Big Bounce Baryogenesis

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Matter-antimatter Asymmetry

The asymmetry is described quantitatively by,

$$\eta = \frac{n_b - n_{\bar{b}}}{s} \simeq 8.5 \times 10^{-11}$$

The Sakharov Conditions

1. Baryon number violation
2. $\mathcal{C}$ and $\mathcal{CP}$ violation
3. Period of non-equilibrium

Standard Model $\rightarrow \eta_{sm} \sim 10^{-18}$.

Inflationary dilution $\Rightarrow$ Typically generated during or after reheating.

Inflationary Baryogenesis

- Pseudoscalar inflaton coupled to $F\tilde{F}$,
- Generation of Chern-Simons number from rolling of scalar field,

$$\frac{\phi}{\Lambda} Y^a_{\mu\nu} \tilde{Y}^{a\mu\nu}, \quad \frac{\phi}{\Lambda} W^a_{\mu\nu} \tilde{W}^{a\mu\nu}$$

- Can seed galactic magnetic fields, and generate gravitational wave signatures.
- Y suffers from uncertainties of EWPT and MHD.

Inflation and Bounce Cosmology

Alternative Cosmology to usual inflation paradigm,

- Can solve cosmological issues and source perturbations, like inflation,
- Geodesic completion and remove singularity problem,
- Energy below the Planck scale but requires violation of NEC,
- Many models including Ekpyrotic and matter-bounce.

Here we will consider the Ekpyrotic contracting background.

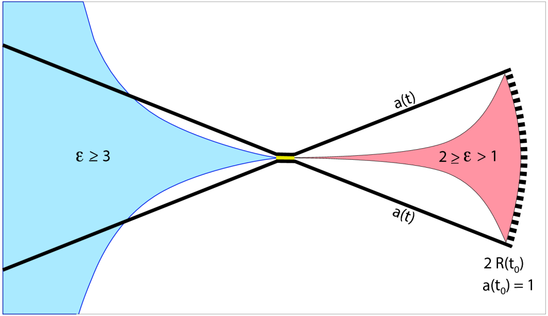
Ekpyrosis: A period of $\omega \gg 1$ contraction prior to a bounce

Ekpyrotic Bounce

Ekpyrotic Contraction: $a = (\epsilon H_b t)^{\frac{1}{\epsilon}} = (\epsilon H_b|\tau|)^{\frac{1}{\epsilon-1}}$ with $H = -\frac{1}{\epsilon|\tau|}$

Require $\epsilon \geq 3$, leading to very slow contraction for large ϵ.

$$\rho = \frac{\rho_k}{a^2} + \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4} + \frac{\rho_a}{a^6} + ... + \frac{\rho_\phi}{a^{2\omega}} + ...$$



Single Field Ekpyrotic Bounce

The equation of state parameter for a scalar φ,

$$\omega = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)} \ ,$$

To obtain $\omega \gg 1$,

$$\frac{1}{2}\dot{\varphi}^2 + V(\varphi) \approx 0 \quad \text{and} \quad \frac{1}{2}\dot{\varphi}^2 - V(\varphi) \gtrsim 0 \ .$$

Achieved if the φ is fast-rolling down a negative exponential potential,

$$V(\varphi) \approx -V_0 e^{-\sqrt{2\epsilon}\frac{\varphi}{M_p}} \quad \text{and} \quad \epsilon = \frac{3}{2}(1+\omega) \ .$$

Scaling solution,

$$\varphi \simeq M_p \sqrt{\frac{2}{\epsilon}} \ln(-\sqrt{\epsilon V_0}\tau/M_p) \quad \text{and} \quad \varphi' \simeq \sqrt{\frac{2}{\epsilon}}\frac{M_p}{\tau} \ .$$

Characteristics of Ekpyrotic Bounce

- Solves the problem of the rapid growth of anisotropies.
- Anisotropic instabilities which may arise can be suppressed because the Ekpyrotic field dominates the evolution.
- Permits trajectories which are attractors.
- Predict small r.
- Models with a single scalar field generate spectra with strong blue tilt. Require a second field to convert the isocurvature perturbations into adiabatic ones to give a nearly scale invariant spectrum.
- Can produce large non-gaussianities.

The Model and Gauge Field Dynamics

The Model and Gauge Field Dynamics

Lagrangian terms in contracting background:

$$\mathcal{L} = -\frac{1}{4}\eta^{\mu\rho}\eta^{\nu\sigma}F_{\mu\nu}F_{\rho\sigma} - \frac{\varphi}{8\Lambda}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F^{\rho\sigma} \ ,$$

Satisfying the Sakharov Conditions

1. Anomalous currents,
2. Pseudoscalar coupling to Chern-Simons terms,
3. Ekpyrotic Contracting phase.

Pseudoscalar Ekpryotic Scalar

A possible choice of potential for a Pseudoscalar Ekpryotic Scalar is,

$$V(\varphi) = \frac{V_0}{2\cosh\left(\sqrt{2\epsilon}\frac{\varphi}{M_p}\right)} \ ,$$

where for large $|\varphi|$,

$$V(\varphi) \approx -V_0 e^{-\sqrt{2\epsilon}\frac{|\varphi|}{M_p}} \ .$$

Taking the scaling solution,

$$\varphi \simeq -M_p\sqrt{\frac{2}{\epsilon}}\ln(-\sqrt{\epsilon V_0}\tau/M_p) \quad \text{and} \quad \varphi' \simeq \sqrt{\frac{2}{\epsilon}}\frac{M_p}{-\tau} \ .$$

require φ' positive to produce a positive asymmetry.

Particle Production and Chern-Simons Number

We will analyse the evolution of the F field in this background,

- Bogoliubov transformation,
- Anomalous currents lead to the generation of Chern-Simons number and Hypermagnetic field helicity.

The Chern-Simons number density for W_i,

$$n_{CS} = n_g \frac{g_2^2}{32\pi^2} \int d^3x \epsilon^{ijk} Tr(W_i \partial_j W_k + \frac{2ig_2}{3} W_i W_j W_k) \ .$$

will consider linearised approximation.

Field Quantisation and Mode Functions

- Derive equations of motion F_i, in weak field limit,
- Solving for circularly polarised wave modes ($\alpha = +, -$),

$$F_i = \int \frac{d^3\vec{k}}{(2\pi)^{3/2}} \sum_\alpha \left[G_\alpha(\tau, k)\epsilon_{i\alpha}\hat{a}_\alpha \mathrm{e}^{i\vec{k}\cdot\vec{x}} + G^*_\alpha(\tau, k)\epsilon^*_{i\alpha}\hat{a}^\dagger_\alpha \mathrm{e}^{-i\vec{k}\cdot\vec{x}} \right] \ .$$

- Thus,

$$G''_\pm + \left(k^2 \mp \frac{2\kappa k}{-\tau} \right) G_\pm = 0 \ ,$$

where $\kappa = \frac{M_p}{\sqrt{2\epsilon}\Lambda}$

Wave Mode Functions

- By matching to planewave modes at $\tau \to -\infty$,

$$A_{\pm}(\tau, k) = \frac{1}{\sqrt{2k}} e^{-ik\tau}$$

The wave mode functions are,

$$G_{\pm} = \frac{e^{-ik\tau}}{\sqrt{2k}} e^{\pm\pi\kappa/2} U\left(\pm i\kappa, 0, 2ik\tau\right)$$

- Interested in the exponentially enhanced positive frequency modes.
- Calculate accumulated n_{CS} at the bounce $\tau_b \to -\frac{1}{3H_b}$, by a Bogoluibov transformation.

Scenario 1: $\varphi W\tilde{W}$

Baryon Number from $\varphi W\tilde{W}$

Related to the baryon number,

$$\partial_\mu\left(\sqrt{-g}j_B^\mu\right) = \frac{3g_2^2}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}W^a_{\mu\nu}W^a_{\rho\sigma} = \frac{3g_2^2}{16\pi^2}\partial_\mu\left(\sqrt{-g}K^\mu\right) \ .$$

Baryon number density at τ,

$$\begin{aligned}\frac{n_B(\tau)}{a(\tau)^3} &\simeq \frac{9g_2^2}{8\pi^4}\int_\mu^{2\epsilon\kappa|H|} k^3(|G_+(\tau)|^2 - |G_-(\tau)|^2)dk \\ &\simeq \frac{9g_2^2}{16\pi^4}(-\epsilon|H|)^3C(\kappa) \ ,\end{aligned}$$

where

$$C(\kappa) \sim 0.007\frac{e^{2\pi\kappa}}{\kappa^4}, \ \text{for} \ \ \kappa > 1 \ .$$

Can now calculate the asymmetry parameter.

Generated Baryon Asymmetry

- No significant entropy production after reheating ($s \simeq \frac{2\pi^2}{45} g^* T_{\rm rh}^3$),
- Heavy majorana ν_R and reheating temperature $T_{\rm rh} > 10^{12}$ GeV
- Evaluating $n_B(\tau)$ near the bounce,

$$\eta_B = \frac{28}{79} \frac{n_B(\tau_c)}{s} \simeq \frac{5}{8\pi^5 g^*} C(\kappa) \left(\frac{\epsilon |H_c|}{T_{\rm rh}}\right)^3 ,$$

and hence,

$$\frac{\eta_B}{\eta_B^{obs}} \simeq 2 \cdot 10^5 C(\kappa) \left(\frac{\epsilon |H_c|}{T_{\rm rh}}\right)^3 .$$

Energy Density Constraint

Require $\rho_{CS}^{W}(\tau) \ll 3M_p^2 H^2$,

$$\rho_{CS}^{W}(\tau) = \langle 0| W_{\mu\nu} \tilde{W}^{\mu\nu} |0\rangle \simeq \frac{12}{\pi} D(\kappa)(\epsilon H)^4 \ ,$$

which has the approximate form, for $\kappa > 1$,

$$D(\kappa) \sim 0.01 \frac{e^{2\pi\kappa}}{\kappa^4} \sim 1.5 C(\kappa) \ .$$

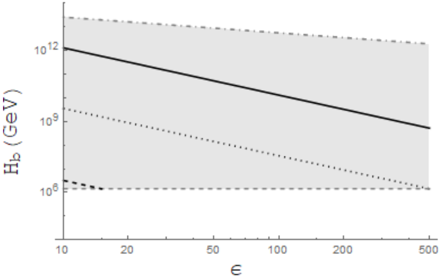
Thus, to ensure that the dynamics of the gauge fields do not effect the background evolution induced by φ we require that,

$$M_p \gg \sqrt{\frac{6C(\kappa)}{\pi}} \epsilon^2 |H_c| \ .$$

For $H_c = H_b$

Successful Baryogenesis requires,

$$|H_b| \simeq \frac{2 \cdot 10^{14}\ \text{GeV}}{\epsilon^2 C(\kappa)^{2/3}} \quad \text{and} \quad T_{\text{rh}} \simeq \frac{10^{16}\ \text{GeV}}{\epsilon C(\kappa)^{1/3}}$$



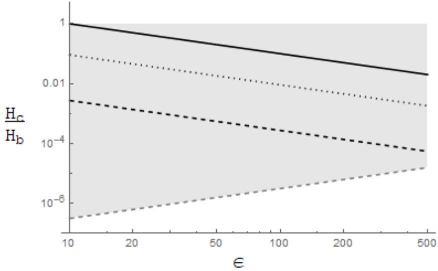
Energy density constraint,

$$1 \gg 10^{-4} \kappa^{2/3} e^{-\pi\kappa/3} \quad \text{or} \quad 1 \gg \epsilon \left(\frac{T_{\text{rh}}}{10^{25}\ \text{GeV}} \right)$$

For $|H_c| < |H_b|$

Successful Baryogenesis requires,

$$|H_c| = 2 \cdot 10^{-2} \frac{T_{\rm rh}}{\epsilon C(\kappa)^{1/3}} \ ,$$



A κ-independent bound on H_c for the energy density constraint,

$$\frac{H_c}{H_b} > \epsilon \frac{T_{\rm rh}}{4 \cdot 10^{22} GeV}$$

Scenario 1: Summary

- Ample parameter space for which successful Baryogenesis,
- Performed simplified calculation using the linearised approximation,
- This approximation will likely break down for large κ. A more detailed analysis is required.
- Indicates that Baryogenesis may be possible through this mechanism.

Scenario 2: $\varphi Y \tilde{Y}$

Hypermagnetic Field Helicity from $\varphi Y \tilde{Y}$

The Hypermagnetic helicity generated during the Ekpyrotic phase is matched to the end of the reheating epoch. This magnetic field is,

$$B_{\rm rh}(\tau_b)^2 = \frac{1}{2\pi^2}\int_{\mu}^{2\epsilon\kappa|H_c|} k^4(|G_+(\tau)|^2 - |G_-(\tau)|^2)dk$$

The magnetic field at the onset of reheating can be expressed as,

$$B_{\rm rh}(\tau_b) \simeq \frac{1}{2\pi}(\epsilon H_c)^2\sqrt{\frac{2C(\kappa)}{\kappa}} \ .$$

while the approximate correlation length of these magnetic fields,

$$\lambda_{\rm rh}(\tau_b) \simeq \frac{4\pi\kappa}{\epsilon|H_c|} \ .$$

These follow known evolution from $T_{\rm rh}$ to the EWPT.

Case 2: $\varphi Y\tilde{Y}$

The baryon asymmetry parameter produced at the EWPT,

$$\eta_B \simeq 5\cdot 10^{-12} f(\theta_W, T_{BAU}) C(\kappa) \left(\frac{H_c}{H_b}\right)^3 \left(\frac{\epsilon^2 H_b}{10^{14}\ \mathrm{GeV}}\right)^{3/2} ,$$

where $f(\theta_W, T_{BAU})$ parametrises the time dependence of the hypermagnetic helicity during the EWPT. There is significant uncertainty,

$$5.6\cdot 10^{-4} \lesssim f(\theta_W, T_{BAU}) \lesssim 0.32\ , \quad \mathrm{for} \quad T_{BAU}\sim 135 \quad \mathrm{GeV}$$

Hence, the generated baryon asymmetry is within the range,

$$C(\kappa)\left(\frac{H_c}{H_b}\right)^3 \left(\frac{\epsilon^2 |H_b|}{10^{17}\ \mathrm{GeV}}\right)^{3/2} < \frac{\eta_B}{\eta_B^{obs}} < C(\kappa)\left(\frac{H_c}{H_b}\right)^3 \left(\frac{\epsilon^2 |H_b|}{1.5\cdot 10^{15}\ \mathrm{GeV}}\right)^{3/2} .$$

Energy Density Constraint

Requiring $\rho^Y_{CS}(\tau) \ll 3M_p^2 H^2$,

$$\rho^Y_{CS}(\tau) = \langle 0| Y_{\mu\nu} \tilde{Y}^{\mu\nu} |0\rangle \simeq \frac{6}{\pi} C(\kappa)(\epsilon H_c)^4 \ ,$$

To ensure that the dynamics of the hypermagnetic fields do not effect the background evolution induced by φ we require that,

$$M_p \gg \sqrt{\frac{2C(\kappa)}{\pi}} \epsilon^2 |H_c|.$$

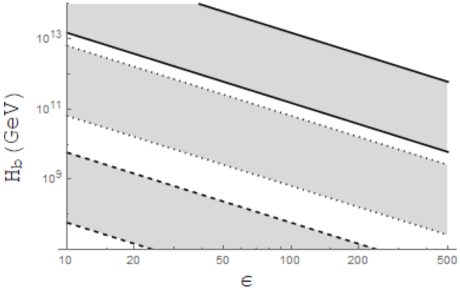
Can now consider the allowed parameters for Successful Baryogenesis.

$H_c = H_b$

$$\frac{1.5 \cdot 10^{15}\ \text{GeV}}{C(\kappa)^{2/3}} < \epsilon^2 |H_b| < \frac{10^{17}\ \text{GeV}}{C(\kappa)^{2/3}} \ .$$

hence considering the maximum value, Eq. (24) becomes,

$$C(\kappa) \gg 10^{-9} \ ,$$

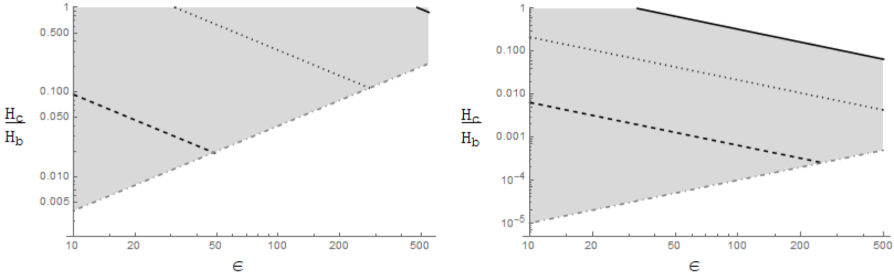


Upper bound corresponds to lower bound uncertainty on asymmetry generation, and vice versa. $\kappa = \ 1, \ 3, \ 5$

$|H_c| < |H_b|$

$$\frac{H_c}{H_b} \gg \frac{\epsilon T_{\rm rh}}{2.5 \cdot 10^{20}\ \mathrm{GeV}}\ , \quad \text{and} \quad \frac{H_c}{H_b} \gg \frac{\epsilon T_{\rm rh}}{10^{23}\ \mathrm{GeV}}\ .$$

Parameter space for successful Baryogenesis, considering a reheating temperature of $T_{\rm rh} \sim 10^{15}$ GeV.



For the lower bound and upper bound on asymmetry generation, respectively, for $\kappa = 1, 3, 5$.

Present Day Magnetic Fields

Preset day magnetic fields are,

$$B_p^0 \simeq 2 \cdot 10^{-18}\ \mathrm{G}\ C(\kappa)^{1/3} \frac{H_c}{H_b} \left(\frac{\epsilon^2 H_b}{10^{13}\ \mathrm{GeV}} \right)^{1/2}$$

and

$$\lambda_p^0 \simeq 6 \cdot 10^{-5}\ \mathrm{pc}\ C(\kappa)^{1/3} \frac{H_c}{H_b} \left(\frac{\epsilon^2 H_b}{10^{13}\ \mathrm{GeV}} \right)^{1/2}$$

Taking the parameters required for successful Baryogenesis,

$$2.4 \cdot 10^{-17}\ \mathrm{G} < B_p^0 < 2 \cdot 10^{-16}\ \mathrm{G}$$

and

$$7 \cdot 10^{-4}\ \mathrm{pc} < \lambda_p^0 < 6 \cdot 10^{-3}\ \mathrm{pc}$$

Below constraints, but unable to explain Blazar observations.

Conclusion and Future Work

- Ekpyrotic phase, induced by a fast-rolling pseudoscalar field,
- Chern-Simons number density generated through coupling to φ
- Successfully produce η_B^{obs} through both the Y_i and W_i gauge fields.
- For Y_i, also source galactic magnetic fields, similar to inflation case.

Future Investigations

- Detail the bounce dynamics and back-reaction effects,
- Possibly gravitational wave signature.