Mainz Institute for Theoretical Physics (1)

MITP Workshop "The mysterious Universe : DM, DE, cosmic magnetic fields" 29/05/2019

BARYOGENESIS WITH CHIRAL HYPERMAGNETIC FIELDS FROM AXION INFLATION

1905 xxxxx V. Domcke, EM, K. Mukaida, B. von Harling

Generate chiral magnetic fields during axion inflation, and use them to source baryogenesis at EWPT.

1) review baryogenesis at EWPT w/ chiral magnetic fields [see Kamada & Long 1606.08891 1610.03074 + Kohei's talk]

2) magnetogenesis during axion inflation [Domcke & Mukaida 1806.08769]

3) evolution from inflation to EWPT

4) results

1) BARYOGENESIS AT EWPT W/ CHIRAL MAGNETIC FIELDS

[K. Kamada & A. Long 1606.08891, 1610.03074 + Kohei's talk here]

Chiral anomaly in the SM model

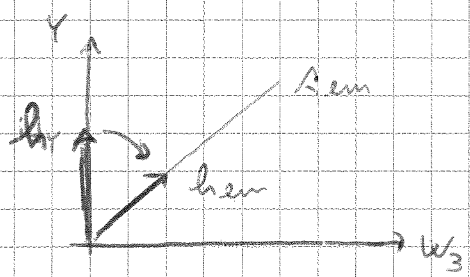
$$\Delta Q_B = \Delta Q_L = 3\left(\Delta N_{CS} - \frac{g_1^2}{16\pi^2}\,\Delta \mathcal{H}_Y\right)$$

$$h = \frac{1}{V}\mathcal{H} = \frac{1}{V}\int d^3x\, \vec{A}_Y\cdot\vec{B}_Y \qquad\qquad \vec{B}_Y = \vec{\nabla}\times\vec{A}_Y$$

$$\eta_B = \frac{\hat{n}_B}{\hat{s}} \qquad\qquad \dot{\eta}_B \approx \#\,\dot{h} - \Gamma_{\text{washout}}$$

⟶ sphalerons (Yukawas)

EWSB



before — after

$$h_Y \longrightarrow h_{em}^{after} = h_Y^{before} \Rightarrow h_Y^{after} = \cos^2\theta_W\, h_Y^{before}$$

+ similar term from the W^3

$$\dot{h}_Y \approx -2\cos\theta_W \sin\theta_W\, \dot{\theta}_W\, h_Y \qquad (+\ \dot{h}_Y \text{ suppressed by } \sigma)$$

At equilibrium ~~η_B~~ $\eta_B = 0$

Fit to lattice simulation:

$$\eta_B = \frac{17}{37}\left[(g_w^2 + g_Y^2)\, \frac{f(\theta_w, \hat{T})\, \mathcal{S}}{\gamma_{w\,sph}}\right]_{T = 135\,\mathrm{GeV}}$$

- $f(\theta_w, \hat{T}) = -\hat{T}\,\dfrac{d\theta_w}{d\hat{T}}\,\sin(2\theta_w)$
- $\gamma_{w,sph} \approx 3.3 \times 10^{-16}$
- $\mathcal{S} = \dfrac{H}{\hat{\sigma}\hat{T}}\,\dfrac{h}{8\pi^2 a^3}$

$f(\theta_w, \hat{T})$ rather uncertain

$$5.6\times 10^{-4} < f(\theta, \hat{T})\big|_{\hat{T}=136\,\mathrm{GeV}} < 0.32$$

f is the main source of uncertainty in estimating η_B.

η_B reproduced for $B_0 \sim 10^{-17}\,G$, $\lambda_0 \sim 10^{-3}\,pc$

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2) HYPER-MAGNETO GENESIS IN AXION INFLATION

[V. Domcke, K. Mukaida
1806.08769, JCAP]

Start from the action

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} + \sum_a \hat{\bar{\psi}}_a i \hat{\not{D}}_a \hat{\psi}_a \right] + \right.$$

$$\left. + \frac{\alpha}{4\pi} \frac{\phi}{f_a} \hat{F}_{\mu\nu} \hat{\tilde{F}}^{\mu\nu} \right.$$

ϕ inflaton $\qquad \alpha = \frac{g_Y^2}{4\pi}$ hypercharge fine structure constant

ψ SM fermions: e_i, L_i, u_i, d_i, Q_i, $i = 1,2,3$ (defined w/ $P_{R/L} = \frac{1 \pm \gamma_5}{2}$)

F, A $U(1)_Y$ gauge field ($\simeq U(1)_{em}$ apart from a rotation and different charges)

$\hat{}$: physical quantities (no $\hat{}$ = conformal quantities)

metric: $ds^2 = dt^2 - a^2 dx^2$

$\hat{\tilde{F}}^{\mu\nu} = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} \hat{F}_{\rho\sigma} \qquad \varepsilon^{0123} = 1$ (Levi Civita symbol)

vierbeins $e_\mu^a = a \delta_\mu^a \qquad e_a^\mu = \delta_a^\mu / a$

$$\hat{\bar{\psi}}_a i \hat{\not{D}}_a \hat{\psi}_a = \hat{\bar{\psi}}_a \hat{\gamma}^\mu \left(\partial_\mu + i g Q_a \hat{A}_\mu + \frac{1}{4} \omega_\mu^{ab} \gamma_{ab} \right) \hat{\psi}_a$$

$$= \hat{\bar{\psi}}_a \left[\hat{\gamma}^\mu \left(\partial_\mu + i g Q_a \hat{A}_\mu \right) + \frac{3}{2} a H \hat{\gamma}^0 \right] \hat{\psi}_a$$

ω_μ^{ab} spin connection

$\gamma_{ab} = \frac{1}{2} [\gamma_a, \gamma_b]$

$\{ \hat{\gamma}^\mu, \hat{\gamma}^\nu \} = 2 g^{\mu\nu}$

Fermions and vectors are conformal, ie by means of a proper rescaling (and using conformal time) they behave as in Minkowski.

$$\psi \equiv a^{3/2}\hat{\varphi}$$

$$A_\mu \equiv \hat{A}_\mu = (A_0, -\vec{A})$$

$$A^\mu = (A_0, \vec{A}) \equiv a^2 \hat{A}^\mu \quad \Big\} \quad A^\mu = \eta^{\mu\nu} A_\nu \qquad F^{\mu\nu} = \eta^{\mu\rho}\eta^{\nu\sigma}F_{\rho\sigma}$$

$$ds^2 = a^2(d\eta^2 - dx^2)$$

$$\hat{\gamma}^\mu = e^\mu_a \gamma^a = \gamma^\mu / a \qquad \{\gamma^\mu, \gamma^\nu\} = \eta^{\mu\nu} \qquad \gamma_\mu = \eta_{\mu\nu}\gamma^\nu$$

$$\Rightarrow S = \int d^4x \left\{ \sqrt{-g}\left[\frac{g^{\mu\nu}}{2}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_a(i\not{\partial} - gQ_a\not{A})\psi_a + \frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}\right\}$$

Define also $\vec{E} = -\left(\frac{\partial}{\partial\eta}\vec{A} + \vec{\nabla}A_0\right) \equiv a^2\hat{\vec{E}}$

$$\vec{B} = \vec{\nabla}\times\vec{A} \equiv a^2\hat{\vec{B}}$$

$$F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\vec{E}\cdot\vec{B} = -4a^4\hat{\vec{E}}\cdot\hat{\vec{B}}$$

Let us neglect fermions for the moment

Gauge choice: $\partial_\mu A^\mu = 0$, $A^0 = 0$, (To quantize I need Feynman gauge (g.f. $\frac{1}{\rho}\partial_\mu A^\mu$ w/ $\rho = 1$))

Fourier ~~expan~~transform

$$\vec{A} = \int \frac{d^3x}{(2\pi)^3} \sum_{\lambda=\pm} \hat{\varepsilon}^\lambda_k A^\lambda_k(\eta)\, e^{i\vec{k}\cdot\vec{x}}$$

(w/ $\vec{k}\cdot\hat{\varepsilon}^\lambda_k = 0$ $\quad \hat{\varepsilon}^{\lambda *}_k \hat{\varepsilon}^{\lambda'}_k = \delta_{\lambda\lambda'}$ $\quad \vec{k}\times\hat{\varepsilon}^\lambda_k = -i\lambda|\vec{k}|\hat{\varepsilon}^\lambda_k$ $\quad \varepsilon^{\lambda *}_k = \varepsilon^\lambda_{-k} = \varepsilon^{-\lambda}_k$

$(A^\lambda_k)^* = A^\lambda_{-k}$)

~~$\Rightarrow$ eom:~~ $\cancel{\partial_\eta^2 A_\pm + (k^2 \pm 2\lambda\xi aH)A_\pm = 0}$ ~~(when quantizing the usual subtleties appear but the eom is the same)~~

$\cancel{\lambda = \dot{\phi}/|\dot{\phi}|}$

$\cancel{\xi = \frac{\alpha\dot{\phi}}{2\pi f_a H} > 0}$

~~N/B~~ $\cancel{\xi \propto aH\xi \propto aH\frac{\dot{\phi}}{H} \approx a\dot{\phi} = \frac{\partial}{\partial\eta}\phi \Rightarrow}$ ~~the eq is conformal~~

Eom: $A_\pm'' + \left(k^2 \pm \frac{\alpha}{\pi f_a} k \phi'\right) A_\pm = 0$

in Minkowski $\eta = t$, and for $\dot\phi$ = const > 0 $\quad A_- \sim e^{\omega t}$

in de Sitter, $\dot\phi$ almost constant

$$A_\pm'' + \left(k^2 \pm \frac{2\lambda\xi}{\eta}\right) A_\pm = 0$$

(+ usual subtleties when quantizing)

$$\lambda = \dot\phi/|\dot\phi| \qquad \xi = \frac{\alpha\lambda\dot\phi}{2\pi f_a H} > 0$$

(typically $\xi \lesssim 50$)

Exact solution (matching the Bunch-Davies vacuum inside the horizon)

$$A_\pm(\eta, \vec k) = \frac{e^{\pi\xi/2}}{\sqrt{2k}} W_{\pm i\xi, \frac{1}{2}}(2ik\eta)$$

(Whittaker funct.)

On super-horizon scales it becomes constant (and exp large)

$$A_\pm(\eta, \vec k) \xrightarrow{\eta k \to 0^-} \frac{1}{\sqrt{2k}} \frac{e^{\pi\xi/2}}{\Gamma(1 \mp i\xi)} \sim e^{\pi\xi}$$

From this one can compute the fields $\vec E$, $\vec B$ and the helicity h

$$\hat h \simeq 2\lambda Q^2 \left(10^{-4} \frac{e^{\pi\xi}}{\xi^4} H^3\right)$$

$$h = a^3 \hat h$$

Also $\hat E$, $\hat B$ are constant (and so is $\hat\rho_A$)

and parallel (maximally helical field)

Correlation length $\lambda \approx aH$

<u>Fermion backreaction</u>

SM chiral anomaly: for the current

$$J_a^\mu = \bar{\psi}_a \gamma^\mu \psi_a \quad (= \bar{\psi}_a \gamma^\mu P_{L/R} \psi_a)$$

$$\Rightarrow \langle \partial_\mu J_a^\mu \rangle = - \varepsilon_a N_a \frac{g_1^2 Q_a^2}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

$$\begin{pmatrix} a = e_i, L_i, u_i, d_i, Q_i \\ N_a = 1, 2, 3, 3, 6 \\ Q_a = -1, -1/2, 2/3, -1/3, 1/6 \\ \varepsilon_a = \pm \text{ for } R/L \end{pmatrix} \Rightarrow 0 = \partial_\mu \left(J_a^\mu + \varepsilon_a \frac{N_a Q_{Y_a}^2}{2} J_{cs}^\mu \right)$$

$$\text{w/ } J_{cs}^\mu = \frac{\alpha}{\pi} \varepsilon^{\mu\nu\rho\sigma} A_\nu \partial_\rho A_\sigma$$

NB:
- γ_5 does not appear explicitly, but it's in the ε_a
- neglect $SU(2)_L$ and $SU(3)_c$ because
  - non abelian interactions suppress their production
  - after reheating quickly thermalize $\Rightarrow h \rightsquigarrow 0$
  - crucial role will be played by e_R
- neglect Yukawas. Assumption: during inflation Higgs stabilized to 0

<u>Fermion asymmetry is generated</u>

$$n_a - n_{\bar{a}} = q_a \equiv \frac{1}{V} \int d^3x \, \langle J_a^0 \rangle$$

$$= - \varepsilon_a \frac{N_a Q_a^2}{2} q_{cs}$$

$$q_{cs} = \frac{\alpha}{\pi} h \quad \longleftarrow \quad \text{helicity} \Rightarrow \text{fermion production generation}$$

How to compute the backreaction (sketch)

Energy conservation: ψ suppress the generation of B

$$\hat\rho_\phi = \frac{1}{V}\int d^3x \left\langle \frac{1}{2}\dot\phi^2 + V(\phi)\right\rangle$$

$$\hat\rho_A = \frac{1}{V}\int d^3x \, \frac{1}{2a^4}\langle \vec E^2 + \vec B^2\rangle \qquad \vec A\cdot\vec J$$

$$\hat\rho_\psi = \frac{1}{V}\int d^3x \, \frac{1}{a^4}\sum_a \langle \bar\psi_a(-i\vec\nabla\cdot\vec\gamma - gQ_a \vec A\cdot\vec\gamma)\psi_a\rangle$$

One can compute the induced vector current

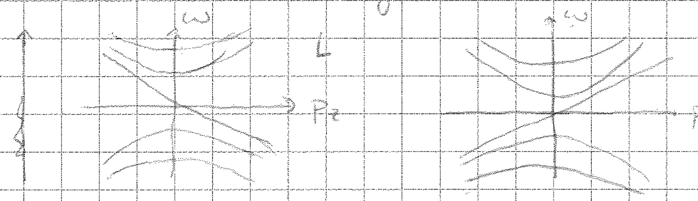
$$J^\mu = \sum_a Q_a \bar\psi_a \gamma^\mu \psi_a$$

as

$$g\langle|\hat{\vec J}|\rangle = \frac{1}{a^3} g\langle|\vec J|\rangle \simeq \sum_a N_a \frac{(g|Q_a|)^3}{12\pi^2}\coth\left(\frac{\pi\hat B}{\hat E}\right)\hat E\,\hat B\,\frac{1}{H}$$

EoM w/ external $\vec E \parallel \vec B \parallel \hat z$ $\quad (i\partial_\eta \pm \vec\nabla\cdot\vec\sigma - gQ_a A_0 \pm gQ\vec A\cdot\vec\sigma)\psi_{R/L} = 0$

Discrete Landau levels + asymmetric zero mode



The $n=0$ level leads to an asymmetry q_5.

Because q_5 can contribute to the vector current because they are multiplied $B q_5 \to (-B)(-q_5) = +$

~~and insert into the eq. for~~

and the equation for the energy density

$$\dot{\hat\rho}_A = -4H\hat\rho_A + 2\xi H\hat E\cdot\hat B - \hat E g\langle|\hat J|\rangle$$

Consistency relation: Assuming equilibrium

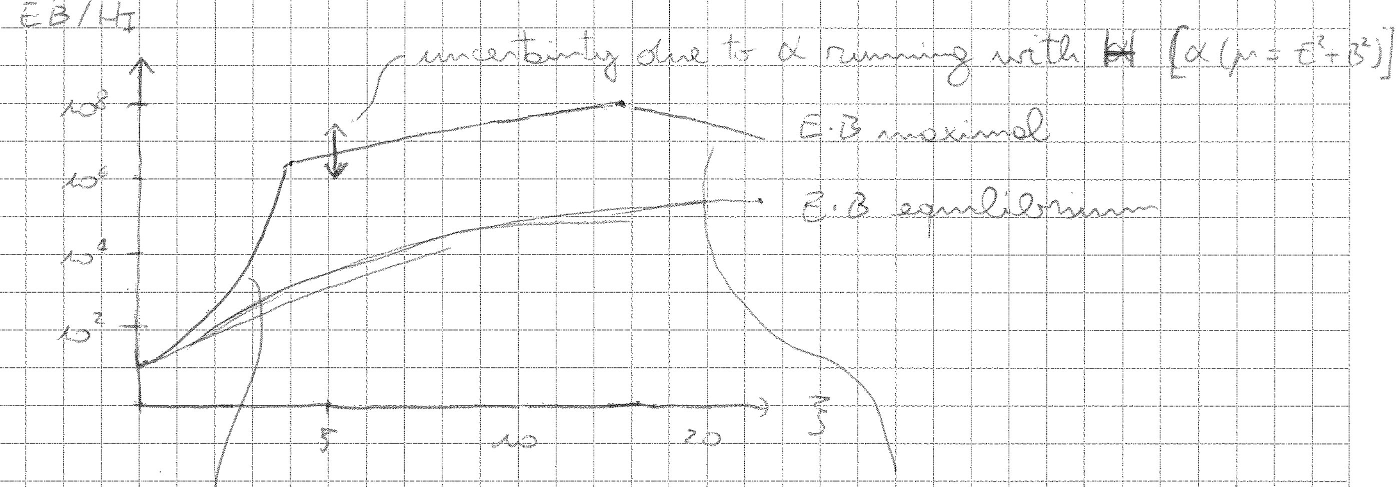
$$\dot{\hat\rho}_A = 0 \Rightarrow -2H(\hat E^2 + \hat B^2) + 2\xi_{eff} H\hat E\cdot\hat B = 0$$

w/ $$\xi_{eff} = \xi - \sum_a N_a \frac{(g|Q_a|)^3}{24\pi^2}\coth\left(\frac{\pi\hat B}{\hat E}\right)\frac{\hat E}{H}$$

This is a upper bound on $\hat{E}, \hat{B}$.

• Two estimates for $\hat{E}\cdot\hat{B}$: ~~other~~

- just take the upper bound
- ~~the~~ assume equilibrium is instantaneously reached, insert ξ_{eff} in the Whittaker function and solve self-consistently for $\hat{E}\cdot\hat{B}$



for $\xi \lesssim 4$ the "maximal" case has no backreaction

additional constraint: $(\dot{\rho}_A + \dot{\rho}_\psi) H^{-1} < \rho_\phi$

Recap: - ~~h~~ ~~amplified~~ generated by ~~...~~ CS coupling $\phi F \tilde{F}$

- fermion backreaction is important
- anomaly equation $\Rightarrow$ all charges are proportional to q_{CS} (or h) through $q_a = -\epsilon_a \frac{N_a Q_a^2}{2} q_{CS}$

$\Rightarrow$ compute q_{CS} at the end of inflation

$$\partial_t q_{CS} = -a^3 \frac{2\alpha}{\pi} \langle \hat{E}\cdot\hat{B} \rangle$$ w/ assumption $\hat{E}\cdot\hat{B} = \text{const}$, $\xi = \text{const}$

$$\Rightarrow \quad q_{CS}^{rh} = \frac{2}{3} a_{rh}^3 \frac{\alpha}{H_{rh}} \langle \hat{E}\cdot\hat{B} \rangle_{rh}$$ (assuming instantaneous RH)

3) EVOLUTION ~~of~~ AFTER INFLATION

After inflation → assume instantaneous reheating (RH in less than 1 efold for $\frac{\alpha}{f} \geq \frac{10}{M_{Pl}}$, ie $\xi \geq 4$ 1812.03132)

Follow the simultaneous evolution of h and μ_b

In the thermal plasma

$$n_a - \bar{n}_a = q_a = \frac{1}{6} N_a \mu_a T^2 \qquad \left(\text{and } q_H = \frac{2}{3}\mu_H T^2\right)$$

Achtung: notation $T = a\hat{T}$ constant for constant y_* and adiabatic exp.

Yukawa + sphalerons reshuffle μ_a's to reach chemical eq.

At $T \gtrsim 10^5$ GeV all these processes except for the ones mediated by the electron Yukawa are in equilibrium

EW sphalerons: $\sum_i (3\mu_{Q_i} + \mu_{L_i}) = 0$

strong sphalerons: $\sum_i (2\mu_{Q_i} - \mu_{u_i} - \mu_{d_i}) = 0$

up-Yukawas $\mu_{Q_i} + \mu_H - \mu_{u_j} = 0$

down-Yukawas $\mu_{Q_i} - \mu_H - \mu_{d_j} = 0$

$\Rightarrow$ $\mu_{Q_i} = \mu_Q$, $\mu_{u_i} = \mu_u$, $\mu_{d_i} = \mu_d$

leptons $\mu_{L_i} - \mu_H - \mu_{e_i} = 0 \qquad i = 2,3$

Conserved quantities: $U(1)_Y$ charge and $B-L$ $(B/3 - L_i)$

$$3(\mu_Q + 2\mu_u - \mu_d) - \sum_i (\mu_{L_i} + \mu_{e_i}) + 2\mu_H$$

$$2\mu_Q + \mu_u + \mu_d - 2\mu_{L_i} - \mu_{e_i}$$

9 independent equations for 10 variables. Can express all μ_as

$$\mu_a = \#_a \, \mu_{e_1}$$

When Y_e enters equilibrium at $T < 10^5$ GeV $\mu_{e_1} = 0$ and all asymmetries are erased.

μ_{e_1} evolves following

$$\frac{\partial \mu_{e_1}}{\partial \eta} = -\frac{3}{T^2}\frac{\partial q_{cs}}{\partial \eta} - \Gamma_{Y_e}\frac{711}{481}\mu_{e_1}$$

- $\Gamma_{Y_e} \approx 1.3\times 10^{-2}\, y_e^2\, T \qquad y_e = \frac{m_e}{v} = \frac{511\,\mathrm{keV}}{174\,\mathrm{GeV}} \approx 3\times 10^{-6}$
- $\frac{711}{481}$ comes from $y_e\, \bar{e}_1 H^\dagger L_1 \rightsquigarrow \mu_{L_1} - \mu_H - \mu_{e_1}$
- First term from the anomaly

We keep μ_{e_1} because it has an important effect for the chiral plasma instability.

Chiral MHD

Maxwell + Ohm equations

$$\frac{\partial B}{\partial \eta} + \nabla\times E = 0 \qquad \nabla\times B = J$$

$$J = \sigma(E + v\times B) + \frac{2\alpha}{\pi}\mu_{Y5} B \qquad (\text{for } \mu_5/T \ll \alpha)$$

w/
- $\sigma \approx 4.5\,\frac{T}{\alpha \ln(\alpha^{-1})} \approx 10^2\, T$
- $\sigma = a\hat{\sigma} \qquad \mu_{Y5} = a\,\hat{\mu}_{Y5}$
- $\mu_{Y5} = \sum_a \varepsilon_a N_a Q_a^2 \mu_a$ again, Q_a are hypercharges

$$\Rightarrow \frac{\partial \vec{B}}{\partial \eta} = \frac{1}{\sigma}\nabla^2\vec{B} + \vec{\nabla}\times(\vec{v}\times\vec{B}) + \frac{2\alpha}{\pi}\frac{\mu_{Y5}}{\sigma}\vec{\nabla}\times\vec{B}$$

Navier Stokes $\left[\frac{\partial\vec{v}}{\partial\eta} + (\vec{v}\cdot\vec{\nabla})\vec{v}\right] = \frac{1}{\rho+p}\left[-\frac{1}{2}\vec{\nabla}(\vec{B}^2) + (\vec{B}\cdot\vec{\nabla})\vec{B}\right] + D\nabla^2 v$

(assume incompressible fluid $\vec{\nabla}\cdot\vec{v} = 0$ $\qquad D \approx \frac{20}{T}$

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Different effects: - diffusion dissipates h
- turbulence $\rightsquigarrow$ scaling regime $\rightsquigarrow$ conserved h
- chiral plasma instability $\rightsquigarrow$ partially cancels h

Neglect CME for the moment

- diffusion : timescale $\eta_d \sim \sigma L^2 \sim \frac{\sigma}{(aH)^2} \Rightarrow \hat{T}_{dif} \sim \frac{H_{reh}}{100}$

- Avoid exponential diffusion

$$\frac{v \cdot B}{L} > \frac{B}{\sigma L^2} \Leftrightarrow R_m = (\sigma L v)\big|_{reh} > 1$$

To impose this condition we need ~~to impose~~ an ansatz for v

* <u>Equipartition</u> : $\rho v^2 \sim B^2$

Require $(\vec{v}\cdot\vec{\nabla})\vec{v} > \nu \nabla^2 \vec{v}$ ie $R_k = \frac{Lv}{\nu}\Big|_{reh} > 1$

$\Rightarrow$ B eq. $\partial_\eta B \sim \frac{vB}{L} \propto B^2$

$$B(\eta) \sim \left(\frac{\eta_t}{\eta}\right)^{\frac{1}{3}} B(\eta_t) \qquad L(\eta) \sim \left(\frac{\eta}{\eta_t}\right)^{2/3} L(\eta_t) \qquad v(\eta) \sim \left(\frac{\eta_t}{\eta}\right)^{1/3} v(\eta_t)$$

$h \sim L B^2 \sim$ const

<u>But</u> $R_k > 1$ is not realized in our parameter space

$\Rightarrow$ assuming equipartition right after ~~for~~ reheating is <u>inconsistent</u>

* a different scaling

v from balancing diffusion and source term

$$\nu \nabla^2 v \sim \frac{1}{p+\rho}\left(-\frac{1}{2}\vec{\nabla}B^2 + (\vec{B}\cdot\vec{\nabla})\vec{B}\right)$$

$$\frac{\nu v}{L^2} \sim \frac{B^2}{L\rho}$$

$$\boxed{R_m \sim \frac{\sigma L^2 B^2}{\nu\rho}} \Leftarrow v \sim \frac{L B^2}{\nu\rho} \Leftrightarrow \rho v^2 \sim R_k B^2 < B^2$$

$$\rightsquigarrow \partial_\eta B \sim \frac{v B}{L} \sim B^3$$

$$\Rightarrow B \sim \eta^{-1/2} \quad L \sim \eta \quad v \sim \text{const}$$

$$\Rightarrow R_m, R_k \sim \eta$$

assumption: the system falls in this scaling regime until $R_k > 1$, then we recover the usual inverse cascade scaling

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Another argument (which results in a weaker condition)

Chiral plasma instability

preserved by μ conv. for $\Gamma_Y = 0$

$$\mu_{Y5} = \frac{711}{481}\mu_{e_R} = -\frac{711}{481}\frac{3}{T^2}\frac{\alpha}{\pi}h \qquad T \gtrsim 10^5\,\mathrm{GeV}$$

$\mu_{Y5} \lessgtr 0$ for $h \gtrless 0$

I can write the equation for the helicity as

$$\partial_\eta h_k = \frac{2k}{\sigma_Y}\left(\frac{k_{CPI}}{r_k} - k\right) h_k$$

$$h_k = \frac{1}{k}\left(|B_k^+|^2 - |B_k^-|^2\right) \qquad h = \int \frac{d^3k}{(2\pi)^3} h_k e^{ikx}$$

$$r_k = \frac{k\, h_k}{2\rho_k} \qquad \text{"degree of helicity"}$$

$$\rho_k = \frac{1}{2}\left(|B_k^+|^2 + |B_k^-|^2\right)$$

$$k_{CPI} \equiv \frac{2\alpha_Y}{\pi}\mu_{Y5}$$

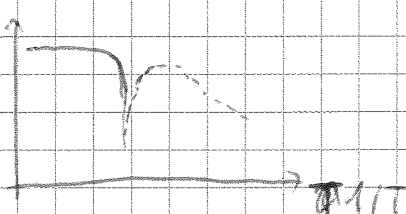
Take eg $h > 0$, $h_k < 0$, $r_k = -1$

$\hookrightarrow \mu < 0 \Rightarrow k_{CPI} < 0$

$\Rightarrow \partial_\eta h_k = (>0)\, h_k$ negative helicity grows

$\ldots \Rightarrow h$ gets reduced

In practice, for a quasi maximally helical $h_k > 0$,



$$\eta_{CPI} \sim \frac{\pi^2\sigma}{2\alpha^2\mu_{Y5}^2} \Rightarrow \hat{T}_{CPI} \sim 1.5 \times 10^5\,\mathrm{GeV}\,\frac{\ln\alpha_Y^{-1}}{4.5}\left(\frac{100}{g_*}\right)^{1/2}\left(\frac{\alpha}{0.01}\right)^3\left(\frac{\mu_{Y5}/T}{10^{-3}}\right)^2$$

If $\hat{T}_{CPI} \cancel{\gtrsim}$ ~~ooo~~ $\hat{T}_{Y_{e1}} \simeq 10^5\,\mathrm{GeV}$

$\Rightarrow$ h decays, μ_{e1} decays because $\mu_{e1} + \cancel{\mathrm{QED}}\,\frac{c_{CS}}{T^{2/3}} = 0$
all asymmetries are erased

If $\hat{T}_{CPI} \ll \hat{T}_{Y_{e1}}$ ~~see~~ $\partial_\eta \mu_{e1} = -\frac{3}{T^2}\frac{\pi}{\alpha}\frac{\partial h}{\partial \eta} - \Gamma_{Y_e}\frac{711}{481}\mu_{e1}$

$\Rightarrow$ 1) Yukawa erases μ_{e1}

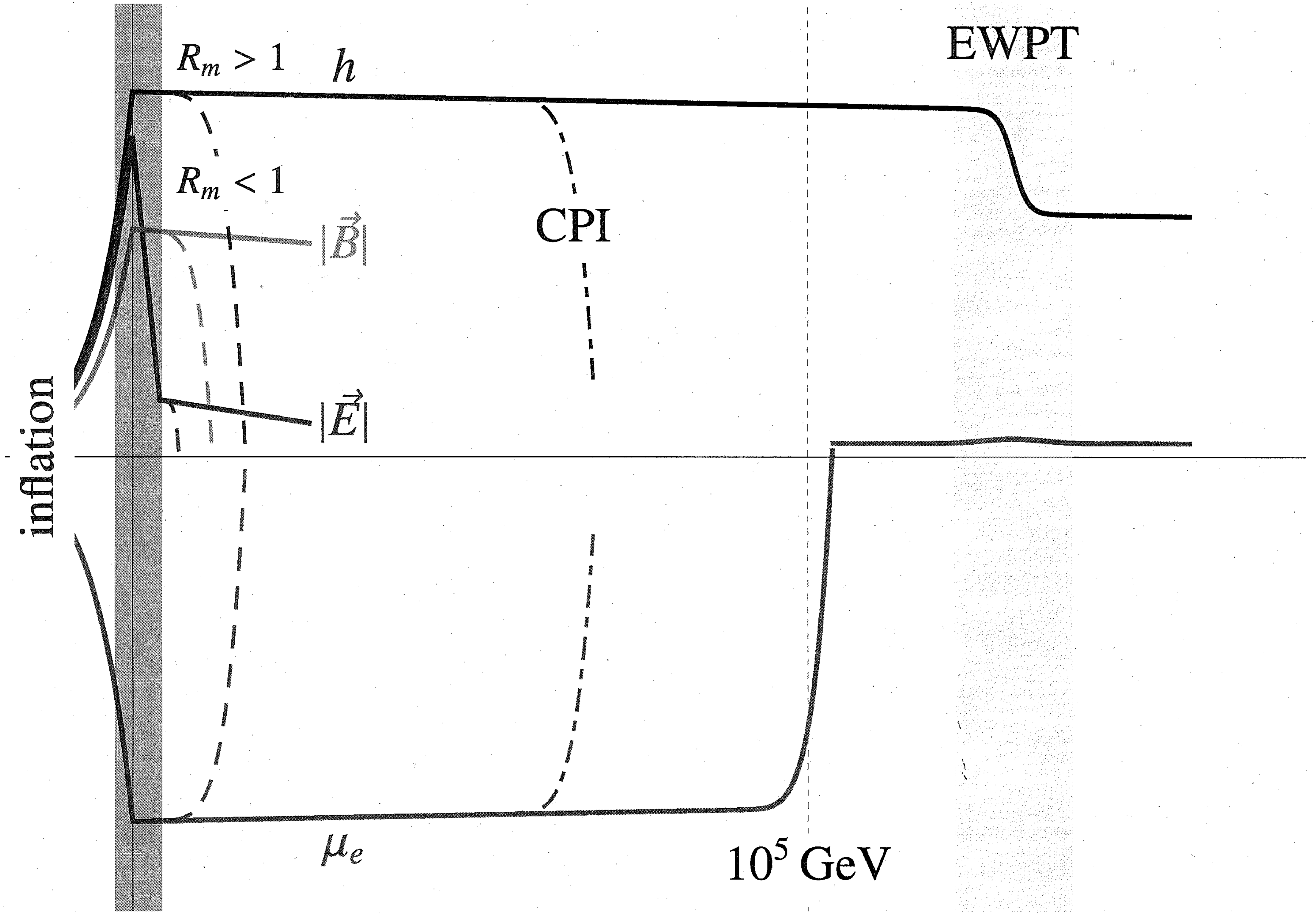
2) h survives

3) μ_{e1} regenerated by (small) $\partial_\eta h$ but now with same sign as $h \Rightarrow$ no decay of h

Summary: we can have a sizeable h at EWPT, assuming that ~~Rm~~

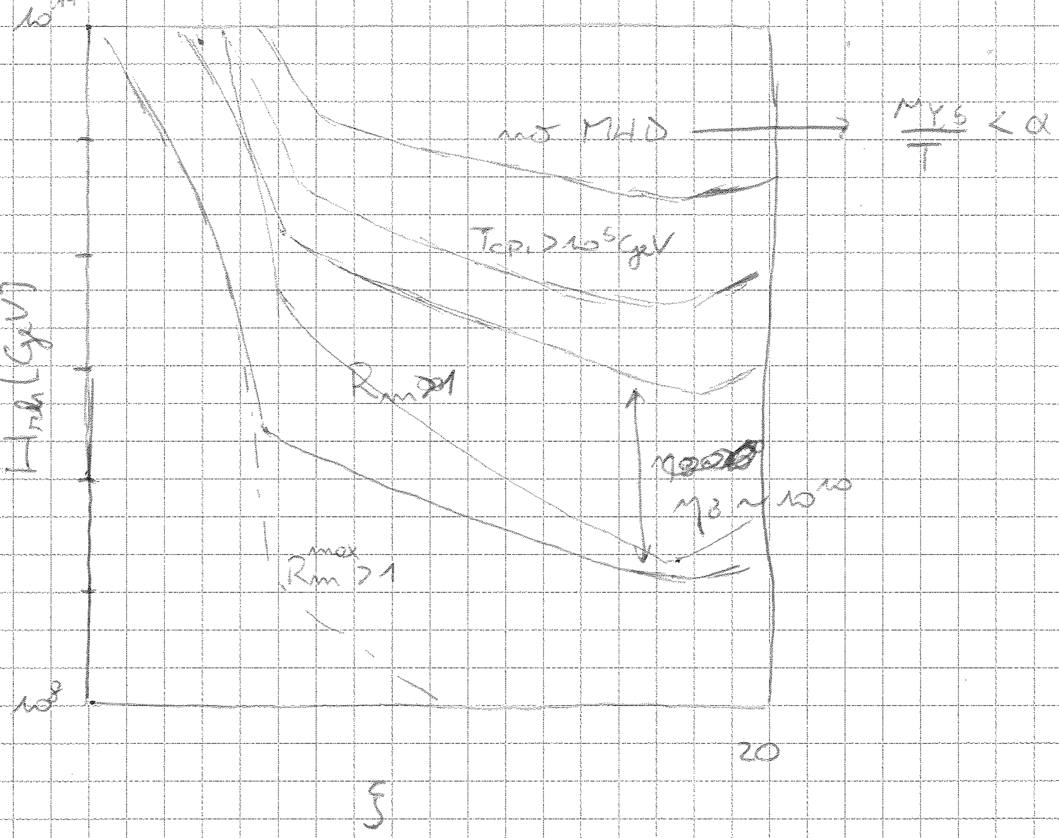
$Rm|_{t_{L}} > 1 \Rightarrow$ ~~catalog~~ inverse cascade $\Rightarrow h \sim$ const

$\hat{T}_{CPI} < \hat{T}_{Y_{e1}} \Rightarrow$ no CPI



EWPT
$R_m > 1$
h
$R_m < 1$
CPI
$|\vec{B}|$
$|\vec{E}|$
inflation
μ_e
10^5 GeV

Result


10^{14}
10^{8}
H_{inf} (GeV)
not MHD
$\frac{\mu_{Y5}}{T} < \alpha$
$T_{CPI} > 10^5$ GeV
$R_m > 1$
$R_m^{max} > 1$
$\eta_B \sim 10^{-10}$
20
ξ