Magneto-genesis from Higgs Inflation

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[arXiv:1405.3091[hep-th]] accepted for publication in Phys. Rev. D

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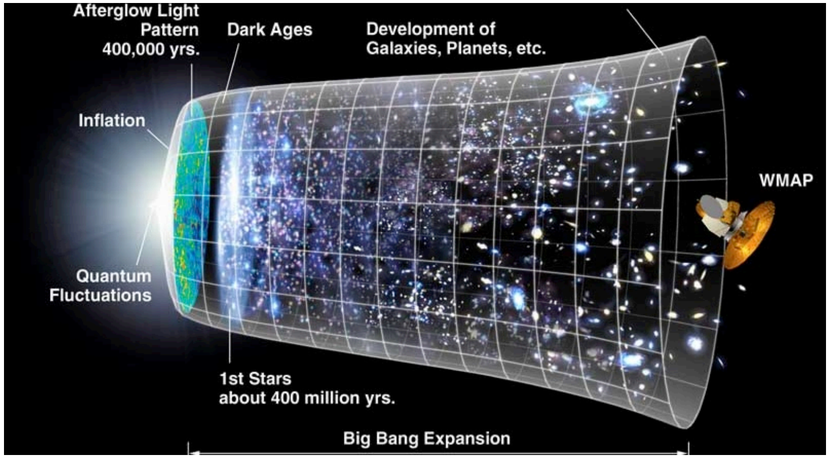
The inflationary paradigm

The best idea explaining the early universe!



- There have been various models induced by high energy theories.

SUSY, super string, extra dimension…

However…

- There exists no signal of such theories in experiments.

⟶ some physicists want to explain the inflation without using them.

⟶ Higgs Inflation might meet their expectation!

What is Higgs Inflation?

- Action is as follows [1] :

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{pl}^2}{2}R + \underline{\xi\Phi^\dagger\Phi R} - (\partial_\mu\Phi)^\dagger(\partial^\mu\Phi) - \lambda\left(\Phi^\dagger\Phi - \frac{v_0^2}{2}\right)^2\right]$$

appears in the curved space-time

Φ : Higgs field (inflaton)

- **It explains the inflation in the framework of Standard Model!**

- for successful inflation, required conditions are:

$$n_s \simeq 0.97,\ r \simeq 0.0033,\ \xi \simeq 2\times 10^4$$

⟶ Planck's data strongly support! ~~against the BICEP2 data~~

[1]F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**,703(2008) [arXiv:0710.3755 [hep-th]].

If there exist gauge fields in early universe...

- It is worth investigating a possible role of gauge fields in inflationary universe.

Several models with gauge fields

- Anisotropic Inflation
- Gauge-flation
- Chromo-natural Inflation etc.

- What happens if electroweak gauge fields are included in Higgs Inflation model?

As a result... ↓

- Higgs Inflation can make sizable primordial magnetic fields.

Motivation of generating primordial magnetic fields

- Magnetic fields in clusters of galaxies have been observed.

Very little astrophysical substances

↓

They might be generated from inflation!

> ➢ M. S. Turner and L. M. Widrow, Phys. Rev. D **37**, 2743 (1988).
> ➢ B. Ratra, Astrophys. J. **391**, L1 (1992).
> ➢ K. Bamba and J. Yokoyama, Phys. Rev. D **69**, 043507 (2004) [astro-ph/0310824].
> Etc.

Observational constraint [2]: $10^{-15}[\mathrm{G}] \lesssim B_{obs} \lesssim 10^{-9}[\mathrm{G}]$

Higgs Inflation might satisfy this constraint!

[2]A. Neronov and I. Vovk, Science 328, 73 (2010) [arXiv:1006.3504 [astro-ph.HE]].
D. G. Yamazaki, T. Kajino, G. J. Mathew and K. Ichiki, Phys. Rept. **517**, 141 (2012) [arXiv:1204.3669 [astro-ph.CO]].
Etc.

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Higgs Inflation with gauge fields

- Action is as follows:

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{pl}^2}{2}R + \xi\Phi^\dagger\Phi R \underbrace{- \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}}_{SU(2)_L \times U(1)_Y} - (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda\left(\Phi^\dagger\Phi - \frac{v_0^2}{2}\right)^2\right]$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu , \qquad D_\mu\Phi = \left(\partial_\mu - i\frac{g}{2}\tau^a A^a_\mu - i\frac{g'}{2}B_\mu\right)\Phi$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \ .$$

- We assume a homogeneous and closed universe:

$$\begin{aligned} ds^2 &= -dt^2 + a(t)^2 d\Omega_3^2 \\ &= -dt^2 + a(t)^2((\sigma^1)^2 + (\sigma^2)^2 + (\sigma^3)^2) \ . \end{aligned}$$

Configurations of gauge fields

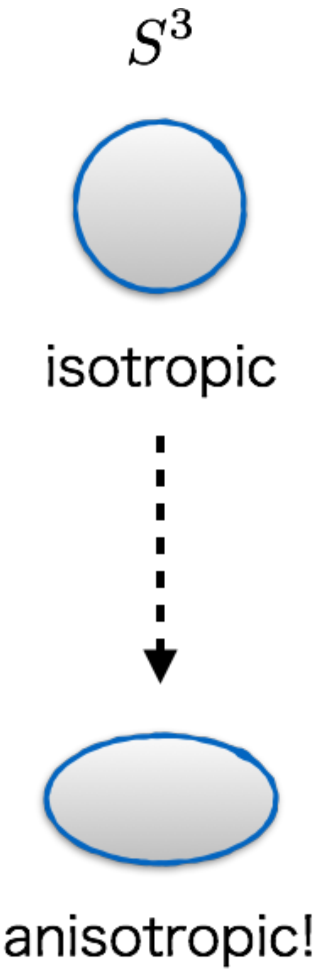
- If only $SU(2)_L$ gauge field exists…

$$
\left(
\begin{aligned}
ds^2 &= -dt^2 + a(t)^2 d\Omega_3^2 \\
&= -dt^2 + a(t)^2((\sigma^1)^2 + (\sigma^2)^2 + (\sigma^3)^2)\ . \\
\mathbf{A} &= \frac{1}{2g} f(t)(\sigma^1\tau^1 + \sigma^2\tau^2 + \sigma^3\tau^3)\ ,\ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v(t) \end{pmatrix}\ .
\end{aligned}
\right.
$$

- Considering $U(1)_Y$ gauge field…

$$\mathbf{B} = h(t)\sigma^3$$

$$
\left(
\begin{aligned}
ds^2 &= -dt^2 + a_1(t)^2((\sigma^1)^2 + (\sigma^2)^2) + a_3(t)^2(\sigma^3)^2, \\
&\quad \text{where } a_1(t) \equiv e^{\alpha(t)+\beta(t)},\ a_3(t) \equiv e^{\alpha(t)-2\beta(t)}\ . \\
\mathbf{A} &= \frac{1}{2g}\left[f_1(t)(\sigma^1\tau^1 + \sigma^2\tau^2) + f_3(t)\sigma^3\tau^3\right]\ ,\ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v(t) \end{pmatrix}\ .
\end{aligned}
\right.
$$



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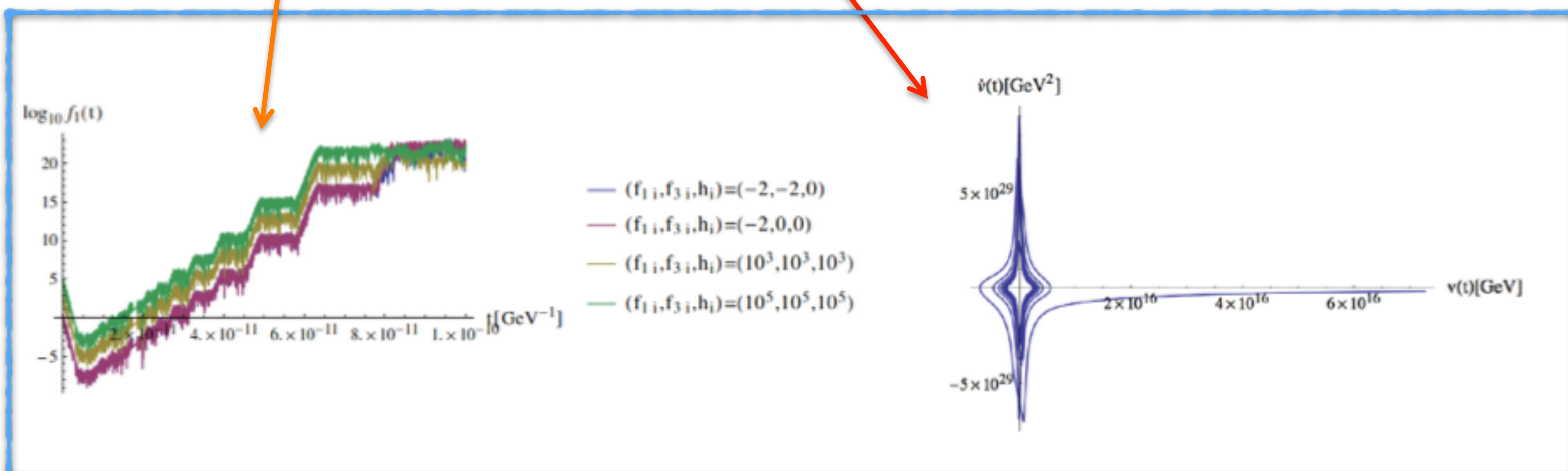
Solving calculation...

- Solving six parameters:

$$(f_1(t), f_3(t), h(t), v(t), \alpha(t), \beta(t))$$

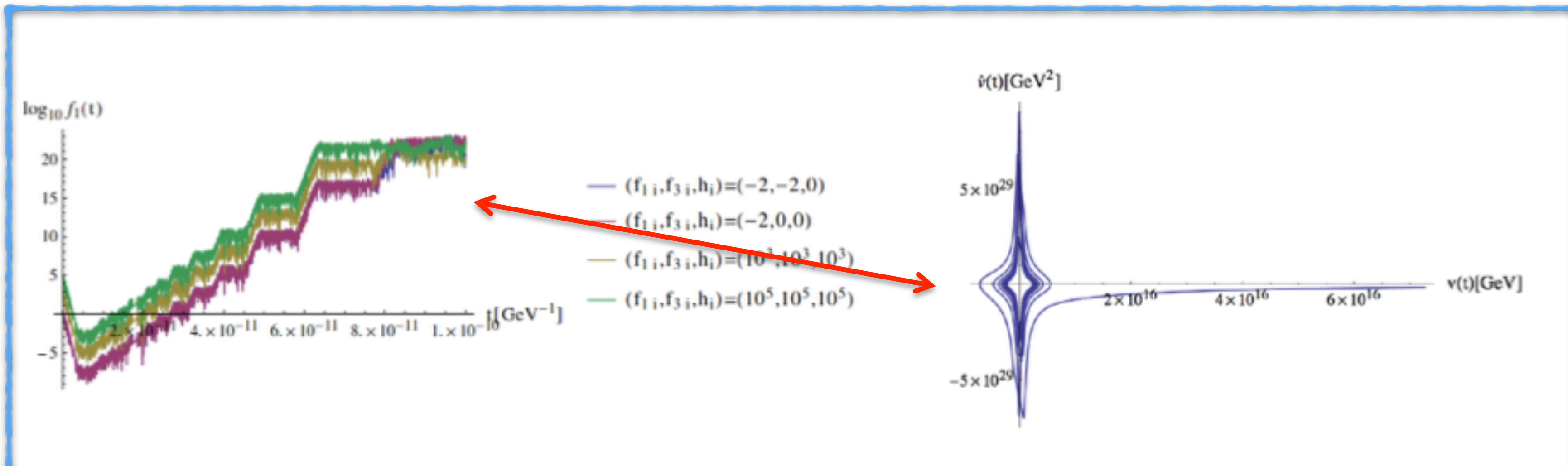


(Other two gauge components evolve like this one.)

Solving calculation…

- After inflation, the equation for gauge fields approximate the following ones:

$$\ddot{f}_1 + \frac{g^2}{4} v(t)^2 f_1 \simeq 0, \;\; (\ddot{f}_3 - g' \ddot{h}) + \frac{g^2 + g'^2}{4} v(t)^2 (f_3 - g' h) \simeq 0 \; .$$

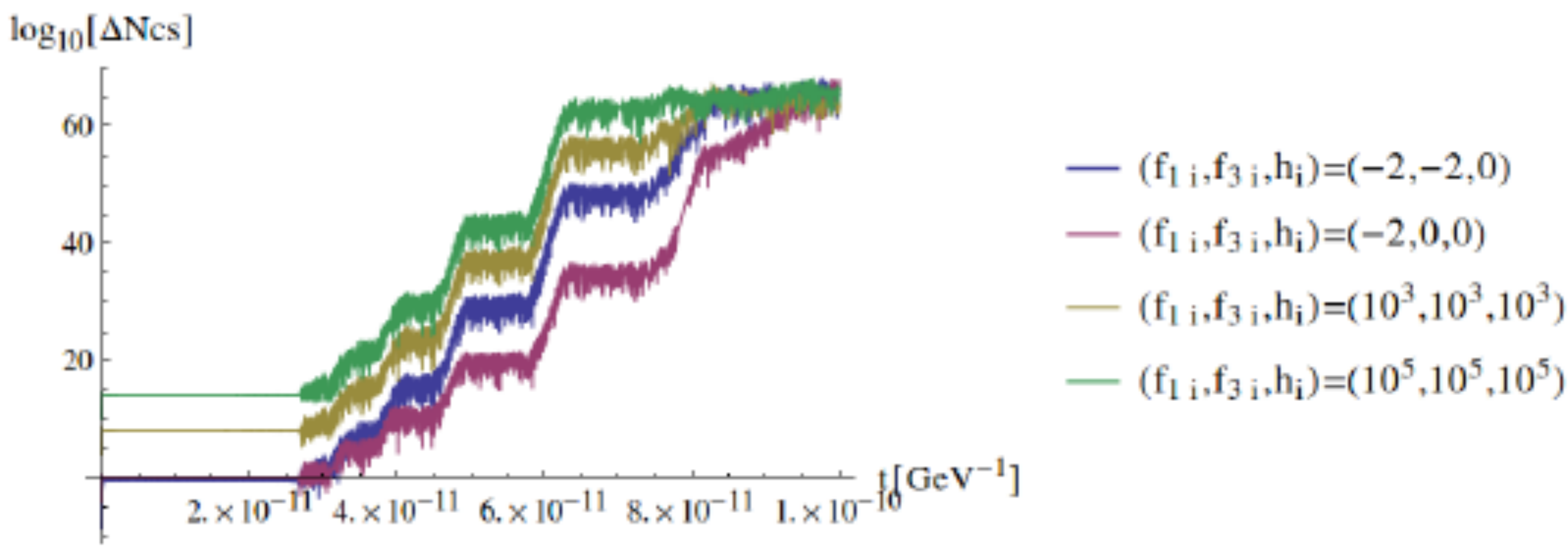


resonance happens!

Topological Configuration

- The change of Chern-Simons number is

$$
\begin{aligned}
\Delta N_{CS} &\equiv \frac{g^2}{16\pi^2}\int_0^t dt\,\sqrt{-g}\,\mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) \\
&= -\frac{1}{8}\int_0^t \frac{d}{dt}\left[f_1^2 f_3 + 2f_1^2 + f_3^2\right] dt\,.
\end{aligned}
$$



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Generation of magnetic fields

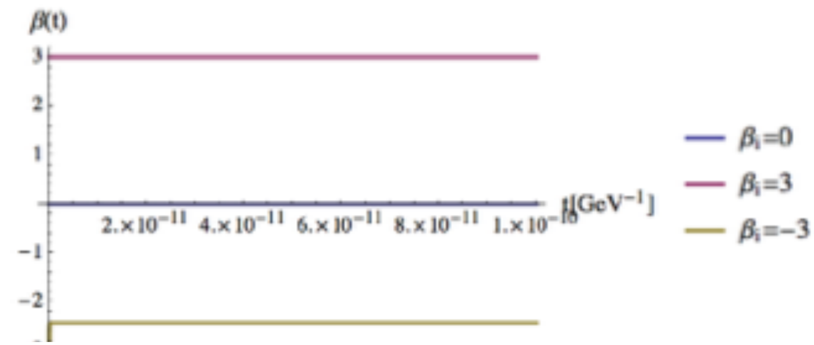
- The magnetic field is given by: $B \sim \frac{1}{a_1^2}(f_3 + h)$

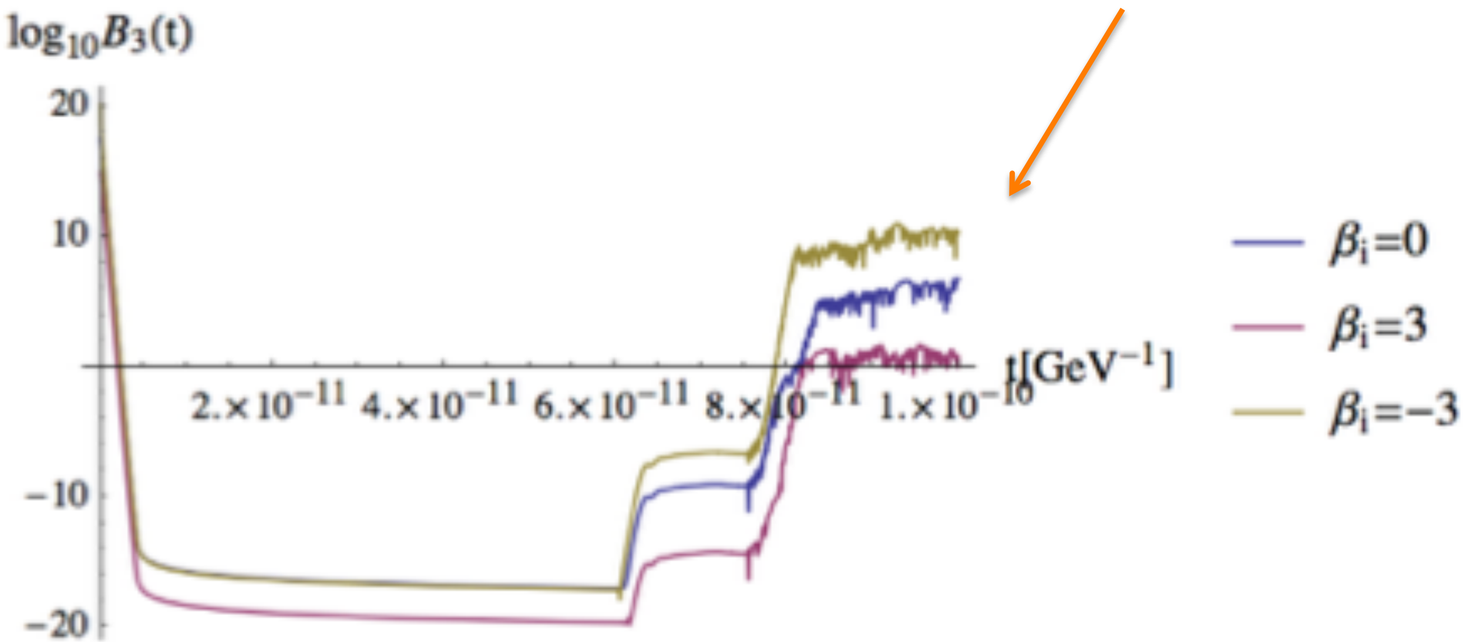
<u>Observational constraint</u>

$$10^{-15}[\mathrm{G}] \lesssim B_{obs} \lesssim 10^{-9}[\mathrm{G}] \longrightarrow 10^{11}\left(\frac{T_{reh}}{10^{10}[\mathrm{GeV}]}\right)^2[\mathrm{GeV}^2] \lesssim B_{reh} \lesssim 10^{17}\left(\frac{T_{reh}}{10^{10}[\mathrm{GeV}]}\right)^2[\mathrm{GeV}^2]$$

Anisotropy from Higgs Inflation

- The anisotropy survives during and after Higgs Inflation.





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Conclusion and outlook

- We studied cosmological dynamics of electroweak gauge fields during and after Higgs Inflation.
- Gauge fields rapidly grow due to parametric resonances after inflation and then sizable primordial magnetic fields which might be compatible with observation.
- Remarkably, the resultant amplitude of magnetic fields depends on the anisotropy survived during inflation.
- To obtain precise results on magnetic fields, we need to introduce matter fields and investigate reheating processes. Moreover, we have to study evolution of inhomogeneity during and after Higgs Inflation.