The Big bang nucleosynthesis theory accurately reproduces the abundances of light elements in the Universes, except for $^7\text{Li}$ abundance. Calculated $^7\text{Li}$ abundance with the baryon to photon ratio fixed by the observations of the cosmic microwave background (CMB) is inconsistent with the observed lithium abundances on the surface of metal-poor halo stars, and this problem is called "$^7\text{Li}$ problem". Previous studies proposed to resolve this $^7\text{Li}$ problem include photon cooling (possibly via the Bose-Einstein condensation of a scalar particle), the decay of a long-lived $X$ particle (possibly the next-to-lightest supersymmetric particle), or an energy density of a primordial magnetic field (PMF) [1,2].

We then used a maximum likelihood analysis to constrain the parameters of the $X$ particle and the energy density of the PMF by the observed abundances of light elements up to Li (Fig. 1) [3].

As a result, we obtained allowed ranges for the $X$-particle parameters and find that the new hybrid model with a PMF gives the better likelihood than that without a PMF (Table 1) [3].

We discussed the degeneracy between the parameters of the $X$ particle and the PMF. Since the $X$ particle parameters are mainly limited by the D and $^7\text{Li}$ abundances, while the PMF energy density is mainly limited by the $^4\text{He}$ abundance, we found that the parameters of the PMF and the $X$ particle have no significant degeneracies [3].

We also discussed the effective number of neutrino species $N_{\text{eff}}$ with our new hybrid model. Since the constraint on $N_{\text{eff}}$ from the CMB observations is different from the $N_{\text{eff}}$ value in our hybrid model which is consistent with the observed light elements, it is difficult to directly compare these two $N_{\text{eff}}$ values. We will report a new limit on $N_{\text{eff}}$ derived by taking into account analyses of both BBN and the CMB simultaneously in our future work [3].

![Figure 1](image.png)

**Figure 1:** Allowed region in the ($\tau_X, \zeta_X$) plane by the observational constraints on the light element abundances for $\eta = 4.57 \times 10^{-10}$ and $B = 1.89 \mu G$. The curves denote the allowed regions derived from observational limits on the primordial elemental abundances. The narrow dark band and the region bounded by the solid curves (color version: blue and aqua regions) show the $2\sigma$ (95\%) confidence limits determined from the observed abundances of D and $^7\text{Li}$, respectively. Dashed, dot-dashed and dotted curves (color version: purple, orange and black curves) are the $2\sigma$ (95\%) confidence limits determined from the upper limits on the $^3\text{He}$, $^4\text{He}$ and $^6\text{Li}$ abundances.

**Table 1:** Agreement with observed light element abundances for the four models considered here.

<table>
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<th>Model</th>
<th>$\gamma$-cooling</th>
<th>$X$</th>
<th>PMF</th>
<th>$\gamma$-cooling +$X$+PMF</th>
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<td>$\checkmark$</td>
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**References**