Baryogenesis from Helical Magnetic Fields

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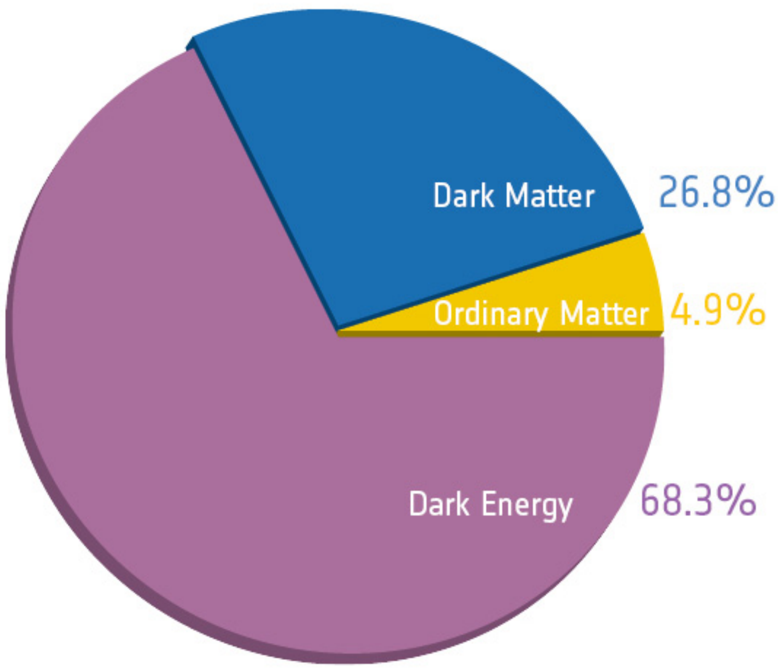
based on work with Kohei Kamada 1606.08891 (PRD) & 1610.03074 (PRD)

The "Ordinary Matter" Problem

Cosmologists say that "We don't understand 95% of the universe."



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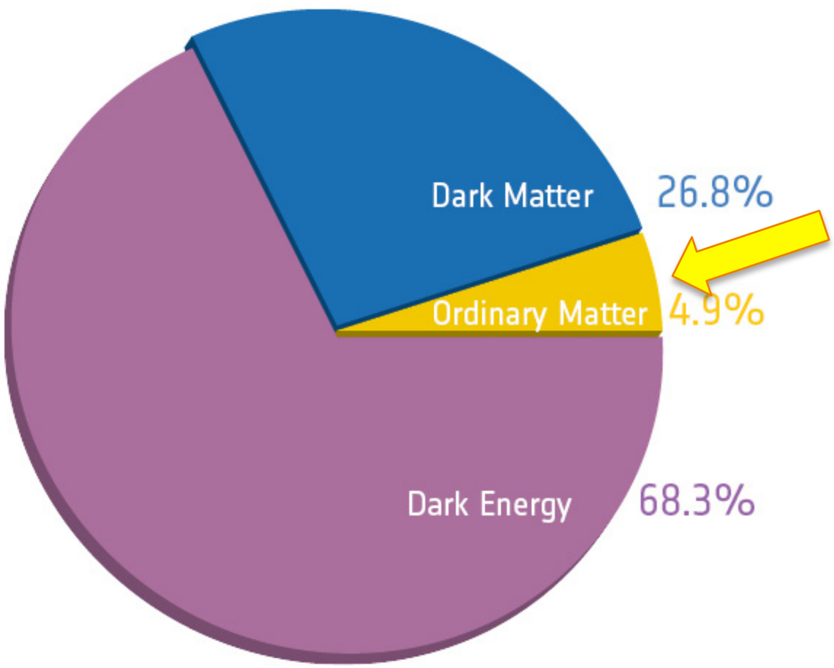
But this is not true … in fact, we don't understand 100%!

The "ordinary matter" problem = why is there more matter than anti-matter? → baryogenesis is the endeavor to solve this problem



Matter / Antimatter Asymmetry

$$\Omega_b \sim 5\% \quad \Rightarrow \quad n_B/s \sim 10^{-10}$$

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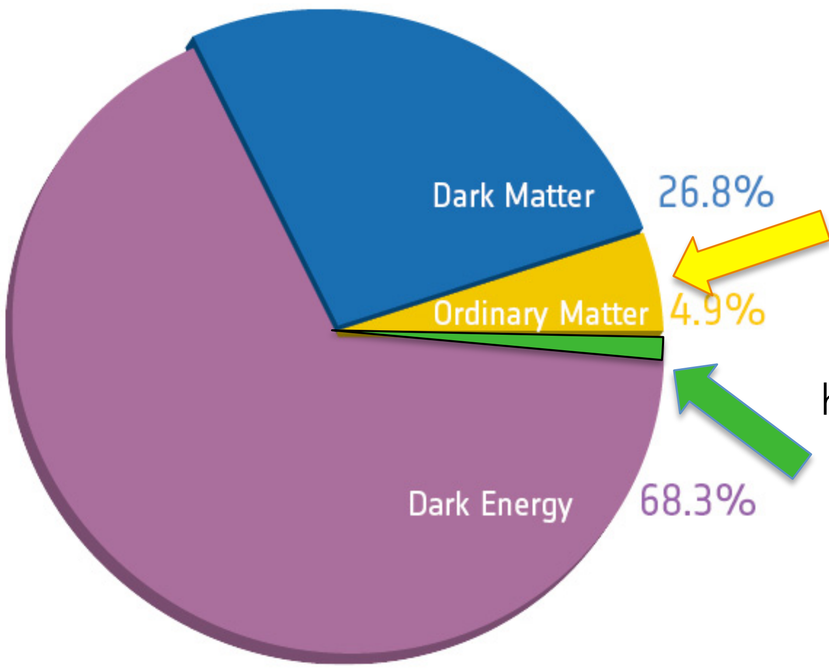


Matter / Antimatter Asymmetry

$$\Omega_b \sim 5\% \quad \Rightarrow \quad n_B/s \sim 10^{-10}$$

hiding in the “cracks” (error bars):

Primordial Magnetic Field

Executive Summary

In this talk, I'm going to …

… assume that a helical magnetic field was created in the early universe prior to the EW epoch. (e.g., arises naturally in axion inflation)

… show that the decaying helicity of this field gives rise to a baryon asymmetry through the Standard Model B+L anomaly (builds on earlier work by Joyce, Shaposhnikov, Giovannini, Bamba, Geng, Ho, …)

… calculate the evolution of the magnetic field and baryon asymmetry from magnetogenesis until today, while paying particular attention to the EW crossover (this is my work with Kohei Kamada; see also Fujita & Kamada, 2016)

… conclude that the predicted relic baryon asymmetry suffers from a large theoretical uncertainty, because we don't understand well how magnetic fields behave at the EW crossover (even though this is just SM physics!)

Standard Model anomalies & primordial magnetic fields

Standard Model B & L Violation

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

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

't Hooft (1976)

Thermal fluctuations of the weak isospin field (EW sphaleron), provide support for the SU(2)$_L$ term.

Kuzmin, Rubakov, Shaposhnikov (1985)

The sphaleron is responsible for B-violation in many models of baryogenesis, including EW baryogenesis & leptogenesis.

Can we use the U(1)$_Y$ term to accomplish baryogenesis?

B-Number from Magnetic Helicity

Joyce & Shaposhnikov (1997); Giovannini & Shaposhnikov (1997) see also Rubakov & Tavkhelidze (1985)

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

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = N_{\rm gen}\left(\frac{g^2}{16\pi^2}{\rm Tr}\left[W_{\mu\nu}\tilde{W}^{\mu\nu}\right] - \frac{1}{2}\frac{g'^2}{16\pi^2}Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$

A hypermagnetic field provides support for the U(1)$_Y$ term.

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

To induce a change in B-number, the helicity must change

$$\Delta Q_B = -N_{\rm gen}\frac{g'^2}{16\pi^2}\Delta\mathcal{H}_Y \qquad \text{where} \qquad \mathcal{H}_Y = \int {\rm d}^3\boldsymbol{x}\,\boldsymbol{A}_Y\cdot\boldsymbol{B}_Y$$

In a plasma, the helicity decays because of ohmic losses

$$\boldsymbol{E}_Y = \boldsymbol{j}_Y/\sigma_Y \approx \boldsymbol{\nabla}\times\boldsymbol{B}_Y/\sigma_Y$$

$$\langle Y_{\mu\nu}\tilde{Y}^{\mu\nu}\rangle = -4\langle\boldsymbol{B}_Y\cdot\boldsymbol{\nabla}\times\boldsymbol{B}_Y\rangle/\sigma_Y$$

Decaying hypermagnetic helicity sources B-number!

E.g., field generation via axion inflation

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

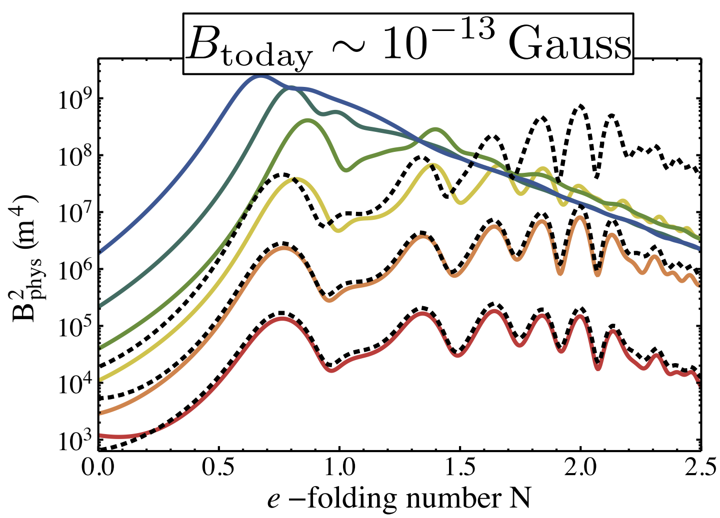
Garretson, Field, & Carroll (1992); Anber & Sorbo (2006)
Durrer, Hollenstein, Jain (2010)
Barnaby, Moxon, Namba, Peloso, Shiu, & Zhou (2012)
Caprini & Sorbo (2014)
Fujita, Namba, Tada, Takeda, Tashiro (2015)
Anber & Sabancilar (2015)

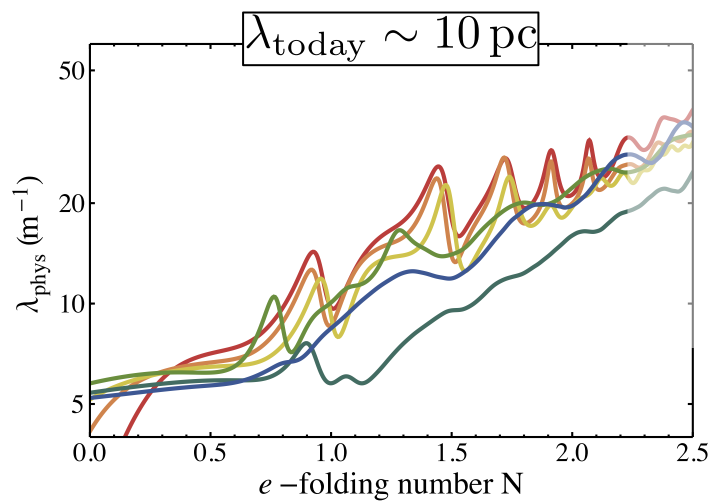
axion coupled to EM … rolling sources helicity … opens tachyonic instability

$$-\mathcal{L}_{\rm int} = \frac{\varphi}{4f} F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{d\varphi/dt}{2f}\mathbf{A}\cdot\mathbf{B} + \cdots$$

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

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



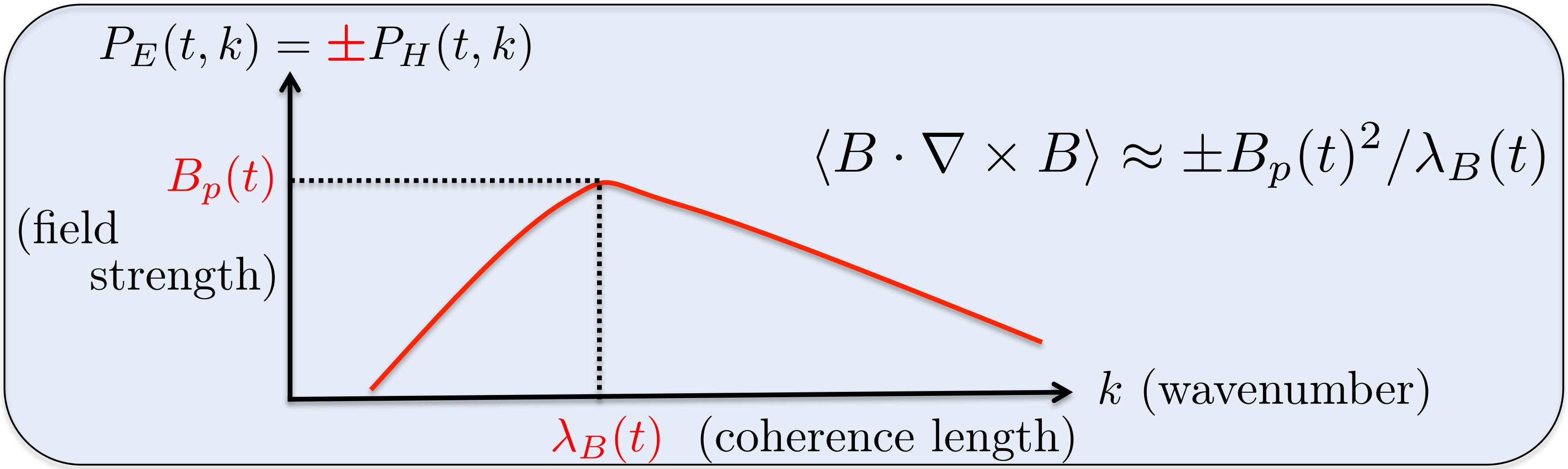


Lattice simulation of B-field growth during preheating after axion inflation
Adshead, Giblin, Scully, Sfakianakis (2016)

How do we formulate the problem?

Background B-Field Evolution

Simplified model for the background B-field:



MHD evolution of B-field leads to inverse cascade scaling behavior.

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

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

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

Baryon Asymmetry Evolution

Roughly speaking, you integrate the anomaly equation to obtain the kinetic equation for B-number:

$$\partial_\mu j_B^\mu = N_{\rm gen} \left(\frac{g^2}{16\pi^2} \mathrm{Tr}\big[W_{\mu\nu} \tilde{W}^{\mu\nu} \big] - \frac{1}{2} \frac{g'^2}{16\pi^2} Y_{\mu\nu} \tilde{Y}^{\mu\nu} \right)$$

$$\frac{d}{dt} n_B = -\Gamma_{\rm sphaleron}\, n_B + \mathcal{S}_{\rm hypermagnetic}$$

This glosses over Yukawa interactions which communicate B-number violation between the left- and right-chiral fermions.

SM Boltzmann eqns. w/ anomaly terms

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\eta = n/s$$

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

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

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

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

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

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

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

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

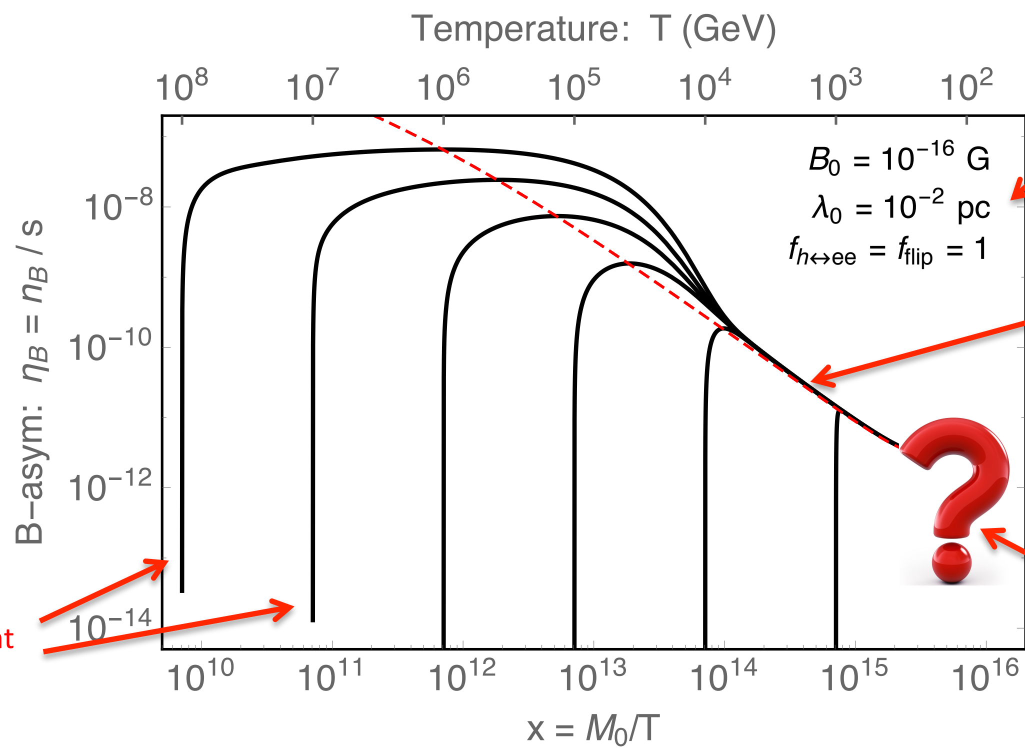
$$\mathcal{S}_{\rm hw} \equiv \gamma_{\rm hw}\left(\frac{\eta_{\phi^+}}{k_{\phi^+}} - \frac{\eta_{W^+}}{k_{W^+}}\right)$$

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

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

Numerical Results

Evolution before EW crossover



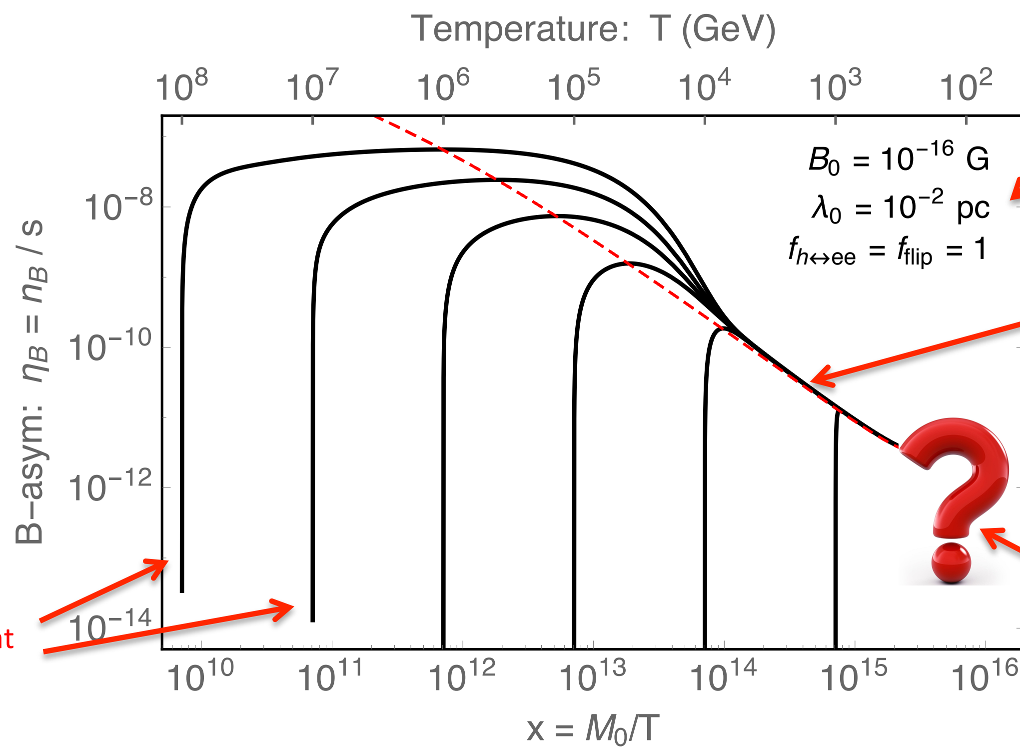
field strength & coherence length today

source term balances against washout by sphaleron

we'll discuss evolution through the EW crossover next

turn on B-field at different times

Evolution before EW crossover



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turn on B-field at different times

equilibrium baryon asymmetry: nB / s

source from decaying magnetic helicity

washout due to sphaleron + Yukawa interactions + chiral magnetic effect

$$\eta_B^{(\mathrm{eq})} \approx \frac{\# \frac{\alpha_{\mathrm{y}}}{sT} \big(\boldsymbol{B}_Y \cdot \boldsymbol{\nabla} \times \boldsymbol{B}_Y \big) / \sigma_Y}{\# |y_e|^2 m_h^2(T)/T^2 + \# \frac{\alpha_{\mathrm{y}}^2}{T^3} |\boldsymbol{B}_Y|^2 / \sigma_Y} \simeq \big(4 \times 10^{-12}\big) \frac{B_{14}^2}{\lambda_1} \frac{\big(T/T_{\mathrm{w}}\big)^{4/3}}{0.08\, m_h^2(T)/T^2 + B_{14}^2 \big(T/T_{\mathrm{w}}\big)^{2/3}}$$

order 1 numbers

$$\big(\; B_{14} \equiv B_0/(10^{-14}\,\mathrm{G}) \,, \;\; \lambda_1 \equiv \lambda_0/(1\,\mathrm{pc}) \,, \;\; T_{\mathrm{w}} \equiv 162\,\mathrm{GeV} \; \big)$$

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

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

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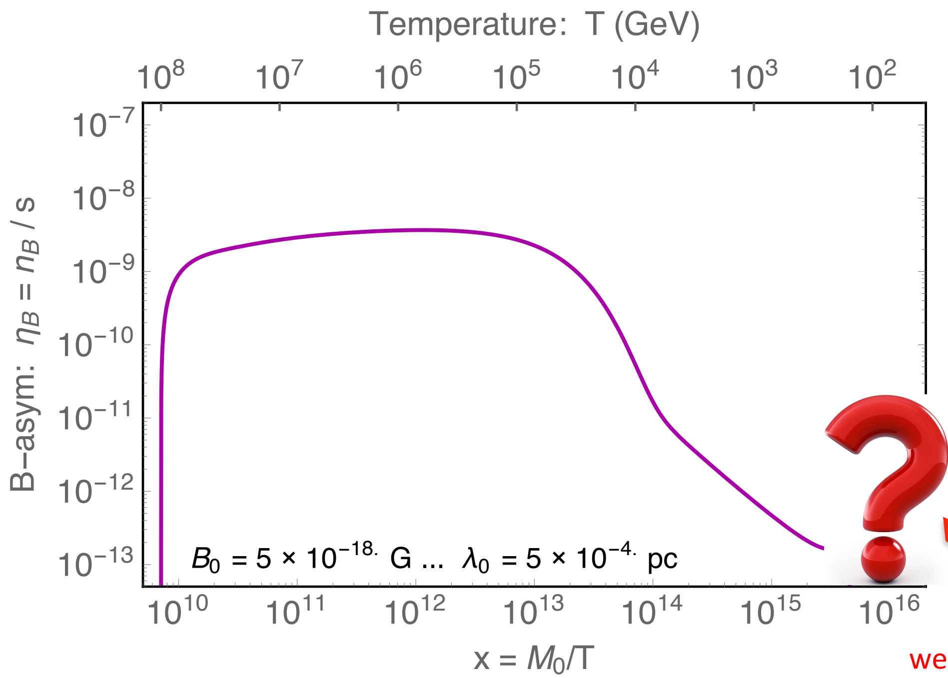

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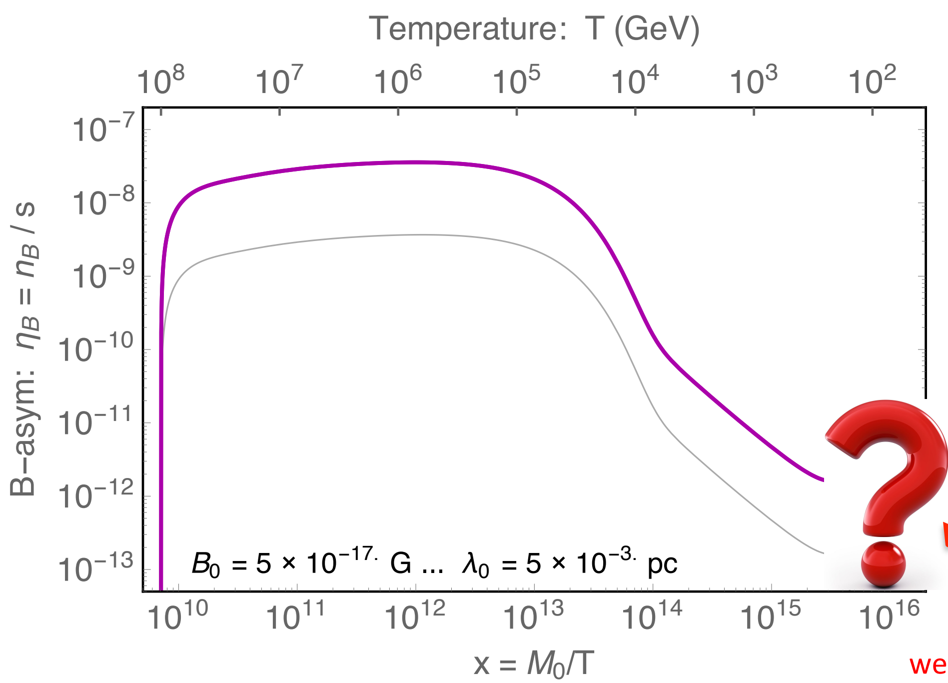

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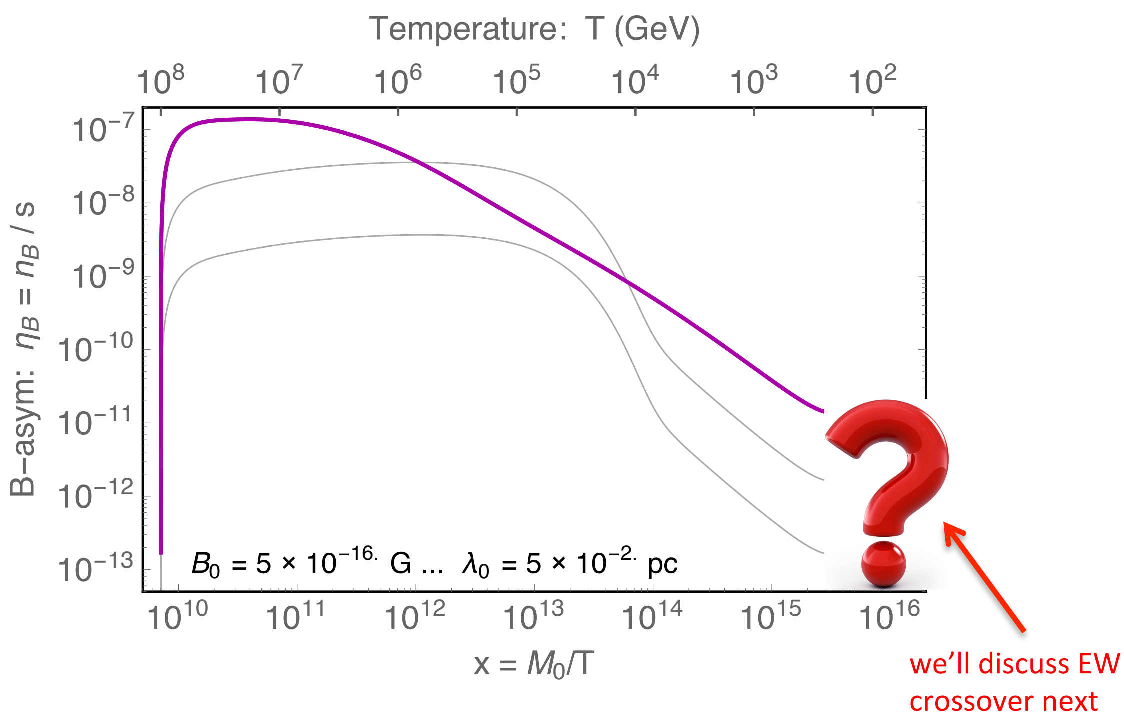

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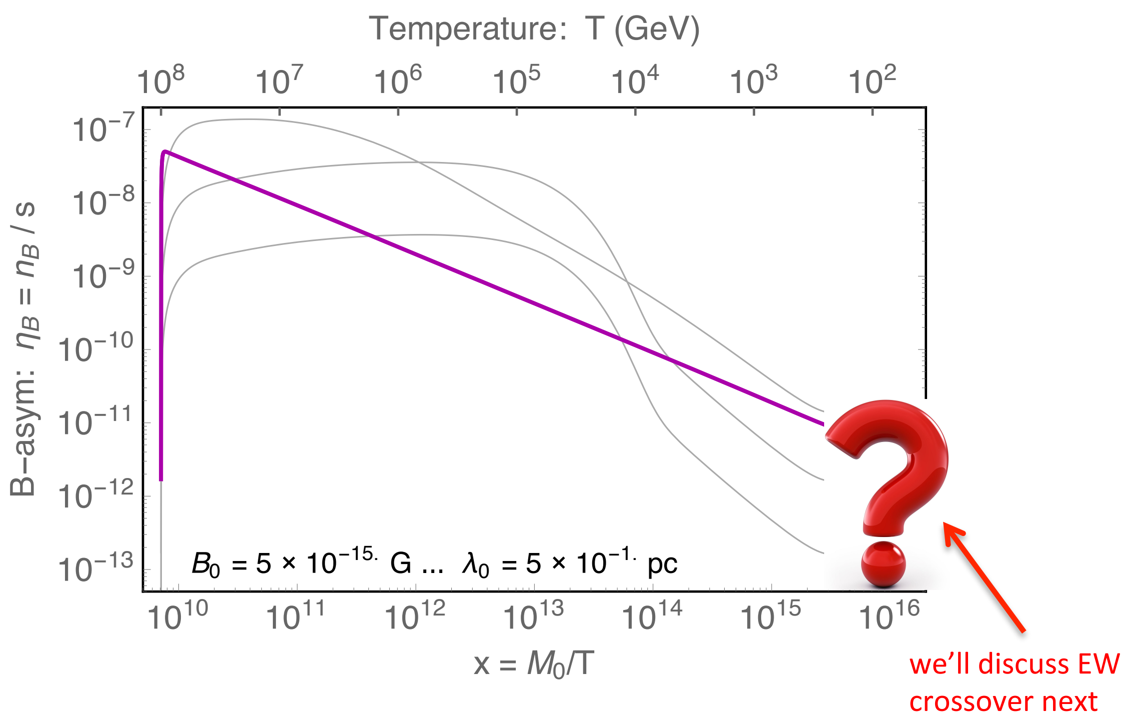

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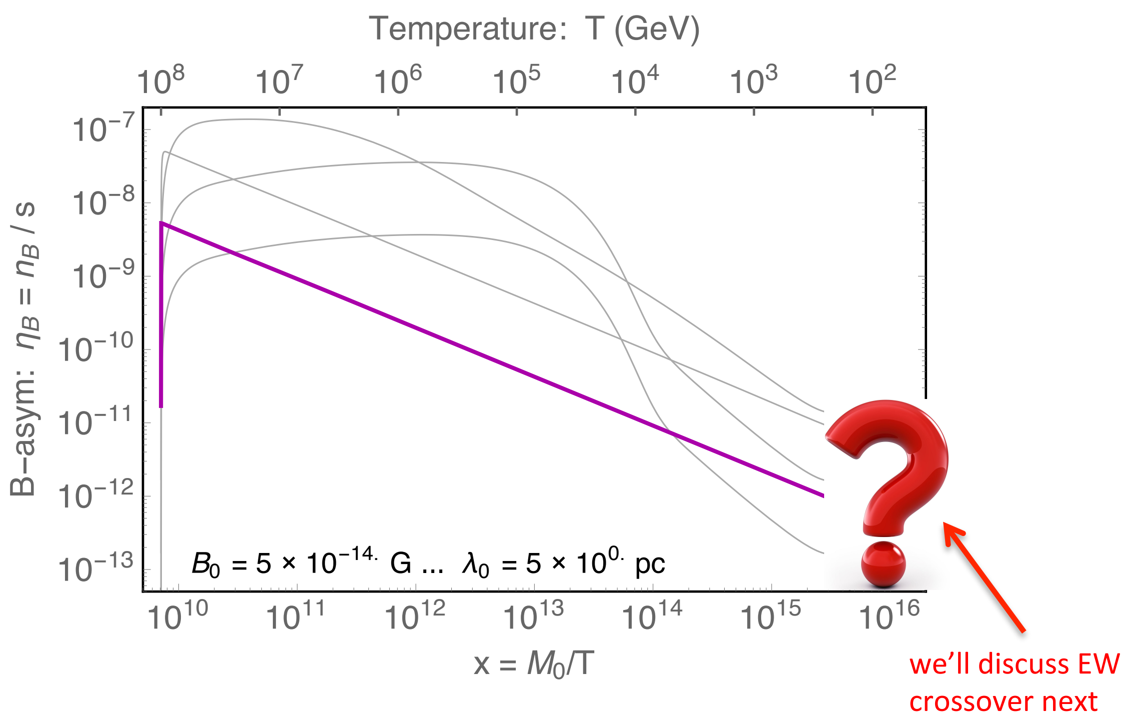

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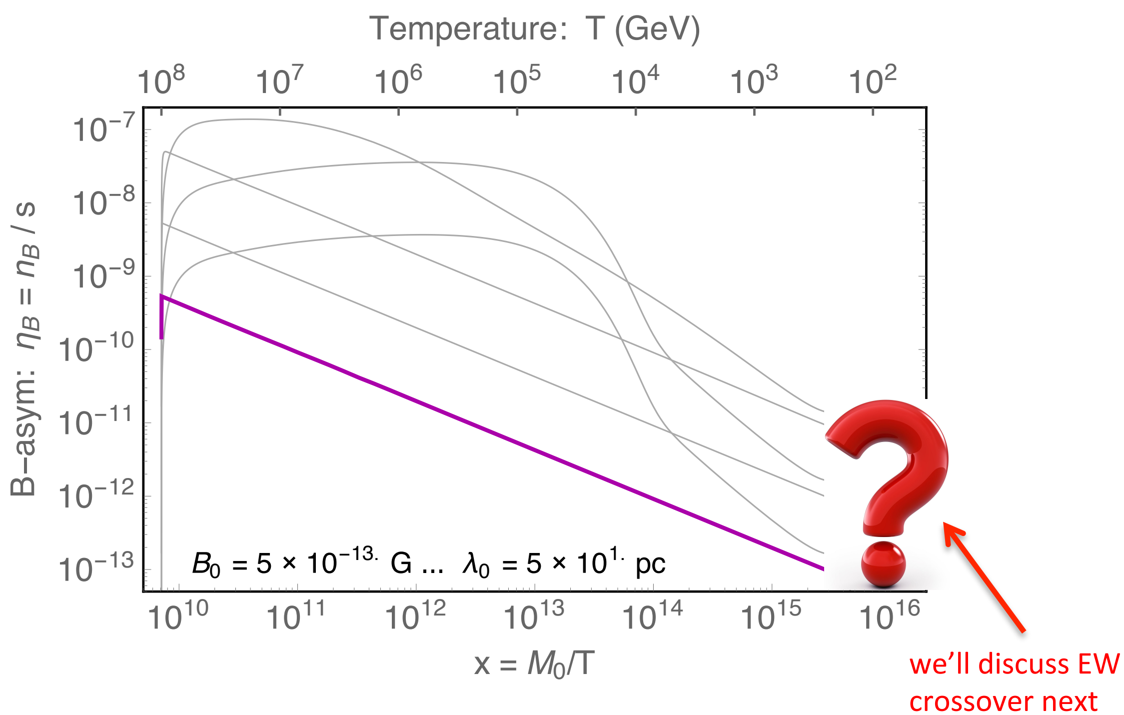

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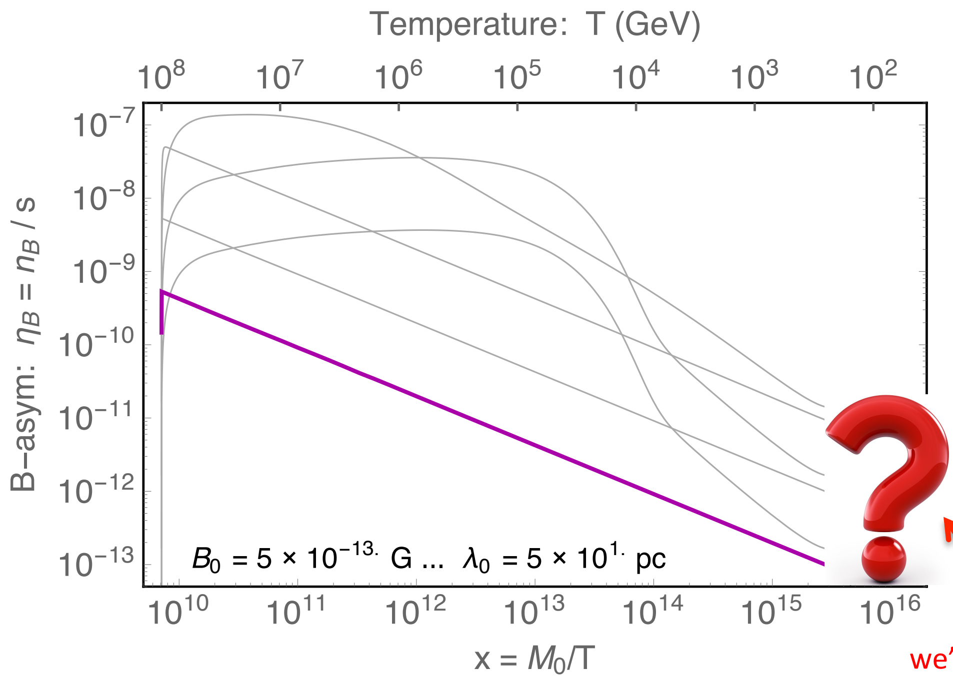

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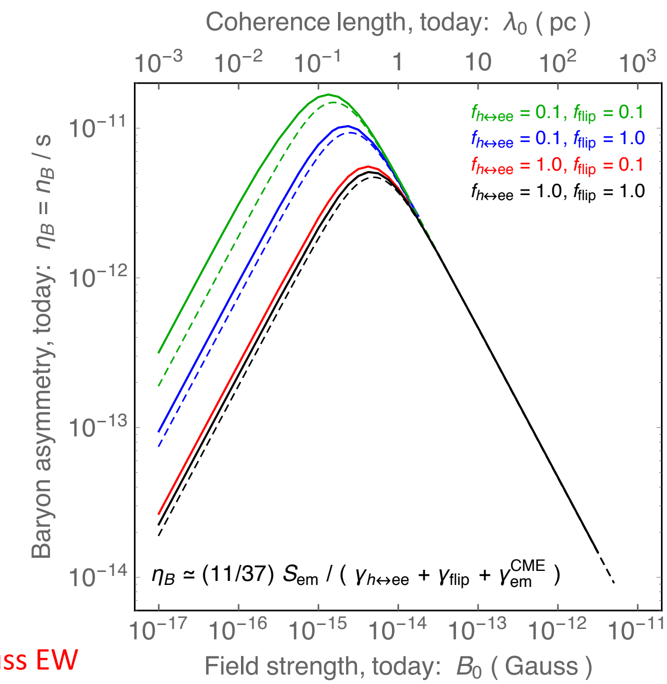


$$\eta_B^{(\mathrm{eq})} \approx \frac{\#\frac{\alpha_{\rm y}}{sT}\left(\boldsymbol{B}_Y \cdot \boldsymbol{\nabla} \times \boldsymbol{B}_Y\right)/\sigma_Y}{\#|y_e|^2 m_h^2(T)/T^2 + \underbrace{\#\,\frac{\alpha_{\rm y}^2}{T^3}|\boldsymbol{B}_Y|^2/\sigma_Y}} \simeq \left(4 \times 10^{-12}\right)\frac{B_{14}^2}{\lambda_1}\,\frac{\left(T/T_{\rm w}\right)^{4/3}}{0.08\, m_h^2(T)/T^2 + B_{14}^2\left(T/T_{\rm w}\right)^{2/3}}$$

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!

What happens at the EW crossover?

Evolution through EW Crossover

$$\frac{d}{dt} n_B = -\Gamma_{\text{sphaleron}}\, n_B + \mathcal{S}_{\text{hypermagnetic}}$$

At this time…

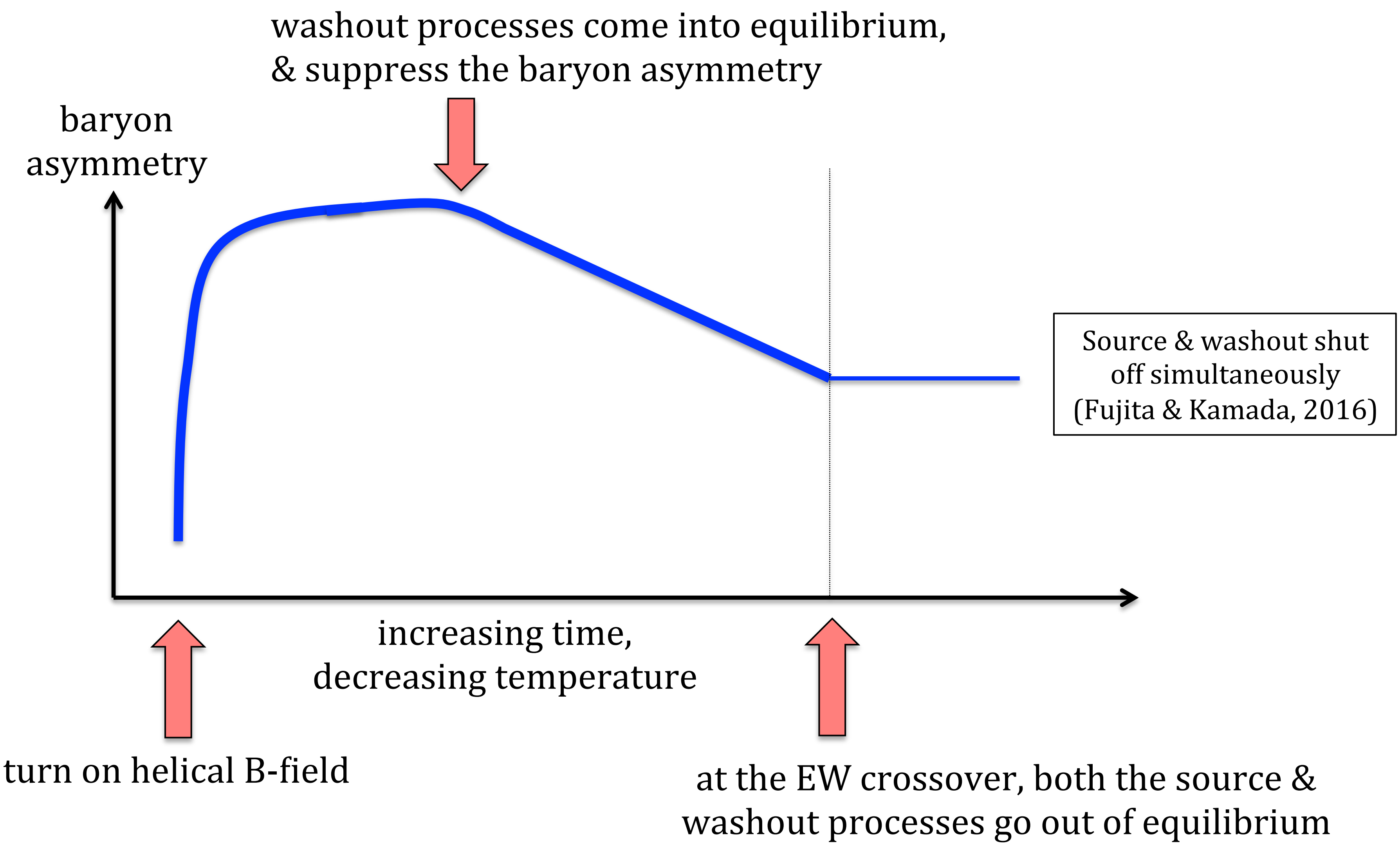
… the *source shuts off*, because the $U(1)_Y$ field is converted into a $U(1)_{em}$ field, which does not source B-number.

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

… the *washout shuts off*, because the W-boson mass grows, suppressing EW sphaleron transitions.

$$\Gamma_{\text{sph.}} \propto \exp\Big[-\#\, M_W(T)/\alpha_W\Big]$$

Crossover Evolution Scenarios



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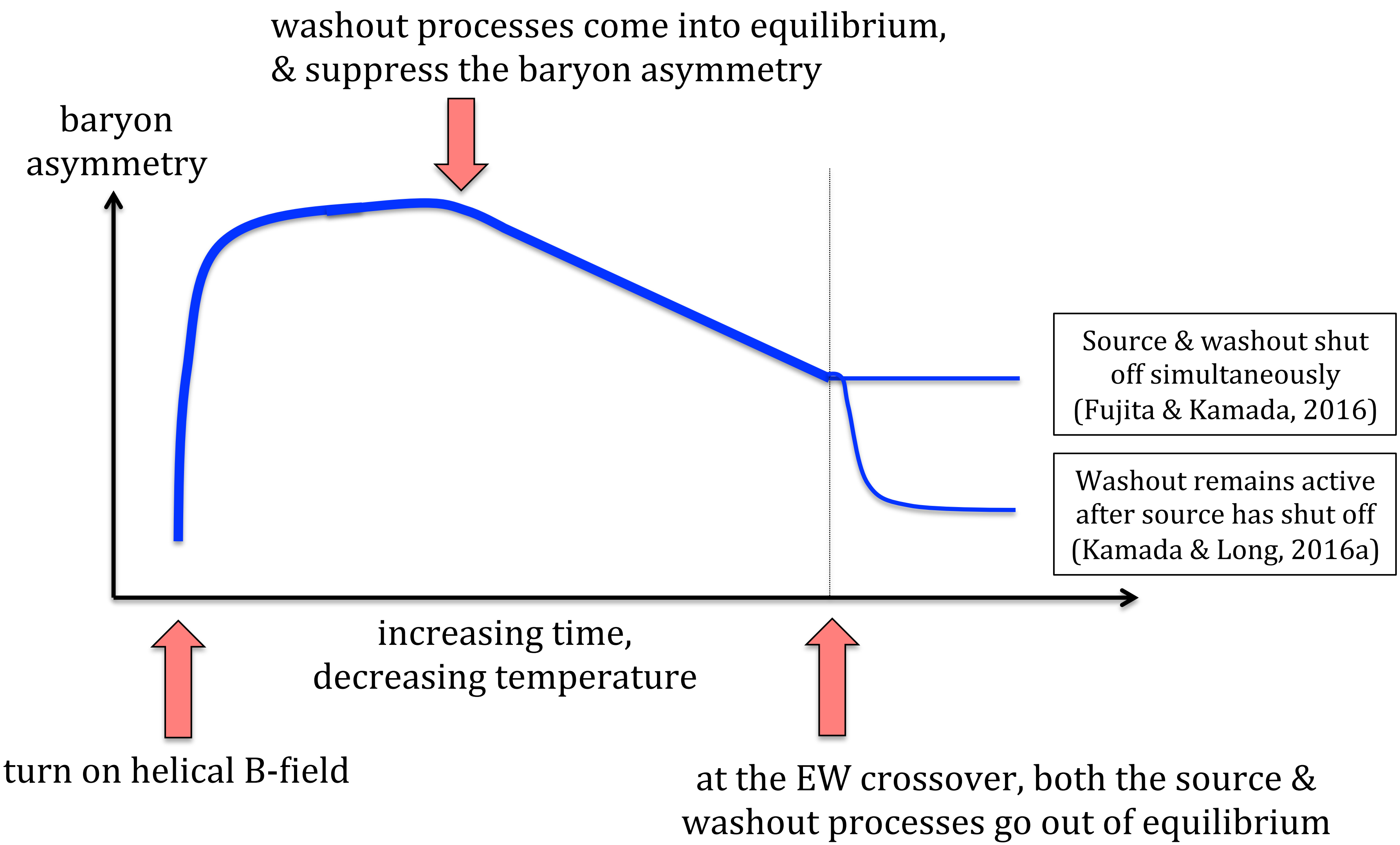
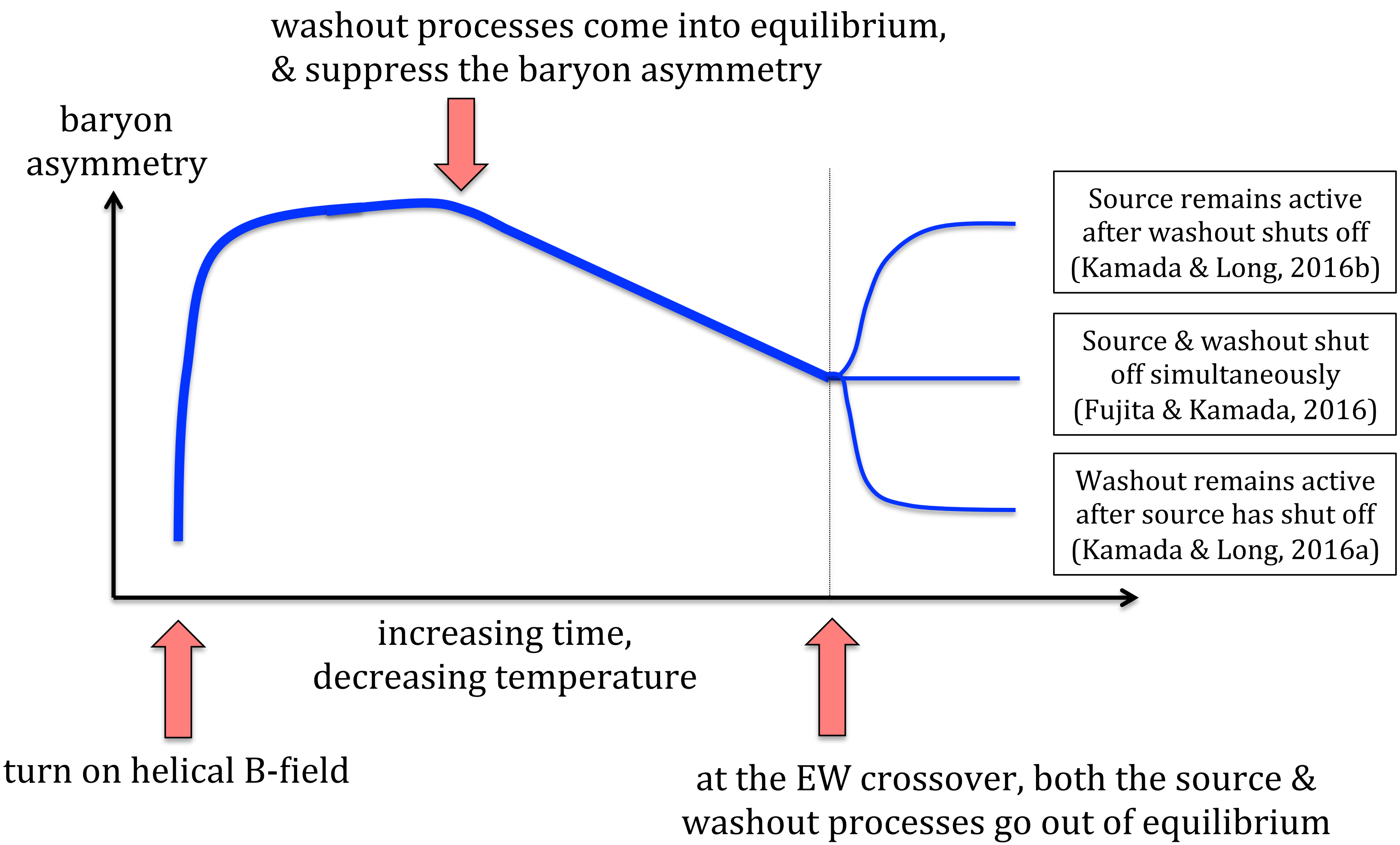


Crossover Evolution Scenarios

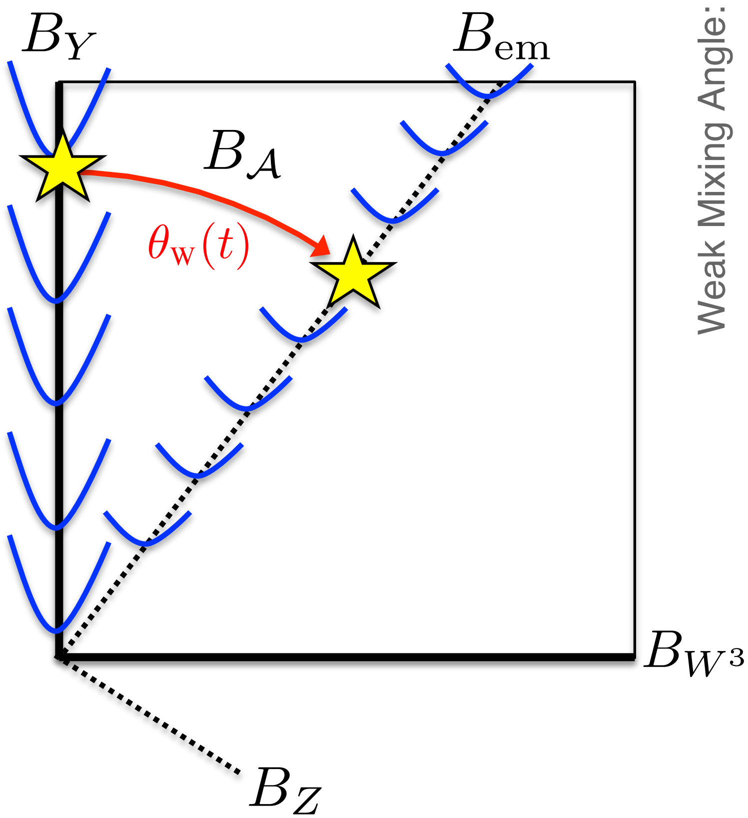


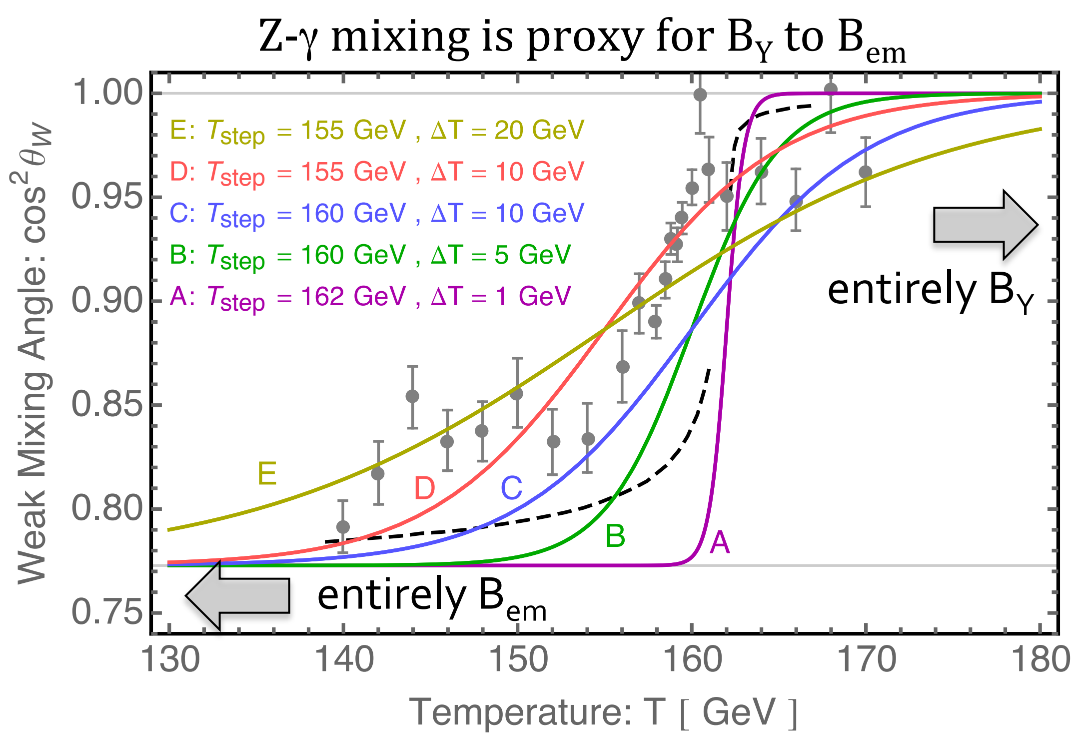
Model the $U(1)_Y$ to $U(1)_{em}$ conversion

$$\langle W^1_\mu(x)\rangle = \langle W^2_\mu(x)\rangle = 0$$

$$\langle W^3_\mu(x)\rangle = \sin\theta_{\rm w}(t)\,\mathcal{A}_\mu(x)$$

$$\langle Y_\mu(x)\rangle = \cos\theta_{\rm w}(t)\,\mathcal{A}_\mu(x)$$



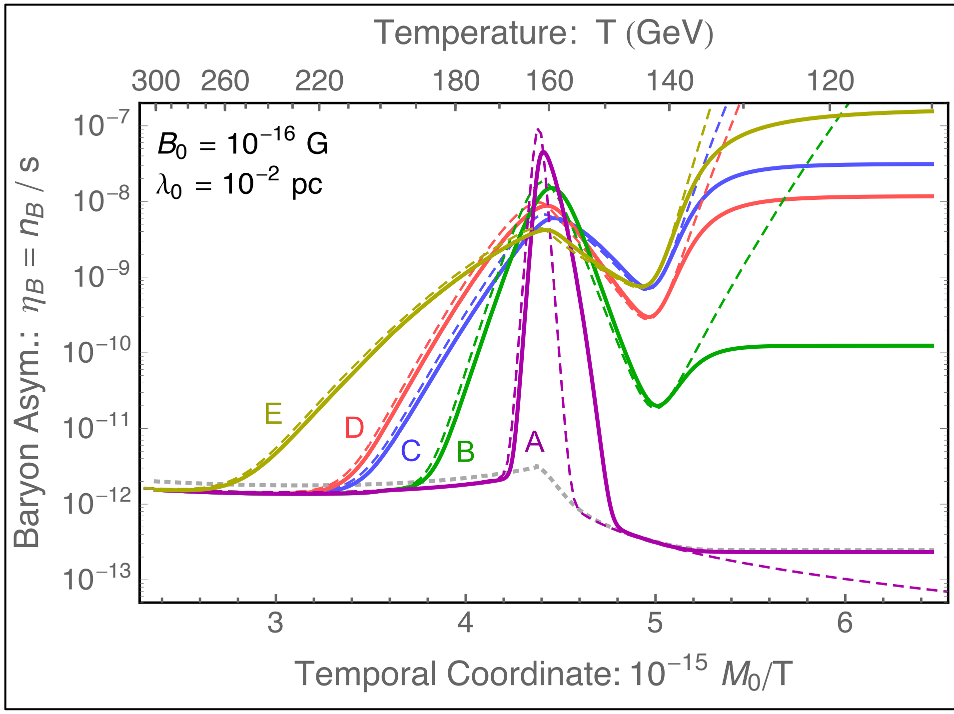


dots & error bars = lattice simulation from D'Onofrio & Rummukainen (2015).

black dashed = analytic approx. from Kajantie, Laine, Rummukainen, & Shaposhnikov (1996)

colored curves = we use tanh functions to model the crossover

BAU Evolution through EW Crossover



realistic regime … source active after washout shuts off

pessimistic regime … washout active after source shuts off

$$\eta_B^{\rm eq} \approx \frac{11}{37} \frac{g'^2 \left(\cos^2\theta_w \, \mathcal{S}_{\rm BdB} + \frac{d\theta_w}{d\ln x} \sin 2\theta_w \, \mathcal{S}_{\rm AB} \right)}{\frac{1}{2}\left(\gamma_{\rm Ehe}^{11} + \gamma_{\nu {\rm he}}^{11}\right) + \gamma_{\rm Ee}^{11} + g'^4 \cos^4\theta_w \gamma^{\rm CME}}$$

$A \cdot B$

$B \cdot \nabla \times B$

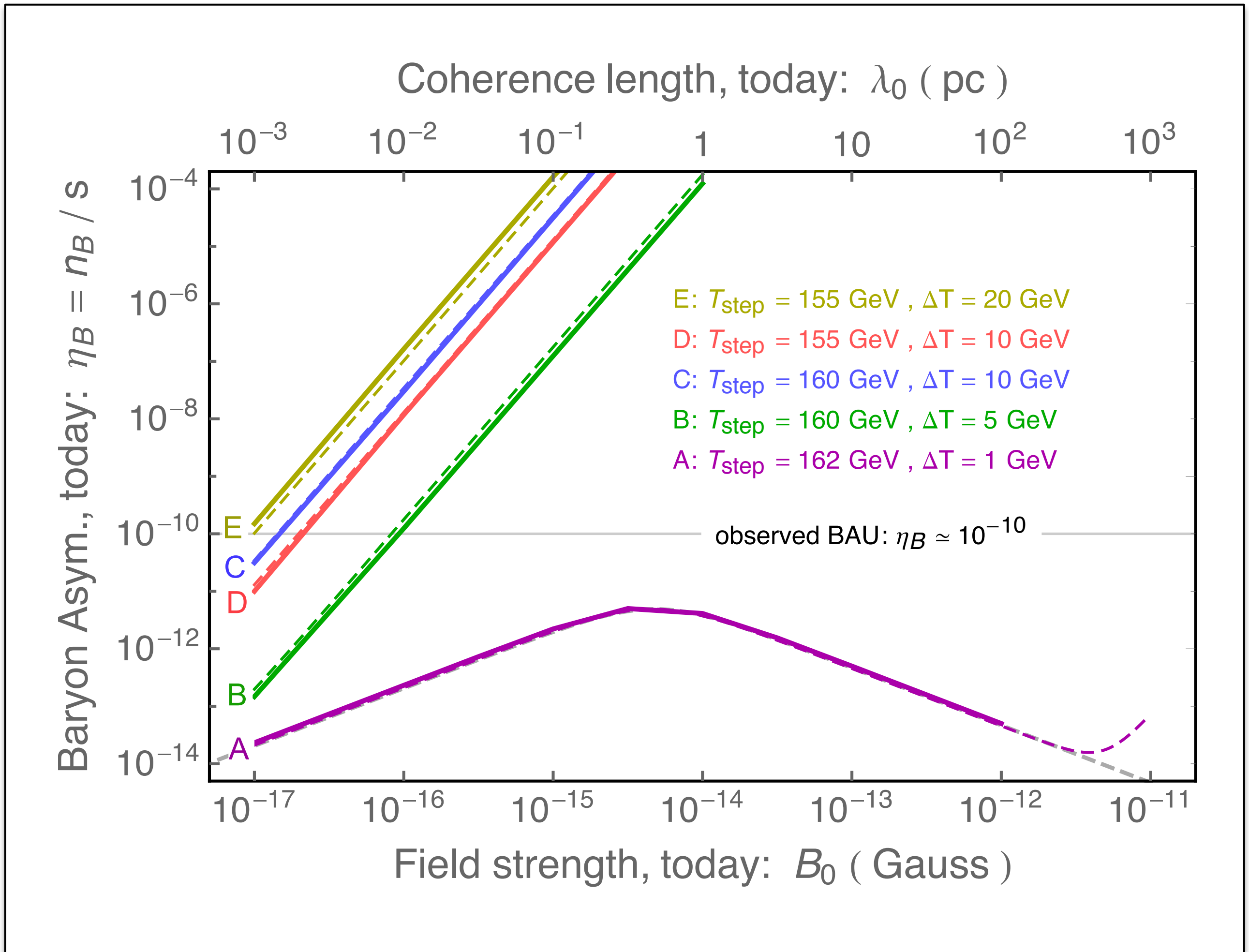
Result: Predicted Baryon Asymmetry

The conversion of $U(1)_Y$ B-field into $U(1)_{em}$ B-field at the EW crossover is not well-understood.

However, the relic baryon asymmetry depends sensitively on these details.

Consequently, the predicted baryon asymmetry is very uncertain.

Need to understand the crossover better!



Where to go from here?

Refinements:

Study conversion of magnetic fields at EW crossover

➔ main message in this talk

Calculate helicity decay directly with MHD simulations

➔ "not difficult" to implement

Implications & Applications:

Study baryogenesis from axion inflation (etc.) self-consistently

➔ Various studies: Anber & Sabancilar (2015); Cado & Sabancilar (2016); Jimenez, Kamada, Schmitz, & Xu (2017)

Observation side – develop new probes of relic (helical) magnetic fields

➔ E.g., using cascade halos around TeV blazars

Study "dark" magnetic field (hidden sector U1) and /or dark matter production

➔ E.g., Cado & Sabancilar (2016)

Executive Summary

In this talk, I'm going to …

… assume that a helical magnetic field was created in the early universe prior to the EW epoch. (e.g., arises naturally in axion inflation)

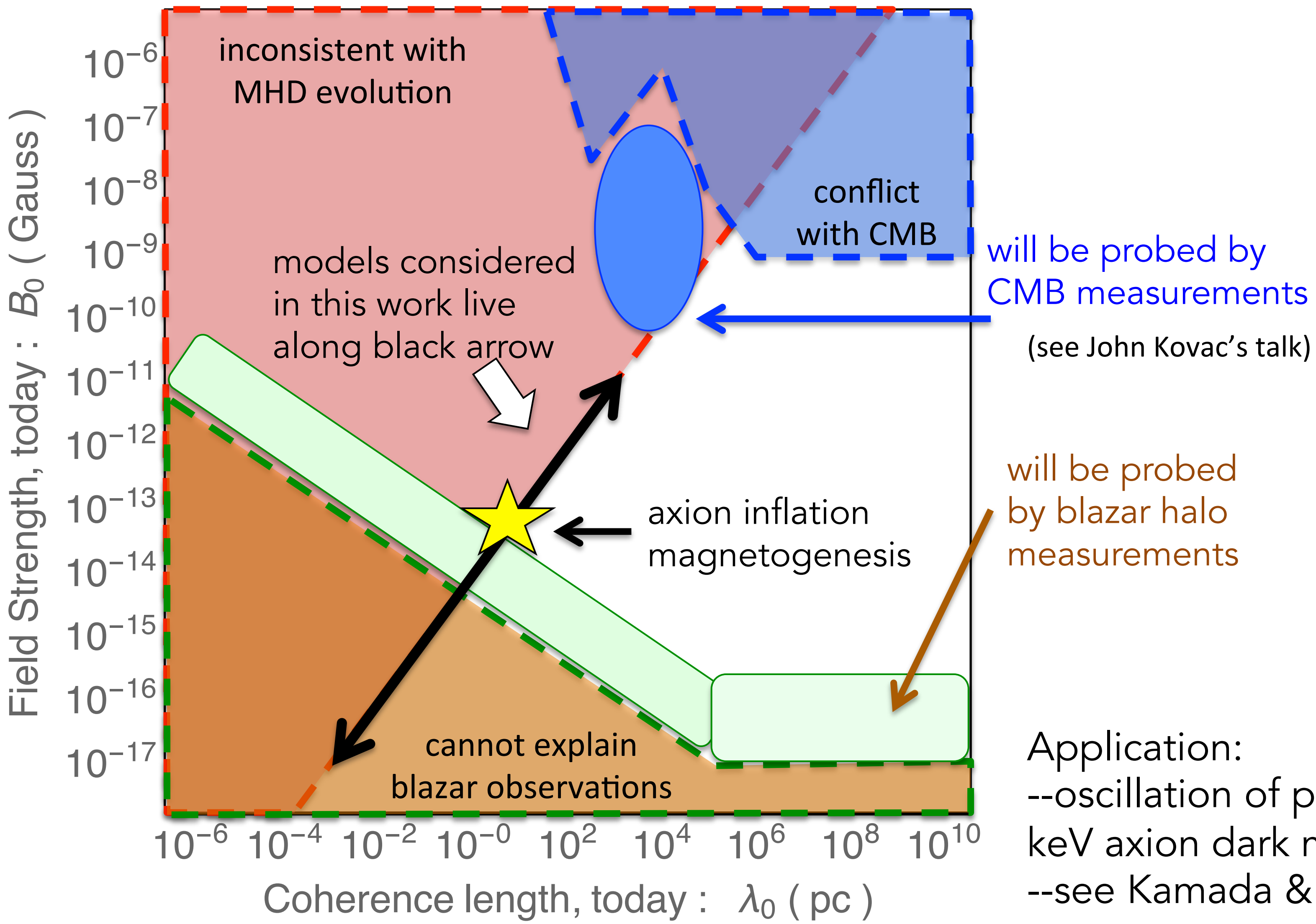
… show that the decaying helicity of this field gives rise to a baryon asymmetry through the Standard Model B+L anomaly (builds on earlier work by Joyce, Shaposhnikov, Giovannini, Bamba, Geng, Ho, …)

… calculate the evolution of the magnetic field and baryon asymmetry from magnetogenesis until today, while paying particular attention to the EW crossover (this is my work with Kohei Kamada; see also Fujita & Kamada, 2016)

… conclude that the predicted relic baryon asymmetry suffers from a large theoretical uncertainty, because we don't understand well how magnetic fields behave at the EW crossover (even though this is just SM physics!)

backup

Implications & Applications



Application:
--oscillation of photons into keV axion dark matter
--see Kamada & Nakai (2017)

(figure adapted from Durrer & Neronov, 2013)

Magnetic Field Scaling Law

Comoving quantities: $\tilde{B}(\tau) = a(t)^2 B_p(t)$ $\quad \tilde{\lambda}(\tau) = a(t)^{-1} \lambda_B(t)$

Adiabatic evolution after recombination: $\tilde{B}_{\rm rec} = B_0$ $\quad \tilde{\lambda}_{\rm rec} = \lambda_0$

Coherence length tracks eddy scale:

$$\tilde{\lambda}(\tau) = C\, v_A(\tau)\tau$$

$$v_A(\tau) = c/\sqrt{1 + (\rho + P)/(2P_m)} \propto \tilde{B}(\tau)$$

$$P_m(\tau) = \tilde{B}(\tau)^2/2$$

Helicity is quasi-conserved: $\tilde{\lambda}\tilde{B}^2 = \tilde{\lambda}_{\rm rec}\tilde{B}^2_{\rm rec}$ $\quad$ H ~ λ B[2] for maximally helical field

Solution:

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

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

"inverse cascade"

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

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