



Venus, Earth & habitable exoplanetary worlds

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But this conference is about Venus!
Could Venus have been in the habitable zone?

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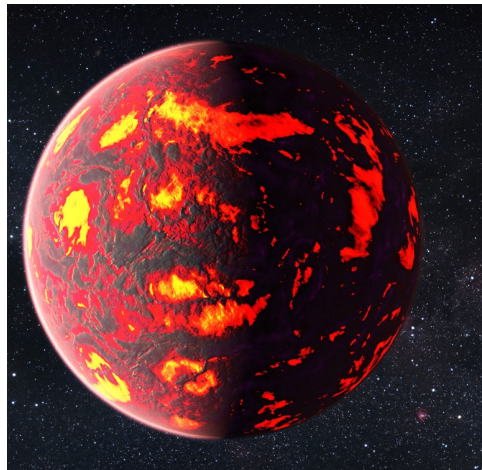
And will the explosion in the discovery of extrasolar planets tell us more?

How could Venus ever be Habitable?!

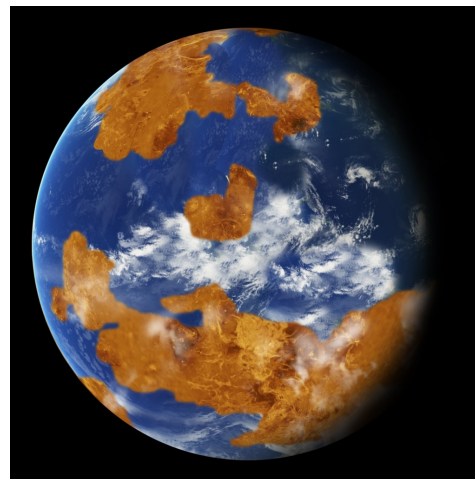
Venus (W/m^2)	Earth (W/m^2)	Ratio
1900 (4.2Ga)	1361 (today)	1.4
2601 (today)		1.9

Two traditional views

Venus
4.5 Ga



~3.5 Ga



- Magma Ocean ~100Myr
- Primordial water lost
- Bone dry for 4+ Gyr
- PV D/H from this epoch

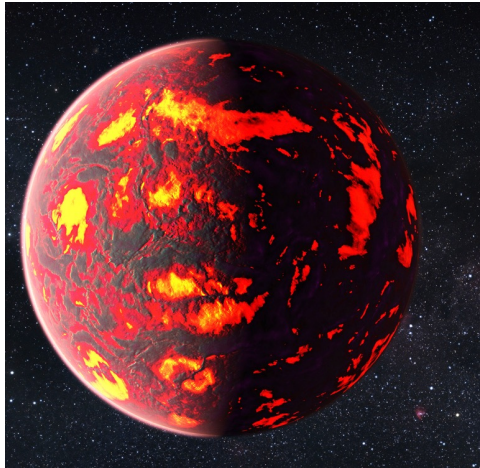
Ingersoll 1969 -> Hamano 2013
Lebrun 2013, Turbet 2021

- Magma Ocean 1-5Myr
- Water condenses on surface
- ~1Gyr 'habitable phase'
- Sun's luminosity increases
 - Runaway greenhouse
 - PV D/H from this epoch

Pollack 1971 -> Grinspoon 2003
& fellow travelers

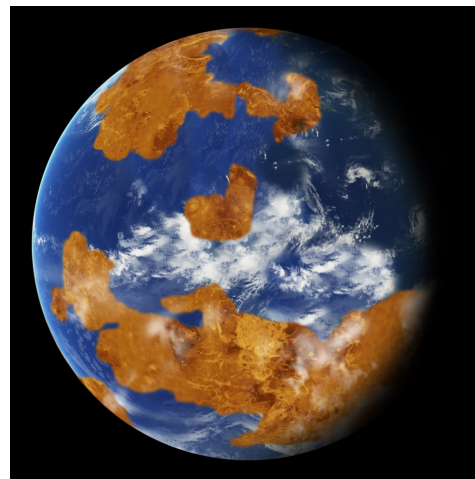
Two traditional views

Venus
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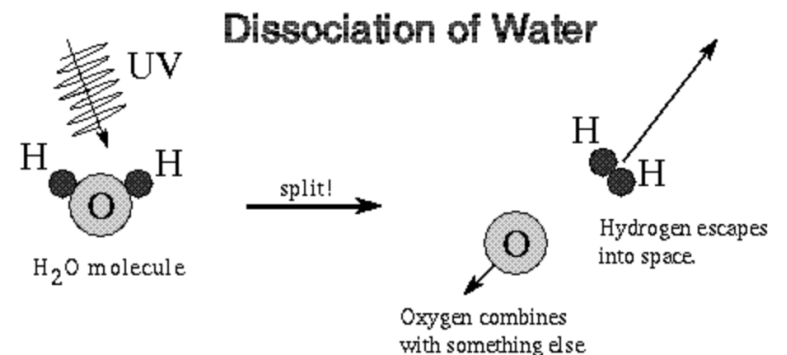


~3.5 Ga

- Explains present day state
- H_2 -> escapes to space
- O_2 absorbed in magma ocean
- Never had plate tectonics
- Why still thick atmosphere!?



- Doesn't explain present day state
- Where is the O_2 ?!
 - Luger & Barnes (2014)
 - Wordsworth & Pierrehumbert (2014)



**Major problem to distinguish
Between the two EARLY scenarios!**

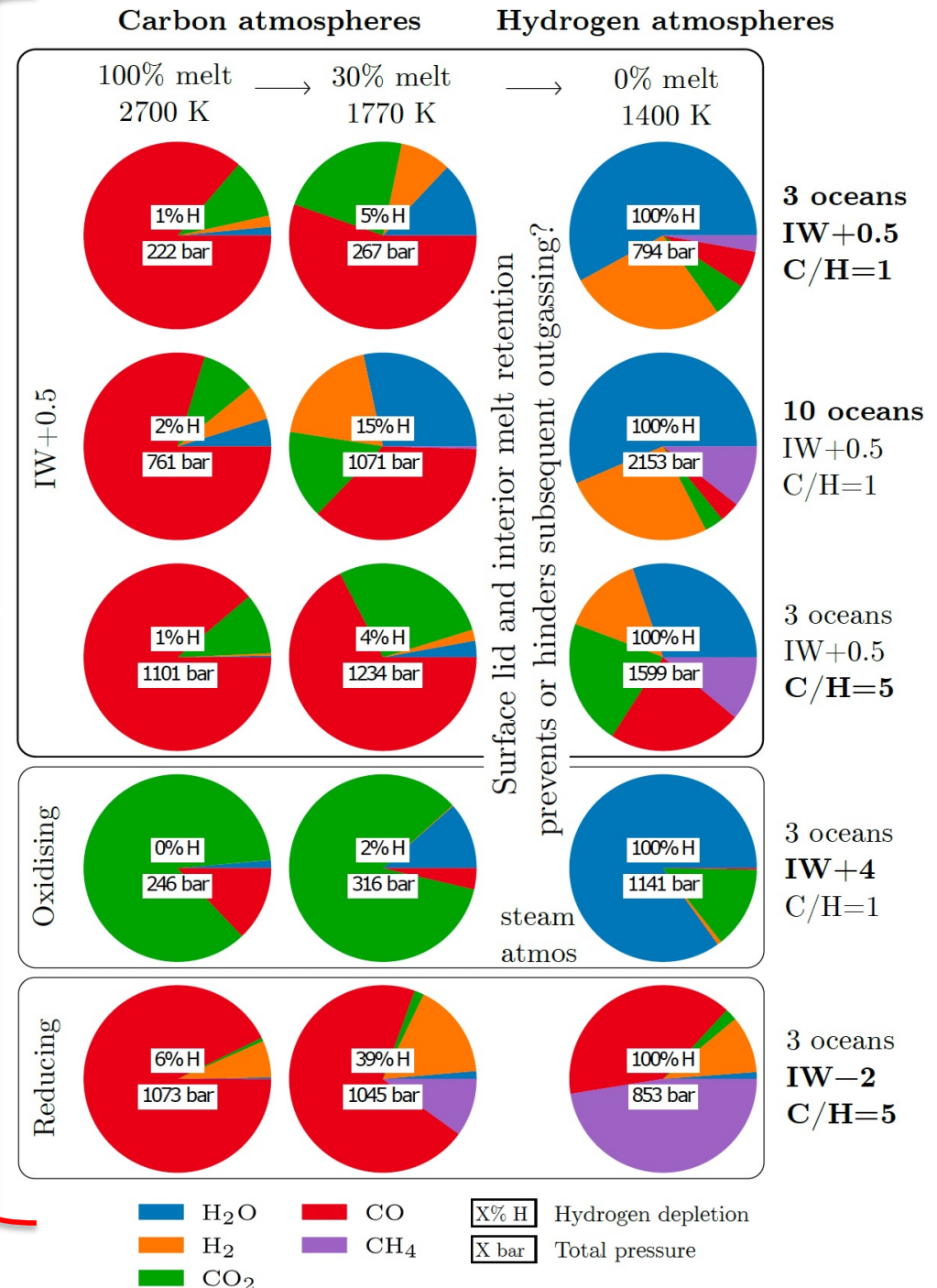
Highly unconstrained parameter space

**“Retention of water in terrestrial
magma oceans and carbon-rich
early atmospheres”**

Bower et al. (2022) PSJ 3:93

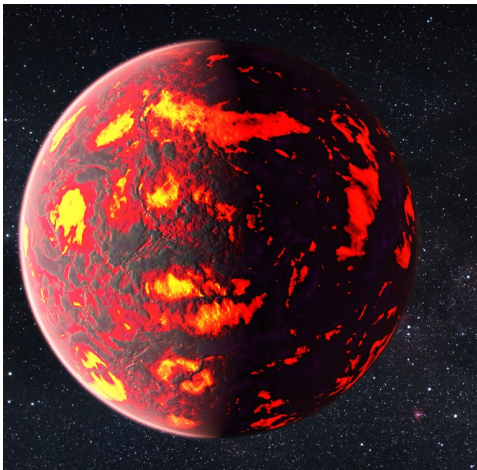
**No compositional constraints on
the magma ocean atmosphere**

**DAVINCI mission and
Young Exoplanets may help**

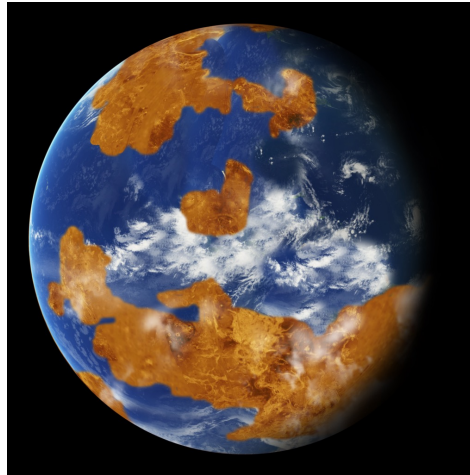


Newer view

Venus
4.5 Ga



Happy Habitable Venus
4.2->1.0 Ga



Hothouse Venus
~1.0 Ga -> Today



- **Assume** short lived magma ocean or late water delivery
- **Long?** period of habitability (Volatile cycling/plate tect)
- *Transition: How?*

Grinspoon & Bullock 2003, Abe 2011, Leconte 2013, Yang 2014, Way 2016, Way 2021
Not so many fellow travelers

Newer view

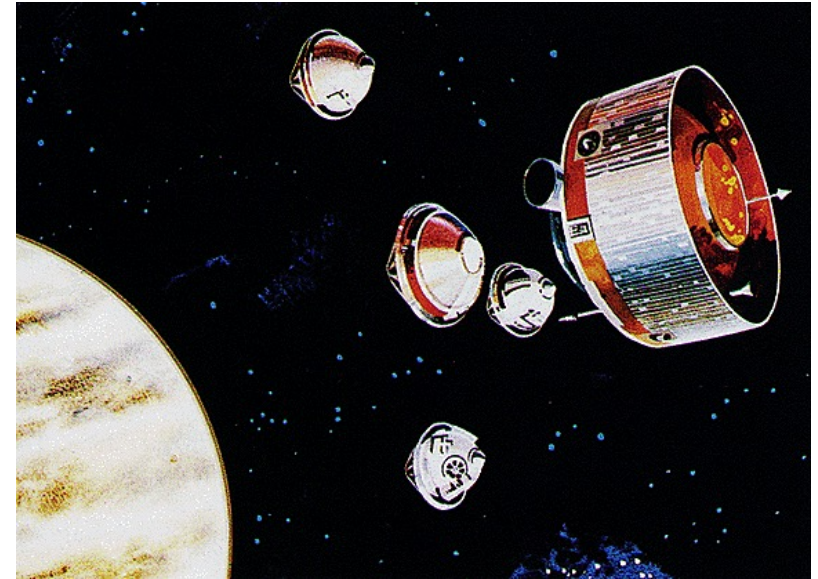
Is there evidence for surface liquid water
in Venus' history?

If yes: then **clouds** in concert with **rotation rate** may
have played a key role in Venus' climate

Evidence for surface liquid water on Venus:

- PV High D/H ~ 150 x Earth's
 - H₂O loss (type/timescale unknown)
- Watson (2007) [⁴⁰Ar]
- Galileo/NIMS (Hashimoto 2008)
 - Highlands **felsic** rocks -> **Granitic?**
- Nikolayeva 1990, Shellnut 2019
 - Venera 8 found greenstone belt?
- Khawja, Ernst et al. 2020
 - Fluvial Erosion in tesserae?
- **DAVINCI, VERITAS, Envision**

NASA Pioneer Venus (1978)



Soviet Venera 13

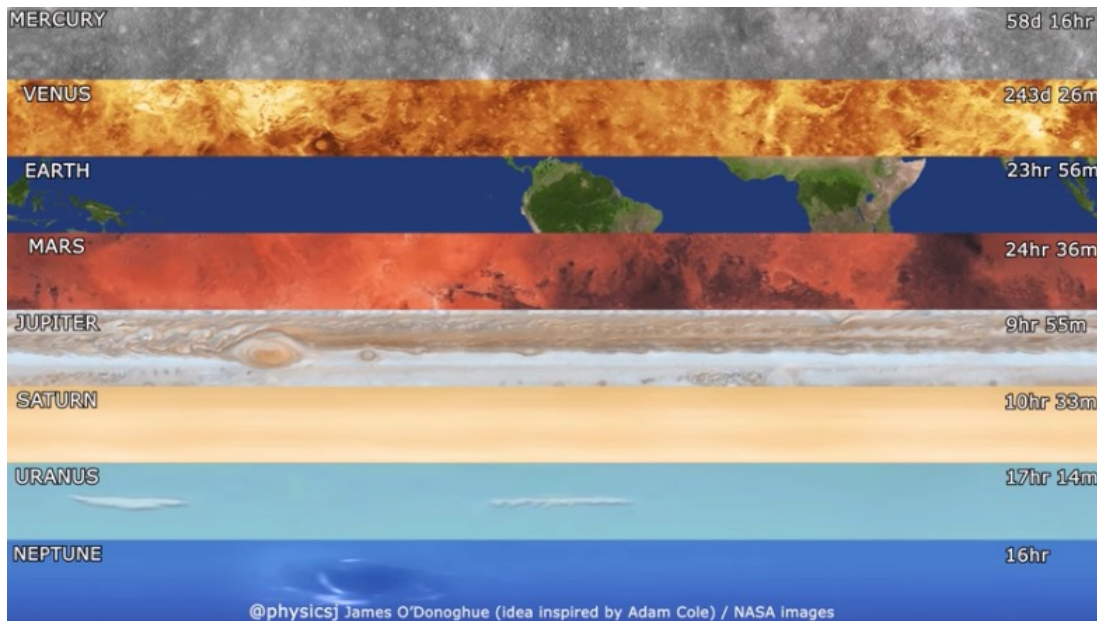


Newer view Continued

Let's move on to clouds:



and then
rotation rate



Climatic Importance of Clouds

(Or how to keep your world **habitable!**)

Jim Pollack (1971) Icarus
 “A Nongrey Calculation of the
 Runaway Greenhouse:
 Implications for Venus' Past and
 Present”. << 1-D Climate Model >>

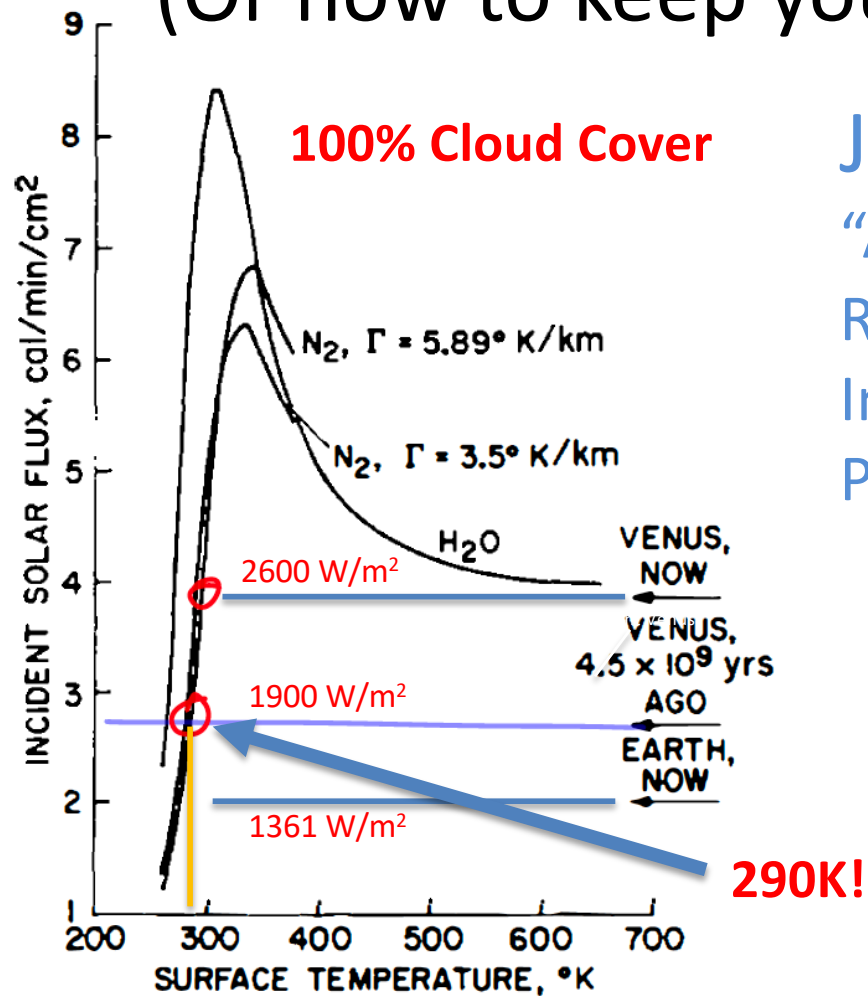
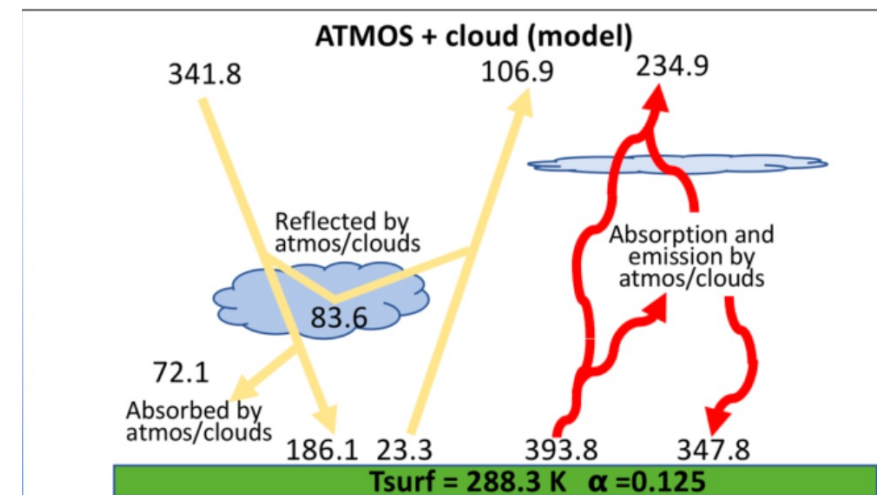


FIG. 5. Surface temperature as a function of the amount of incident solar flux for the same models used in Fig. 4, but with a **100% cloud cover**.

Why??

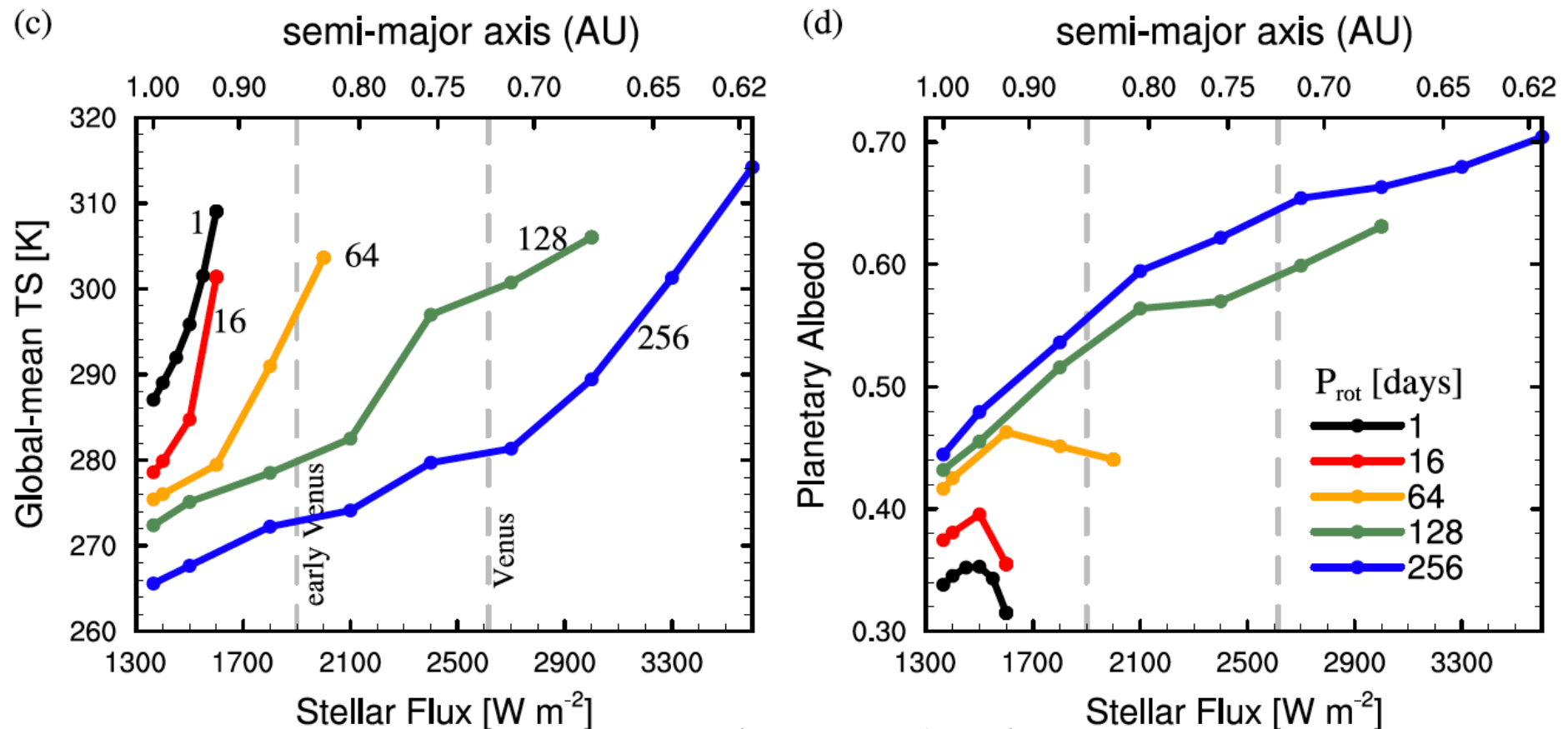


Climatic Importance of Clouds

(43 years later ~100% cloud cover)

Yang et al. 2014 ApJL 787

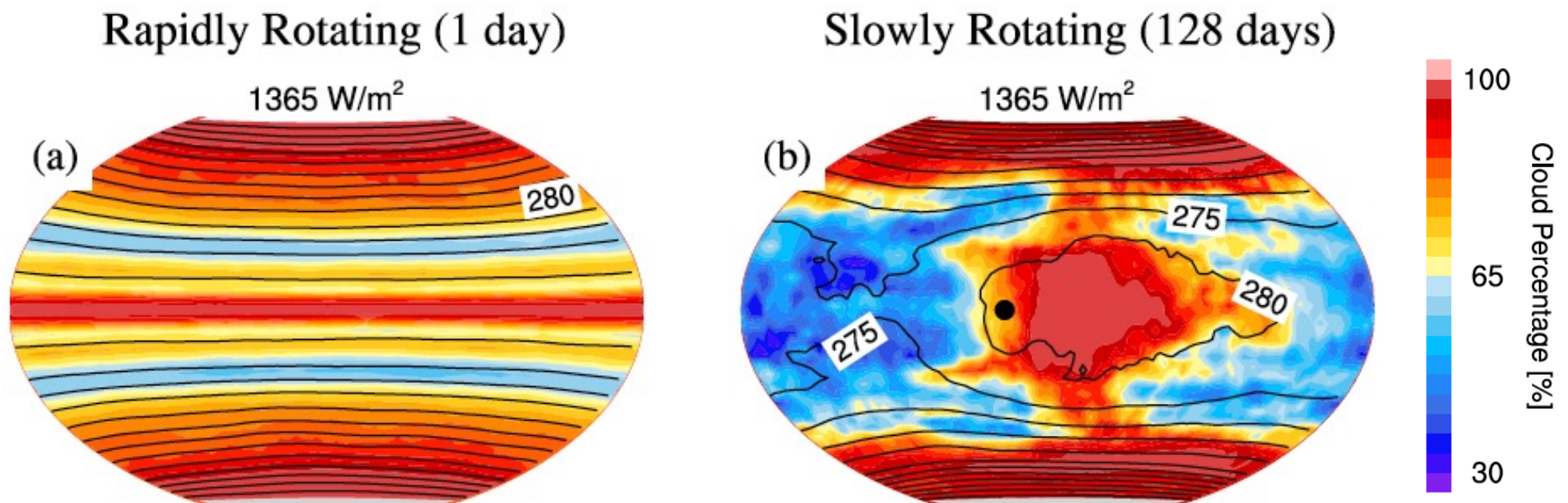
Strong Dependence of the inner edge of the habitable zone on planetary rotation rate



Climatic Importance of Clouds

Yang et al. 2014 ApJL 787

Strong Dependence of the inner edge of the habitable zone on planetary rotation rate



What was Venus' early rotation rate?

Was it rotating slowly enough??

Many ways to make Venus a slow/retrograde rotator with 'odd' ($-2.6/177.4$) obliquity:

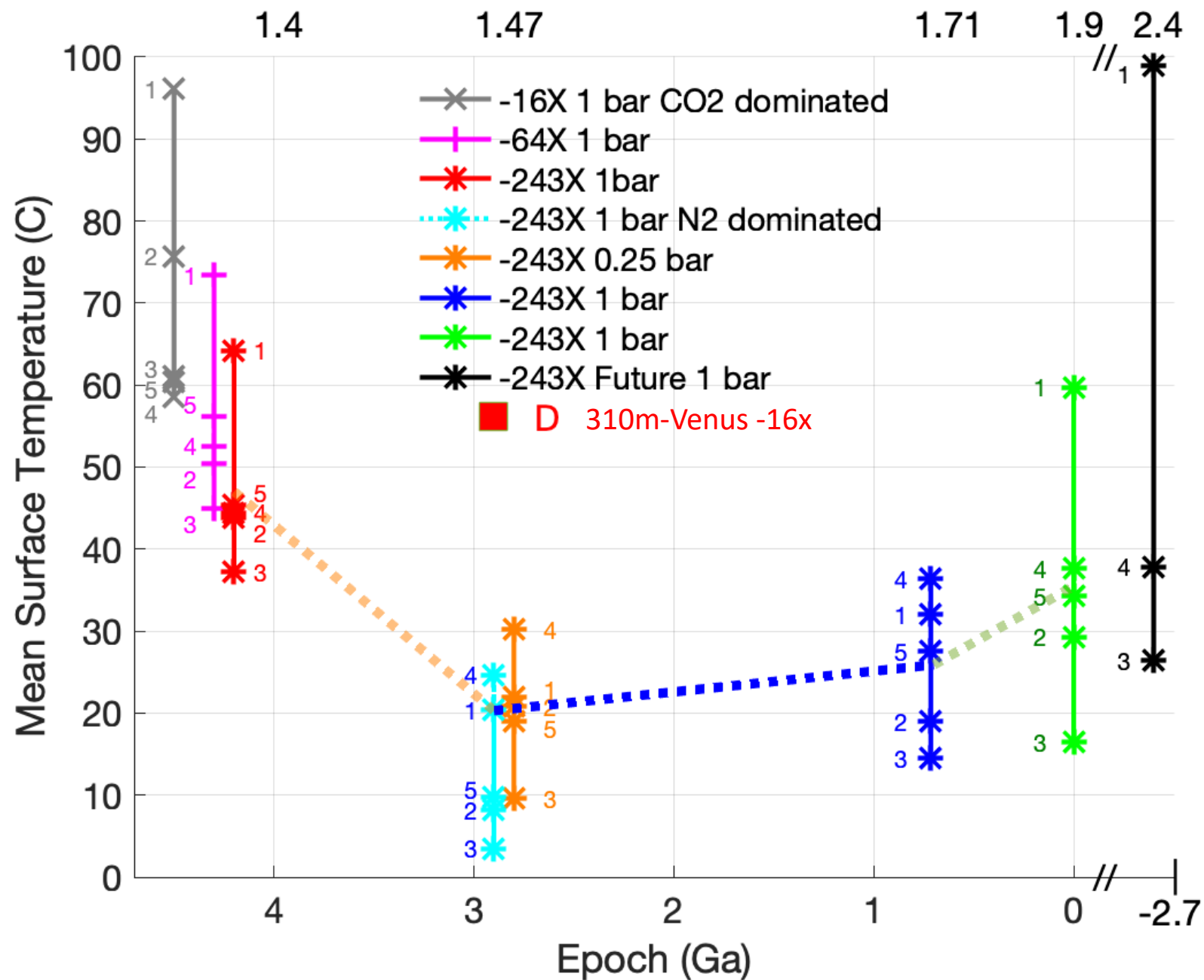
- 1.) Large Impactor
- 2.) Solid Body Tidal Dissipation
- 3.) Core-Mantle Friction
- 4.) Atmospheric Tides
- 5.) Ocean Tidal Dissipation

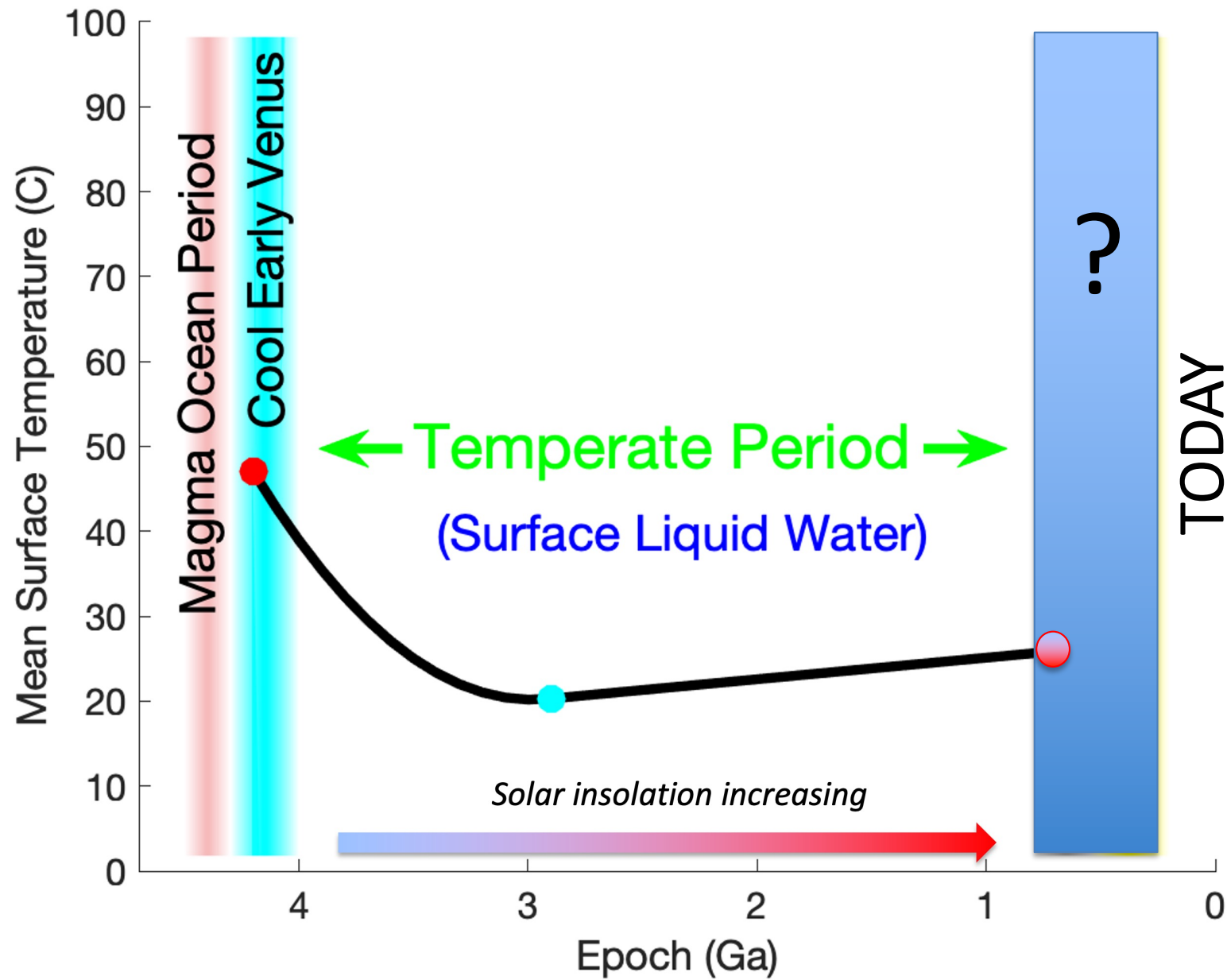
**There are several way for Venus being a
slow rotator for much of its history**

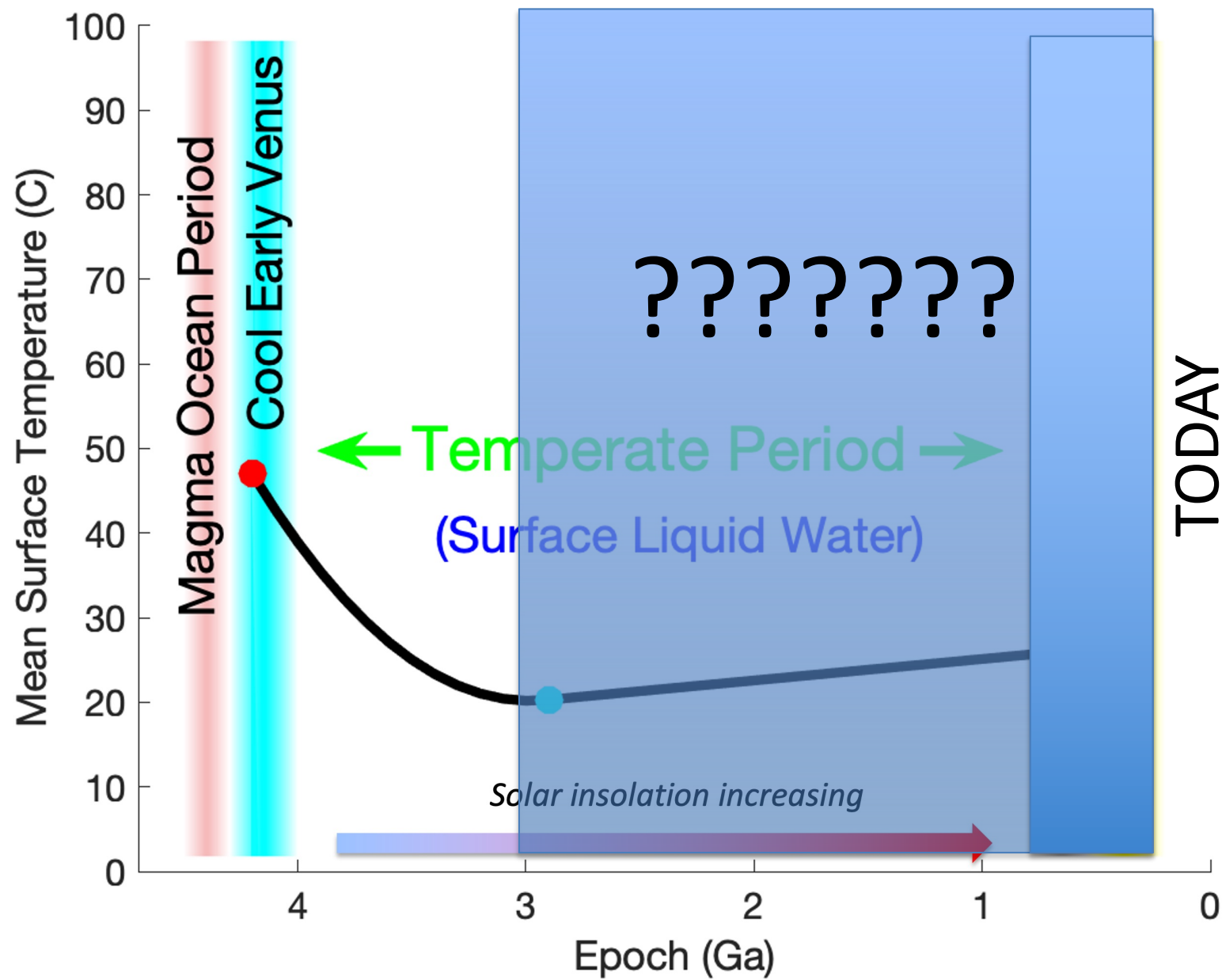
Can exoplanetary studies help confirm?

**Let's test Venus habitability with
assumptions above.**

We'll use the ROCKE-3D Climate Model







Models Show Venus could have been habitable.

But (at least) three questions remain:

1.) How long might it have been habitable?

a.) Longevity of Volatile Cycling sets limits:

b.) Water → DAVINCI, how long was it around?

Models Show Venus could have been habitable.

But (at least) three questions remain:

1.) How long might it have been habitable?

2.) What caused the “Great Climate Transition”
from temperate to hot-house?

Could it have been volcanism? (new)

Overlapping Large Igneous Provinces (e.g. Siberian Traps)



Large-scale Volcanism and the Heat Death of Terrestrial Worlds

M. J. Way^{1,2,3} , Richard E. Ernst^{4,5}, and Jeffrey D. Scargle⁶ 

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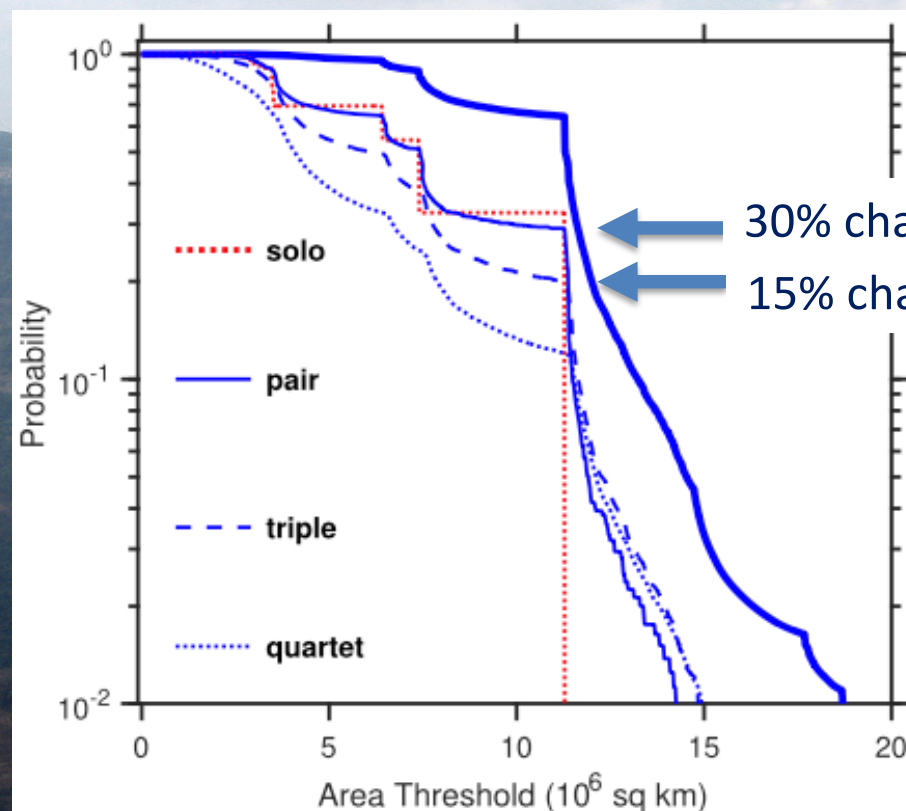
³GSFC Sellers Exoplanet Environments Collaboration, NASA Goddard Space Flight Center, MD, USA

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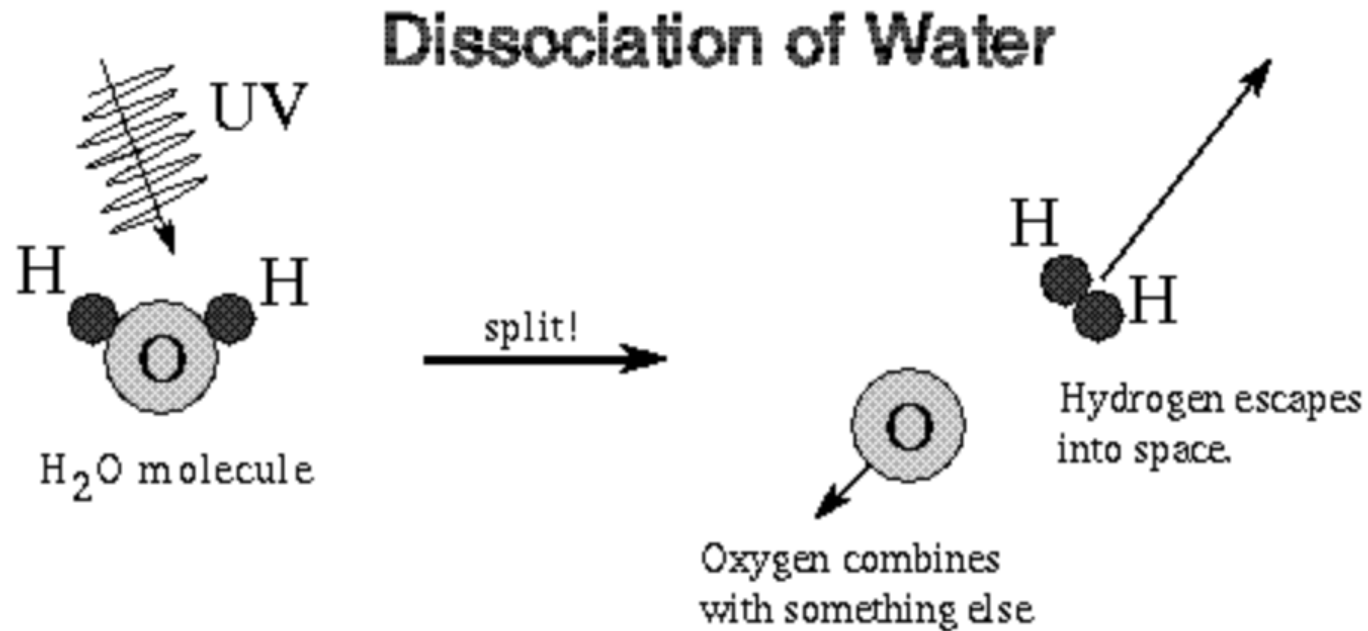
If it was Large Igneous Provinces can we find
their remains in VERITAS/Envision images?

Models Show Venus could have been habitable.

But (at least) three questions remain:

- 1.) How long might it have been habitable?
- 2.) What caused the “Great Climate Transition”
- 3.) Where is the ocean remnant oxygen?

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Where is the O_2 ?!

- Luger & Barnes (2014)
- Wordsworth & Pierrehumbert (2014)

3.) Where is the ocean remnant oxygen?

What about atmospheric loss to space?

- Our diffusion limited escape calculations (Hydrogen only): 3×10^5 yrs $\rightarrow$ 11 Gyr
- Persson et al. 2020 GRL: Venus can have only lost ~ 30 cm of water via atmospheric escape of O^+
 - Ion escape alone cannot remove large water inventory
 - **Requires removal of O^+ via other means!**

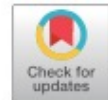
3.) Where is the ocean remnant oxygen? What about surface absorption?

“We propose that the large-scale resurfacing evident on Venus today, which took place over hundreds of millions of years, is a possible effective answer.” -- Way & Del Genio (2020)

PNAS

RESEARCH ARTICLE

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES



Narrow range of early habitable Venus scenarios permitted by modeling of oxygen loss and radiogenic argon degassing

Alexandra O. Warren^{a,1}  and Edwin S. Kite^a 

Can Venus inform Exoplanetary studies?

Can Exoplanetary studies inform Venus?

Space Science Reviews (2023) 219:13
<https://doi.org/10.1007/s11214-023-00953-3>



Synergies Between Venus & Exoplanetary Observations

Venus and Its Extrasolar Siblings

M.J. Way^{1,2} · Colby Ostberg³ · Bradford J. Foley⁴ · Cedric Gillmann⁵ ·
Dennis Höning^{6,7} · Helmut Lammer⁸ · Joseph O'Rourke⁹ · Moa Persson¹⁰ ·
Ana-Catalina Plesa¹¹ · Arnaud Salvador^{12,13,14} · Manuel Scherf^{8,15,16} · Matthew Weller¹⁷

Can Venus inform Exoplanetary studies?

Can Exoplanetary studies inform Venus?

Exo-Venuses: They exist & we can characterize them
(JWST, ELT, HWO, etc.).

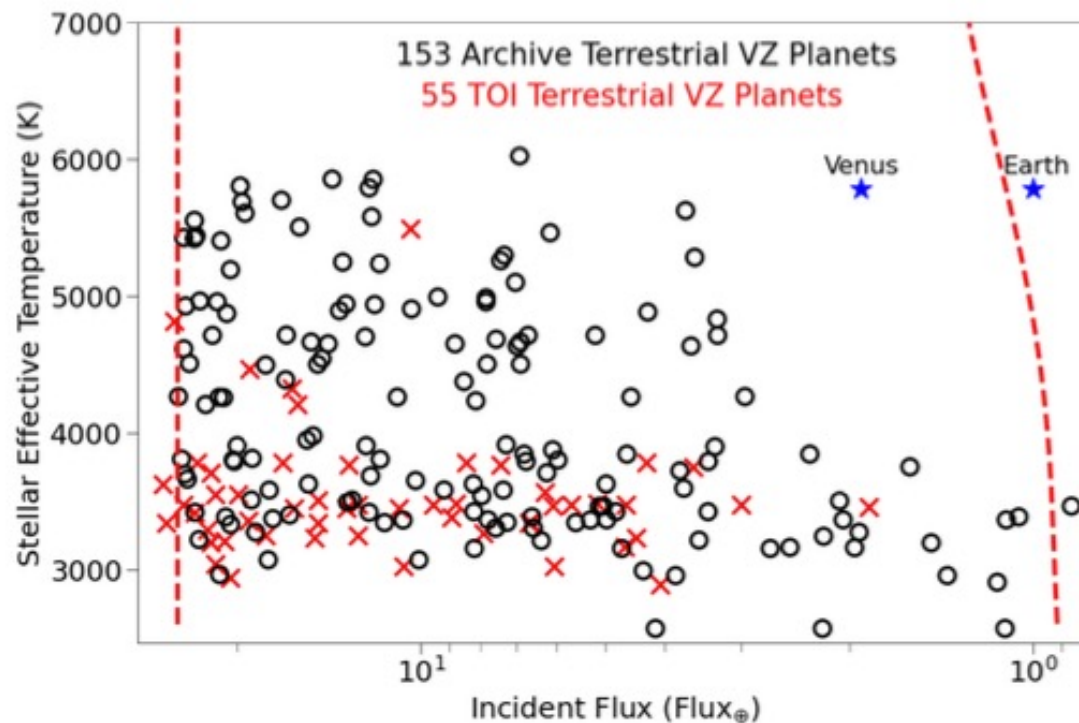


Fig. 1 The locations of terrestrial VZ planets ($R_p < 1.5 R_{\oplus}$) from the NASA Exoplanet Archive and TOI list in reference to the VZ as a function of planetary insolation flux. Earth and Venus are shown for reference

Can Venus inform Exoplanetary studies?

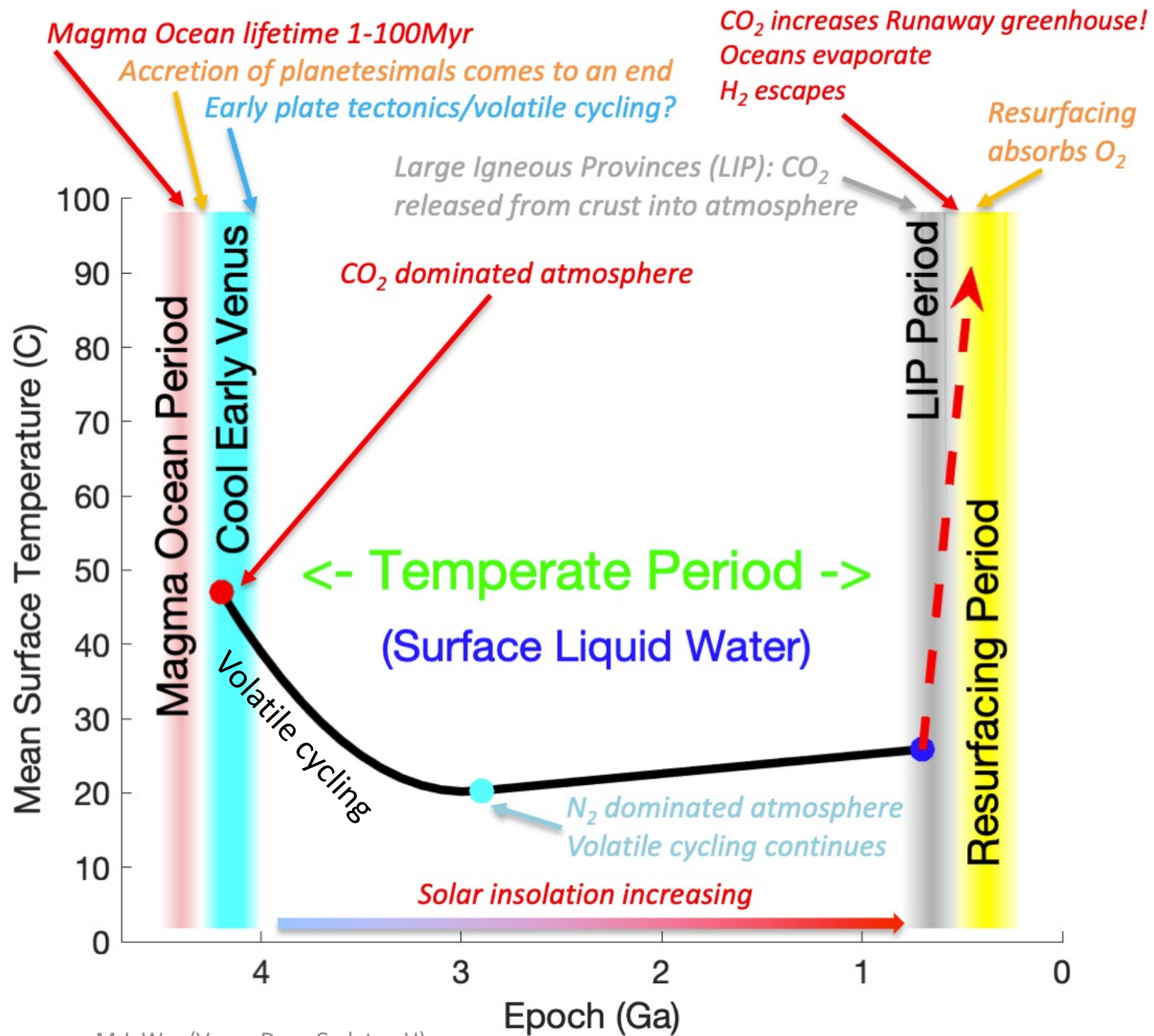
Can Exoplanetary studies inform Venus?

2.1 Volatile Cycling and Weathering on Venus through time

2.2 Venus' Magnetic Field (or lack thereof?)

2.3 Atmospheric Escape and Importance of a Magnetic Field

2.4 Critical Dependence of and on Planetary Thermal History



Conclusions

- Venus may have had habitable conditions
- Need Venus in-situ observations to confirm its geologic & volatile history
- We need ground truth (DAVINCI) imaging for the IR imagers on VERITAS/Envision + radar to characterize any LIPs or ancient aqueous features.
- Exoplanets WILL inform Venus' early history. Earth AND Venus WILL inform Exoplanets.

Optimistic Venusian Stromatolites 3.5Ga ;-)



Evidence of 3.5 billion-year-old bacterial ecosystems found in Australia