Large-scale magnetic fields from the coupling of electromagnetic fields with a higher curvature term in inflationary cosmology

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I. Introduction

It is known that cosmic magnetic fields are observed not only in galaxies but also in clusters of galaxies. One of the most natural origin of large-scale magnetic fields is considered to be the quantum fluctuations of the electromagnetic fields in the inflationary stage.

→ **We explore the generation of magnetic fields from inflation through the breaking of the conformal invariance of the electromagnetic fields due to its coupling with the Ricci scalar and the Gauss-Bonnet invariant.**

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It is shown that if there occurs a reheating phase with a non-zero e-fold number, the magnetic fields with their enough strength to explain the observations can be generated.

I. Origin of cosmic magnetic fields

- Coherence scale
- Strength

→ It is difficult that these processes generate the magnetic fields on megaparsec scales with sufficient field strength to account for the observed magnetic fields in galaxies and clusters of galaxies without requiring any dynamo amplification.

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The most natural origin of large-scale magnetic fields:

Electromagnetic quantum fluctuation generated at the inflationary stage

II. Model

Action: $S = S_{grav} + S_{em}^{(can)} + S_{CB}$

(1) $$S_{grav} = \int d^4x\sqrt{-g}\left[\frac{R}{2\kappa^2} - \frac{1}{2}\partial_\mu\Phi\partial_\nu\Phi - V(\Phi) - \xi(\Phi)\mathcal{G}\right]$$

$\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta}$: Gauss-Bonnet invariant

$V(\Phi)$: Potential of an inflaton Φ

$\xi(\Phi)$: Coupling between Φ and $\mathcal{G}$

R : Scalar curvature

(2) $$S_{em}^{(can)} = \int d^4x\sqrt{-g}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right]$$: Maxwell theory

(3) Non-minimal coupling between electromagnetic fields and gravity

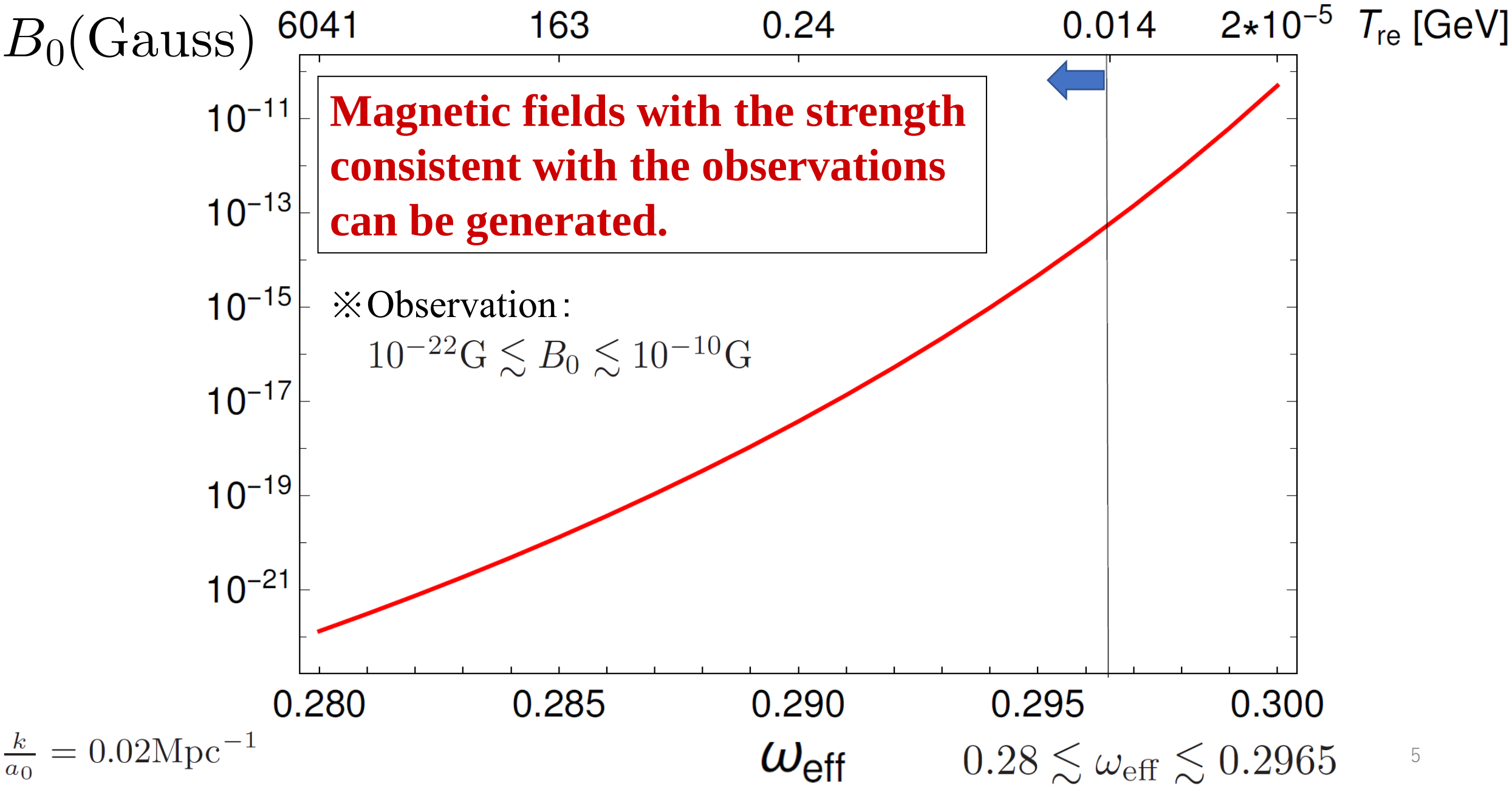
$$S_{CB} = \int d^4x\sqrt{-g}\left[f(R,\mathcal{G})F_{\mu\nu}F^{\mu\nu}\right]$$

$$\boxed{f(R,\mathcal{G}) = \kappa^{2q}\left(R^q + \mathcal{G}^{q/2}\right)}$$

q: Model parameter

⇨ **Breaking of the conformal invariance of the electromagnetic fields.**

III. Present magnetic strength



$\frac{k}{a_0} = 0.02\mathrm{Mpc}^{-1}$

$0.28 \lesssim \omega_{\rm eff} \lesssim 0.2965$

IV. Conclusions

- **We have investigated the generation of magnetic fields from inflation for the case that the electromagnetic fields couple with the Ricci scalar and the Gauss-Bonnet invariant.**

- **We have analyzed the evolution of the quantum fluctuations of the electromagnetic fields during inflation due to the breaking of the conformal invariance of the electromagnetic fields.**

- **It has been shown that for the case of the reheating phase with a non-zero e-folding number, the present strength of magnetic fields can be consistent with the observations.**