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MEMORANDUM

To: Mike Sipser, all others concerned

From: Peter Fisher

Subject: LIGO event, black holes and dark matter

Date: Thursday, March 24, 2016

LIGO has observed the merger of two thirty mass black holes and expects to observe more black hole mergers in the coming years. Bird, et al. (arXiv:1603.00464v1) have considered the question, “Did LIGO detect dark matter?”, in a paper so titled. This memo summarizes the experimental situation in dark matter, puts the LIGO event and Bird et al. paper in the larger dark matter context and poses questions that further LIGO measurements and the dark matter community will answer in the next few years.

In the current cosmology, dark matter comprises 23% of the matter content of the universe. Dark matter concentrates in galaxies and the gravitational potential created by dark matter largely dictates the dynamics of visible matter at galactic and larger scales. No experimental evidence indicates that dark matter interacts strongly, weakly or electromagnetically with itself or visible matter.

In the last thirty years, the dominant theories of dark matter have been extensions to the Standard Model. A class of theories called supersymmetry postulates massive (10-1,000 proton masses) called Weakly Interacting Massive Particles (WIMPs). Modification to the strong interaction results in a very light (a thousandth or less of a proton mass) neutral particle called the axion. Both supersymmetry and axion theories seek to provide mechanisms to explain other aspects of the Standard Model viewed as theoretically “unnatural”. That the new particle could also explain dark matter is viewed as a strength of each theory.

Accelerators, cosmic rays detectors and nuclear recoil experiments have searched for WIMPs for nearly thirty years with no conclusive evidence. A series of specialty experiments have searched for axions for twenty years, also with no evidence. In both cases, theory does not provide an obvious sensitivity or dark matter particle mass at which to give up searching.

Hawking in 1971 proposed that black holes could be produced in the primordial[1] universe. Before the production of normal matter in the early universe, quantum mechanical density fluctuations could have been large enough to cause portions of space time to collapse, forming black holes. The state and dynamics of the universe at this time is very poorly understood, so there mass range of primordial black holes (PBHs) is 1-10^{50} g. The gravity describes black holes, but the description of the production of PBHs requires a quantum theory of gravity. String theory describes

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[1] *primordial* (adj.) existing at the beginning of time.

a broad class of ideas that may lead to the unification of gravity with the quantum theories of the weak, strong and electromagnetic theories, but success in this regard lies in the future.

Consideration of PBHs as dark matter has led attempts to observe them using gravitational lensing, gamma ray bursts, light from their evaporation and their influence on the cosmic microwave background (CMB). In particular, several calculations indicate PBH's in the tens of solar mass range with the density needed for them to be dark matter should have left a discernible signature in the CMB. Radio telescopes have mapped the CMB with better than a part per million precision with no evidence for a PBH signature, which would be ten times larger. However, Paul Schechter's measurements of the amount of light in multiple images quasars caused by gravitational lensing by a foreground galaxy excludes black holes with masses more than 0.1 solar mass as dark matter. This limit seems pretty strong.

Supernovas produce black holes with 1-20 solar masses ($M_\odot$) while galactic mergers produce many fewer black holes with masses of millions of solar masses. That LIGO observed the merger of two black holes with thirty solar masses, a circumstance viewed as unlikely, caused Bird et al. to give serious consideration to the idea that PBHs in this mass range could be dark matter. A strong argument is that, unlike WIMPs or axions, there is a signal to look at. Bird et al. question the calculation of the CMB signature caused by PBHs in this mass range.

LIGO has observed one event, will observe many more and the better statistics will shed some light on the whether or not PBHs are dark matter. The LIGO event and Bird et al. paper should cause LIGO and the dark matter community to do some important thinking along the following directions in the coming five or ten years:

1. PBH models predict PBHs will be produced in a small mass range. LIGO observing merges between black holes of similar masses in a small range would be important.
2. The black hole merger rate depends on the black hole density and merger cross section – both are highly uncertain. Theoretical progress on the calculation of the merger cross section coupled with a merger rate measurement from LIGO may lead to a better understanding of the black hole density. Detailed analysis of the merger waveforms collected by LIGO may inform the the cross section calculation.
3. The impact of PBHs on the CMB needs careful examination by several independent groups to understand if PBHs in the 10-100 $M_\odot$ range are really excluded or not.

The WIMP and axion theories of dark matter and the experiments testing them will and should persist. It is important that the large investment in WIMPs and axions not discourage careful examination of PBHs as an important dark matter candidate.