Community paper „The Early Universe from Inflation to Reionization“

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Executive summary

How did the Universe begin? What is the origin of matter? What is the origin of the structures we see today in the Universe, such as galaxies, stars, planets, and eventually ourselves? Where did the magnetic fields come from? These fundamental questions about the origin of everything we see in the Universe can be addressed by peering deep into the *early Universe*, when the Universe was less than a billion years old. Scientists in Germany have made major contributions to uncovering the physics of the early Universe through dedicated experiments in the underground, on the ground, and in space, as well as through developments of theory and sophisticated computer simulations. We recommend the continued financial support for the experimental, theoretical, and computational research on the early Universe sciences, which are expected to lead to a host of breakthroughs in the coming decade including, but not limited to, discovery of primordial gravitational waves from cosmic inflation, discovery of dark matter particles, determination of the mass of neutrinos, discovery of the inter-galactic magnetic fields, and discovery of the first generations of stars and galaxies.

1. Introduction

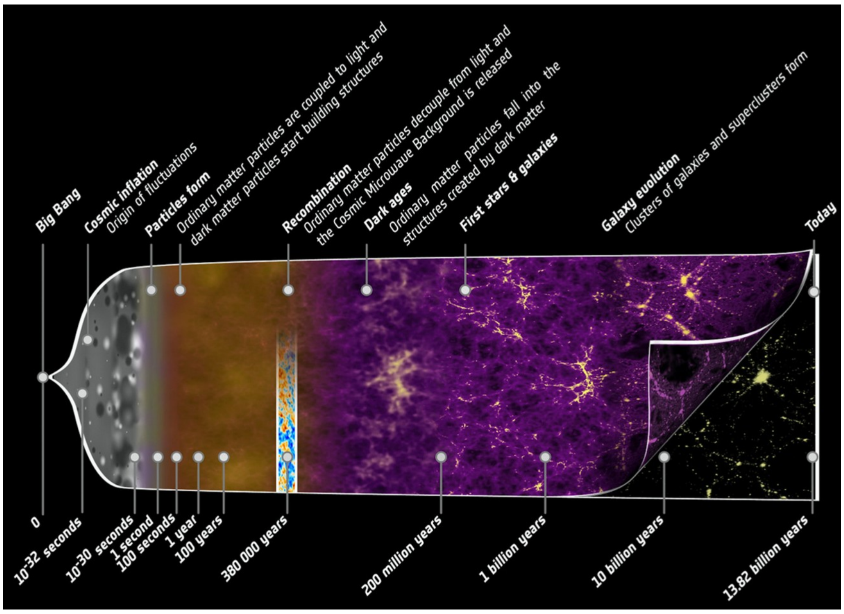

Fig. 1: History of the Universe (Credit: ESA)

Our Universe has experienced a number of dramatic transformations in the physical states in the early Universe, when the Universe was less than a billion years old (Fig. 1). We have evidence that the Universe underwent a rapid, *inflationary* expansion in a tiny fraction of a second after its birth, and became extraordinarily hot once this epoch of "cosmic inflation" ended. The ordinary matter as well as the dark matter particles were created in this hot Universe. The Universe cooled down as it continued to expand at much slower rate. The cosmic plasma combined to form atoms when the Universe was four hundred thousand years old, and fully ionized again when the Universe was between half a billion and a billion years old. As such, these epochs in the early Universe played essential roles in creating and shaping the Universe we see today.

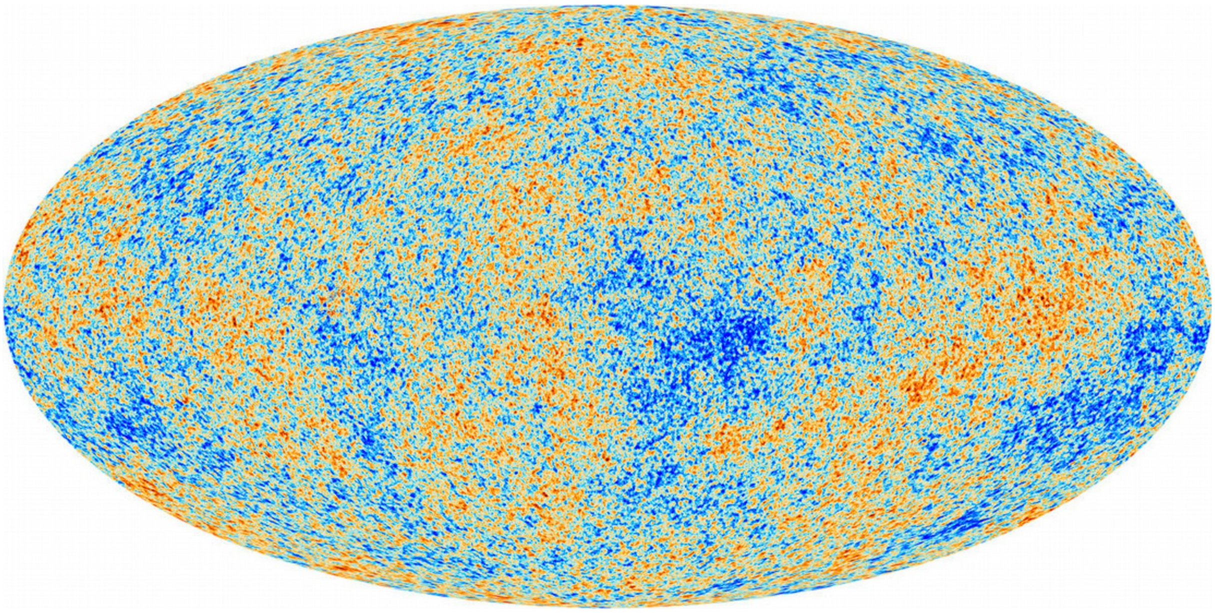

Fig. 2: Full-sky map of temperature of the CMB measured by Planck (Credit: ESA)

Origin of the Universe and the structures it contains - The cosmic microwave background (CMB), the fossil light of the fireball Universe (Fig. 2), gave us much information on the basic framework of how the Universe works. The standard model of the Universe, called the "ΛCDM model", has been firmly established by the detailed measurements of CMB using the ground-based, balloon-borne, and space-borne telescopes and its theoretical interpretations over the last two decades. The ΛCDM model is based upon General Relativity with homogeneous and isotropic expansion of space, with energy contents including the ordinary matter, cold dark matter (CDM), and the so-called cosmological constant (denoted often as "Λ"); hence the name of the model. With the success of the ΛCDM model, the investigation of the earliest moment of the Universe, i.e., inflation, will split into two branches. One branch will target the subsequent evolution of structures in the Universe from the initial conditions seen in the CMB, which are believed to have been generated during inflation by the laws of quantum mechanics. The other branch will turn to the origin of the Universe and the structures it contains. To this end, precise observations and analyses of the CMB - in particular its polarization - will continue to form the crucial empirical input. Such observations must be accompanied by theoretical progress on competing models of inflation (or even alternatives to inflation) aiming at excluding as many of the theoretical models as possible by direct comparison with the data.

Origin of matter - The majority of the matter in the Universe is dark. Currently we can only infer the existence of *dark matter* via indirect observations like the rotation velocity of the stars around the center of galaxies, the dynamics of galaxy clusters, the large-scale distribution of galaxies in the Universe, the anisotropies of the temperature and polarization of the CMB, and through the gravitational lensing effect. However, we do not know much about the fundamental nature of the dark matter or its origin. The main prevailing assumption is that dark matter is associated with massive fundamental particles, which are only weakly interacting and are yet to be discovered directly. The dark matter particles could be in the spectrum of some extensions of the Standard Model of particle physics. To discover these particles directly using underground detectors and powerful accelerators, or gamma-ray photons and cosmic-ray particles produced by the dark matter particles, is at the center stage of many ongoing and future experiments in particle and astro-particle physics. Another pressing issue is the origin of *ordinary* matter. Although the presence of light elements in the Universe, such as hydrogen and helium, is well understood as the products of fusion in a hot Universe, the ultimate origin of the ordinary matter is not known. The standard hypothesis is that the Universe was in a highly symmetric state in the early time, having equal amounts of matter and anti-matter. However, as our Universe appears to contain only matter, we must have a mechanism to produce more matter than anti-matter. Finding a fundamental explanation of this fact is one of the remaining key open questions for the description of the early Universe.

Physics of the cosmic reionization - as the Universe expanded, it cooled down and electrons, protons, and helium nuclei combined to form neutral hydrogen and helium atoms. That point, when the Universe was four hundred thousand years old, marked its transition from a fully ionized to a fully atomic state. However, as we observe that the average location in the current Universe is fully ionized, another transformation must have occurred from a neutral to an ionized state. This is known as the reionization process. With powerful telescopes both in space and on the ground, we can observe the physical states of the Universe all the way to the epoch of reionization, when the Universe was half a billion years old. Theory and sophisticated computer simulations indicate that the bulk of reionization was done by the first generations of stars and galaxies. Understanding this epoch is important because it is a major change in the state of the Universe, impacting the subsequent formation and evolution of galaxies and ultimately shaping the Universe we see today.

Origin of magnetic fields - Magnetic fields are ubiquitous in the Universe. They exist all around us: Earth, Sun, Solar System, Milky Way and other galaxies, clusters of galaxies, and potentially in the intergalactic medium (IGM). However, we do not yet know where and how the magnetic fields first emerged in the Universe. Finding and understanding their origins is one of the most profound unsolved tasks in astrophysics. To this end we must use as many observational clues as possible in the complete electromagnetic spectrum and at all spatial scales, and interpret them correctly on solid theoretical ground. The simplest way to produce a strong magnetic field is to compress it by a collapse of a cloud or by turbulent amplification. Now we know that any weak field will be amplified to a reasonable level of the kinetic energy density. The turbulent amplification works particularly well in collapsing systems and during very early epochs in the cosmic evolution, generating small-scale magnetic fields. Small seed fields can also be easily generated during the radiation dominated regime if they are not yet present from inflation. Hence, structure formation during the early Universe should be magnetized to a level which might influence the subsequent evolution. Nevertheless, it is still unknown how the observed large-scale magnetic fields in late times, e.g. around galaxy clusters, are generated and how they are maintained.

2. Key Questions for the Upcoming Decade

Origin of the Universe and the structures it contains - Two questions on the primordial universe appear to be most important for the next decade. The first question concerns the origin of our Universe as a whole and asks whether there was a beginning or whether the Universe evolves in an eternal cycle (e.g., expanding phases following contractions after a bounce, which may avoid a singularity). The second question concerns the origin of structures in the Universe and asks what the precise physical mechanisms were that shaped the structures we see in the Universe today.

Answers to these questions are likely to become within reach of sufficiently precise observations within a decade. Essentially, two classes of theories exist for the early evolution of the Universe. The *inflation* paradigm assumes that the Universe underwent a phase of exponential expansion, in which the Universe was driven apart for example by an otherwise unknown quantum field called the “inflaton”. One possible alternative, the *ekpyrotic* or *cyclic* paradigm, assumes that the Universe is evolving in cycles and experienced a bounce between a preceding contracting phase and the current expanding phase. While both paradigms are able to explain the empirical signatures of a hot phase in the early evolution of the Universe visible to us, in particular the CMB and its temperature fluctuations, they differ in their predictions of the polarization patterns expected in the CMB. More precisely, they differ in their predictions of the amounts of primordial gravitational waves, which can be detected via the CMB polarization. While inflation predicts that polarization patterns with helicity (the so-called "B-mode polarization"; Fig.3) should appear in the CMB, such modes would be absent in the ekpyrotic or cyclic models. Another possible alternative, *string gas cosmology*, predicts a different spectrum of primordial gravitational waves than inflation. Thus, precise observations of the CMB polarization will play a crucial role for our understanding of the primordial Universe.

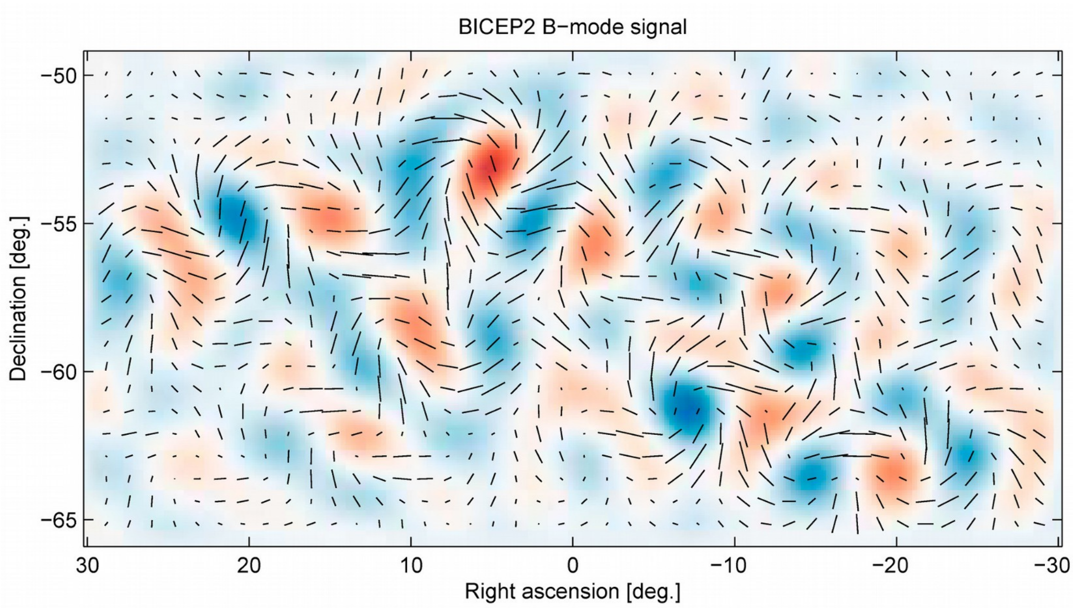

Fig. 3: B-mode polarization measured by BICEP2 (Credit: BICEP2/Keck Collaboration) So far, it is unclear what fraction of this signal comes from dust in the Galaxy and what fraction may come from the early universe.

These scenarios predict that all the structures we see in the Universe, i.e., galaxies, stars, planets, and eventually ourselves, originate from small fluctuations generated by the laws of quantum mechanics in the primordial Universe. Such fluctuations are predicted to obey Gaussian statistics to the first order; however, non-zero deviations from Gaussian statistics, called *non-Gaussianity*, should also be present, depending on the details of the models of the primordial Universe. While the current CMB measurements by the Planck satellite show that the primordial fluctuations are consistent with Gaussian statistics, improving sensitivity to non-Gaussianity will be important in furthering our understanding of the physics of the primordial Universe. In particular, local measurements of non-Gaussianity will be able to distinguish between different models for the early universe. For this purpose, not only the next CMB missions but also measurements of fluctuations using the large-scale matter distribution in the Universe, e.g., galaxies, will play important roles.

Origin of matter - If the Universe had an inflationary phase, the inflaton field was the only form of energy remaining at the end of inflation. For our Universe to contain the forms of matter and energy we observe, the inflaton field must have decayed into the known particle species of the Standard Model of particle physics in a process called *reheating*. This reheating process is largely unknown. It is likely to have involved a violent process known as the parametric resonance, but the details depend on how the inflaton field couples to the ordinary matter. Precise observations of the CMB, again of its polarization pattern, will be able to constrain the mechanism of inflation, if it existed. The parametric resonances may also generate a copious amount of gravitational waves, which can be constrained by direct detections of the gravitational waves, which were recently achieved by the ground-based laser interferometer LIGO.

Direct and indirect searches for the dark matter particles will continue to be at the center stage of research on the origin of matter. The existing searches have already tightly constrained the possible properties of dark matter particles, such as their masses and strengths of interactions with the ordinary matter and within themselves. Discovery of dark matter particles, either via direct detections or direct productions in the accelerator, or indirect detections via gamma-ray photons and cosmic-ray particles they create, will have profound implications for the basic physics.

Neutrinos may hold the key to the mystery of the origin of ordinary matter over anti-matter. The most popular scenario for producing more matter than anti-matter relies on the existence of very heavy neutrinos in the early Universe, which decay to more matter than anti-matter. This scenario, called "Leptogenesis", makes some predictions for the mass of ordinary neutrinos. While we know that neutrinos have masses, we do not yet know the precise value of the masses. The upcoming experiments both in particle physics and astrophysics have a potential to finally determine the masses of neutrinos, shedding light on the physics of neutrinos, as well as on the origin of ordinary matter in the Universe.

Cosmic reionization - Which are the sources of cosmic reionization and their characteristics? While there is a consensus that the bulk of the ionizing photons must have been produced by stars, smaller contributions from different populations of sources such as quasars, blazars, dark matter annihilation and decay, cosmic rays, etc, are not well constrained. The relative importance of the various sources strongly depends on their characteristics. In this respect it will be paramount to increase the effort for a deeper understanding of the physical properties of various sources, for example: when and where the first stars and black holes formed; which is their initial mass and how it depends on time and environment; what is their output in terms of amount and frequency distribution of ionizing photons; how and when the transition from primordial stars devoid of elements heavier than Helium to more standard stars happened; how the super-massive black holes observed at relatively early times managed to gain their masses so quickly.

When did reionization start, how did it proceed, and how did it influence the subsequent formation and evolution of galaxies? The beginning of the process is associated with the birth of the first sources of ionizing photons. The conditions under which the first stars (and thus black holes) formed are poorly known. It has also been speculated that the presence of primordial magnetic fields or of a velocity offset between the atoms and dark matter particles should delay the star formation process. In addition, even before the birth of stars and black holes, dark matter annihilation and decay might induce a partial ionization and heating of the IGM. The history and morphology of reionization are presently unknown and are shaped by the relative contributions of the various sources of ionizing radiation and their specific characteristics. The deposition of ionizing photons into the IGM changes its physical state, by reducing its neutral component and increasing its temperature. As the extent of the feedback effect of reionization on the subsequent star and galaxy formation process is largely unknown, additional effort should be devoted to a deeper understanding of how reionization shapes the Universe we observe today.

An equally important and connected topic for investigation is the reionization of Helium, the second most abundant element in the Universe. While existing observations suggest that Helium was fully ionized when the Universe was two billion years old, this interpretation is still debated and the detailed history of Helium of reionization is still not well understood.

Origin of magnetic fields - The pressing question is how strong the magnetic fields are in the IGM. We have established already that the magnetic fields exist in all collapsed objects in the Universe, the biggest of which are galaxy clusters. If the IGM is magnetized at the level of nano Gauss today, simply compressing gas in the IGM to the density of galaxy clusters can explain the magnetic field strength of micro Gauss seen in galaxy clusters. The fields of order nano Gauss in the IGM would be difficult to generate by astrophysical means, and thus discovery of such fields would call for an explanation by the physics in the early Universe, such as inflation. Such a discovery would have profound implications for fundamental physics. If the strength of the fields in the IGM is much smaller than nano Gauss, then dynamos and battery mechanism operating inside galaxies are likely responsible for amplifying tiny seed fields to the required levels.

It can be shown that the small-scale dynamo should have operated very efficiently on the scales of the first star-forming, early galaxies. The fields expected from this process are larger than what would arise from compressing field lines during collapse. A fair fraction of the large-scale magnetic fields inferred in the IGM at high redshifts may come from inside of the early galaxies, when the gas was expelled by supernovae and other forms of feedback. How this happened, and how such fields left galaxies and became distributed over galaxy clusters, is not known, and studying these processes using theory and computer simulations including magneto-hydrodynamics (MHD) will be important astrophysics problems.

3. Key Results of the Previous Decade

Origin of the Universe and the structures it contains - The previous decade was characterized by a spectacular consolidation of the cosmological standard model. Four main classes of observations were essential for this development: The abundances of the light elements, mainly hydrogen, deuterium and helium, probe primordial nucleosynthesis and constrain the amount of ordinary matter in the Universe. The large-scale structures seen in the galaxy distribution today allow to infer the amplitude and the statistics of early cosmic structures. Exploding stars called "Supernovae of type Ia" constrain the cosmic expansion history. When combined with precise observations of the CMB temperature and polarization fluctuations, a remarkably simple, consistent cosmological model, i.e., ΛCDM model, has emerged. It implies that the total matter density in the Universe is approximately six times higher than the density of ordinary matter, and that the expansion of the Universe is accelerating as if gravity was repulsive on large cosmological scales. This acceleration could either be caused by a cosmological constant or by some unknown form of quantum field with negative pressure, similar to the inflaton. The unknown form of matter and the unknown agent of the accelerating expansion have been called dark matter and dark energy, respectively. Within the cosmological standard model, both dark substances are firmly established even though their nature is unclear.

Within the ΛCDM model, the precise observations of the CMB have accumulated evidence for the structures in the early Universe to have followed Gaussian statistics, which corroborates their origin in the vacuum fluctuations of a quantum field. Moreover, these observations have confirmed one expectation from inflation with impressive significance, namely that the power spectrum of the primordial cosmic structures should be almost, but not exactly, scale-invariant. It has not been possible yet to firmly constrain further parameters describing the physics of the inflaton field. A strong signature of most models of cosmological inflation, i.e. the helical or B-mode pattern in the polarization of the CMB, has neither been confirmed yet.

Origin of matter - The ΛCDM model contains dark matter as the dominant form of matter in the Universe. Its existence has strong observational support from a number of observational results accumulated over the last decade, including, but not limited to: the precise measurements of the CMB; the construction of dark matter maps with, e.g., the Canada-France-Hawaii Telescope Lens Survey (CFHTLenS) and Dark Energy Survey (DES); the observation of the baryon acoustic oscillation signature in the galaxy distribution with, e.g., the Sloan Digital Sky Survey (SDSS); and the strong lensing observations of galaxy clusters within the CLASH program. Of prominent importance in this context are the observations associated with the so-called "Bullet Cluster" and similar clusters. These observations have established that the introduction of a dark matter component is the only model that can explain all these phenomena. These observations have been corroborated by theoretical achievements in the simulations of structure and galaxy formation, which are now in excellent agreement with the observations on nearly all scales.

Direct dark matter searches such as SNOLAB in Canada and CDMS in USA, have severely constrained the allowed parameter space for the mass and the interaction strengths of dark matter particles with nucleons. Space-borne observatories such as the Fermi gamma ray satellite with its large area telescope are sensitive to gamma-rays from the annihilation and decay products of dark matter particles. The measured gamma-ray emissions (or the lack thereof) from the center of the Milky Way, satellite galaxies of the Milky Way, and galaxies outside the Milky Way constrained the mass and self-interaction strengths of dark matter particles. The USA-led AMS-2 experiment on the International Space Station collects cosmic-ray particles such as positrons and protons with unprecedented statistics, some of which may originate from the annihilation and decay products of dark matter.

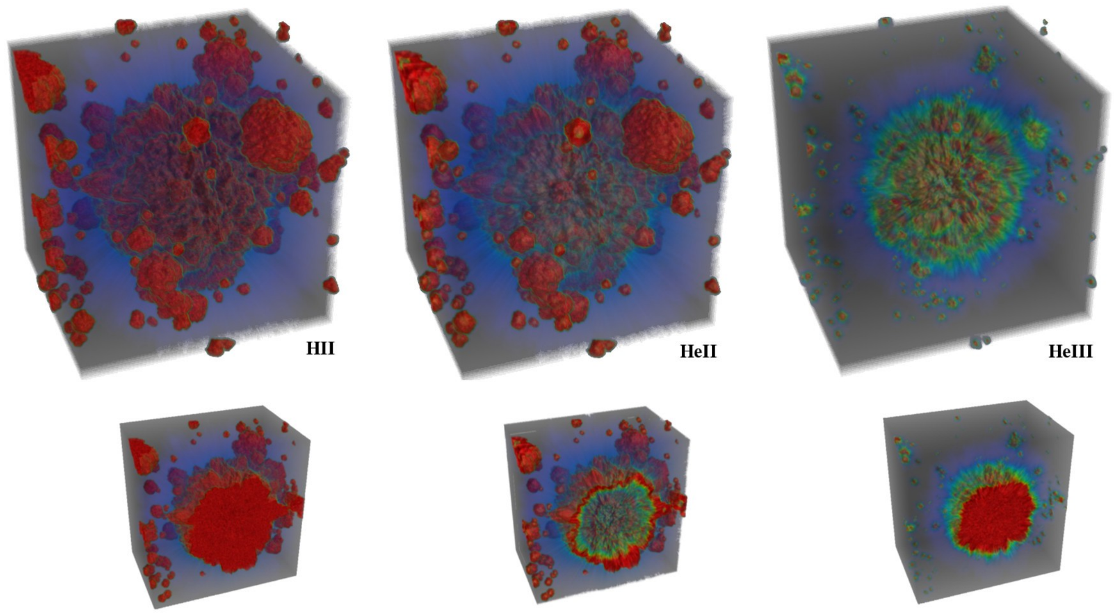

Fig. 4: Simulated ionization structure around a z=10 QSO. The bottom panels are a cut-out of the upper panels (Credit: K. Kakiichi, MPA)

Cosmic reionization - The past decade has seen a flourishing of activity in the observational as well as theoretical study of cosmic reionization and the structure formation in the early Universe. While the physical state of the IGM was investigated traditionally through absorption spectra of distant quasars (QSOs), galaxy surveys are pushing increasingly further the observational frontier of the early universe (e.g. with Subaru telescope, Hubble Space Telescope, Spitzer infrared telescope), and Gamma Ray Bursts (GRBs) retain the record for the furthest sources ever detected (with a spectroscopically confirmed GRB at a redshift of z=8.2). These observations are routinely used to tighten constraints on the hydrogen content of the IGM and its temperature during the final stages of the reionization process. While the vast majority of the sources (i.e., galaxies) responsible for reionization still remain below the detection limit of the current instruments, their cumulative, redshifted light should be visible as background radiation in different bands and provide information on the spectra of the sources of reionization. Observations of the Cosmic Infrared and X-ray Backgrounds (CIB and CXB) have been trying to quantify the contribution of these objects to the intensity and the fluctuations of the CIB and CXB. Additionally, Galactic archeology has been used to infer properties of the very first stars through their feedback effects, the impact of which should still be visible at later times (via, e.g., metal abundance patterns of the Milky Way stars).

The CMB data complement nicely the constraints on the final stages of reionization discussed above, by offering an estimate of the global amount of electrons produced during reionization. This is achieved by measurements of the polarization of the CMB, which originates from scattering of the CMB photons by free electrons produced during reionization. The most recent and tightest measurements have been announced by the Planck Consortium in 2015.

Observations of the 21cm line from neutral hydrogen in the IGM are considered the “holy grail” for researchers working in the field, as they promise to offer unique insights into the progress of reionization and the characteristics of the sources responsible for it. In fact, 21cm spectral features should display angular structure as well as structure in redshift space due to inhomogeneities in the gas density and temperature fields, as well as hydrogen ionized fraction. A number of radio observational facilities (LOFAR, MWA, PAPER) have become operational in the past couple of years and are already setting unprecedented constraints on the reionization history.

Origin of magnetic fields - Measurements of the CMB temperature and polarization anisotropies can be used to place an upper bound on the magnetic field strengths in the IGM in many ways, and the current bounds from the Planck satellite are of order nano Gauss. Improving the sensitivity of this method further to much below the key nano Gauss level would be a major milestone. Completely independent measurements, possibly indicating a lower bound to the fields in the IGM, are the gamma-ray photons from high-energy astrophysical sources such as "blazars", which are a subclass of Active Galactic Nuclei (AGNs). High-energy, TeV photons from the directions of blazars have been detected routinely by the ground-based Cherenkov telescopes such as H.E.S.S. and MAGIC. However, the fact that the Fermi gamma-ray satellite did not find the expected GeV photons from cosmic-ray particles created by collisions of TeV photons with the extragalactic background light has been interpreted as deflection of cosmic-ray particles from our lines of sight by the magnetic fields in the IGM. If this interpretation is correct, it implies a lower bound to the IGM magnetic field of order 10^{-15} Gauss. Scrutinizing this result with better data, and scrutinizing this interpretation with better modeling of blazars and interactions of TeV photons in the IGM will be the key to confirming or revising this important conclusion.

On the theoretical side, it has been quite a challenge to have significant magnetic fields generated during inflation. The so-called "strong coupling problem" for charged fields during inflation imposes serious limits to the amplitudes of magnetic fields that can be generated during inflation. Constructing viable models of inflation that can generate large enough magnetic fields has been an active area of research over the last decade.

4. Particular Role/Strengths of Research Groups in Germany

Scientists in Germany have made major contributions to advancing our knowledge of the origin of the Universe and the structures it contains, the origin of matter and the nature of dark matter, the physics of cosmic reionization, and the origin of the magnetic fields in the Universe. The contributions take various forms, from experimental contributions to data analysis and theoretical interpretations, and the development of theory of the early Universe.

The Planck satellite mission, the first European satellite mission dedicated to the CMB, yielded significant results on all of the areas covered by this document. Scientists at MPA developed software, data analysis pipelines, and simulations, and those at MPA, MPE, LMU, U. Heidelberg, RWTH Aachen, and U. Bielefeld contributed the analysis and theoretical interpretations of the Planck data.

Scientists in Germany play leading roles in gamma-ray astrophysics, which probes the nature of dark matter and the magnetic fields in the IGM. MPIK, RWTH Aachen, U. Tübingen, HU Berlin, and DESY are the leading institutions of the H.E.S.S. gamma-ray telescope, and MPP, TU Dortmund, U. Würzburg, and DESY are the leading institutions of the MAGIC telescope. They now jointly lead the CTA project. There are theoretical and computational efforts in U. Hamburg, U. Heidelberg, and U. Bochum to study the origin and amplification processes of magnetic fields in the early Universe.

Scientists at MPP, MPIK, RWTH Aachen and U. Tübingen lead direct dark matter searches with CRESST, XENON100 and EDELWEISS and are strongly involved in SNOLAB, XENON-N tons and Axion search developments. Developments of theory for the origin of ordinary matter, i.e., Leptogenesis, are actively pursued at TUM and DESY, while the determinations of the neutrino masses, which play an important role in constraining models of Leptogenesis, are also led by scientists in Germany. The ongoing particle physics projects include GERDA (MPIK) and KATRIN (Karlsruhe Institute of Technology – KIT) and the ongoing ground-based astrophysical projects include SDSS (MPA, MPE), HETDEX (MPA, MPE, LMU, AIP, U. Göttingen), and DES (LMU). Two space missions have been funded and are scheduled for launch: eROSITA (MPE, U. Tübingen, AIP, U. Erlangen, U. Bonn, U. Hamburg) and Euclid (many institutes). Theoretical and computational calculations of the structure formation in the Universe relevant to these projects are also led by scientists in Germany (MPA, LMU, U. Heidelberg, U. Bonn, AIP, RWTH Aachen, DESY).

Scientists in Germany have a dominant role in studies of the reionization processes and their sources (see Fig. 4 as an example), and the structure formation in the early Universe. Theoretical contributions, among others, are from MPA, Bonn, U. Heidelberg, U. Bielefeld, AIP, and U. Göttingen. They also have strong presence in the experimental efforts in long-wavelength radio bands, such as SKA and the SKA pathfinder LOFAR. While most of LOFAR antenna fields are located in the Netherlands, Germany is the second largest partner in LOFAR, which is fully operational and producing unprecedented scientific results at radio wavelengths in various fields, such as transient sources, reionization, radio galaxies and clusters. LOFAR will be upgraded to further enhance several of its functionalities. It is strongly desirable that Germany contributes to this development to maintain its privileged position in the project.MPE is the leading institute of the next L-class ESA space mission "ATHENA", which a large X-ray mission capable of finding blackholes and Gamma-ray Bursts out to large distances. This mission will give unique information on the reionization processes.

Scientists at LMU, TUM, U. Bielefeld, U. Heidelberg, U. Bonn, U. Erlangen, U. Göttingen, and AEI are developing fundamental theoretical ideas about the physics the early Universe, e.g., models of cosmic inflation and Leptogenesis, as well as about the nature of dark matter and the origin of the cosmic acceleration at late times.

5. Key Infrastructures needed/relevant for Researchers in Germany

The CMB observations will continue to play dominant roles in answering some of the fundamental questions about the Universe, such as the origin of the Universe and the structures it contains, the nature of dark matter, the neutrino mass, the epoch of cosmic reionization, and the magnetic field strength in the IGM. Both ground-based efforts and the next satellite mission after Planck, designed specifically for its polarization sensitivity, are important. Scientists at several German institutions (MPA, MPE, MPIfR, LMU, RWTH

Aachen) participate in the international collaboration on the **post-Planck CMB satellite** proposal “CORE” submitted to ESA M5. We recommend to support this type of space-mission proposals. There is discussion on a large, coherent program of ground-based CMB experiments called the "CMB Stage 4 (**CMB-S4**)" in both USA and Europe. We recommend the support from relevant funding agencies for contributing toward the CMB-S4 effort in Europe. This can include, but not limited to, building telescopes, building instruments, and the data analysis efforts. Contributions to the operating costs of large experiments are a pressing problem in particular for German university institutions.

For the large-scale structure survey projects, Germany is a leader in the **Euclid** and **eROSITA/SRG** missions. The continued support for these missions and their scientific exploitation is immensely important. Further a national involvement in **LSST**, a ground-based survey telescope project led by USA, would be key in this area. It is likely that the next improvement of constraints of models for the early universe will come from galaxy surveys, such as those of Euclid and LSST.

Direct detections of gravitational waves from inflation and reheating after inflation will transform our knowledge about the early Universe. While the current instruments such as LIGO (to which Germany has made significant contributions) and GEO600 (which is operated by German and British institutions) may not have sufficient sensitivity for the predicted signals in the interesting parameter space, the future instruments such as the European pulsar timing array (**EPTA**) and the space-borne laser interferometer **eLISA** may put interesting constraints. Scientists at German institutions such as MPIfR and AEI are making significant contributions to these missions. The key technologies for eLISA have been proven by the LISA Pathfinder mission in 2016.

Germany is also a leader in the **ATHENA** X-ray mission, and we recommend the continued support for this mission and its scientific exploitation.

Germany has been leading high-energy gamma-ray astrophysics, and the continued support for this area, in particular for **CTA**, is important.

We strongly recommend the German participation in **SKA**. Due to the low signal-to-noise ratio, the first observations of the 21cm signal will measure only statistical properties of the IGM, and thus imaging will not be feasible before SKA. With SKA, it will be possible to create maps of the neutral hydrogen distribution at different epochs. These will be invaluable to e.g. reconstruct the history and topology of reionization, as well as to put more stringent constraints on the relative contributions to the ionization budget from different sources. SKA will also provide much improved sensitivities for measurements of magnetic fields in galaxy clusters and groups.

In parallel, theoretical models must be developed, studied, and refined, such that observable consequences can be derived from them robustly. We recommend the **infrastructures for distributed data centers and data analysis methods**. We also recommend the continued support for **high-performance computing facilities**, which are absolutely necessary for theoretical calculations of the structure formation in the Universe and reionization processes, and the extensive analysis and simulations of the experimental data sets.

6. Summary and Conclusion

The early Universe offers rich information regarding some of the most fundamental questions about the Universe: How did it begin? How did the structures we see in the Universe originate? Where did the matter come from? What is the nature of dark matter? How did the Universe become neutral, and fully ionized again? Where did the magnetic fields come from?

Scientists in Germany have been playing leading roles in advancing our knowledge in all of these areas by leading experimental projects, by making major contributions to the development of software necessary for the analysis of the data, and by providing the key theoretical insights using formal theory as well as sophisticated computer calculations.

We recommend Germany's continued support for the key future European missions, including space-borne observatories such as the CMB polarization satellite and the galaxy survey satellites Euclid and eROSITA/SRG, and the ground-based observatories such as CMB-S4 and CTA. The participations in international observatories such as SKA and LSST are also recommended. Last but not least, the continued support for the infrastructures necessary for the data centers and high-performance computing facilities is the key to maximize the scientific returns from these missions, and is strongly recommended.

Fig. 5: From top-left to the bottom-right: Euclid, CORE, ATHENA, SKA, LSST, and CTA