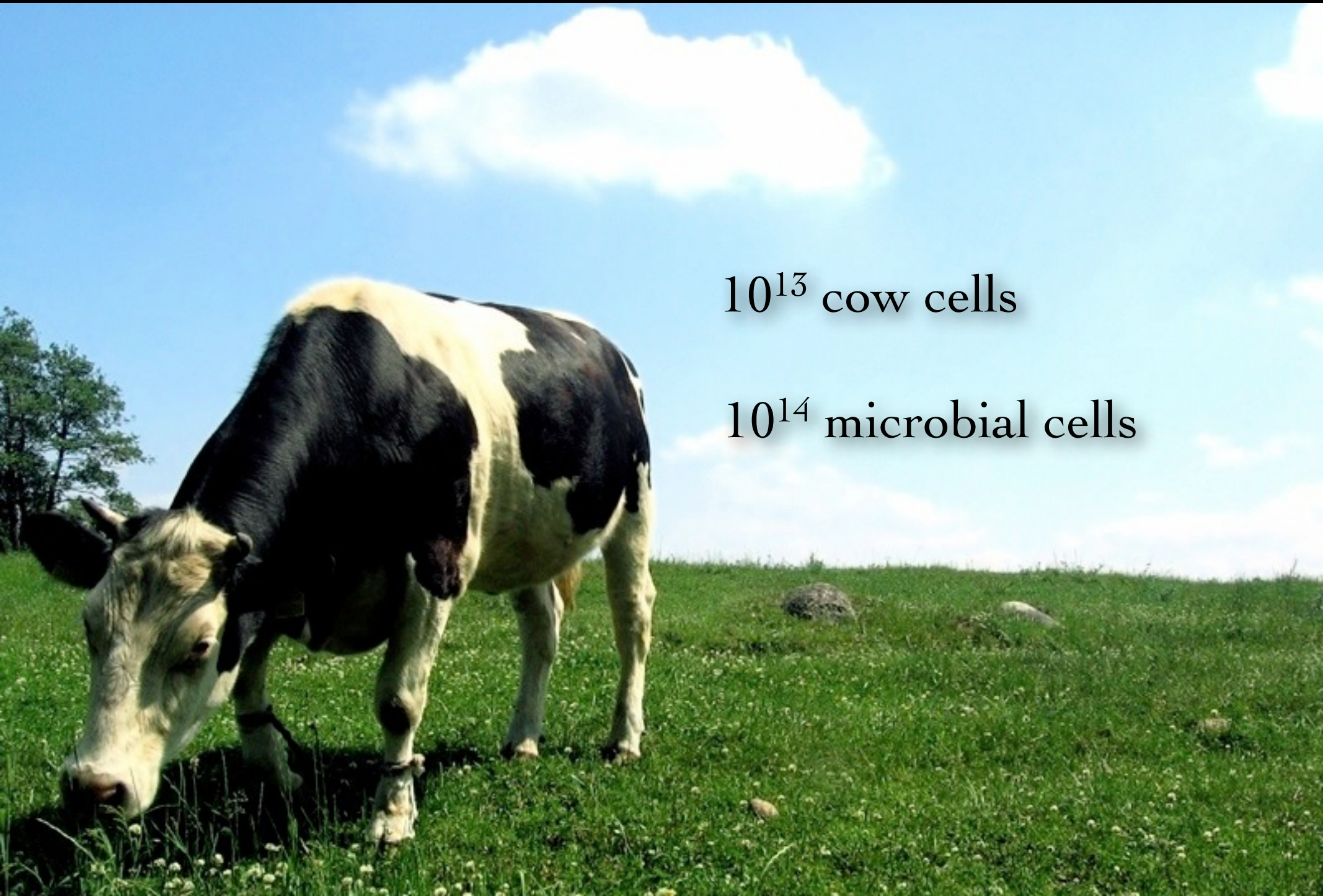
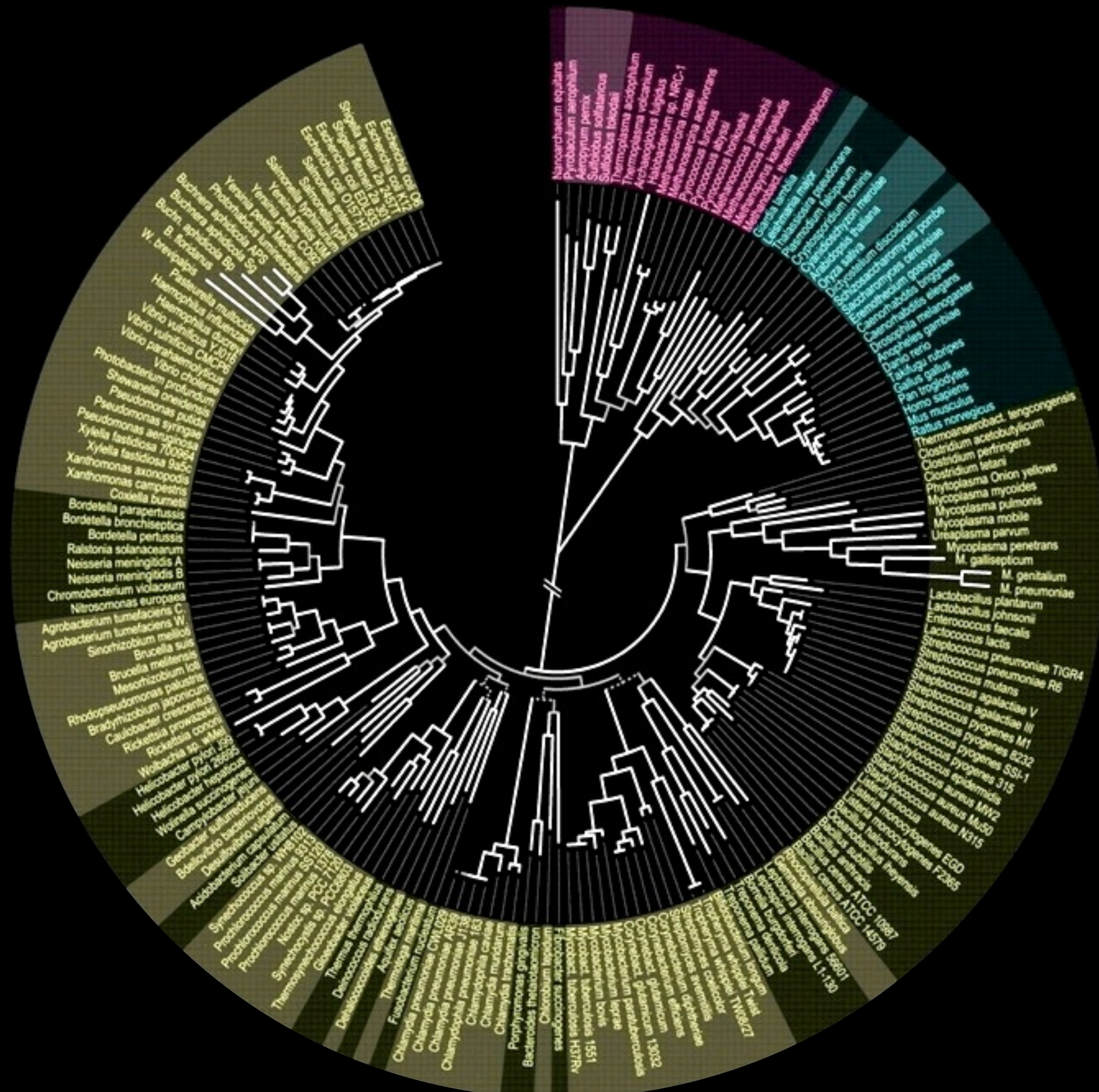


What is life on Earth - really?



Globally, life is mostly microbial: bacteria and archaea



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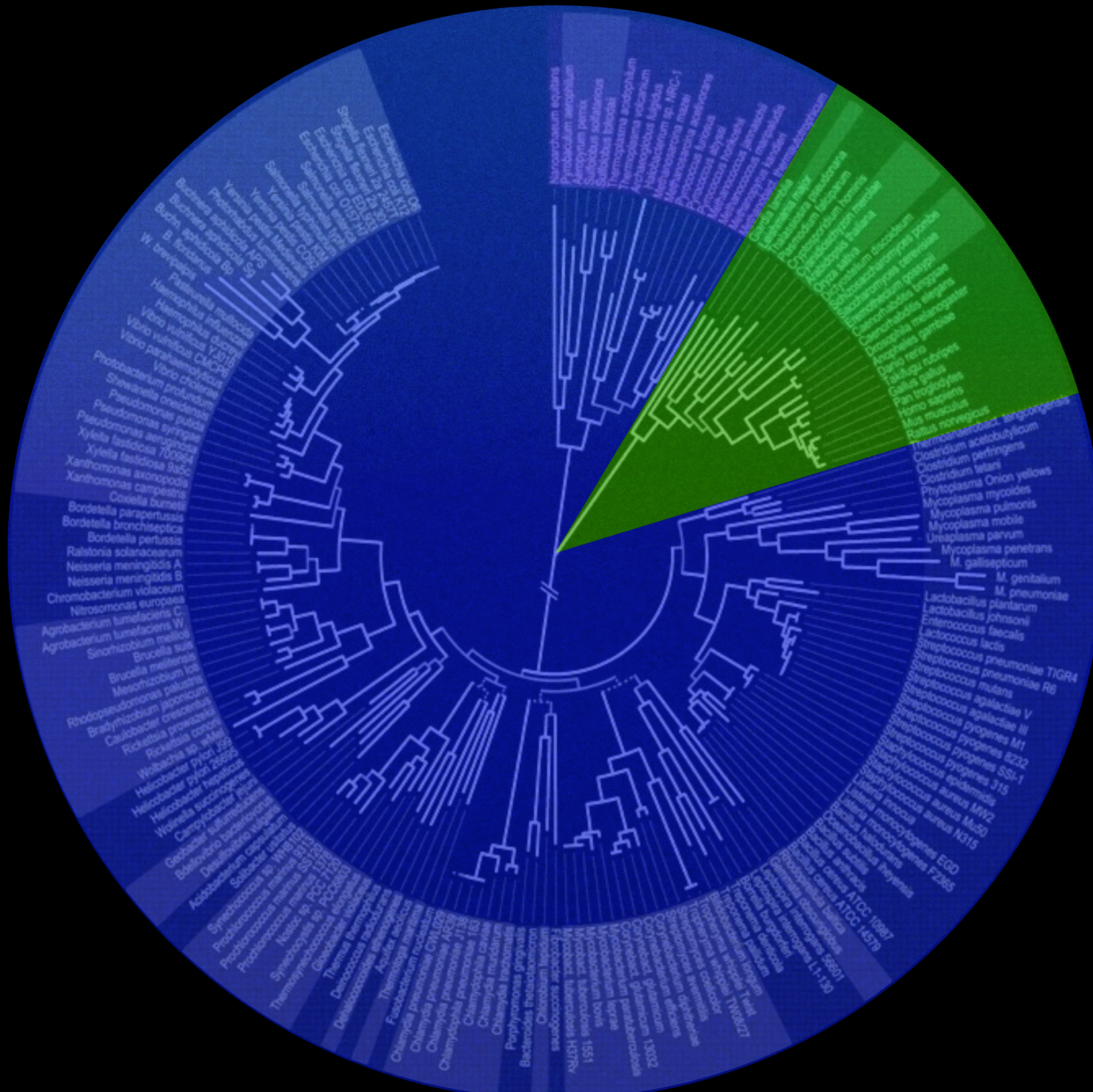
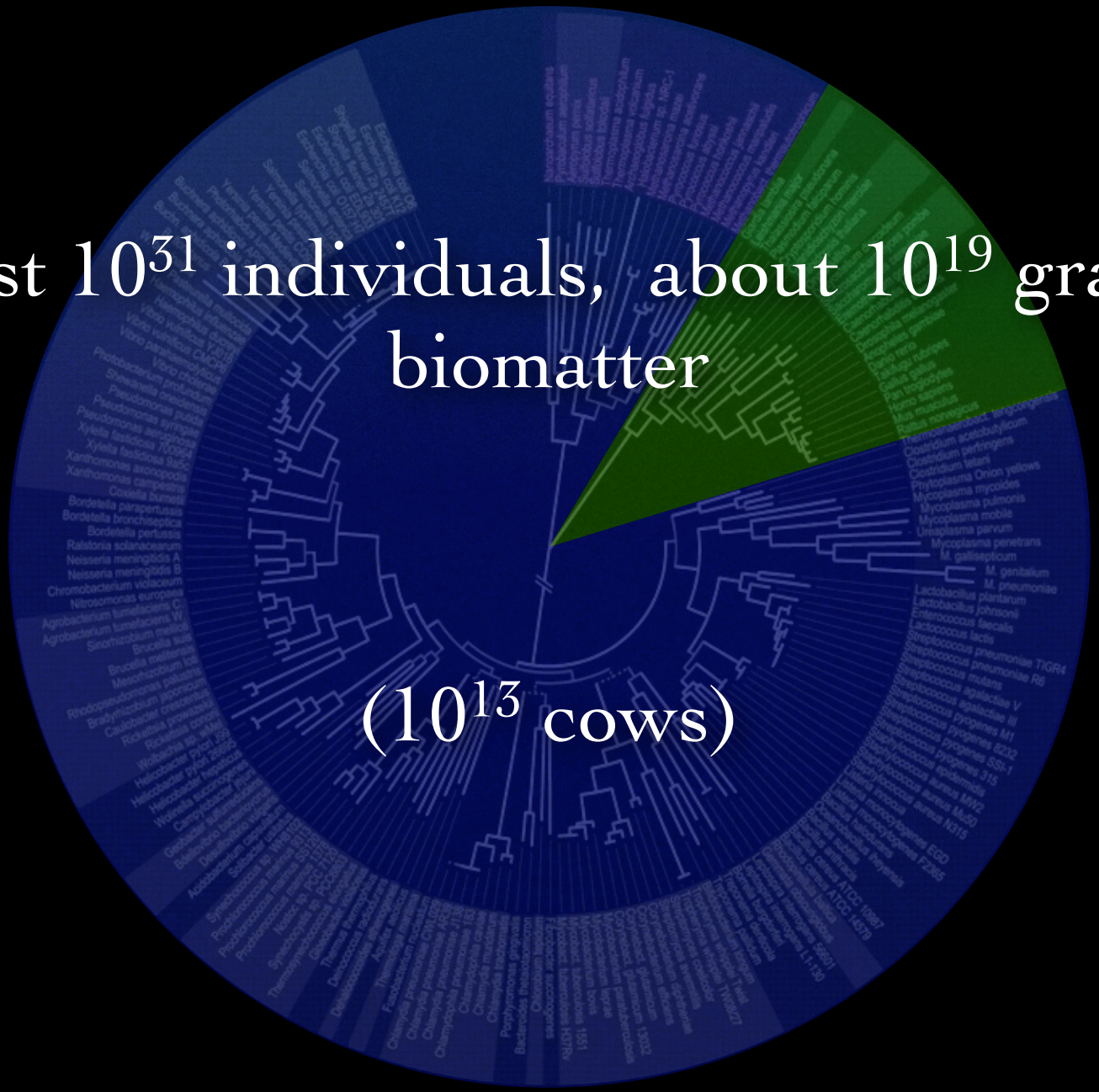


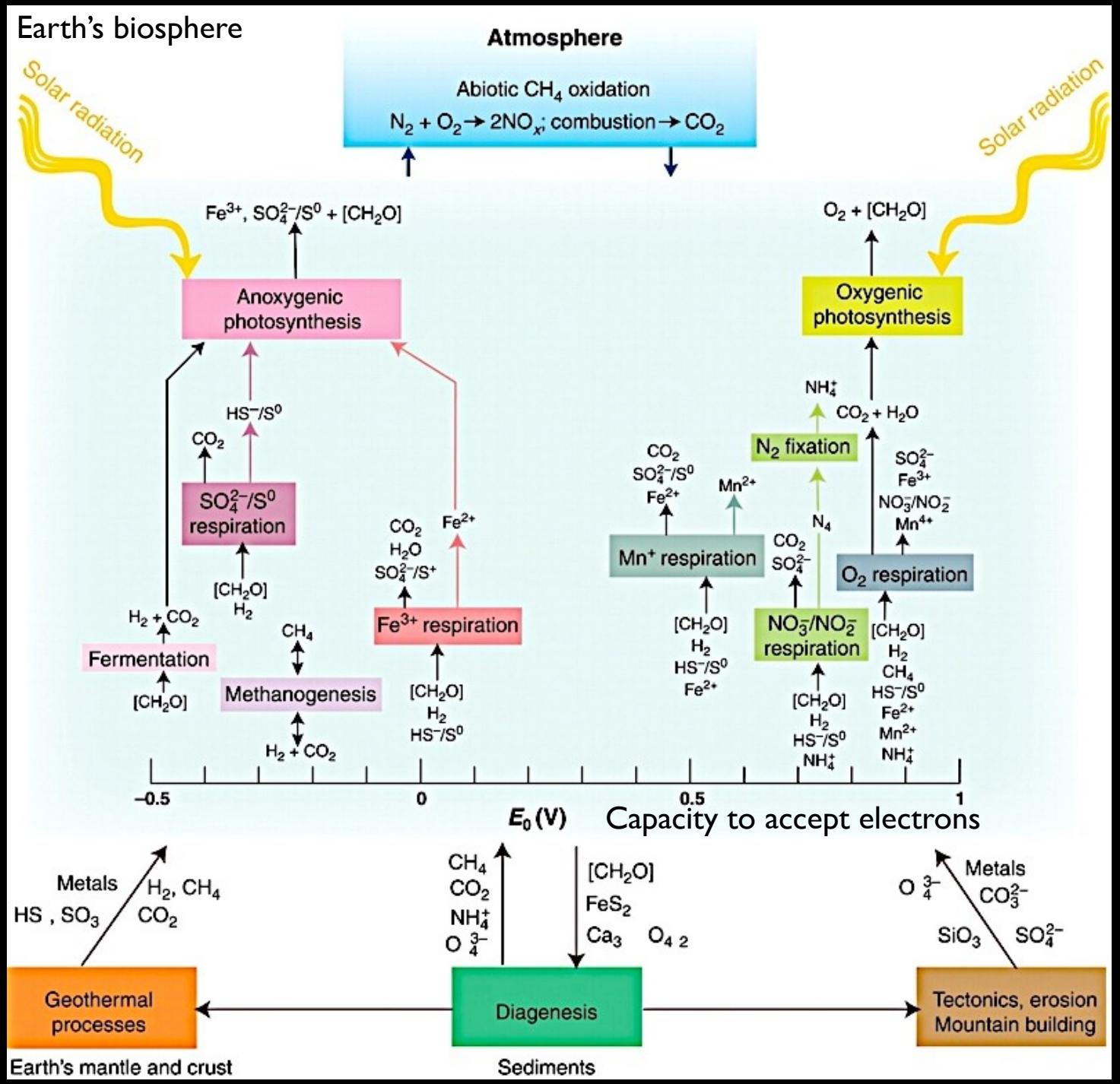
At least 10^{31} individuals, about 10^{19} grams of biomatter



(10^{13} cows)

Over the past 4 billion years, microbial metabolic processes have helped reshape the planet

Life on Earth harvests energy and brings electron donors and acceptors together (REDOX) in vast network of interleaved cycles...



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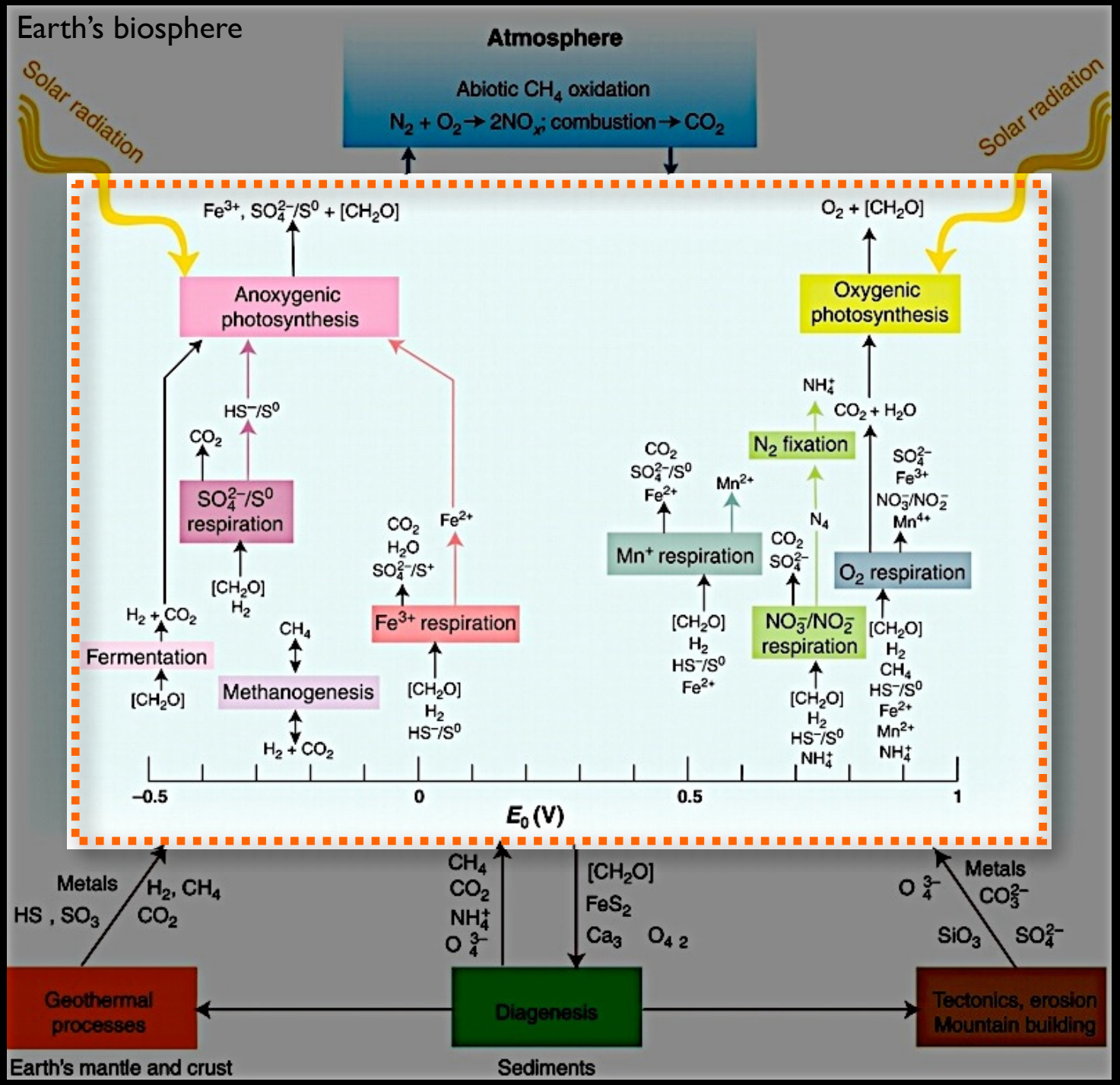

Life on Earth harvests energy and brings electron donors and acceptors together (REDOX) in vast network of interleaved cycles…

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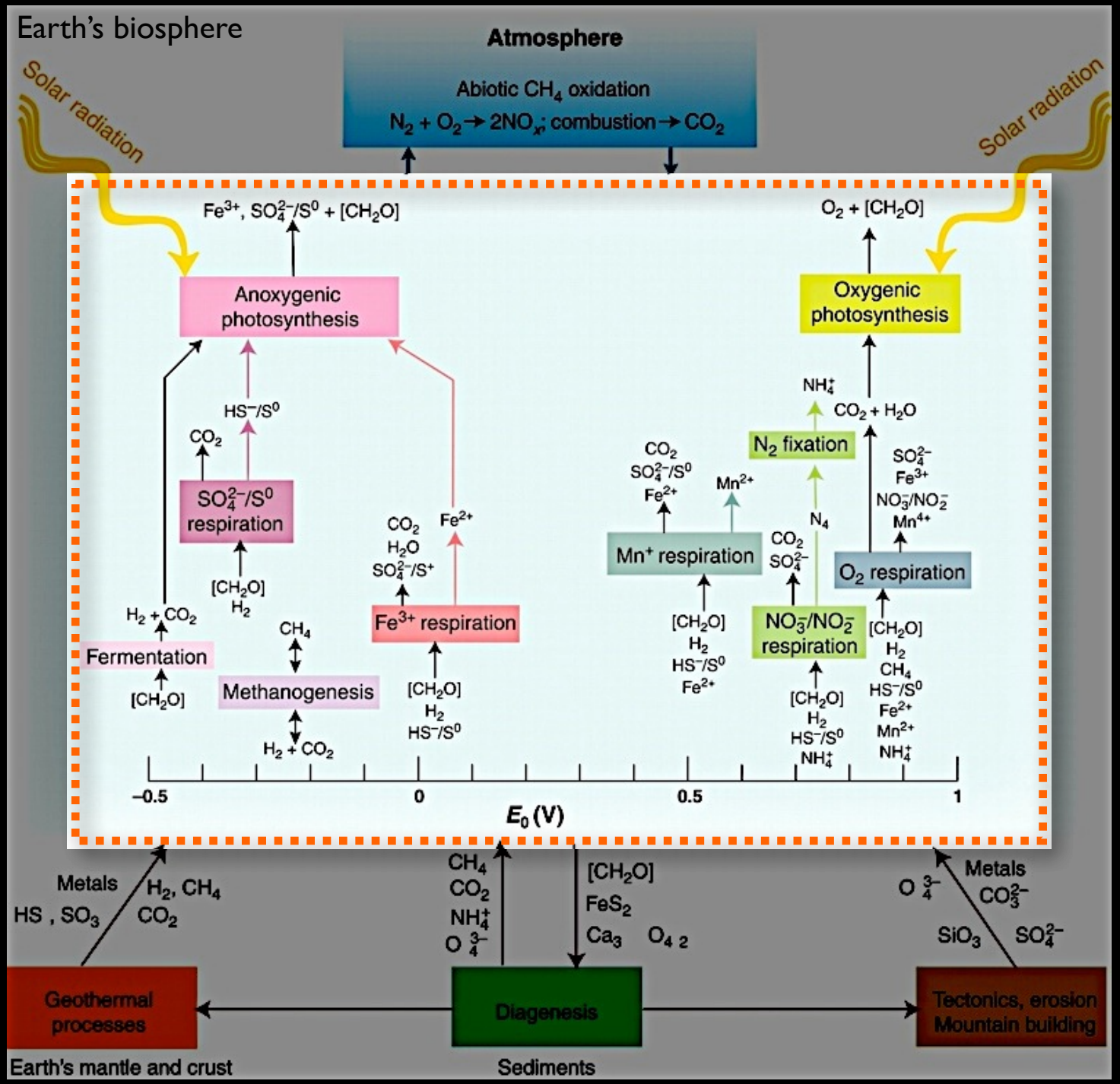

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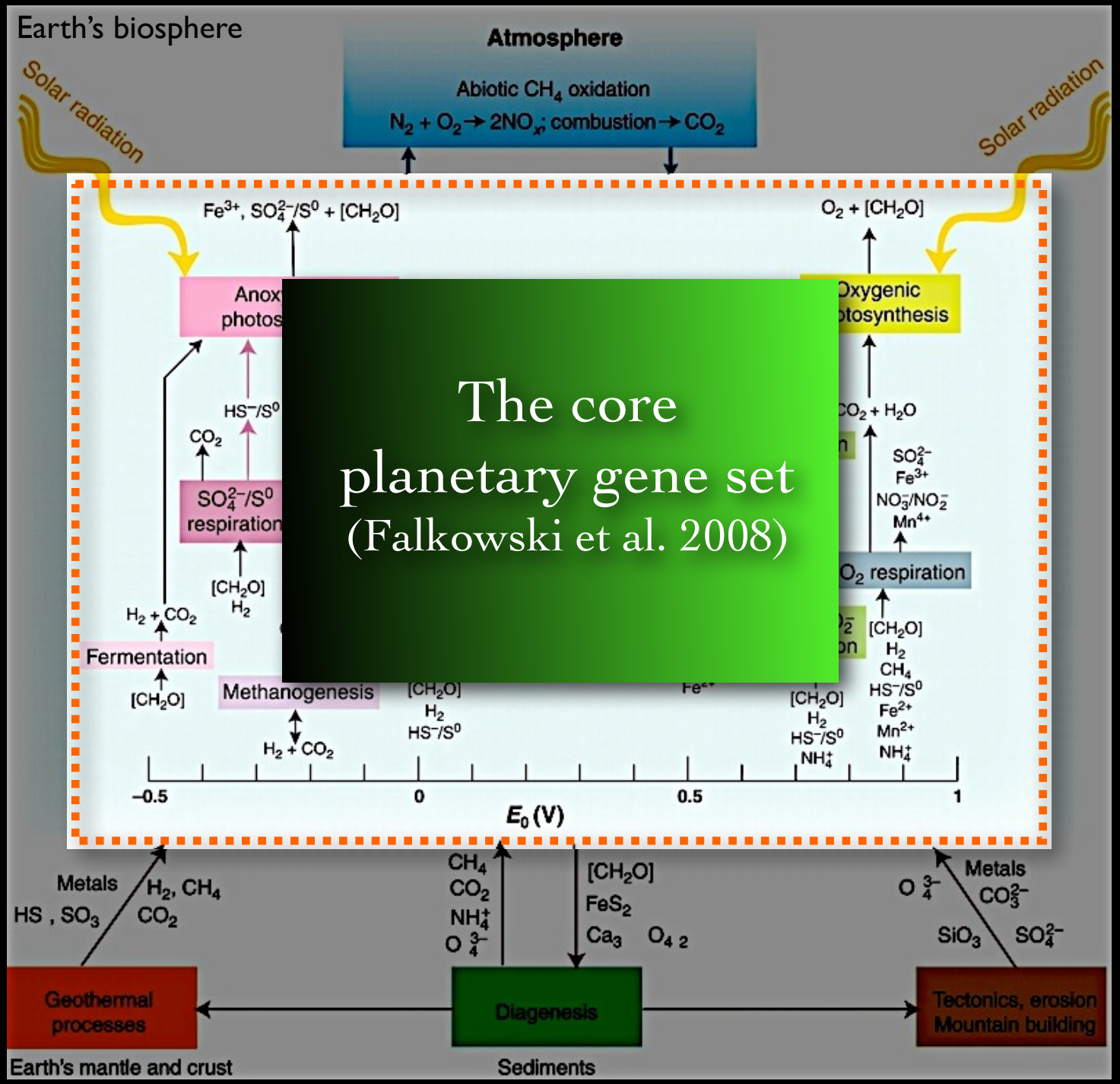

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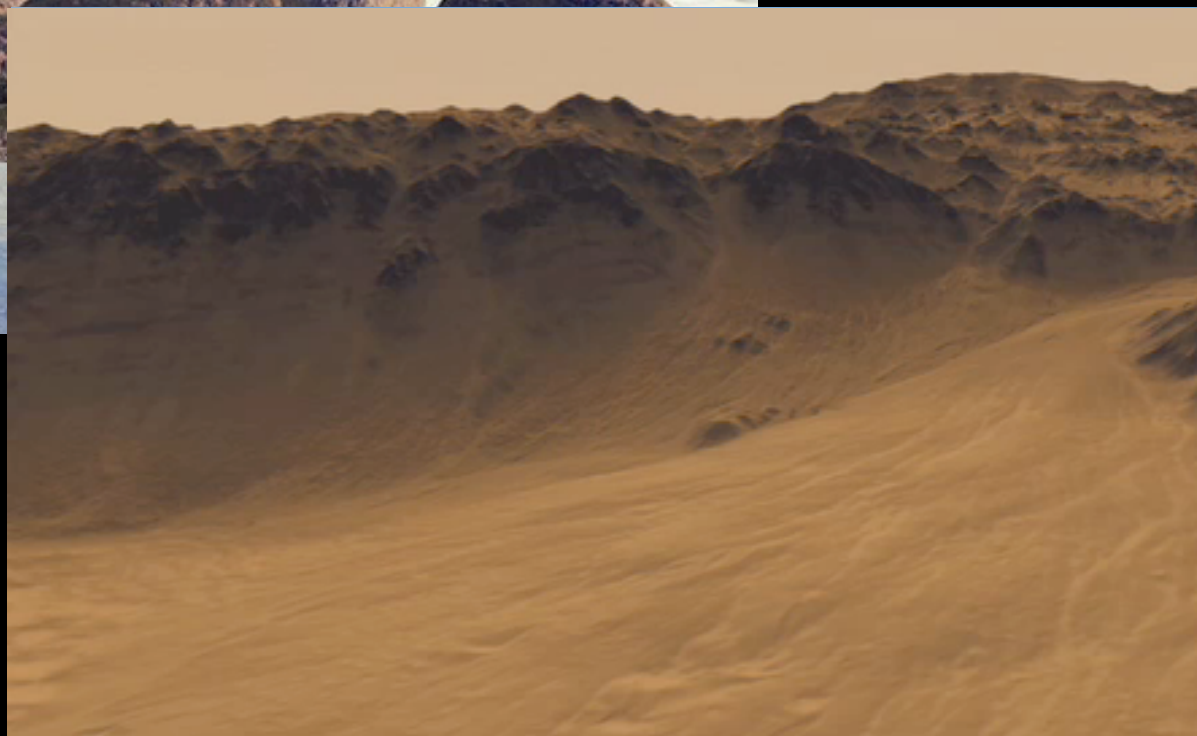

Majority of Earth's microbial life inhabits the planetary subsurface - continental and marine

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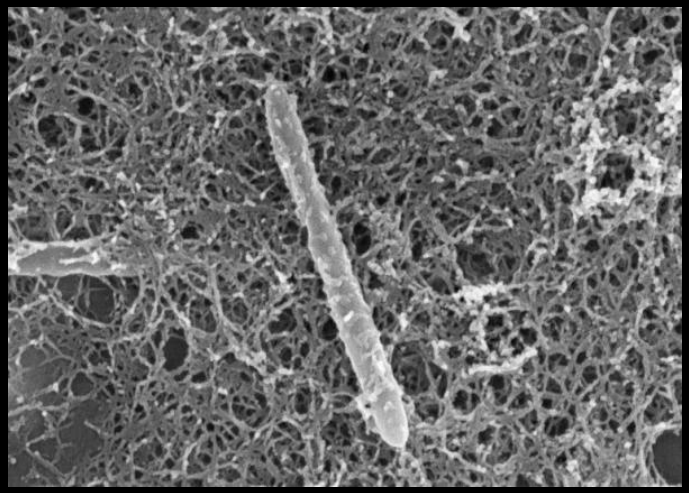

Desulforudis audaxviator ("bold traveler") from 2.8 km deep water bearing rock fracture in South African gold mine (Chivian et al. 2008)

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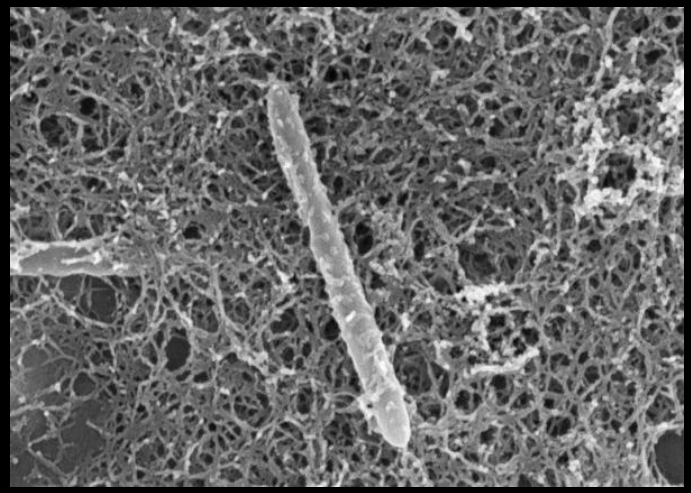

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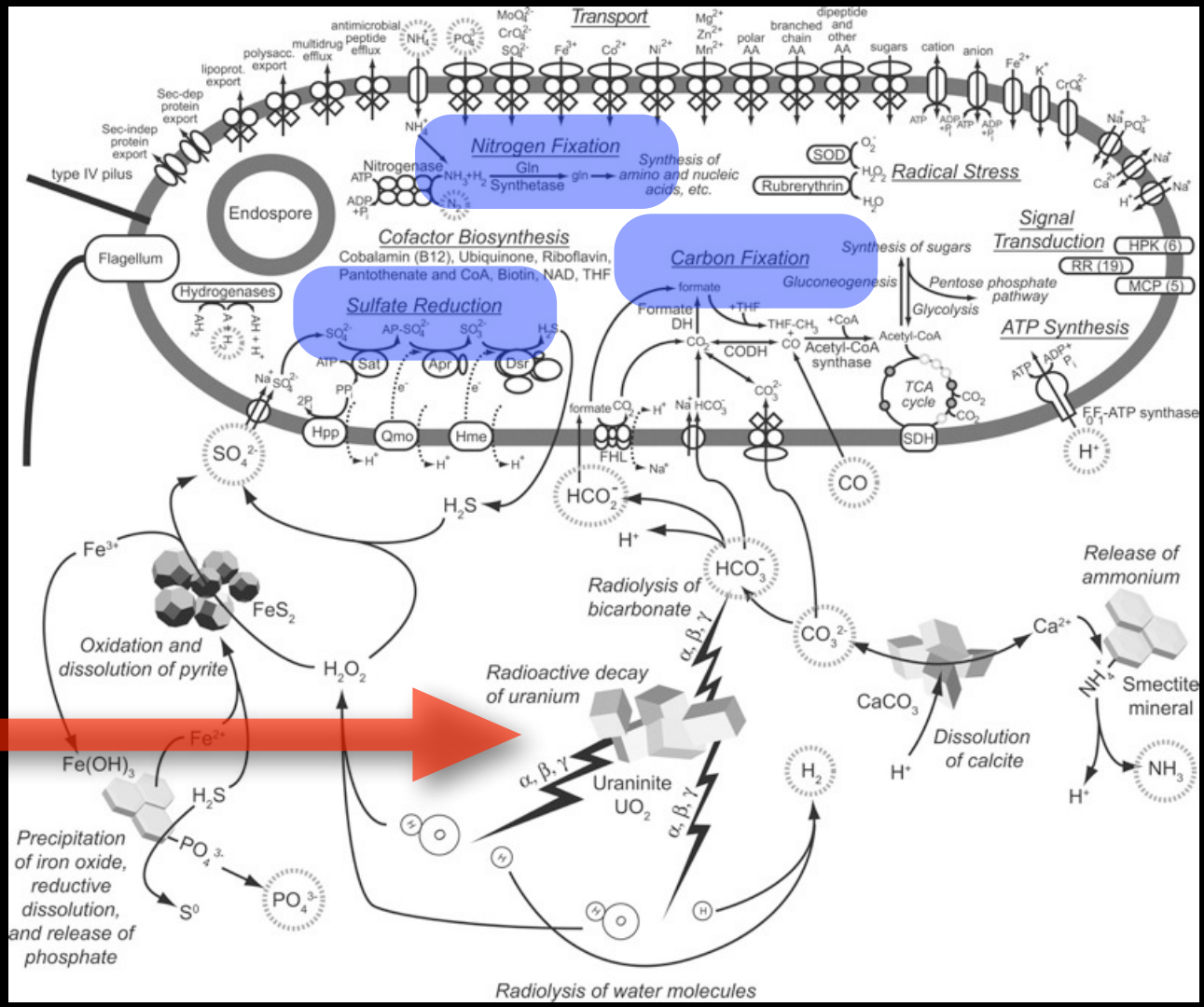
Energy and nutrients derived from processes due to uranium decay !



The local strategy - looking for favorable past & present environments

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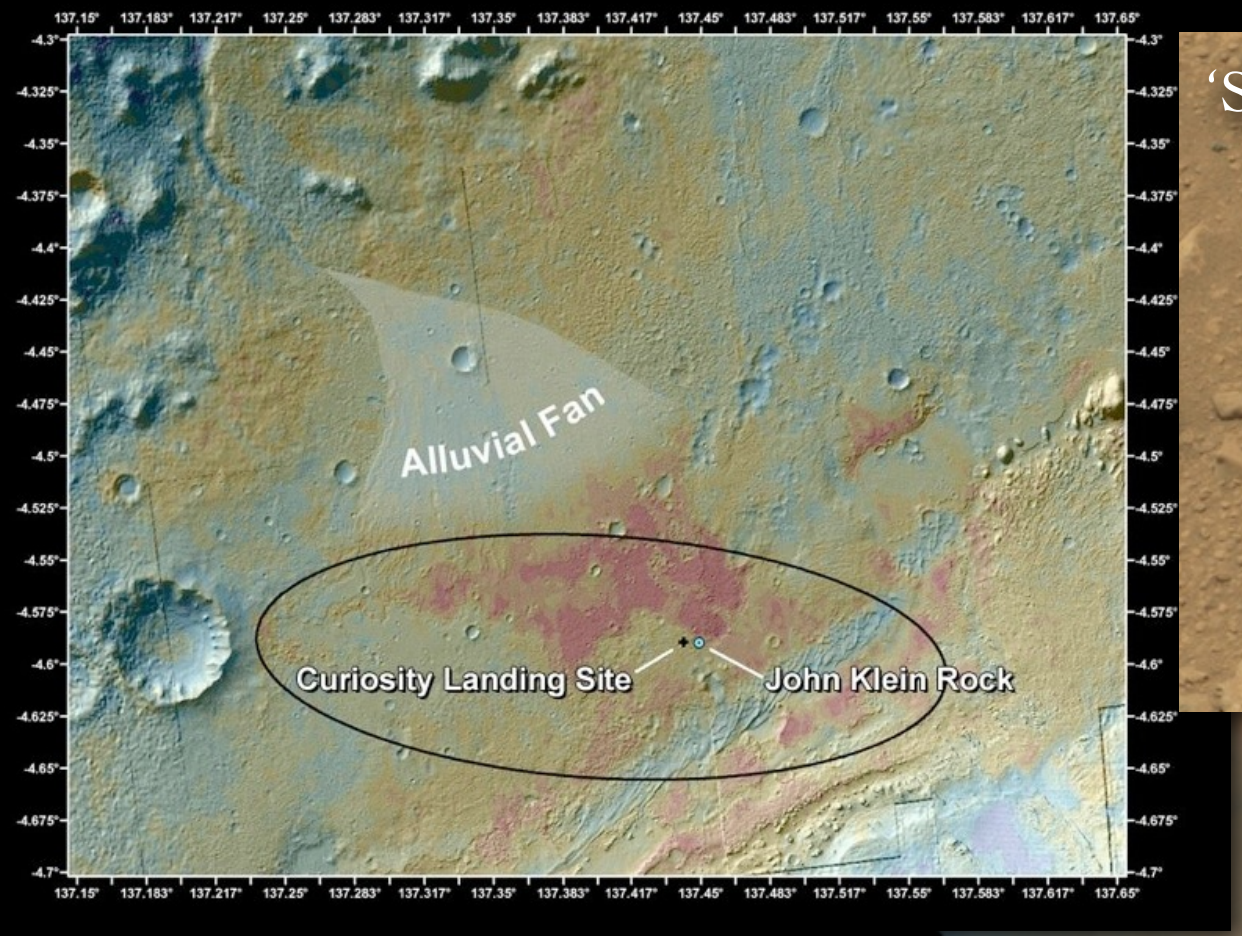

Evidence of past and present aqueous surface and *subsurface* environments - possibly short lived, possibly long-lived

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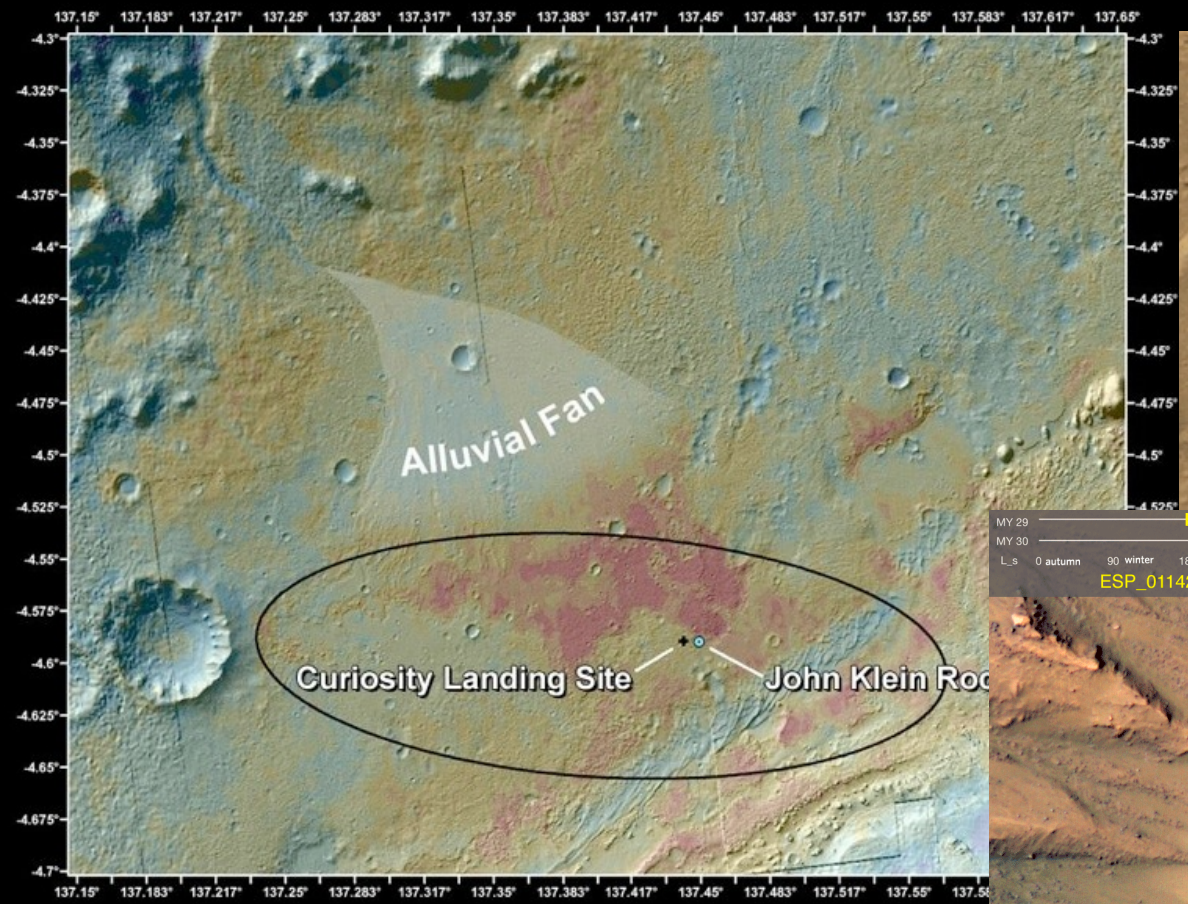

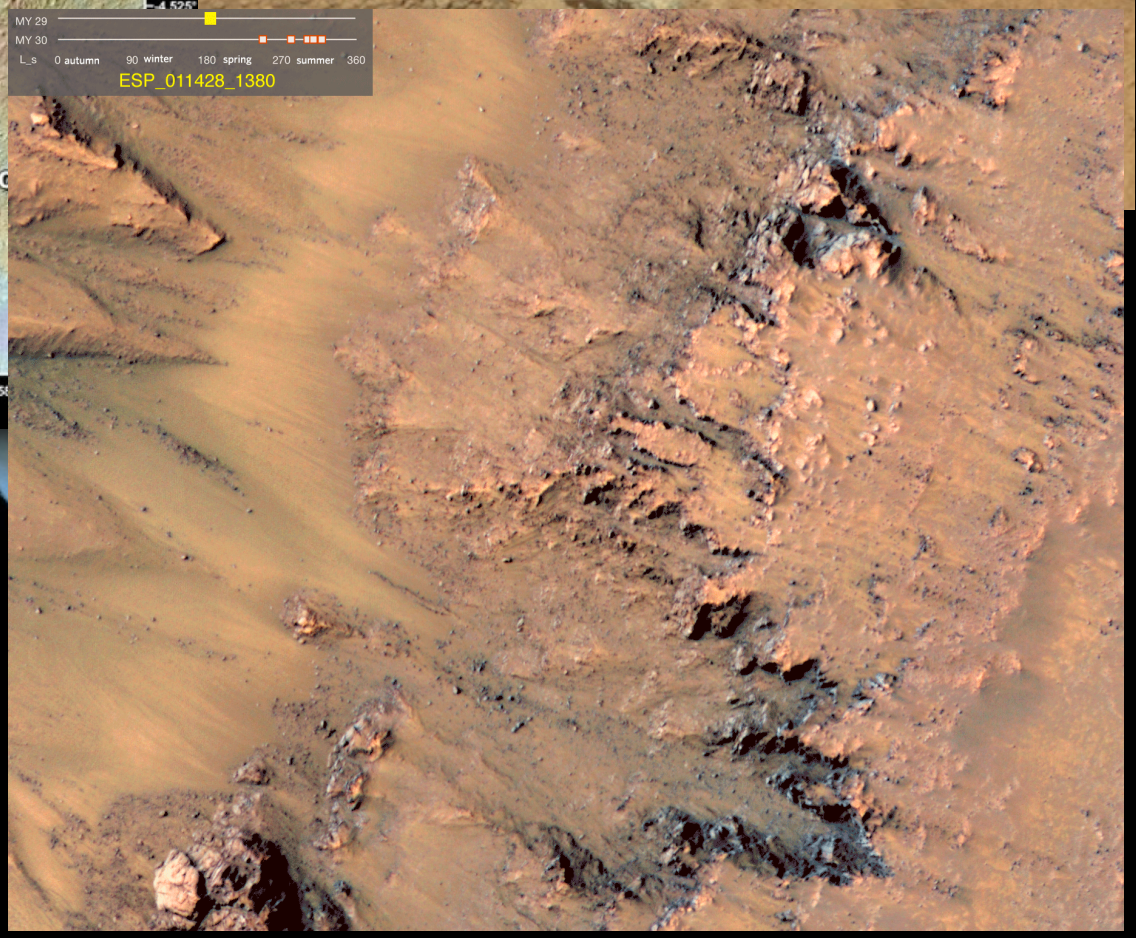

Evidence of past and present aqueous surface and *subsurface* environments - possibly short lived, possibly long-lived

Enceladus & Europa: expect the unexpected

Ammonia + sodium salts in cryovolcanic water plumes suggests liquid interior 'sea'

Hubble detection of episodic Europa water ejecta, ocean potentially 2x Earth ocean volume

Any signs yet?

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Hints of methane on Mars
(Mumma et al. 2009) but
not yet confirmed by ground truth
measurements...or later studies
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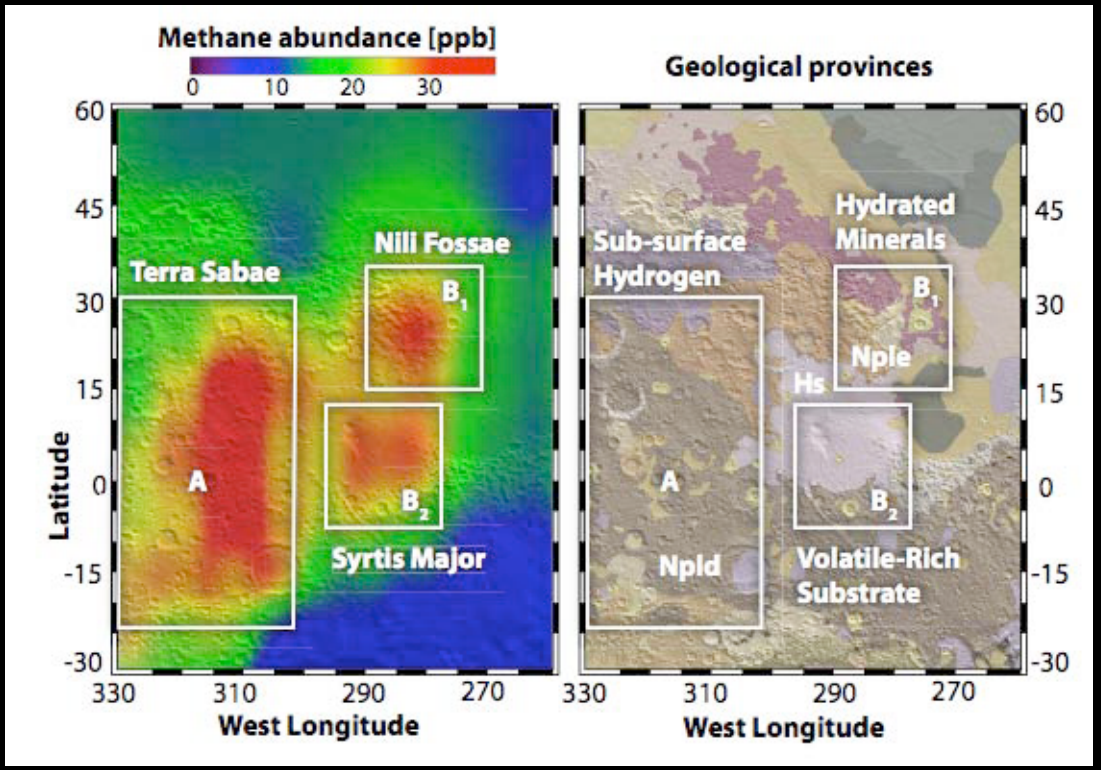

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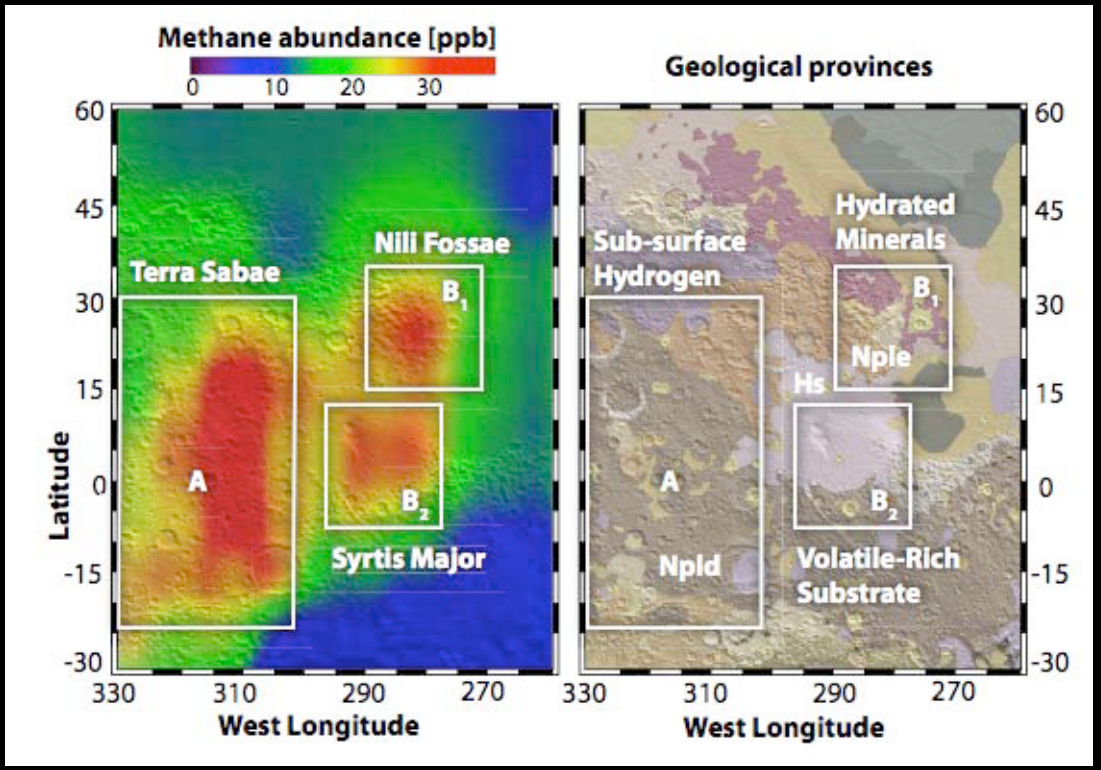
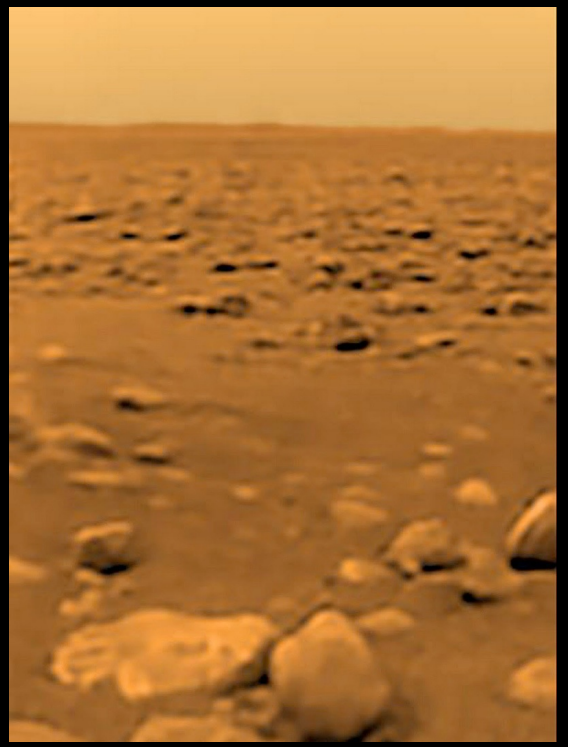


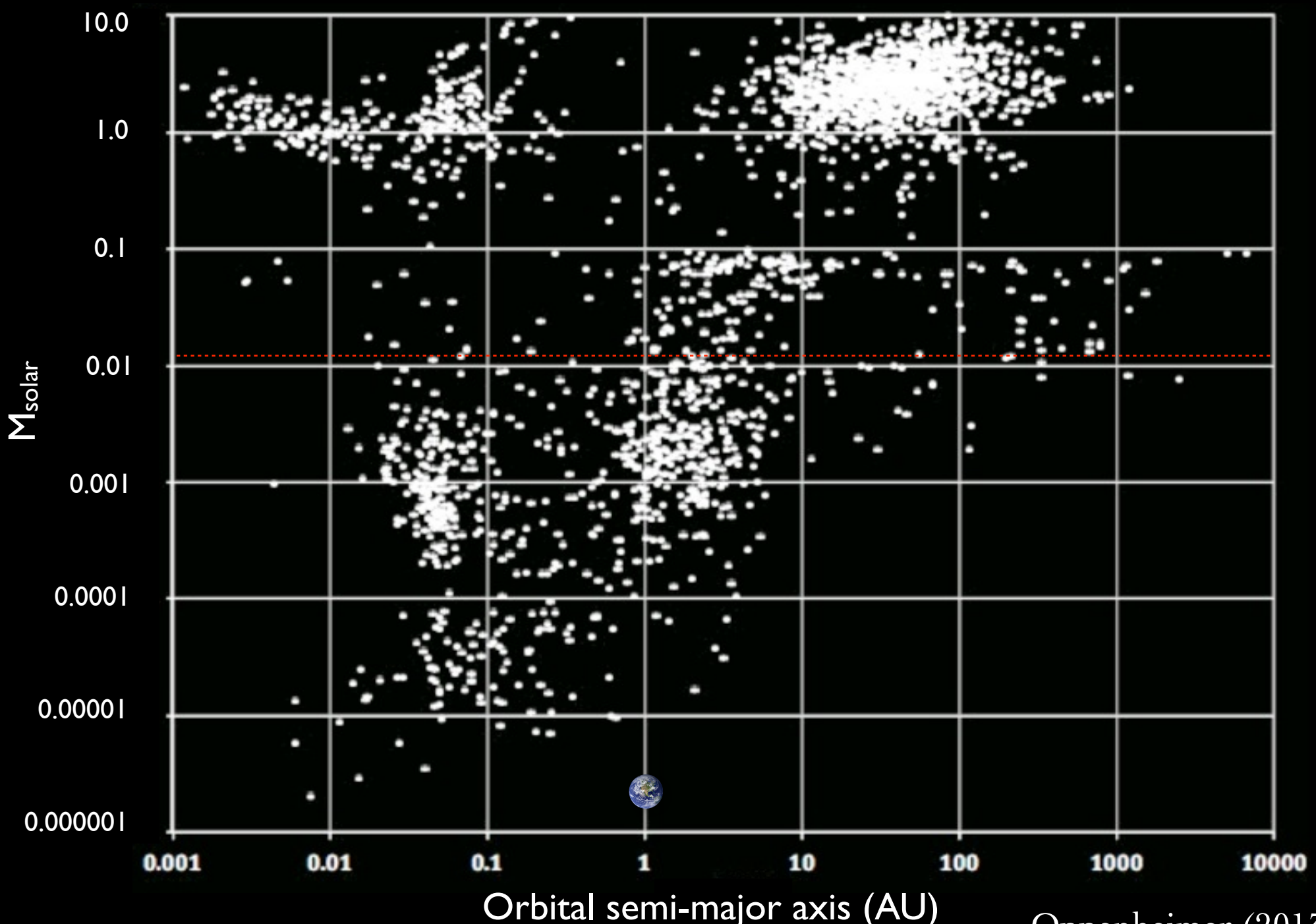
Titan: downwards flux of H_2, but no surface accumulation + acetylene expected in atmosphere yet no accumulation on surface.

$H_2 + C_2H_2$ = metabolic resource for methanogenic life...(Strobel 2010, Clark et al 2010).



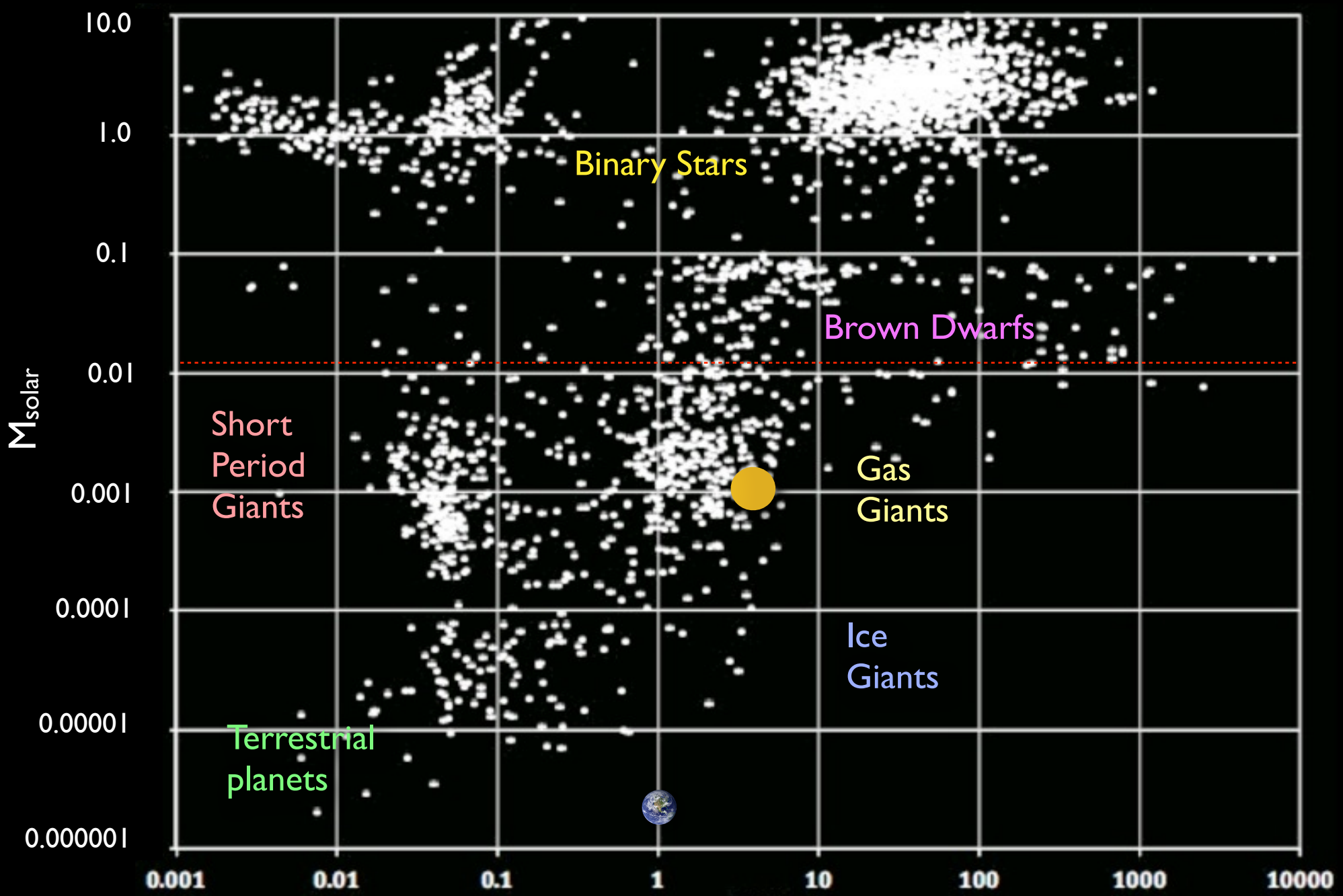
Looking for new worlds

Extrasolar companions



Oppenheimer (2013)

Extrasolar companions



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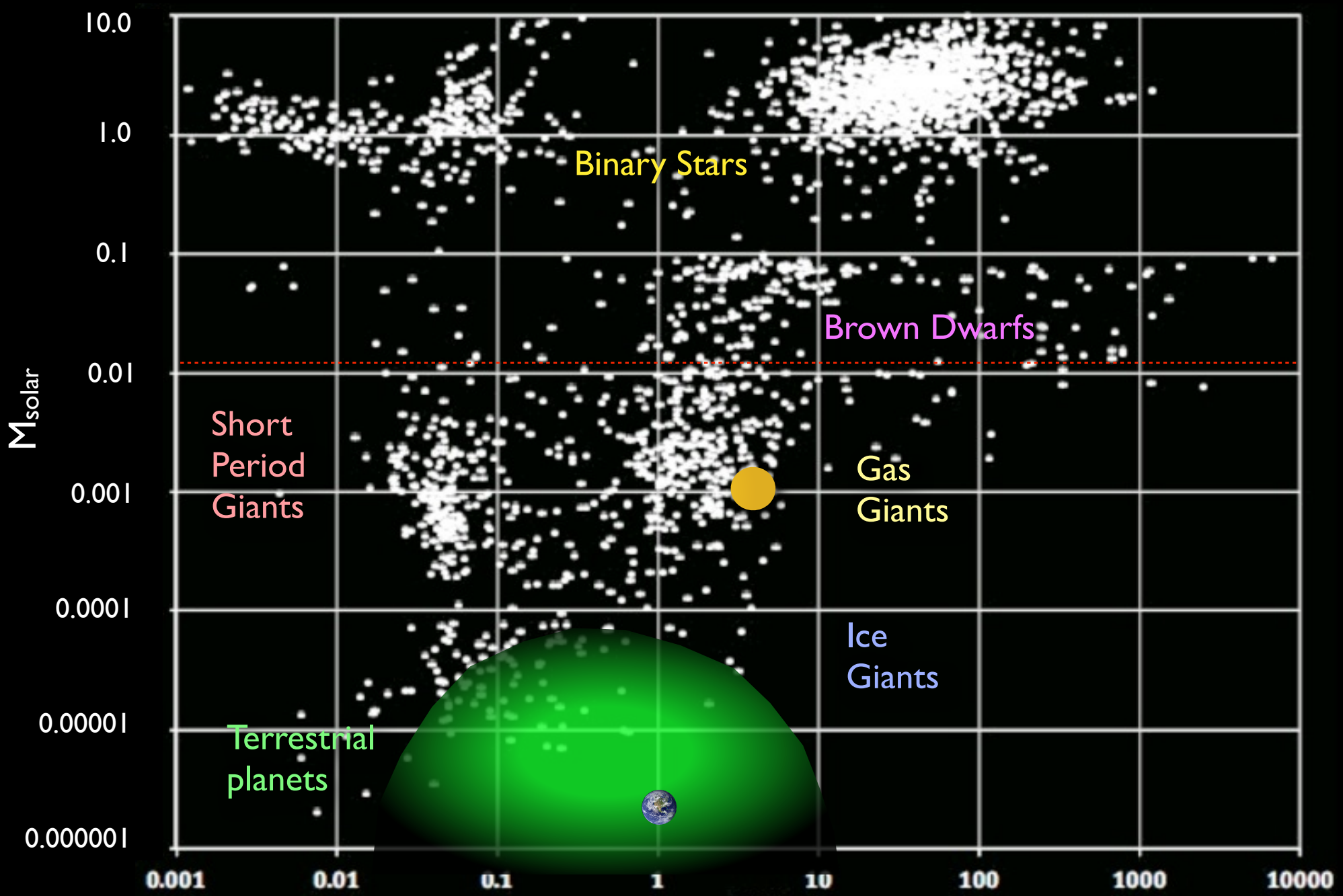

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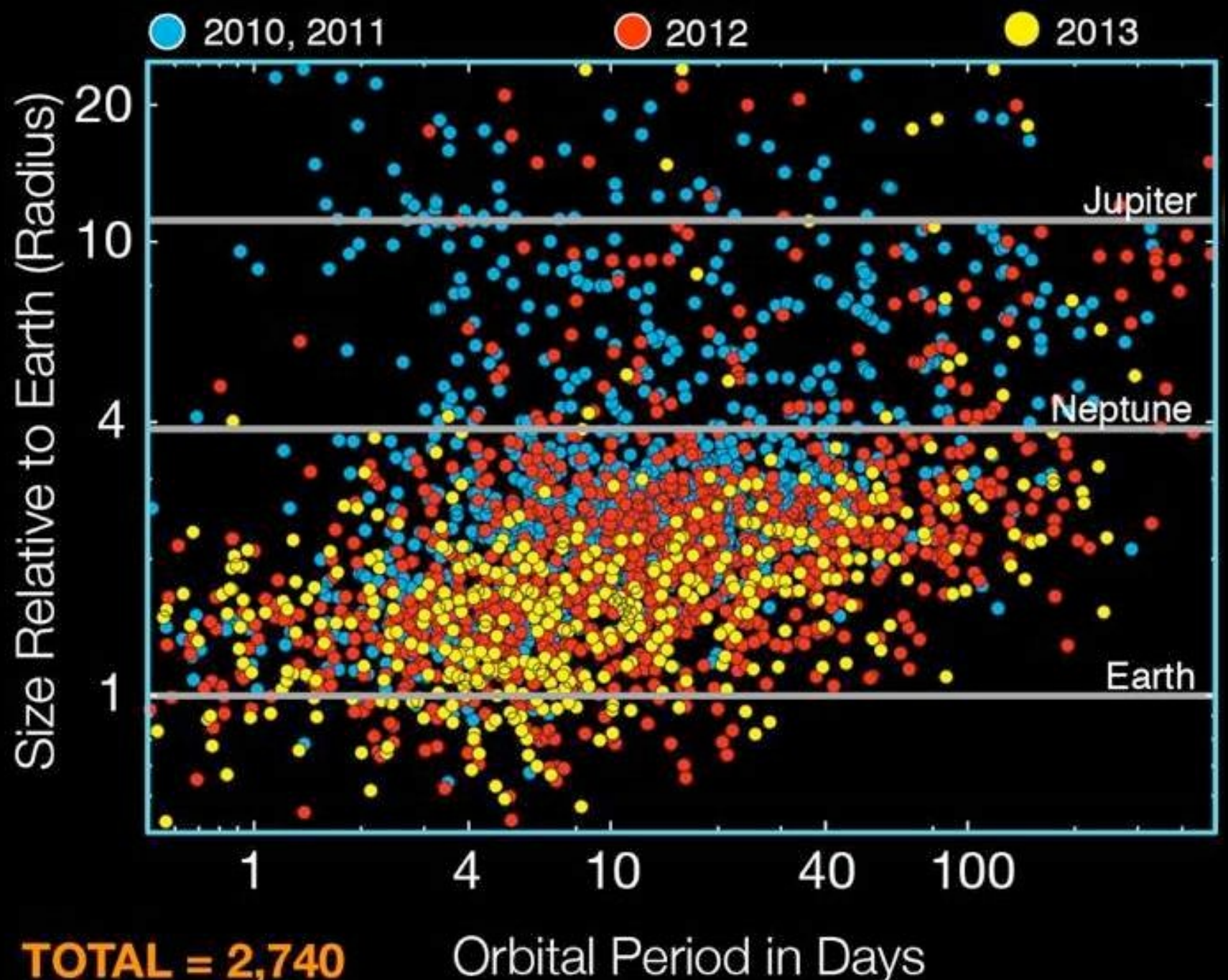
NASA's Kepler results, transiting planets



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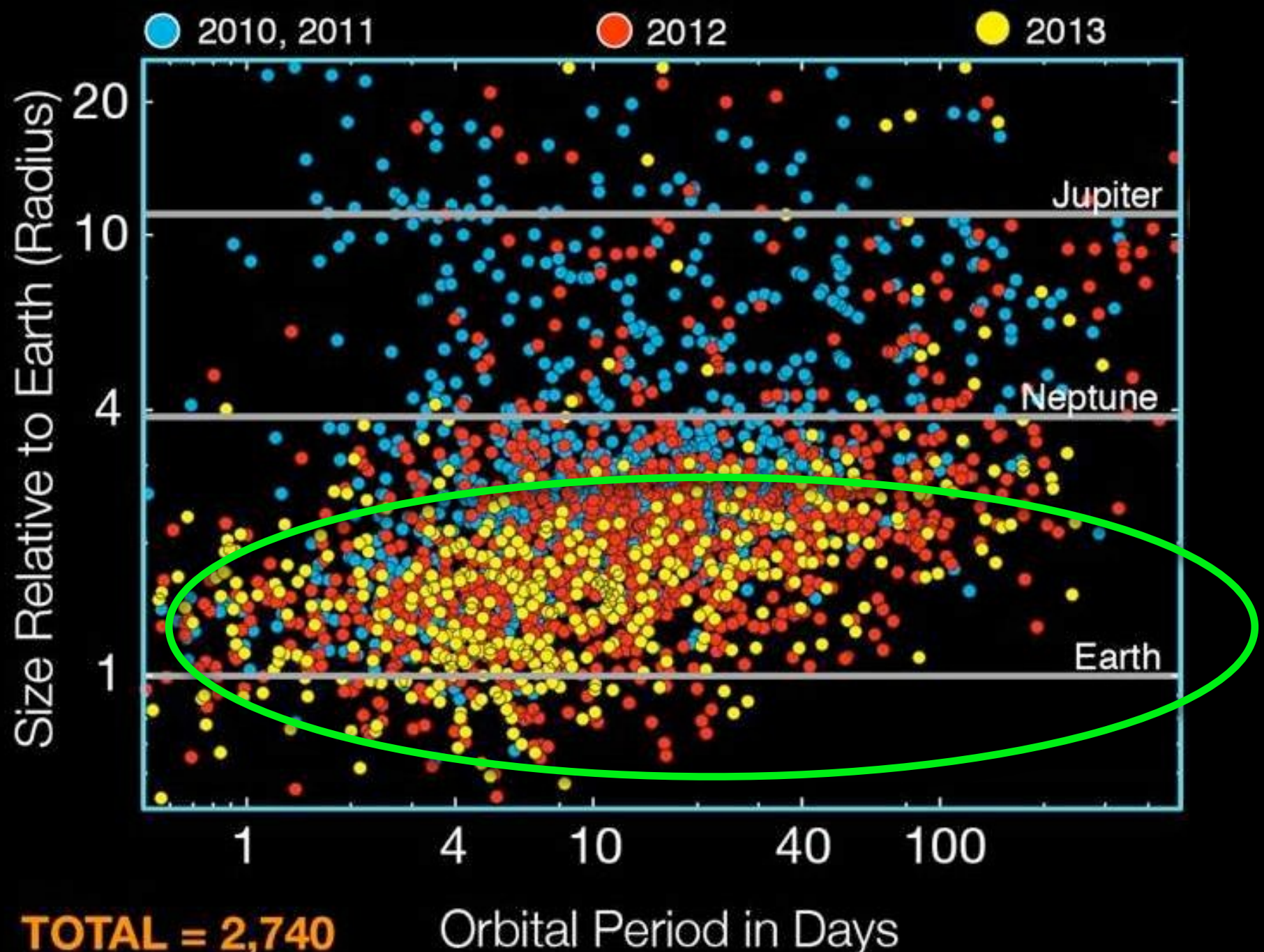
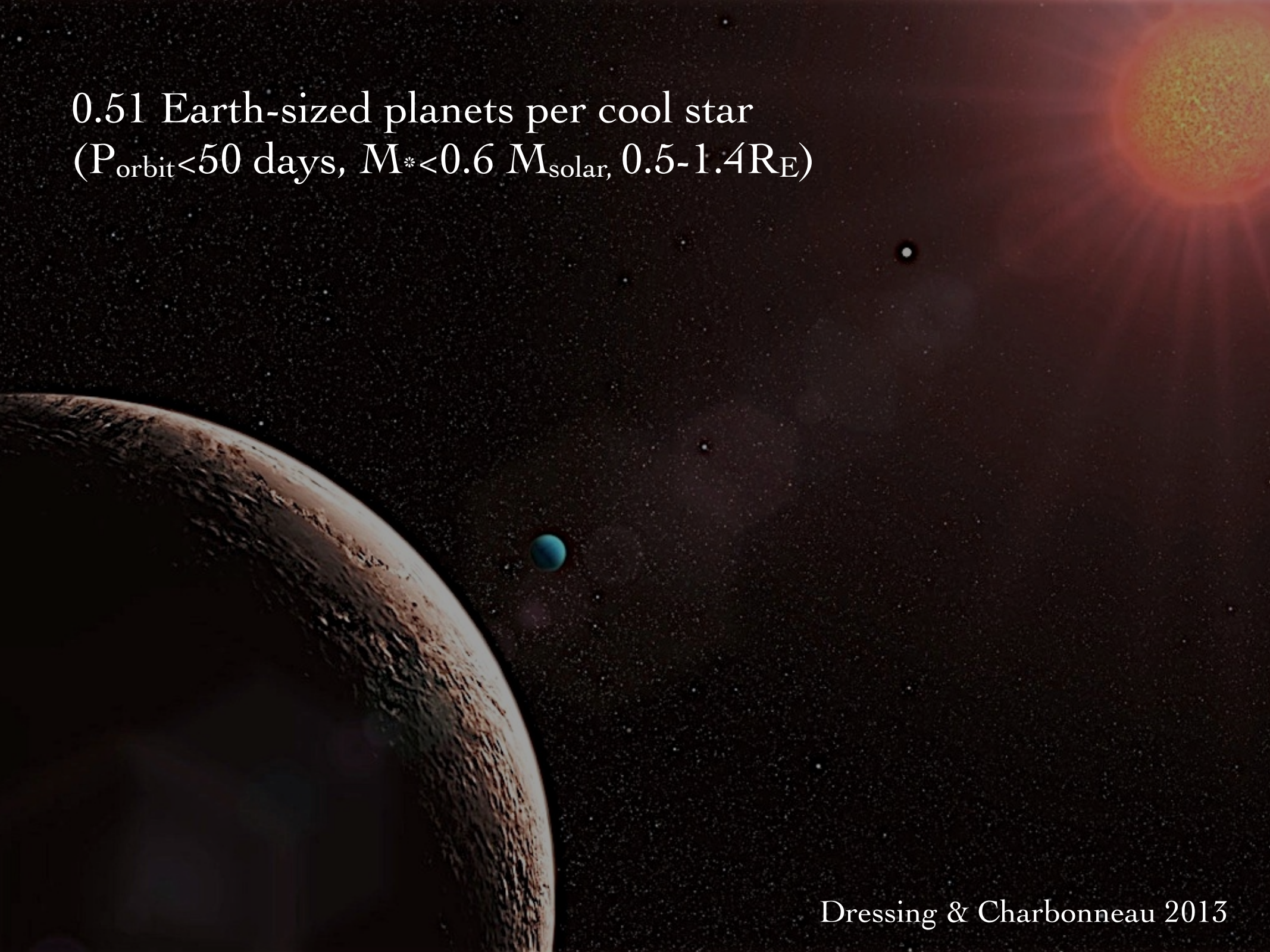
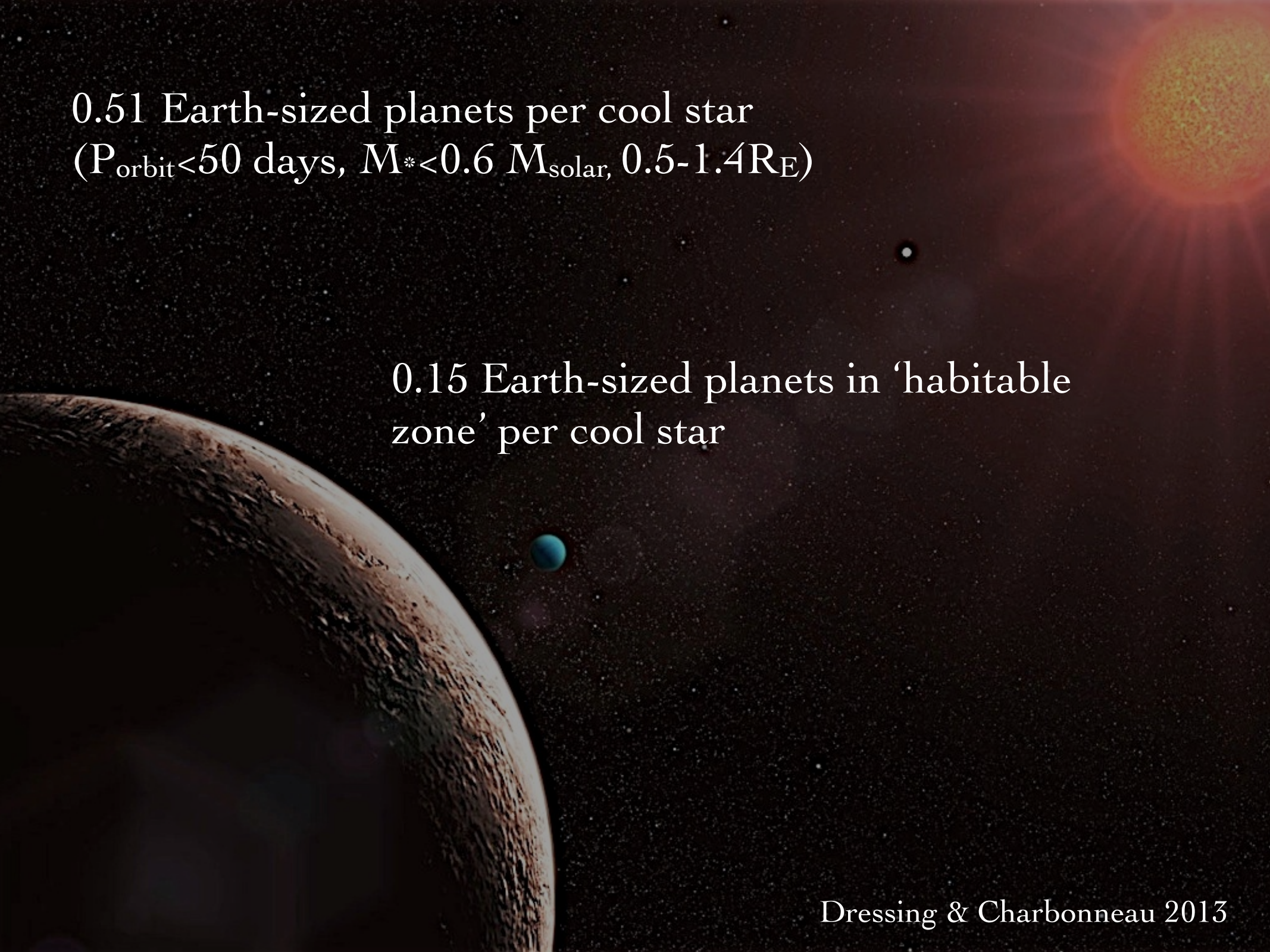



0.51 Earth-sized planets per cool star
(P_{orbit}<50 days, M_*<0.6 M_{solar}, 0.5-1.4R_E)
Dressing & Charbonneau 2013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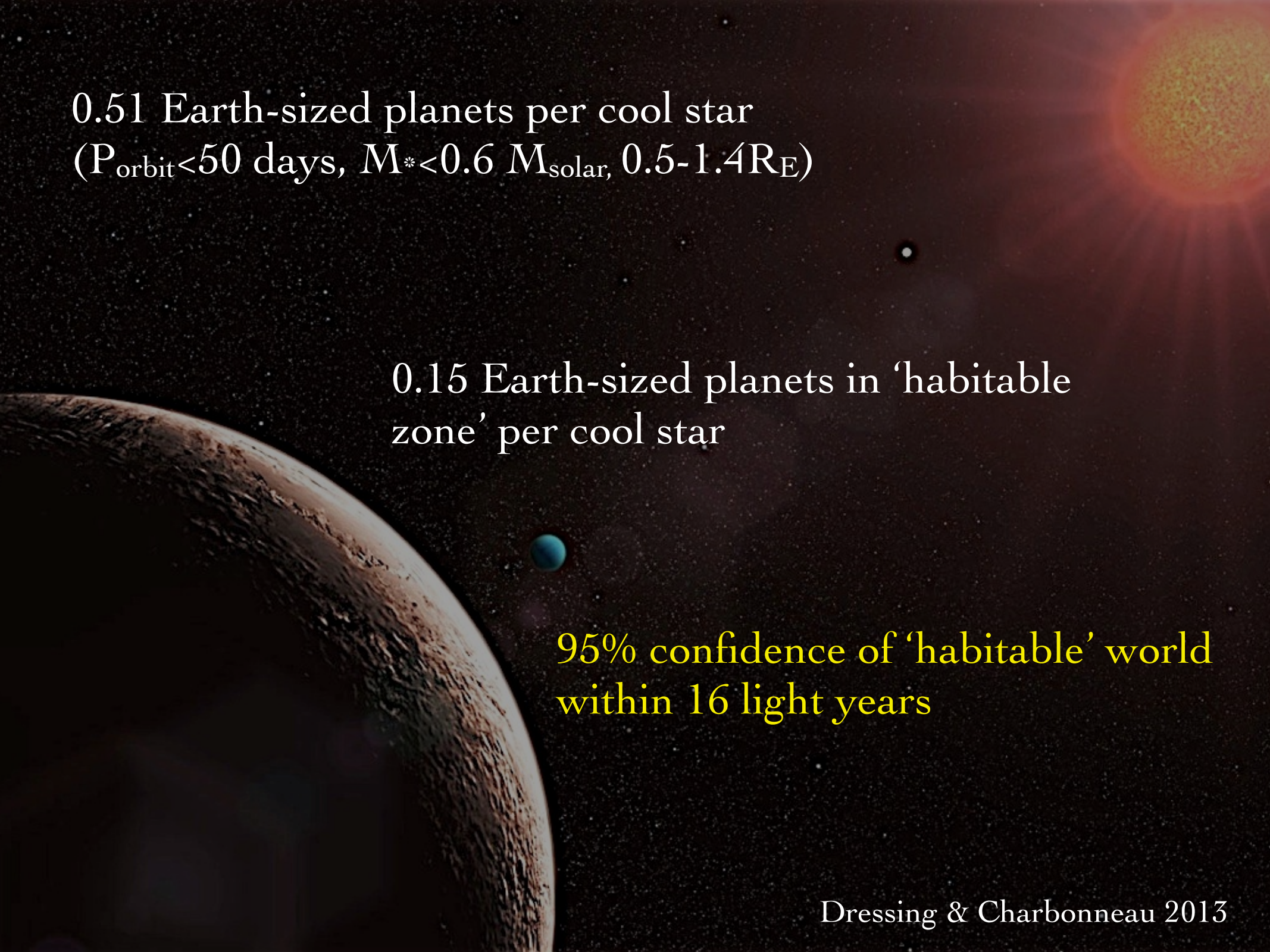
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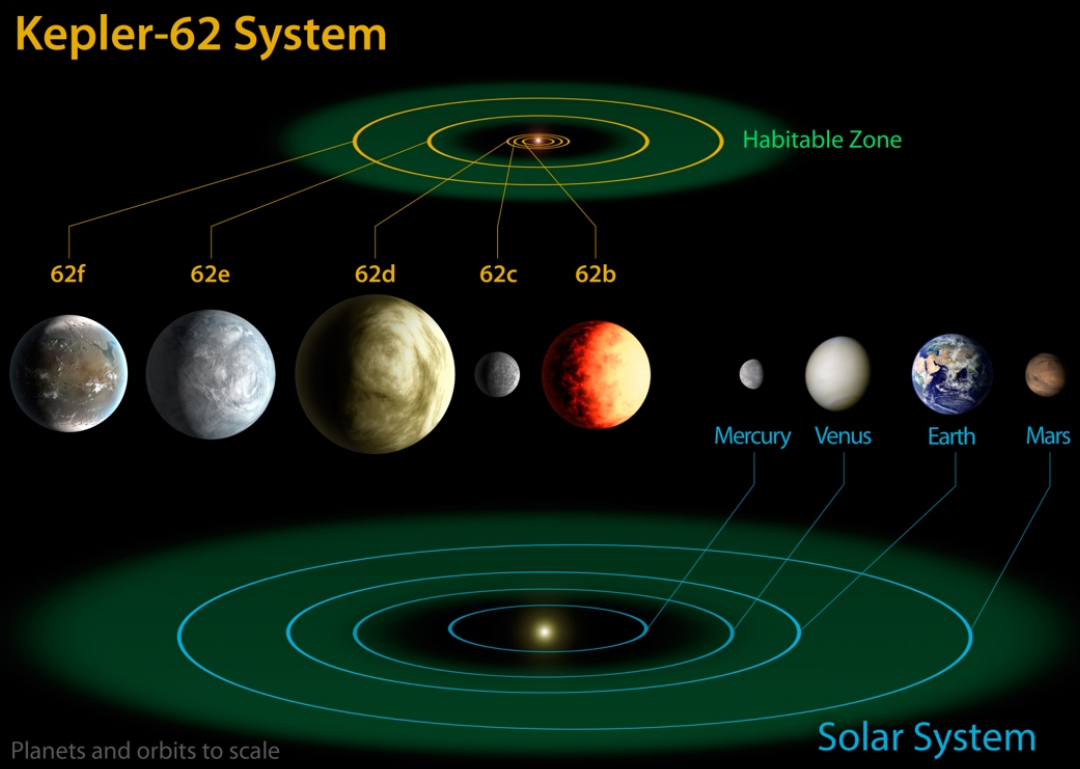
95% confidence of 'habitable' world within 16 light years
Dressing & Charbonneau 2013

Astronomers usually use globally averaged, time-independent, energy balance models to evaluate likely planetary surface temperatures and 'habitability'



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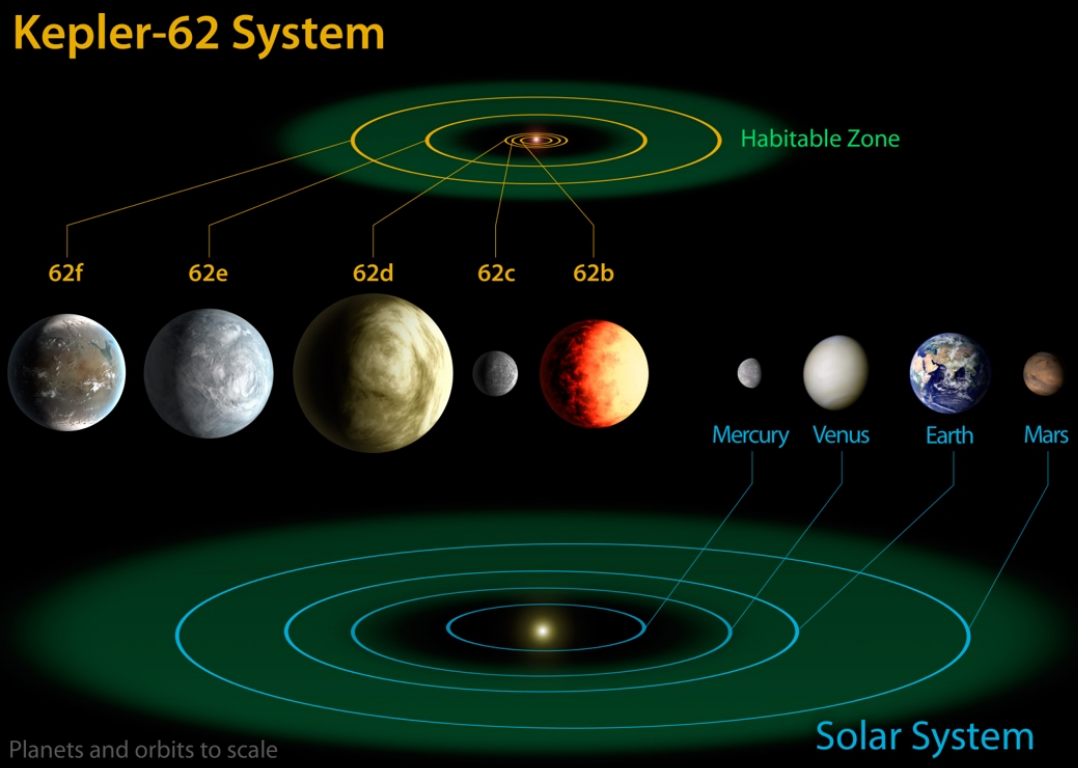


These assume just steady-state radiative equilibrium:

$$I[T] = S(1-A[T])$$

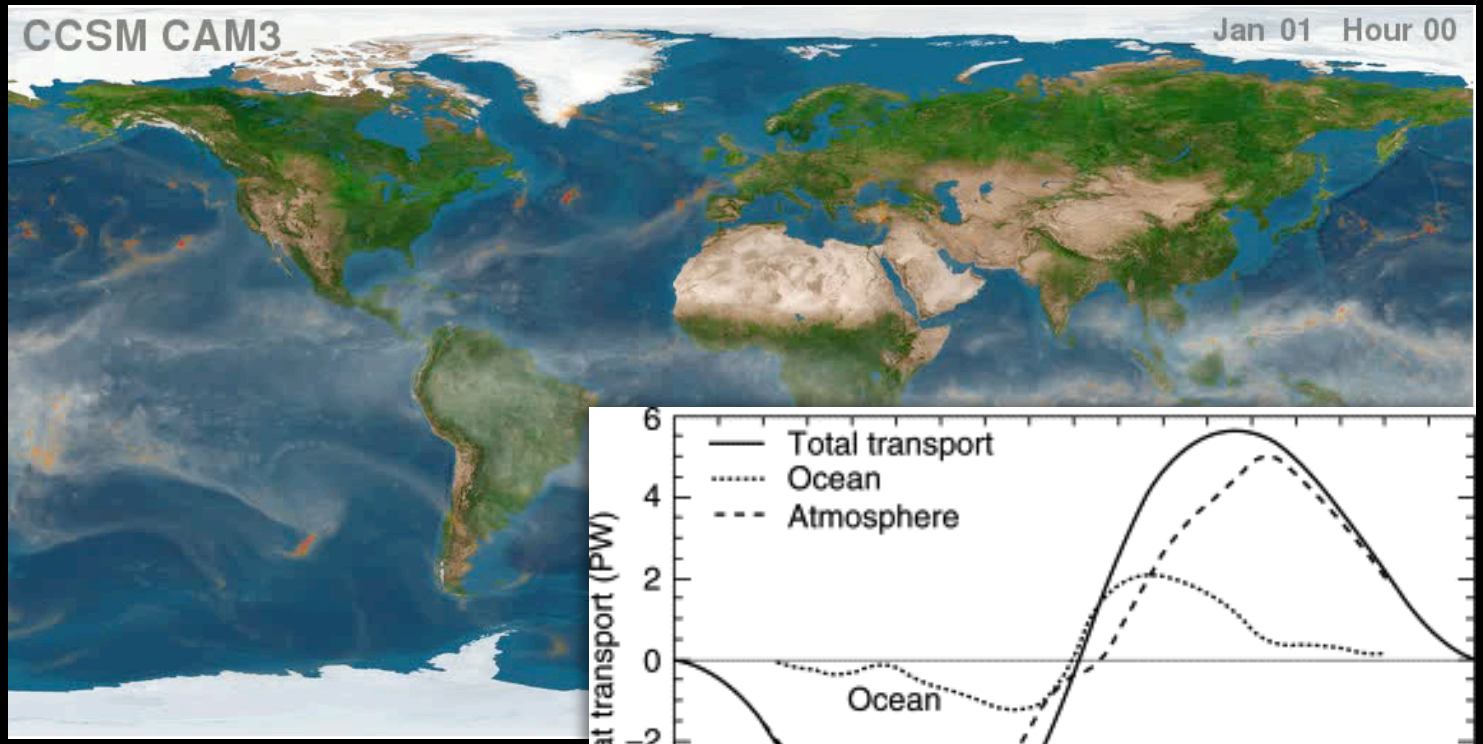
Infrared cooling flux

Annual mean stellar flux

Global planetary albedo

But planets are dynamic…

Atmospheres/oceans transport heat, and there is thermal inertia to external forcings



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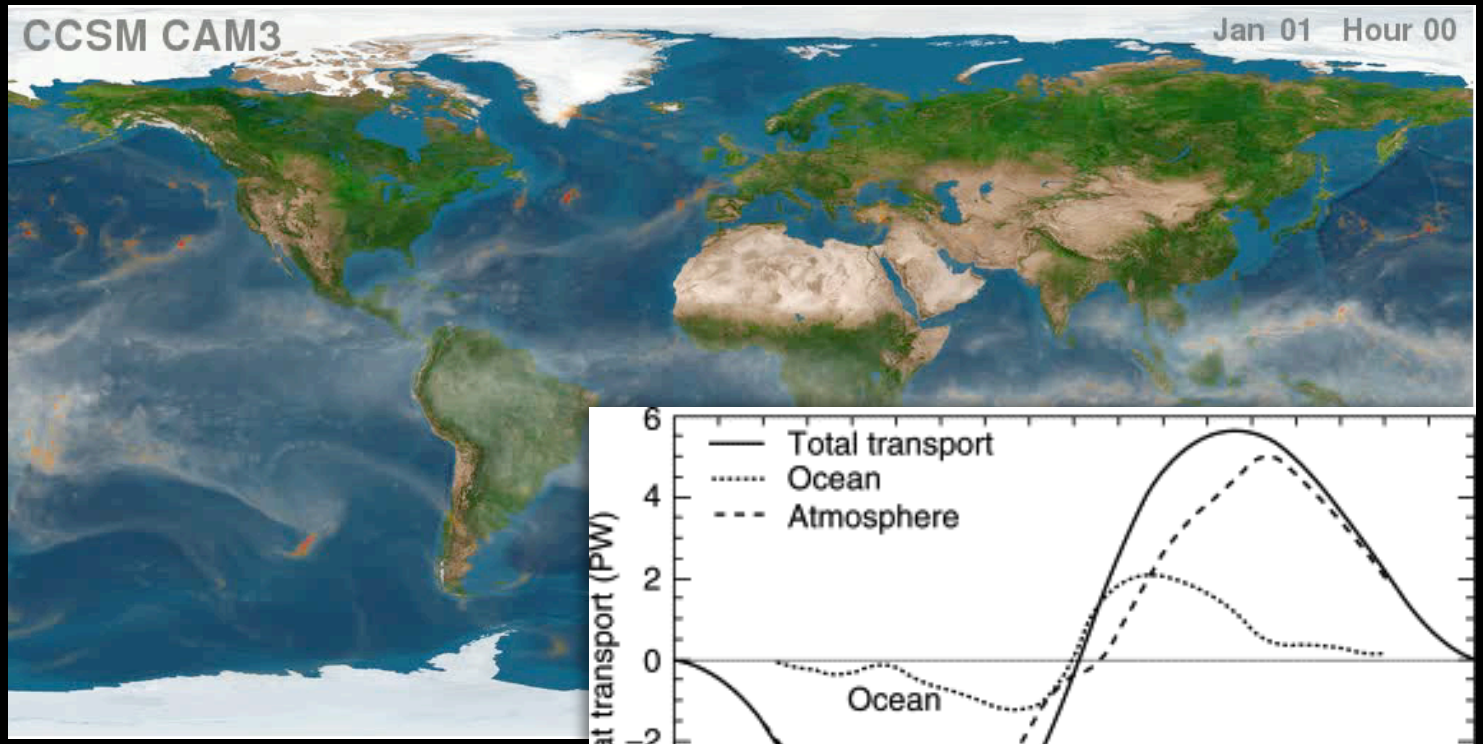

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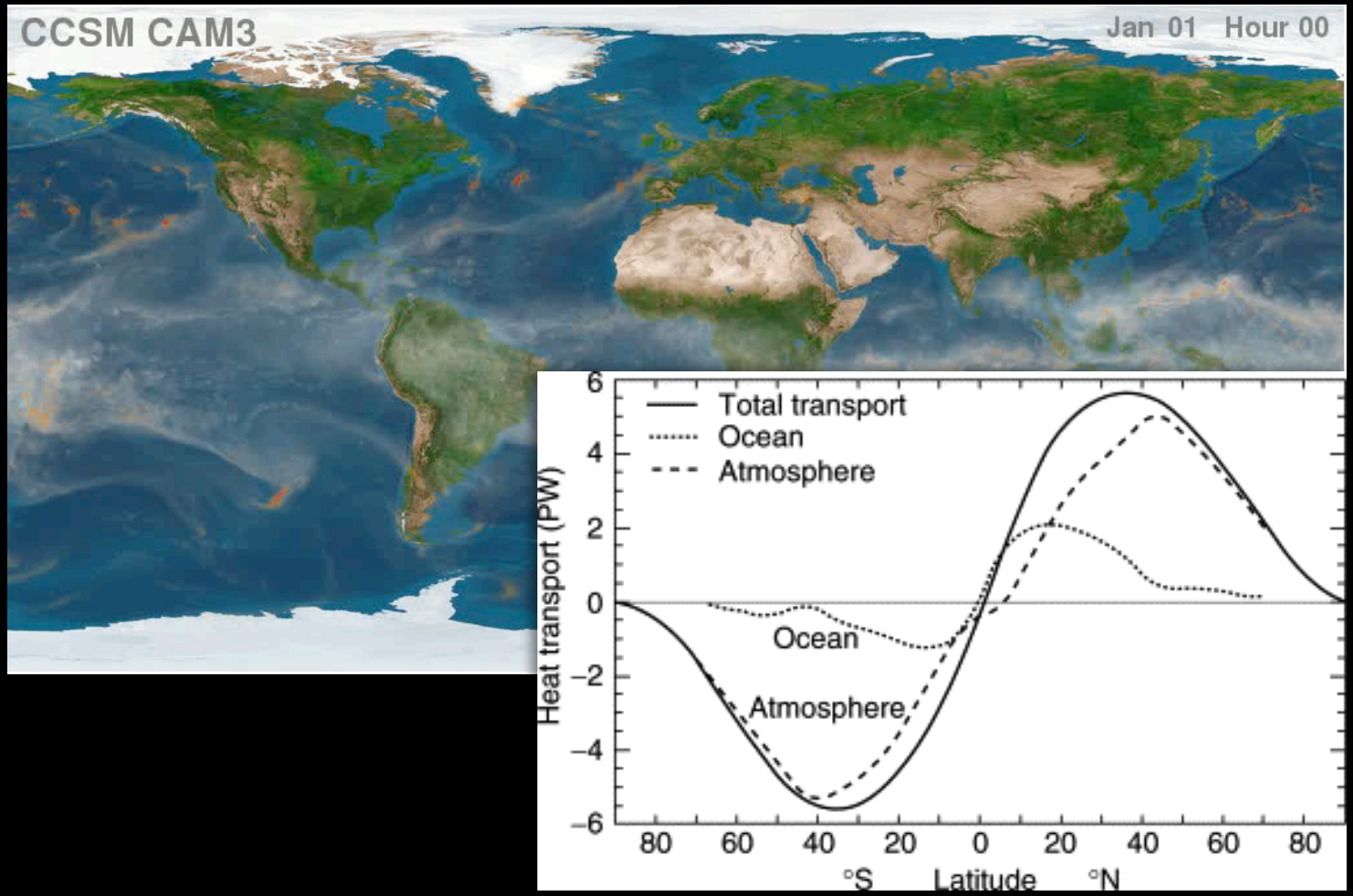

A planet may *not* be in global radiative equilibrium at any given time (e.g. eccentric orbits)

Only 85% of Earth's surface is on average between 0 and 100 Celsius

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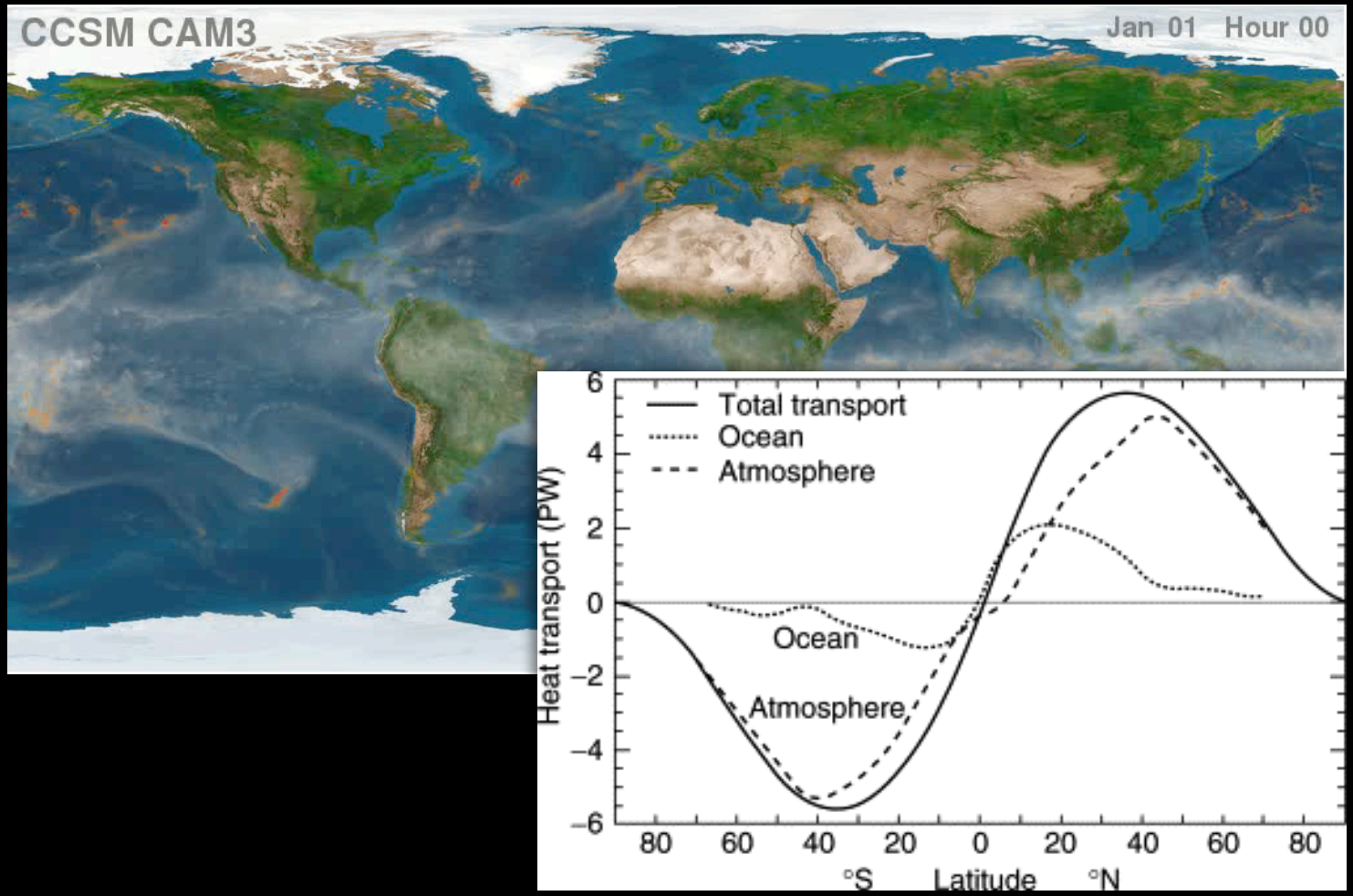

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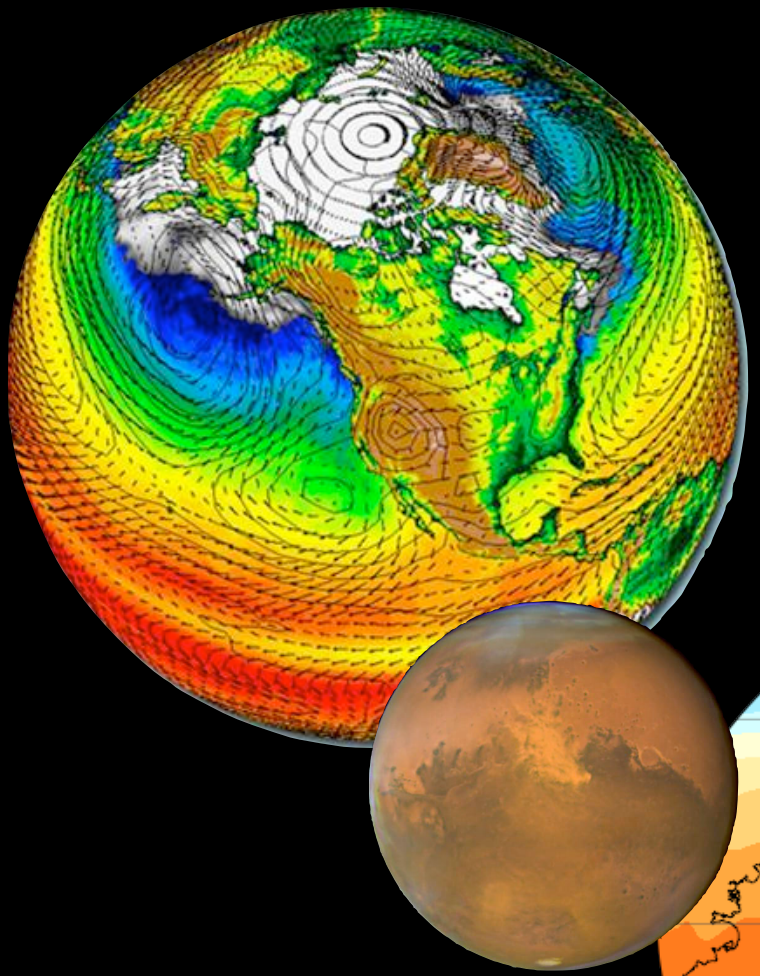
Only 85% of Earth's surface is on average between 0 and 100 Celsius

So a time-dependent, zonal model is really the minimum for trying to capture the fundamentals of climate *dynamics*…and habitability.

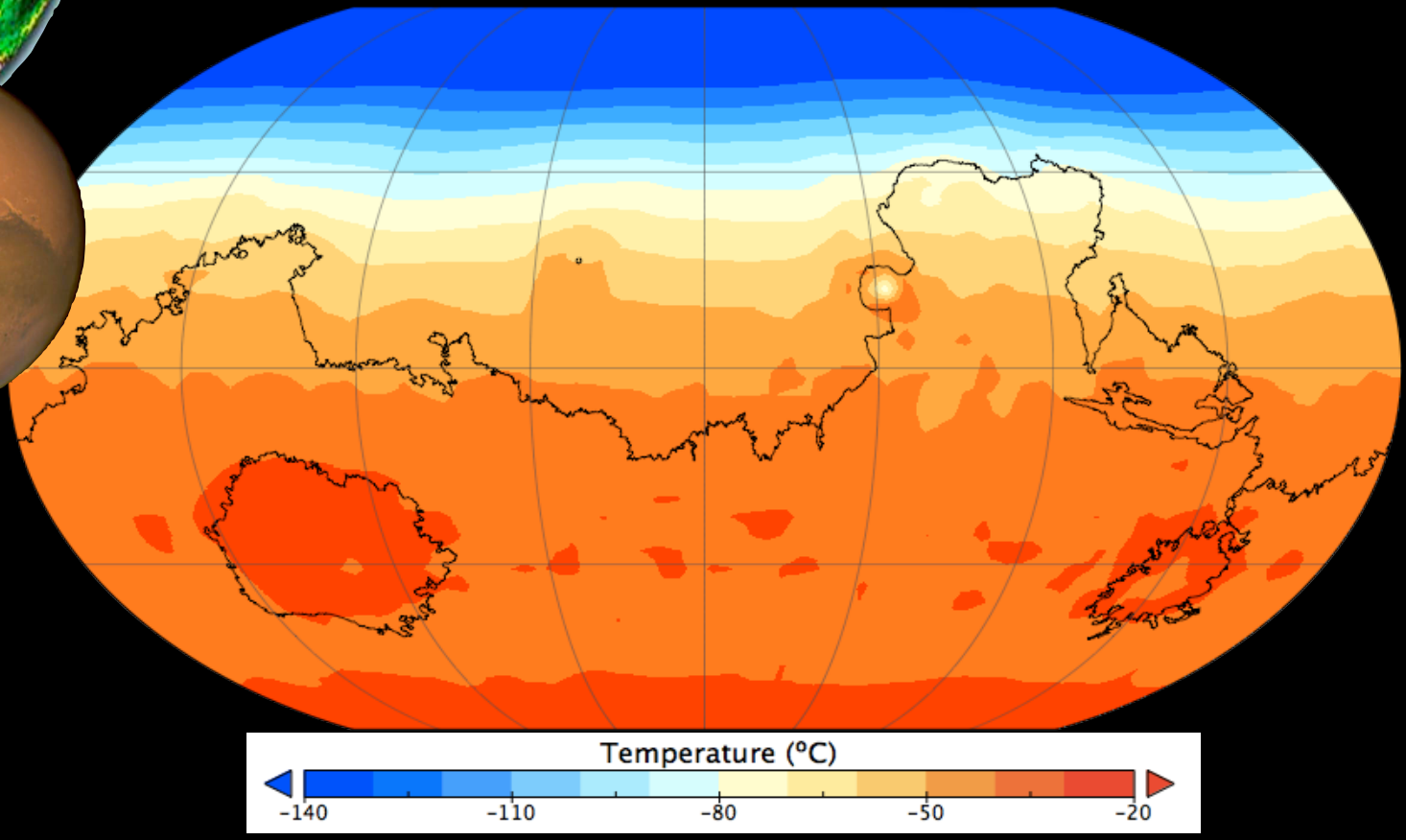
3D General Circulation Model (GCM) for rocky planets

NASA GISS/GSFC, Columbia

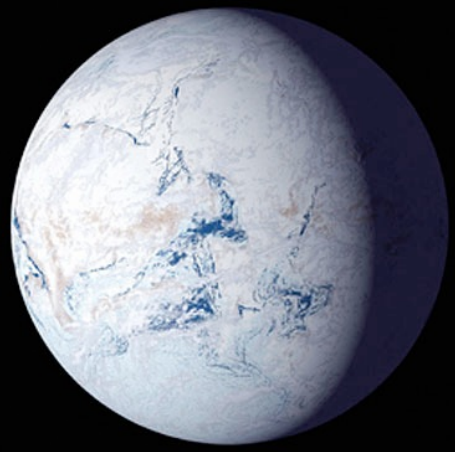
Based on the ModelE GCM



Northern Martian winter (modern)

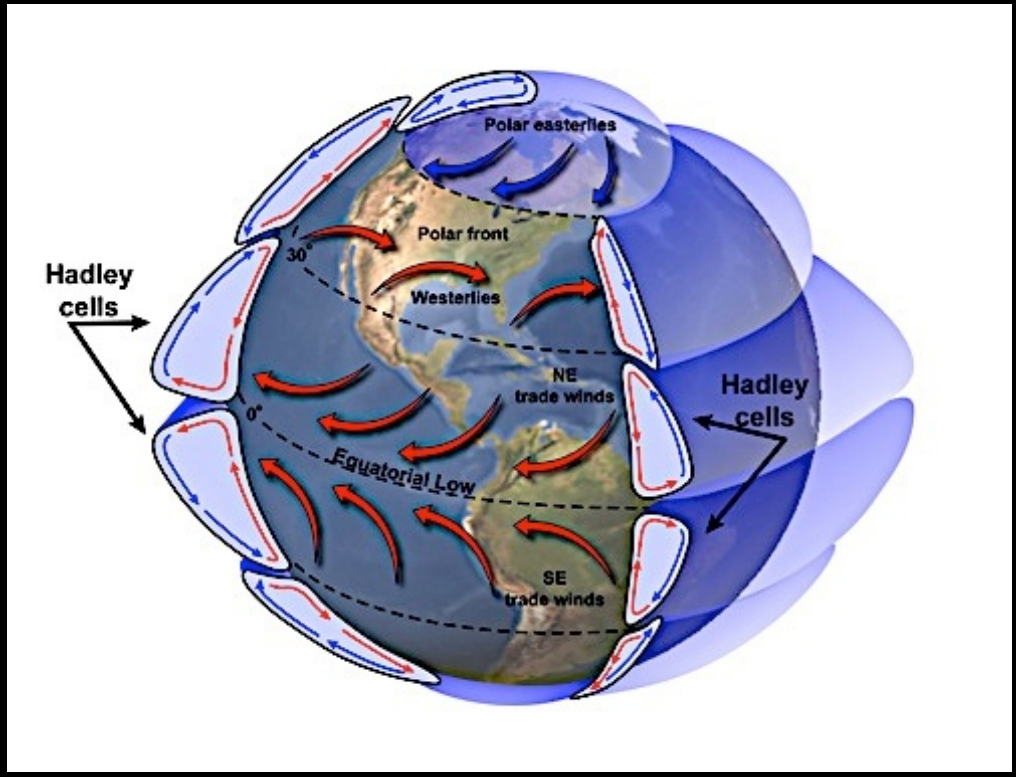


Climate dynamics typically move liquid water zone to smaller orbits compared to global models (mainly due to 'snowball' instability)



But high eccentricity effects can extend liquid water range outwards, and snowball collapse can also be offset by high obliquity!

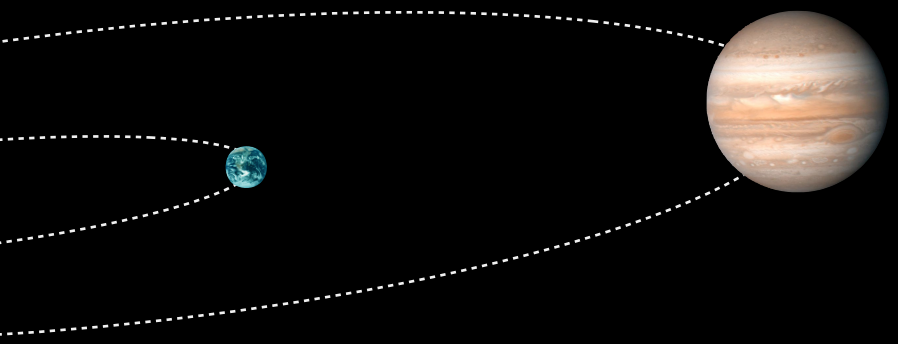
Spin matters…faster spin reduces heat flow across latitudes

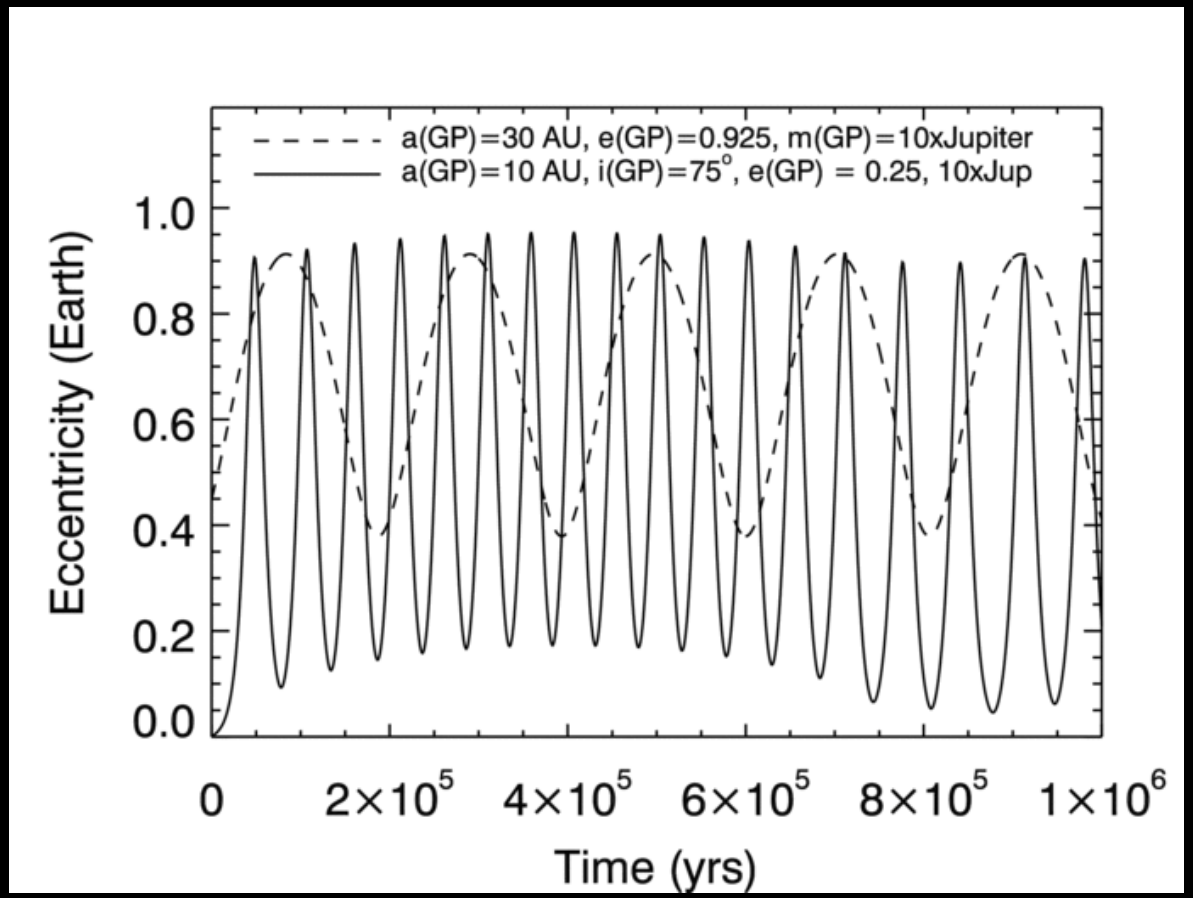


Thermal inertia of oceans (>10% surface) critical for climate stability

One conclusion: To address 'habitability' we *must* couple spin-orbit dynamics to climate dynamics...

Total system architecture is a critical ingredient...





(Spiegel, Raymond, Dressing, Scharf, Mitchell 2010)

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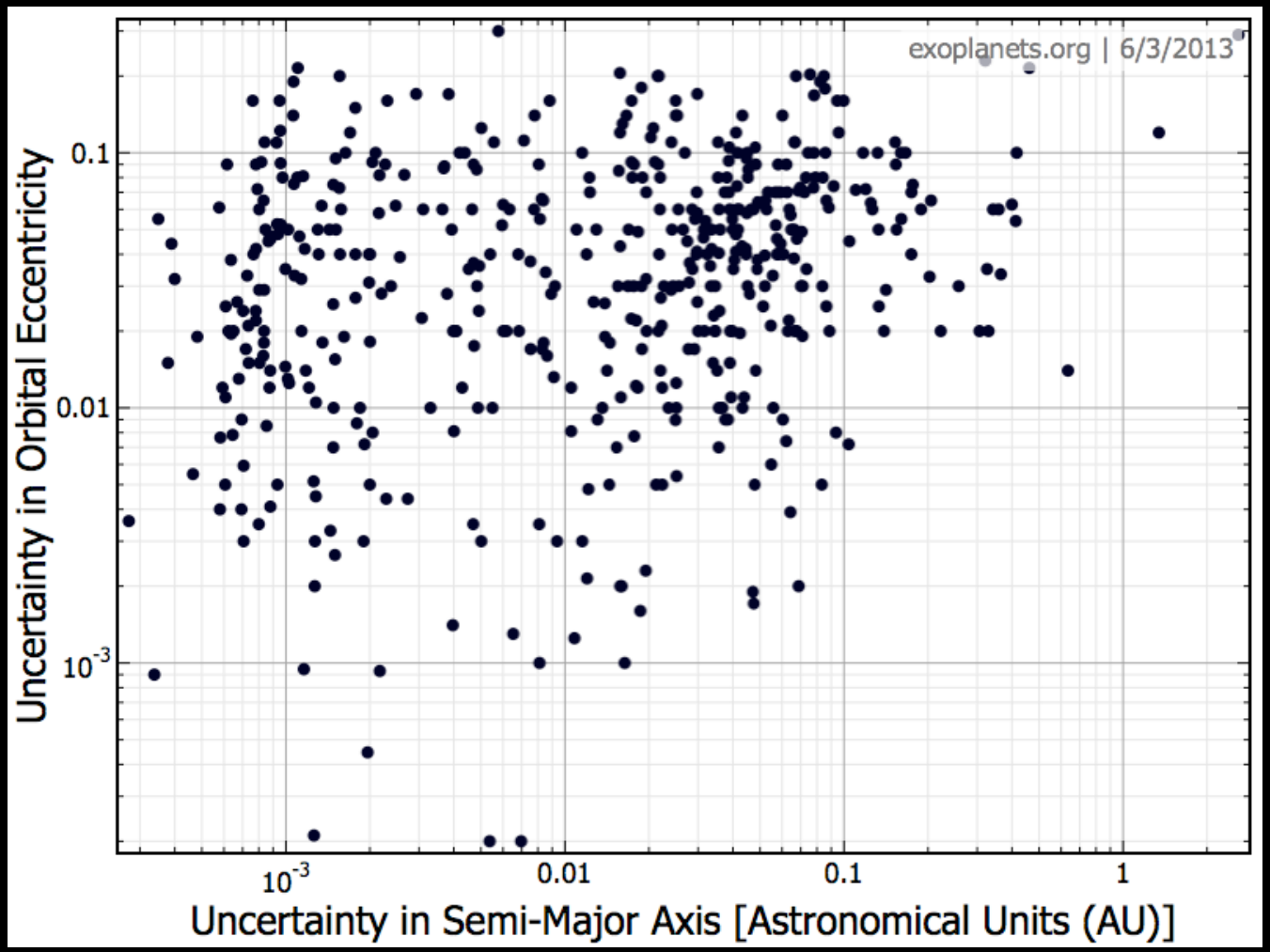
Orbit size and eccentricity



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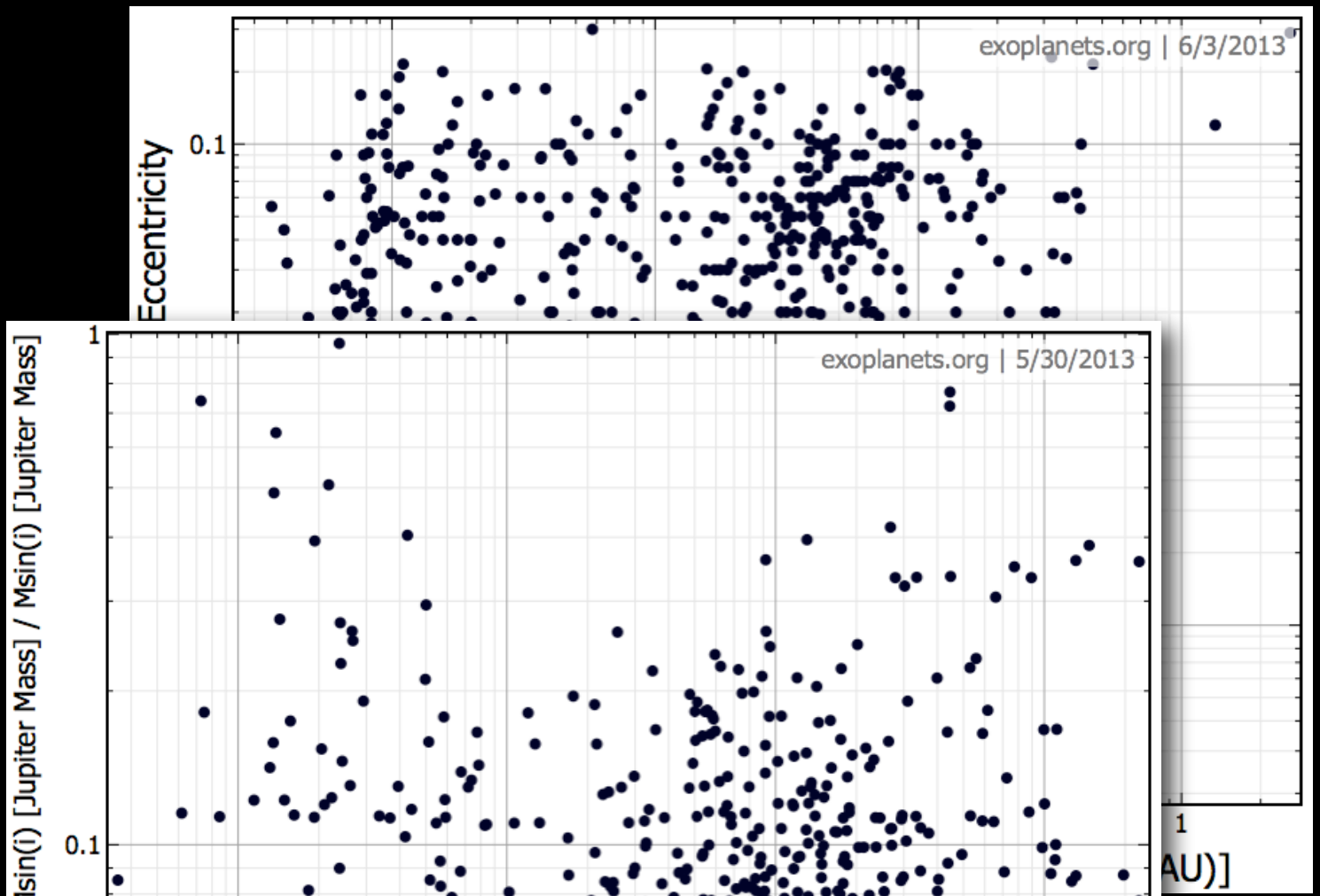
Planetary masses



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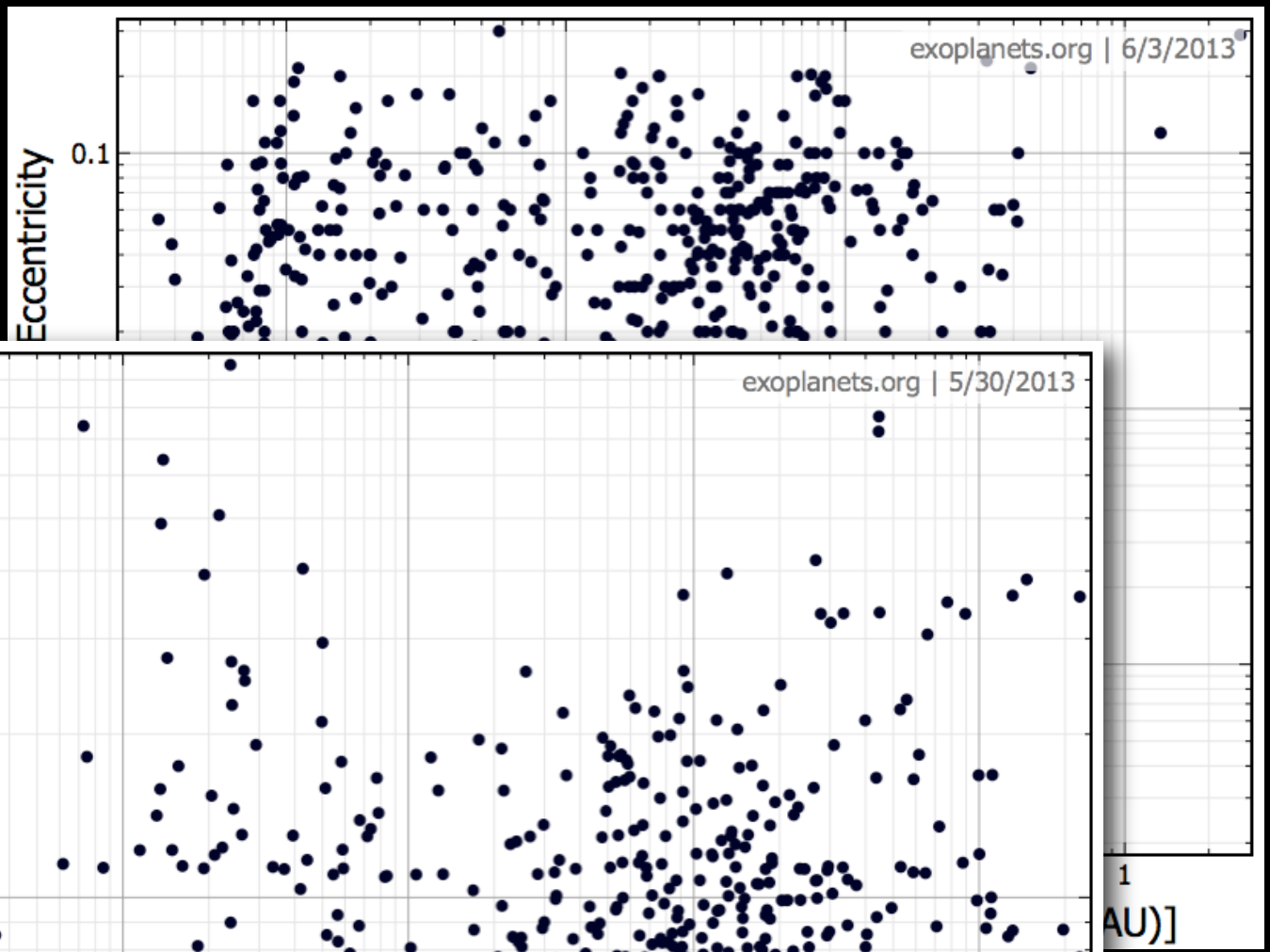
Orbit size and eccentricity

Planetary masses

Obliquity, spin, precession?



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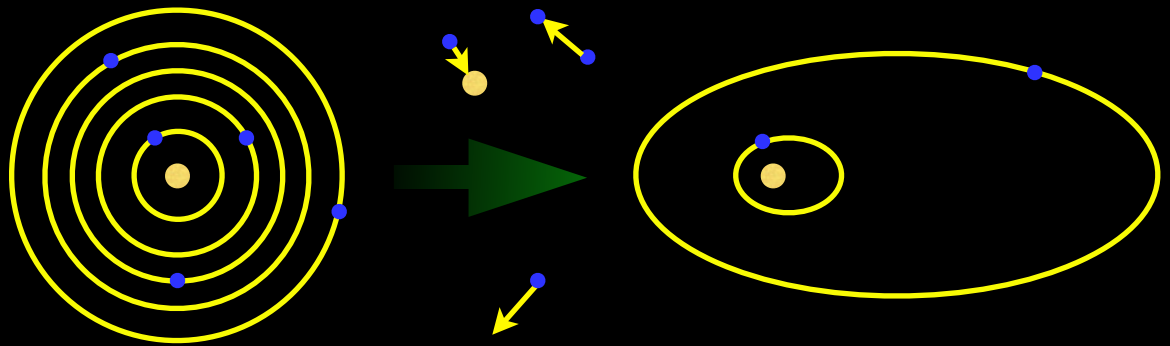

Henri Poincaré

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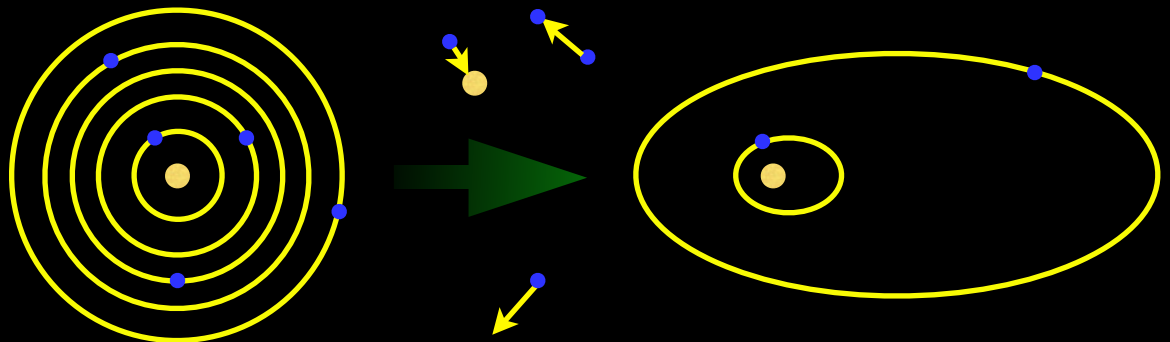

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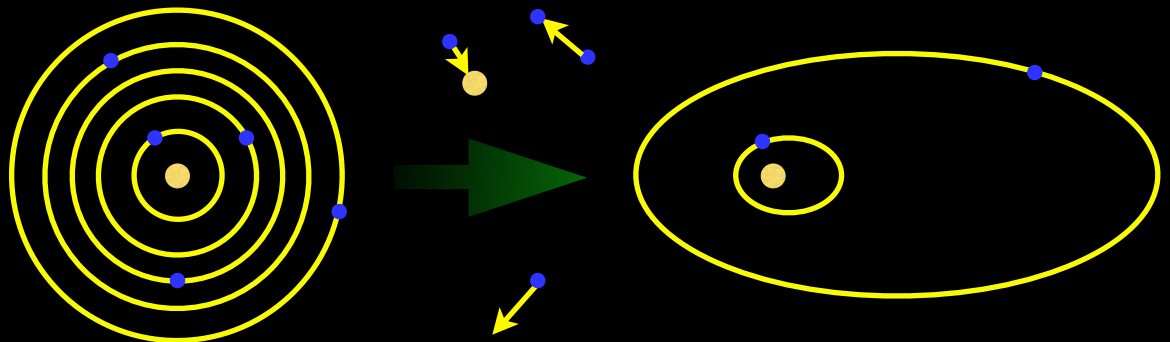

Henri Poincaré

But for long-lived systems, close encounters only occur on ~$10^{8\text{-}9}$ yr timescales.

Timescale of system stability is therefore a key indicator of 'goodness of fit' for present orbital elements & planet masses - and can be modeled with gravitational simulations

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515 GFlops
(double precision)

[About 500% improvement over high end CPU]

Over 21,000 threads (processes) [Versus 12 in hexacore CPU]

What is the gain?

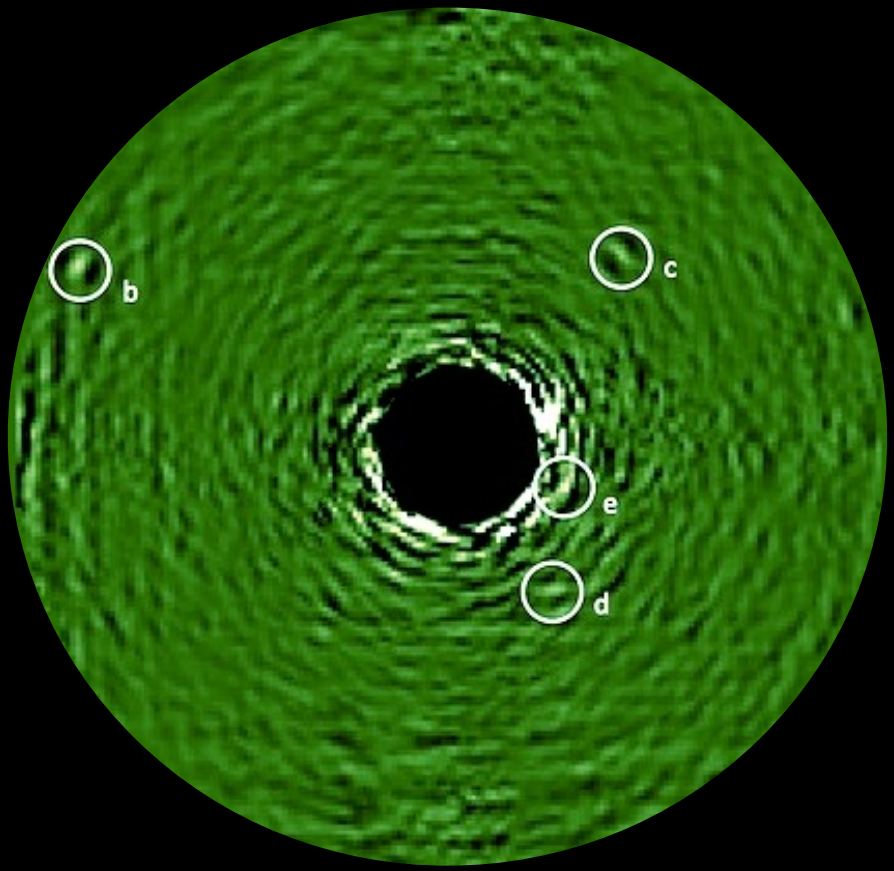
Each *planet* is a separate 'thread' in the GPU, thus force calculation scales as N rather than N^2

For example, we evolved 1,500 instances of the 8 major planets of our solar system for 10^8 years in 4 days - on ***one*** GPU

This test with a 'comparable' CPU takes 10 days, for (e.g.) 12 instances

Pathfinding dynamical study of directly imaged system

HR 8799, Project 1640



(Veicht, Scharf, Oppenheimer et al. 2014)

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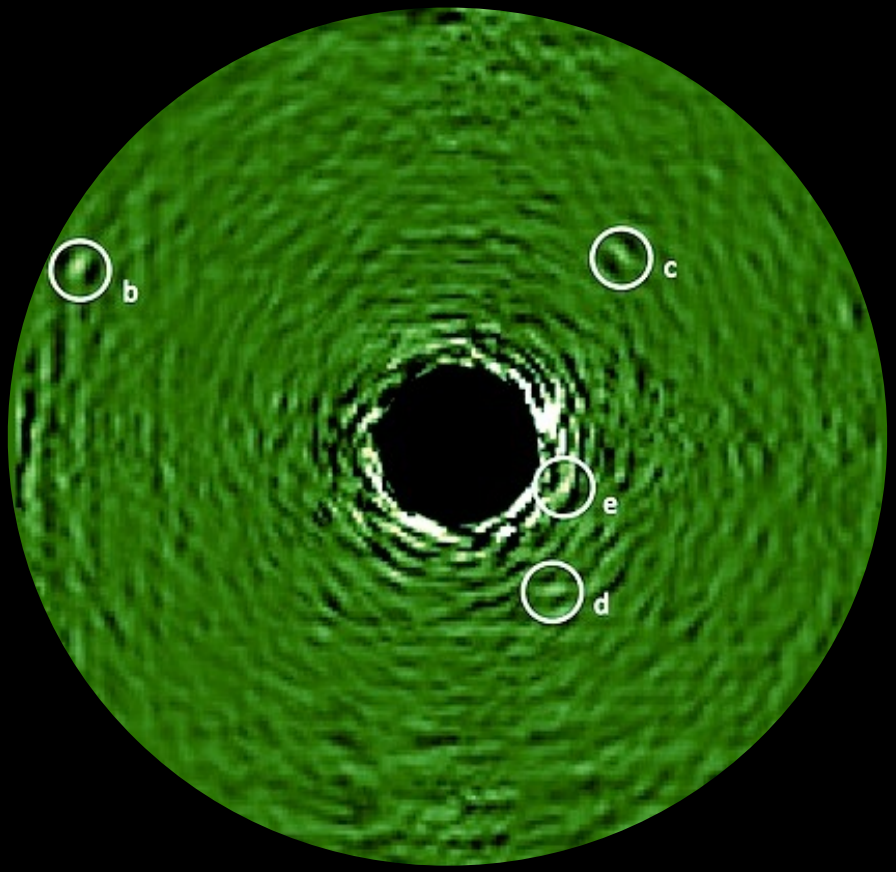

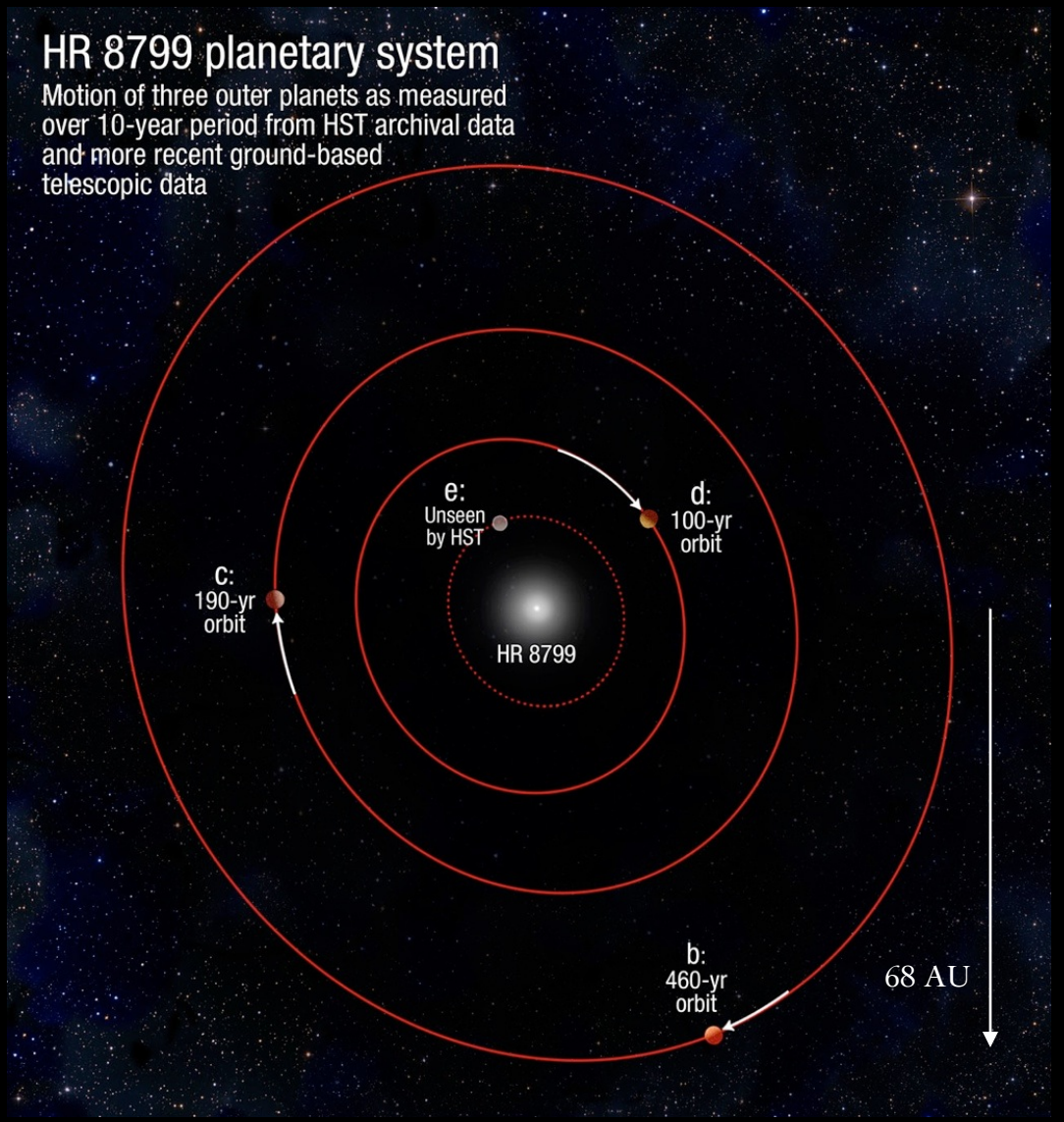

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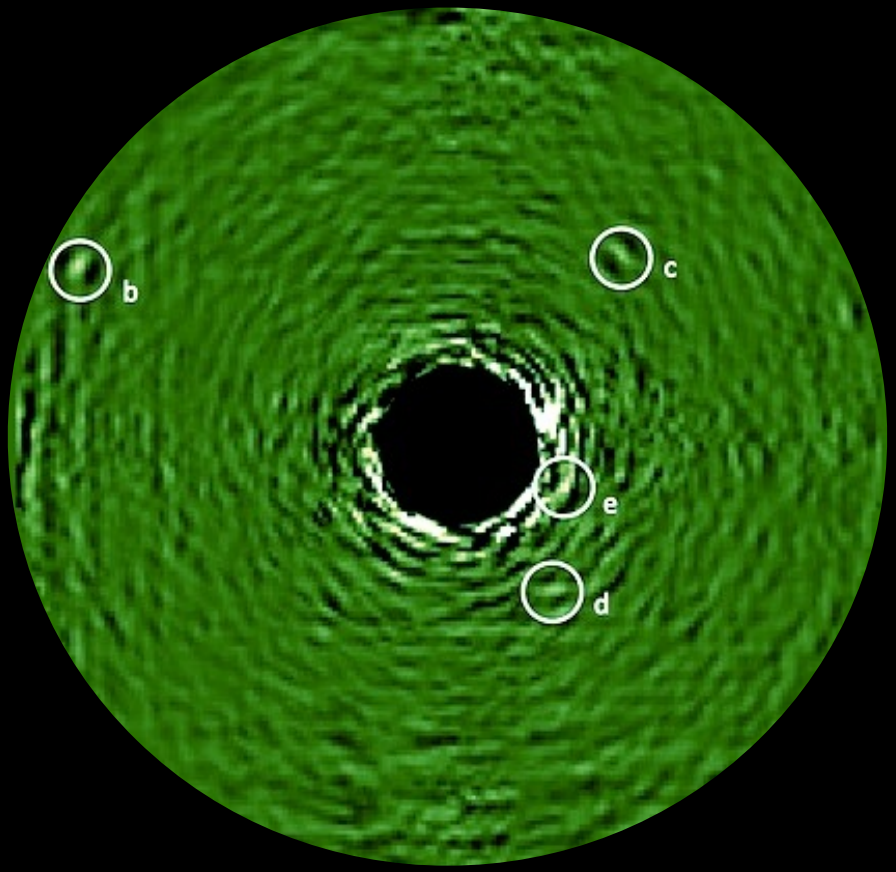

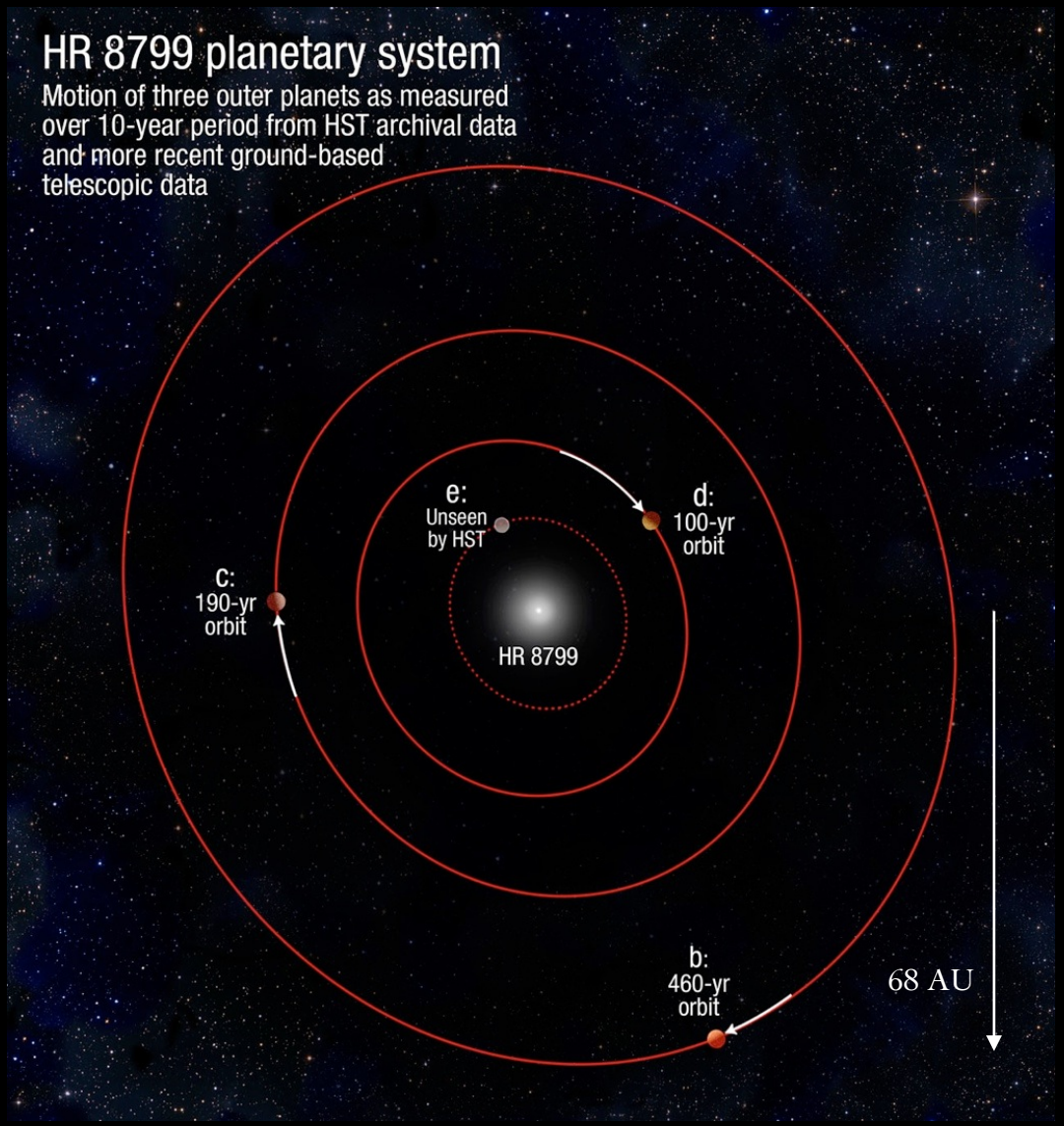

First results: Published orbital parameters can result in instability within 100,000 years!

(Veicht, Scharf, Oppenheimer et al. 2014)

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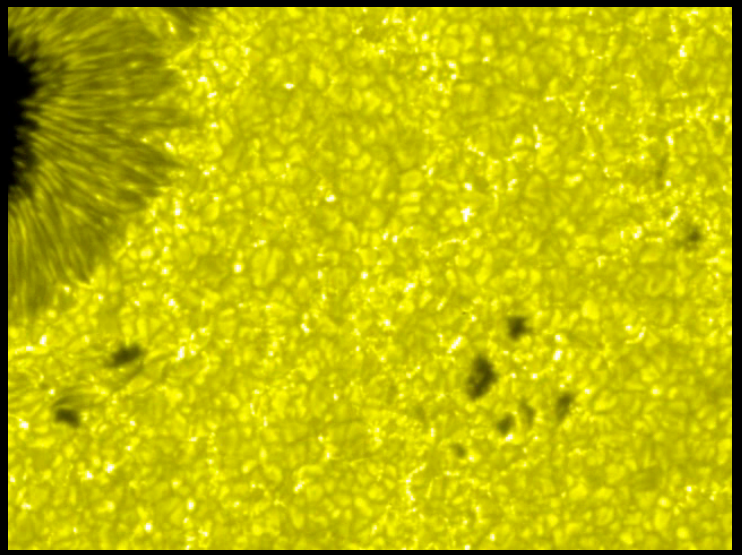

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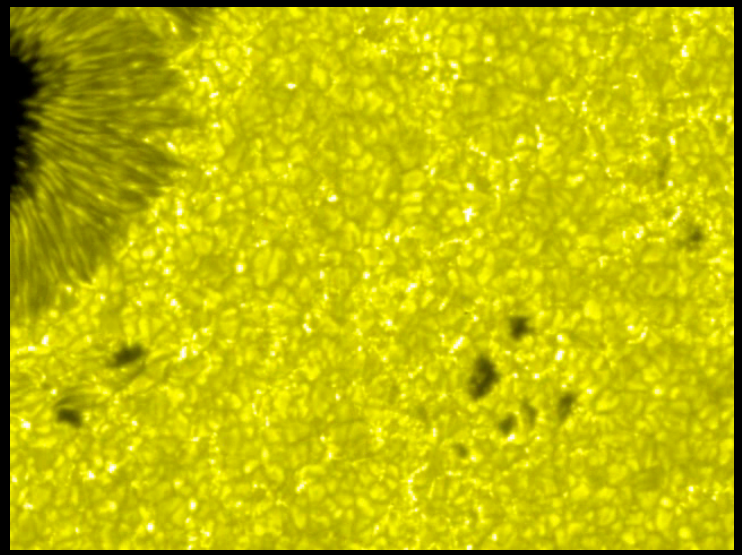
2) Transit candidates for spectroscopy may be few, and system architecture may be uncertain...



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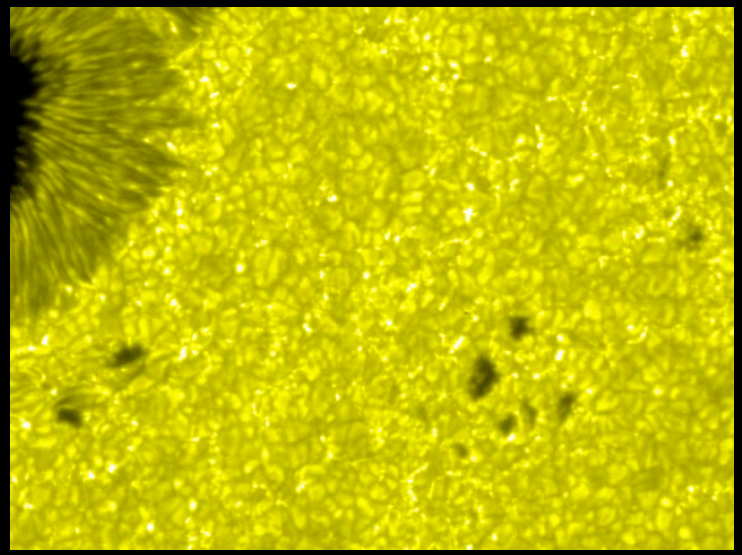

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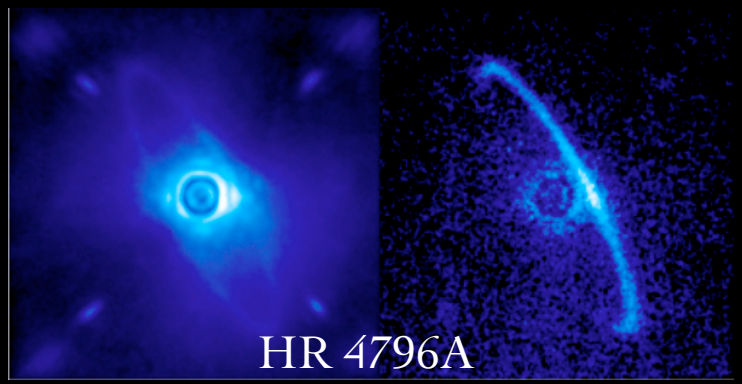
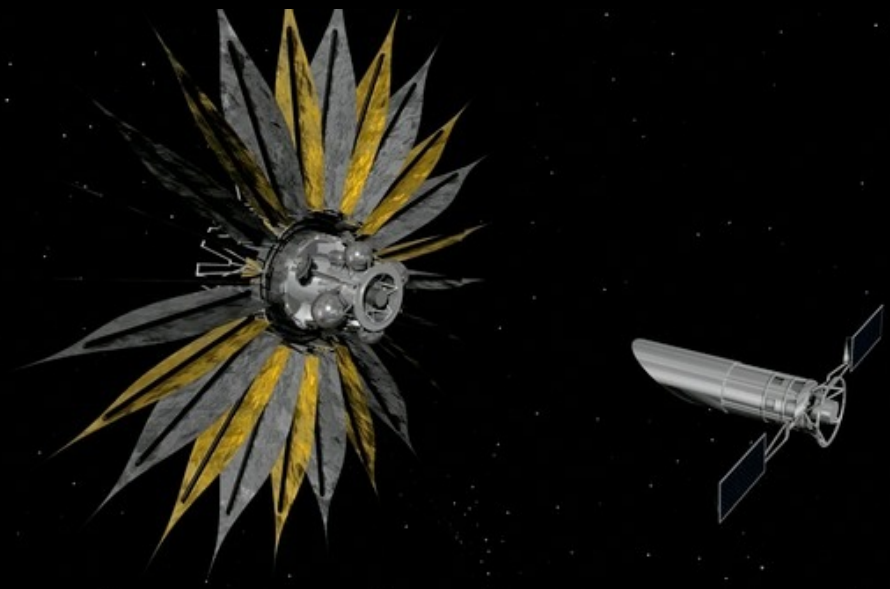
2) Transit candidates for spectroscopy may be few, and system architecture may be uncertain...

3) Coronography and Starshades show great promise...



GPI first light



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