Dear Frits Hilgen,

Thank you very much for taking the time to provide a very constructive review.

Here we reply directly to your comments.

1) Statistical identification of the very long period ~2-Myr eccentricity minima. The eccentricity nodes associated with the very long, 2-Myr, eccentricity cycle are now visually determined in their proxy records, but preferably they should also be pinpointed by means of statistical analysis, such as complex amplitude modulation or the method outlined in Meyers (2015). Such an independent statistical confirmation of the position of these nodes is critically important next to their visual determination to convince the reader of the correctness of the conclusions drawn in the ms. Otherwise the authors have to clearly state why they did not carry out the necessary and logical statistical analysis. Especially the statistical method introduced by Meyers (2015) seems very helpful to reconstruct eccentricity and capture the nodes associated with the very long term eccentricity cycle, so the question is why such statistical methods have not been applied. I guess that the authors may well have given it a try, so in that case, why was it not included in the ms (even to show that these statistical approaches do not work well in this particular case)? The authors may thus wish to discuss in some detail the (dis)advantages of a visual versus a statistical approach. This topic is discussed in some detail by Hinnov (2013) and has been presented in more detail by Steve Meyers in some of his presentations. The point here is that visual recognition of cycle patterns albeit being subjective can be considered an expert system, being able to identify distortions of the signal that are very commonly encountered in cyclostratigraphic records (see e.g. point 2) and that may cause problems when applying statistical techniques (see also Hilgen et al., 2015)

This is a very important point. Extraction of the amplitude modulation (AM) using statistical methods like those implemented in the *Astrochron* package (Meyers 2014) or the ENVELOPE (Schulz et al. 1999) routine are important for independently testing the visual recognition of cycle patterns. AM analysis on XRF core data using the ENVELOPE routine was applied at ODP Site 1262 (52-60 Ma) and ODP Site 1258 (47-54 Ma) records in Westerhold et al. (2012) in order to search for the very long eccentricity minima. Meyers (2015) used a* values (red over green ratio from [shipboard] color core scanning) from ODP Site 1262 between PETM and ETM2 (Elmo) to test the existing astrochronologies (Lourens et al. 2005, Westerhold et al. 2007). Both methods (Astrochron, ENVELOPE) already provide sound statistical testing of chronologies at ODP Site 1258 and Leg 208 sites.

In our manuscript we have not explicitly included results of these statistical analysis. But based on the reviewer´s recommendation we will now provide the statistical analysis on XRF Fe intensity data from ODP 1258, 1262, and 1263 in the revised ms: these data and analyses have already proven their great potential in testing astronomical solutions (Lourens et al. 2005, Westerhold et al. 2007, Westerhold et al. 2012, Meyers 2015). Following the approach of Zeeden et al. (2015) we filtered out the short eccentricity cycle (100-kyr) and applied a broad bandpass filter (0.004 to 0.016 cycles/kyr; 250-62.5 kyr per cycle; Tukey window) and subsequently made a Hilbert transform to extract the AM using the *Astrochron* software package (Meyers 2015) for Site 1258 and 1263 data. As a basic age model we used the 405-kyr age model as given in Table 46 of the submitted dataset. The resulting 405-kyr

AM of the XRF Fe intensity data are plotted against the La2004, La2010, and La2011 orbital solutions (Fig. 1 of this reply). The AM of the orbital solutions were extracted as described in Westerhold et al. 2012. For ODP Site 1262 we plotted the 405-kyr AM of XRF Fe intensity data using the Option2 age model of Westerhold et al. 2012 (the Option2 W12 405-kyr age model is at Site 1262 almost identical with the updated 405-kyr age model in the submitted manuscript for the 53 to 58 Ma interval). We followed this procedure to demonstrate that similar results can be obtained with different approaches (Astrochron vs ENVELOPE).

The position of the very long eccentricity minima in the AM of XRF Fe intensity data in the interval from 46 to 59 Ma (blue bars in Fig. 1 below) best fits with minima in the La2010b and La2010c orbital solutions. In contrast, the minima do not match minima in the La2004 solution suggesting that this solution is not appropriate for testing geological data. The La2010a-d and La2011 solutions fit to geological data back to 50 Ma. Beyond 50 Ma these solutions diverge (as discussed in detail in Westerhold et al. 2012). Only the La2010b and La2010c solutions exhibit very long eccentricity minima at ~53.3 and ~54.5 Ma and thus were chosen for detailed astronomical tuning of the records presented in our manuscript. The minimum at ~54.5 Ma is a very prominent feature in the data of the Leg 208 sites that has been intensively discussed (Lourens et al. 2005, Westerhold et al. 2007, Meyers 2015). The minimum at ~53.3 Ma is also detectable using the statistical methods but can be much better seen by visual inspection of the data (see manuscript Fig. 2b, 3, and 4).

As pointed out by the reviewer the latter leads to the discussion of the (dis)advantages of a visual versus a statistical approach. With respect to our study for the revised manuscript we will have both a statistical and visual approach which lead to the same results.

We do not want to repeat what already was discussed by Hinnov (2013) and Hilgen et al. (2015). But one important aspect complicating the analysis of the data is the strong influence of the hyperthermal layers on sedimentary features and data. We will further comment on this aspect in the reply to issue 2 below.

Clean AM can be extracted from eccentricity modulated precession dominated records. This is the case for the Leg 208 sections from 56 to 54 Ma, as already shown in Lourens et al. (2005), Westerhold et al. (2007) and Meyers (2015). Due to a drop in sedimentation rates around the ETM2 event at Leg 208 sites (54.050 Ma), precession cycles are not the dominant frequency over the 52 to 47 Ma interval of Leg 208 sites. Instead, the lower sedimentation rates resulted in the recording of more pronounced eccentricity cycles. Isolating the AM of the 100 and 405 eccentricity cycles in the sediments should be easy, and as mentioned by Laskar (1999): *"… in the climatic precession, the two terms p+g4 and p+g3 should induce also a modulation of frequency g4 − g3 … (period ca. 2.475 Ma) in the 19 ka term of the climatic precession, as well as in the 95 and 125 ka terms in the eccentricity. For these two last terms, it should be noted that even if the resolution of the data does not make it possible to discriminate between the 95 and 125 ka terms, the modulation of the amplitude of these terms is the same, and thus could still be discernible in the geological record*". Indeed, Site 1263, which is characterized by the highest sedimentation rate of the Leg 208 sites, still preserves the best AM record of the sites in the transect (Fig. 1 below).

We agree that visual recognition of cycle patterns in data benefits from many years of experience. Aberrations in the data by additional effects (e.g. dissolution during hyperthermal events) will surely cause issues when applying statistical techniques as also already discussed in Hilgen et al. (2015).

For the revised manuscript we will add a section on the issues mentioned above and add a new figure (presented as Fig. 1 below).

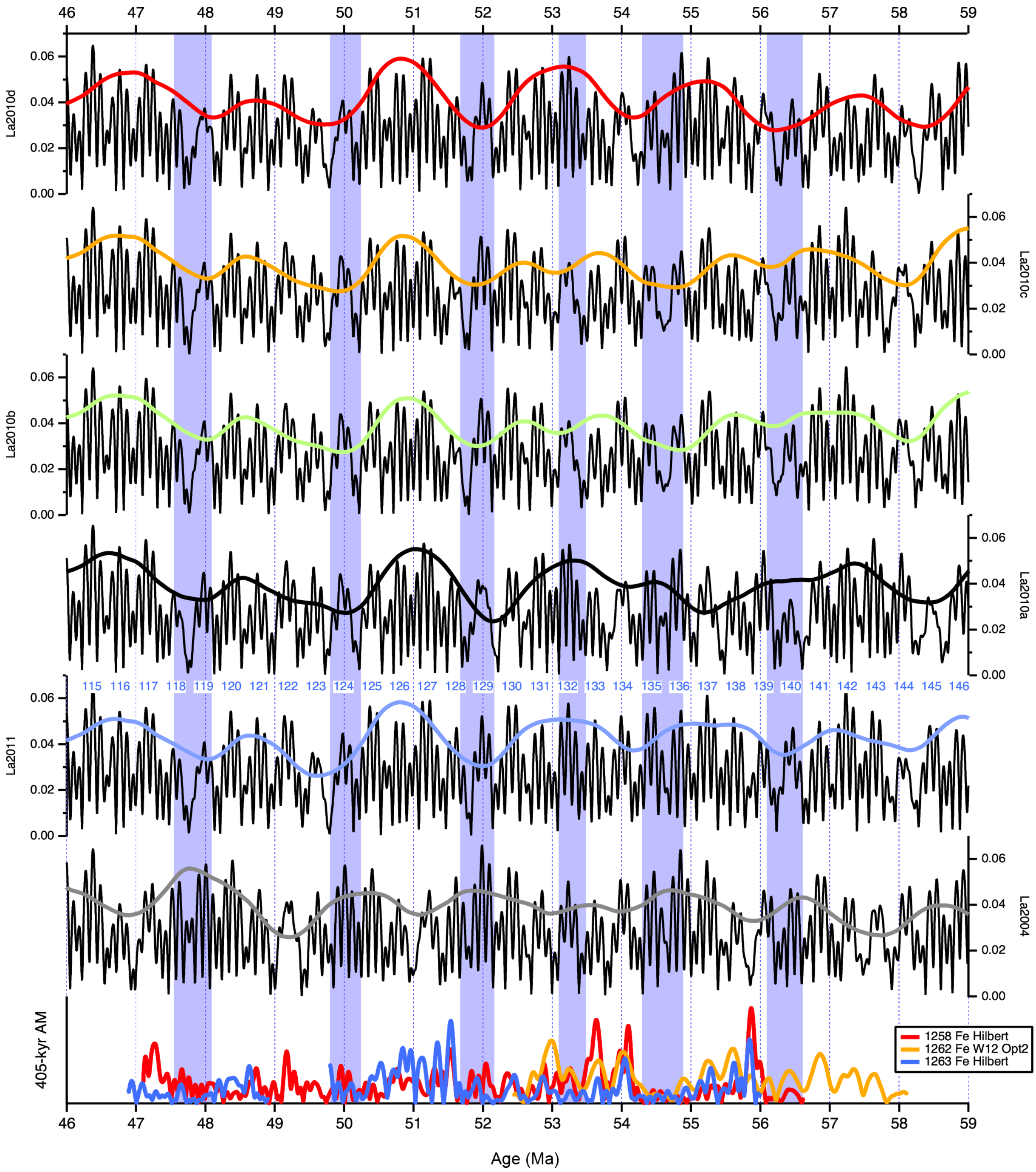

Figure 1 – Comparison of the amplitude modulation (AM) of the short eccentricity cycle between the La2004, La2010, and La2011 orbital solutions and Fe intensity data from ODP Sites 1258 (red), 1262 (orange) and 1263 (blue). For the orbital solutions we also plotted the 405-kyr AM. The short eccentricity AM of Sites 1258, 1262 and 1263 Fe intensity data are plotted on the 405-kyr scale model (Table 46 of the submitted manuscript). The very long eccentricity minima are highlighted by light blue bars in the orbital solutions and the Fe intensity data. Statistical and visual recognition of cycle pattern suggest that the La2010b and La2010c solutions are most consistent with the geological data.

2) Potential distortion by non-linear response of the climate system. The authors have to explain that the amplitude changes they see in their proxies are related to the amplitude of the ~100-kyr eccentricity cycle and not caused by a non-linear response of the climate system to the eccentricity forcing through associated changes in the precession amplitude. This issue might become critical when dealing with the proxy expression of early Eocene hyperthermals. Evidently, the "distortion" caused by such a non-linear response will also have consequences for the outcome of the statistics as I guess that these usually start from linear relationships. This issue has to be addressed in the discussion.

It is not fully clear what the referee exactly refers to in the first part of his comment. Because the precession amplitude is modulated by eccentricity, it would be nearly impossible in most records to rule out "*a non-linear response of the climate system to the eccentricity forcing through associated changes in the precession amplitude"*.

Non-linear response of climate is critical in the Ypresian, as also pointed out by the referee in the second part of his comment. Multiple carbon cycle perturbations are documented in the stable isotope records (CIEs). These hyperthermal events are likely caused by massive releases of carbon to the ocean-atmosphere system including the dissolution of carbonates at the seafloor. Because the extend of the CIE's are scaled to the amount of carbon injected (Pagani et al., 2006) and the residence time of carbon is in the order of 100 kyr (Broecker and Peng, 1982), the events will influence the amplitude of the bulk and benthic stable carbon isotope data and thus any AM analysis of early Eocene records. On top of this, the added carbon leads also to dissolution of carbonates at the seafloor increasing the relative amount of non-carbonate material in the sediment (as detected by higher XRF Fe values). This will influence the statistical and visual recognition of cyclicity. Modeling suggests that hyperthermals, except for the PETM, seem to be paced by eccentricity forcing of the carbon cycle with the amplitude of the events being partly driven by the eccentricity amplitude itself (Kirtland-Turner et al. 2014). The carbon isotope data (see Figure 4 of the submitted manuscript) do show a good correspondence to the short eccentricity AM. In particular, the very long eccentricity minima are expressed as an interval of very low AM in the benthic carbon isotope data. Almost all hypothermal events occur outside the very long eccentricity minima. Only slight excursions at C21R5, C22r5, and C23n.2nH1 coincide with these nodes, but with comparatively reduced CIE than hyperthermals suggesting these are not hyperthermals. Hyperthermal layers are very well documented in the XRF data by prominent peaks due to dissolution of carbonate. Larger CIEs show higher XRF Fe peaks. This tends to exaggerate the AM in the statistical analysis (see Fig. 1). Hyperthermal events could be interpreted as amplifiers of the eccentricity amplitude with a bias toward higher amplitudes. As our focus lies on the very long eccentricity minima, this ensures that the distortion by hyperthermal events is not significantly altering the results of our study.

In the revised manuscript we will add a chapter carefully addressing this issue.

3) Exclusion of expression of 1.0-Myr eccentricity cycle. The authors claim that they have detected the expression of the transition from libration to circulation of the very long period eccentricity cycle in the geological record. However, to be sure, they have to address the following two points. In the first place, what is the role of the relatively strong ~1.0 Myr eccentricity component (related to g5-g1, and can also be written as a combination of ~100-

kyr components) , especially in determining the node around 53 Ma that they attribute to the ~2-Myr cycle. They should thus make clear what the exact expression of the ~2-Myr cycle (related g4-g3) both in the solutions and their records is.

As stated by Laskar (1999) one needs to extract the AM of both obliquity and precession in a geological dataset in order to detect the libration to circulation. This is almost impossible as mentioned by Laskar et al (2011), because this would require a record that is both influenced (or driven) by high latitude and low latitude processes. Obliquity AM could be extracted from benthic d18O records if the deep sea temperature is continuously affected by obliquity. This is not the case for the Paleocene and early Eocene (see for example Littler et al., 2014), thus investigation of the AM of obliquity is difficult with the currently available records. Laskar et al. 2011 recommended: "It may be more direct to search only for a modulation of the g4 − g3 (or s4 − s3) period, as it appears in Fig. 11 (of Laskar et al. 2011)."; g4 − g3 is the ~2.4 myr eccentricity modulation.

It is not clear what the reviewer is referring to with the g5-g1 argument. This roughly 1-myr cycle was never mentioned by Laskar. Clarification would be very welcome.

The transition from libration to circulation should be visible according to Laskar (1999), Laskar et al. (2004), and Laskar et al. (2011) (see also Pälike et al. 2004) by a switch from a ~2.4 myr period to a ~1.2 myr period in the modulation of eccentricity and climatic precession. And very importantly, it can switch back to ~2.4 myr shortly after (see Laskar 1999, Figure 9 therein and in the response to reviewer Stephen Meyers). Comparing orbital solutions with geological data indicates such a switch occurred between 52 and 55 Ma. The AM minima in the data from 47 to 52 Ma are 2 to 2.4 myr spaced (Fig. 1 above), from 52 to 55 Ma they are roughly 1.2 myr spaced, and after 55 Ma the spacing is ~2.4 myr.

The transition we have found is the first of the Cenozoic. Earlier transitions are likely as proposed by Laskar (1999). Indeed, one transition has recently been identified in the Cretaceous, ~86 Ma ago in a paper that was just published after our initial submission (Ma et al. 2017). We will take these findings into account in the revised version (please also see reply to reviewer Stephen Meyers). Both new observations of transitions from the 1:2 to the 1:1 resonance "*could make it possible to obtain very precise information on the initial conditions and (or) parameters of the model. One could even dream that if the succession of the transitions from the 1:2 to the 1:1 resonance were found and dated over an interval of 200 Ma that this could be the ultimate test for the gravitational model. It would make it possible, for example, to obtain the J2 value of the Sun with high accuracy, or to test the model of general relativity*." (Laskar 1999)

In the revised manuscript we will elaborate more on the fingerprint of the transition from libration to circulation.

4) Reliability of astronomical solution 1. And secondly, how certain are the authors now that the preferred solution of La2010b (or c) is reliable back to ~56 Ma, as before they have stated (in Westerhold et al., 2015) that the solution is only reliable to 48 Ma. Indeed more and better records are now available, which seem to have led to their different appreciation of the solution. However, the pattern of the ~100-kyr eccentricity cyclicity also needs to be reliable before the ~2-Myr cycle can be thrusted as the latter cycle can also be written as a *combination of two ~100-kyr eccentricity components (95 and 99, and 124 and 132 kyr). One reason that Lauretano et al. (2016) had a preference for the 2 cycle age model rather than the alternative 3 cycle model for C23n was the apparently good fit of the distinct four 100-kyr maxima in the d13C records with the pattern in 400-kyr cycle no. 127 now (correctly) tuned to no. 126. However, this 400-kyr cycle (i.e., no. 126) does not show the expected 4 relatively strong ~100-kyr maxima in its maximum in addition to less distinct ~100-kyr maxima in d13C in the 400-kyr minima above and below. To me this suggests that the pattern of the ~100-kyr eccentricity cyclicity might already not be fully reliable around 50.8 Ma, so this raises doubts about the reliability of the solution further back in time. This uncertainty and lack of perfect fit should be addressed. The authors should know how careful you have to be when comparing the details observed in proxy records with the solution when its reliability becomes less certain, as they also state in the ms.*

This is a valid concern. None of the available orbital solutions perfectly fit the geological data. However, it is important that we isolated the transition in the data, which is also present in the La2010b and La2010c solutions. The short eccentricity cycle pattern both in the solutions and the geological data will not match perfectly beyond 50 Ma where the uncertainty in the solutions increase (as discussed in Westerhold et al. 2012). Surprisingly the geological data and La2010b/c solutions are very similar from 53.5 Ma to the PETM. The Westerhold et al. (2012) paper did not include stable isotope data and new XRF core scanning data from Leg 208, and relied on Site 1258 XRF data in the interval from 47 to 53 Ma only.

The 51 to 52 Ma interval mentioned by the reviewer is the most difficult part to tune in the Ypresian, in large part because of the multiple hyperthermal events and the shift in carbon isotope data (discussed in detail in the manuscript). We agree that the eccentricity solutions from La2010b/c might not be completely reliable in this interval. We will detail this and the potential limits in the revised manuscript.

Despite the uncertainties we decided to provide a tuned age model to La2010b/c because the match in the 53.5 Ma to the PETM interval is good enough to do so. If in doubt, readers can still make use the 405-kyr age model, also given in the submitted manuscript.

5) Reliability of astronomical solution 2. The authors discuss shortly the origins of the different La2010 and La2011 solutions. This is an important issue as their from a cyclostratigraphic perspective preferred La2010b (and c) solutions have been adjusted to the short-term INPOP08 ephemeris solution, which is considered less stable and reliable than either INPOP06 (La2010a) or INPOP10 (La2011 solution), as there is a bias in INPOP08 regarding the position of Jupiter. This point should preferably be elaborated in somewhat more detail as the authors claim that they find the best fit with the La2010b or c) solutions which are considered less reliable from an astronomical point of view. But see also points 3 and 4.

We present a data-compliant manuscript including a revised 405-kyr stable eccentricity cyclostratigraphy for the Ypresian. Comparing the geological data with astronomical solutions exhibits the consistent transitions from the 1:2 to the 1:1 resonance present in the La2010b and La2010c solution. We are fully aware that the La2010b and La2010c solution from an astronomer's point of view are considered less reliable because they used a less stable ephemeris (Fienga et al. 2011, Laskar et al. 2011). It should be the task of the astronomers to explore the consequences of our findings. It is by far beyond the scope of our manuscript to evaluate the ephemerides in detail, an exercise which by the way can only be undertaken by experts in the field (e.g. Agnes Fienga, Jacques Laskar, etc.).

We were surprised by our results because previous publications suggested that the La2010d and La2011 solutions would fit better to the then available geological data (see Westerhold et al. 2012, Lauretano et al. 2016). But our new results offer an alternative, if not controversial, perspective. Please be aware that the La2010 solutions are all very similar up to 54 Ma (see Westerhold et al. 2012 Figure 2b), but only the La2010b/c solutions show the AM minimum at 53.2 Ma, as in the geological data from Leg 208 (see manuscript Fig. 4 and Fig. 2 of this reply). The La2010d and La2011 solutions, deemed most reliable in the Westerhold et al. (2012) paper, also exhibit no clear minimum around 54.5 Ma but the geological data suggest low amplitude variability from 54.2 to 55.0 Ma in this interval (as in La2010b/c).
In the revised version we will add a comment on the orbital solutions to make this more clear.

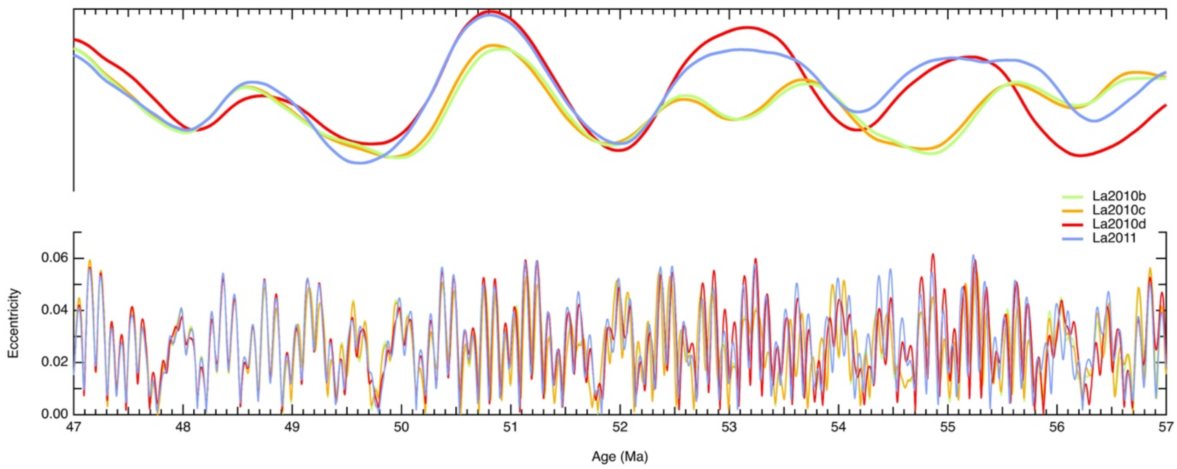

Figure 2 – Amplitude modulation (AM) in the La2010b,c,d and La2011 orbital solutions for eccentricity from 47 to 57 Ma. Note that La2010b/c are so similar that the individual eccentricity curves are difficult to separate.

Minor points:
The use of the word random in l.1, p.14. This is not a correct word/term to describe the outcome of non-linear complex systems such as the Solar System, as such systems do not behave in a random way.

The full sentence referred to is: "Older than 50 Ma the location of the very long eccentricity nodes in available orbital solutions (La2004 – Laskar et al., 2004; La2010 – Laskar et al., 2011a; La2011 – Laskar et al., 2011b) are considered to appear randomly (Westerhold et al., 2015)". Of course the Solar System is not behaving randomly. The sentence says that the very long eccentricity nodes we want to look for in the geological data appear randomly in different numerical solutions. This means their position in any of the solutions cannot be used for direct anchoring of astrochronologies for older than 50 Ma until the solution is identified which best fits to geological data.

We will now rephrase the sentence as follows: "Older than 50 Ma the location of the very long eccentricity nodes in available orbital solutions (La2004 – Laskar et al., 2004; La2010 – Laskar et al., 2011a; La2011 – Laskar et al., 2011b) are much more uncertain."

Referenzes for the reply:

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