Surface-interior exchange on rocky and icy planets

Edwin Kite

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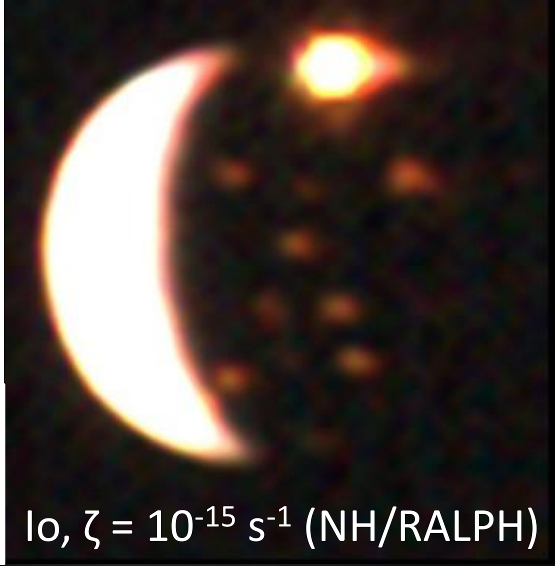
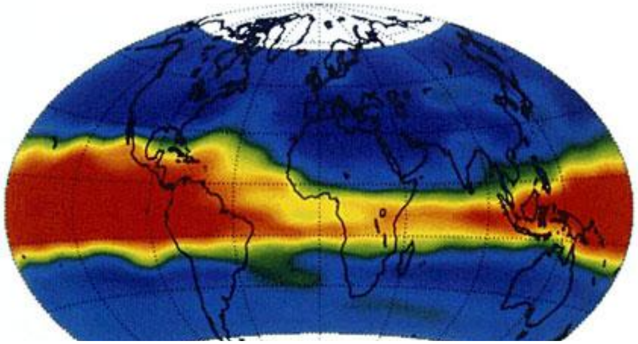


Io, $\zeta = 10^{-15}$ s^{-1} (NH/RALPH)

Enceladus, $\zeta = 10^{-16}$ s^{-1} (Cassini/ISS)



Earth, $\zeta = 10^{-18}$ s^{-1} (Pinatubo Plume)

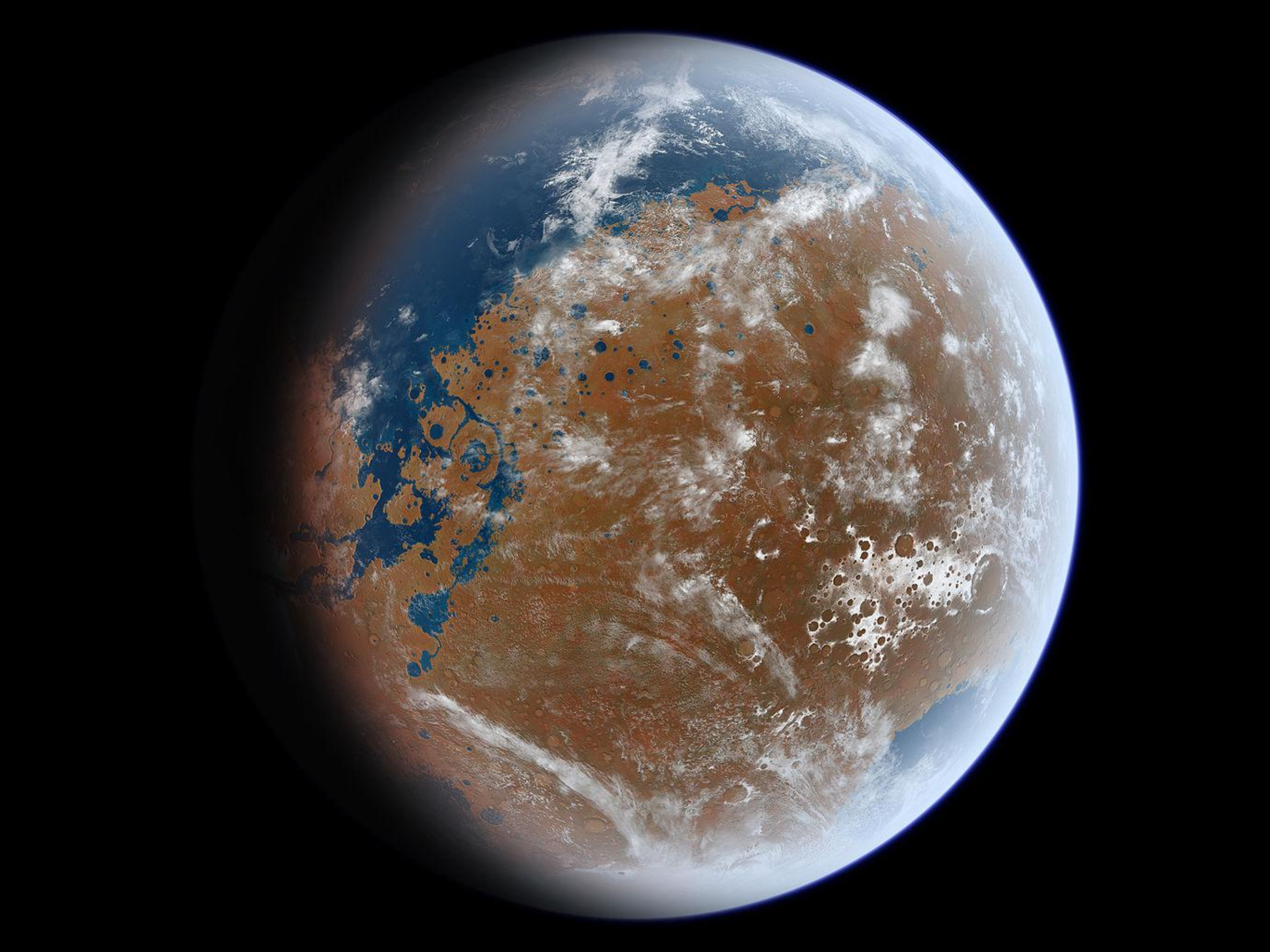
Testability requires linking processes of interest (mineralogical, metabolic, …) to atmospheric properties that we can **measure**; this requires basic theory for **surface-interior exchange rate (ζ , s^{-1})** that is currently undeveloped

Today: What can we infer about ζ on planets in general from the 3 data points in hand?


If volcanism ceased, Earth's biosphere would become undetectable over interstellar distances within 1 Myr

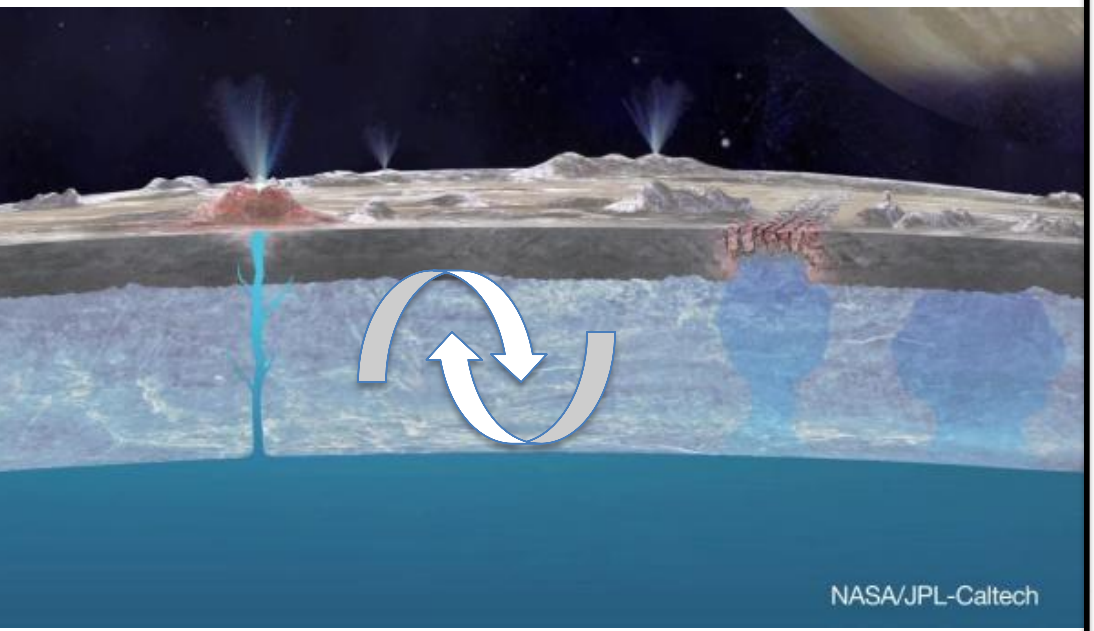
J. Guarinos


Kasting et al. Icarus 1993
Kite, Gaidos & Manga ApJ 2011
Maher et al. Science 2014
Image: C.-T. Lee



High ζ : Potentially Habitable Near-Surface Ocean

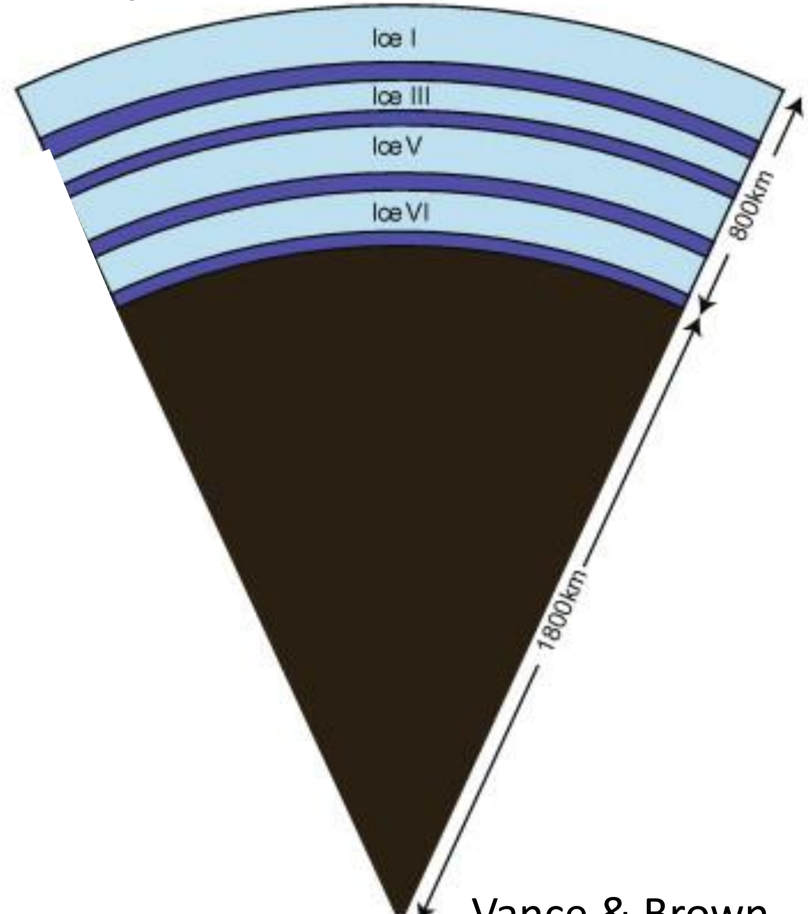
Europa



e.g. Hand et al. Astrobiology 2007
Sleep & Zoback, Astrobiology 2007

Low ζ : Sterile Near-Surface Ocean

Ganymede



Vance & Brown, Geochim. Cosmochim. Acta 2013

Understanding surface-interior exchange (ζ) after the epoch of formation is necessary to understand super-Earth atmospheres, H_2/H_2O ratios, and habitability

Understanding surface-interior exchange (ζ) after the epoch of formation is necessary to link hypotheses to measurable properties

- How much H_2 can be produced $>10^8$ yr after formation?
- Short-period rocky planet atmospheres
- Climate stabilization on planets with modest atmospheres *Kasting et al. 1993; Kite et al. 2011; Kopparapu et al. 2013*.
- Nutrient resupply for chemosynthetic biosphere on planets with atmospheres that are opaque in the visible
- Testability via short-lived species e.g. SO_2
- Loss rates vary between gases, so atmospheres could be a mix of gases left over from accretion and those replenished by volcanism.

Open questions

How does silicate volcanism scale to Super-Earths?
Earth, $\zeta = 10^{-18}\ s^{-1}$**:**

Effect of mass and galactic cosmochemical evolution minor; age moderately important; thickness of volatile overburden critical.

How do rocky planets dispose of extreme internal heating?
Io, $\zeta = 10^{-15}\ s^{-1}$**:**

Heat-pipe volcanism simply relates ζ *to heat input; magma planet implications?*

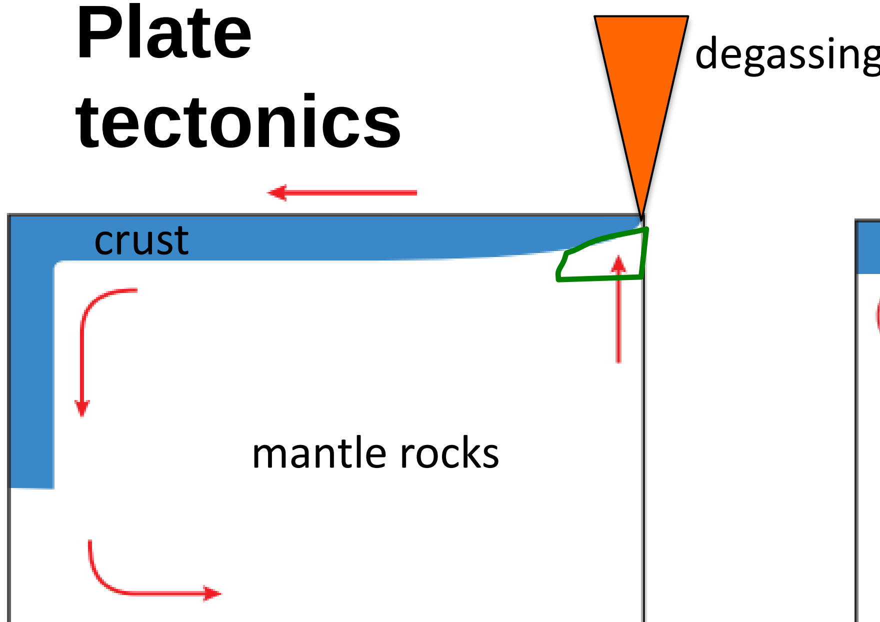
What governs the rate of cryo-volcanism?
Enceladus, $\zeta = 10^{-16}\ s^{-1}$**:**

Earth, $\zeta = 10^{-18}\ s^{-1}$: partial melting by decompression

Planet's mantle is cooled by **conduction** through a thin boundary layer <u>lithosphere</u>
Decompression **(partial) melting** of mantle to form a <u>crust</u>

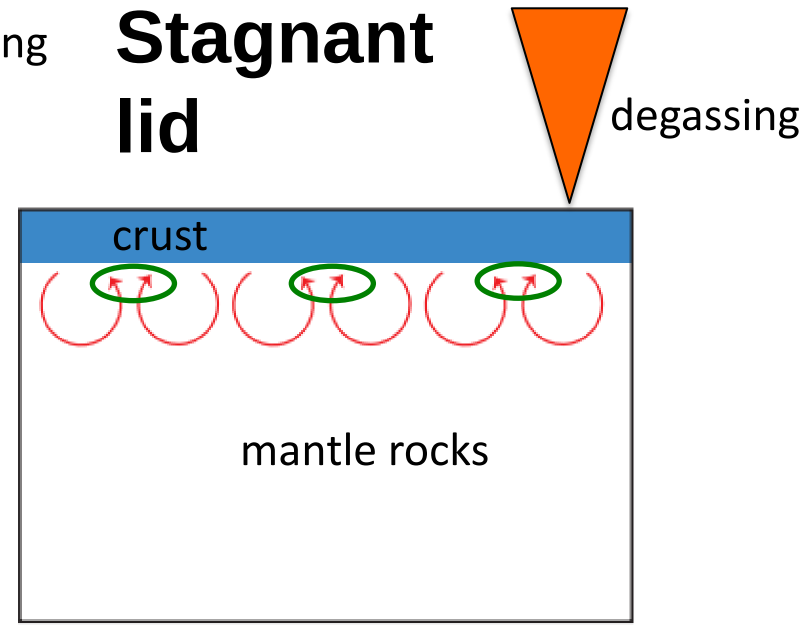
Volatiles partition efficiently into even small-% melts

Plate tectonics



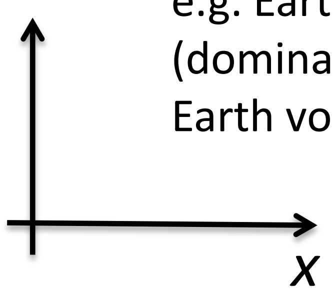
e.g. Earth oceanic crust (dominates Earth heat flow and Earth volcanism)

Stagnant lid



e.g. Earth continents
Venus, Mars …

Partial melt zones



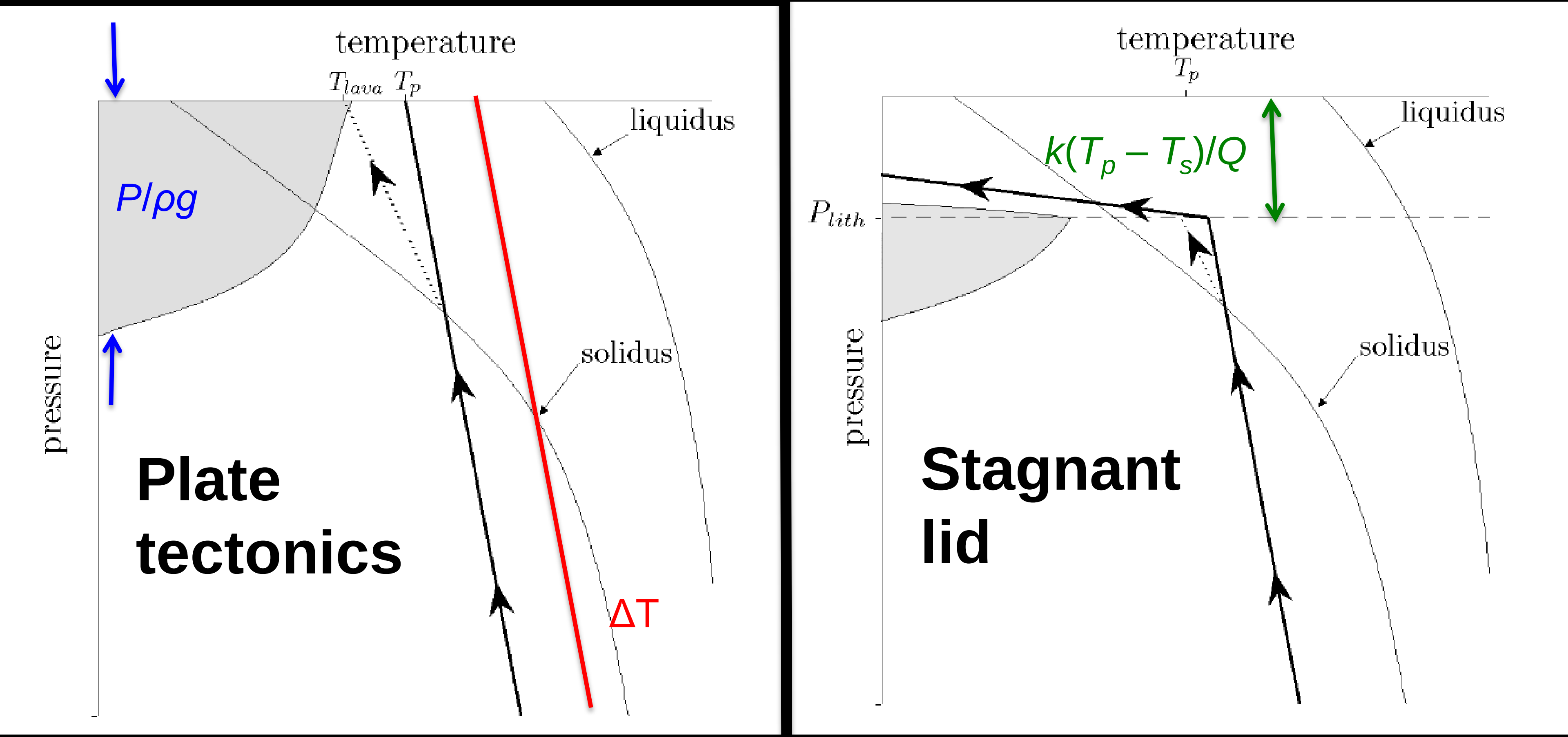
Korenaga, Annual Reviews EPS, 2013

Kite, Manga & Gaidos, ApJ, 2009
Tackley et al., IAU Symp. 293, 2014
Stamenkovic, 2014

- How does melt flux vary with time and planet mass?
- What is the role of galactic cosmochemical evolution?
- Can volcanism occur on volatile-rich planets?

How Earth-like melting scales to Super Earths

Kite, Manga & Gaidos ApJ 2009



Melt fraction

Mantle parcel ascending beneath mid-ocean ridge

Mantle parcel ascending beneath stagnant lid

Simple thermal model and simple melting model

Kite, Manga & Gaidos ApJ 2009

$$\frac{\partial T}{\partial t} = \frac{H}{c} - k_1 (T_m - T_s)^{(1+\beta)} \exp\left(\frac{-\beta A_0}{T_m}\right)$$

where

$$k_1 = \frac{Ak}{c d M_{\mathrm{mantle}}} \left(\frac{\alpha g d^3}{\kappa \nu_0 Ra_{\mathrm{cr}}}\right)$$

Thermal models tuned to 7km thick oceanic crust on today's Earth

Cooling rate 50-100 K/Gyr

Korenaga AREPS 2013

Assume:

Small residual porosity

Melts separate quickly

X(*T*,*P*):

McKenzie & Bickle, 1988

Katz et al., 2003

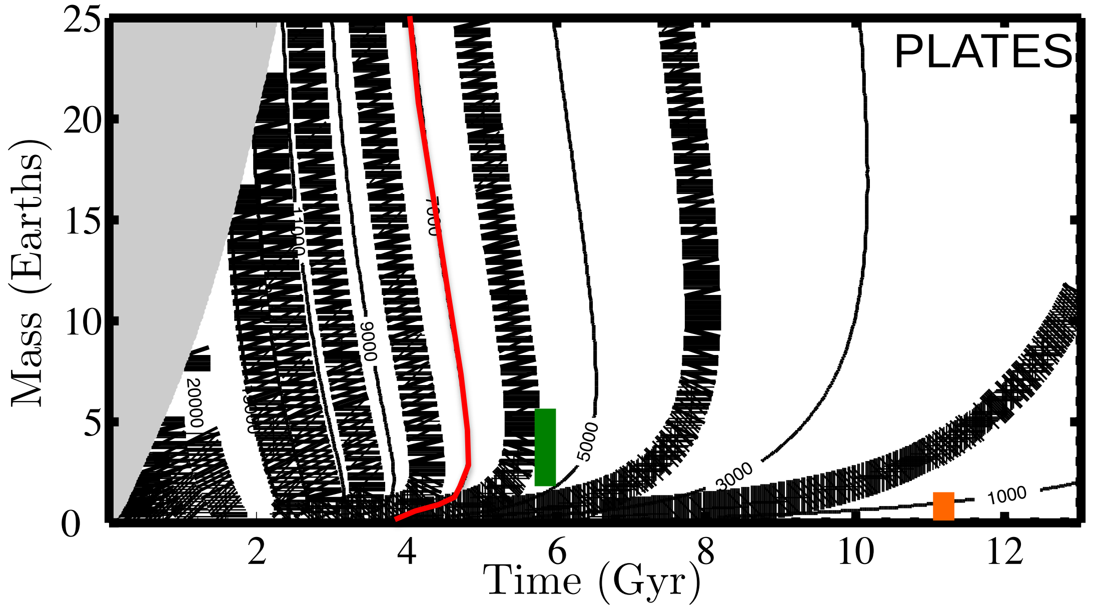
pMELTS (Asimow et al.,2001)

$$P_{\mathrm{crust}} = -\int_{P_o}^{P_f} X(T, P)\, dP$$

$$T(P) = T(P + \delta P) - \left(\frac{\partial V}{\partial S}\right) \delta P + \left(\frac{\partial X}{\partial P}\right) L$$

Super-Earth volcanism

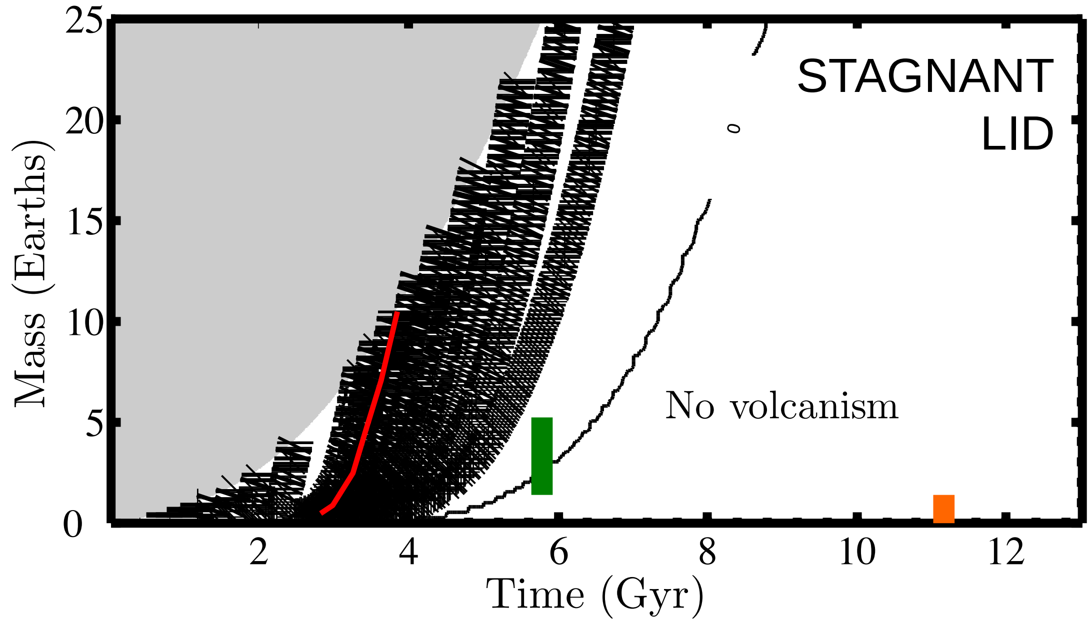
Kite, Manga & Gaidos, ApJ, 2009



Earth today

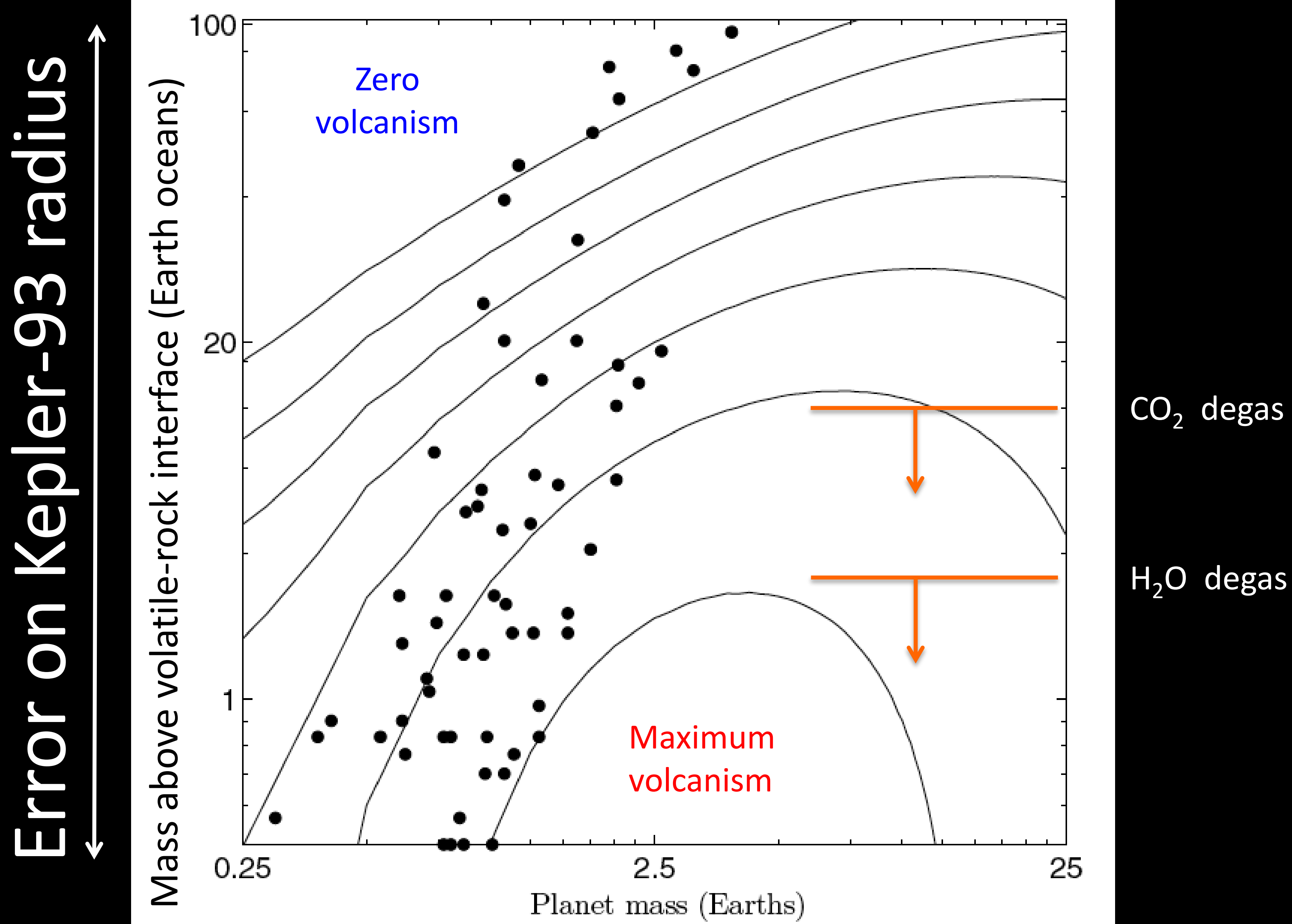
Kepler-444

Tau Ceti



Galactic cosmochemical evolution unimportant

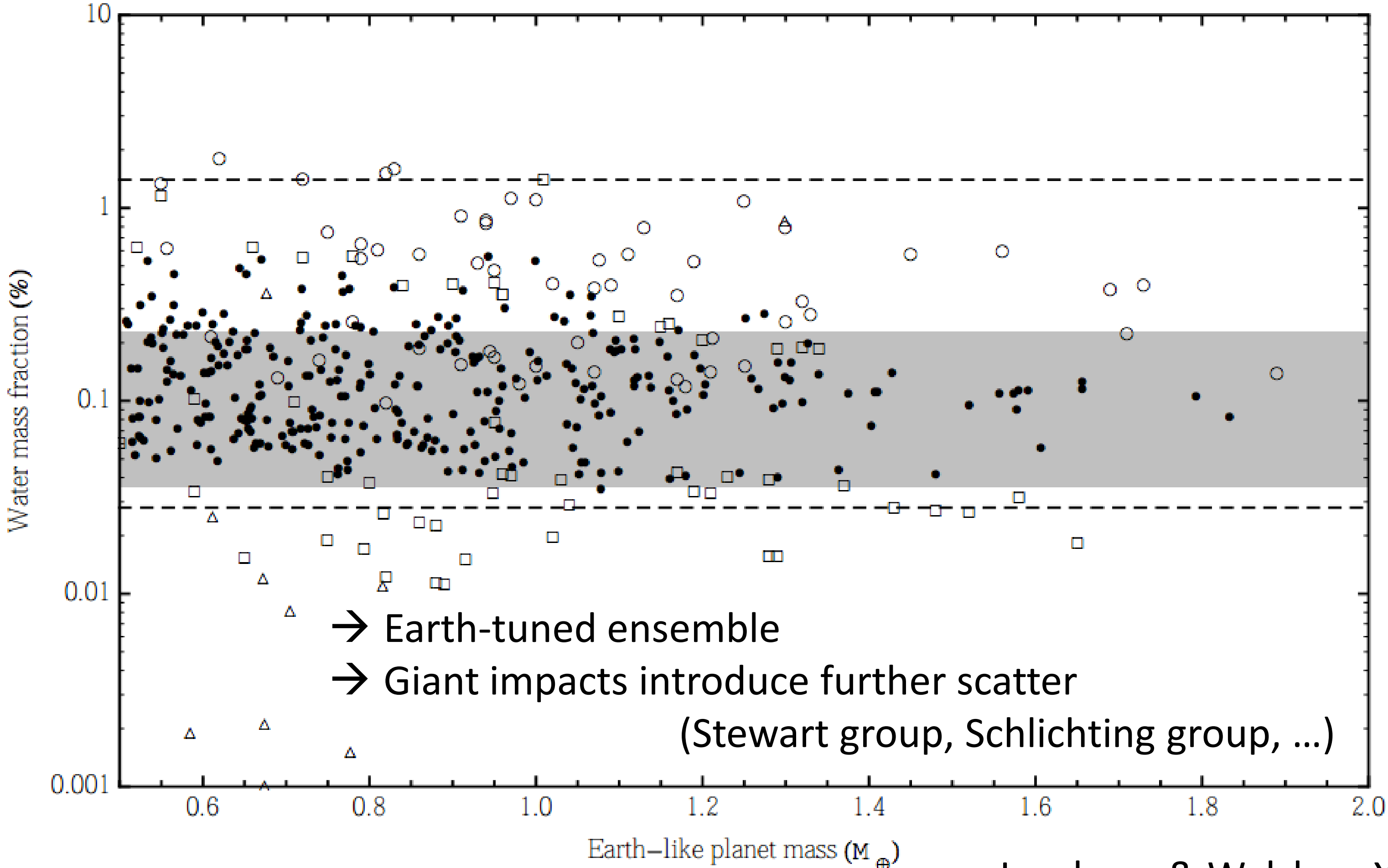
= beyond limits of X(T,P) database



Kite, Manga & Gaidos, ApJ, 2009;
Black dots from simulations (Raymond et al., Icarus, 2006)

Many "Earths" defined using 5% radius error will lack volcanism

Both hydrogen mass fraction and water mass fraction are very variable:



→ Earth-tuned ensemble

→ Giant impacts introduce further scatter

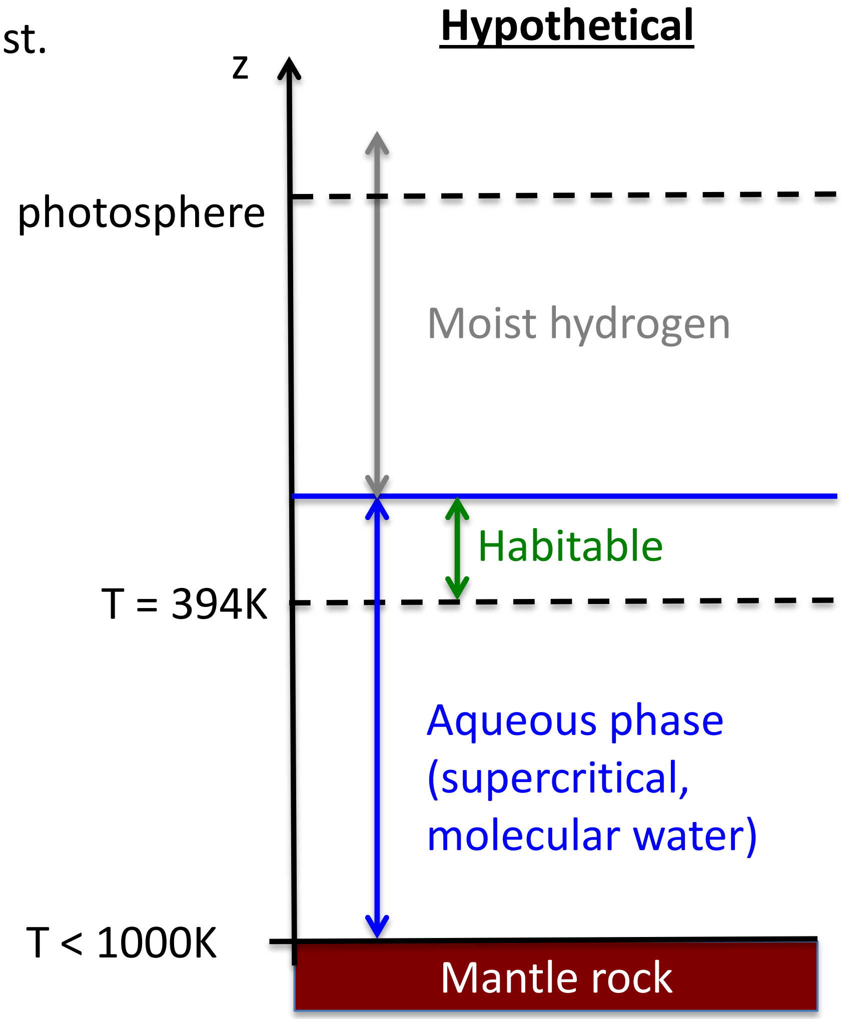
(Stewart group, Schlichting group, …)

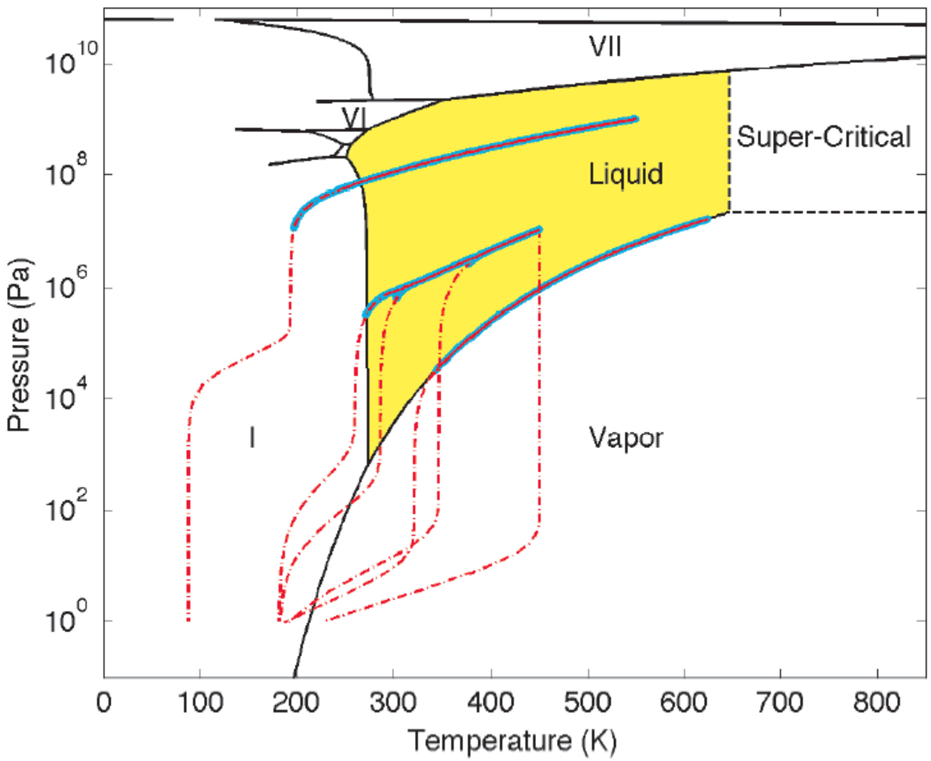
Jacobsen & Walsh, arXiv, 2015

Volcanism-free planets are primed for H_2 production

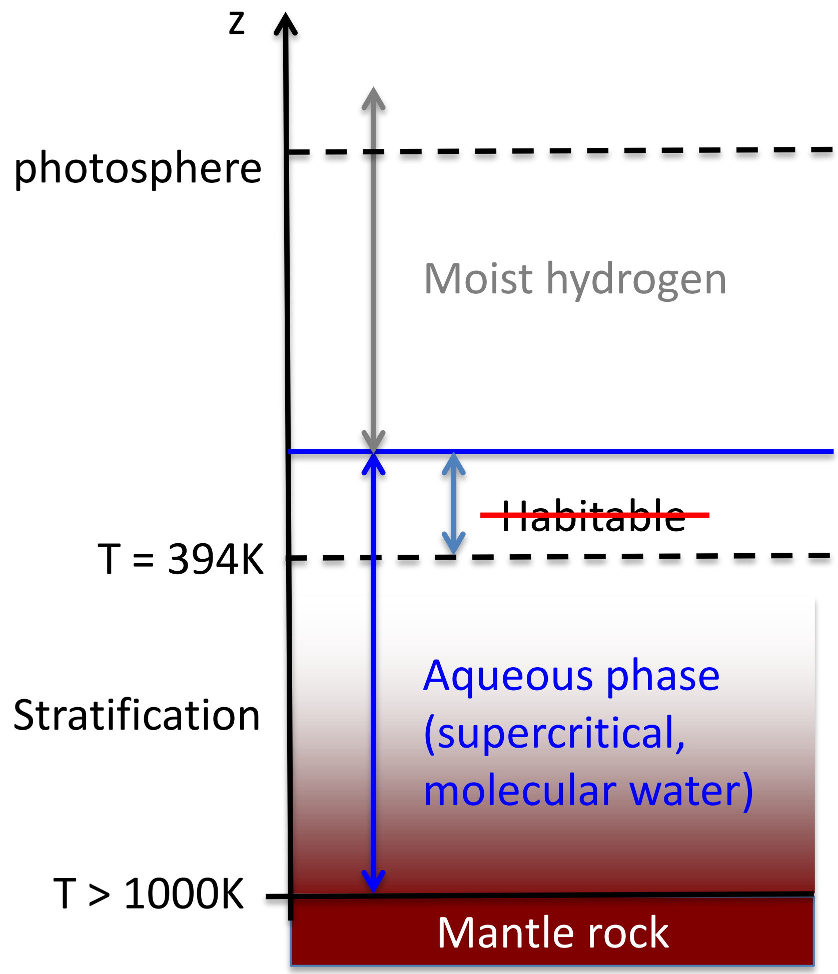
Serpentinization: rapid for mantle rocks, slow for crust. Serpentinization rare on Earth because mantle rocks are usually shrouded by crust

D. Kelley et al. Nature 2001





L. Rogers, PhD thesis, 2012
Kreidberg et al. ApJ 2014



Newton & Manning, GCA 2002

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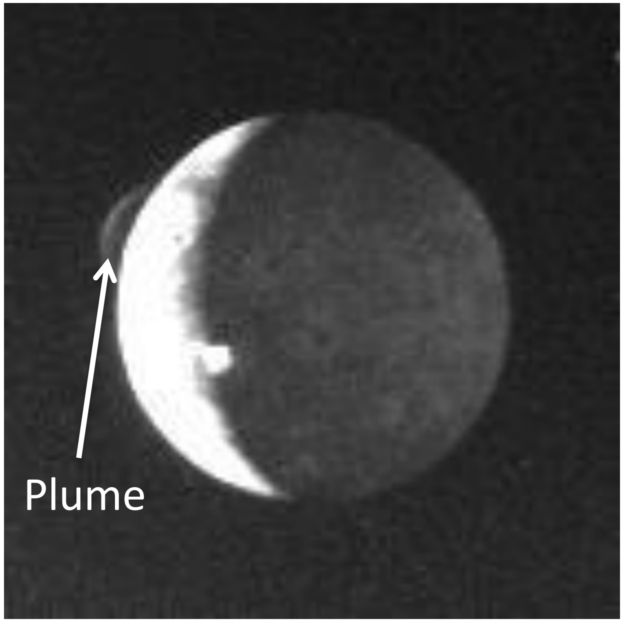
What governs the rate of cryo-volcanism?
Enceladus, $\zeta = 10^{-16}\ s^{-1}$**:**

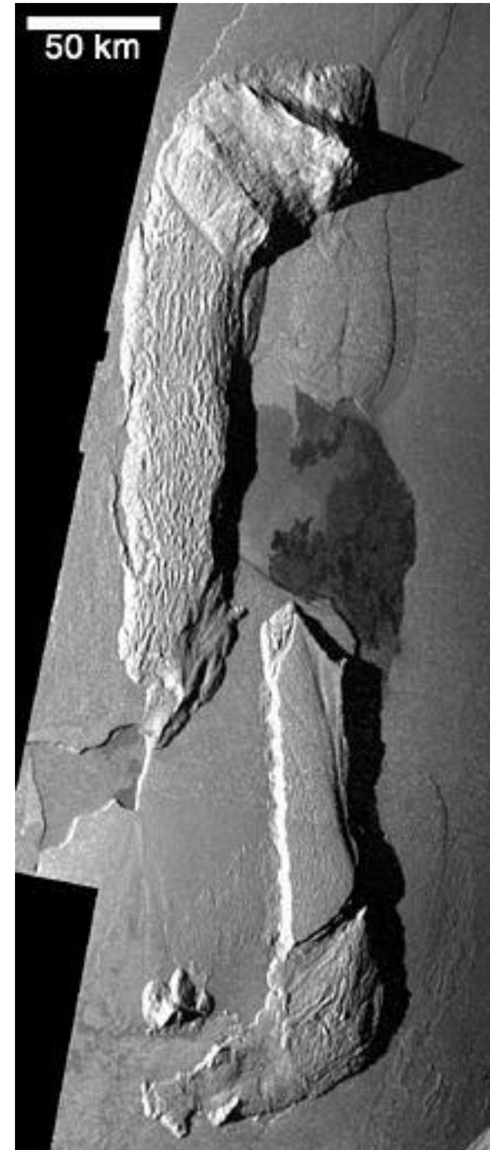
Io (Jupiter I), $\zeta = 10^{-15}\ s^{-1}$: fastest surface-interior exchange rate known

L. Morabito et al., Science 1979



Total heat flow 40 x Earth
(Veeder et al. Icarus 2012)

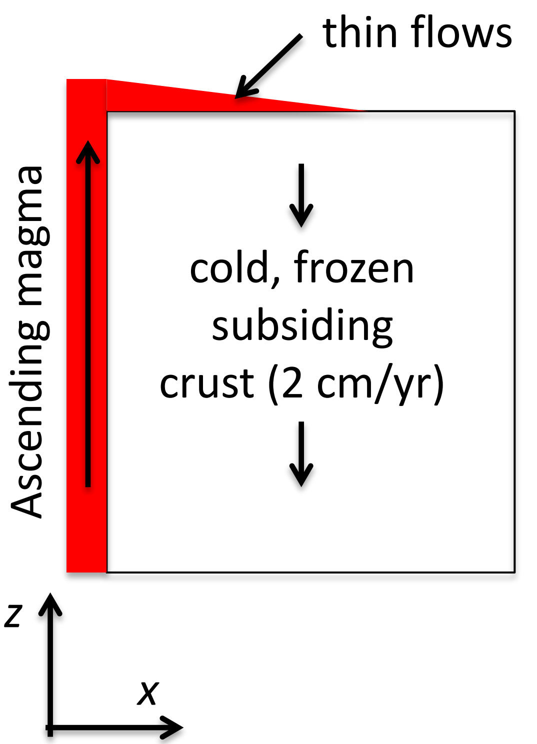
Conductive lithosphere would be
1500/(Q/k) ~ 2 km thick
But mountains are up to 18 km high!



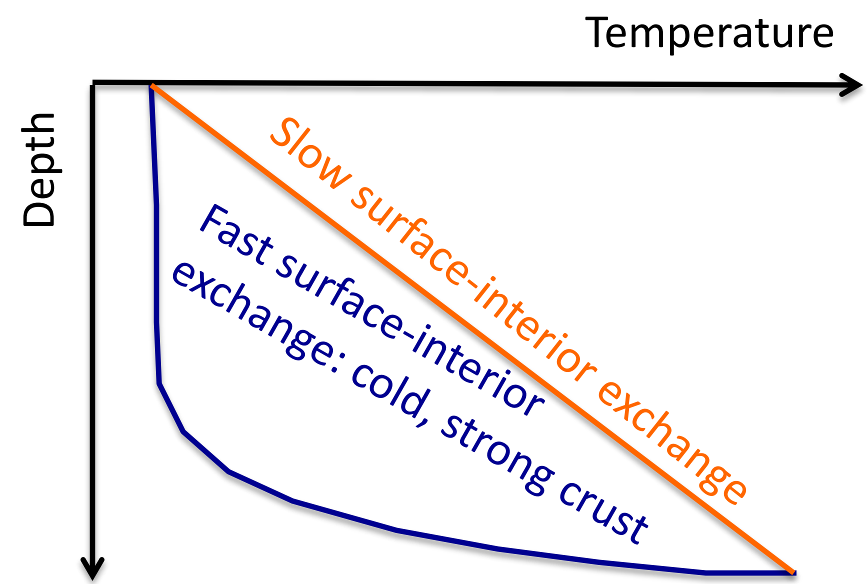
Surface-interior exchange in heat-pipe mode on Io: explaining $\zeta = 10^{-15}\ \mathrm{s}^{-1}$

From tidal heating calculations

$$\frac{Q_{tidal}}{\rho(L_{melt}+\Delta T c_p)} = 2\mathrm{cm/yr}$$



O'Reilly & Davies, GRL, 1981

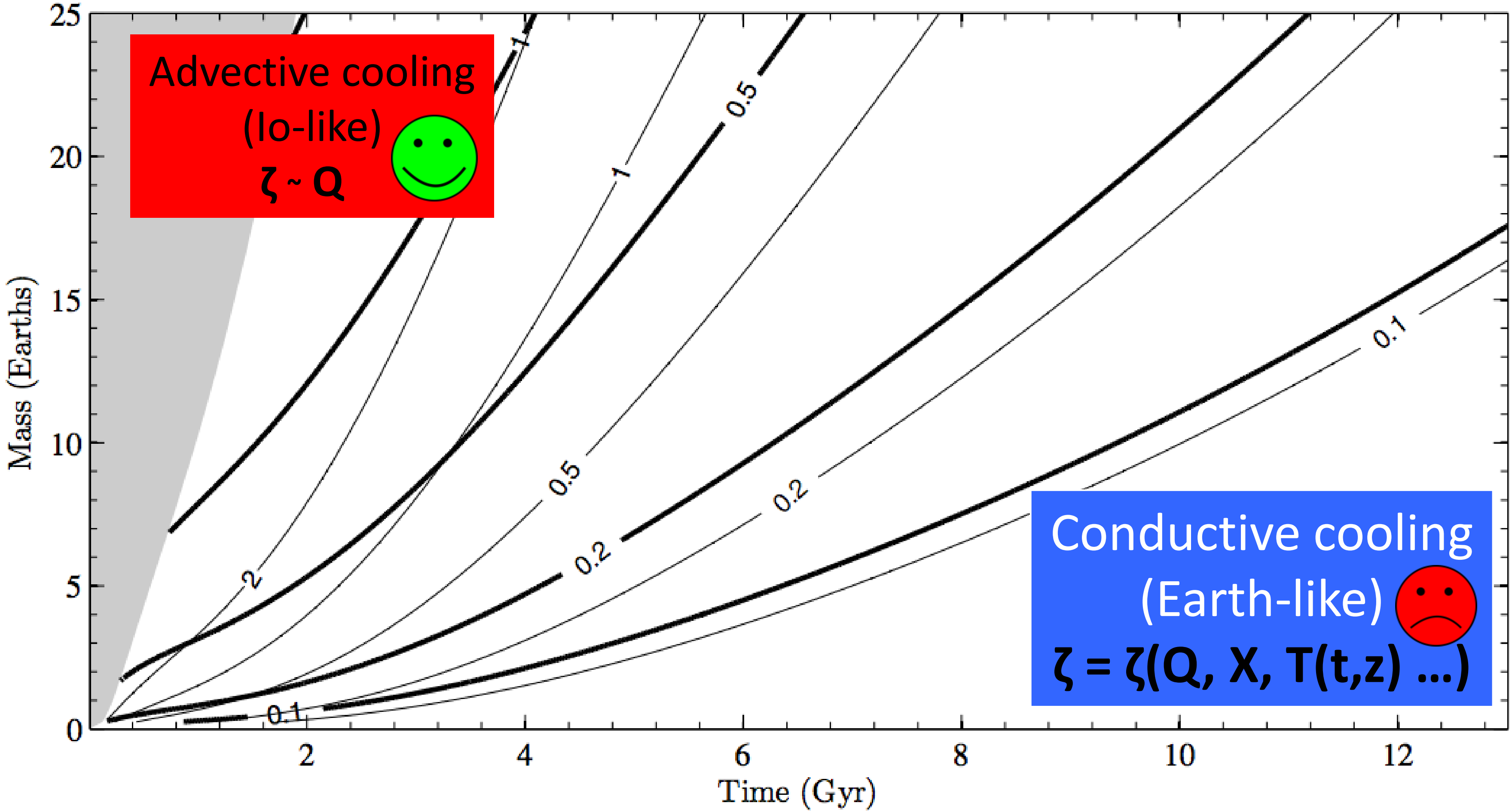


Moore et al. *in* Lopes & Spencer, "Io after Galileo," 2007.

ζ is more predictable for massive and/or young rocky planets than for old and/or small rocky planets

Kite, Manga & Gaidos, ApJ 2009
Moore et al. J. Geophys. Res. 2003

Spreading rate (m/yr): No heat pipes / With heat pipes



How does ζ affect magma planet / disintegrating planet observables?

Kepler-10b, -32b, -42c, -78b, -407b , CoRoT-7b, KIC 12557548b …

Low ζ: Thin Al + Ti + O atmosphere
Slow mass loss

High ζ: Thick atmosphere including Na, K
Fast mass loss

Rappaport et al. 2012
Perez-Becker & Chiang MNRAS 2013
Sanchis-Ojeda et al. ApJ 2014
Croll et al. arXiv 2014
Bochinski et al. ApJL 2015

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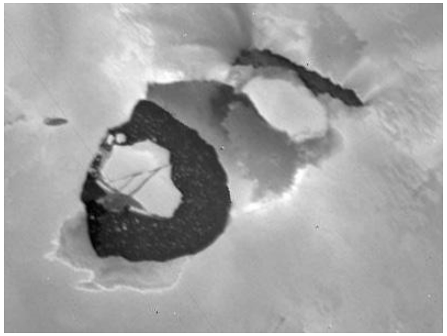
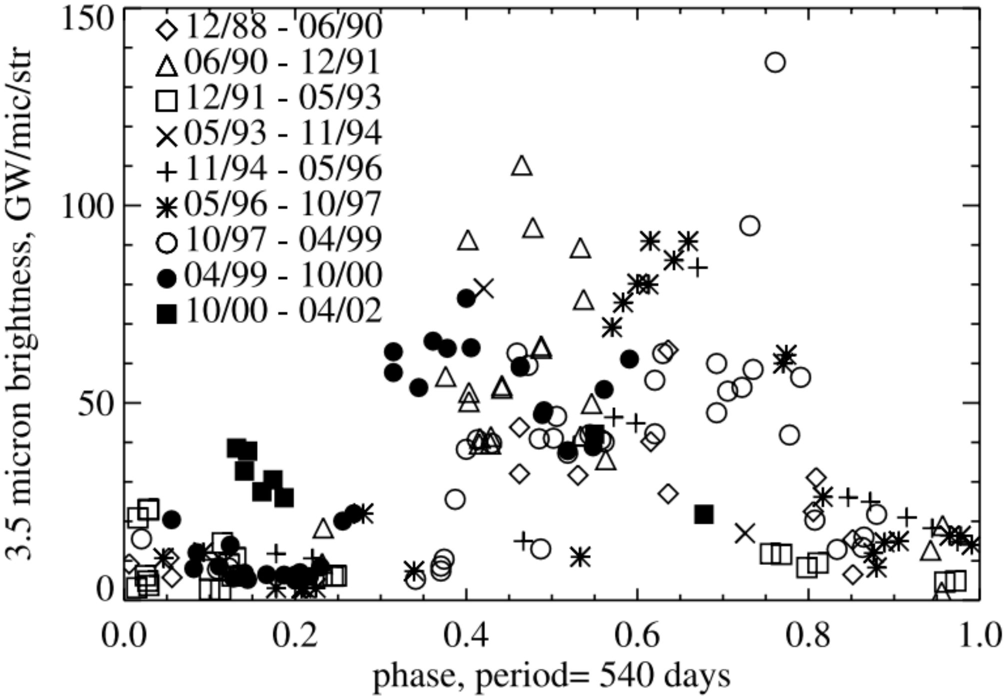


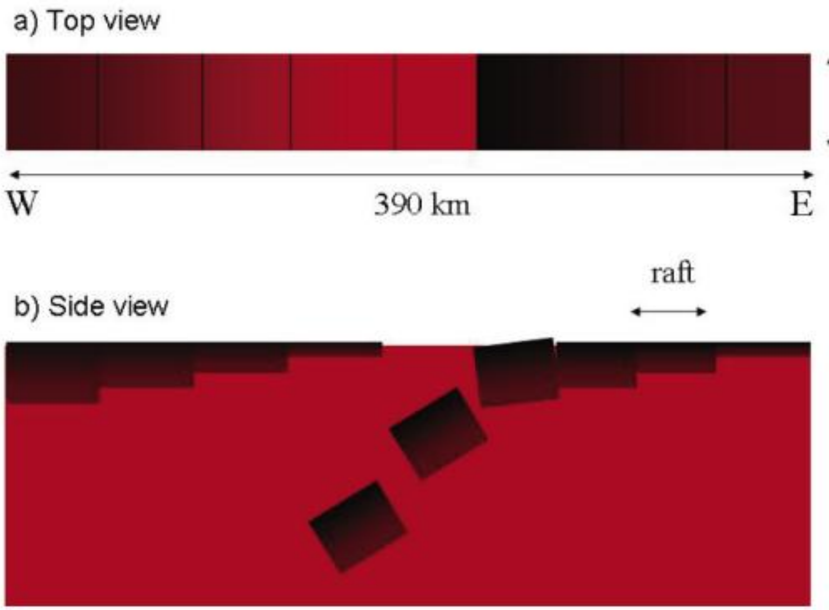
400 km across

strong time variability and outbursts?



Loki Patera, Io: a periodic volcano

J. Rathbun et al. GRL 2002



Rathbun & Spencer 2003

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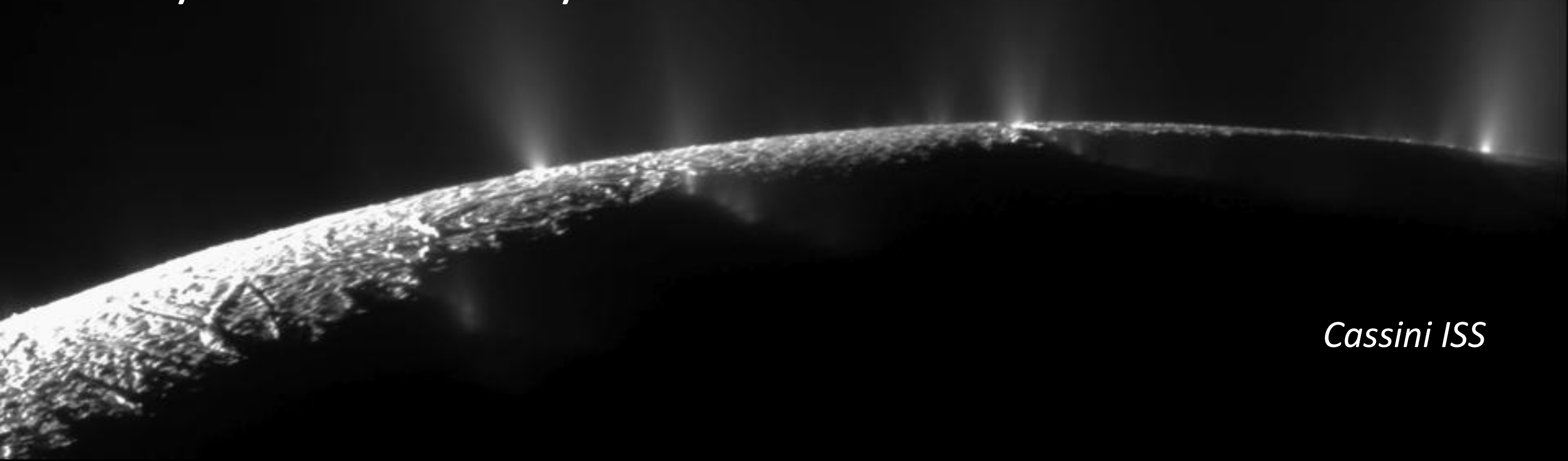
Enceladus, ζ = 10^{-16} s^{-1}**:**

Enceladus (Saturn II), $\zeta = 10^{-16}\ s^{-1}$:

the only known active cryovolcanic world



Cassini ISS

<u>Problems:</u>

Why $\zeta = 10^{-16}\ s^{-1}$?

Persistence of eruptions through diurnal tidal cycle

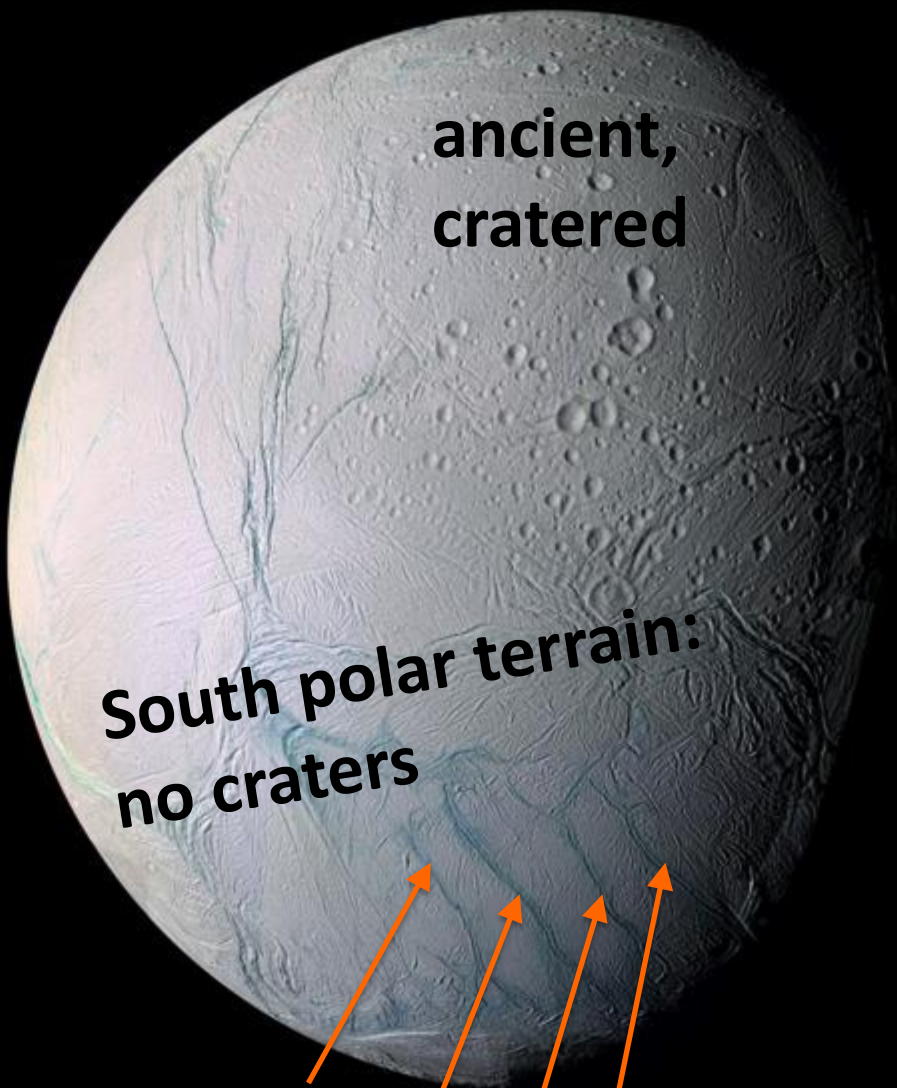
Fissure eruptions maintained for >>Kyr

Preventing sub-ice ocean from refreezing over Gyr

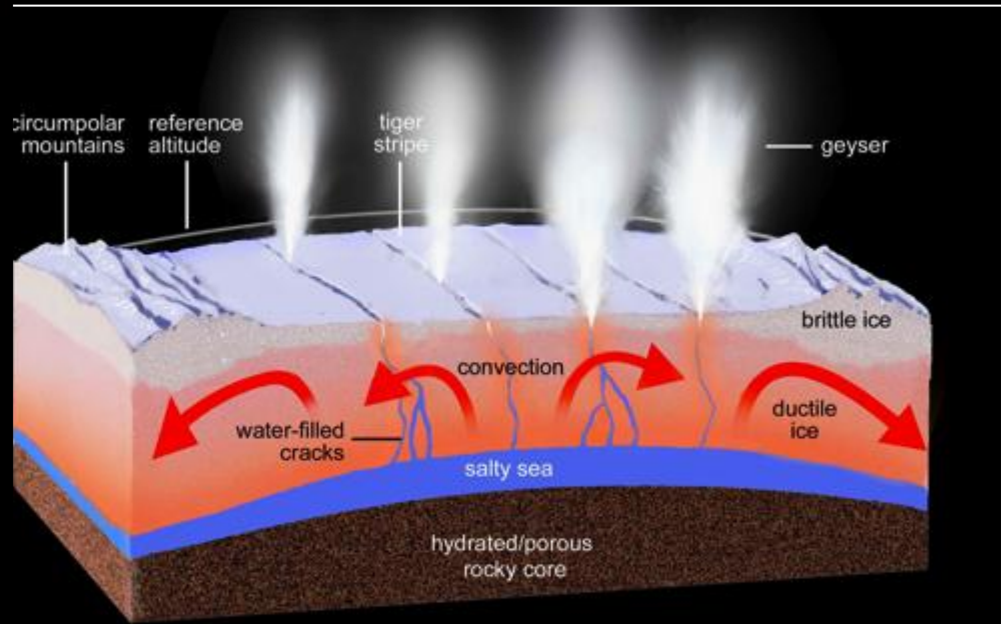
addressed today; collaboration with Allan Rubin (Why ζ; persistence of eruptions; fissure eruptions)

longer timescales (preventing sub-ice ocean from refreezing)

Cryo-volcanism on Enceladus has deep tectonic roots



4 continuously-active “tiger stripes”

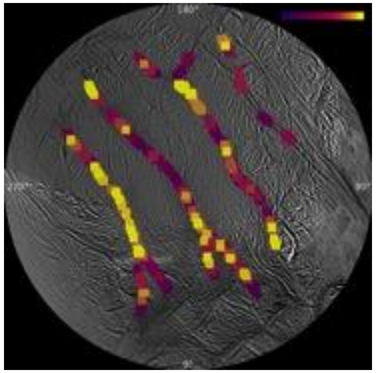


Density = 1.6 g/cc

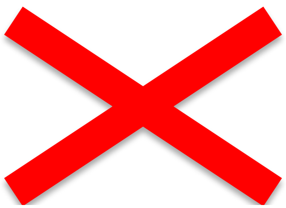
Probing tectonics

Enceladus

Volcanism

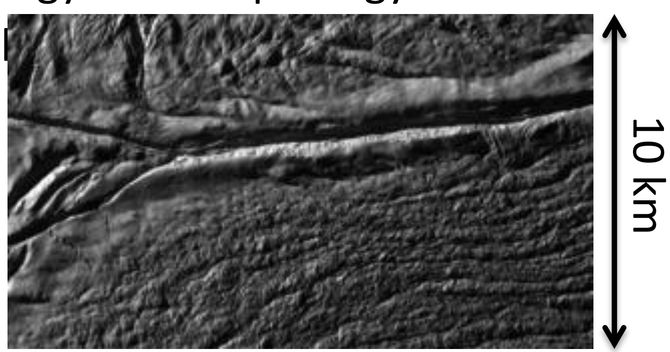


Seismicity

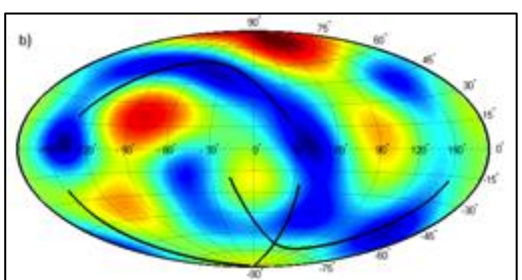


~~Geology~~ Geomorphology

Geol



Gravity



Tectonic mode:

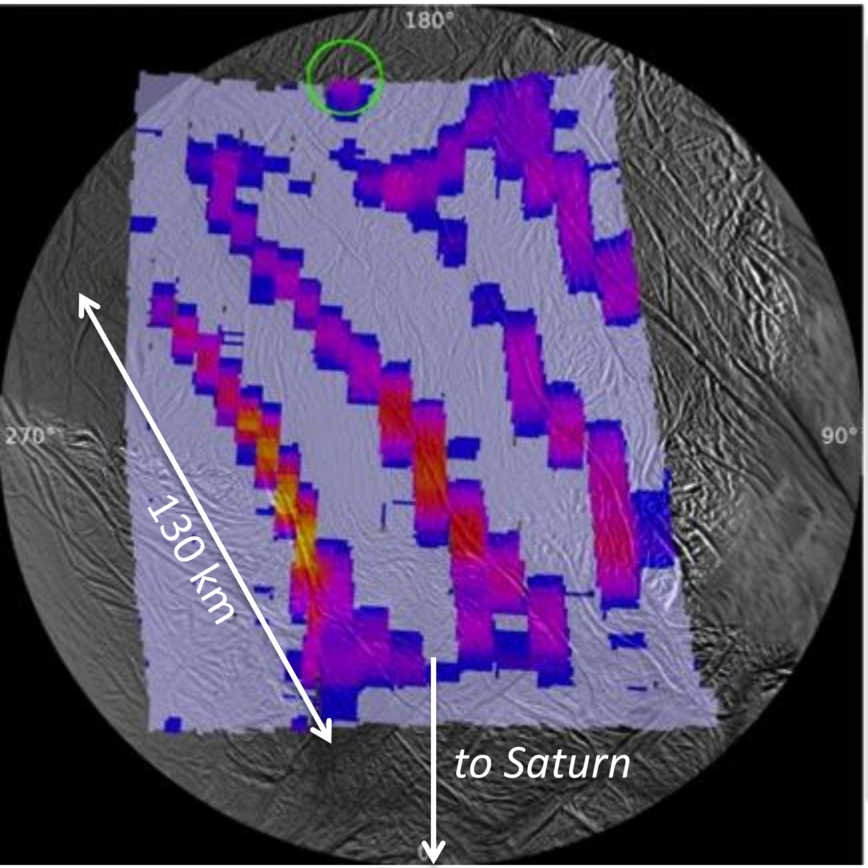
?

(4.6±0.2) GW excess thermal emission from surface fractures

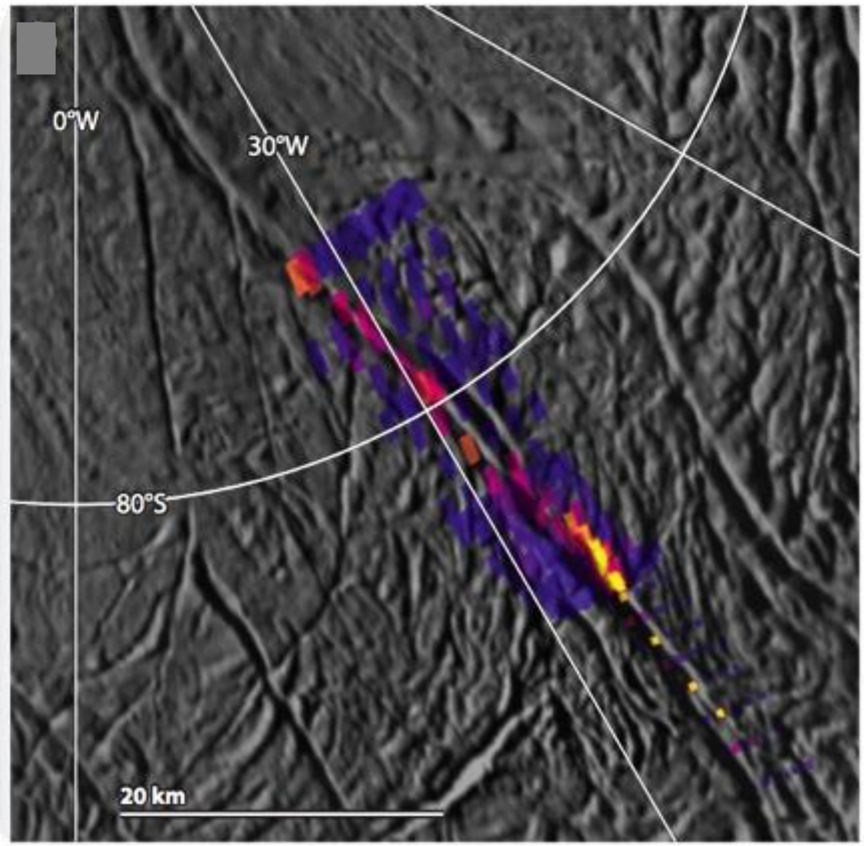
(~10 KW/m length; all four tiger stripes erupt as "curtains")

Spitale et al., Nature accepted

South polar projection



Porco et al. Astron. J. 2014

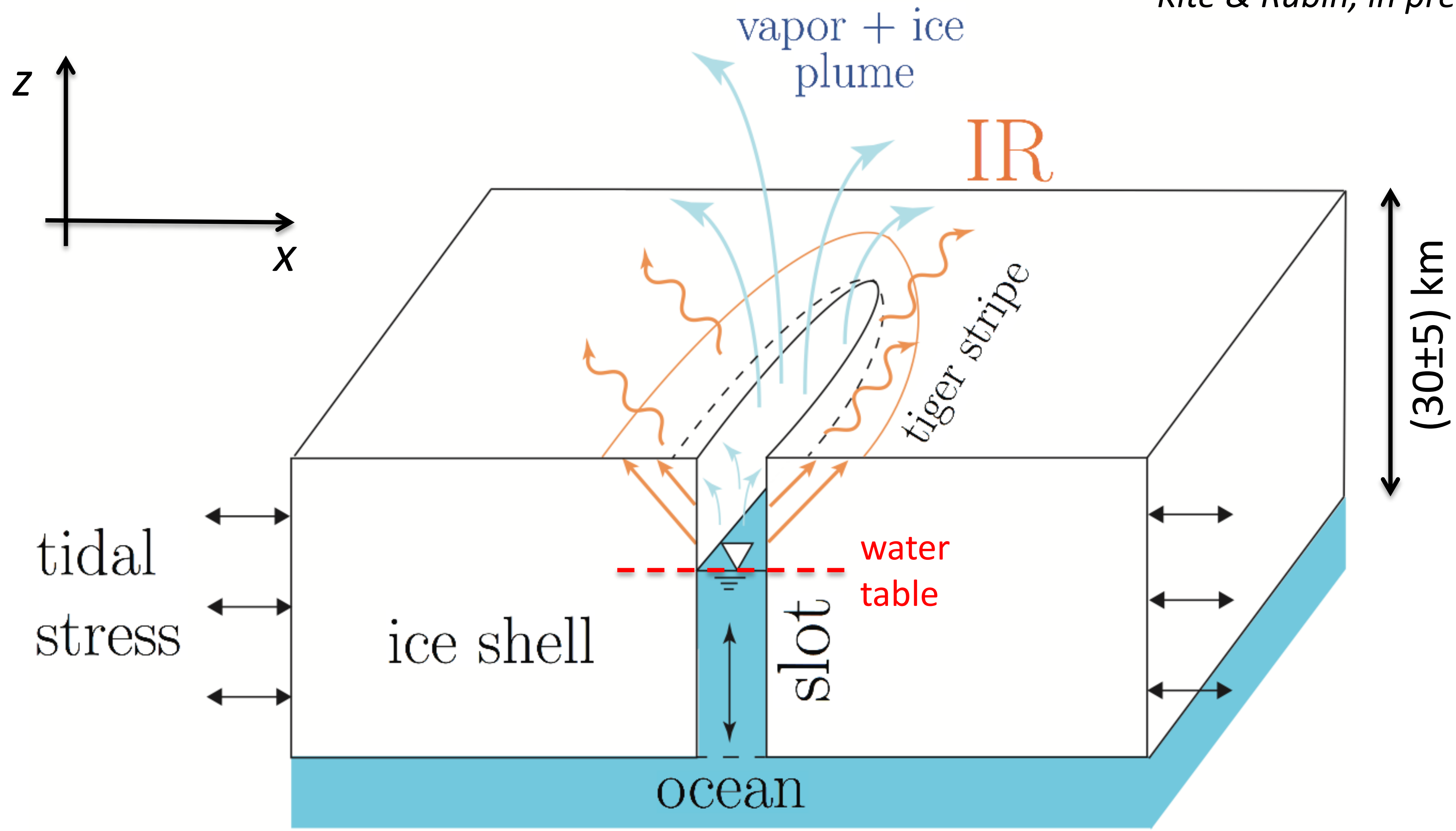


Spencer & Nimmo AREPS 2013

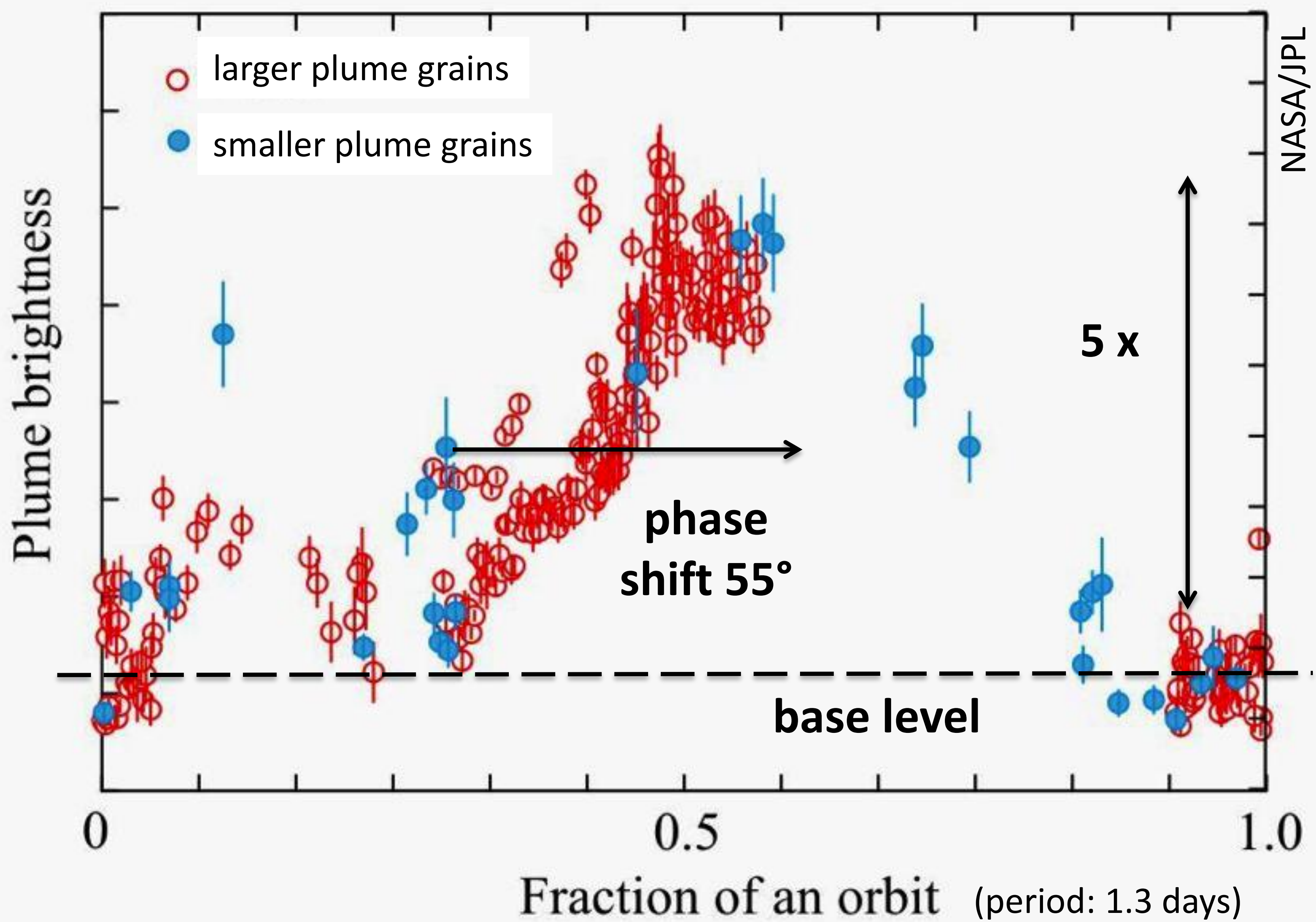
Hotspots up to 200K
No liquid water at surface
Latent heat represented by plumes < 1 GW

Key constraint #1: avert freeze-up at water table

Kite & Rubin, in prep.



Key constraint #2: match tidal response of plumes

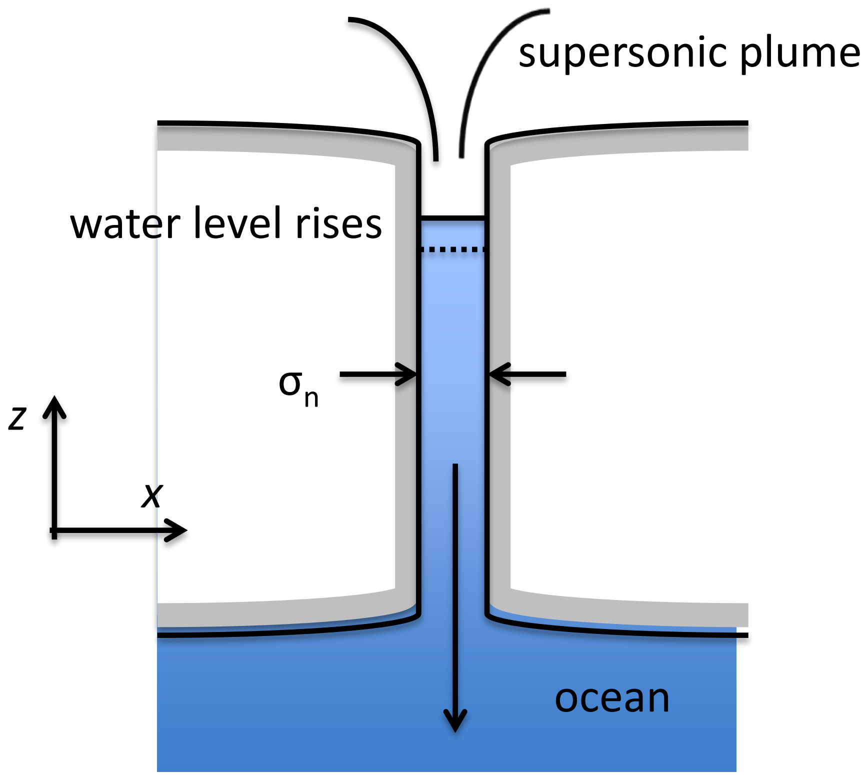


(period: 1.3 days)
Ascent-time correction < 1 hour

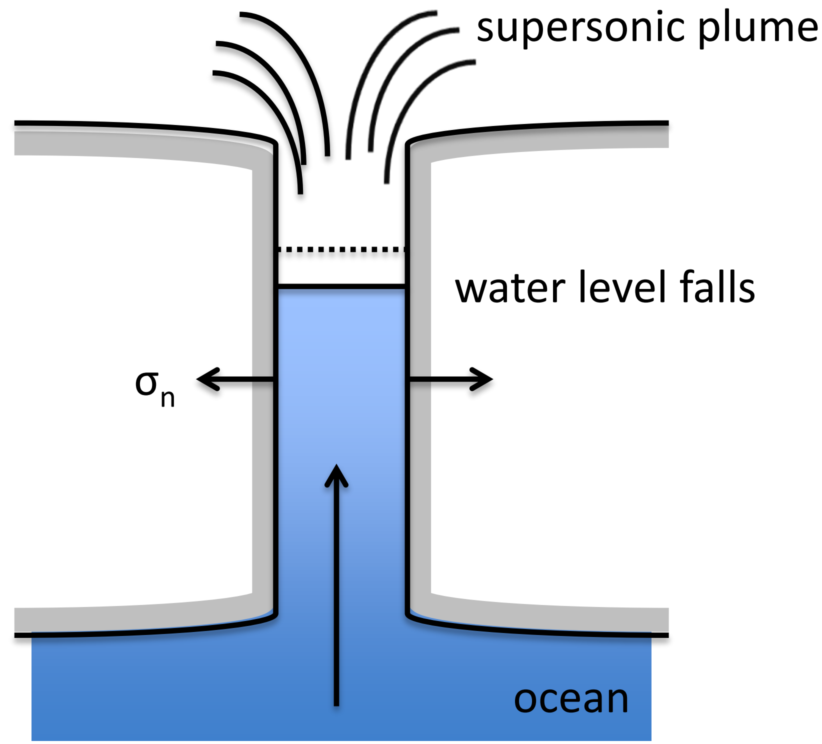
New model: Melted-back slot

Kite & Rubin, in prep.

Compression



Tension



<u>Attractive properties:</u>

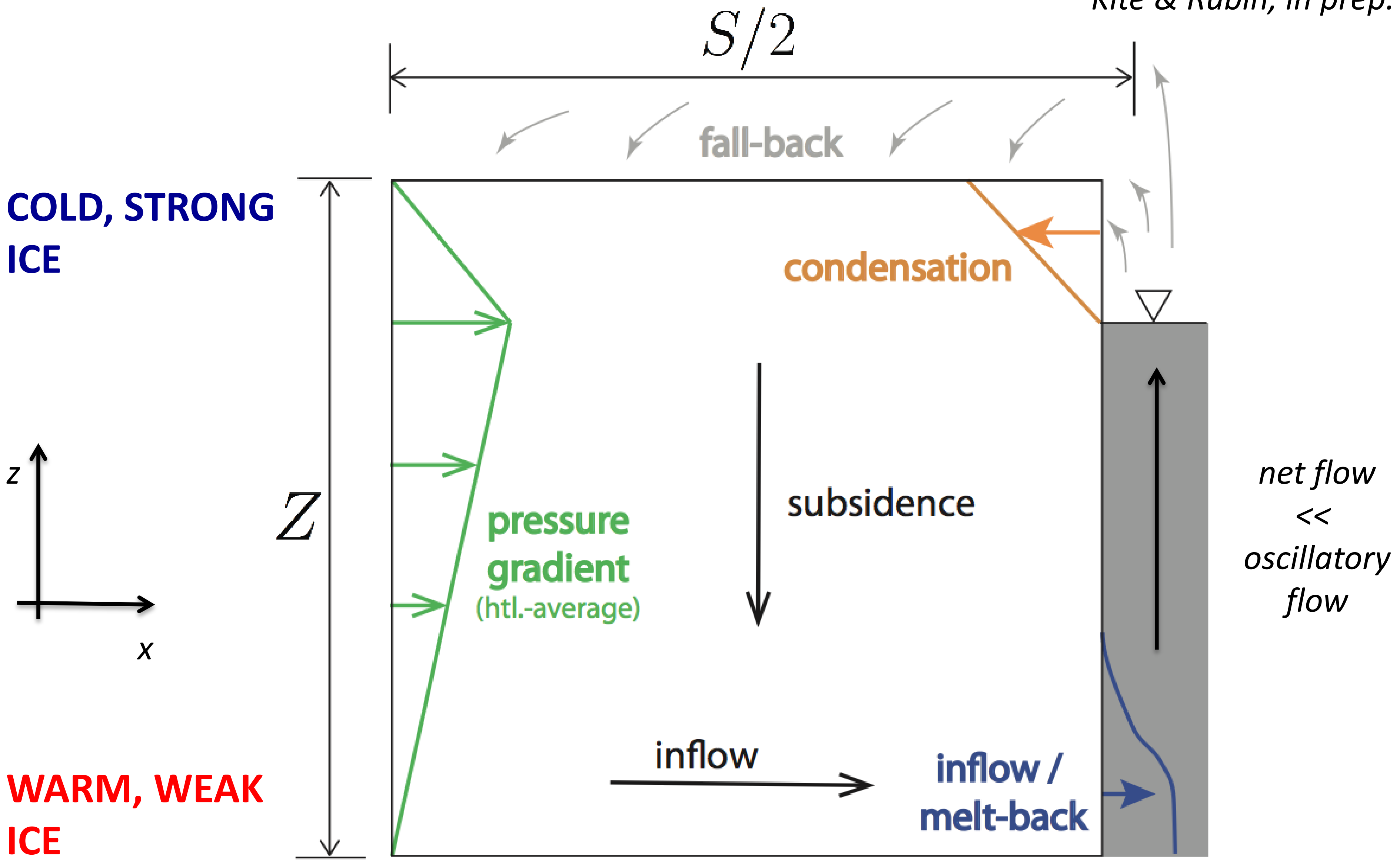
- Matches (resonant) phase lag
- Eruptions persist through 1.3d cycle
- Matches power output
- Pumping disrupts ice formation
- Slot evolves to stable width

$$\rho_w g \frac{\partial h}{\partial t} = \left(\frac{2\pi}{p}\right) \sigma_n \cos\left(\frac{2\pi}{p} t\right) - \frac{\partial \Delta W_{max}(t)}{\partial t} \frac{2E}{L_{ts}}$$

$$\nabla P = (D+h)^{-1}(\sigma_n(t) - 2W_{max}(t)E/L_{ts})$$

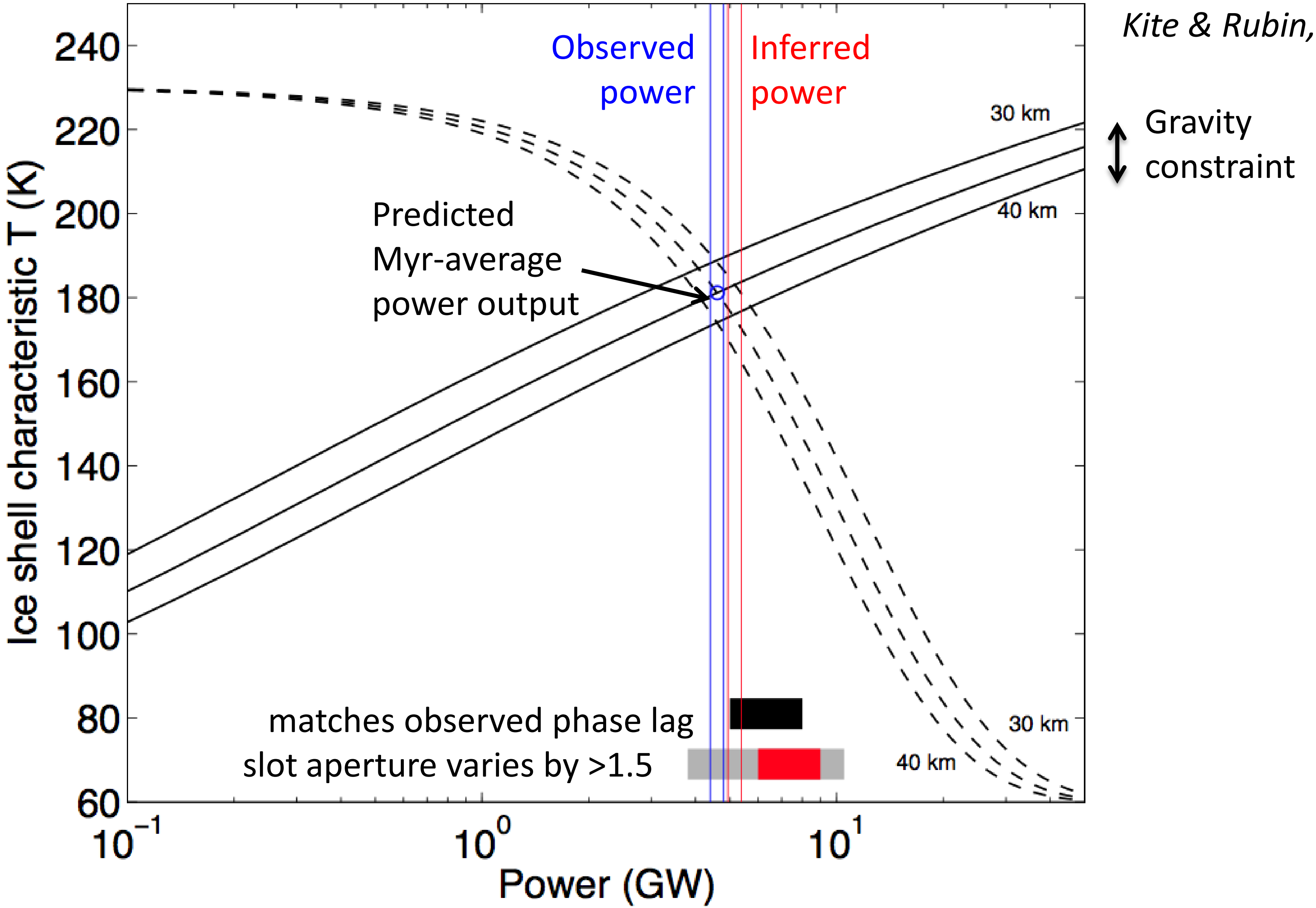
Long-lived water-filled slots drive tectonics

Kite & Rubin, in prep.

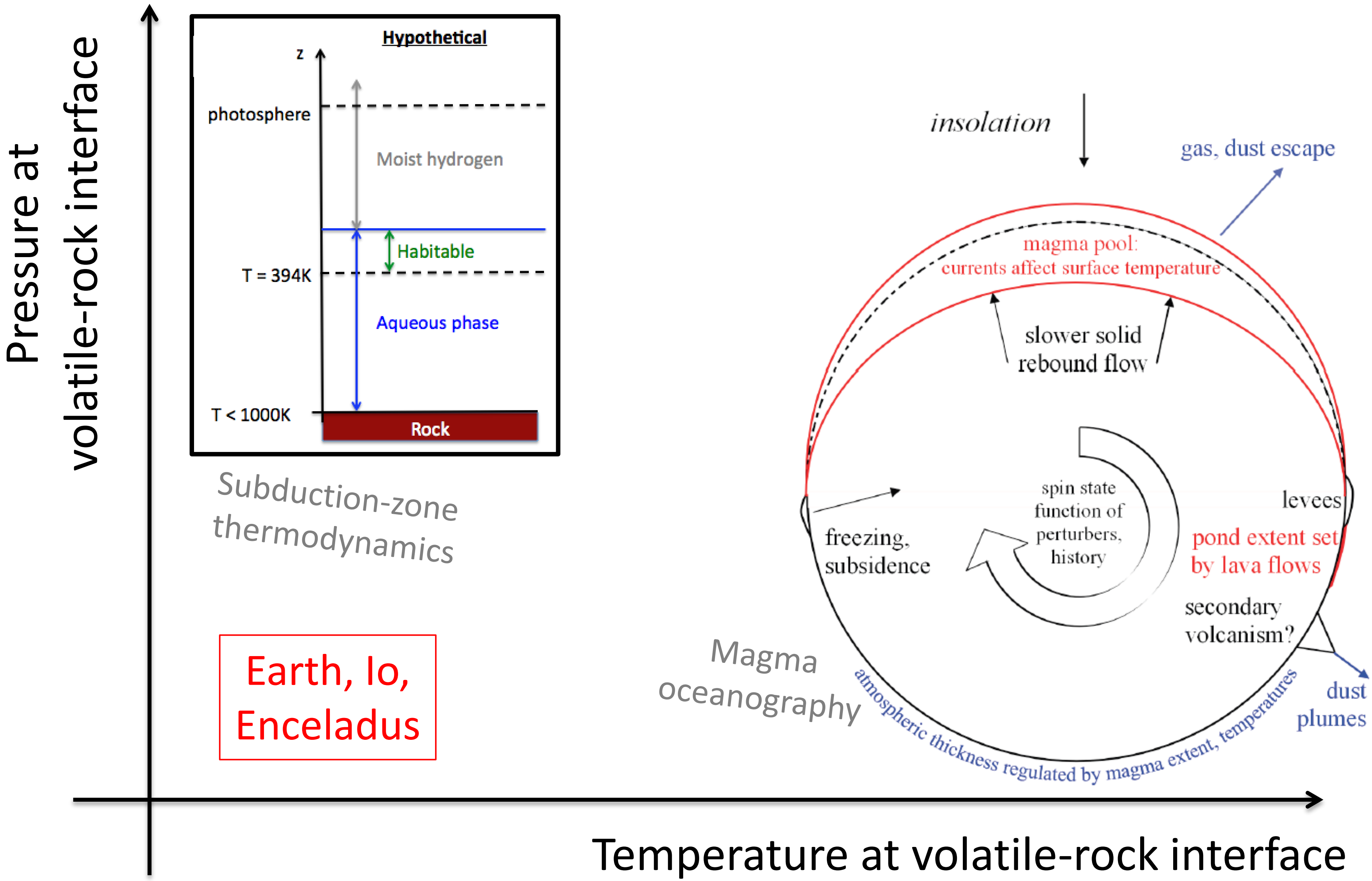


Slot model explains and links surface-interior exchange (ζ) on diurnal through Myr timescales

Kite & Rubin, in prep.



Future: research requiring only existing data: ζ = ζ (R, X, t …)



Summary: ζ (R, X, t) = ?

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Turbulent dissipation within tiger stripes may explain the power output of Enceladus.

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