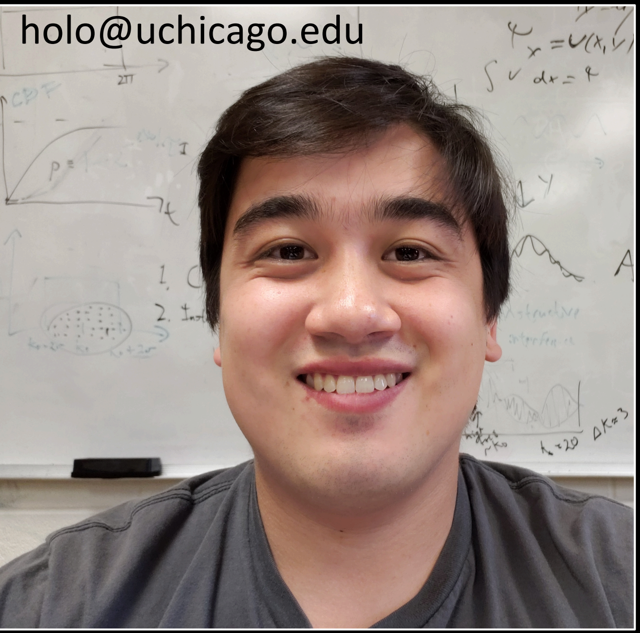
Mars obliquity through deep time:
New constraints from the Bombardment Compass



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Mars obliquity is crucial to Mars' long term climate evolution, but neither Mars' instantaneous nor mean obliquity are known prior to 10^8 yr .

Today: Use a new technique to directly retrieve post-3.5 Ga Mars mean obliquity.

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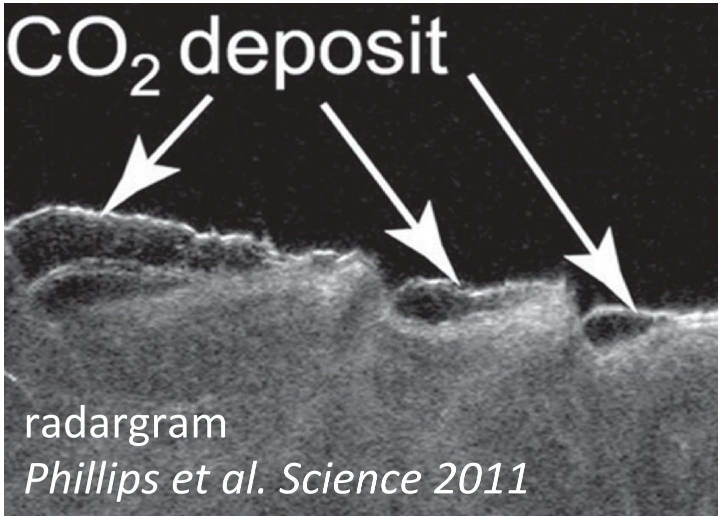
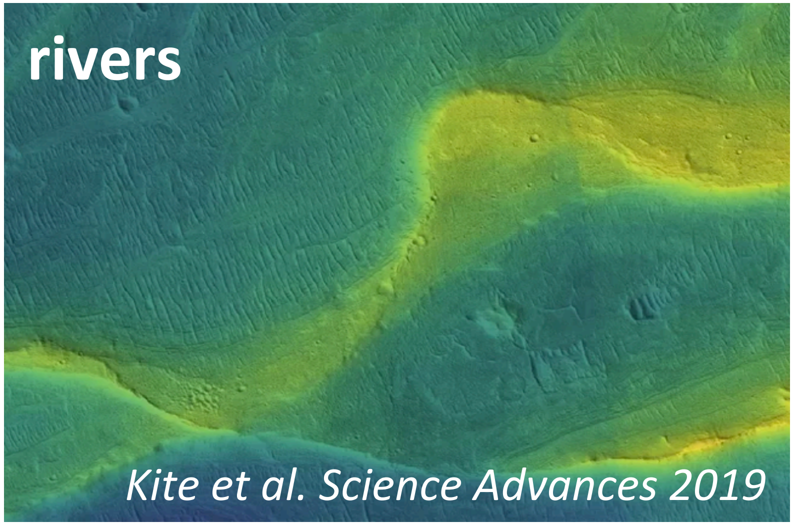
Mars obliquity matters

big changes in Mars obliquity (e.g. *Laskar et al. 1993*) affect climate (e.g. *Forget et al. 2006*):

ice & atmospheric pressure

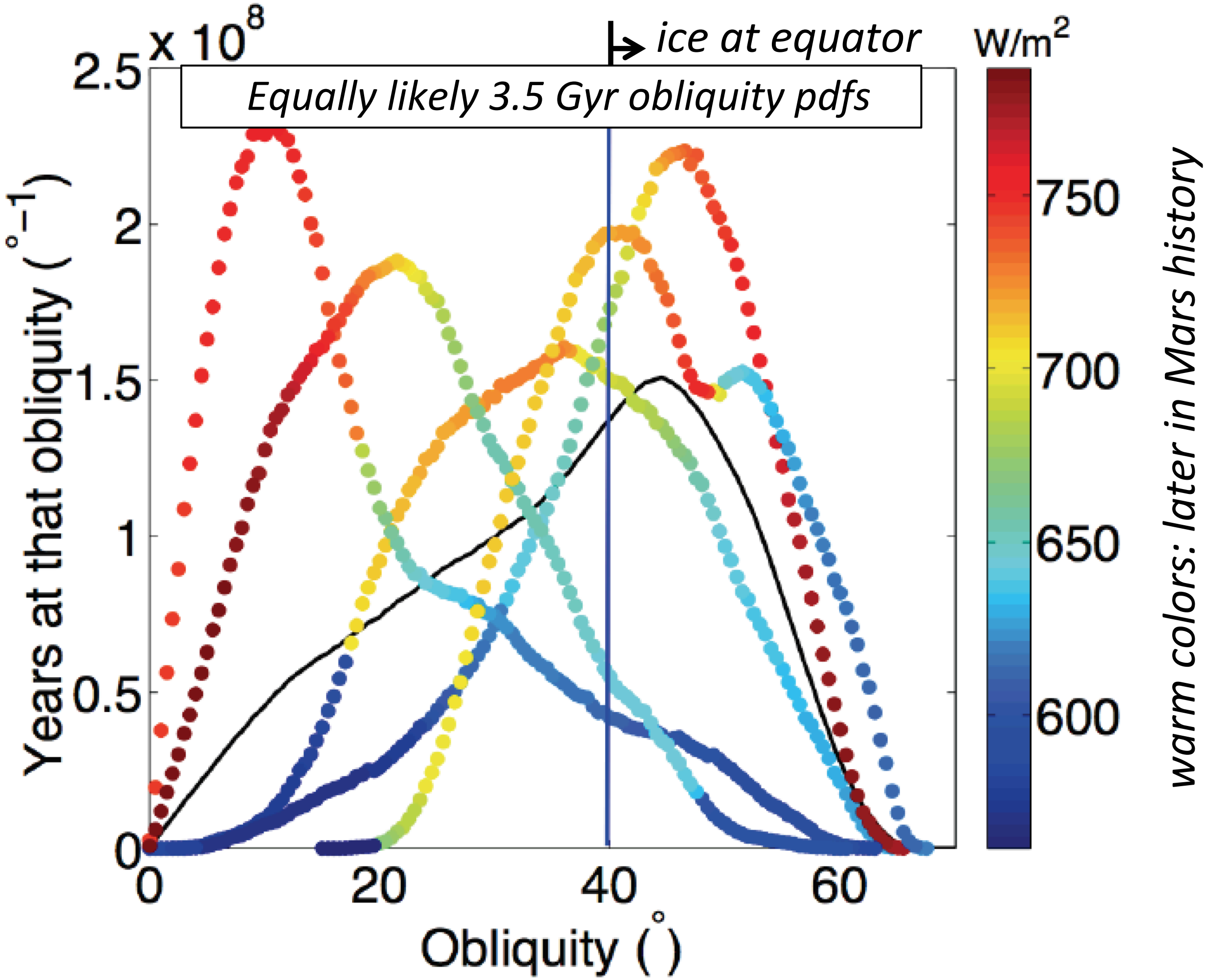




H_2O ice shifts from Poles to Equator when obliquity > 40°! *(Jakosky & Carr Nature 1985)*

However, the true values of Mars' pre-0.1 Ga obliquity history are wildly uncertain: a fundamental mystery in solar system dynamics

Mars obliquity is probably chaotic



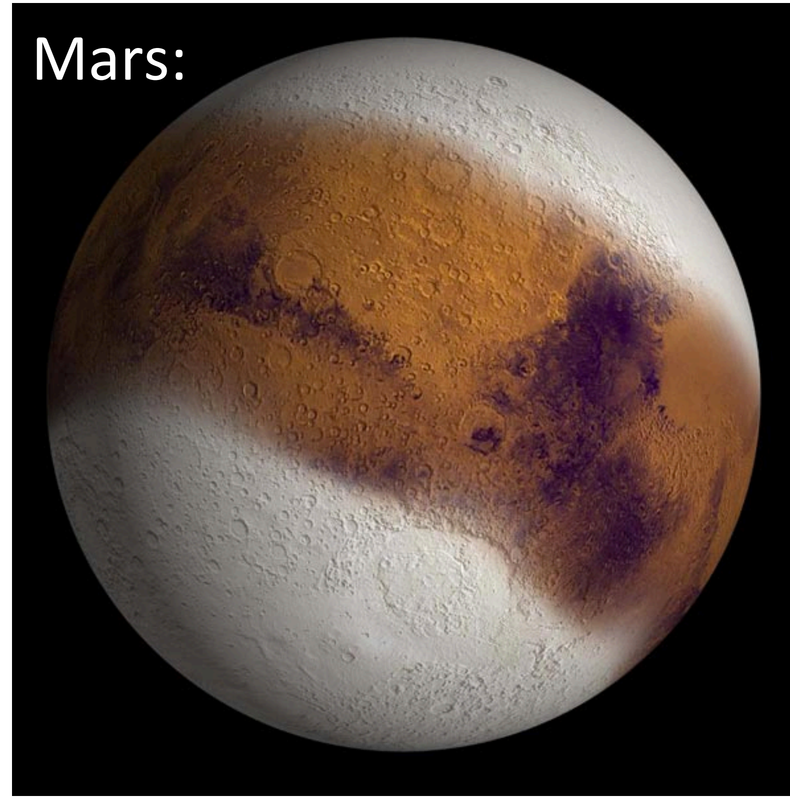
Both the full obliquity history *and* the historical obliquity PDF are highly uncertain.

Mars obliquity today = 25°

Touma & Wisdom 1993 Science, Laskar & Robutel 1993 Nature, Laskar et al. 2004 Icarus, Armstrong et al. 2004 Icarus, Kite et al. Icarus 2015; see also Bills & Keane LPSC 2019.
Potentially more complicated pre-3.8 Ga - Brasser & Walsh 2011.

Previous attempts to vault this fundamental barrier of the chaotic diffusion of the Solar System have been indirect …

e.g. Olsen et al. 2019 PNAS
Kent et al. 2018 PNAS
Pälike et al. 2004 Geology
Ma et al. 2017 Nature



e.g. Head et al. 2003 Nature
Fassett et al. 2014 Geology

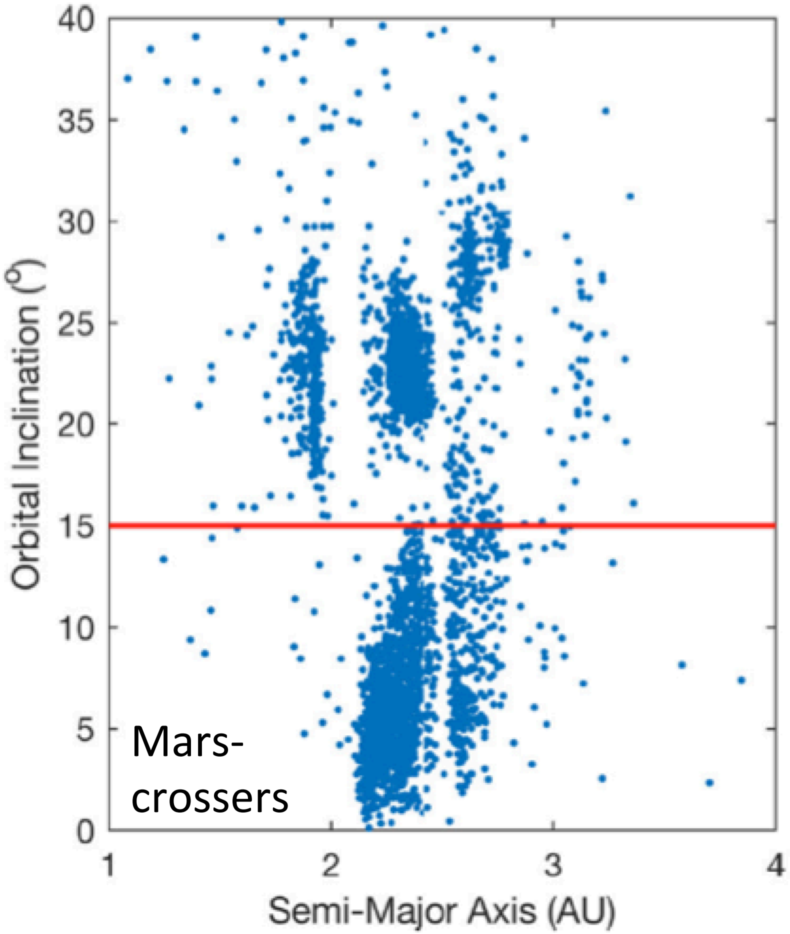
Indirect:

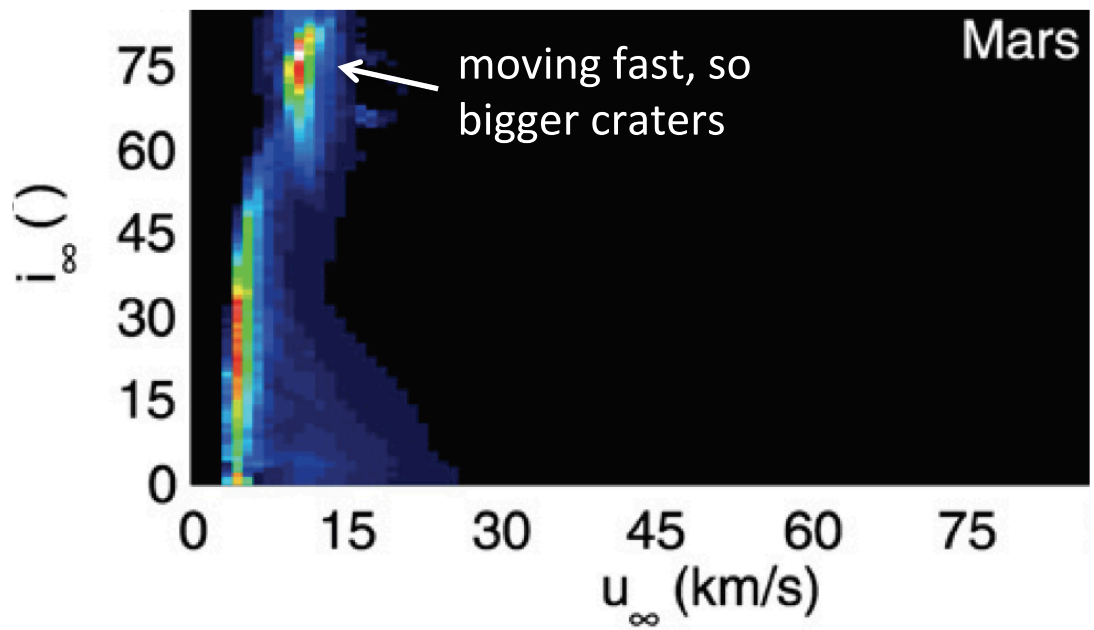
obliquity **x** *(nonlinear climate response)* **x** *(geologic processes)* **=** *observation*

… we seek a direct method!

Starting point for our new, direct method: anisotropic bombardment

Holo, Kite, & Robbins 2018 EPSL

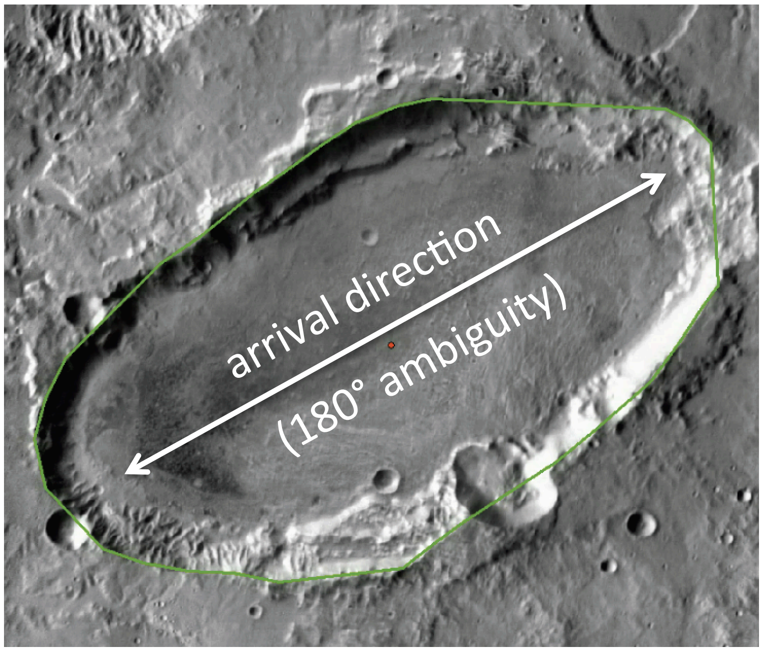


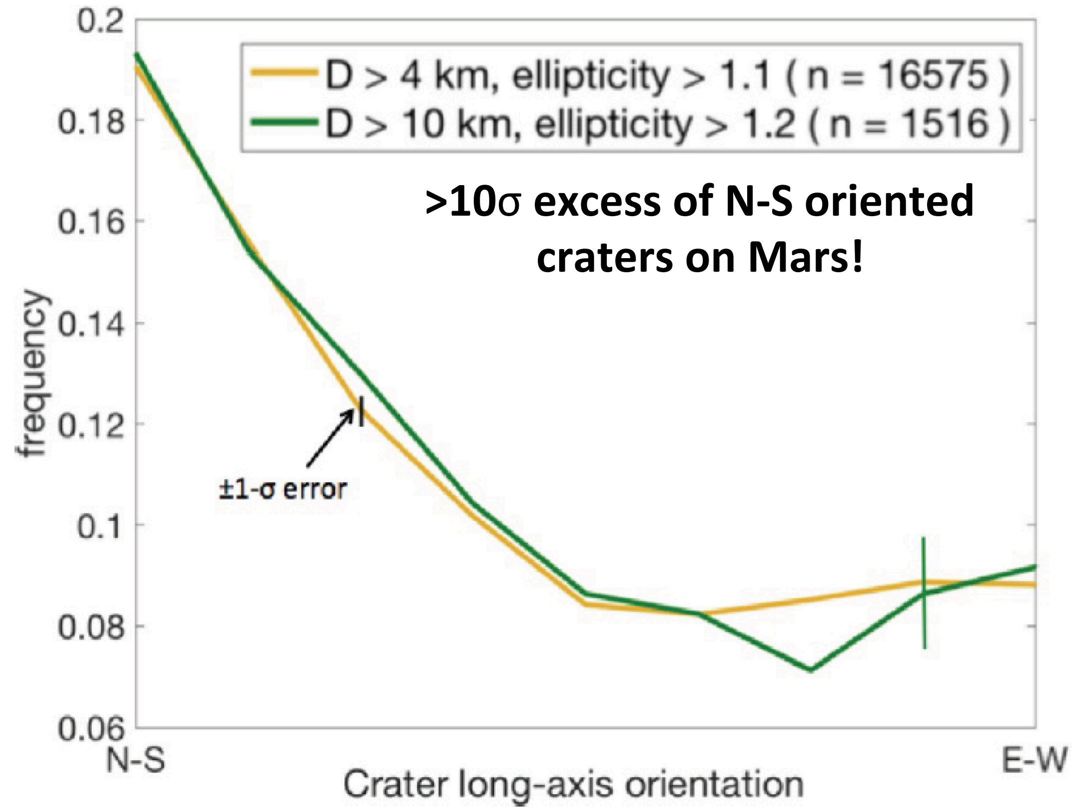


Le Feuvre & Weiczorek 2008
(also Bottke et al. 2000, 2002)

Elliptic crater long axis orientation records arrival direction of impactors.
As expected (given anisotropic bombardment), Mars elliptic crater long-axis distribution is anisotropic.

Holo, Kite, & Robbins 2018 EPSL





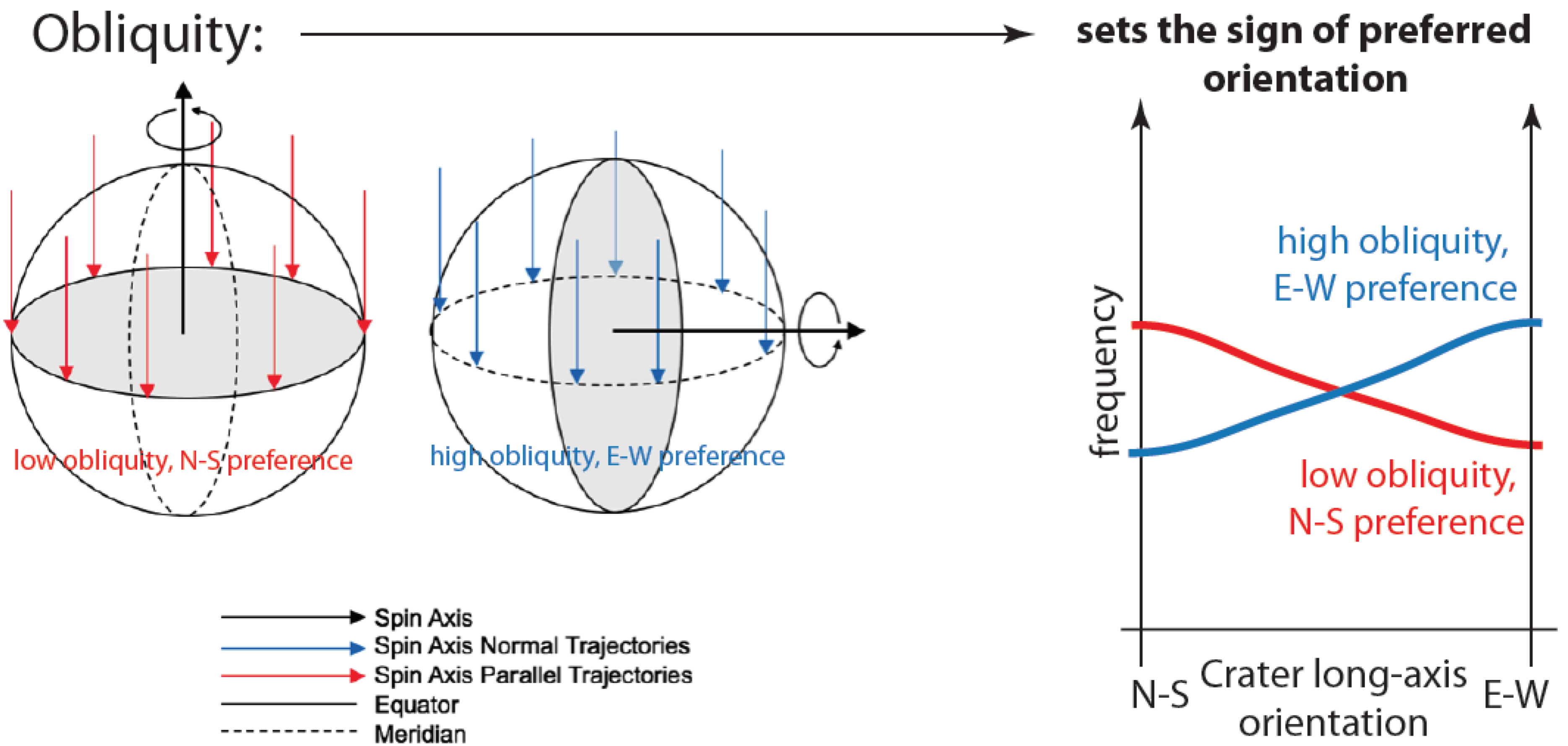
A few % of craters are elliptic → >10^3-elliptic-crater database (*Robbins et al. 2012 JGR*)

Human-human variance is small (*Holo, Kite, & Robbins, EPSL 2018*)

Rim outline little-affected by post-impact modification (erosion is minor since 3.5 Ga)

New method: The **Bombardment Compass** for Mars

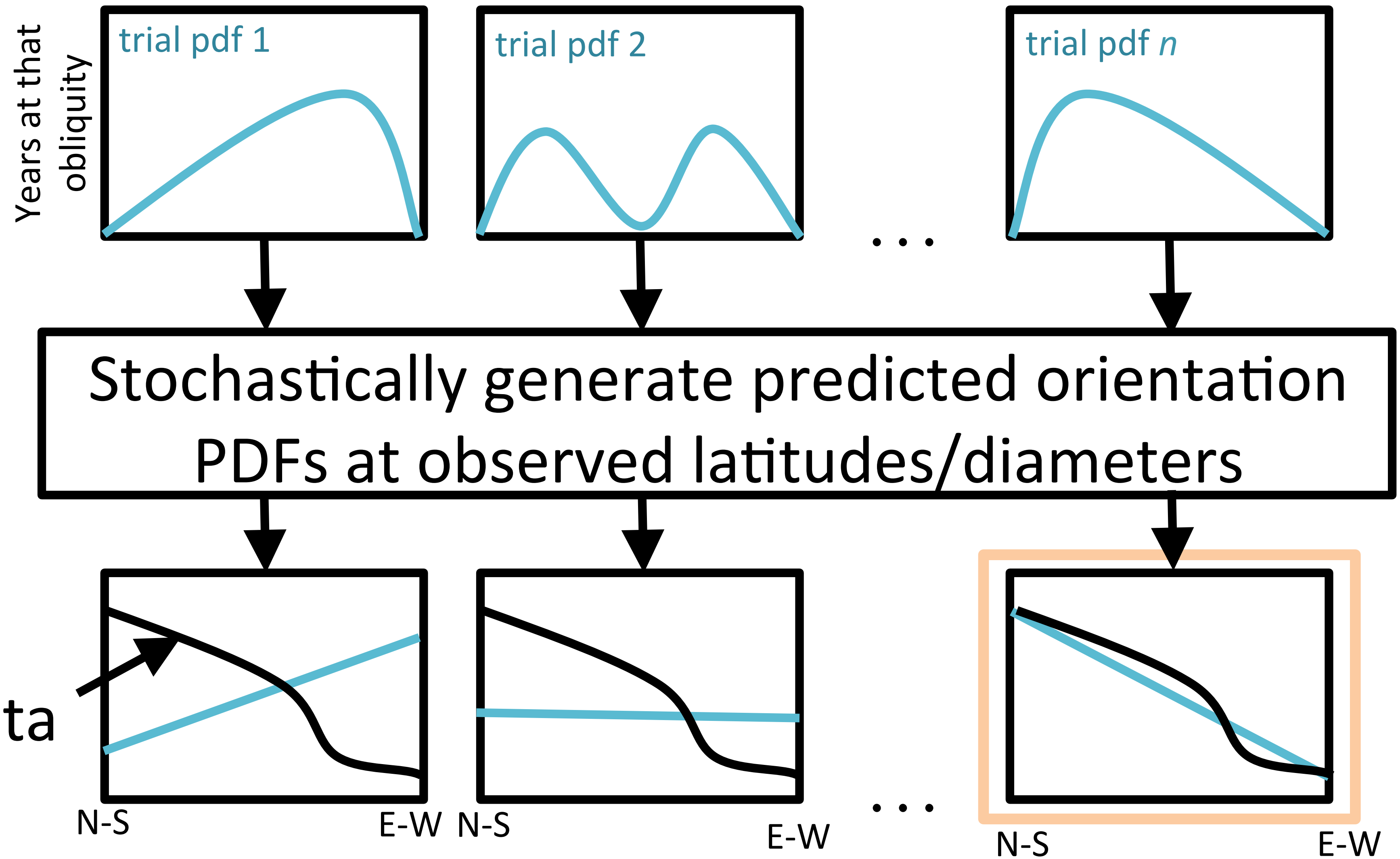
Holo, Kite, & Robbins, 2018 EPSL



How to read the Bombardment Compass

Holo, Kite, & Robbins 2018 EPSL

Equally likely obliquity PDFs

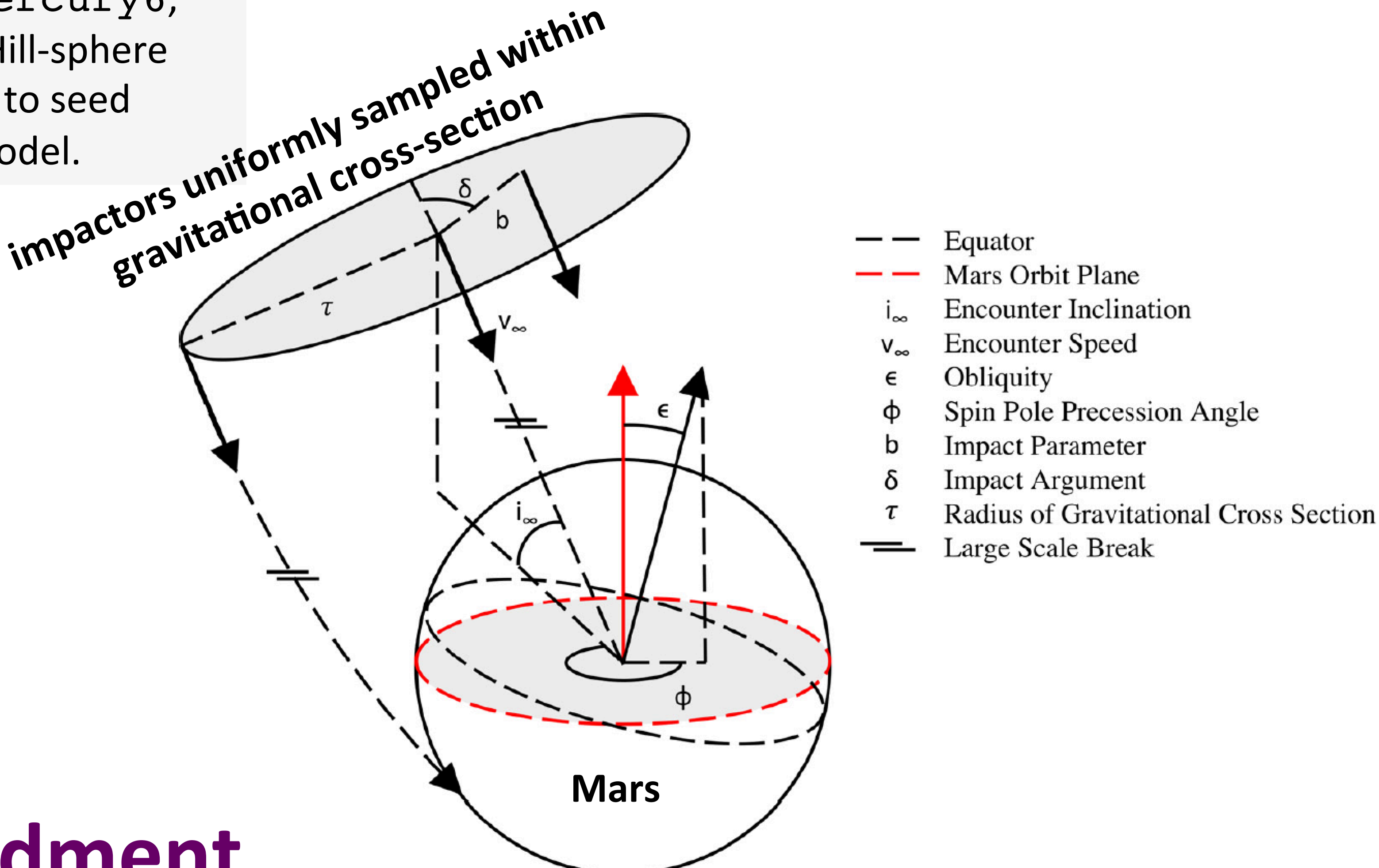


Choose best fit to data and repeat x 1000

We used the orbits of today's Mars-crossers as a proxy for the orbits of Mars-crater-formers since 3.5 Gya

Holo, Kite, & Robbins 2018 EPSL

`MPCORB.dat`, $H < 14$, n ~ 10^3 Mars-crossers, `mercury6`, 20 Myr.· Within-Hill-sphere approaches used to seed bombardment model.

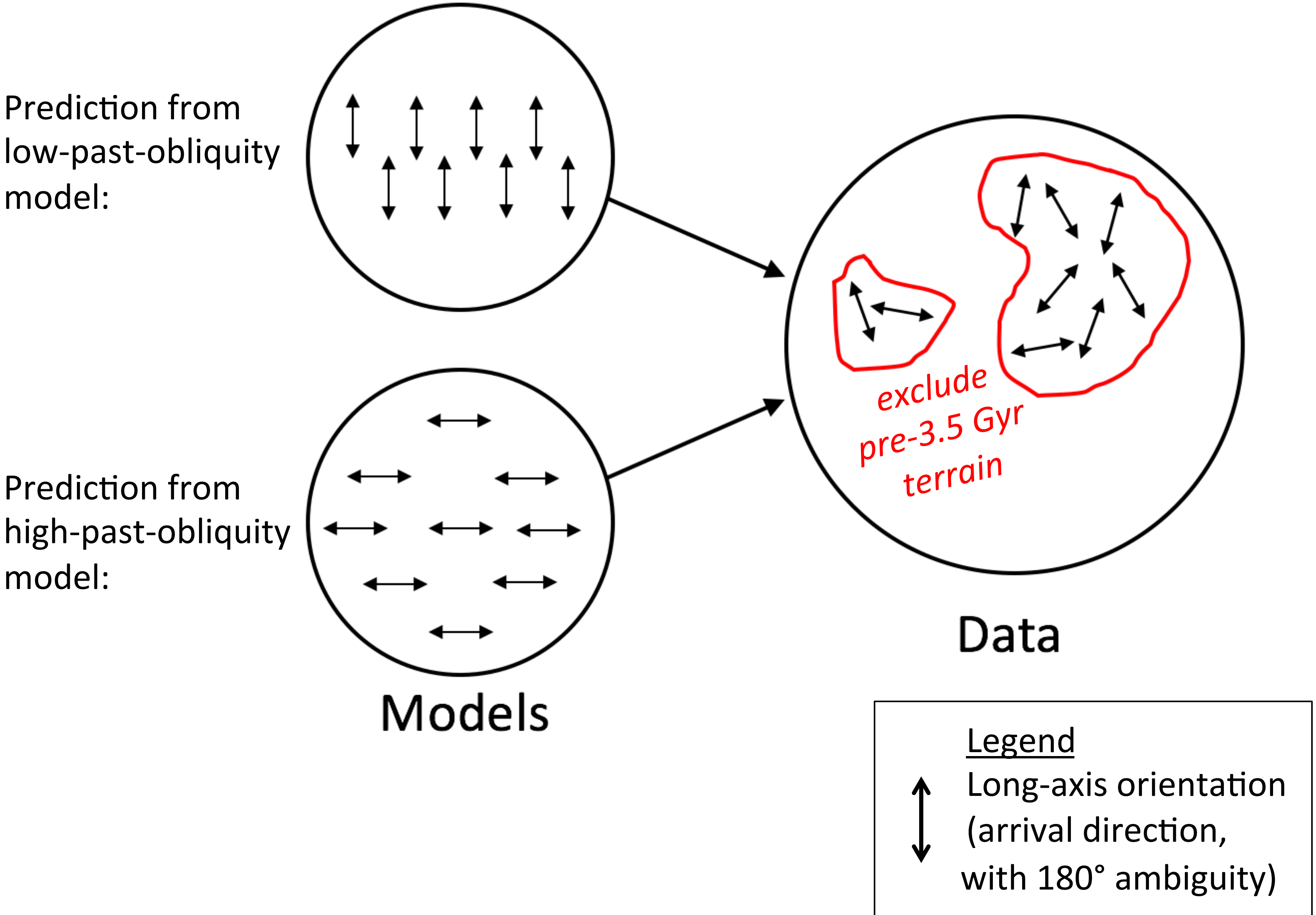


Bombardment

Long enough to average over the long eccentricity cycles computed by Bill Ward, and which have been shown to be important for Mars impact flux (e.g. Jeong-Ahn & Malhotra 2015)

Data-model comparison

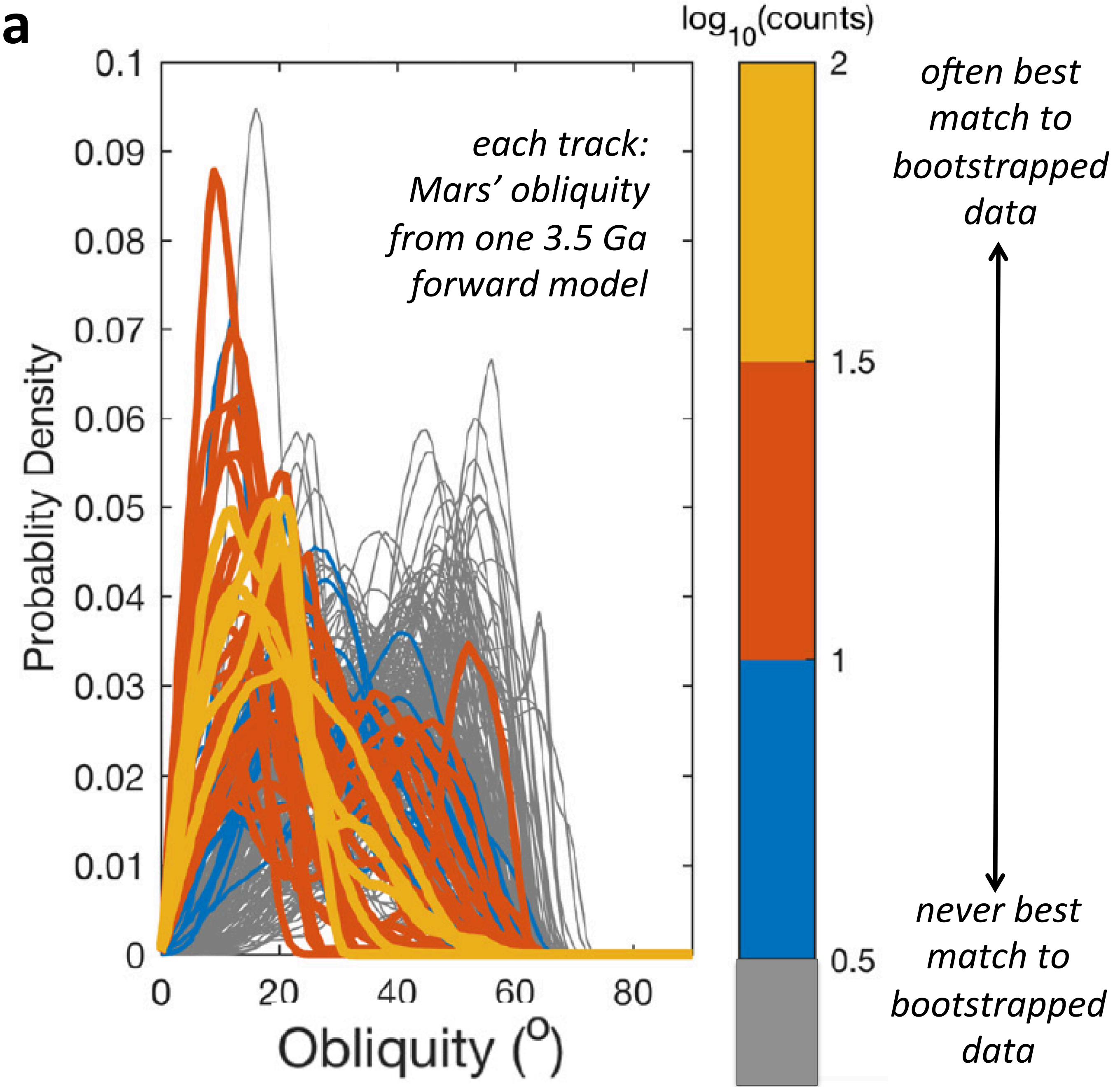
Holo, Kite, & Robbins 2018 EPSL



Geology + Retrieval

We compared bootstrapped data to 250 forward-models of Mars' chaotic orbital and spin history over the past 3.5 Ga

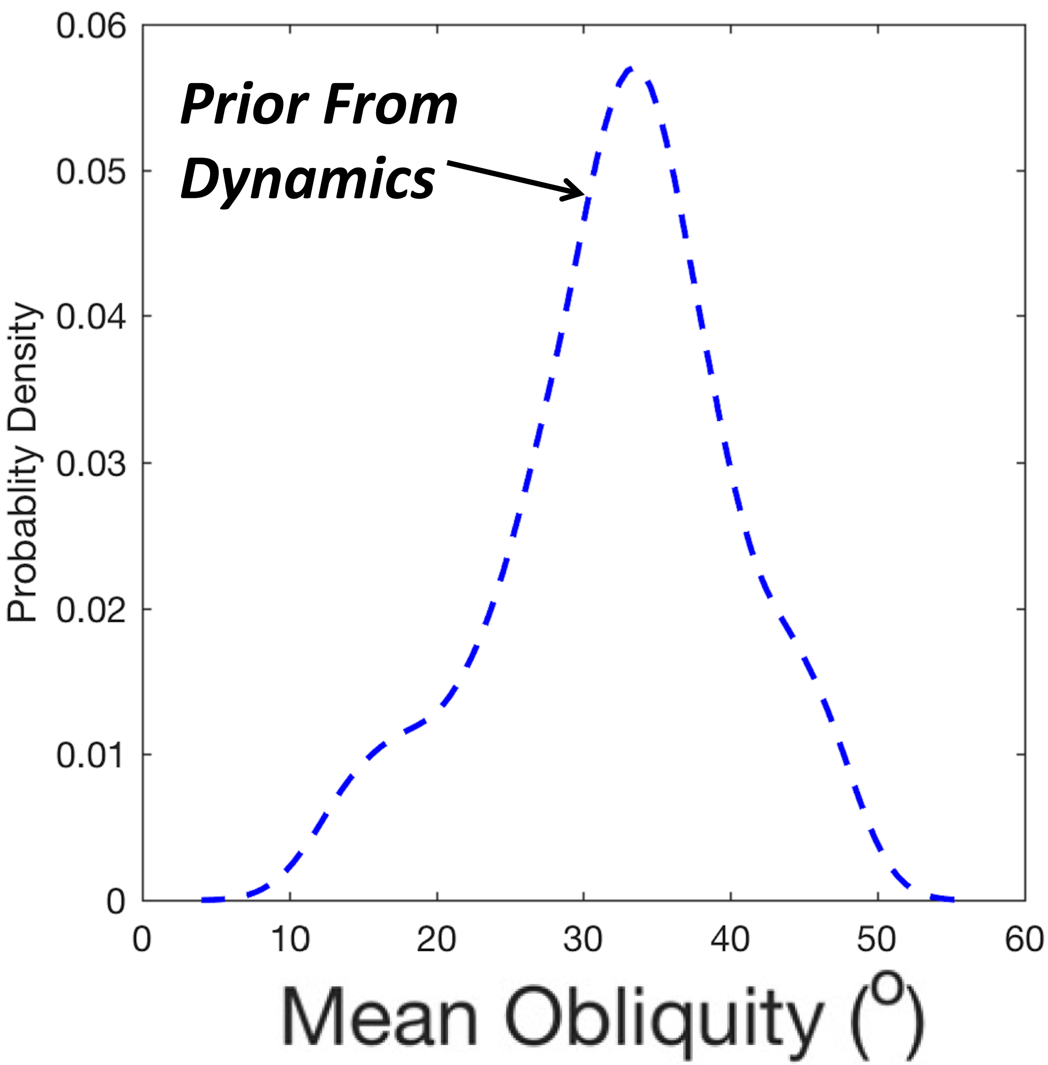
Holo, Kite, & Robbins 2018 EPSL



Lower-obliquity tracks (but not the lowest) are most favored

Retrieval

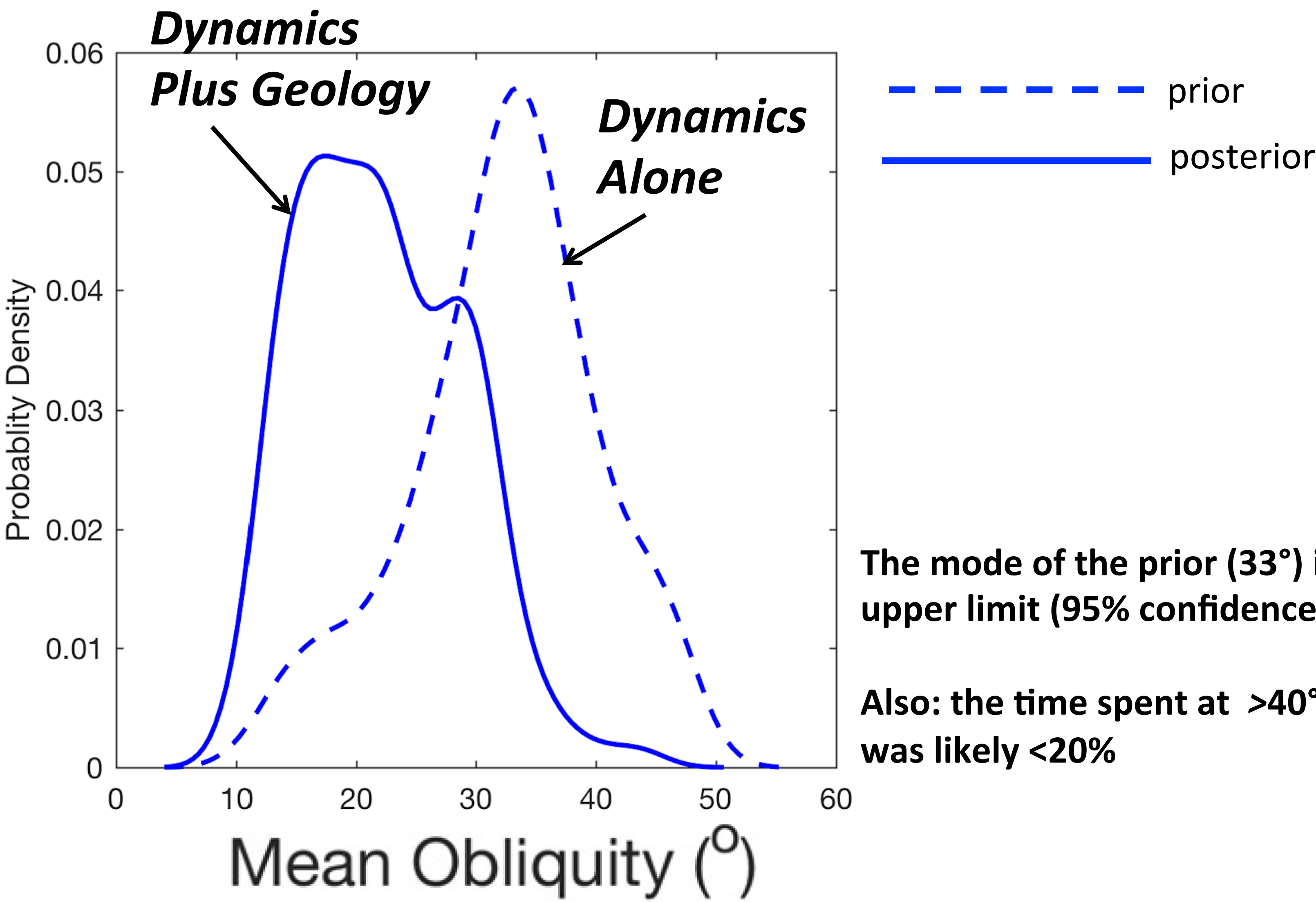
Mars obliquity, averaged over the past 3.5 Gyr = ?



Gaussian kernel (bandwidth of 2◦) smoothed PDF.
Neukum chronology model
(Hartmann results are similar)

Our stacked instantaneous-obliquity PDF is consistent with Laskar et al. (2004);

Mars obliquity, averaged over the past 3.5 Gyr, was <33°



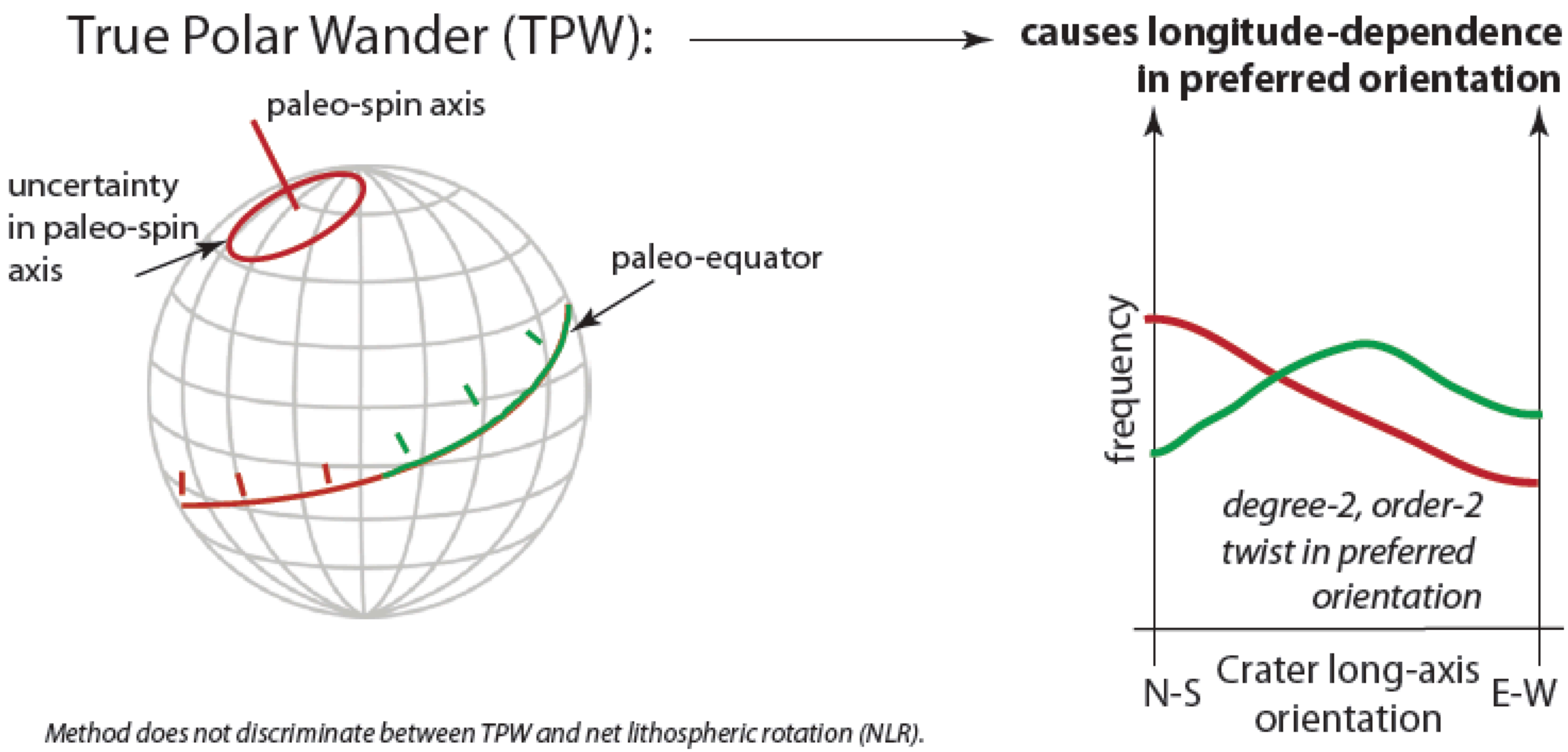
The mode of the prior (33°) is the new upper limit (95% confidence)!

Also: the time spent at >40° obliquities was likely <20%

Gaussian kernel (bandwidth of 2◦) smoothed PDF.
Neukum chronology model
(Hartmann results are similar)

Our work, by itself, does not exclude the hypothesis of non-chaotic obliquity (Bills & Keane 2019 LPSC).

Next steps for the **Bombardment Compass**:



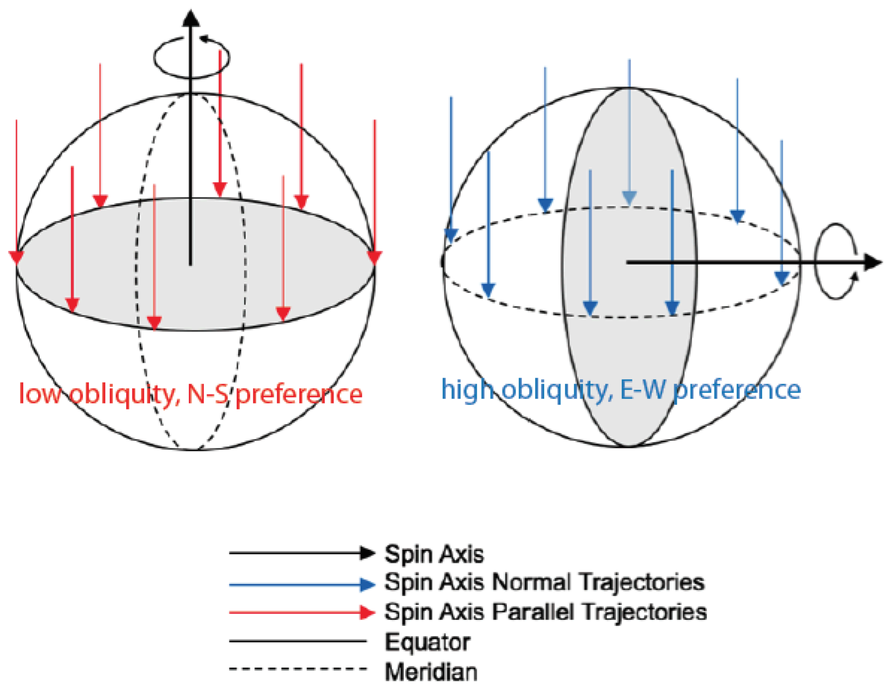
Possible future extension: The source of pre-3.5 Ga bombarders sets the maximum amplitude envelope of preferred orientation (which is modulated by obliquity). For example, clean-up of Mars' orbit would predict an isotropic distribution of impactor relative-velocity vectors. The possibility of constraining the source population of the Mars bombarders is particularly intriguing because this method is independent of geochemistry.

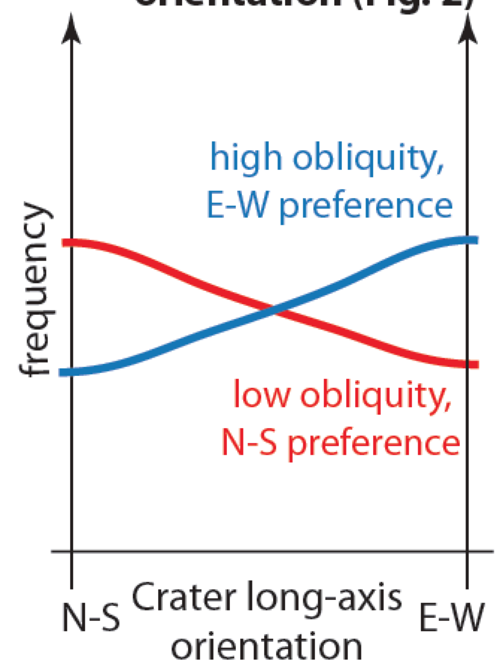
Conclusion: **The Bombardment Compass** for Mars

Holo, Kite, & Robbins 2018 EPSL

The pdf of orientations of the long axes of elliptical craters on Mars record the convolution of past obliquity, past True Polar Wander (TPW), and the past relative-velocity vectors of objects that bombard Mars: **a bombardment compass.** Mars obliquity cannot be deterministically reverse-integrated beyond ~0.1 Gya. Using the bombardment compass for the first time, **we found that Mars' mean obliquity was likely low for the last ~3 Gyr, between ~10° and ~30°,** and the fraction of time spent at high obliquities >40° was likely <20%.

Obliquity: → **sets the sign of preferred orientation (Fig. 2)**





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Bonus Slides

How to read the bombardment compass

Holo, Kite, & Robbins 2018 EPSL

Candidate obliquity histories

Candidate 3.5 Gyr obliquity pdfs

250 randomly-initiated obliquity tracks
(3.5 Gyr, 9-body simulations)

Geology

Correct for (e.g.)
burial by young lava flows,
and glacial resurfacing

Exclude terrain >3.5 Ga

Bombardment

20-Myr, >1500-body simulations
close encounters seed
bombardment geometry model,
Standard scalings relate impact
parameters to crater size

Retrieval

Compare bootstrapped geology data to candidate obliquity histories
from obliquity simulations (250x 4.5 Gyr 9-body simulations)
→ Likelihood for each candidate obliquity history

Example obliquity tracks

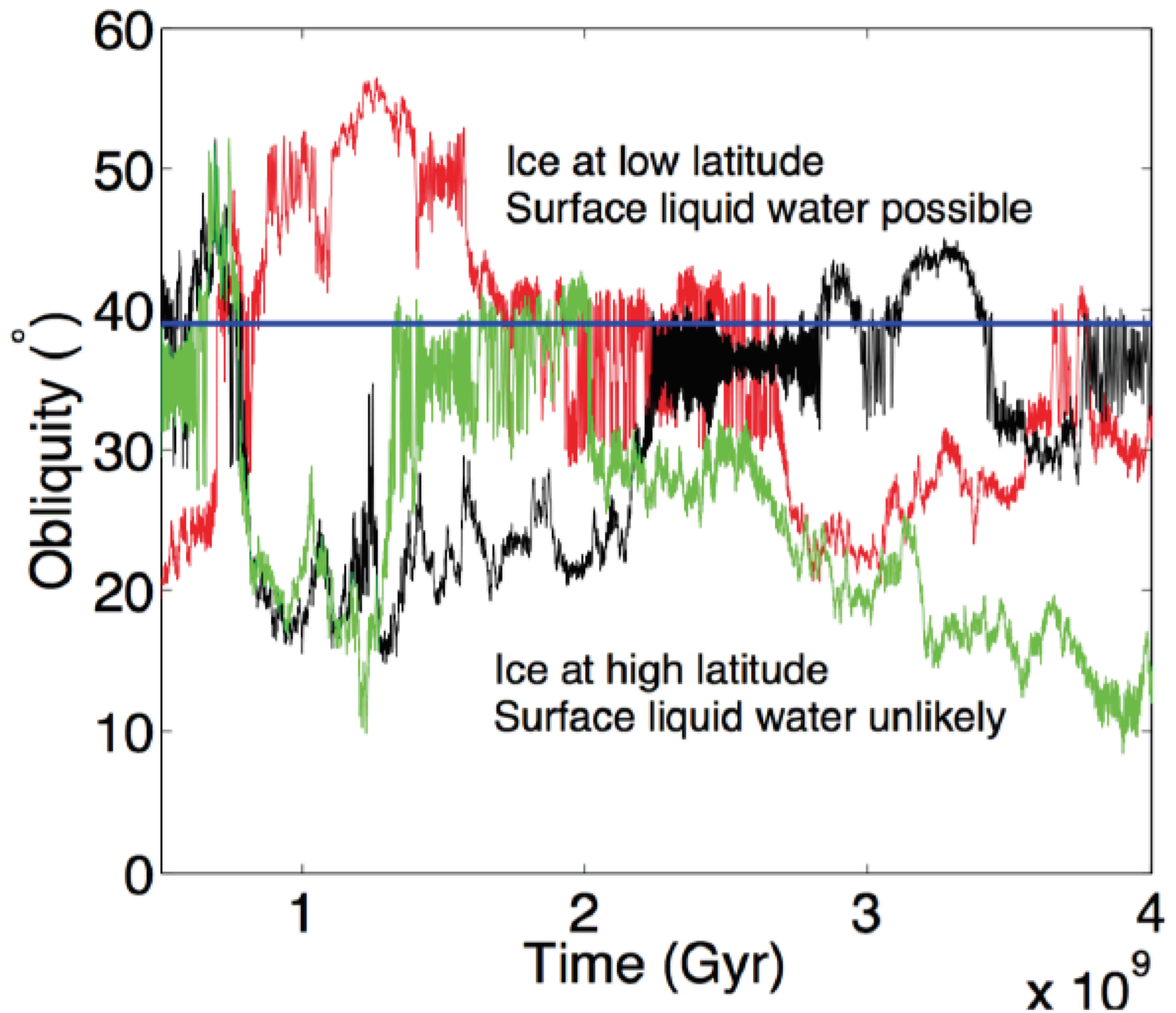


Figure 1. Obliquity histories for three equally likely obliquity trajectories (from Kite et al. NASA proposal). Above 40^0 obliquity, low-latitude ice and runoff from melting is possible.

Human-human variance is small for the purpose of retrieving post-3.5 Ga mean obliquity

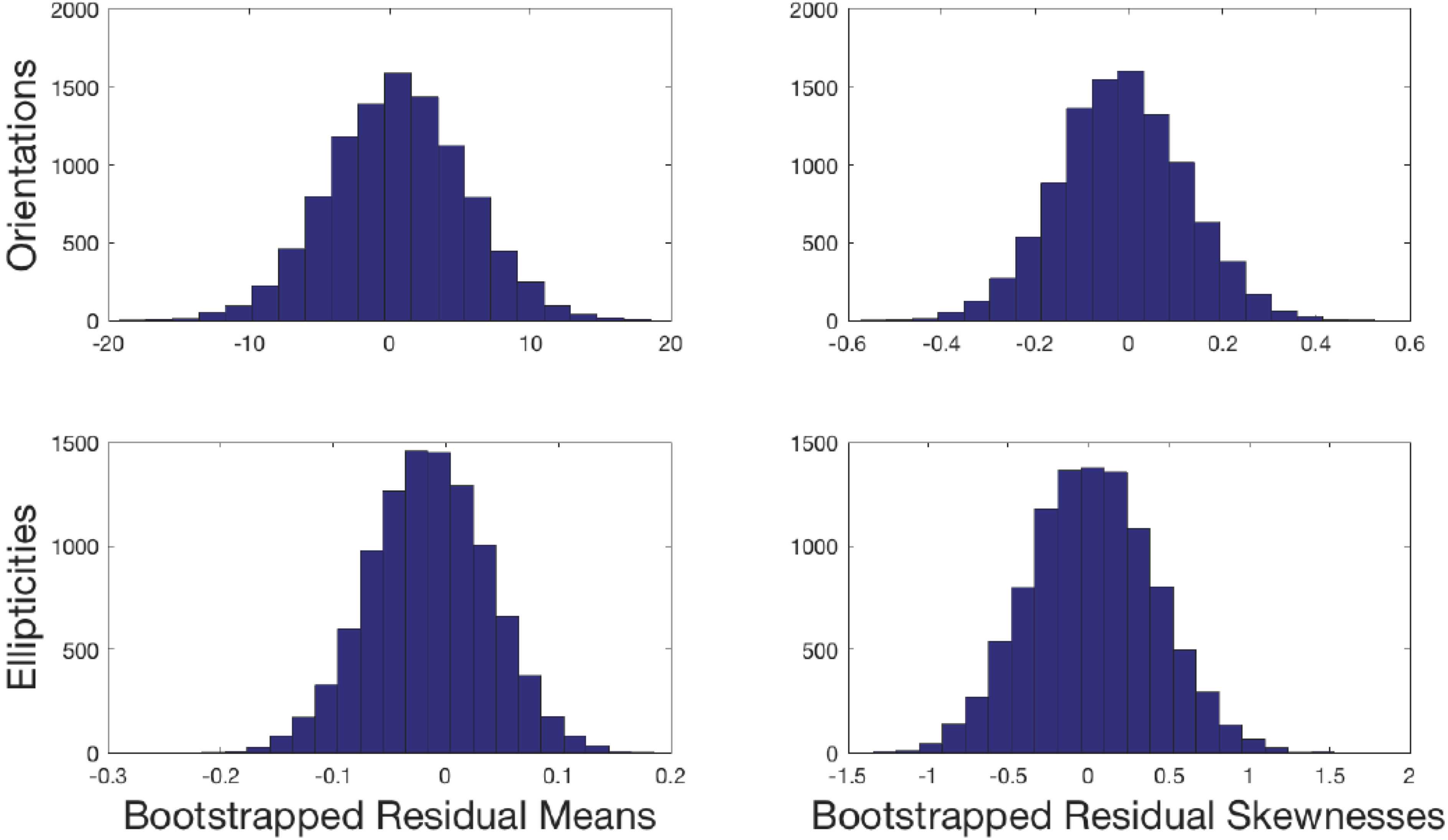
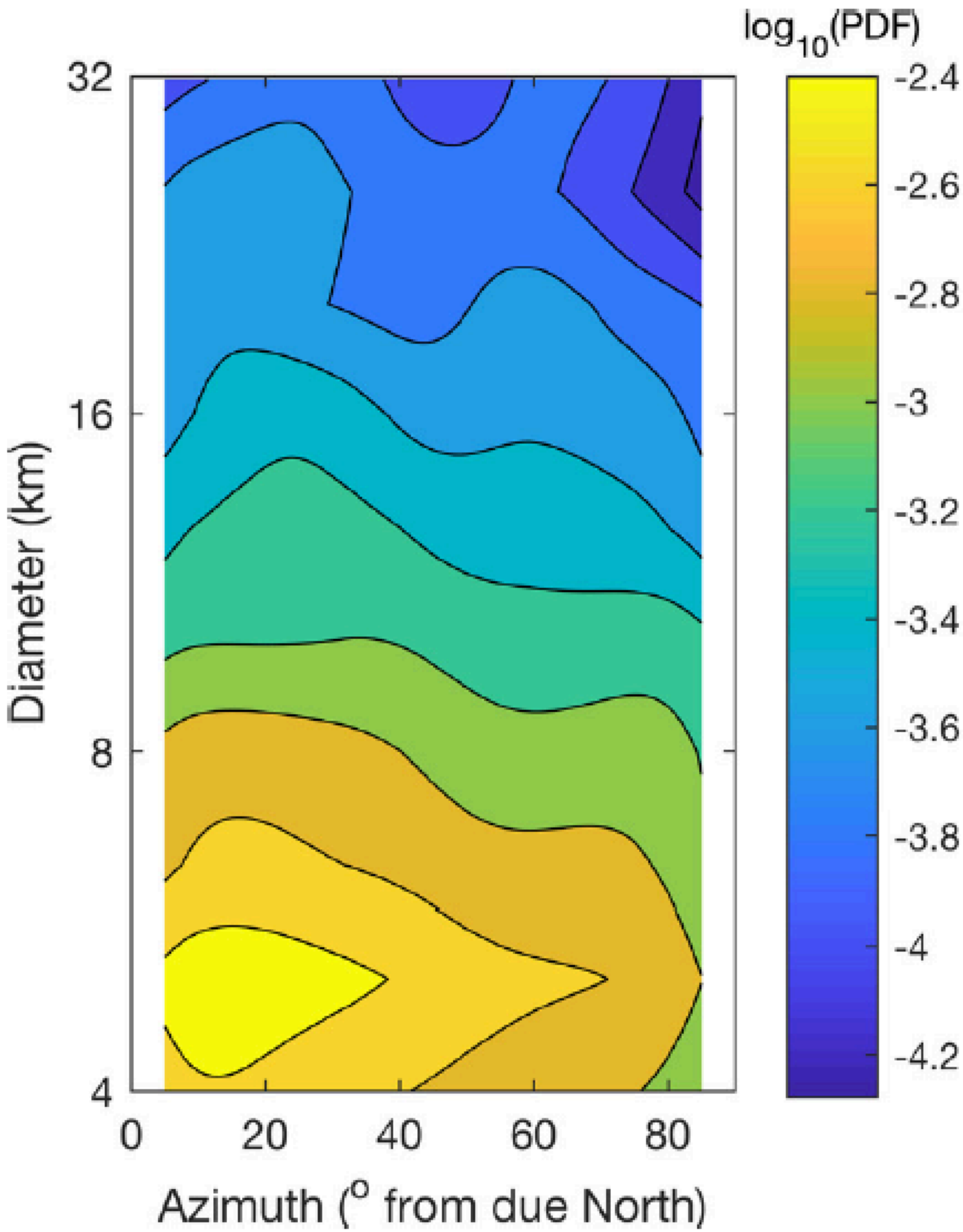


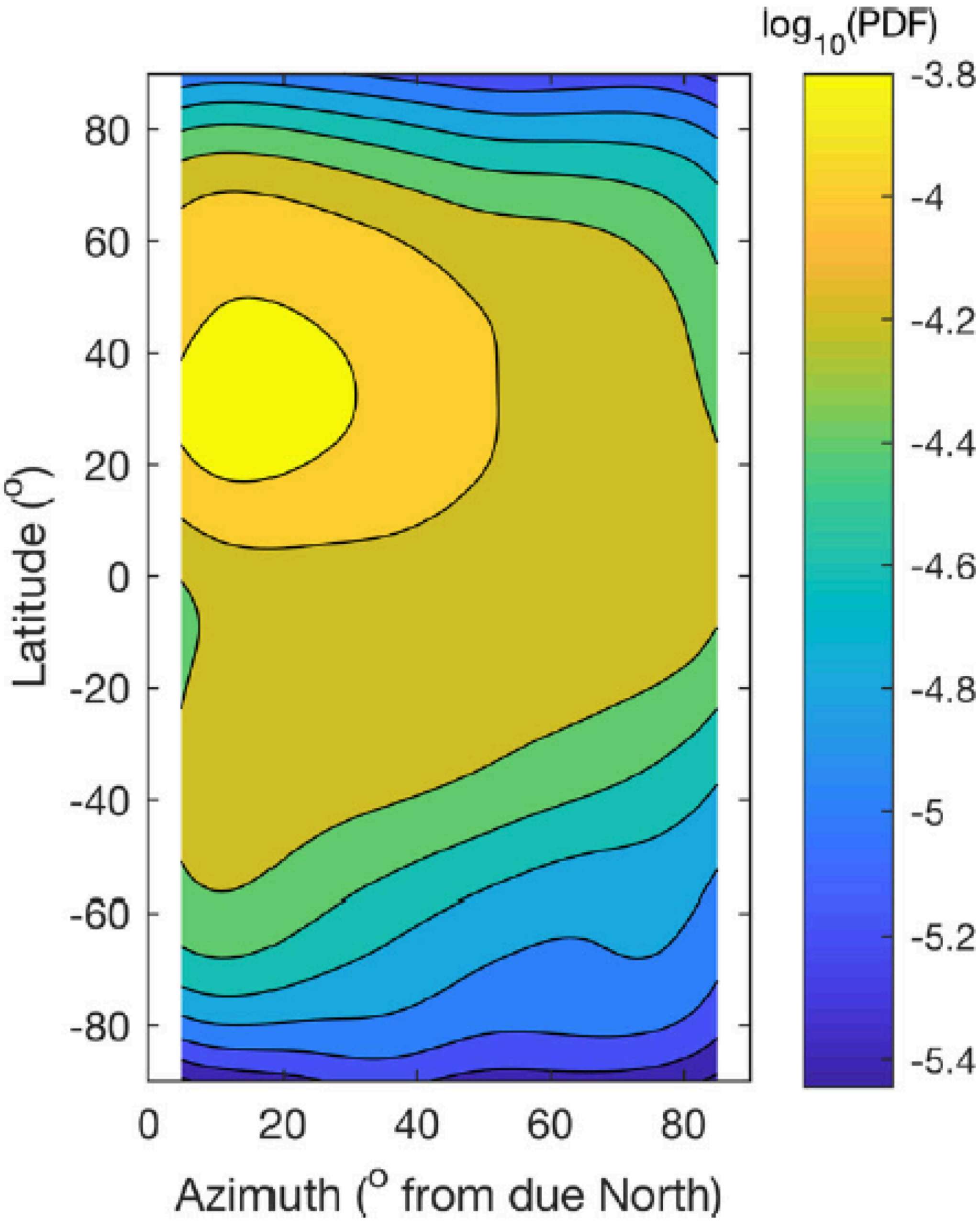
Figure 3. Histograms of bootstrapped inter-analyst residual means (left) and skewnesses (right) for both orientations (top) and ellipticities (bottom).

Mars elliptic craters show N-S orientation preference at all diameters



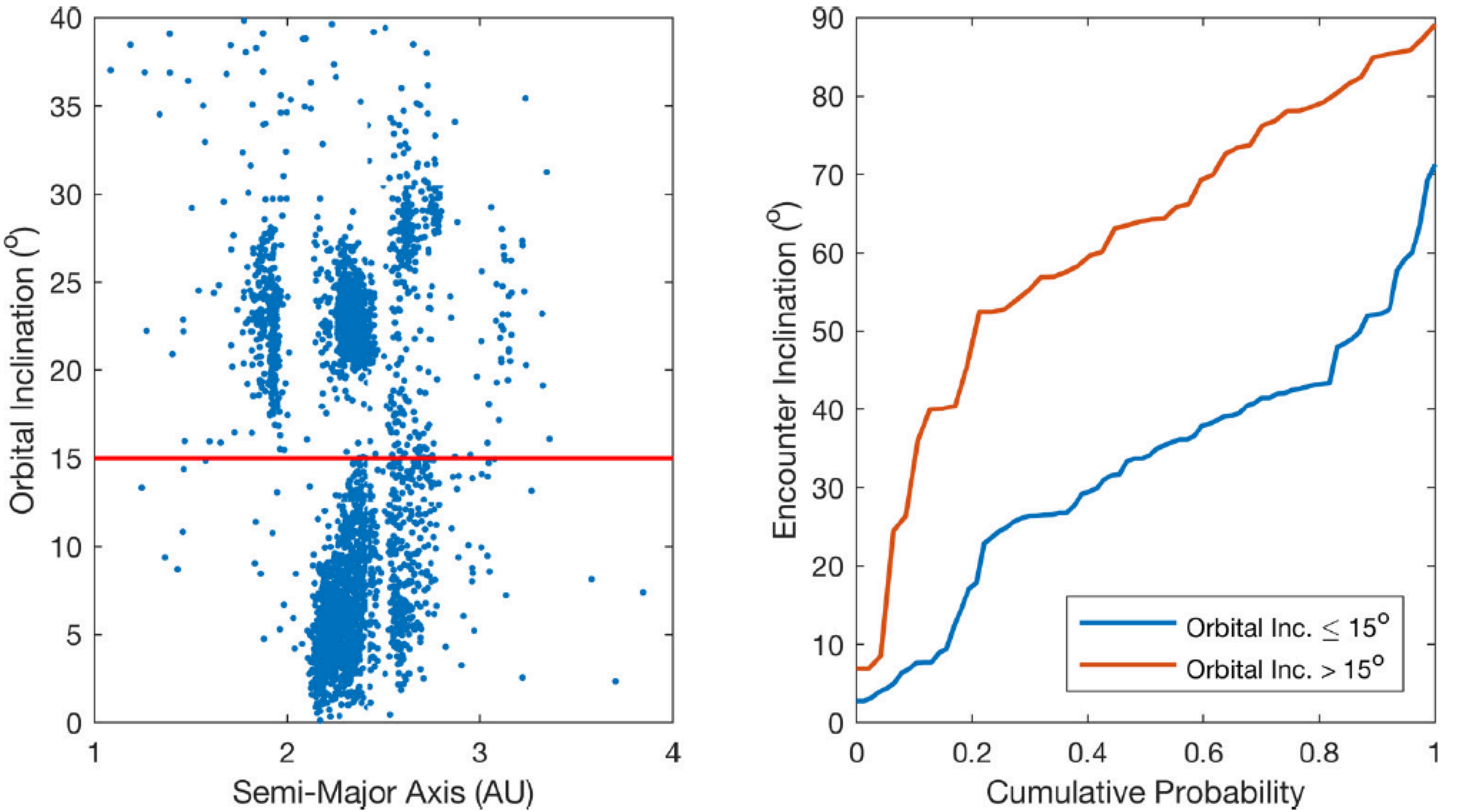
Smoothed heat maps of crater diameter vs. major axis orientation. Azimuth data has been trimmed below 5◦ and above 85◦ to minimize artifacts of the smoothing kernel. The smoothing bandwidth for both azimuth and latitude is 5◦. Diameters were smoothed in $\log_{10}$space (bandwidth of .05)

Mars elliptic craters show N-S orientation preference at all latitudes



Smoothed heat maps of latitude vs major axis orientation. Azimuth data has been trimmed below 5◦and above 85◦to minimize artifacts of the smoothing kernel. The smoothing bandwidth for both azimuth and latitude is 5◦. Diameters were smoothed in log10space (bandwidth of .05).

Modest orbital inclinations ←→ Large encounter inclinations



Model predictions for constant Mars obliquity (planet average)

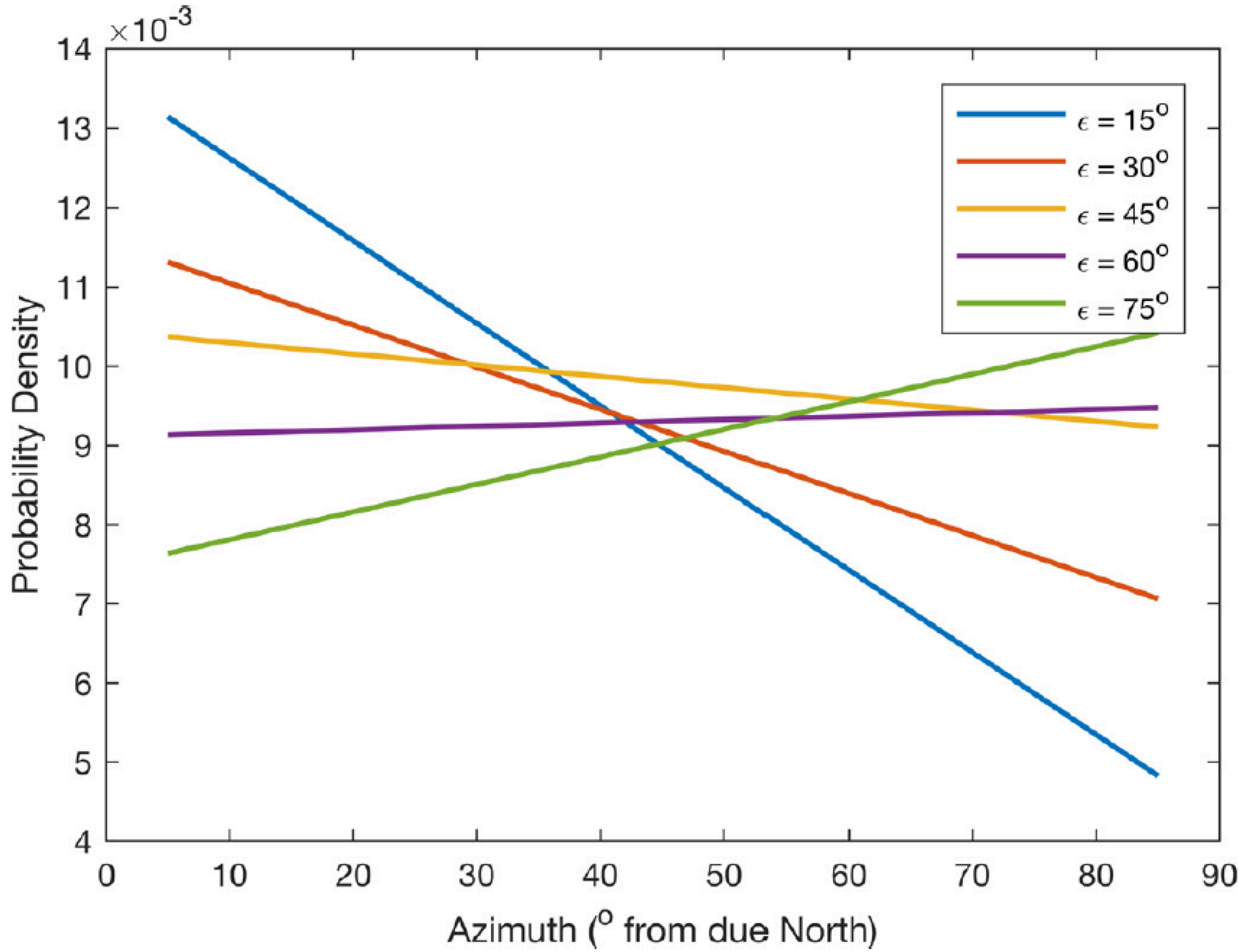
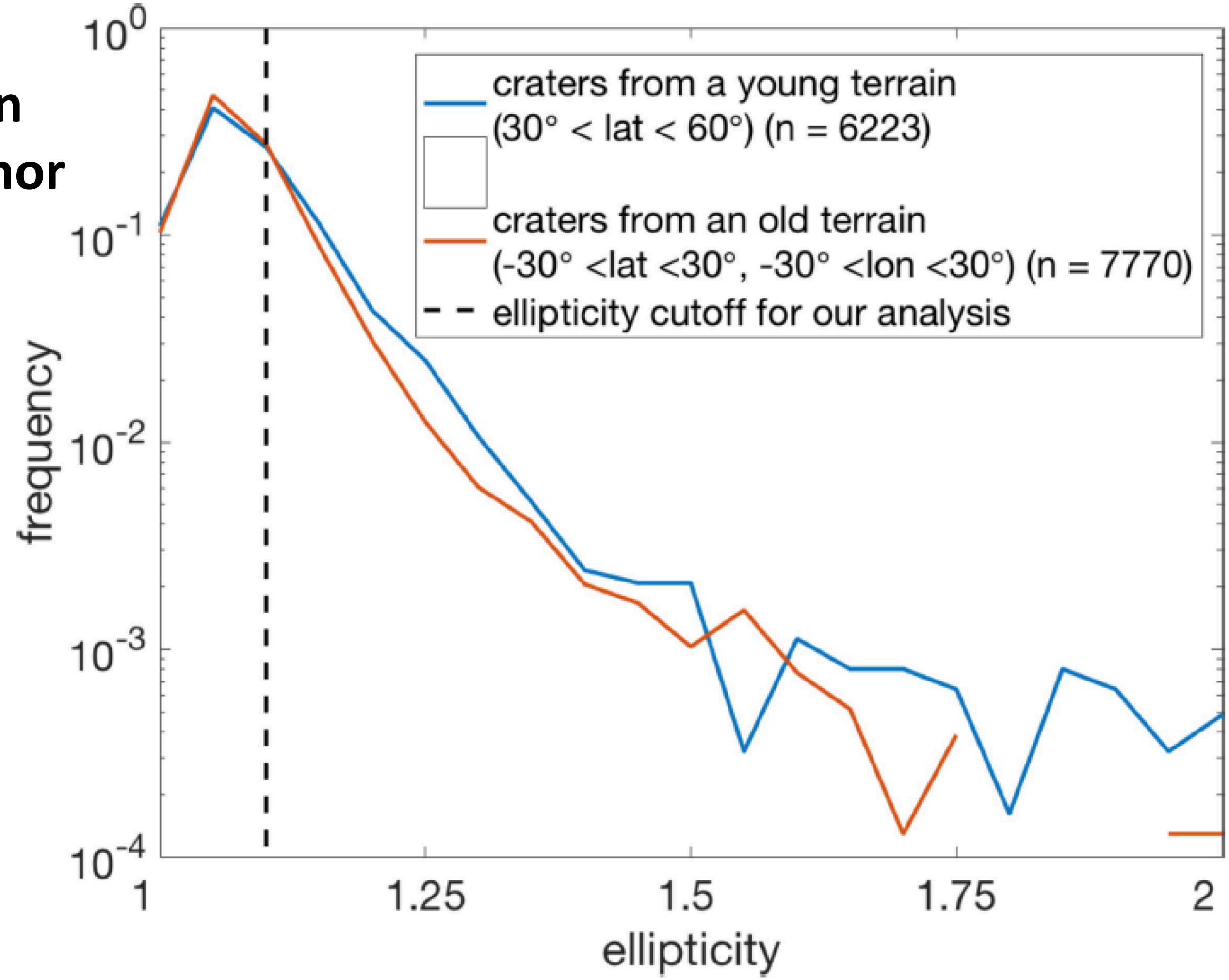


Fig.7. Gaussian kernel estimate of crater azimuth PDF (5◦ bandwidth) as a function of a single fixed obliquity prior to geologic correction. At low obliquities, there is a preference for North–South oriented elliptic craters. This trend is reversed at high obliquities. Azimuth data has been trimmed below 5◦and above 85◦to remove artifacts of the kernel smoothing process.

Demonstration that post-impact modification of crater ellipticity is minor



The ellipticity histograms of fresh craters and ancient-terrain craters are almost the same. There is a slight deficit of elliptical craters on old terrains. This demonstrates that anisotropic post-impact modification is minor, because ancient craters are more modified by surface processes than fresh craters. Thus, anisotropic modification would produce an excess of elliptical ancient craters, not the slight deficit that we observe. This excludes e.g. snowmelt-driven anisotropic erosion as a major contributor to N-S crater elongation.

Alternative hypothesis for Mars elliptical craters does not survive comparison with the newly available large global databases

Alternative hypothesis: Elliptical craters on Mars resulted from inspiralling Mars-orbiting satellites and rings (Schultz & Lutz-Garihan 1982, Arkani-Hamed 2005).

Prediction: One or more bands of elliptical craters that are tightly-collimated in (i) space, (ii) orientation, and (iii) ellipticity. These should be (respectively) (i) a great circle, (ii) E-W after TPW correction, and (iii) high and distinct from the background flux of circumsolar impactors.

These predicted collimations have not been observed by us in the database of Robbins & Hynek (2012).

Moreover, there is no trend to a greater frequency of higher ellipticity craters at lower latitudes (as might be expected for areocentric impactors with modest TPW).

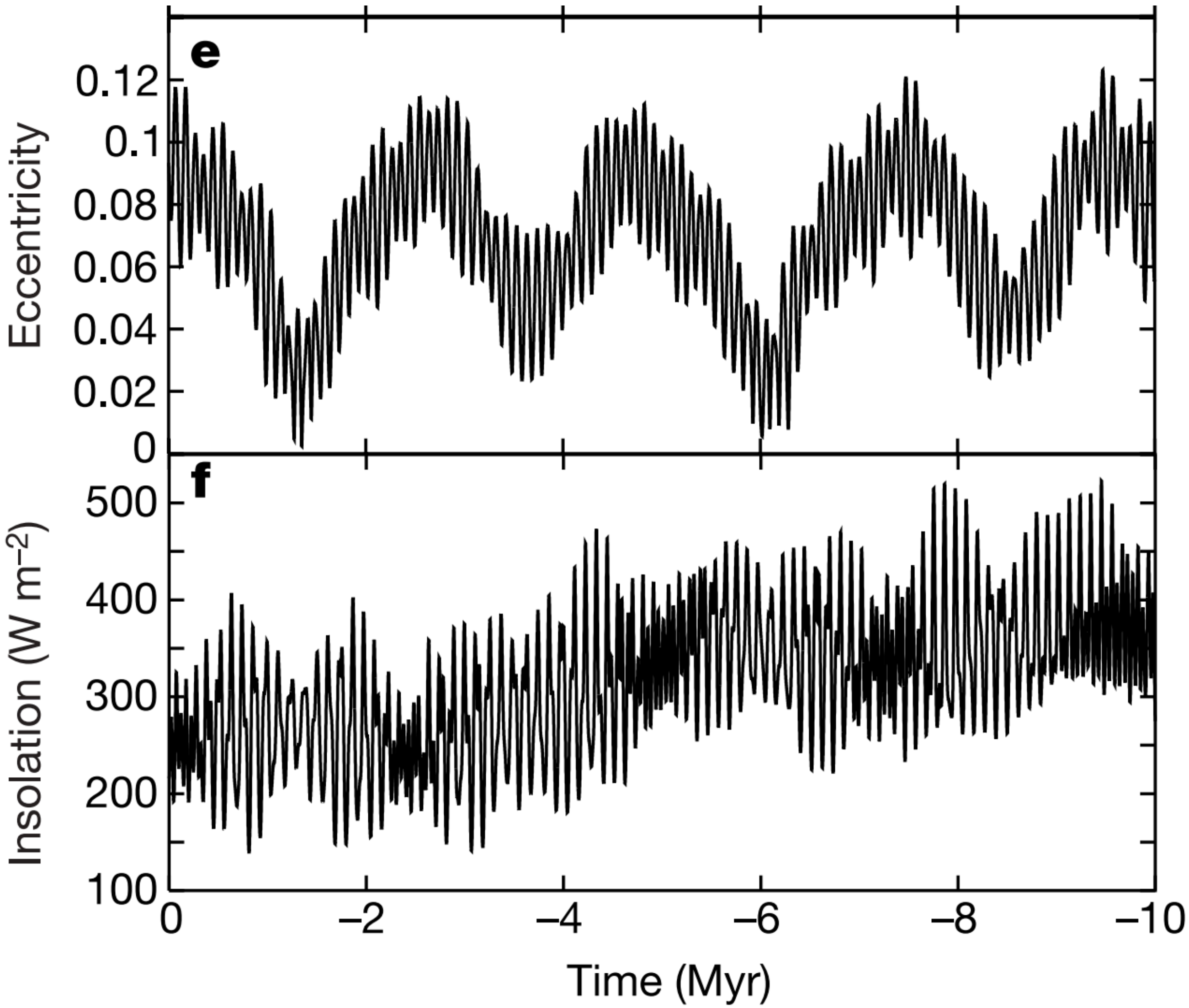
Moreover, theory predicts that inspiralling moons are tidally shredded and yield a ridge, not craters (Dombard et al. 2012, Black & Mittal 2015, Hesselbrock & Minton 2017, Fan & Kite LPSC 2018).

Bottom Line: We do not think that inspiralling moons, if any existed, were a <u>major</u> contributor to the elliptical-crater orientation anisotropies on Mars (see Sefton-Nash et al. 2019 for an alternative view).

We want to determine:

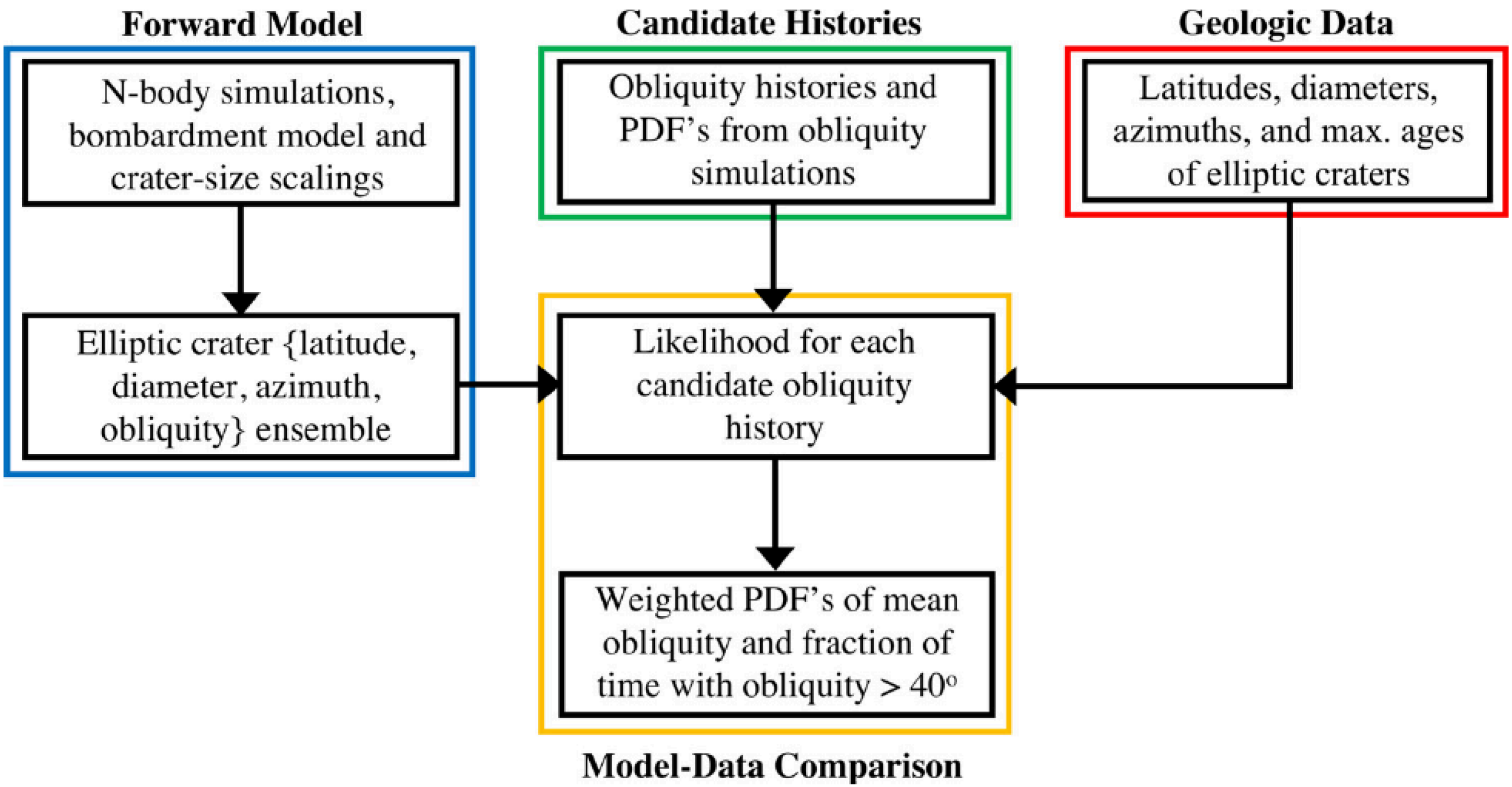
$P(\theta \mid P(\lambda, D), N_{craters}, M_i)$, which describes the PDF of elliptic crater long-axis orientations, where $P(\lambda, D)$ is the joint latitude-diameter PDF, $N_{craters}$ is the number of craters that bombard the surface, and M_i is the obliquity model used. $P(\lambda, D) \sim edf(\lambda, D) + noise$ where edf is the empirical distribution function, which is estimated by bootstrapping.

Q: Why 20 Myr for bombardment integrations?
A: Long eccentricity cycles!



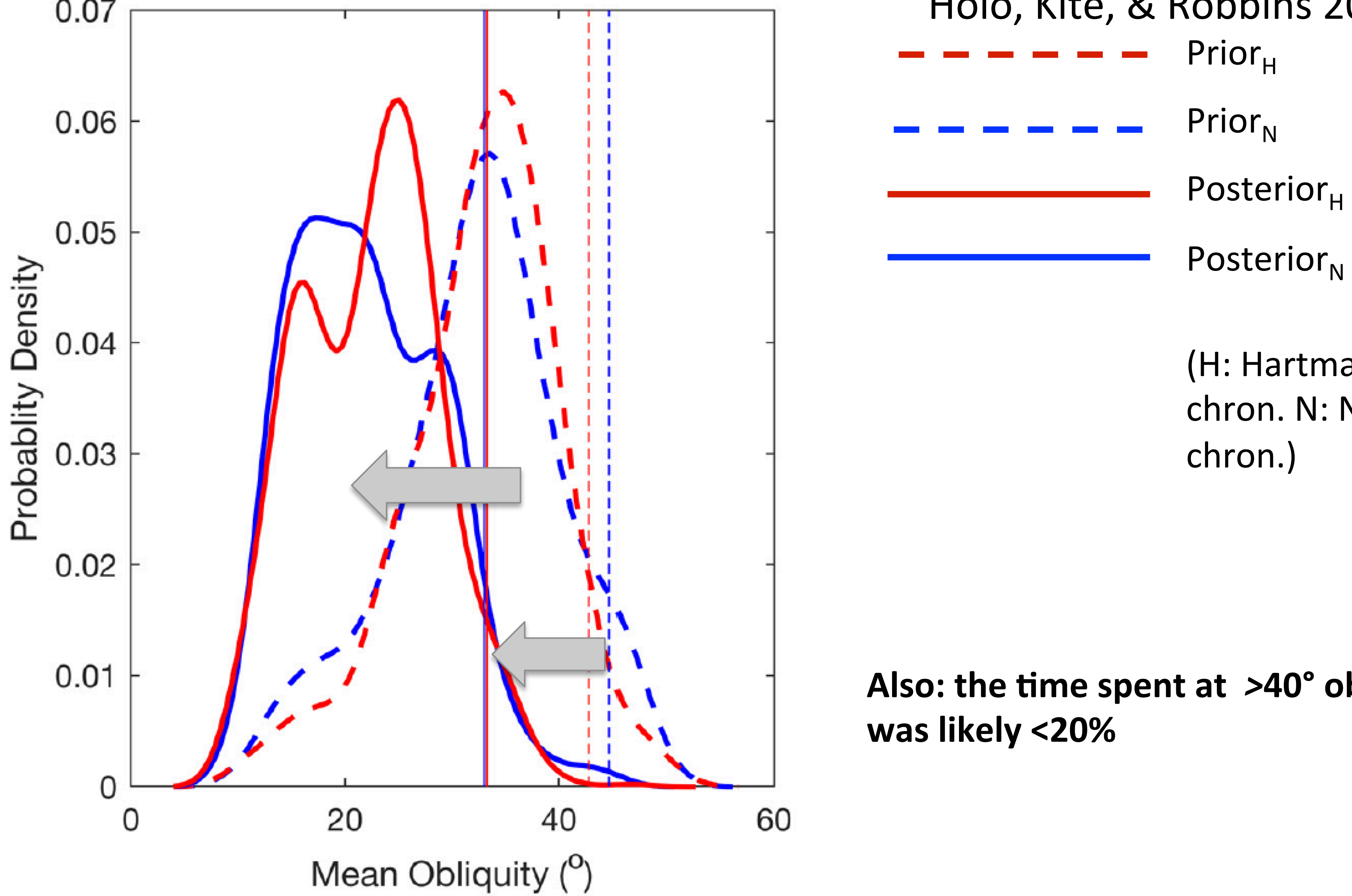
Laskar 2002
Nature

Details of retrieval



Mars obliquity, averaged over the past 3.5 Gyr, was <35°

Holo, Kite, & Robbins 2018 EPSL



(H: Hartmann chron. N: Neukum. chron.)

Also: the time spent at >40° obliquities was likely <20%

Gaussian kernel (bandwidth of 2◦) smoothed PDF. Vertical lines show 95th percentile locations.

Our work, by itself, does not exclude the hypothesis of non-chaotic obliquity (Bills & Keane 2019 LPSC).

The time spent at >40° obliquities was likely <20%

Prior$_H$

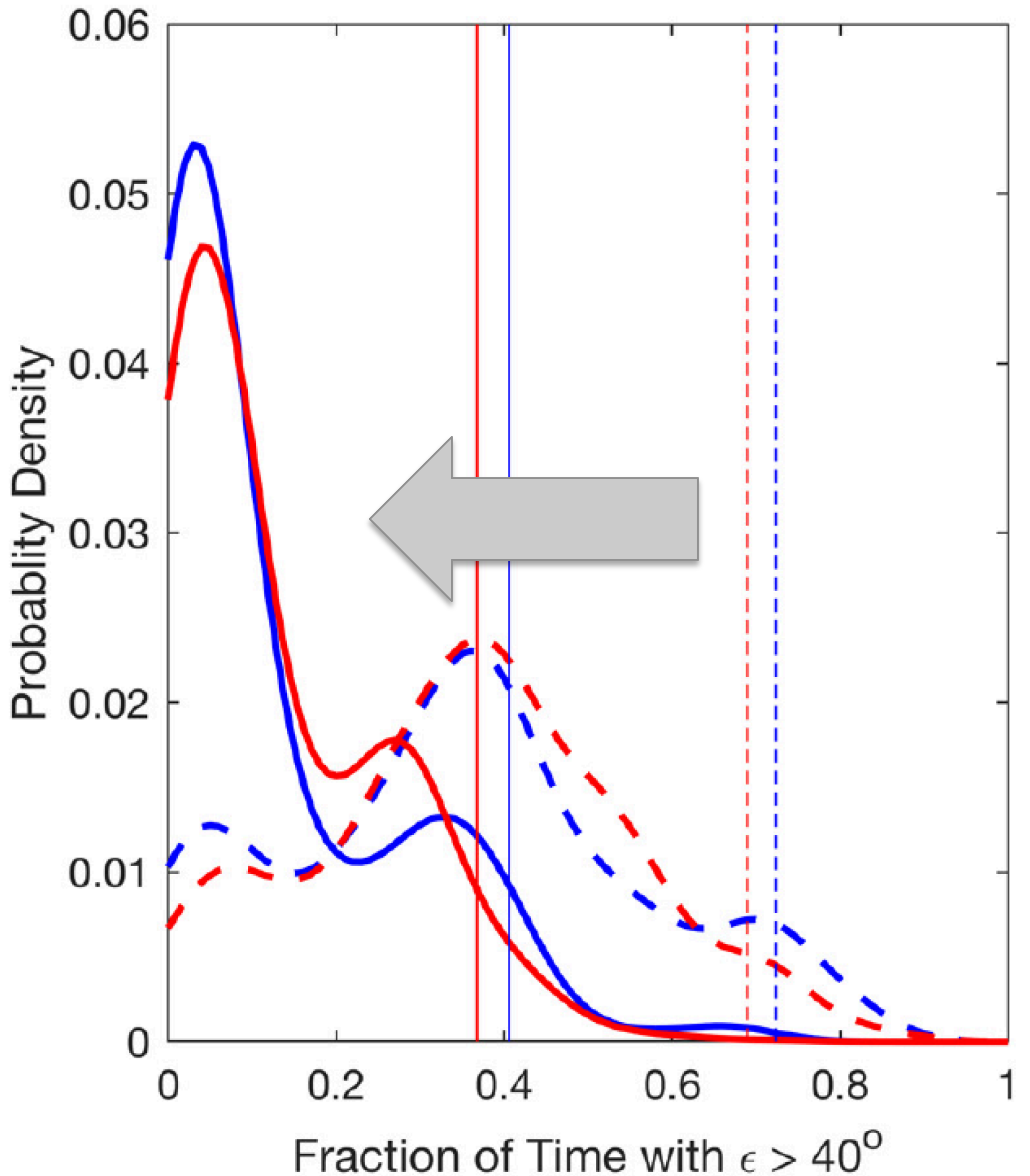
Prior$_N$

Posterior$_H$

Posterior$_N$

(H: Hartmann chron. N: Neukum. chron.)

Gaussian kernel (bandwidth of 5%) smoothed PDF. Vertical lines show 95th percentile locations.



Hungarias

Only 1 Hungaria hits and it doesn't matter

It could matter if there's a long-lasting Hungaria population, and this is a possible hypothesis

→

But Bottke et al (2012), which claims there's a long-lasting Hungaria population is objected to by newer papers.

There's another problem with the long lasting Hungaria hypothesis. The removal of the Hungarias must have been size insensitive, in contrast to modern Mars crossers which have a NEO like SFD. But that would produce a different crater SFD on Mars. Such a different crater SFD is indeed observed, but ONLY IN THE NOACHIAN and we are looking exclusively at post-Noachian terrains in this paper.

(*Bombarder-orbit uncertainty is not important for the last ~3.5 Ga of Mars history, for which we expect that small bodies sourced from the asteroid belt are the main bombarders of Mars (Nesvorný et al. 2017).*

The Hungarias, which have high albedo, are only a minor contributor (~1%) to the impact flux at the present day (as for the past ~3.5 Ga; note that the conclusions of Bottke et al. 2012 and Ćuk 2012 have been significantly modified by the findings of Ćuk & Nesvorný 2018).