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Is dark matter a primordial black hole?

The latest gravitational wave observations reveal mysteries of the early universe

How did the 13.8-billion-year-old Universe begin? If only we could observe the very farthest reaches of the Universe, by using gravitational waves (GWs), whose penetrating power is much stronger than that of visible light, we would be able to see the birth of the Universe. A primordial inflationary process caused the Universe to expand more rapidly than that of the Big Bang. Inflation created the vast Universe in which we can see the same scenery everywhere we look. It also created a density fluctuation δ quantum-mechanically on approximately the order of $\delta = 1$ in 100,000 on a large scale. Galaxies were created when matter gravitationally coalesced to form them. Then, star systems like Solar System consisting of stars and planets were produced within galaxies. Inflation also produced a cosmic GW background at the same time. Observations of the cosmic microwave background (CMB) have revealed that temperature fluctuations were caused by curvature fluctuations, and the spiral-pattern polarization in the sky (called, the B-mode polarization) caused by GWs is expected to be observed in the future to verify inflation. To unravel the mysteries of the birth of the Universe by detecting the B-mode, KEK is conducting the POLARBEAR2 and LiteBIRD experiments [1].

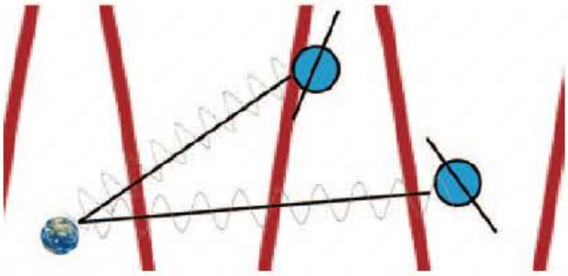

Fig. 1. Schematic picture showing modification of correlations for periods of pulsar's signals due to GW background.

In 2020, it was reported that the GW background, which has existed since the early Universe, may have been observed [2]. The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) observed the correlation of radio signals periodically emitted by multiple pulsars for 12.5 years and found a significant modulation in the nanohertz band. Pulsars are neutron stars with strong magnetic fields and, in a sense, are the lighthouses of the Universe, rotating several hundred times per second and emitting periodic radio signals. If a GW background exists, it would cause space-time to expand and contract, which in turn would affect the period of pulsar radio-wave signals (Fig. 1). We have not yet confirmed that the signal is due to GWs. However, if the signal is real, it is an amazing discovery.

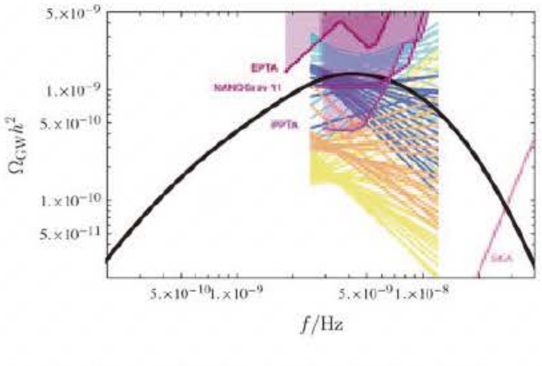

Fig. 2. Signals of the induced GW produced by large-scalar perturbations at the small scales (thick solid line), which agrees with observationally allowed region (shaded region). The vertical axis shows the energy-density fraction parameter of GWs Ω_{GW} multiplied by a constant h^2 (~0.5) as a function of GW frequency in units of Hz [4]. The solid lines in the upper regions show the upper bounds from various existing observations. SKA indicates the sensitivity forecast for the future Square Kilometer Array (SKA) project.

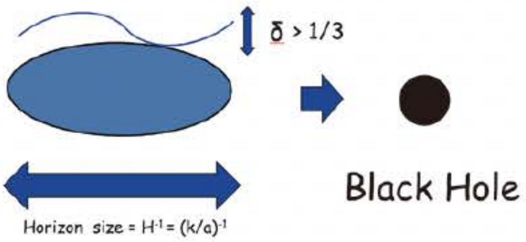

Fig. 3. Schematic image of the formation of PBHs by collapsing density perturbation $\delta > 1/3$ with the horizon size $H^{-1} = (k/a)^{-1}$, wavenumber k, and the scale factor a.

GWs in the nanohertz band are thought to be generated by collisions of supermassive black holes (SMBHs) [3]. However, the astrophysical uncertainties are too large to make a definite determination. The observed value is more than seven orders of magnitude larger than that of the primary GWs directly produced by inflation in the early Universe.

On the other hand, if the small-scale (density) fluctuations δ are large (e.g., $\delta \approx 1/3$), an extremely large number of secondary GWs can be created on small scales via nonlinear effects. In Ref. [4], the authors pointed out that this secondary GW background emission exactly matches the NANOGrav 12.5-yr signal (Fig. 2). The above large density fluctuations are expected to collapse in the early Universe to form a black hole with a solar mass (Fig. 3). This is called a primordial black hole (PBH) to distinguish it from a black hole of astrophysical origin.

The abundance of PBHs may be as large as about 1% of dark matter. GWs with larger frequencies can be also used as a way to test this model. Those primordial black holes formed a binary star in the early Universe and are now merging (Fig. 4). The LIGO-Virgo-IndIGO-KAGRA collaboration (named HLVIK) [5] may hopefully detect the GWs emitted by such systems shortly (Fig. 5). The day is expected to come soon when future GW experiments will be used to verify the early cosmic inflation and discover PBHs as a component of dark matter.

Fig. 4. Schematic image of the formation of binary PBHs though the three-body effect induced by another black hole on the right side.

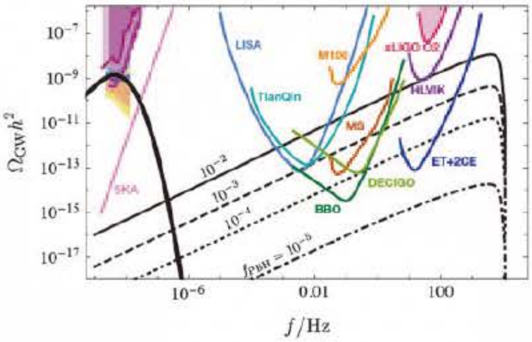

Fig. 5. Same as Fig. 2, but for signals of GWs emitted by merging PBHs (diagonal solid and dashed lines) [4] with the energy fractions of PBHs to dark matter $f_{\rm PBH}$ of 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, respectively. The solid convex lines show the expected sensitivity of various future observational projects including LIGO-Virgo-IndIGO-KAGRA (denoted to be HLVIK in the figure).

References

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