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.

See: Benedict von Harling's talk later today

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.

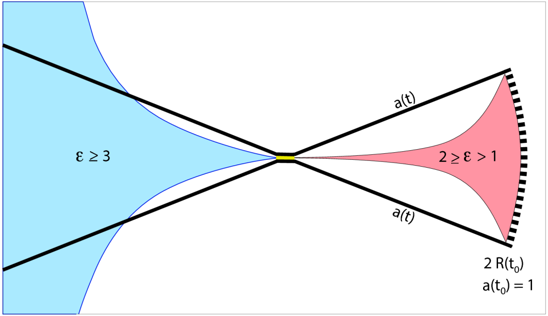
Ekpyrosis: A period of $\omega \gg 1$ contraction prior to a bounce.

Ekpyrotic Bounce

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

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

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



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.
- 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.

Ekpyrotic Cosmology Gravitational waves

Ekpyrotic Cosmologies predict a blue-tilted tensor power spectrum,

$$\mathcal{P}_T^{v(\mathrm{ekp})} \simeq \frac{4k^2}{\pi^2 M_p^2}\ , \quad \text{while} \quad \mathcal{P}_T^{v(\mathrm{inf})} \simeq \frac{4H^2}{\pi^2 M_p^2}\ ,$$

compared to the inflationary case,

- Predicts a small tensor-to-scalar ratio r on CMB scales,
- If near future experiments such as LiteBIRD are able to observe a tensor-to-scalar ratio, the inflationary scenario will be favoured,
- Enhanced production of gauge fields may lead to additional high frequency gravitational wave signatures.

Non-Gaussianities in Ekpyrotic Bounce

- The current Planck constraints are,

$$f_{NL}^{\mathrm{local}} - 0.9 \pm 5.1 \ ,$$

- Predictions for two scalar Ekpyrotic scenario, with a period of kination prior to the bounce,

$$f_{NL} \propto \sqrt{\epsilon} \ ,$$

- Models in which zero non-gaussianities are generated during the Ekpyrotic contraction phase, but rather they are only produced during the conversion process prior to the bounce; with $f_{NL} \sim \mathcal{O}(1)$.
- Important tool with increased precision in measurements alongside improvements in the theoretical understanding.

The Model and Gauge Field Dynamics

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.
- Ekpyrotic Contraction: $a = (\epsilon H_b t)^{\frac{1}{\epsilon}} \simeq (\epsilon H_b|\tau|)^{\frac{1}{\epsilon-1}}$ with $H \simeq -\frac{1}{\epsilon|\tau|}$
- At the EWPT the decay of the hypermagnetic field helicity will result in the production of magnetic fields and a baryon asymmetry.

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, with $\tau \in (-\infty, -\frac{1}{\epsilon H_b})$.

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 $\kappa \to \xi = \sqrt{\frac{\epsilon_{\rm inf}}{2}} \frac{M_p}{\Lambda}$.

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.
- Bogoluibov transformation to find n_{CS} at the bounce $\tau_b \to -\frac{1}{3H_b}$.
- Consider modes with $k\tau < 2\kappa$.

Baryogenesis from Hypermagnetic Field

The End of the Ekpyrotic Phase

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

- Evaluating the hypermagnetic near the bounce point (or H_c),
- Instantaneous reheating,
- No significant entropy production after reheating ($s \simeq \frac{2\pi^2}{45} g^* T_{\rm rh}^3$),
- Onset of usual expanding radiation dominated epoch at bounce point.

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.

Source: Daniel Jimenez, Kohei Kamada, Kai Schmitz, and Xun-Jie Xu, 1707.07943, and see Benedict von Harling's talk today.

Energy Density Constraint

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

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

where,

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

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.

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

The magnetic field at τ_b,

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

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.

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,

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

Hence, the generated baryon asymmetry is within the range,

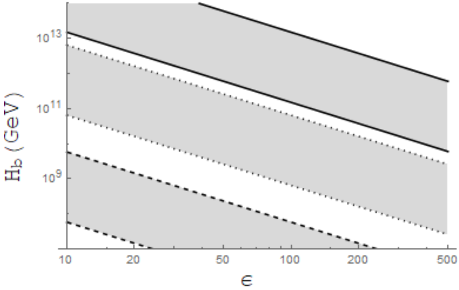
$$C(\kappa) \left(\frac{H_c}{H_b}\right)^3 \left(\frac{\epsilon^2 |H_b|}{10^{17}\ \mathrm{GeV}}\right)^{3/2} < \frac{\eta_B}{\eta_B^{obs}} < C(\kappa) \left(\frac{H_c}{H_b}\right)^3 \left(\frac{\epsilon^2 |H_b|}{1.5 \cdot 10^{15}\ \mathrm{GeV}}\right)^{3/2} .$$

$H_c = H_b$

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

hence considering the maximum value, the energy constraint becomes,

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

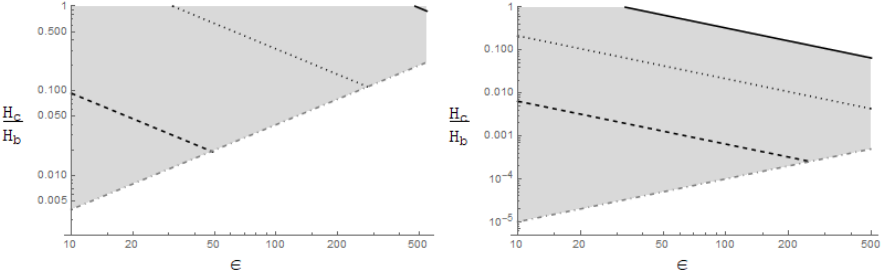


Upper bound corresponds to lower bound of uncertainty on asymmetry generation, and vice versa. $\kappa = \ 1, \ 3, \ 5$

$|H_c| < |H_b|$

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

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

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,

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

As an example, consider $\mathcal{P}_T^s(k_e = \epsilon H_b) \geq \mathcal{P}_T^v(k_e = \epsilon H_b)$,

$$H_b \geq 10^3 \frac{\kappa M_p}{e^{2\pi\kappa}\sqrt{\epsilon}} \ ,$$

can be compared with the requirements for Baryogenesis.

- They do not dominate for any of the allowed range for $\kappa < 3.7$,
- The observational consequences are not currently detectable,
- Similar conclusions can likely be drawn for the $H_c < H_b$.

Source: Ido Ben-Dayan, 1604.07899

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

Possibility of $\varphi W\tilde{W}$ Route

- Producing a non-zero n_{B+L}, details of EWPT not required,
- Must prevent washout by $B+L$ violating sphalerons,
- Require a single heavy majorana neutrino ν_R and reheating temperature $T_{\rm rh} > 10^{12}$ GeV,
- Smaller κ and ϵ required compared to $\varphi Y\tilde{Y}$ case,
- Non-abelian nature of the weak gauge field will lead to additional back-reaction effects,
- Linearised approx. $gW^2 \ll \partial W$ begins to breakdown for $\kappa \gtrsim 1$,
- Possible Warm Ekpyrosis scenario.

See: Aaron M. Levy, Gustavo Turiaci, 1603.06608.

Gravitational Leptogenesis in Ekpyrotic Cosmology

Gravitational Leptogenesis in Ekpyrotic Cosmology

Generation of a lepton asymmetry through gravitational-lepton anomaly,

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

Two possible ways to do so,

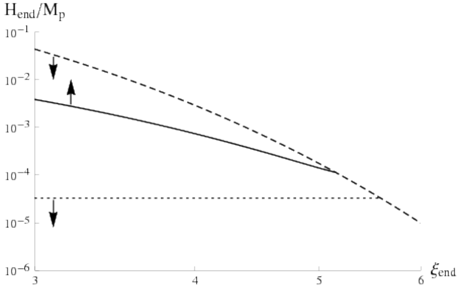
- Direct coupling between the Ekpyrotic scalar to the $\varphi R\tilde{R}$
- Chiral gravitational wave generation through gauge field amplification via $\varphi F\tilde{F}$

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

See: Kohei Komada's talk later today

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

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 (2007/8.XXXXX)