Baryogenesis from axion inflation

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based on 1905.13318 w/ V. Domcke, E. Morgante & K. Mukaida

Gauge field production during axion inflation

- Consider inflation driven by axion-like scalar with coupling to hypercharge gauge boson:

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] - \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + \frac{\alpha_Y \phi}{4\pi f_a} Y_{\mu\nu} \tilde{Y}^{\mu\nu} \right\}$$

- $\Rightarrow$ eom in momentum space of gauge field with helicity $\pm$:

$$0 = \left[\partial_\eta^2 + k \left(k \pm 2\xi a H \right) \right] A_Y^\pm(\eta, \vec{k})$$

with

$$\xi \equiv \frac{\alpha_Y \dot{\phi}}{2\pi f_a H}$$

$\Rightarrow$ tachyonic instability for modes with helicity $-\text{sign}(\xi)$ (and $k < 2|\xi| aH$) $\Rightarrow$ production of gauge bosons with fixed helicity

Why is this interesting?

- Axion inflation on steep potentials
  `[M. Anber & L. Sorbo, 0908.4089]`
  - Axion potential
    $$V(\phi) = \Lambda^4(\cos(\phi/f) + 1)$$
    Slow roll conditions $|V'| \ll V/M_P, |V''| \ll V/M_P^2 \;\Rightarrow\; f \gg M_P$.
    Such super-Planckian decay constants difficult to get (WGC).
  - Gauge field production slows inflaton down
    $\Rightarrow$ inflation possible for $f < M_P$ (requires $N \sim 10^5$ gauge fields though)
- Generation of primordial magnetic fields
  `[W. Garretson, G. Field & S. Carroll, hep-ph/9209238]`
  - Magnetic fields ubiquitous in Universe. In particular, blazar observations hint at primordial magnetic fields in intergalactic voids.
  - Hypermagnetic fields from inflation can survive till late times due to turbulence and helicity conservation (see later).
  - At EW phase transition transformed into magnetic fields.

Baryogenesis from decaying helicity

- Let's define helicity:

$$h \equiv \frac{1}{\mathrm{vol}\,(\mathbb{R}^3)} \int d^3x \, \langle \vec{A}_Y \, \vec{B}_Y \rangle \;\propto\; \int dk \frac{k^3}{2\pi^2} \left(|A_Y^+(\eta, \vec{k})|^2 - |A_Y^-(\eta, \vec{k})|^2 \right)$$

- Only modes with helicity $-\mathrm{sign}(\xi)$ produced during inflation
  $\Rightarrow$ maximally helical
- Helicity linked to $B+L$ charge via $B+L$ anomaly:

$$\partial_\mu J^\mu_{B+L} = -\frac{3g_Y^2}{16\pi^2} Y^{\mu\nu} \tilde{Y}_{\mu\nu} + \frac{3g_W^2}{16\pi^2} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$

$$\Rightarrow \partial_\eta q_{B+L} = -\frac{3\alpha_Y}{\pi} \partial_\eta h + \ldots$$

$\Rightarrow$ Change in h induces change in q_{B+L} (and vice versa)!
`M. Joyce & M. Shaposhnikov, astro-ph/9703005`

Baryogenesis from decaying helicity

- Assume helicity h from inflation survives till EW phase transition.
- EW phase transition: hypercharge fields $\rightarrow$ electromagnetic fields. $U(1)_{\rm em}$ does not contribute to $B + L$ anomaly
  $\Rightarrow$ Conversion sources baryon asymmetry
  M. Giovannini & M. Shaposhnikov, hep-ph/9708303

$$\partial_\eta q_B = -\text{const.}\, \partial_\eta h \, - \, \text{const.}\, \gamma_{W,\text{sph}} q_B$$
$$= \text{const.}\, (\partial_\eta \theta_W)\, h_{\rm ini} \, - \, \text{const.}\, \gamma_{W,\text{sph}} q_B$$

- But competing effects from EW sphalerons!
- Competition between EW sphalerons and source term $\partial_\eta h$ studied in
  K. Kamada & A. Long, 1606.08891 & 1610.03074
  $\Rightarrow$ Sizeable baryon asymmetry remains!
  D. Jimenez, K. Kamada, K. Schmitz & X.-J. Xu, 1707.07943

Fermion production during inflation

- Anomaly equation again

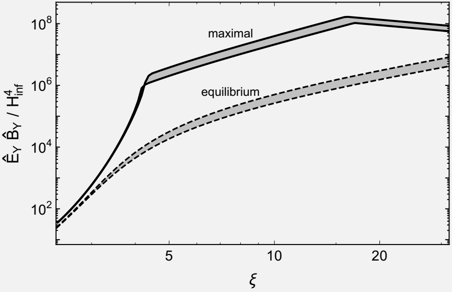
$$\partial_\eta q_{B+L} = -\frac{3\alpha_Y}{\pi}\partial_\eta h + \dots$$

⇒ Fermions produced together with hypercharge gauge fields!

`V. Domcke & K. Mukaida, 1806.08769`

- Chirally-asymmetric production (⇒ anomaly) + Schwinger effect
- Fermions in $\vec{E}_Y$ and $\vec{B}_Y$ field during inflation ⇒ Induced current

⇒ Backreaction on gauge field production!



Conditions for surviving helicity till EW scale

- In particular for right-handed electron ($q_{e_1} \equiv n_{e_1} - n_{\bar{e}_1}$):

$$\partial_\eta q_{e_1} = -\frac{3\alpha_Y}{\pi}\partial_\eta h + \text{Yukawa interactions}$$

- $\Rightarrow$ After inflation $q_{e_1} = -(3\alpha_Y/\pi)h$.
- Yukawa coupling out of equilibrium for temperatures $\gtrsim 10^5$GeV $\Rightarrow q_{e_1}$ (approximately) conserved for constant h.
- $\Rightarrow$ Chiral plasma instability can drive both q_{e_1} and h to zero!
  `M. Joyce & M. Shaposhnikov, astro-ph/9703005`
- Estimate time scale:

$$\hat{T}_{\rm CPI} \sim 10^5\,\text{GeV} \times \frac{g_*}{100}\left(\frac{\alpha_Y}{0.01}\right)^5\left(\frac{H_{\rm rh}}{10^{14}\,\text{GeV}}\right)^3 \frac{\langle \hat{\vec{E}}_Y \cdot \hat{\vec{B}}_Y\rangle_{\rm rh}/H_{\rm rh}^4}{10^5}$$

- Require $\hat{T}_{\rm CPI} \lesssim 10^5$GeV.

Conditions for surviving helicity till EW scale

- Evolution of hypercharge gauge field described by magnetohydrodynamics: Navier-Stokes equation plus

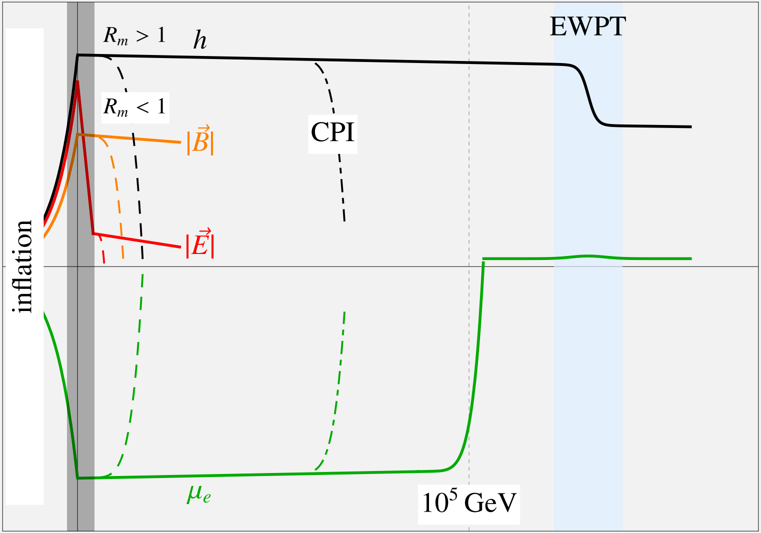
$$\partial_\eta \vec{B}_Y = \frac{\vec{\nabla}^2}{\sigma_Y} \vec{B}_Y + \vec{\nabla} \times \left(\vec{v} \times \vec{B}_Y \right) + \frac{2\alpha_Y}{\pi} \frac{\mu_{Y,5}}{\sigma_Y} \vec{\nabla} \times \vec{B}_Y \, .$$

- Induction term dominates over diffusion term if magnetic Reynolds number satisfies (v, L typical velocity, length scale)

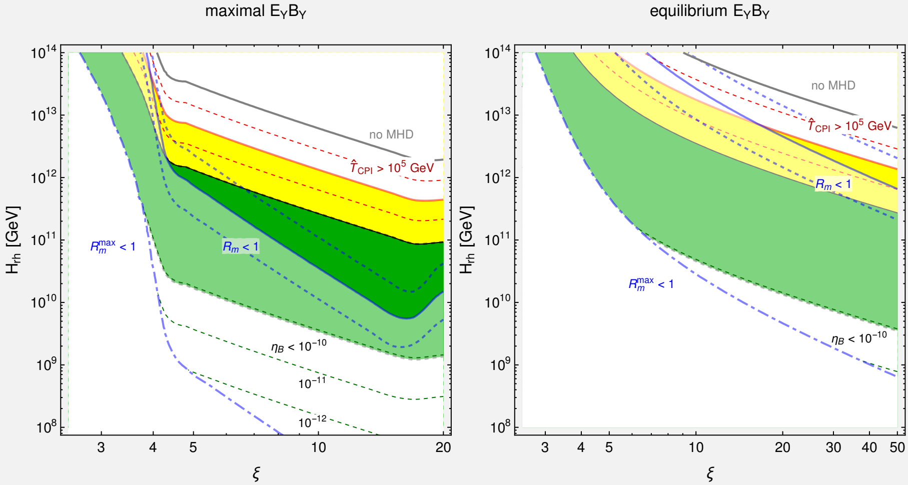
$$R_m \sim \sigma_Y \, v \, L \gg 1$$

- Helicity then stays constant by means of inverse cascade
- Well supported by numerical magnetohydrodynamics simulations e.g. R. Banerjee, K. Jedamzik, astro-ph/0410032

Conditions for surviving helicity till EW scale



Results



maximal $E_Y B_Y$
equilibrium $E_Y B_Y$
H_{rh} [GeV]
ξ
no MHD
$\hat{T}_{CPI} > 10^5$ GeV
$R_m < 1$
$R_m^{max} < 1$
$\eta_B < 10^{-10}$
10^{-11}
10^{-12}

Conclusions

- Helical hyper gauge fields can generate baryon asymmetry during EW transition.
- Conditions for helicity to survive till EW phase transition
  - Avoid magnetic diffusion $\Rightarrow R_m \gtrsim 1$
  - Avoid chiral plasma instability $\Rightarrow \hat{T}_{\rm CPI} \lesssim 10^5\,\text{GeV}$
- $\Rightarrow 6 \times 10^{-13} < \eta_B < 4 \times 10^{-7}$ or $\eta_B \simeq 0$
- $\Rightarrow H_{\rm inf} \sim 10^{10} - 10^{12}\text{GeV}$ and only mild dependence on ξ for $\xi \gtrsim 4$
- Theoretical uncertainties (somewhat large) purely due to SM physics $\Rightarrow$ reducible, can falsify scenario
- Magnetic fields $\hat{B}_{\rm em,0} \lesssim 10^{-17}$ Gauss with correlation lengths $\gtrsim 0.1$ parsec insufficient to explain blazar observations