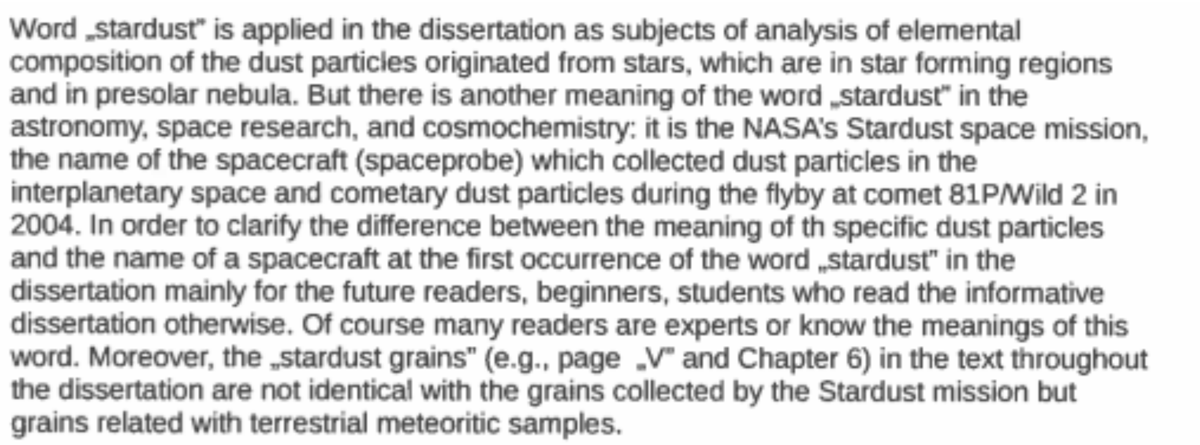
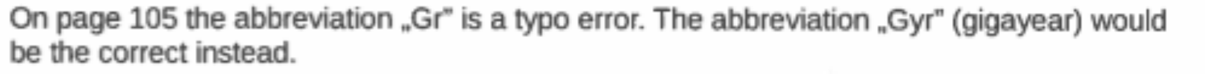
Replies to the questions from Imre Tóth



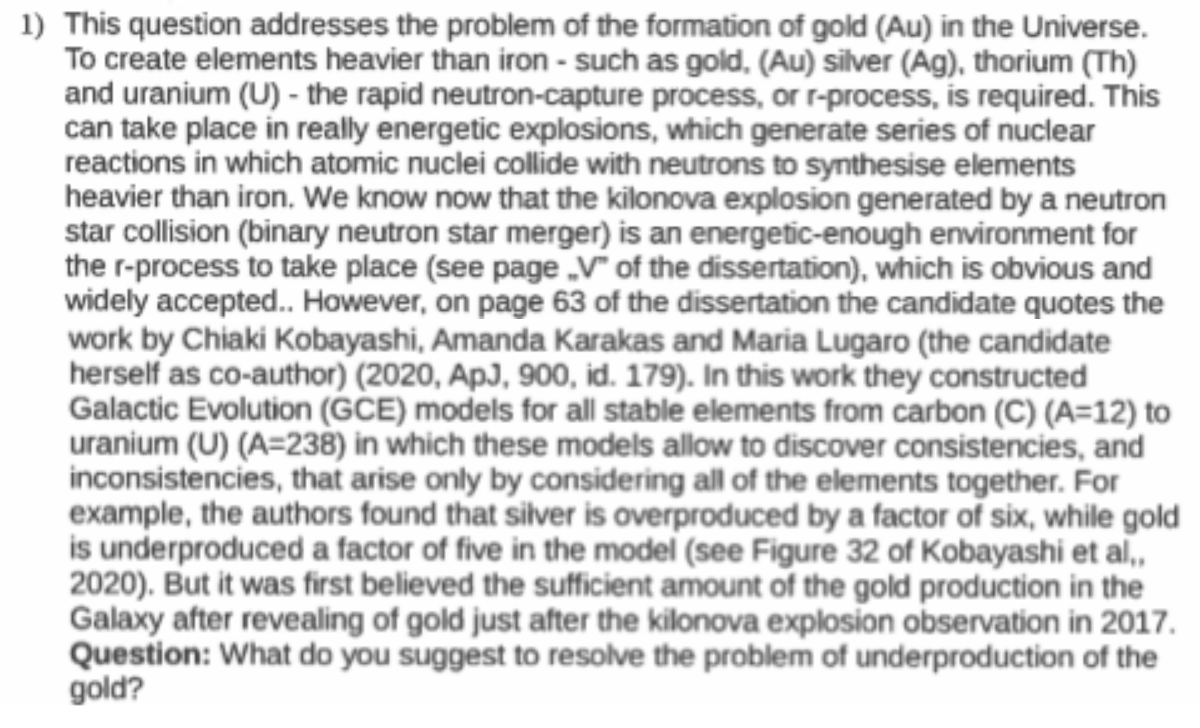
Word „stardust" is applied in the dissertation as subjects of analysis of elemental composition of the dust particles originated from stars, which are in star forming regions and in presolar nebula. But there is another meaning of the word „stardust" in the astronomy, space research, and cosmochemistry: it is the NASA's Stardust space mission, the name of the spacecraft (spaceprobe) which collected dust particles in the interplanetary space and cometary dust particles during the flyby at comet 81P/Wild 2 in 2004. In order to clarify the difference between the meaning of th specific dust particles and the name of a spacecraft at the first occurrence of the word „stardust" in the dissertation mainly for the future readers, beginners, students who read the informative dissertation otherwise. Of course many readers are experts or know the meanings of this word. Moreover, the „stardust grains" (e.g., page „V" and Chapter 6) in the text throughout the dissertation are not identical with the grains collected by the Stardust mission but grains related with terrestrial meteoritic samples.

<u>ANSWER:</u> Thank you for pointing out this word degeneracy, which may cause potential confusion. As suggested by the referee, a footnote would have helped, if introduced the first time on the word "stardust", i.e., already in the prologue. Thankfully, the Stardust spacecraft is always written starting with a capital letter, therefore, once indicated explicitly it would have been easy for the reader to keep the difference in mind.



On page 105 the abbreviation „Gr" is a typo error. The abbreviation „Gyr" (gigayear) would be the correct instead.

<u>ANSWER:</u> Thanks for noting the typo at page 105: "the age of the Sun is 4.6 Gr" should have been in fact "the age of the Sun is 4.6 Gyr".



1) This question addresses the problem of the formation of gold (Au) in the Universe. To create elements heavier than iron - such as gold, (Au) silver (Ag), thorium (Th) and uranium (U) - the rapid neutron-capture process, or r-process, is required. This can take place in really energetic explosions, which generate series of nuclear reactions in which atomic nuclei collide with neutrons to synthesise elements heavier than iron. We know now that the kilonova explosion generated by a neutron star collision (binary neutron star merger) is an energetic-enough environment for the r-process to take place (see page „V" of the dissertation), which is obvious and widely accepted.. However, on page 63 of the dissertation the candidate quotes the work by Chiaki Kobayashi, Amanda Karakas and Maria Lugaro (the candidate herself as co-author) (2020, ApJ, 900, id. 179). In this work they constructed Galactic Evolution (GCE) models for all stable elements from carbon (C) (A=12) to uranium (U) (A=238) in which these models allow to discover consistencies, and inconsistencies, that arise only by considering all of the elements together. For example, the authors found that silver is overproduced by a factor of six, while gold is underproduced a factor of five in the model (see Figure 32 of Kobayashi et al,, 2020). But it was first believed the sufficient amount of the gold production in the Galaxy after revealing of gold just after the kilonova explosion observation in 2017. **Question:** What do you suggest to resolve the problem of underproduction of the gold?

<u>ANSWER:</u> Thanks for this question, which allows me to address two significant points of our current knowledge of the *rapid* neutron-capture process.

I) The first point is that unfortunately gold (Z=79) itself was not revealed to be present just after the kilonova explosion observation in 2017. Gold was only inferred to possibly have been present, but it was extensively used as the example of an element produced by *rapid* neutron captures because it is one of the most well-known chemical elements, also by the public. In reality, what we know of kilonovae in general is that their light is broadly consistent with an outflow of radioactive heavy elements, however, uncertainties and ambiguities in the modelling of their optical and infrared emission make it very difficult to identify specific elements. After 2017, the work on interpreting such light curves has greatly expanded and many groups worldwide are now improving our ability of extracting direct observational signatures from different model prediction, for example:

- Fontes et al. 2023 *Actinide opacities for modelling the spectra and light curves of kilonovae* MNRAS, 519, 2
- Gillander et al. 2022 *Modelling the spectra of the kilonova AT2017gfo - I. The photospheric epochs* MNRAS 515, 631

Actually, in 2019 there was a report of the first identification of a line of the element Sr (Z=38):

- Watson et al. 2019, *Identification of strontium in the merger of two neutron stars* Nature, 574, 497 (179 citations)

Since then, other groups have also attempted to identify specific elements, e.g.:

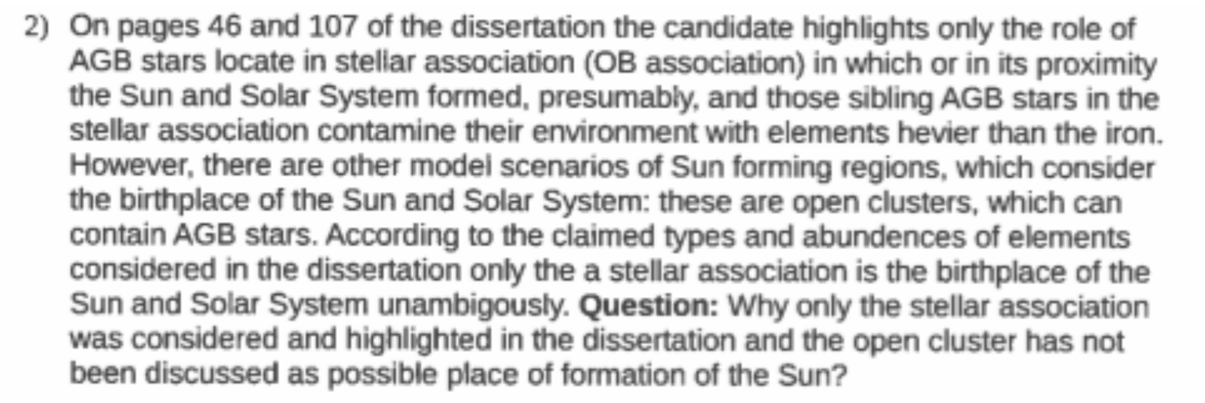
- Domoto et al 2022 *Lanthanide Features in Near-infrared Spectra of Kilonovae* ApJ 939, Issue 1, id.8
- Hotokezaka et al. 2022 *Tungsten versus Selenium as a potential source of kilonova nebular emission observed by Spitzer* MNRAS 515, L89

In summary, there is no clear evidence so far that the 2017 event produced gold.

II) To specifically answer the question of how to solve the underproduction of gold by current galactic chemical evolution (GCE) models, my answer lies in the fact that predictions from models of the *rapid* neutron-capture process are extremely uncertain. The yields from these models are included in GCE models such as those presented by Kobayashi et al. (2020), and they control most of the results for elements like gold. There are two different types of uncertainties in calculating the *rapid* neutron-capture process yields. **a)** There are difficulties in modelling the physics of the astrophysical sites, including the merger of neutron stars, which encompass their dynamical ejecta, their neutrino winds and the effect of neutrinos, and their accretion disks outflows (see, e.g., recent review by Cowan et al. 2020 Reviews of Modern Physics, 93, id.015002 on the *rapid* neutron-capture process). **b)** The other main difficulty is that we do not know the properties of most of the nuclei that are located on the path of the *rapid* neutron captures (as illustrated by the example figure below). Furthermore, other nuclear processes on top of neutron captures can have a main role, for example, the fission of nuclei heavier than lead (e.g., Giuliani et al 2020, Physical Review C, 102, id.045804). Therefore, in my opinion, we will need to wait for significant improvements in the accuracy and precision of current *rapid* neutron-capture yields before we can draw robust conclusions on the origin of gold from GCE models.

138Ce ≥0.9E+14 Y 0.251% 2ϵ: 100.00%	139Ce 137.641 D ϵ: 100.00%	140Ce STABLE 88.4	141Ce 32.508 D β-: 100.00%	142Ce >2.6E+17 Y 11.114% 2β-	143Ce 33.039 H β-: 100.00%	144Ce 284.91 D β-: 100.00%	145Ce 3.01 M β-: 100.00%	146Ce 13.52 M β-: 100.00%	147Ce 56.4 S β-: 100.00%	148Ce 56 S β-: 100.00%	149Ce 5.3 S β-: 100.00%	150Ce 4.0 S β-: 100.00%	151Ce 1.02 S β-: 100.00%	152Ce 1.4 S β-: 100.00%
137La 6E+4 Y ϵ: 100.00%	138La 1.02E+11 Y 0.090% ϵ: 65.60% β-: 34.40%	139La STABLE 99.9	140La 1.67855 D β-: 100.00%	141La 3.92 H β-: 100.00%	142La 91.1 M β-: 100.00%	143La 14.2 M β-: 100.00%	144La 40.8 S β-: 100.00%	145La 24.8 S β-: 100.00%	146La 6.27 S β-: 100.00%	147La 4.015 S β-: 100.00% β-n: 0.04%	148La 1.26 S β-: 100.00% β-n: 0.15%	149La 1.05 S β-: 100.00% β-n: 1.43%	150La 0.51 S β-: 100.00% β-n: 2.70%	151La >300 NS β- β-n
136Ba STABLE	137Ba STABLE	138Ba STABLE	139Ba 83.06 M β-: 100.00%	140Ba 12.7527 D β-: 100.00%	141Ba 18.27 M β-: 100.00%	142Ba 10.6 M β-: 100.00% β-n: 0.09%	143Ba 14.5 S β-: 100.00%	144Ba 11.5 S β-: 100.00% β-n: 3.60%	145Ba 4.31 S β-: 100.00%	146Ba 2.22 S β-: 100.00%	147Ba 0.893 S β-: 100.00% β-n: 0.06%	148Ba 0.612 S β-: 100.00% β-n: 0.40%	149Ba 0.344 S β-: 100.00% β-n: 0.43%	150Ba 0.3 S β-: 100.00%
135Cs 2.3E+6 Y β-: 100.00%	136Cs 13.04 D β-: 100.00%	137Cs 30.08 Y β-: 100.00%	138Cs 33.41 M β-: 100.00%	139Cs 9.27 M β-: 100.00%	140Cs 63.7 S β-: 100.00%	141Cs 24.84 S β-: 100.00% β-n: 0.04%	142Cs 1.684 S β-: 100.00% β-n: 0.09%	143Cs 1.791 S β-: 100.00% β-n: 1.64%	144Cs 0.994 S β-: 100.00% β-n: 3.20%	145Cs 0.594 S β-: 100.00% β-n: 14.30%	146Cs 0.321 S β-: 100.00% β-n: 14.20%	147Cs 0.235 S β-: 100.00% β-n: 43.00%	148Cs 146 MS β-: 100.00% β-n: 25.10%	149Cs >50 MS β- β-n
134Xe >5.8E+22 Y 10.436% 2β- ≥ 0.00%	135Xe 9.14 H β-: 100.00%	136Xe >2.4E+21 Y 8.857% 2β-	137Xe 3.818 M β-: 100.00%	138Xe 14.08 M β-: 100.00%	139Xe 39.68 S β-: 100.00%	140Xe 13.60 S β-: 100.00%	141Xe 1.73 S β-: 100.00% β-n: 0.04%	142Xe 1.250 S β-: 100.00% β-n: 0.21%	143Xe 0.511 S β-: 100.00% β-n: 1.00%	144Xe 0.388 S β-: 100.00% β-n: 3.00%	145Xe 188 MS β-: 100.00%	146Xe 146 MS β-: 100.00% β-n: 6.90%	147Xe 0.10 S β-: 100.00% β-n < 8.00%	
133I 20.8 H β-: 100.00%	134I 52.5 M β-: 100.00%	135I 6.58 H β-: 100.00%	136I 83.4 S β-: 100.00%	137I 24.5 S β-: 100.00% β-n: 7.14%	138I 6.23 S β-: 100.00% β-n: 5.56%	139I 2.280 S β-: 100.00% β-n: 10.00%	140I 0.86 S β-: 100.00% β-n: 9.30%	141I 0.43 S β-: 100.00% β-n: 21.20%	142I ≈0.2 S β-: 100.00%	143I >150 NS β-	144I >300 NS β-			
132Te 3.204 D β-: 100.00%	133Te 12.5 M β-: 100.00%	134Te 41.8 M β-: 100.00%	135Te 19.0 S β-: 100.00%	136Te 17.63 S β-: 100.00% β-n: 1.31%	137Te 2.49 S β-: 100.00% β-n: 2.99%	138Te 1.4 S β-: 100.00% β-n: 6.30%	139Te >150 NS β-n β-	140Te β- β-n	141Te >150 NS β- β-n	142Te >150 NS β-				
131Sb 23.03 M β-: 100.00%	132Sb 2.79 M β-: 100.00%	133Sb 2.5 M β-: 100.00%	134Sb 0.78 S β-: 100.00%	135Sb 1.679 S β-: 100.00% β-n: 22.00%	136Sb 0.923 S β-: 100.00% β-n: 16.30%	137Sb 450 M β-: 100.00% β-n: 49.00%	138Sb >300 NS β- β-n	139Sb >150 NS β-						
130Sn 3.72 M β-: 100.00%	131Sn 56.0 S β-: 100.00%	132Sn 39.7 S β-: 100.00%	133Sn 1.45 S β-: 100.00% β-n: 0.08%	134Sn 1.050 S β-: 100.00% β-n: 17.00%	135Sn 530 MS β-: 100.00% β-n: 21.00%	136Sn 0.25 S β-: 100.00% β-n: 30.00%	137Sn 190 MS β-: 100.00% β-n: 58.00%							
129In 0.61 S β-: 100.00% β-n: 0.25%	130In 0.29 S β-: 100.00% β-n: 0.93%	131In 0.28 S β-: 100.00% β-n≤ 2.00%	132In 0.207 S β-: 100.00% β-n: 6.30%	133In 165 MS β-: 100.00% β-n: 85.00%	134In 140 MS β-: 100.00% β-n: 65.00%	135In 92 MS β-: 100.00% β-n > 0.00%								
128Cd 0.28 S β-: 100.00%	129Cd 0.27 S β-	130Cd 162 MS β-: 100.00% β-n≈ 3.50%	131Cd 68 MS β-: 100.00% β-n: 3.50%	132Cd 97 MS β-: 100.00% β-n: 60.00%										
127Ag 79 MS β-: 100.00%	128Ag 58 MS β-: 100.00% β-n	129Ag 46 MS β-: 100.00% β-n	130Ag ≈50 MS β-											

Example of a section of the nuclei chart from the USA National Nuclear Data Centre (Brookhaven National Laboratory) showing some isotopes of the elements from Ag to Ce. Black and coloured boxes represent stable and unstable nuclei, respectively. The slow neutron-capture process path is shown by the green arrows. The rapid neutron-capture process path is shown by the red boxes, which represent the location of the r-process "waiting" points, where an equilibrium between neutron capture rates (n,γ) and photo-disintegration (γ,n) is reached and the flow has to "wait" for β decays to proceed. Many of the isotopes involved in the rapid neutron-capture path are not even included in this nuclide chart, which means that we do not have any experimental information about them. In fact, even the inclusion of some of these isotopes on the rapid neutron-capture path in this figure may be uncertain as it is based on a specific nuclear mass model (the ETFSI-Q model).

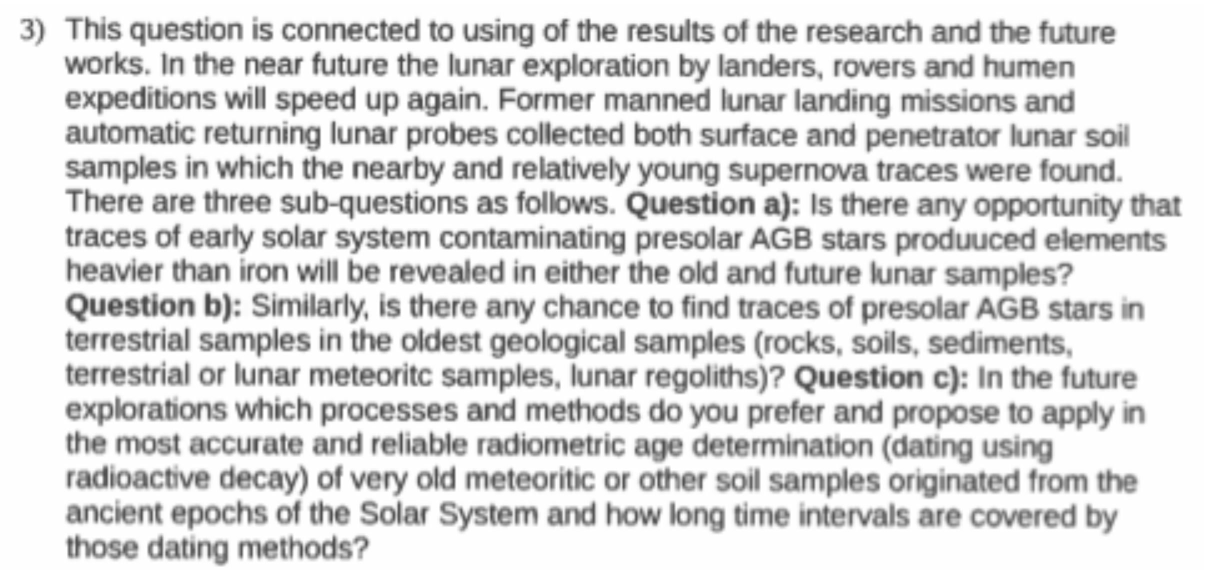


2) On pages 46 and 107 of the dissertation the candidate highlights only the role of AGB stars locate in stellar association (OB association) in which or in its proximity the Sun and Solar System formed, presumably, and those sibling AGB stars in the stellar association contamine their environment with elements hevier than the iron. However, there are other model scenarios of Sun forming regions, which consider the birthplace of the Sun and Solar System: these are open clusters, which can contain AGB stars. According to the claimed types and abundences of elements considered in the dissertation only the a stellar association is the birthplace of the Sun and Solar System unambigously. **Question:** Why only the stellar association was considered and highlighted in the dissertation and the open cluster has not been discussed as possible place of formation of the Sun?

ANSWER: I am sorry for the confusion on this point. I should clarify that the AGB stars discussed in the thesis as the origin of the short-lived radioactive isotopes (^{107}Pd and ^{182}Hf) cannot have been present in the birth environment of the Sun, whichever it might have been (an OB association or an open cluster, or else). The reason is that the progenitors of these AGB stars have initial masses below 4 solar masses. Therefore, they live at least ~200 Myr on the main sequence before they reach the AGB phase, when they produce these radioactive isotopes via the *slow* neutron-capture process and eject them via their winds. The timescales of star formation, in an OB association, an open cluster, or else, are one to two order of magnitude shorter than these stellar evolution timescales, which means that no siblings of the Sun could have evolved to the AGB phase on time to affect the material from which the Sun formed.

The AGB stars discussed in the thesis as the origin of the short-lived radioactive isotopes were therefore not present within the star-forming region of the Sun, so their winds must have affected the original matter from which the whole star-forming region formed. In other words, the presence of these nuclei was *primordial* relative to the formation of the natal cloud. In this respect, using AGB stars we cannot distinguish between the two places of formation of the Sun mentioned above, although we can say that the Sun's birth must have happened roughly 20-30 Myr from the production of ^{107}Pd and ^{182}Hf in their AGB star(s) of origin, which may provide us with a timescale for the lifetime of the natal cloud.

Indications of the Sun's birth within or close to an OB association come instead from radioactive isotopes other than those with an AGB origin. For example, ^{26}Al is produced in massive stars, which have lifetimes on the main sequence comparable to the timescale of star formation (e.g., Brinkman et al. 2021, ApJ, 923, 47), but this is beyond the aim of the thesis.



3) This question is connected to using of the results of the research and the future works. In the near future the lunar exploration by landers, rovers and humen expeditions will speed up again. Former manned lunar landing missions and automatic returning lunar probes collected both surface and penetrator lunar soil samples in which the nearby and relatively young supernova traces were found. There are three sub-questions as follows. **Question a):** Is there any opportunity that traces of early solar system contaminating presolar AGB stars produuced elements heavier than iron will be revealed in either the old and future lunar samples? **Question b):** Similarly, is there any chance to find traces of presolar AGB stars in terrestrial samples in the oldest geological samples (rocks, soils, sediments, terrestrial or lunar meteoritc samples, lunar regoliths)? **Question c):** In the future explorations which processes and methods do you prefer and propose to apply in the most accurate and reliable radiometric age determination (dating using radioactive decay) of very old meteoritic or other soil samples originated from the ancient epochs of the Solar System and how long time intervals are covered by those dating methods?

ANSWER: Thanks for these informative questions. I answer Questions a) and b) together because they have the same answer: it is not possible to recover individual stardust from lunar or terrestrial samples because it would have been completely destroyed by thermal or chemical processes. In fact, stardust is typically found in primitive meteorites, i.e. carbonaceous chondrites (e.g., Davidson et al. 2014, Geochim. Cosmochim. Acta, 139, 248.) However, and excitingly, bulk rock analysis can nowadays be performed with precision to the level of 1 part per million, and these have revealed the signature of original presence of stardust, which was subsequently destroyed and mixed with the rest of the rock. As mentioned in the thesis, these analyses have shown, for example, that the Earth is at the level of 1/10^5 richer in SiC stardust from AGB stars than any other bodies in the Solar System (e.g., Ek et al. 2020, Nature Astronomy, 4, 273; and see also the recent Burkhardt et al. 2021, Science Advances, 7, abj7601).

Related to Question c), I can suggest to experimental colleagues what would be my wish list as a theoretician as the feasibility and practicality of the sample and data taken is beyond my expertise. My main interest from a theory point of view would be the establishment of the initial abundances of radioactive isotopes that are known with still too high systematic uncertainties or only as upper limits, for example, ^{135}Cs and ^{205}Pb. These are produced in AGB stars and their robust determination would allow us to confirm the lifetime of the natal cloud mentioned above in relation to the previous question. We are currently focusing our models on ^{205}Pb; however, the meteoric data are inconclusive, with very different values reported in the literature. This is partially due to the fact that Pb is easily contaminated and that mass-fractionation correction to derive the abundance of the daughter ^{205}Tl is difficult to determine because Tl has only two stable isotopes. Another crucial information comes from the determination the initial abundances of different radioactive nuclei in the same sample, as done for example for ^{182}Hf and ^{26}Al (Holst, et al. 2013, PNRAS 110, 88198823). This provides us with stringent constraints because it can tell us if different nuclei had the same stellar origin, or not. However, these opportunities depend on the mineralogy of the available samples, sometimes luck can help us to discover the right sample for new breakthrough measurements, as in the case of the peculiar U-depleted CAI, *Curious Marie,* which allowed Tissot et al. 2016 (Science Advances, 2, e1501400) to accurately infer its initial ^{247}Cm abundance.