Where, and How Probable, is Life?
Climatic Habitability and Abiogenesis

Dave Spiegel
Institute for Advanced Study

Colalborators: Ed Turner, Sean Raymond, Kristen Menou, Courtney Dressing, Caleb Scharf, Jonathan Mitchell

CIERA

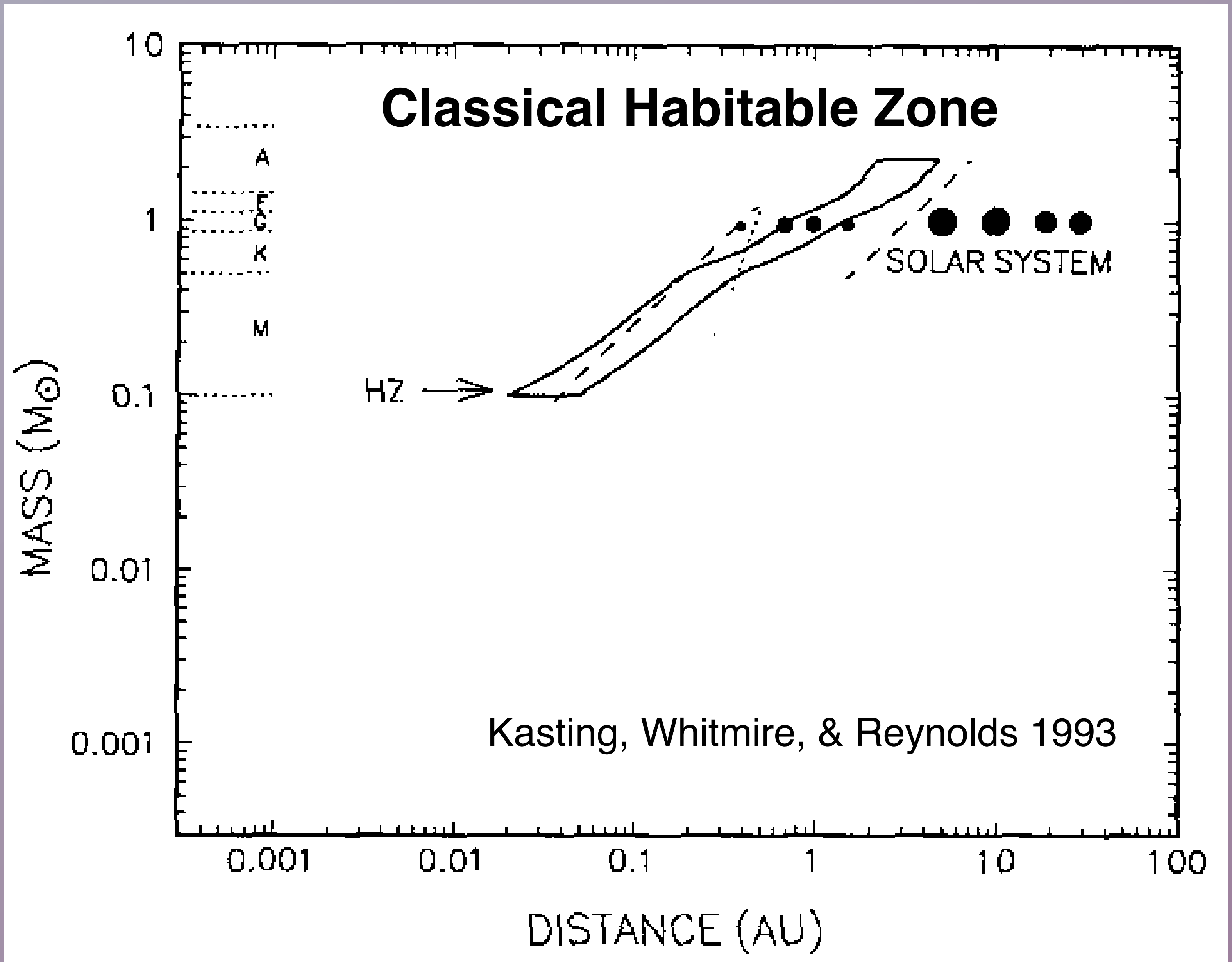
9/1/2011

Overview

1. What factors influence climatic habitability?

2. What are the astrobiological implications of the early emergence of life on Earth?

Dependence on Stellar Properties

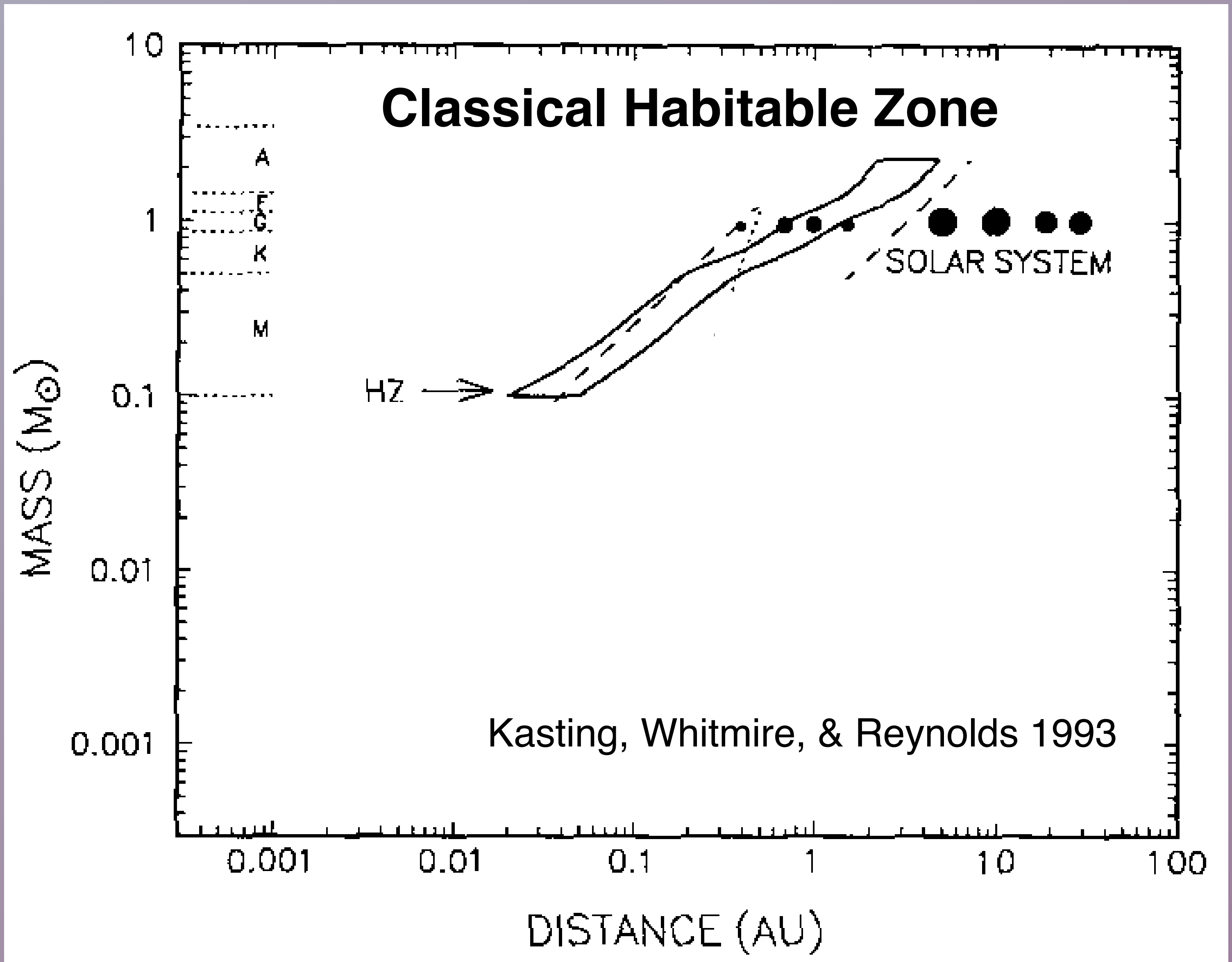


CIERA

9/1/2011

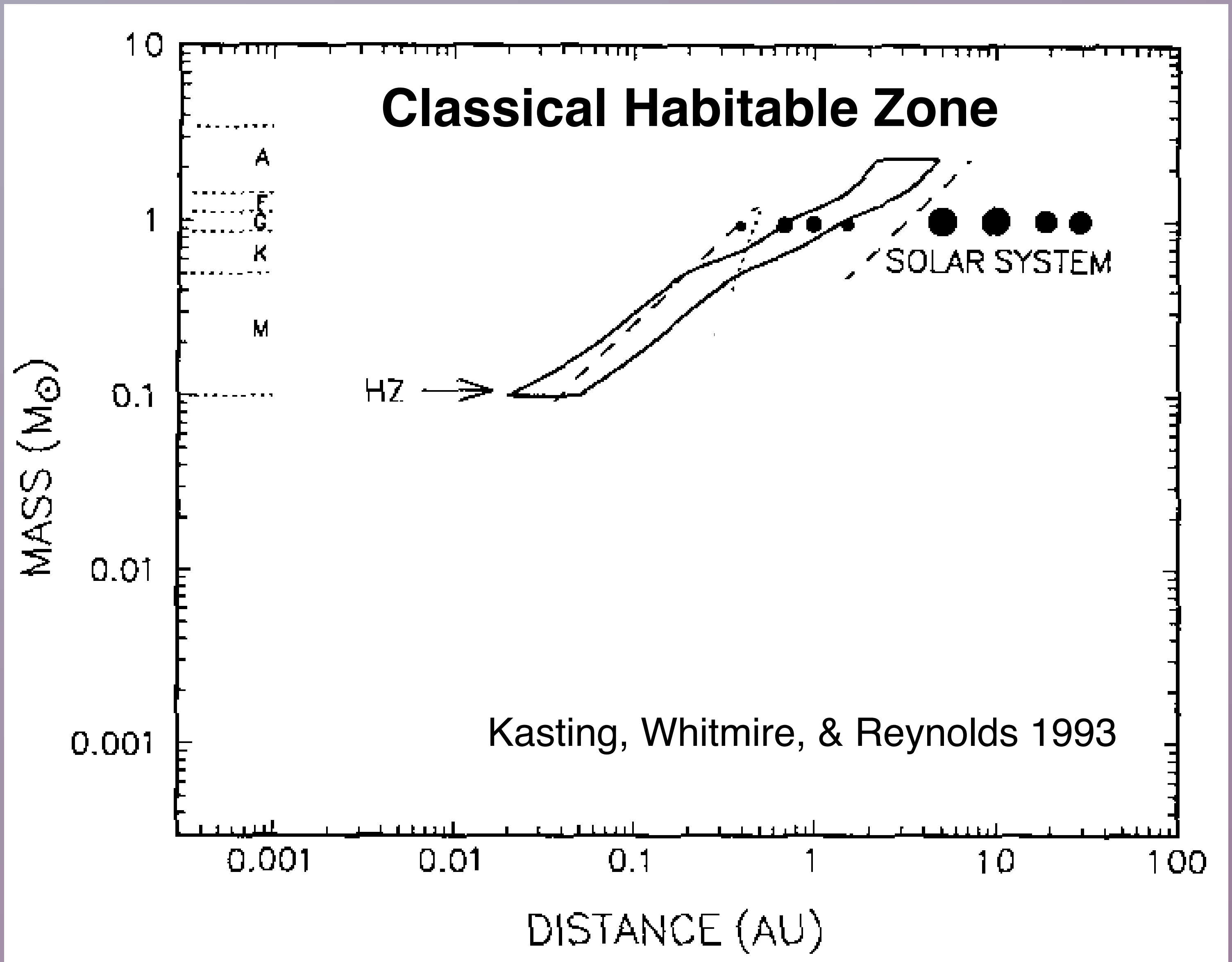
Climatic habitability depends on stellar properties,
But what about planet properties, planetary system properties?

Dependence on Stellar Properties



Climatic habitability depends on stellar properties, But what about planet properties, planetary system properties?

Dependence on Stellar Properties



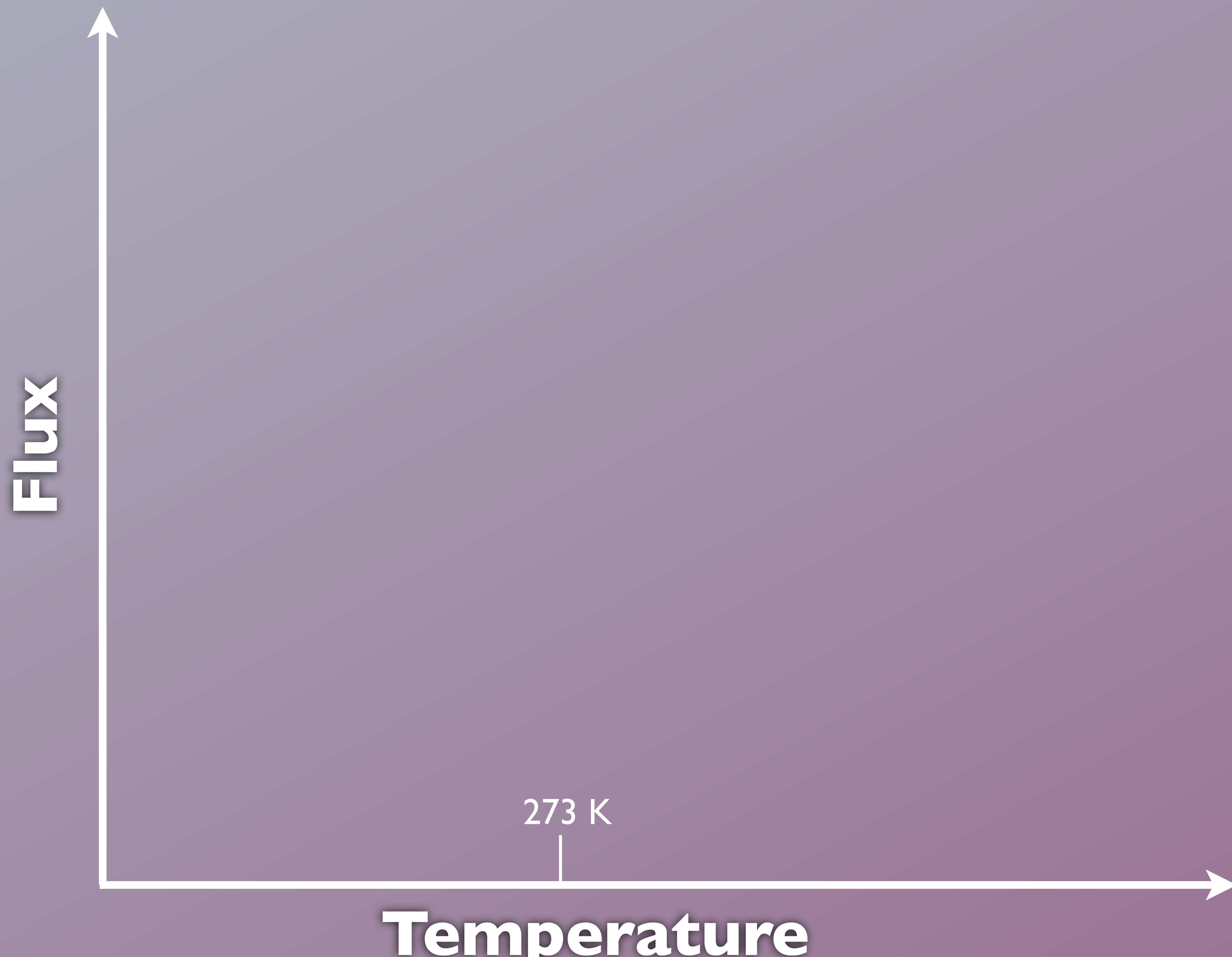
Dependence on Planet Properties?

- Rotation rate?
- Continent/ocean distribution?
- Atmospheric composition?
- Obliquity (tilt of spin axis)?
- Eccentricity?
- Longterm history of climate?

(initial conditions)

(influenced by planetary system architecture)

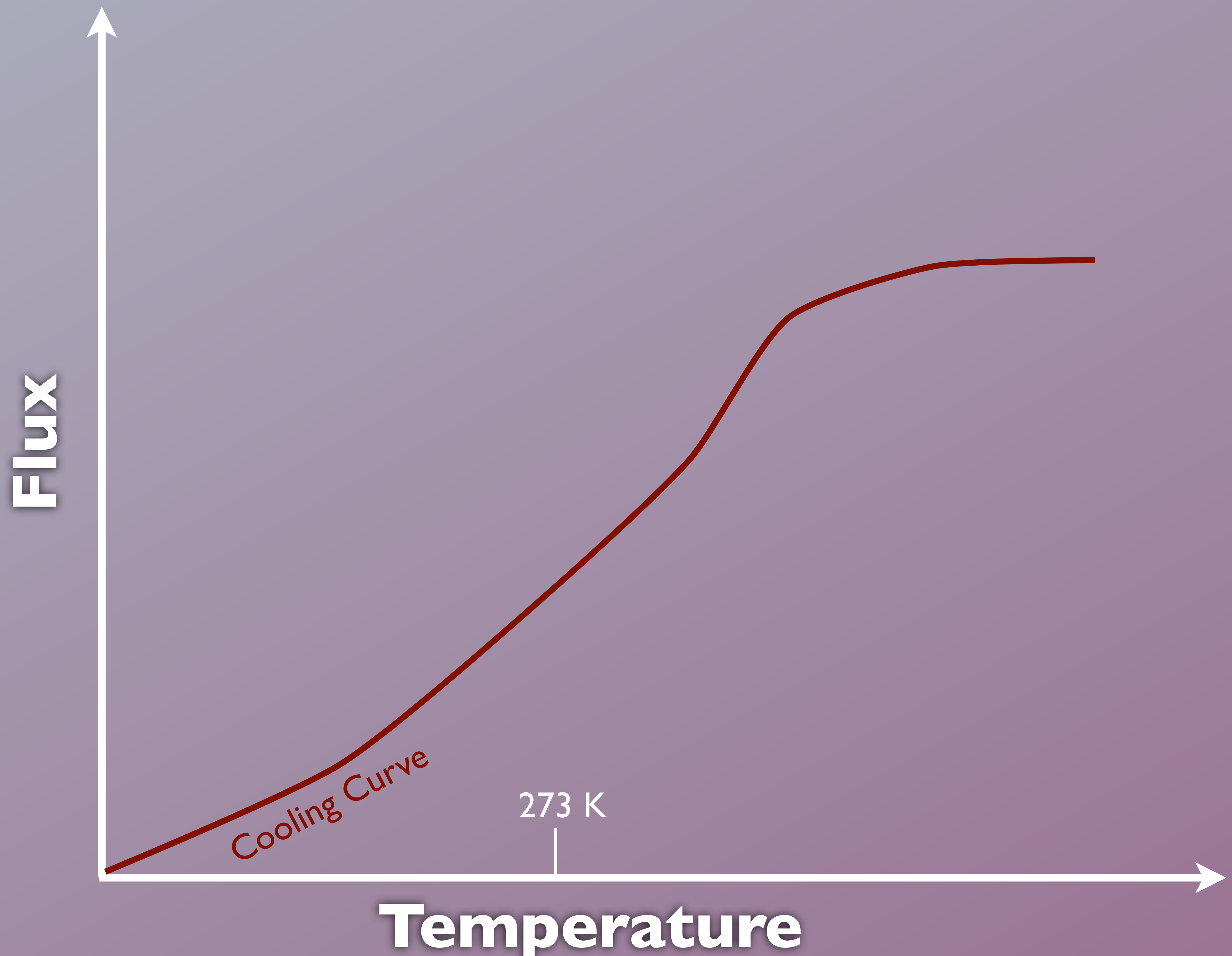
(0-D) Energy Balance on a Water-rich Planet



CIERA

9/1/2011

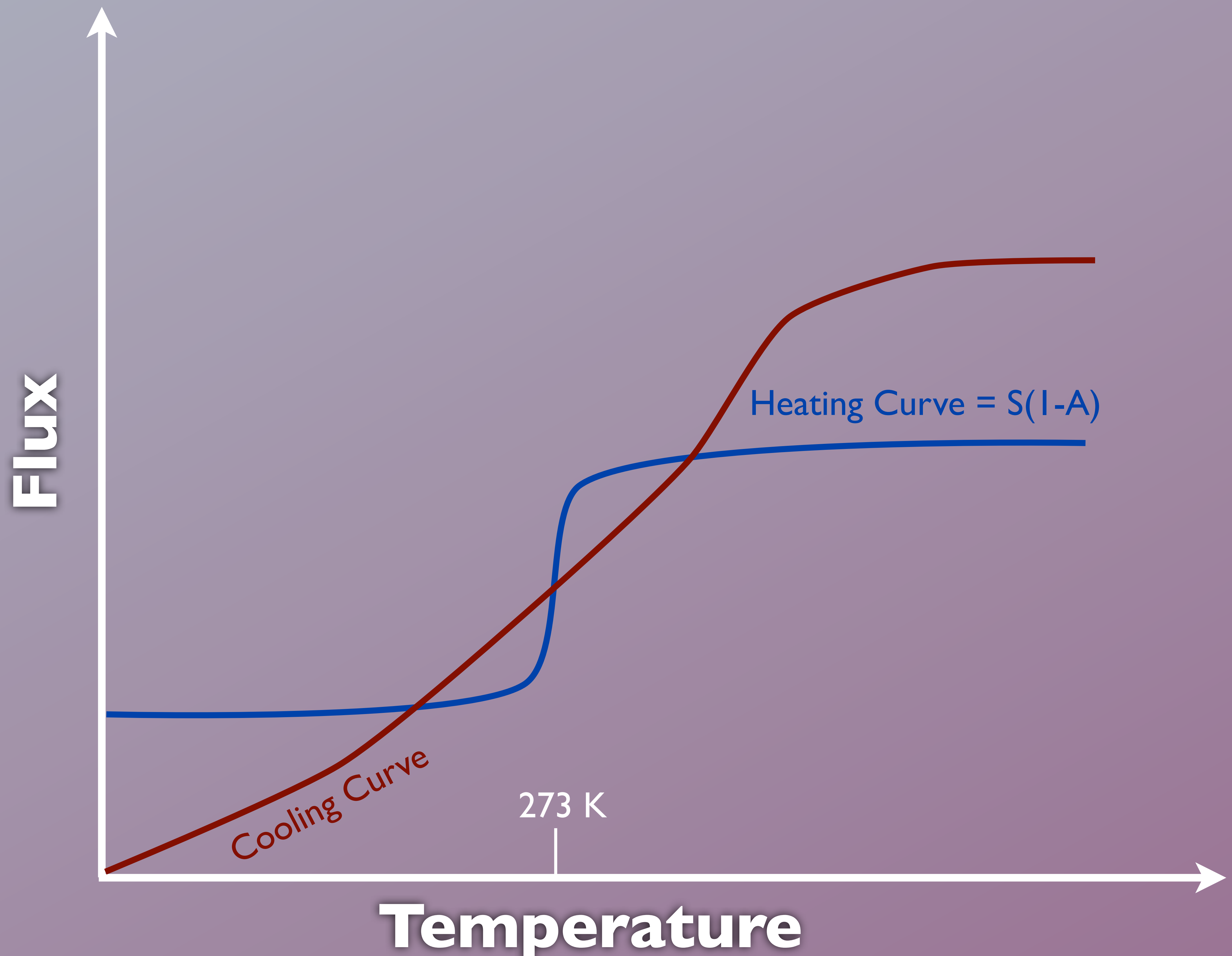
(0-D) Energy Balance on a Water-rich Planet



CIERA

9/1/2011

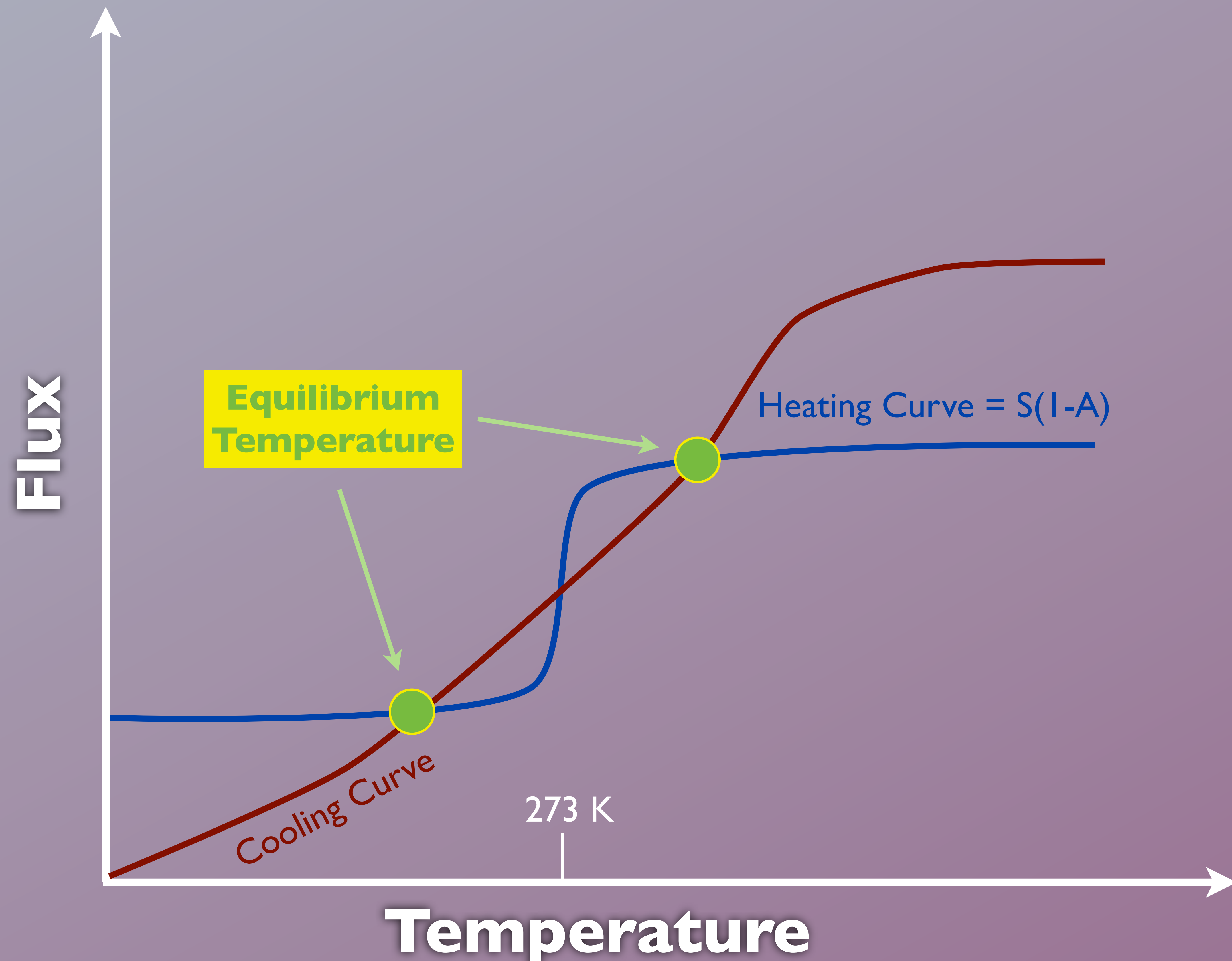
(0-D) Energy Balance on a Water-rich Planet



CIERA

9/1/2011

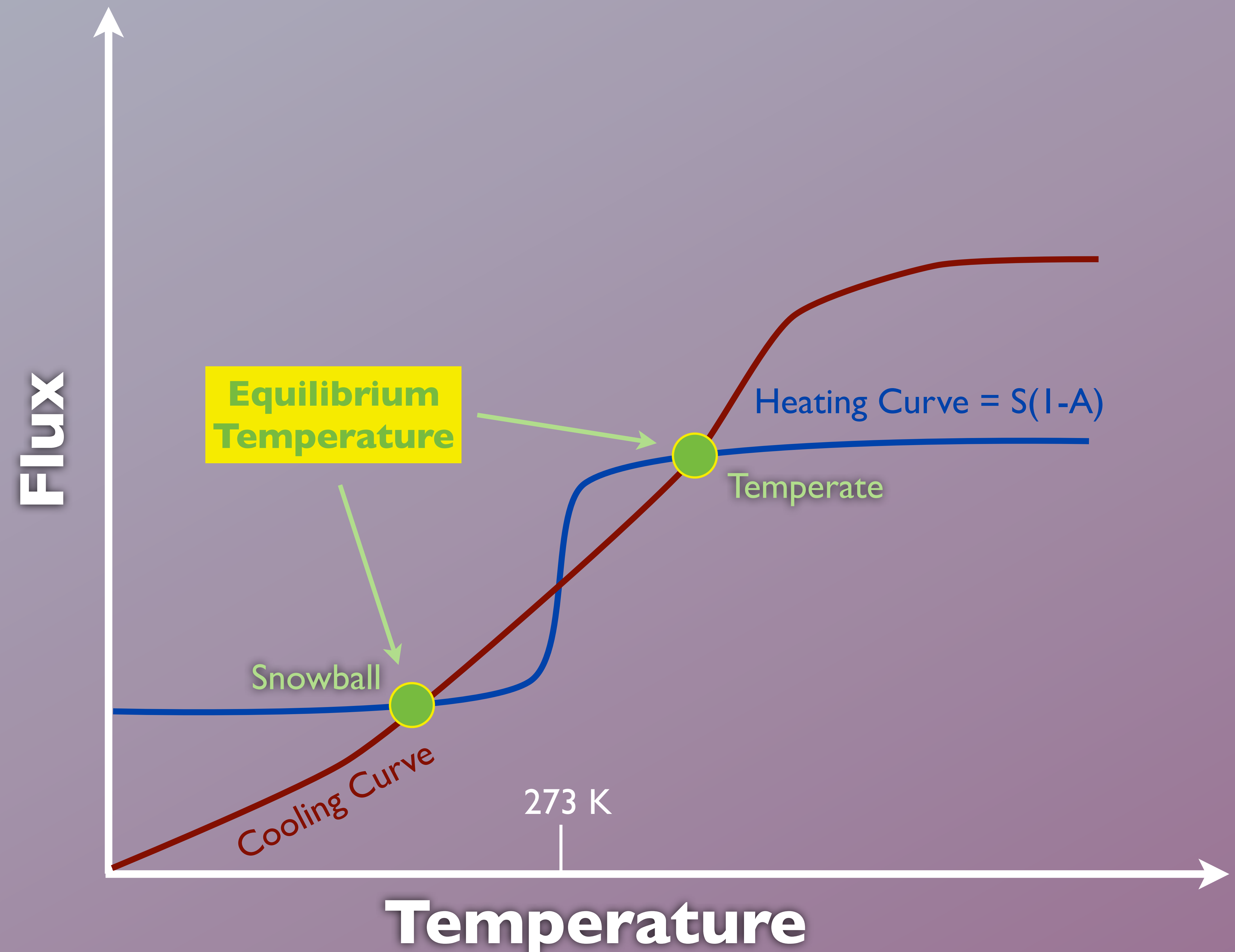
(0-D) Energy Balance on a Water-rich Planet



CIERA

9/1/2011

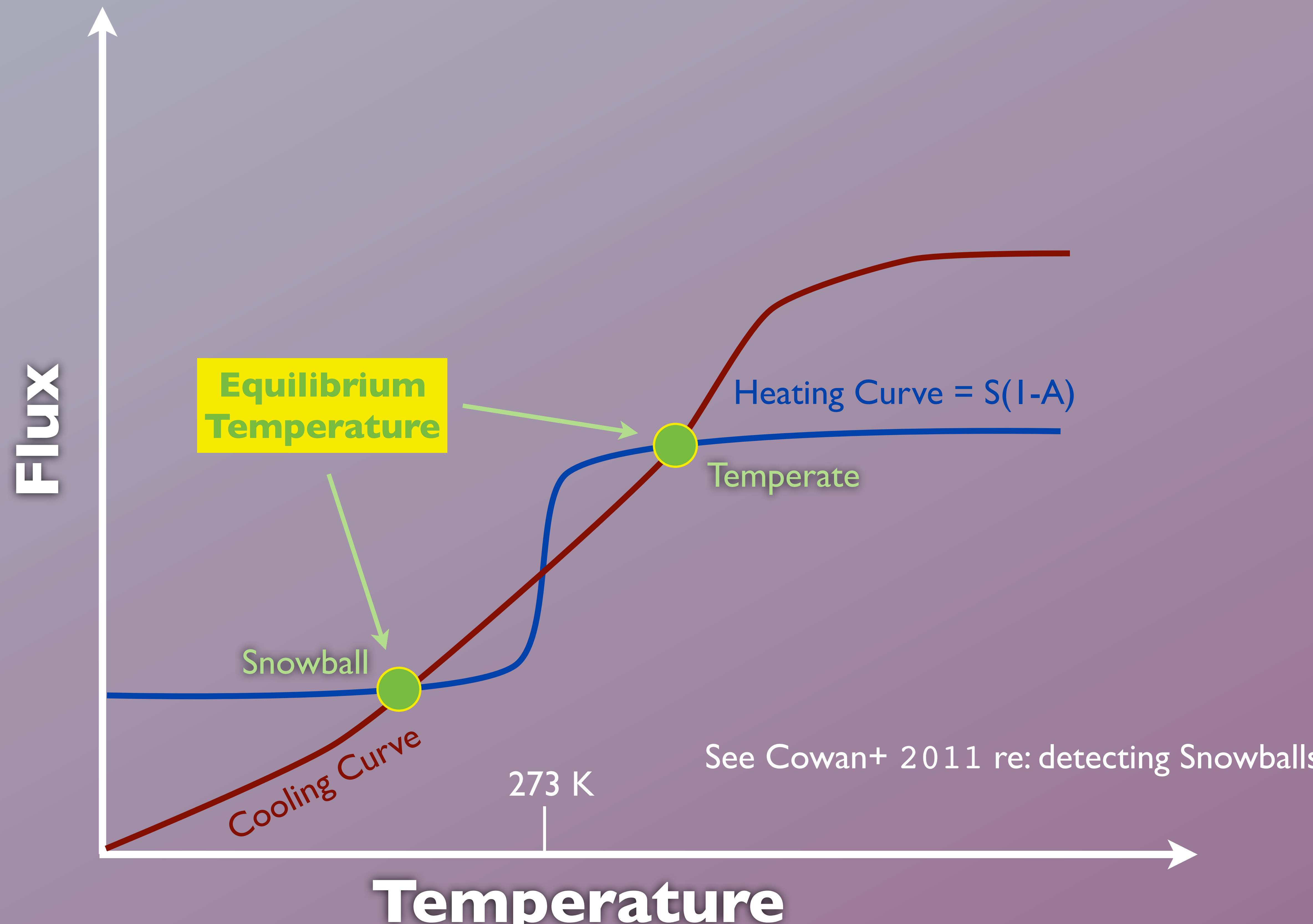
(0-D) Energy Balance on a Water-rich Planet



CIERA

9/1/2011

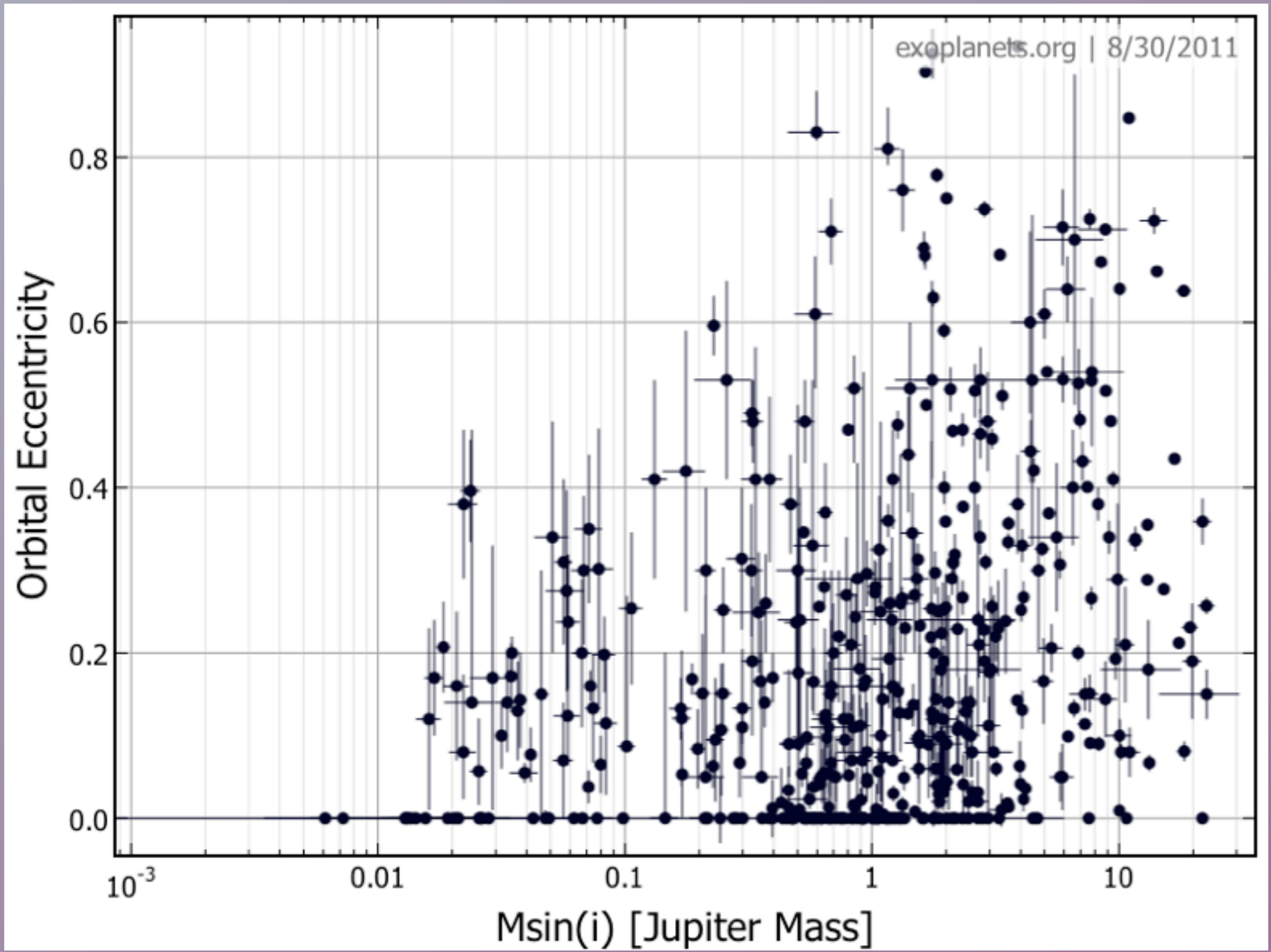
(0-D) Energy Balance on a Water-rich Planet



CIERA

9/1/2011

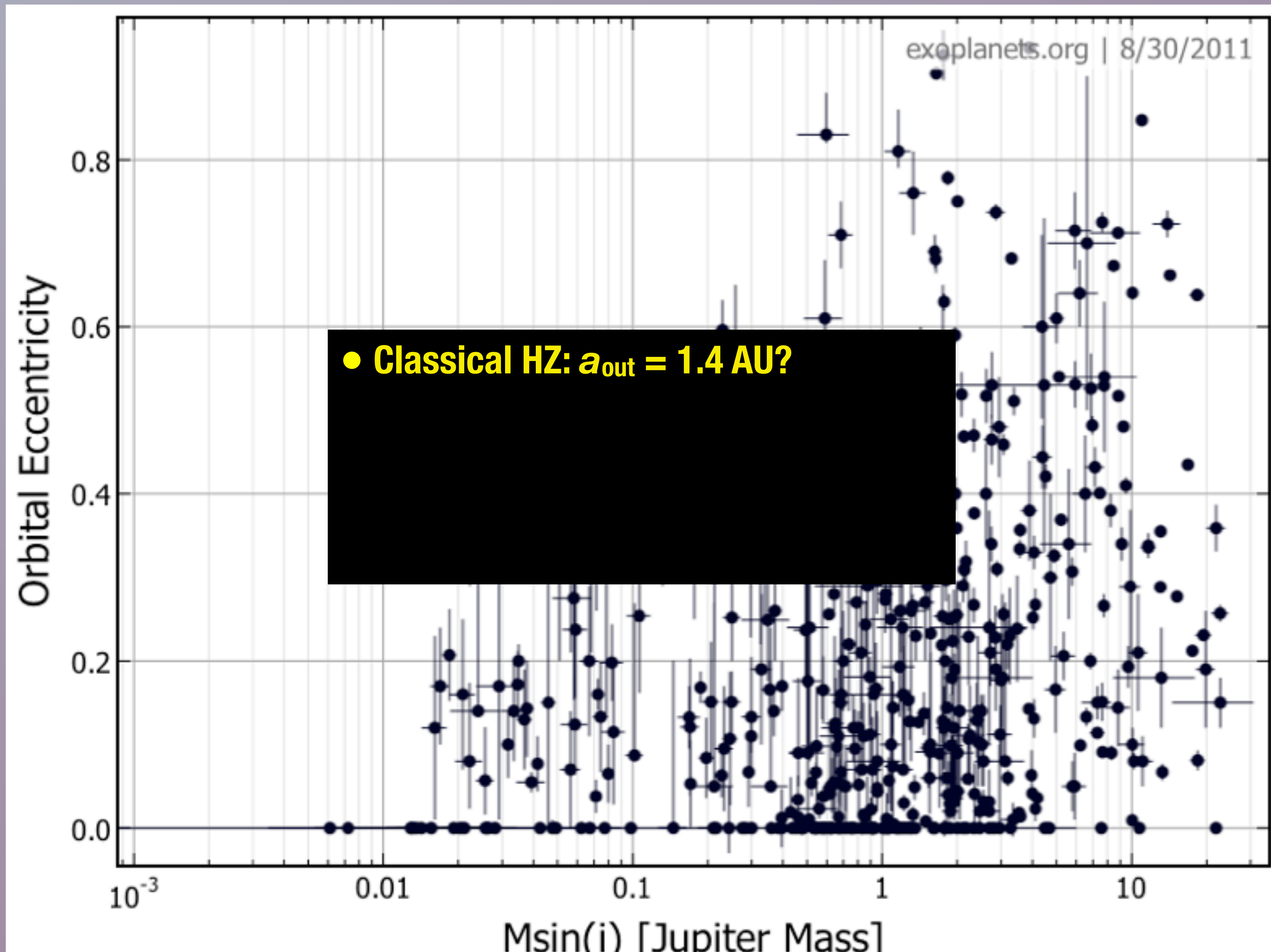
High eccentricity planets are common!



CIERA
9/1/2011

~20% have e > 0.4

High eccentricity planets are common!



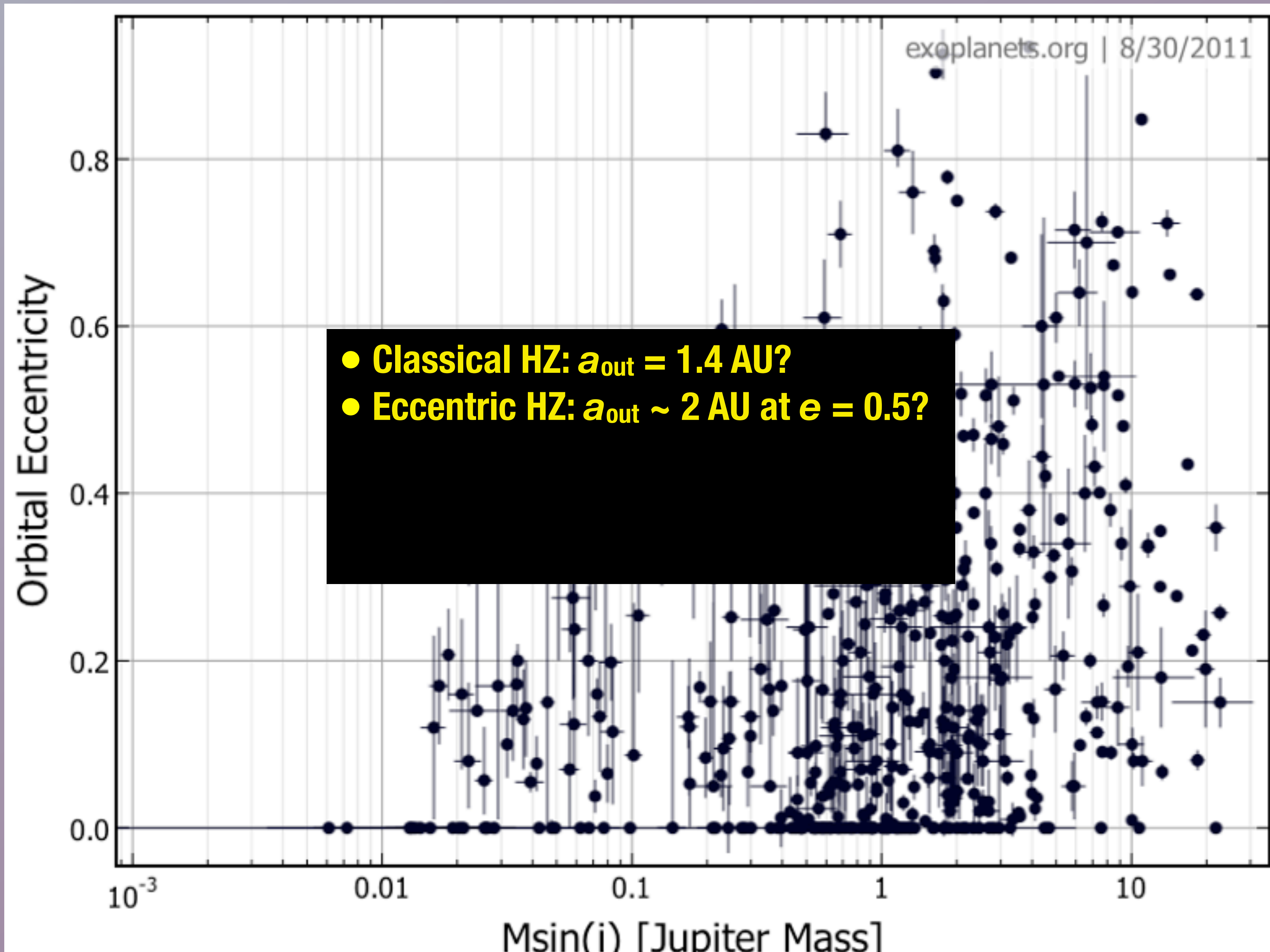
- Classical HZ: a_{out} = 1.4 AU?

~20% have e > 0.4

CIERA

9/1/2011

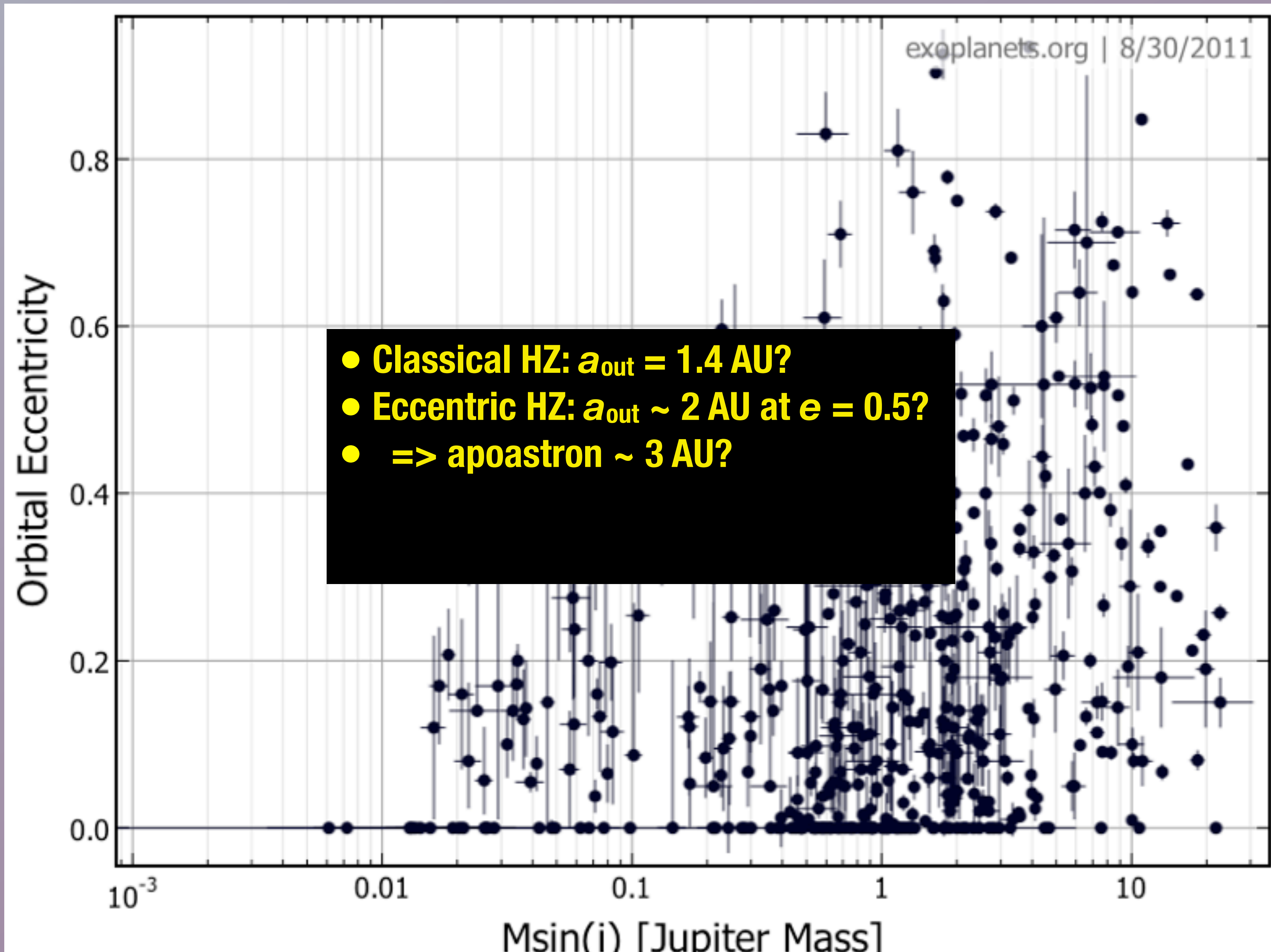
High eccentricity planets are common!



- Classical HZ: a_{out} = 1.4 AU?
- Eccentric HZ: a_{out} ~ 2 AU at e = 0.5?

~20% have e > 0.4

High eccentricity planets are common!

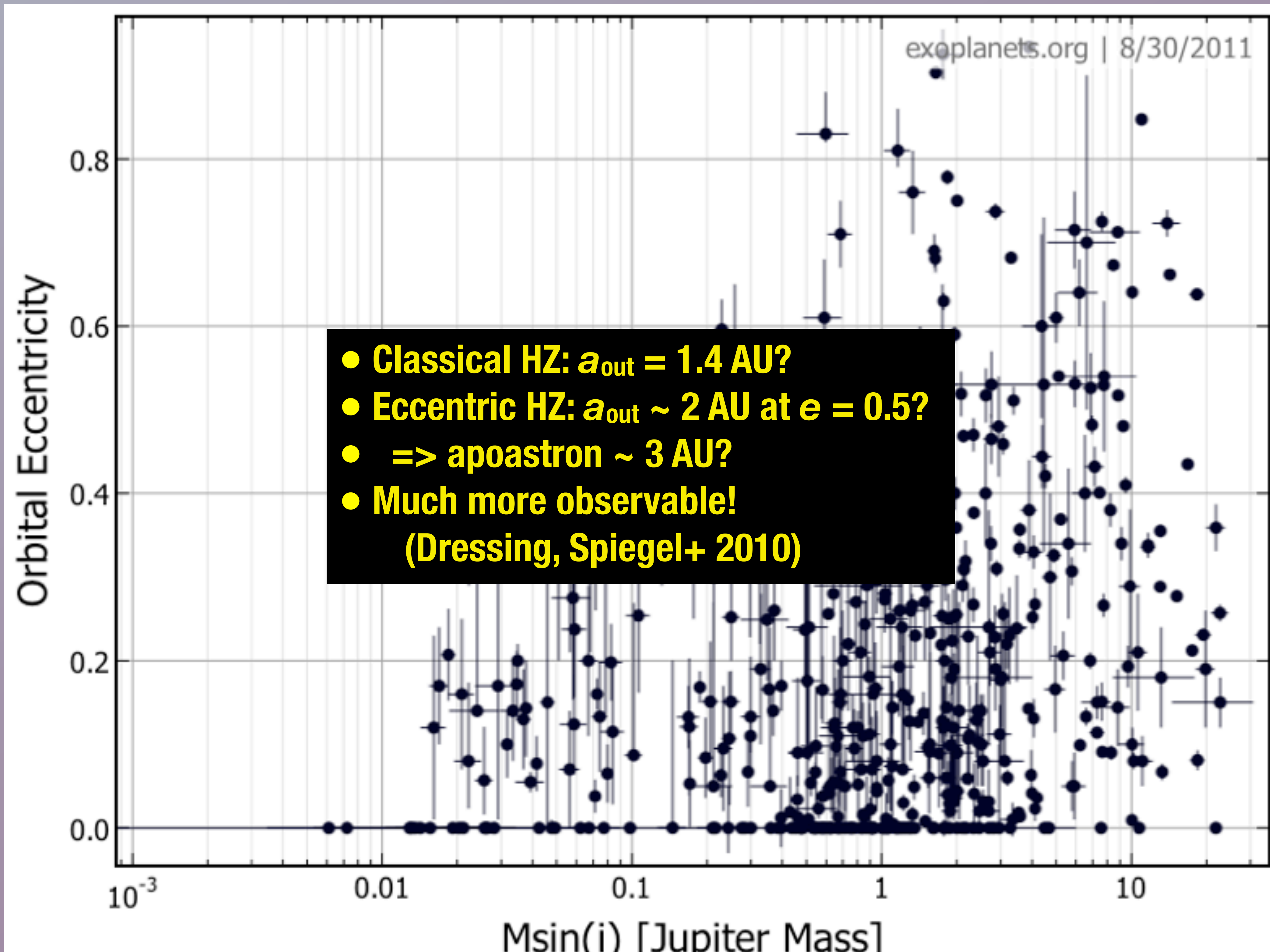


- Classical HZ: a_{out} = 1.4 AU?
- Eccentric HZ: a_{out} ~ 2 AU at e = 0.5?
- => apoastron ~ 3 AU?

CIERA
9/1/2011

~20% have e > 0.4

High eccentricity planets are common!



- Classical HZ: a_{out} = 1.4 AU?
- Eccentric HZ: a_{out} ~ 2 AU at e = 0.5?
- => apoastron ~ 3 AU?
- Much more observable!
  (Dressing, Spiegel+ 2010)

CIERA

9/1/2011

~20% have e > 0.4

Generalized Milankovitch Cycles:

Spiegel, Raymond et al. 2010,
see also Kita, Rasio, & Takeda 2010,
see also Barnes, Jackson, Kopparapu, etc.

Generalized Milankovitch Cycles:

- Very mild cyclic changes in Earth's obliquity and eccentricity lead to dramatic changes in climate.

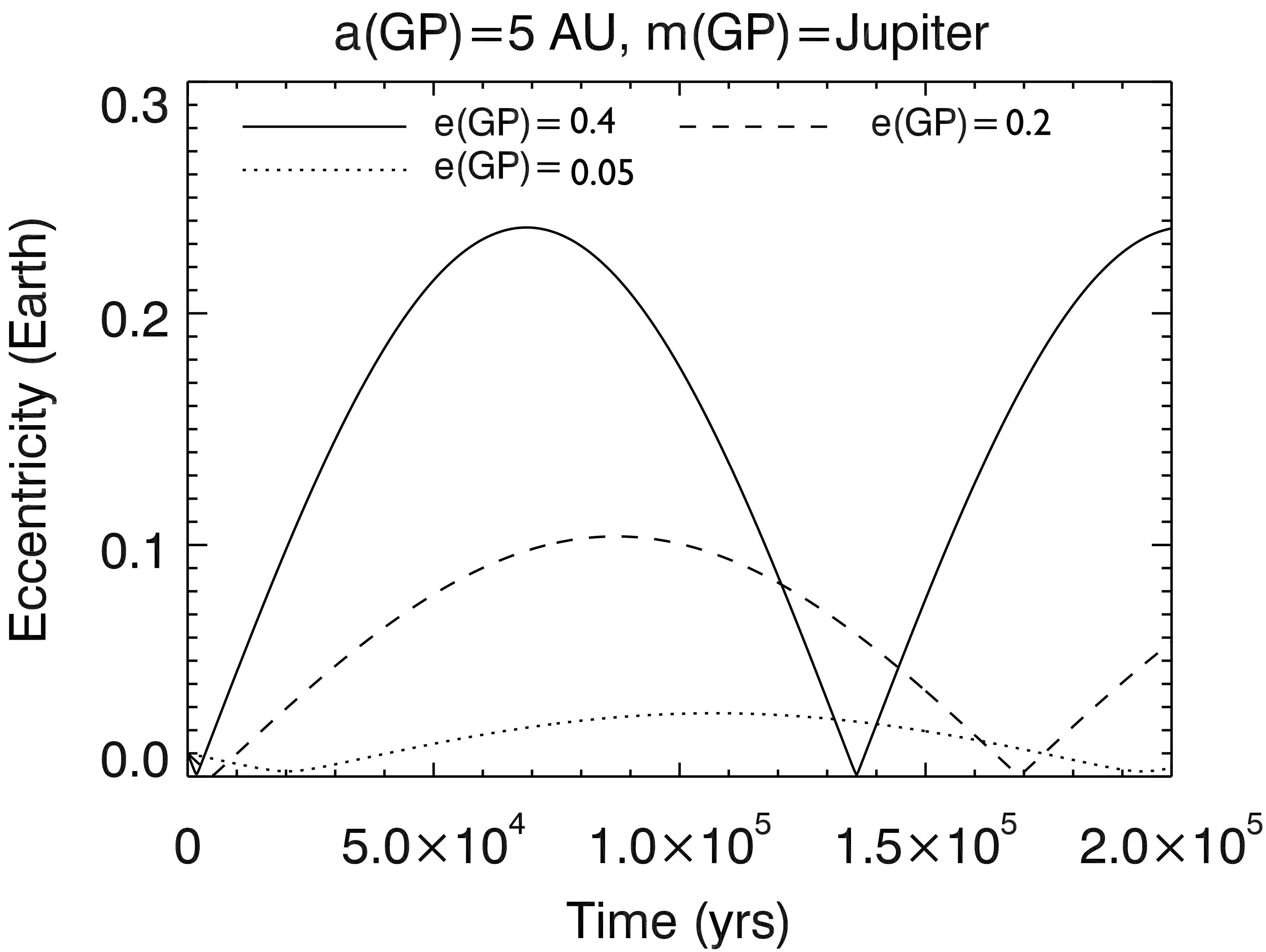
Spiegel, Raymond et al. 2010,
see also Kita, Rasio, & Takeda 2010,
see also Barnes, Jackson, Kopparapu, etc.

Generalized Milankovitch Cycles:

- Very mild cyclic changes in Earth's obliquity and eccentricity lead to dramatic changes in climate.
- Extrasolar systems could undergo exaggerated versions of these cycles.

Spiegel, Raymond et al. 2010,
see also Kita, Rasio, & Takeda 2010,
see also Barnes, Jackson, Kopparapu, etc.

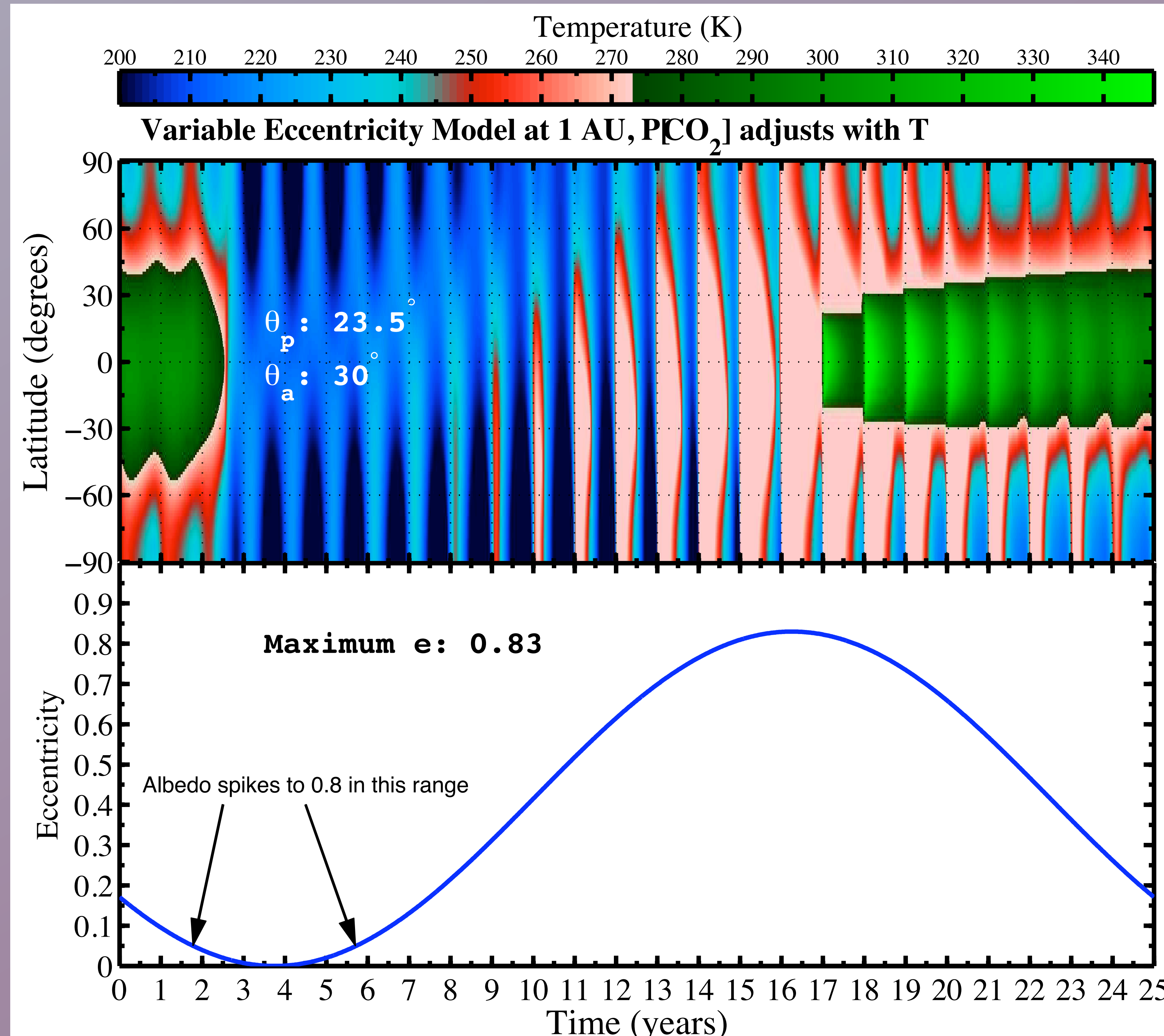
More eccentric companions cause faster *and larger amplitude* oscillations



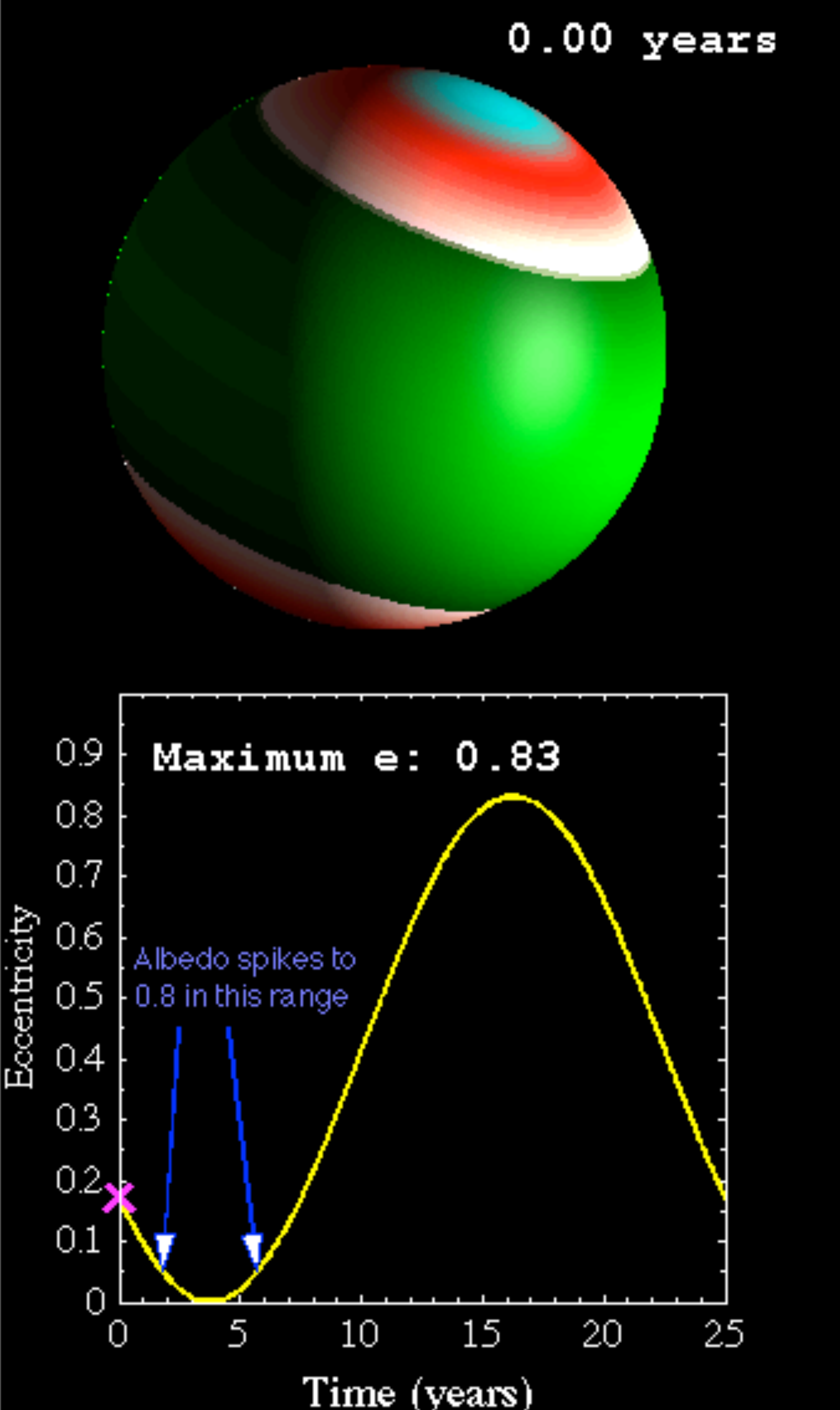
Spiegel, Raymond, et al. (2010)

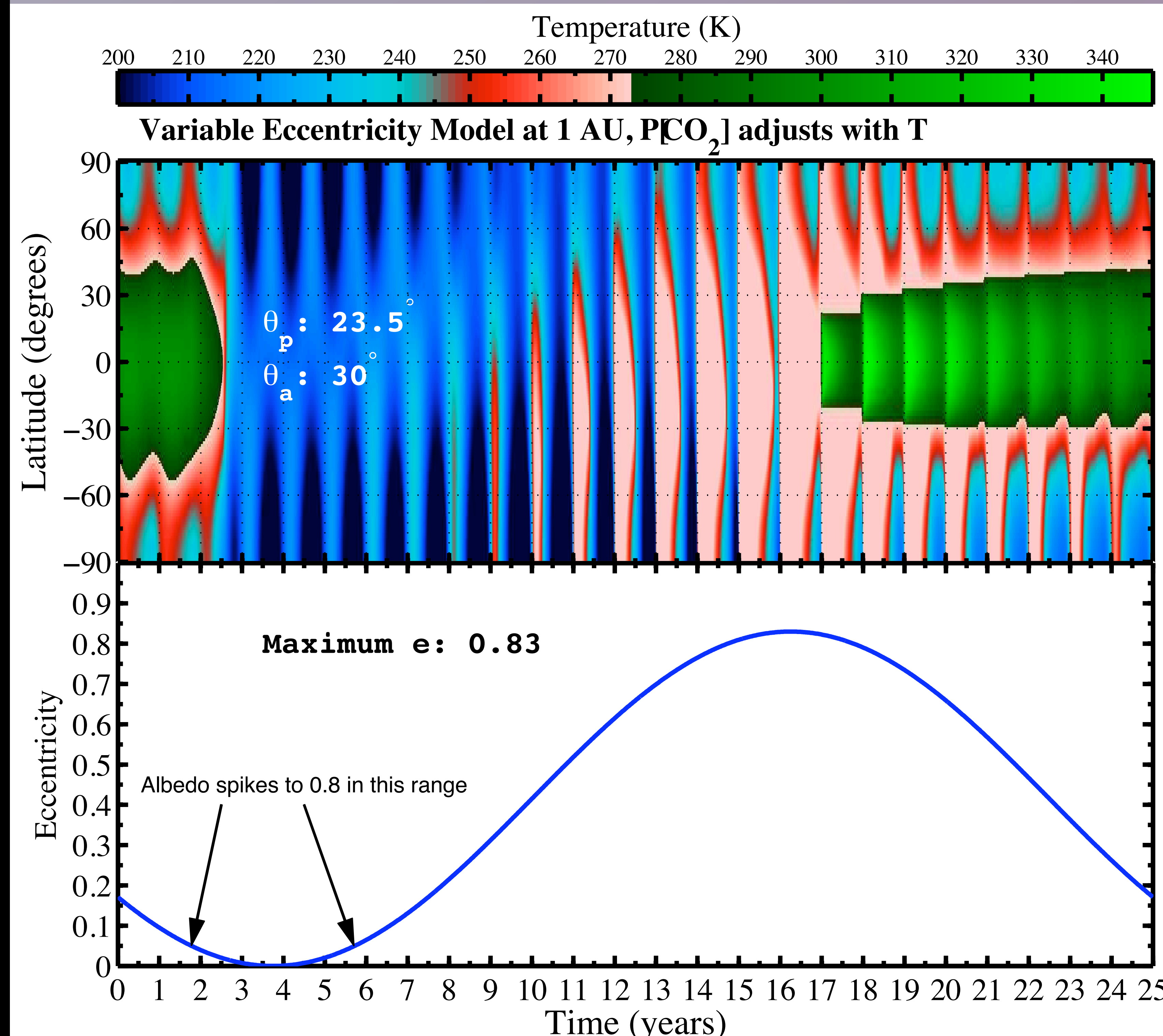
Simulations by Sean Raymond

Spiegel+ (2010)



Spiegel+ (2010)





CIERA

9/1/2011

Timeline of Life on Earth

Earth Formed (4.54 Gyr ago)

Present

Timeline of Life on Earth

Earth Formed (4.54 Gyr ago)

Present

CIERA

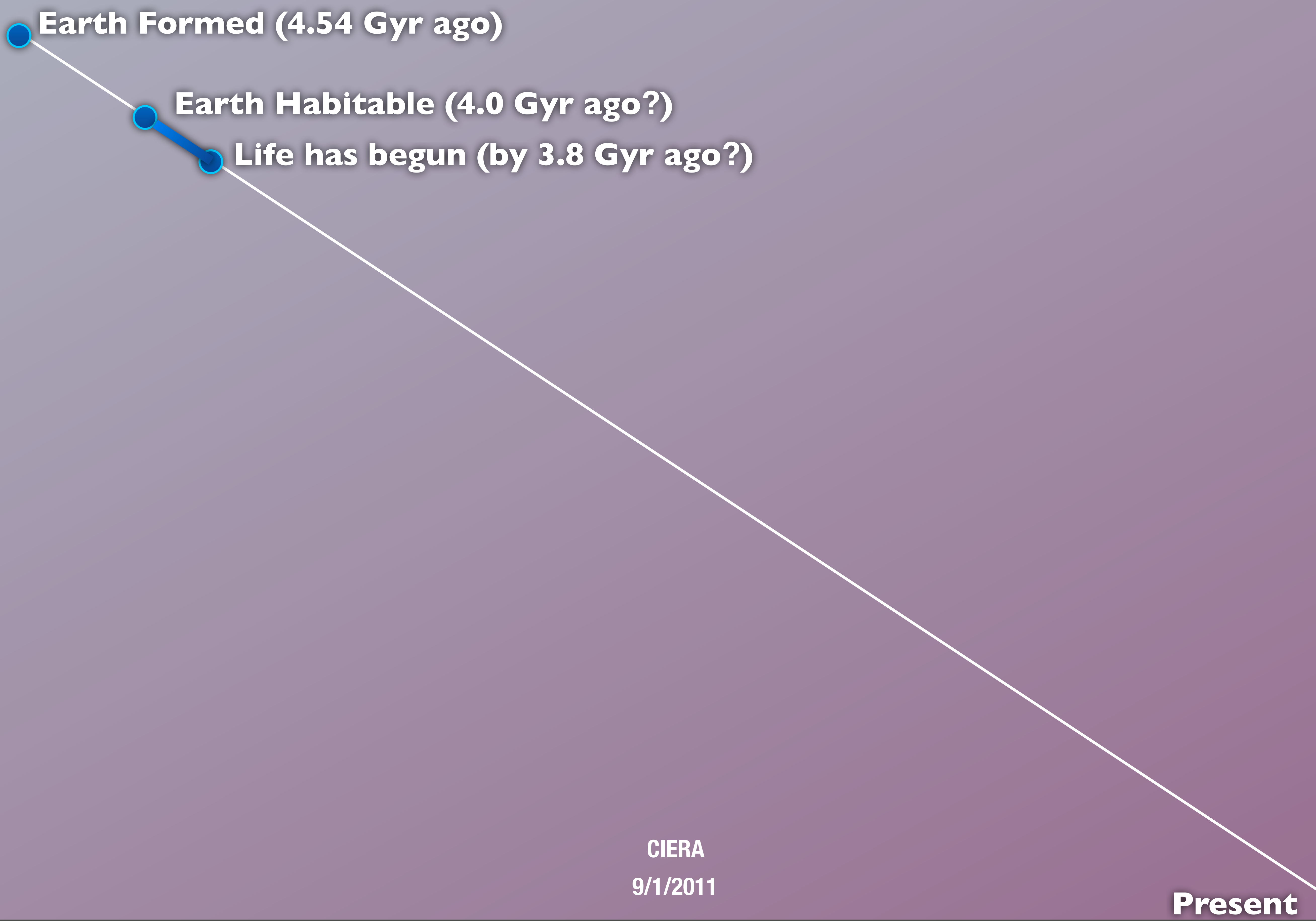
9/1/2011

Timeline of Life on Earth

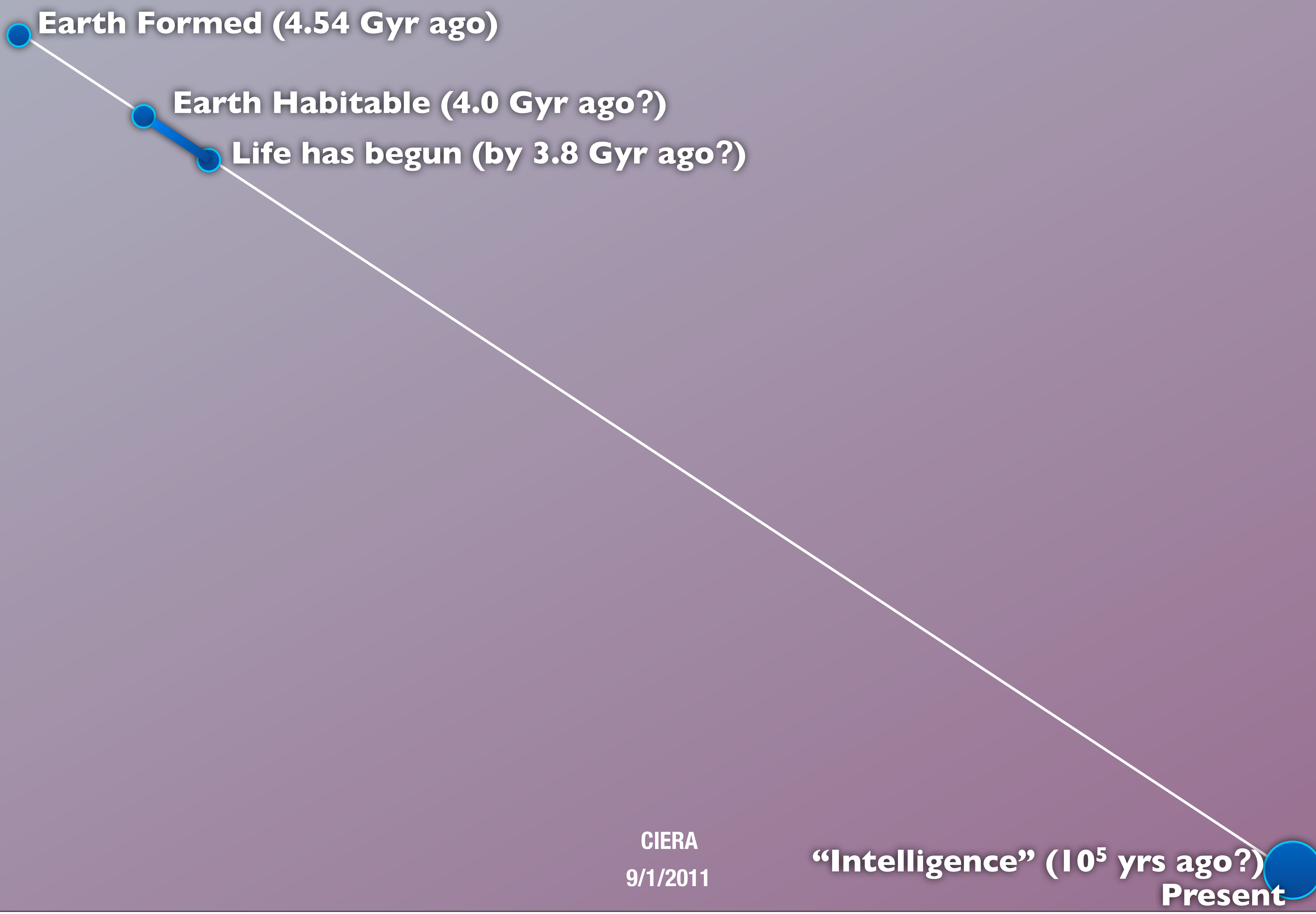
CIERA

9/1/2011

Timeline of Life on Earth



Timeline of Life on Earth



Timeline of Life on Earth

Earth Formed (4.54 Gyr ago)

Earth Habitable (4.0 Gyr ago?)

Life has begun (by 3.8 Gyr ago?)

Life arose early, so abiogenesis is probably a likely process.

“Intelligence” (10^5 yrs ago?)

Present

Timeline of Life on Earth

Earth Formed (4.54 Gyr ago)

Earth Habitable (4.0 Gyr ago?)

Life has begun (by 3.8 Gyr ago?)

Life arose early, so abiogenesis is probably a likely process.

But, how probable is it?

"Intelligence" (10^5 yrs ago?)

Present

A Common Sense Argument

CIERA

9/1/2011

A Common Sense Argument

Even if life is rare throughout the Universe,

A Common Sense Argument

Even if life is rare throughout the Universe,

- ***Still,*** it's not surprising that life arose early on the planet on which we find ourselves –

A Common Sense Argument

Even if life is rare throughout the Universe,

- ***Still,*** it's not surprising that life arose early on the planet on which we find ourselves –
- ***Especially*** if evolution requires possibly billions of years to develop "intelligence"

A Common Sense Argument

Even if life is rare throughout the Universe,

- ***Still,*** it's not surprising that life arose early on the planet on which we find ourselves –
- ***Especially*** if evolution requires possibly billions of years to develop "intelligence"

But finding life somewhere where we didn't have to would count a lot more.

CIERA

9/1/2011

Spiegel & Turner (2011)

Simple Assumption:

- Abiogenesis: a Poisson process
- Poisson rate parameter λ (measured in [time^{-1}])

Spiegel & Turner (2011)

Simple Assumption:

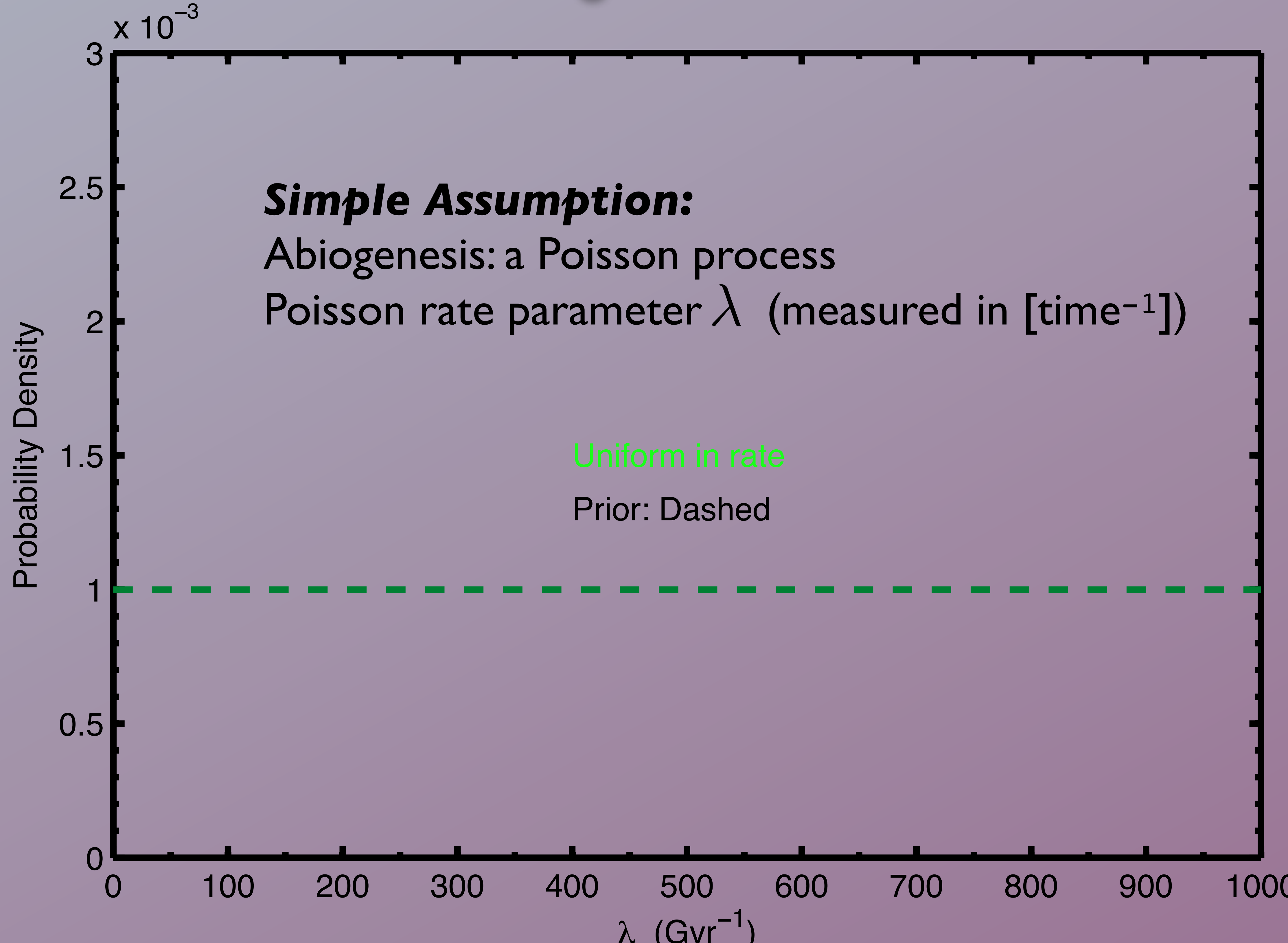
- Abiogenesis: a Poisson process
- Poisson rate parameter λ (measured in [time^{-1}])

Bayesian Inference:

- Calculate *Likelihood* function – P[D | λ].
- Use appropriate (uninformative) prior.

Spiegel & Turner (2011)

Abiogenesis PDF

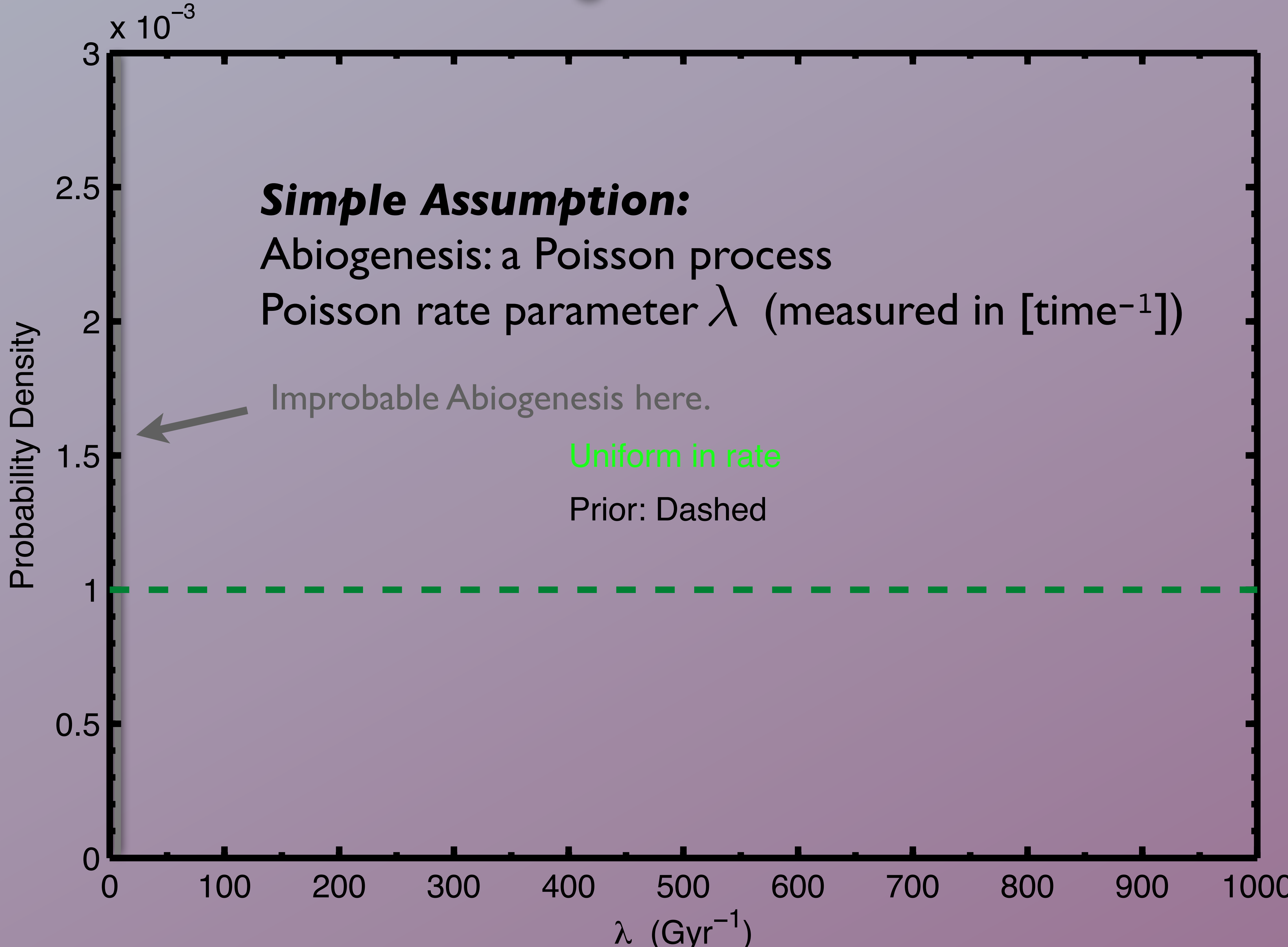


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis PDF

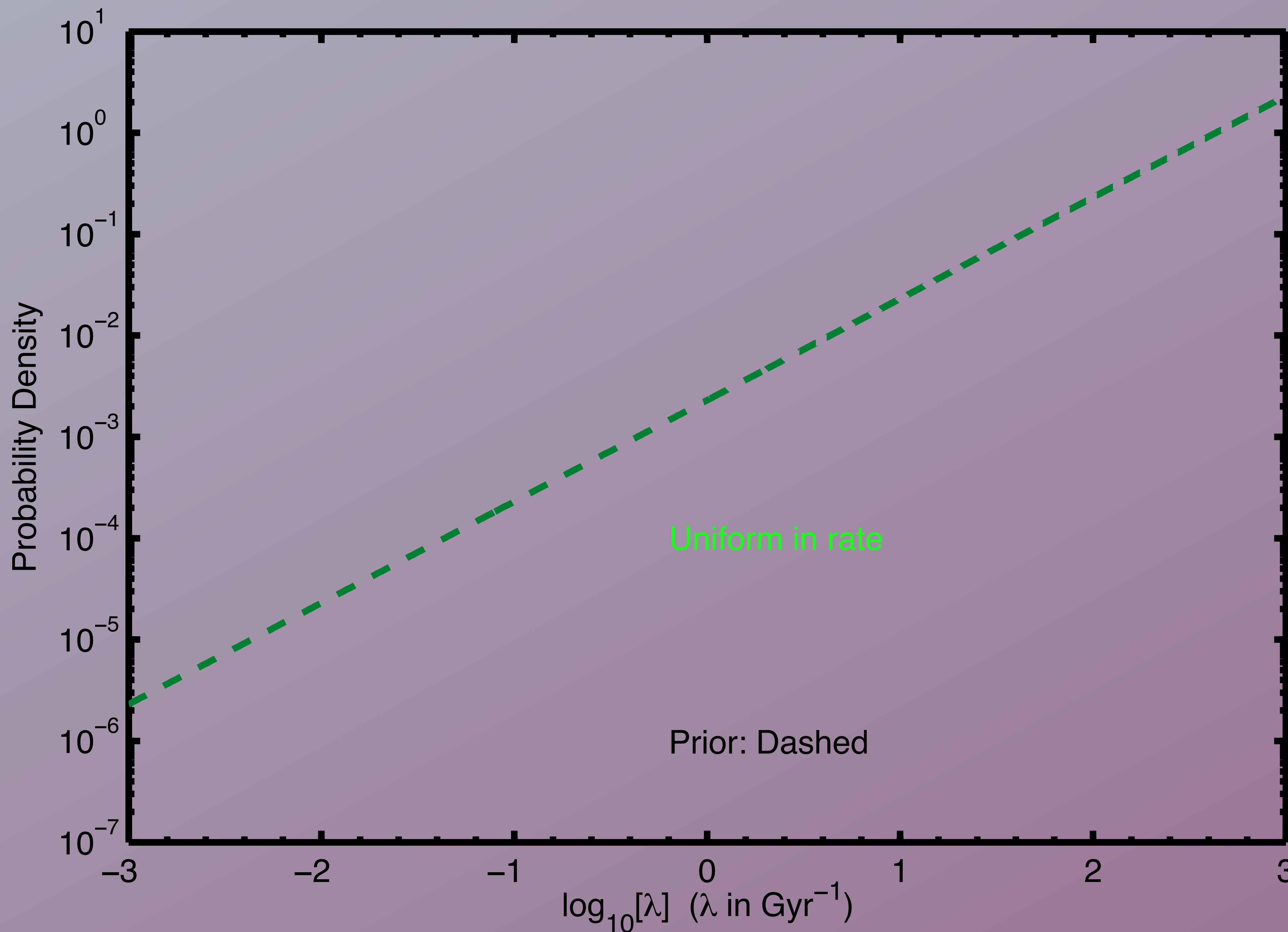


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis PDF

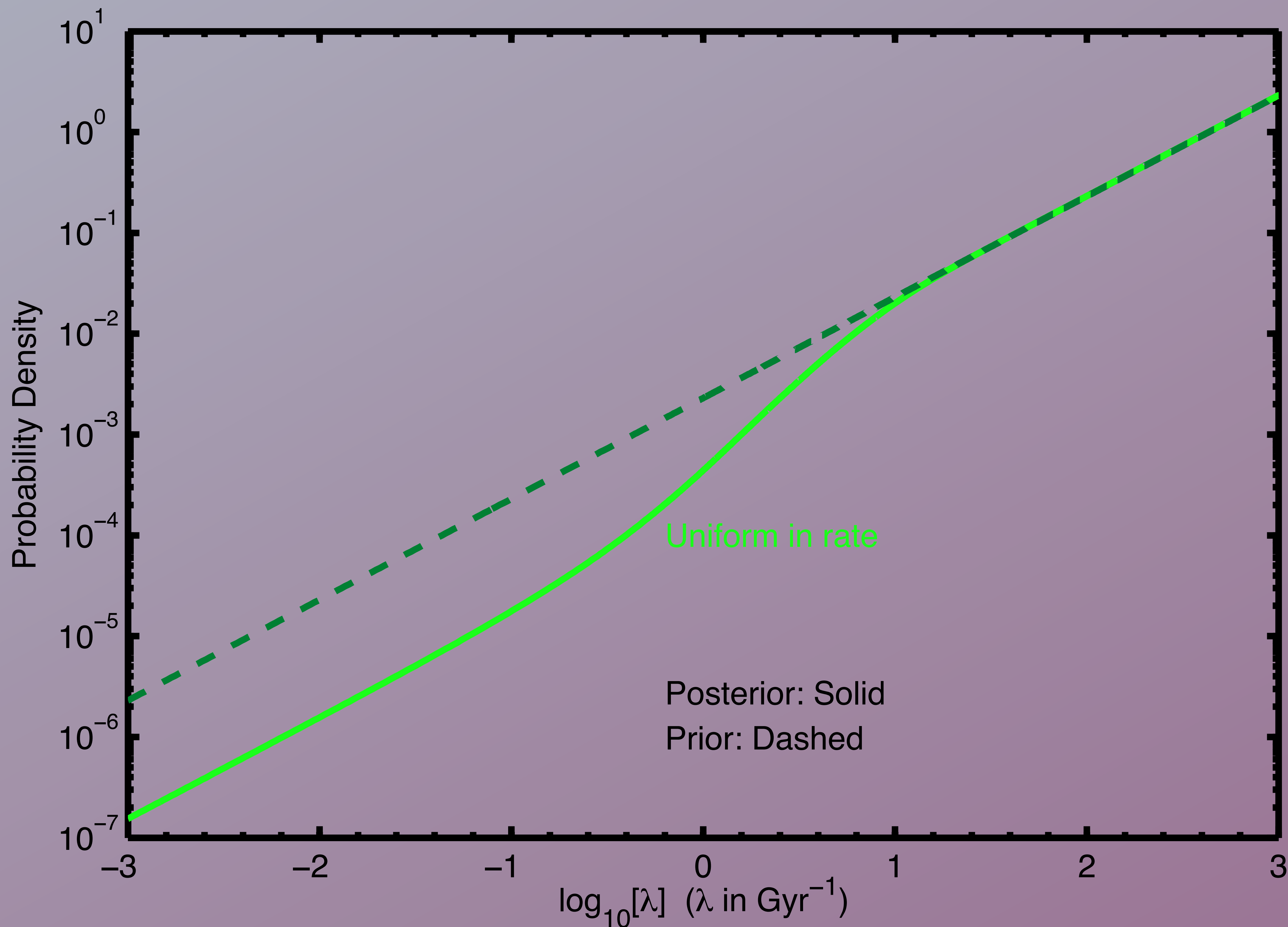


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis PDF

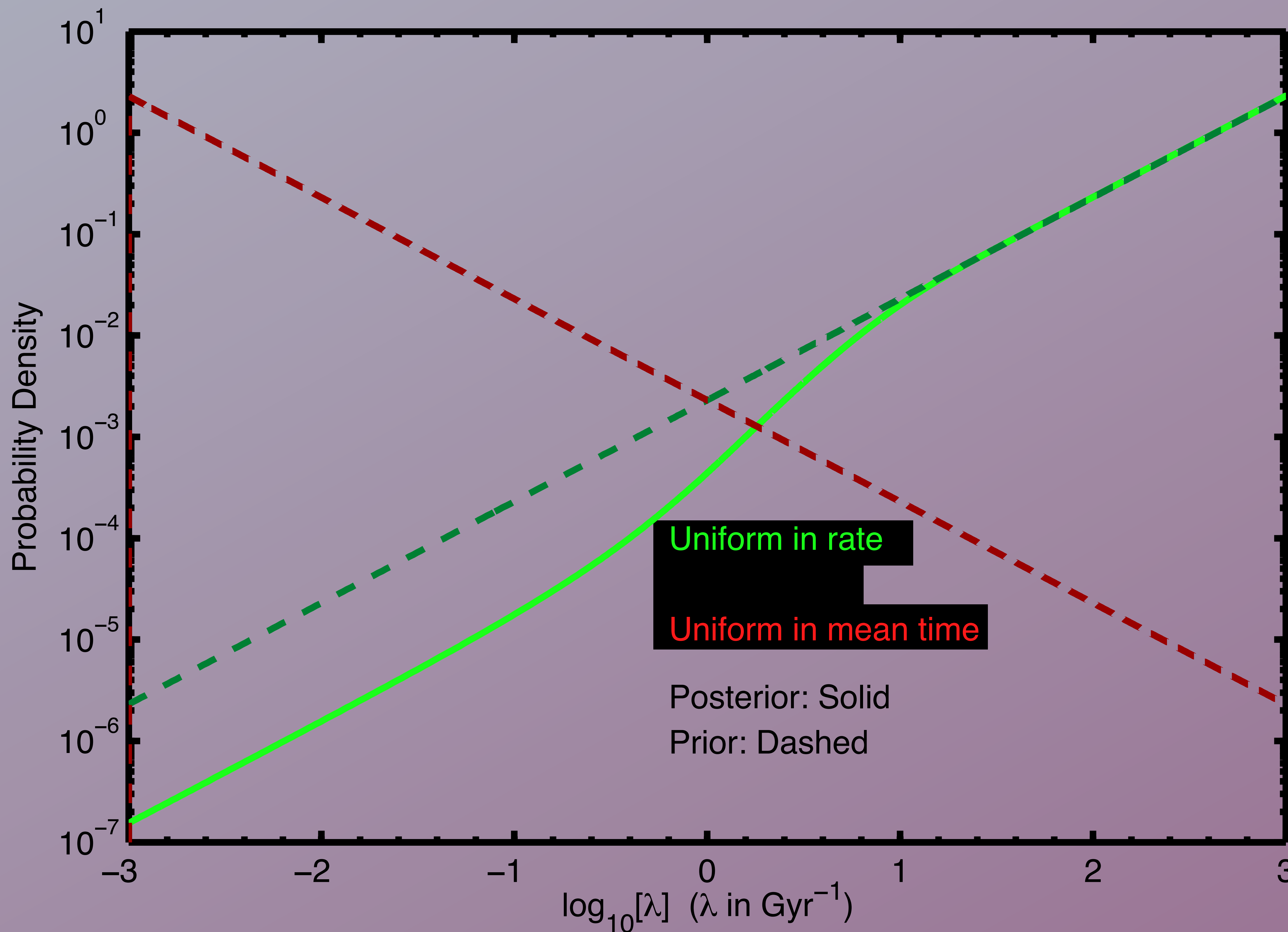


CIERA

9/1/2011

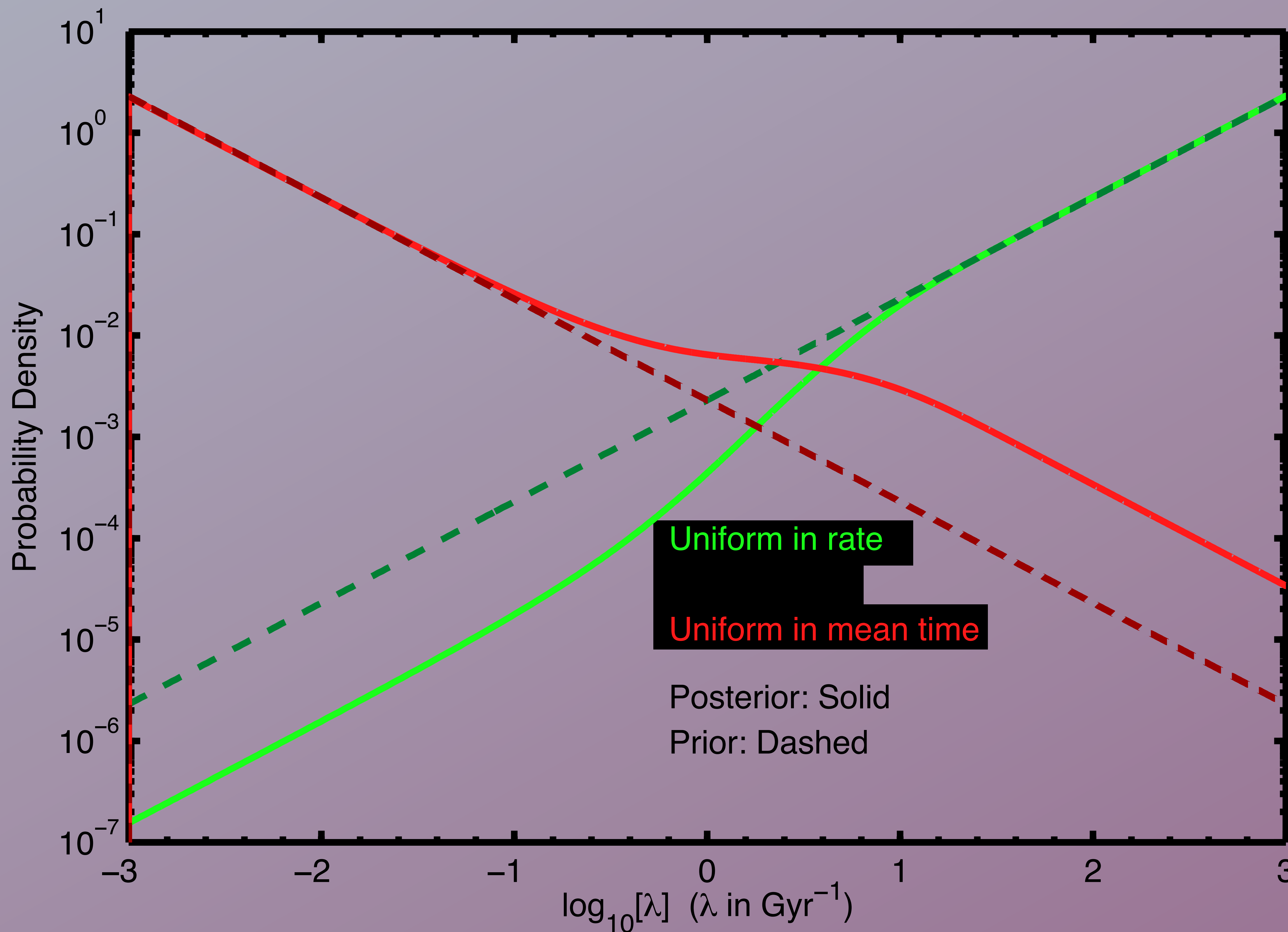
Spiegel & Turner (2011)

Abiogenesis PDF



Spiegel & Turner (2011)

Abiogenesis PDF

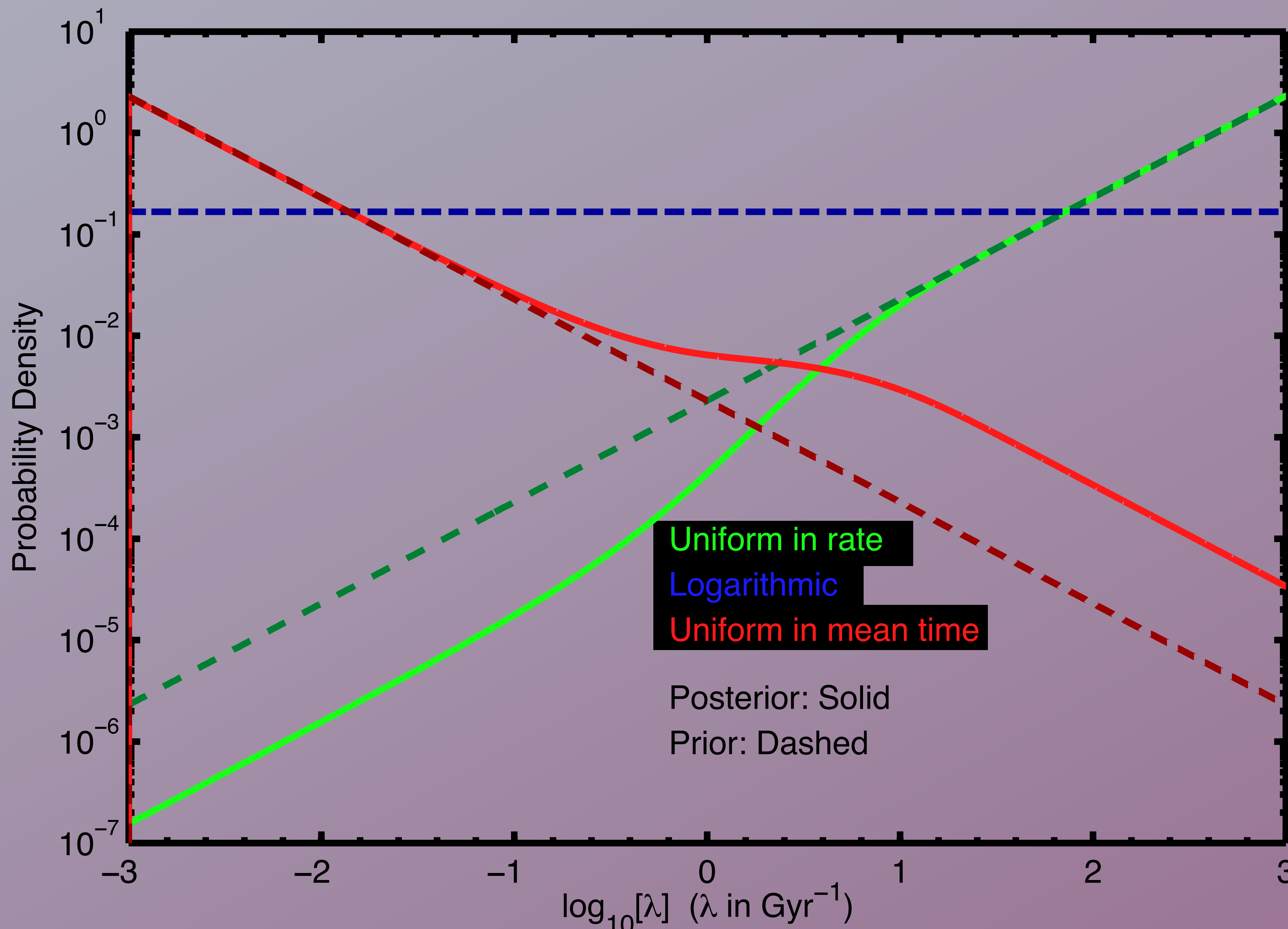


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis PDF

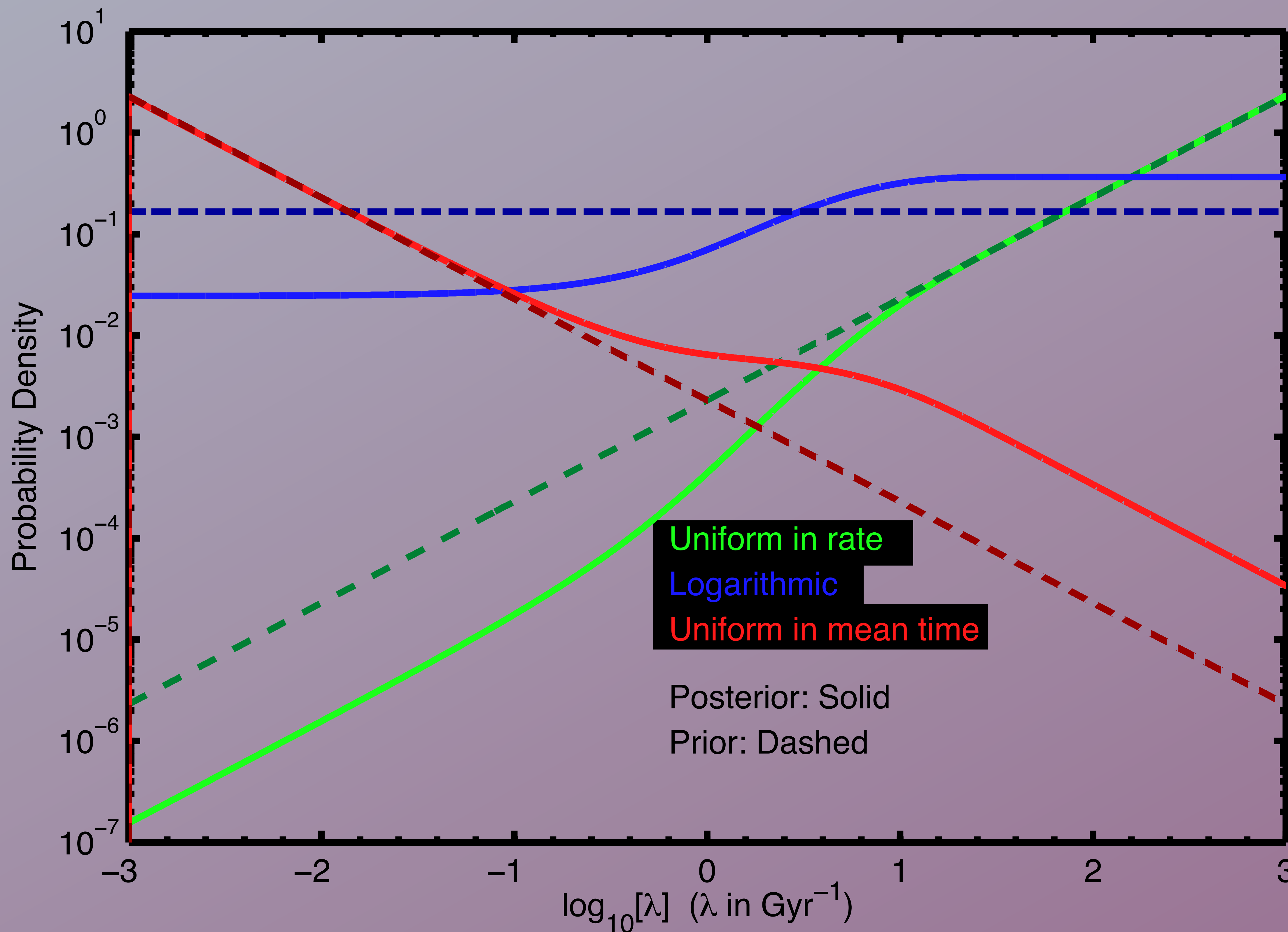


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis PDF

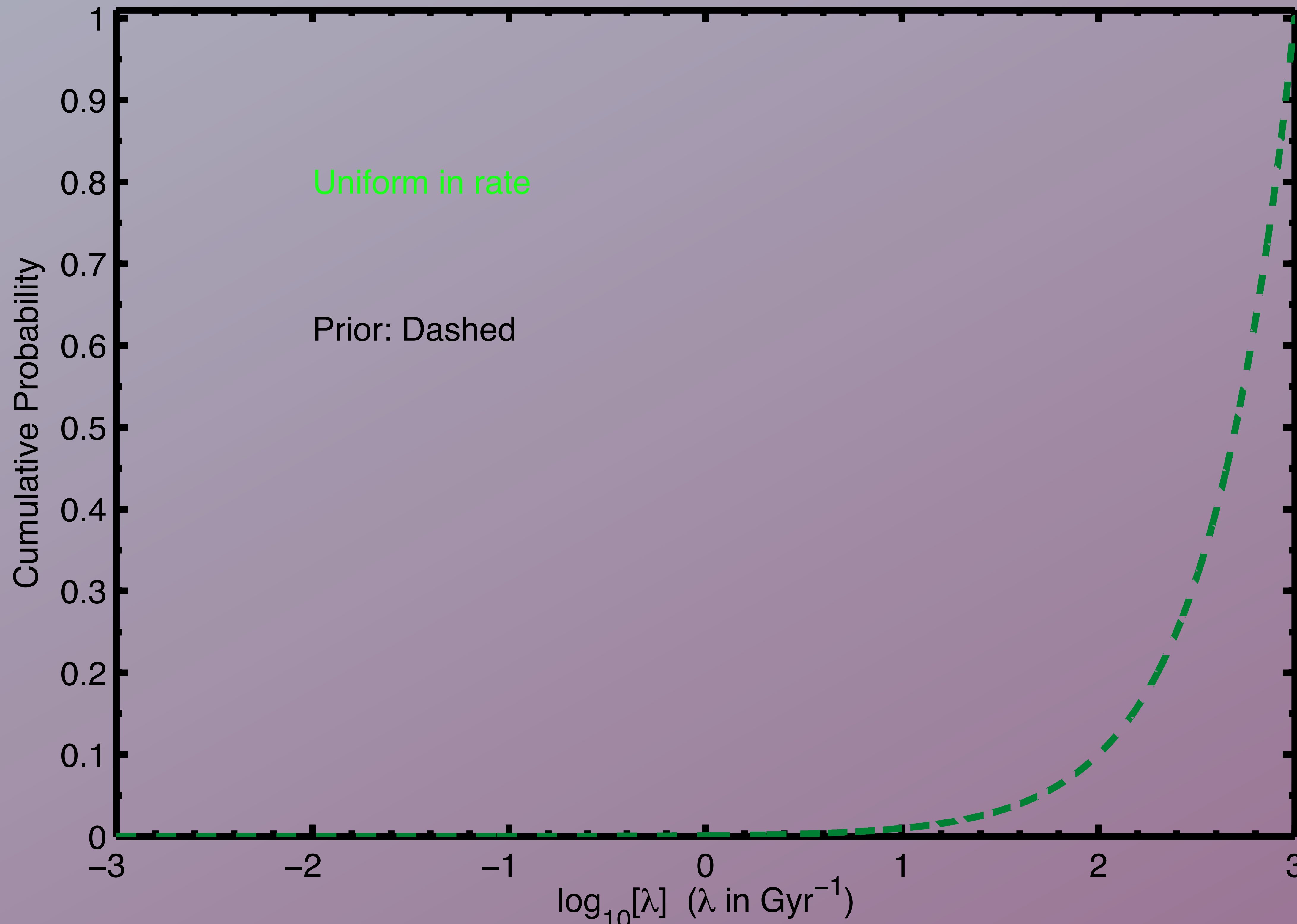


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF

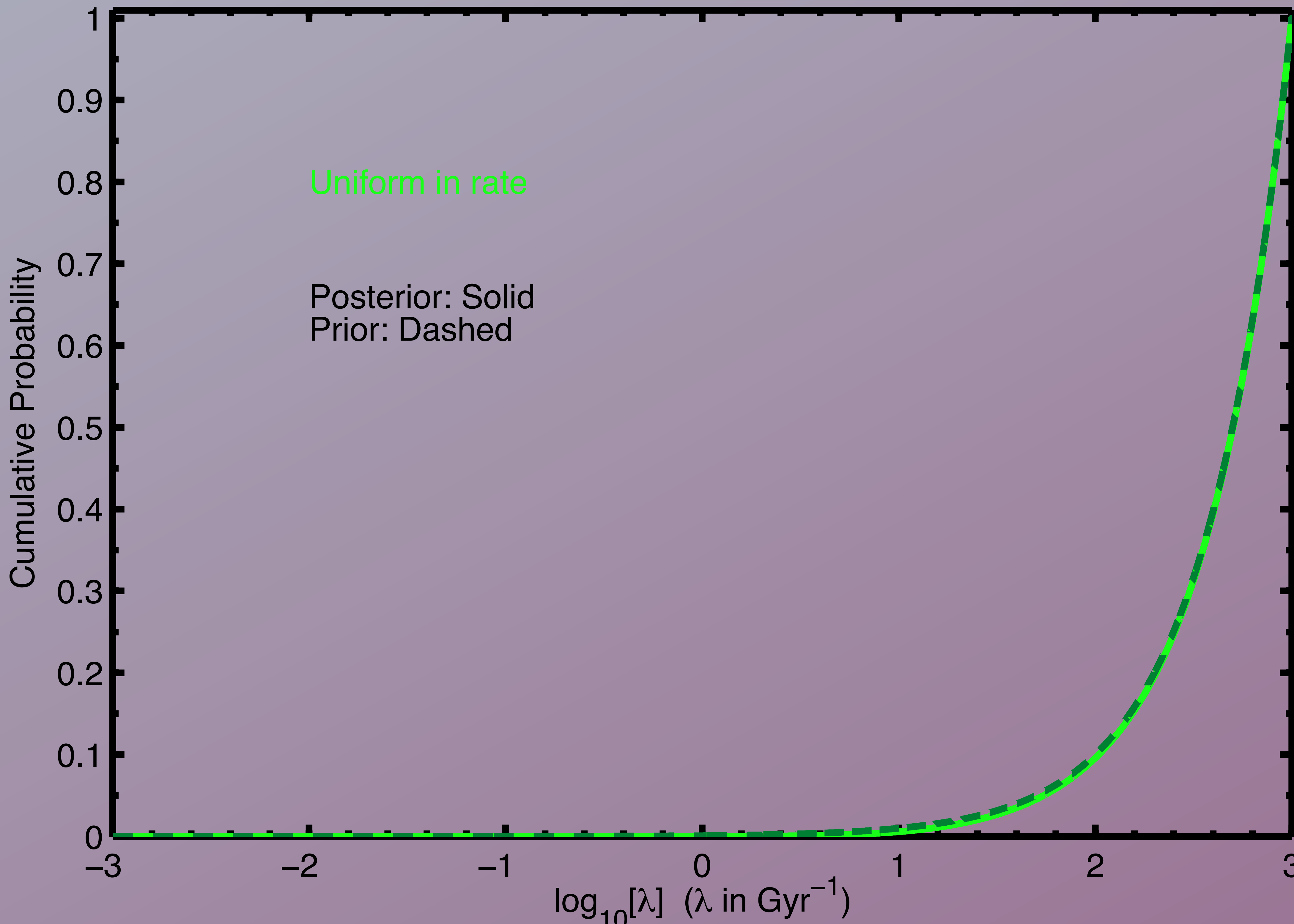


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF

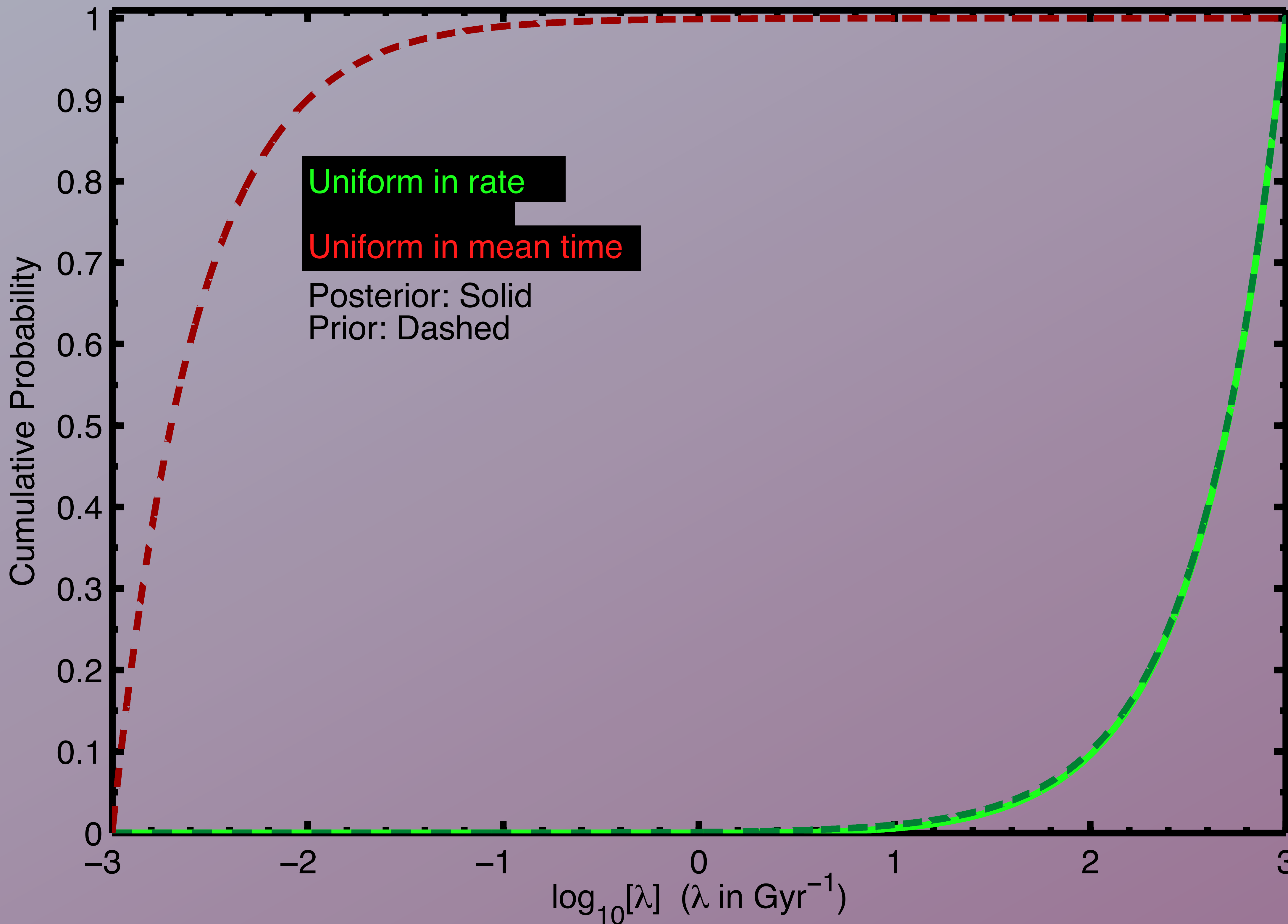


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF

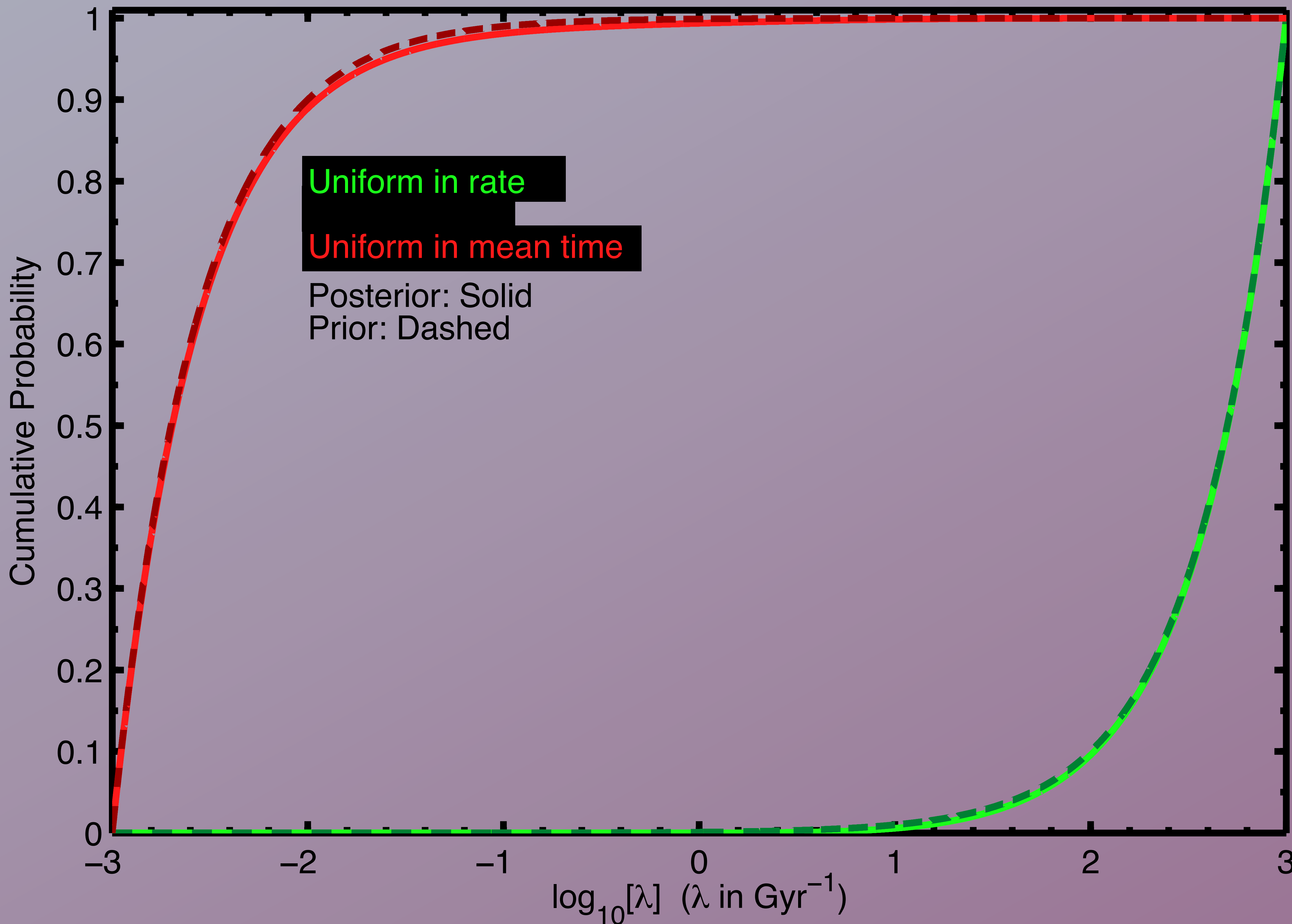


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF

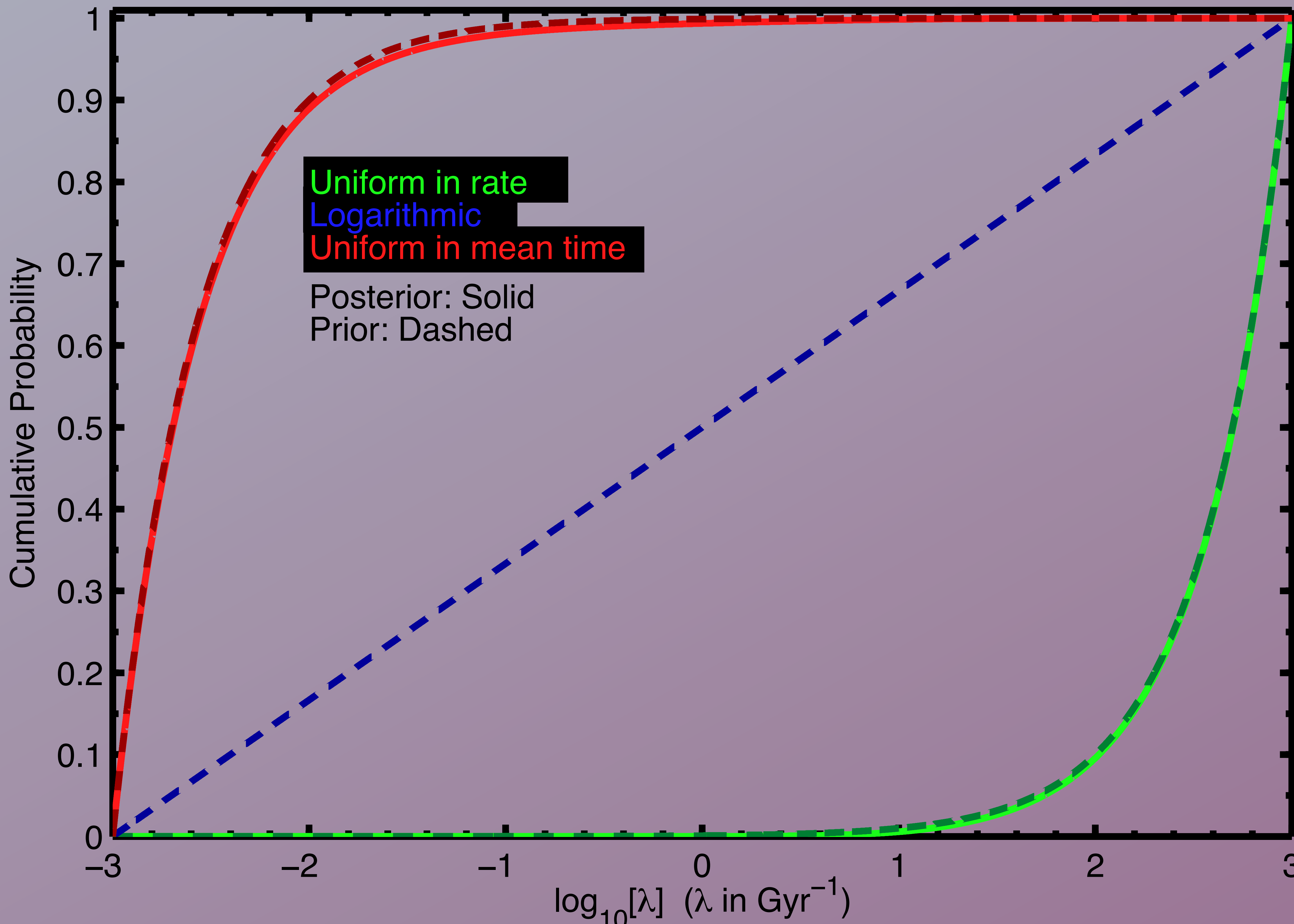


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF

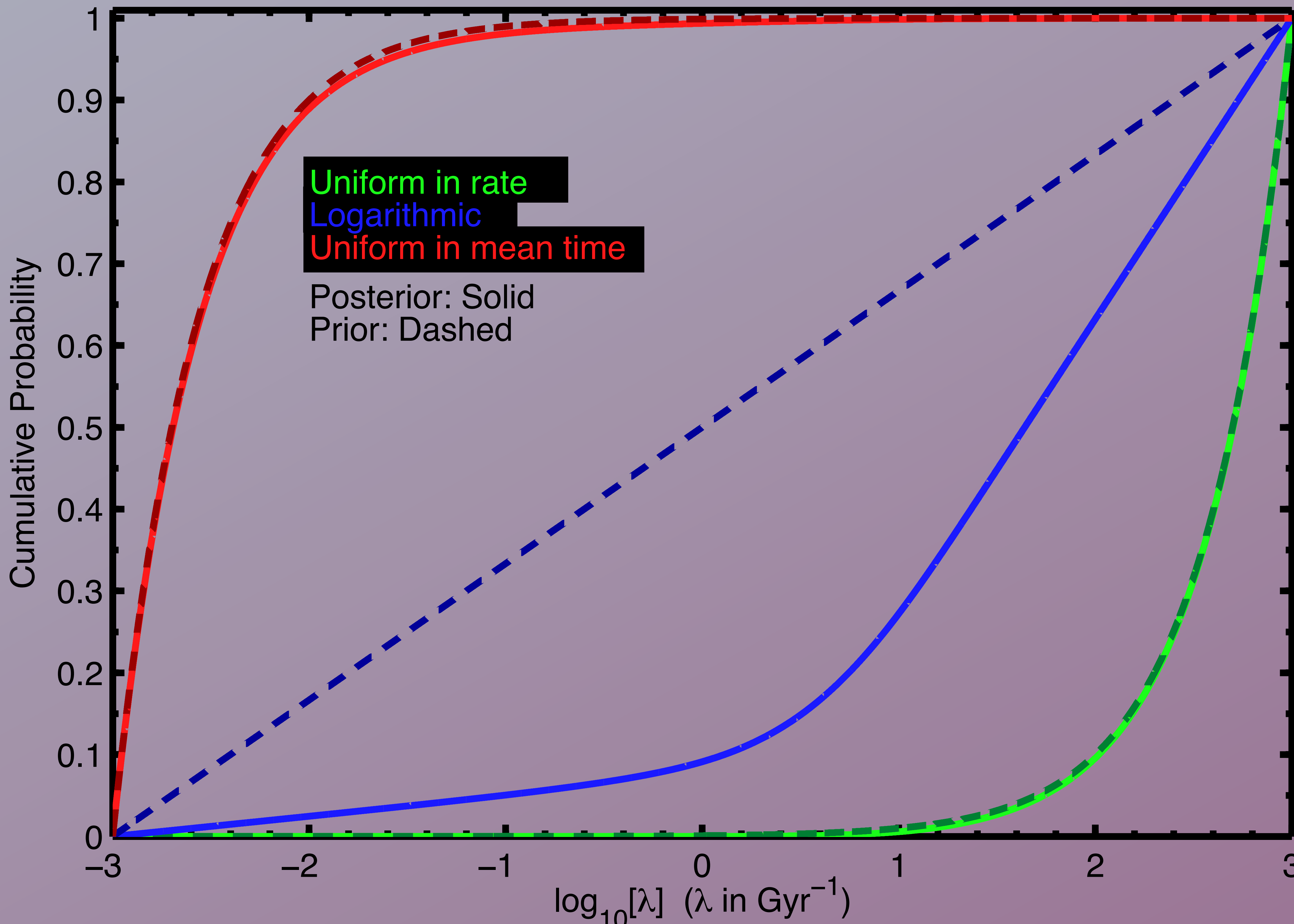


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF

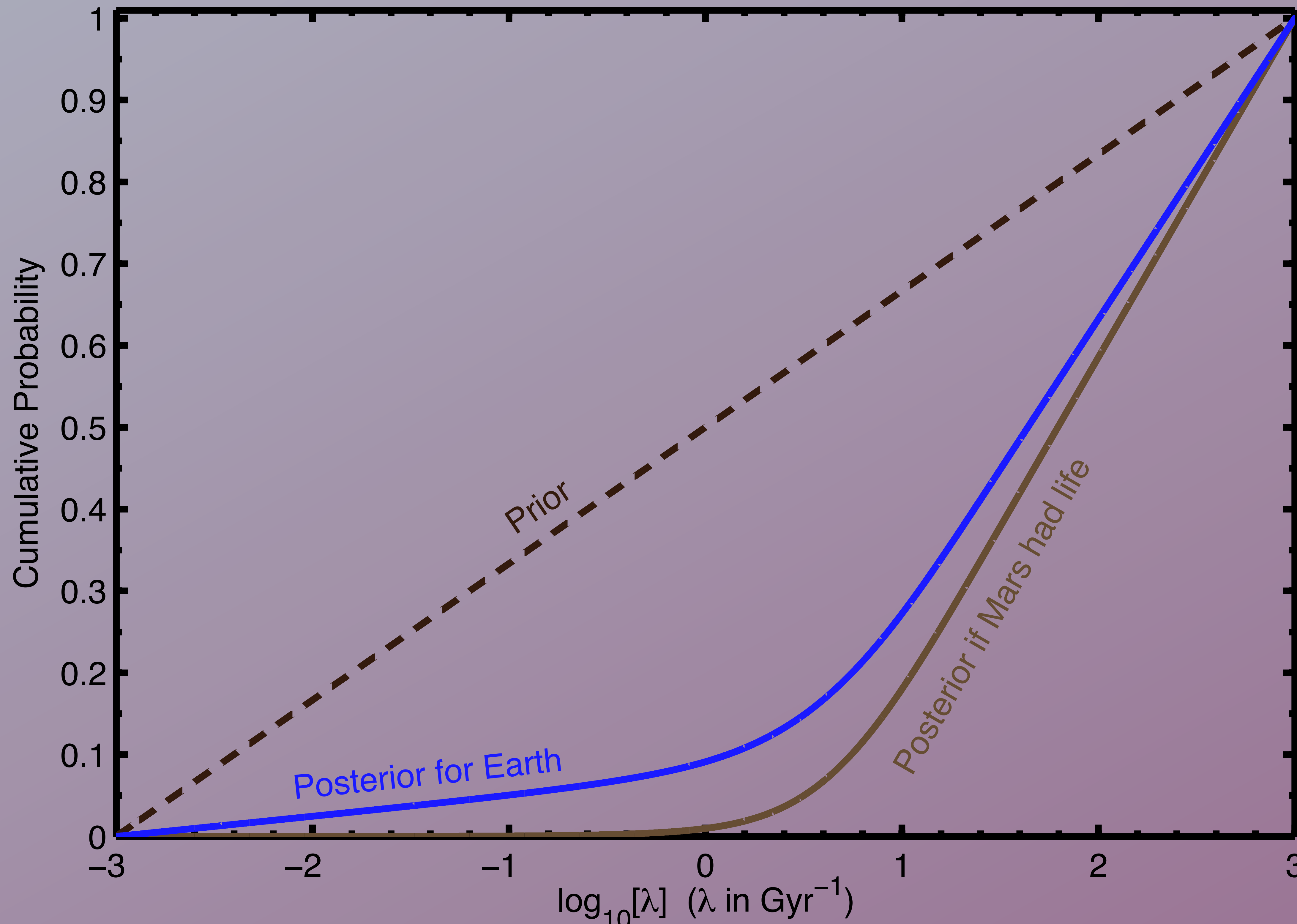


CIERA

9/1/2011

Spiegel & Turner (2011)

Abiogenesis CDF, for Exo-Life



CIERA

9/1/2011

Spiegel & Turner (2011)

Conclusions

Habitability depends on properties of a star, planet, *and long-term history of planetary system*.

Early life on Earth suggests life might be common, but is not inconsistent with life being rare in the Universe.

Model Details

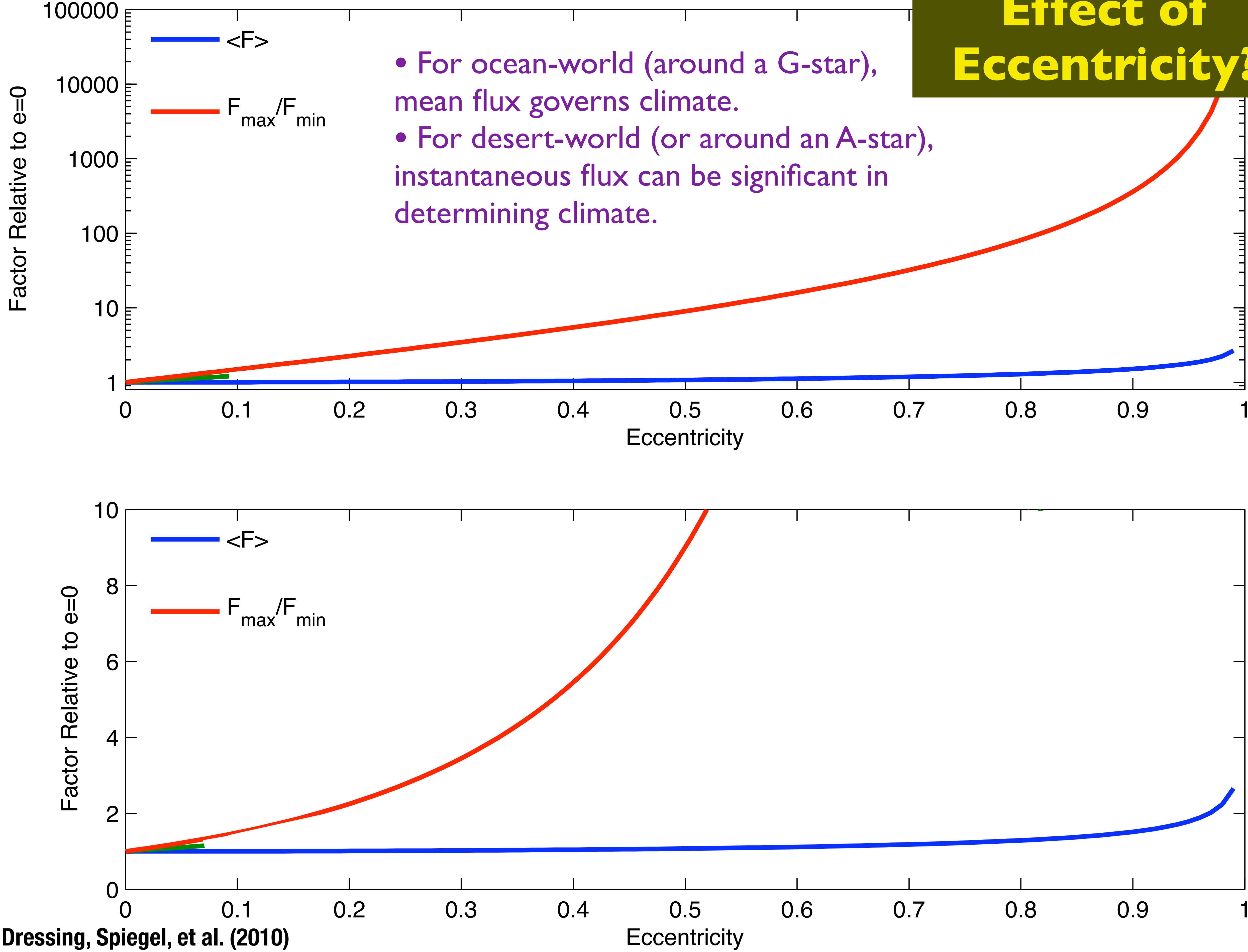
Bayes' Theorem: $$\mathrm{P}[\mathcal{M}|\mathcal{D}] = \frac{\mathrm{P}[\mathcal{D}|\mathcal{M}] \times \mathrm{P}_{\mathrm{prior}}[\mathcal{M}]}{\mathrm{P}[\mathcal{D}]}$$

Likelihood function: $$\mathrm{P}[\mathcal{D}|\mathcal{M}] = \frac{1 - \exp[-\lambda(t_{\mathrm{emerge}} - t_{\mathrm{min}})]}{1 - \exp[-\lambda(t_{\mathrm{required}} - t_{\mathrm{min}})]}$$

Likelihood function for Mars life & Earth life: $$\mathrm{P}_{ii}[\mathcal{D}|\mathcal{M}] = \left(1 - \exp[-\lambda(t_{\mathrm{emerge}}^{\mathrm{Mars}} - t_{\mathrm{min}}^{\mathrm{Mars}})]\right) \times \frac{1 - \exp[-\lambda(t_{\mathrm{emerge}}^{\mathrm{Earth}} - t_{\mathrm{min}}^{\mathrm{Earth}})]}{1 - \exp[-\lambda(t_{\mathrm{required}}^{\mathrm{Earth}} - t_{\mathrm{min}}^{\mathrm{Earth}})]}$$

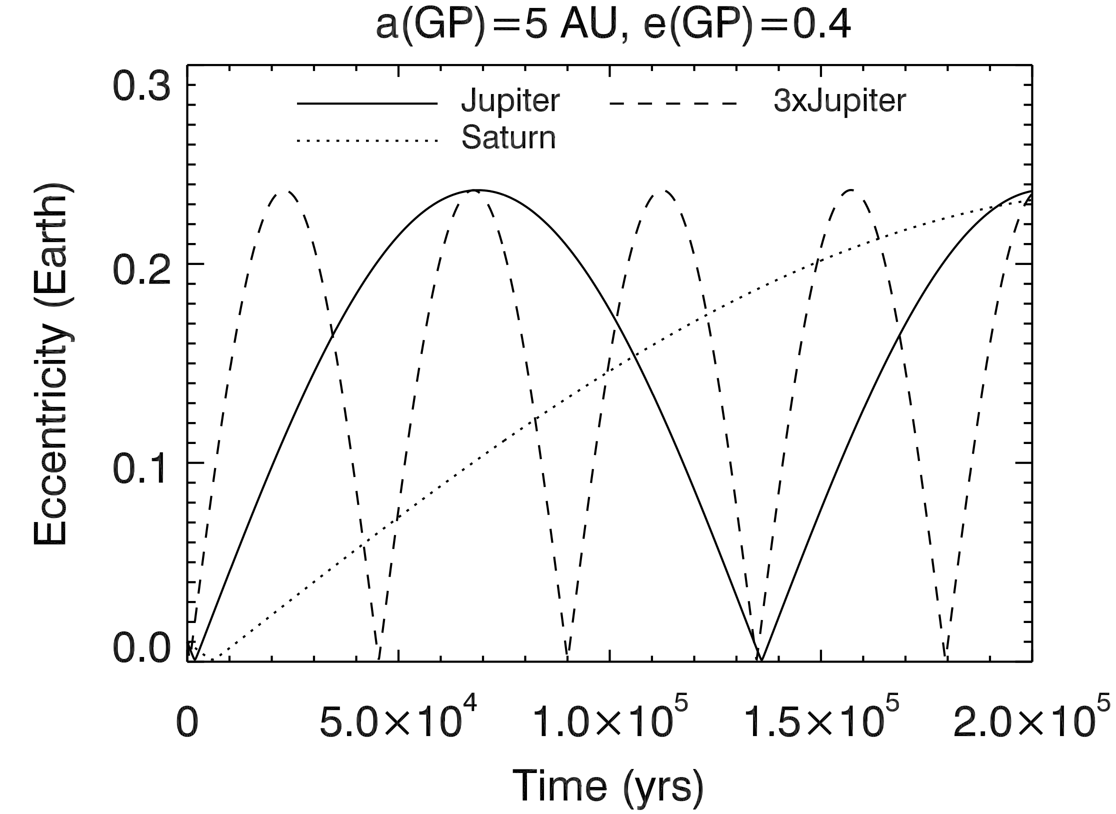
Effect of Eccentricity?

- For ocean-world (around a G-star), mean flux governs climate.
- For desert-world (or around an A-star), instantaneous flux can be significant in determining climate.

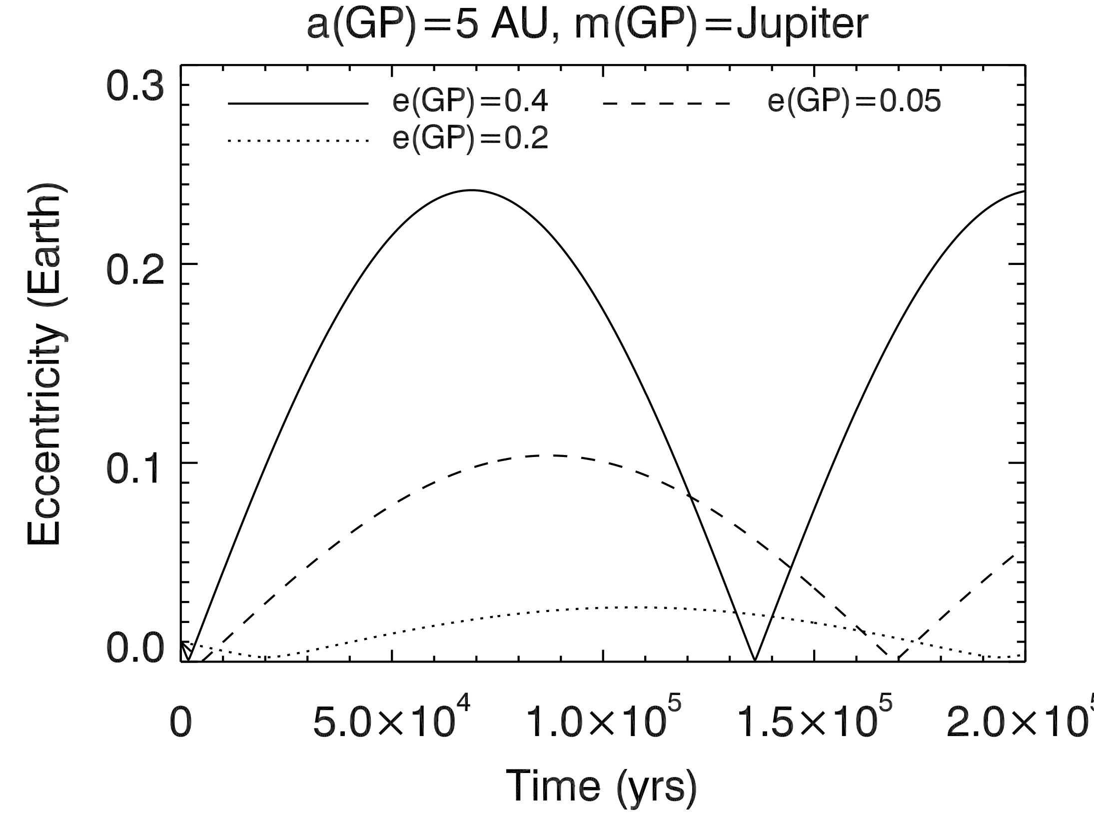


Dressing, Spiegel, et al. (2010)

More massive companions cause faster oscillations

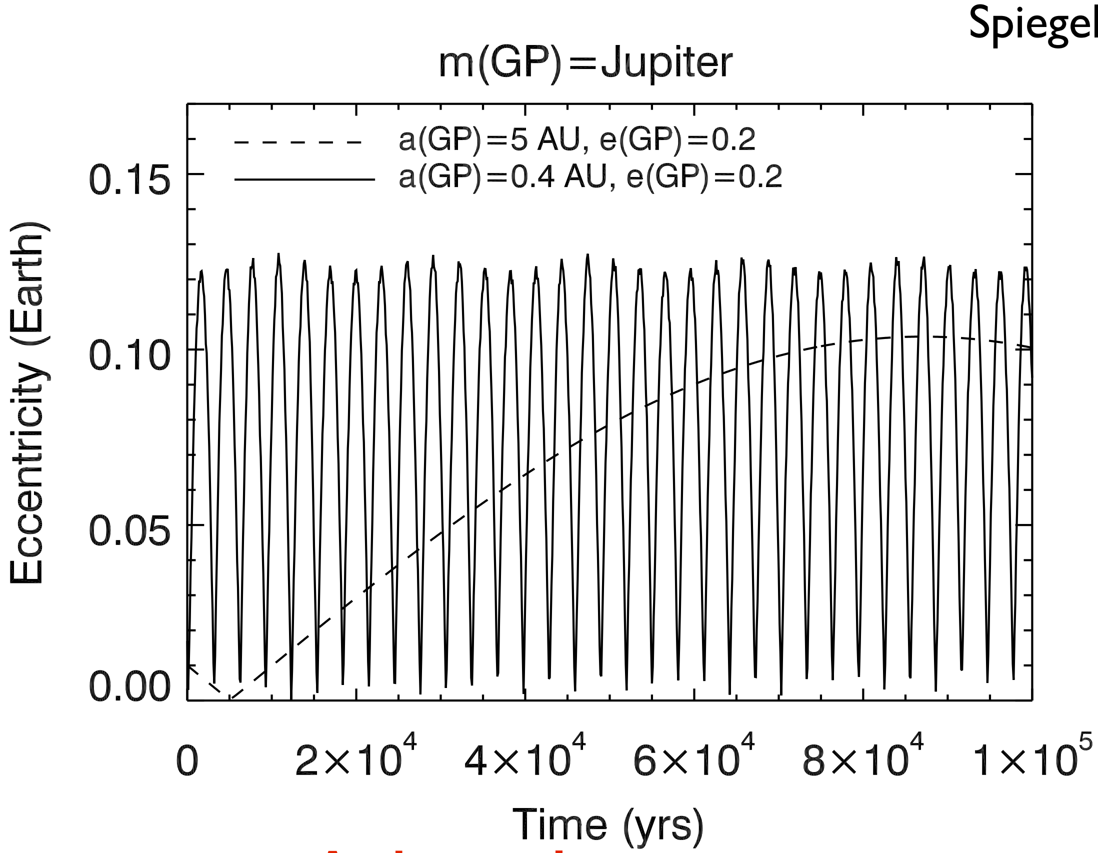


More eccentric companions cause faster *and larger amplitude* oscillations

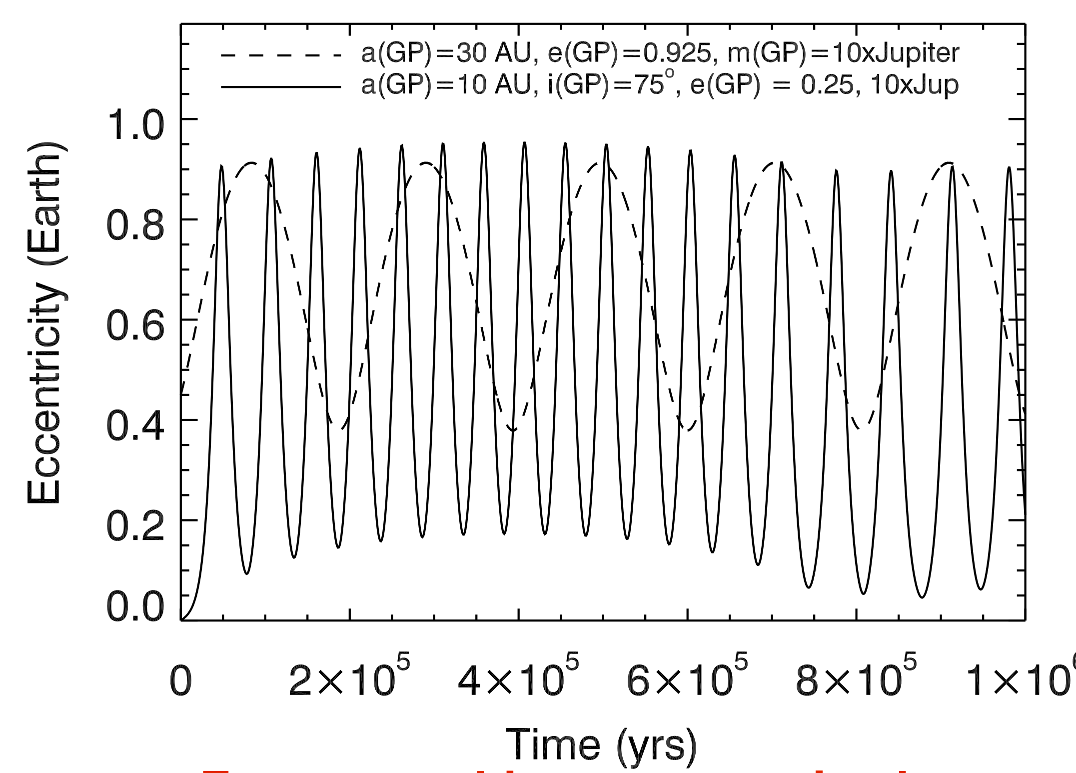


Spiegel, Raymond, et al. (2010)

Simulations by Sean Raymond

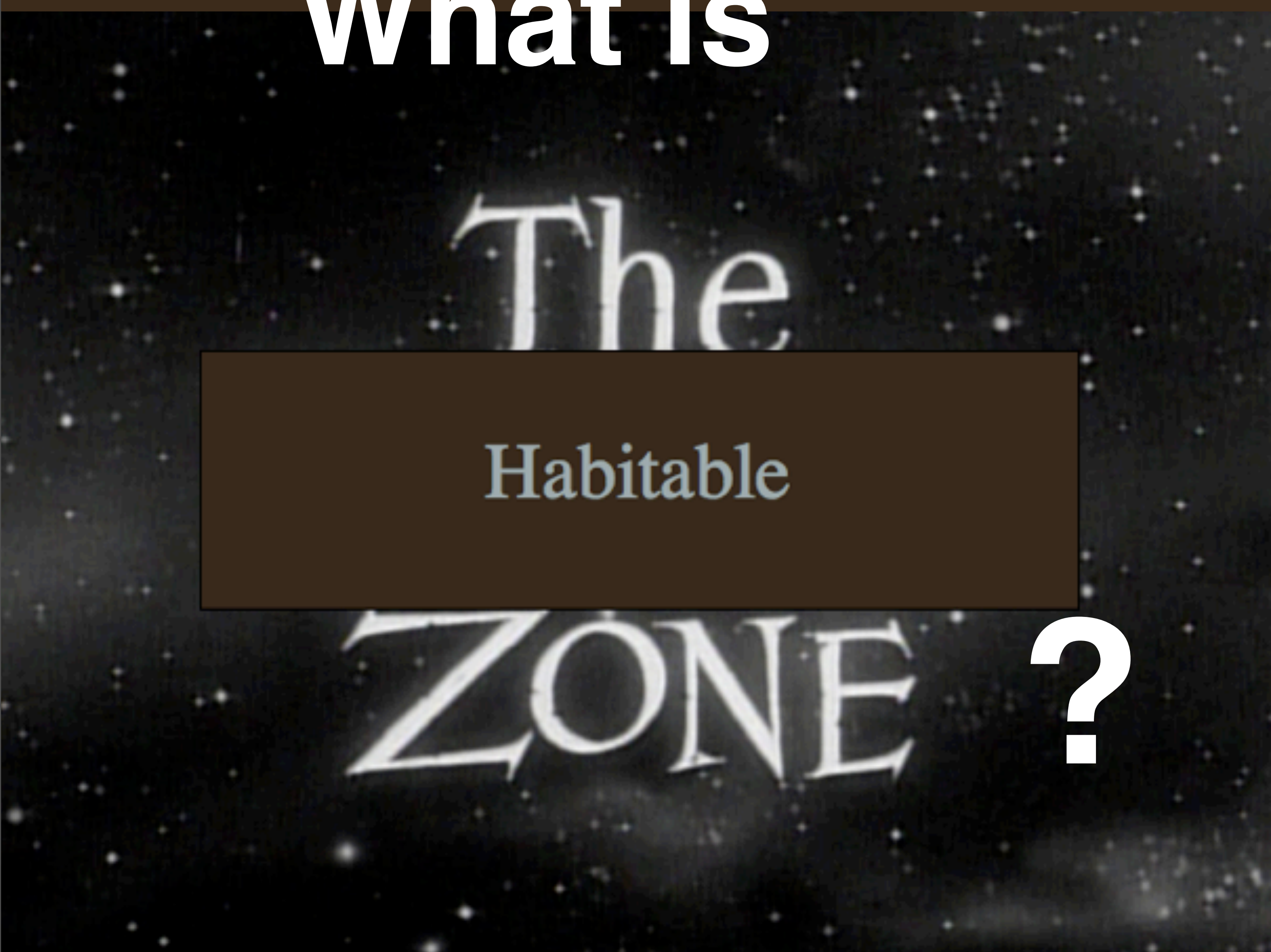


An inner planet can cause very rapid oscillation



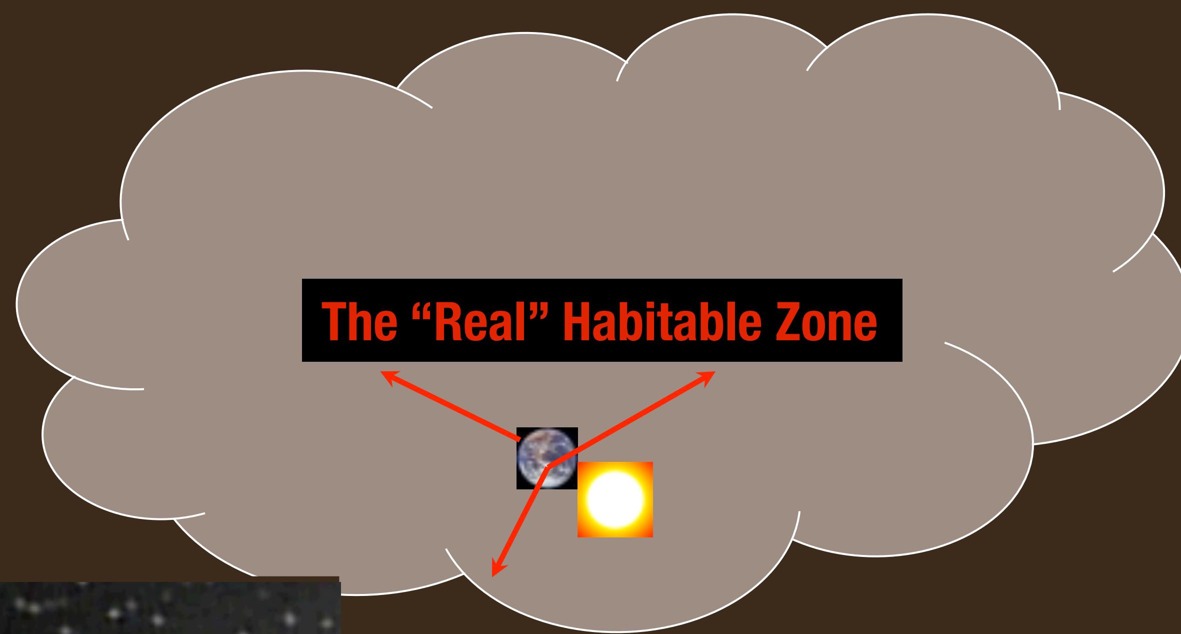
Extreme architectures can lead to extreme eccentricity oscillations

What is

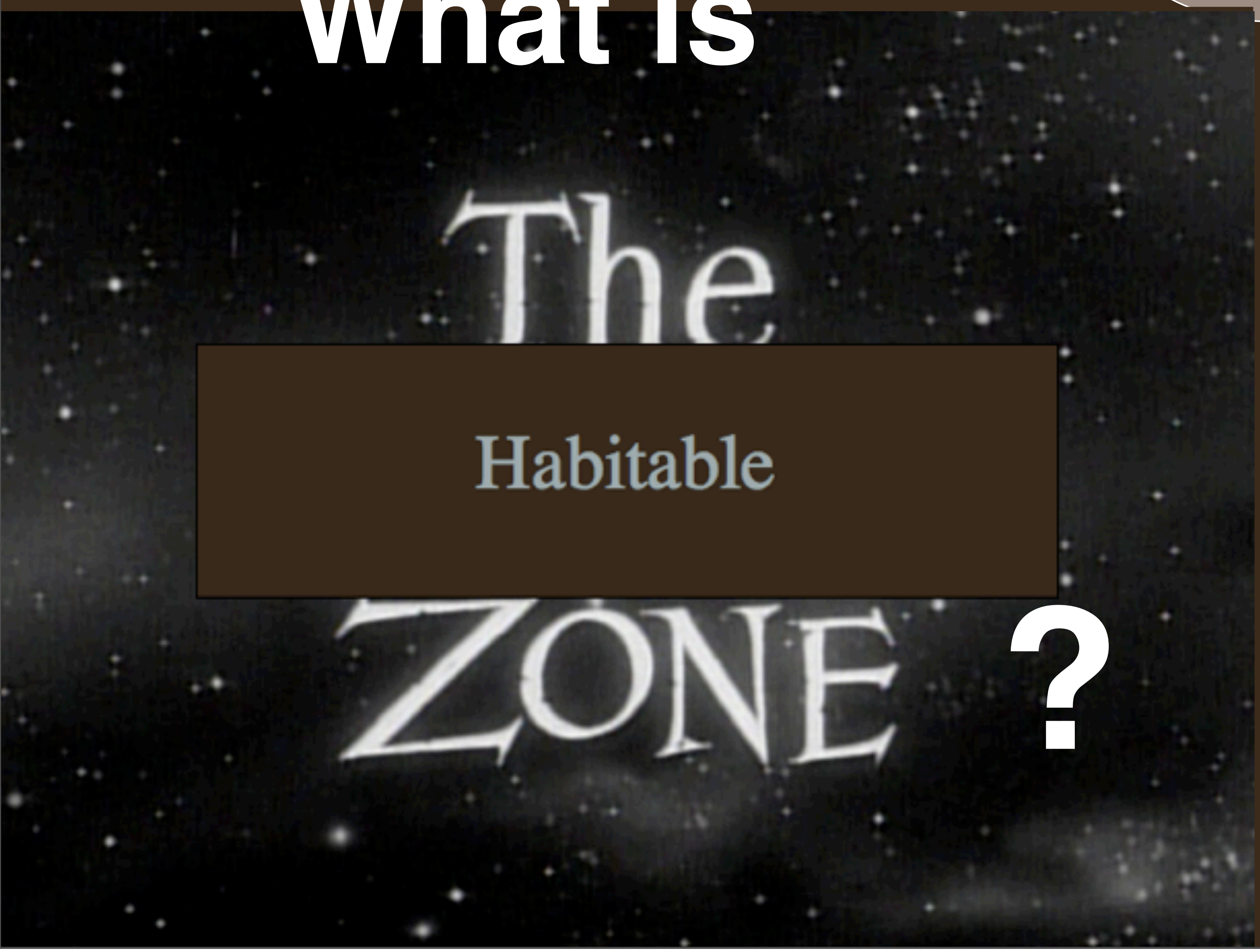


Habitable

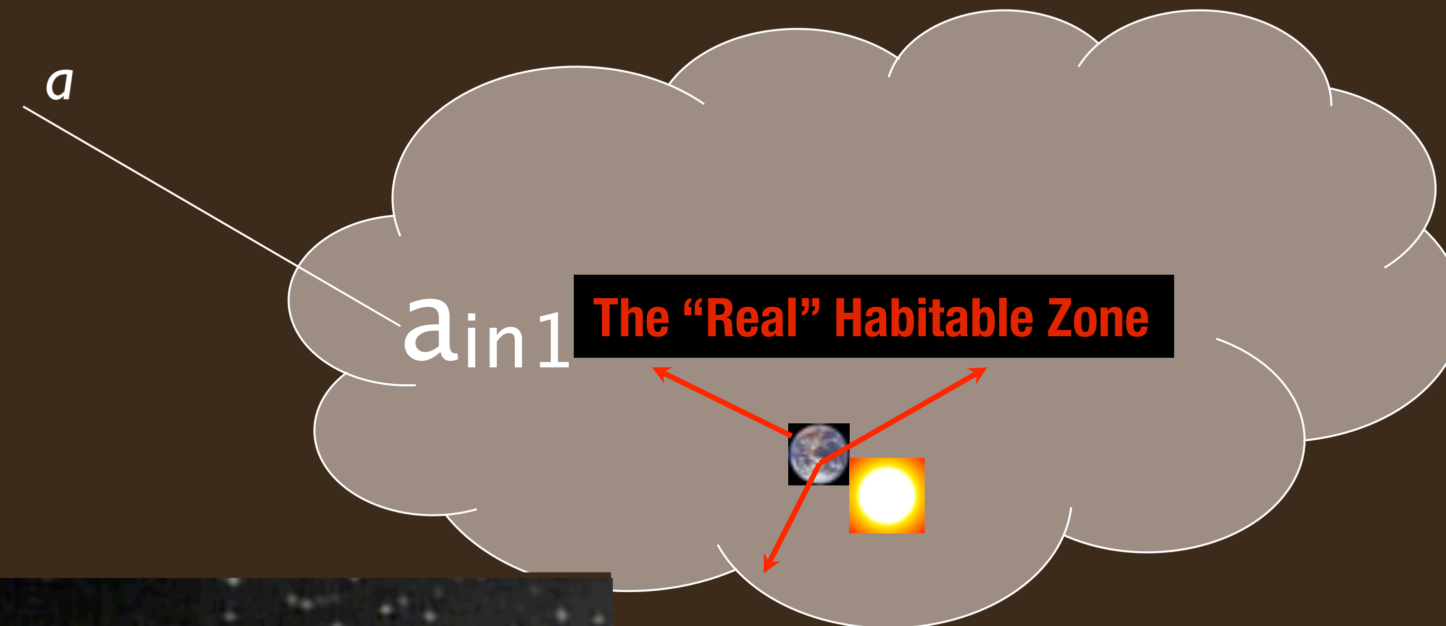
?



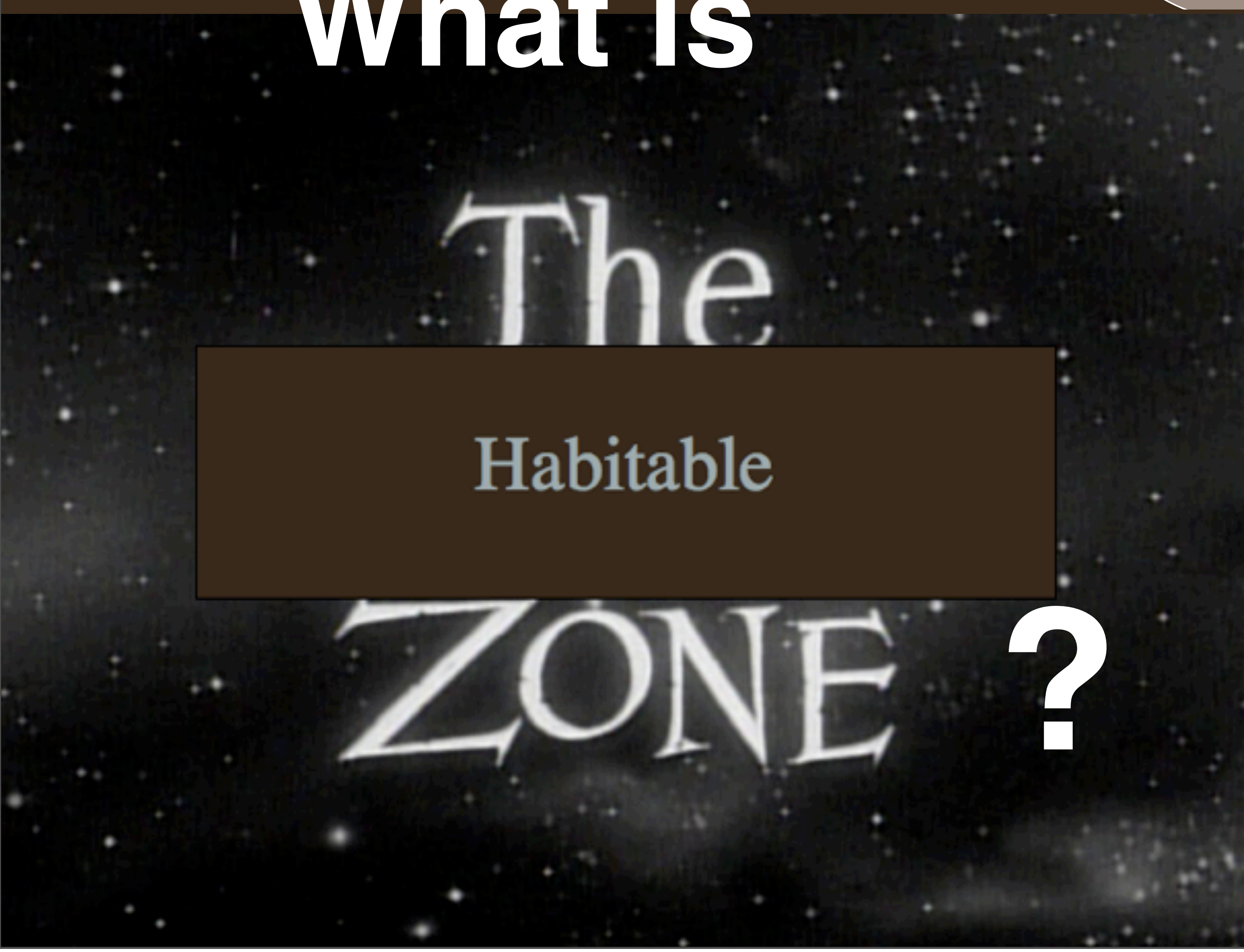
What is

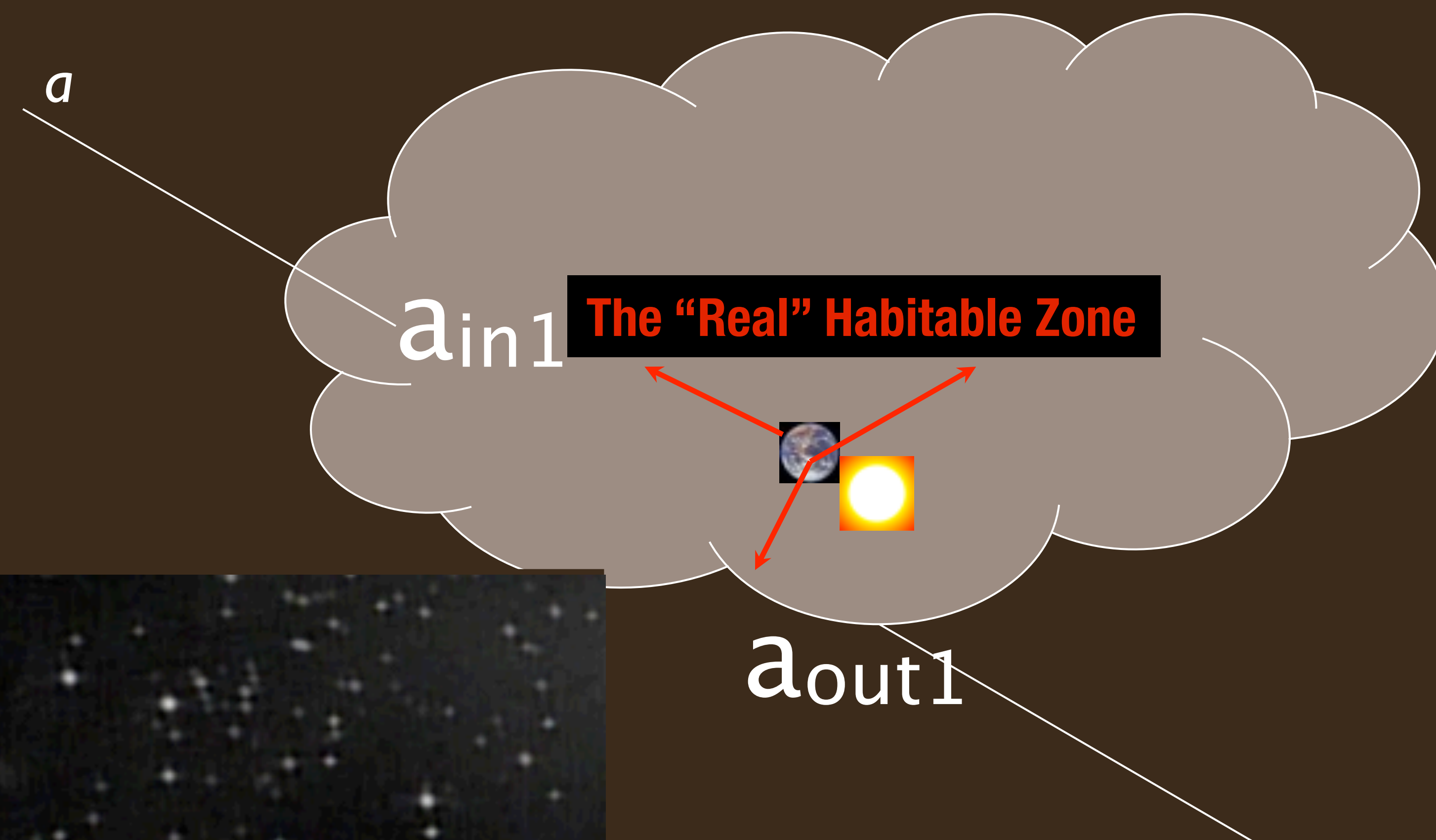


?

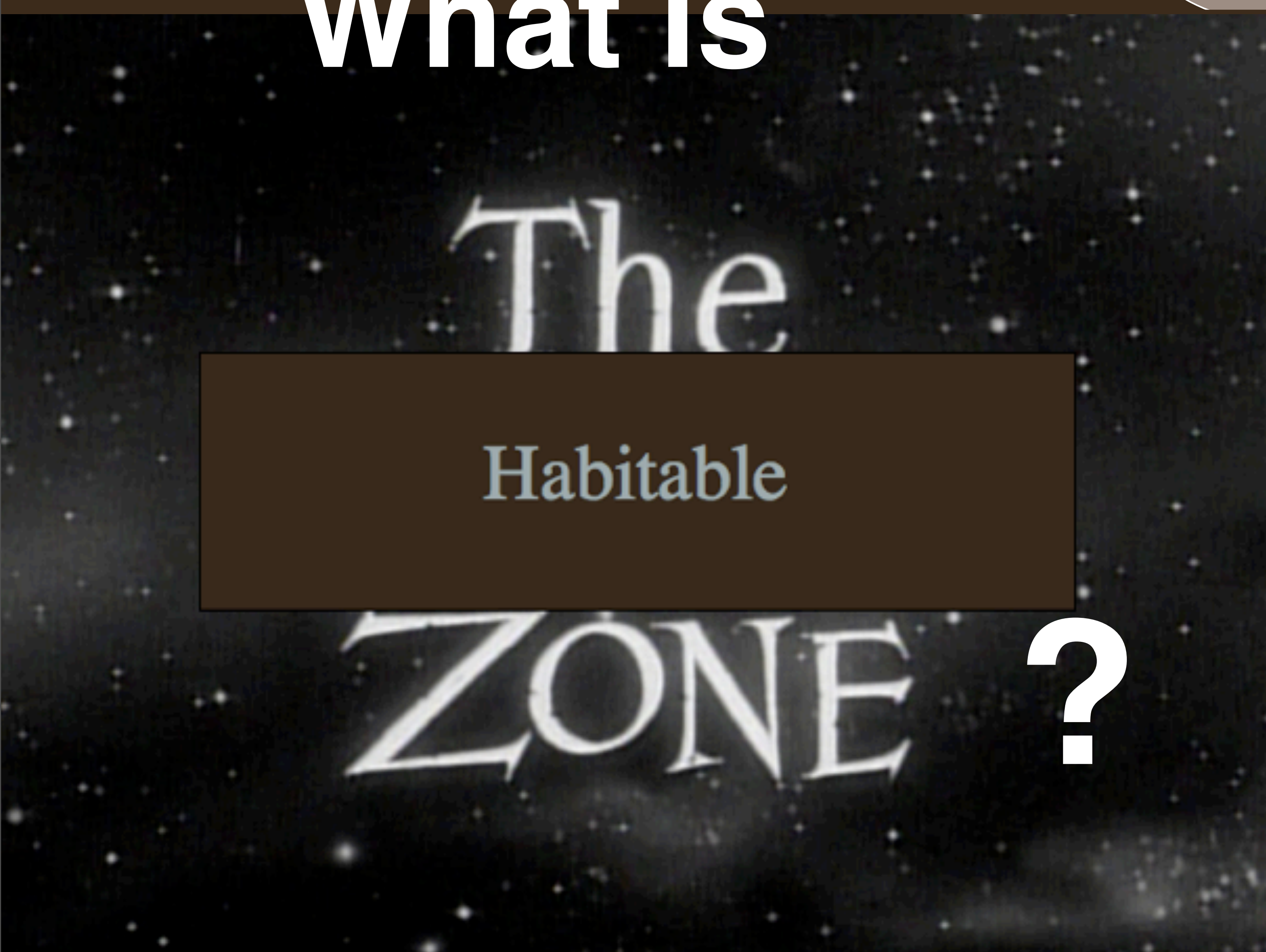


What is

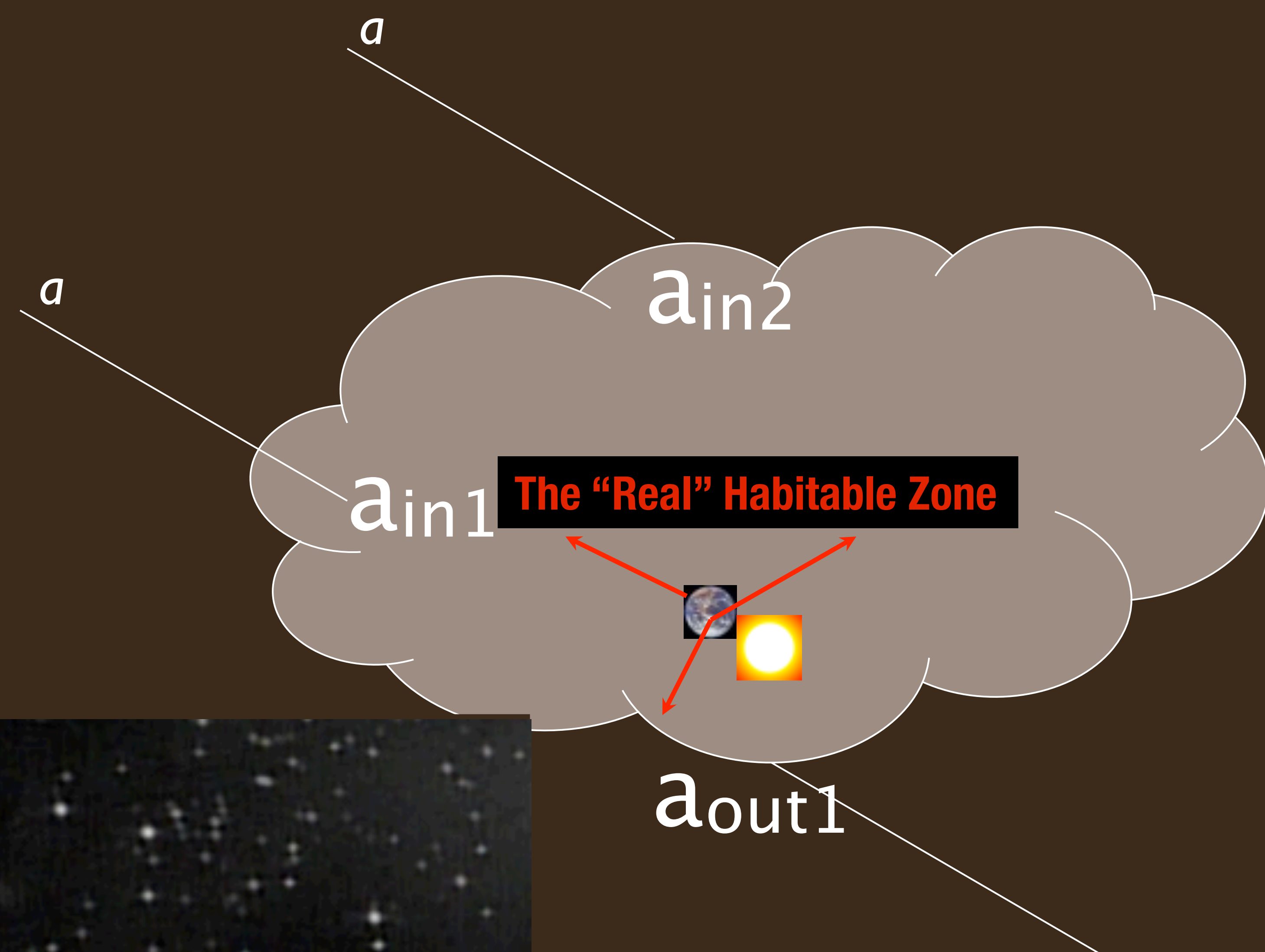




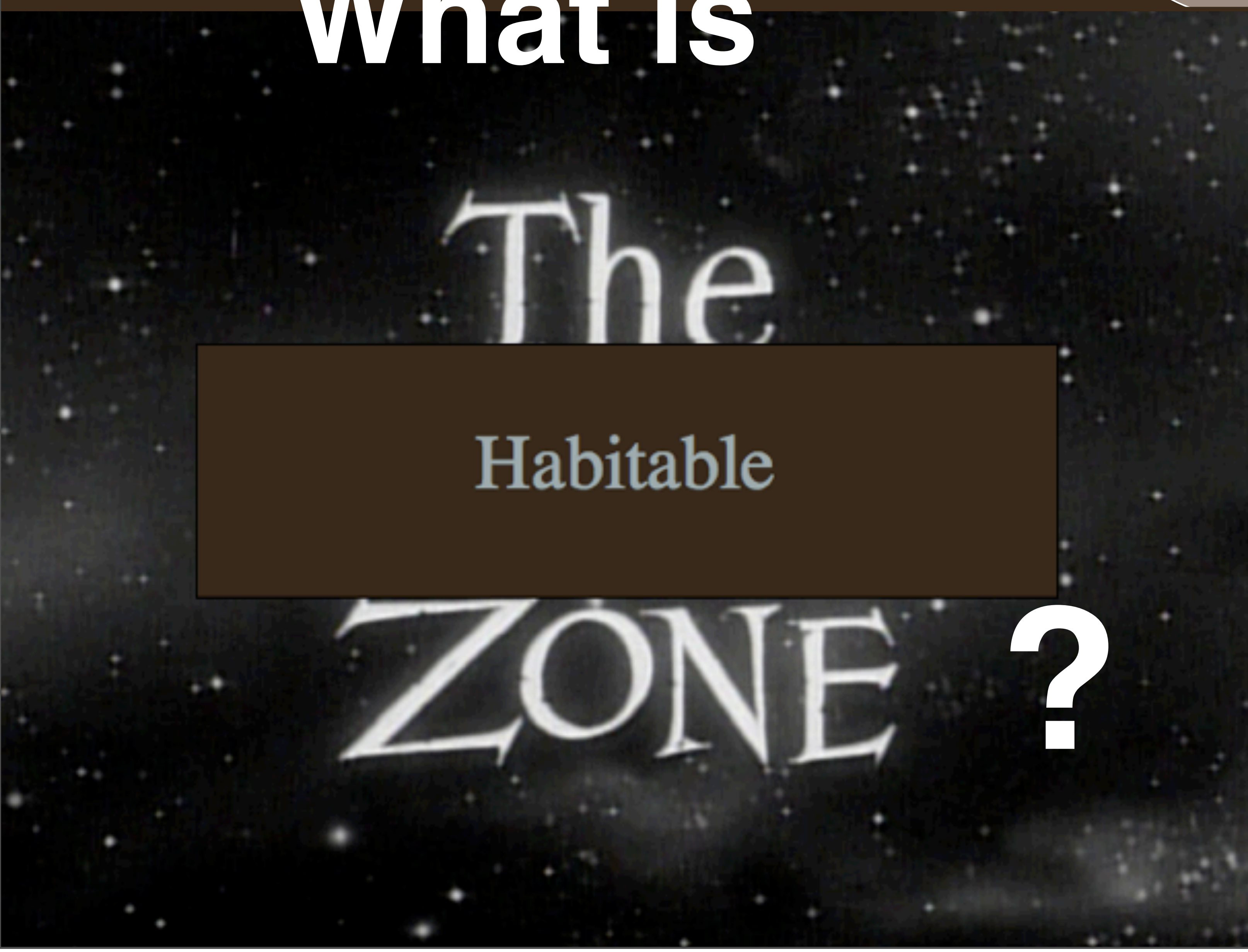
What is



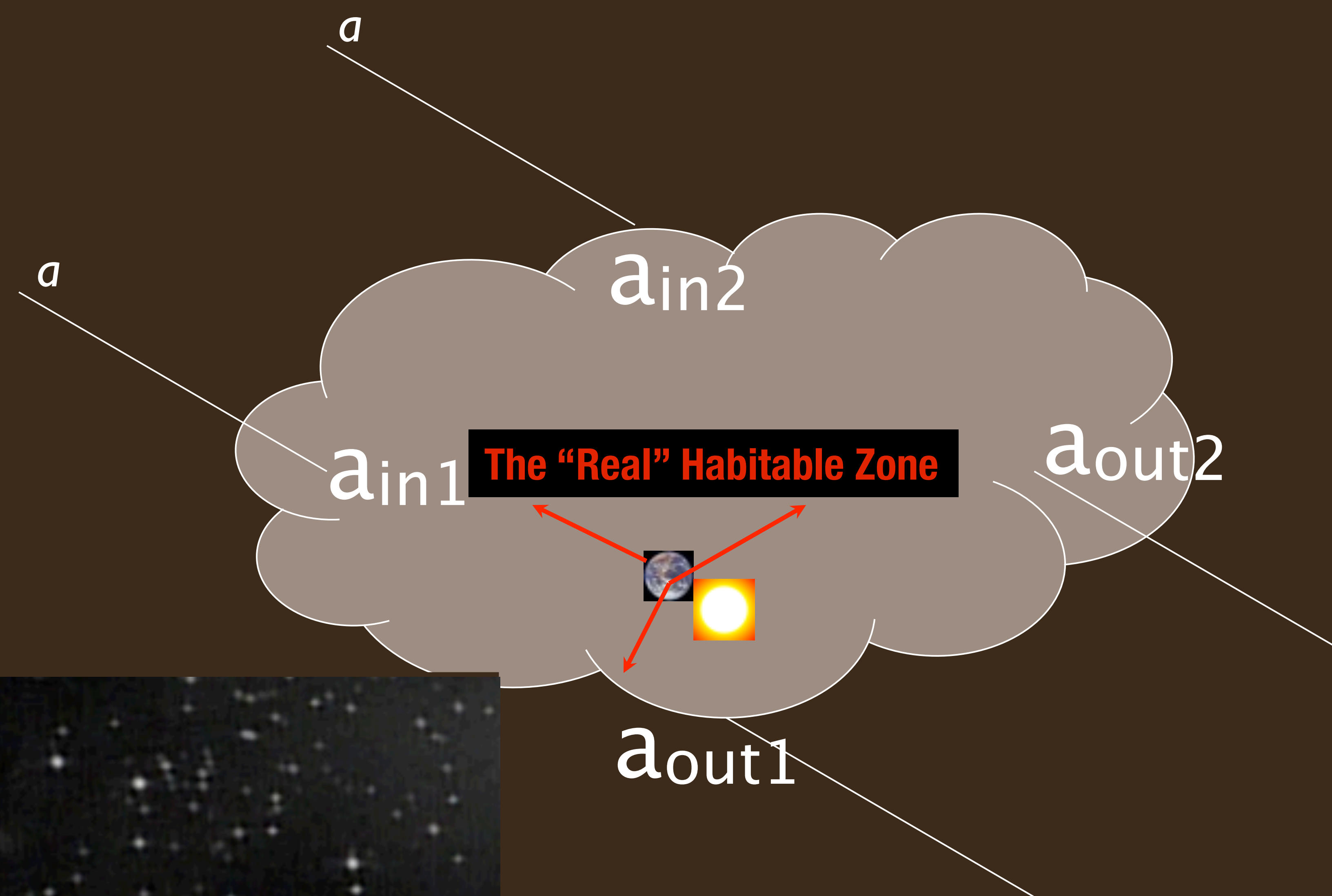
?


a
a
a_{in2}
a_{in1}
The "Real" Habitable Zone
a_{out1}

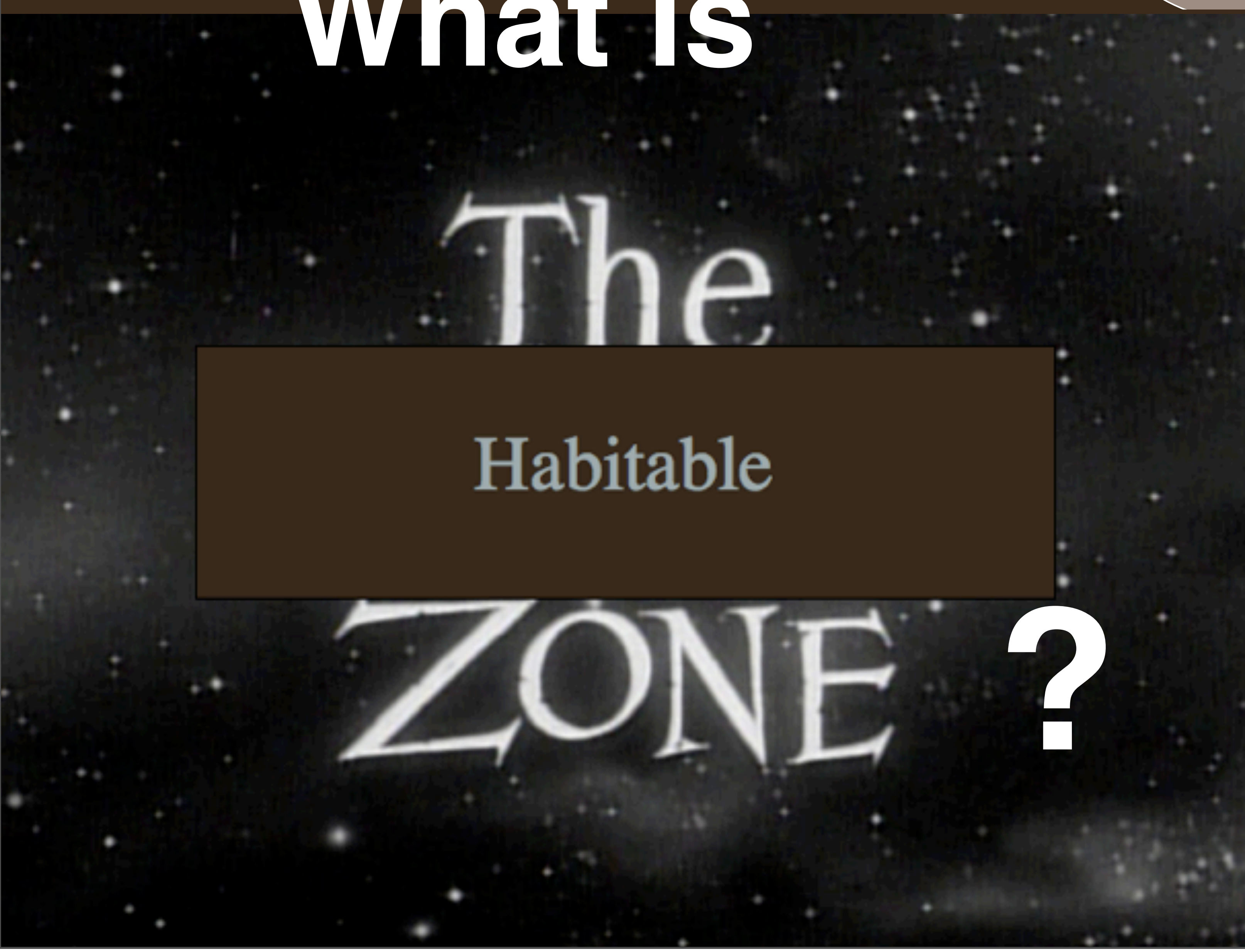
What is

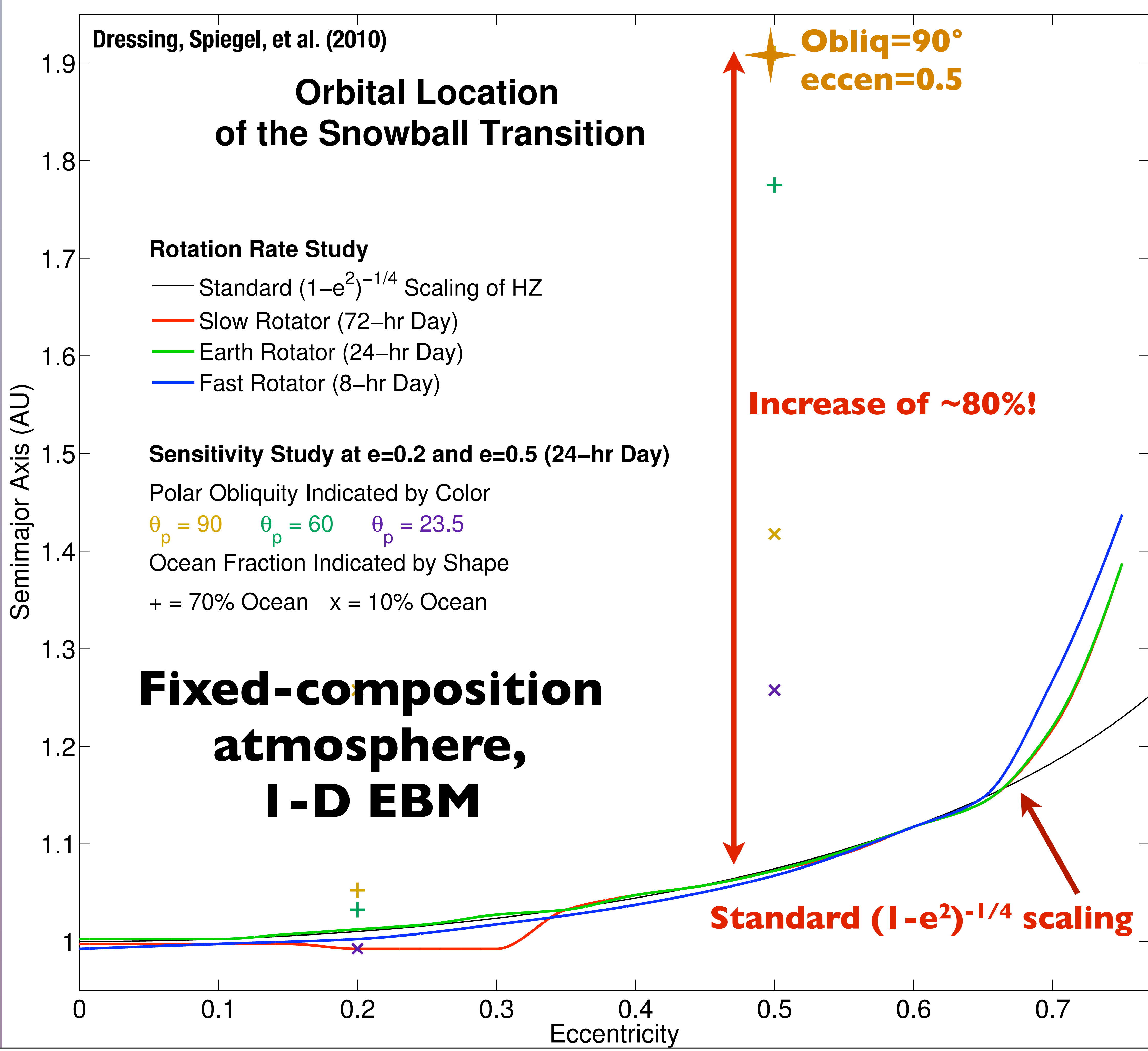

The
Habitable
ZONE

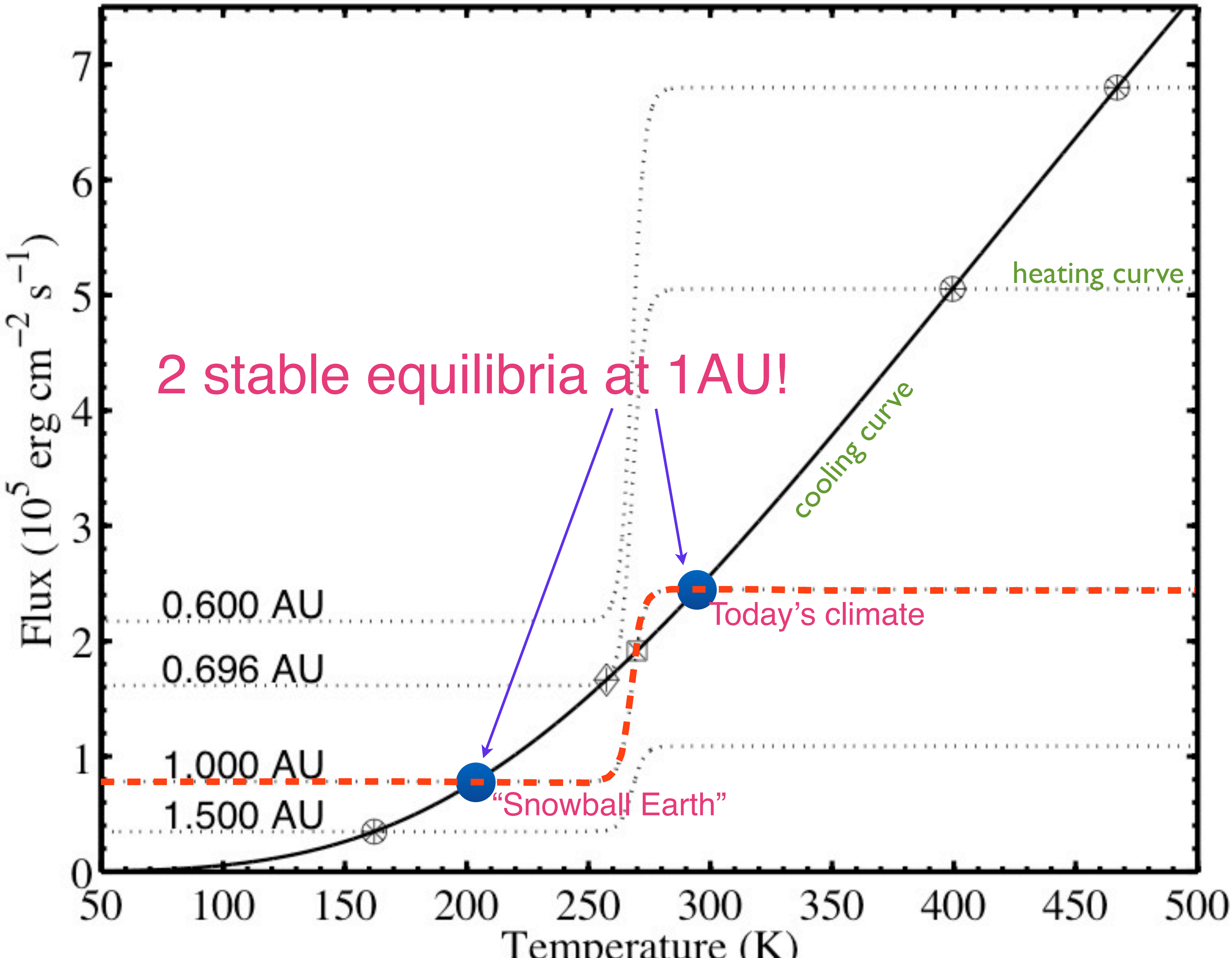
?


a
a
a_{in2}
a_{in1}
The “Real” Habitable Zone
a_{out2}
a_{out1}

What is


The
Habitable
ZONE
?


Dressing, Spiegel, et al. (2010)
Orbital Location of the Snowball Transition
Rotation Rate Study
Standard $(1-e^2)^{-1/4}$ Scaling of HZ
Slow Rotator (72–hr Day)
Earth Rotator (24–hr Day)
Fast Rotator (8–hr Day)
Sensitivity Study at e=0.2 and e=0.5 (24–hr Day)
Polar Obliquity Indicated by Color
$\theta_p = 90$ $\theta_p = 60$ $\theta_p = 23.5$
Ocean Fraction Indicated by Shape
+ = 70% Ocean x = 10% Ocean
Fixed-composition atmosphere, 1-D EBM
Obliq=90°
eccen=0.5
Increase of ~80%!
Standard $(1-e^2)^{-1/4}$ scaling
Semimajor Axis (AU)
Eccentricity
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7



2 stable equilibria at 1AU!
heating curve
cooling curve
0.600 AU
0.696 AU
1.000 AU
1.500 AU
Today's climate
"Snowball Earth"
Flux (10^5 erg cm^{-2} s^{-1})
Temperature (K)
0
1
2
3
4
5
6
7
50
100
150
200
250
300
350
400
450
500

Timeline of Life on Earth

Earth Formed
(4.54 Gyr ago)

Earth Habitable
(4.0 Gyr ago?)

Life Begins
(by 3.8 Gyr ago?)

Uninhabitable/Sterilized
due to Late-Heavy
Bombardment, etc.?

Alternate Logic:

We have sample size of one,
so we can't draw any conclusions
about the probability of abiogenesis.

"Intelligence"
Arises
(10^5 yrs ago?)

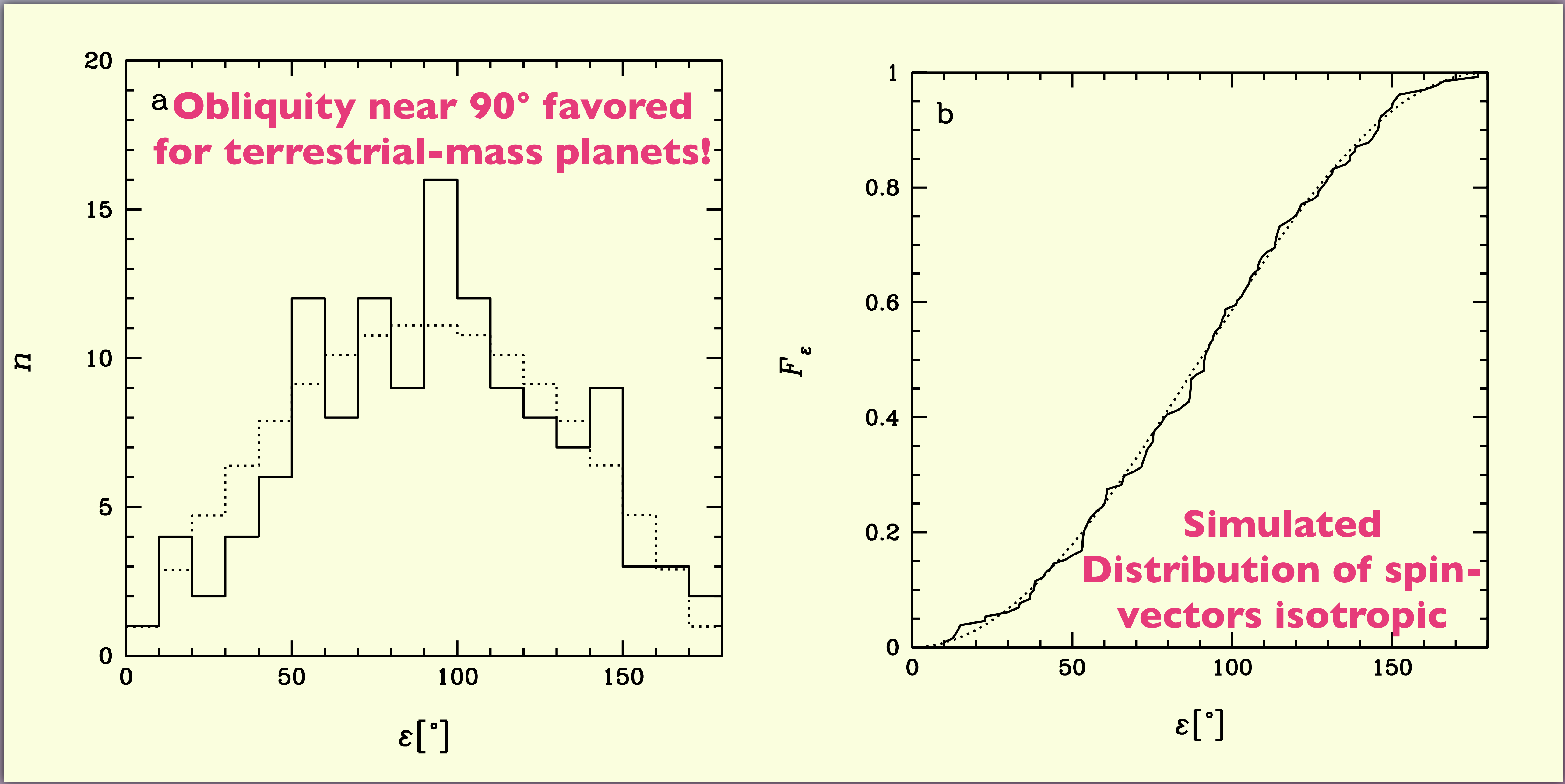
Present

CIERA

9/1/2011

What obliquities are expected?

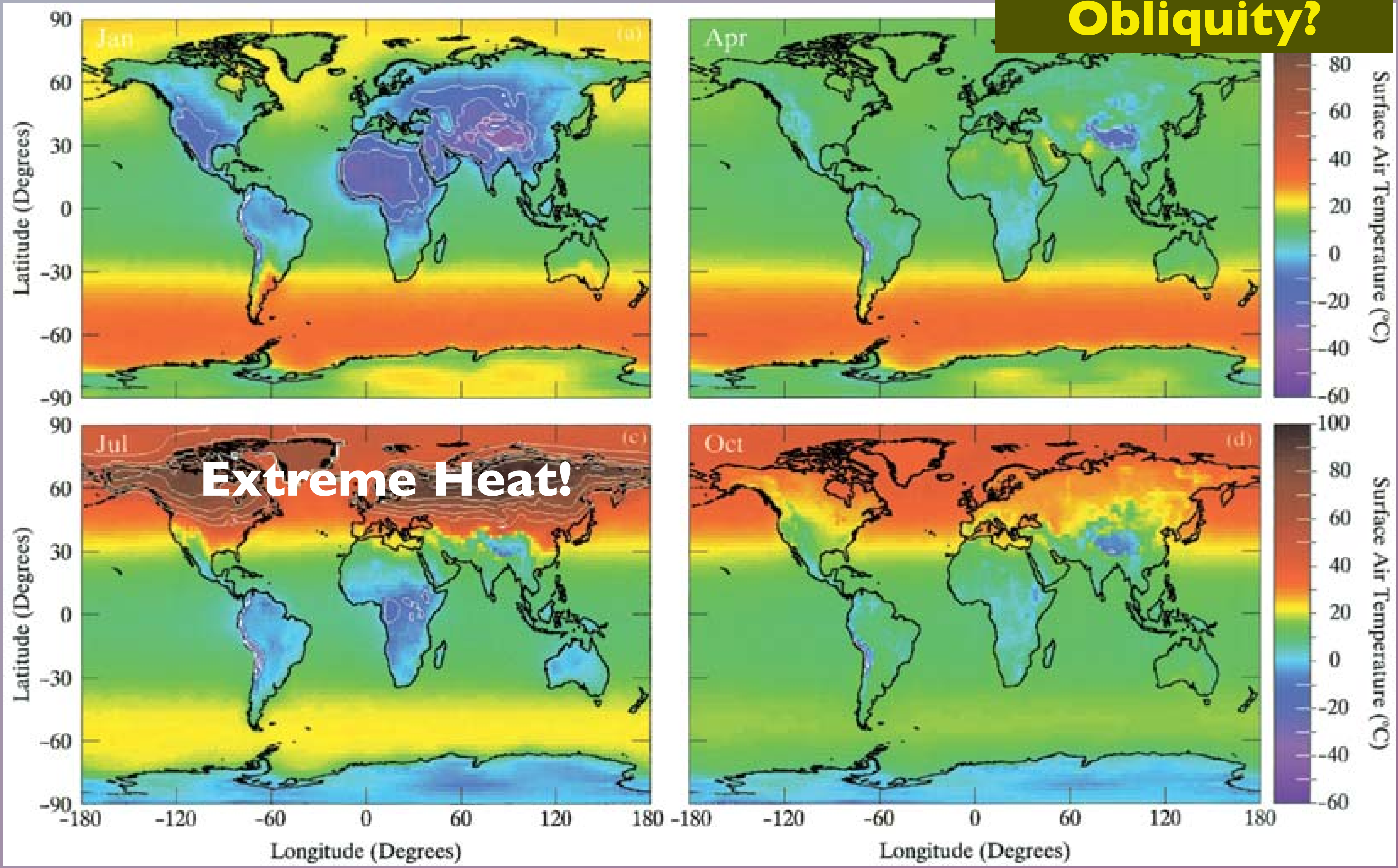
Isotropic spin distribution?



Kokubo & Ida 2007

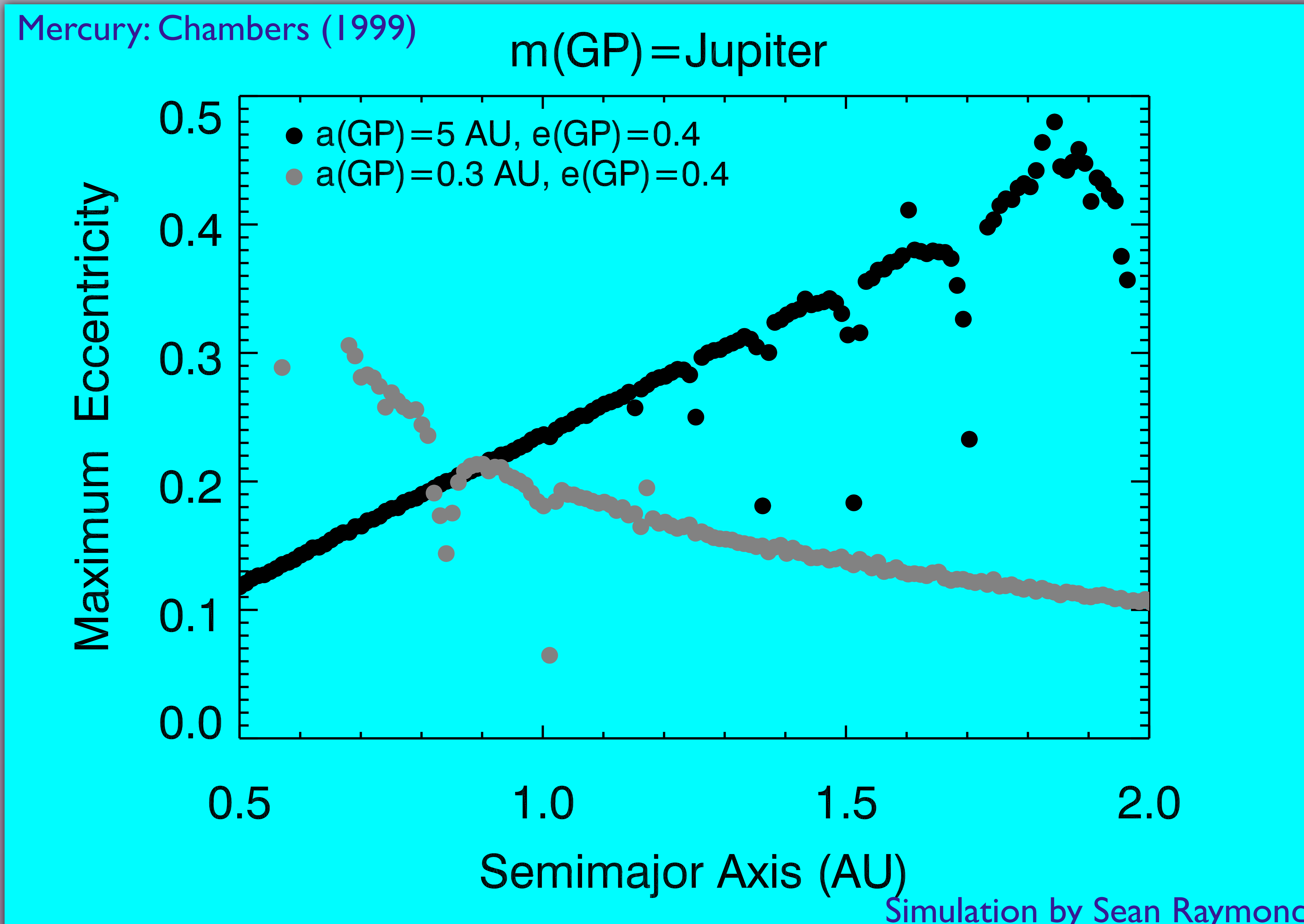
85° obliquity Earth

Effect of Obliquity?



Williams & Pollard 2003

Eccentricity oscillations up to ~0.5 are possible for entirely prosaic architectures



Summary

• Unobservable or barely observable features of a planet can have a profound and nonintuitive influence on climate and habitability: "HZ" depends on properties of planet in addition to star.

• HZ also depends on properties of solar system in which planet resides.

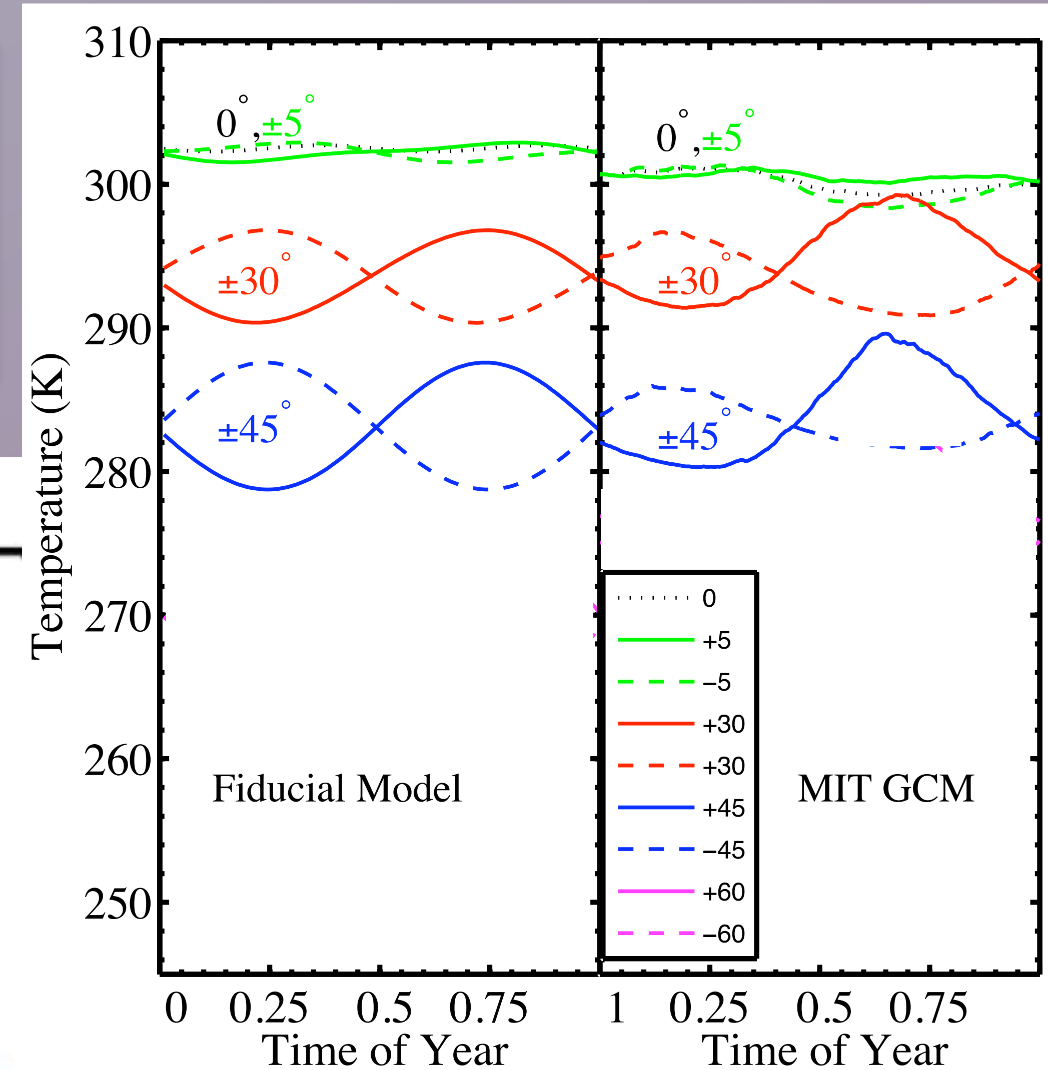
• For potentially habitable terrestrial planets around other stars, nearly any amplitude and frequency oscillation of eccentricity is possible.

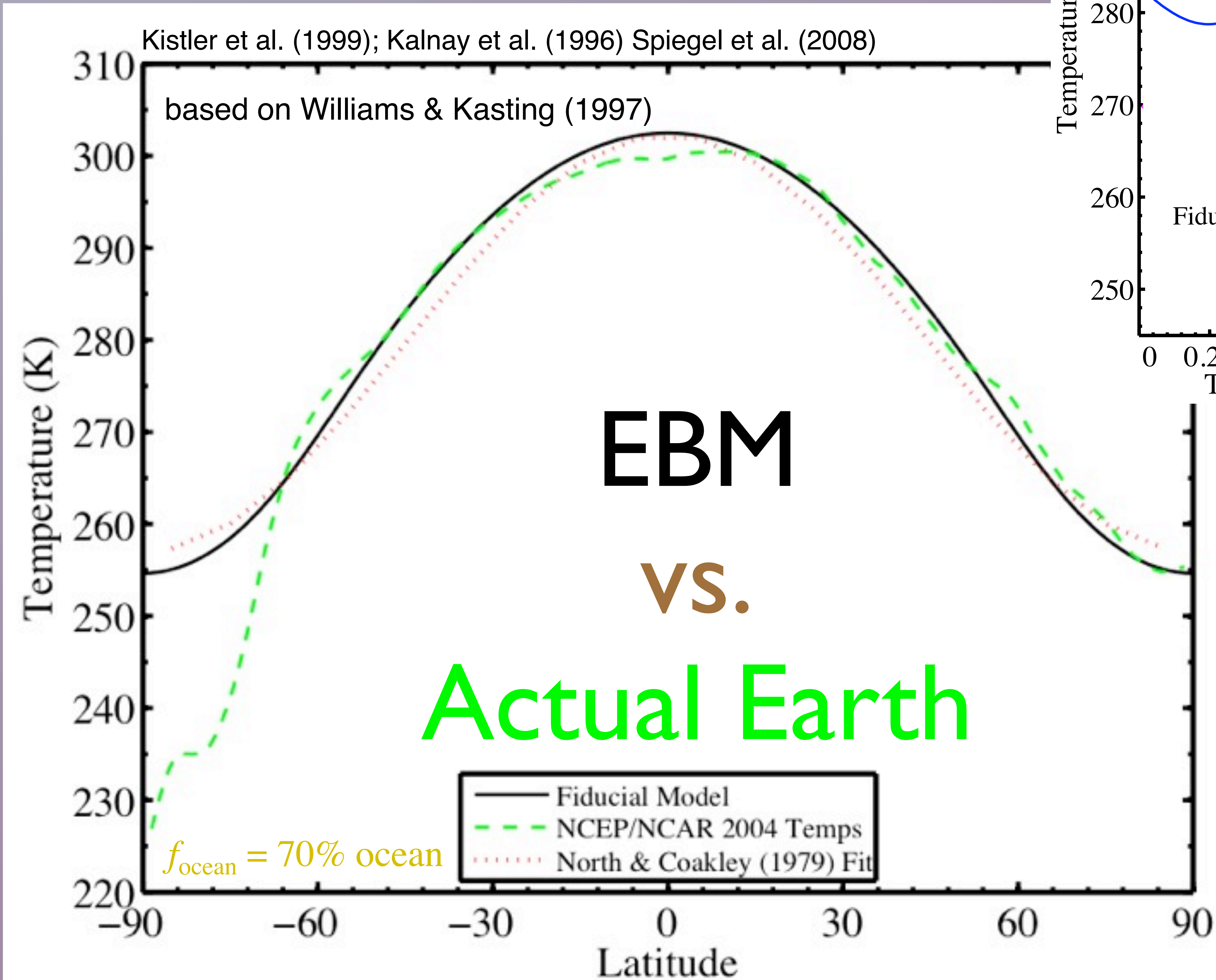
• This might be harmful to (some kinds of) life, but might also restore habitability to a frozen-over world in far less than ~10 million years.

A Few Scattered Questions to Address

- To what extent is an outer giant planet like Jupiter useful for protecting us from damaging impacts? Does more work remain to be done after the Horner & Jones studies?
- What are key observational degeneracies?
- For instance, how would we know if a planet is in a snowball state? Can we tell the difference between (1) a snowball Earth that is shiny and has cold CO_2 clouds, and (2) a Venus?
- How can we discern obliquity?
- What actually happens at a highly eccentric planet's periastron? Does it suffer severe atmospheric loss?
- What is an appropriate metric of habitability? Should it be based on whether life there would be observable?
- (Is it easier to tell whether a world is inhabited than whether it is habitable?)

$$\frac{\partial T}{\partial t} - \frac{K_{yy}}{\cos[s/R]}\frac{\partial}{\partial s}\left\{\cos[s/R]\frac{\partial T}{\partial s}\right\} = \frac{1}{C}\left\{S(1-A) - I\right\} .$$





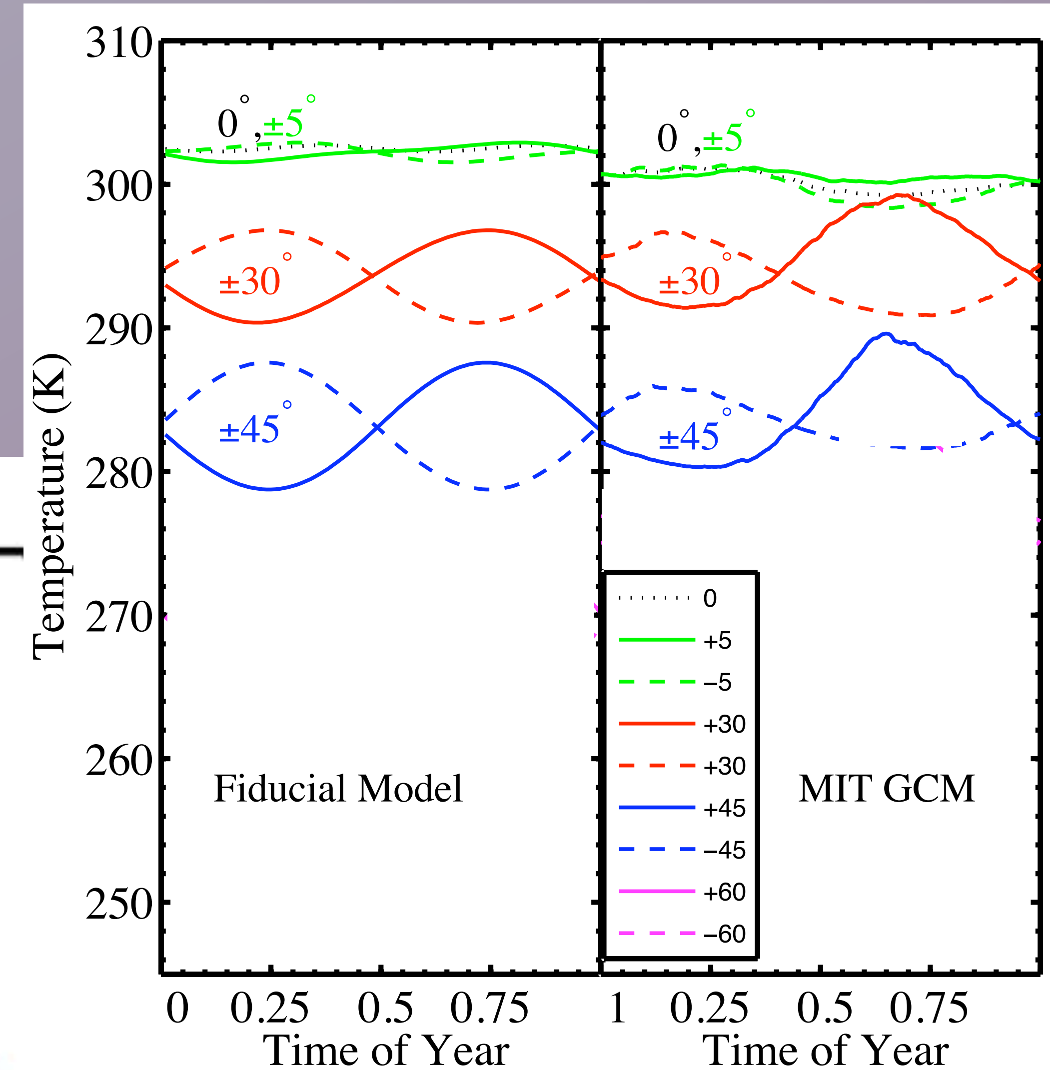
EBM vs. Actual Earth

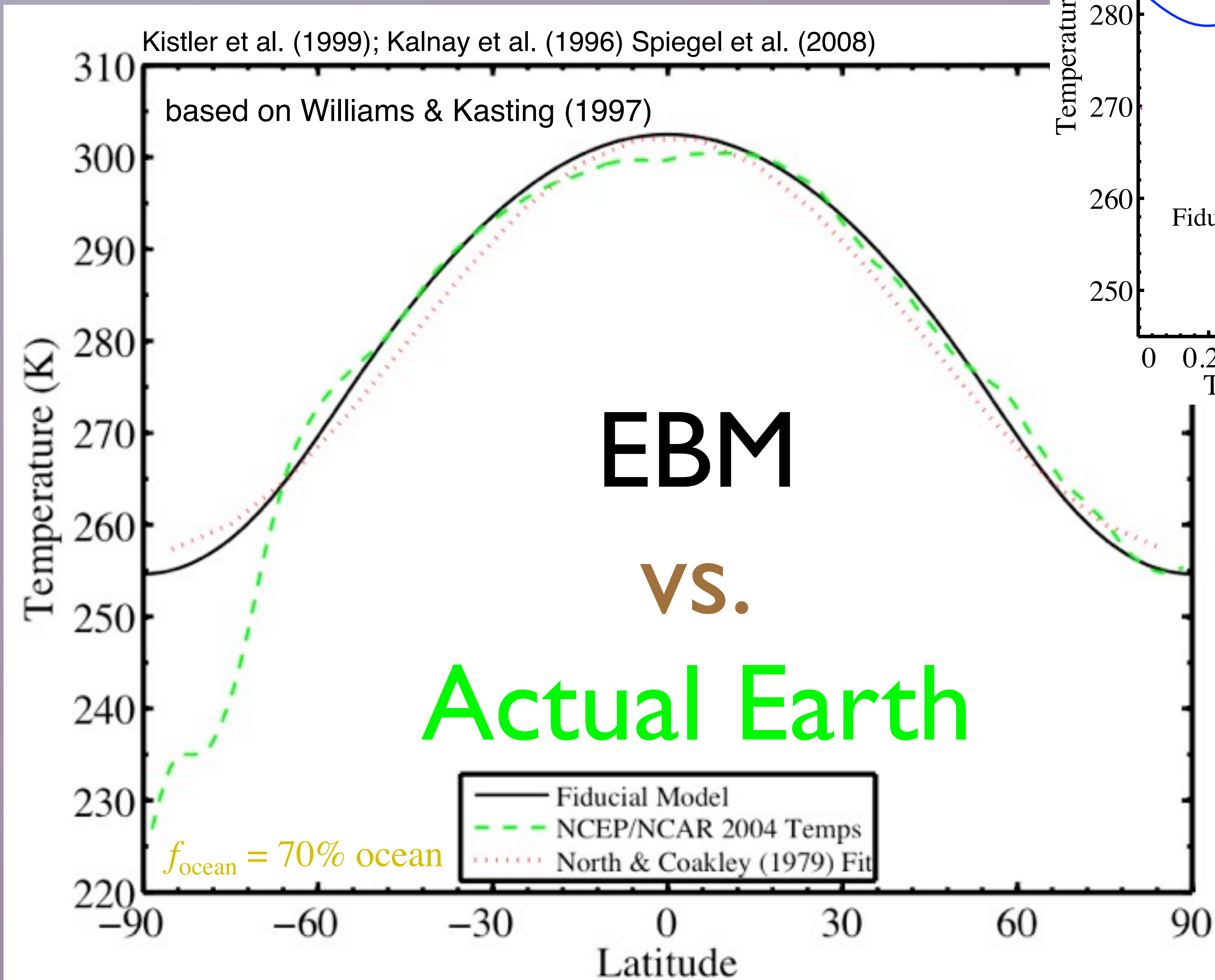
Model Validation: In defense of simple EBMs

$\tau_{\rm rad} \equiv CT_0/I_0 = (C/\sigma)T_0^{-3}$, we are left with the following nondimensional form of the equation:

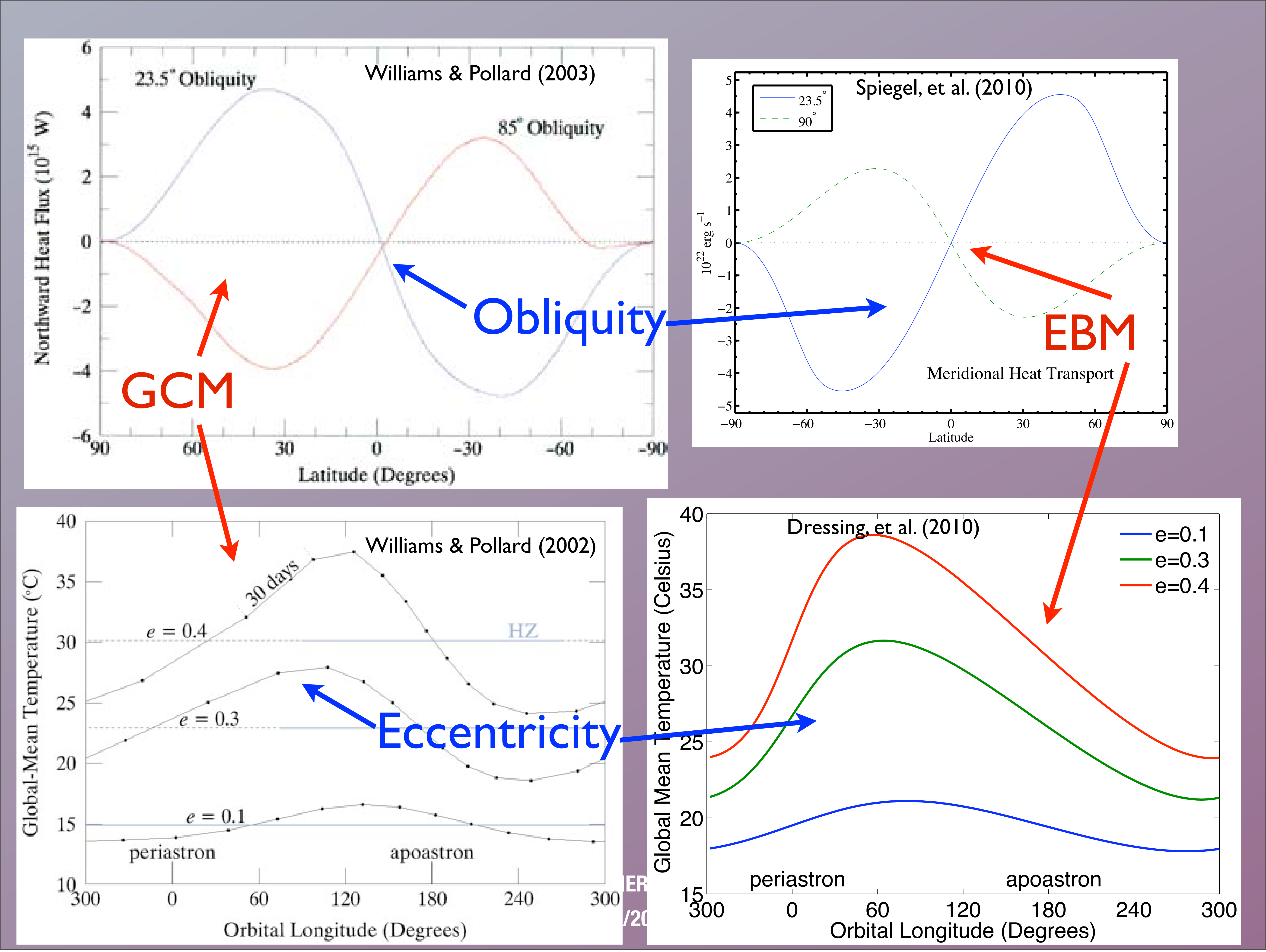
$$\frac{\partial T^*}{\partial t^*} - \mathcal{K}^* \frac{\partial}{\partial x}\left\{(1-x^2)\frac{\partial T^*}{\partial x}\right\} = \mathcal{R}^*\left\{S^*(1-A) - I^*\right\} .$$

Here, $\mathcal{K}^* \equiv P_{\rm orb}/\tau_{\rm diff}$ may be thought of as a dimensionless thermal diffusivity, while $\mathcal{R}^* \equiv P_{\rm orb}/\tau_{\rm rad}$ may





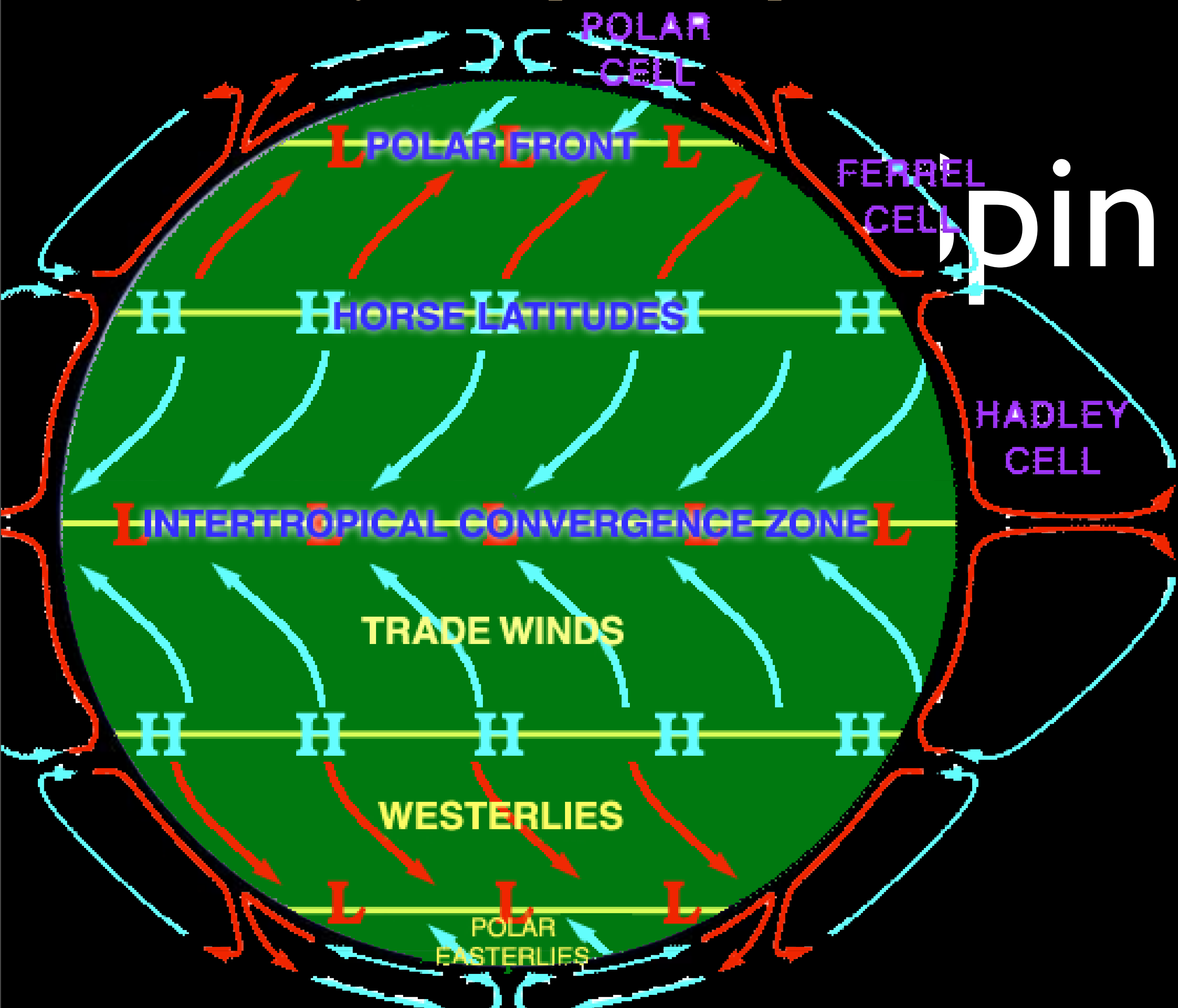
Model Validation: In defense of simple EBMs



Williams & Pollard (2003)
23.5° Obliquity
85° Obliquity
Northward Heat Flux (10^{15} W)
Latitude (Degrees)
Spiegel, et al. (2010)
23.5°
90°
10^{22} erg s^{-1}
Meridional Heat Transport
Latitude
Obliquity
GCM
EBM
Williams & Pollard (2002)
30 days
e = 0.4
e = 0.3
e = 0.1
HZ
periastron
apoastron
Global-Mean Temperature (°C)
Orbital Longitude (Degrees)
Eccentricity
Dressing, et al. (2010)
e=0.1
e=0.3
e=0.4
Global Mean Temperature (Celsius)
periastron
apoastron
Orbital Longitude (Degrees)

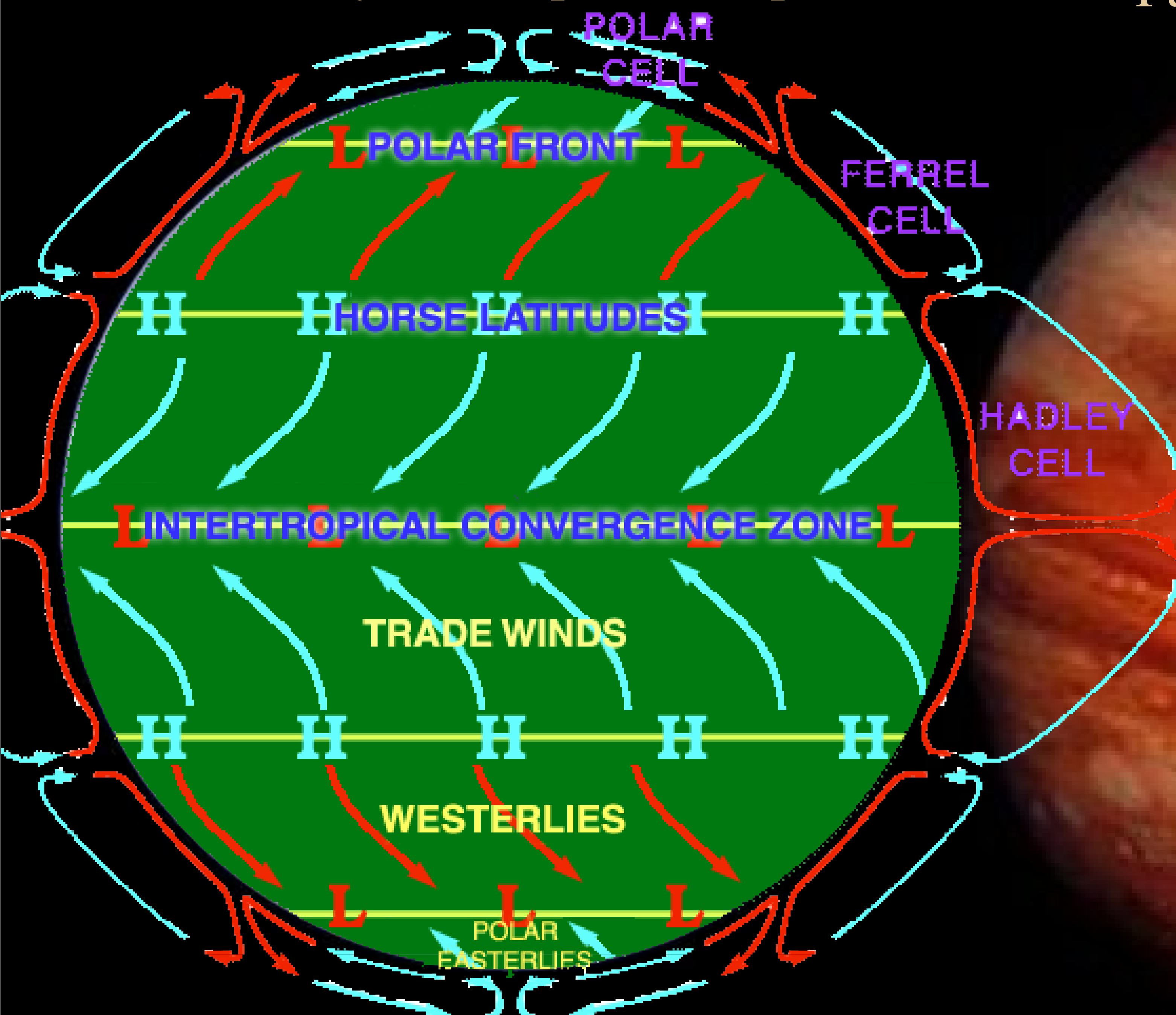
Spin Rate

3 "Hadley" Cells per hemisphere

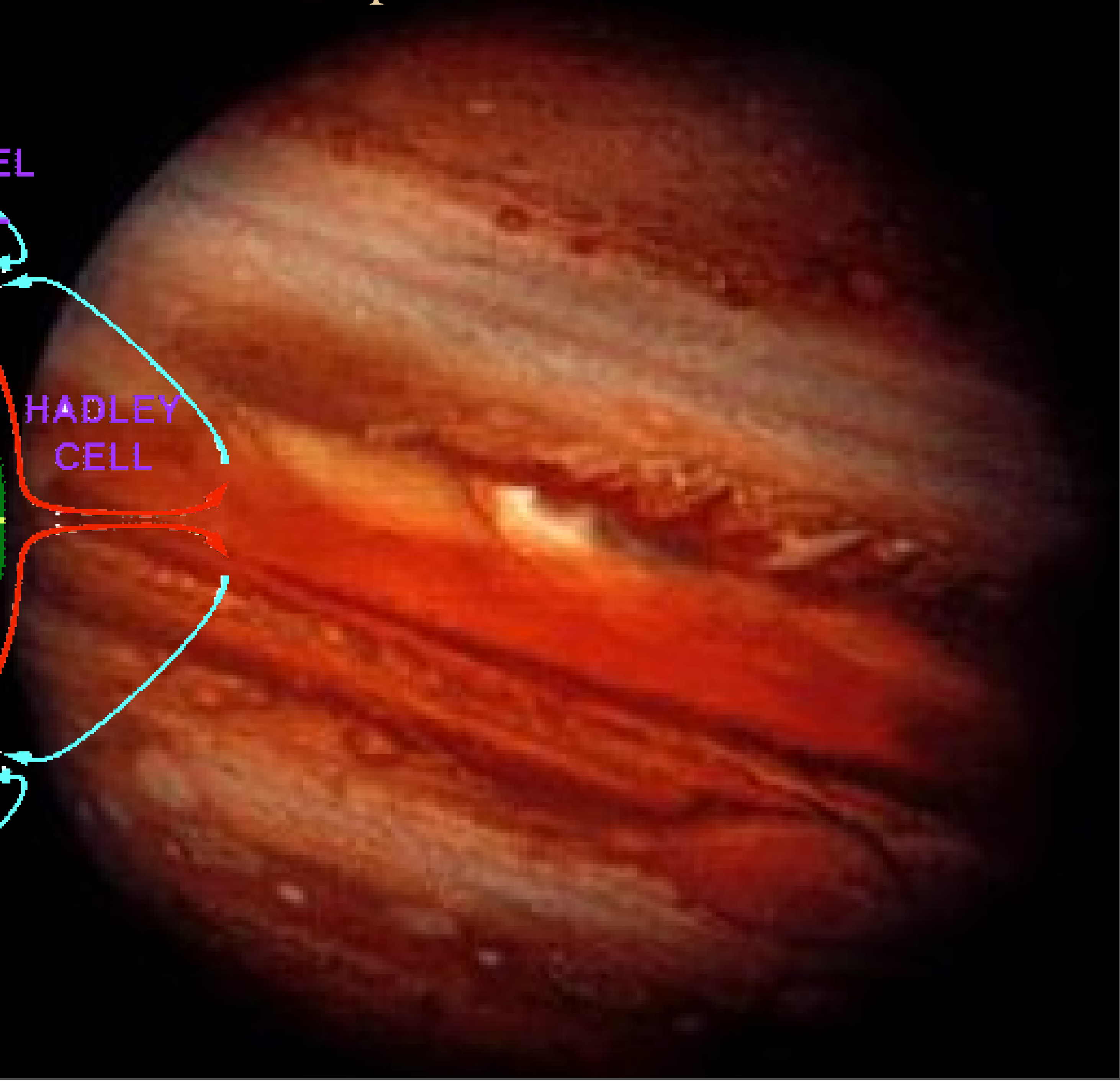


pin Rate

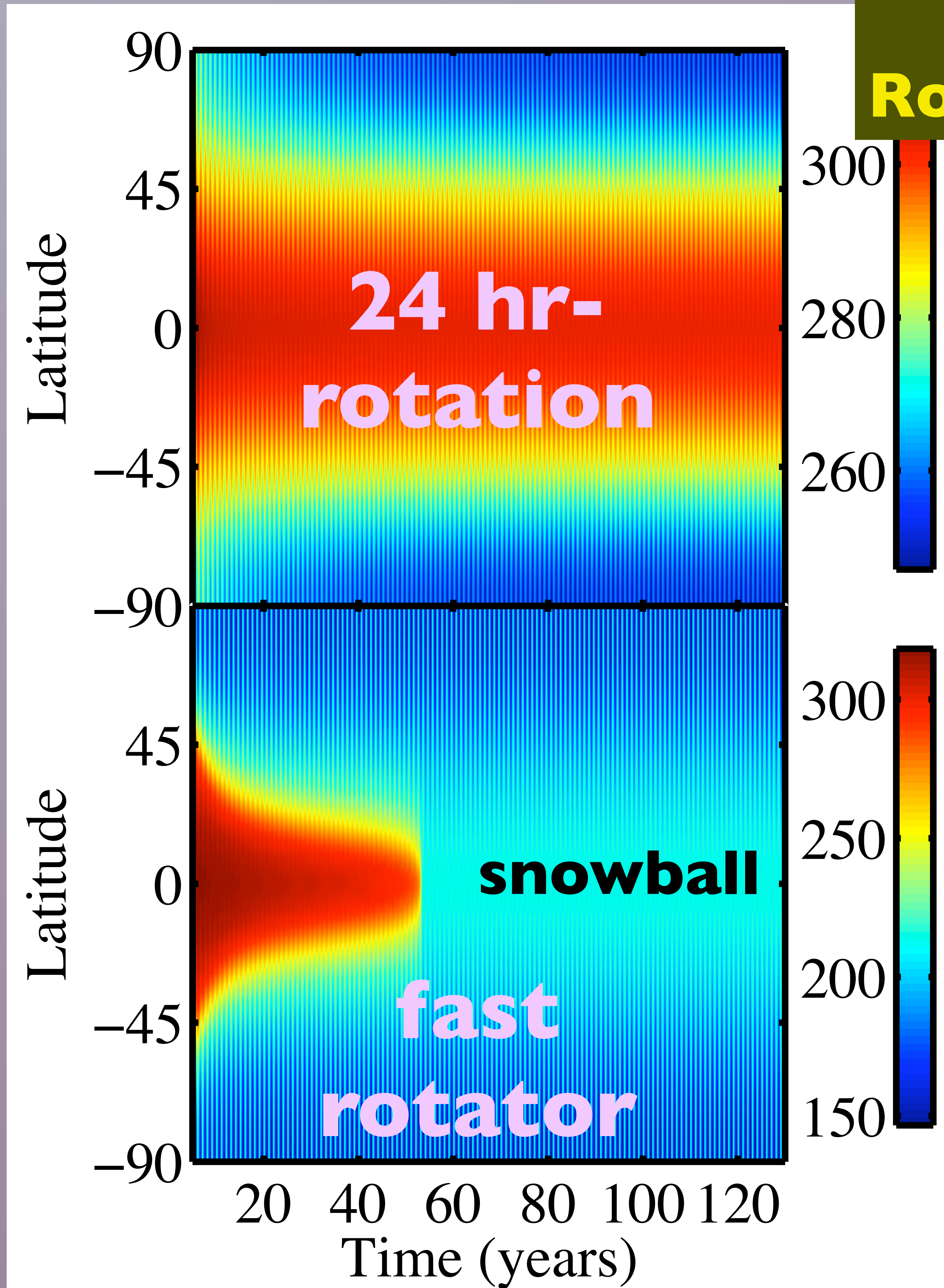
3 “Hadley” Cells per hemisphere



Faster Spin => ≥15 total cells



Effect of Rotation Rate?



Faster Rotation
=> Stronger Coriolis
=> less efficient transport of heat

Habitability Fractions

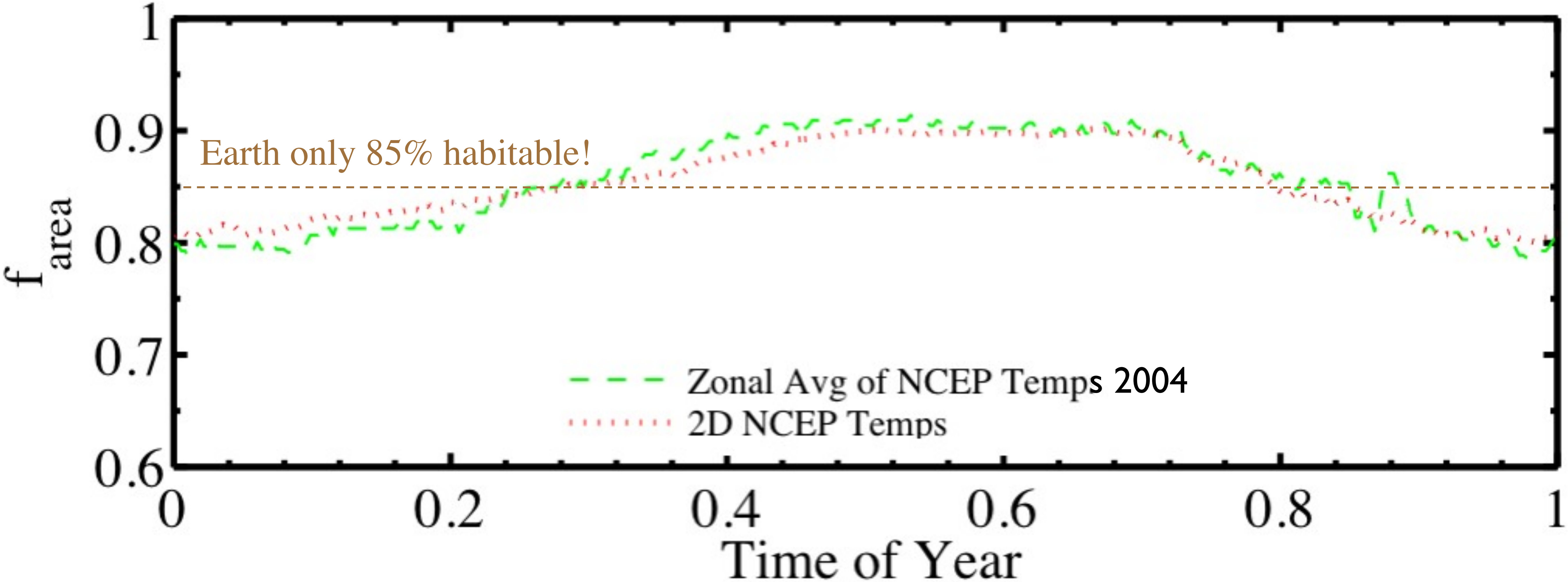
$f_{time}[a,\lambda]$ = fraction of the year that latitude λ is in habitable temperature range (0°-100° C).

$f_{area}[a,t]$ = fraction of the surface area that is in habitable temperature range at time t.

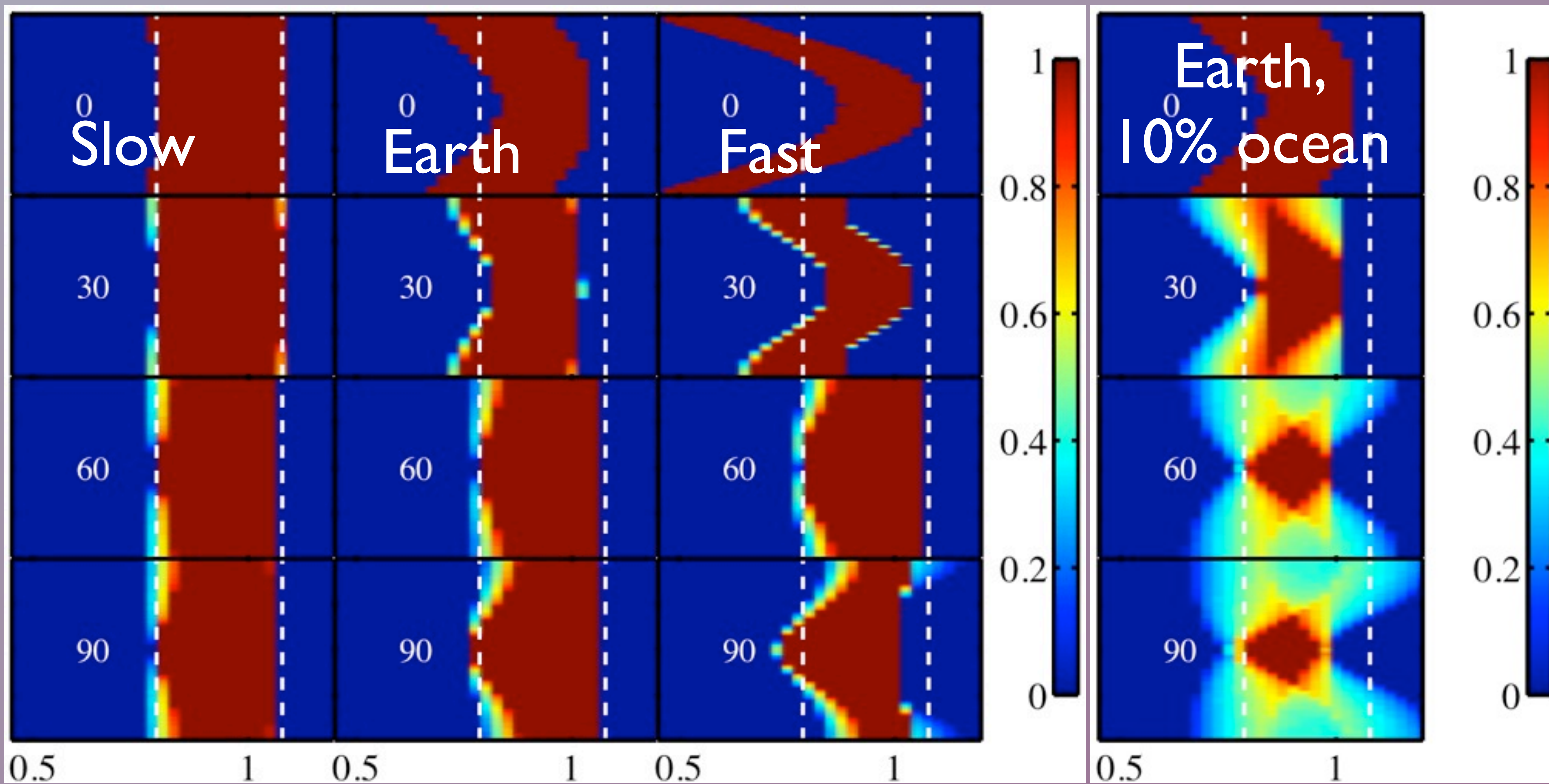
$f_{hab}[a]$ = fraction of year and surface area that is habitable.

Fractional Habitability of Earth

Spiegel, Menou, Scharf (2008)



Spiegel, Menou, Scharf (2009)



Building a Simple Climate Model

Feedbacks?

-

- Blackbody Cooling
- H_2O Cloud Albedo
- Carbonate-Silicate Weathering

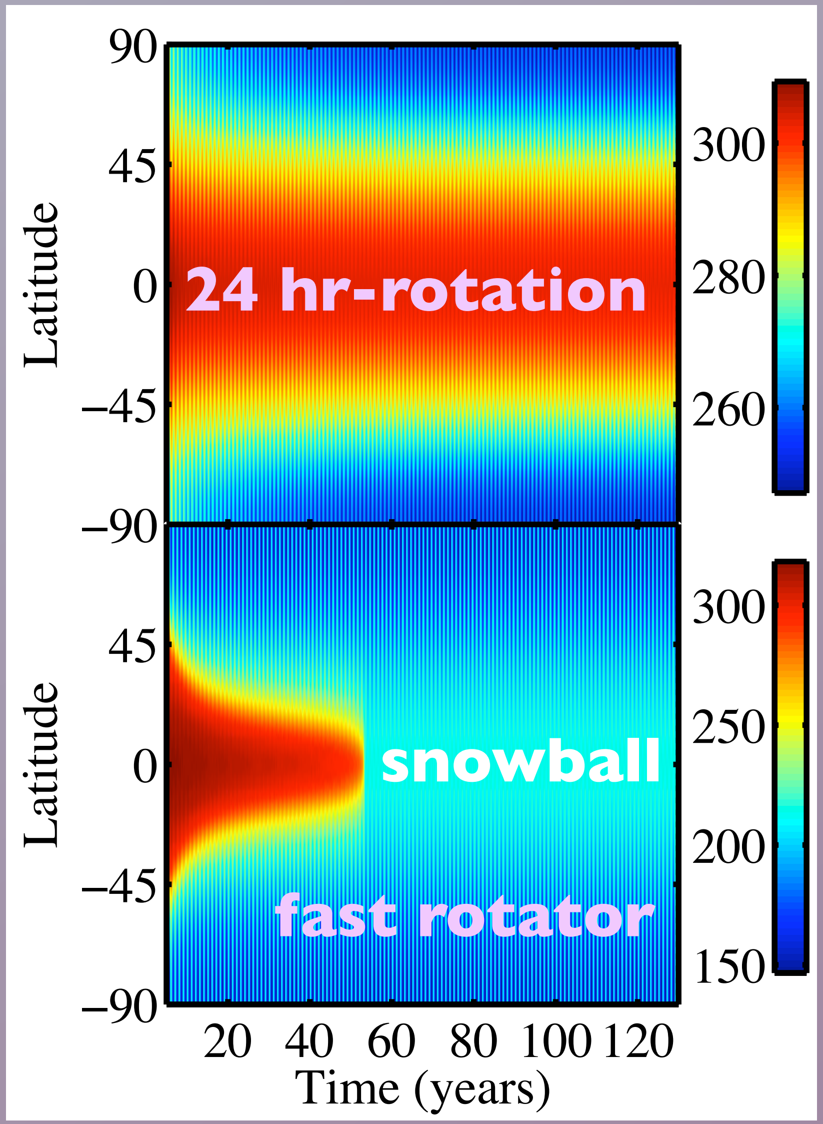
+

- Ice Albedo
- Greenhouse Due to H_2O
- CO_2 Cloud Albedo
- Water-Solubility of CO_2

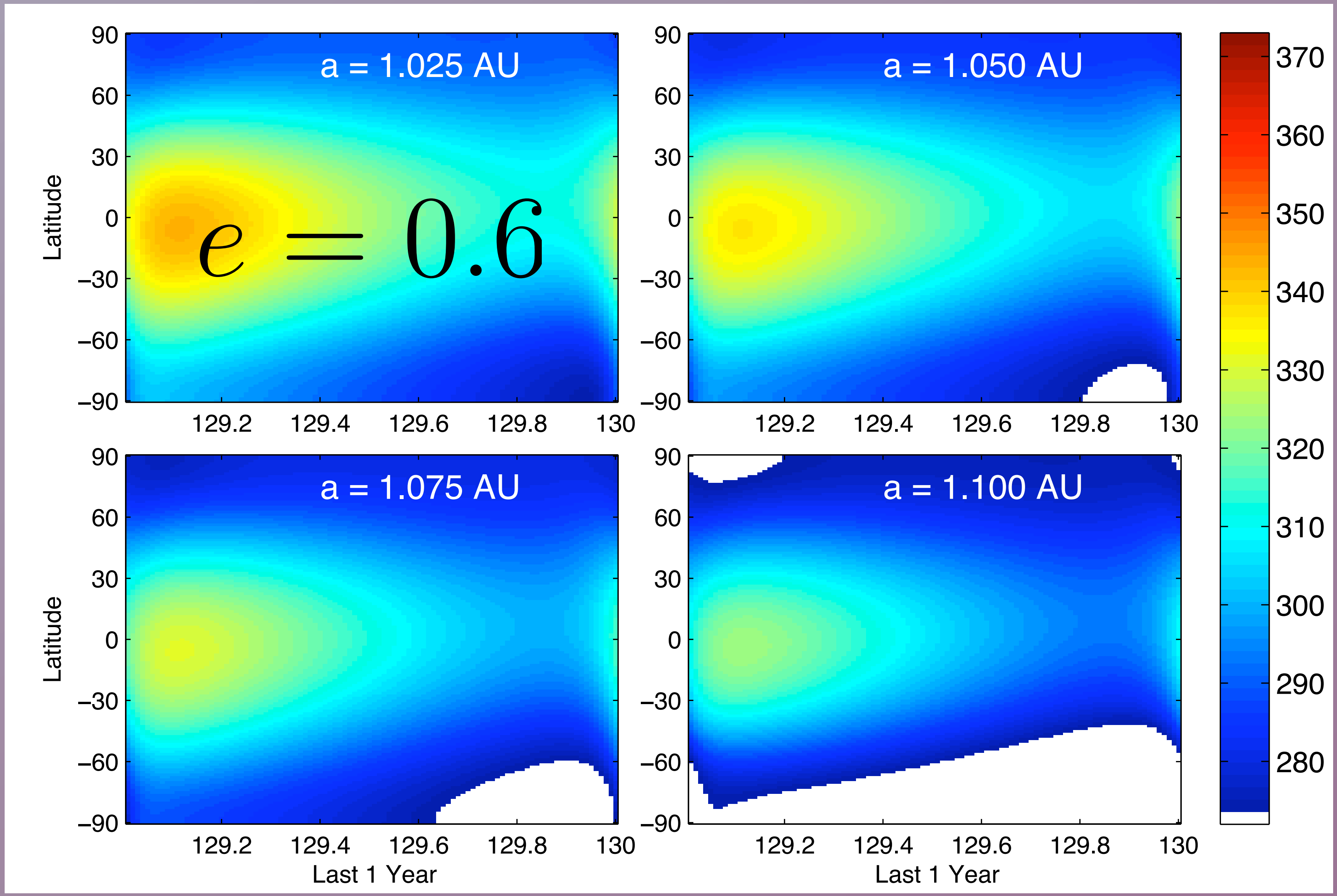
Parameterizations?

- Heat transport
- Greenhouse effect
- Albedo

Faster Rotation
=> Stronger Coriolis
=> less efficient transport of heat



Higher Eccentricity
=> Warmer average climate
=> Greater habitable semimajor axis



CIERA
9/1/2011

(incomplete list of)

Types of Habitability

- Surface habitability
- Subsurface habitability
- "Spectral habitability"
- Galactic habitability
- Chemical habitability
- Continuous habitability
- Regional/Temporal Habitability
- *Dynamical habitability*
- *Climatic habitability*

} Intertwined concepts

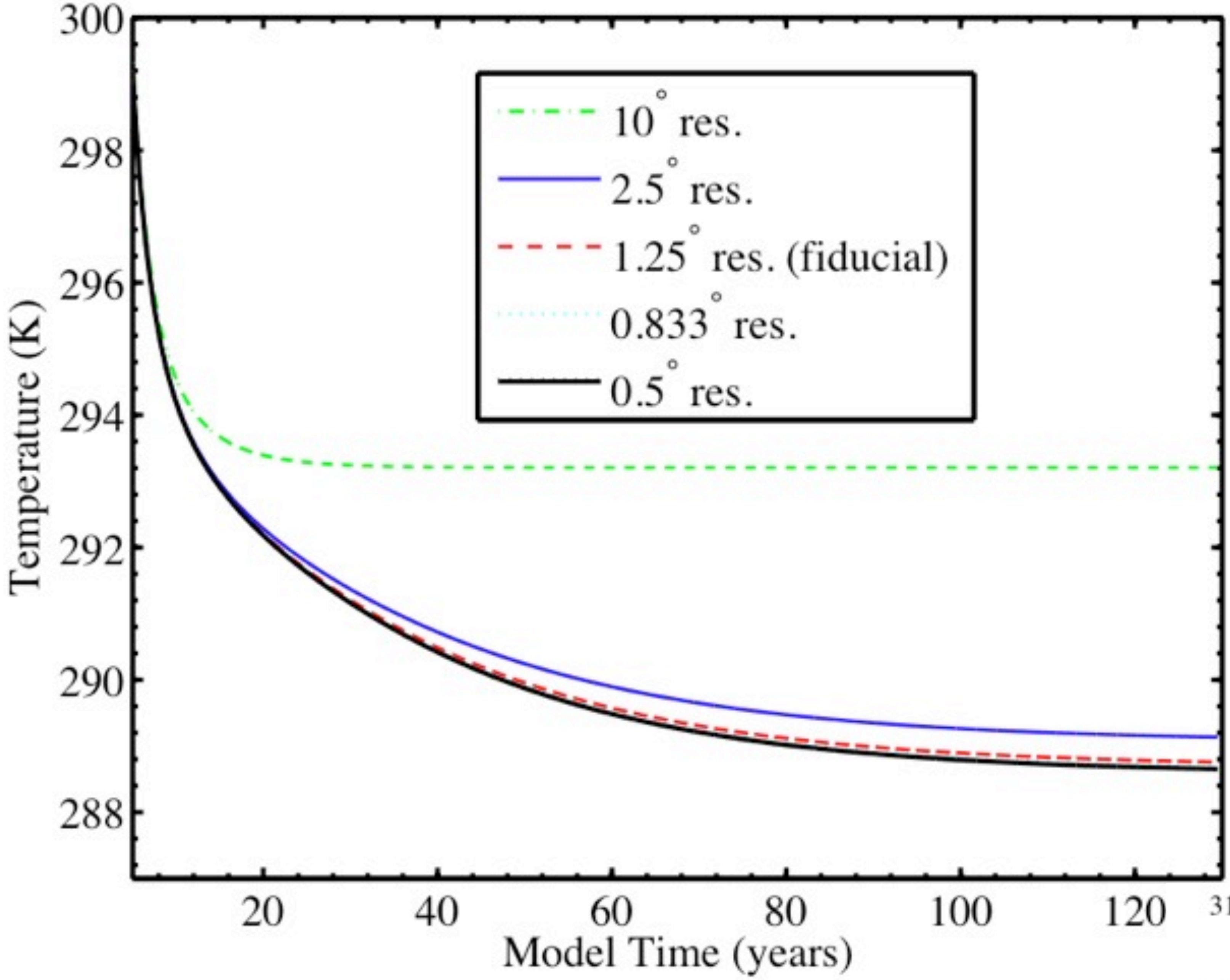
(incomplete list of)

Types of Habitability

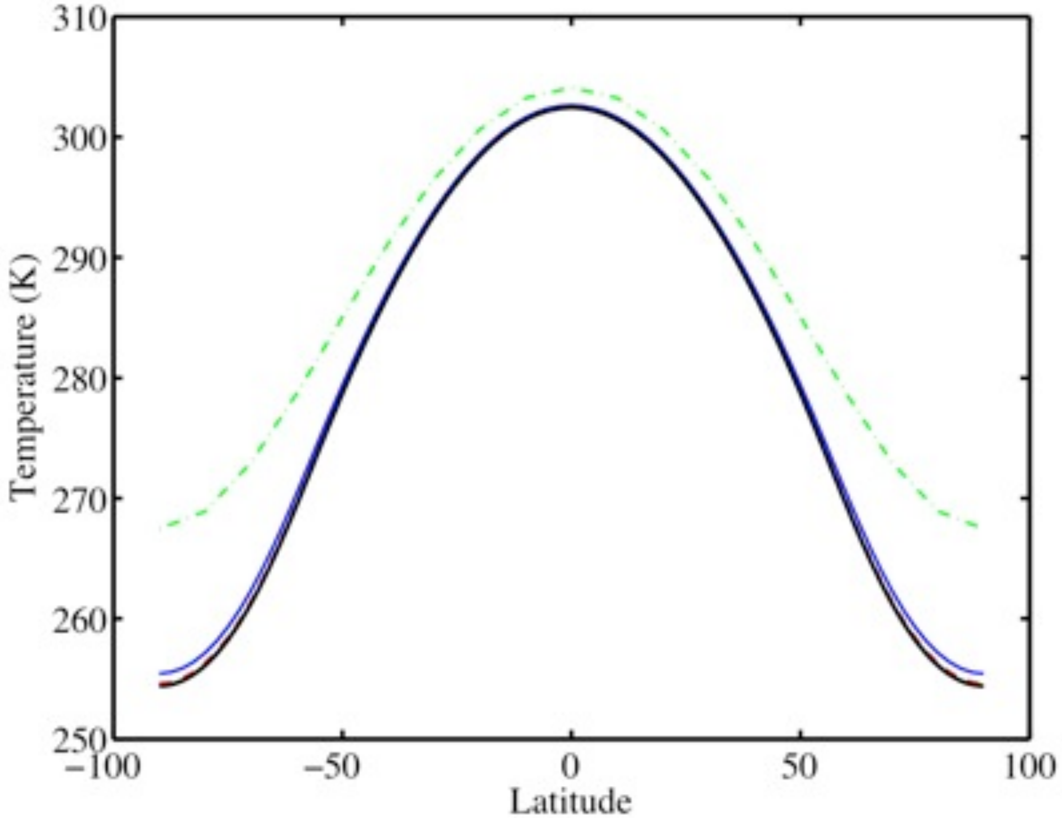
Surface habitability
Subsurface habitability
"Spectral habitability"
Galactic habitability
Chemical habitability
Continuous habitability
Regional/Temporal Habitability
Dynamical habitability
Climatic habitability

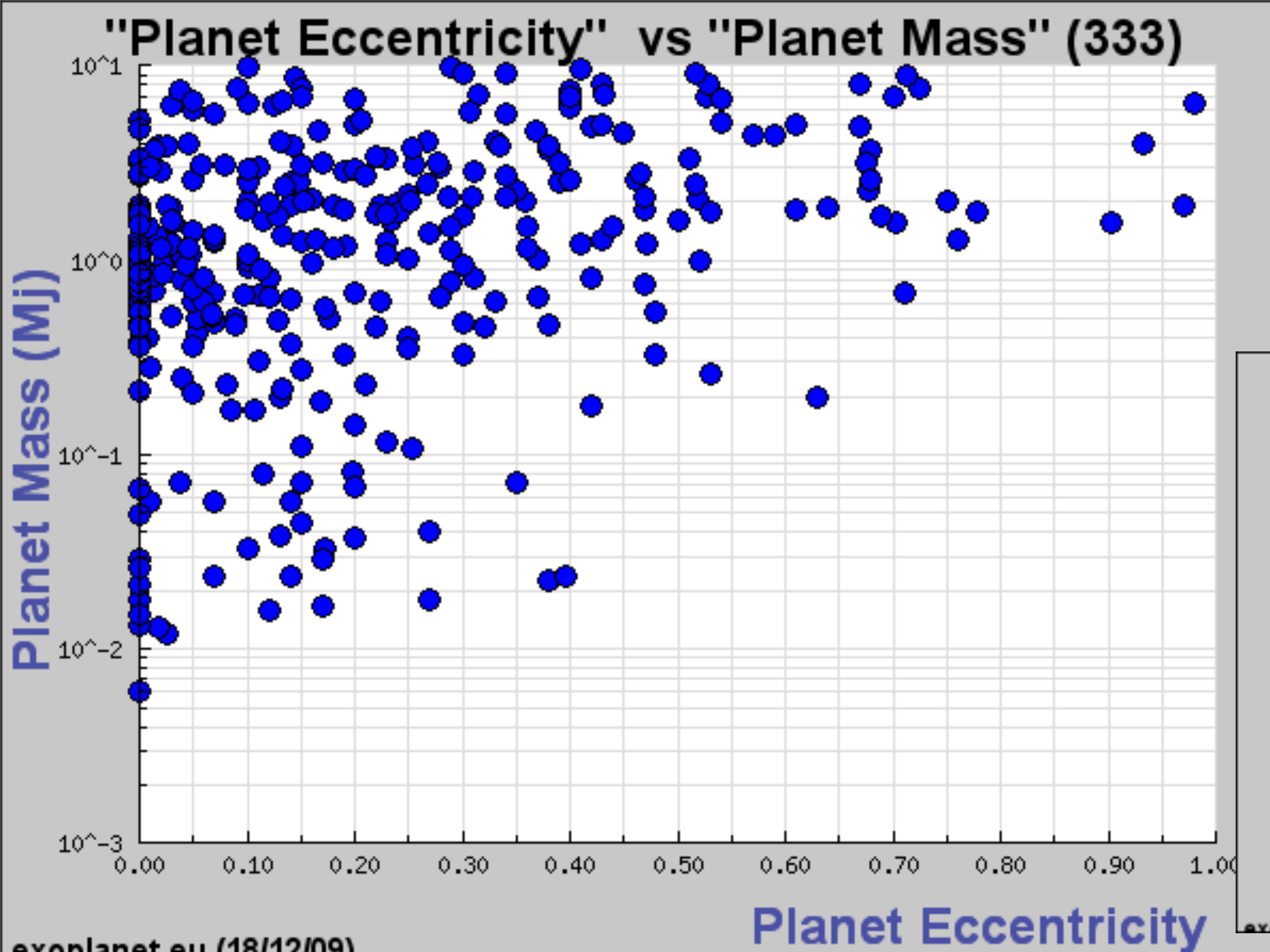
} Intertwined concepts

Variations of orbital elements of terrestrial planet and other objects in a system.

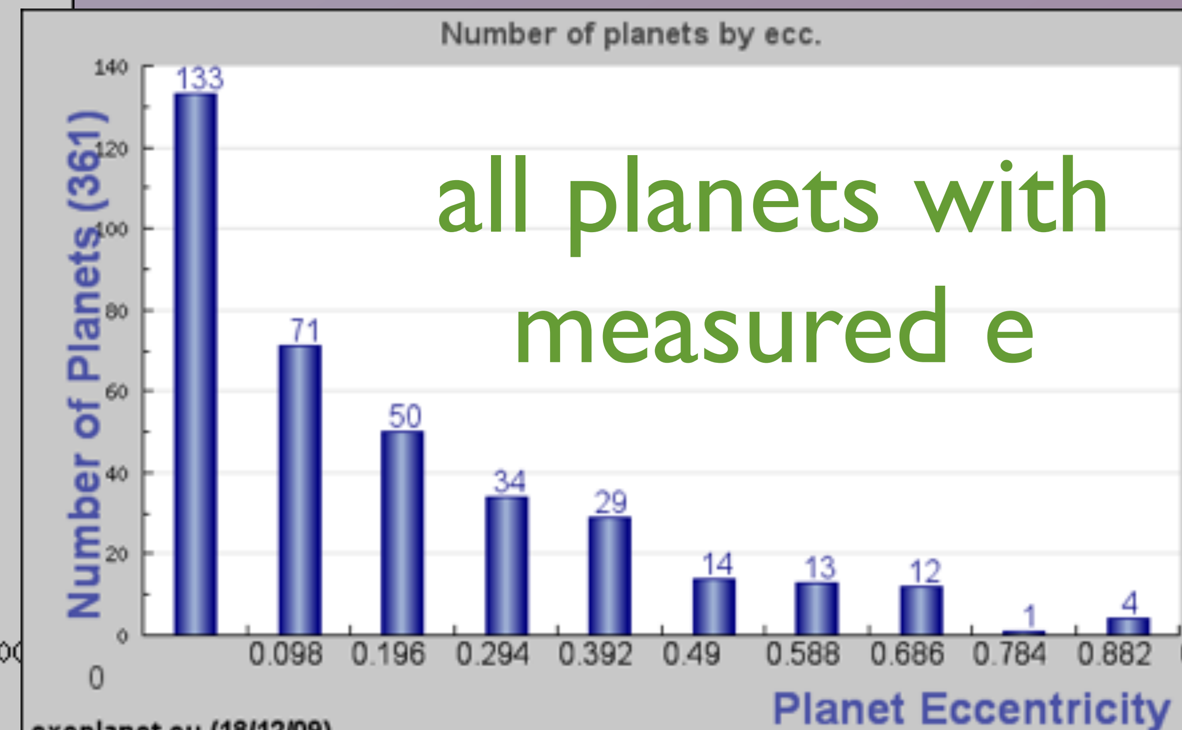


Spatial Resolution Comparison

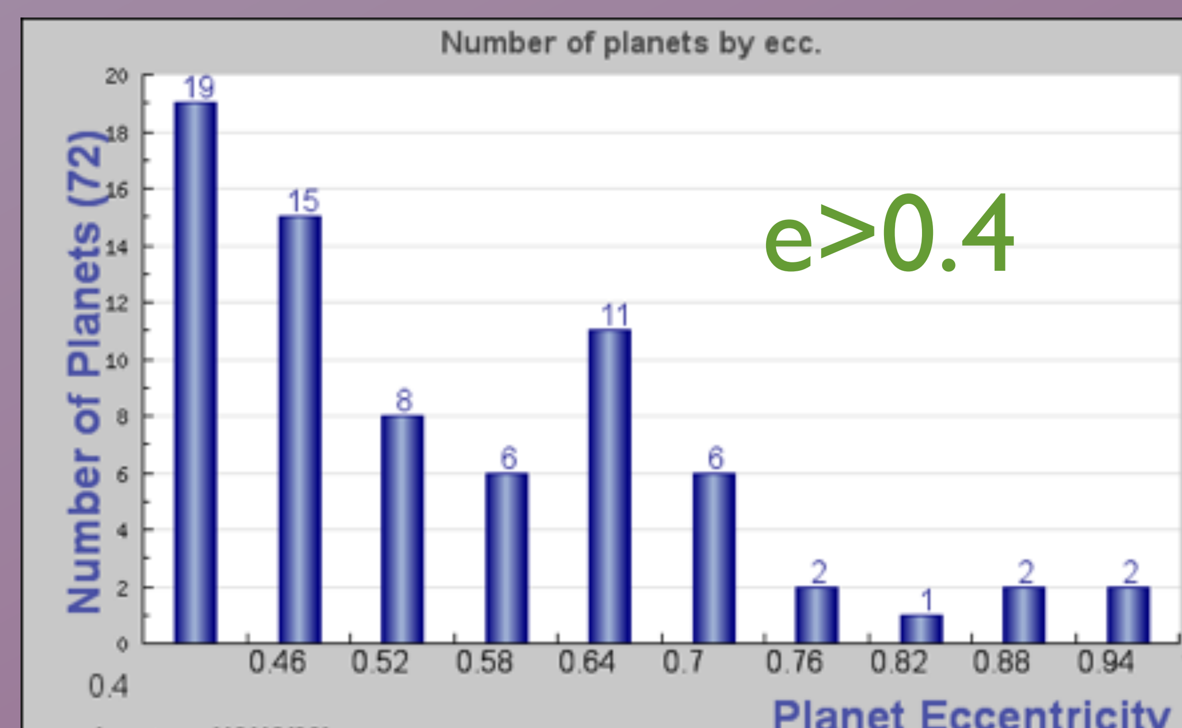




High eccentricity planets are common!



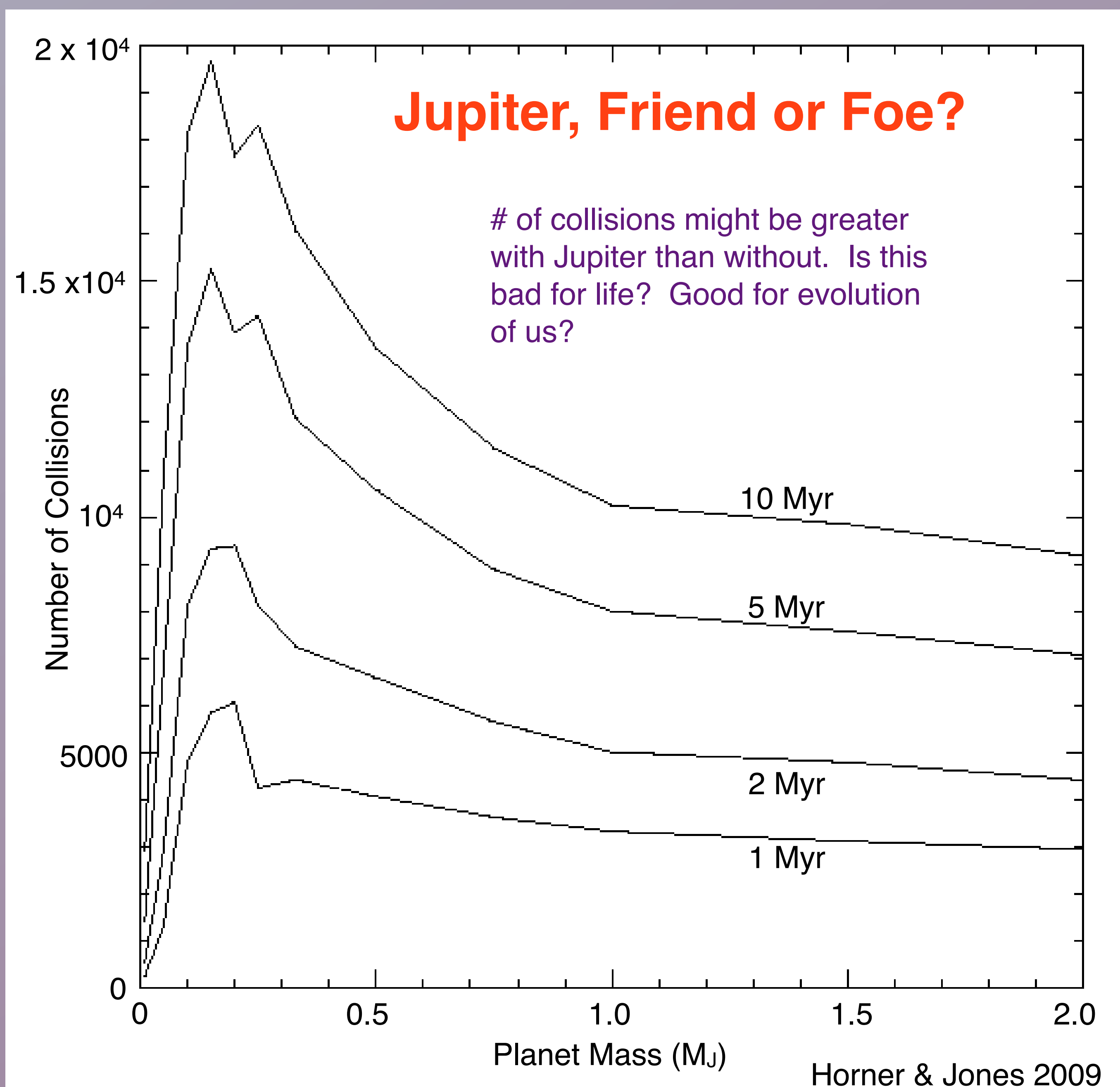
~20%, have e>0.4



Dynamical Habitability

What is the influence of a giant planet on a terrestrial planet's habitability?

Effects on Impact Rate

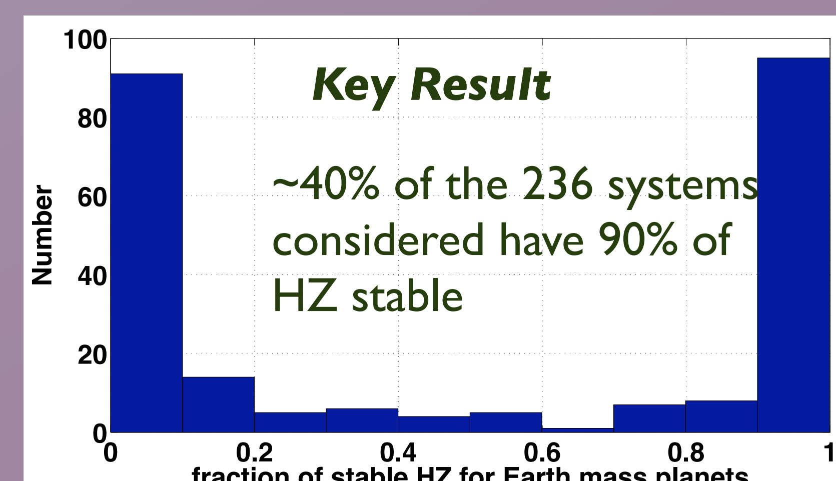


Effects on Orbit Stability

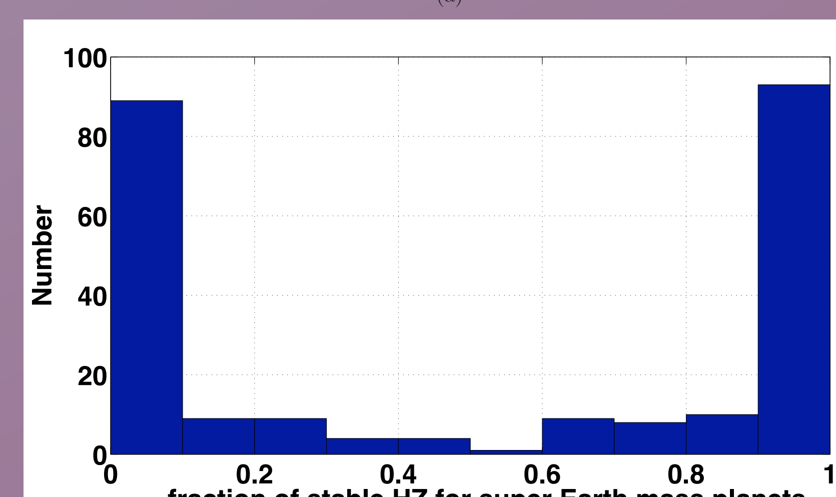
A Jovian companion can excite the eccentricity of a potentially habitable terrestrial planet and can eject planets from the system.

Menou & Tabachnik (2003)

Kopparapu & Barnes (2010)



(a)



Tuesday, September 6, 2011