Baryogenesis from Axion Inflation

Kyohei Mukaida

DESY, HAMBURG

Based on **1806.08769**, **1905.13318**
In collaboration with V. Domcke, B. von Harling, E. Morgante

1.

Introduction

Introduction

Inflaton w/ CS-coupling

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

- **Flat** potential v.s. **Couplings** to visible sector
  - **Flatness** protected by the shift sym. $\phi \longmapsto \phi + c$
  - **Reheating** via the CS coupling

- Efficient **helical-gauge field** production by $\dot{\phi} \neq 0$.

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

where $\xi \equiv \dfrac{\alpha \dot{\phi}}{2\pi f_a H}$

$$0 \neq \langle F_{\mu\nu} \tilde{F}^{\mu\nu} \rangle = -4 \langle \boldsymbol{E} \cdot \boldsymbol{B} \rangle$$

➡ (Pre)Reheating, chiral GWs, **baryogenesis**, magnetogenesis,…

Introduction

Coupling to the SM Gauge Group ?

$$S = \int \mathrm{d}^4 x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] - \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + \frac{\alpha_Y \phi}{4\pi f_a} Y_{\mu\nu} \tilde{Y}^{\mu\nu} + \sum_\alpha \psi_\alpha^\dagger \sigma \cdot (i\partial - g_Y Q_\alpha A_Y) \psi_\alpha + \cdots \right\}$$

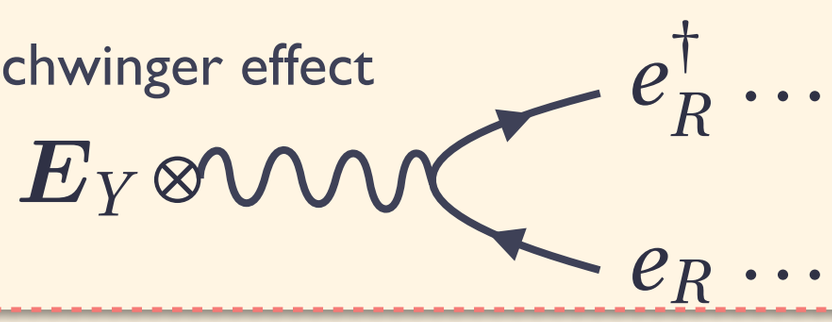
U(1)$_Y$

Matters charged under **U(1)$_Y$**

- Production of **matters** charged under the **SM gauge group**.
  - **B+L asymmetry** generation via the **SM chiral anomaly**

$$\partial_\mu J^\mu_{B+L} = \frac{3}{16\pi^2} \left(g_2^2 W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - g_Y^2 Y_{\mu\nu} \tilde{Y}^{\mu\nu} \right) \neq 0$$

  - **Pair** production via the Schwinger effect



➡ Does **Baryon/Lepton asymmetry** survive?

Our Idea

Baryogenesis from B+L asymmetry?

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{3}{32\pi^2}\left(g_2^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g_Y^2 Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$

Inflation

Dual production of **B+L asym.** and **helical U(1)$_Y$** via $\phi Y_{\mu\nu}\tilde{Y}^{\mu\nu}$.

$$\Delta q_B = \Delta q_L = -\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$$

$T_{Y_e} \sim 10^5\,\mathrm{GeV}$

$T_{\mathrm{EW}} \sim 10^2\,\mathrm{GeV}$

Now

Time

Our Idea

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{3}{32\pi^2}\left(g_2^2 \; \partial\cdot K_{\rm CS} - g_Y^2 \; \partial\cdot h_Y\right)$$

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via **Sphaleron + Yukawa**

Inefficient **diffusion**

No **CPI** (chiral plasma instability)

$$0 \qquad +\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y \qquad -\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$$

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$+\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

$T_{\rm EW} \sim 10^2\,\mathrm{GeV}$

⊿ **h$_Y$** is converted to **U(1)$_{em}$**
+ **Sphaleron freezes out**

Now

$\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

$* \, \Gamma_{\text{EW-inst}} \ll H_0$

0

Time

Outline of this Talk

Baryogenesis from B+L asymmetry?

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{3}{32\pi^2}\left(g_2^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g_Y^2 Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$

Inflation — Dual production of **B+L asym.** and **helical U(1)$_Y$** via $\phi Y_{\mu\nu}\tilde{Y}^{\mu\nu}$.

$\Delta q_B = \Delta q_L =$ $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ **2.**

$T_{Y_e} \sim 10^5\,\mathrm{GeV}$ — via **Sphaleron + Yukawa**

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0 $+\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ **3.**

$T_{\mathrm{EW}} \sim 10^2\,\mathrm{GeV}$ — ⊿ **h$_Y$** is converted to **U(1)$_{em}$** + **Sphaleron freezes out**

Now $\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ $*\,\Gamma_{\text{EW-inst}} \ll H_0$ 0 **4.**

Time

2.

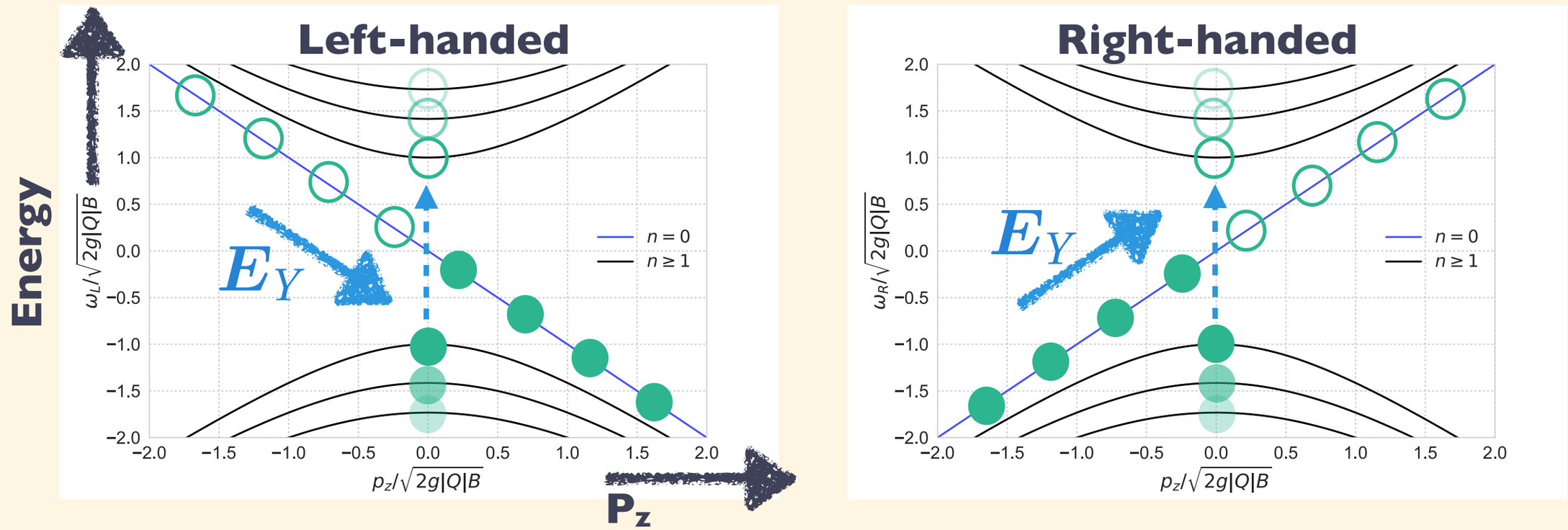
Production of

Helical gauge & **Chiral** fermion

Fermion Production

Fermion Production in $B_Y \parallel E_Y$

V.Domcke and **KM** 1806.08769



- **ABJ anomaly** from **Lowest Landau Level** (n=0)

$$\dot{q}_\alpha = \epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y = -\epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{16\pi^2} Y^{\mu\nu}\tilde{Y}_{\mu\nu} \qquad \text{w/ } \epsilon_\alpha = \pm \text{ for R/L}$$

Nielsen, Ninomiya, Phys.Lett. **130B** (1983)

- **Schwinger pair-production** from **Higher ones** (n=1,2,…)

$$\dot{n}_{\alpha,R}^{(n\geq 1)} = \dot{\bar{n}}_{\alpha,R}^{(n\geq 1)} = \dot{n}_{\alpha,L}^{(n\geq 1)} = \dot{\bar{n}}_{\alpha,L}^{(n\geq 1)} = N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y \frac{1}{e^{\frac{2\pi B_Y}{E_Y}} - 1}$$

Fermion Production

Fermion Production in $B_Y \parallel E_Y$

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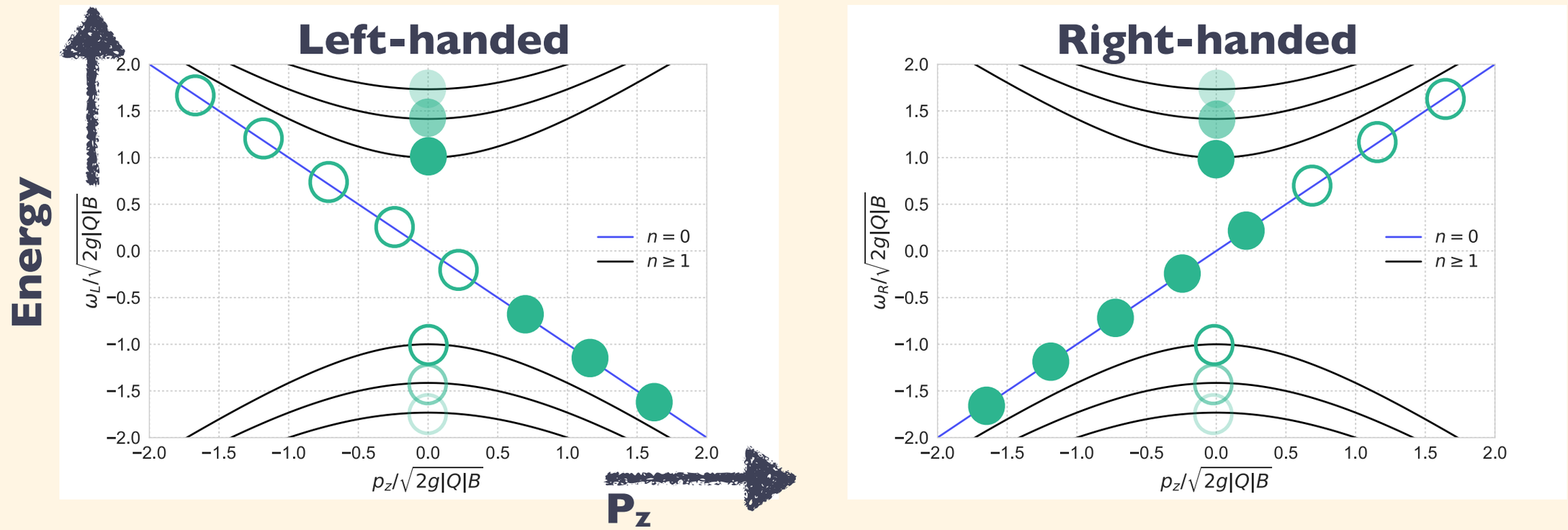

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Fermion Production

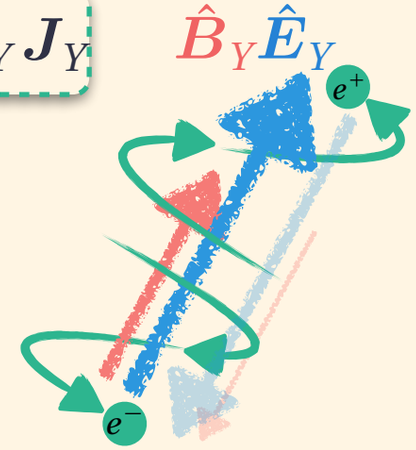
Implications on Axion Inflation

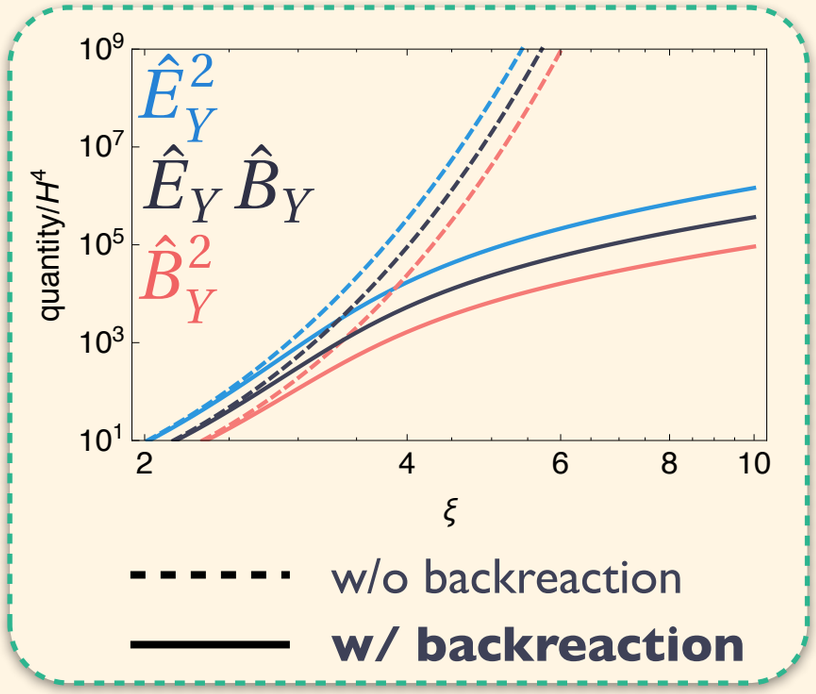
V.Domcke and **KM** 1806.08769

- **Backreaction** suppresses gauge field

$$0 = -\partial_t \boldsymbol{E}_Y + \nabla \times \boldsymbol{B}_Y + a \frac{g_Y^2}{4\pi^2} \frac{\dot{\phi}}{f_a} \boldsymbol{B}_Y - g_Y \boldsymbol{J}_Y$$

$$g_Y \boldsymbol{J}_Y = a \left[\sum_\alpha N_\alpha \frac{g_Y^3 |Q_\alpha|^3}{12\pi^2} \coth\left(\frac{\pi \hat{B}_Y}{\hat{E}_Y} \right) \frac{\hat{B}_Y}{H} \right] \boldsymbol{E}_Y$$





- **Primordial** generation of **B+L asym**.

$$\Delta q_{B+L}^{\rm rh} = -\frac{3}{2} \frac{\alpha_Y}{\pi} \Delta h_Y^{\rm rh} \quad \text{where} \quad \frac{\Delta h_Y^{\rm rh}}{a_{\rm rh}^3} = -\frac{2}{3H_{\rm rh}} \langle \hat{\boldsymbol{E}}_Y \cdot \hat{\boldsymbol{B}}_Y \rangle_{\rm rh}$$

$$\frac{\hat{\mu}_{B+L}^{\rm rh}}{\hat{T}_{\rm rh}} = \frac{6\alpha_Y}{\pi} \left(\frac{H_{\rm rh}}{M_*} \right)^{\frac{3}{2}} \frac{\langle \hat{\boldsymbol{E}}_Y \cdot \hat{\boldsymbol{B}}_Y \rangle_{\rm rh}}{H_{\rm rh}^4} \sim 10^{-3} \left(\frac{H_{\rm rh}}{10^{14}\,{\rm GeV}} \right)^{\frac{3}{2}} \left(\frac{\langle \hat{\boldsymbol{E}}_Y \cdot \hat{\boldsymbol{B}}_Y \rangle_{\rm rh} / H_{\rm rh}^4}{10^5} \right)$$

3.

Survival of Helical Gauge Field

Outline of this Talk

Baryogenesis from B+L asymmetry?

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{3}{32\pi^2}\left(g_2^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g_Y^2 Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$

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No **CPI** (chiral plasma instability)

0 $+\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ **3.**

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Now $\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ $*\,\Gamma_{\text{EW-inst}} \ll H_0$ 0 **4.**

Time

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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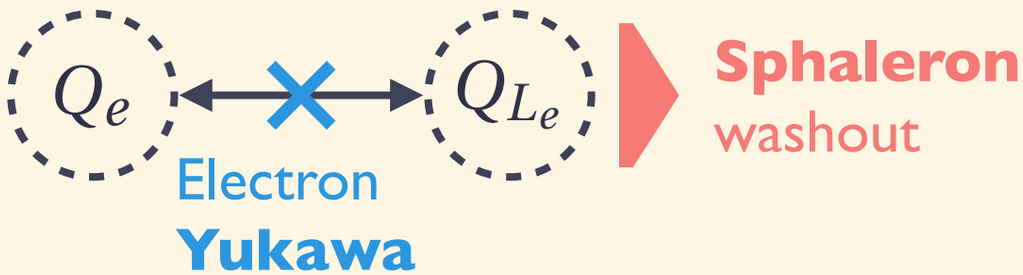
1905.13318

- **Survival of Q_e** from **Sphaleron** + **Yukawa** washout



Electron Yukawa is **NOT** efficient till

$$\hat{T} < \hat{T}_{Y_e} \sim 10^5\,\mathrm{GeV}$$

- **Chiral Plasma Instability** (CPI) as inverse process

$$\partial \cdot J_e = -\frac{g_Y^2}{16\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + (\text{Yukawa}) \quad \blacktriangleright \quad \dot{q}_e = -\frac{\alpha_Y}{2\pi}\dot{h}_Y - \frac{711}{481}\Gamma_{Y_e} q_e$$

$$\hat{T}_{\rm CPI} \sim 10^5\mathrm{GeV}\left(\frac{H_{\rm rh}}{10^{14}\mathrm{GeV}}\right)^3\left(\frac{\langle \hat{\boldsymbol{E}}_Y\cdot\hat{\boldsymbol{B}}_Y\rangle_{\rm rh}/H_{\rm rh}^4}{10^5}\right)^2$$

	q_e	$\frac{\alpha_Y}{2\pi}h_Y$
Inflation $\dot{\phi}h_Y$	$-\frac{\alpha_Y}{2\pi}\Delta h_Y$	$\frac{\alpha_Y}{2\pi}\Delta h_Y$
$\dot{\phi}=0$	0	0

Chiral Plasma
Instability

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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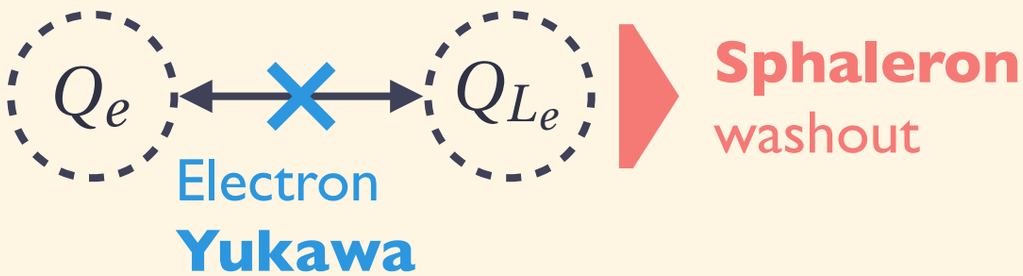
- **Survival of Q_e** from **Sphaleron** + **Yukawa** washout



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	q_e	$\frac{\alpha_Y}{2\pi}h_Y$
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$$\hat{T}_{\rm CPI} < \hat{T}_{Y_e} \sim 10^5\,\mathrm{GeV}$$

Chiral Plasma
Instability

Sphaleron+Yukawa
washout

	0	$\frac{\alpha_Y}{2\pi}\Delta h_Y$

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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- **Chiral Magneto Hydro Dynamics** (ChMHD)

$$\frac{\partial}{\partial \eta}\boldsymbol{v} + \boldsymbol{v}\cdot\nabla\boldsymbol{v} = \nu\nabla^2\boldsymbol{v} + \frac{1}{\rho+P}\left(-\frac{1}{2}\nabla B_Y^2 + (\boldsymbol{B}_Y\cdot\nabla)\boldsymbol{B}_Y\right)$$

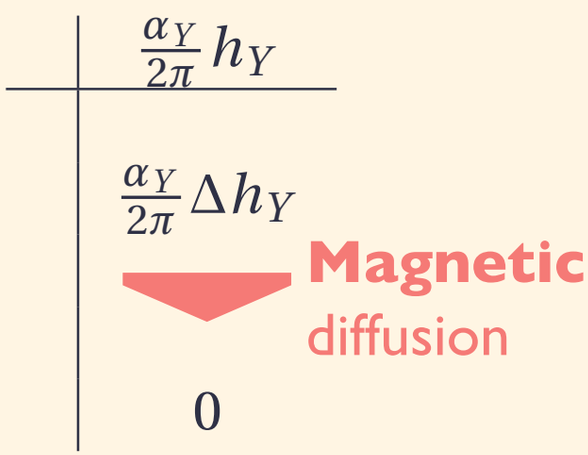
$$\frac{\partial \boldsymbol{B}_Y}{\partial \eta} = \frac{\nabla^2}{\sigma_Y}\boldsymbol{B}_Y + \nabla\times(\boldsymbol{v}\times\boldsymbol{B}_Y) + \frac{2\alpha_Y}{\pi}\frac{\mu_{Y,5}}{\sigma_Y}\nabla\times\boldsymbol{B}_Y$$

Chiral Plasma
Instability

w/ $\mu_{Y,5} = \sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha}^2 \mu_\alpha$

Magnetic
Diffusion

$$\hat{T}_{\rm diff} \sim \frac{\alpha_Y \ln \alpha_Y^{-1}}{5} H_{\rm rh}$$



Survival of Helical Gauge Field

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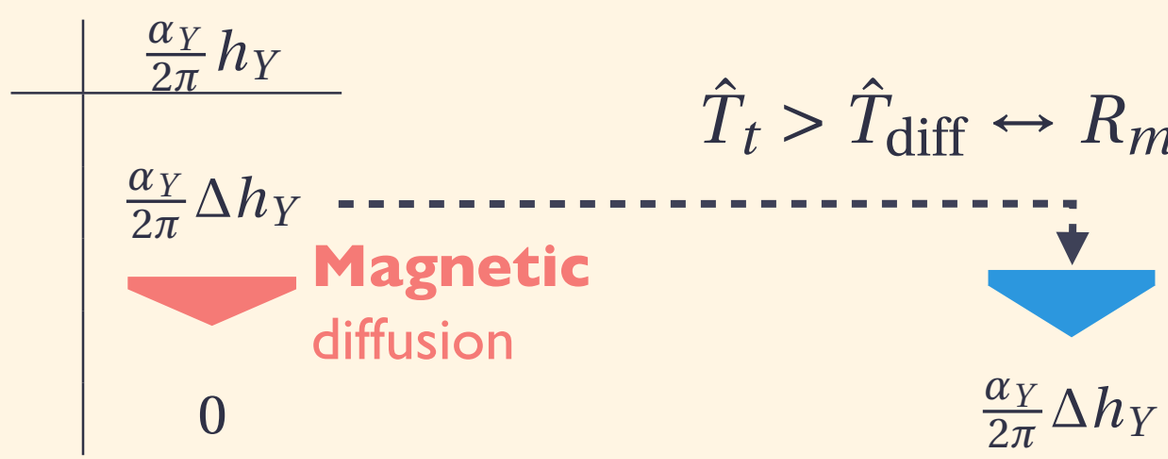
$$\hat{T}_{\rm diff} \sim \frac{\alpha_Y \ln \alpha_Y^{-1}}{5} H_{\rm rh}$$

Inverse
cascade

$$\hat{T}_{\rm t} \sim v_{\rm rh} \hat{T}_{\rm rh}$$

- **Large Magnetic Reynolds #** ← Inverse cascade



$$\hat{T}_t > \hat{T}_{\rm diff} \leftrightarrow R_m \equiv \sigma_Y L_{\rm rh} v_{\rm rh} > 1$$

- Transfer from short to long wave length.
- Approximate **conservation of h_Y**.

4.

Regeneration of Baryon Asymmetry

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Time

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

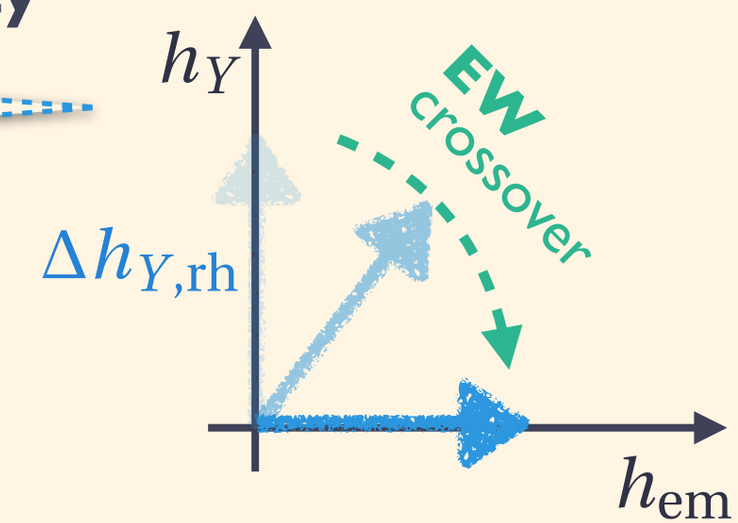
T. Fujita, K.Kamada 1602.02109
K.Kamada, A.Long 1610.03074

- Transport equation @ **EW Crossover**
  - Slowest processes: **EW sphaleron** & **Decaying helicity**

$$\partial_\eta q_B = -\frac{111}{34}\Gamma_{W,\mathrm{sph}}\, q_B + \frac{3}{2}\left(g_2^2+g_Y^2\right)\sin(2\theta)\left(\partial_\eta\theta\right)\frac{\Delta h_Y^{\mathrm{rh}}}{8\pi^2}$$

$$\begin{cases}\Gamma_{\mathrm{W,sph}} \propto e^{-\frac{M_{\mathrm{sph}}(T)}{T}} \\ M_{\mathrm{sph}}(T) \propto v(T)\end{cases}$$

$$\propto \partial_\eta h_Y$$



  - Final **baryon asym**: **EW sphaleron** washout v.s. **Decaying helicity**

$$\eta_B = \frac{\hat{q}_B}{\hat{s}} \simeq \left[\frac{34}{111}\left(1+\frac{\alpha_2}{\alpha_Y}\right)\frac{H}{\Gamma_{W,\mathrm{sph}}} f\left(\theta,\hat{T}\right)\right]_{T_{\mathrm{EW}}} \frac{3\alpha_Y}{4\pi}\frac{\Delta\hat{h}_Y}{\hat{s}}\Bigg|_{\mathrm{rh}} \quad \text{w/ } f\left(\theta,\hat{T}\right) = -\hat{T}\frac{\mathrm{d}\theta}{\mathrm{d}\hat{T}}\sin(2\theta)$$

EW sphaleron
Washout-factor

$$\Delta\hat{h}_Y^{\mathrm{rh}} = -\frac{2}{3H_{\mathrm{rh}}}\left\langle \hat{E}_Y\cdot\hat{B}_Y\right\rangle_{\mathrm{rh}}$$

EW crossover
- Huge uncertainties…

$$f_{T_{\mathrm{EW}}} \in \left[6\times10^{-4}, 0.3\right]$$

Result

Viable parameters for Baryogenesis

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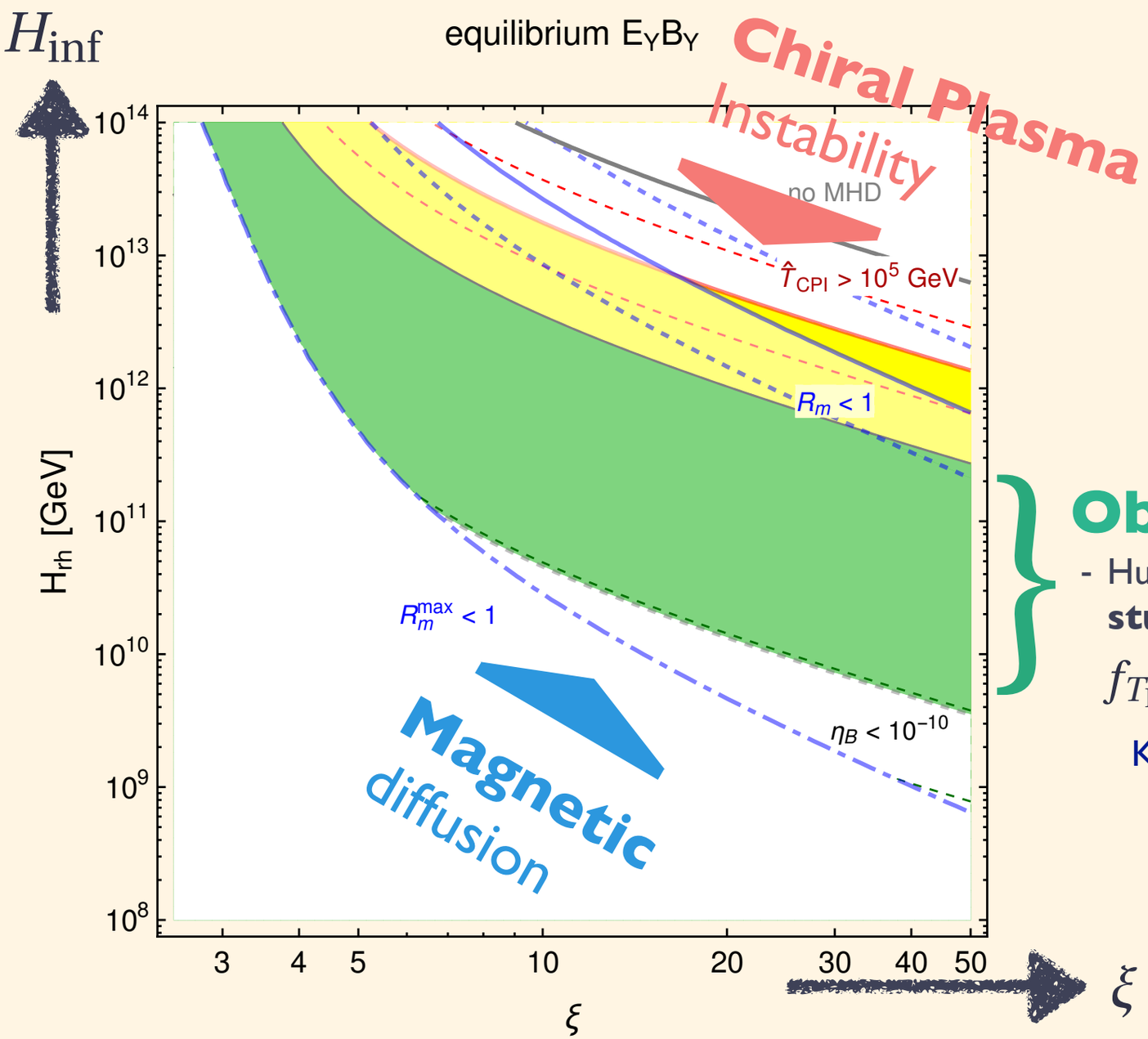

Observed η_B

- Huge uncertainties from **lattice studies of EWPT**…

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K.Kamada and A.Long 1610.03074

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

Summary

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1905.13318

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] - \frac{1}{4} Y_{\mu\nu} Y^{\mu\nu} + \frac{\alpha_Y \phi}{4\pi f_a} Y_{\mu\nu} \tilde{Y}^{\mu\nu} + \sum_\alpha \psi_\alpha^\dagger \sigma \cdot (i\partial - g_Y Q_\alpha A_Y) \psi_\alpha + \cdots \right\}$$

Dual production of **B+L asym.** and **helical U(1)$_Y$** via $\phi Y_{\mu\nu} \tilde{Y}^{\mu\nu}$.

$$\Delta q_B = \Delta q_L = -\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$$

via **Sphaleron + Yukawa**

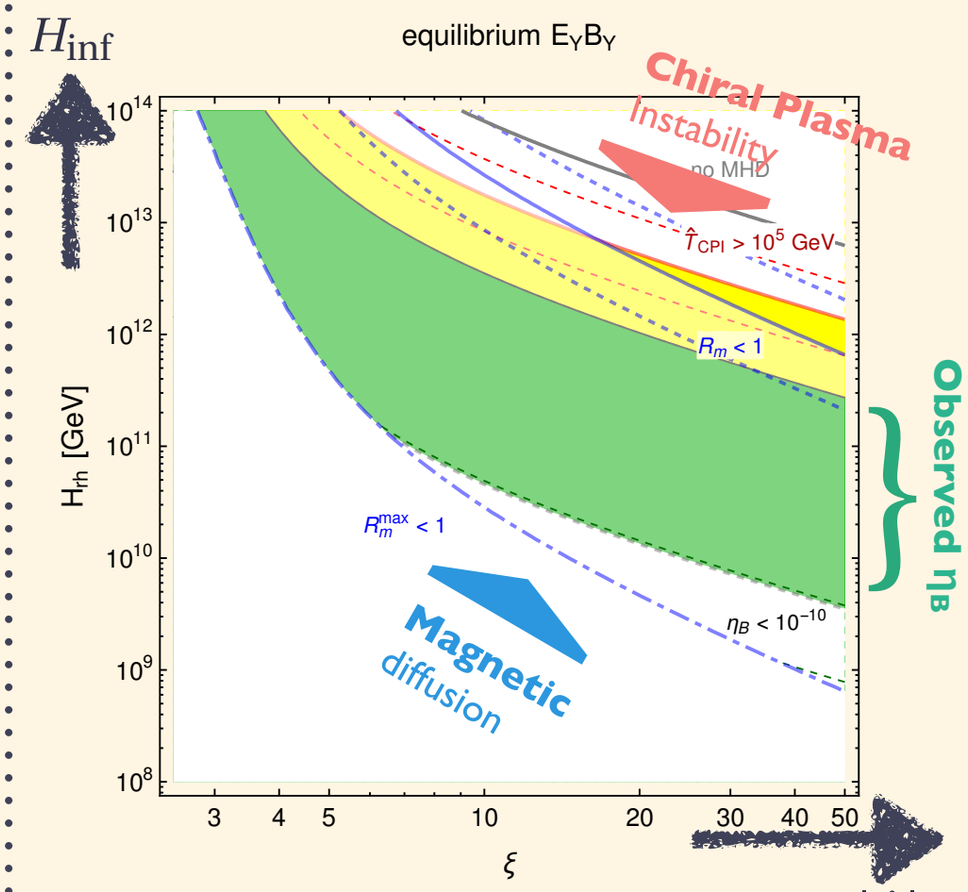
Inefficient **diffusion**
No **CPI**

$$0 \qquad -\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$$

⊿ **h$_Y$** is converted to **U(1)$_{em}$**
+ **Sphaleron freezes out**

$$\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y \qquad 0$$

Time



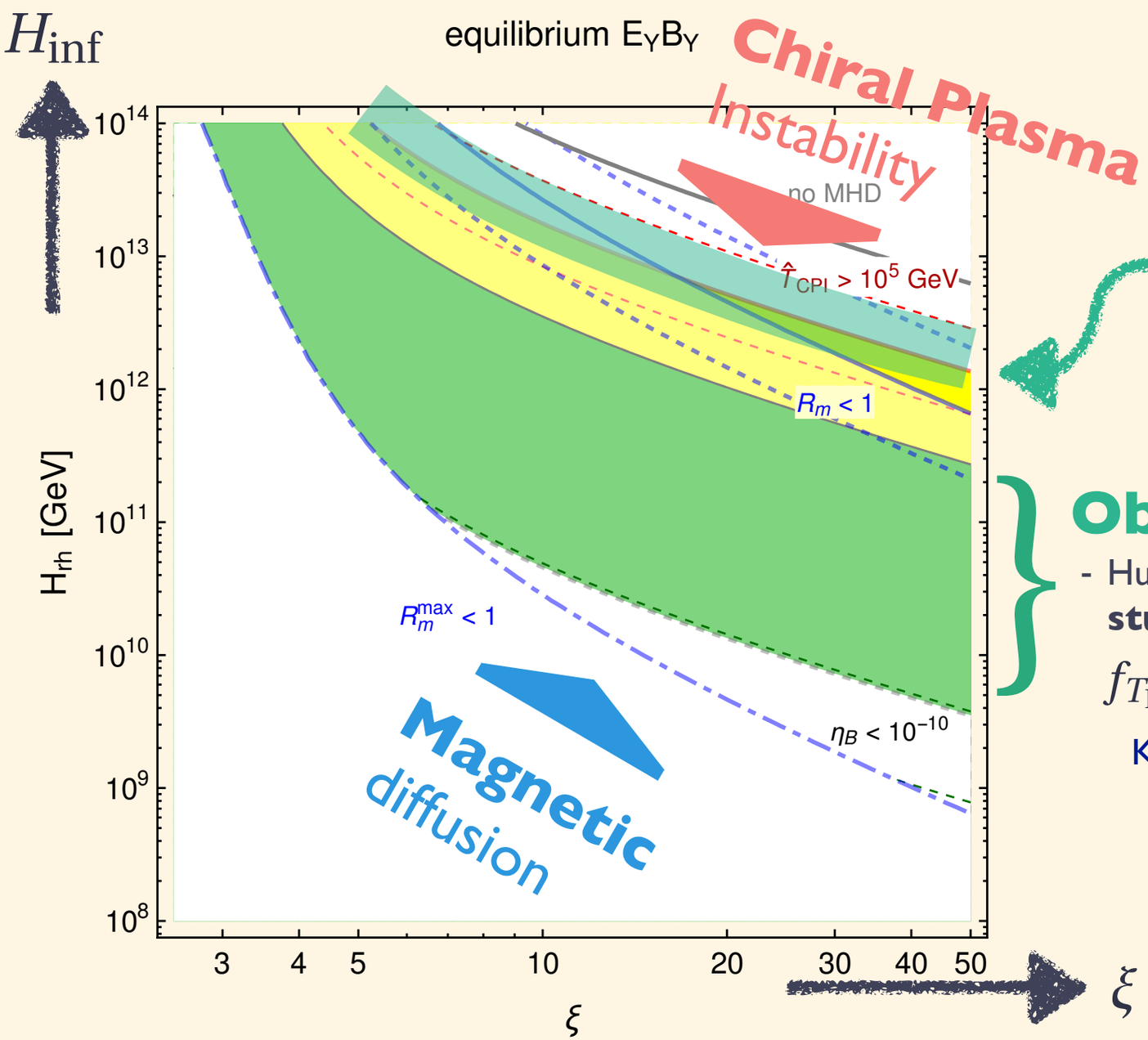
$$\xi \equiv \frac{\alpha_Y |\dot{\phi}|}{2\pi f_a H}$$

Back up

Result

Viable parameters for Baryogenesis

V.Domcke, B.Harling, E.Morgante, **KM**
1905.13318



Viable prm???

- Competition btw overproduction and CPI.
- **Need ChMHD simulation**…

Observed η_B

- Huge uncertainties from **lattice studies of EWPT**…

$$f_{T_{\rm EW}} \in \left[6 \times 10^{-4}, 0.3\right]$$

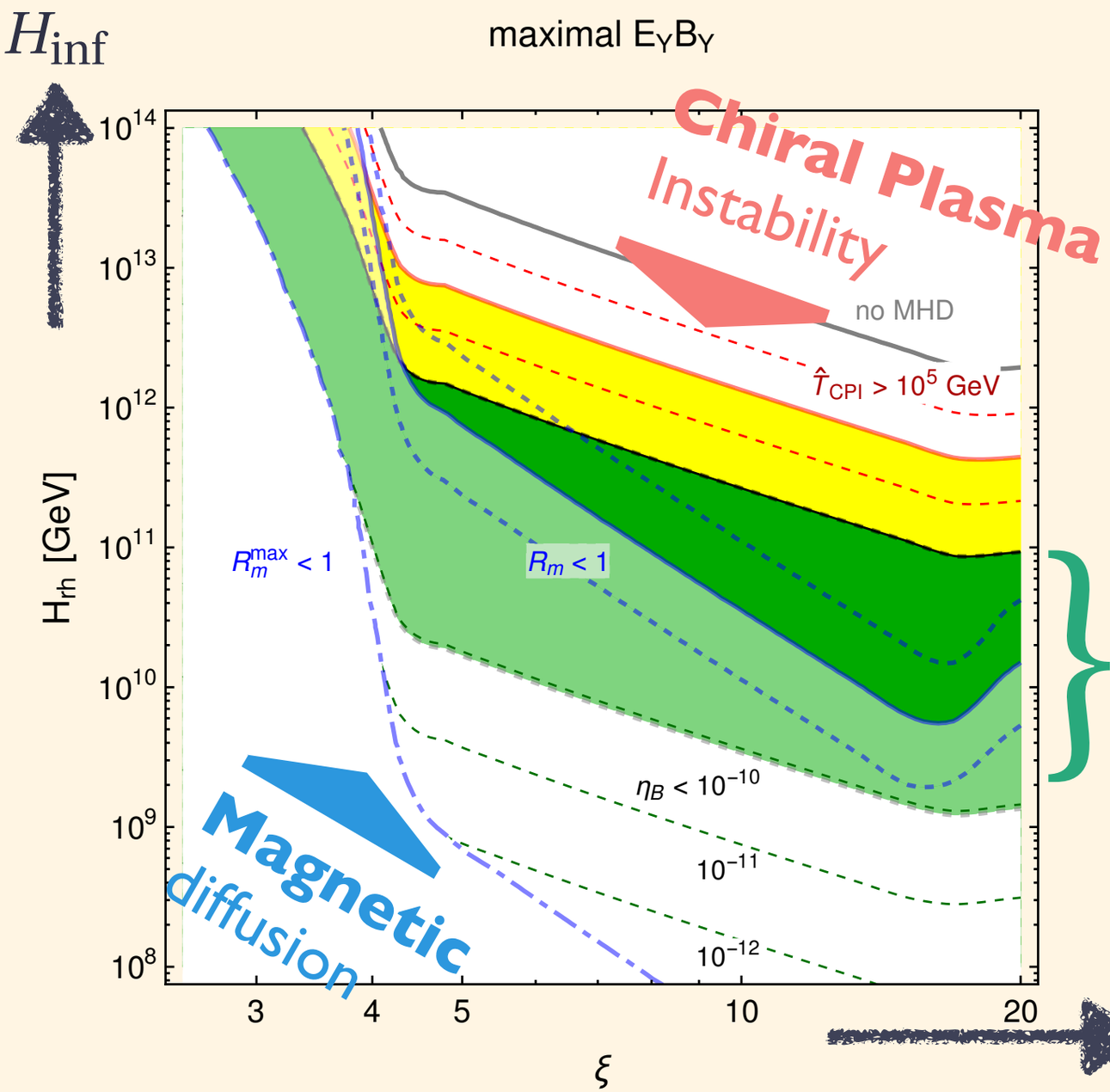
K.Kamada and A.Long 1610.03074

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

Result

Viable parameters for Baryogenesis

V.Domcke, B.Harling, E.Morgante, **KM**
1905.13318



Observed η_B

- Huge uncertainties from **lattice studies of EWPT**…

$$f_{T_{\rm EW}} \in \left[6 \times 10^{-4}, 0.3\right]$$

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

Introduction

Inflaton w/ CS-coupling

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

non-Abelian

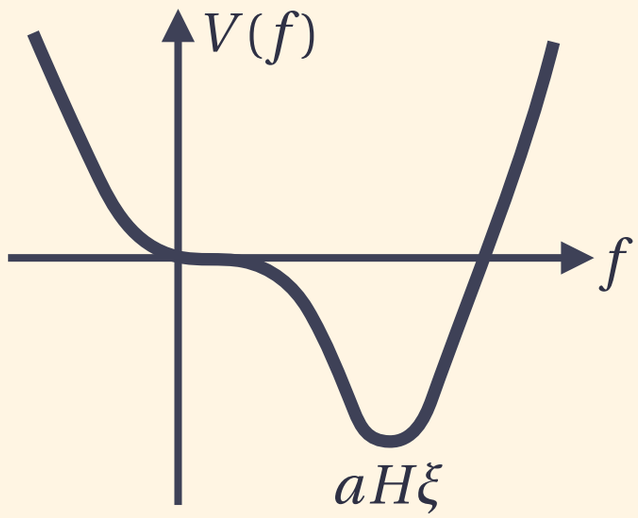
- "Lightness" protected by the shift symmetry (classically): $\phi \longmapsto \phi + c$
- Efficient **helical-gauge field** production by $\dot{\phi} \neq 0$.

  + **Homogeneous** & **isotropic** gauge field may develop.

$$f''(\eta) + 2f^3(\eta) - 2aH\xi f^2(\eta) = 0$$

where $A_0^a = 0, \quad A_i^a = -g^{-1} f(\eta) \delta_i^a, \quad \xi \equiv \frac{\alpha\dot{\phi}}{2\pi f_a H}$

$$0 \neq \langle F_{a\mu\nu} \tilde{F}^{a\mu\nu} \rangle = -4 \langle \boldsymbol{E}^a \cdot \boldsymbol{B}^a \rangle$$

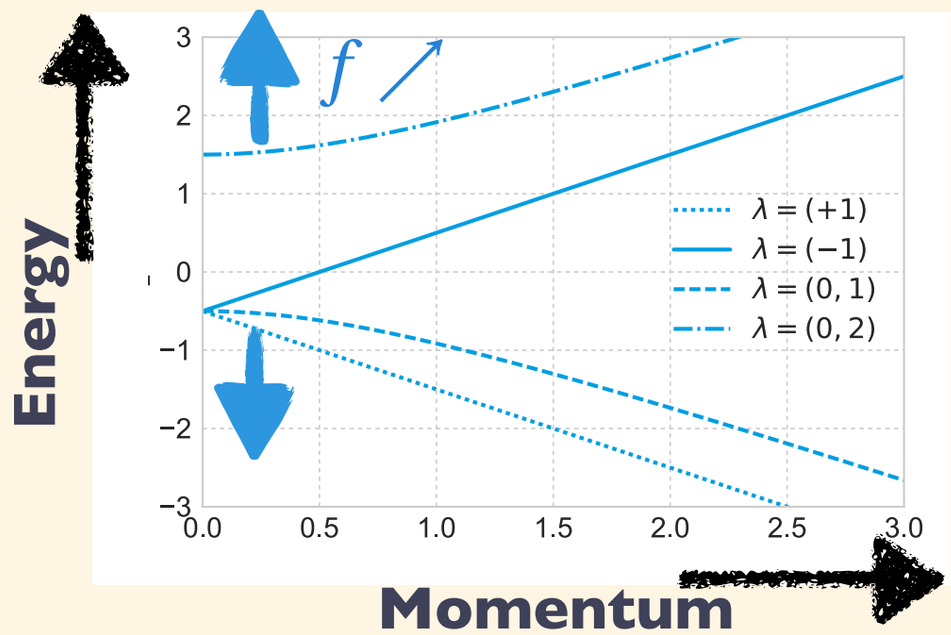


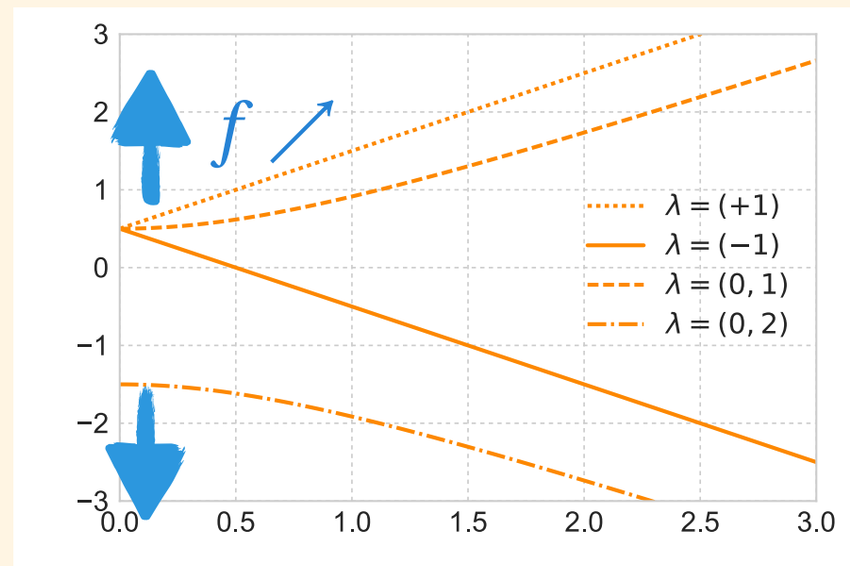
➡ **axion inflation, relaxion, chiral GWs, baryogenesis, magnetogenesis,...**

Fermion Production

Subtleties for $A_0^a = 0, \quad A_i^a = -g^{-1} f(\eta)\delta_i^a$ V.Domcke, Y.Ema, **KM**, R.Sato 1812.08021

- **No Landau levels**, but we can still play the same game…





- The spectrum is different between the **initial** and **final** states.

➡ Need to include the contributions from **vacuum** not only **normal ordering**.

$$Q_\alpha = :Q_\alpha: + Q_\alpha^{(\mathrm{vac})} \quad \text{w/} \quad Q_\alpha^{(\mathrm{vac})} \equiv \lim_{\hat{\Lambda}\to\infty} \mathrm{vol}(\mathbb{R}^3) \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \left[-\frac{1}{2} \sum_\lambda \mathrm{sgn}\left(\omega_\alpha^{(\lambda)}\right) R\left(\frac{\left|\omega_\alpha^{(\lambda)}\right|}{a\hat{\Lambda}} \right) \right]$$

Fundamental repr: $\frac{1}{6}$(Anomaly) $\quad \frac{5}{6}$(Anomaly)

The eta-invariant; see Atiyah and Singer

Induced Current

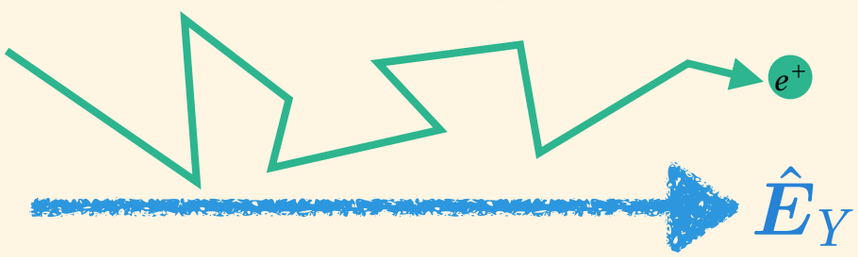
How does Induced Current look like?

- **Weak** electromagnetic field in thermalized plasma

$$\hat{J}_Y = \hat{\sigma}_Y \hat{E}_Y + \frac{2\alpha_Y}{\pi}\hat{\mu}_{Y,5}\hat{B}_Y$$ i.e., Generalized Ohm's law (neglecting velocity field)

  - **No magnetic mass** for transverse mode of Abelian gauge field. E. Fradkin, Proc. of the Lebedev Institute 29, 6 (1965).
  - This expression holds if **energy by acceleration** ≪ **temperature**

$$g_Y |Q| \hat{E}_Y \hat{\tau}_{\rm int} \ll \hat{T}$$



- **Strong** electromagnetic field ?
  - Estimate the current operator for the **accelerated energy** ≫ **temperature**

$$\hat{J}^z_Y = \sum_\alpha \frac{(g|Q_\alpha|)^3}{12\pi^2}\coth\left(\frac{\pi\hat{B}_Y}{\hat{E}_Y}\right)\hat{E}_Y\hat{B}_Y\frac{1}{H} \quad \rightarrow \quad \hat{J}^z_Y = \sum_\alpha \frac{(g|Q_\alpha|)^3}{6\pi^3}\frac{\hat{E}_Y^2}{H} \quad \text{for} \quad B_Y \rightarrow 0$$

Reproduce e.g., Kobayashi, Afshordi 1408.4141

Chiral Plasma Instability

Chiral Plasma Instability

- **Equation for Magnetic Helicity**

$$\frac{\partial h_Y}{\partial \eta} = \int \frac{\mathrm{d}^3 x}{\mathrm{vol}(\mathbb{R}^3)} \frac{Y_{\mu\nu}\tilde{Y}^{\mu\nu}}{2} = -2\int \frac{\mathrm{d}^3 x}{\mathrm{vol}(\mathbb{R}^3)} \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y$$

$$0 = \boldsymbol{\nabla} \times \boldsymbol{B}_Y - \boldsymbol{J}_Y\,, \quad \boldsymbol{J}_Y = \sigma_Y(\boldsymbol{E}_Y + \boldsymbol{v} \times \boldsymbol{B}_Y) + \frac{2\alpha_Y}{\pi}\mu_{Y,5}\boldsymbol{B}_Y \quad \text{w/ } \mu_{Y,5} = \sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha}^2 \mu_\alpha$$

$$\frac{\partial}{\partial \eta} h_Y = \int \frac{\mathrm{d}^3 x}{\mathrm{vol}(\mathbb{R}^3)} \left(2\boldsymbol{B}_Y \cdot \frac{\boldsymbol{\nabla}^2}{\sigma_Y}\boldsymbol{A}_Y + \frac{4\alpha_Y}{\pi}\frac{\mu_{Y,5}}{\sigma_Y}\boldsymbol{B}_Y^2 \right)$$

- **Mode equation**

$$\frac{\partial}{\partial \eta} h_{Y,\boldsymbol{k}} = -\frac{2k^2}{\sigma_Y} h_{Y,\boldsymbol{k}} + \frac{8\alpha_Y}{\pi}\frac{\mu_{Y,5}}{\sigma_Y}\rho_{B,\boldsymbol{k}} = -\frac{2k^2}{\sigma_Y} h_{Y,\boldsymbol{k}} + \frac{4\alpha_Y}{\pi}\frac{\mu_{Y,5}}{\sigma_Y r_{\boldsymbol{k}}} k h_{Y,\boldsymbol{k}} \quad \text{w/ } r_{\boldsymbol{k}} \equiv \frac{k\, h_k(\eta)/2}{\rho_{B,k}(\eta)}$$

Kinetic Reynolds

Scaling in Turbulent & Viscous Regimes

- **Velocity equation** in ChMHD

$$\frac{\partial}{\partial \eta} \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = \nu \nabla^2 \boldsymbol{v} + \frac{1}{\rho + P}\left(-\frac{1}{2}\nabla B_Y^2 + (\boldsymbol{B}_Y \cdot \nabla)\boldsymbol{B}_Y\right)$$

Kinetic Reynolds # $R_e = \frac{Lv}{\nu} \gtrless 1 : \sim \frac{v^2}{L} \gtrless \sim \frac{\nu v}{L^2} \qquad \sim \frac{B_Y^2}{L\rho}$

- **Turbulent** regime: $R_m > R_e > 1$

$\rho v^2 \sim B_Y^2$ & const. $= h_Y \sim L B_Y^2$ ▶ $\partial_\eta B_Y \sim \frac{v B_Y}{L} \propto B_Y^4$ ▶ $B_Y \sim \left(\frac{\eta_t}{\eta}\right)^{\frac{1}{3}} B_{Y,t}, \; L \sim \left(\frac{\eta}{\eta_t}\right)^{\frac{2}{3}} L_t$

- **Viscous** regime: $R_m > 1 > R_e$

$\rho v^2 \sim R_e B_Y^2$ & const. $= h_Y \sim L B_Y^2$ ▶ $\partial_\eta B_Y \sim \frac{v B_Y}{L} \propto B_Y^3$ ▶ $B_Y \sim \left(\frac{\eta_t}{\eta}\right)^{\frac{1}{2}} B_{Y,t}, \; L \sim \left(\frac{\eta}{\eta_t}\right) L_t$