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COSMIC CONNECTIONS

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ABSTRACT

A National Research Council study on connecting quarks with the cosmos has recently posed a number of the more important open questions at the interface between particle physics and cosmology. These questions include the nature of dark matter and dark energy, how the Universe began, modifications to gravity, the effects of neutrinos on the Universe, how cosmic accelerators work, and whether there are new states of matter at high density and pressure. These questions are discussed in the context of the talks presented at this Summer Institute.

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1 Connecting Quarks with the Cosmos

My task in this closing lecture is to preview possible future developments at the interface between particle physics on one side, and astrophysics and cosmology on the other side. Though these cosmic connections may benefit from some theoretical advice, they must rely on the firm facts provided by accelerator experiments, as well as non-accelerator experiments and astronomical observations. To guide the discussion, I structure this talk around a report with the same title as this section, published recently by the U.S. National Research Council,[1] that poses eleven major cosmological questions for the new century:

- 1: *What is the dark matter?*
- 2: *What is the nature of dark energy?*
- 3: *How did the Universe begin?*
- 4: *Did Einstein have the last word on gravity?*
- 5: *What are the effects of neutrinos on the Universe?*
- 6: *How do cosmic accelerators work?*
- 7: *Are protons unstable?*
- 8: *Are there new states of matter at high density and pressure?*
- 9: *Are there additional space-time dimensions?*
- 10: *How were heavy elements formed?*
- 11: *Do we need a new theory of matter and light?*

The last two questions primarily concern nuclear physics and plasma physics, respectively, and I do not discuss them here. A particle physicist's answer to the fourth question about the completeness of general relativity is inextricably linked to the ninth question about extra dimensions. Likewise, the fifth and seventh questions about neutrinos and protons, respectively, are linked in grand unified theories. Therefore, I treat these questions in pairs.

1: What is the dark matter?

We have heard repeatedly at this institute that dark matter is necessary for the formation of structures in the Universe.[2–4] The latest data from the Sloan Digital Sky Survey,[5] shown here by Kent,[6] are very consistent with the power spectrum measured in the CMB and by previous sky surveys, weak lensing and the Lyman-α forest. At the level of galaxy clusters, as we heard here from Henry,[7] some resemble train wrecks and are still forming today, whereas others have relaxed and are good probes of the dark matter content. Even before the combination of Type-1a supernovae and the CMB, cluster data indicated that $\Omega_m \ll 1$: current cluster data yield[7]:

$$\Omega_m \; = \; 0.30^{+0.04}_{-0.03} \tag{1}$$

after marginalizing over Ω_b and h. Moreover, as discussed here by Dekel,[3] the motion of luminous matter in the neighbourhood of our galaxy provides a detailed profile of the local dark matter density.

Is this dark matter composed of particles or of larger objects such as white dwarfs or black holes? The recently-demonstrated concordance between the values of Ω_b extracted from Big-Bang Nucleosynthesis and the CMB[8] confirms that the dark matter cannot be composed of baryons, excluding a dominant white dwarf component and implying that any substantial black hole component must have been primordial. Microlensing searches exclude the possibility that our own galactic halo is composed of objects weighing between $\lesssim 10^{-3}$ and $\gtrsim 10^{+3}$ times the mass of the Sun.[9] Therefore, in the following, we concentrate on particle candidates for the dark matter.

Is this dark matter hot, warm or cold? The recent WMAP,[8] 2dF[10] and SDSS data[5] are very consistent with the standard cold dark matter paradigm. In particular, the combination of WMAP with other data implies that

$$\Omega_{HDM} h^2 \; < \; 0.0076, \tag{2}$$

corresponding to $\Sigma_\nu m_\nu \; < \; 0.7$ eV. Moreover, the early reionization of the Universe recently discovered by WMAP[11] requires some structures to have started forming very early, which is evidence against warm dark matter.

However, there are problems with the cold dark matter paradigm. For one thing, the density profiles of galactic cores appear less singular than calculated in some cold dark matter simulations[12] - but these may be changed by interactions with ordinary matter and by mergers and black hole formation.[13] For another thing, there is little observational evidence for the halo substructures predicted by cold dark matter simulations - but the formation of stars may be dynamically inhibited in small structures near larger galaxies. Therefore, we continue to focus on cold dark matter candidates.

Generally speaking, these might have been produced by some thermal mechanism in the very early Universe, or non-thermally. A good example of the latter is the axion,[14] which is my second-best candidate for cold dark matter. Recent data from the LLNL axion search, reported here by Nelson,[15] excludes the possibility that a KSVZ axion weighing between 1.9 and 3.4 μeV could constitute our galactic halo.

Another example of non-thermally produced cold dark matter could be a superheavy particle produced around the epoch of inflation,[16] called by Kolb[17] the ‘wimpzilla’. A natural example of a wimpzilla is a metastable ‘crypton’ from the hidden sector of some string model.[18] If metastable, a wimpzilla could be the orgin of the ultra-high-energy cosmic rays discussed here by Ong.[19]

The classic thermally-produced cold dark matter candidate is the lightest supersymmetric particle (LSP),[20] but another possibility proposed recently is the lightest Kaluza-Klein particle (LKP) in some scenarios with universal extra bosonic dimensions (UED).[21] The spectra in some UED models are strikingly similar to those in supersymmetric models, but with bosons and fermions switched around.

During this institute, there was an important update for the accelerator constraints on supersymmetry, with a re-analysis of the e^+e^- data used to estimate the Standard Model contribution to the anomalous magnetic moment of the muon, $g_\mu - 2$.[22] These now bring the Standard Model prediction to within 2 σ of the experimental value, leaving less room for a supersymmetric contribution.[23]

The direct searches for LSP dark matter were reviewed here by Spooner.[24] As he mentioned, the long-running DAMA claim to have observed a possible annual modulation signal for cold dark matter scattering has recently been reinforced by new data from the same experiment that show the annual modulation persisting for seven years.[25] However, several other experiments, including CDMS,[26] EDELWEISS[27] and most recently ZEPLIN 1[24] exclude a spin-independent scattering cross section in the range proposed by DAMA. This range is also far above what one calculates in the Constrained Minimal Supersymmetric Standard Model (CMSSM) when one takes into account all the constraints.[28] More worryingly, the ICARUS collaboration has recently measured a large annual modulation in the neutron flux in the Gran Sasso laboratory where DAMA is located.[29]

What are the prospects for detecting dark matter at a particle accelerator? First at bat is the Fermilab Tevatron collider, which, as we heard here from Thomson,[30] now aims at an integrated luminosity of 2 fb^{-1} by 2007 and 4 fb^{-1} by 2009. This will enable it to search for squarks and gluinos with masses considerably heavier than the present limits. Next at bat will be the LHC, which is scheduled to start making collisions in 2007. With a centre-of-mass energy of 14 TeV and a luminosity of 10^{34} cm^{-2}s^{-1}, it will be able to find squarks and gluinos if they weigh $\lesssim 2.5$ TeV.[31] If the squark and gluino masses are relatively low, measurements at the LHC may fix the supersymmetric model parameters sufficiently accurately to enable $\Omega_\chi h^2$ to be calculated with an accuracy comparable to the uncertainty currently provided by WMAP.[32] The LHC will also address many other issues of interest to cosmology, such as the origin of mass, which may be linked to the mechanism for inflation, the primordial plasma in the very early Universe, and the cosmological matter-antimatter asymmetry.

Most analyses of supersymmetric dark matter assume that the lightest supersymmetric particle (LSP) is the lightest neutralino, a mixture of spartners of Standard Model particles. However, another possibility, discussed here by Feng,[33] is that the LSP is the supersymmetric partner of the graviton, the gravitino.[34] This possibility is severely constrained by the concordance between Big-Bang nucleosynthesis and CMB.[35] However, the possibility remains of a deviation from standard Big-Bang nucleosynthesis calculations and/or a distortion of the CMB spectrum.

2: What is the nature of dark energy?

The necessity of dark energy became generally accepted when data on high-redshift supernovae were combined with the CMB data favouring $\Omega_{tot} \simeq 1$.[36] This conclusion has been supported by recent data extending the previous supernova samples to larger redshift z, in particular,[37] but how robust is this conclusion? As has already been mentioned, the pre-existing data on dark matter in clusters have long favoured $\Omega_{matter} \simeq 0.3$ which, combined with the CMB data, favour dark energy Λ with $\Omega_\Lambda \simeq 0.7$ independently from the supernova data.[38] Moreover, as was discussed here by Kolb[17] and Pinto,[39] there are good reasons to think that the Type-1a supernovae are indeed good standard candles. Also, as discussed here by Wright,[40] radical alternatives to the standard ΛCDM scenario such as modified Newtonian dynamics (MOND)[41] do not agree with the CMB data. So it seems that we have to learn to live with dark energy. Supporting evidence for dark energy comes from the recent observation of the integrated Sachs-Wolfe effect,[42] a correlation between galaxy clusters and features in the CMB that appears only if there is dark energy causing the space between clusters to expand.

The next question is whether this dark energy is constant, or whether it is varying with time. The latter option offers the hope of understanding why the dark energy density in the Universe today is similar in magnitude to the density of matter, through some sort of 'tracker solution'.[43] In this case, the dark energy would have non-trivial dynamics described by an equation of state that can be parametrized by $w(z) \equiv p(z)/\rho(z)$, where

I emphasize that $w(z)$ depends in general on the redshift z. Discarding this possibility for the moment, the present cosmological data favour $w \simeq -1$, corresponding to a cosmological constant, as discussed here by Kolb.[17] The SNAP satellite project[44] aims at increasing substantially the available sample of high-z supernovae, and offers the prospect of constraining $w(z)$ much more tightly. This may enable a clear distinction to be drawn between time-varying 'quintessence' models and a cosmological constant.

If the vacuum energy Λ is indeed constant, the next step will be to calculate it. This is surely the ultimate challenge for any pretender for a full quantum theory of gravity, such as string/M theory. For some time, the efforts of the string community were directed towards proving that $\Lambda = 0$. However, this was never achieved, despite searches for a suitable symmetry or dynamical relaxation mechanism. Presumably a non-zero value of Λ is linked to microphysical parameters such as $m_W, m_t, m_{susy}, \Lambda_{QCD}$, etc., and the challenge is to find the right formula [*].

If, on the other hand, Λ is really varying, the next question is: what is the asymptotic value? Is it zero, a non-zero constant, or even $-\infty$? Quintessence only postpones the problem.

3: How did the Universe begin?

By now, the standard answer to this question is: inflation.[45] But this answer is far from being established. Simple models predict a near-scale-invariant spectrum of near-Gaussian perturbations with a model-dependent ratio of tensor and scalar modes. Some of these predictions are successful: for example, the spectral index of the scalar perturbations seen so far is consistent with being scale-invariant, with an accuracy of a few % when WMAP data are combined with data on large-scale structure.[46] However, one can never 'prove' that a statistical distribution is Gaussian: one can apply various tests, but if they are passed, one can never be sure that the distribution will not fail some future test. And there are some puzzles in the WMAP spectrum, for example glitches around $\ell \simeq 100, 200$ and 340, as discussed here by Wright.[40] As for the possible tensor modes, the first CMB polarization measurements have been published by DASI and WMAP, whose sensitivity is close to expectations in some inflationary models, but far above some predictions, as discussed here by Winstein.[47]

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[*] String theorists are also worried that, whether Λ is constant or not, the existence of an event horizon appears inevitable. In this case, it is never possible to make exact predictions because of information loss across the horizon.

Assuming the validity of the basic inflationary paradigm poses a new series of questions. Was inflation driven by some simple field-theoretical mechanism, such as an $m^2\phi^2$ or $\lambda\phi^4$ potential, or was some more subtle (quantum-gravitational? stringy?) mechanism responsible? a'string plasma'? The WMAP measurements strongly disfavour the simplest $\lambda\phi^4$ potential,[46] but the $m^2\phi^2$ potential survives for now.[48] If inflation was driven by some scalar inflaton ϕ, how can it be related to the rest of particle physics? The most suitable candidate in the present particle menagerie appears to me to be the supersymmetric partner of the heavy neutrino in a seesaw model of light neutrino masses.[48] Even if inflation was driven by a scalar inflaton field, the CMB might reveal some traces of Planckian physics in the form of some effects suppressed by powers of the planck scale m_P.

However, to answer the question in the title of this section, one must look beyond inflation, which presumably occurred when the energy density in the Universe was ($\sim 10^{16}$ GeV)^4, back to when it approached the Planck energy density ($\sim 10^{19}$ GeV)^4. At this epoch, perhaps the Universe was described by some form of string cosmology or pre-Big-Bang scenario.[49] How to test such an idea? One possibility might be provided by gravitational waves[50] from this epoch.

4/9: Does completing Einstein's theory of gravity require extra dimensions?

Einstein certainly did not have the last word on gravity. His General Theory of Relativity was one of the greatest physics achievements of the first half of the twentieth century, the other being Quantum Mechanics. Combining them into a true quantum theory of gravity was the greatest piece of unfinished business of twentieth-century physics: in particular, how to make sense of the uncontrollable infinities encountered when gravitational interactions are treated perturbatively, and how to deal with the loss of information apparently inherent in non-perturbative gravitational phenomena such as black holes? Presumably the answers to these questions involve modifying either General Relativity, or Quantum Mechanics, or both.

The best/only candidate we have for a quantum theory of gravity is string/M theory, which relies heavily on the existence of extra dimensions. These include fermionic dimensions, in the form of supersymmetry with its accompanying superspace,[51] as well as 'conventional' extra bosonic dimensions.[52] If they are to aid in stabilizing the mass hierarchy, provide the cold dark matter and facilitate unification of the particle interactions, the fermionic dimensions should appear at the TeV scale, within reach of colliders.[53] But what might be the scales of the extra bosonic dimensions? Consistency of string theory at the quantum level requires extra dimensions at the scale of $\sim 10^{-33}$ cm, and unification of gravity with the other interactions suggests they might appear at $\sim 10^{-29}$ cm.[54] Colliders can probe distance scales down to $\sim 10^{-17}$ cm, but there is no particular reason to expect that extra dimensions will show up at such a large scale.

What other signatures might there be for a quantum theory of gravity? One possibility might be gravitational waves, or there might be signatures in the CMB, as discussed earlier. It could even be that the inflation now being probed by the CMB was produced by some stringy effect. As also discussed earlier, the value of the vacuum energy should be calculable in a complete quantum theory of gravity. Other possible tests of models of quantum gravity include the propagation of energetic particles - which might be retarded by space-time foam, as could be probed by measurements of photons from AGNs or GRBs[55] - or their interactions, as could be probed by UHECRs. Modifications of quantum mechanics could be probed by laboratory studies of K mesons, B mesons and neutrons.[56] There are plenty of ways in which theories completing Einstein's theory of gravity can be tested.

5/7: What are the effects of GUTs on the Universe?

The direct upper limits on neutrino masses: $m_{\nu_e} \lesssim 2.5$ eV, $m_{\nu_\mu} \lesssim 190$ keV, $m_{\nu_\tau} \lesssim 18$ MeV,[57] have left open the possibility that neutrinos might be an important contribution to the dark matter. However, the combination of WMAP data with previous astrophysical and cosmological data provides the more stringent upper limit[8]:

$$\Sigma_\nu m_\nu \; < \; 0.7\,\mathrm{eV} \; \leftrightarrow \; \Omega_\nu h^2 \; < \; 0.0076, \tag{3}$$

implying that neutrinos can provide only a small fraction of the dark matter.

On the other hand, neutrino oscillation experiments tell us that neutrinos do have masses and mix.[58,59] The minimal renormalizable model of neutrino masses requires the introduction of weak-singlet 'right-handed' neutrinos N. These will in general couple to the conventional weak-doublet left-handed neutrinos via Yukawa couplings Y_ν that yield Dirac masses $m_D = Y_\nu \langle 0|H|0\rangle \sim m_W$. In addition, these 'right-handed' neutrinos N can couple to themselves via Majorana masses M that may be $\gg m_W$, since they do not require electroweak symmetry breaking. Combining the two types of mass term, one obtains the seesaw mass matrix[60]:

$$(\nu_L, N) \begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}, \tag{4}$$

where each of the entries should be understood as a matrix in generation space. The Dirac masses M_D and large singlet-neutrino masses M arise naturally in GUTs, but could appear even without all the GUT superstructure such as new gauge interactions.

The low-mass eigenstates resulting from the diagonalization of (4) do not, in general, coincide with flavour eigenstates, leading to neutrino oscillations described by the matrix

$$V \; = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13}e^{-i\delta} \end{pmatrix}. \tag{5}$$

Atmospheric neutrino oscillation experiments have established that $\sin^2 2\theta_{23} \sim 1$ with $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2,[58] which is also consistent with data from the K2K experiment.[61] Solar neutrino experiments, particularly SuperKamiokande[62] and SNO,[59] have established that $\tan^2\theta_{12} \sim 0.5$ with $\Delta m^2 \sim 7 \times 10^{-5}$ eV^2, which is also consistent with data from the KamLAND experiment.[63] On the other hand, we have only an upper limit on the third mixing angle θ_{13}, and no information on the CP-violating phase δ in (5).

The phase δ could in principle be measured by comparing the oscillation probabilities for neutrinos and antineutrinos and computing the CP-violating asymmetry[64]:

$$\begin{aligned} P\left(\nu_e \to \nu_\mu\right) - P\left(\bar{\nu}_e \to \bar{\nu}_\mu\right) \qquad &= \; 16 s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta \\ &\sin\left(\frac{\Delta m_{12}^2}{4E}L\right)\sin\left(\frac{\Delta m_{13}^2}{4E}L\right)\sin\left(\frac{\Delta m_{23}^2}{4E}L\right), \end{aligned} \tag{6}$$

using an intense neutrino super-beam, a β-beam or a neutrino factory.[65]

What does all this have to do with the Universe? In total, the minimal seesaw model outlined above has 18 parameters, 9 of which are observable at low energies: 3 light neutrino masses, 3 real mixing angles and 3 CP-violating phases (the oscillation phase δ and two others that appear in neutrinoless double-β decay. The other 9 parameters are associated with the heavy neutrino sector, and comprise 3 more masses, 3 more real mixing angles and 3 more CP-violating phases. CP violation in the neutrino sector offers the possibility of generating the baryon asymmetry of the Universe via heavy neutrino decays,[66] which could generate a lepton asymmetry via

$$\Gamma(N \to \ell + H) \neq \Gamma(N \to \bar{\ell} + H). \tag{7}$$

Non-perturbative electroweak interactions would then transform part of this lepton asymmetry into the required baryon asymmetry.

The question then arises whether this baryon asymmetry is directly related to the CP-violating parameter δ that could be observed in neutrino oscillations. Unfortunately, the answer is no in general.[67] Except in specific models,[68] this leptogenesis mechanism is independent of the mixing angles and phases in the light neutrino sector. However, neutrino oscillation experiments can demonstrate the principles on which the leptogenesis mechanism is based.

There is another role that neutrino physics might have played in the early Universe: the inflaton could have been a heavy sneutrino.[48] The WMAP data on the scalar spectral index, the tensor/scalar ratio, etc., are consistent with a simple $m^2\phi^2$ model for inflation with $m \simeq 2 \times 10^{13}$ GeV.[48] This is comfortably within the range favoured by the seesaw model for a heavy (s)neutrino. Moreover, if inflation was driven by a sneutrino, leptogenesis would have followed automatically. In order to avoid over-producing gravitinos following inflation, the reheating temperature should not exceed a few $\times 10^7$ GeV, which constrains the inflaton sneutrino couplings as well as its mass.

How may one test such a scenario? Accelerators may play a role, since the sneutrino inflaton model makes some relatively precise predictions for processes violating charged-lepton number conservation.[48] These are quite close to the present experimental upper limits, and we heard from Aihara[69] of a new upper limit $B(\tau \to \mu\gamma) < 3.2 \times 10^{-7}$, with the prospect of further improvement as the B factories gather more data.

As we heard here from Prell,[70] the B factory measurements of CP violation in $B^0 \to J/\psi K^0$ decays agree well with the Standard Model: $\sin 2\beta = 0.731 \pm 0.056$. On the other hand, data on $B^0 \to \phi K_s^0$ and other decays dominated by $b \to s$ penguin diagrams do not agree so well with each other or with the Standard Model.[71] This is a place where the first deviations from the Standard Model of CP violation are expected in some scenarios, such as GUT extensions of the seesaw model.[72] However, any such effect must respect the constraint imposed by the electric dipole moment of ^{199}Hg.[73] If a deviation does get confirmed by future data from B factories, CP violation in the quark sector might be reinstated as a candidate for baryogenesis, a role that the Standard Model of CP violation cannot play.

6: How do cosmic accelerators work?

Candidates for the origins of the cosmic rays include neutron stars, white dwarfs, supernova remnants, AGNs, GRBs, colliding galaxies and more, where the first two might be responsible for the lower-energy cosmic rays believed to originate within our galaxy, and the latter might be responsible for the higher-energy cosmic rays believed to come from outside our galaxy, as discussed here by Ong.[19]

As we heard here from Kahn,[74] the cosmic X-ray background is now getting much better understood, and seems to be largely due to discrete sources. As reported here by Teegarden,[75] the INTEGRAL satellite has recently discovered a new class of X-ray sources for us to understand, even if they do not contribute to the cosmic rays.

Progress was reported here in observations of some of the prospective cosmic-ray sources. As discussed by Tanimori,[76] CANGAROO observations of photons from RXJ1713.7-3946 provide evidence of π^0 production by accelerated protons. Meanwhile observations of AGNs indicate that they are probably powered by the accretion of matter onto black holes weighing $10^6 - 10^9$ solar masses, which produce jets of relativistic outflow. There is no strong evidence yet that they contribute to the observed cosmic-ray spectrum, though a correlation between the arrival directions of UHECRs and BL-Lac objects has been claimed.[77]

As for GRBs, the evidence is strengthening that (at least some of) the longer-duration GRBs are associated with supernovae at high redshifts $z \sim 1$. However, the shorter-duration GRBs with harder spectra may have different origins.

We can expect light to be cast on γ-ray sources such as galactic objects, AGNs, and GRBs by the GLAST satellite,[78] which should see $\sim 10^4$ sources each year. One of the interesting places to look for γ-ray emission is the core of the galaxy. In some models, the annihilations of supersymmetric relic particles in the core of the galaxy would produce γ rays detectable by GLAST.[28]

The origin of the UHECRs with energies $\gtrsim 10^{20}$ GeV remains an enigma. One would have expected these to be cut off by photo-absorption on CMB photons,[79] so their observation by AGASA came as a surprise.[80] However, more recently HiRes[81] has filed to reproduce the AGASA data, so it is unclear whether there is any excess to explain. Perhaps they are just the tail of conventional cosmic rays produced by some bottom-up mechanism. Alternatively, perhaps they are produced by the decays of metastable ultra-massive particles.[82] As discussed here by Kolb,[17] these might have been produced non-thermally around the epoch of inflation. There are stringy models with suitably long-lived metastable particles - ‘cryptons’,[18] and simulations of such a top-down decay mechanism are consistent with the UHECR spectrum reported by AGASA.[83] It will be exciting to see whether the Auger project[84] now starting to take data in Argentina is able to reproduce the AGASA data.

In addition to photons and protons, one might also expect the Cosmos to send energetic neutrinos in our direction. Various projects to look for these - AMANDA, ANTARES, NESTOR and IceCube - are underway, and will have sufficient sensitivity to see some of the postulated extragalactic sources. They may also be able to see the neutrino produced by the photo-absorption reaction $p+\gamma \to n+(\pi^+ \to \nu)$ on the CMB. These detectors might also be able to observe energetic neutrinos from the annihilations of supersymmetric relic particles inside the Sun or Earth.[28]

8: Are there new states of matter at high density and pressure?

Heading back towards the very early Universe, the first new state of matter that we expect to encounter is the quark-gluon plasma. Lattice gauge-theory simulations indicate a transition to this phase when the temperature exceeds about 170 MeV,[85] which would have been the case when the Universe was less than a few $\times 10^{-6}$ s old. There is recurrent speculation that the transition to hadronic matter might generate inhomogeneities with observable consequences. There have also been conjectures that the cores of (at least some) neutron stars might be made of quark-gluon matter, which could have implications for core-collapse supernovae, neutron-star mergers and GRBs.

Accelerator experiments, first at CERN and more recently at the BNL RHIC heavy-ion collider, produce in the laboratory dense and hot conditions under which the quark-gluon transition should occur. There have been tantalizing hints of quark-gluon matter, such as enhanced abundances of strange particles and the suppression of J/ψ production. As we heard here from Gagliardi,[86] the RHIC experiments have recently observed an exciting new effect that points towards the quark-gluon plasma. In high-energy proton-proton or deuteron collisions, the production of a high-p_T jet due to hard parton-parton scattering is accompanied by another jet in the opposite azimuthal direction. However, this balancing jet is absent in central Au-Au collisions.[87] The quark-gluon plasma interpretation is that the parton that should have produced the opposite jet was quenched by scattering on the naked quarks and gluons in the plasma, dispersing its transverse energy.

However, although this interpretation looks very natural, it cannot yet be regarded as established.

Heading further back to when the temperature of the Universe exceeded about 100 GeV and its age was $< 10^{-10}$ s, we believe that the Universe was dominated by an electroweak plasma in which the Higgs mechanism was switched off and Standard Model particles lost their masses. This picture is supported by lattice simulations, but only experiments at the LHC will provide us with all the information we need to calculate this phase transition reliably. If this electroweak phase transition was first order, it would have provided an opportunity for electroweak baryogenesis, an alternative to the leptogenesis scenario discussed earlier.[88]

Heading even further back, in GUTs there could have been an analogous phase transition in the very early Universe when it was $< 10^{-30}$ s old. However, it is unclear what experimental signatures this might have produced. Also in the very early Universe, there may have been a transition to a 'string plasma' phase. perhaps this is what laid down the perturbations seen in the CMB?

The most important question of all ...

... is undoubtedly the one we have not yet had the 'branes' to ask.

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