BARYOGENESIS FROM PRIMORDIAL MAGNETIC FIELDS

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About me

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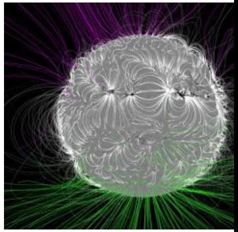
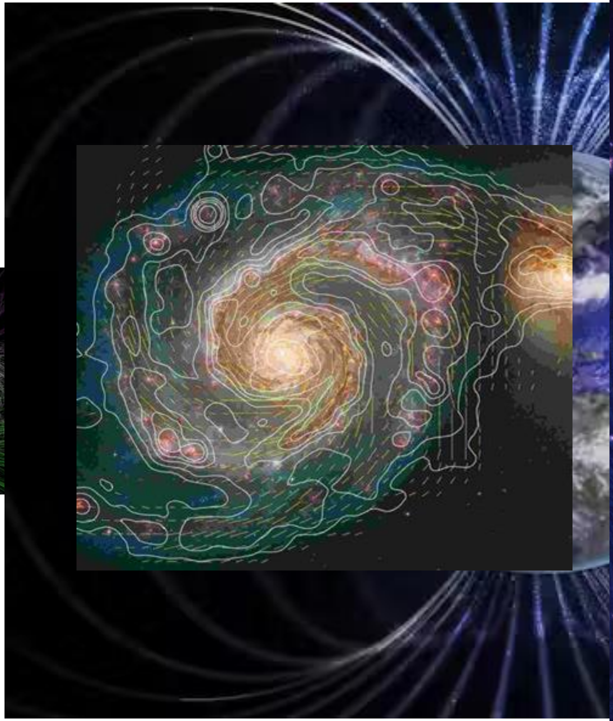
PhD at APC 2022-2025

Introduction





Electroweak phase transition

Step 1 : Universe is stuck in the Φ=0 ground state

SU(2) x U(1)_y

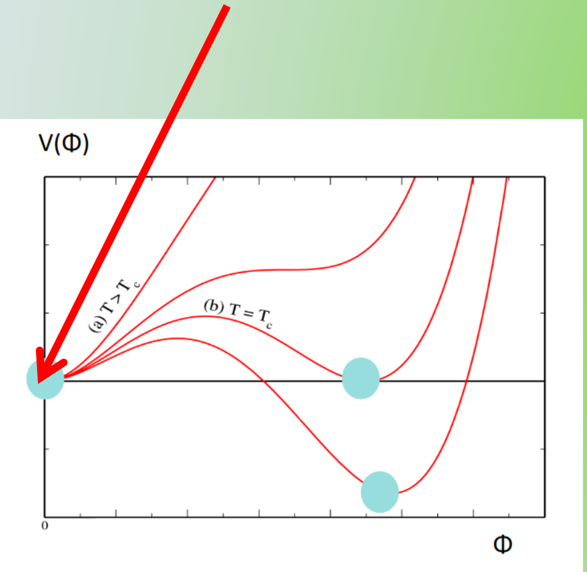
T_EWPT ~ 160 GeV

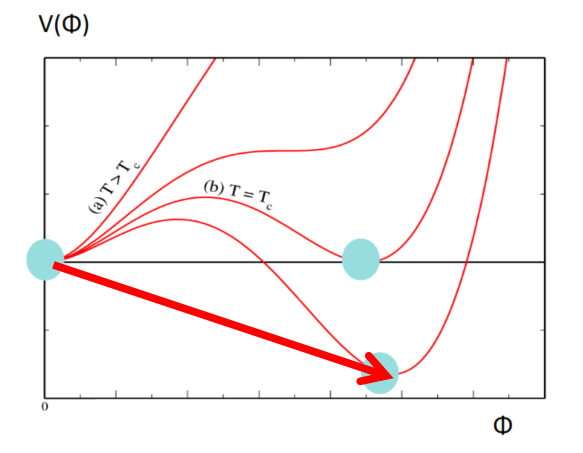
Step 2 : Universe is tunneling through the barrier to reach the true vacuum (on a 3-sphere actually)

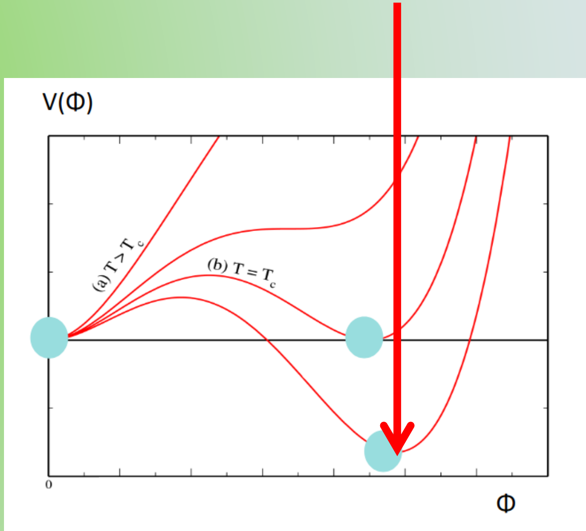
$T \lesseqgtr T_{EWPT}$

Step 3 : Universe has transitioned totally into the true vacuum

U(1)_em







PMF and Baryogenesis

Since the baryons and leptons are only interacting with SU(2) gauge fields through L-H particles, we can expect an anomaly conducting to a violation of B+L such that (‘t Hooft (1976)):

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = N_\mathrm{g} \frac{g^2}{16\pi^2} \,\mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - N_\mathrm{g} \frac{g'^2}{32\pi^2} Y_{\mu\nu}\widetilde{Y}^{\mu\nu}$$

We can simplify this expression by integrating it over time :

$$\Delta Q_B = \Delta Q_L = N_\mathrm{g} \left(\Delta N^L_\mathrm{CS} - \frac{g'^2}{16\pi^2}\Delta\mathcal{H}_Y\right)$$

→ **Baryogenesis from a decaying Hyperhelical magnetic field !**

PMF and Baryogenesis

Electroweak phase transition (EWPT) system of interacting particles (Kamada & Long arXiv:1606.08891) :

- 3 generation of quarks and leptons, 2 W+/- bosons and 1 Higgs doublet + corresponding antiparticles
- Separation between Left-handed and Right-handed particles
- neutral particles do not intervene in this system

→ System of many kinetic equations

$$\frac{d\vec{\eta}}{dx} = \mathbf{M}\vec{\eta} + \vec{S}$$

x = M0/T

M0~10^{17} GeV

$\vec{n_B}/s$

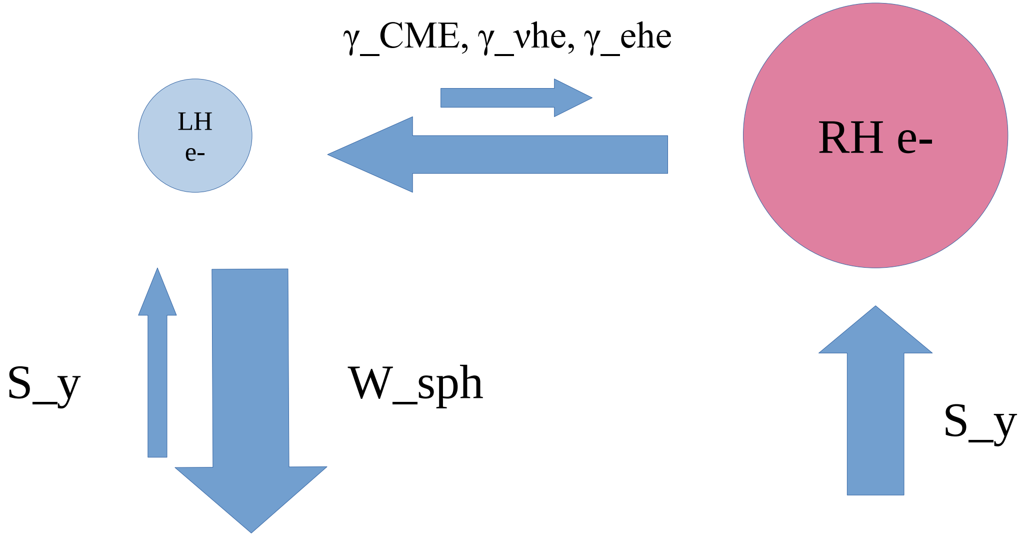
M = transport coefficients for interacting particles

S = anomaly source terms

PMF and Baryogenesis

Key mechanism and equilibrium solution for Lepto(baryo)genesis **BEFORE EWPT** :

First generation electron has the smallest Yukawa coupling => last to be at equilibrium



Weak sphaleron is the dominant term but only affects LH particles

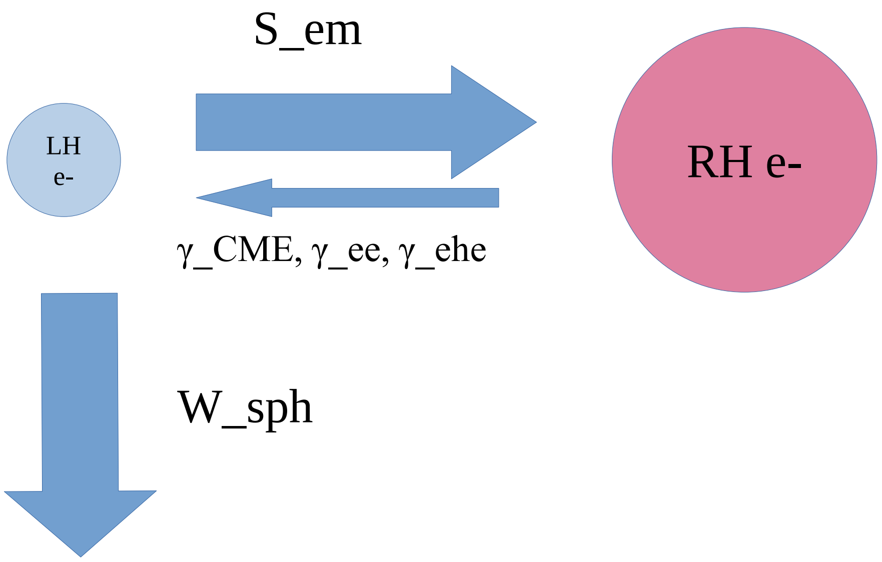
→ competition and equilibrium between the source term from decaying hyperhelical magnetic field S_y and flipping terms

→ Equilibrium reached between RH-LH conversion and sourcing by Hyperhelical fields

PMF and Baryogenesis

Key mechanism and equilibrium solution **AFTER EWPT** :

First generation electron has the smallest Yukawa coupling => last to be at equilibrium



S_em does not source B+L anymore but sources chiral asymmetry instead

→ metastable equillibrium between S_em and flipping terms

→ quasi-equilibrium reached between the sourcing of R-H electrons and the weak sphaleron washout

PMF and Baryogenesis

We obtain an equilibrium solution in each phase

Symmetric Phase

$$\eta_{B,\mathrm{eq}} = \eta_{L,\mathrm{eq}} \approx \frac{\mathcal{S}_{\mathrm{y}}}{\gamma_{h\leftrightarrow ee} + \gamma_{\mathrm{y}}^{\mathrm{CME}}}$$

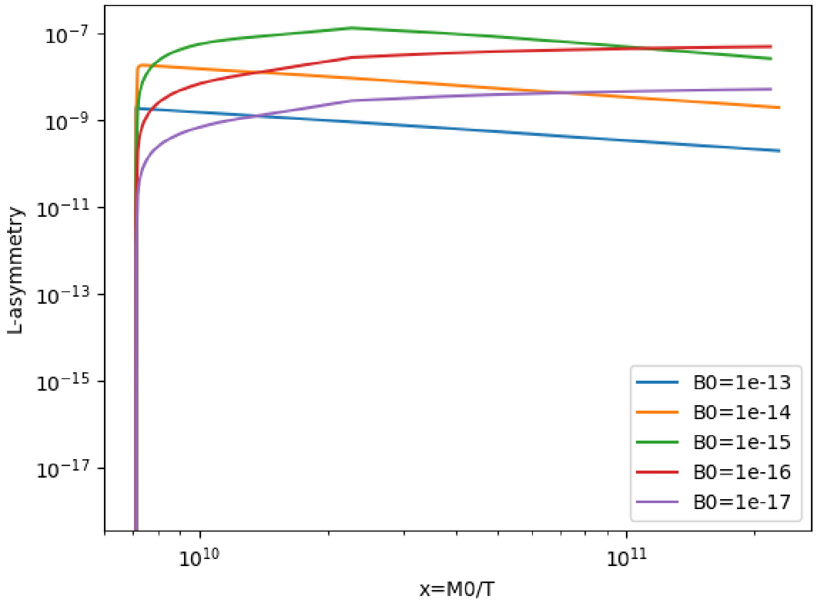
Broken phase

$$\eta_{B,\mathrm{eq}} = \eta_{L,\mathrm{eq}} \approx \frac{\mathcal{S}_{\mathrm{em}}}{\gamma_{h\leftrightarrow ee} + \gamma_{\mathrm{flip}} + \gamma_{\mathrm{em}}^{\mathrm{CME}}}$$

→ B asymmetry preserved at sphaleron freeze-out

T_fo ~135 GeV

Simulations are in agreement with the analytical solutions



Constraints on PMF/IGMF

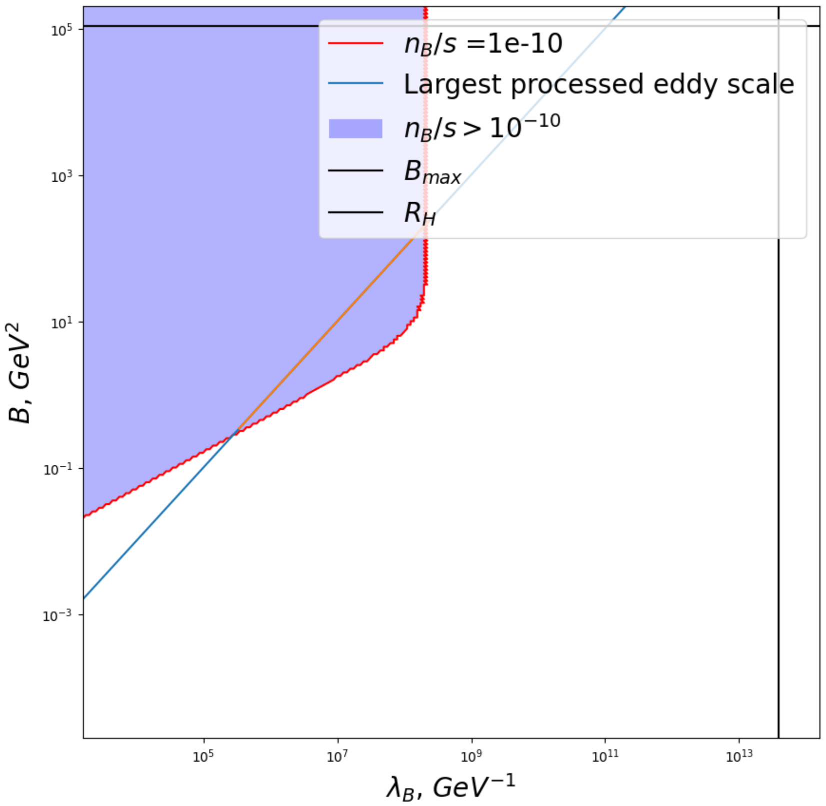
$$\eta_B = 7.3 \times 10^{-2} \frac{\frac{B_p^2}{\lambda_{B,p} T^5}}{3.5 \times 10^{-8} \frac{m_h^2(T)}{T^2} + 2.1 \times 10^{-9} \frac{v(T)^2}{T^2} + \frac{B_p^2}{T^4}}$$

Constraints in the parameters space (B,λ_B) by overproduction of baryons at the time of freeze-out.

→ 2 distincts regimes : **strong field** and **weak field**

$$\lambda_B \gtrsim \begin{cases} 10^{10} T_*^{-1} & , B \gg 5 \times 10^{-4} T_*^2 \\ 10^{10} T_*^{-1} \left(\frac{B}{5 \times 10^{-4} T_*^2} \right)^2 & , B \ll 5 \times 10^{-4} T_*^2 \end{cases}$$

However, B<B_max (equipartition with photons)



Constraint on magnetic field parameters at the time of sphaleron freeze-out T ~ 135 GeV compared to the largest processed eddy relation*

Evolution of PMF to nowadays

For a fully helical magnetic field, **helicity conservation** imposes :

$$\lambda_{B,c} B_c^2 = a^3 \lambda_{B,p} B_p^2 = \lambda_0 B_0$$

Once the **largest processed eddy scale** catches up the magnetic field correlation length, the system enters the inverse cascade process. From this point :

$$\lambda_{B,p} = v_A t = \frac{B_p}{\sqrt{\mu_0 \rho_{rad}}} t$$

We get the evolution law for the correlation length and the amplitude of a fully helical magnetic field :

$$B_p \simeq (1 \times 10^{20}\mathrm{G}) \left(\frac{T}{100\mathrm{GeV}}\right)^{7/3} \left(\frac{B_0}{10^{-14}\mathrm{G}}\right)$$

$$\lambda_B \simeq (2 \times 10^{-29}\mathrm{Mpc}) \left(\frac{T}{100\mathrm{GeV}}\right)^{-5/3} \left(\frac{\lambda_0}{1\mathrm{pc}}\right)$$

PMF and Baryogenesis

Supposing an inverse cascade process :

→ We retreive the results from 1606.08891

→ Baryogenesis from decaying hypermagnetic fields not compatible with MHD constraints

η_B_max ~

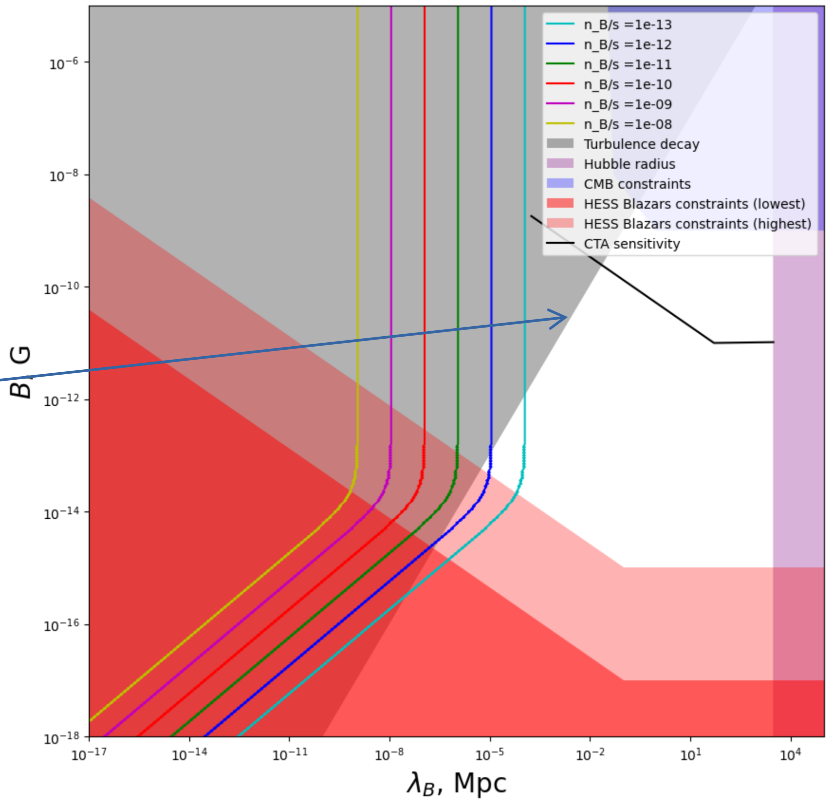
$$10^{-11}$$

$$\left(\frac{\lambda_0}{1\ \mathrm{pc}}\right) \sim \left(\frac{B_0}{10^{-14}\ \mathrm{G}}\right)$$

However if the hypermagnetic field is sourced on a fixed scale (for example from a 1st order phase transition)

→ no constraints from MHD turbulence

→ Baryogenesis can be made and current magnetic fields can satisfy the MHD constraint at the same time



Values of B, λ_B nowadays compatible with different amounts of baryon asymmetry, supposing an inverse cascade process

PMF and Baryogenesis

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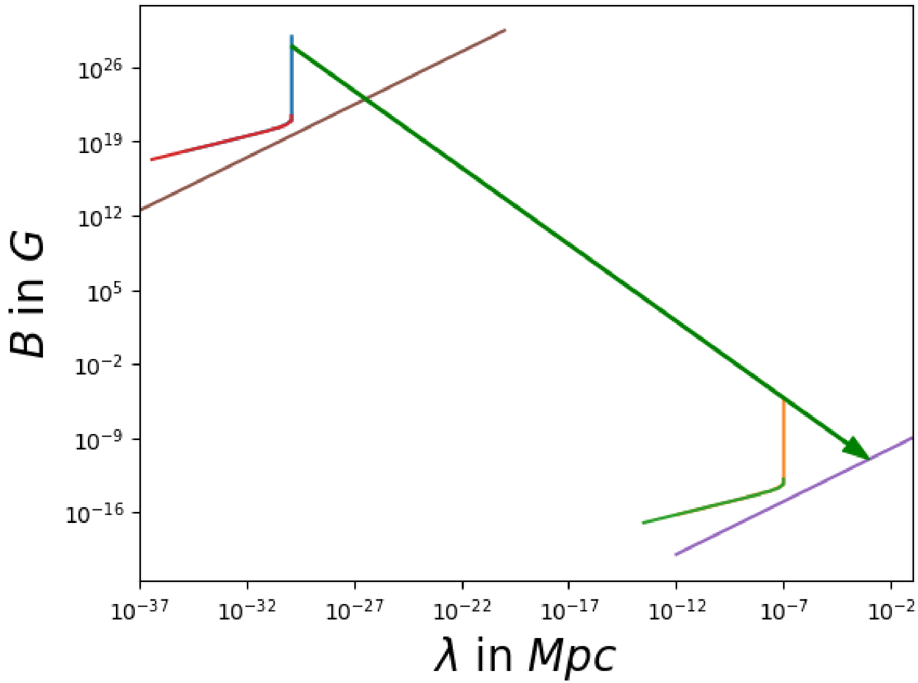


Trajectory of evolution of a magnetic field generated at EWPT- on a fixed scale

Evolution of PMF to nowadays

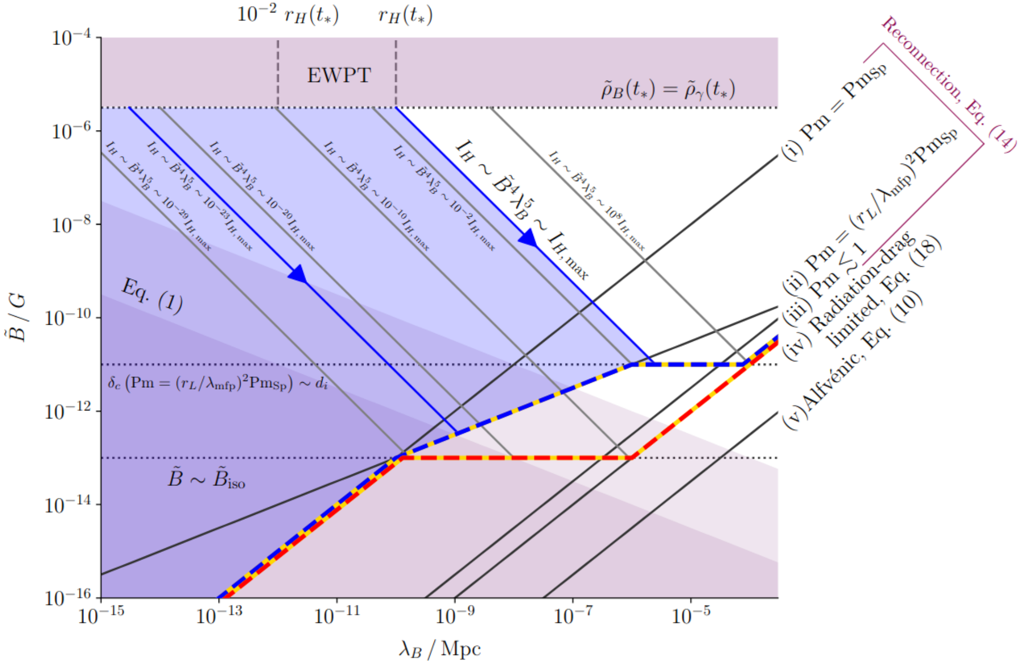
However, the alfvenic decay of magnetic field is questionable :

From 2203.03573 : reconnection seems to be the dominant process in the evolution behavior of magnetic fields.

$$\tau_{\rm rec} = (1 + {\rm Pm})^{1/2} \min\left\{S^{1/2}, S_c^{1/2}\right\} \frac{\lambda_B}{\tilde{v}_A}$$

To simplifly the situation and express our ignorance on the behavior of decaying magnetic fields we introduce the free parameter **C_rec** such that :

$$\lambda_{B,p} = C_{rec} v_A t = C_{rec} \frac{B}{\sqrt{\mu_0 \rho_{rad}}} t$$



Plot from 2203.03573 David N. Hosking and Alexander A. Schekochihin

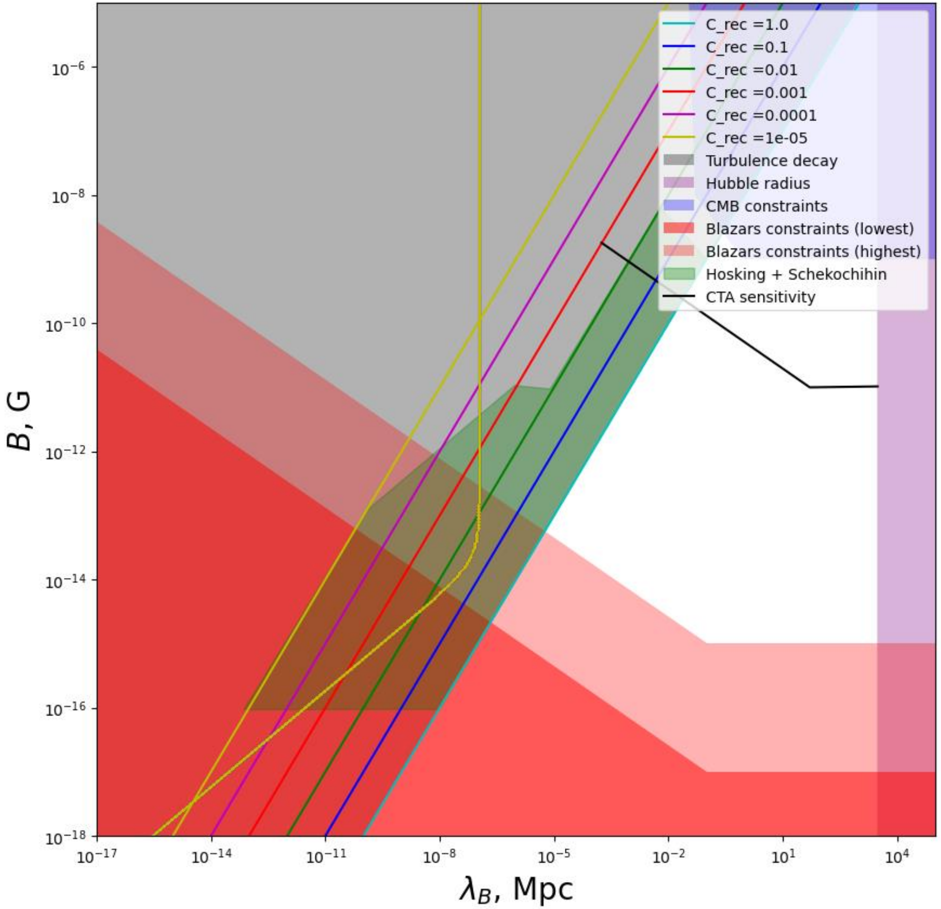
PMF and Baryogenesis

→ Range of values for **C_rec** compatible with the amount of baryon asymmetry observed

→ Intersection with plot from gives us the range of values for C_rec compatible with Hyperhelical baryogenesis and MHD evolution constraints.

→ $5 \times 10^{-4} < C_{rec} < 0.06$

Different points of compatibility between MHD evolution and baryogenesis before EWPT



PMF and Baryogenesis

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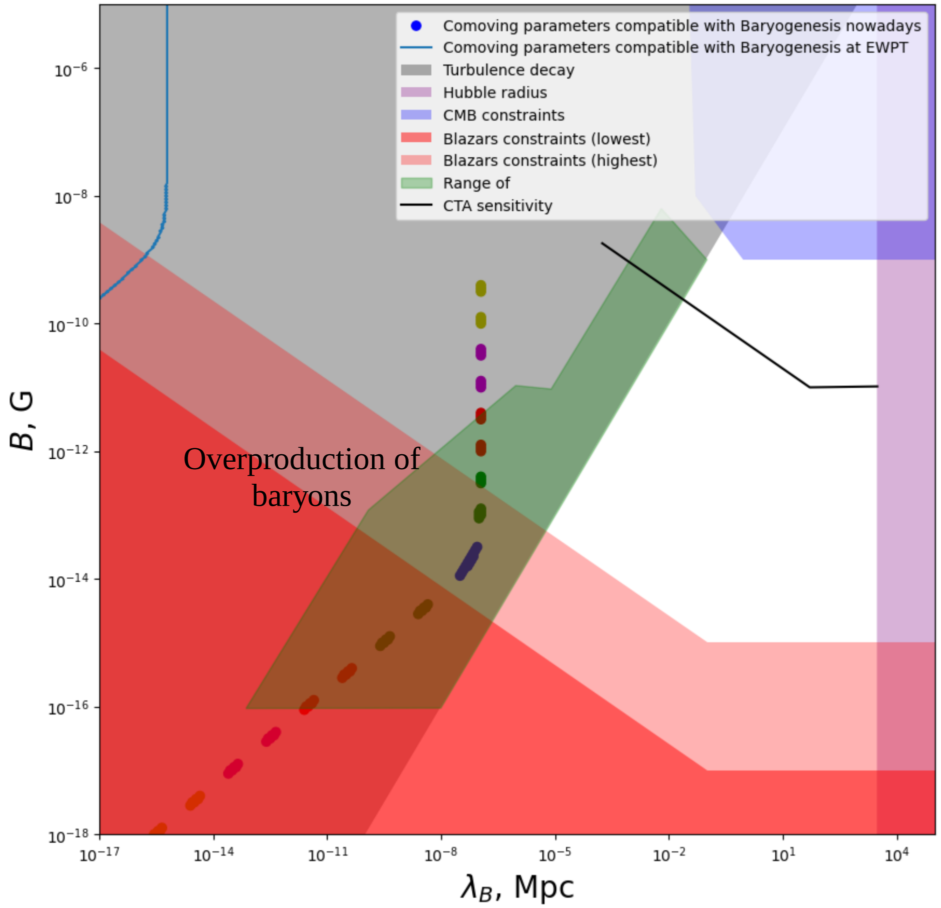
$$\rightarrow \quad 5 \times 10^{-4} < C_{rec} < 0.06$$



Different points of compatibility between MHD evolution and baryogenesis before EWPT

Isocurvature Perturbations at BBN

Baryogenesis from hyperhelical magnetic fields can be inhomogeneous.

Locally we have :

$$\eta_B = \eta_B(\mathbf{r}) = \eta_L(\mathbf{r}) \approx \frac{11}{37}\frac{\mathcal{S}_{\rm em}(\mathbf{r})}{\gamma_{\rm emE}^{\rm CME}(\mathbf{r})}$$

$$\mathcal{S}_{\rm em}(\mathbf{r}) = \frac{\alpha_{\rm em}}{\pi\sigma_{\rm em} sT}\vec{B}_p \cdot \vec{\nabla} \times \vec{B}_p(\mathbf{r})$$

$$\gamma_{\rm em}^{\rm CME}(\mathbf{r}) = \frac{12}{\pi^2}\alpha_{\rm em}^2 \frac{\vec{B}_p \cdot \vec{B}_p(\mathbf{r})}{\sigma_{\rm em} T^3}$$

So finally :

$$\eta_B(r) = \mathcal{F}\frac{\vec{B}_p \cdot \vec{\nabla} \times \vec{B}_p}{B_p^2}$$

We are interested in spatial fluctuations of η_B(r), following 9710234 (M. Giovannini, M. E. Shaposhnikov) 2012.14435 (K. Kamada, F. Uchida, J. Yokoyama) :

$$\langle \eta_B(\vec{x})\eta_B(\vec{x}+\vec{r})\rangle = \mathcal{F}^2 \left\langle \frac{\vec{B}_p \cdot \nabla \times \vec{B}_p}{B_p^2}(\vec{x}) \frac{\vec{B}_p \cdot \nabla \times \vec{B}_p}{B_p^2}(\vec{x}+\vec{r}) \right\rangle$$

Isocurvature Perturbations at BBN

A recent constraint at 2σ on isocurvature perturbations at BBN was presented by K. Inomata, M. Kawasaki, A. Kusenko, L. Yang in 1806.00123 such that :

$$\overline{S^2_{B,\mathrm{BBN}}(\boldsymbol{x})} < 0.016 \quad (2\sigma)$$

$$\langle y_d \rangle = 18.754 - 1534.4\,\bar{\omega}_B + 48656\,\bar{\omega}_B^2 - 552670\,\bar{\omega}_B^3 + (48656\,\bar{\omega}_B^2 - 1658010\,\bar{\omega}_B^3)\,\langle S_B^2 \rangle,$$

→ **constrained by Deuterium production** that depends on iscoruvature perturbations to the 2nd order

We introduce the function

$$S_B(\vec{x}) = \frac{\delta\eta_B(\vec{x})}{\overline{\eta}_B}$$

with

$$\delta\eta_B = \eta_B(\vec{x}) - \overline{\eta}_B$$

Taking into account the **neutron diffusion** between EWPT and recombination

where D=3/2 **comoving neutron diffusion length**

$$\overline{S^2_{B,\mathrm{BBN}}} = \int \frac{d^3k}{(2\pi)^3} e^{-\frac{k^2}{2D}} \mathcal{G}(\vec{k})$$

Where $\mathcal{G}(\vec{k})$ is the Fourier transform of

$$\mathcal{G}(\vec{r}) = \langle S_B(\vec{x}) S_B(\vec{x}+\vec{r}) \rangle = \frac{\langle \eta_B(\vec{x})\eta_B(\vec{x}+\vec{r}) \rangle}{\overline{\eta}_B^2} - 1$$

Isocurvature Perturbations at BBN

We can express the magnetic field spectrum such as : $\left\langle B_i^*(\vec{k}) B_j(\vec{k}')\right\rangle = (2\pi)^3 \delta^3\left(\vec{k}-\vec{k}'\right) \tilde{\mathcal{F}}_{ij}^B(\vec{k})$

With $\tilde{\mathcal{F}}_{ij}^B(\vec{k}) = P_{ij}(\vec{k}) \tilde{S}^B(k) + i\epsilon_{ijm} k_m \tilde{A}^B(k)$ $A^B(k) = \epsilon S^B(k)$ fraction

We assume that PMF are **not responsible** of the baryon asymmetry of the Universe. (for now)
Inserting this expression in the isocurvature fluctuation equation :

$$\begin{aligned}
\overline{S_{B,\mathrm{BBN}}^2} = \frac{\mathcal{C}^2}{4\pi^4 \bar{\eta}_B^2} \int dk_1 dk_2 k_1^2 k_2^2 S^B(k_1) S^B(k_2) \\
\left\{ \frac{(k_1+k_2)^2}{2}(1+\epsilon^2)\frac{D}{k_1k_2}\left(1-\frac{D}{k_1k_2}\right) + \left[\frac{k_1^2+k_2^2}{2}+\epsilon^2 k_1 k_2\right]\left(\frac{D}{k_1k_2}\right)^3 \right\} \exp\left[-\frac{(k_1-k_2)^2}{2D}\right] \\
-\left\{ \frac{(k_1-k_2)^2}{2}(1-\epsilon^2)\frac{D}{k_1k_2}\left(1+\frac{D}{k_1k_2}\right) + \left[\frac{k_1^2+k_2^2}{2}+\epsilon^2 k_1 k_2\right]\left(\frac{D}{k_1k_2}\right)^3 \right\} \exp\left[-\frac{(k_1+k_2)^2}{2D}\right]
\end{aligned}$$

Isocurvature Perturbations at BBN

To evaluate the isocurvature fluctuations we need a model for the magnetic field spectrum.

As in 2012.14435 we use a delta function model such that :

$$S^B(k) = \pi^2 \frac{B_0^2}{k_B^2} \delta\left(k - k_B\right)$$

where k_B is the wavenumber of the magnetic field.

By inserting this into the expression of the isocurvature fluctuations we get :

$$\langle S^2_{B,\mathrm{BBN}} \rangle = \frac{(1+\epsilon^2)}{4\bar{\eta}_b^2 T_*^2} \left[D\left(1 - \frac{D}{k_B^2}\right) + k_B^2 \left(\frac{D}{k_B^2}\right)^3 \left(1 - \exp\left[-\frac{2k_B^2}{D}\right].\right)\right]$$

Isocurvature Perturbations at BBN

In the approximation where $k_B^2 \gg D$

$$\langle S^2_{B,\mathrm{BBN}} \rangle \simeq \frac{(1+\epsilon^2)}{4\bar{\eta}_b^2 T_*^2 \lambda_n^2} \sim 10^{-11}(1+\epsilon^2)$$

→ Well below the current constraint $\overline{S^2_{B,\mathrm{BBN}}(\boldsymbol{x})} < 0.016 \quad (2\sigma)$

However interesting tool : also works for non helical magnetic fields → average helicity 0 but local helicity may vary

→ **constraints on the helicity fraction** of the field if this one is responsible for baryogenesis

Be carefull : magnetic helicity != current helicity ! Although maybe same sign … (A. J. B. Russell and al. (2019))

+ Non-helical fields evolution (Hosking integral etc.)

Current investigations

2012.14435 , 9707513 , T.Vashaspati (1991) …

→ Additional contribution during (2nd order / crossover) EWPT ? Term due to varying Weinberg angle ? Magnetic fields generated from Higgs gradients ?

→ Simulations of the EWPT through a toy model in the Cosmolattice code