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Double beta decay: experimental challenges

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This paper introduces the rare nuclear transition known as neutrinoless double beta decay and highlights its importance for neutrino physics and in general for particle physics and cosmology. When discussed in terms of mass mechanism, the search for this process is not blind: well defined targets emerge from the present context of neutrino physics. After presenting general experimental concepts and different proposed technological approaches, we discuss how the experimentalists cope with the challenges posed by this difficult investigation in the current framework of known neutrino properties. The elements which guide the choice of the sources and of the detectors are introduced and debated. We make then the point on the experimental situation and discuss the status of the ^{76}Ge claim. Two possible technologies which may lead to the exploration of the inverted hierarchy region of the neutrino mass pattern are presented. As a conclusion, we try to envisage what we expect round the corner and at a longer time scale.

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1. Introduction

The double beta decay, which is the rarest nuclear weak process, takes place between two even-even isobars, when the transition to the intermediate odd-odd nucleus is energetically forbidden due to the pairing interaction. The decay with emission of two neutrinos (2νββ) conserves the lepton number and was originally proposed by Goeppert-Mayer in 1935 [1]. It is a second order weak process – which explains its low rate– and it has been observed for a dozen of nuclei, with lifetimes in the range 10^{18} – 10^{22} y [2].

Besides the 2νββ, a much more intriguing process, the so-called neutrinoless double beta decay (0νββ) [3], was proposed by Furry [4] short after the Majorana theory of the neutrino [5]. In this case the simultaneous transformation of two neutrons into two protons is accompanied by the emission of two electrons and nothing else. The main implication of 0νββ is the violation of the lepton number. In a Standard Model perspective, this is as important as the violation of the baryon number. In full generality, we can imagine this process as a mechanism capable to *create* electrons in a nuclear transition.

After the discovery that neutrinos are definitely massive particles, it is natural to invoke the exchange of light Majorana neutrinos (mass mechanism) as a leading contribution to 0νββ. However, it is remarkable that a wide variety of mechanisms can possibly induce it, proving in full generality that neutrinos are Majorana particles [6]. The mass mechanism occupies anyway a special place: it relates neatly the 0νββ to important parameters of neutrino physics, fixes clear experimental targets and provides a clue to compare on equal footing experiments which present considerable differences from the methodological and technological points of view. In fact, the mass mechanism prescripts that the decay probability in the 0νββ is proportional to the square of the so-called effective Majorana neutrino mass m_{ee}, a crucial parameter that contains the three neutrino masses m_1, m_2 and m_3, the elements of the first row of the neutrino mixing matrix and the unknown CP-violating Majorana phases, which make cancellation of terms possible: m_{ee} could be smaller than any of the three neutrino masses. The pattern of neutrino masses and mixing admits an elegant explanation, the so-called see-saw mechanism, based on the Majorana nature of neutrino. At the same time the only viable explanation of the matter-antimatter asymmetry available today – the justification for our very existence – is based on the leptogenesis, which once again requires that neutrinos are Majorana particles [7]. This well motivates why 0νββ plays a central role in particle physics and cosmology.

Thanks to the information we have from oscillations, and assuming the standard three active neutrino scenario, it is useful to express the effective Majorana neutrino mass m_{ee}, in terms of three unknown quantities: the mass scale, represented by the mass of the lightest neutrino m_{min} and the two Majorana phases. It is then common to distinguish three mass patterns: normal hierarchy (NH), where $m_1 < m_2 < m_3$, inverted hierarchy (IH), where $m_3 < m_1 < m_2$, and the quasi-degenerate (QD) spectrum, where the differences between the masses are small with respect to their absolute values. We ignore the neutrino mass ordering at the moment, and 0νββ has the potential to provide this essential information.

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2. Experimental challenges

In the standard interpretation of 0νββ in terms of mass mechanism, three challenges are in front of the experimentalists who study this process. The first consists in scrutinizing the much debated ^{76}Ge claim [8,9] from a part of the Heidelberg-Moscow collaboration, which would imply a QD neutrino mass spectrum: recent experimental results are close to accomplish this task.[1] The second challenge consists in approaching and then covering the IH region of the neutrino mass pattern. The third and ultimate goal is to explore the DH region.

While checking the ^{76}Ge claim can be done in principle with only ~10 kg isotope, we need typically 1 ton of isotope mass in order to explore the IH region, just to accumulate a few signal counts. The DH region looks for the moment out of the reach of the present technologies, since one would need sources of the order of 1 Mmol (typically 100 tons). Just having a large source is not enough: in order to appreciate such tiny signal rates, the experimentalists are obliged to operate in conditions of almost zero background. Acceptable background rates are of the order of 1-10 counts/y/ton if the goal is just to approach or touch the IH region, whereas one needs at least one order of magnitude lower values to explore it fully, around or even less than 1 counts/y/ton.

2.1 The desired features of a 0νββ detector

The experimental strategy pursued to investigate the 0νββ consists of the development of a proper nuclear detector, with the purpose to reveal the two emitted electrons in real time (see figure 1) and to collect their sum energy spectrum as minimal information. Indeed, the shape of the two electron sum energy spectrum enables to distinguish between the two discussed decay modes. In case of 2νββ, this spectrum is a continuum between 0 and the $Q_{\beta\beta}$-value with a maximum around $(1/3)Q_{\beta\beta}$. For 0νββ, the spectrum is just a peak at the transition energy, enlarged only by the finite energy resolution of the detector.

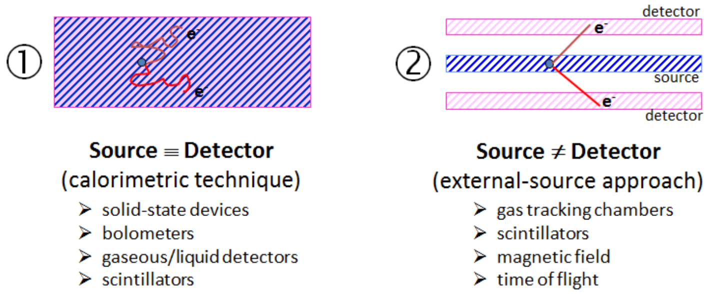

Figure 1: Nuclear detectors to study 0νββ can be classified according two alternative approaches: (1) in the so-called calorimetric technique the source and the detector coincide; (2) in the external-source approach a thin source is surrounded by tracking and

The ideal desirable features of this nuclear detector are: (i) a high energy resolution, as a peak must be identified over an almost flat background; (ii) a large source, in order to monitor many candidate nuclides; (iii) a low background, which requires underground detector operation to shield from cosmic rays, very radiopure materials, well-designed passive

[1] There are actually two versions of the ^{76}Ge claim, one relative to Ref. [8] (2004-claim), which indicates a most probable value of 1.2×10^{25} y for the 0νββ half-life of ^{76}Ge, and a second one discussed in Ref. [9] (2006-claim), in which the half-life is increased to 2.3×10^{25} y.

and/or active shielding against local environmental radioactivity and possibly event tracking and topology capability. This last point is useful not only to reject background but also to provide additional kinematical information on the emitted electrons. Typically, the listed features cannot be met simultaneously in a single detection method.

As depicted in figure 1, the searches for 0νββ can be further classified into two main categories: the so-called calorimetric technique, in which the source is embedded in the detector itself and which provide extremely high efficiency, and the external-source approach, in which source and detector are two separate systems, allowing excellent event reconstruction.

2.2 Choice of the isotope

Which are the best isotopes to search for the 0νββ? Experimental practice shows that the following three factors are the most relevant in the design of an experiment: (i) the $Q_{\beta\beta}$-value; (ii) the isotopic abundance together with the ease of enrichment; last but not least, (iii) the compatibility with an appropriate detection technique.

The $Q_{\beta\beta}$-value is probably the most important criterion. It influences both the phase space [10] (which grows as $Q_{\beta\beta}^5$ considering the leading term) and the background. On the basis of $Q_{\beta\beta}$-value selection, at the moment there are only 9 experimentally relevant isotopes, as appreciable in figure 2. The transition energies of all these isotopes are larger than 2.4 MeV, with the important exception of ^{76}Ge ($Q_{\beta\beta}$-value = 2.039 MeV). There are two important energy markers in terms of background which have to be compared with the $Q_{\beta\beta}$-value: (i) the 2615 keV line represents the end-point of the bulk of the natural gamma radioactivity; (ii) the 3270 keV line represents the Q-value of the ^{214}Bi β-decay, which, among the ^{222}Rn daughters, is the one releasing the highest-energy β's and γ's. The 9 candidates are divided by these two markers in three groups of three isotopes each.

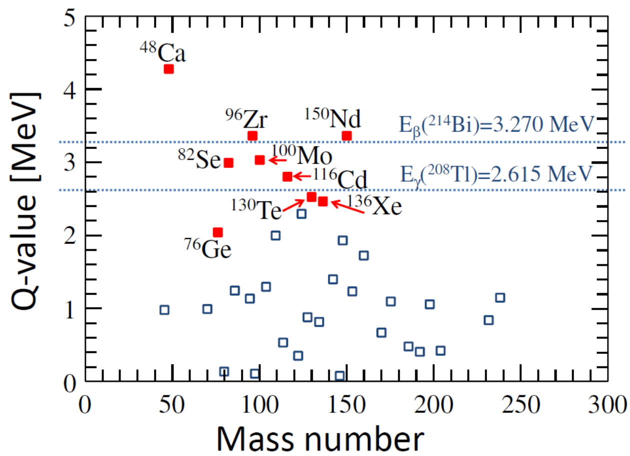

Figure 2: Double Beta Decay candidates and their Q-values. The 9 most promising candidates are highlighted in red and two background-relevant energy markers are indicated (see text).

The first group (^{76}Ge, ^{130}Te and ^{136}Xe) has to cope with some γ background and with the radon-induced one; however, very sensitive experiments can be performed with these nuclides since they are particularly suitable to be studied with a calorimetric approach. Germanium semiconductor diodes, as those used in the GERDA and MAJORANA experiments, are excellent devices for the study of the isotope ^{76}Ge; TeO_2 bolometers used in CUORE are at the forefront due to their high content of ^{130}Te, while the last of these three isotopes can be easily embedded in liquid or gaseous TPC as in EXO-200 or NEXT or in large volumes of a liquid scintillator as in KamLAND-Zen.

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The second group (^{82}Se, ^{100}Mo and ^{116}Cd) is out of the reach of the bulk of the γ environmental background; they belong to the realm of the scintillating bolometers, which are almost perfectly suited to investigate these isotopes. The LUCIFER, AMoRE and LUMINEU experimental results show that at least two of them, namely ^{82}Se and ^{100}Mo, can be studied with high sensitivity.

The candidates of the third group (^{48}Ca, ^{96}Zr and ^{150}Nd) are in the best position to realize a background-free experiment. For a sort of conspiracy of Nature, however, these three golden-plated elements cannot be enriched at low cost and high throughput as they do not form gaseous compounds at room temperature and cannot therefore be enriched by centrifugation. If new efficient techniques for isotope enrichment should be demonstrated, like those based on laser separation, ion cyclotron resonance method or high temperature centrifugation, these candidates would be ideally studied with the external-source approach, as proposed in the SuperNEMO program, since this would constitute the best approximation of a zero background experiment.

3. Experimental situation and prospects

We are now (December 2013) at a turning point in the experimental search for 0νββ. The ^{76}Ge claim is strongly disfavored after the results provided by EXO-200 [11], KamLAND-Zen [12] and especially GERDA (phase I) [13], which investigates the same isotope as the claim and is therefore free from the systematics induced by the calculation of the nuclear matrix elements. The follow-up of these searches and others which are in an advanced construction phase (CUORE [14] and SNO+[15]) promise to go well below 0.2 eV. Therefore, the first of the three aforementioned challenges is very close to be achieved, and it will be in the near future.

However, there is no univocal strategy to deal with the second challenge, namely to explore deeply the IH band. Searches in preparation can only approach the onset of this region at m_{ee}, ~ 0.05 eV. In order to improve the sensitivity by at least a further factor 3 (necessary to cover fully the IH band), two approaches seem to be in a very good position: an expansion of the present EXO-200 experiment and the very promising technique of the scintillating bolometers, which however has not been proved yet with a reasonable-scale demonstrator.

3.1 Experiments taking data and in construction

We discuss below a number of projects that do not complete the full range of existing 0νββ searches, but, according to our judgment, include the experiments with the highest chances to give important contributions to the field under discussion.

EXO is an experiment based on a liquid or gaseous Xe TPC for the study of the isotope ^{136}Xe. A possible option under study, unique case in direct-detection 0νββ experiments, considers the possibility of tagging the Barium single ion – the 0νββ daughter – by means of optical spectroscopy methods, in particular through laser fluorescence [16]. If successful, this approach would eliminate any form of background, with the exception of that due to the 2νββ. A first phase of EXO, known as EXO-200 [11], is taking data since May 2011 in the WIPP facility in the US. The EXO-200 liquid TPC contains 200 kg of enriched liquid xenon, with a fiducial volume of ~100 kg. The detector measures both the scintillation light (which provides the start signal for the TPC) and the ionization. The apparatus is capable to get topology information and to distinguish between single-site events (potential signal) and multi-site events (certain background). The energy resolution is 3.8 % FWHM in the region of interest. No signal was observed after an exposure of 32.6 kg×y, with a background of 1.5×10^{-3} counts/keV/kg/y in the region of interest, the lowest ever achieved in a 0νββ experiment. This sets a lower limit on the half-life of the 0νββ of ^{136}Xe of 1.6×10^{25} y at 90 % C.L. [11], corresponding to bounds on m_{ee} of 140–380 meV, depending on the matrix element calculation. EXO-200 has provided also the first remarkable measurement of the 2νββ half-life of ^{136}Xe [17], which resulted to be $[2.11\pm 0.04_{stat}\pm0.21_{syst}]\times10^{21}$ y. Possible improvements in the radon-induced background and in the data analysis could lead the EXO-200 sensitivity up to 5×10^{25} y at 90 % C.L. in 4 y live time.

KamLAND-Zen [12] is a follow up of the KamLAND experiment, used for the detection of reactor neutrinos and located in the Kamioka mine in Japan. It was converted into an apparatus capable to study 0νββ by dissolving Xe gas in an organic liquid scintillator contained in a nylon balloon, which, being immersed in the KamLAND set-up, is surrounded by 1 kton of liquid scintillator. The mass of the Xe-loaded scintillator is 13 tons and the Xe weight fraction is about 2.5 %, resulting in 300 kg of enriched ^{136}Xe. The external scintillator works as a powerful active shield. A reasonable space resolution for interaction vertices allows to define a fiducial volume in the Xe-loaded scintillator, corresponding to 129 kg ^{136}Xe. The energy resolution is 10 % FWHM in the region of interest. The experimental data showed an unexpected bump in the background structure rather close to the region of interest of 0νββ, which prevented to achieve the primary goal of the experiment, the background level being about 30 times worse than what initially expected. The most accredited interpretation for this peak refers to a contamination of the isotope ^{110}Ag, whose decay releases a total energy about 200 keV higher than the $Q_{\beta\beta}$-value of ^{136}Xe. Xe and liquid scintillator purification is ongoing in order to reduce this background contribution. The ^{110}Ag affair is a good example of the limitation of the low-energy resolution experiments. In spite of this unexpected background source, the collaboration was able to set a significant limit on the half-life of the 0νββ process after an exposure of 89.5 kg×y, equal to 1.9×10^{25} y at 90 % C.L. (corresponding to 130–350 meV for m_{ee} when using the same matrix element range as for EXO). KamLAND-Zen has confirmed the 2νββ half-life of ^{136}Xe, set at $[2.3\pm 0.02_{stat}\pm0.12_{syst}]\times10^{21}$ y, in excellent agreement with the EXO-200 results. Even if obtained with another isotope, the EXO-200 and KamLAND-Zen limits are so stringent to be in considerable tension with the ^{76}Ge claim [12].

A further experiment based on ^{136}Xe is in preparation: NEXT [18] is a proposed 10-15 bar gaseous-xenon TPC, to be located in the Canfranc underground laboratory in Spain. Small-scale prototypes have shown that clear two-track signature is achievable, thanks to the use of gaseous rather than liquid xenon, and a good energy resolution – of the order of 1 % FWHM – can be obtained thanks to the electroluminescence signal associated to the ionization electrons produced by particle energy releases. This is the only calorimetric experiment which is in principle capable to get reasonably high energy resolution in addition to topology capability. The experiment is in the R&D phase, but a large scale prototype, using many of the final NEXT

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infrastructures, will be assembled in 2014 in Canfranc, enabling a full test of the technology and of the background level.

GERDA [13] is an experiment based on an array of Ge diodes enriched in ^{76}Ge and immersed in liquid argon (LAr) – working as refrigerant and shielding material – rather than cooled down in a conventional cryostat as in the Heidelberg-Moscow set-up. The experiment is located in LNGS, Italy. When compared to the previously described searches, the GERDA detectors have a very high energy resolution, with $\Delta E_{FWHM} \cong 0.2\%$ in the region of interest. The experimental program envisages two phases. The first phase, which uses LAr as a passive shielding, has collected an exposure of 21.6 kg×y from November 2011 to May 2013. The results of the first phase [13] show no indication of a peak at the $Q_{\beta\beta}$-value, with a limit on ^{76}Ge half-life of 2.1×10^{25} y at 90 % C.L. According to the 2004-claim, the number of counts expected for the collected exposure in a $\pm2\sigma_E$ region around the $Q_{\beta\beta}$-value is 5.9±1.4, to be compared with 2.0±0.3 expected background counts and 3 observed counts. A statistical analysis based on a Bayesian approach allows to determine the ratio between the probabilities of two models, i.e. the one including the 2004-claim and the one assuming background only. This ratio is 0.024. The 2004-claim is therefore strongly disfavored in a model-independent approach. On the contrary, the GERDA results looks still compatible with the 2006-claim. Even though this latter claim was strongly criticized because of inconsistencies in the related analysis, discussed in Ref. [19], a prudent conclusion is that although the tension between the ^{76}Ge claim and the recent ^{76}Ge and ^{136}Xe results is now very strong, we need probably further statistics combined to a lower background to declare this affair completely closed. This goal could be achieved by the second phase of GERDA, which foresees the addition of further 20 kg and a background index 10 times smaller than in the phase 1, i.e. of the order of 10^{-3} counts/keV/kg/y. This will be achieved thanks to the improved pulse shape discrimination (capable to separate single-site from multi-site events) of the advanced BEGe detectors, which will be used in the phase 2, and to the instrumentation of LAr that will work as a scintillating active shield.

Besides GERDA, we recall that in the US the MAJORANA project [20] is ongoing, consisting of arrays of enriched Ge diodes operated in conventional Cu cryostats. Merging with GERDA is discussed in view of a hypothetical 1 ton set-up corresponding to the so-called third phase of GERDA.

CUORE [14], a natural expansion of its precursor Cuoricino [21], will be an array of 988 natural TeO_2 bolometers arranged in 19 towers and operated at 10 mK in a specially designed dilution cryostat installed in LNGS, Italy. The total sensitive mass will be 741 kg, while the source will correspond to 200 kg of the isotope ^{130}Te. As in Ge diodes, the FWHM energy resolution is about 0.2%. The 90 % C.L. 5 y sensitivity to the $0\nu\beta\beta$ half-life is 9.7×10^{25} y, corresponding to a limit range of 51-133 meV for m_{ee}, one of the most promising among the experiments in construction. CUORE data taking is foreseen to start in 2015. A general test of the CUORE detector, comprising a single tower and named CUORE-0, is operational since 2012 and has shown that the background target for CUORE, of the order of 10^{-2} counts/keV/kg/y, is reachable.

SNO+ [15] is an upgrade of the solar neutrino experiment SNO, located at Snolab in Canada. The basic idea consists in filling the SNO detector (which contained heavy water in the solar-neutrino mode) with a liquid scintillator loaded with a $0\nu\beta\beta$ candidate, in particular ^{130}Te as in CUORE. Data taking is foreseen in 2015.

SuperNEMO [22] is a search based on the NEMO3 experience [23] and composed by several modules containing source foils, tracking and calorimetric sections. This experiment will investigate ^{82}Se, but the use of the golden-plated isotopes ^{150}Nd, ^{96}Zr and ^{48}Ca is not excluded, if enrichment with innovative technologies should become feasible. SuperNEMO is the only experiment of the next generation having access to the energy distribution of the single electron and to the two-electron angular distribution. A background of 1 count/(100 kg)/y is foreseen thanks to full event reconstruction. A possible configuration envisages 20 modules with 5 kg source for each module, providing 100 kg of isotope mass (but the efficiency is only 30 %). The predicted 5 y sensitivity in terms of m_{ee} is 55-140 meV. The project is in an advanced R&D phase: the first module, operating as a demonstrator containing 7 kg of ^{82}Se, will take data in 2015 in LSM, France.

3.2 Towards the inverted hierarchy region

In this section we will discuss two possible paths to a 1 ton experiment with an estimated background low enough to enable the exploration of IH region of the neutrino mass pattern. Given the clear success of EXO-200, a follow-up of this experiment looks an obvious promising choice for a high sensitive future search. In fact, a second phase of EXO-200 is under study. It consists in scaling up the current set-up, aiming at a sensitive mass of ~4 tons of enriched xenon. This project is called nEXO [24], and it could reach in a few years a sensitivity of the order of 10^{27} y, allowing to explore deeply the IH region.

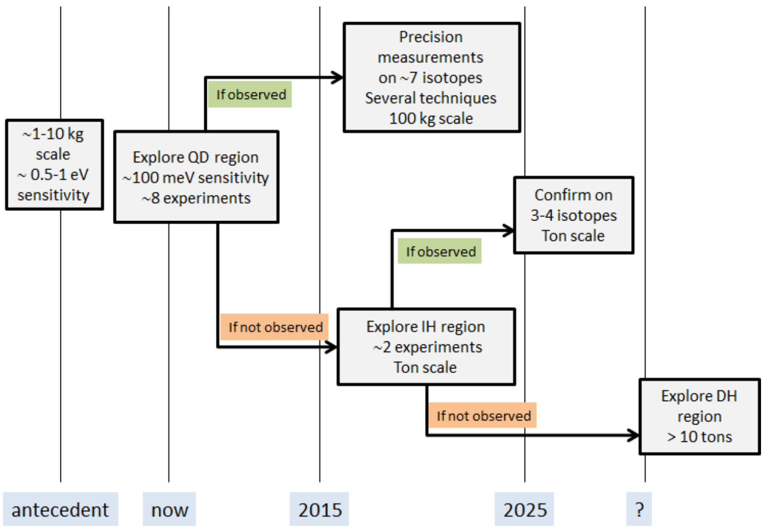

Figure 3: The race to the discovery of neutrinoless double beta decay.

A second possible way to get similar sensitivities consists of a very promising development of the bolometric technology, now employed only in the CUORE experiment. This new approach envisages the use of scintillating bolometers [25] and is at the basis of the LUCIFER [26], LUMINEU [27] and AMoRE [28] projects. The simultaneous detection of heat and scintillation light for the same event allows to reject α particles with efficiency close to 100 %, since the ratio between the photon and phonon yield is different for α and for γ/β interactions. In addition, rejection by pulse shape analysis looks possible in some cases both in the heat and light channel. The α rejection capability becomes formidably promising when applied to candidates of the second group described in Section 2.2, for which the signal is expected to fall outside the bulk of the natural γ background. Background levels of the order of 10^{-4} counts/keV/kg/y look reachable [29], in combination with a CUORE-like or GERDA-like energy resolution of a few keV FWHM. A research program in this field has identified as promising scintillating compounds $ZnMoO_4$ (used in LUMINEU and LUCIFER) [29,30], $CaMoO_4$ (used in AMoRE) [28], ZnSe (used in LUCIFER) [26] and $CdWO_4$ [30]. These compounds are suitable to study ^{100}Mo, ^{82}Se and ^{116}Cd. In non-scintillating materials like TeO_2 employed in CUORE, the α rejection can be achieved exploiting the weak Cerenkov light emitted by the two 0νββ electrons [31, 32].

4. Conclusions

In the above discussion we have given many elements which allow drawing a possible flow diagram describing the hard race towards the discovery of 0νββ. We present it in figure 3, which, we believe, represents the best summary of the impressive effort that the 0νββ community is making in order to observe that elusive peak, capable to change deeply our view of the elementary particle physics and of the evolution of the Universe.

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