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 via Axion

- Pseudoscalar inflaton coupled to $F\tilde{F}$,

- Generation of Chern-Simons number from rolling of scalar field,

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

- Net helicity converted to magnetic fields and η_B at EWPT,

- Can seed galactic magnetic fields, and generate gravitational wave signatures.

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.

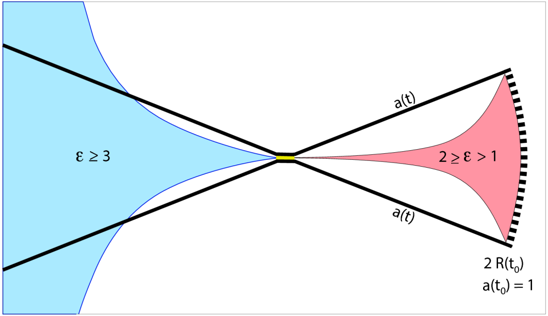
Ekpyrosis: A period of $\omega \gg 1$ contraction prior to a bounce.

Ekpyrotic Bounce

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

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

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



Source: Anna Ijjas, Paul J. Steinhardt, 1803.01961

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 $\omega \gg 1$,

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

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

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

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 Cosmology

- 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, a blue-tilted tensor power spectrum.
- 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, but is model-dependent.

The Model and Gauge Field Dynamics

Hypermagnetic field Lagrangian terms in contracting background:

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

- φ responsible for the Ekpyrotic phase, and secondary field giving period of kination.
- Will consider $\epsilon \in [10, 500]$ for illustrative purposes.
- At the EWPT the decay of the hypermagnetic field helicity will result in the production of magnetic fields and a baryon asymmetry.

Field Quantisation and Mode Functions

- Derive equations of motion Y_i,
- Solving for circularly polarised wave modes ($\alpha = +, -$),

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

- Thus,

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

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

Directly analogous to the inflationary case, but $\kappa \to \xi = \sqrt{\frac{\epsilon_{\rm inf}}{2}} \frac{M_p}{\Lambda}$. The wave mode functions are,

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

The End of the Ekpyrotic Phase

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

- Evaluating the hypermagnetic near the bounce point (or H_c),
- Instantaneous reheating and no subsequent significant entropy production ($s \simeq \frac{2\pi^2}{45} g^* T_{\rm rh}^3$),
- Onset of usual expanding radiation dominated epoch at bounce point,
- Energy density constraint: $M_p \gg \sqrt{\frac{6C(\kappa)}{\pi}} \epsilon^2 |H_c|$.
- Follow known evolution of Y_μ from $T_{\rm rh}$ to $T_{\rm EWPT}$, and resultant η_B.

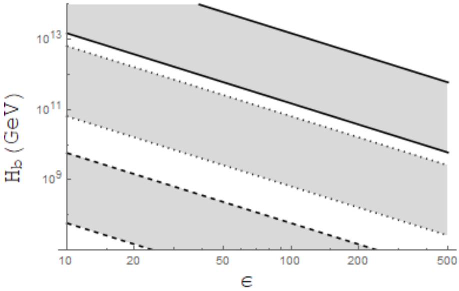
Consider two scenarios $H_c = H_b$ and $H_c < H_b$, to accommodate the length of kination period after Ekpyrotic phase and the bounce.

$H_c = H_b$

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

hence considering the maximum value, the energy constraint becomes,

$$C(\kappa)^{\frac{1}{6}} \gg 0.05\ ,$$

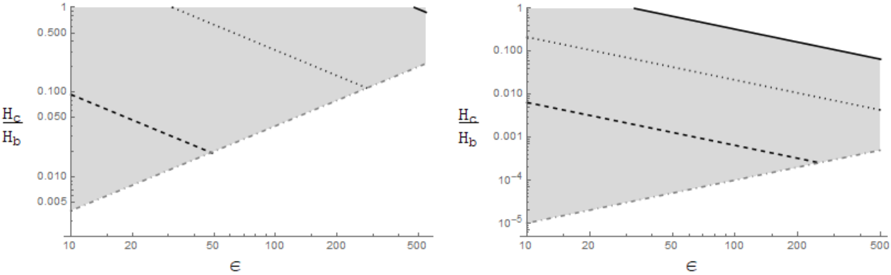


Upper bound corresponds to lower bound of uncertainty on asymmetry generation, and vice versa. $\kappa =\ 1,\ 3,\ 5$

$|H_c| < |H_b|$

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

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

Present 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.

Gravitational Waves from Gauge Field Production

Gravitational waves sourced by $\phi F\tilde{F}$ term exhibit a bluer spectrum,

$$\mathcal{P}_T^v + \mathcal{P}_T^s \simeq \frac{4}{\pi^2}\frac{k^2}{M_p^2} + 3.3\cdot 10^{-7}\frac{e^{4\pi\kappa}}{\kappa^2}\frac{H_b}{M_p}\frac{k^3}{M_p^3} ,$$

We have $\mathcal{P}_T^s(k) \geq \mathcal{P}_T^v(k)$, for the frequency range:

$$300 \text{ MHz}\left(\frac{\kappa}{5}\right)^{8/3} e^{\frac{2\pi}{3}(5-\kappa)} > f > 31 \text{ kHz}\left(\frac{\epsilon}{25}\right)^{3}\left(\frac{\kappa}{5}\right)^{-2} e^{2\pi(5-\kappa)} ,$$

for the upper bound for successful Baryogenesis, and for the lower bound,

$$37 \text{ MHz}\left(\frac{\kappa}{5}\right)^{8/3} e^{\frac{2\pi}{3}(5-\kappa)} > f > 16 \text{ MHz}\left(\frac{\epsilon}{25}\right)^{3}\left(\frac{\kappa}{5}\right)^{-2} e^{2\pi(5-\kappa)} .$$

Comparing the Ekpyrotic and Inflationary Scenarios

Similar features

- Successful Baryogenesis
- Present day magnetic fields
- Spectral index n_s

Differentiating features

- Gravitational waves: both from r and gauge field production.
- Non-gaussianities: model dependencies and sourced from gauge field coupling.

Conclusion and Future Work

- Ekpyrotic phase, induced by a fast-rolling pseudoscalar field,
- Net helicity generated can successfully produce η_B^{obs}
- Source galactic magnetic fields, similar to inflation case.
- Gravitational waves key to differentiating these scenarios.

Future Investigations

- Detail the bounce dynamics and scalar sector
- Determination of non-gaussianities in specified model
- $\varphi W\tilde{W}$ case and back-reaction
- Gravitational Leptogenesis in Bounce Cosmology

Gravitational Leptogenesis in Ekpyrotic Cosmology

Generation of a lepton asymmetry through gravitational-lepton anomaly,

$$\nabla_\mu J^\mu_L = \frac{N_{R-L}}{384\pi^2} R\tilde{R} \ ,$$

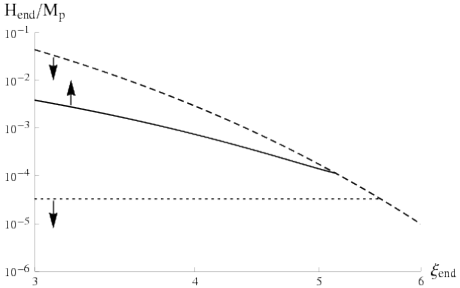
Two possible ways to do so,

- Direct coupling between the Ekpyrotic scalar to the $\varphi R\tilde{R}$
- Chiral gravitational wave generation through gauge field amplification via $\varphi F\tilde{F}$

In Ekpyrosis, possibly gain enhanced production of chiral gravitational waves without conflict with measurements of r.

Possible path for Gravitational Leptogenesis

Inflaton coupling to $\phi F\tilde{F}$ leading to Gravitational Leptogenesis is incompatible with observation:



Advantages of Ekpyrotic scenario:

- In the energy density constraint, take $H_{end} \to \epsilon H_{end}$,
- Not subject to the constraint on r,
- Significant production of high frequency chiral gravitational waves.

Source: Alexandros Papageorgiou, Marco Peloso, 1708.08007