Leptogenesis and baryon asymmetry in the early Universe for the case arbitrary hypermagnetic helicity

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Astrophysical origin (A) vs Cosmological one (B)

(A) Seed fields are produced during epoch of galaxy formation, or ejected by first supernovae or active galactic nuclei.

(A) Seed field might originate from much earlier epoch of the Universe expansion: inflation epoch, phase transitions in radiation epoch.

We consider a second scenario

Bounds on cosmological magnetic fields (t_{now})

Upper bound:

1) $\boxed{B < 10^{-9} - 10^{-10}\ G}$ (Ruzmaikin & Sokoloff, 1977) from Faraday RM (subtracting Milky Way contribution), $L \gg L_{gal}$;

2) $\boxed{B < 10^{-8} - 10^{-9}\ G}$ (Barrow, Ferreira, Silk, 1997) from CMB anisotropy + uniform field at the start t_{rec}.

Lower bound:

$\boxed{B > 10^{-16}\, G \quad \text{if} \quad \lambda_B \ll D_e}$

$\boxed{B > 10^{-18}\, G \quad \text{if} \quad \lambda_B \gg D_e}$ (Neronov , D. Semikoz, 2009)
(Neronov , Vovk, 2010)

Maxwell equations for hypercharge fields E_Y and B_Y in hot plasma at $T >> T_{EW}$

$$\nabla \cdot \mathbf{B}_Y = 0,$$

$$\nabla \cdot \mathbf{E}_Y = 0,$$

$$\frac{\partial \mathbf{B}_Y}{\partial t} = -\nabla \times \mathbf{E}_Y,$$

$$-\frac{\partial \mathbf{E}_Y}{\partial t} + \nabla \times \mathbf{B}_Y = \mathbf{J}^Y(\mathbf{x}, t) - \frac{g'^2 \mu_{eR}}{4\pi^2}\mathbf{B}_Y =$$
$$= \sigma_{cond}\left[\mathbf{E}_Y + \mathbf{V} \times \mathbf{B}_Y + \alpha_Y \mathbf{B}_Y\right]$$

where $\alpha_Y = -g'^2 \mu_{eR}/4\pi^2 \sigma_{cond}$ and we used Ohm law

$$\mathbf{J}_Y/\sigma_{cond} = \mathbf{E}_Y + \mathbf{V} \times \mathbf{B}_Y$$

Hypermagnetic fields & Baryon asymmetry

[M. Dvornikov & V.S. (2012)]

We consider temperature cooling at $T_{RL} > T \geq T_{EW}$ before EWPT while after chirality flip rate becomes faster than Hubble expansion, $\Gamma_{RL} \sim T > H \sim T^2$. Left electrons and neutrinos enter equilibrium through Higgs decays, $\bar{e}_R e_L \leftrightarrow \varphi^{(0)}$, and Abelian anomalies $(e \to g^{'} Y_a/2)$:

$$\frac{\partial j^{\mu}_{eR}}{\partial x^{\mu}} = +\frac{g^{'2}\mathbf{Y}_R^2}{64\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} = \frac{g^{'2}}{4\pi^2}(\mathbf{E}_Y \mathbf{B}_Y), \quad Y_R = -2,$$

$$\frac{\partial j^{\mu}_{eL}}{\partial x^{\mu}} = -\frac{g^{'2}\mathbf{Y}_L^2}{64\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} = -\frac{g^{'2}}{16\pi^2}(\mathbf{E}_Y \mathbf{B}_Y), \quad Y_L = -1,$$

Hypermagnetic fields & Baryon asymmetry at EWPT

(V.S., D.D. Sokoloff, J.W.F. Valle, 2009)

As Kuzmin, Rubakov & Shaposhnikov (1985, 1987) for BAU generated at EWPT, or BAU generation by electroweak reprocessing of an earlier lepton asymmetry as proposed by Fukugita & Yanagida (1986) and initial BAU stored in e_R (Campbell, Davidson, Ellis, Olive, 1993) we rely on Abelian anomaly for e_R (Shaposhnikov,Joice, Giovannini, 1997, 1998):

$$\partial_\mu j^\mu_{eR} = -\frac{g'^2}{16\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu},$$

that means

$$\frac{\mathrm{d}L_{eR}}{\mathrm{dt}} = -\frac{g'^2}{4\pi^2 s}\mathbf{E_Y}\cdot\mathbf{B}_Y,$$

$$2\frac{\mathrm{d}L_{eL}}{\mathrm{dt}} = -\frac{\mathrm{d}L_{eR}}{\mathrm{dt}} + \frac{1}{3}\dot{B}.$$

Kinetic equations for leptons

For simplicity we neglect Higgs boson asymmetry, $n_{\varphi^{(0)}} = n_{\bar{\varphi}^{(0)}}$, then only inverse decays contribute.

$$\frac{\mathrm{d}L_{eR}}{\mathrm{d}t} = \frac{g'^2}{4\pi^2 s}\mathbf{E}_{\mathrm{Y}} \cdot \mathbf{B}_{\mathrm{Y}} + 2\Gamma_{\mathrm{RL}}\left(L_{eL} - L_{eR}\right),$$

for inverse decays $e_R\bar{e}_L \to \tilde{\varphi}^{(0)}$, $e_R\bar{\nu}_{eL} \to \varphi^{(-)}$,

$$\frac{\mathrm{d}L_{eL}}{\mathrm{d}t} = -\frac{g'^2}{16\pi^2 s}\mathbf{E}_{\mathrm{Y}} \cdot \mathbf{B}_{\mathrm{Y}} + \Gamma_{\mathrm{RL}}\left(L_{eR} - L_{eL}\right),$$

for $\bar{e}_R e_L \to \varphi^{(0)}$ and

$$\frac{\mathrm{d}L_{\nu_{eL}}}{\mathrm{d}t} = -\frac{g'^2}{16\pi^2 s}\mathbf{E}_{\mathrm{Y}} \cdot \mathbf{B}_{\mathrm{Y}} + \Gamma_{\mathrm{RL}}\left(L_{eR} - L_{eL}\right)$$

for $\bar{e}_R\nu_{eL} \to \varphi^{(+)}$

Lepton asymmetry evolution

$$L_e(\eta)=(n_e - n_{\tilde{e}})/s \approx T^3\xi_e(\eta)/6s$$

$$\begin{aligned}
\frac{d\xi_{eR}(\eta)}{d\eta} &= -\frac{3\alpha^{'}}{\pi}\int d\tilde{k}\frac{d\tilde{h}_Y(\tilde{k},\eta)}{d\eta} - \Gamma[\xi_{eR}(\eta)-\xi_{eL}(\eta)], \\
\frac{d\xi_{eL}(\eta)}{d\eta} &= +\frac{3\alpha^{'}}{4\pi}\int d\tilde{k}\frac{d\tilde{h}_Y(\tilde{k},\eta)}{d\eta} - \frac{\Gamma(\eta)}{2}[\xi_{eL}(\eta)-\xi_{eR}(\eta)] \\
&\quad -\frac{\Gamma_{sph}}{2}\xi_{eL}(\eta),
\end{aligned} \tag{1}$$

where $\Gamma_{sph} = C\alpha_W^5 = C(3.2\times 10^{-8})$ is the sphaleron transition probability, $\alpha_W = g^2/4\pi$; $\quad \alpha^{'} = g^{'2}/4\pi$

$$\Gamma(\eta) = \left(\frac{242}{\eta_{EW}}\right)\left[1-\left(\frac{\eta}{\eta_{EW}}\right)^2\right], \quad \eta_{RL} < \eta < \eta_{EW} \tag{2}$$

Hypermagnetic helicity density evolution at $T_{RL} \geq T \geq T_{EW}$

$$\tilde{h}_Y(\tilde{k},\eta) = \frac{\tilde{k}^2 a^3}{2\pi^2 V}\tilde{\mathbf{Y}}(\tilde{k},\eta)\cdot\tilde{\mathbf{B}}_Y^*(\tilde{k},\eta), \qquad \tilde{\mathbf{Y}} = a\mathbf{Y}, \quad \tilde{k} = ka = const,$$

$$\tilde{\rho}_{B_Y}(\tilde{k},\eta) = \frac{\tilde{k}^2 a^3}{4\pi^2 V}\tilde{\mathbf{B}}_Y(\tilde{k},\eta)\cdot\tilde{\mathbf{B}}_Y^*(\tilde{k},\eta), \qquad \tilde{\mathbf{B}}_Y = a^2\mathbf{B}_Y$$

For the maximum helicity $\tilde{h}_Y(\tilde{k},\eta) = 2\tilde{\rho}_{B_Y}(\tilde{k},\eta)/\tilde{k}$:

$$\frac{d\tilde{h}_Y(\tilde{k},\eta)}{d\eta} = -\frac{2\tilde{k}^2\tilde{h}_Y(\tilde{k},\eta)}{\sigma_c} + \left(\frac{2\alpha'[\xi_{eR}(\eta) + \xi_{eL}(\eta)/2]\tilde{k}}{\pi\sigma_c}\right)\tilde{h}_Y(\tilde{k},\eta)$$

Arbitrary helicity density

$$\frac{d\tilde{h}_Y\left(\tilde{k},\eta\right)}{d\eta} = -\frac{2\tilde{k}^2}{\sigma_c}\tilde{h}_Y\left(\tilde{k},\eta\right) + \frac{4\alpha'}{\pi\sigma_c}\Xi_{eR}\left(\eta\right)\cdot\rho_{B_Y}\left(\tilde{k},\eta\right)$$

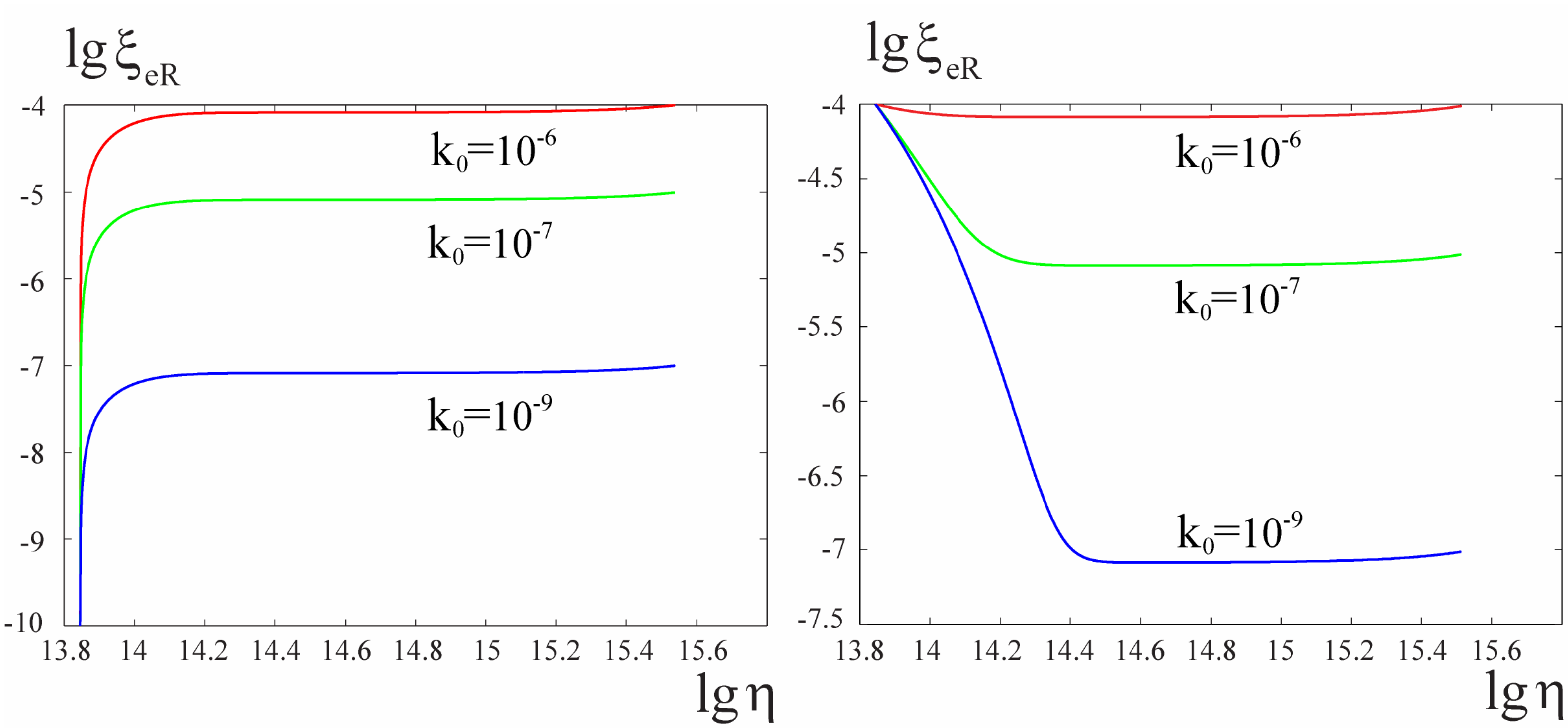
$$\frac{d\rho_{B_Y}\left(\tilde{k},\eta\right)}{d\eta} = -\frac{2\tilde{k}^2}{\sigma_c}\rho_{B_Y}\left(\tilde{k},\eta\right) + \frac{\alpha'}{\pi\sigma_c}k^2\cdot\Xi_{eR}\left(\eta\right)\cdot\tilde{h}_Y\left(\tilde{k},\eta\right)$$

$$\Xi_{eR}\left(\eta\right) = \xi_{eR}\left(\eta\right) + \frac{1}{2}\xi_{eL}\left(\eta\right)$$

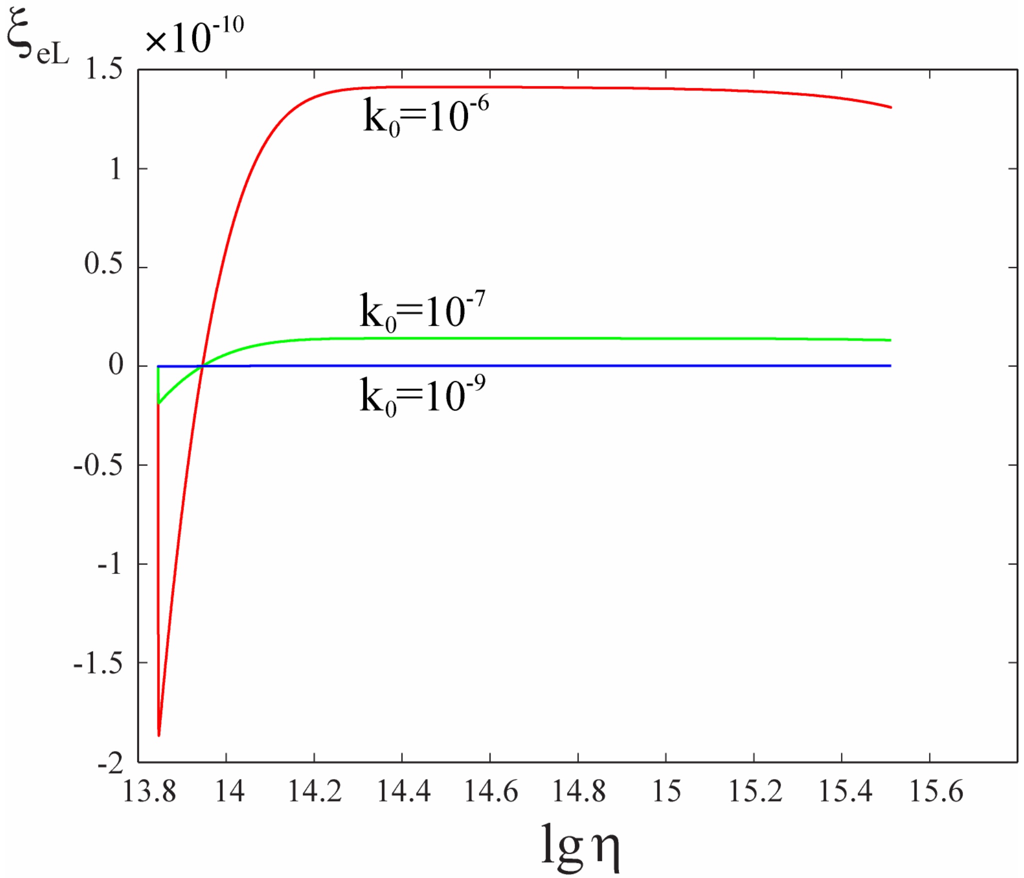
$$\tilde{h}_Y\left(\tilde{k},\eta\right) = q\cdot 2\rho_{B_Y}\left(\tilde{k},\eta\right)/k$$

Right electron asymmetry, $\xi_{eR}(T)=\mu_{eR}/T$, $T_{RL} \geq T \geq T_{EW}$

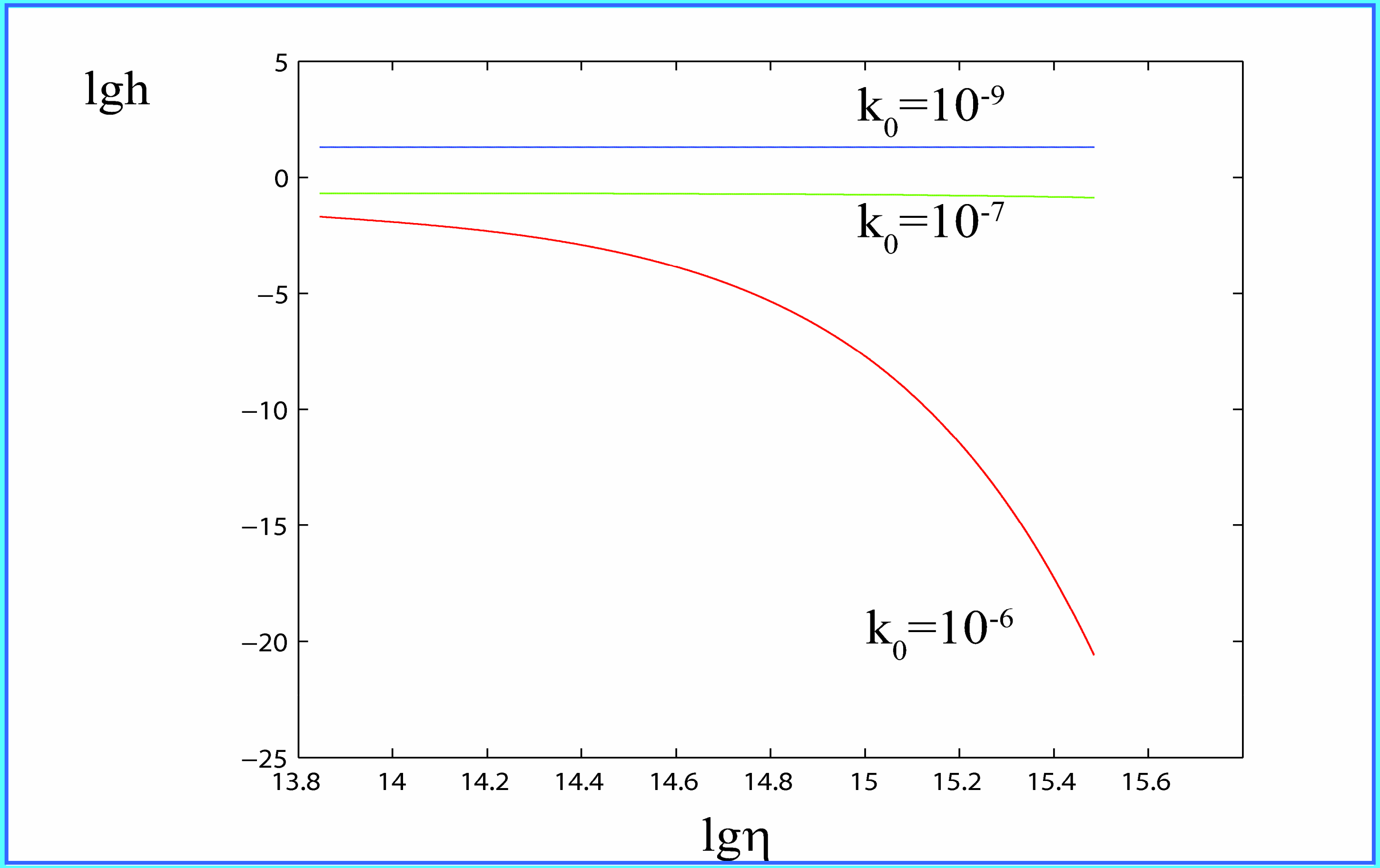
Left panel: $\xi_{eR}(\eta_0)=10^{-10}$, Right panel: $\xi_{eR}(\eta_0)=10^{-4}$



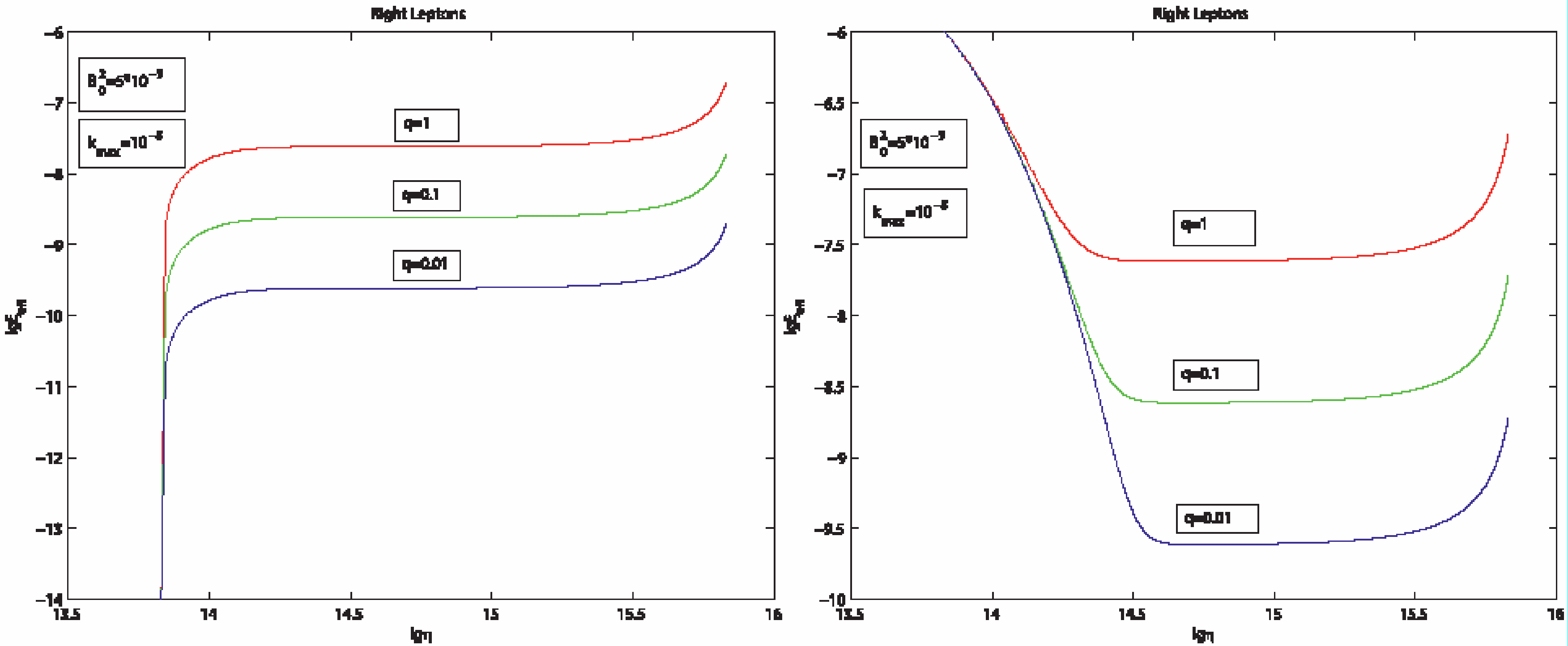
Left electron asymmetry before EWPT, $T_{RL} \geq T \geq T_{EW}$



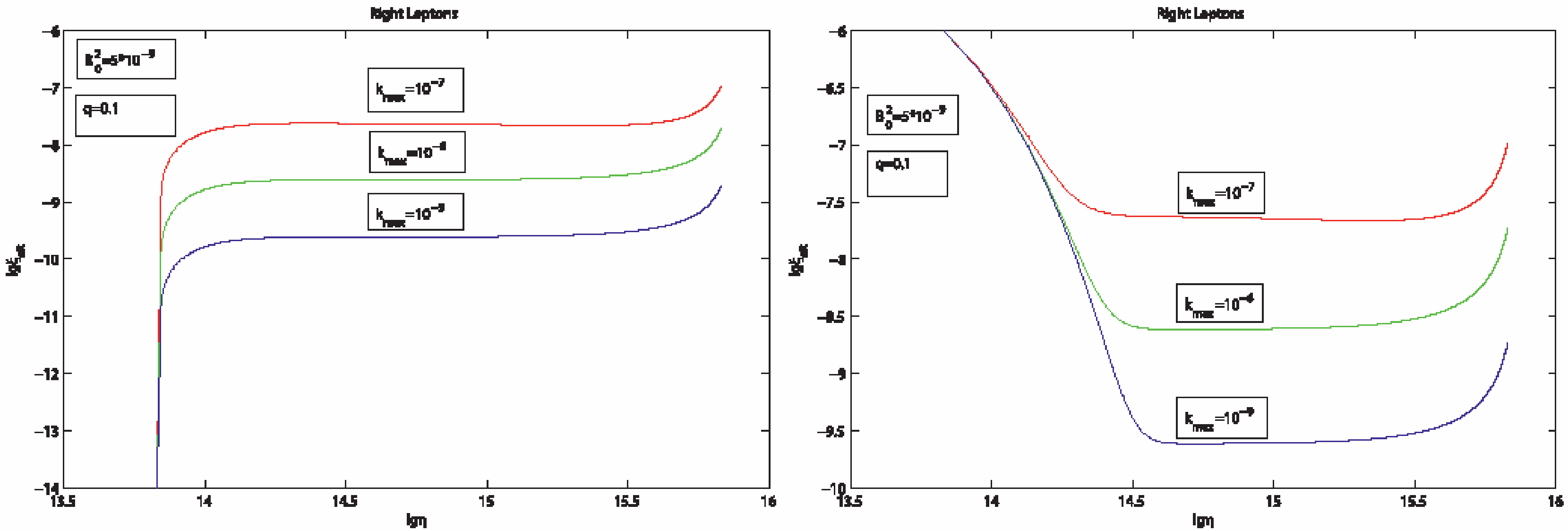
Hypermagnetic helicity density, monochromatic spectrum, $h = h_Y(k_0,\eta)/h_Y(k_0,\eta_0)$



Right lepton asymmetry evolution for arbitrary helicity and same k_{max}

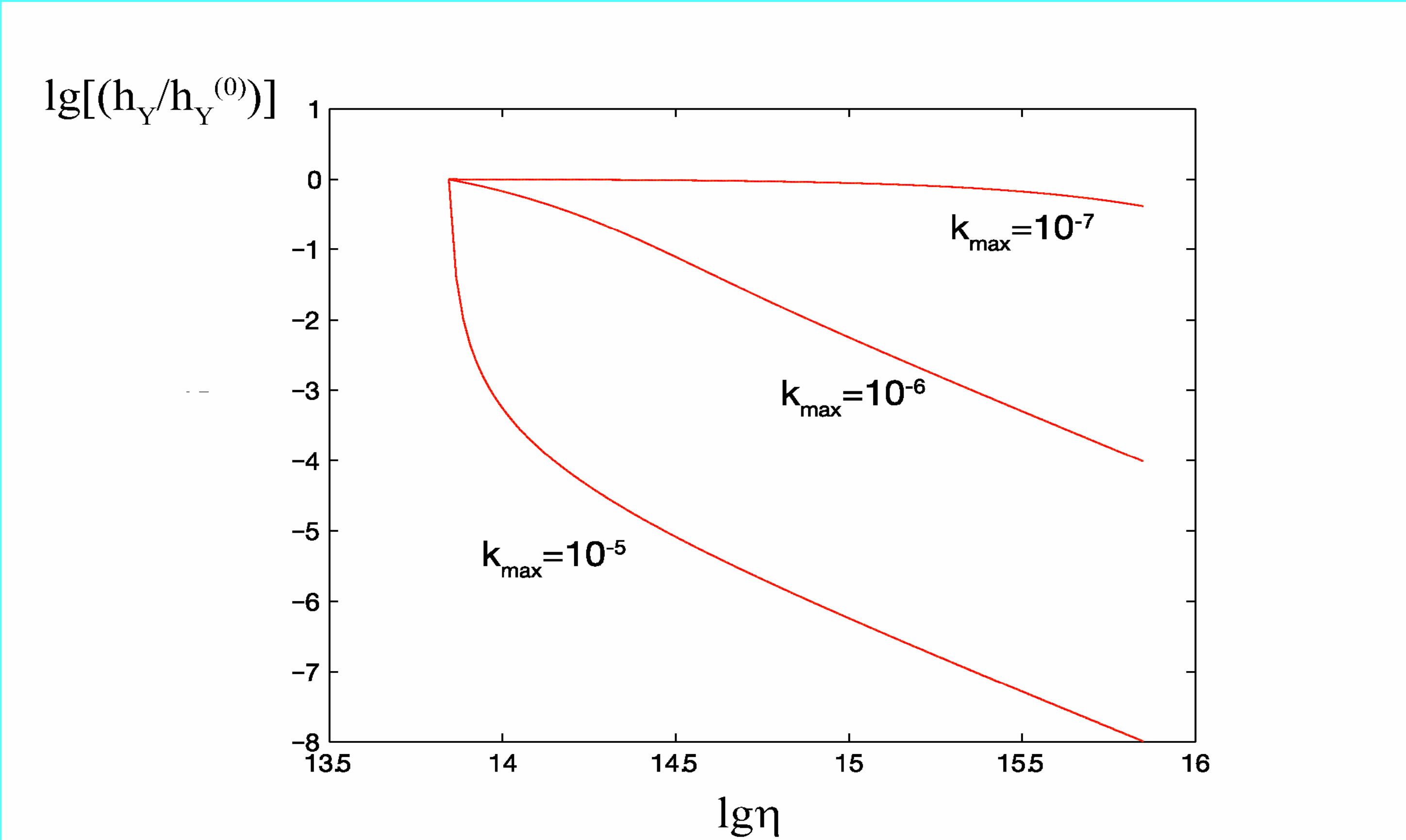


Right leptons evolution for arbitrary helicity and same q



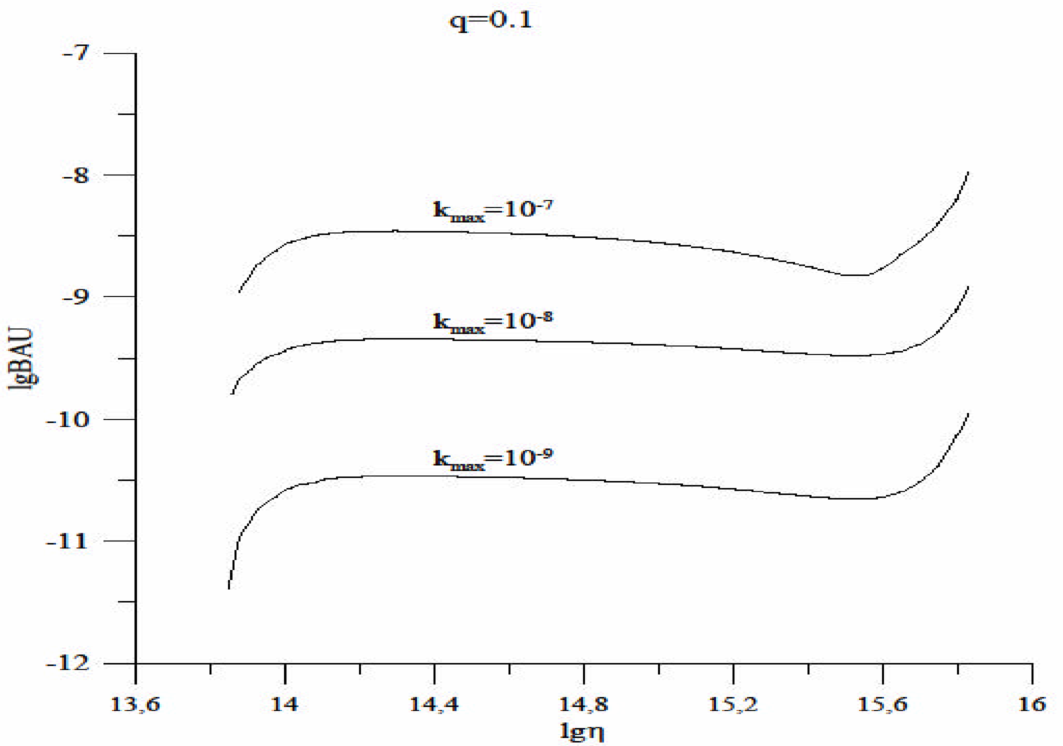
Hypermagnetic helicity density, continuous spectrum, $0 \le k \le k_{max}$

$h_Y(k,\eta_0)=C_1 k^n,\ \ n \ge 3$

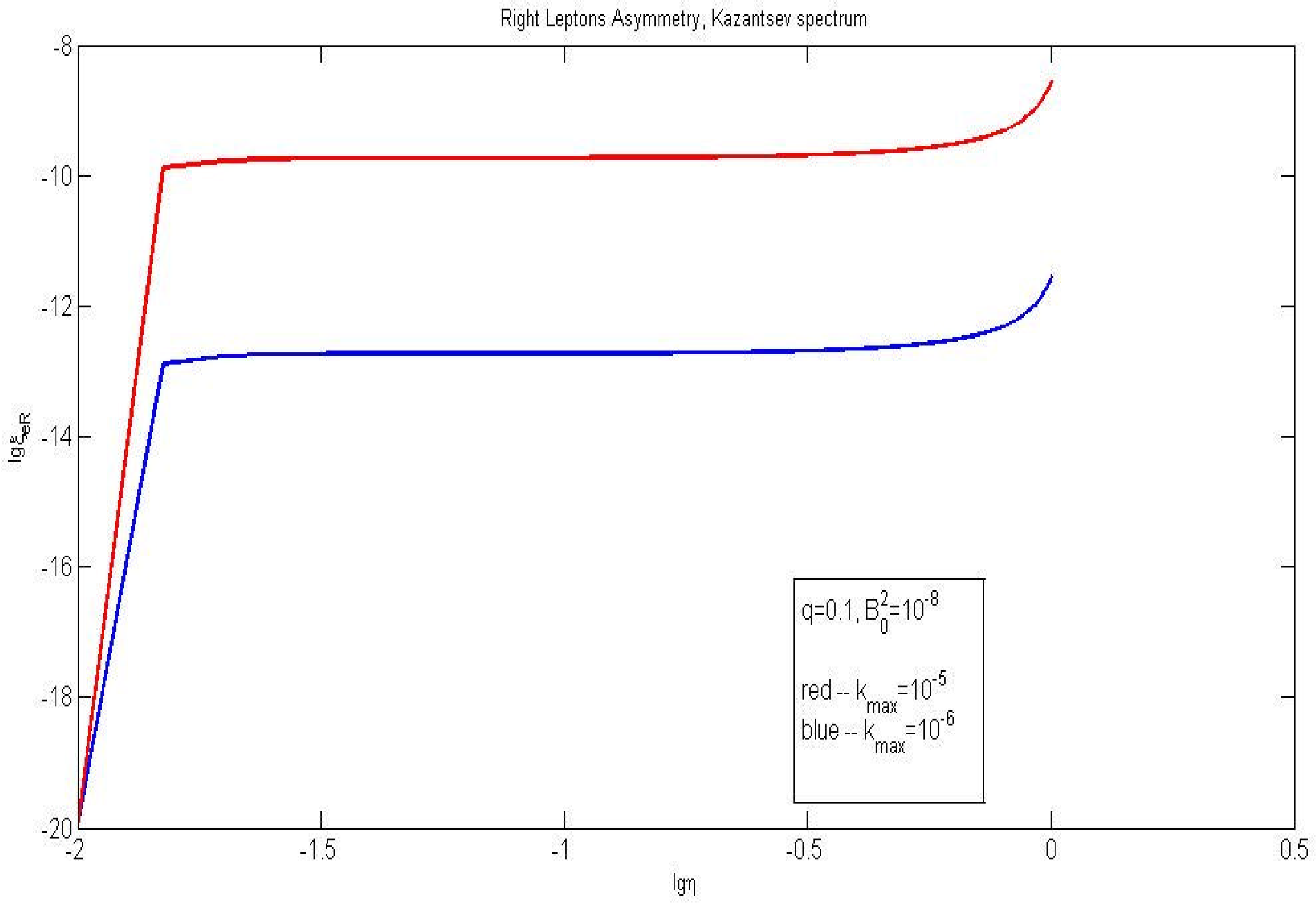


Baryon Asymmetry of Universe

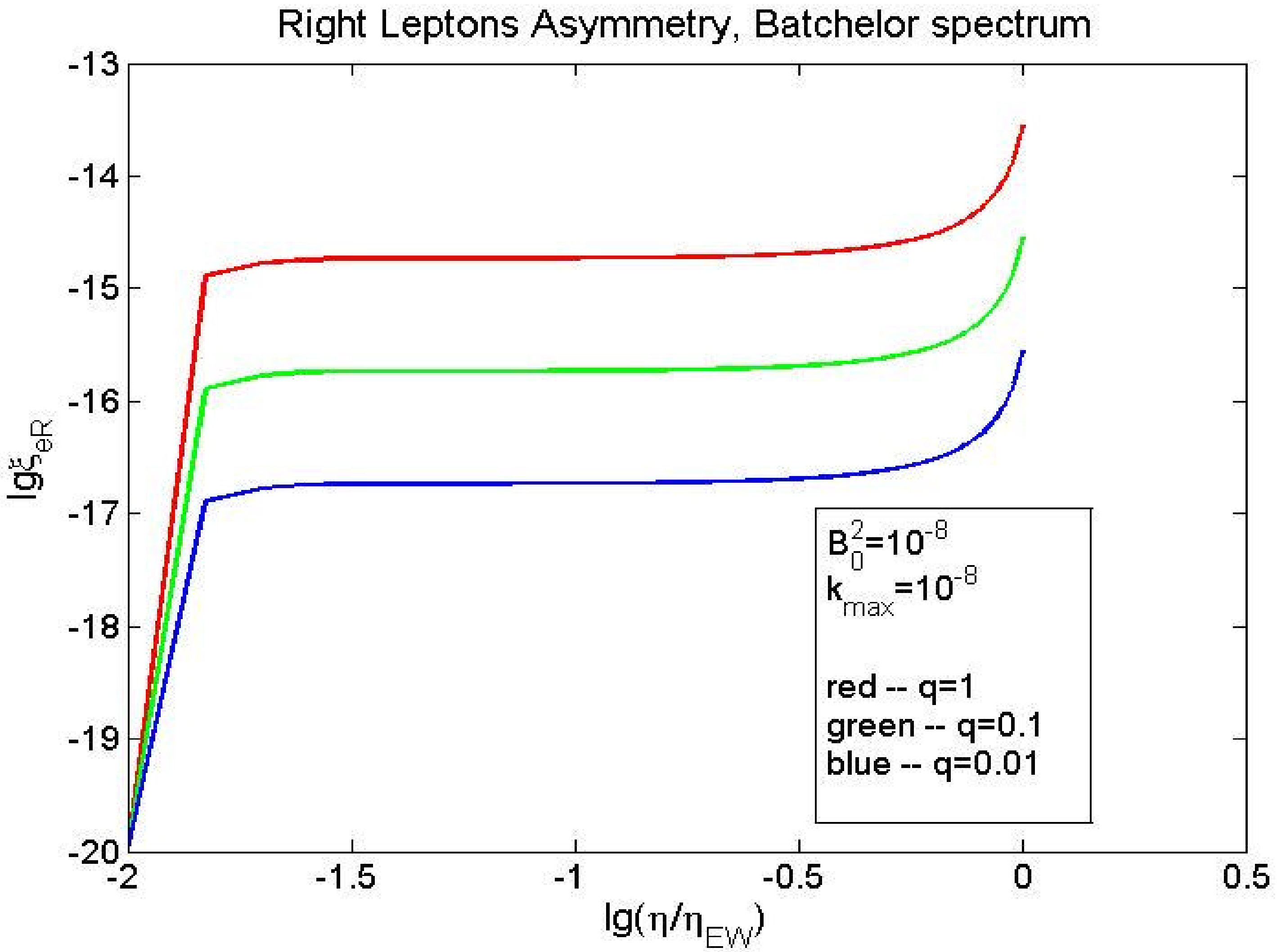
$$B(\eta)=5.3\cdot 10^{-3}\int_{\eta_0}^{\eta} d\eta\left\{\frac{d\xi_{eR}}{d\eta}+\Gamma(\eta)\cdot(\xi_{eR}-\xi_{eL})\right\}-\frac{6\cdot 10^{-7}}{\eta_{EW}}\int_{\eta_0}^{\eta}\xi_{eL}\,d\eta$$



Kazantsev spectrum



Batchelor spectrum



Summary

- The right electron asymmetry (ξ_{eR}) rises soon down to T_{EW} from a negligible initial value at $T \gg T_{EW}$ up to $\xi_{eR} \sim 10^{-4}$ at $T \leq T_{EW}$. This happens due to the Abelian anomaly.

- This provides both the α^2 dynamo for $\mathbf{B_Y}$ and baryon asymmetry growth since fermion number sits in hypercharge fields.

- The initial Maxwellian field $\mathbf{B} = \mathbf{B_Y} \cos\theta_{\mathbf{W}}$ can be a seed field for galactic magnetic fields.

Thank you!