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 winding number in $Y\tilde{Y}$, $W\tilde{W}$ or $R\tilde{R}$ from rolling of scalar field,

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

- May be able to provide seeds 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.

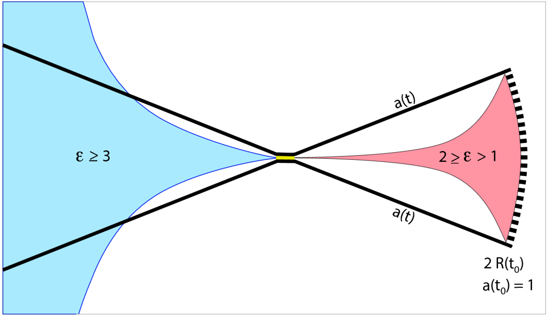
Simplest: A scalar field rolling down an $\sim$ exponential negative potential.

Ekpyrotic Bounce

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

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

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



Some Advantages 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.

The Model

Lagrangian terms of sub-dominant pseudoscalar in contracting background:

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}\partial_\nu\phi\partial_\nu\phi + \frac{\phi}{\Lambda}Y^a_{\mu\nu}\tilde{Y}^{a\mu\nu} + \frac{\phi}{\Lambda}W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$

Satisfying the Sakharov Conditions

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

Will firstly consider simplest $p = 3$, $a \propto t^{\frac{1}{3}}$, KE dominated contraction.

Particle Production and Chern-Simons Number

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

- Time dependent spacetime $\rightarrow$ time dependent vacuum state,
- Bogoliubov transformation $\rightarrow$ accumulated particle number,
- Anomalous currents lead to the generation of Chern-Simons number.

The Chern-Simons number density,

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

Field Quantisation and Mode Functions

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

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

- Thus, where $\kappa = \frac{\phi_0'}{\Lambda H_b}$ and $\phi' = \frac{\phi_0'}{a(\tau)^2}$,

$$F''_\pm + \left(k^2 \mp \frac{\kappa k}{\tau} \right) F_\pm = 0 \; .$$

- To avoid instabilities we will impose the cut-off $k\tau > \kappa$.

Wave Mode Functions

- The wave mode functions are,

$$F_{\pm} = \frac{-i}{\sqrt{2k}} e^{-ik\tau} e^{\pm\pi\kappa/4} U\left(\pm i\kappa/2, 0, 2ik\tau\right) \ .$$

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

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

- Calculate accumulated n_{CS} at the bounce $\tau_b \to -\frac{1}{3H_b}$, by a Bogoluibov transformation.

- Related to the baryon number,

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

Generated Chern-Simons Number

The B density generated is given by,

$$n_B(\tau) = \frac{3g_2^2}{32\pi^2}\int_{-\infty}^{\tau}\langle 0|W^a_{\mu\nu}\tilde{W}^{a\mu\nu}|0\rangle$$
$$\simeq \frac{9g_2^2}{8\pi^3}\int_{-\infty}^{\tau} d\tau \int_{\mu}^{\Lambda} k^3 dk\delta(k\tau-\kappa)\left((F_+F_+'^* + F_+^*F_+') - (F_-F_-'^* + F_-^*F_-')\right)$$

where

$$\left((F_+F_+'^* + F_+^*F_+') - (F_-F_-'^* + F_-^*F_-')\right)\delta(k\tau-\kappa) \simeq \begin{cases} 0.3\kappa & \kappa \ll 1 \\ 0.44 & \kappa = 1 \\ \frac{1}{\sqrt{\pi}} & \kappa \gg 1 \end{cases},$$

The dependence of κ is important for whether a mode is cut-off before exiting the horizon, or at the horizon crossing.

The cases of κ

Where τ is evaluated is dependent on the relation between Λ and H_b,

$$n_B \simeq \begin{cases} \frac{3g_2^2}{\pi^3}\kappa H_b^3 & , \text{ for } \kappa < 1 \\ \frac{9g_2^2}{2\pi^3} H_b^3 & , \text{ for } \kappa = 1 \\ \frac{81 g_2^2}{8\pi^3\sqrt{\pi}}\kappa^3 H_b^3 & , \text{ for } \kappa > 1 \end{cases}$$

where this considers $\Lambda > 3H_b$ and $\Lambda > 3H_b\kappa$ respectively.

Note, we require $\kappa \ll \frac{M_p}{\Lambda}$ so ϕ is sub-dominant.

For the moment, we will just consider the $\kappa = 1$ case.

Generated Baryon Asymmetry

- No significant entropy production after reheating ($s \simeq \frac{2\pi^2}{45} g^* T_{\rm rh}^3$),
- Evaluating near the bounce,

$$\eta_B = \frac{n_B}{s} \approx 5 \cdot 10^{-4} \kappa \left(\frac{H_b}{T_{\rm rh}}\right)^3 \left(\frac{a_b}{a_{\rm rh}}\right)^3 ,$$

for $\kappa \sim 1$ and assuming instantaneous reheating,

$$\frac{\eta_B}{\eta_B^{obs}} \approx \left(\frac{T_{\rm rh}}{2 \cdot 10^{15}\ \mathrm{GeV}}\right)^3 \approx \left(\frac{H_b}{10^{13}\ \mathrm{GeV}}\right)^{\frac{3}{2}} .$$

Parameter Constraints from Generated Baryon Asymmetry

Some conclusions:

$\kappa \ll 1$: The baryon number generation is suppressed by the the reduction of the scalar velocity.

$\kappa = 1$: Baryon number consistent with observation can be produced for a large bounce generation and short reheating time.

$\kappa > 1$: Allows larger baryon number generation once generation stops, but it stops earlier in the evolution bringing closer to the $\kappa = 1$ case

Conclusion and Future Work

- Pseudoscalar field coupled to Chern-Simons term,
- Utilise dynamics of Ekpyrotic contraction prior to bounce.
- Can successfully produce η_B^{obs} with a big bounce.

Future Investigations

- Detail the bounce dynamics,
- Magnetogenesis from hypercharge anomaly,
- Possibly gravitational wave signature,
- Possible LHC Phenomenology.