Baryo/Leptogenesis from Axion Inflation

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Based on **1905.13318**, **20xx.xxxxx**, 1806.08769, 1812.08021, 1910.01205

Collaboration with Y. Ema, V. Domcke, B. von Harling, K. Kamada, E. Morgante, R. Sato, K. Schmitz, M. Yamada

1.

Introduction

Introduction

Cosmic Inflation v.s. Baryon Asymmetry

- **Inflation**: accelerated expansion of Universe
  - **Solve** horizon/flatness problems + **Provide** density perturbations.
  - Dilute unwanted relics, **but also SM particles such as baryons**.

- **Baryogenesis**: production of baryon asymmetry after inflation.
  - Baryon to photon ratio (BBN) → $\eta = \dfrac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$

➡ Baryogenesis from Inflation?

- Reheating requires couplings btw inflaton and the SM particles.

Introduction

Inflaton w/ Chern-Simons coupling

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

- **Flat** potential v.s. **Coupling** to radiation
  - **Flat potential** protected by the shift sym. $\phi \mapsto \phi + c$
  - **Reheating** via the Chern-Simons coupling

Introduction

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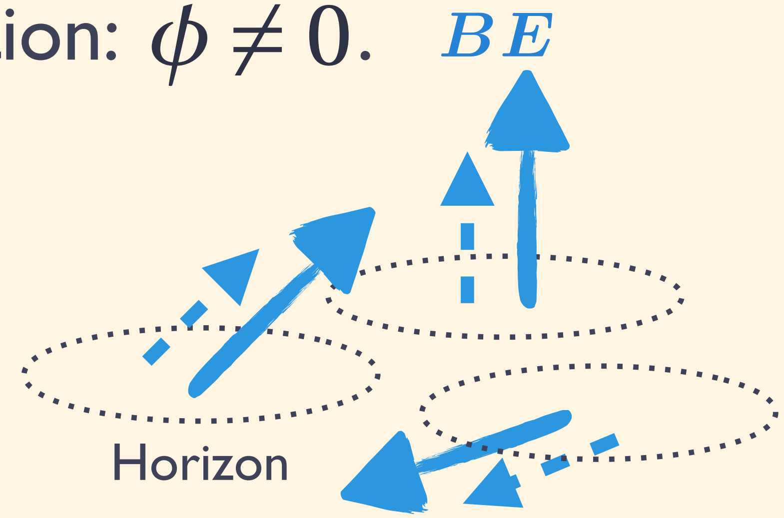
  - **Flat potential** protected by the shift sym. $\phi \mapsto \phi + c$
  - **Reheating** via the Chern-Simons coupling

❖ **Helical-gauge field** production during inflation: $\dot{\phi} \neq 0.$

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

where $\xi \equiv \dfrac{\dot{\phi}}{2\Lambda H}$

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



W.Garretson+ 9209238, M.Anber, L.Sorbo 0606534,…

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

Helical gauge & Chiral fermion

Inflaton w/ Chern-Simons coupling to $U(1)_Y$

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

$$\left. + \sum_\alpha \psi_\alpha^\dagger \sigma\cdot(i\partial - g_Y Q_\alpha A_Y)\psi_\alpha + \cdots \right\}$$

$U(1)_Y$

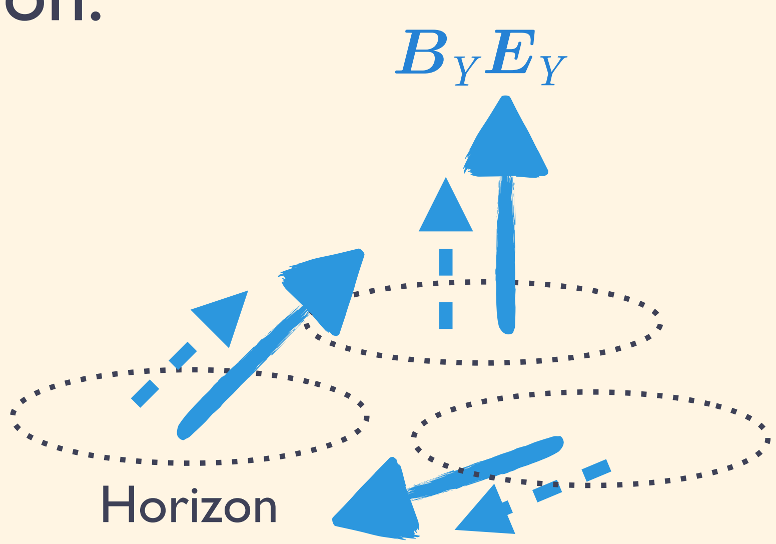
SM particles
charged under **$U(1)_Y$**

- **Helical-gauge field** production during inflation.

$$0 = \left[\partial_\eta^2 + k(k \pm 2\xi aH)\right] A_{Y,\pm}(\eta, k)$$

where $\xi \equiv \frac{\dot{\phi}}{2\Lambda H}$

$$0 \neq \langle Y_{\mu\nu}\tilde{Y}^{\mu\nu}\rangle$$
$$= -4\langle \boldsymbol{E}_Y \cdot \boldsymbol{B}_Y\rangle$$



Helical gauge & Chiral fermion

Inflaton w/ Chern-Simons coupling to U(1)$_Y$

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

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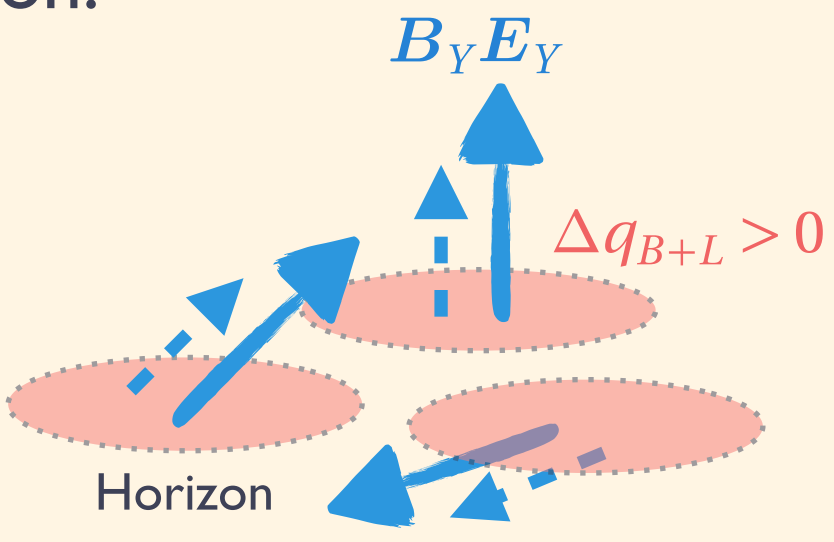


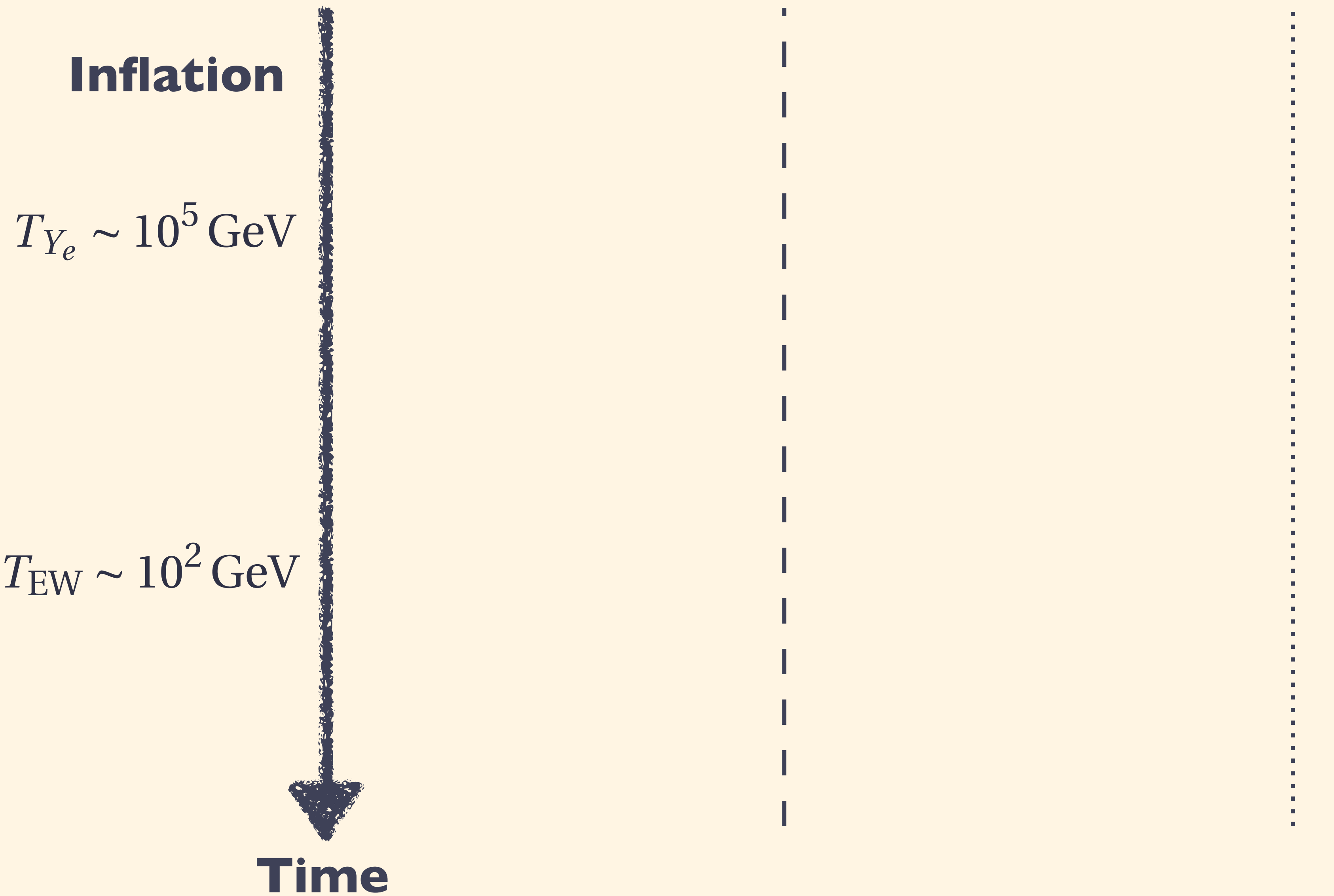
❖ **B+L generation** during inflation!

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

Our Idea

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{3}{32\pi^2}\left(g_2^2 W_{\mu\nu}^a \tilde{W}^{a\mu\nu} - g_Y^2 Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$



Our Idea

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 3\partial_\mu K_{\mathrm{CS}}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

	$3\partial_\mu K_{\mathrm{CS}}^\mu$	$-\frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$
Inflation: $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	**Inefficient**	$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$
$T_{Y_e} \sim 10^5\,\mathrm{GeV}$		
$T_{\mathrm{EW}} \sim 10^2\,\mathrm{GeV}$		

Time

Our Idea

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

Time	$3\partial_\mu K_{CS}^\mu$		$-\frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$
Inflation	$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	**Inefficient**	$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$
$T_{Y_e} \sim 10^5\,\text{GeV}$	via **Sphaleron** + **Yukawa** →		Inefficient **diffusion** No **CPI** (chiral plasma instability)
	0	$\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$
$T_{EW} \sim 10^2\,\text{GeV}$			

Our Idea

Baryogenesis from B+L asymmetry?

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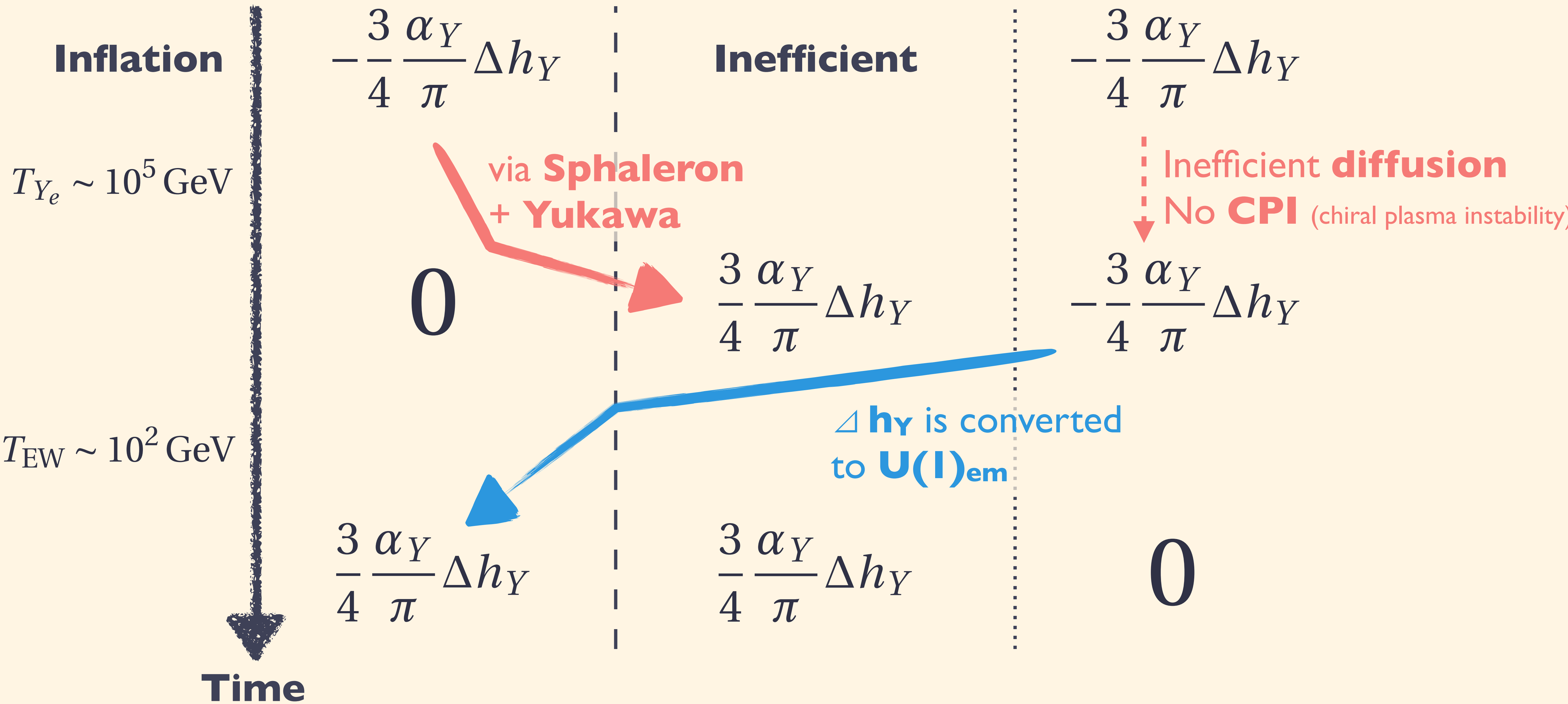


Our Idea

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

Inflation

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

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

via **Sphaleron** + **Yukawa**

Inefficient **diffusion**
No **CPI** (chiral plasma instability)

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

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

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

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

Sphaleron freezes out

Time

Outline of this Talk

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

Inflation

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

$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | **Inefficient** | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ **2.**

via **Sphaleron** + **Yukawa**

Inefficient **diffusion**
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.**

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

⊿ **h_Y** is converted to **$U(1)_{em}$**

K.Kamada's talk @ PPP2019

$\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ → $\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | 0 **4.**

Sphaleron freezes out

Time

2.

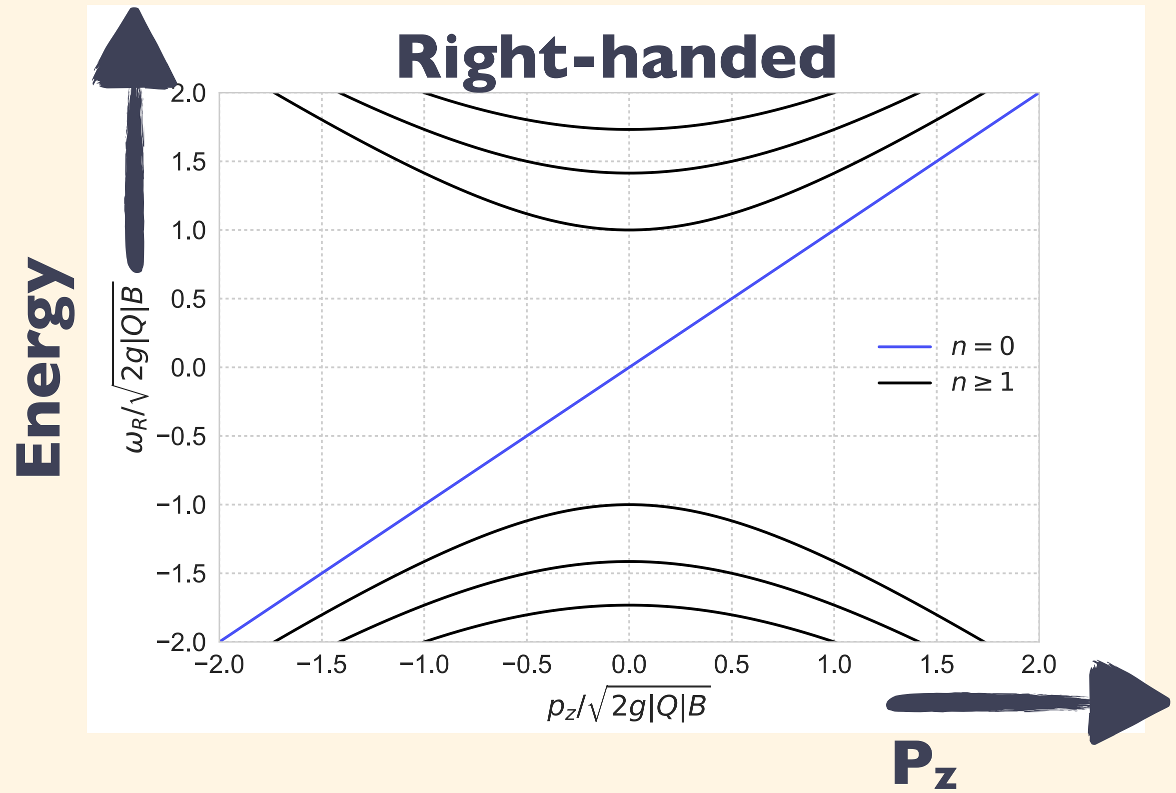
Production of

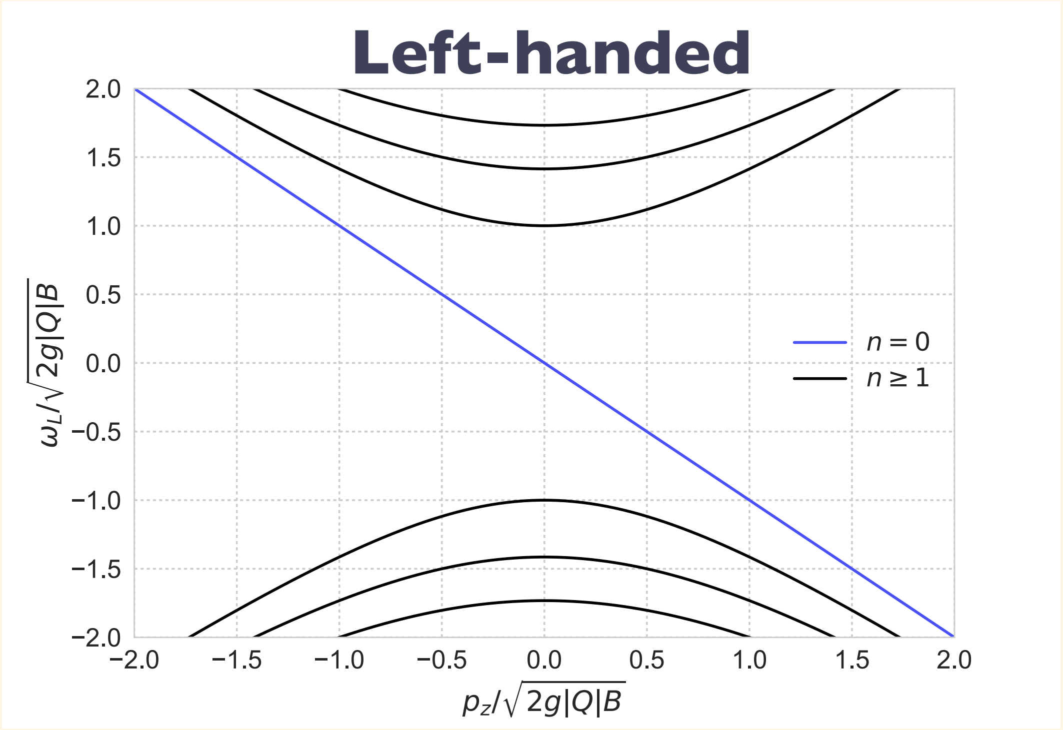
Helical gauge & **Chiral** fermion

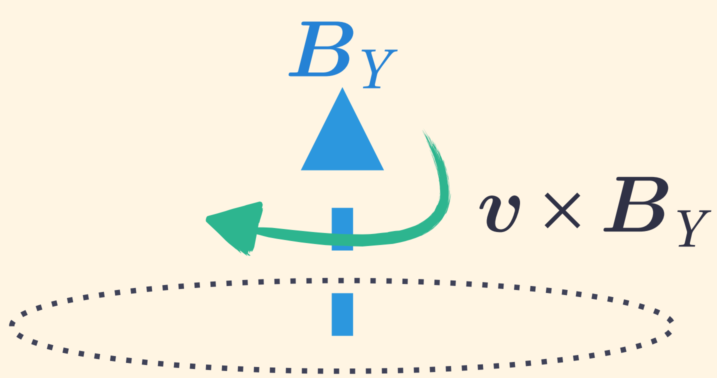
Fermion Production

Landau Levels

- Turn off E_Y; B_Y field modifies the **dispersion relation**.







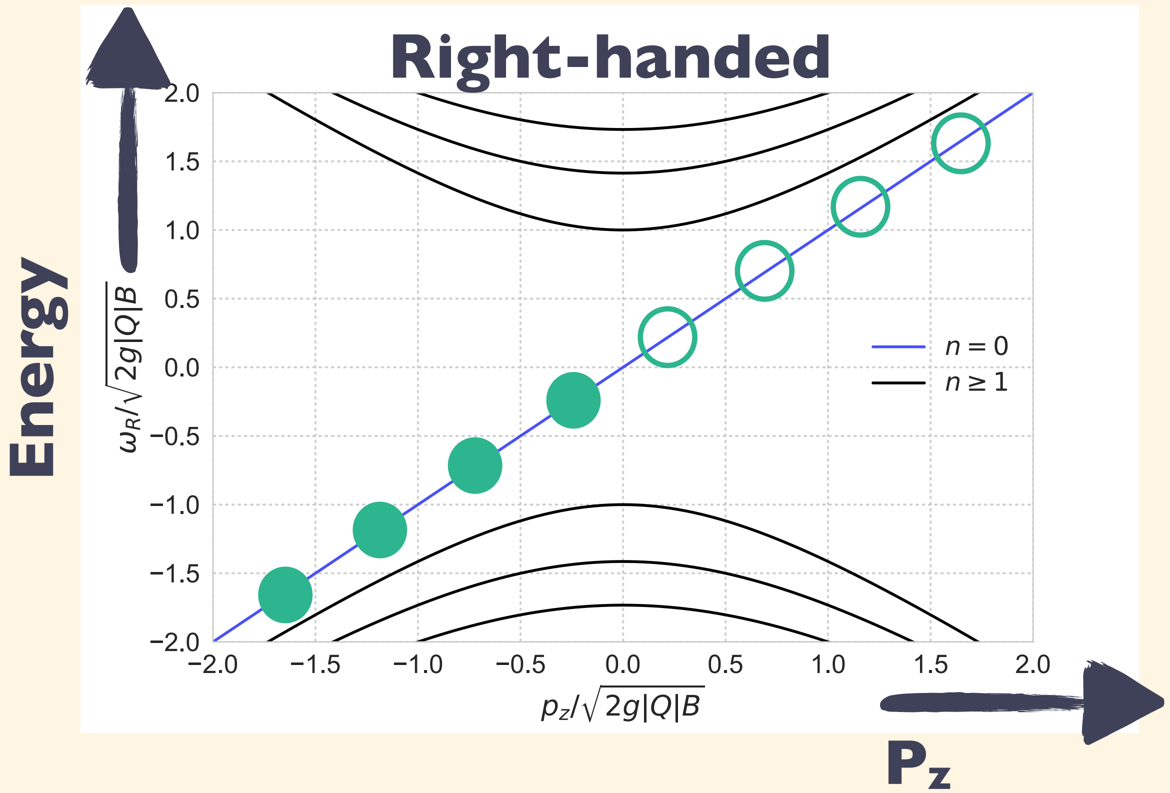
- **Landau level n** : transverse motion
- $\mathbf{P_z}$: parallel motion

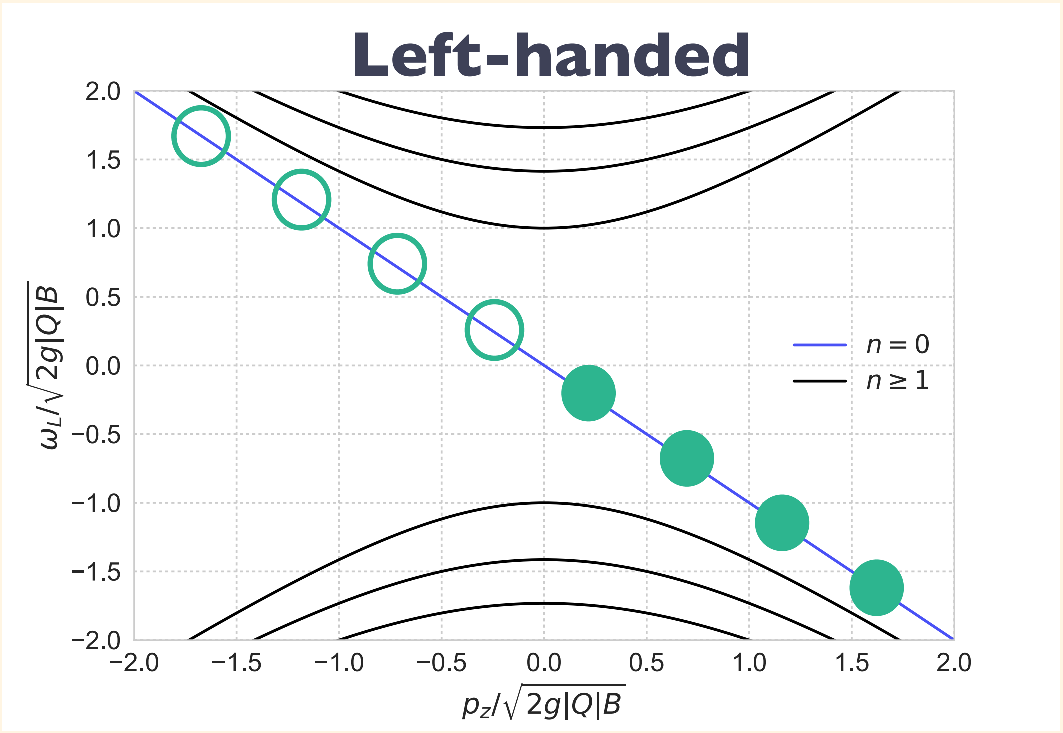
Fermion Production

Lowest Landau Level (n=0) & **Chiral Anomaly**

- **Turn on E_Y** and see what happens.

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





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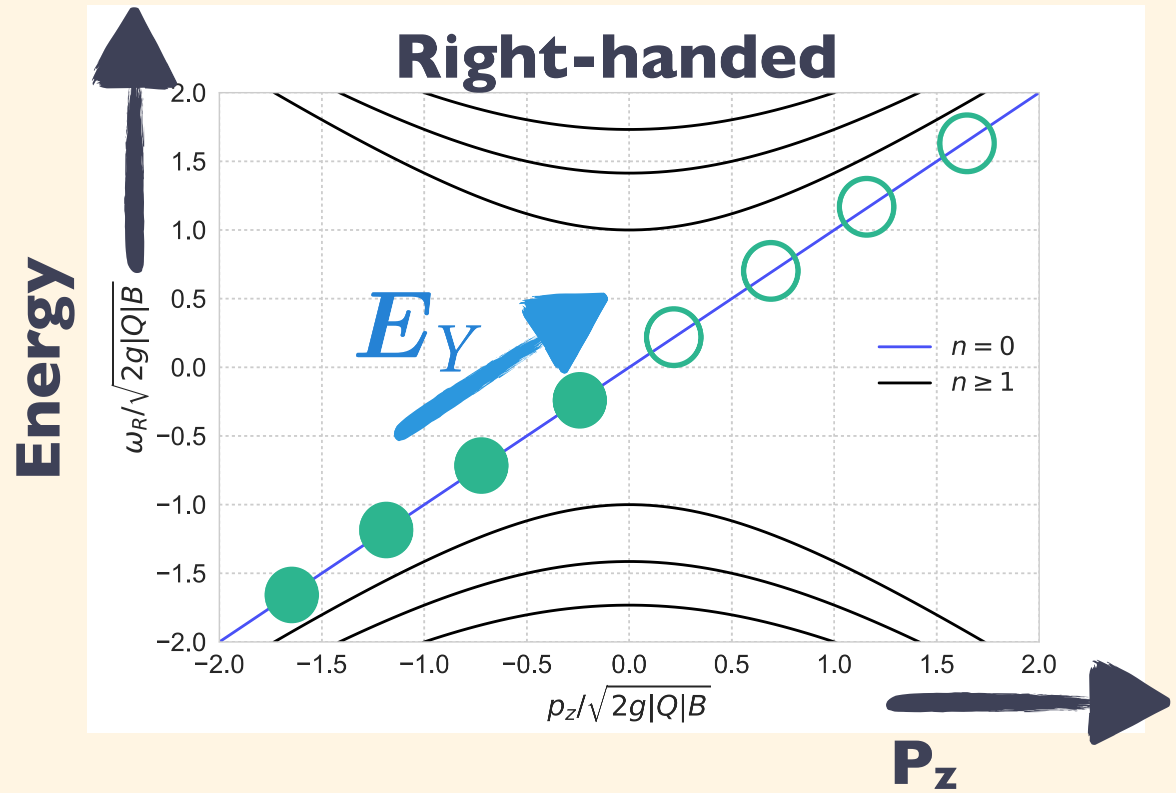

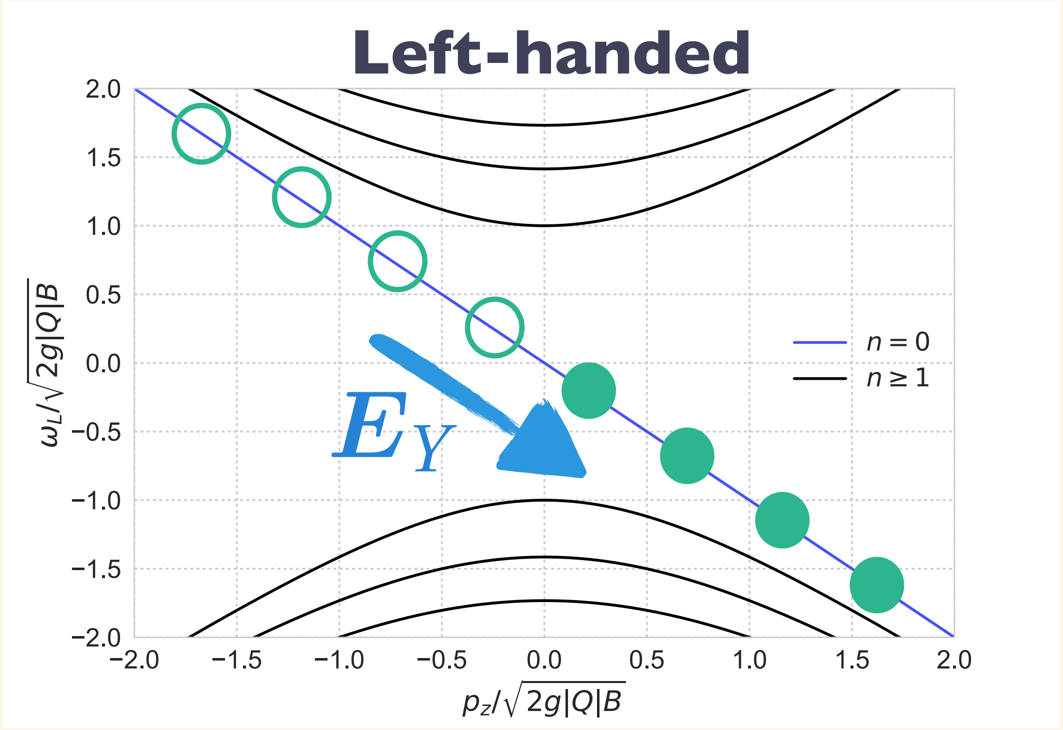

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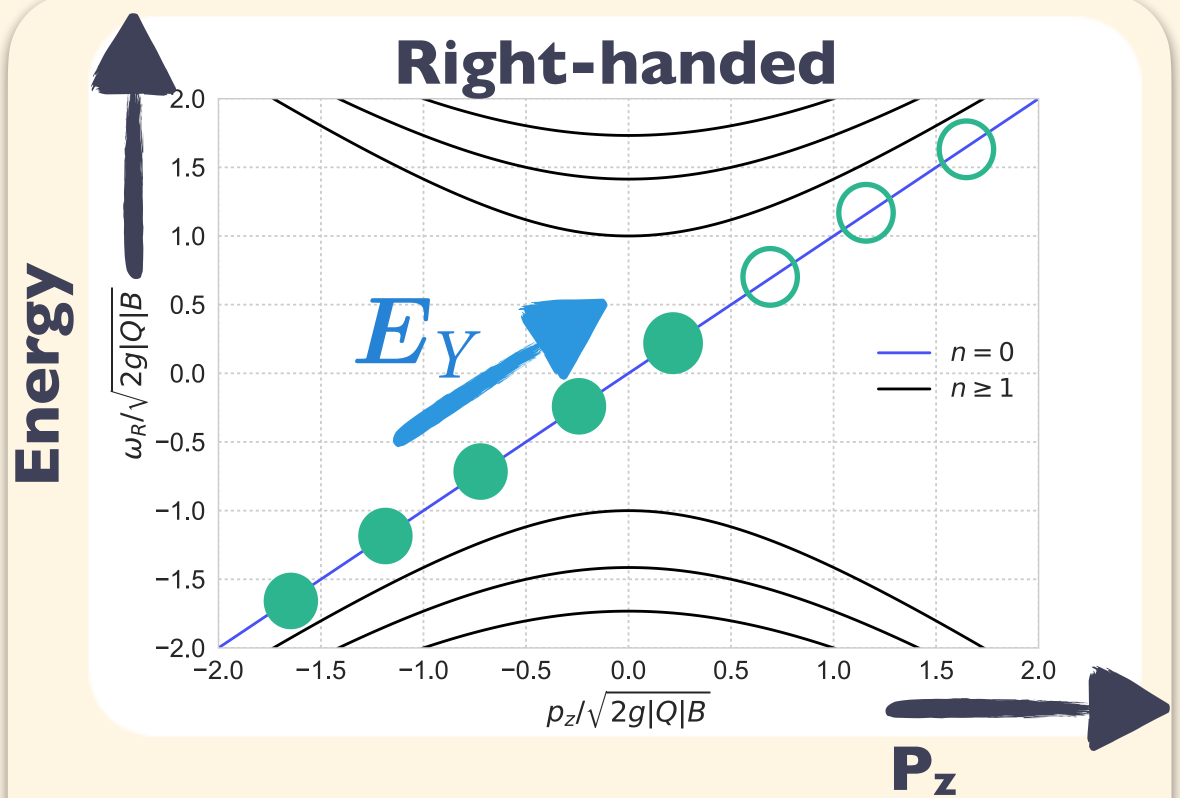
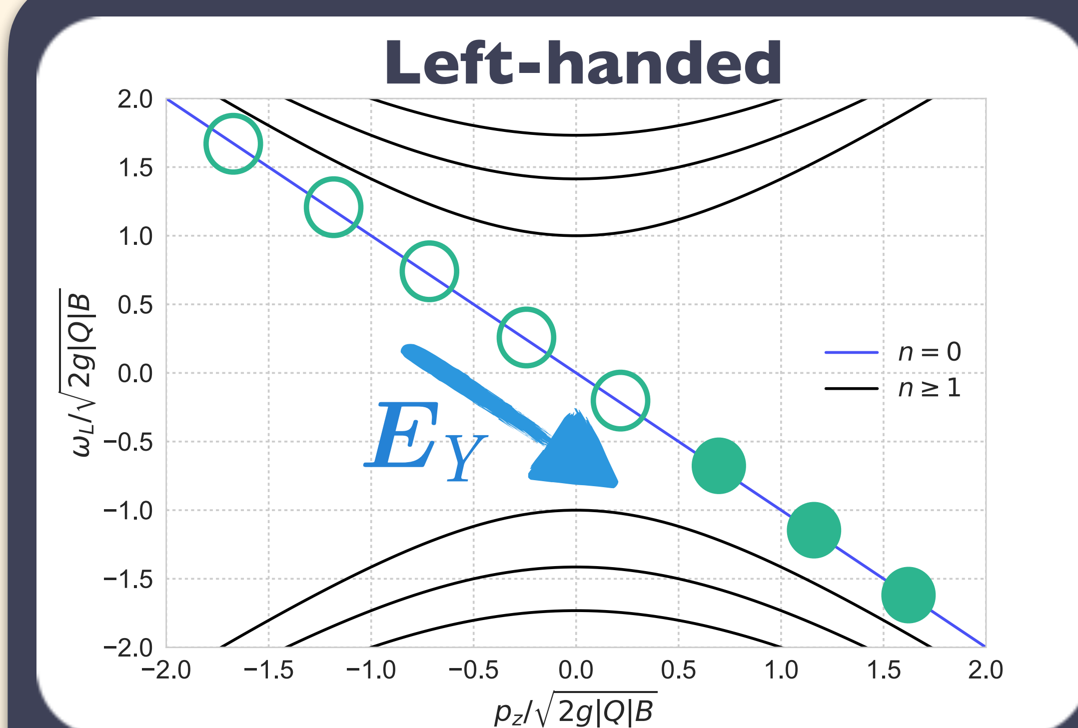


Particle production



Anti-particle production

➡ Reproduce chiral anomaly!

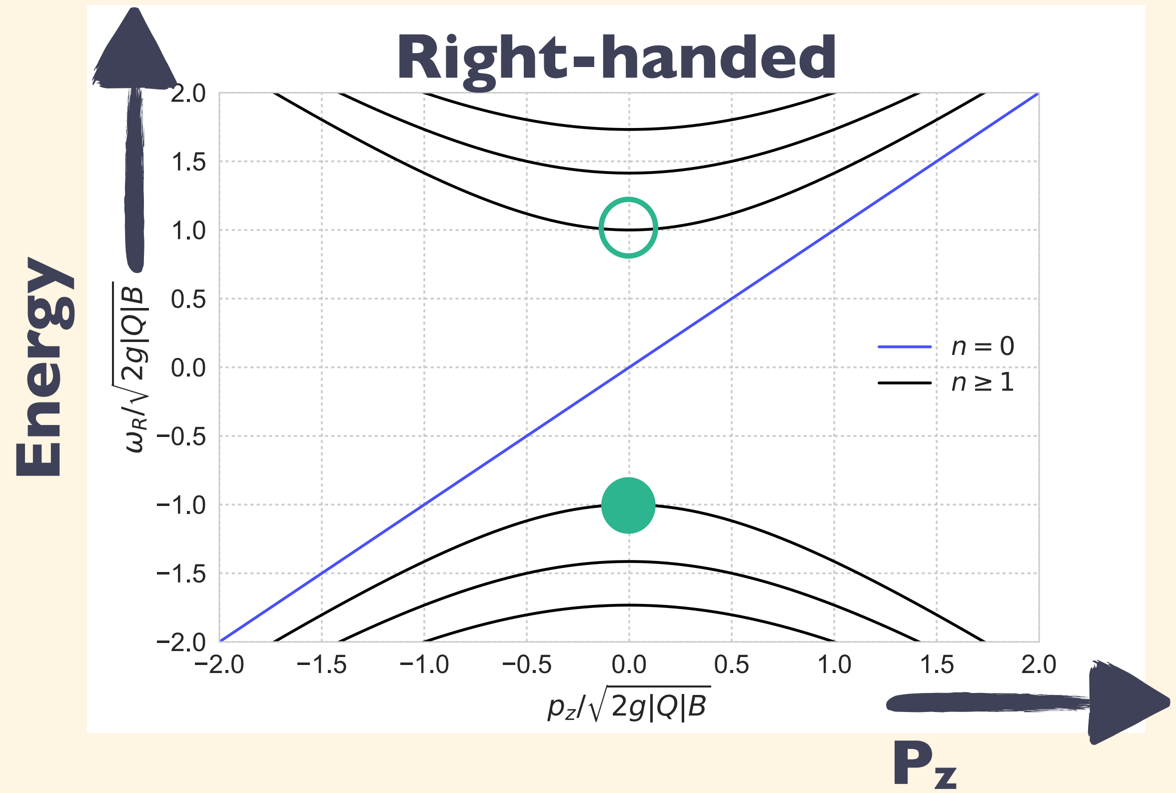
$$\dot{q}_\alpha = \dot{n}_\alpha - \dot{\bar{n}}_\alpha = \epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y = -\epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{16\pi^2} Y^{\mu\nu}\tilde{Y}_{\mu\nu} \quad \text{w/} \quad \epsilon_\alpha = \pm \text{ for R/L}, \quad N_\alpha = \text{dof}$$

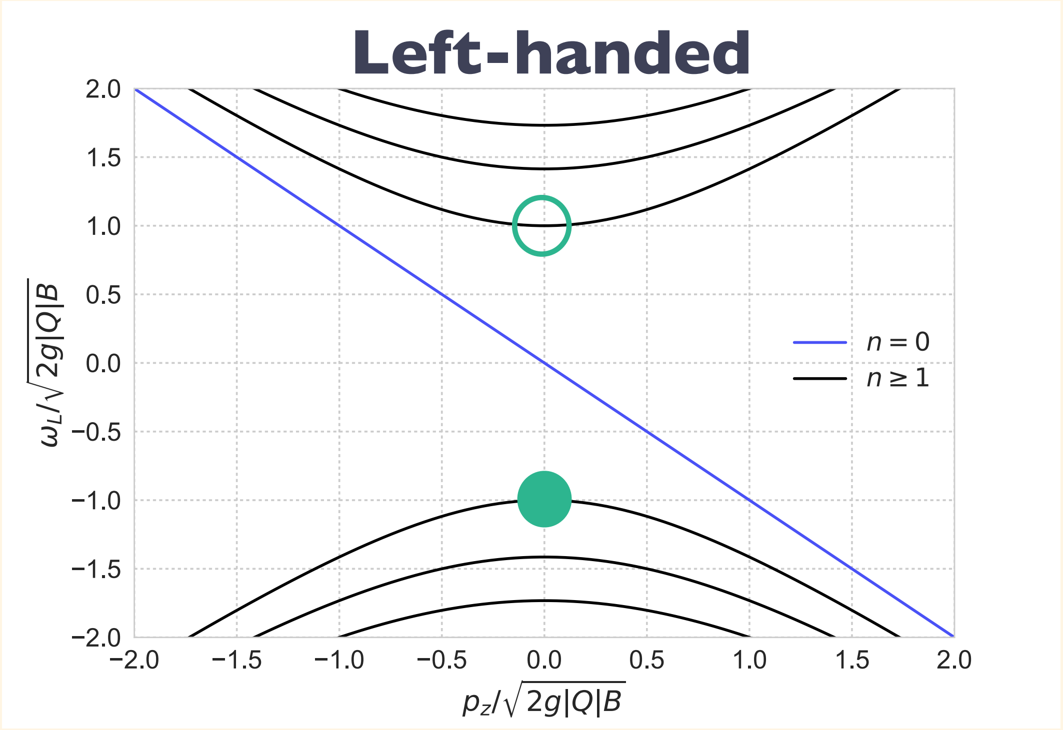
Fermion Production

Higher Landau Levels (n≧1) & **Pair Production**

e.g., V.Domcke and **KM** 1806.08769

- **Turn on E_Y** and see what happens.





Fermion Production

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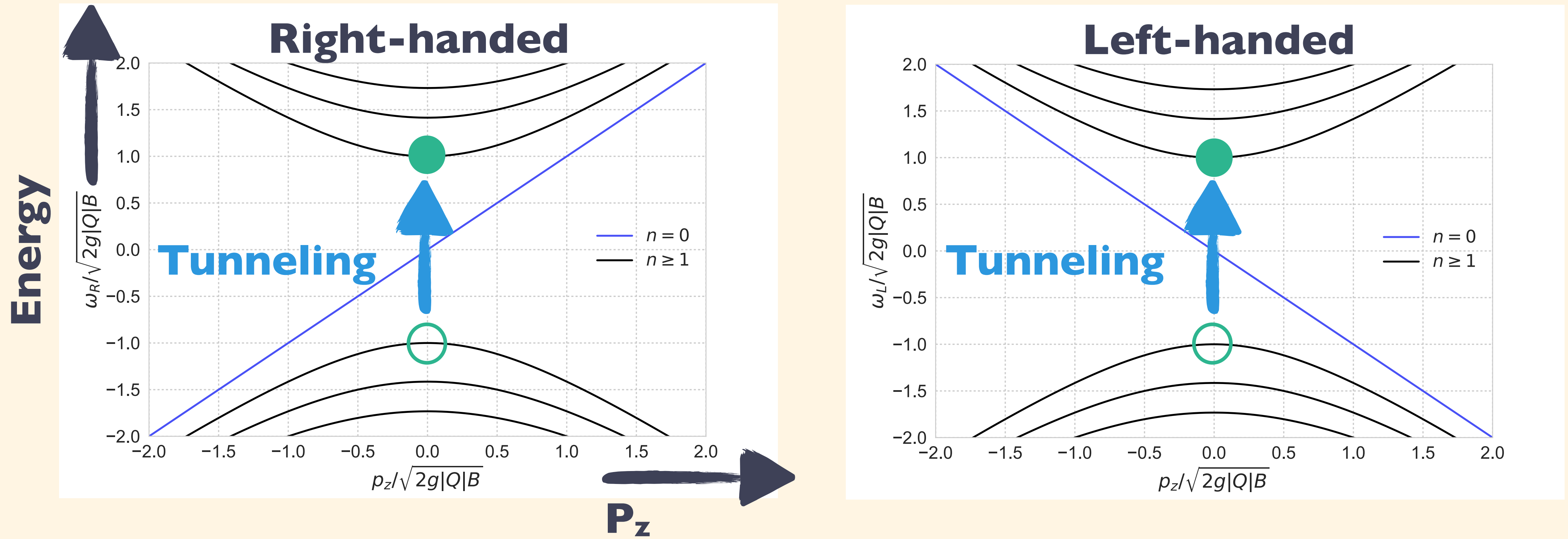

➡ Pair-production via Schwinger effect

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

- Never contribute to asymmetries!

Fermion Production

Higher Landau Levels (n≧1) & Pair Production

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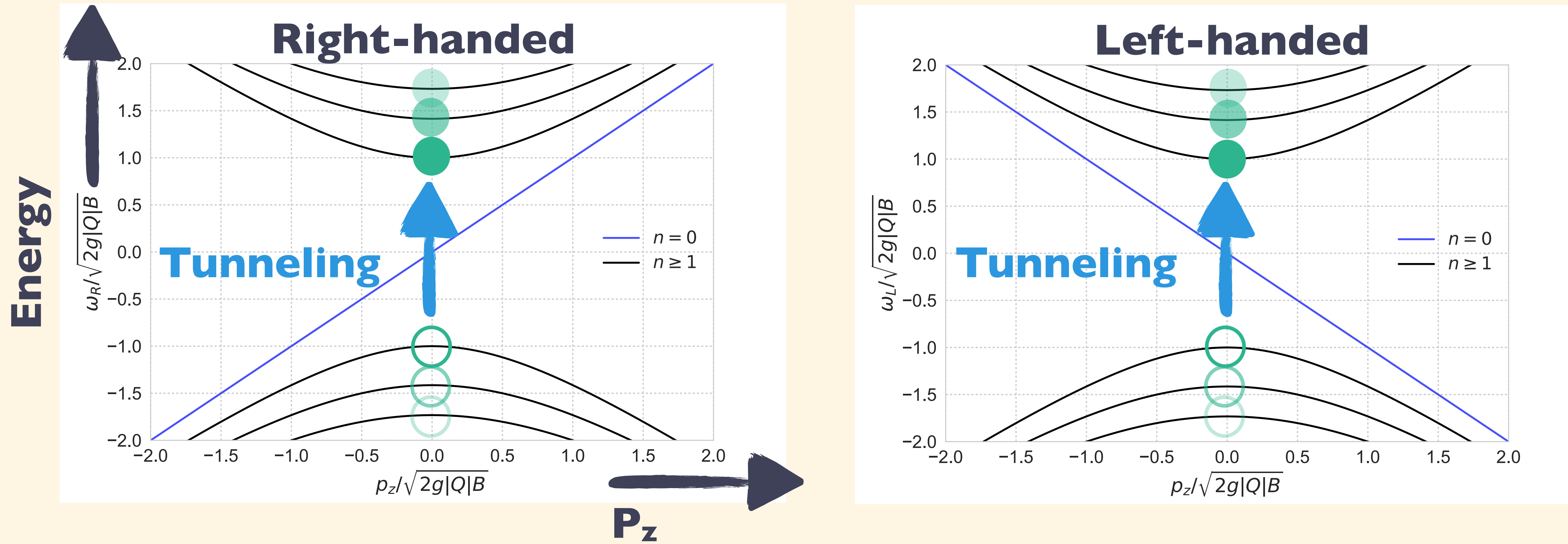


➡ Pair-production via Schwinger effect

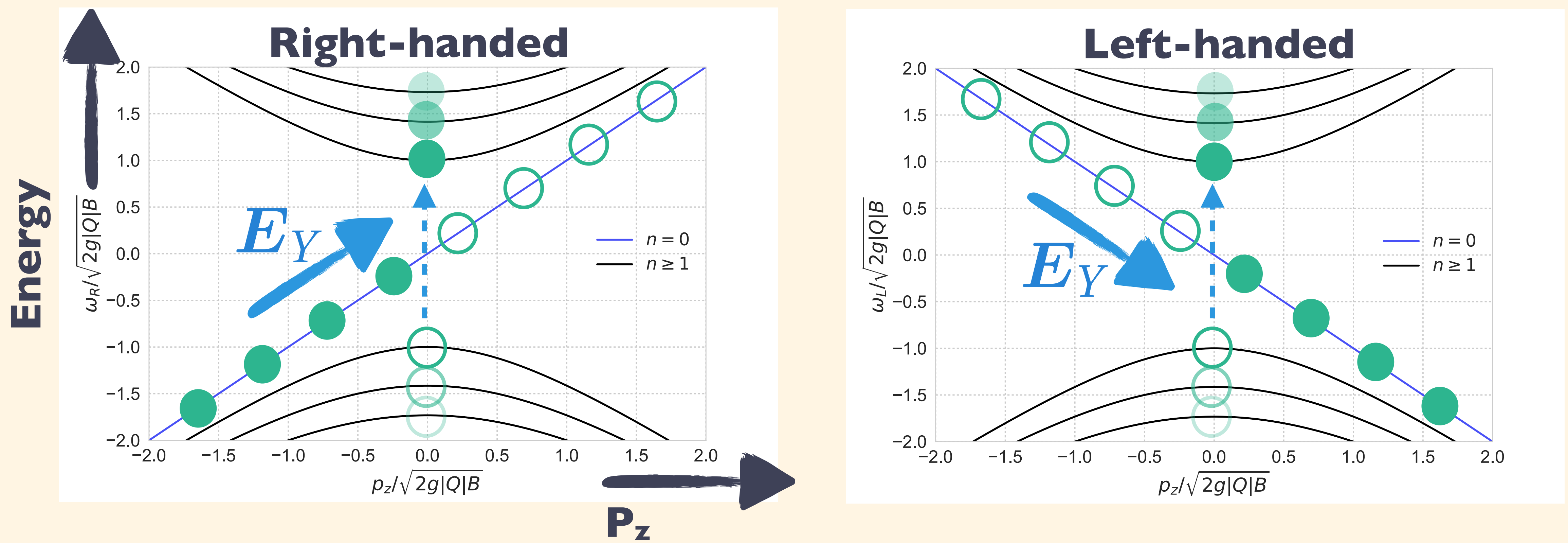
$$\dot{n}_\alpha^{(n)} = \dot{\bar{n}}_\alpha^{(n)} = N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y e^{-\frac{2\pi n B_Y}{E_Y}} \quad \blacktriangleright \quad \sum_{n=1} \dot{n}_\alpha^{(n)} = N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y \frac{1}{e^{\frac{2\pi B_Y}{E_Y}} - 1}$$

- Never contribute to asymmetries!

Fermion Production in $B_Y \parallel E_Y$

- **Turn on E_Y** and see what happens.

e.g., V.Domcke and **KM** 1806.08769



- **Chiral anomaly** from the lowest Landau level (n=0).

- **Pair production** from higher Landau levels (n=1,2,…).

Helical gauge & Chiral fermion

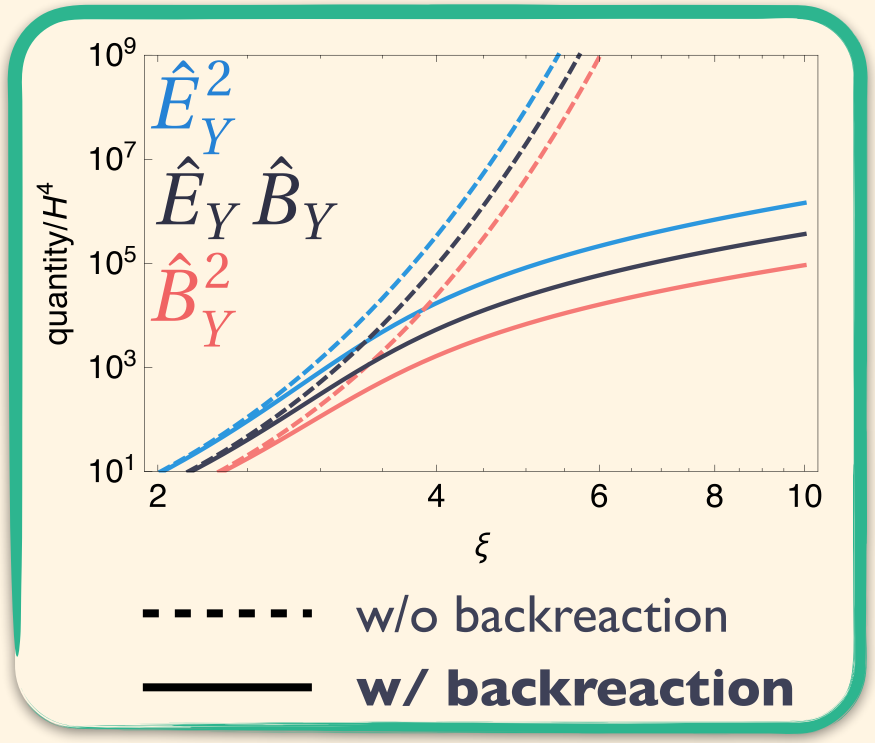
Implications on Axion Inflation

V.Domcke and **KM** 1806.08769

- **Backreaction** suppresses gauge field

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

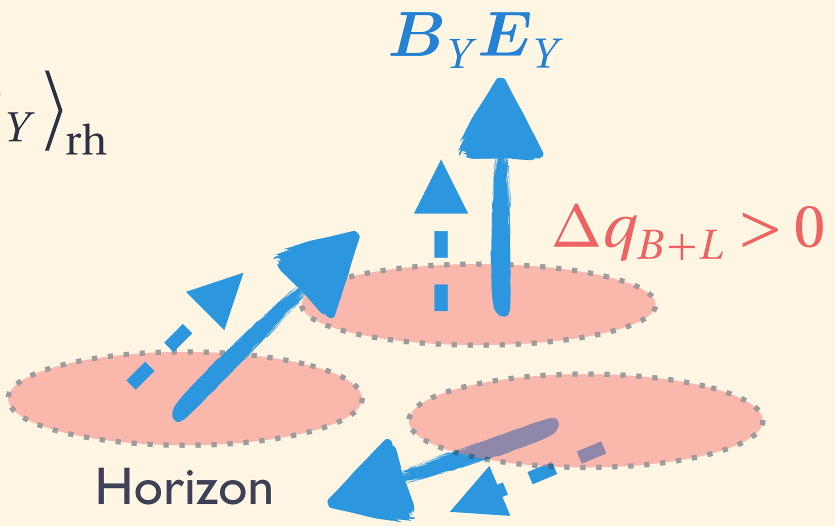
$$g_Y \boldsymbol{J}_Y = a \left[\sum_\alpha N_\alpha \frac{g_Y^3 |Q_\alpha|^3}{12\pi^2} \coth\left(\frac{\pi \hat{B}_Y}{\hat{E}_Y} \right) \frac{\hat{B}_Y}{H} \right] \boldsymbol{E}_Y$$



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

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

$$\frac{\mu_{B+L}^{\rm rh}}{T_{\rm rh}} \sim 10^{-3} \left(\frac{H_{\rm rh}}{10^{14}\,{\rm GeV}} \right)^{\frac{3}{2}} \left(\frac{\langle \hat{\boldsymbol{E}}_Y \cdot \hat{\boldsymbol{B}}_Y \rangle_{\rm rh} / H_{\rm rh}^4}{10^5} \right)$$



3.

Survival of Helical Gauge Field

Outline of this Talk

Baryogenesis from B+L asymmetry?

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

Inflation | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | **Inefficient** | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | 2.

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

via **Sphaleron** + **Yukawa**

Inefficient **diffusion**
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.

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

⊿ **hY** is converted to **U(1)em**

K.Kamada's talk @ PPP2019

$\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ → $\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | 0 | 4.

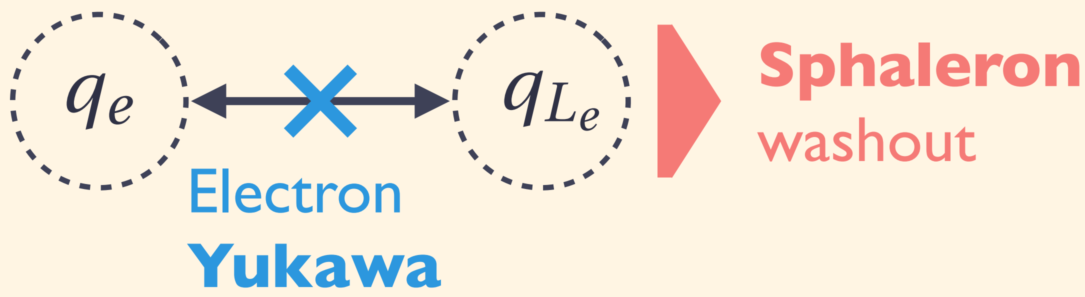
Sphaleron freezes out

Time

Avoid Chiral Plasma Instability

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

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



Electron Yukawa is **NOT** equilibrated till

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

Survival of Helical Gauge Field

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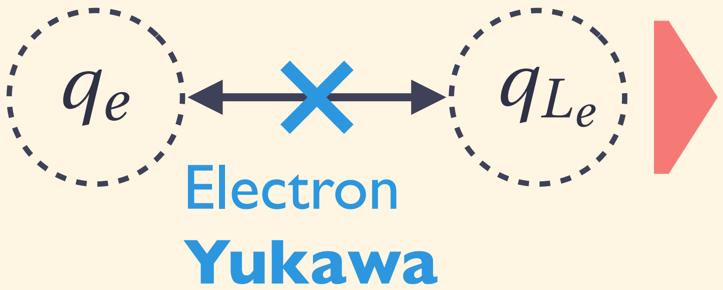

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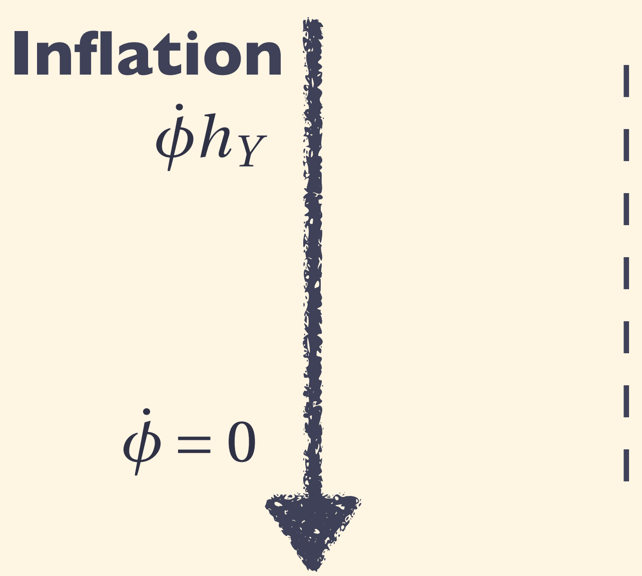
- **Chiral Plasma Instability** (CPI) as an inverse process

$$\partial \cdot J_e = -\frac{g_Y^2}{16\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + (\text{Yukawa})$$



Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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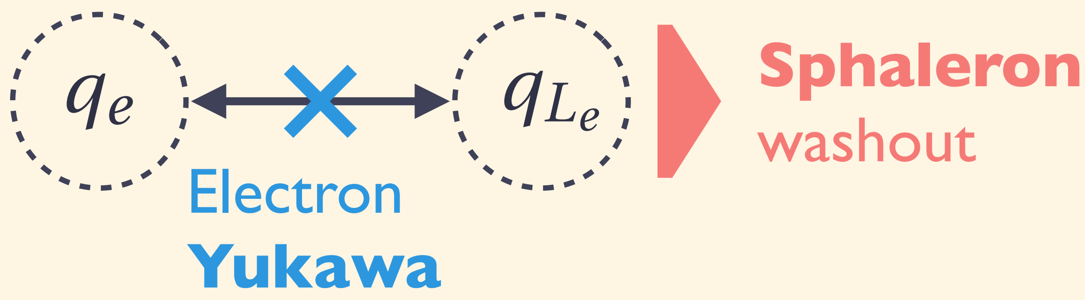

Electron Yukawa is **NOT** equilibrated till

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

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

$$\partial \cdot J_e = -\frac{\alpha_Y}{2\pi}\partial \cdot h_Y + (\text{Yukawa})$$

Inflation

$\dot{\phi} h_Y$ $\qquad -\frac{\alpha_Y}{2\pi}\Delta h_Y \quad \Big| \quad -\frac{\alpha_Y}{2\pi}\Delta h_Y$

$\dot{\phi} = 0$

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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

q_e ←✕→ q_{L_e} — Electron **Yukawa**

Sphaleron washout

Electron Yukawa is **NOT** equilibrated till

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

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

$$\partial \cdot J_e = -\frac{\alpha_Y}{2\pi}\partial \cdot h_Y + (\text{Yukawa})$$

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

$$\partial_\eta h_{Y,k}(\eta) = \frac{2k}{\sigma_Y}\left(\frac{k_{\mathrm{CPI}}}{r_k(\eta)} - k\right) h_{Y,k}(\eta)$$

w/ $$k_{\mathrm{CPI}} = \frac{2\alpha_Y}{\pi}\frac{95}{18}\mu_e, \quad r_k(\eta) = \frac{k h_{Y,k}(\eta)/2}{\rho_{B,k}(\eta)}$$

Joyce, Shaposhnikov 9703005, Akamatsu, Yamamoto 1302.2125,…

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

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V.Domcke, B.Harling, E.Morgante, **KM**
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- **Survival of q_e** from Sphaleron + Yukawa washout

q_e ←✕→ q_{L_e} (Electron **Yukawa**) ▶ **Sphaleron** washout

Electron Yukawa is **NOT** equilibrated till

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

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

$$\partial \cdot J_e = -\frac{\alpha_Y}{2\pi}\partial \cdot h_Y + (\text{Yukawa}) \longrightarrow \dot{q}_e = -\frac{\alpha_Y}{2\pi}\dot{h}_Y - \frac{711}{481}\Gamma_{Y_e} q_e$$

Inflation $\dot{\phi} h_Y$: $-\frac{\alpha_Y}{2\pi}\Delta h_Y$ ¦ $-\frac{\alpha_Y}{2\pi}\Delta h_Y$

Chiral Plasma Instability

$\dot{\phi} = 0$: 0 ¦ 0

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

Sphaleron + Yukawa: 0 ¦ $-\frac{\alpha_Y}{2\pi}\Delta h_Y$

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

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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

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

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

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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

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

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

Chiral Plasma Instability

Magnetic Diffusion

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

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

Magnetic diffusion

$$0$$

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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

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

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

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

Chiral Plasma Instability

Magnetic Diffusion $T_{\rm diff} \sim \frac{\alpha_Y \ln \alpha_Y^{-1}}{5} H_{\rm rh}$

Inverse cascade $T_{\rm ic} \sim v_{\rm rh} T_{\rm rh}$

- **Inverse cascade**: transfer from short to long wave length.

$T_{\rm ic} > T_{\rm diff} \leftrightarrow R_m \equiv \sigma_Y L_{\rm rh} v_{\rm rh} > 1$ i.e., Large magnetic Reynolds #

$-\frac{\alpha_Y}{2\pi}\Delta h_Y$ → **Magnetic** diffusion → 0

$-\frac{\alpha_Y}{2\pi}\Delta h_Y$ → $-\frac{\alpha_Y}{2\pi}\Delta h_Y$

Inverse cascade
- Approximate **conservation of** $\boldsymbol{h_Y}$.

See e.g., R.Durrer, A.Neronov 1303.7121

4.

Regeneration of Baryon Asymmetry

Outline of this Talk

Baryogenesis from B+L asymmetry?

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = 3\partial_\mu K^\mu_{CS} - \frac{3\alpha_Y}{4\pi}\partial_\mu h^\mu_Y$$

Time				
Inflation	$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	Inefficient	$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	2. ✓
$T_{Y_e} \sim 10^5\,\mathrm{GeV}$	0 (via **Sphaleron** + **Yukawa** →)	$\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	(Inefficient **diffusion**, No **CPI** (chiral plasma instability) ↓) $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	3. ✓
$T_{EW} \sim 10^2\,\mathrm{GeV}$	$\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ (← ⊿ $\mathbf{h_Y}$ is converted to $\mathbf{U(1)_{em}}$)	→ (**Sphaleron** freezes out) $\epsilon \times \frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$	0	4.

K.Kamada's talk @ PPP2019

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

- **Transport equation @ EW Crossover**

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

  - Slowest processes: EW sphaleron & Decaying helicity

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

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

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

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  - Slowest processes: EW sphaleron & Decaying helicity

T. Fujita, K.Kamada 1602.02109
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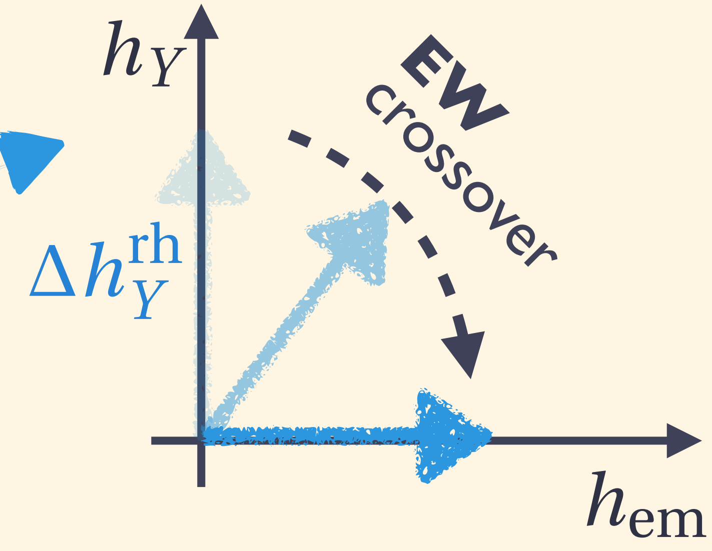
$$\begin{cases} \Gamma_{\mathrm{W,sph}} \propto e^{-\frac{M_{\mathrm{sph}}(T)}{T}} \\ M_{\mathrm{sph}}(T) \propto v(T) \end{cases}$$

$$\propto \partial_\eta h_Y$$



Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

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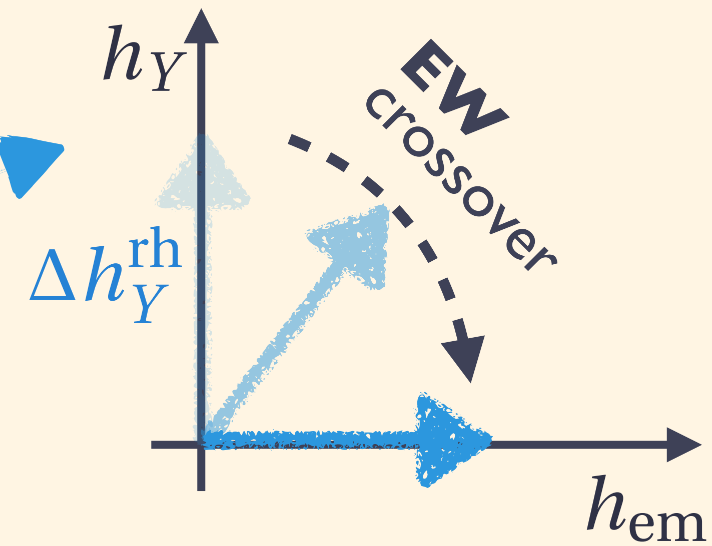


- EW sphaleron washout v.s. Decaying helicity

$$\eta_B = \frac{q_B}{s} \simeq \epsilon \times \frac{3\alpha_Y}{4\pi}\frac{\Delta h_Y}{s}\bigg|_{\mathrm{rh}}$$

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

Sphaleron washout factor

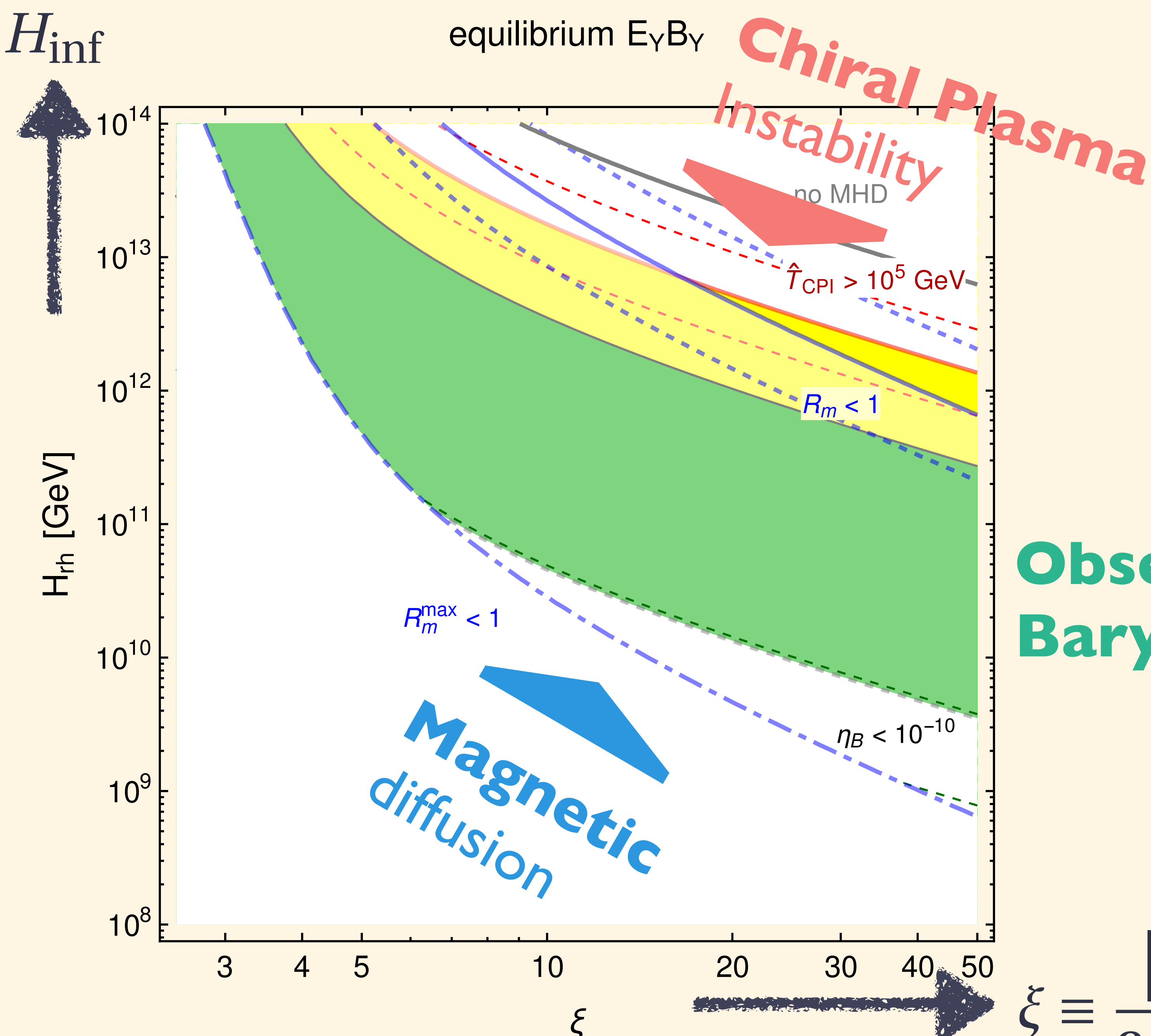
$$\epsilon \equiv \left[\frac{34}{111}\left(1+\frac{\alpha_2}{\alpha_Y}\right)\frac{H}{\Gamma_{W,\mathrm{sph}}} f(\theta, T)\right]_{T_{\mathrm{EW}}}$$

- Huge uncertainties…

w/ $f(\theta,T) = -T\frac{\mathrm{d}\theta}{\mathrm{d}T}\sin(2\theta)$

Baryogenesis from axion inflation

Viable parameters for Baryogenesis



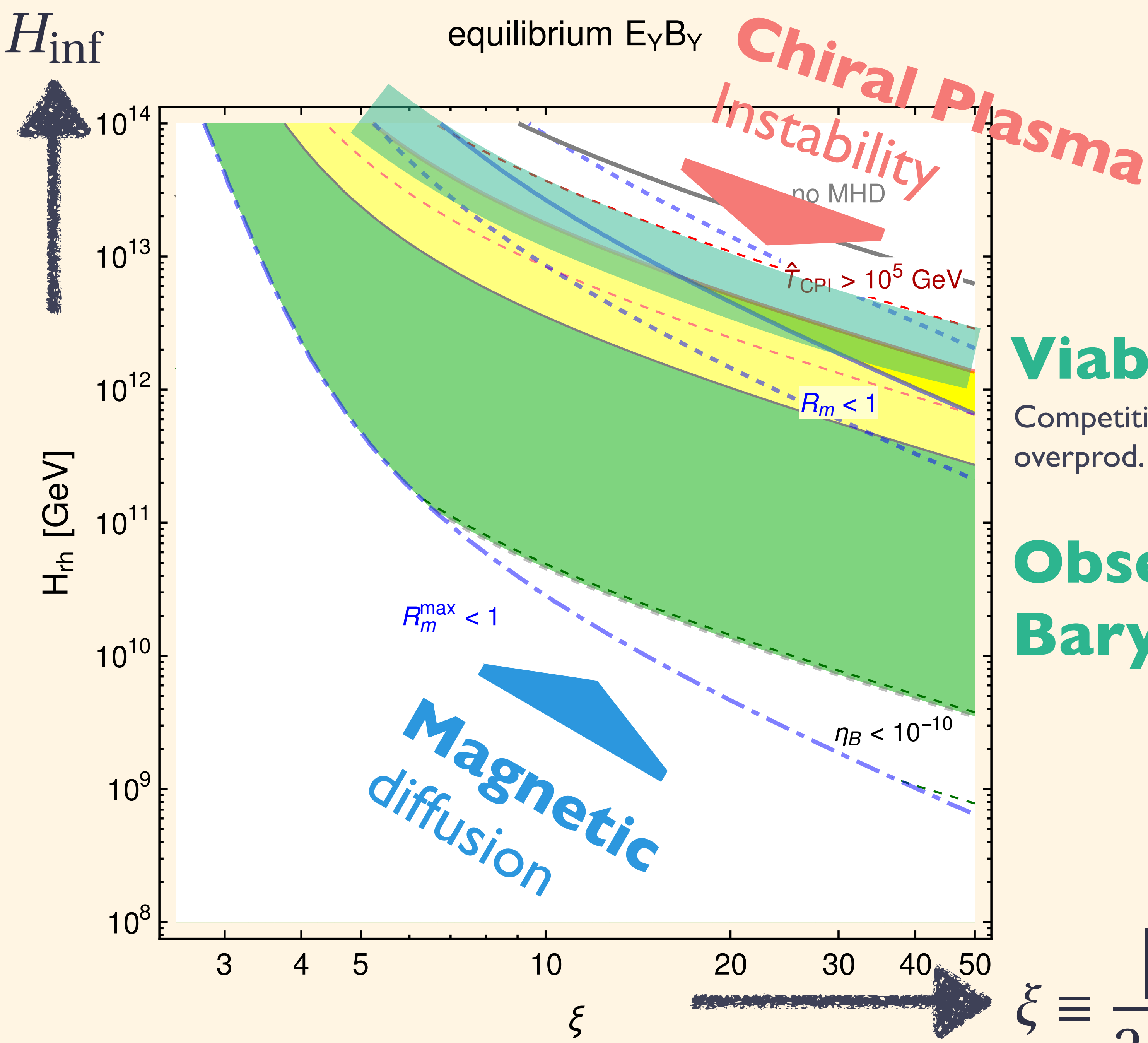
- Successful baryogenesis **only with SM + inflaton**
- ChMHD puts **lower**/**upper** bounds.
- **Mild dependence** on the Chern-Simons coupling

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

$$\xi \equiv \frac{|\dot{\phi}|}{2\Lambda H} \sim \epsilon^{1/2} \frac{M_P}{\Lambda}$$

Baryogenesis from axion inflation

Viable parameters for Baryogenesis



- Successful baryogenesis **only with SM + inflaton**
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$$\xi \equiv \frac{|\dot{\phi}|}{2\Lambda H} \sim \epsilon^{1/2}\frac{M_P}{\Lambda}$$

5.

Leptogenesis from axion inflation

Leptogenesis?

What we have discussed so far...

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- Setup: inflaton + SM

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{3}{32\pi^2}\left(g_2^2 W_{\mu\nu}^a \tilde{W}^{a\mu\nu} - g_Y^2 Y_{\mu\nu}\tilde{Y}^{\mu\nu}\right)$$

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

Time (↓)

Leptogenesis?

Leptogenesis from B+L asymmetry?

- Setup: inflaton + SM **+ Majorana N_R**

V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
20xx.xxxxx

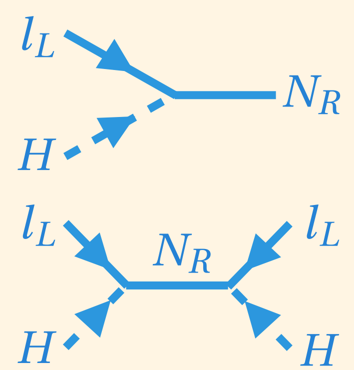
$$\partial_\mu J_B^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

$$\partial_\mu J_L^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu + (ih\overline{N}L\cdot H + \text{H.c.})$$

Inflation

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

$-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $-(1-\kappa)\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | Washout via **Majorana ν_R** | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $\kappa\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$



$\kappa \sim \mathcal{O}(1)$

Time

Leptogenesis from B+L asymmetry?

- Setup: inflaton + SM **+ Majorana N_R**

V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
20xx.xxxxx

$$\partial_\mu J_B^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu$$

$$\partial_\mu J_L^\mu = 3\partial_\mu K_{CS}^\mu - \frac{3\alpha_Y}{4\pi}\partial_\mu h_Y^\mu + (ih\overline{N}L\cdot H + \text{H.c.})$$

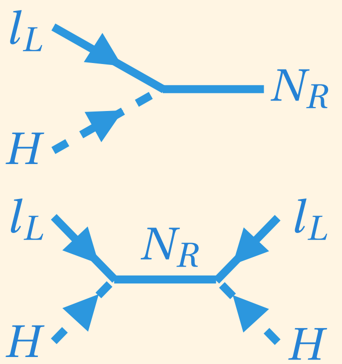
Inflation: $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | **Inefficient** | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

$T \sim T_{N_R}$: $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $-(1-\kappa)\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | Washout via **Majorana ν_R** | $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $\kappa\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

$T \sim 10^5\,\text{GeV}$: via **Sphaleron + Yukawa**

$-\frac{28\kappa}{79}\times\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $\frac{51\kappa}{79}\times\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$ | $\left(1-\frac{28\kappa}{79}\right)\times\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

Time



$\kappa \sim \mathcal{O}(1)$

Leptogenesis?

Leptogenesis from B+L asymmetry?

- Setup: inflaton + SM **+ Majorana N_R**

V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
20xx.xxxxx

$$\partial_\mu J^\mu_B = 3\partial_\mu K^\mu_{\rm CS} - \frac{3\alpha_Y}{4\pi}\partial_\mu h^\mu_Y$$

$$\partial_\mu J^\mu_L = 3\partial_\mu K^\mu_{\rm CS} - \frac{3\alpha_Y}{4\pi}\partial_\mu h^\mu_Y + (i h \overline{N} L \cdot H + \text{H.c.})$$

- **Resultant baryon asymmetry**

$$\frac{q_B}{s} \sim 10^{-9}\kappa \left(\frac{H_{\rm rh}}{10^{10}\,\text{GeV}}\right)^{\frac{3}{2}} \left(\frac{\langle \hat{E}_Y \cdot \hat{B}_Y\rangle_{\rm rh}/H^4_{\rm rh}}{10^5}\right)$$

Majorana N_R washout factor

- Depends on when N_R decouples.

$$\kappa \sim \mathcal{O}(0.1)$$

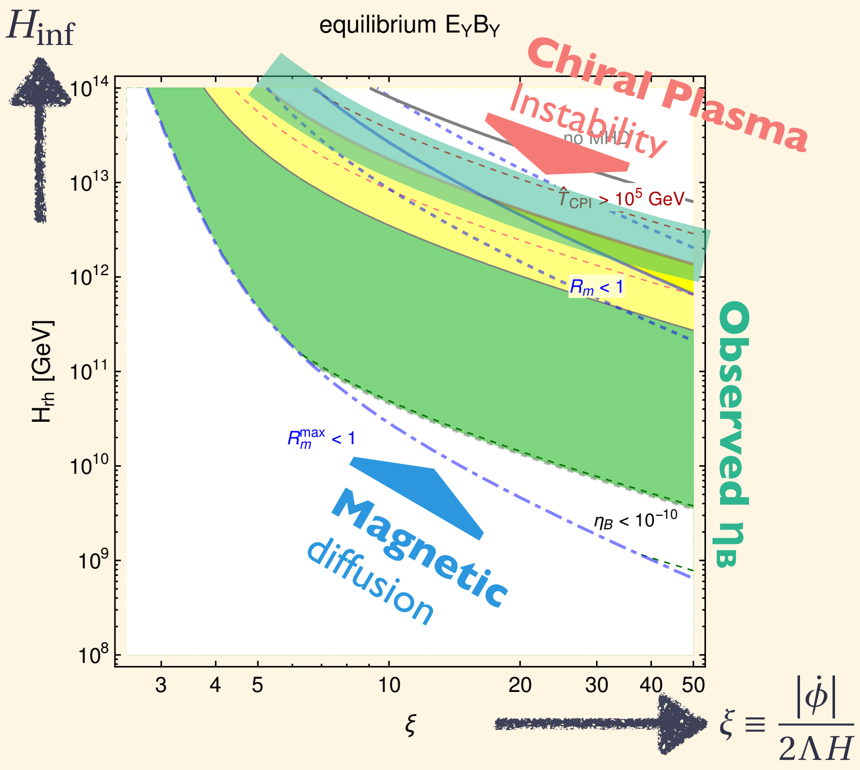
- N_R has to decouple before B+L is completely washed out.

$$T_{N_R} > T_{Y_e} \sim 10^5\,\text{GeV}$$

Summary

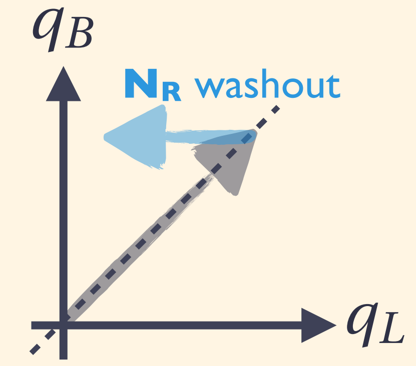
Inflaton w/ CS coupling to U(1)$_Y$

- Dual production of **B+L asymmetry & helical U(1)$_Y$**
- **Baryogenesis** only with SM + inflaton
  - BAU connected to H_{inf}
  - Mild dependence on the CS coupling
  - Upper/Lower bounds from ChMHD
  - Uncertainties: SM physics & backreaction



- **Leptogenesis** with SM + inflaton + Majorana N_R
  - Washout via N_R generates B-L asym. from B+L asym.

$$\frac{q_B}{s} \sim 10^{-9}\kappa\left(\frac{H_{\rm rh}}{10^{10}\,{\rm GeV}}\right)^{\frac{3}{2}}\left(\frac{\langle \hat{\boldsymbol{E}}_Y\cdot\hat{\boldsymbol{B}}_Y\rangle_{\rm rh}/H_{\rm rh}^4}{10^5}\right)$$

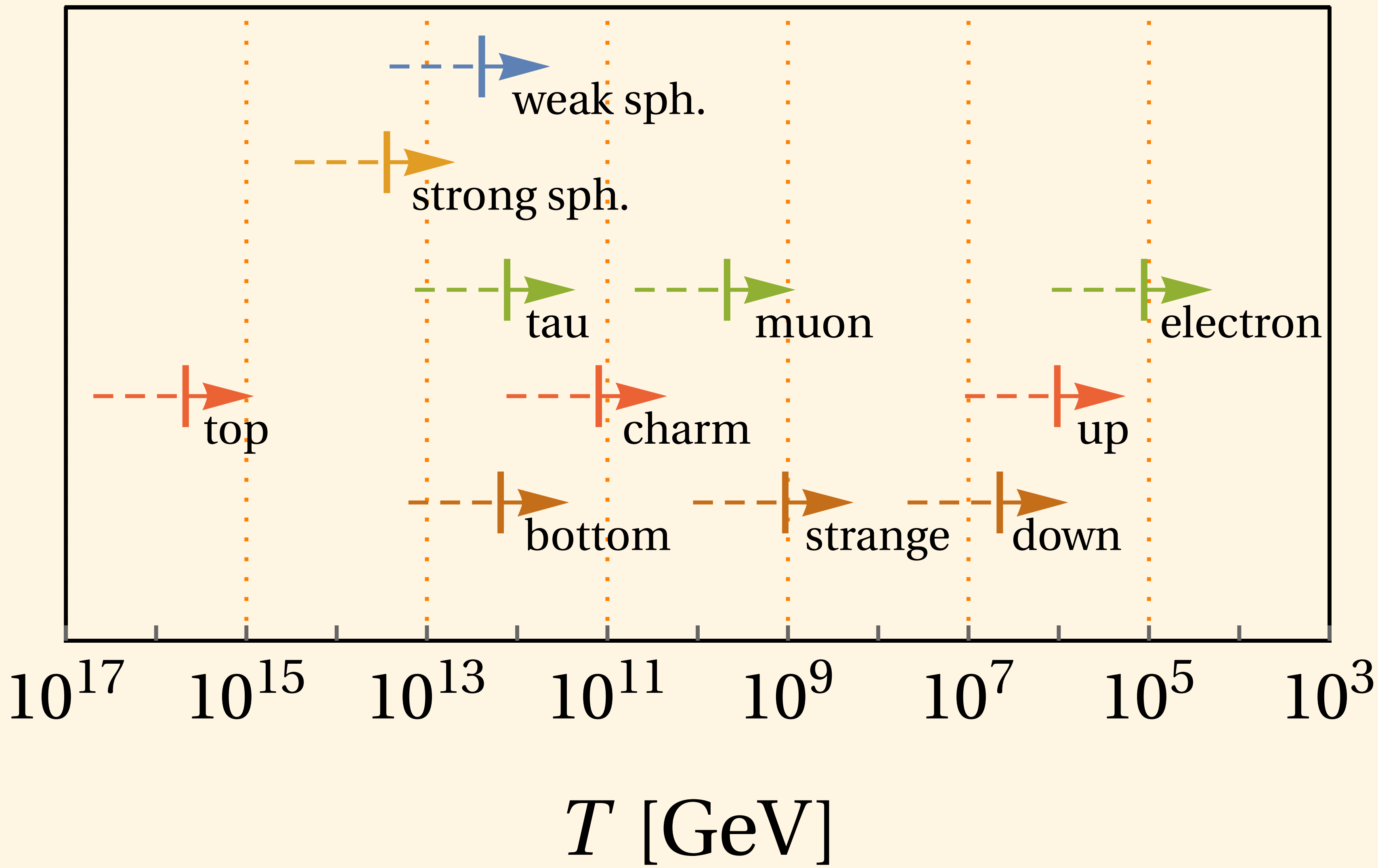


Back up

Decoupling Temperature

Summary plot of decoupling temperatures

- Assume radiation dominated Universe.
  - During inflation, equilibration is more difficult because $H^2 > \frac{\rho_{\rm rad}}{3M_P^2}$.



Field Rotation Invariance

Redundancies in inflaton-SM coupling

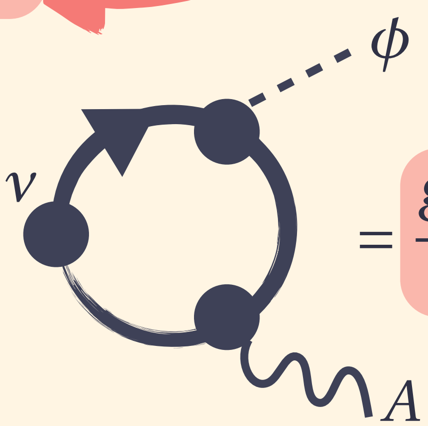
- **Warm up**: coupling to CS term in massless QED

$$\frac{g^2\phi}{16\pi^2 f}F_{\mu\nu}\tilde{F}^{\mu\nu} \longrightarrow 0 = \partial_\mu F^{\mu\nu} - \frac{g^2\partial_\mu\phi}{4\pi^2 f}\tilde{F}^{\mu\nu} - gJ^\nu$$

Equivalent!

Chiral rot. $\psi \mapsto e^{-i\gamma_5\frac{\phi}{2f}}\psi$

$$-\frac{\phi}{2f}\partial_\mu J_5^\mu \longrightarrow 0 = \partial_\mu F^{\mu\nu} - gJ^\nu \supset$$



$$= \frac{g^2\partial_\mu\phi}{4\pi^2 f}\tilde{F}^{\mu\nu}$$

- **Coupling to CS term of U(1)$_Y$**

$$\frac{g_Y^2\phi}{16\pi^2 f}Y_{\mu\nu}\tilde{Y}^{\mu\nu} \longrightarrow 0 = D_\mu W^{a\mu\nu} - g_2 J^{a\nu}$$

Equivalent!

B+L rot.

$$\supset + \frac{g_2^2\partial_\mu\phi}{4\pi^2 f}\tilde{W}^{a\mu\nu}$$

$$\frac{\phi}{f}\left(-\frac{1}{3}\partial_\mu J^\mu_{B+L} + \frac{g_2^2}{16\pi^2}W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\right) \longrightarrow 0 = D_\mu W^{a\mu\nu} - \frac{g_2^2\partial_\mu\phi}{4\pi^2 f}\tilde{W}^{a\mu\nu} - g_2 J^{a\nu}$$

➡ Field rotation never changes physics! (see also **KM+** 2006.03148)

Field Rotation Invariance

Redundancies in inflaton-SM coupling

- **Warm up**: coupling to CS term in massless QED

$$\frac{g^2\phi}{16\pi^2 f}F_{\mu\nu}\tilde{F}^{\mu\nu} \longrightarrow 0 = \partial_\mu F^{\mu\nu} - \frac{g^2\partial_\mu\phi}{4\pi^2 f}\tilde{F}^{\mu\nu} - gJ^\nu$$

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$$\frac{g_Y^2\phi}{16\pi^2 f}Y_{\mu\nu}\tilde{Y}^{\mu\nu} \longrightarrow 0 = D_\mu W^{a\mu\nu} - g_2 J^{a\nu}$$

Equivalent!

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$$\supset + \frac{g_2^2\partial_\mu\phi}{4\pi^2 f}\tilde{W}^{a\mu\nu}$$

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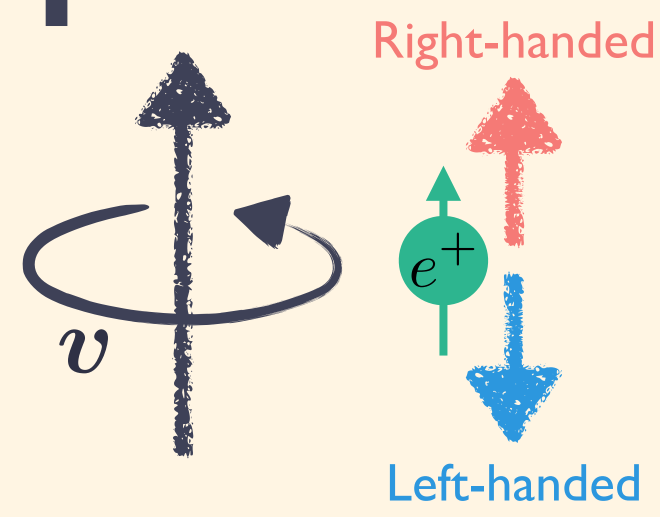
Chiral Vortical Effect

Chiral vortical effect as NLO in μ/T



- Generalized Ohm' law w/ velocity & its **vortex**
  - Assump: weak hyper gauge field & thermalized plasma.

$$\hat{\boldsymbol{J}}_Y = \sigma_Y \left(\hat{\boldsymbol{E}}_Y + \boldsymbol{v} \times \hat{\boldsymbol{B}}_Y\right) + \frac{2\alpha_Y}{\pi}\mu_{Y,5}\hat{\boldsymbol{B}}_Y + c_{\mathrm{CVE}}\frac{\boldsymbol{\nabla}}{a} \times \boldsymbol{v}$$

w/ $c_{\mathrm{CVE}} = g_Y\left(\sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha}\frac{\mu_\alpha^2}{4\pi^2} + \frac{T^2}{12}\sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha}\right) = \frac{g_Y}{4\pi^2}\sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha}\mu_\alpha^2$

where $\epsilon_\alpha = \pm$ for R/L

$N_\alpha = \mathrm{d.o.f.}$

$$\sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha} = 0 \quad \because \mathscr{A}\left(\mathrm{U}(1)_Y - \mathrm{grav.} - \mathrm{grav.}\right) = 0$$

A.Vilenkin, Phys. Rev. D 21, 2260 (1980)

  - **Small chemical potential** in the early Universe: **μ/T** ≪ **1**.

$$\hat{\boldsymbol{J}}_Y = \sigma_Y \left(\hat{\boldsymbol{E}}_Y + \boldsymbol{v} \times \hat{\boldsymbol{B}}_Y\right) + \frac{2\alpha_Y}{\pi}\mu_{Y,5}\hat{\boldsymbol{B}}_Y + \frac{g_Y}{4\pi^2}\left(\sum_\alpha \epsilon_\alpha N_\alpha Q_{Y,\alpha}\mu_\alpha^2\right)\frac{\boldsymbol{\nabla}}{a} \times \boldsymbol{v}$$

$$\sim \frac{\mu}{T}\frac{\hat{B}_Y}{\alpha_Y^{-1}T^{-1}} \gg \sim g_Y\mu^2\frac{v}{L} \sim \frac{\mu^2}{T^2}\frac{\hat{B}_Y}{g_Y^{-1}L}$$

@ equipartition: $\hat{B}_Y^2 \sim T^4 v^2$

Induced Current

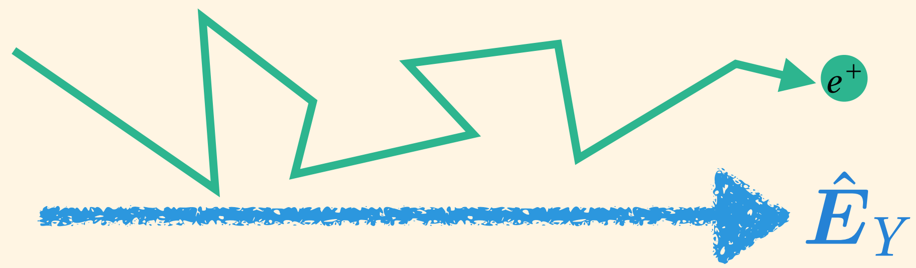
How does Induced Current look like?

- **Weak** electromagnetic field in thermalized plasma

$$\hat{\boldsymbol{J}}_Y = \hat{\sigma}_Y \hat{\boldsymbol{E}}_Y + \frac{2\alpha_Y}{\pi} \hat{\mu}_{Y,5} \hat{\boldsymbol{B}}_Y$$ 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**

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

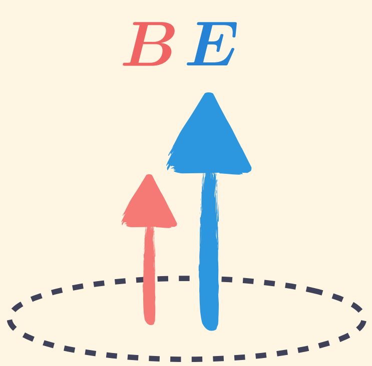
Reproduce e.g., Kobayashi, Afshordi 1408.4141

Massive Fermion Production

Schwinger effect for massive fermion

V.Domcke, Y.Ema, **KM**
1910.01205

- **Anomalous** current equation w/ mass term



$$\partial_\mu J_5^\mu = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} + 2im\bar{\psi}\gamma_5\psi$$

See e.g., K.Fukushima+ 1807.04416

$$\dot{q}_5 \simeq \frac{g^2 Q^2}{2\pi^2} EB \exp\left(-\frac{\pi m^2}{g|QE|}\right) \qquad \frac{g^2 Q^2}{2\pi^2} EB \qquad 2m\langle \bar{\psi} i\gamma_5\psi\rangle \simeq \frac{g^2 Q^2}{2\pi^2} EB\left[\exp\left(-\frac{\pi m^2}{g|QE|}\right) - 1\right]$$

- Production of W bosons is more violent. Ambjorn, Olesen, *Phys.Lett.B* 218 (1989) 67; Kajantie+, *Nucl.Phys.B* 544 (1999) 357-373

➡ **Backreact to Higgs potential**

- **Induced current**

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

Vacuum cont. Involves gauge coupling running **finite terms**, i.e., Euler-Heisenberg

$$gQ\langle J\rangle_{\rm ind} = a^3 \frac{(g|Q|)^3}{6\pi^2}\hat{\boldsymbol{E}}|\hat{B}|\coth\left(\frac{\pi|\hat{B}|}{\hat{E}}\right) e^{-\frac{\pi m^2}{g|Q|\hat{E}}}\frac{1}{H}$$

Massive Fermion Production

Schwinger effect for massive fermion

V.Domcke, Y.Ema, **KM**
1910.01205

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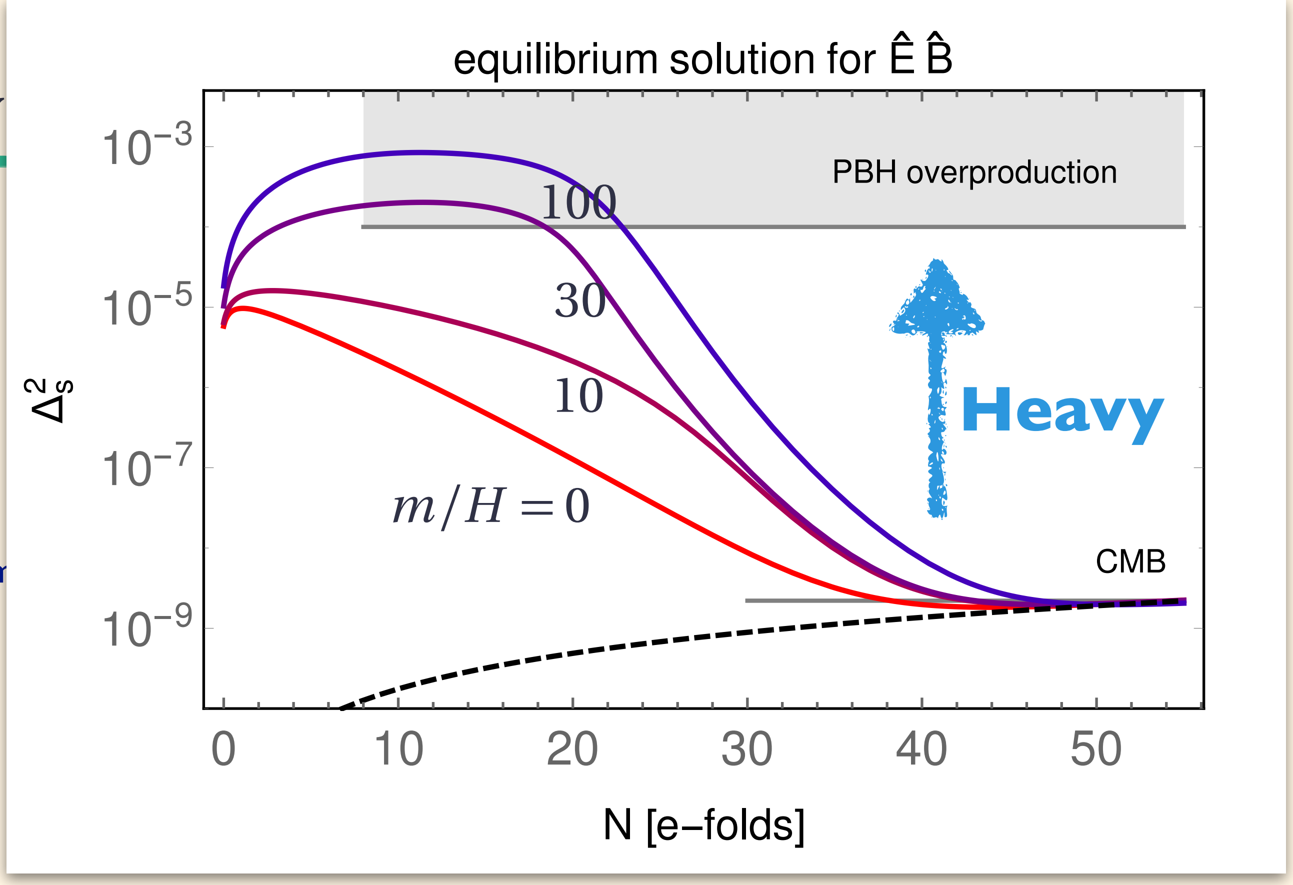
B E



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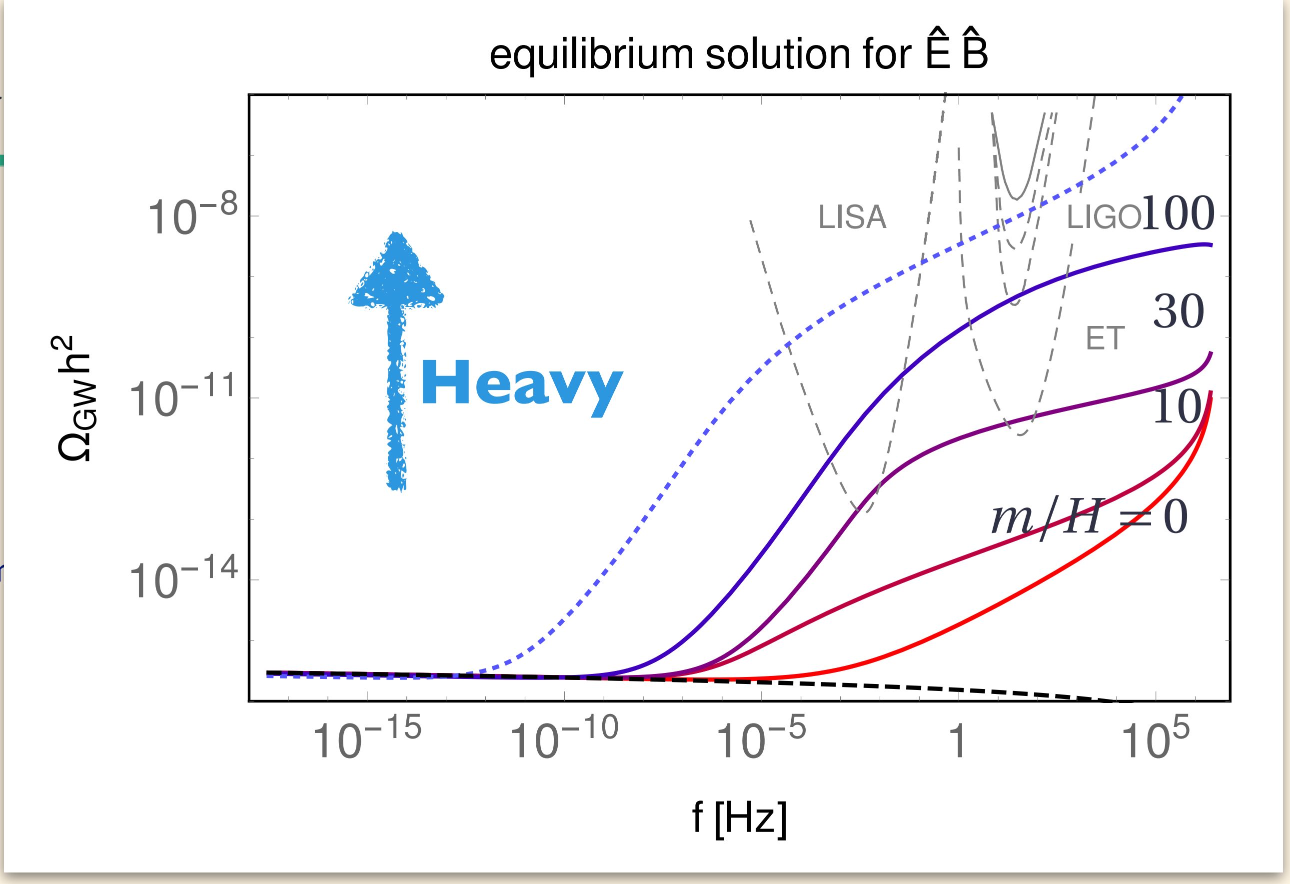

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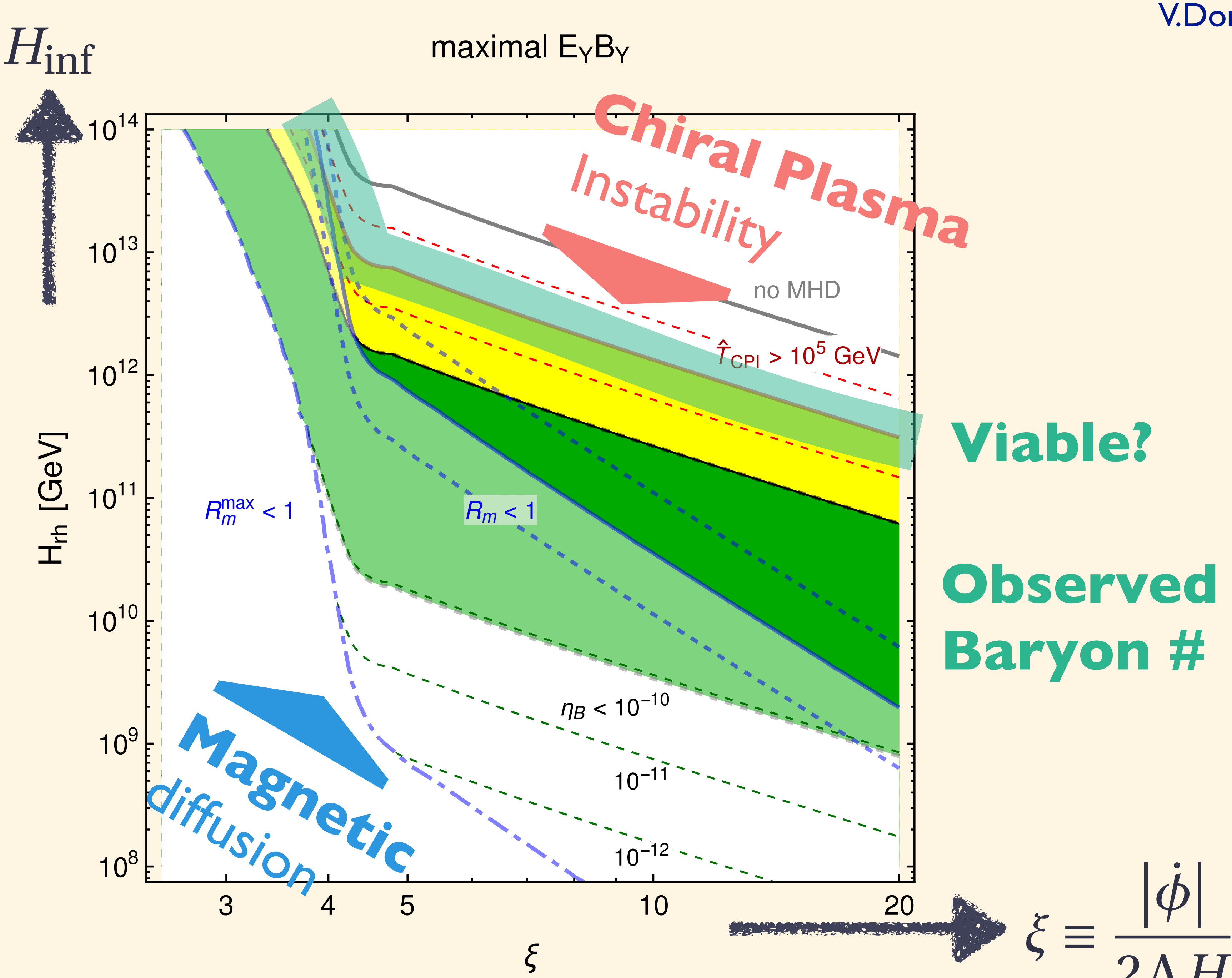
Result

Viable parameters for Baryogenesis

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

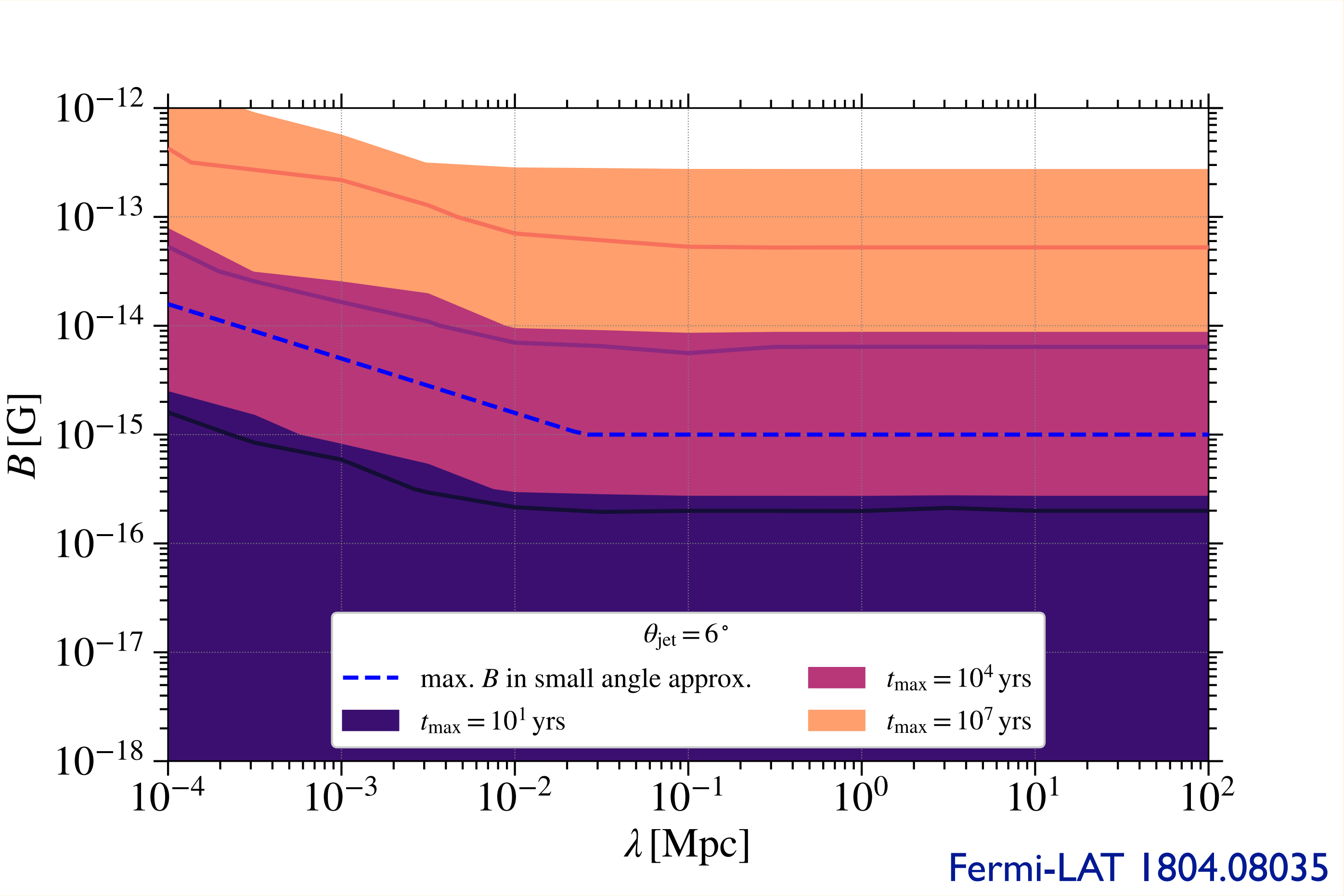


$$\xi \equiv \frac{|\dot{\phi}|}{2\Lambda H} \sim \epsilon^{1/2} \frac{M_P}{\Lambda}$$

Magnetic field

Implications to intergalactic B-field?

- Current lower limits to explain the intergalactic B-field.

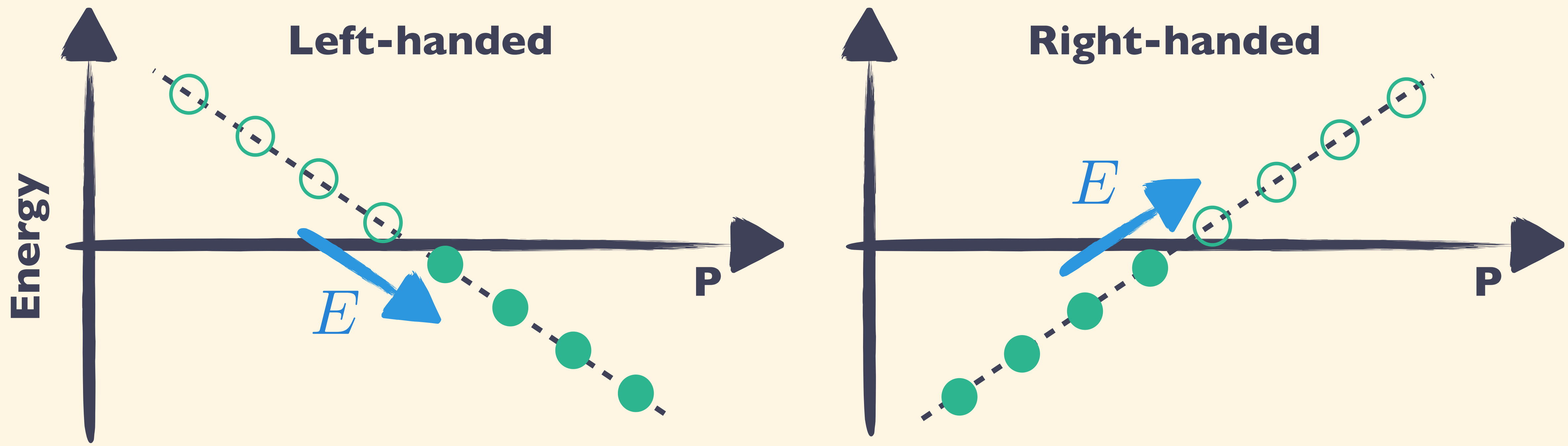


- Our baryogenesis model yields $B \lesssim 10^{-17}\mathrm{G}$ for $\lambda \sim 0.1\mathrm{pc}$ **too small...**

Vacuum Contribution

Chiral anomaly in finite volume

- Consider (1+1) QED on S[1]: $\partial \cdot J_5 = \frac{g}{2\pi} \epsilon^{\mu\nu} F_{\mu\nu} = \frac{gE}{\pi}$



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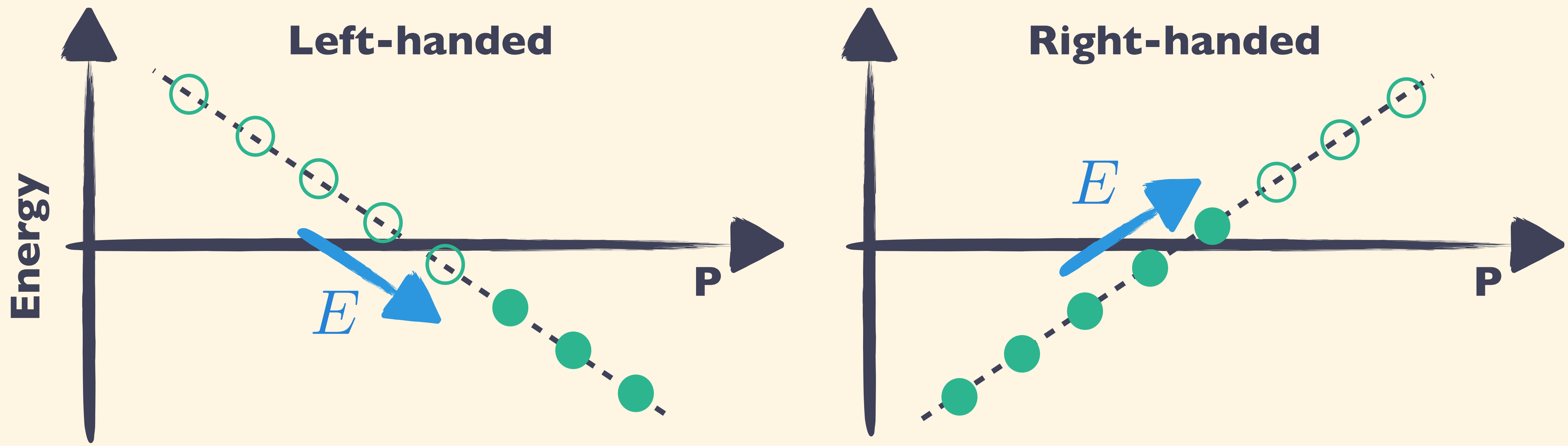

Vacuum Contribution

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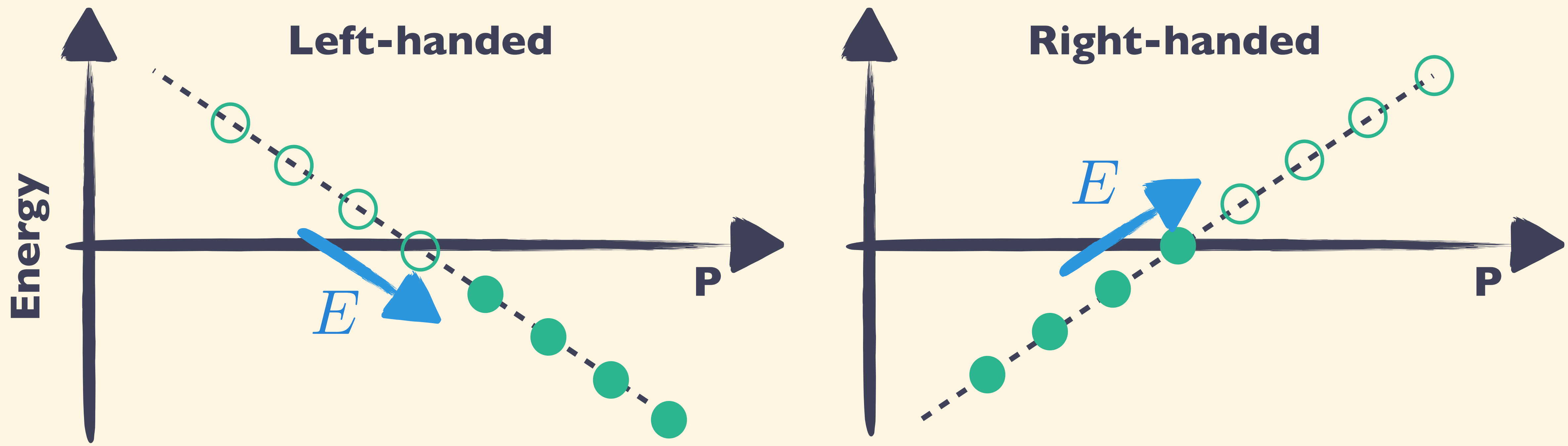


➡ Particles are not yet generated… How do we fulfill the anomaly eq?

$$Q_{\mathrm{R/L}} = \sum_p \left[\left(\hat{b}^\dagger \hat{b} - \frac{1}{2} \right) - \left(\hat{d}^\dagger \hat{d} - \frac{1}{2} \right) \right] \longrightarrow Q^{(\mathrm{vac})}_{\mathrm{R/L}} = \lim_{\Lambda \to \infty} \sum_p \left[-\frac{1}{2} \operatorname{sgn}(\omega_{\mathrm{R/L}}) R \left(\frac{|\omega_{\mathrm{R/L}}|}{\Lambda} \right) \right]$$

➡ Vacuum contribution accounts for the anomaly eq!

$$:Q_{\mathrm{R/L}}: = 0 \qquad Q^{(\mathrm{vac})}_{\mathrm{R/L}} = \frac{gE}{\pi} TL \qquad \int \mathrm{d}t \mathrm{d}x \frac{gE}{\pi} = \frac{gE}{\pi} TL$$

Inflaton w/ CS-coupling

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

non-Abelian

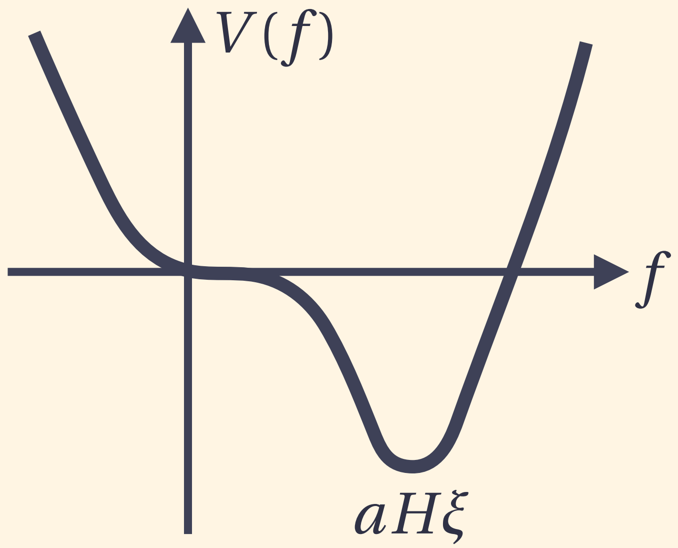
- "Lightness" protected by the shift symmetry (classically): $\phi \mapsto \phi + c$
- Efficient **helical-gauge field** production by $\dot{\phi} \neq 0$.

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

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

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

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



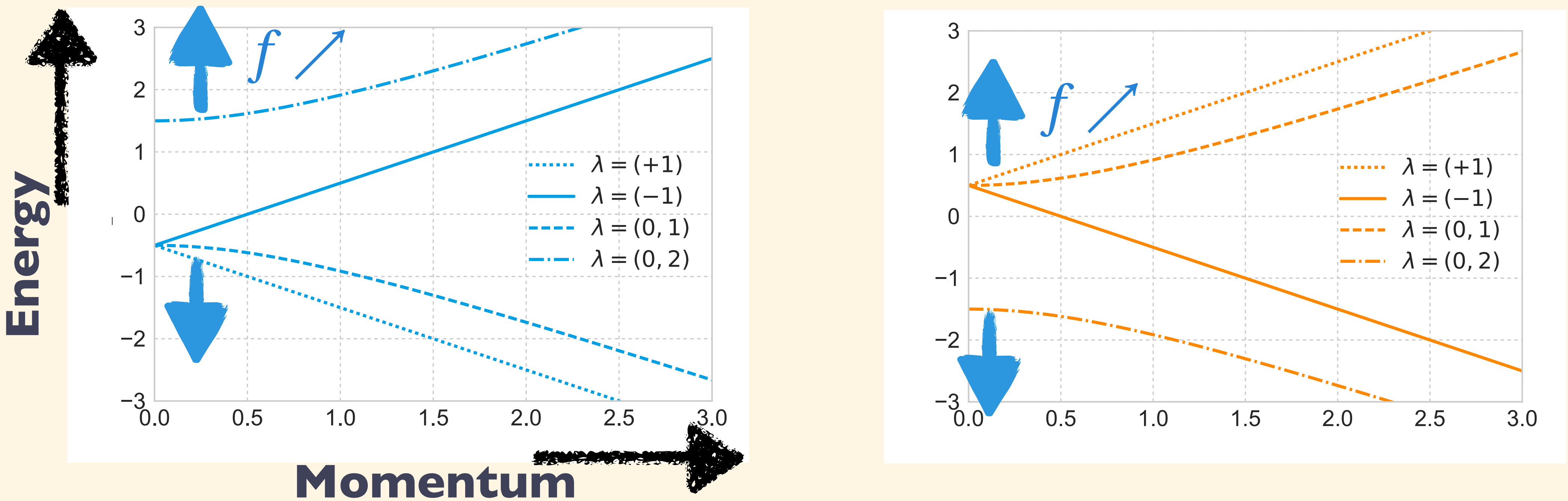
➡ **axion inflation, relaxion, chiral GWs, baryogenesis, magnetogenesis,...**

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 particles.

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

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

The eta-invariant; see Atiyah and Singer

Chiral Plasma Instability

Chiral Plasma Instability

- **Equation for Magnetic Helicity**

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

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

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

- **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

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

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

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

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

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

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