Replies to the questions from György Tarczay

If I could gently raise some mild criticism, I would mention that in some cases I had the impression that either the uncertainty in the input parameters, the uncertainties in the measured chemical or isotopic distribution, or the neglects in the physical models, or the limitations in the numerical computations (i.e., simulation time or resolution) could limit the accuracy of the results or could weaken the robustness of conclusions. Many times the main limitations are highlighted in the thesis. Nonetheless, it could have been interesting to see a rigorous sensitivity analysis of the parameters. I wonder if at least intuitively, the results and the conclusions could be located (visualized) in a coordinate system with coordinate axes of uncertain-robust input parameters or measured data used for comparison (i.e., nuclear physics rate constants and/or elemental or isotopic ratios) *vs* uncertain-robust modelling simulations. (Maybe these axes could be separated into more axes.) Either a mathematically rigorous sensitivity analysis or a semi-qualitative coordinate system representation could demonstrate how rigorous a conclusion is or what should be revised in the future to make the statement more rigorous.

ANSWER: This is a stimulating question and I thank the referee for it. I decided to answer it by using a semi-quantitative analysis, as reported in the table below. (Thesis Number 4 had to be split in four different parts because the robustness analysis is different for each part.) Most of my thesis points are relatively robust against all the various uncertainties and limitations listed above. This is because they are based on well-known properties of the atomic nuclei. There are still some exceptions, which are the focus of current research. Not explicitly reported in the table is the fact that data from the analyses of stardust grains is generally very accurate and precise, and most of the time it is reported (and used in the thesis) with conservative 2σ error bars. The isotopic ratios of relevance here prone to contamination, which generates unknow systematic errors, are those of Fe, which I have not considered as a constrain in the thesis exactly because of the potential contamination problem (see footnote at Page 76), and of $^{18}O/^{16}O$, which is discussed at Point 3. in the table below.

Thesis number and summary	Robustness	Comments
1. An *intermediate* neutron-capture (i) process exists in nature.	High	This is based on the possible paths of neutron captures, controlled by the properties of atomic nuclei and the existence of nuclear magic numbers, combined with high-resolution spectroscopic data of roughly 50 stars.
2. Stardust SiC grains formed in C-rich AGB stars and the grain size increases when decreasing metallicity.	High	As above, this is also based on the existence of nuclear magic numbers, combined with the overall abundance trend of 169 Ba stars observed at high-resolution.
3. Grains depleted in ^{18}O originated from AGB stars with initial masses above roughly 4 $M_\odot$.	High/Medium	The match of the observed $^{17}O/^{16}O$ ratio is based on the accurate, underground measurement of the $^{17}O(p,\alpha)^{14}N$ reaction and its trend with temperature. There is no match, however, with the $^{18}O/^{16}O$ ratio: there is too much ^{18}O

		depletion in the models (though some data may be affected by contamination), which is the weak point open to speculations.
4a. The origin of radioactive nuclei made by the *rapid* and the *slow* processes in the early Solar System is decoupled.	High	This is based on well-established experimental features of the nuclear structure of the ^{181}Hf nucleus and the low frequency of the *rapid*-process events (i.e., neutron star mergers, as confirmed by LIGO).
4b. The last *rapid*-process event occurred ~100 Myr before Solar System formation.	High	This is confirmed using 3 (^{129}I/^{127}I, ^{247}Cm/^{235}U, ^{244}Pu/^{238}U) +1 (^{129}I/^{247}Cm) independent constraints (see latest discussion in Lugaro et al. 2022, Universe, 8, 343).
4c. The last *slow*-process event occurred ~30 Myr before Solar System formation.	Medium/High	The time of this last event has been confirmed to be ~25 Myr, however, AGB stars are common and therefore there may be no *last event*, but *continuous production* (summary in Lugaro et al. 2022, Universe, 8, 130). In this case we still find a self-consistent *isolation time* of 9 to 26 Myr, when considering all the uncertainties.
4d. The abundances of the heavy radioactive nuclei of *p*-process origin should be produced by both Type Ia and core-collapse supernovae.	Low	Our knowledge of the production of *p*-nuclei is still affected by too many of the uncertainties and limitations listed in the referee's question (we are now pursuing this topic thanks to the support of NKFI project K138031). Even the half life itself of ^{146}Sm is not well established yet, although new experiments are in progress (e.g., at the Swiss Paul Scherrer Institute).

Further questions and comments:

It seems to me that ^{96}Zr(n,γ)^{97}Zr(β^-)^{96}Mo and ^{96}Zr(n, γ)^{96}Mo on p29 are wrong.

ANSWER: Thank you for spotting these typos, indeed, the correct text should be ^{96}Zr(n,γ)^{97}Zr(β^-)^{97}Mo and ^{96}Zr(n, γ)^{97}Mo.

Why Se, Rb, and Cd do not condense into dust (p38)? (Or did I misunderstand the sentence?)

ANSWER: This assumption is based on the 50% condensation temperature of the different elements. For Se, Rb, and Cd these are 697, 800, and 652 K, respectively (according, for example, to Lodders 2003, ApJ, 591, 1220). The temperature at which dust is expected to condense around AGB stars is roughly >1000 K. Therefore, incorporation of the elements above is not expected. Elements such as Sr, Zr, and Ba, with 50% condensation temperature of 1464, 1741, and 1455 K, respectively, are instead expected to be in the dust. This is a qualitative consideration because it is based on temperatures for equilibrium condensation in a gas of Solar System composition, both of which assumptions are incorrect for AGB stars. Still, we may expect the overall condensation process to be similar. Lodders & Fegley (1997, ApJ, 484, L71) compared models of equilibrium condensation to observations of elemental abundances in SiC grains and in AGB stars and found that the patterns are consistent. For example, the grains are enriched in Zr relative to Sr while for the stars is the other way around, which reflects the lower condensation temperature of Sr relative to Zr. In general, however, the topic of dust formation in AGB is much debated because the assumption of equilibrium condensation in the dynamical winds of AGB stars may be incorrect.

- It is well-explained in the dissertation, that in the case of stellar spectra – due to limited spectral resolution – the abundances of different elements, while in the case of dust particles – due to possible chemical separations of different elements – the isotopic mixing ratios could be compared to the results of the simulations. As it is mentioned in the dissertation, at cooler spectral atmospheres the formation of molecular species can result in uncertainties in elemental ratios. In geochemistry and in planetary atmospheric chemistry there are well-known thermal and photochemical processes that cause isotopic fractionations. Similar processes could also occur on the surface of dust particles. Can X-processes considerably change the isotopic ratios on grain surfaces? Are there any attempts in the literature to consider and take into account these effects, and correct the elemental/isotopic ratios?

ANSWER: Mass-independent fractionation can in fact have different origins, not only nucleosynthetic. These are more likely to be present for the lighter element, in fact, these effects are well known in the Solar System for H and N and they most likely happened for O too. Robert et al. (2020 Nature Astronomy, 4, 762), after stating that "*No chemical reaction has ever been shown to be able to generate mass-independent fractionation effects for heavy elements such as Ti, Mo, Cr or Ca.*", proceeded to present the first discovery of such possible effect on Ti, using new experimental data. Robert et al. (2021, PNAS, 118, id.e2114221118) further reported similar possible effects on O and Mg. These recent works represent a clear warning about ignoring possible mass-independent fractionation effects of not-nucleosynthetic origin, at least in the case of the elements lighter than Fe. Still, it remains to be seen if the experimental conditions presented in those works are a good proxy to mimic dust condensation in stellar environments.

In the case of the elements heavier than iron in stardust SiC grains, the *slow* neutron-capture process signatures are prominently obvious. These signatures are naturally predicted by nuclear processes based mostly on experimental determinations of neutron-capture cross sections and the existence of nuclear magic numbers. It would therefore appear to be extremely difficult to reproduce the same pattern by other processes. For such heavy elements, it seems most reasonable not to expect any other effects to be of significant impact.