Baryogenesis from Axion Inflation

Kyohei Mukaida

DESY, HAMBURG

Based on 1806.08769, 1812.08021, 1905.13318
In collaboration with Y. Ema, V. Domcke, B. von Harling, E. Morgante, R. Sato

1.

Introduction

Introduction

Inflaton w/ CS-coupling

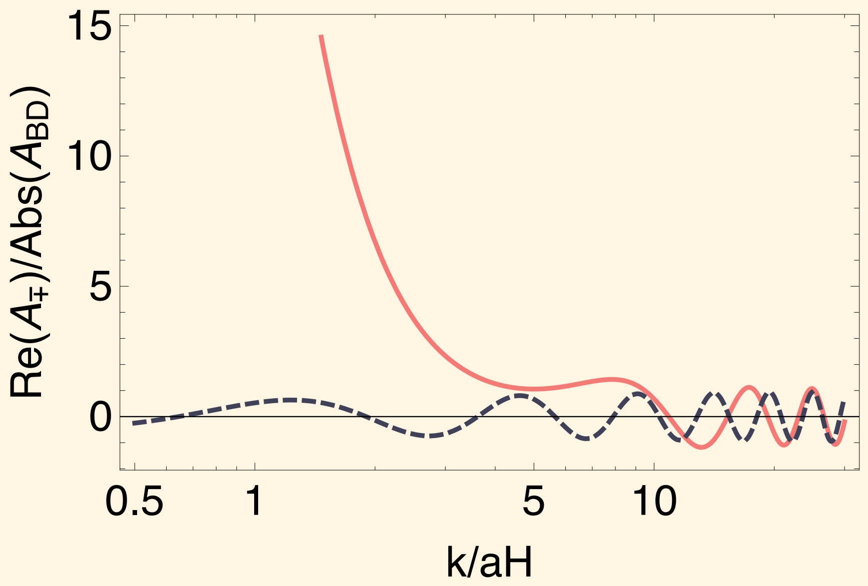
$$S=\int d^4x\left\{\sqrt{-g}\left[\frac{g^{\mu\nu}}{2}\partial_\mu\phi\partial_\nu\phi-V(\phi)\right]-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}\right\}$$

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

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

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

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



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

Introduction

Coupling to the SM Gauge Group ?

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

U(1)$_Y$

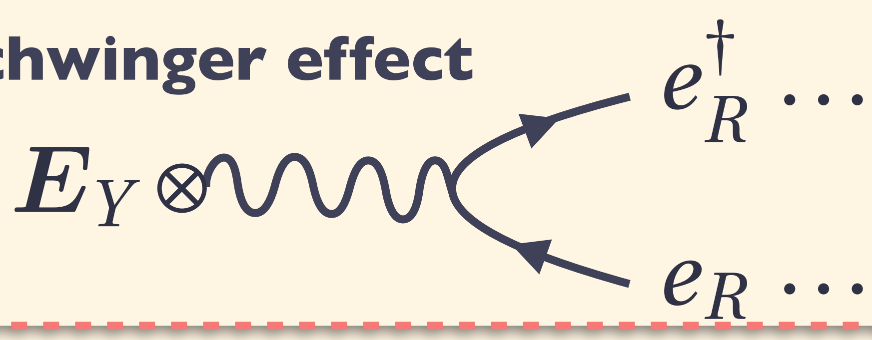
Matters charged under **U(1)$_Y$**

- Production of **matters** charged under the **SM gauge group**.
  - **Asymmetry** generation via the **SM chiral anomaly**

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

Helical gauge
⇔ **B+L asym.**

  - Pair production via the **Schwinger effect**



Does **Baryon/Lepton asymmetry** survive?

Introduction

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)$_{\mathbf{Y}}$** 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

Introduction

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

via **Sphaleron + Yukawa** → 0

Inefficient **diffusion**
No **CPI** (chiral plasma instability)
→ $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

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

Now

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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 $\phi Y_{\mu\nu}\tilde{Y}^{\mu\nu}$.

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

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

- Left ($\Delta q_B = \Delta q_L$): via **Sphaleron** + **Yukawa** → 0
- Right ($-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$): Inefficient **diffusion**, No **CPI** (chiral plasma instability) → $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

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

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

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

Time

Outline of this Talk

Baryogenesis from B+L asymmetry?

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

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2.

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

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Now

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

4.

Time

2.

Production of

Helical gauge & **Chiral** fermion

Setup

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

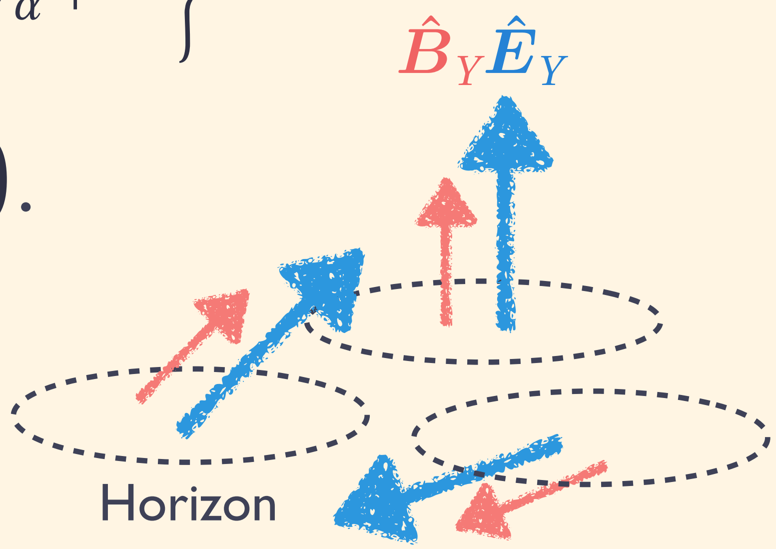
$$S = \int d^4x \left\{ \sqrt{-g}\left[\frac{g^{\mu\nu}}{2}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] - \frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} + \frac{\alpha_Y\phi}{4\pi f_a}Y_{\mu\nu}\tilde{Y}^{\mu\nu} + \sum_\alpha \psi_\alpha^\dagger \sigma\cdot(i\partial - g_Y Q_\alpha A_Y)\psi_\alpha + \cdots \right\}$$

- Production of **helical-gauge field** by $\dot{\phi} \neq 0$.

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

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

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



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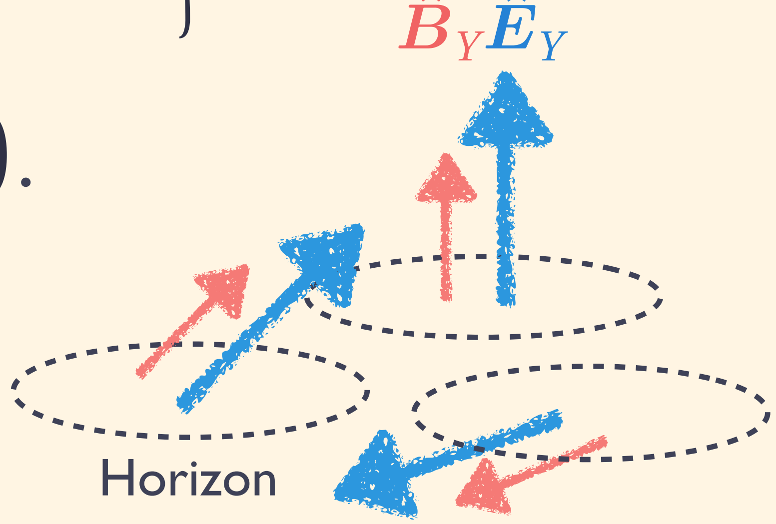


- Production of **matters** charged under the **SM gauge group**.
  - Asymmetry generation via the **SM chiral anomaly**

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

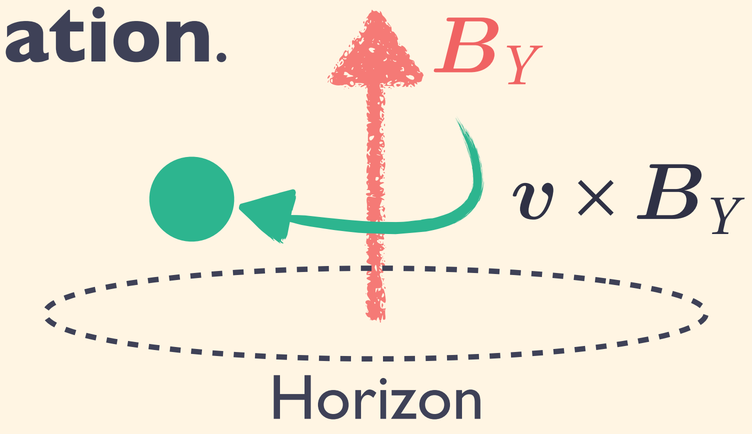
  - Pair production via the **Schwinger effect**

Landau Levels

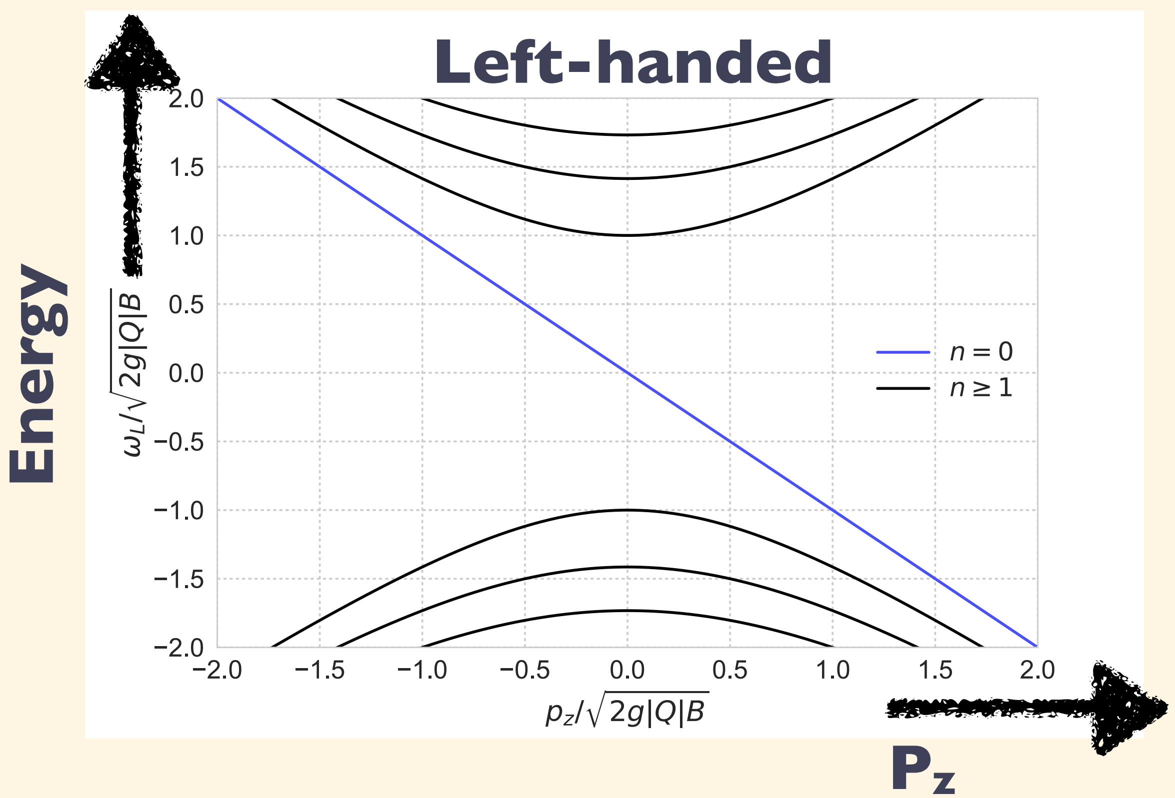
- Turn off E_Y; B_Y field modifies the **dispersion relation**.

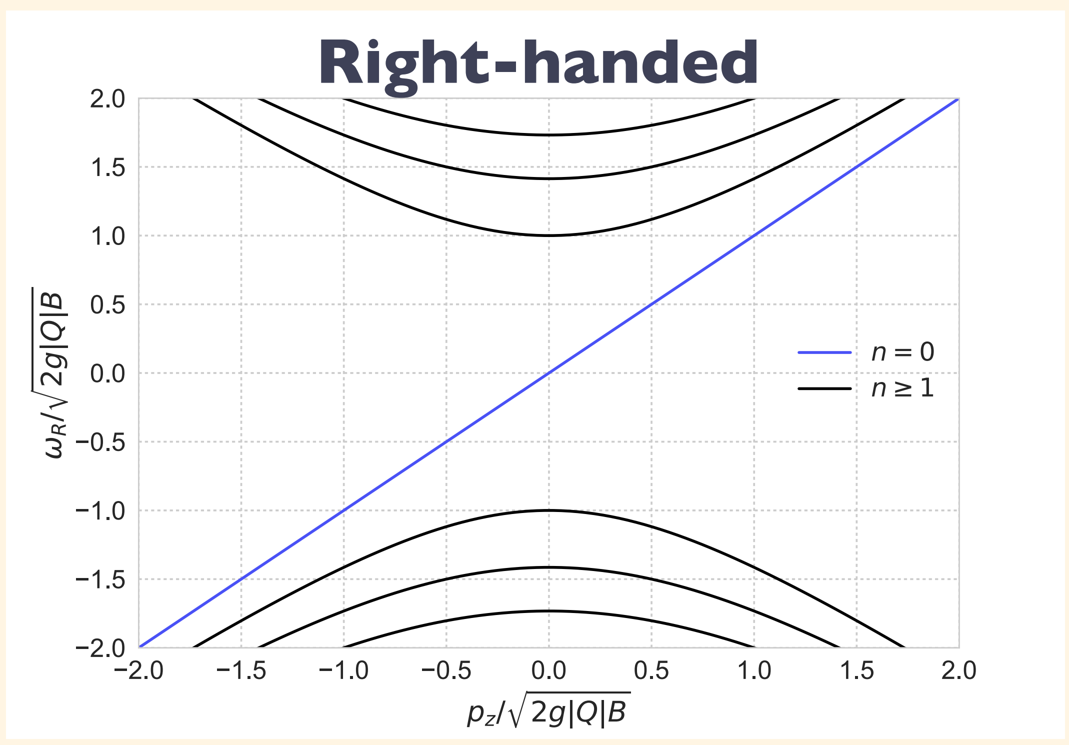
$$0 = \left(i\partial_\eta \pm i\boldsymbol{\nabla}\cdot\boldsymbol{\sigma} - gQ_\alpha A_{Y,0} \pm gQ_\alpha \boldsymbol{A}_Y \cdot \boldsymbol{\sigma} \right) \psi_{\alpha,\mathrm{R/L}}$$

where $(A_{Y,\mu}) = (0, 0, -B_Y x, 0)$



- **Landau Level n**: transverse motion; **p_z**: parallel motion



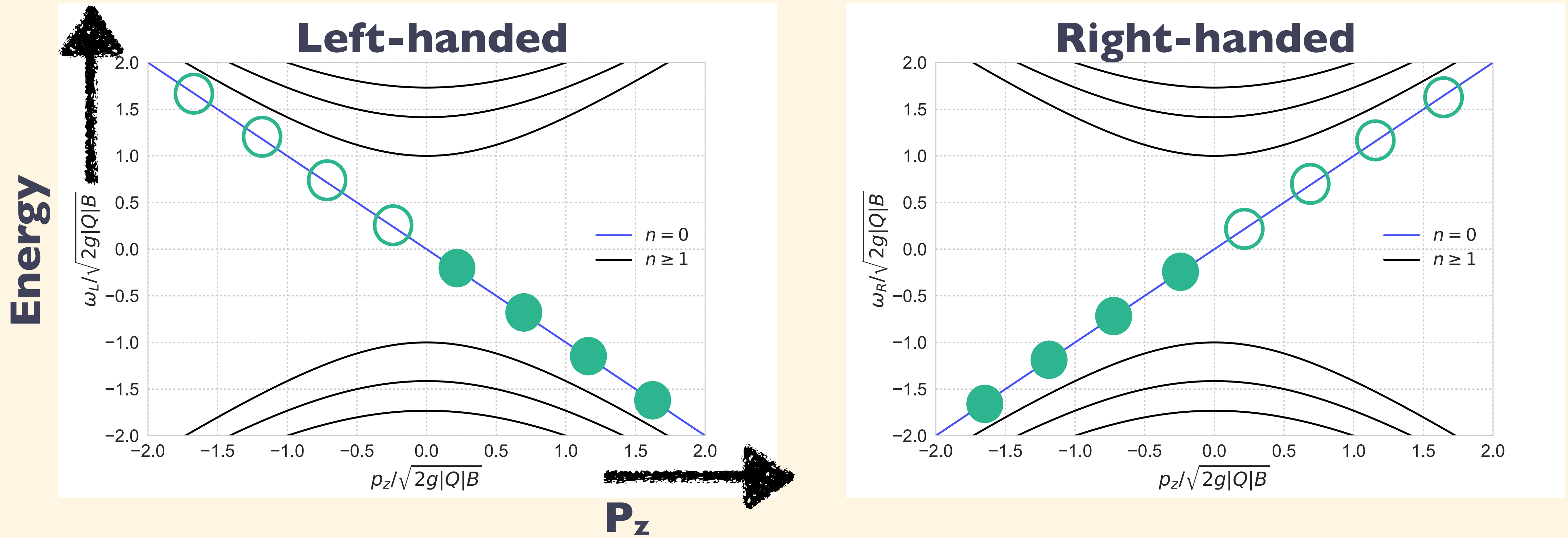


Fermion Production

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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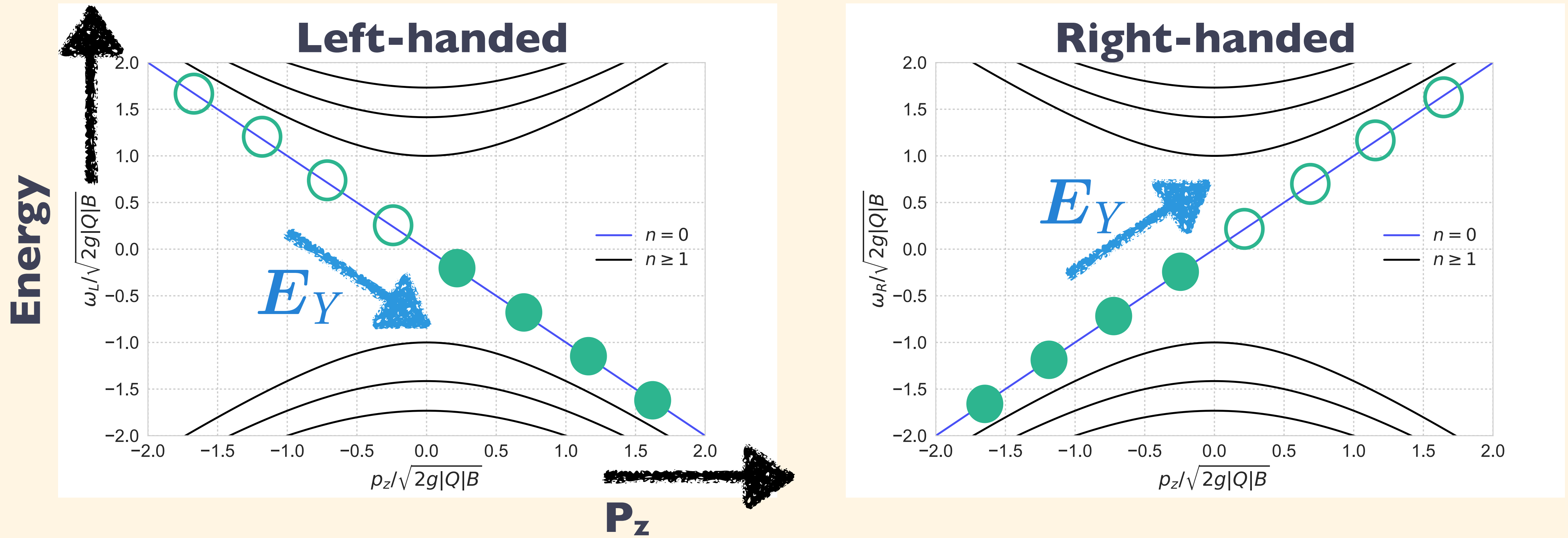

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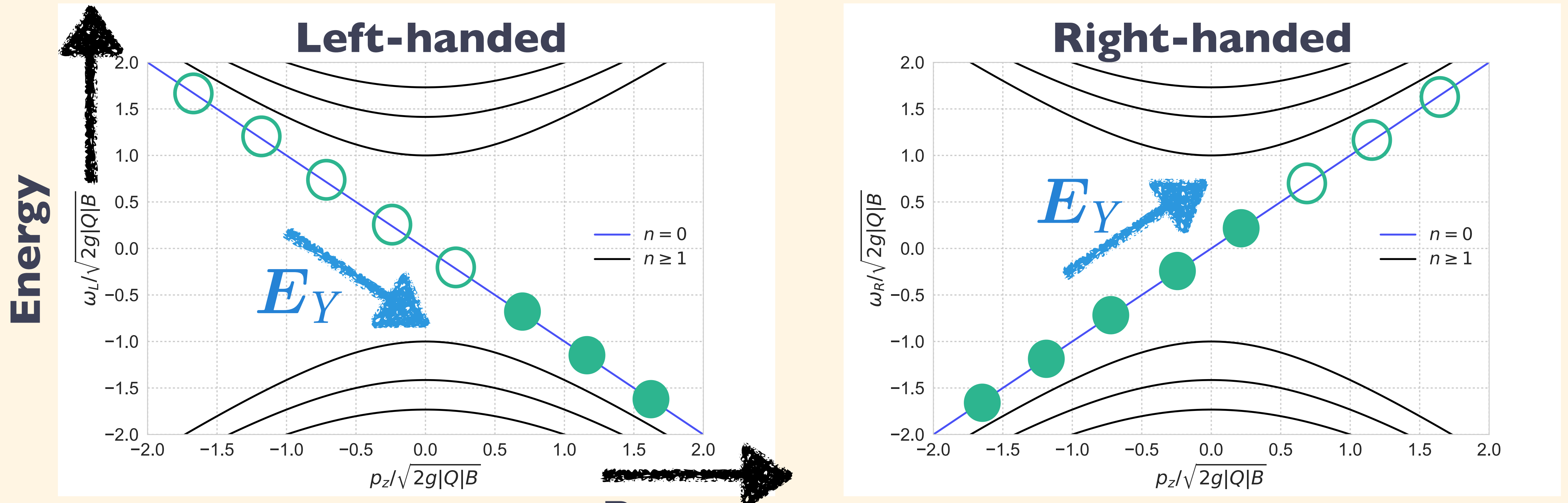


Anti-particle prod:

$$\dot{q}_{\alpha,L} = \dot{n}_{\alpha,L} - \dot{\bar{n}}_{\alpha,L} = -N_\alpha \frac{g^2 Q_\alpha^2}{4\pi^2} E_Y B_Y$$

Particle prod:

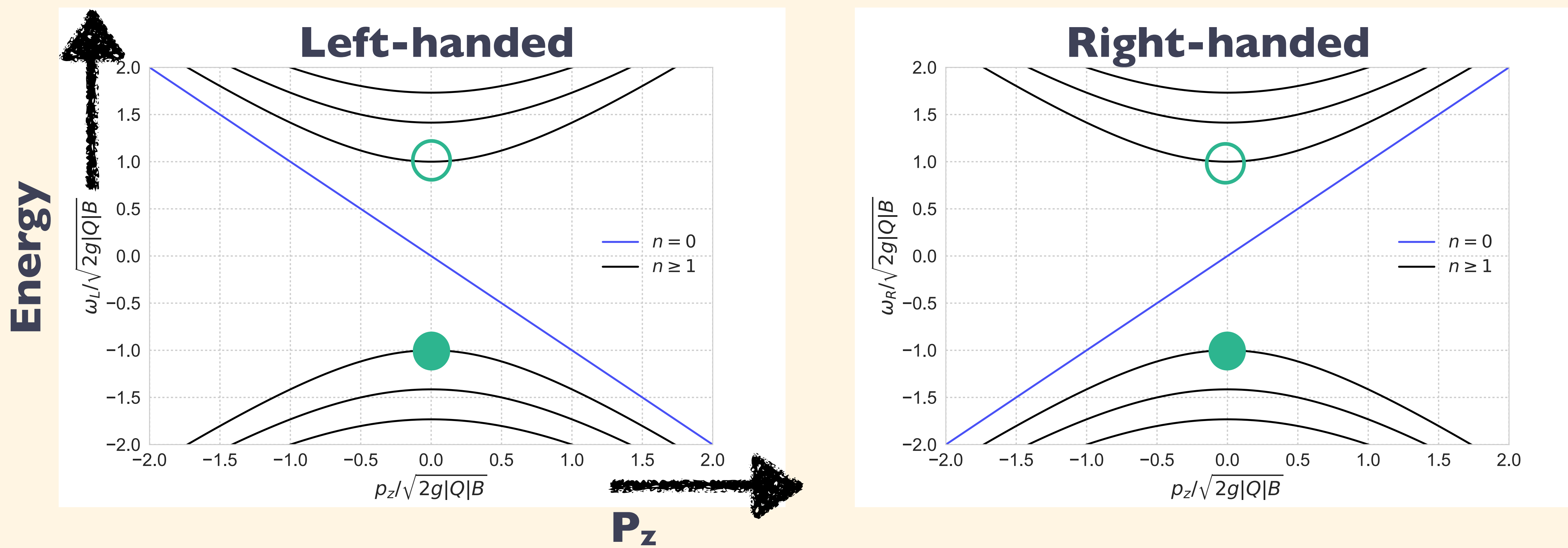
$$\dot{q}_{\alpha,R} = \dot{n}_{\alpha,R} - \dot{\bar{n}}_{\alpha,R} = +N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y$$

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

Higher Landau Levels (n≧1) & Pair Production

V.Domcke and **KM** 1806.08769

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



Fermion Production

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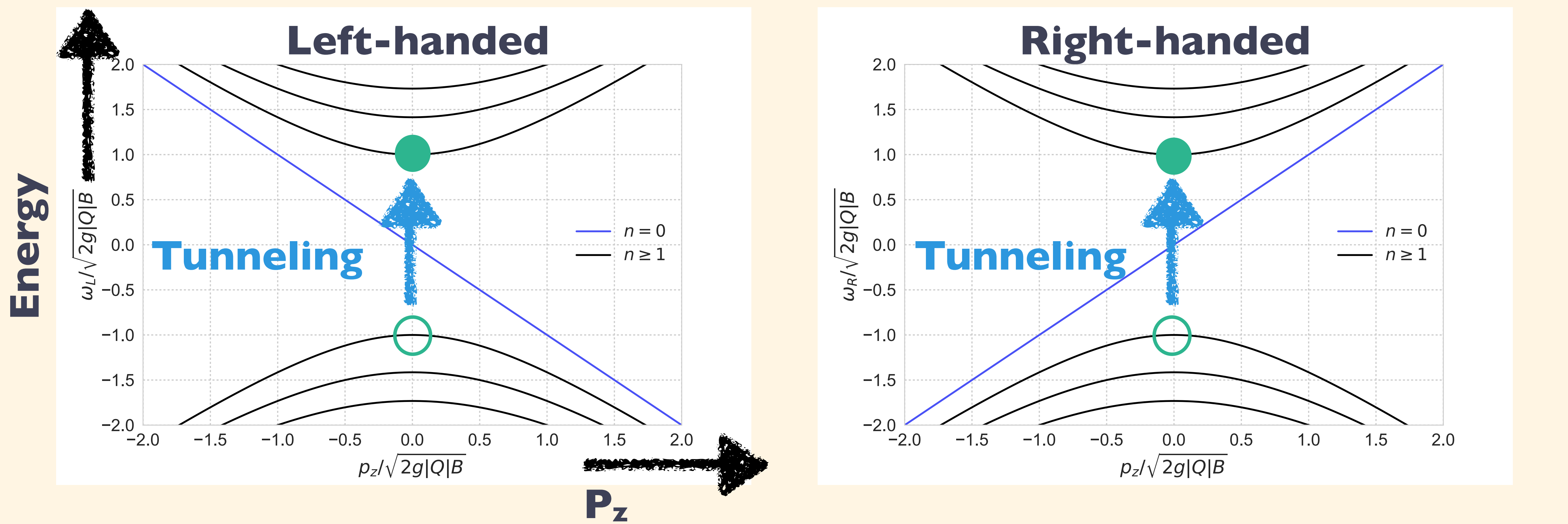

➡ **Pair**-production via Schwinger effect

Fermion Production

Higher Landau Levels (n≧1) & Pair Production

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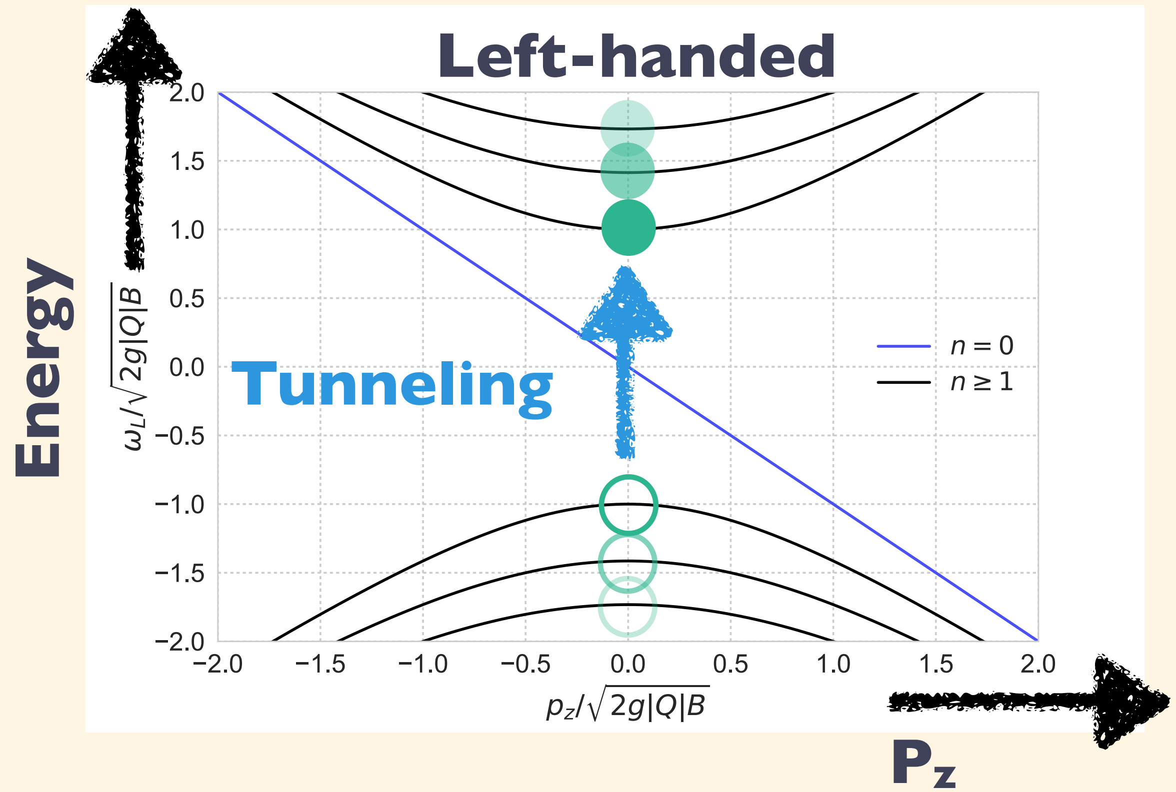

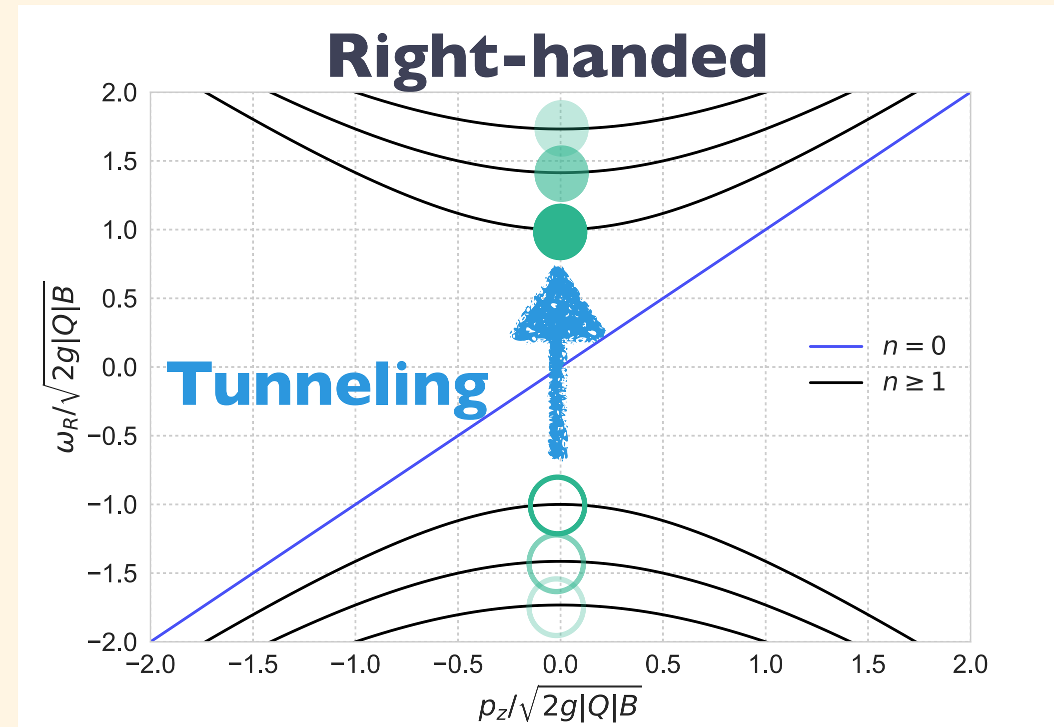

➡ **Pair**-production via Schwinger effect

$$\dot{n}^{(n\geq1)}_{\alpha,R} = \dot{\bar{n}}^{(n\geq1)}_{\alpha,R} = \dot{n}^{(n\geq1)}_{\alpha,L} = \dot{\bar{n}}^{(n\geq1)}_{\alpha,L} = \sum_{n=1} N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y e^{-\frac{2\pi n B_Y}{E_Y}} = N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y \frac{1}{e^{\frac{2\pi B_Y}{E_Y}} - 1}$$

✤ Never contribute to the asymmetry! $\dot{q}_L|_{n\geq1} = (\dot{n}_L - \dot{\bar{n}}_L)_{n\geq1} = 0, \quad \dot{q}_R|_{n\geq1} = (\dot{n}_R - \dot{\bar{n}}_R)_{n\geq1} = 0$

Fermion Production

Fermion Production in $B_Y \parallel E_Y$

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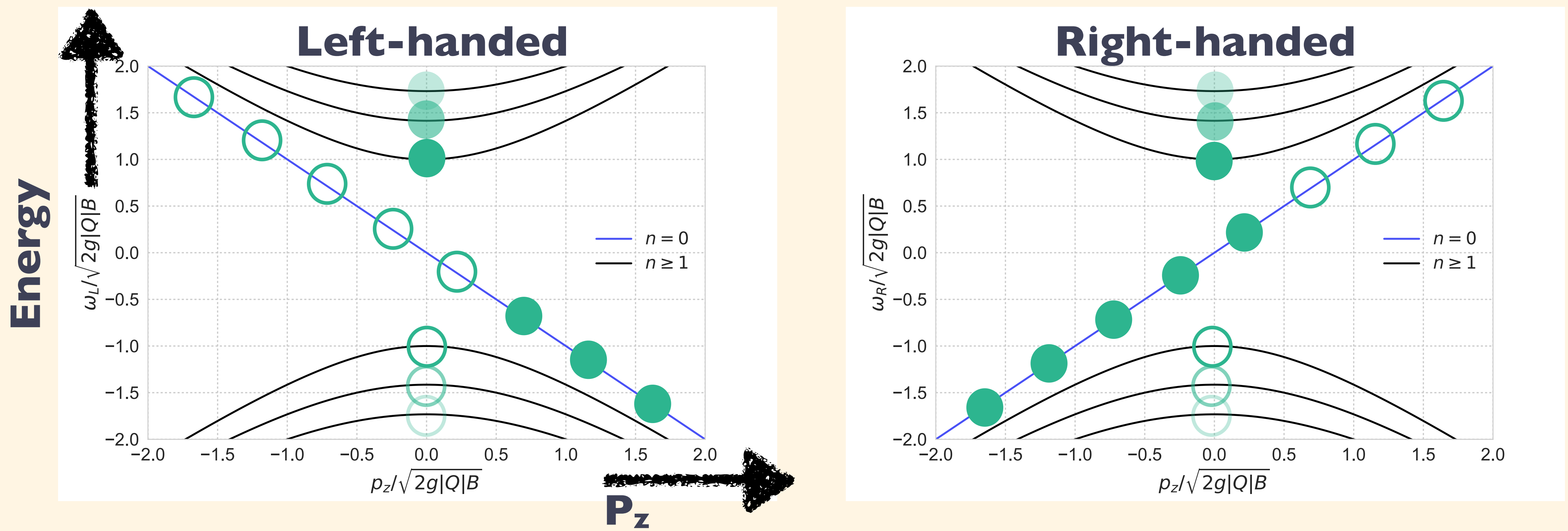

- **ABJ anomaly** from **LLL**

$$\dot{q}_\alpha = \epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y = -\epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{16\pi^2} Y^{\mu\nu}\tilde{Y}_{\mu\nu} \to 0 \quad \text{for } B_Y \to 0 \qquad \text{w/ } \epsilon_\alpha = \pm \text{ for R/L}$$

- **Schwinger pair-production** from **HLLs**

$$\dot{n}_{\alpha,R}^{(n\geq1)} = \dot{\bar{n}}_{\alpha,R}^{(n\geq1)} = \dot{n}_{\alpha,L}^{(n\geq1)} = \dot{\bar{n}}_{\alpha,L}^{(n\geq1)} = N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y \frac{1}{e^{\frac{2\pi B_Y}{E_Y}} - 1} \to N_\alpha \frac{g_Y^2 Q_\alpha^2}{8\pi^3} E_Y^2 \quad \text{for } B_Y \to 0$$

Implications on Axion Inflation

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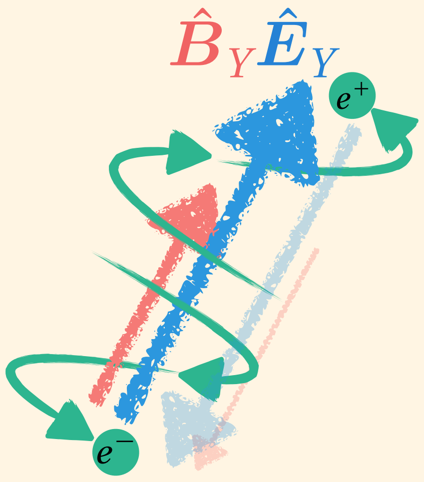
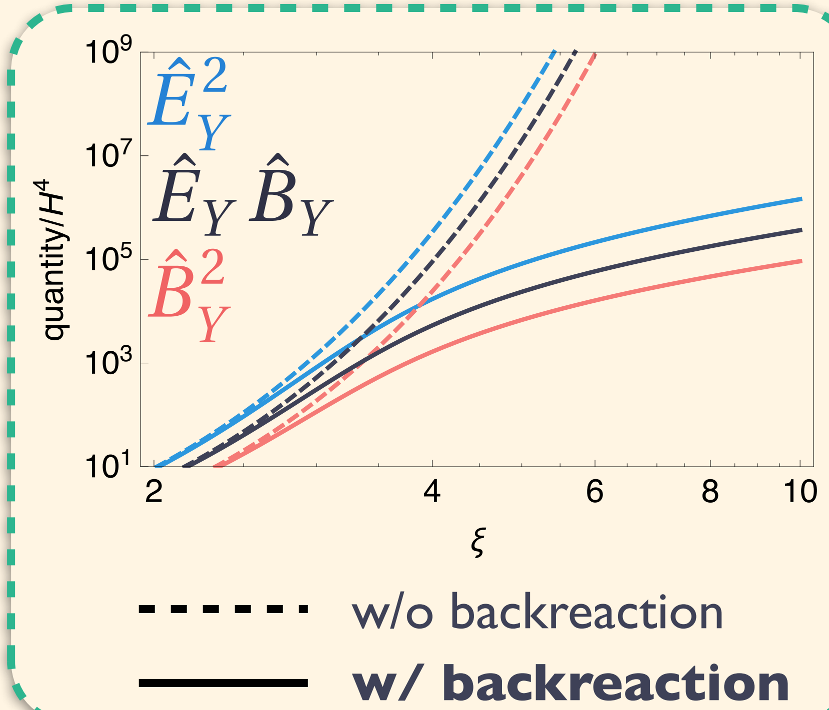
- **Backreaction** suppresses gauge field

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

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





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

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

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

3.

Survival of Helical Gauge Field

Outline of this Talk

Baryogenesis from B+L asymmetry?

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

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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**

Inefficient **diffusion**

No **CPI** (chiral plasma instability)

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

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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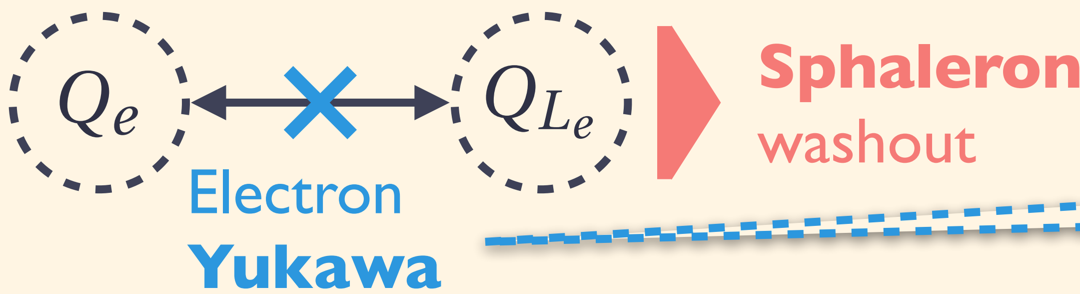
1905.13318

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



Electron Yukawa is **NOT** efficient till

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

Survival of Helical Gauge Field

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

Q_e ←✕→ Q_{L_e} **Sphaleron** washout

Electron **Yukawa**

Electron Yukawa is **NOT** efficient till

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

- **Chiral Plasma Instability** (CPI)

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

$$\propto \partial \cdot h_Y$$

Inflation

$(\partial_\eta \phi) h_Y$

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

Avoid Chiral Plasma Instability

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

Q_e ← ✕ → Q_{L_e} ▶ **Sphaleron** washout

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- **Chiral Plasma Instability** (CPI)

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$$\propto \partial \cdot h_Y$$

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

Inflation $(\partial_\eta \phi) h_Y$

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

Reheating $\dot{\phi} = 0$

0 0

Chiral Plasma Instability

- Annihilation between ⊿ $\mathbf{q_e}$ and ⊿ $\mathbf{h_Y}$.

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

- **Chiral Plasma Instability** (CPI)

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

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Inflation $(\partial_\eta \phi) h_Y$

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

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

Reheating $\dot{\phi} = 0$

Chiral Plasma Instability

- Annihilation between Δ $\mathbf{q_e}$ and Δ $\mathbf{h_Y}$.

M.Joyce and M.Shaposhnikov 9703005, ,...

0 0

Sphaleron + Yukawa washout

0 $\Delta h_Y \neq 0$

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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Chiral Plasma Instability

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

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

Magnetic Diffusion

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

$$\Delta h_Y \neq 0$$

Magnetic diffusion

$$0$$

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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- **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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Chiral Plasma Instability

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

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

- **Large Magnetic Reynolds #**

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

$\Delta h_Y \neq 0$

Magnetic diffusion → 0

Inverse cascade → $\Delta h_Y \simeq \text{const.}$

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

4.

Regeneration of Baryon Asymmetry

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 $\phi Y_{\mu\nu}\tilde{Y}^{\mu\nu}$.

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

2.

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

via **Sphaleron + Yukawa**

Inefficient **diffusion**

No **CPI** (chiral plasma instability)

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

3.

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

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

+ Sphaleron freezes out

Now

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

4.

Time

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

- Transport equation @ **EW Crossover**

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  - 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.

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$$\propto \partial_\eta h_Y$$

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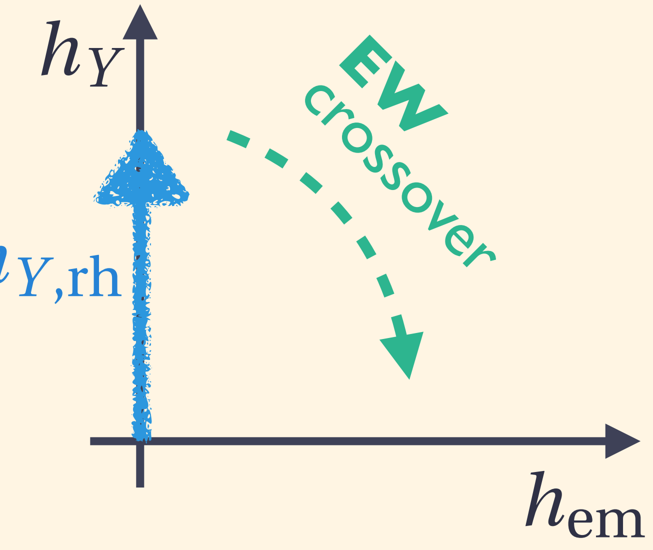
$\Delta h_{Y,\mathrm{rh}}$



Regeneration of Baryon Asym.

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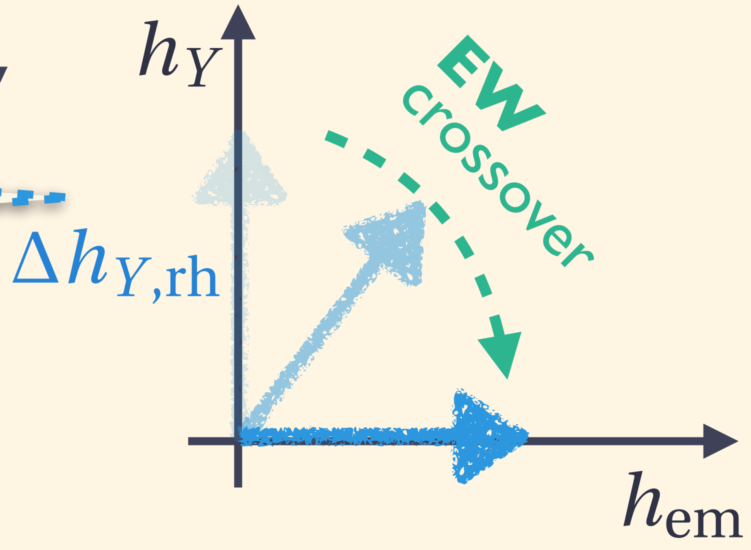

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

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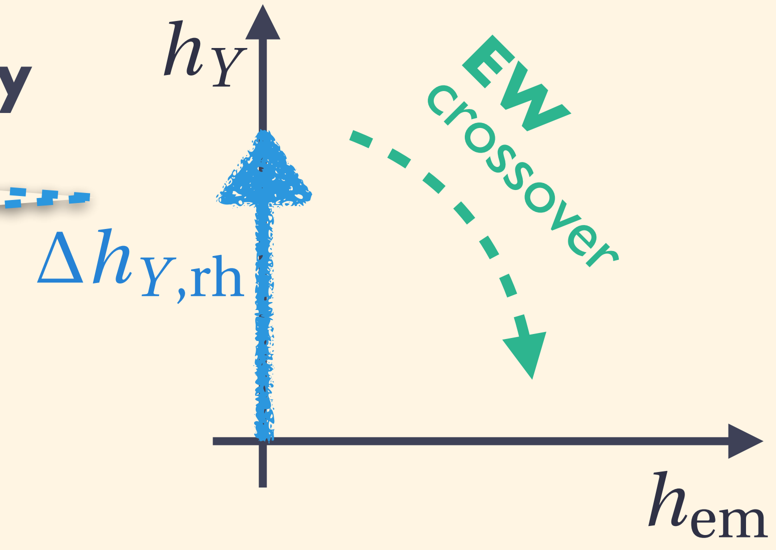
$$\begin{cases} \Gamma_{\mathrm{W,sph}} \propto e^{-\frac{M_{\mathrm{sph}}(T)}{T}} \\ M_{\mathrm{sph}}(T) \propto v(T) \end{cases} \qquad \propto \partial_\eta h_Y$$



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

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

EW sphaleron
Washout-factor

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

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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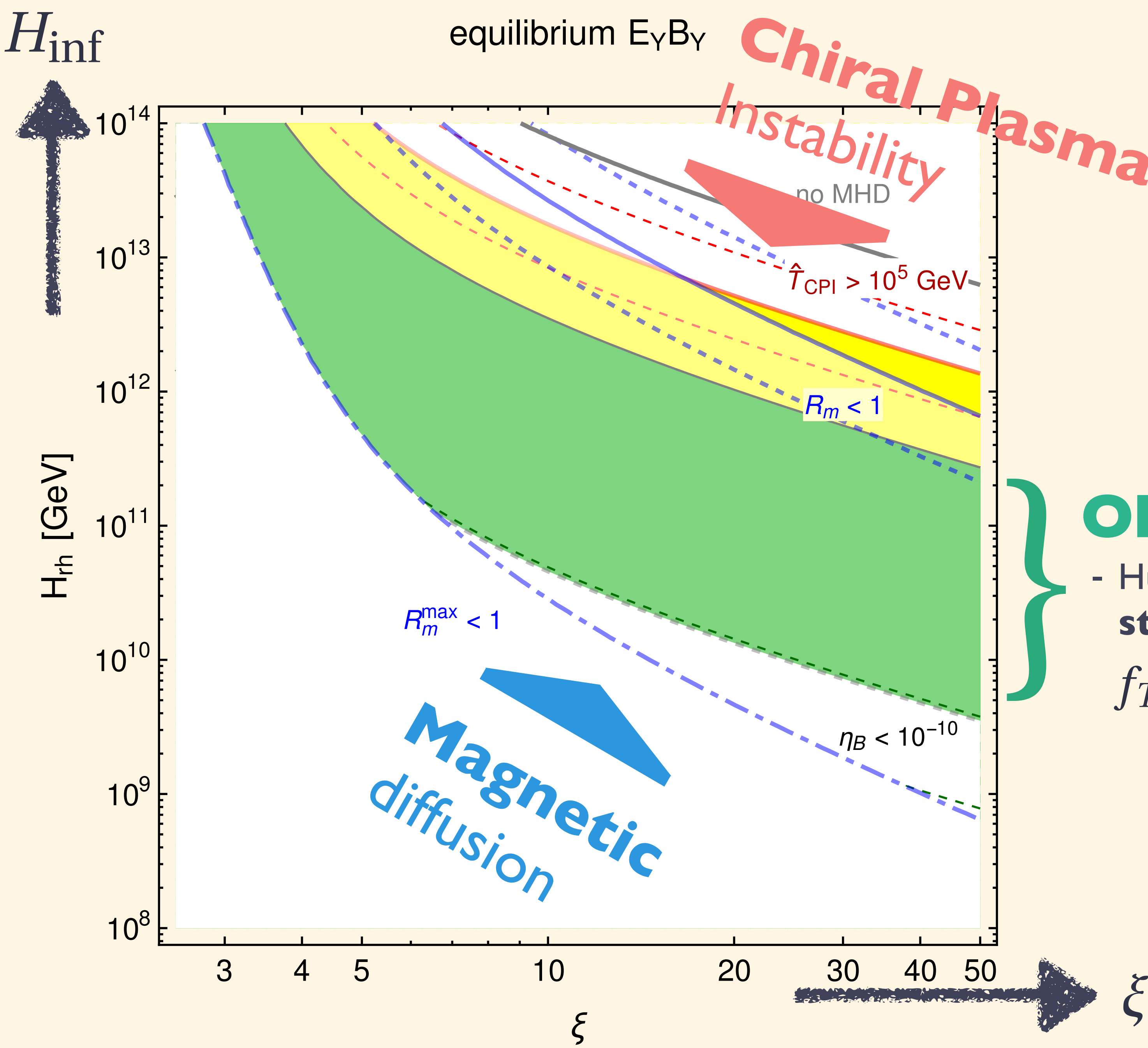

Observed η_B

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

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

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

Result

Viable parameters for Baryogenesis

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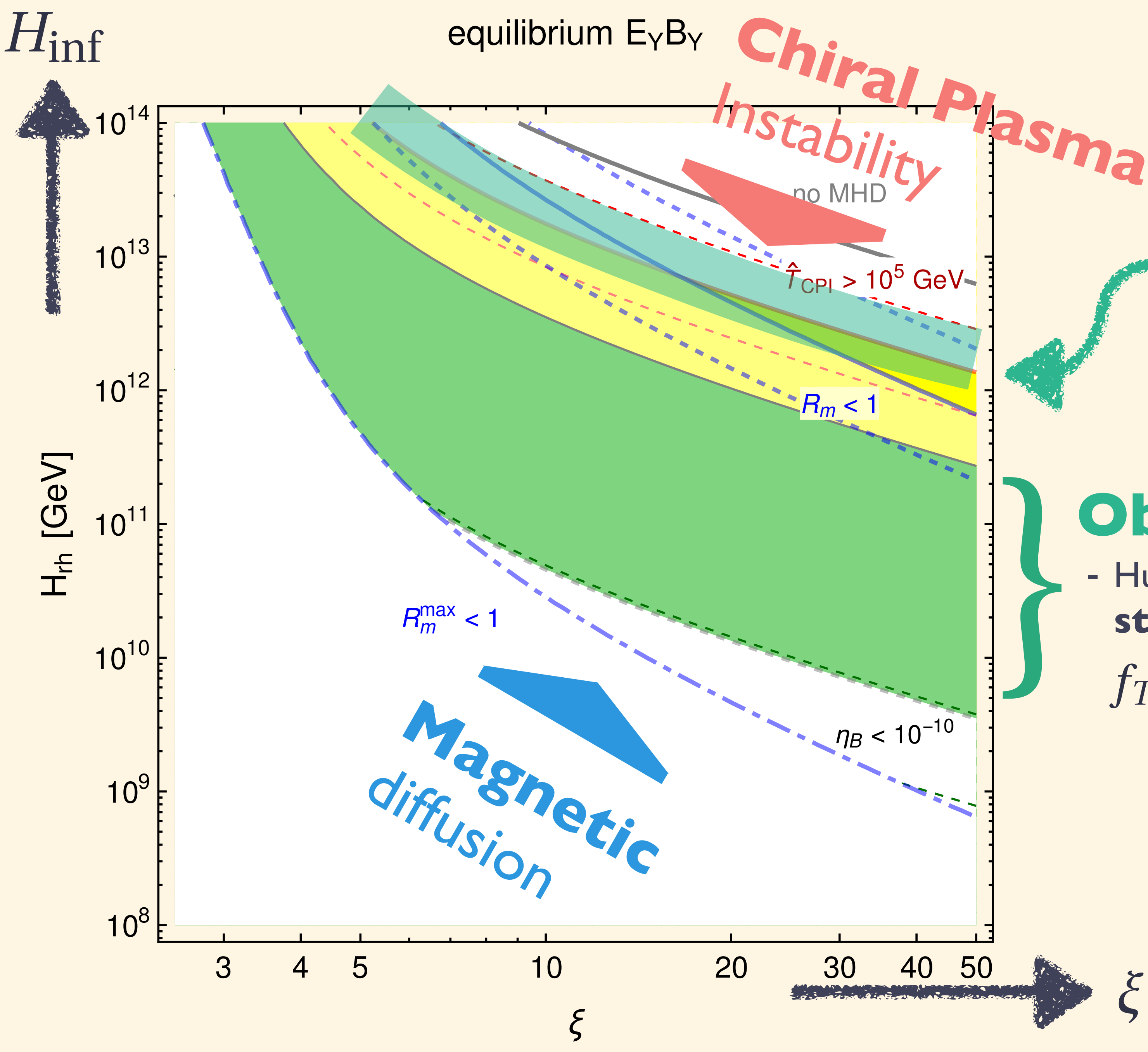

Viable prm???

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

Observed η_B

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

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

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

Summary

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

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

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

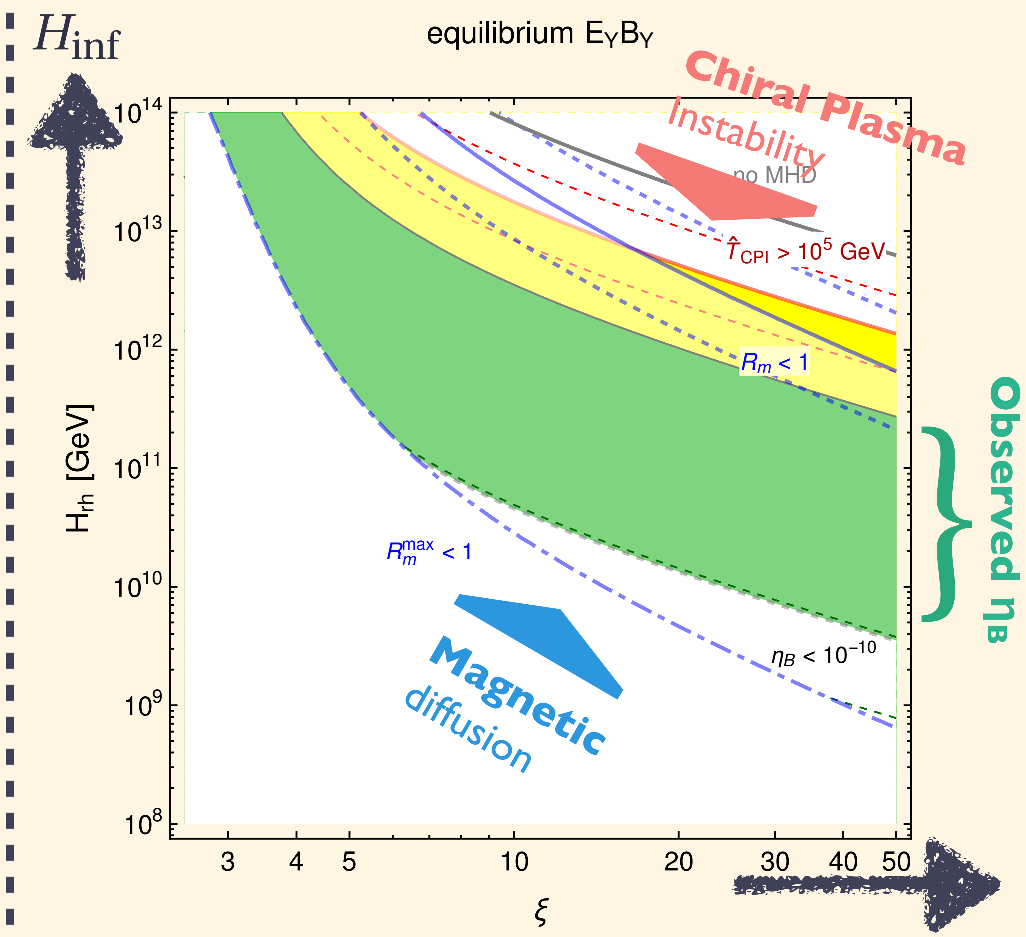
via **Sphaleron** + **Yukawa** → 0

Inefficient diffusion, No **CPI** → $-\frac{3}{4}\frac{\alpha_Y}{\pi}\Delta h_Y$

Δh_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



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