論文内容の要旨

論文題目　Inflationary braneworld probed with primordial black holes
(原始ブラックホールで探るインフレーション期のブレーンワールド)

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This thesis is devoted to investigation of inflationary Randall–Sundrum type-2 braneworld via radiative nature of primordial black holes (PBHs).

First we construct a formulation to describe the mass function of PBHs formed by density perturbation in the radiation-dominated era. The density contrast is induced by inflationary comoving curvature perturbation parameterised as

$$\mathcal{P}_{\mathcal{R}_c} = A \left(\frac{k}{k_0} \right)^{n-1} .$$

The emerging mass function includes three peculiar effects of the brane early universe, i.e., modified expansion-law in the earliest radiation-dominated era, gravitational collapse, and accretion of radiation fluid onto PBHs. The mass function contains two scales. One corresponds to the scale of the transition from the earliest era to the ordinary radiation-dominated era. This scale is nothing but ℓ, the size of the extra dimension. The other is of the transition from power-law to exponentially decreasing form. This is determined by the condition $\delta_{\mathrm{h,min}} \sim \sigma_{\mathrm{h}}$, where $\delta_{\mathrm{h,min}}$ expresses the threshold of gravitational collapse and σ_{h} the root-mean-square of the density-perturbation power-spectrum evaluated at

horizon reentry. The index of the mass function is affected by the efficiency of accretion. Large increase of PBHs arises in the presence of accretion.

Then we formulate cosmic rays which are emitted by PBHs in late times and then propagate to the earth. General properties of two sorts of diffuse cosmic rays, neutral massless particles from outside the galaxy and charged heavy particles from inside the galaxy, are investigated. The effect of braneworld lowers Hawking temperature of PBHs thereby modifying cosmic-ray spectra. The analyses are applied to extragalactic photon and galactic sub-GeV antiproton. Comparison of those cosmic-ray spectra with observation constrains the abundance of PBH as cosmic-ray source. Since contribution to the cosmic rays of current interest is dominated by currently evaporating holes, the constraint is set on those particular ones.

Finally, the constraint on the PBH abundance is interpreted as a constraint on the original inflationary perturbation. The comoving length scale constrained through PBHs typically ranges between $\sim$ 1–1000 km, which is dependent on the size of the extra dimension and the efficiency of accretion. We can probe smaller scales with braneworld PBHs than the 4D case, that is, $\sim$ 1000 km. The perturbation amplitude $\sqrt{\mathcal{P}_{\mathcal{R}_c}}$ on that scale must be $\lesssim 0.05$ to prohibit copious gravitational collapse. This is typically stronger than 4D upper bound since collapse more easily occurs in the braneworld. Once the normalisation of the perturbation spectrum is tentatively given at the Lyman-α Forest scale $k_0 = k_{\mathrm{Ly}\alpha}^{-1} \sim$ Mpc, the upper limits on the blue spectral-index are given as $n \sim 1.3$ in the effective accretion case ($F = 1$) and $n \sim 1.35$ in the null case ($F = 0$). They are also stronger than $n \sim 1.4$ obtained for the 4D case mainly due to the change of the scale at which the amplitude is constrained.

Although the large-scale perturbation spectrum is observed to be nearly scale-invariant, there is little reason to believe that the feature also applies to small-scale perturbation. In this point, the power of PBH is its unique ability to probe scales far below large scale structures.

Based on the results, constraints on the geometry of the braneworld is also discussed. It is pointed out that if the apparent sub-GeV excess of antiproton observation is real and due to PBH evaporation, then the upper bound on the size of the extra dimension is set around 10^{-11} m, which is 7 orders of magnitude tighter than that from gravitational experiment, i.e., $\lesssim 0.1$ mm.