Baryogenesis from Helical Magnetic Fields

Andrew Long
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KICP
Kavli Institute
for Cosmological Physics
at The University of Chicago

Outline

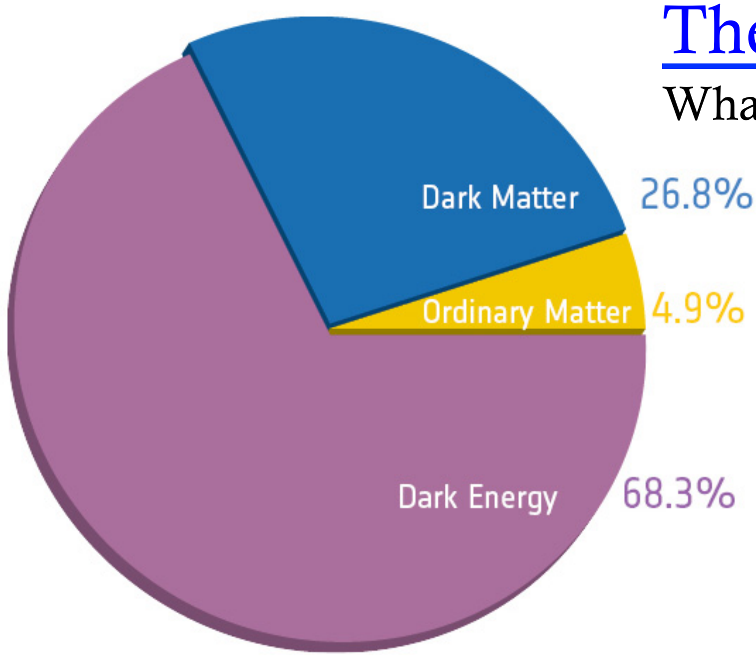
① How should we approach a problem like baryogenesis, and what in the world does it have to do with magnetic fields?

② Exploring the interplay between quantum anomalies and magnetic fields in (the relative safety of) QED.

③ How does it all work in the Standard Model?

based on 1606.08891 (also PRD) with Kohei Kamada (postdoc @ ASU)

Three BIG PROBLEMS of Modern Cosmology



The DARK MATTER Problem

What's responsible for the large scale structure?

The "ordinary matter" Problem

Why is there so much more matter than anti-matter?

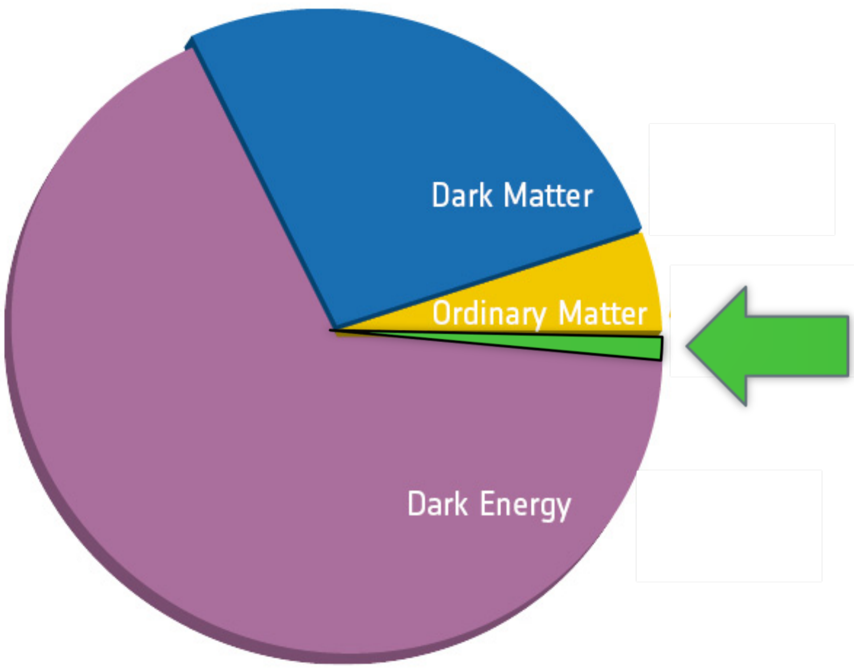
$$\frac{\left(n_{\mathrm{matter}} - n_{\mathrm{anti-matter}}\right)_{\mathrm{obsv}}}{\text{expected rms fluctuation}} \sim 10^8$$

The DARK ENERGY Problem

What's causing the accelerated expansion of the universe?

Solving the "ordinary matter" problem

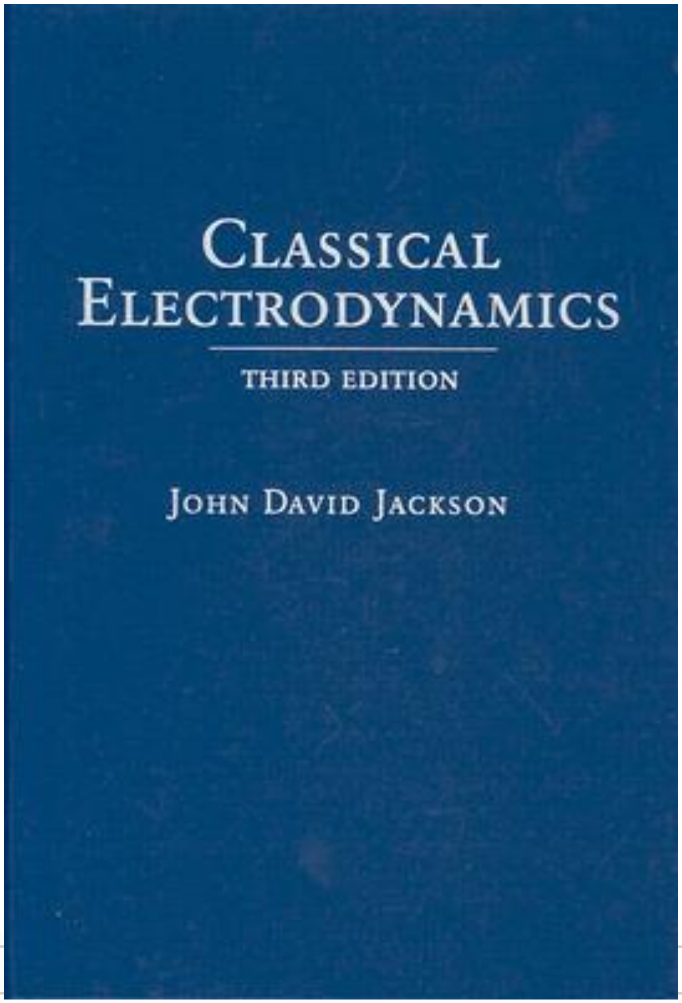
Suppose that the matter / anti-matter asymmetry was created in association with some other cosmological relic. By probing the associated relic today, we may learn about baryogenesis in the early universe.



Potential Associated Relics:

Gravitational Wave Background
Topological Defect Network
...
Primordial Magnetic Field

Why Primordial Magnetic Fields?



… waveguides

… Bessel functions

… multipole moments

… diffraction

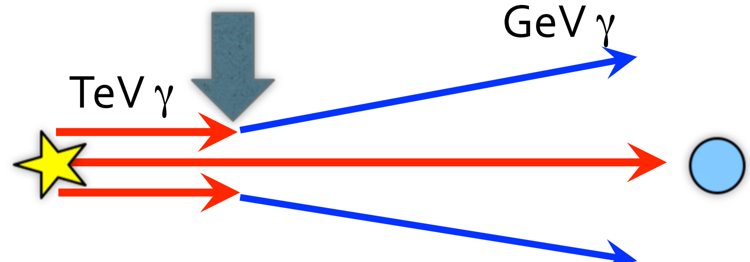
… "Effect of a Circular Hole in a Perfectly Conducting Plane with an Asymptotically Uniform Tangential Magnetic Field on One Side" (sec 5.13)

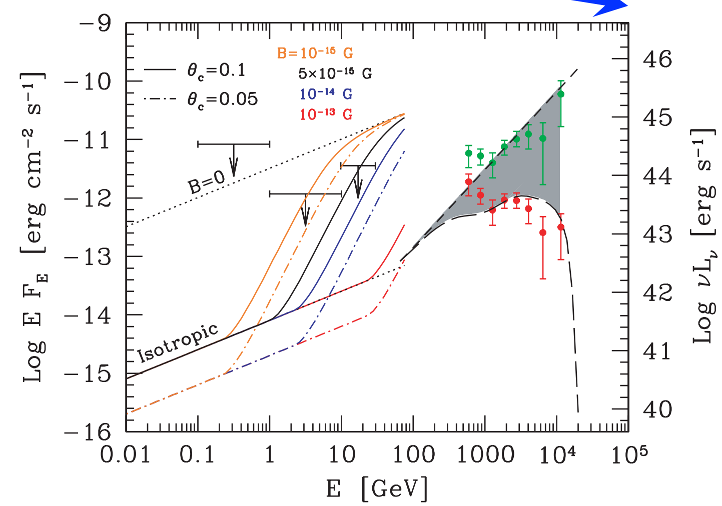
Why Primordial Magnetic Fields?

<u>Observation Motivation</u>:

- A relic of the PMF can persist today as an inter-galactic magnetic field. We know very little about magnetic fields on cosmological scales.
- Galaxies and clusters are observed to possess a micro-G level magnetic field. The origin of this field is a mystery. Galactic field may have been generated from the dynamo amplification of a much weaker seed field, possibly primordial.
- Observations of TeV blazar spectra are consistent with magnetic broadening of the EM cascade.
- The IGMF might be discovered -- and its nature probed -- by future observations of TeV blazars.

EM cascaded broadened by intergalactic B-field





Neronov & Semikoz (2009); **Tavecchio, et. al. (2010)**
Neronov & Vovk (2010); Taylor, Vovk, & Neronov (2011)

Why Magnetic Fields?

Theory Motivation:

- The Standard Model provides a link between magnetic field and baryon number.
- This is through the well-known B+L anomaly: ‘t Hooft (1976)

baryon & lepton number — $SU(2)_L$ gauge field — $U(1)_Y$ gauge field

$$\underbrace{\partial_\mu j^\mu_B = \partial_\mu j^\mu_L}_{\text{baryon \& lepton number}} = N_{\rm gen}\left(\underbrace{\frac{g^2}{16\pi^2}{\rm Tr}\left[W_{\mu\nu}\tilde{W}^{\mu\nu}\right]}_{SU(2)_L\text{ gauge field}} - \underbrace{\frac{1}{2}\frac{g'^2}{16\pi^2}Y_{\mu\nu}\tilde{Y}^{\mu\nu}}_{U(1)_Y\text{ gauge field}}\right)$$

- $SU(2)_L$ term … plays a role in many models of baryogenesis (EW sphaleron)
  Kuzmin, Rubakov, Shaposhnikov (1985)
- $U(1)_Y$ term … usually neglected … but let’s take a closer look …

Why Magnetic Fields?

Theory Motivation:

- The $U(1)_Y$ term is built from the pseudo-scalar source

$$\langle Y_{\mu\nu}\tilde{Y}^{\mu\nu}\rangle = -4\boldsymbol{E}_Y \cdot \boldsymbol{B}_Y = 2\Big[\frac{\partial}{\partial t}(\boldsymbol{A}\cdot\boldsymbol{B}) + \boldsymbol{\nabla}\cdot(\phi\boldsymbol{B} + \boldsymbol{E}\times\boldsymbol{A})\Big]$$

- Performing the volume integral gives …

$$\int \mathrm{d}^3x\, \langle Y_{\mu\nu}\tilde{Y}^{\mu\nu}\rangle = 2\,\partial_t\mathcal{H} \qquad \text{where} \qquad \mathcal{H} \equiv \int \mathrm{d}^3x\, \boldsymbol{A}\cdot\boldsymbol{B} \quad \text{(helicity)}$$

- ... which leads to …

$$\partial_t n_B = \partial_t n_L = -N_{\mathrm{gen}}\frac{g'^2}{16\pi^2}\partial_t\mathcal{H}_Y$$

A changing hyper-magnetic helicity sources baryon-number!

Other approaches to BAU-from-PMF: Bamba, Geng, & Ho (2007)

Quantum Effects in QED at Finite Density

Massless Electrodynamics

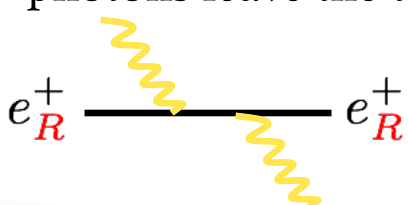
Let's think about massless electrodynamics.

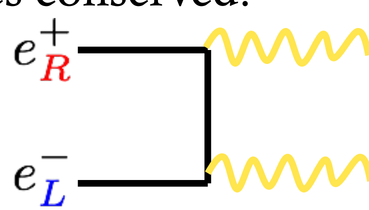
There are four kinds of particles, classified by their quantum numbers under two charges.

chiral charge == helicity (h=**S.p**)

electric charge		
	e_R^+	e_L^+
	e_R^-	e_L^-

Interactions between these particles and the photons leave the two charges conserved.





$$\mathcal{L} = \overline{\Psi}(i\gamma^\mu D_\mu - \cancel{m})\Psi - \frac{1}{4}F^2$$

$$U(1)_V : \Psi \to e^{i\theta}\Psi$$

$$U(1)_A : \Psi \to e^{i\theta\gamma^5}\Psi$$

$$\partial_\mu j_V^\mu = 0$$

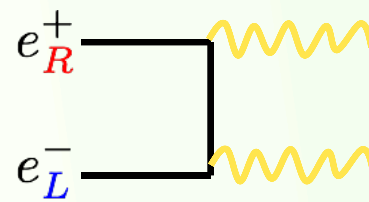
$$\partial_\mu j_A^\mu = 0$$

Bring System to Finite Temperature and Density

We are interested in how the various particle densities evolve. (Analogous to baryon number in the Standard Model.)

We describe the evolution with a system of Boltzmann equations. (schematic!)

These terms account for particle-changing processes like annihilations:



$$\partial_t n_{\mathrm{R}+} = -\Gamma_{\mathrm{em}} \left(n_{\mathrm{R}+} + n_{\mathrm{L}-} \right)$$
$$\partial_t n_{\mathrm{L}-} = -\Gamma_{\mathrm{em}} \left(n_{\mathrm{R}+} + n_{\mathrm{L}-} \right)$$
$$\partial_t n_{\mathrm{R}-} = -\Gamma_{\mathrm{em}} \left(n_{\mathrm{R}-} + n_{\mathrm{L}+} \right)$$
$$\partial_t n_{\mathrm{L}+} = -\Gamma_{\mathrm{em}} \left(n_{\mathrm{R}-} + n_{\mathrm{L}+} \right)$$

These equations encode the electric & chiral charge conservation:

$$\partial_t n_{\mathrm{electric}} = \text{“+”} - \text{“-”} = 0$$
$$\partial_t n_{\mathrm{chiral}} = \text{“R”} - \text{“L”} = 0$$

Including Quantum Effects

When quantum effects are taken into account, the chiral charge is not conserved. This is the well-known chiral (or axial) anomaly of QED [Adler, Bell, Jackiw, '69]

$$\partial_\mu \mathbf{j}^\mu_{\mathbf{V}} = \mathbf{0} \quad \text{but} \quad \partial_\mu \mathbf{j}^\mu_{\mathbf{A}} = -2\frac{\mathbf{e}^2}{16\pi^2}\mathbf{F}_{\mu\nu}\tilde{\mathbf{F}}^{\mu\nu}$$

How does this affect our Boltzmann equations? In the presence of a mag. field…

$$\partial_t n_{\mathrm{R}+} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}+} + n_{\mathrm{L}-}\right) + \mathcal{S}_{\mathrm{anomaly}}$$
$$\partial_t n_{\mathrm{L}-} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}+} + n_{\mathrm{L}-}\right) - \mathcal{S}_{\mathrm{anomaly}}$$
$$\partial_t n_{\mathrm{R}-} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}-} + n_{\mathrm{L}+}\right) + \mathcal{S}_{\mathrm{anomaly}}$$
$$\partial_t n_{\mathrm{L}+} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}-} + n_{\mathrm{L}+}\right) - \mathcal{S}_{\mathrm{anomaly}}$$

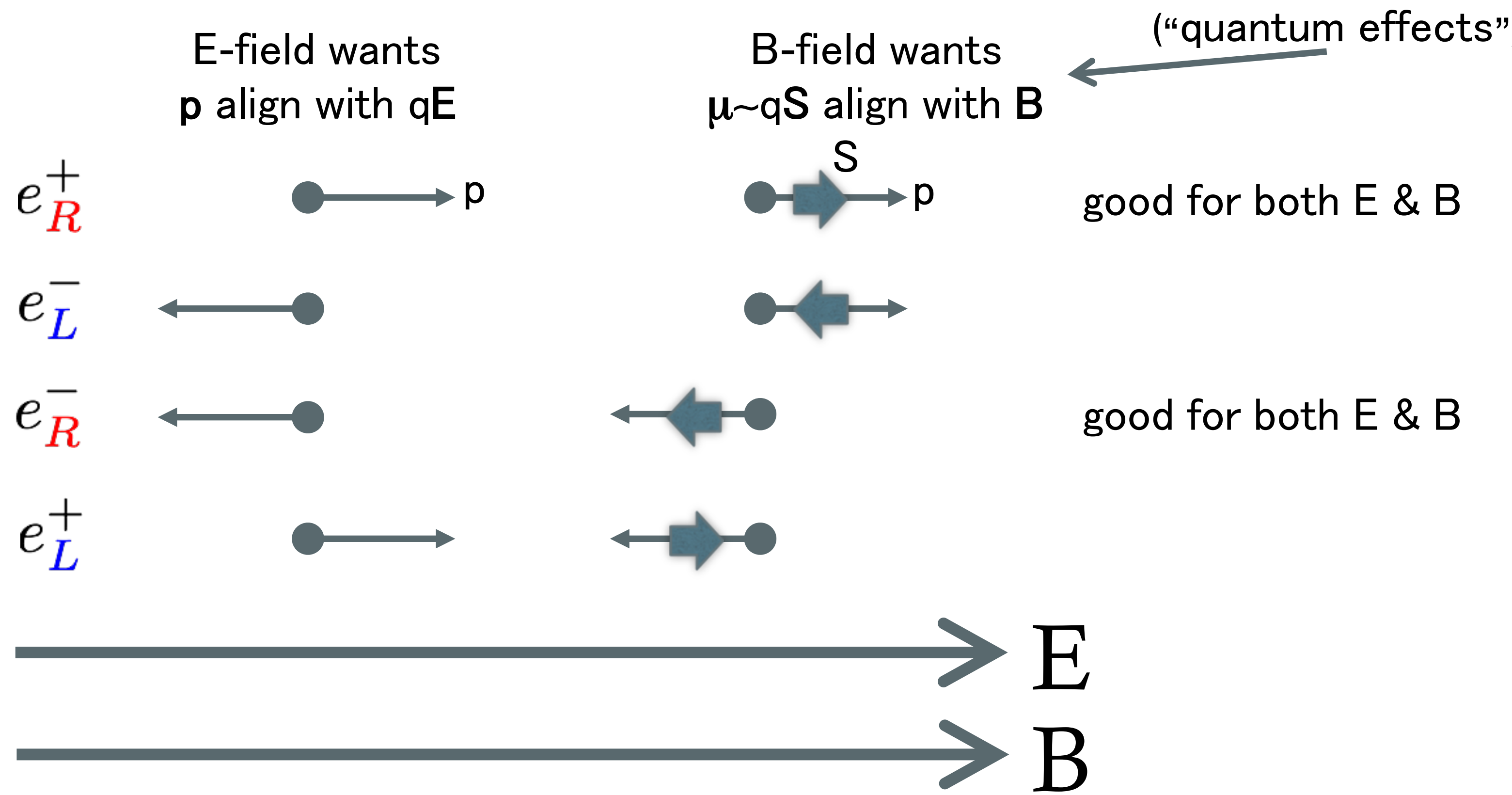
The anomaly violates the conservation of chiral charge

$$\partial_t n_{\mathrm{electric}} = 0$$
$$\partial_t n_{\mathrm{chiral}} = 4\mathcal{S}_{\mathrm{anomaly}}$$

where the source term is

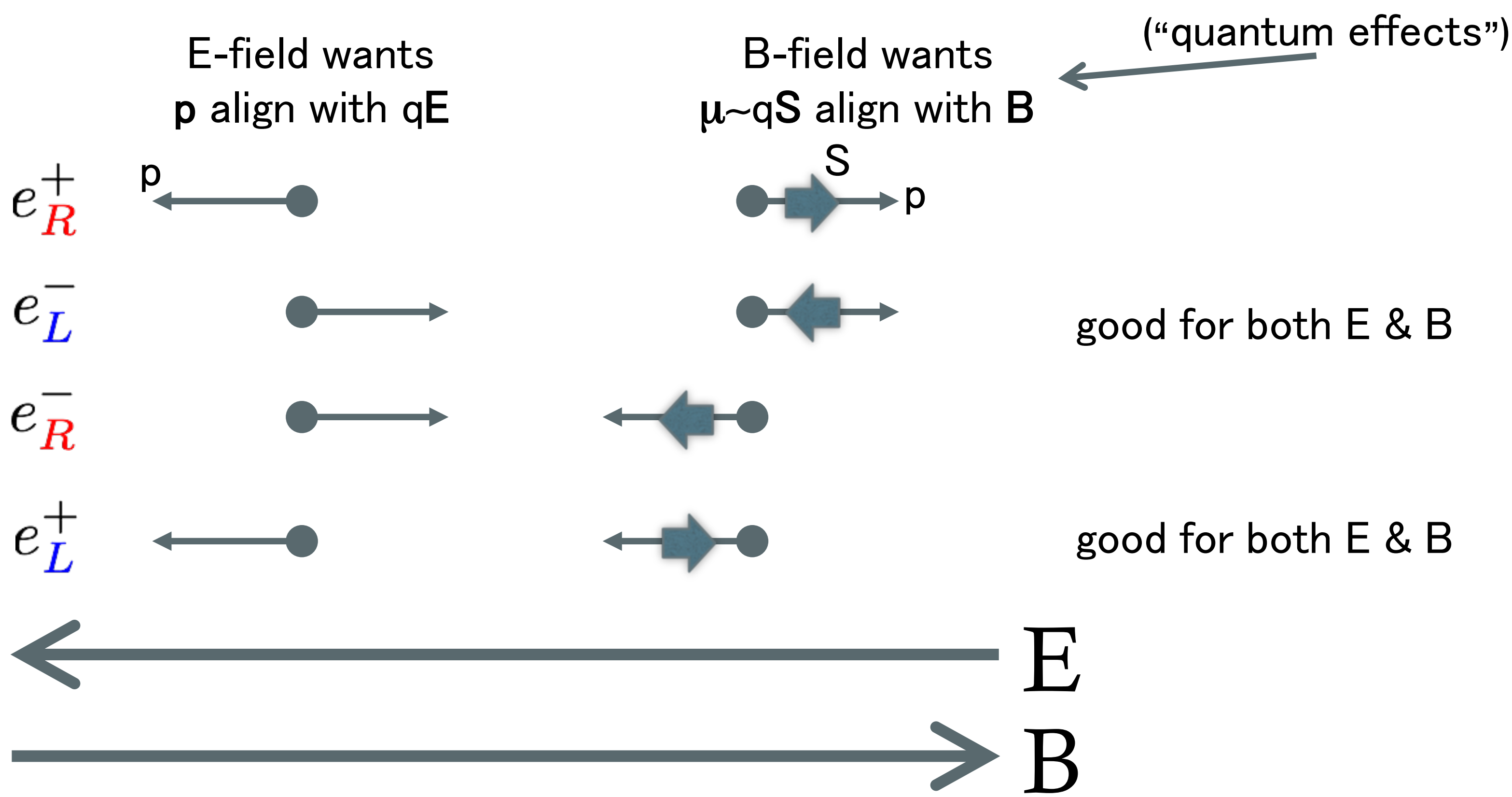
$$\mathcal{S}_{\mathrm{anomaly}} \propto \boldsymbol{E}\cdot\boldsymbol{B} \qquad \left(\text{recall } \langle F_{\mu\nu}\tilde{F}^{\mu\nu}\rangle = -4\boldsymbol{E}\cdot\boldsymbol{B}\right)$$

Semi-Classical Understanding



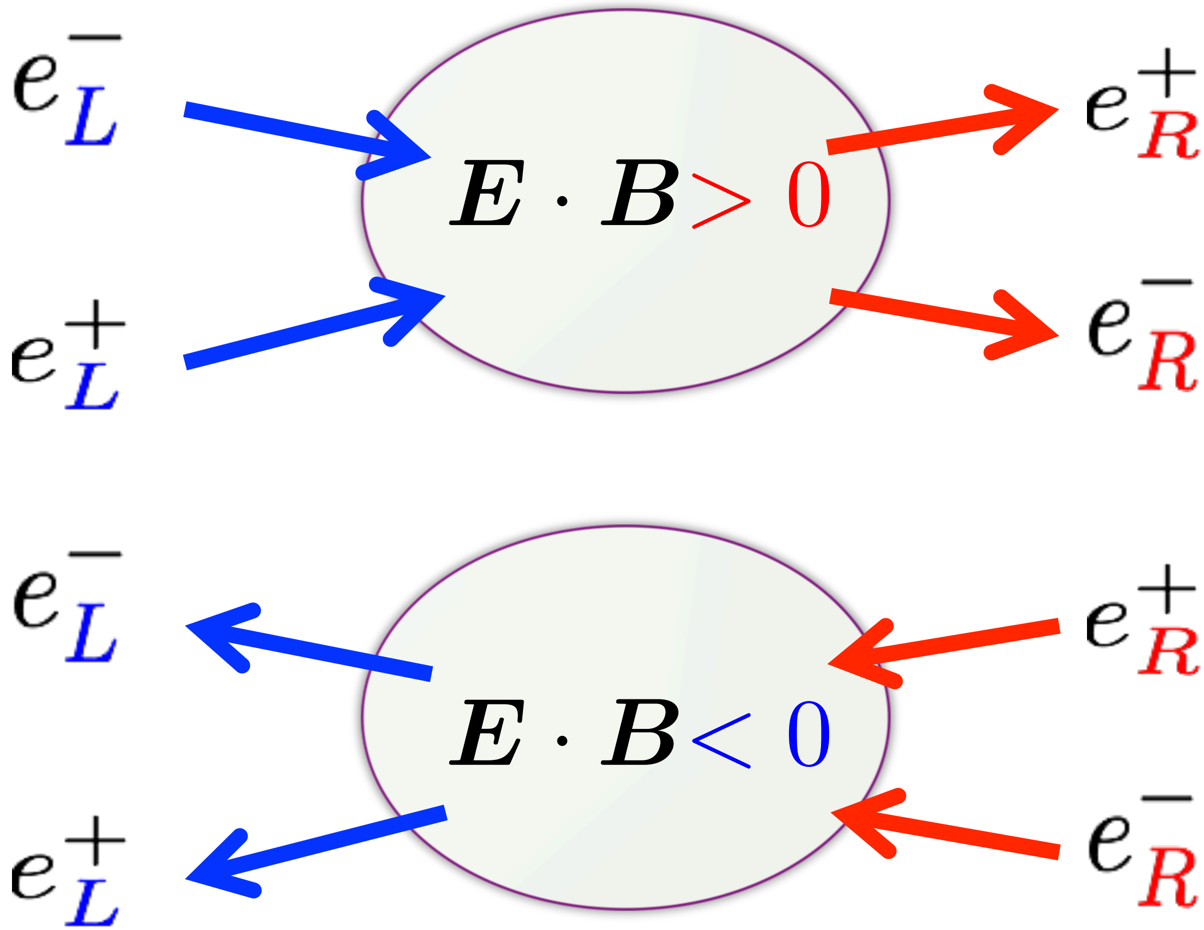
If $\boldsymbol{E} \cdot \boldsymbol{B} > 0$ then adding e_R^+ and e_R^- is energetically preferred

Semi-Classical Understanding



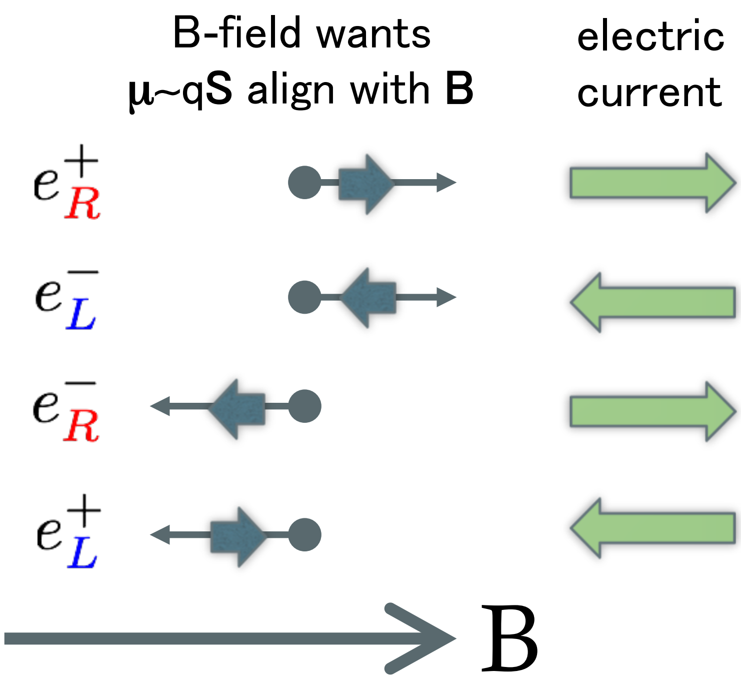
If $\boldsymbol{E} \cdot \boldsymbol{B} < 0$ then adding e_L^+ and e_L^- is energetically preferred

Diagrammatic Understanding



The Chiral Magnetic Effect

In a medium with a chiral asymmetry (nonzero net chiral charge) a magnetic field induces a current in electric charge. Also well-known, [Vilenkin, '80 … Fukushima, Kharzeev, & Warringa, '08].



Ohm's law — chiral mag. effect

$$\boldsymbol{J}_{\rm elec} = \overbrace{\sigma \boldsymbol{E}}^{\text{Ohm's law}} + \overbrace{\frac{e^2}{2\pi^2}\mu_{\rm chiral}\boldsymbol{B}}^{\text{chiral mag. effect}}$$

$$\mu_{\rm chiral} \approx \frac{6}{T^2}\left(n_{\rm R+} - n_{\rm L-} + n_{\rm R-} - n_{\rm L+}\right)$$

The Chiral Magnetic Effect

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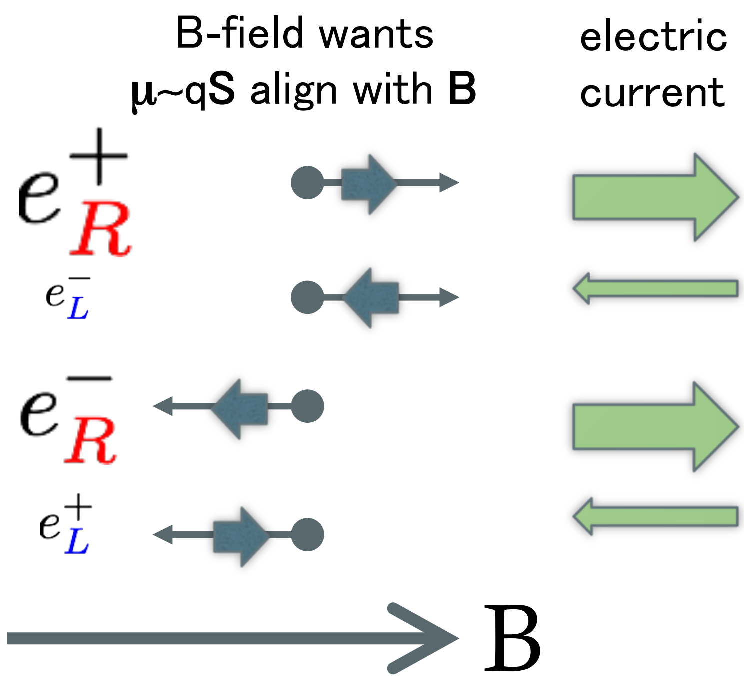


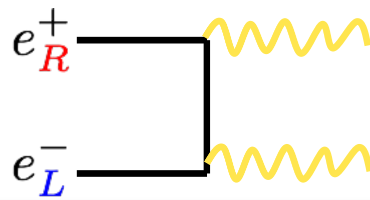
Ohm's law / chiral mag. effect

$$\boldsymbol{J}_{\mathrm{elec}} = \overbrace{\sigma \boldsymbol{E}}^{\text{Ohm's law}} + \overbrace{\frac{e^2}{2\pi^2}\mu_{\mathrm{chiral}}\boldsymbol{B}}^{\text{chiral mag. effect}}$$

$$\mu_{\mathrm{chiral}} \approx \frac{6}{T^2}\left(n_{\mathrm{R}+} - n_{\mathrm{L}-} + n_{\mathrm{R}-} - n_{\mathrm{L}+}\right)$$

QED at Finite Density in a Magnetic Field

electron-positron annihilation via interactions with photons



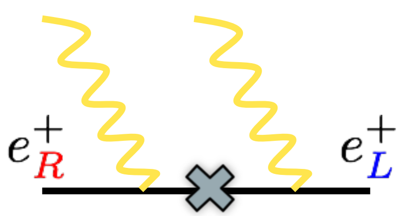
Source term is a pseudo-scalar. Arises in presence of a _helical_ magnetic field.

$$\partial_t n_{\mathrm{R}+} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}+} + n_{\mathrm{L}-}\right) - \Gamma_{\mathrm{flip}}\left(n_{\mathrm{R}+} - n_{\mathrm{L}+}\right) + 2\frac{e^2}{16\pi^2}\left[\frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}}{\sigma} - \frac{e^2}{2\pi^2}\frac{\mu_{\mathrm{chiral}}}{\sigma}|\boldsymbol{B}|^2\right]$$

$$\partial_t n_{\mathrm{L}-} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}+} + n_{\mathrm{L}-}\right) + \Gamma_{\mathrm{flip}}\left(n_{\mathrm{R}-} - n_{\mathrm{L}-}\right) - 2\frac{e^2}{16\pi^2}\left[\frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}}{\sigma} - \frac{e^2}{2\pi^2}\frac{\mu_{\mathrm{chiral}}}{\sigma}|\boldsymbol{B}|^2\right]$$

$$\partial_t n_{\mathrm{R}-} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}-} + n_{\mathrm{L}+}\right) - \Gamma_{\mathrm{flip}}\left(n_{\mathrm{R}-} - n_{\mathrm{L}-}\right) + 2\frac{e^2}{16\pi^2}\left[\frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}}{\sigma} - \frac{e^2}{2\pi^2}\frac{\mu_{\mathrm{chiral}}}{\sigma}|\boldsymbol{B}|^2\right]$$

$$\partial_t n_{\mathrm{L}+} = -\Gamma_{\mathrm{em}}\left(n_{\mathrm{R}-} + n_{\mathrm{L}+}\right) + \Gamma_{\mathrm{flip}}\left(n_{\mathrm{R}+} - n_{\mathrm{L}+}\right) - 2\frac{e^2}{16\pi^2}\left[\frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}}{\sigma} - \frac{e^2}{2\pi^2}\frac{\mu_{\mathrm{chiral}}}{\sigma}|\boldsymbol{B}|^2\right]$$



spin-flip reactions that violate chiral charge conservation, induced by the electron mass

chiral magnetic effect tends to erase any chiral asymmetry.

Recent applications to early universe: Frohlich & Pedrini, '00; Boyarsky, Frohlich, & Ruchaiskiy, '12; Pavlovic, Leite, & Sigl, '16

QED at Finite Density in a Magnetic Field

$$\partial_t n_{\rm electric} = 0$$

$$\partial_t n_{\rm chiral} = \left(8\frac{e^2}{16\pi^2}\frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}}{\sigma}\right) - \left(2\Gamma_{\rm flip} + 8\frac{e^2}{16\pi^2}\frac{e^2}{2\pi^2}\frac{6}{\sigma T^2}|\boldsymbol{B}|^2\right) n_{\rm chiral}$$

source

washout

$$n_{\rm chiral}^{(eq)} \approx \frac{\left(8\frac{e^2}{16\pi^2}\frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}}{\sigma}\right)}{\left(2\Gamma_{\rm flip} + 8\frac{e^2}{16\pi^2}\frac{e^2}{2\pi^2}\frac{6}{\sigma T^2}|\boldsymbol{B}|^2\right)}$$

→ magnetic helicity wants to grow the chiral asymmetry

→ spin-flip and CME want to washout the asymmetry

BAU from PMF in the full Standard Model

Re-Orientation

(1) Particle content and interactions described by the Standard Model (no BSM).

(2) Consider the early universe at T > 100 GeV where the EW symmetry is restored.

(3) Suppose that initially all particle / anti-particle asymmetries are vanishing.

➔ If (B-L)=0 how do you avoid washout by EW sphalerons?

(4) Inject a helical hyper-magnetic field at some (arbitrary) temperature T_{ini}

➔ Where does this magnetic field come from?

➔ Aren't you displacing the problem of baryogenesis into magnetogenesis?

(5) Solve the Boltzmann equations. Determine evolution of the various asymmetries.

Origin of the Magnetic Field

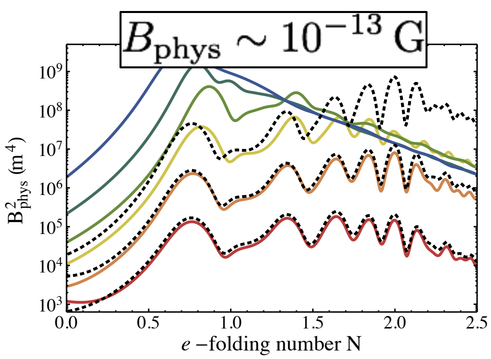
For example, a helical magnetic field may be generated during inflation from a pseudo-scalar inflaton or spectator field.

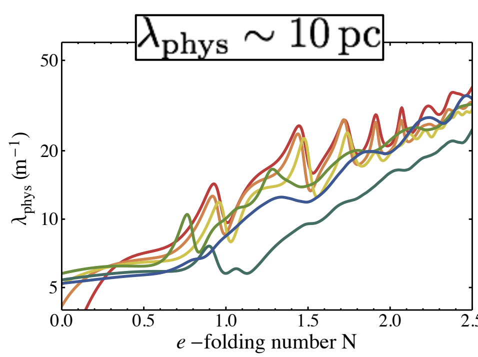
Garretson, Field, & Carroll (1992); Anber & Sorbo (2006)
Durrer, Hollenstein, Jain (2010)
Barnaby, Moxon, Namba, Peloso, Shiu, & Zhou (2012)
Fujita, Namba, Tada, Takeda, Tashiro (2015)
Anber & Sabancilar (2015)

axion coupled to EM … rolling sources helicity … opens kinetic instability

$$\xi \equiv \frac{d\varphi/dt}{fH}$$

$$-\mathcal{L}_{\text{int}} = \frac{\varphi}{4f} F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{d\varphi/dt}{2f}\mathbf{A}\cdot\mathbf{B} + \cdots \qquad \left(\frac{\partial^2}{\partial\eta^2} + k^2 \pm k\frac{\xi}{\eta}\right) A_\pm(\eta, k) = 0$$





Lattice simulation of B-field growth during preheating:
Adshead, Gilpin, Scully, Sfakianakis (2016)

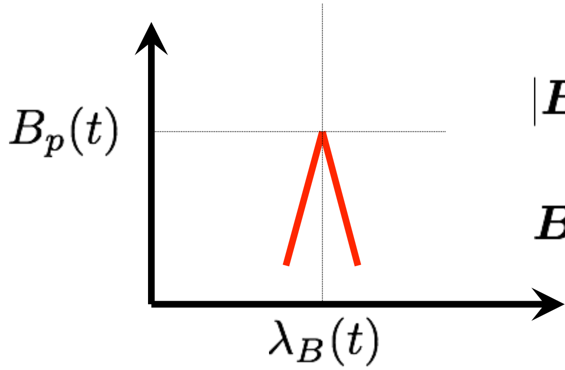
How will we *model* the magnetic field?

In general, a stochastic magnetic field is specified by two spectra:

$$\langle B_i(t,\boldsymbol{k}) B_j(t,\boldsymbol{k}')^* \rangle = (2\pi)^3 \delta(\boldsymbol{k}-\boldsymbol{k}') \Big[\big(\delta_{ij} - \hat{k}_i \hat{k}_j\big) \underbrace{P_B(t,k)}_{\text{energy spec.}} - i\epsilon_{ijm}\hat{k}_m \underbrace{P_{aB}(t,k)}_{\text{helicity spec.}} \Big]$$

Simplifying Assumptions:

- mono-chromatic: $P_B \sim \delta(k - 2\pi/\lambda_B)$
- maximally-helical: $P_{aB} = \pm P_B$



$$|\boldsymbol{B}|^2 \approx B_p(t)^2$$

(feeds into chiral mag. effect)

$$\boldsymbol{B}\cdot\nabla\times\boldsymbol{B} \approx \pm \frac{2\pi B_p(t)^2}{\lambda_B(t)}$$

(feeds into source term)

Evolution:

- Can be described by equations of magneto-hydrodynamics (turbulence).
- A freely decaying, helical magnetic field experiences the inverse cascade.

$$B_p = (a/a_0)^{-2} (\tau/\tau_{\rm rec})^{-1/3} B_0$$

$$\lambda_B = (a/a_0)(\tau/\tau_{\rm rec})^{2/3} \lambda_0$$

Frisch, Pouquet, Leorat, Mazure, 75,76
Banerjee & Jedamzik, 2004
Campenelli, 2007
Kahniashvilli et. al. 2013

Standard Model Boltzmann Equations w/ Anomalous Sources

$$\frac{d\eta_{u_L^i}}{dx} = -\mathcal{S}^i_{\rm UDW} - \sum_{j=1}^{N_{\rm g}} \left(\mathcal{S}^{ij}_{\rm Uhu} + \mathcal{S}^{ij}_{\rm Uu} + \mathcal{S}^{ij}_{\rm Uhd} \right) - \mathcal{S}_{\rm s,sph} - \frac{N_{\rm c}}{2} \mathcal{S}_{\rm w,sph} + \left(N_{\rm c} y_{Q_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{N_{\rm c}}{2} \mathcal{S}_{\rm w}^{\rm bkg} + N_{\rm c} \frac{y_{Q_L}}{2} \mathcal{S}_{\rm yw}^{\rm bkg} \right)$$

$$\frac{d\eta_{d_L^i}}{dx} = \mathcal{S}^i_{\rm UDW} - \sum_{j=1}^{N_{\rm g}} \left(\mathcal{S}^{ij}_{\rm Dhd} + \mathcal{S}^{ij}_{\rm Dd} + \mathcal{S}^{ij}_{\rm Dhu} \right) - \mathcal{S}_{\rm s,sph} - \frac{N_{\rm c}}{2} \mathcal{S}_{\rm w,sph} + \left(N_{\rm c} y_{Q_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{N_{\rm c}}{2} \mathcal{S}_{\rm w}^{\rm bkg} - N_{\rm c} \frac{y_{Q_L}}{2} \mathcal{S}_{\rm yw}^{\rm bkg} \right)$$

$$\frac{d\eta_{\nu_L^i}}{dx} = -\mathcal{S}^i_{\nu{\rm EW}} - \sum_{j=1}^{N_{\rm g}} \mathcal{S}^{ij}_{\nu{\rm he}} - \frac{1}{2} \mathcal{S}_{\rm w,sph} + \left(y_{L_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{1}{2} \mathcal{S}_{\rm w}^{\rm bkg} + \frac{y_{L_L}}{2} \mathcal{S}_{\rm yw}^{\rm bkg} \right)$$

$$\frac{d\eta_{e_L^i}}{dx} = \mathcal{S}^i_{\nu{\rm EW}} - \sum_{j=1}^{N_{\rm g}} \left(\mathcal{S}^{ij}_{\rm Ehe} + \mathcal{S}^{ij}_{\rm Ee} \right) - \frac{1}{2} \mathcal{S}_{\rm w,sph} + \left(y_{L_L}^2 \mathcal{S}_{\rm y}^{\rm bkg} + \frac{1}{2} \mathcal{S}_{\rm w}^{\rm bkg} - \frac{y_{L_L}}{2} \mathcal{S}_{\rm yw}^{\rm bkg} \right)$$

$$\frac{d\eta_{u_R^i}}{dx} = \sum_{j=1}^{N_{\rm g}} \left(\mathcal{S}^{ji}_{\rm Uhu} + \mathcal{S}^{ji}_{\rm Uu} + \mathcal{S}^{ji}_{\rm Dhu} \right) + \mathcal{S}_{\rm s,sph} - N_{\rm c} y_{u_R}^2 \mathcal{S}_{\rm y}^{\rm bkg}$$

$$\frac{d\eta_{d_R^i}}{dx} = \sum_{j=1}^{N_{\rm g}} \left(\mathcal{S}^{ji}_{\rm Dhd} + \mathcal{S}^{ji}_{\rm Dd} + \mathcal{S}^{ji}_{\rm Uhd} \right) + \mathcal{S}_{\rm s,sph} - N_{\rm c} y_{d_R}^2 \mathcal{S}_{\rm y}^{\rm bkg}$$

$$\frac{d\eta_{e_R^i}}{dx} = \sum_{j=1}^{N_{\rm g}} \left(\mathcal{S}^{ji}_{\rm Ehe} + \mathcal{S}^{ji}_{\rm Ee} + \mathcal{S}^{ji}_{\nu{\rm he}} \right) - y_{e_R}^2 \mathcal{S}_{\rm y}^{\rm bkg}$$

$$\frac{d\eta_{\phi^+}}{dx} = -\left(\mathcal{S}_{\rm hhw} + \mathcal{S}_{\rm hw} \right) + \sum_{i,j=1}^{N_{\rm g}} \left(-\mathcal{S}^{ij}_{\rm Dhu} + \mathcal{S}^{ij}_{\rm Uhd} + \mathcal{S}^{ij}_{\nu{\rm he}} \right)$$

$$\frac{d\eta_{\phi^0}}{dx} = \mathcal{S}_{\rm hhw} - \mathcal{S}_{\rm h} + \sum_{i,j=1}^{N_{\rm g}} \left(-\mathcal{S}^{ij}_{\rm Uhu} + \mathcal{S}^{ij}_{\rm Dhd} + \mathcal{S}^{ij}_{\rm Ehe} \right)$$

$$\frac{d\eta_{W^+}}{dx} = \left(\mathcal{S}_{\rm hhw} + \mathcal{S}_{\rm hw} \right) + \sum_{i=1}^{N_{\rm g}} \left(\mathcal{S}^i_{\rm UDW} + \mathcal{S}^i_{\nu{\rm EW}} \right) .$$

$$\mathcal{S}^{ij}_{\rm Dhu} \equiv \frac{\gamma^{ij}_{\rm Dhu}}{2} \left(\frac{\eta_{d_L^i}}{k_{d_L^i}} + \frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{u_R^j}}{k_{u_R^j}} \right) , \quad \mathcal{S}^{ij}_{\rm Uhu} \equiv \frac{\gamma^{ij}_{\rm Uhu}}{2} \left(\frac{\eta_{u_L^i}}{k_{u_L^i}} + \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{u_R^j}}{k_{u_R^j}} \right) ,$$

$$\mathcal{S}^{ij}_{\rm Uhd} \equiv \frac{\gamma^{ij}_{\rm Uhd}}{2} \left(\frac{\eta_{u_L^i}}{k_{u_L^i}} - \frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{d_R^j}}{k_{d_R^j}} \right) , \quad \mathcal{S}^{ij}_{\rm Dhd} \equiv \frac{\gamma^{ij}_{\rm Dhd}}{2} \left(\frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{d_R^j}}{k_{d_R^j}} \right) ,$$

$$\mathcal{S}^{ij}_{\nu{\rm he}} \equiv \frac{\gamma^{ij}_{\nu{\rm he}}}{2} \left(\frac{\eta_{\nu_L^i}}{k_{\nu_L^i}} - \frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{e_R^j}}{k_{e_R^j}} \right) , \quad \mathcal{S}^{ij}_{\rm Ehe} \equiv \frac{\gamma^{ij}_{\rm Ehe}}{2} \left(\frac{\eta_{e_L^i}}{k_{e_L^i}} - \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{e_R^j}}{k_{e_R^j}} \right) ,$$

$$\mathcal{S}^i_{\rm UDW} \equiv \gamma^i_{\rm UDW} \left(\frac{\eta_{u_L^i}}{k_{u_L^i}} - \frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{W^+}}{k_{W^+}} \right)$$

$$\mathcal{S}^i_{\nu{\rm EW}} \equiv \gamma^i_{\nu{\rm EW}} \left(\frac{\eta_{\nu_L^i}}{k_{\nu_L^i}} - \frac{\eta_{e_L^i}}{k_{e_L^i}} - \frac{\eta_{W^+}}{k_{W^+}} \right)$$

$$\mathcal{S}_{\rm hhw} \equiv \gamma_{\rm hhw} \left(\frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{\phi^0}}{k_{\phi^0}} - \frac{\eta_{W^+}}{k_{W^+}} \right)$$

$$\mathcal{S}_{\rm s,sph} \equiv \gamma_{\rm s,sph} \sum_{i=1}^{N_{\rm g}} \left(\frac{\eta_{u_L^i}}{k_{u_L^i}} + \frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{u_R^i}}{k_{u_R^i}} - \frac{\eta_{d_R^i}}{k_{d_R^i}} \right) ,$$

$$\mathcal{S}_{\rm w,sph} \equiv \gamma_{\rm w,sph} \sum_{i=1}^{N_{\rm g}} \left(\frac{N_{\rm c}}{2} \frac{\eta_{u_L^i}}{k_{u_L^i}} + \frac{N_{\rm c}}{2} \frac{\eta_{d_L^i}}{k_{d_L^i}} + \frac{1}{2} \frac{\eta_{\nu_L^i}}{k_{\nu_L^i}} + \frac{1}{2} \frac{\eta_{e_L^i}}{k_{e_L^i}} \right)$$

$$\eta = n/s$$

$$x = T/H \sim M_{\rm pl}/T$$

$$k = \#\ \text{degree of freedom}$$

$$\mathcal{S}^{ij}_{\rm Uu} \equiv \gamma^{ij}_{\rm Uu} \left(\frac{\eta_{u_L^i}}{k_{u_L^i}} - \frac{\eta_{u_R^j}}{k_{u_R^j}} \right) ,$$

$$\mathcal{S}^{ij}_{\rm Dd} \equiv \gamma^{ij}_{\rm Dd} \left(\frac{\eta_{d_L^i}}{k_{d_L^i}} - \frac{\eta_{d_R^j}}{k_{d_R^j}} \right) ,$$

$$\mathcal{S}^{ij}_{\rm Ee} \equiv \gamma^{ij}_{\rm Ee} \left(\frac{\eta_{e_L^i}}{k_{e_L^i}} - \frac{\eta_{e_R^j}}{k_{e_R^j}} \right) ,$$

$$\mathcal{S}_{\rm hw} \equiv \gamma_{\rm hw} \left(\frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{W^+}}{k_{W^+}} \right)$$

$$\mathcal{S}_{\rm h} \equiv \gamma_{\rm h} \frac{\eta_{\phi^0}}{k_{\phi^0}} .$$

$$\mathcal{S}_{\rm y}^{\rm bkg} = \frac{1}{sT} \frac{\alpha_{\rm y}}{4\pi} \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} \overline{\langle Y_{\mu\nu} \rangle \langle Y_{\rho\sigma} \rangle}$$

$$\mathcal{S}_{\rm w}^{\rm bkg} = \frac{1}{sT} \frac{1}{2} \frac{\alpha_{\rm w}}{4\pi} \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} \overline{\langle W^a_{\mu\nu} \rangle \langle W^a_{\rho\sigma} \rangle}$$

$$\mathcal{S}_{\rm yw}^{\rm bkg} = \frac{1}{sT} \frac{gg'/4\pi}{4\pi} \epsilon^{\mu\nu\rho\sigma} \overline{\langle Y_{\mu\nu} \rangle \langle W^3_{\rho\sigma} \rangle} .$$

Related work: Giovannini & Shaposhnikov; Fujita & Kamada; AL, Sabancilar, & Vachaspati; Semikoz, Dvornikov, Smirnov, Sokoloff, Valle

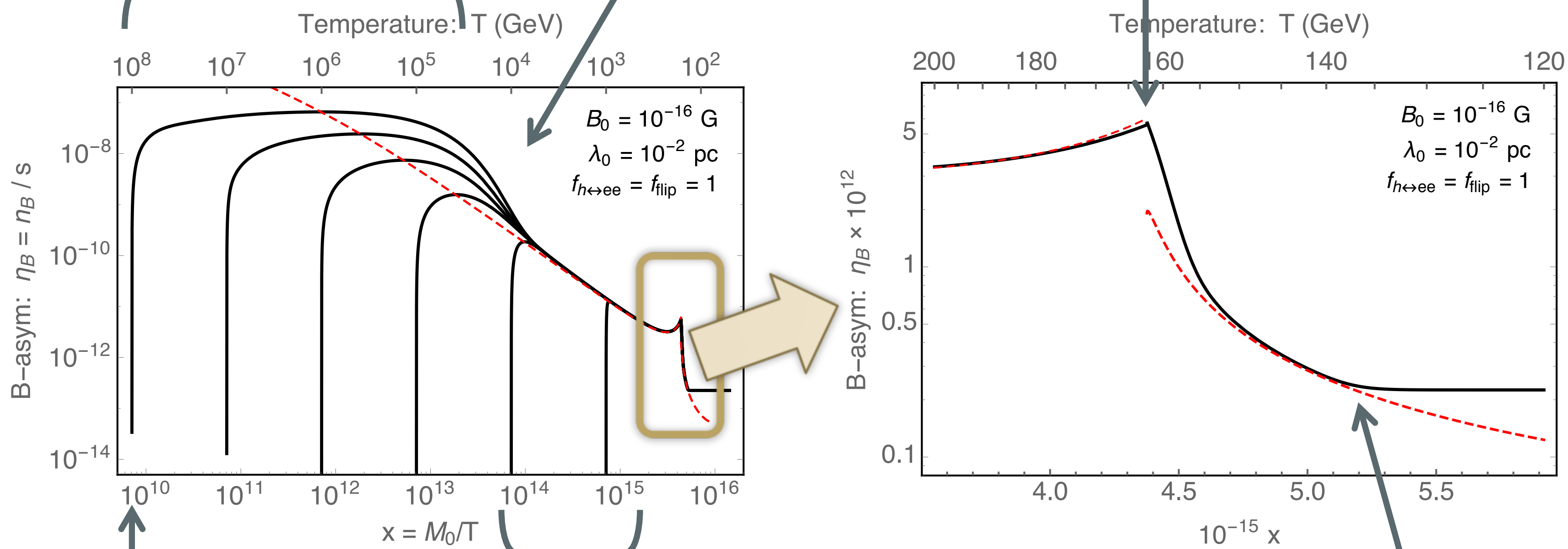
Evolution of Baryon Asymmetry

BAU stored in e_R ($y_{eR} \sim 10^{-6}$)

[Campbell, Davidson, Ellis, & Olive (1992)]

electron spin-flip comes into equilibrium, T~80 TeV

$U(1)_Y$ field becomes $U(1)_{em}$ field … no longer sources (B+L)



Initially all η = 0. Inject helical magnetic field, which quickly induces η_B

Equilibrium solution reached. Symmetric phase evolution was studied previously by Fujita & Kamada, 2016

Sphaleron goes out of equilibrium. B-number conserved.

Baryogenesis without (B-L)?

Recall that (B-L) = 0 at all times! But, Kuzmin, Rubakov, & Shaposhnikov ('85) taught us that B → 0 and L → 0 in equilibrium. **How is washout avoided?**

In the **symmetric phase** (T > 160 GeV), the EW sphaleron tries to drive (B+L) to zero, but the $U(1)_Y$ field sources (B+L) and prevents B,L → 0.

$$\partial j_B \sim W\tilde{W} - Y\tilde{Y}$$

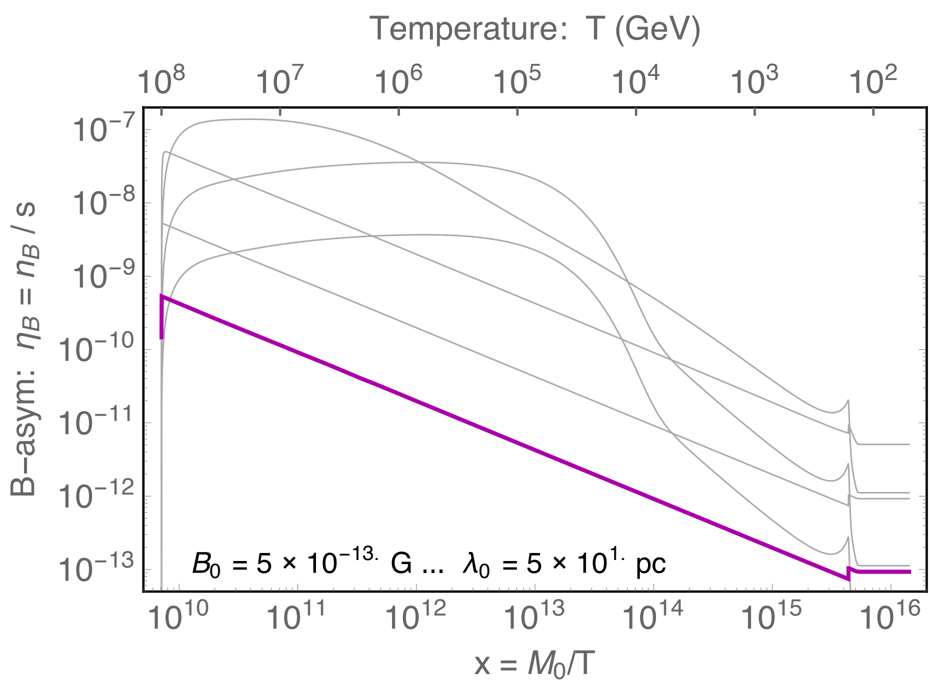
In the **broken phase** (T < 160 GeV), the EW sphaleron remains in equilibrium until T~140 GeV. Since the $U(1)_{em}$ field doesn't source B-number (because, vector-like interactions), why doesn't B-number washout? … The $U(1)_{em}$ field sources chiral charge (like in QED) and prevents B-washout in the R-chiral fermions.

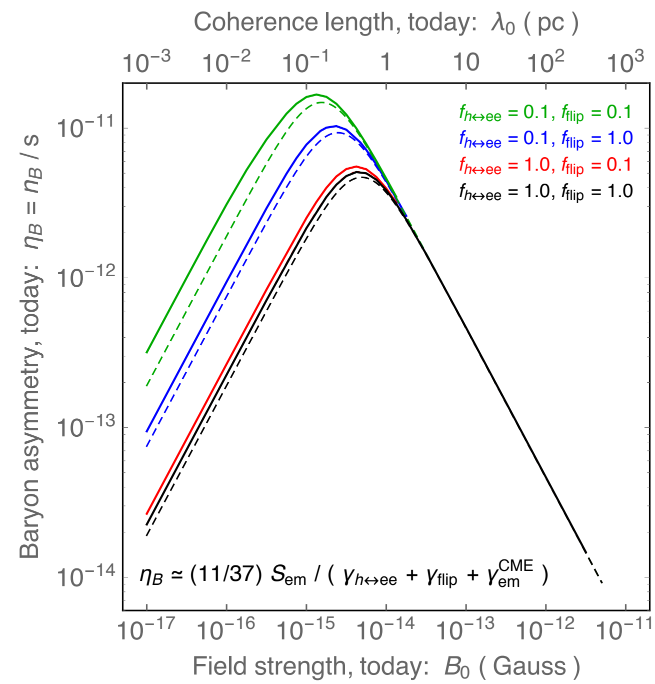
toy model

$$\left.\begin{aligned} \frac{d\eta_L}{dx} &= -\gamma_{\text{sph}}\eta_L + \gamma_{\text{flip}}\big(\eta_R - \eta_L\big) - \mathcal{S}_{\text{em}} \\ \frac{d\eta_R}{dx} &= -\gamma_{\text{flip}}\big(\eta_R - \eta_L\big) + \mathcal{S}_{\text{em}} \end{aligned}\right\} \Rightarrow \quad \begin{aligned} \eta_{L,\text{eq}} &= 0 \\ \eta_{R,\text{eq}} &= \frac{\mathcal{S}_{\text{em}}}{\gamma_{\text{flip}}} \end{aligned}$$

Let's play with the parameters until we get $\eta_B \sim 10^{-10}$ to match observed BAU

… while keeping $\left(\frac{\lambda_0}{1\ \text{pc}}\right) \sim \left(\frac{B_0}{10^{-14}\ \text{Gauss}}\right)$





$$\eta_B^{(eq)} \sim \frac{e^2\,\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}/(\sigma s T)}{y_e^2 + e^4|\boldsymbol{B}|^2/(\sigma T^3)} \sim \pm(4\times 10^{-12})\left(\frac{B_0}{10^{-14}\,\text{G}}\right)^2\left(\frac{\lambda_0}{1\,\text{pc}}\right)^{-1}\left[0.2+\left(\frac{B_0}{10^{-14}\,\text{G}}\right)^2\right]^{-1}$$

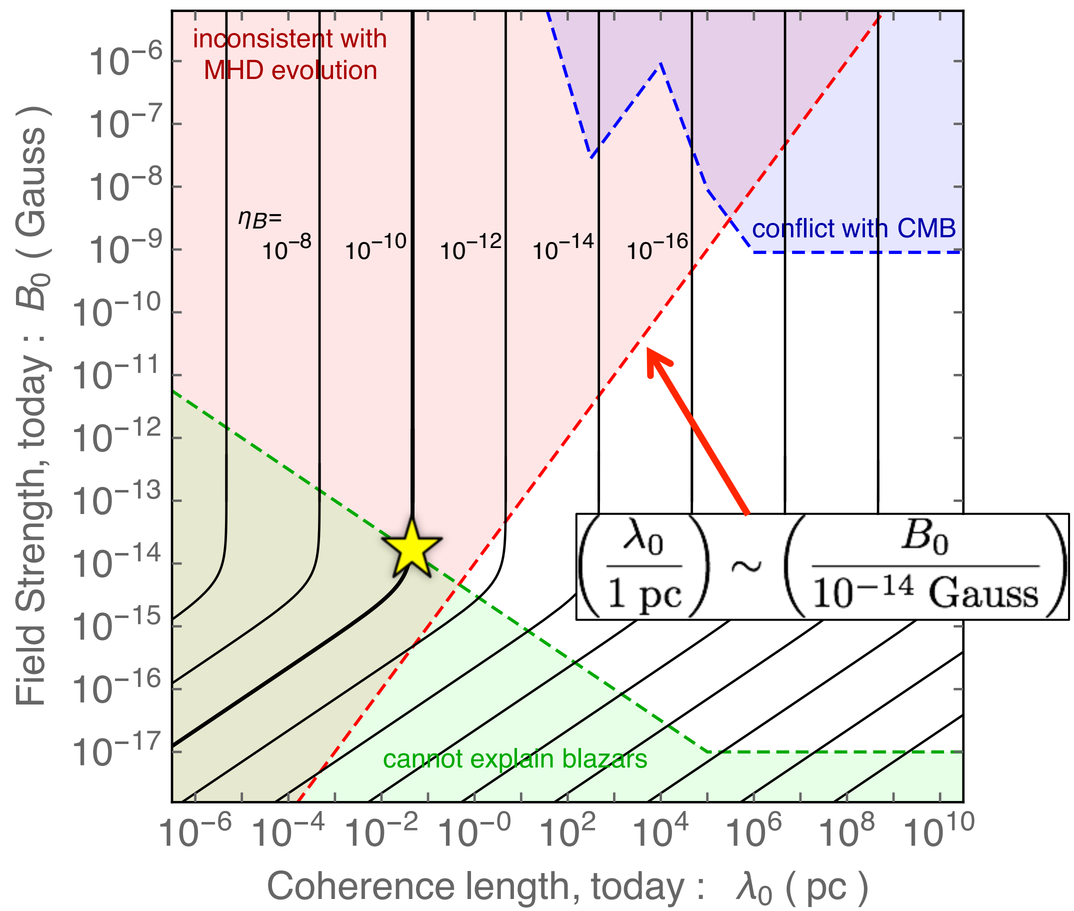
Washout induced by chiral magnetic effect … prevents η_B from reaching 10^{-10} for large B_0.
This behavior was overlooked in some previous studies. The CME cannot be neglected!

Broader Parameter Space

Sweet Spot (star)

- Yields observed baryon asymmetry, $\eta_B=10^{-10}$
- Magnetic field is strong enough to seed the galactic dynamo …
- … and explain blazar spectra data (missing GeV gamma rays).
- Possible to probe directly with future blazar observations (possibly via halo morphology).

  [Long & Vachaspati, 2015]
- Consistent with MHD evolution of a causally generated B-field within theoretical uncertainties.



B-field evolution through the Electroweak Crossover

How does the $U(1)_Y$ field become a $U(1)_{em}$ field at the crossover?

The Higgs condensate v(T) starts to grow from zero at T = 162 GeV.

The Z-part of the $U(1)_Y$ field becomes massive and decays leaving the $U(1)_{em}$ field.

For the analysis I've just described, we assumed that the Z-field decays away entirely at T = 162 GeV. In other words, we calculate B_{em} by matching

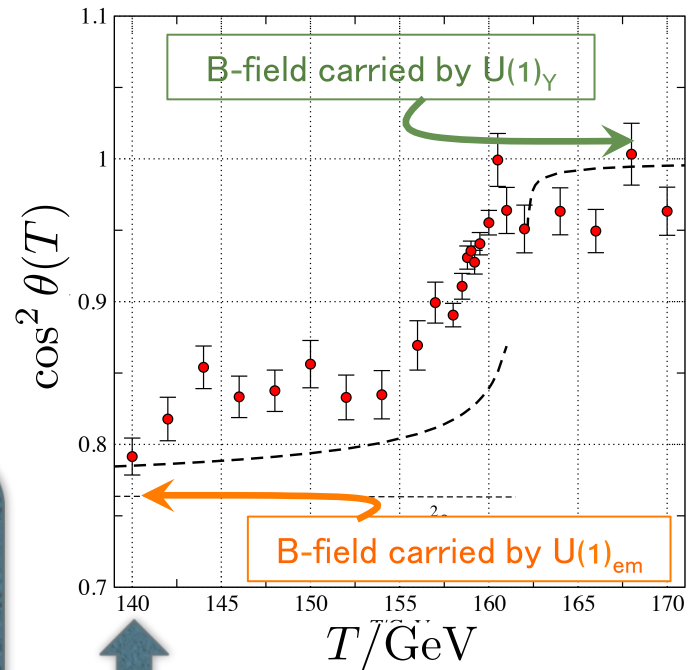
$$\text{matching:} \qquad \boldsymbol{B}_{\rm em} = \cos\theta_W \, \boldsymbol{B}_Y \quad \text{at} \quad T = 162 \text{ GeV}$$

This is a conservative approach. Since the $U(1)_{em}$ field does not violate B-number, the source term for (B+L) shuts off instantaneously at 162 GeV, in our model.

The instantaneous transformation approximation may have led us to under-estimate the baryon asymmetry. Let's take a closer look.

B-field evolution through the Electroweak Crossover

Analytic estimates (Kajantie, Laine, Rummukainen, & Shaposhnikov, '97) and lattice simulations (D'Onofrio & Rummukainen, '15) reveal that the mixing angle varies slowly during crossover.



Preliminary calculations reveal a large enhancement of the relic baryon asymmetry.

$\eta_B = 10^{-10}$ is easily accommodated and too-strong field may be ruled out by baryon over-production!

Washout by EW sphaleron stops here, but source remains active. Enhances (B+L).

Conclusion: What have we learned about the "ordinary matter" problem?

I have discussed how the matter / anti-matter asymmetry may have arisen from a primordial magnetic field in the symmetric phase of the electroweak plasma.

A few interesting features to emphasize:
① No (B-L)-violation is required even though T > 100 GeV.
② No BSM physics is required (except for generating the initial B-field).
③ Thus, some amount of helical-PMF→BAU conversion is inevitable!

Under conservative assumptions, the observed BAU is reproduced for a "sweet spot" … $B_0 \sim 10^{-14}$ G and $\lambda_B \sim 0.1$ pc … and relaxing these assumptions is expected to open up the parameter space (ongoing work).

With such a strong B-field, it could be possible to uncover the relic inter-galactic magnetic field, possibly with future observations of TeV blazars. With these measurements, we indirectly probe the origin of the matter/antimatter asymmetry.