Research Highlights

Marc Kamionkowski

Kamionkowski has published over 250 refereed research articles and several review articles. He is perhaps best known for his earlier work on particle dark matter and on the CMB, but he has also made important contributions in nuclear and neutrino physics and astrophysics, inflation, cosmological phase transitions, dark-energy (models and observational issues), large-scale structure, galaxy formation, galaxy clusters, stellar astrophysics, gravitational-wave astrophysics, gravitational microlensing, and weak gravitational lensing.

Here are some highlights of his research:

Precision cosmology. The geometry of the Universe—is it flat? open? or closed?—remained elusive from Hubble's 1929 discovery of the cosmic expansion until the turn of the century when precise CMB experiments showed conclusively that the Universe is flat. This remarkable endeavor was set in motion largely by Kamionkowski's work [1] that proposed that the spatial geometry of the Universe can be determined from the location of the first acoustic peak in the CMB power spectrum. (This work also pioneered estimates for the redshift of the epoch of reionization, when the first stars reionized the Universe.) Shortly thereafter, he showed in Ref. [2] that high-sensitivity high-resolution maps of the CMB could make this geometry measurement precise, even after marginalizing over other undetermined cosmological parameters. A longer paper [3] showed that such measurements would further determine the classical cosmological parameters (Hubble constant, cosmological constant, baryon density), inflationary observables (amplitudes and spectral indexes for density perturbations and primordial gravitational waves), as well as the reionization optical depth. This paper was also the first to suggest that the number of relativistic degrees of freedom could be determined with the CMB. These two papers [2, 3] thus introduced the notion of "precision cosmology." This work, which seemed futuristic at the time, articulated clearly the scientific motivation for the generation of suborbital and satellite CMB experiments (including WMAP and Planck) that revolutionized cosmology over the past quarter decade. In addition to showing that the Universe is flat, these experiments have nailed the empirical case for a nonzero cosmological constant; shown that reionization occurred at a redshift $z \simeq 10$ (consistent with those first estimates in that paper); determined other cosmological parameters with a precision unimaginable just before the new century; and provided strong evidence for a period of inflationary expansion in the early Universe—all as anticipated by Kamionkowski's work. Finally, this work also introduced to cosmology the Fisher-matrix technique, used to forecast the precision of parameter estimation, that is now ubiquitous in cosmology and much of astrophysics.

CMB polarization and inflationary gravitational waves. Given the precise agreement between the results of these experiments with several of the predictions of inflation, attention in early-Universe cosmology has now focussed on further tests of inflation and measurements that may shed light on the new physics responsible for inflation. Kamionkowski's work has been instrumental in guiding these future directions. In Refs. [5, 4], Kamionkowski developed a formalism for CMB polarization that has been not just useful, but absolutely essential, for all subsequent theoretical and experimental work on CMB polarization. In addition to the better-known multipole-space description of this decomposition, this paper also developed a description of the configuration-space two-point correlations. These correlation functions were then used by WMAP (in their Seven-Year release) to demonstrate that the observed pattern of polarization around hot and cold spots agreed with that predicted in CDM models.

More importantly, these papers further predicted that inflationary gravitational waves leave a unique signature (a curl component, or B mode) in the polarization of the CMB. This prediction has provided the principal science motivation for CMBPol/EPIC, a post-Planck CMB experiment in NASA's roadmap. Another paper [6] showed that the sensitivity to the signal can be optimized by a deep integration on a small patch of sky, an argument that has motivated a number of sub-orbital CMB-polarization experiments like BICEP, SPIDER, QUIET, EBEX, PolarBear, ABS, the Keck Array, and others, and other suborbital experiments (e.g., CLASS and PIPER) are also pursuing this CMB polarization signal.

Dark matter. Much of Kamionkowski's work has been on the hypothesis that dark matter is composed of some new elementary particle. He amassed a significant body of work earlier in his career on predictions for signatures of supersymmetric dark matter in direct-detection experiments and accelerator experiments, as well as experiments that seek the signature of these particles in cosmic-ray, gamma-ray, and astrophysical-neutrino experiments. Ref. [7] calculated the relic abundance of supersymmetric dark-matter candidates in a very broad class of models and thus helped establish these particles as perhaps the most promising dark-matter candidate. Another paper [8] showed that unitarity provides a model-independent upper limit to the mass of a thermal-relic dark-matter particle. His paper [9] on cosmic-ray positrons from neutralino annihilation in the Galactic halo layed the groundwork for much of the vast body of work that followed recent cosmic-ray results. His 1996 review [10] provided a valuable overview of the subject. It assembled many of his early results on supersymmetric dark matter and added many new ones to provide a fully comprehensive and clear collection of all the calculational ingredients required for direct and indirect searches for supersymmetric dark matter. The review is now a classic; it has proved over the years to be an invaluable resource for theorists and experimentalists, and it still remains the principal reference in the field. He has in the intervening years continued to work on supersymmetric and more general particle dark matter, refining earlier calculations, adding new ingredients, and considering more general dark-matter candidates. This work includes, for example, an important study of kinetic-decoupling for WIMPs [11], highly-cited work on constraints to decaying dark matter [12], and a new theory of dark matter and dark radiation [13]. In 2006, he showed [14, 15] that the tidal tails of the Sagittarius dwarf galaxy can be used to infer that dark matter falls the same way as ordinary matter in a gravitational potential well, thus extending the conclusions of several centuries of equivalence-principle tests (starting with Galileo), which have focussed entirely on baryonic matter, to dark matter. A 2013 paper [16] which introduced the possibility of heat transfer between dark matter baryons has received considerable attention, particularly in light of the interpretation of the 21-cm absorption signal seen by EDGES in 2018 in terms of such heat transfer.

Following LIGO's 2016 discovery of gravitational waves from the merger of two $\sim 30\,M_{\odot}$, Kamionkowski and collaborators speculated that primordial black holes might make up the dark matter [17]. They showed that if such black holes make up the dark matter they merge at roughly the rate inferred from LIGO's initial detection. The idea received considerable attention, led to intense renewed interest on compact dark matter, and had an array of interesting implications—many worked out by Kamionkowski's group—for gravitational-wave measurements [18, 19, 20], galaxy dynamics, the CMB [21], the early Universe, gravitational microlensing, high-energy astrophysics, galaxy clustering, and fast radio bursts [22].

Intrinsic alignments. In 2000, Kamionkowski showed [23] that if galaxy spins arise from long-range tidal fields, then the ellipticities of galaxies should have long-range correlations. Kamionkowski showed in this paper, that these intrinsic alignments of galaxy ellipticities may present a possible contaminant for weak-lensing surveys aimed at studying dark energy, and he also provided several ways to distinguish the effects of intrinsic alignments from weak lensing. Since then, the intrinsic alignments that Kamionkowski predicted have been detected and measured now with some precision. Intrinsic alignments are now recognized as an issue to contend with for weak-lensing measurements. They are also being seen increasingly as a new tool to probe large-scale structure.

Cosmic birefringence, chiral gravity, parity breaking, and other exotic phenomena in the CMB. Kamionkowski has over the years developed a number of other ideas for novel cosmological and new-physics probes that can be constructed with the CMB. For example, a pioneering paper [24] of his showed how the CMB could be used to look for parity-violating cosmological effects. In addition to describing the observational signals, this paper provided cosmological birefringence and chiral gravitational waves as physical examples of such parity-violating effects. A vast subsequent literature has expanded on both chiral gravity and cosmic birefringence, and the proposed measurements have now been made, fairly precisely, by WMAP and suborbital CMB experiments. He more recently extended the algorithms to search for direction-dependent cosmic birefringence as well [25]. The notion of "amplitude biregringence"—that Chern-Simons gravity can amplity one circular polarization of gravitational waves and suppress the other—was also introduced in Ref. [24].

In Ref. [26], he showed how the CMB could be used to look for departures from statistical isotropy; the tests proposed in this work have subquently been carried out with WMAP and Planck data. In Ref. [27] he discussed constraints to physical models and presented theoretical ideas for the hemispherical power asymmetry in the CMB. These ideas have proved to be essential ingredients in all subsequent investigations into this asymmetry.

Kamionkowski has also made contributions to the now-considerable effort to search for non-Gaussianity in the CMB and in large-scale structure. These include an early connection between the non-Gaussian amplitude measured in the CMB to the predictions of inflationary models [28] as well as the first forecasts [29] of the detectability of the local-model non-Gaussianity parameter in the CMB. He more recently showed how the large-scale halo bias induced in the local model of non-Gaussianity extends to more general models of non-Gaussianity [30].

Dark energy, the Hubble tension, and early dark energy. Kamionkowski's principal contribution to dark-energy theory is his 2003 work [31] that identified a a new possible end for the Universe, the "Big Rip," in which a super-accelerated cosmological expansion leads to infinite spacetime stretching in finite time. He also presented a new dark-energy theory ("spintessence") in

Ref. [32], and collaborated on a novel dark-energy measurement [33]. He also has important work on Solar System tests of alternative-gravity theories for cosmic acceleration [34, 35].

In 2016, he and a student pointed out [36] that the Hubble tension could be explained by a period in which the expansion rate is increased by some early dark energy (EDE), and in 2018 they (along with Poulin and Smith) showed with an explicit exploration of the parameter space that this idea could be made to work [37]. The idea now provides the arena for the most promising new-physics explanations for the Hubble tension.

Global symmetries and quantum gravity, nuclear/neutrino astrophysics, and other contributions to particle astrophysics. In 1992, Kamionkowski argued that quantum gravity should generically spoil the Peccei-Quinn solution to the strong-CP problem [38], an idea now known as the "axion quality problem." He also has classic work on the proton-proton reaction that initiates nuclear burning in stars [39] and a calculation of electron-neutrino scattering [40] that has been essential for neutrino experiments like Kamiokande and SNO. His 1994 paper [41] on gravitational waves from first-order cosmological phase transitions has been an essential resource for work on the dynamics of such transitions. He showed [42] that broken scale invariance during inflation might account for the dearth of dwarf galaxies. In Ref. [43], Kamionkowski derived a CMB constraint to the amplitude of small-wavelength gravitational waves. This bound is competitive with that from LIGO in LIGO's frequency range but actually extends to a far broader range of frequencies than can be accessed with LIGO.

Other contributions in astrophysics: The cosmic infrared background, galaxy clusters, gravitational microlensing, and the interstellar medium. Kamionkowski has also worked on subjects in traditional astrophysics. For example, his 2002 predictions [44] of the contribution from the first stars to the cosmic infrared background have been the subject of a number of telescope searches over the past decade. Other work includes a novel solution to the galaxy-cluster cooling-flow problem [45] and an explanation for cluster magnetic fields [46]. His work on gravitational microlensing includes the first paper [47] to discuss light blending from a stellar lens in gravitational-microlensing light curves. A 2016 paper [48] showed how the E and B modes in dust-polarization maps are related to the magnetohydrodynamic slow, fast, and Alfven waves in the interstellar medium. This work has had implications in the study of MHD turbulence and the physics of the interstellar medium.

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