2 Assessment of the DTP, by department

We are very impressed by the quality of the TIFR Department of Theoretical Physics. This department is strong by world standards. Rated against theoretical physics departments in the United States, we would consider the DTP to be in the top 20. Its strongest subgroup is the string theory group, which we rank in the top 10. This is a quite nontrivial ranking, since in the US the top 7 positions would be claimed by Berkeley, Caltech, Chicago, Harvard, MIT, Princeton, and Stanford. The DTP merits serious comparison to the theoretical physics groups at these institutions.

The 2006 review committee also gave a strong appraisal of the DTP. That committee recommended building on this strength by expanding the scope of the DTP in several directions. We feel that this is not realistic advice to give now. Any group on the TIFR site is cramped by restrictions of space and number of students. It is possible that some major structural change to the institute can provide a significant increase in office space and on-campus housing. Unless this can happen, our advice is quite different from that in 2006. The DTPs goal should be to remain a small, elite department. The DTP should concentrate on increasing its strength by identifying and recruiting the top Indian theorists in the world community in the fields in which it is already strong.

The constraints on the DTP, and, more generally, the TIFR in Colaba, are significant. They are growing in impact and seriously threaten the future of the institute. We will discuss these constraints and their impact in Section 3 of this report. First, though, we present a more detailed evaluation of the various subgroups in the department.

2.1 Condensed matter and statistical physics

The Condensed Matter and Statistical Physics (CM) group at TIFR has four faculty members: Kedar Damle, Rajdeep Sensarma, Vikram Tripathi, and Tridib Sadhu. Of these, the first three work on the area called "quantum materials", while Sadhu works on classical statistical physics. We discuss each of these areas in turn.

Condensed matter physics is a very broad subject. It spans territory from mathematical aspects of statistical mechanics to practical materials science and divides further into the study of "hard" and "soft" matter. The major discoveries in condensed matter physics, whether experimental or theoretical, have usually not resulted from deliberate planning of large-scale experiments but rather have come from discoveries by individual scientists or laboratories. It is not possible for a small group such as that at the TIFR to cover the breadth of this field. Rather, the goal should be to stake out specific areas that demand high theoretical sophistication and make leading contributions in those areas.

The theory of quantum materials is an area of the subject that is now a major research frontier, where the classical theory of phase transitions in magnetism—now well established—breaks down. Here, possible phases are characterized by new order parameters and intrinsically quantum correlations and are linked by nontrivial "quantum phase transitions". The three TIFR faculty involved in quantum materials carry out analytical and numerical work on a variety of forefront problems, including frustrated magnetism, disordered materials, and quantum dynamics. Several of these projects reflect a high level of collaboration with TIFR experimental groups.

The area of quantum matter is typically the largest subfield within the leading US and UK condensed matter groups. TIFR has successfully recruited faculty who are fully competitive in international terms. We find this particularly impressive given the mid-career or junior status of the three members.

Classical statistical physics has historically been one of the major strengths of the DTP, but recently TIFR has seen the retirements of the two major figures in this area, Deepak Dhar and Mustansir Barma. The one faculty member now representing this subfield, Tridib Sadhu, is on leave at the École Normale Supérieure in Paris and did not participate in this review. The subfield has connections with probability theory and computer science and thus bridges to other areas of strength within TIFR. It would be valuable to see this interdisciplinary branch of science continue at TIFR, but, we stress, this should not trump the more important imperative to bring the strongest possible new faculty members to the institute.

Given the small size of the condensed matter group, it is appropriate to consider expansion of the group into new subfields. Such an expansion should take into account the ability of new members to interact with and complement the current TIFR theory faculty and experimental groups in the Department of Condensed Matter and Materials Science. Possible targets of interest for expansion, beyond continuation of the statistical physics program, include: an expert in quantum field theory who could connect technical advances from field theory and string theory to specific systems studied in condensed matter; an expert in quantum information; an expert in computational many-body physics who could build on TIFR's strength in lattice gauge theory. The primary factor in deciding on offers should be to find exceptional individuals who can take advantage of TIFR's unique environment. Of these areas, we feel that the most promising is an expansion in the applications of insights and methods from string theory. Excellent scientists are emerging in this area. The right candidate could link TIFR's current groups in condensed matter and string theory, to the great benefit of both.

The condensed matter group is producing a steady stream of good Ph.D.'s and is the largest contributor to DTP's gender diversity. An advantage of TIFR's broad excellence is that it can offer a unique level of graduate training in condensed matter theory in India, comparable to top global institutions. Students benefit from exposure to high-level research in related fields such as high-energy theory and condensed matter experiments. In US terms, TIFR's training might be analogous to Harvard or MIT, while ICTS, with its focus on theory and on short-term programs, may be more analogous to the Institute for Advanced Study or the Kavli Institute of Theoretical Physics. The committee believes that the current location of theoretical condensed matter research within DTP is the correct one, but that connections with experimental work are a growing strength of TIFR's program in this area.

We are impressed also by the fact that the condensed matter faculty is also engaged with efforts to build up the Indian condensed matter physics community more generally, and to point the large number of condensed matter faculty in India in productive and modern directions. Their planning of an annual Indian meeting of research-active scientists in condensed matter is a worthwhile contribution to science, particularly given the nature of this field, and should be supported.

2.2 Cosmology and astroparticle physics

The Cosmology and Astroparticle Physics (CAP) group at TIFR has three faculty members: Basudeb Dasgupta, Rishi Khatri, and Subhabrata Majumdar. This is a new group founded in 2010 by the move by Majumdar from the Astronomy and Astrophysics Department to DTP. Since 2014, the two junior members of the group were hired thanks, in substantial measure, to the recruitment efforts of Majumdar.

The creation of CAP was motivated in part by recommendations provided by the last external review in 2006. We applaud the DTP on the success of this initiative. In the new CAP, TIFR has put together a group with international excellence in cosmic microwave background (CMB) studies, galaxy cluster cosmology, dark matter, and neutrino astrophysics. A particular area of strength is the study of spectral distortions of the CMB due to the wide variety of absorption and scattering processes due to cosmic structures between the emission of this radiation 380,000 years after the Big Bang and the present day. In addition to these core areas, CAP faculty have made contributions to other issues, from galaxy formation to dark-matter related collider physics. We emphasize that these areas of research are distinct from those being pursued in the TIFR Astronomy and Astrophysics Department, and that they include some of the most important questions about the universe now under study. The group is well funded by external grants, and all three faculty are leaders in the international community.

There is one further subfield that plays an important role in CAP toward which the current CAP group should consider expansion. This is the area of computer simulations of cosmic structure formation. Large numerical simulations are playing an ever larger role in the landscape of theoretical cosmology. They are used both to understand the physics principles that drive the observed properties of large cosmological datasets now *under study, and to design new observational strategies. We believe that a faculty hire in this area would interact strongly with the current CAP faculty, to the benefit of all.* Such a hire would also benefit from the computational infrastructure and numerical expertise in other groups of the DTP. We understand that TIFR has made a faculty offer to Girish Kulkarni; if this offer is accepted, Kulkarni would do well to fill this gap.

In addition to access to numerical simulation results, cosmological theorists need direct access to observational data sets. Increasingly, research in cosmology involves the mining of enormous data sets gathered by collaborations of observers. Though in other fields of physics experimental data is held by experimental collaborations and reported only in the context of published papers, it has become the standard practice in cosmology for theorists to join observational collaborations and participate directly in the data analysis. Theorists shape the experimental design, take leadership roles, and, through this contribution, secure early data rights for all faculty, students, and postdocs. Several new surveys, which promise to tackle some of the deepest questions in cosmology, are being planned and are looking for partners. TIFR should make an effort to ensure that the faculty of CAP, as well as faculty in the Astronomy and Astrophysics Department, are able to participate, by joining a large survey effort as an institutional member. From the point of view of CAP, the Dark Energy Spectroscopic Instrument (DESI) offers one particularly attractive opportunity. With membership in DESI, the CAP group would be well positioned to lead the world in several key questions in cosmology, including, for example, constraints on modified gravity using galaxy clusters.

This proposal that TIFR join such a collaboration requires a monetary contribution and so runs into conflict with the institutional policy that TIFR can join a collaboration only through in-kind contributions. We would like to make clear our opinion that this policy is the product of a different era and should not be applied to the current situation. *In order for TIFR to be a leader in modern astrophysics, it needs to be able to buy access to observational data.* It is our understanding that adequate funds are available. Which collaborations should be joined should be discussed between CAP and the Department of Astronomy and Astrophysics to maximize the benefit to the institute that comes from these resources. We will discuss this further in Sec. 3.7.1.

One collaboration now in the planning stage that could be a major opportunity for CAP is the next-generation space mission on the cosmic microwave background, CMB-BHARAT. This mission is envisaged as a collaboration of the Indian and European space agencies. It aims to to provide near-ultimate measurements of CMB polarization. One of the capabilities of CMB-BHARAT will be the measurement of the CMB in a large number of spectral bands, providing detailed information on spectral distortion as a function of position on the sky that speaks directly to a principal area of expertise of the TIFR CAP group. If it is funded, CMB-BHARAT would promote India to the forefront in its impact on cosmology and early-universe physics. The CAP group is perfectly positioned to help support this project and to advise TIFR on how best to take advantage of the opportunity.

2.3 Elementary particle physics – lattice gauge theory and low energy QCD

For the purpose of this review, we divide the Elementary Particle Physics group of the DTP into two subgroups, one devoted to lattice gauge theory and low energy QCD, one devoted to weak interactions, flavor, and collider physics.

The Lattice Gauge Theory and QCD (LQCD) group at TIFR has five faculty members: Saumen Datta, Rajiv Gavai, Sourendu Gupta, Nilmani Mathur, and Rishi Sharma.

Historically, the LQCD group has been producing world class research on QCD at finite temperature and density which has influenced the international community by introducing new ideas and methods. One of the most notable examples during the period under this review is the detailed study of thermal fluctuation of baryon number (cumulant ratios) using a Taylor expansion in the baryon chemical potential. Their contributions to the understanding of the QCD phase diagram have given important theoretical motivation for heavy-ion collision programs such as the Beam Energy Scan program of the RHIC collider at Brookhaven National Laboratory. The group also successfully studied the heavy-quark momentum diffusion constant. Their predictions agree with the experimental results, highlighting the non-perturbative nature of the transport properties of the quark-gluon plasma.

Another important development of the past few years has been the use of effective field theories (EFT) to study the transport properties of finite temperature and density matter. The group proposed an effective fermionic theory near the crossover from hadron to quark-gluon behavior and determined its parameters from lattice QCD inputs. The behavior of the pion decay constant around the critical temperature T_c was correctly reproduced from the EFT. It is difficult to see how this method will apply to the deeply non-perturbative regime well beyond the phase transition, but this seems an important direction to explore. If successful, this approach would have a large number of applications to important and difficult problems, such as the structure of neutron star interiors.

After the previous review in 2006, the group has also started a research program on QCD spectroscopy. This work is quite timely, since lattice QCD is now ready to deliver precise results to be compared to the new experimental data that has been accumulating in this area over the past decade. Their results on charmed hadrons (*e.g.*, Ω_c^0) were obtained a few years prior to the experimental discovery of these states by LHCb. The current studies also include tetraquarks and dibaryons made of heavy quarks. These results on spectroscopy will become an input for the QCD thermodynamics needed to interpret proton-proton and heavy-ion collision experiments in terms of the Hadron Gas Model.

Members of the LQCD group have strong partnerships, both domestic and international. They collaborate with the STAR collaboration at RHIC and the ALICE collaboration at LHC, the Indian Lattice Gauge Theory Initiative, and the US groups χQCD and HADSPEC. They serve on the international advisory committees for the Lattice conference series, the Asian Triangle meetings, and Indo-French projects.

In view of the expected upcoming retirements of the leading members of the group, Gavai and Gupta, we see a need to replace at least one faculty member, both to maintain the strength of the group and to maintain the international stature of Indian lattice QCD. The LQCD group has an excellent track record of producing young scientists who are now faculty and postdocs at world-leading institutes. Thus, we hope that one or more appropriate candidates can be found.

Up to now, the computer resources available the LQCD group have been small compared to those of leading groups in the US, Europe, and Japan. It is remarkable how, for the problems described above, the LQCD group has been able to choose problems for which clever insights can produce work with significant impact on the international scene. The work described above on the EFT approach to transport might continue this trend, although at some point they might only produce methods for which the full potential requires larger machines. This is probably true already for their project to calculate the form factors of charm and bottom hadrons, a difficult calculation but one central to quark flavor physics.

At the very least, the LQCD group requires a steady upgrade of their high-performance computing consistent with the speed of technology development, approximately an order of magnitude speed-up every four to five years. The possible Indian initiative that would provide an 100 Petaflop-scale computing resource would put the LQCD group into a very different situation, one in which they could compete directly with leading groups elsewhere. We will discuss and make recommendations for the future of high performance computing accessible to TIFR in Section 3.4.

2.4 Elementary particle physics – electroweak interactions, flavor, and collider physics

The Electroweak interaction, Flavor, and Collider Physics (EFC) group at TIFR has four faculty members: Amol Dighe, Tuhin Roy, Sreerup Rachaudhuri, and K. Sridhar. The latter two are expected to retire within the next few years.

The international community of phenomenologists is typically following closely experiments that are being conducted, and preparing for future ones. Correspondingly, the topics that are at the forefront of high energy physics at present are

- Collider physics, in particular the physics of the ATLAS and CMS experiments;
- Neutrino physics, for both terrestrial experiments (such as the future DUNE experiment) and astroparticle experiments (such as IceCube and the future ICAL at INO).
- Flavor physics, in particular the physics of LHCb and the near-future BELLE-II.

Of the experiments mentioned, CMS, INO, and BELLE-II involve collaboration with many institutes and universities in India.

The group at TIFR has made contributions to all three areas. In collider physics, Sridhar and Raychuadhuri have been involved for a long time in proposing and analyzing signatures of new physics that could be observed at colliders, especially for models with supersymmetry and additional space dimensions. These ideas and others have been pursued by the high transverse momentum experiments at LHC, ATLAS and CMS, but so far no signs of new particles have appeared. It is an urgent matter now to understand the gaps in the search capabilities of ATLAS and CMS and to understand how to fill these gaps, both by inventing new signatures and by exploring additional and novel classes of models, such as models with "dark sectors". The newest member of the group, Tuhin Roy, has made significant and highly original contributions in this direction. He has also developed methods for analyzing hadronic jets at the LHC and for distinguishing boosted heavy particles from standard QCD jets. Both sets of contributions have the potential to advance the program of the CMS experiment.

In neutrino physics, the group has a number of major contributions. In particular, Amol Dighe is one of the world leaders in the study of the dynamics of neutrinos in supernova explosions and the potential for learning about both supernovae and neutrino mass through the observed neutrino emission.

In flavor physics, members of the group have made original contributions in the areas of D, B and B_s decays and CP violation. The group is well prepared to interpret new results that will be coming from the LHCb and Belle-II experiments.

The EFC group has taken on a number of roles that have greatly benefited the Indian phenomenological particle physics committee. TIFR originated the WHEPP series of biennial international conferences on particle phenomenology that have been taking place in India since 1989. Members of the EFC and LQCD groups have consistently played important roles in its organization. In advance of the LHC startup and in its early years, Sridhar was a principle organizer of a series of workshops and schools on LHC physics. Last year, Sridhar, Raychaudhuri, and Monoranjan Guchait in the Department of Elementary Particle Physics were principal organizers of the 2017 international conference on Supersymmetry, held at TIFR, and also of a pre-conference school for Indian students and postdoctoral fellows. Dighe is now serving as the Physics Coordinator for the INO.

While we do not identify a key area of need within the EFC group, it will be at minimal strength after the expected retirements. If an opportunity arises to recruit a new, excellent phenomenologist, this will be very welcome.

There are many close connections between the topics of interest to the EFC group and the CAP group. We understand there have been collaborations on various projects between members of the two groups. We would like to encourage further such interactions, joint seminars, and possibly students that will be supervised by co-advisors from the two groups.

We would also like to encourage additional collaboration between the EFC group and the CMS experimentalists which, we believe, will benefit both sides. Original ideas proposed by the phenomenologists of how to explore new signatures in CMS and ATLAS will benefit from feedback of the experimentalists, and are likely to have greater impact and recognition if introduced by the experimentalists within the greater CMS community. We will discuss the interaction of the DTP with CMS further in Section 3.7.4.

2.5 String theory and gravity

The String Theory (ST) group at TIFR has four faculty members: Abhijit Gadde, Gautam Mandal, Shiraz Minwalla, and Sandip Trivedi.

The string theory group was founded in the early 1980s through the leadership of Spenta Wadia. By the end of the decade, there were six members. Since that time, four of these people have left TIFR Colaba to start string theory groups at ICTS, HRI, and IISER Pune, in the process raising the overall profile of theoretical physics in India. Mandal is now the last of the original members. However, the group has been successful in recruiting young and talented theorists and continues to produce results of worldwide impact in this subject. We are pleased to see that Shiraz Minwalla is now supplying dynamic leadership for the group after the departure of Wadia.The ST group has been successful in mentoring students and postdocs, and many of these people now hold leading positions in both in India and abroad.

The most important contributions from the group in recent years have come from the exploration of novel hydrodynamic equations based on the connection to gravity through AdS/CFT duality. This work has had important implications for the understanding of exotic fluid systems such as superfluids and the quark-gluon plasma and for the classification and dynamics of black holes in conventional and extended gravity theories.

The TIFT ST group, however, is now in a precarious situation. Gautam Mandal will retire within the next decade, and Sandip Trivedi is spending a majority of his time in administration. This will leave only two faculty members, Shiraz Minwalla and Abhijit Gadde. We consider it urgent to make another appointment in this group. Since the TIFR ST group and the other groups mentioned above have been very successful in educating students, many excellent candidates are available.

Since string theory aims to construct the unified theory of all forces and matter, it has connections to many other areas in physics, in particular to high energy physics and cosmology. Research in string theory has also led to powerful concepts and techniques in quantum field theory, and some of these have found applications in condensed matter physics. There have also been productive collaborations between string theorists and quantum information theorists elsewhere. String theory uses some of the most advanced techniques in mathematics, and in return it has inspired new developments in mathematics.

We feel, though, that the opportunities for collaboration between the members of the ST group and other departments at TIFR have not been pursued as energetically as is warranted. Abhijit Gadde works on problems that can be of interest to mathematicians, in particular to geometers, and he has already initiated interactions with them. This connection could be encouraged and perhaps formalized by appointing him as an adjunct member of mathematics department if he wishes. Over the past decade, the string theory group at TIFR has had great impact on condensed matter physics, with their discoveries of fluid-gravity correspondence and of the boson-fermion correspondence in matter-Chern-Simons theories in three dimensions. However, there has not been a faculty member at TIFR well-equipped to make the bridge to the relevant condensed matter systems. In our discussion of condensed matter theory above, we have noted that this might be an area to target in the expansion of the CM group.

The string theory group is the crown jewel of DTP, and it should be an institutional priority to maintain its excellence. The group size is currently below its historical average and in danger of becoming subcritical. The institute should be actively searching for young talent, both in string theory itself and in related areas that might be involved in interdisciplinary research.