Baryogenesis from Axion Inflation

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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

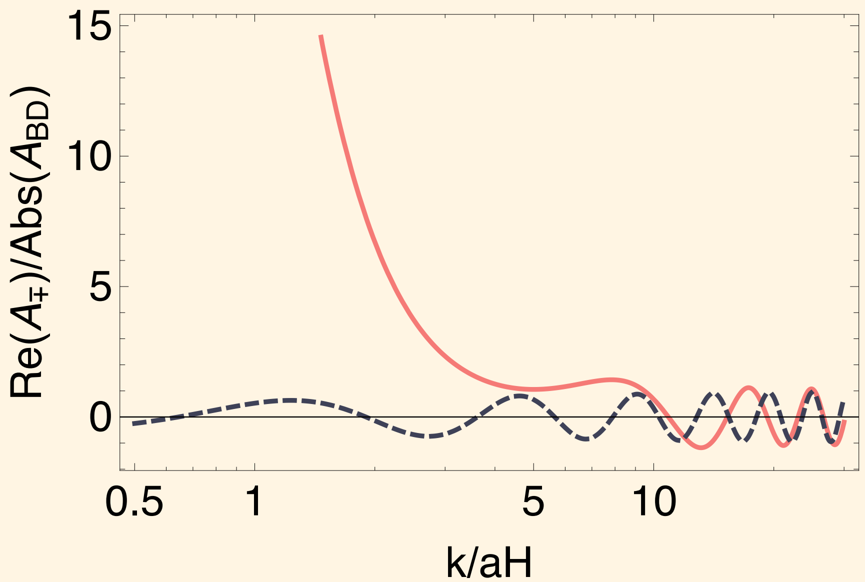
$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha \phi}{4\pi f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \right\}$$

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

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



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

Introduction

Coupling to the SM Gauge Group ?

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

U(1)$_Y$

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

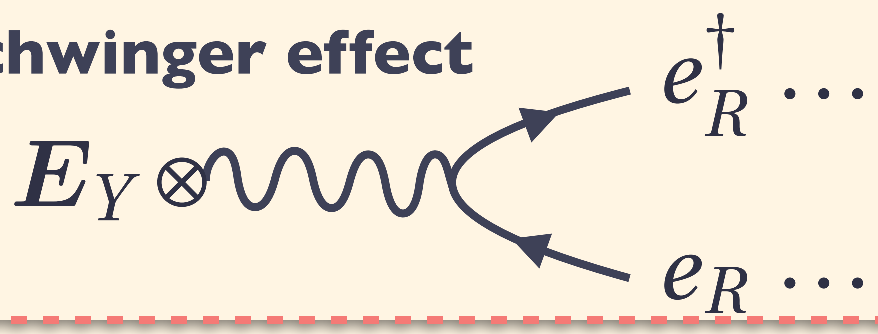
$$\left.+\boxed{\sum_\alpha\psi^\dagger_\alpha\sigma\cdot(i\partial-g_YQ_\alpha A_Y)\psi_\alpha}+\cdots\right\}$$

- 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?

Baryogenesis from B+L asymmetry?

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

Inflation

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

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

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

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

Now

Time

Introduction

Baryogenesis from B+L asymmetry?

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via **Sphaleron + Yukawa**

Inefficient **diffusion**

No **CPI** (chiral plasma instability)

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

Now

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

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

Time

Outline of this Talk

Baryogenesis from B+L asymmetry?

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4.

Time

2.

Production of

Helical gauge & **Chiral** fermion

Setup

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

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

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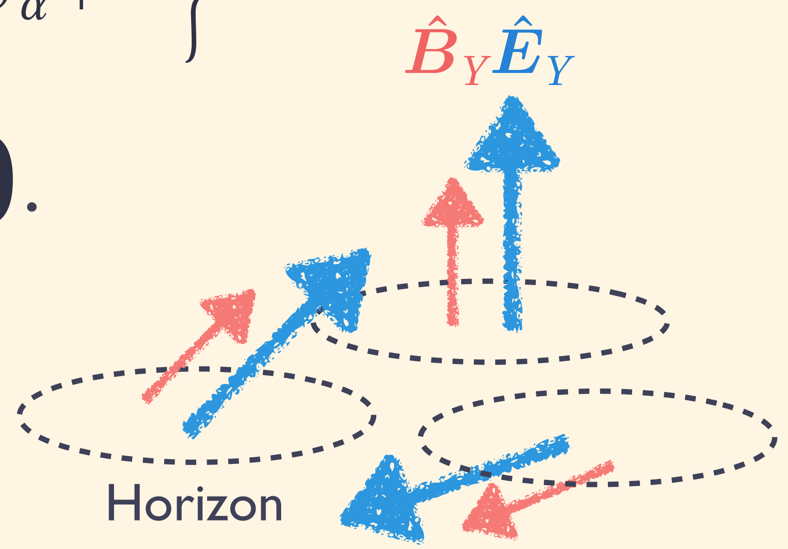

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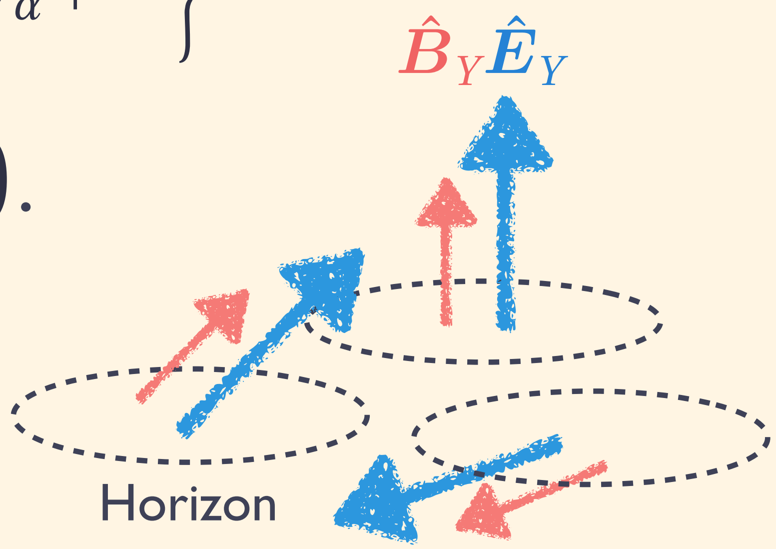

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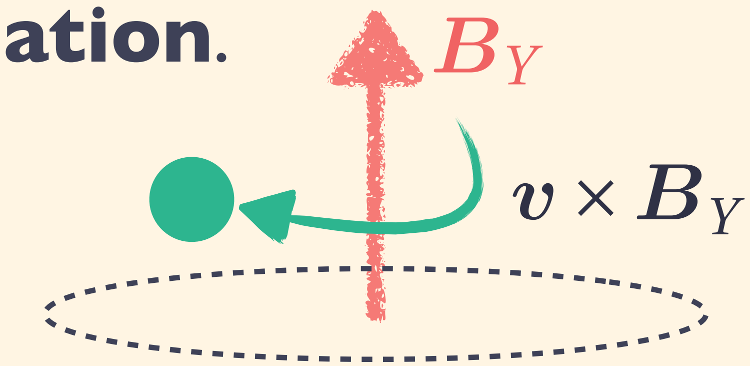
  - Pair production via the **Schwinger effect**

Landau Levels

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

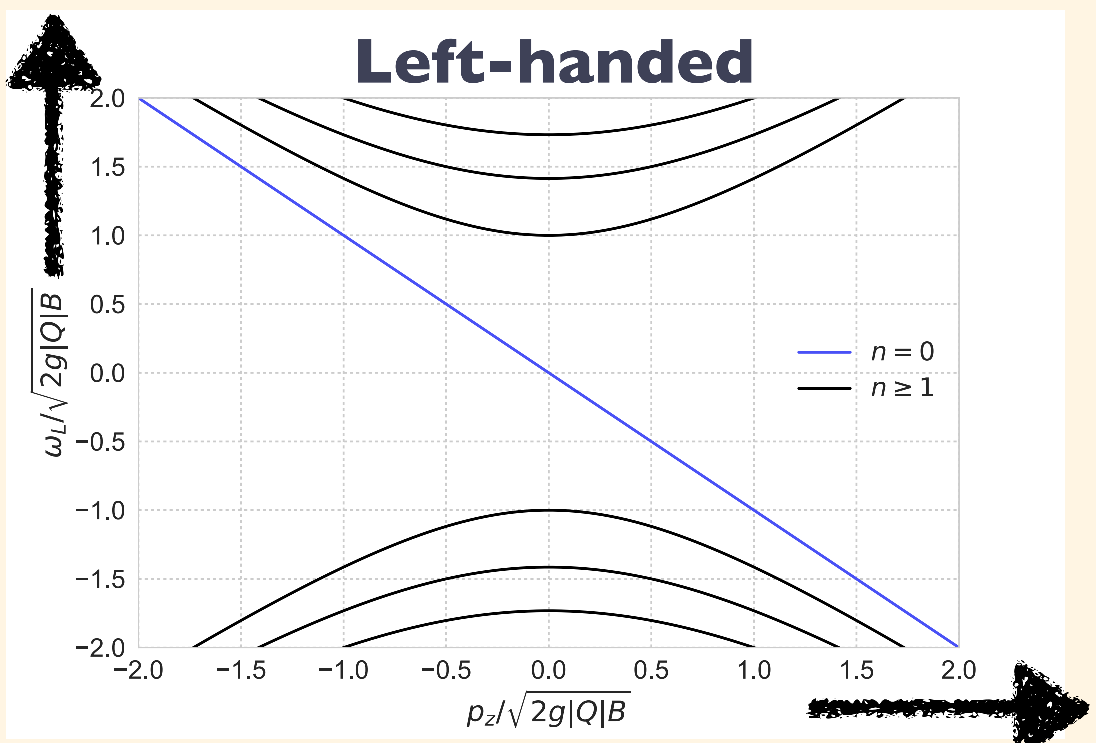
$$0=\left(i\partial_\eta \pm i\boldsymbol{\nabla}\cdot\boldsymbol{\sigma} - gQ_\alpha A_{Y,0} \pm gQ_\alpha \boldsymbol{A}_Y\cdot\boldsymbol{\sigma}\right)\psi_{\alpha,\mathrm{R/L}}$$

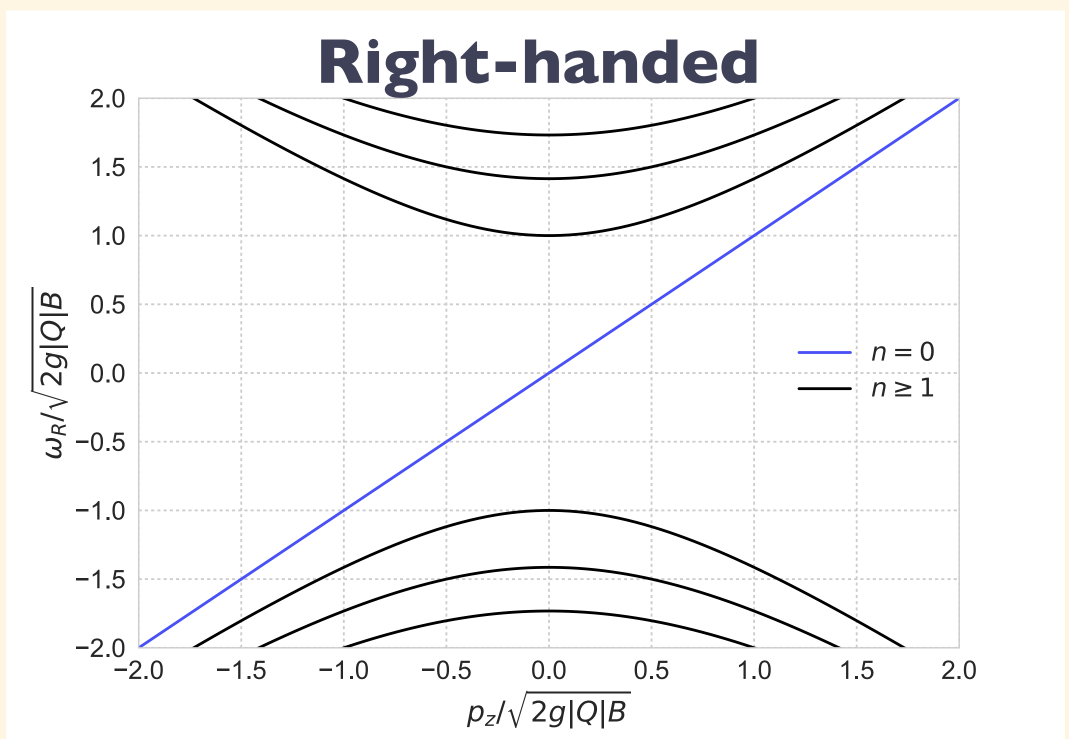
where $(A_{Y,\mu})=(0,0,-B_Y\,x,0)$



- **Landau Level n**: transverse motion; **$\mathbf{p_z}$**: parallel motion

Energy



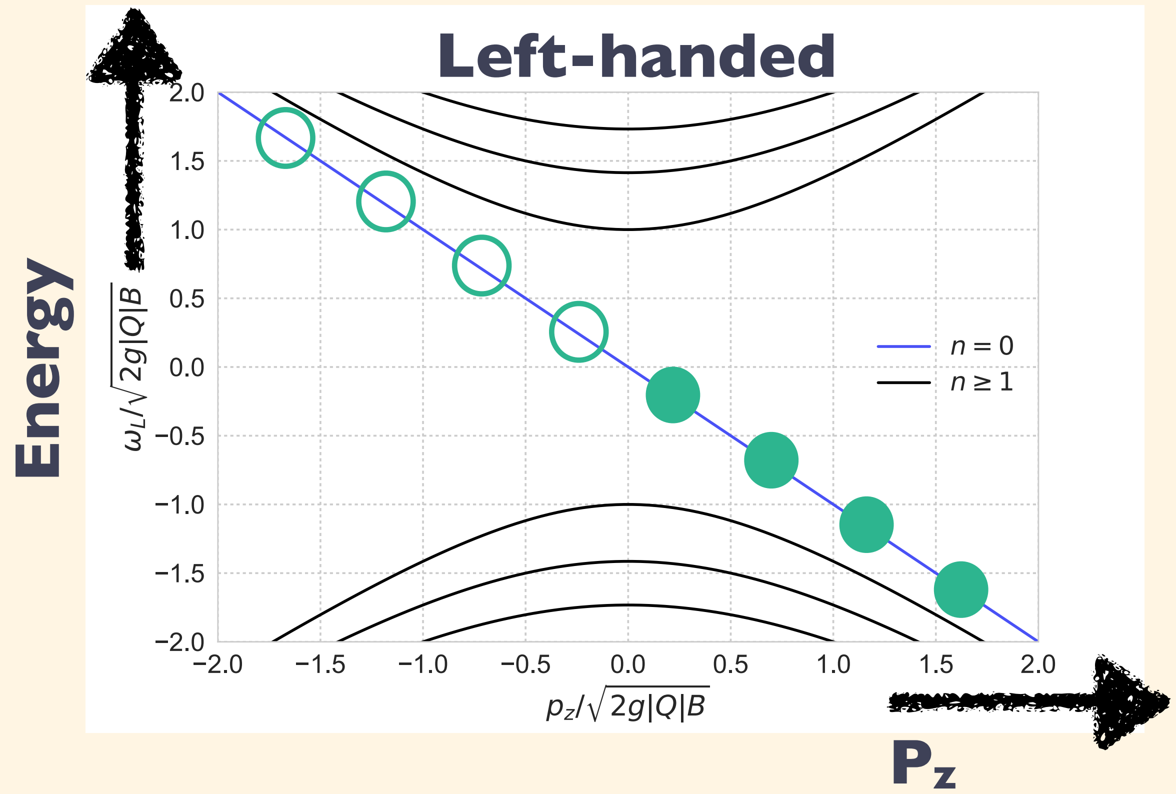


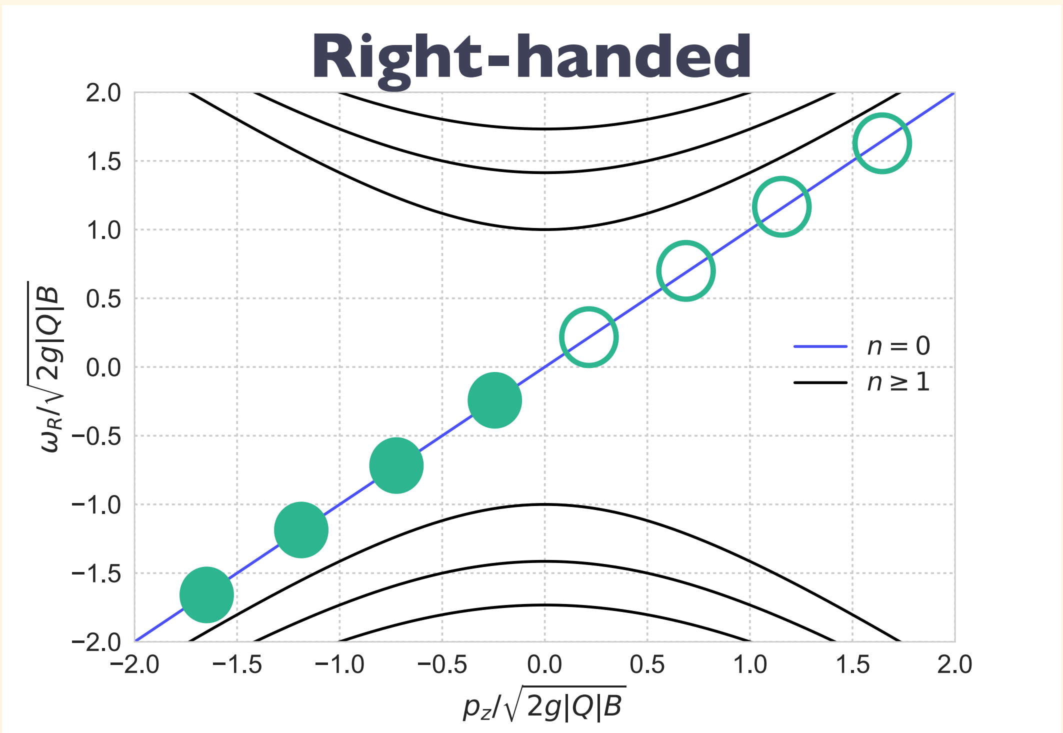
$\mathbf{P_z}$

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

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

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





Fermion Production

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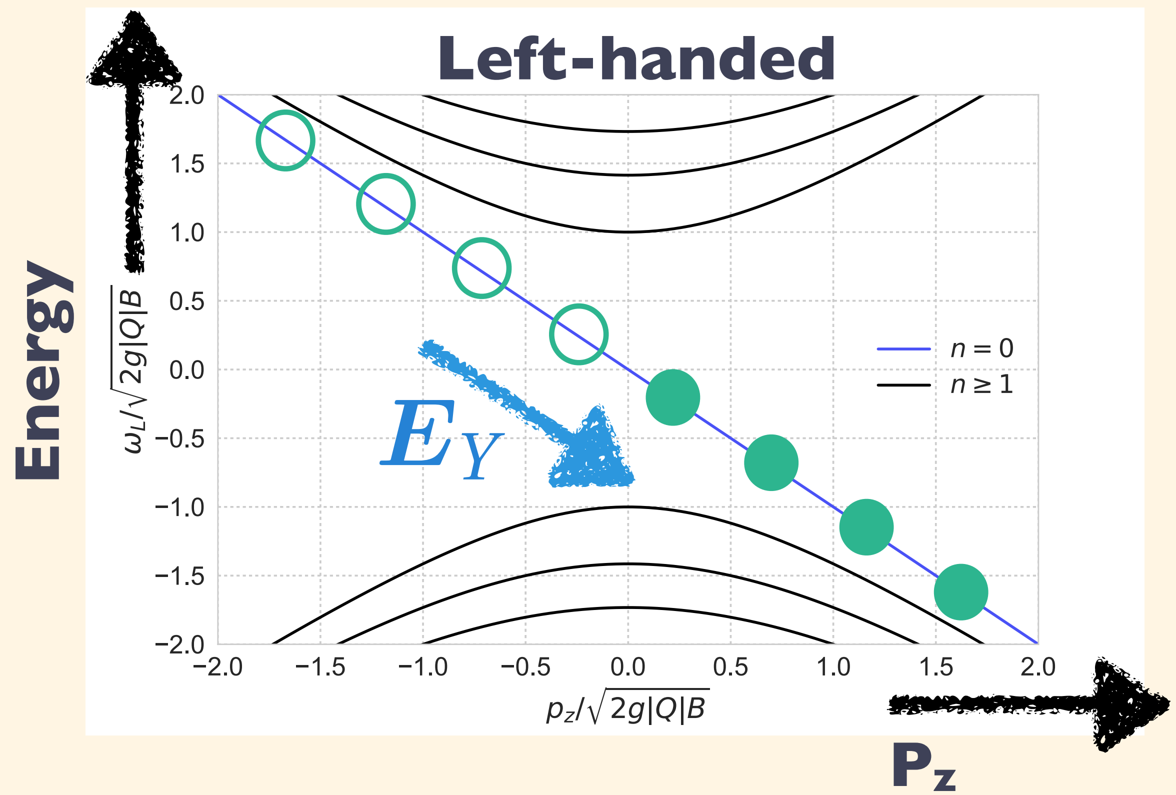

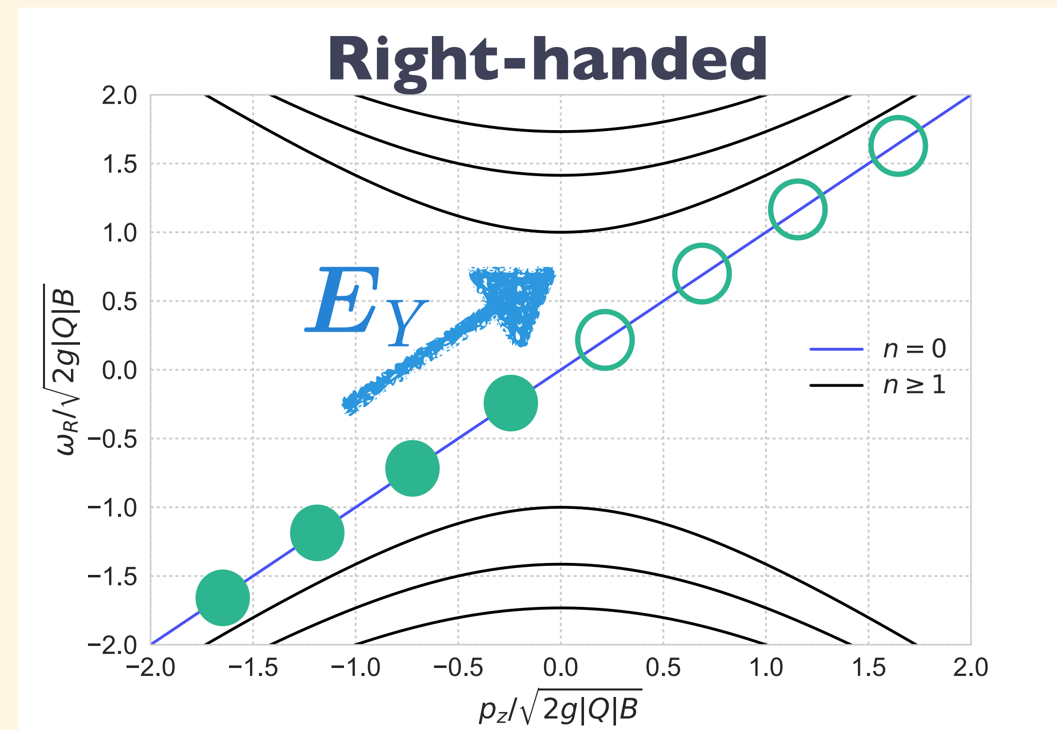

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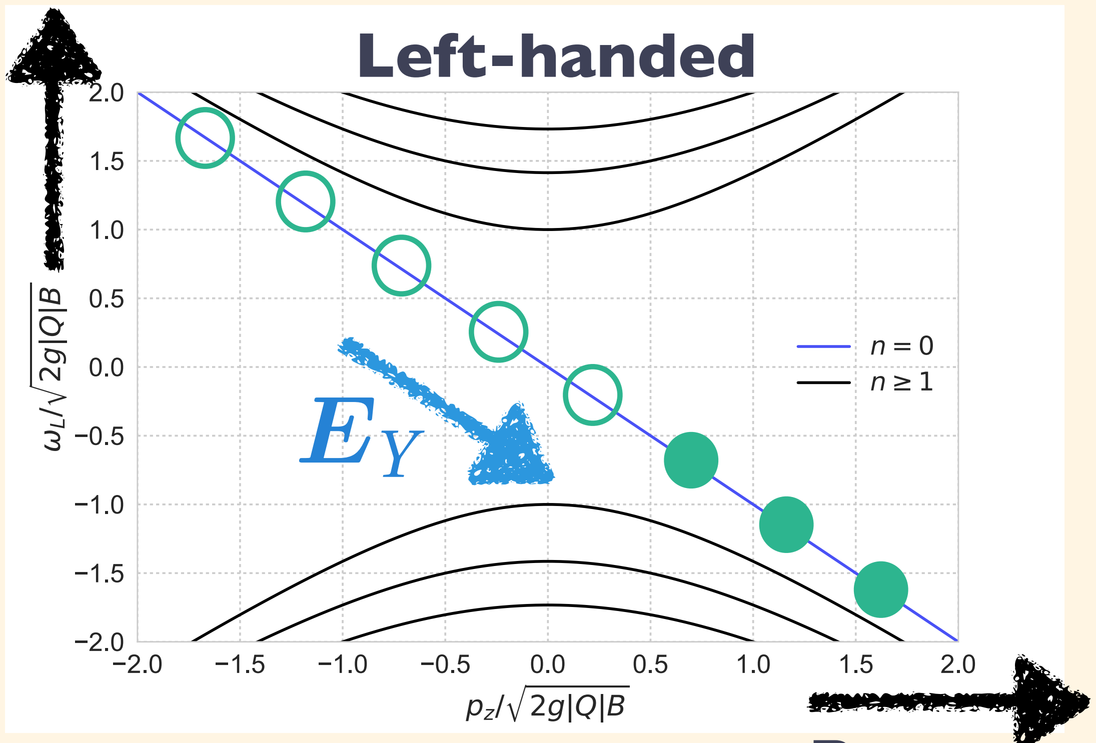
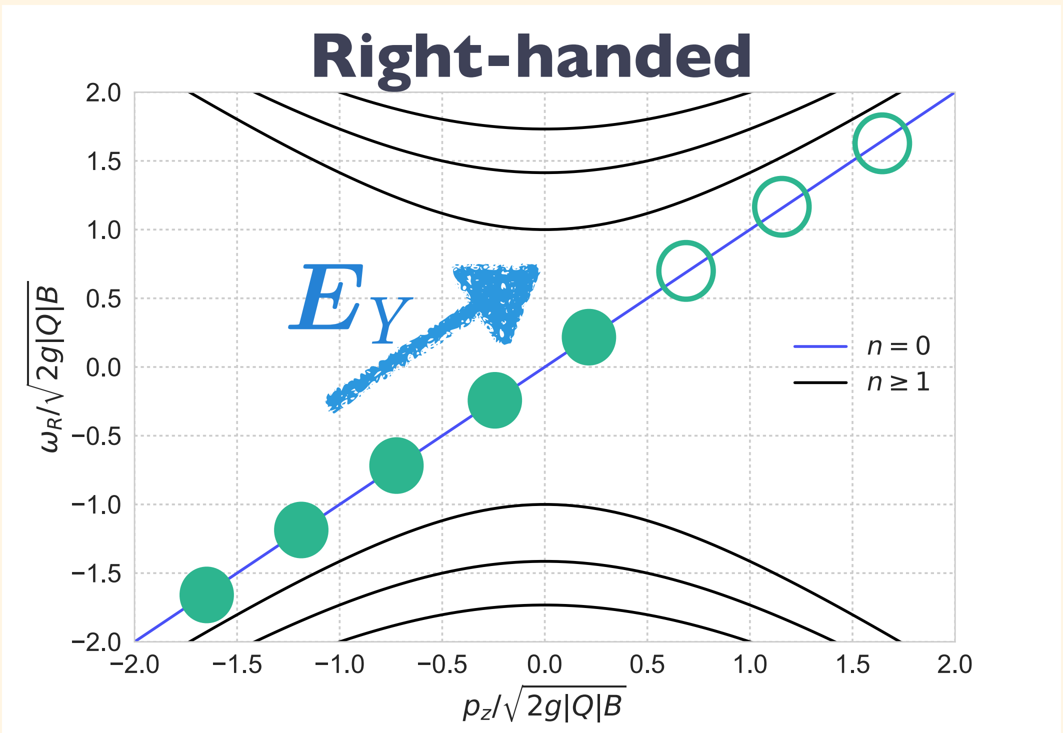


P_z



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:

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

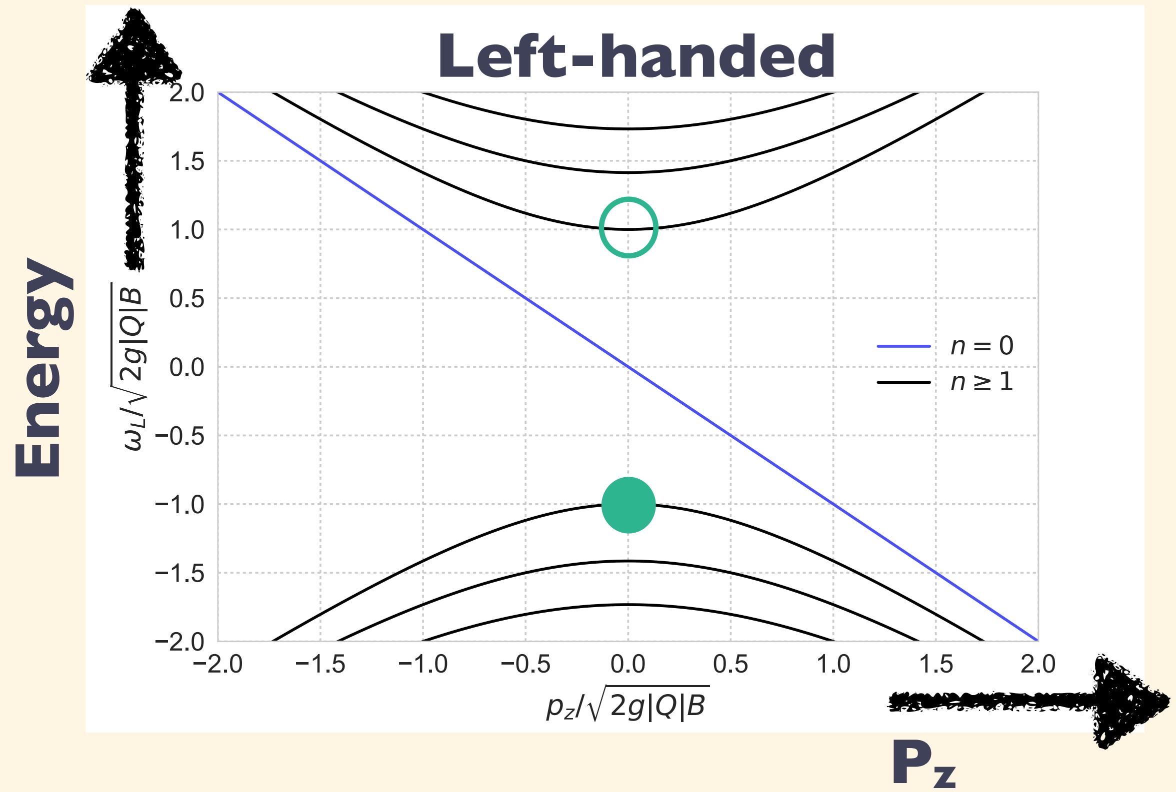
➡ **ABJ anomaly**: $\dot{q}_\alpha = \epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{4\pi^2} E_Y B_Y = -\epsilon_\alpha N_\alpha \frac{g_Y^2 Q_\alpha^2}{16\pi^2} Y^{\mu\nu} \tilde{Y}_{\mu\nu}$ w/ $\epsilon_\alpha = \pm$ for R/L

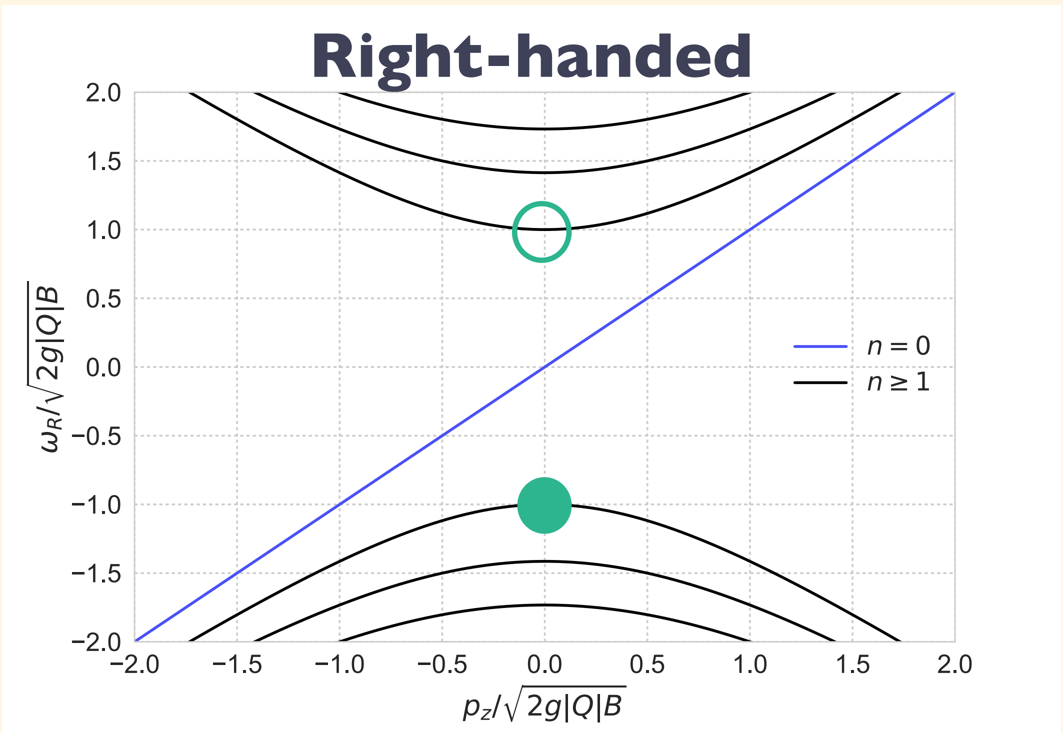
Fermion Production

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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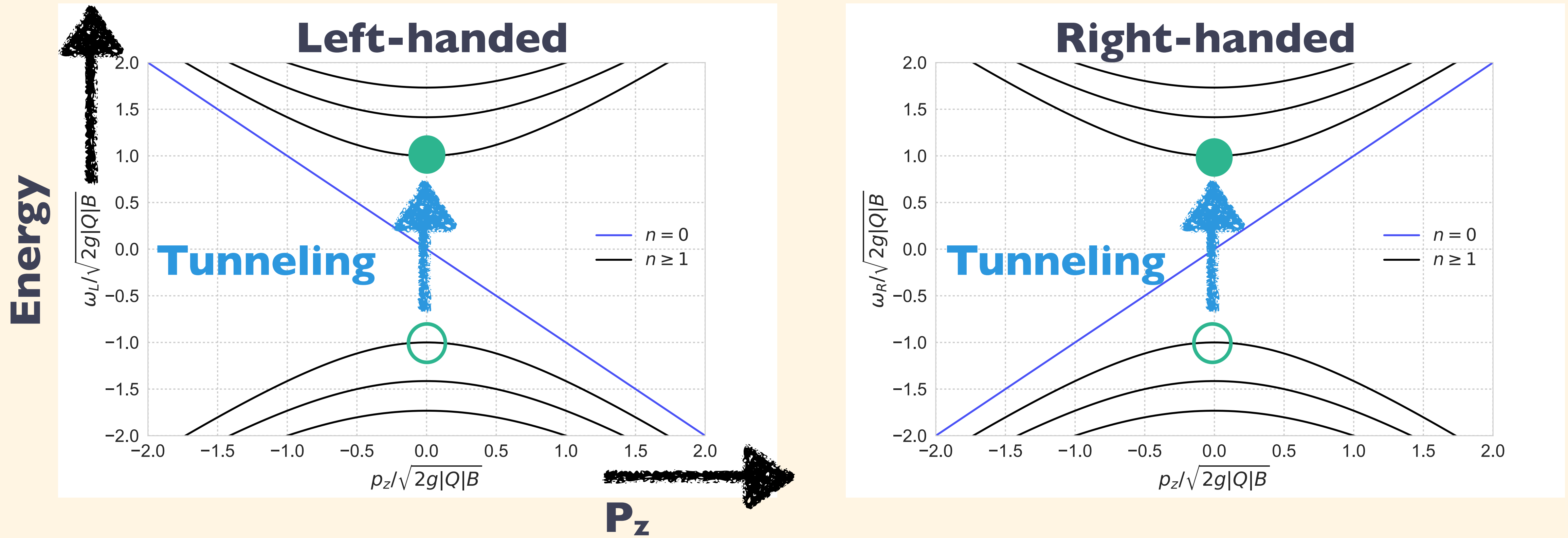

➡ **Pair**-production via Schwinger effect

Fermion Production

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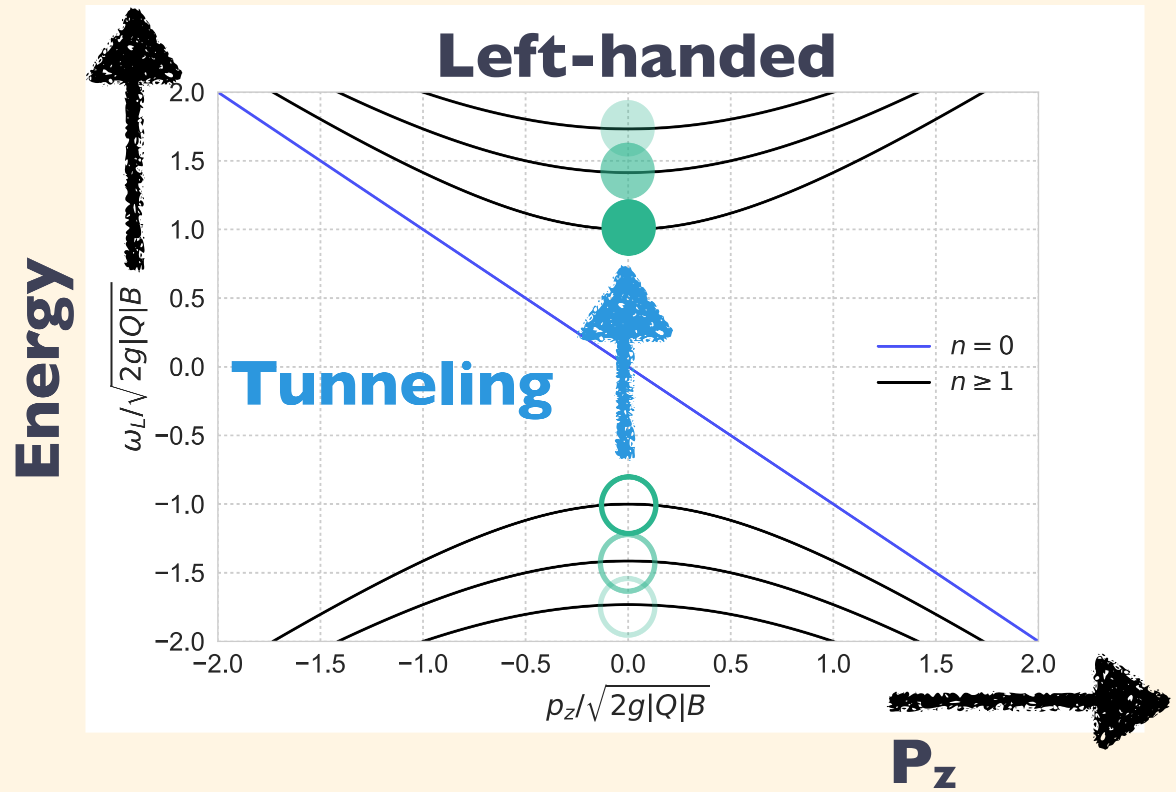

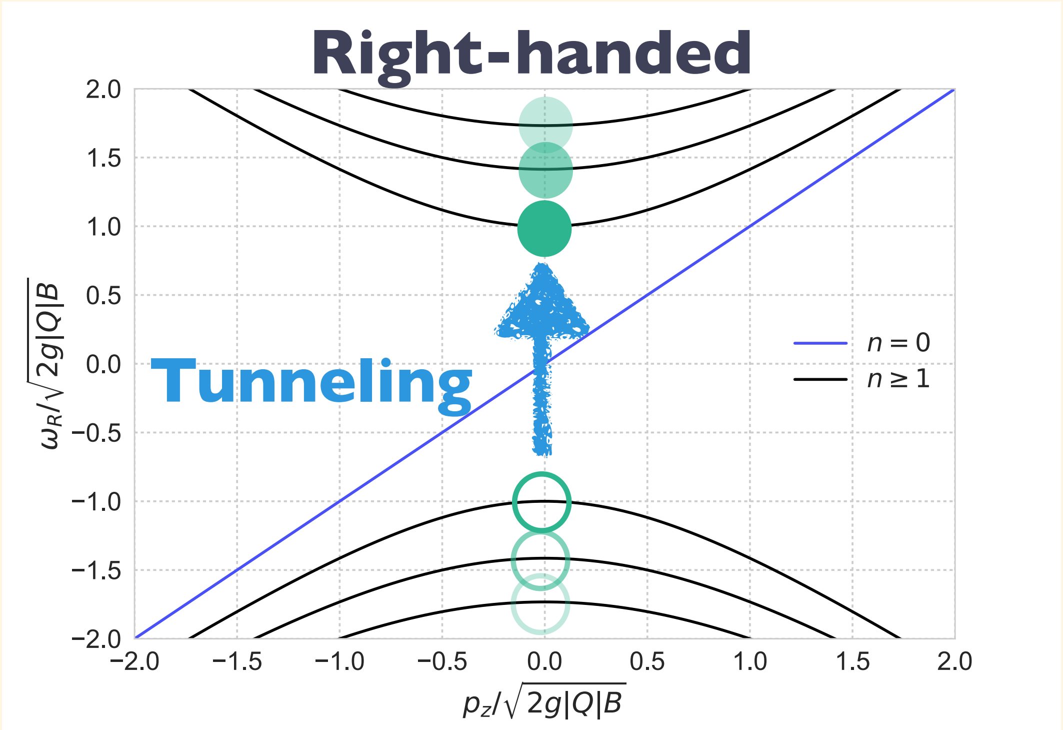

➡ **Pair**-production via Schwinger effect

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

✤ 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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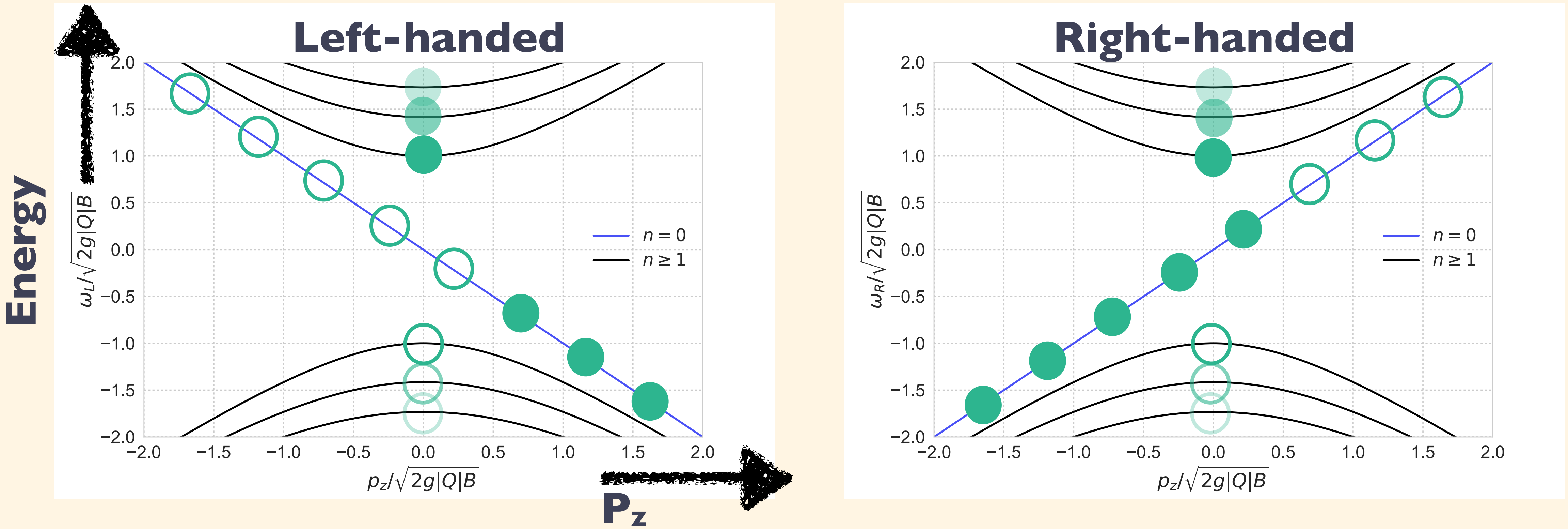


- **ABJ anomaly** from **LLL**

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

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

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

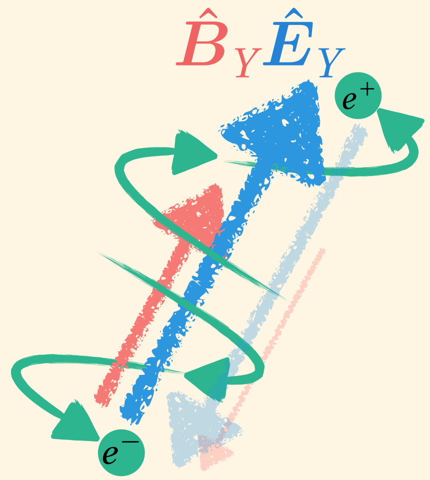
Fermion Production

Implications on Axion Inflation

- **Backreaction** suppresses gauge field

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

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



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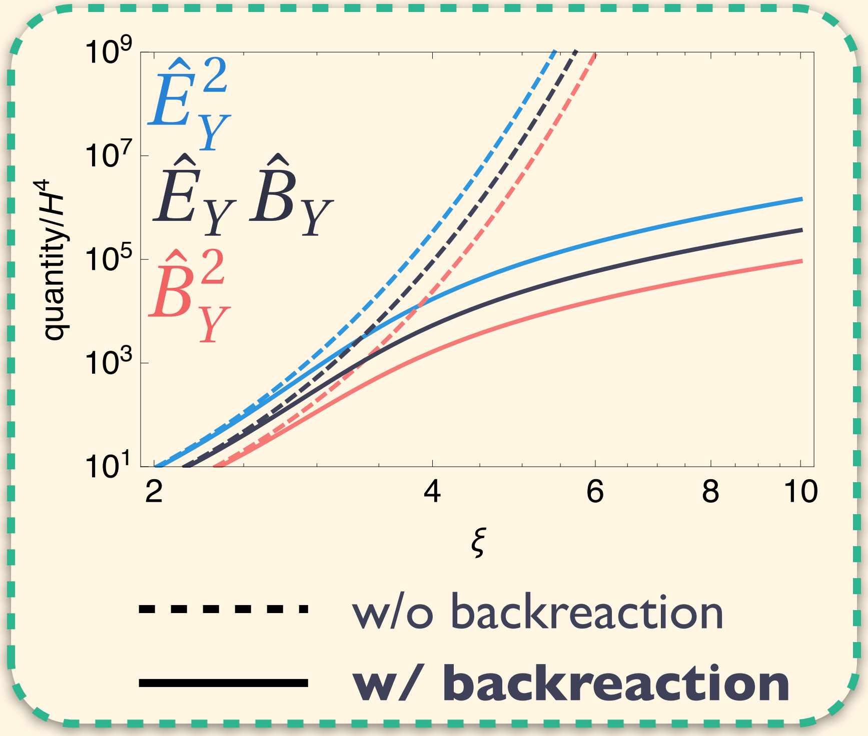

- **Primordial** generation of **B+L asym**.

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

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

3.

Survival of Helical Gauge Field

Outline of this Talk

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

Inefficient **diffusion**

No **CPI** (chiral plasma instability)

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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.

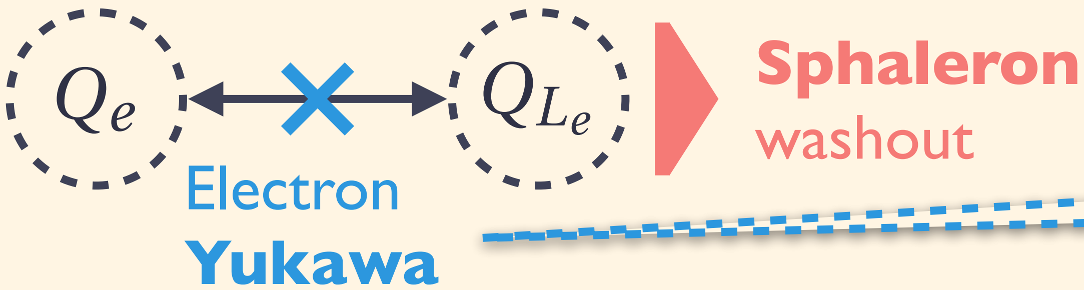
Time

Survival of Helical Gauge Field

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** efficient till

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

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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

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

Q_e ↔ Q_{L_e} (Electron **Yukawa**) ▶ **Sphaleron** washout

Electron Yukawa is **NOT** efficient till
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- **Chiral Plasma Instability** (CPI)

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

$$\propto \partial \cdot h_Y$$

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

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

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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$Q_e \longleftrightarrow Q_{L_e}$

Electron **Yukawa**

Sphaleron washout

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- **Chiral Plasma Instability** (CPI)

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

$$\propto \partial \cdot h_Y$$

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

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

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

Reheating
$\dot{\phi} = 0$

Chiral Plasma Instability

0 0

- Annihilation between Δ **qe** and Δ **hY**.

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

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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

- **Chiral Plasma Instability** (CPI)

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

$$\propto \partial \cdot h_Y$$

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

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

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

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

Reheating
$\dot{\phi} = 0$

Chiral Plasma Instability

Sphaleron + Yukawa washout

$0 \qquad 0$

- Annihilation between Δ **q_e** and Δ **h_Y**.

M.Joyce and M.Shaposhnikov 9703005, ,…

$0 \qquad \Delta h_Y \neq 0$

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

V.Domcke, B.Harling, E.Morgante, **KM**
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- **Chiral Magneto Hydro Dynamics** (ChMHD)

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

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

Survival of Helical Gauge Field

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Chiral Plasma Instability

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

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

Magnetic Diffusion

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

$$\Delta h_Y \neq 0$$

Magnetic diffusion

$$0$$

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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

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

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

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

Chiral Plasma Instability

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

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

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

2.

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

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

Inefficient **diffusion**

No **CPI** (chiral plasma instability)

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

3.

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

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

+ **Sphaleron freezes out**

Now

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

4.

Time

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

- Transport equation @ **EW Crossover**

K.Kamada and A.Long 1610.03074

  - Slowest processes: **EW sphaleron** & **Decaying helicity**

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

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

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

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  - Slowest processes: **EW sphaleron** & **Decaying helicity**

K.Kamada and A.Long 1610.03074

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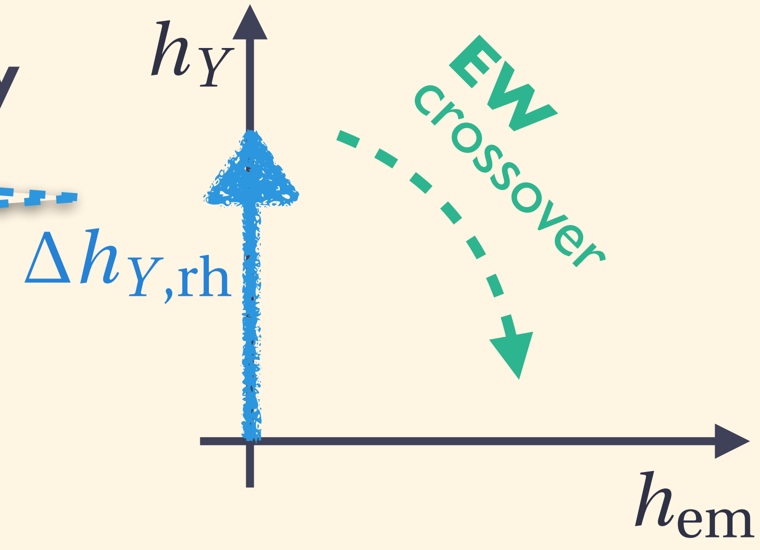

Regeneration of Baryon Asym.

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K.Kamada and A.Long 1610.03074

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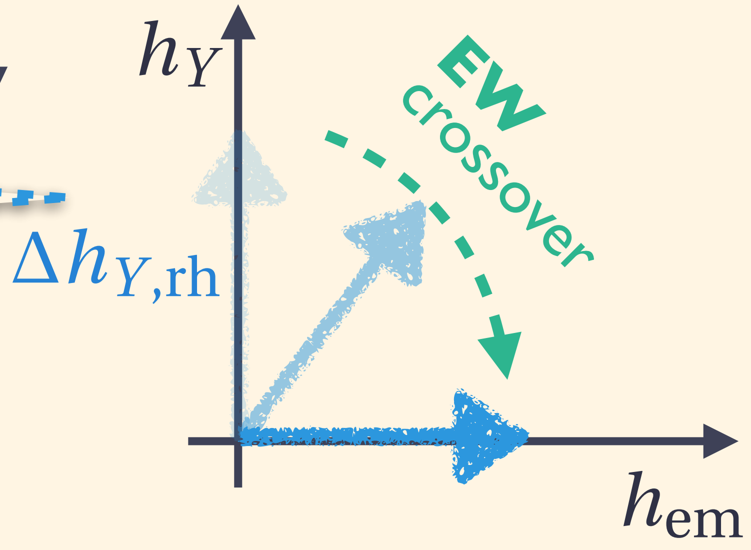

Baryogenesis from Decaying Helicity

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

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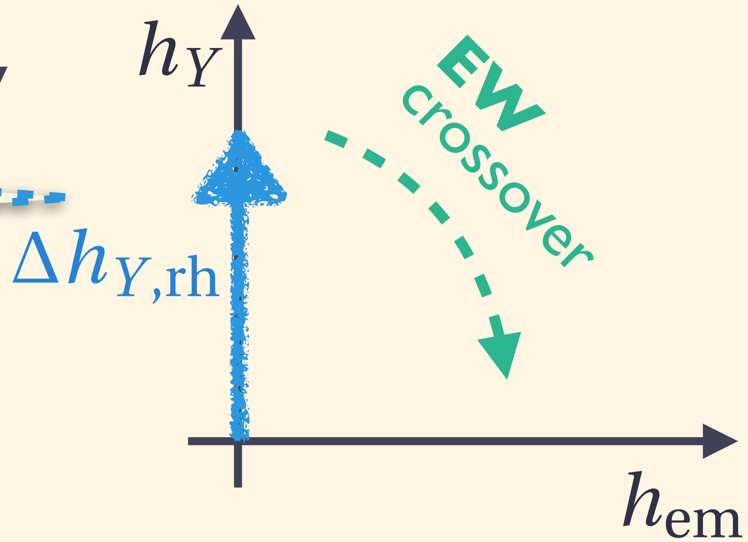
$$\partial_\eta q_B = \boxed{-\frac{111}{34}\Gamma_{W,\mathrm{sph}} q_B} + \boxed{\frac{3}{2}\left(g_2^2 + g_Y^2\right)\sin(2\theta)\left(\partial_\eta \theta\right)\frac{\Delta h_Y^{\mathrm{rh}}}{8\pi^2}}$$

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

$\propto \partial_\eta h_Y$



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

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

EW sphaleron

Washout-factor

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

EW crossover

- Huge uncertainties…

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

Result

Viable parameters for Baryogenesis

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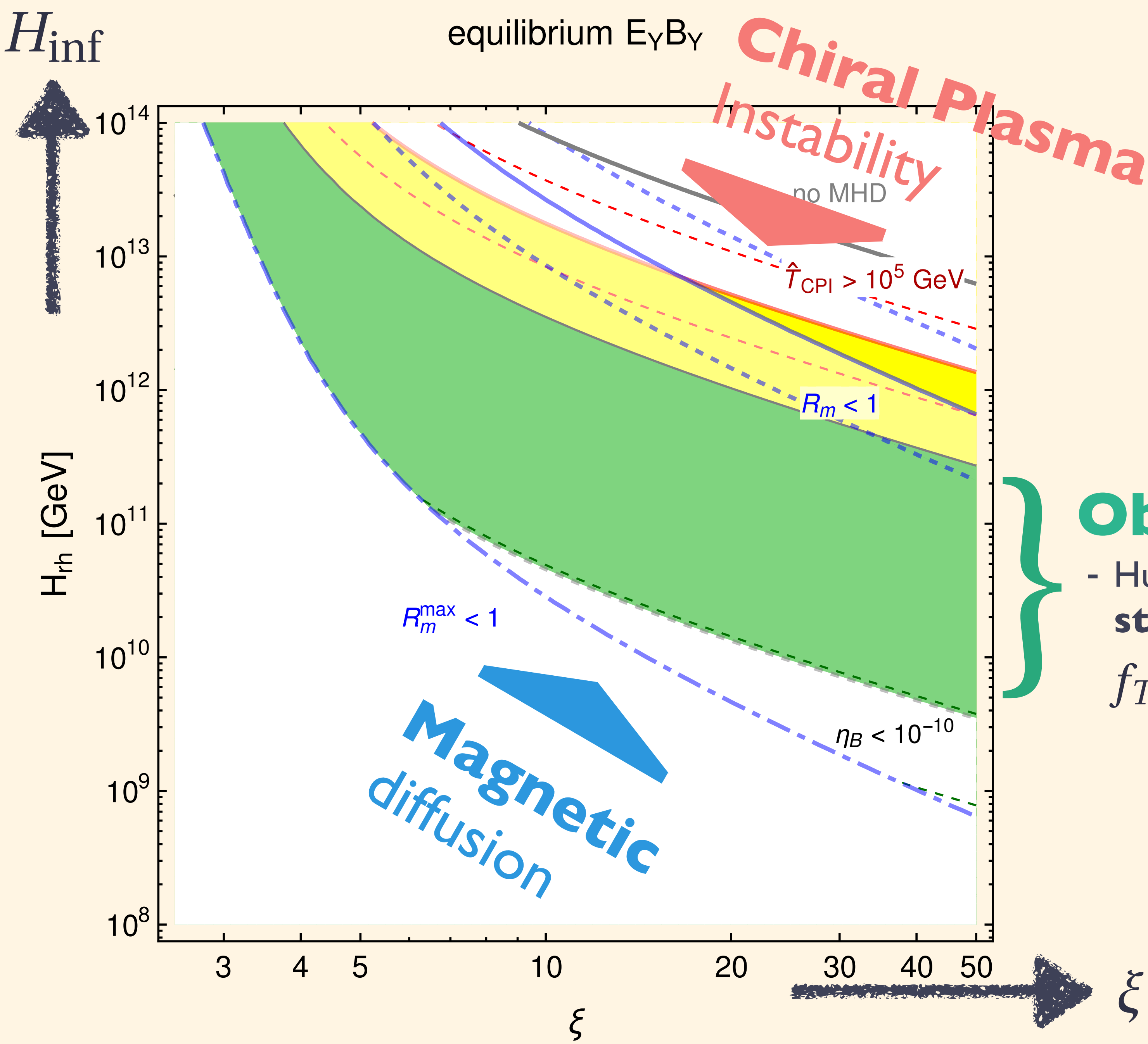

Observed η_B

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

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

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

Viable parameters for Baryogenesis

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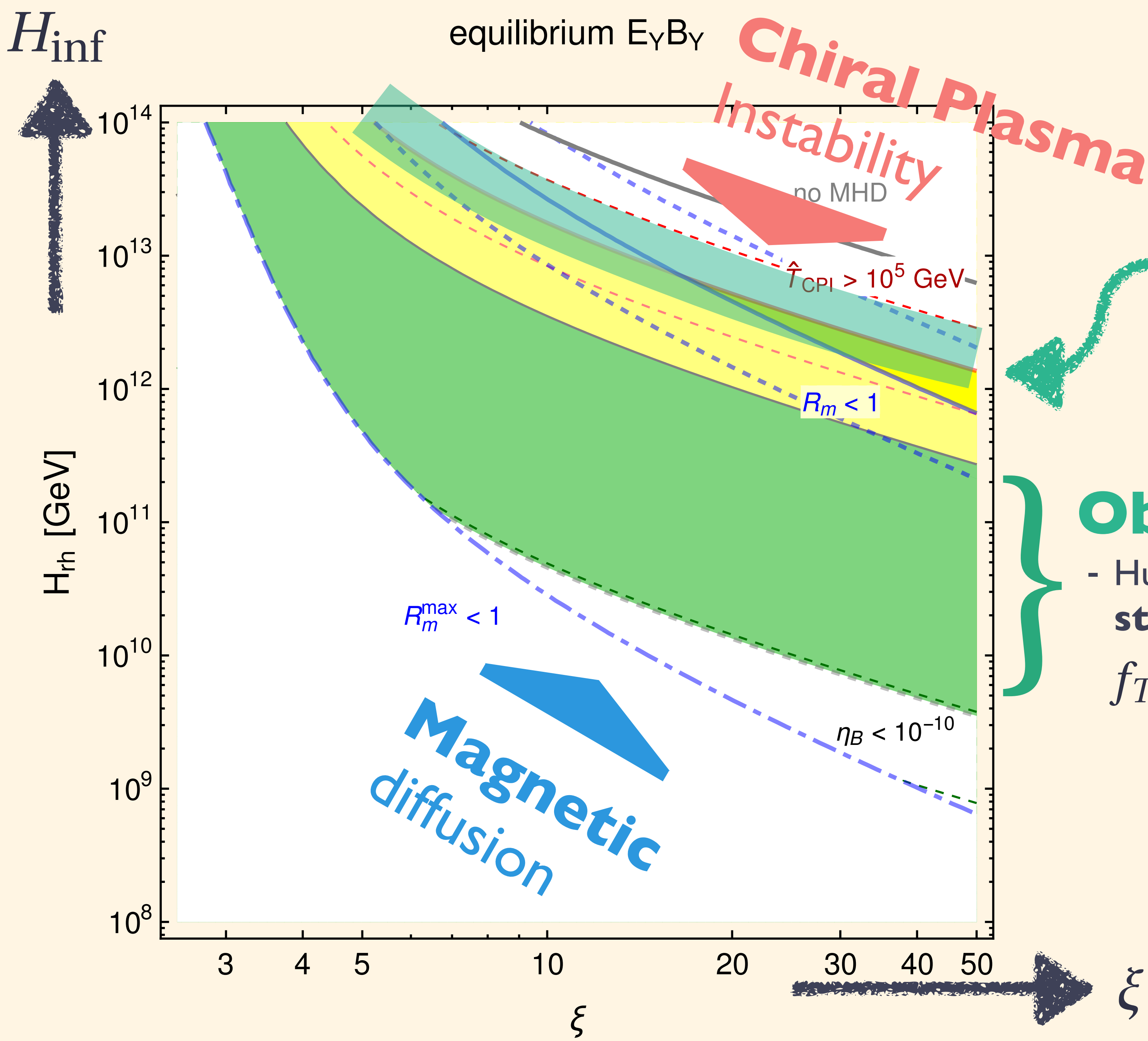

Viable prm???

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

Observed η_B

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

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

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

Summary

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

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**

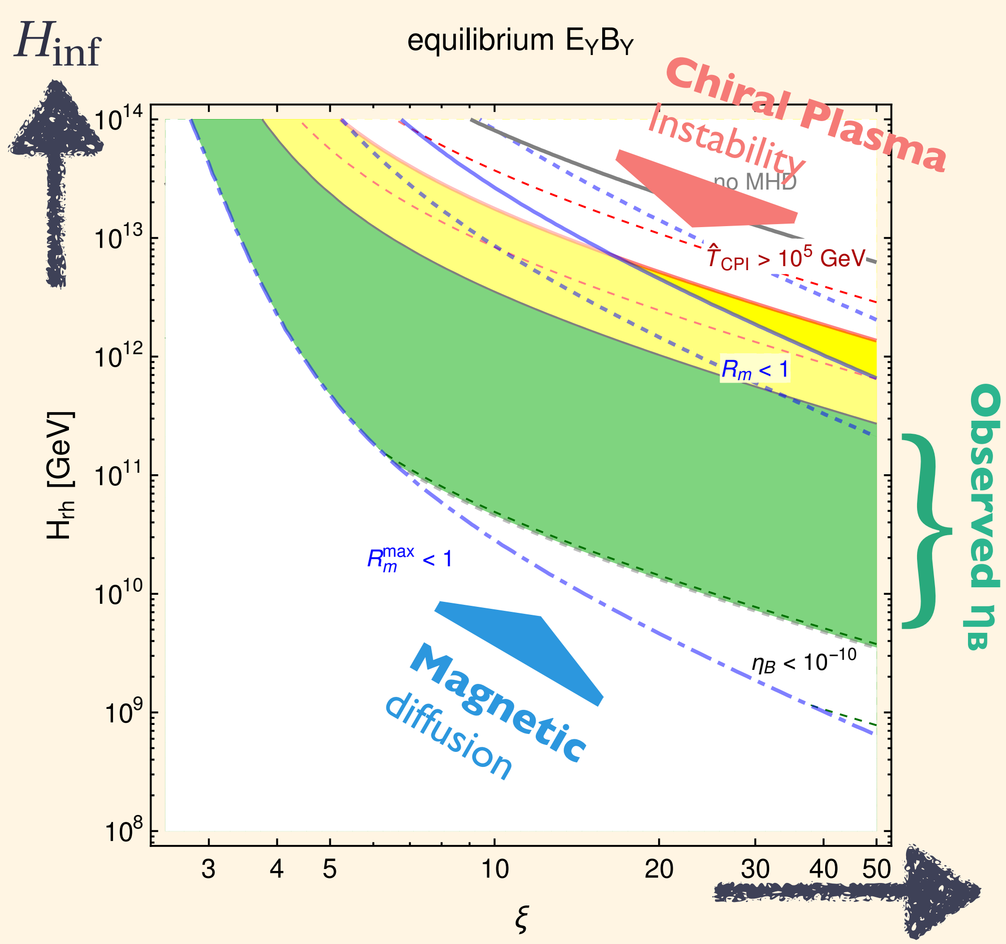
Inefficient **diffusion**
No **CPI**

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

⊿ **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



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