Research summary: Ashoke Sen

All scientific papers are based on the work of many others in the past. Mine are no exceptions. However in the summary of my research given below, I'll not add references to the many papers on which my work was based, even though I may mention some of the names. The original references may be found in my papers, some of which I have listed at the end.

I have not attempted to cover everything that I have worked on. I also have not tried to follow the chronological order in which the work was done. This would have been difficult anyway since some of the topics were studied over many years, often with gaps of several years in between. Instead I have attempted to group together related topics. Even though as a graduated student I started by analyzing high energy behaviour of gauge theory scattering amplitudes, the main theme of my research has been string theory – the theory that attempts to give a unified description of all the constituents of matter and all the forces acting between them, including gravity. I'll first describe my work as a graduate student, then describe the various aspects of string theory that I have worked on. I'll end this summary by a somewhat provocative topic involving the future of our universe.

1   Sudakov form factor in QCD

My work as a graduate student was on the high energy behaviour of scattering amplitudes in gauge theories. In my first paper [1] I analyzed the three point amplitude a highly off-shell photon and a pair of on-shell quarks in non-abelian gauge theories. Working at the leading order in the power series expansion in inverse powers of the photon momentum, I gave a systematic procedure for resumming all the logarithms of the photon momentum to all orders in perturbation theory. These include the logs arising from the infrared, collinear and ultraviolet regions of loop momentum integration. Later I extended the analysis to four point scattering of quarks for large values of the Mandelstam invariants s, t and u [2].

2   String theory and conformal field theory

My first major project in string theory involved studying the relationship between the two dimensional σ-models describing string propagation in a given background field, and the space-time properties of these background fields. My main contribution during this project was to establish the relation between classical equations of motion of massless fields in string theory and conformal invariance of the two dimensional sigma model describing string propagation in background of these massless fields [3,4]. Later similar results were found by Callan, Friedan, Martinec and Perry. Working along this line I also showed that in order to get a string compactification that preserves $N = 1$ space-time supersymmetry, the corresponding two dimensional σ-model should have (2,0) world-sheet supersymmetry [5,6]. This provided a way of looking for space-time supersymmetric vacua of string theory.

3   Solution generating techniques

I developed a method for generating new classical solutions of string theory from a known classical solution, when the original solution is independent of some of the space-time coordinates [7–9]. Using string field theory I also argued that these solution generating transformations can be extended to the full classical effective action of string theory, going beyond the leading two derivative approximation. Later, I used this method to generate the most general electrically charged rotating black hole solution in four dimensional heterotic string theory [10] and also a string solution carrying charge current that was used to give evidence for the proposal of Hull and Townsend and Witten that type IIA string theory compactified on K3 is dual to heterotic string theory compactified on T^6 [11].

4   Fayet-Iliopoulos term in string theory

In 1987, Dine, Seiberg and Witten used low energy effective field theory to argue that in some four dimensional string theories with U(1) gauge symmetry one loop effects can generate a Fayet-Iliopoulos D-term that can break supersymmetry. In collaboration with J. Atick and L. Dixon I showed how the presence of such a D-term can be verified in an explicit one loop string computation for any string compactification [12]. We also found that for most of the known string theories, the generation of the D-term does not break supersymmetry, since one can find a new supersymmetric vacuum in the space of field configurations. As described in §13, this was later put on a firmer footing using the tools of string field theory.

5   Strong weak coupling duality

One of my main topics of research has been the subject of strong-weak coupling duality or S-duality in string theory and quantum field theory. The original proposal for such a duality was given by Montonen and Olive in the late 70's, and it became clear through the work of Olive and Witten, Osborn and of Font, Ibanez, Lust and Quevedo that the proposal takes a firmer footing in $N = 4$ supersymmetric Yang-Mills theory and heterotic string theory compactified in T^6 which contains the former as its low energy limit. There were many evidences for this e.g. the BPS mass formula, symmetry of the equations of motions etc. but there was a general feeling in the community that these are simple consequences of supersymmetry and do not give non-trivial evidence for the strong weak coupling duality. While this is true to some extent, not everything follows from supersymmetry. In particular I argued that the existence of this duality requires a precise relation between charge quantization laws in the theory and the period of the θ-parameter that does not seem to follow from supersymmetry [13]. I summarized these evidences in [14] where I also argued that the duality symmetry leads to some precise prediction for the existence of certain dyonic states in the spectrum that were not known to exist at that time. In [15] I explicitly verified some of these predictions which eventually made the community take the idea of this duality more seriously. This also led to some precise

mathematical conjectures on the existence of certain harmonic differential forms in the moduli spaces of monopoles studied earlier by Atiyah and Hitchin. This was then developed and extended by Seiberg and Witten, Vafa and Witten, Hull and Townsend and many others. I also did further work on this subject, finding new examples of dualities in string theory.

6   F-theory and orientifold

In 1996 C. Vafa proposed a new way of compactifying type IIB string theory known as F-theory. These compactifications are not accessible to the standard perturbative analysis, since the coupling constant of the theory becomes large in some regions in the internal space. Nevertheless based on various symmetry arguments Vafa argued that some of these compactifications are dual to more conventional string compactifications. I showed [16] that at least for some of these compactifications, one can take appropriate limits where they reduce to ordinary string compactifications – known as orientifolds – that are amenable to perturbative techniques, and the dualities proposed by Vafa can be understood in terms of more conventional dualities proposed earlier. This method has been used later to find various other dualities involving F-theory, and has also led to the discovery of new string compactifications in the search for duals of F-theory compactification. Extending the method of this paper I later showed [17] how one can take appropriate limit of a general F-theory compactification to map it into an orientifold.

7   Black holes and elementary strings

String theory contains black hole solutions which carry the same quantum numbers as elementary string states. The most general class of such black hole solutions in toroidally compactified heterotic string theory was constructed in [10]. Thus it is natural to ask if the degeneracy of black hole states, as counted by the Bekenstein-Hawking entropy, agrees with the degeneracy of elementary string states. If true, this will indicate that there is no distinction between the black holes and elementary string states, and at the same time, this would provide a statistical interpretation of Bekenstein-Hawking entropy from the counting of microscopic states. The main obstacle to this calculation had been that the degeneracy of elementary string states is calculable only in the weak coupling limit, whereas these states become black holes only for sufficiently large coupling when the gravitational effects are appreciable. I circumvented this problem by looking at the states which preserve part of the space-time supersymmetry (also known as BPS states), since it is known that for such states the degeneracy remains unchanged as we go from the strong to the weak coupling. Comparison of the black hole entropy according to (a stringy modification of) the Bekenstein-Hawking prescription, and the logarithm of the degeneracy of the elementary string states, showed an exact agreement between the two sides as functions of three independent parameters, − the mass and charge of the black hole, and the string coupling constant − up to an overall multiplicative numerical coefficient which could not be calculated explicitly [18]. Later similar agreement was found by Strominger and Vafa and many other authors in many other examples, where the numerical factor could be calculated.

The missing numerical factor in my original analysis was calculated much later by Dabholkar, and shown to agree with the degeneracies of elementary string states.

8   Precision counting of black hole microstates

$\mathcal{N} = 4$ supersymmetric string theories typically contain a spectrum of dyon states which preserve 1/4 of the supersymmetries of the original theory. In collaboration with Justin David and Dileep Jatkar I computed the exact spectrum of dyons in a class of such string theories and verified the duality invariance of the spectrum [19–23]. One surprising feature of our results is that in all the theories, the generating function of the degeneracy / index is given by the inverse of a Siegel modular form. For the specific case of heterotic string theory compactified on T^6 the Siegel modular form is the Igusa cusp form, as conjectured by Dijkgraaf, Verlinde and Verlinde several years earlier. These results were then compared to the contribution from higher derivative and quantum corrections to black hole entropy in a variety of string compactifications that will be described in §9.

9   Stringy and quantum corrections to black hole entropy

The effective action of string theory contains correction to the Einstein-Hilbert action in the form of higher derivative terms in the action. This corrects the black hole solution as well as the black hole entropy. For the latter a general formula was written down by Wald. In 2005 I showed that the analysis simplifies enormously for an extremal black hole. In particular in any theory of gravity coupled to other matter fields with generally covariant higher derivative corrections, the near horizon field configuration of an extremal black hole is obtained by extremizing an 'entropy function [24, 25]. The entropy function is a function of the parameters characterizing the near horizon geometry of the black hole and there is a well defined algorithm for constructing this function from the Lagrangian density of the theory. Furthermore the entropy itself is given by the value of the entropy function at its extremum. This led to a proof of the 'attractor mechanism' in a general higher derivative theory of gravity without invoking supersymmetry. In particular the results show that in a generic situation where the entropy function has no flat directions the near horizon field configuration is determined completely by extremizing the entropy function and hence cannot depend on the asymptotic values of the scalar fields of the theory. On the other hand if the entropy function has flat directions then the near horizon field configuration is not completely determined by extremizing the entropy function and could have some dependence on the asymptotic values of the scalar fields. But the entropy is still independent of the asymptotic data. Although initial studies focussed on spherically symmetric black holes, this analysis was later generalized to black holes carrying angular momentum [26, 27].

As a continuation of this project I also proposed an exact formula – known as the quantum entropy function – that computes the entropy of an extremal black hole after taking into account both stringy corrections and quantum corrections to the black hole entropy [28, 29].

This provides a way to compare the black hole entropy and the degeneracies computed in the microscopic theory to an arbitrary accuracy. This procedure has been used to compute logarithmic corrections to the black hole entropy in N=4 and N=8 supersymmetric string theories [30–32], twisted index that computes the degeneracy weighted by $(-1)^F$ times some discrete symmetry generator [33,34] and the sign of the index [35]. The results are in agreement with the microscopic results. The computation of logarithmic corrections was also generalized to non-extremal black holes [36].

10 Multi-centered black holes and quivers

In supergravity, which is the low energy limit of string theory, we have both single centered and multi-centered black hole solutions. The latter become particularly important for extremal black holes for which the multi-centered black holes can be stable, and contribute to the entropy for a fixed total charge besides the single centered black holes carrying the same charge. It turns out however that as we change the moduli of string compactification, given by the asymptotic values of massless scalars, some of these multi-centered configurations may cease to exist and / or new multi-centered configurations may appear. Therefore the black hole index may jump across codimension one subspaces of the moduli space known as walls of marginal stability. In [37] I classified these walls of marginal stability for a wide class of $N = 4$ supersymmetric string compactification. I also showed that even though the index jumps across the walls of marginal stability, the partition function (generating function of the index) remains unchanged. The same generating function, expanded in different ways, gives the result for the index in different regions of the moduli space. The jumps across the walls, known as the wall crossing formula, are determined by the residues at certain poles of the generating function. I also derived a general form of the wall crossing formula in $N = 4$ supersymmetric theories in [38].

The structure of wall crossing in $N = 2$ supersymmetric string compactification is much more complex. The jumps across the walls was analyzed by Denef and Moore, Kontsevich and Soibelman, Joyce and Song and many others, leading to the wall crossing formula. In [39] with Manschot and Pioline I derived two new versions of the wall crossing formula by analyzing the properties of black hole bound states. These were later shown to agree with each other and with the earlier results of Kontsevich and Soibelman and of Joyce and Song [40]. Later we used these ideas to write down the degeneracies of multi-centered black hole configurations in terms of single centered degeneracies [41] and applied it to derive some results in quiver quantum mechanics [42, 43]. The importance of this work stems from the fact that the microscopic counting of the type described in §8 typically gives the full degeneracy / index without distinguishing between single and multi-centered black holes while the macroscopic analysis based on the quantum entropy function, as described in §9, focuses on the contribution from single centered black holes. Therefore in order to compare the results we need the relation between single and multi-centered black holes.

11 String field theory

The usual formulation of string theory uses a first quantized description, also known as the world-sheet approach. While capable of computing S-matrix elements in a given background, this approach is not very useful for describing a change in the background. A second quantized approach to string theory was proposed by Witten, Zwiebach and others that give a more conventional quantum field theory like formulation of string theory with infinite number of fields. The background independence of the theory however was not manifest. In several papers, some of them in collaboration with Barton Zwiebach, I proved background independence of string field theory for backgrounds that are related by marginal deformation [44–46].

I returned to the subject of string field theory in the context of tachyon condensation, and superstring perturbation theory, described in §12 and §13 respectively, and again much later for the formulation of superstring field theory. Actually my work on superstring field theory started in the mid 90's in a paper with Saroja where we showed how in principle one could write down a consistent field theory for the NSNS sector of superstring theory by making the picture changing operators move as we vary the moduli of the Riemann surface [47]. It was however not fully clear if we can consistently avoid collision of picture changing operators / spurious poles, thereby avoiding possible singularities. I returned to this problem in 2014 and resolved this issue using the notion of vertical integration [48]. A fully systematic procedure for carrying out vertical integration was given later in a paper with Witten [49]. This was needed not just for the formulation of string field theory, but also for a systematic description of superstring perturbation theory.

While this resolved the problem of constructing string field theory action in the NSNS sector, a full string field theory must also include the NSR, RNS and RR sectors. This had been a stumbling block in the formulation of superstring field theory and the absence of an action for type IIB supergravity, which arises as the low energy limit of type IIB string theory, was a clear signal that one cannot have a conventional action. I resolved this problem by introducing an extra set of string fields in the theory. Even though it seems to double the number of degrees of freedom, one finds that one set of fields decouple in the final theory, and the remaining interacting degrees of freedom precisely produce the perturbative amplitudes [50, 51] of superstring theory. Later I used this formalism to write down an action for type IIB supergravity and other theories with chiral bosons [51]. Using the framework of string field theory I, in various collaborations, also discussed the construction of the Wilsonian effective action by integrating out the heavy modes [52], proof of unitarity of string theory [53] and proof of crossing symmetry of four point amplitudes [54].

12 Non-BPS states and tachyon condensation in string theory

Another of my projects involves study of non-supersymmetric solitons in string theory. Most of the earlier studies on solitons in string theory have been on supersymmetric (also known as BPS) configurations. In a series of papers in 1998 I showed that many string theories have

6

stable non-BPS states and that they can also be used to test various duality conjectures [55–57].

During this study, I also found a novel construction of non-BPS states in terms of kink solution involving the tachyon field on a brane anti-brane pair. Tachyons have been known to be present in bosonic string theory almost since its birth but are absent in superstring theory. Nevertheless if we consider a system of coincident D-brane and anti D-brane in superstring theory, the spectrum of open strings contain a tachyonic mode indicating that we have a scalar field for which the potential has a maximum at the origin of the field space. An interesting question that had remained unanswered was 'what describes the minimum of the tachyon potential?' The study of non-BPS branes led to a series of conjectures about tachyon potential on the brane-antibrane system and non-BPS D-branes in superstring theory, as well as on D-branes of bosonic string theory [56, 58–61]. Later, in various collaborations with Zwiebach, Berkovits, and Moeller I found evidence for these conjectures in string field theory [62–65]. The analytic solution describing the tachyon vacuum in open bosonic string field theory was constructed by Schnabl a few years later who verified the conjecture on the energy density of the tachyon vacuum. Many of the other conjectures have also been analytically proven by now.

Although initial studies of the non-BPS branes focussed on their static properties, in 2002 I found a set of time dependent solutions describing the 'decay' of these branes [66,67]. These are among the few time dependent solutions in string theory whose properties have been studied in detail and have been used extensively to build cosmological models out of string theory. Study of these solutions has also led to a new kind of duality conjecture between open and closed string theories [68].

13   Superstring perturbation theory

The original formulation of superstring perturbation theory was based on the world-sheet formulation that expresses the scattering amplitudes as integrals over the moduli spaces of Riemann surfaces. However these integrals often run into divergences from the boundaries of the moduli space where the Riemann surface degenerates. Usually one can deal with these divergences by analytic continuation in the momenta of the external particles – we define the amplitude for the range of momenta where the integrals are finite and then analytically continue the result to other values of the momenta. However this procedure does not always work. By expressing the amplitudes in terms of Feynman diagrams of string field theory one finds that these failures occur precisely when one of more internal propagators in a Feynman diagram is forced to be on-shell due to momentum conservation rules. This is the case for example when we have self energy diagrams on external legs of a Feynman diagram or tadpoles of massless fields. Since in quantum field theory we know precisely how to address these problems – e.g. by mass renormalization in the first case and by finding the correct vacuum in the second case – we can use string field theory to resolve these divergences. We discussed these in a series of papers with Pius and Rudra [52, 69, 70]. In [71] I used the technique of string field theory to reanalyze and extend the analysis described in §4 by showing how the broken supersymmetry generated by the one loop Fayet-Iliopoulos term is restored by shift of the string field. In the broken supersymmetric 'vacuum' we have a non-zero cosmological constant but this becomes zero in

the supersymmetric vacuum. I also used the notion of vertical integration, mentioned in §11 to give a fully systematic description of superstring amplitudes avoiding spurious poles which otherwise plague the usual formulation of the world-sheet theory [48, 49].

14 D-instanton amplitudes

D-instantons describe classical finite action solutions in euclidean string theory and could give non-perturbative contribution to the scattering amplitudes in string theory. In principle D-instanton contribution to string amplitudes can be computed systematically by summing over world-sheets with boundaries, with D-instanton boundary condition at the boundaries. However the resulting integrals over the moduli spaces of Riemann surfaces often run into divergences from the boundary of the moduli space. Again using the language of string field theory one finds that these divergences can be traced to the presence of internal on-shell open string propagators in the Feynman diagram, with the boundaries of the open string lying on the D-instanton. However in this case the problem is more severe since the open strings on the D-instanton are forced to carry zero momentum along the non-compact directions and hence no analytic continuation is possible.

One again finds that using the language of string field theory one can resolve these problems. The main idea is to remove the open string zero mode contributions from the internal propagators of the Feynman diagram and integrate over the zero modes separately at the end. This procedure successfully resolved various open problems that were present in the earlier analysis, *e.g.* in the work of Green and Gutperle in ten dimensional type IIB string theory and in the work of Balthazar, Rodrigues and Yin in two dimensional bosonic string theory. We applied this procedure to analyze D-instanton contribution to string amplitudes in two dimensional bosonic string theory [72–75], ten dimensional type IIB superstring theory [76, 77] and type II string theories compactified on Calabi-Yau threefolds [78, 79].

15 Soft theorem

Leading soft photon and soft graviton theorem, discovered by Weinberg in the mid 1960's, express an amplitude with one or more low momentum (soft) graviton or photon in terms of an amplitude without such soft particles. Interest in the soft theorem was revived recently due to the work of Strominger and others on the connection between soft theorems, asymptotic symmetries and memory effect, and also due to the discovery by Cachazo and Strominger of subleading soft theorem for scattering of massless particles. In various collaborations I gave a general proof of the subsubleading soft graviton theorem in any generally covariant quantum theory of gravity [80–82]. Later with Alok Laddha I showed how by taking appropriate classical limit of the soft theorem, one can derive the form of low frequency classical gravitational radiation in a classical scattering process purely in terms of the incoming and outgoing hard particle momenta. This analysis is straightforward in dimensions five or more, but has interesting logarithmic corrections in four dimensions that produce a late and early time tail

of the gravitational radiation [83, 84]. A classical proof of this was given later [85] and some interesting properties of this formula were explored in [86].

16   Doublet-Triplet splitting in string inspired GUTS

In conventional SU(5) grand unified theories, the Higgs field belongs to a fundamental representation of SU(5) and it requires a high degree of fine tuning (1 in 10^{15}) to keep its color triplet component heavy (which is required to avoid rapid proton decay) and at the same time the weak doublet Higgs light (so that it can induce symmetry breaking responsible for the mass of the $W^{\pm}$ and Z bosons). In a paper in 1985 [87] I showed how in string theory one might be able to get this mass hierarchy naturally, without the need of any fine tuning.

17   Stringy corrections to the Calabi-Yau metric

In 1986, several groups found a new four loop contribution to the β-function in the σ-model describing string propagation on a Calabi-Yau manifold. This led to the possibility that Calabi-Yau manifolds are not valid backgrounds for string compactification as these would not be solutions of the equations of motion. In collaboration with D. Nemeschansky I showed that it is possible to modify the metric on the Calabi-Yau manifold order by order in string perturbation theory so that it continues to remain solutions of the equations of motion, and hence provides a conformally invariant σ-model [88].

18   Classification of rational conformal field theories

In collaboration with Samir Mathur and Sunil Mukhi, I proposed a way to classify rational conformal field theories by using modular properties of their characters [89]. If the theory has n characters then modular transformations acts as an $n \times n$ matrix on these characters. This in turn implies that there is a modular covariant n-th order ordinary differential equation whose solutions give the characters. For a given value of n, one can start with a general form on the modular differential equation parametrized by some unknown constants and then determine those constants by requiring the solutions to the differential equation properties satisfied by characters *e.g.* integrality of the Fourier expansion coefficients.

19   Matrix theory

In 1996, Banks, Fischler, Shenker and Susskind proposed a non-perturbative definition of eleven dimensional supergravity theory in terms of quantum mechanics of infinite dimensional matrices. I gave a systematic description of this theory when we compactify some of the eleven

dimensions [90]. This unified many of the ad hoc descriptions of this theory given earlier.

20 Interpolating function

In string theory and quantum field theories, most expansions are asymptotic. However many string compactifications and quantum field theories have the property that at strong coupling it admits a dual weakly coupled description, thereby admitting a perturbation expansion in inverse powers of the coupling. In [?] I described a general procedure for combining the strong and weak coupling expansion to get an interpolating function. In special cases where the exact result is known, this function gives a better approximation to the exact result than either of the two expansions.

21 The future of our universe

Discovery of the accelerated expansion of the universe in the late 90's has changed our understanding of the future of our universe. We now know that in the far future the universe is going to divide itself into multiple regions which will not be able to communicate with each other even though today we can reach those regions if we try hard enough. Another aspect of our universe is the possibility that we may be living in a metastable vacuum that could decay into a different vacuum by formation of a tiny bubble which would expand at the speed of light and wipe out the whole observable universe. In an essay [92] I suggested that we could in principle increase the chances of survival of our civilization by spreading out in different regions of the universe that are reachable today, but will be out of each others' reach in the far future. In that case if in the future a bubble of more stable vacuum forms in one region, it can wipe out everything that is within its reach, but civilizations settled in other parts of the universe that are out of reach will survive. Detailed calculation of how efficient this process is was performed in a follow up paper with Kashyap, Mondal and Verma [93] where we also calculated how the half-life of our universe changes with time due to the expansion of the universe.

References

[1] A. Sen, "Asymptotic Behavior of the Sudakov Form-Factor in QCD," Phys. Rev. D **24** (1981), 3281 doi:10.1103/PhysRevD.24.3281

[2] A. Sen, "Asymptotic Behavior of the Wide Angle On-Shell Quark Scattering Amplitudes in Nonabelian Gauge Theories," Phys. Rev. D **28** (1983), 860 doi:10.1103/PhysRevD.28.860

[3] A. Sen, "The Heterotic String in Arbitrary Background Field," Phys. Rev. D **32** (1985), 2102 doi:10.1103/PhysRevD.32.2102

[4] A. Sen, "Equations of Motion for the Heterotic String Theory from the Conformal Invariance of the Sigma Model," Phys. Rev. Lett. **55** (1985), 1846 doi:10.1103/PhysRevLett.55.1846

[5] A. Sen, "(2, 0) Supersymmetry and Space-Time Supersymmetry in the Heterotic String Theory," Nucl. Phys. B **278** (1986), 289-308 doi:10.1016/0550-3213(86)90214-2

[6] A. Sen, "Heterotic String Theory on Calabi-Yau Manifolds in the Green-schwarz Formalism," Nucl. Phys. B **284** (1987), 423-448 doi:10.1016/0550-3213(87)90043-5

[7] A. Sen, "O(d) x O(d) symmetry of the space of cosmological solutions in string theory, scale factor duality and two-dimensional black holes," Phys. Lett. B **271** (1991), 295-300 doi:10.1016/0370-2693(91)90090-D

[8] A. Sen, "Twisted black p-brane solutions in string theory," Phys. Lett. B **274** (1992), 34-40 doi:10.1016/0370-2693(92)90300-S [arXiv:hep-th/9108011 [hep-th]].

[9] S. F. Hassan and A. Sen, "Twisting classical solutions in heterotic string theory," Nucl. Phys. B **375** (1992), 103-118 doi:10.1016/0550-3213(92)90336-A [arXiv:hep-th/9109038 [hep-th]].

[10] A. Sen, "Black hole solutions in heterotic string theory on a torus," Nucl. Phys. B **440** (1995), 421-440 doi:10.1016/0550-3213(95)00063-X [arXiv:hep-th/9411187 [hep-th]].

[11] A. Sen, "String string duality conjecture in six-dimensions and charged solitonic strings," Nucl. Phys. B **450** (1995), 103-114 doi:10.1016/0550-3213(95)00320-R [arXiv:hep-th/9504027 [hep-th]].

[12] J. J. Atick, L. J. Dixon and A. Sen, "String Calculation of Fayet-Iliopoulos d Terms in Arbitrary Supersymmetric Compactifications," Nucl. Phys. B **292** (1987), 109-149 doi:10.1016/0550-3213(87)90639-0

[13] A. Sen, "Quantization of dyon charge and electric magnetic duality in string theory," Phys. Lett. B **303** (1993), 22-26 doi:10.1016/0370-2693(93)90037-I [arXiv:hep-th/9209016 [hep-th]].

[14] A. Sen, "Strong - weak coupling duality in four-dimensional string theory," Int. J. Mod. Phys. A **9** (1994), 3707-3750 doi:10.1142/S0217751X94001497 [arXiv:hep-th/9402002 [hep-th]].

[15] A. Sen, "Dyon - monopole bound states, selfdual harmonic forms on the multi - monopole moduli space, and SL(2,Z) invariance in string theory," Phys. Lett. B **329** (1994), 217-221 doi:10.1016/0370-2693(94)90763-3 [arXiv:hep-th/9402032 [hep-th]].

[16] A. Sen, "F theory and orientifolds," Nucl. Phys. B **475** (1996), 562-578 doi:10.1016/0550-3213(96)00347-1 [arXiv:hep-th/9605150 [hep-th]].

[17] A. Sen, "Orientifold limit of F theory vacua," Phys. Rev. D **55** (1997), R7345-R7349 doi:10.1103/PhysRevD.55.R7345 [arXiv:hep-th/9702165 [hep-th]].

[18] A. Sen, "Extremal black holes and elementary string states," Mod. Phys. Lett. A **10** (1995), 2081-2094 doi:10.1142/S0217732395002234 [arXiv:hep-th/9504147 [hep-th]].

[19] D. P. Jatkar and A. Sen, "Dyon spectrum in CHL models," JHEP **04** (2006), 018 doi:10.1088/1126-6708/2006/04/018 [arXiv:hep-th/0510147 [hep-th]].

[20] J. R. David, D. P. Jatkar and A. Sen, "Product representation of Dyon partition function in CHL models," JHEP **06** (2006), 064 doi:10.1088/1126-6708/2006/06/064 [arXiv:hep-th/0602254 [hep-th]].

[21] J. R. David and A. Sen, "CHL Dyons and Statistical Entropy Function from D1-D5 System," JHEP **11** (2006), 072 doi:10.1088/1126-6708/2006/11/072 [arXiv:hep-th/0605210 [hep-th]].

[22] J. R. David, D. P. Jatkar and A. Sen, "Dyon Spectrum in N=4 Supersymmetric Type II String Theories," JHEP **11** (2006), 073 doi:10.1088/1126-6708/2006/11/073 [arXiv:hep-th/0607155 [hep-th]].

[23] J. R. David, D. P. Jatkar and A. Sen, "Dyon spectrum in generic N=4 supersymmetric Z(N) orbifolds," JHEP **01** (2007), 016 doi:10.1088/1126-6708/2007/01/016 [arXiv:hep-th/0609109 [hep-th]].

[24] A. Sen, "Black hole entropy function and the attractor mechanism in higher derivative gravity," JHEP **09** (2005), 038 doi:10.1088/1126-6708/2005/09/038 [arXiv:hep-th/0506177 [hep-th]].

[25] A. Sen, "Entropy function for heterotic black holes," JHEP **03** (2006), 008 doi:10.1088/1126-6708/2006/03/008 [arXiv:hep-th/0508042 [hep-th]].

[26] B. Sahoo and A. Sen, "BTZ black hole with Chern-Simons and higher derivative terms," JHEP **07** (2006), 008 doi:10.1088/1126-6708/2006/07/008 [arXiv:hep-th/0601228 [hep-th]].

[27] D. Astefanesei, K. Goldstein, R. P. Jena, A. Sen and S. P. Trivedi, "Rotating attractors," JHEP **10** (2006), 058 doi:10.1088/1126-6708/2006/10/058 [arXiv:hep-th/0606244 [hep-th]].

[28] A. Sen, "Entropy Function and AdS(2) / CFT(1) Correspondence," JHEP **11** (2008), 075 doi:10.1088/1126-6708/2008/11/075 [arXiv:0805.0095 [hep-th]].

[29] A. Sen, "Quantum Entropy Function from AdS(2)/CFT(1) Correspondence," Int. J. Mod. Phys. A **24** (2009), 4225-4244 doi:10.1142/S0217751X09045893 [arXiv:0809.3304 [hep-th]].

[30] S. Banerjee, R. K. Gupta and A. Sen, "Logarithmic Corrections to Extremal Black Hole Entropy from Quantum Entropy Function," JHEP **03** (2011), 147 doi:10.1007/JHEP03(2011)147 [arXiv:1005.3044 [hep-th]].

[31] S. Banerjee, R. K. Gupta, I. Mandal and A. Sen, "Logarithmic Corrections to N=4 and N=8 Black Hole Entropy: A One Loop Test of Quantum Gravity," JHEP **11** (2011), 143 doi:10.1007/JHEP11(2011)143 [arXiv:1106.0080 [hep-th]].

[32] A. Sen, "Logarithmic Corrections to N=2 Black Hole Entropy: An Infrared Window into the Microstates," Gen. Rel. Grav. **44** (2012) no.5, 1207-1266 doi:10.1007/s10714-012-1336-5 [arXiv:1108.3842 [hep-th]].

[33] A. Sen, "A Twist in the Dyon Partition Function," JHEP **05** (2010), 028 doi:10.1007/JHEP05(2010)028 [arXiv:0911.1563 [hep-th]].

[34] A. Sen, "Discrete Information from CHL Black Holes," JHEP **11** (2010), 138 doi:10.1007/JHEP11(2010)138 [arXiv:1002.3857 [hep-th]].

[35] A. Sen, "How Do Black Holes Predict the Sign of the Fourier Coefficients of Siegel Modular Forms?," Gen. Rel. Grav. **43** (2011), 2171-2183 doi:10.1007/s10714-011-1175-9 [arXiv:1008.4209 [hep-th]].

[36] A. Sen, "Logarithmic Corrections to Schwarzschild and Other Non-extremal Black Hole Entropy in Different Dimensions," JHEP **04** (2013), 156 doi:10.1007/JHEP04(2013)156 [arXiv:1205.0971 [hep-th]].

[37] A. Sen, "Walls of Marginal Stability and Dyon Spectrum in N=4 Supersymmetric String Theories," JHEP **05** (2007), 039 doi:10.1088/1126-6708/2007/05/039 [arXiv:hep-th/0702141 [hep-th]].

[38] A. Sen, "Wall Crossing Formula for N=4 Dyons: A Macroscopic Derivation," JHEP **07** (2008), 078 doi:10.1088/1126-6708/2008/07/078 [arXiv:0803.3857 [hep-th]].

[39] J. Manschot, B. Pioline and A. Sen, "Wall Crossing from Boltzmann Black Hole Halos," JHEP **07** (2011), 059 doi:10.1007/JHEP07(2011)059 [arXiv:1011.1258 [hep-th]].

[40] A. Sen, "Equivalence of three wall-crossing formulae," Commun. Num. Theor. Phys. **6** (2012), 601-659 doi:10.4310/CNTP.2012.v6.n3.a2 [arXiv:1112.2515 [hep-th]].

[41] J. Manschot, B. Pioline and A. Sen, "A Fixed point formula for the index of multi-centered N=2 black holes," JHEP **05** (2011), 057 doi:10.1007/JHEP05(2011)057 [arXiv:1103.1887 [hep-th]].

[42] J. Manschot, B. Pioline and A. Sen, "From Black Holes to Quivers," JHEP **11** (2012), 023 doi:10.1007/JHEP11(2012)023 [arXiv:1207.2230 [hep-th]].

[43] J. Manschot, B. Pioline and A. Sen, "On the Coulomb and Higgs branch formulae for multi-centered black holes and quiver invariants," JHEP **05** (2013), 166 doi:10.1007/JHEP05(2013)166 [arXiv:1302.5498 [hep-th]].

[44] A. Sen, "On the Background Independence of String Field Theory," Nucl. Phys. B **345** (1990), 551-583 doi:10.1016/0550-3213(90)90400-8

[45] A. Sen and B. Zwiebach, "A Proof of local background independence of classical closed string field theory," Nucl. Phys. B **414** (1994), 649-714 doi:10.1016/0550-3213(94)90258-5 [arXiv:hep-th/9307088 [hep-th]].

[46] A. Sen and B. Zwiebach, "Quantum background independence of closed string field theory," Nucl. Phys. B **423** (1994), 580-630 doi:10.1016/0550-3213(94)90145-7 [arXiv:hep-th/9311009 [hep-th]].

[47] R. Saroja and A. Sen, "Picture changing operators in closed fermionic string field theory," Phys. Lett. B **286** (1992), 256-264 doi:10.1016/0370-2693(92)91772-2 [arXiv:hep-th/9202087 [hep-th]].

[48] A. Sen, "Off-shell Amplitudes in Superstring Theory," Fortsch. Phys. **63** (2015), 149-188 doi:10.1002/prop.201500002 [arXiv:1408.0571 [hep-th]].

[49] A. Sen and E. Witten, "Filling the gaps with PCO's," JHEP **09** (2015), 004 doi:10.1007/JHEP09(2015)004 [arXiv:1504.00609 [hep-th]].

[50] A. Sen, "Gauge Invariant 1PI Effective Superstring Field Theory: Inclusion of the Ramond Sector," JHEP **08** (2015), 025 doi:10.1007/JHEP08(2015)025 [arXiv:1501.00988 [hep-th]].

[51] A. Sen, "BV Master Action for Heterotic and Type II String Field Theories," JHEP **02** (2016), 087 doi:10.1007/JHEP02(2016)087 [arXiv:1508.05387 [hep-th]].

[52] R. Pius, A. Rudra and A. Sen, "String Perturbation Theory Around Dynamically Shifted Vacuum," JHEP **10** (2014), 070 doi:10.1007/JHEP10(2014)070 [arXiv:1404.6254 [hep-th]].

[53] R. Pius and A. Sen, "Cutkosky rules for superstring field theory," JHEP **10** (2016), 024 [erratum: JHEP **09** (2018), 122] doi:10.1007/JHEP10(2016)024 [arXiv:1604.01783 [hep-th]].

[54] C. De Lacroix, H. Erbin and A. Sen, "Analyticity and Crossing Symmetry of Superstring Loop Amplitudes," JHEP **05** (2019), 139 doi:10.1007/JHEP05(2019)139 [arXiv:1810.07197 [hep-th]].

[55] A. Sen, "Stable nonBPS states in string theory," JHEP **06** (1998), 007 doi:10.1088/1126-6708/1998/06/007 [arXiv:hep-th/9803194 [hep-th]].

[56] A. Sen, "SO(32) spinors of type I and other solitons on brane - anti-brane pair," JHEP **09** (1998), 023 doi:10.1088/1126-6708/1998/09/023 [arXiv:hep-th/9808141 [hep-th]].

[57] A. Sen, "Type I D particle and its interactions," JHEP **10** (1998), 021 doi:10.1088/1126-6708/1998/10/021 [arXiv:hep-th/9809111 [hep-th]].

[58] A. Sen, "Stable nonBPS bound states of BPS D-branes," JHEP **08** (1998), 010 doi:10.1088/1126-6708/1998/08/010 [arXiv:hep-th/9805019 [hep-th]].

[59] A. Sen, "Tachyon condensation on the brane anti-brane system," JHEP **08** (1998), 012 doi:10.1088/1126-6708/1998/08/012 [arXiv:hep-th/9805170 [hep-th]].

[60] A. Sen, "BPS D-branes on nonsupersymmetric cycles," JHEP **12** (1998), 021 doi:10.1088/1126-6708/1998/12/021 [arXiv:hep-th/9812031 [hep-th]].

[61] A. Sen, "Supersymmetric world volume action for nonBPS D-branes," JHEP **10** (1999), 008 doi:10.1088/1126-6708/1999/10/008 [arXiv:hep-th/9909062 [hep-th]].

[62] A. Sen, "Universality of the tachyon potential," JHEP **12** (1999), 027 doi:10.1088/1126-6708/1999/12/027 [arXiv:hep-th/9911116 [hep-th]].

[63] A. Sen and B. Zwiebach, "Tachyon condensation in string field theory," JHEP **03** (2000), 002 doi:10.1088/1126-6708/2000/03/002 [arXiv:hep-th/9912249 [hep-th]].

[64] N. Berkovits, A. Sen and B. Zwiebach, "Tachyon condensation in superstring field theory," Nucl. Phys. B **587** (2000), 147-178 doi:10.1016/S0550-3213(00)00501-0 [arXiv:hep-th/0002211 [hep-th]].

[65] N. Moeller, A. Sen and B. Zwiebach, "D-branes as tachyon lumps in string field theory," JHEP **08** (2000), 039 doi:10.1088/1126-6708/2000/08/039 [arXiv:hep-th/0005036 [hep-th]].

[66] A. Sen, "Rolling tachyon," JHEP **04** (2002), 048 doi:10.1088/1126-6708/2002/04/048 [arXiv:hep-th/0203211 [hep-th]].

[67] A. Sen, "Tachyon matter," JHEP **07** (2002), 065 doi:10.1088/1126-6708/2002/07/065 [arXiv:hep-th/0203265 [hep-th]].

[68] A. Sen, "Tachyon dynamics in open string theory," Int. J. Mod. Phys. A **20** (2005), 5513-5656 doi:10.1142/S0217751X0502519X [arXiv:hep-th/0410103 [hep-th]].

[69] R. Pius, A. Rudra and A. Sen, "Mass Renormalization in String Theory: Special States," JHEP **07** (2014), 058 doi:10.1007/JHEP07(2014)058 [arXiv:1311.1257 [hep-th]].

[70] R. Pius, A. Rudra and A. Sen, "Mass Renormalization in String Theory: General States," JHEP **07** (2014), 062 doi:10.1007/JHEP07(2014)062 [arXiv:1401.7014 [hep-th]].

[71] A. Sen, "Supersymmetry Restoration in Superstring Perturbation Theory," JHEP **12** (2015), 075 doi:10.1007/JHEP12(2015)075 [arXiv:1508.02481 [hep-th]].

[72] A. Sen, "Fixing an Ambiguity in Two Dimensional String Theory Using String Field Theory," JHEP **03** (2020), 005 doi:10.1007/JHEP03(2020)005 [arXiv:1908.02782 [hep-th]].

[73] A. Sen, "Divergent $\implies$ complex amplitudes in two dimensional string theory," JHEP **02** (2021), 086 doi:10.1007/JHEP02(2021)086 [arXiv:2003.12076 [hep-th]].

[74] A. Sen, "D-instantons, String Field Theory and Two Dimensional String Theory," [arXiv:2012.11624 [hep-th]].

[75] A. Sen, "Normalization of D-instanton Amplitudes," [arXiv:2101.08566 [hep-th]].

[76] A. Sen, "Normalization of Type IIB D-instanton Amplitudes," [arXiv:2104.11109 [hep-th]].

[77] A. Sen, "Muti-instanton Amplitudes in Type IIB String Theory," [arXiv:2104.15110 [hep-th]].

[78] S. Alexandrov, A. Sen and B. Stefański, "D-instantons in Type IIA string theory on Calabi-Yau threefolds," [arXiv:2108.04265 [hep-th]].

[79] S. Alexandrov, A. Sen and B. Stefański, "Euclidean D-branes in Type IIB string theory on Calabi-Yau threefolds," [arXiv:2110.06949 [hep-th]].

[80] A. Sen, "Subleading Soft Graviton Theorem for Loop Amplitudes," JHEP **11** (2017), 123 doi:10.1007/JHEP11(2017)123 [arXiv:1703.00024 [hep-th]].

[81] A. Laddha and A. Sen, "Sub-subleading Soft Graviton Theorem in Generic Theories of Quantum Gravity," JHEP **10** (2017), 065 doi:10.1007/JHEP10(2017)065 [arXiv:1706.00759 [hep-th]].

[82] S. Chakrabarti, S. P. Kashyap, B. Sahoo, A. Sen and M. Verma, "Subleading Soft Theorem for Multiple Soft Gravitons," JHEP **12** (2017), 150 doi:10.1007/JHEP12(2017)150 [arXiv:1707.06803 [hep-th]].

[83] A. Laddha and A. Sen, "Observational Signature of the Logarithmic Terms in the Soft Graviton Theorem," Phys. Rev. D **100** (2019) no.2, 024009 doi:10.1103/PhysRevD.100.024009 [arXiv:1806.01872 [hep-th]].

[84] B. Sahoo and A. Sen, "Classical and Quantum Results on Logarithmic Terms in the Soft Theorem in Four Dimensions," JHEP **02** (2019), 086 doi:10.1007/JHEP02(2019)086 [arXiv:1808.03288 [hep-th]].

[85] A. P. Saha, B. Sahoo and A. Sen, "Proof of the classical soft graviton theorem in $D = 4$," JHEP **06** (2020), 153 doi:10.1007/JHEP06(2020)153 [arXiv:1912.06413 [hep-th]].

[86] B. Sahoo and A. Sen, "Classical Soft Graviton Theorem Rewritten," [arXiv:2105.08739 [hep-th]].

[87] A. Sen, "Naturally Light Higgs Doublet in Supersymmetric E6 Grand Unified Theory," Phys. Rev. Lett. **55** (1985), 33 doi:10.1103/PhysRevLett.55.33

[88] D. Nemeschansky and A. Sen, "Conformal Invariance of Supersymmetric σ Models on Calabi-yau Manifolds," Phys. Lett. B **178** (1986), 365-369 doi:10.1016/0370-2693(86)91394-8

[89] S. D. Mathur, S. Mukhi and A. Sen, "On the Classification of Rational Conformal Field Theories," Phys. Lett. B **213** (1988), 303-308 doi:10.1016/0370-2693(88)91765-0

[90] A. Sen, "D0-branes on T**n and matrix theory," Adv. Theor. Math. Phys. **2** (1998), 51-59 doi:10.4310/ATMP.1998.v2.n1.a2 [arXiv:hep-th/9709220 [hep-th]].

[91] A. Sen, "S-duality Improved Superstring Perturbation Theory," JHEP **11** (2013), 029 doi:10.1007/JHEP11(2013)029 [arXiv:1304.0458 [hep-th]].

[92] A. Sen, "Riding Gravity Away from Doomsday," Int. J. Mod. Phys. D **24** (2015) no.12, 1544004 doi:10.1142/S0218271815440046 [arXiv:1503.08130 [hep-th]].

[93] S. P. Kashyap, S. Mondal, A. Sen and M. Verma, "Surviving in a Metastable de Sitter Space-Time," JHEP **09** (2015), 139 doi:10.1007/JHEP09(2015)139 [arXiv:1506.00772 [hep-th]].