Research Resumé: Thanu Padmanabhan

Executive Summary: Prof. Thanu Padmanabhan's original research contributions have made a significant impact on the subjects of gravitation and cosmology. In the last several years, he provided a clear interpretation of gravity as an emergent phenomenon and showed that this paradigm extends to a wide class of gravitational theories including — but not limited to — Einstein's theory. Such an interpretation explains why gravity is immune to the bulk cosmological constant, thereby providing a framework for solving the cosmological constant problem. The emergent approach to gravity describes the expansion of the universe as an evolution towards holographic equipartition and can explain the numerical value of the cosmological constant in terms of other parameters in high energy physics.

In the earlier part of his career (1980-2000) he has made important contributions to quantum cosmology, the statistical mechanics of gravitating systems and gravitational clustering in the expanding universe, all of which have been well recognized.

He has provided strong scientific leadership in his country and a significant fraction of the younger generation cosmologists working in various institutes and universities in India today have been associated with Padmanabhan and mentored by him during their Ph.D/PDF stage.

His extensive scholarship is reflected in his nine advanced level textbooks, acclaimed as magnificent achievements and used worldwide as standard references.

1 Research Work during 2002 - 2020

Padmanabhan has demonstrated that there is sufficient *internal* evidence in the structure of a wide class of gravitational theories — including, but not limited to, Einstein's theory — to interpret gravity as an emergent phenomenon like elasticity or fluid dynamics[1] [1, 2]. He has uncovered several peculiar aspects of gravitational theories (like e.g., the structure of the action functionals, the equipartition relation, the representation of field equations as equations of fluid dynamics, etc.) all of which find a natural interpretation if gravity is treated as an emergent phenomenon. Unlike in quantum gravitational models, Padmanabhan has done this essentially *within the solid framework of classical gravity, without any speculative inputs*. These ideas have been well received and won prizes eight times (in 2002, 2003, 2006, 2008, 2012, 2014, 2018 and 2020) in the Gravity Research Foundation Essay Contest, USA including the First Award in 2008.

- *The thermodynamic connection goes far beyond Einstein's theory*

  Padmanabhan's results show that the connection between thermodynamics and gravity goes far beyond Einstein's theory of gravity [2]. It is deeply connected with the fact that gravity is described by spacetime structure and is not too specific to the field equations in Einstein's theory. Since this generality is telling us something deep and beautiful, concentrating solely on Einstein's theory would lead only to limited understanding. Padmanabhan's key insight was to realize that *the thermodynamic connection of gravity transcends Einstein's theory* and that different models of gravity correspond to different functional forms of thermodynamical potentials like e.g., entropy density, which can be attributed to the spacetime. This is similar in spirit to the general thermodynamic description of, say, gaseous systems with each gas differing from others only in the form of its entropy function.

- *Gravitational Field equations reduce to thermodynamics/fluid dynamics on null surfaces*

  In 2002, Padmanabhan showed [3] that the field equations of gravity reduce to a thermodynamic identity on a spherically symmetric horizon in Einstein's theory. This result has now been demonstrated (by the work done by several groups) to be valid for an impressive class of spacetimes and models of

[1] The numbers in square brackets refer to the list of papers given at the end of this document.

gravity like, e.g., the Lanczos-Lovelock theory [2]. Further, when the spacetime is not stationary, Padmanabhan could demonstrate [4] that Einstein's field equations, projected onto *any* null surface in *any* spacetime, reduce to the Navier-Stokes equation in suitable variables. This result was previously known in the context of black hole horizons, but Padmanabhan's result shows that it is much more general and reduces gravitational dynamics to the fluid dynamics of spacetime. (This is reminiscent of — but structurally quite different from — similar results obtained in the context of string theory.)

Padmanabhan also realized that, if gravity has thermodynamical origin, then the action functional describing gravity must encode this information. It was known for a long time that the action principle in Einstein's gravity has a bulk term and a surface term and the latter is ignored/canceled while obtaining the field equations. Padmanabhan and his collaborators could show that there is a "holographic" relationship between the surface and bulk terms of the action functionals not only in the case of Einstein's theory but also in a much wider class of gravitational theories [5]. The holographic relation provides a simple explanation for several peculiar features and allows one to interpret the action functional in a wide class of gravitational theories as the free energy of the spacetime.

- *Determining the Avogadro number of spacetime*

  Padmanabhan could show that the microscopic degrees of freedom of the spacetime obey a principle of equipartition in static geometries and *the departure from this equipartition is what drives the evolution of spacetime* [8]. This was done [6] for Einstein's theory in 2004 and was generalized to a wide class of gravitational theories [2, 7, 8] later on. It should be stressed that Boltzmann's equipartition law, $N = E/(1/2)kT$ is a direct link between the microscopic degrees of freedom and macroscopic physics. The E and T in this relation can be defined in the continuum limit of thermodynamics, but N, being infinite in thermodynamics, has no meaning in that realm! The finite value of N contains information about the underlying statistical mechanics. Remarkably enough, Padmanabhan could prove an identical relation in the case of a general class of gravitational theories and read off N - which is like determining the Avogadro number of spacetime [7, 8]. *This work [8] provides the most direct link between the microscopic structure of spacetime and the emergent dynamics of gravity* .

- *Gravitational field equations from the entropy density of spacetime*

  Given this backdrop, it is obvious that one should be able to derive the field equations for gravitational theories from purely thermodynamic arguments. This can be done by introducing an expression for the entropy density of spacetime in terms of the horizons perceived by local Rindler observers and maximizing it for all such observers [8, 9]. The expression for entropy density immediately links macroscopic physics to the underlying microscopic degrees of freedom in a very simple and transparent manner. This work goes far beyond the earlier attempts by others because it addresses a class of models far more general than Einstein's theory and uses extremum principles rather than equations of motion.

- *Distribution function for the atoms of spacetime*

  The equations of motion describing all physical systems, except gravity, remain invariant if a constant is added to the Lagrangian. In the conventional approach, gravitational theories break this symmetry exhibited by all other physical systems. Restoring this symmetry to gravity and demanding that gravitational field equations should also remain invariant under the addition of a constant to a Lagrangian, *leads to* the interpretation [10] of gravity as the thermodynamic limit of the kinetic theory of atoms of space. (This approach selects, in a very natural fashion, Einstein's general relativity in $d = 4$.) Developing this paradigm at a deeper level [11] using the concept of zero-point-length of spacetime, Padmanabhan could obtain the distribution function for the atoms of space and connect it up with the thermodynamic description of spacetime.

- *Implications for cosmology and solution to the cosmological constant problem*

  This interpretation has a direct relevance to the cosmological constant problem. Due to an extra symmetry present introduced in this approach, the field equations of gravity are insensitive to the cosmological constant and the bulk vacuum energy does not couple to gravity [8, 9]. This is an extremely important pre-condition for a successful solution to the cosmological constant problem.

  To determine the numerical value of the cosmological constant — which arises as an integration constant in this approach — Padmanabhan used another unique feature of gravity, viz., its ability to control the information accessible to any specific observer. Quantifying the notion of cosmic information for an eternal observer in the universe and combining it with generic features of the quantum structure of spacetime (e.g., the holographic principle), Padmanabhan has produced a holistic model for cosmology. He could show that: (i) the numerical value of the cosmological constant, as well as (ii) the amplitude of the primordial, scale invariant, perturbation spectrum can be determined in terms of a single free parameter, which specifies the energy scale at which the universe makes a transition from a pre-geometric phase to the classical phase. Using this, Padmanabhan could obtain [12] the correct results for both (i) and (ii). This formalism also shows that the quantum gravitational information content of spacetime can be tested using precision cosmology.

- *Possible solution to the black hole information loss problem*

  Padmanabhan has proposed a possible approach to solve[2] the black hole information loss problem [13]. This work [13] shows that the information about the initial state can be recovered from the distortions in the thermal radiation at late times, if we treat the initial state of the in-falling matter quantum mechanically. The apparent loss of information about the in-falling matter arises, in the conventional approach, because of the following dichotomy: The black hole evaporation is treated quantum mechanically but the in-falling matter is treated classically ignoring the richness of information encoded in the quantum correlations in the initial state. This result also suggests that the *classical* black hole "no-hair theorems" have no *quantum* analogues.

- *Principle of equivalence and quantum gravity*

  Principle of equivalence makes effects of *classical* gravity vanish in local inertial frames. What role does the Principle of equivalence play as regards *quantum* gravitational effects in the local inertial frames? Very recently, Padmanabhan has investigated [14] this question and has uncovered significant connections between the principle of equivalence and physics at Planck scales. At mesoscopic scales close to, but somewhat larger than, Planck length one could describe quantum spacetime and matter in terms of an effective geometry. The key feature of such an effective quantum geometry is the existence of a zero-point-length. When one proceeds from quantum geometry to quantum matter, the zero-point-length will introduce corrections in the propagator for matter fields in a specific manner. On the other hand, one cannot ignore the self-gravity of matter fields at the mesoscopic scales and this will also modify the form of the propagator. Consistency demands that, these two modifications — coming from two different perspectives — are the same. Padmanabhan has shown that this non-trivial demand is actually satisfied (only) because of the Principle of equivalence, operating at sub-Planck scales. This result has far-reaching consequences and allows one to probe the nature of time-evolution and spacetime geometry close to Planck scales. It turns out that the time evolution operator becomes non-unitary for sub-Planckian time intervals while remaining unitary when the time interval is larger than Planck time. This is equivalent to spacetime acquiring a Euclidean signature at sub-Planck scales and becoming Lorentzian at scales larger than Planck length.

[2]This paper has been highlighted as Editor's Selection in Phys. Rev. Letts. in Feb, 2016.

During the last decade, Padmanabhan has also made major contributions to the study of dark energy, both by critical analysis of data [15, 16, 17] and by developing string-inspired cosmological models[18, 19, 20]. His work on dark energy has made a deep impact in the field and the review [21] based on his ideas has more than 2300 citations and has found place in the SPIRES list of 50 highly cited HEP papers.

2 Earlier Research Contributions (1980 - 2001):

- Padmanabhan's thesis work was in quantum cosmology and he came up (in 1984) with an interpretation of the Planck length as a zero point length for the spacetime and established it with well-chosen thought experiments in 1987.
- In the late 80s Padmanabhan worked on the problem of statistical mechanics of gravitating systems and his initial results in the statistical mechanics of gravitating systems were published in the well appreciated invited review [22]. He applied these concepts to study the gravitational clustering in an expanding universe and provided a theoretical understanding of the nonlinear scaling relations observed in two-point correlation functions [23]. He is a recognized authority in these subjects and has been invited to lecture at two Les Houches Schools (in 2002 and 2008) to a broader community about this subject.
- He also developed the complex path method [24] to study black hole thermodynamics which was a precursor to the 'tunneling paradigm' that became quite popular later on.

3 Impact of the Research:

In his entire career, Padmanabhan has written about 300 papers earning about 17,200 citations. He has one paper with more than 2500 citations, another 32 papers with citations above 100 (of which 1 has more than 800 citations, 8 have citations in 300-552 range and 9 have citations in the range of 200-300) and 45 papers with citations in the range 50-100. His total number of normalized citations — in which citations of each paper are divided equally among authors — is also quite high, more than 13,906 (from ADS).

He has a h-index of 62.

During 2002-19, Padmanabhan has published about 144 papers *which alone* have received about 12,511 citations, with an average of 86.9 citations per paper during this period.

4 Academic Mentoring and Scientific Leadership:

Padmanabhan has supervised the Ph.D. work of 16 students (and was was strongly involved, at the level of a co-supervisor, in the Ph.D work of 2 more). Of the past students, 11 have obtained permanent positions in academic institutions in India and many of them are guiding students themselves. *In fact, almost all the young ($\lesssim$ 45 years) cosmologists working in various institutes/universities in India today have been associated with Padmanabhan and mentored by him in the Ph.D/PDF stage of their career.*

Another feature of Padmanabhan's career — which again sets him apart from many other scientists in his peer group — is his willingness and capability to provide scientific leadership. He has served in several key committees and has taken a leading role in the development of astronomy in India. A few examples *from the recent years* are the following:

- He served as the Chairman (2006-09) of the Time Allocation Committee of the Giant Meter-wave Radio Telescope of NCRA, and he has introduced many innovative aspects into its working and has been instrumental in streamlining several aspects of GMRT.

- He was the Chairman (2008-11) of the Indian National Science Academy's National Committee which interfaces with the activities of the International Astronomical Union. In addition to advising the Government on policy issues, this also required him to coordinate the International Year of Astronomy 2009 activities in the country.
- The Department of Science and Technology has appointed him as the Convener of the Advisory Group (2008-10) to facilitate India's entry into one of the international collaborations building the next generation Giant Segmented Mirror Telescopes. He has played a key role in taking this initiative and developing a consensus in the Indian astronomy community in this task which has now led India into joining the TMT.

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