Baryogenesis from Inflation with CS term

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Based on **1806.08769, 1812.08021, 1905.13318, 1910.01205**
In collaboration with Y. Ema, V. Domcke, B. von Harling, E. Morgante, R. Sato

1.

Introduction

Introduction

Inflaton w/ CS-coupling

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

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

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

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

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

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

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

Introduction

Coupling to the SM Gauge Group ?

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

U(1)$_Y$

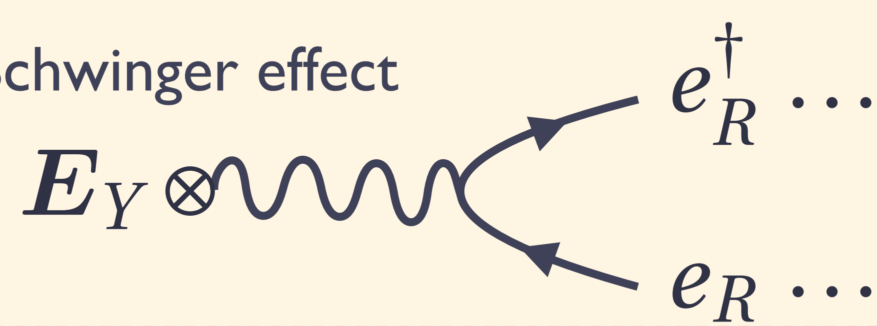
$$\left.+\sum_\alpha\psi_\alpha^\dagger\sigma\cdot(i\partial-g_YQ_\alpha A_Y)\psi_\alpha+\cdots\right\}$$

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

- Production of **SM particles** (during inflation) is **inevitable**!
  - **B+L asymmetry** generation via the **SM chiral anomaly**

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

  - **Pair** production via the Schwinger effect



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

Our Idea

Baryogenesis from B+L asymmetry?

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

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

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

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

Time

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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4.

Time

2.

Production of

Helical gauge & **Chiral** fermion

Setup

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

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

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

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

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

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

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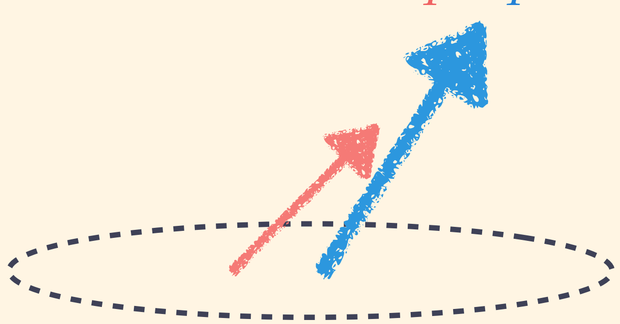

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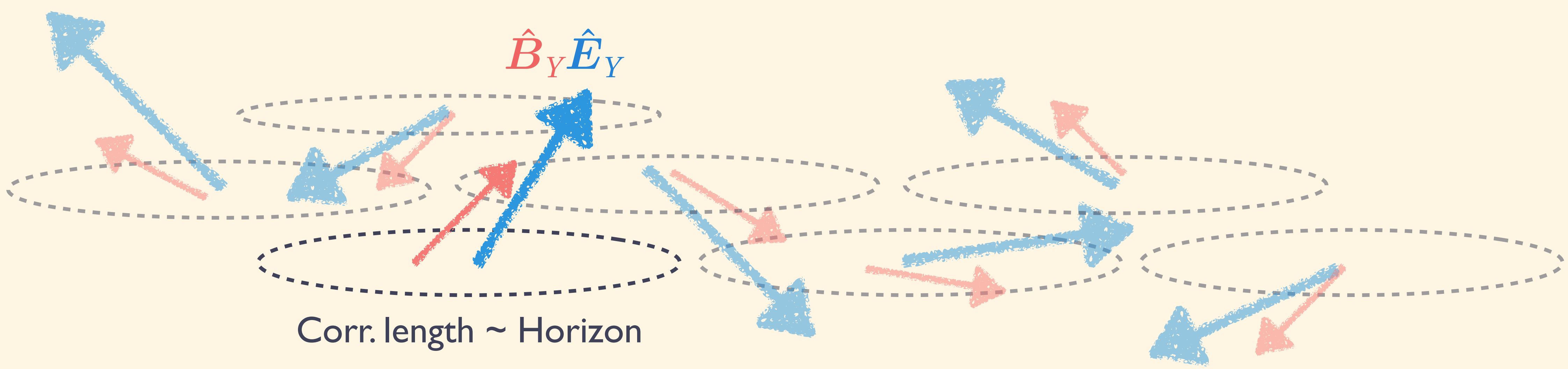


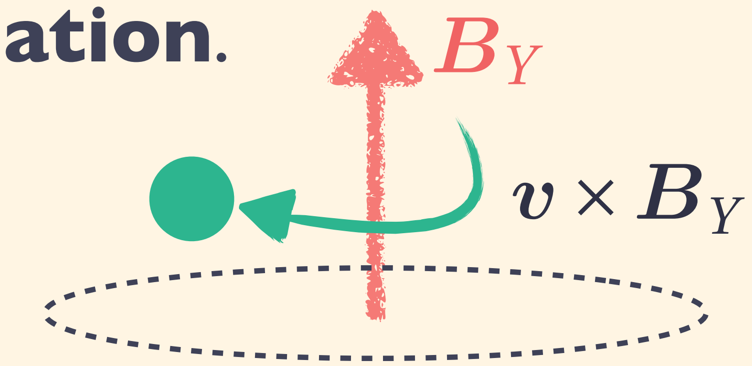
Fermion Production

Landau Levels

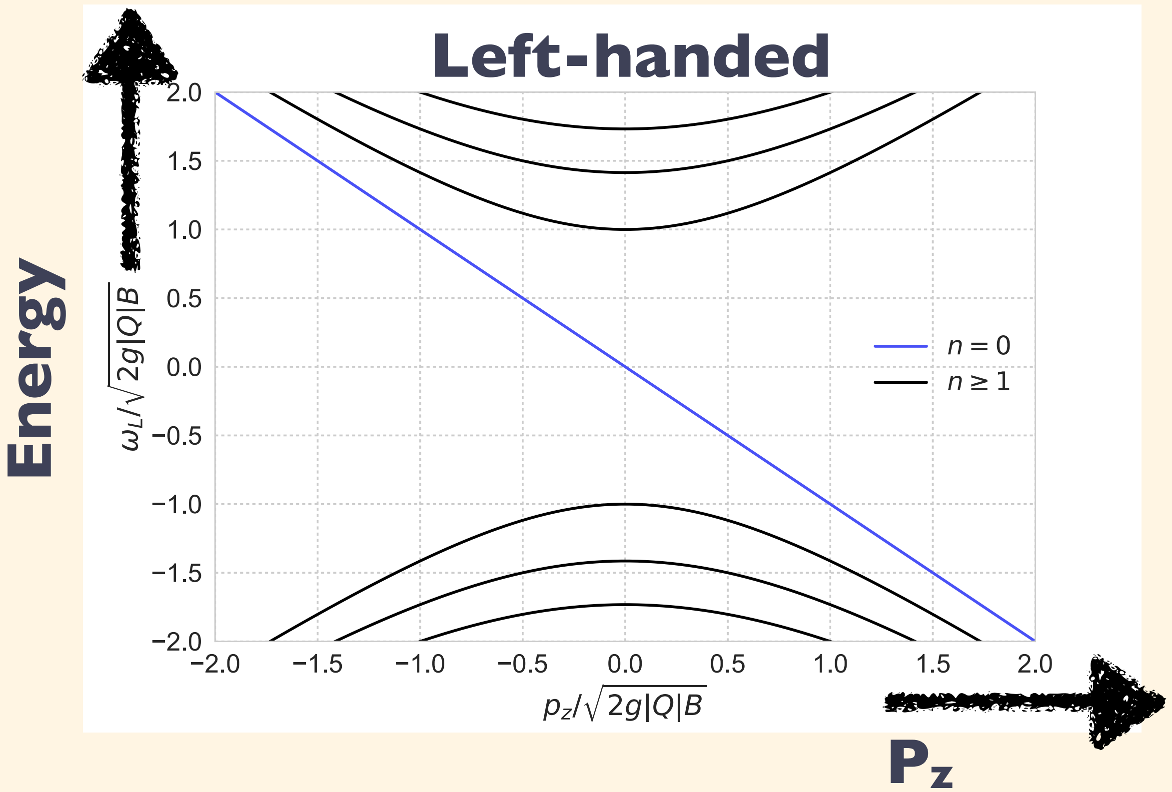
- Turn off E_Y; B_Y field modifies the **dispersion relation**.

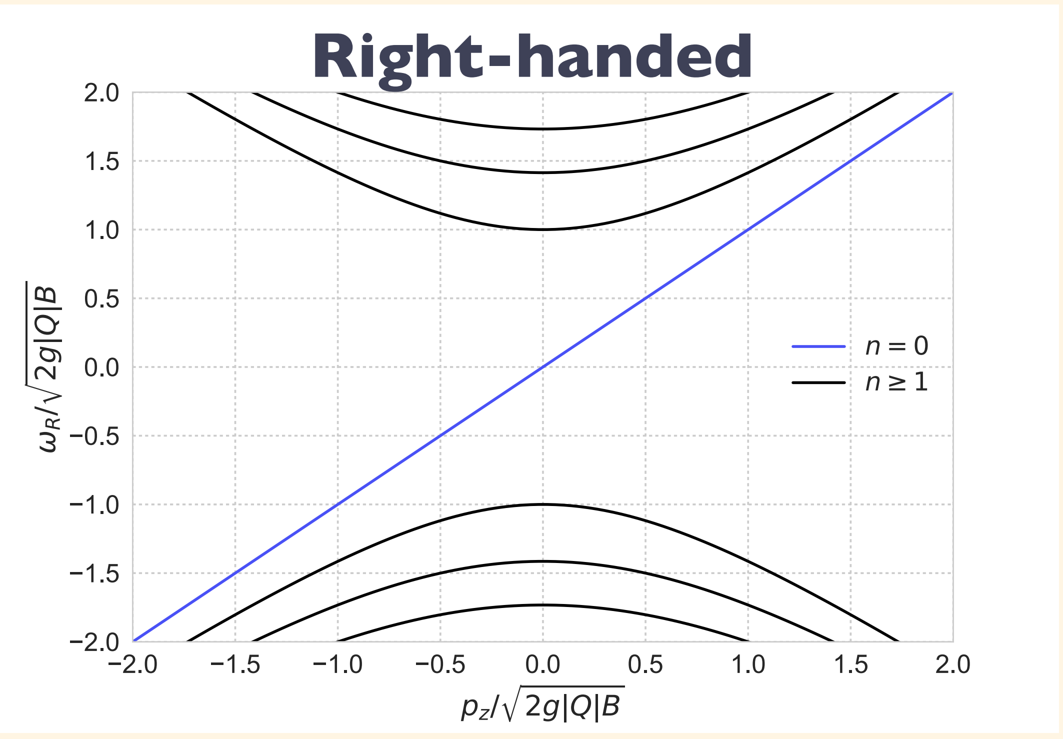
$$0 = \left(i\partial_\eta \pm i\nabla\cdot\boldsymbol{\sigma} - gQ_\alpha A_{Y,0} \pm gQ_\alpha \boldsymbol{A}_Y\cdot\boldsymbol{\sigma}\right)\psi_{\alpha,\mathrm{R/L}}$$

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



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



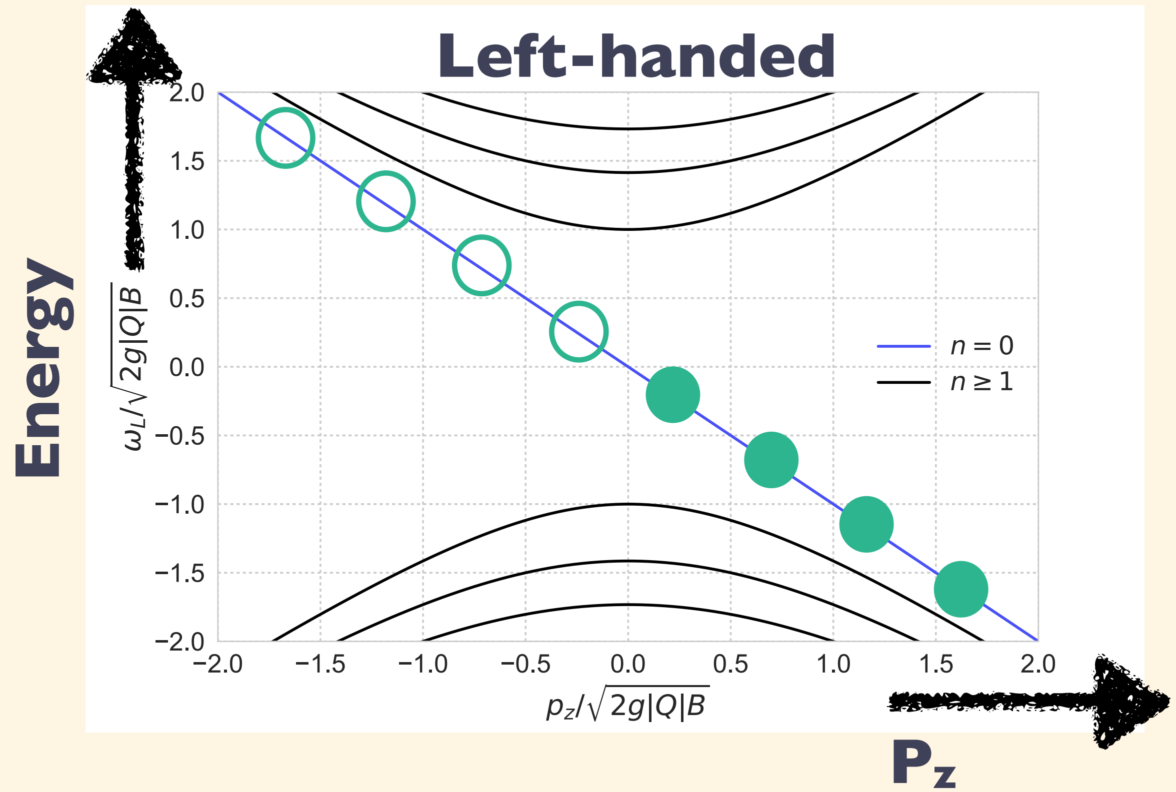


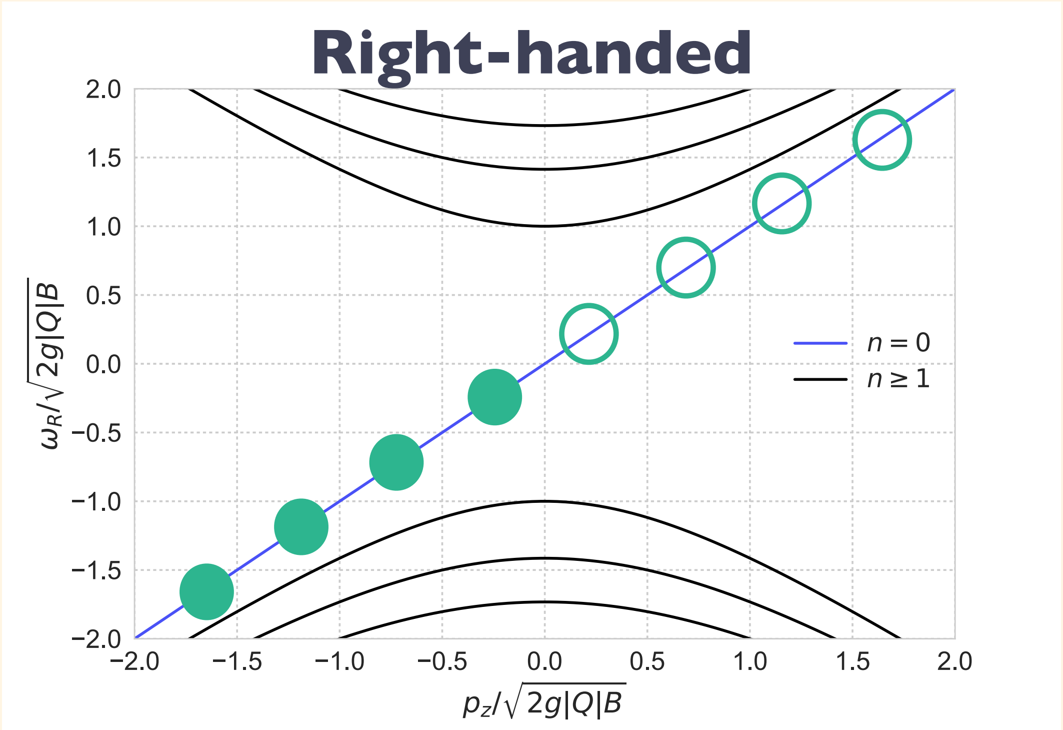
Fermion Production

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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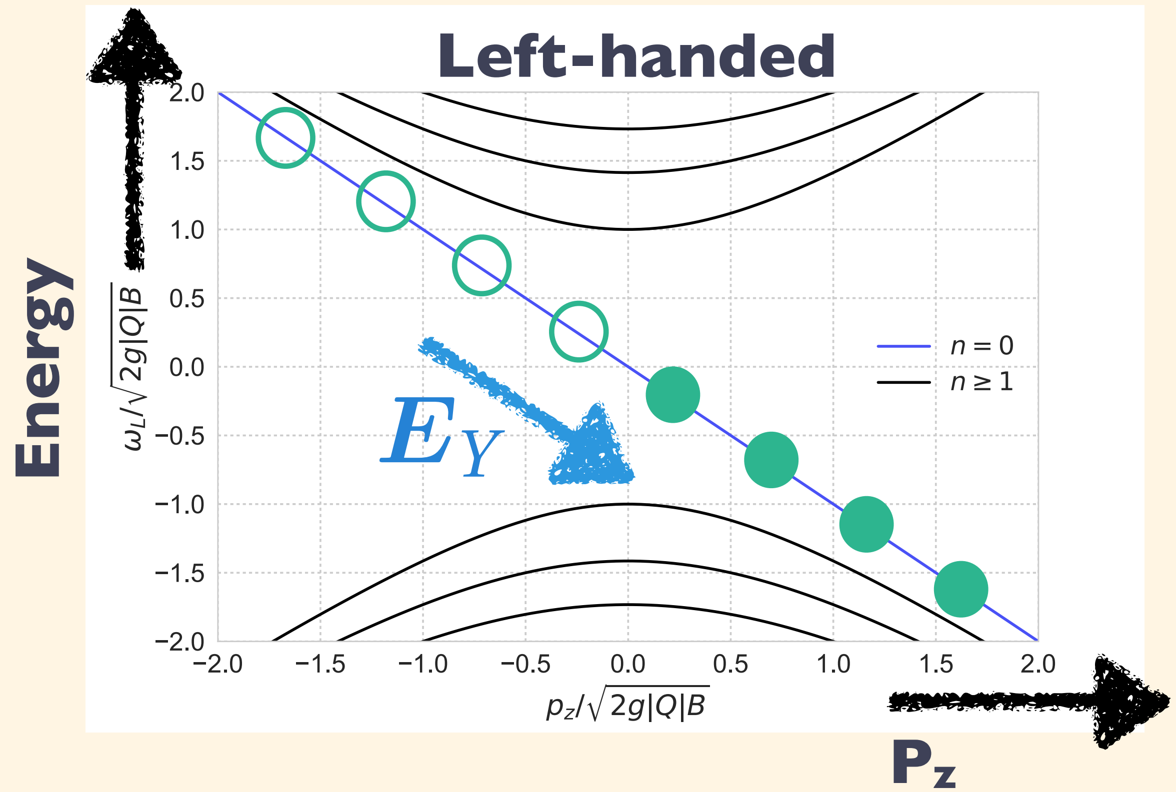

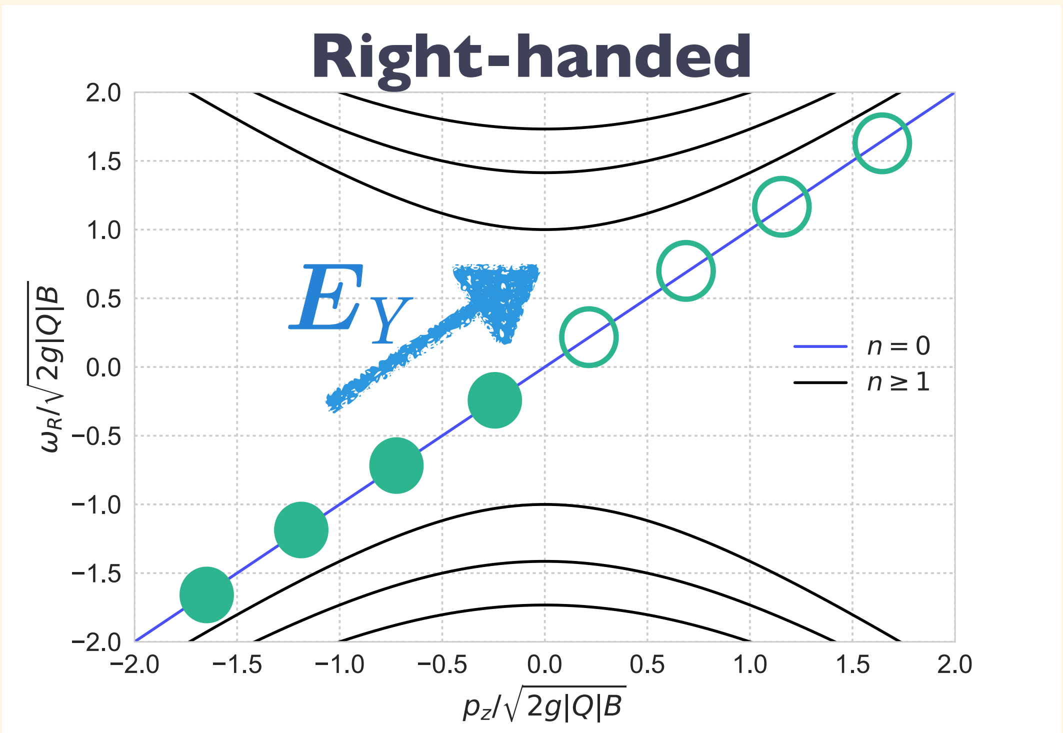

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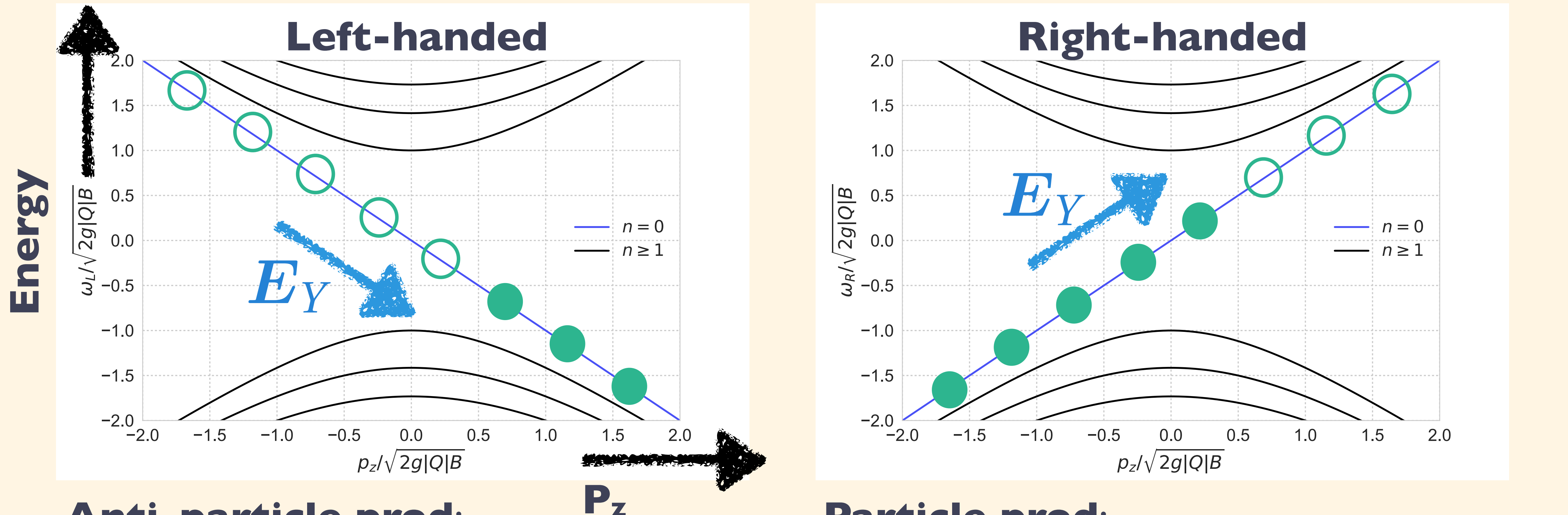


Anti-particle prod:

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

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

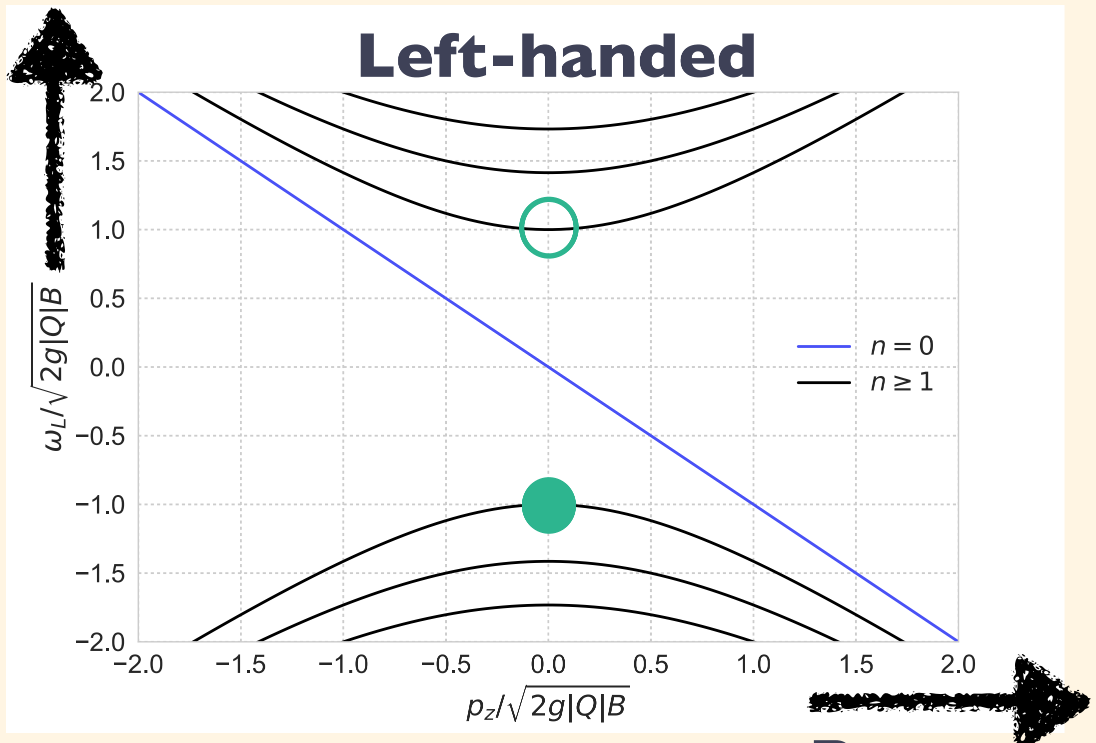
Fermion Production

Higher Landau Levels (n≧1) & Pair Production

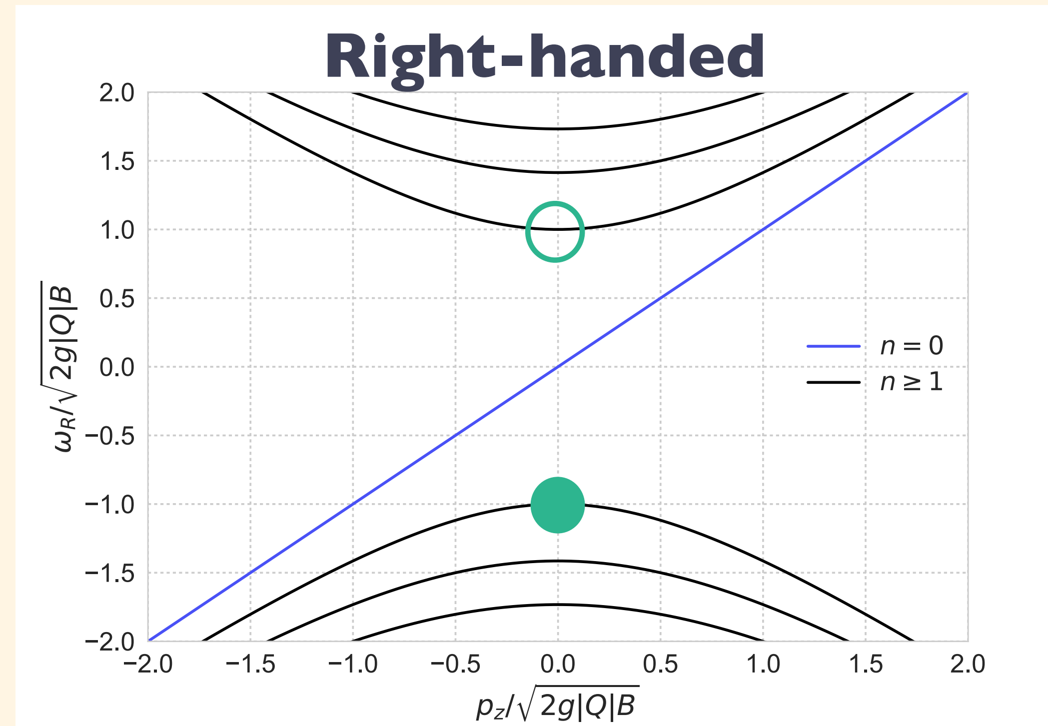
V.Domcke and **KM** 1806.08769

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

Energy



P_z



Fermion Production

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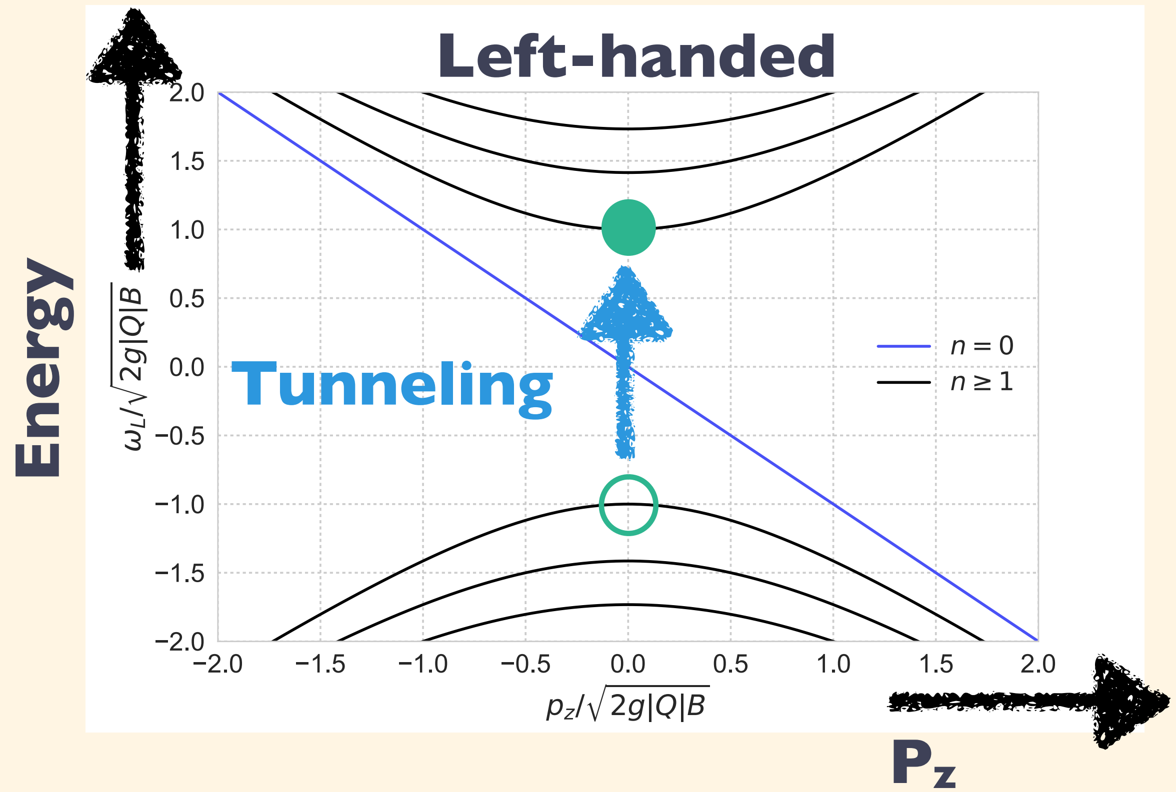

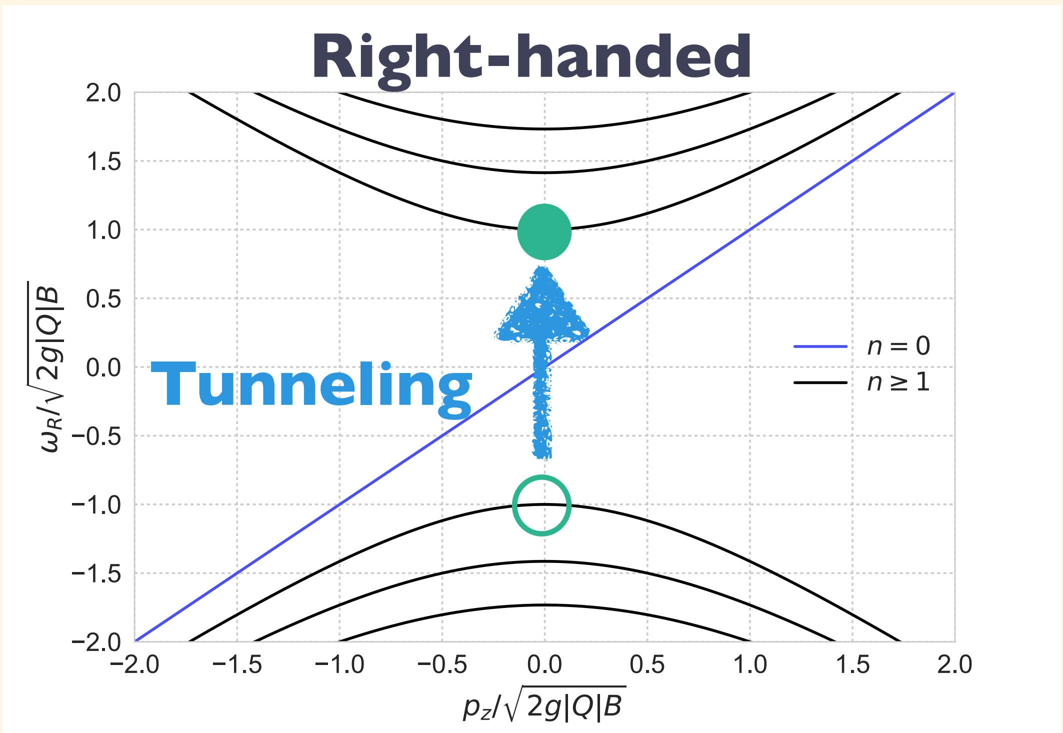

➡ **Pair**-production via Schwinger effect

Fermion Production

Higher Landau Levels (n≧1) & Pair Production

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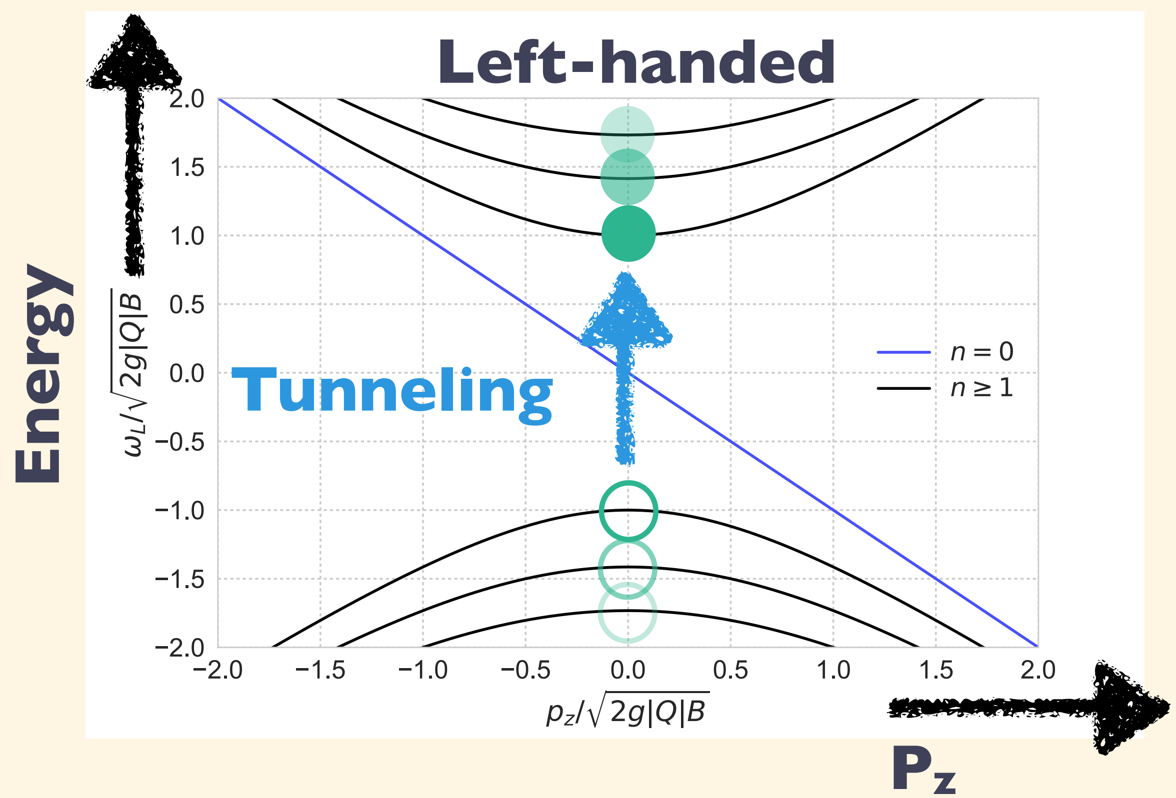

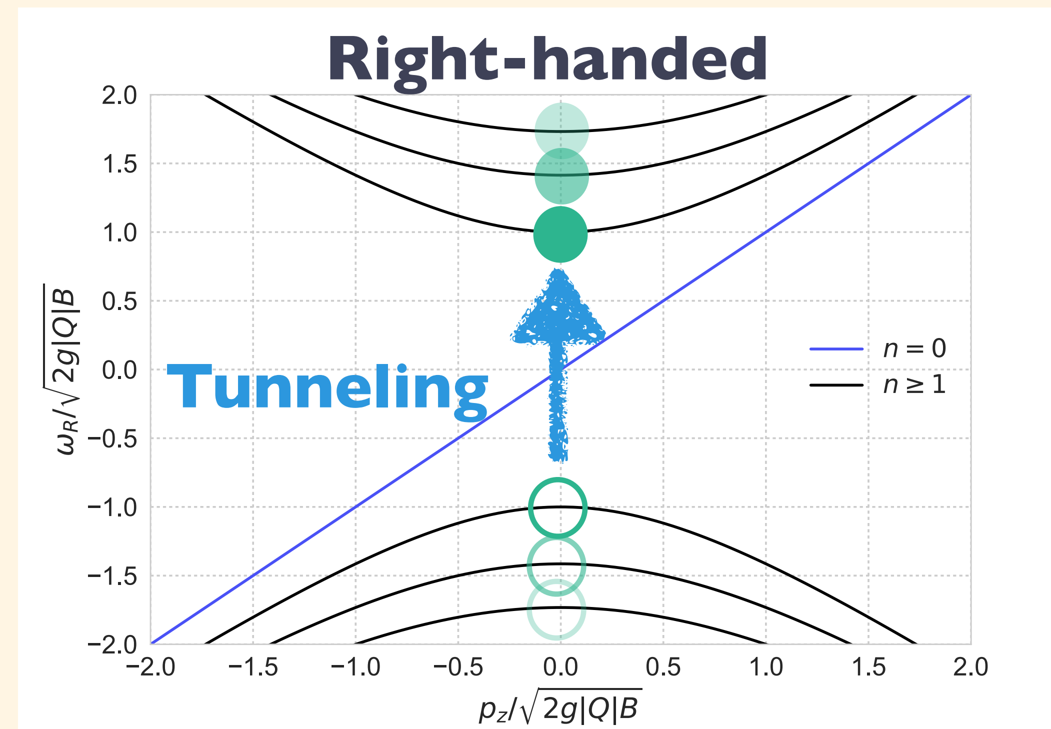

➡ **Pair**-production via Schwinger effect

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

✤ 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 in $B_Y \parallel E_Y$

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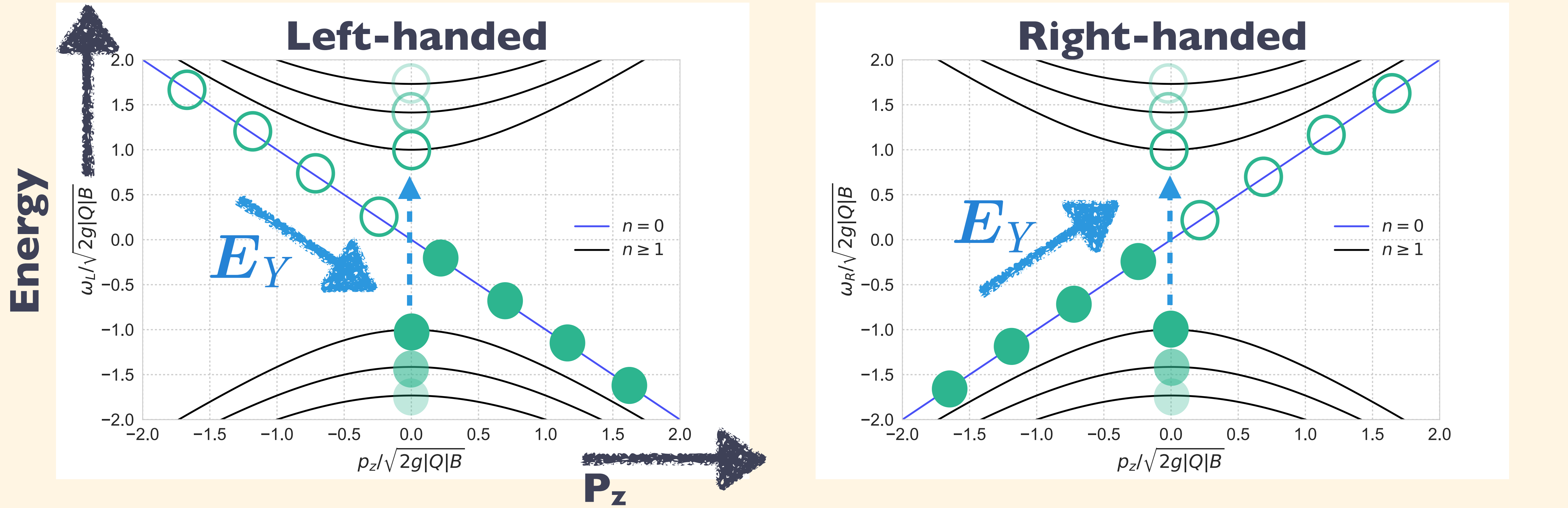

- **ABJ anomaly** from **Lowest Landau Level** (n=0)

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

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

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

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

Fermion Production

Implications on Axion Inflation

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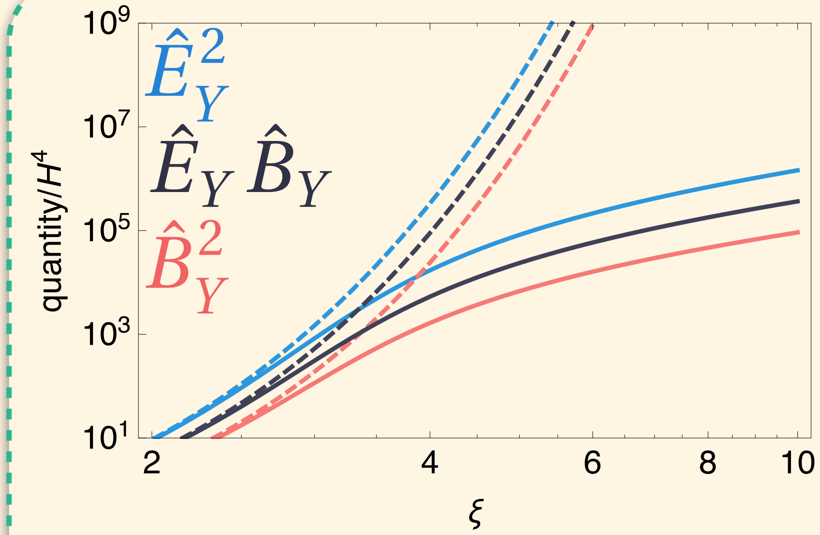
- **Backreaction** suppresses gauge field

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

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



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

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

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

3.

Survival of Helical Gauge Field

Outline of this Talk

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

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

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

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

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

Now

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

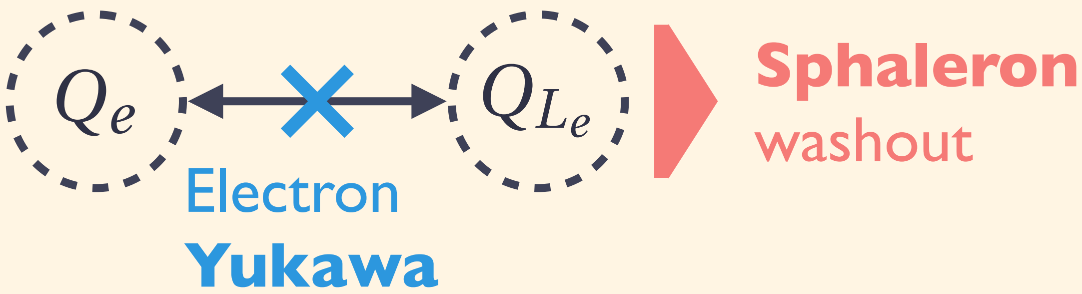
4.

Time

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

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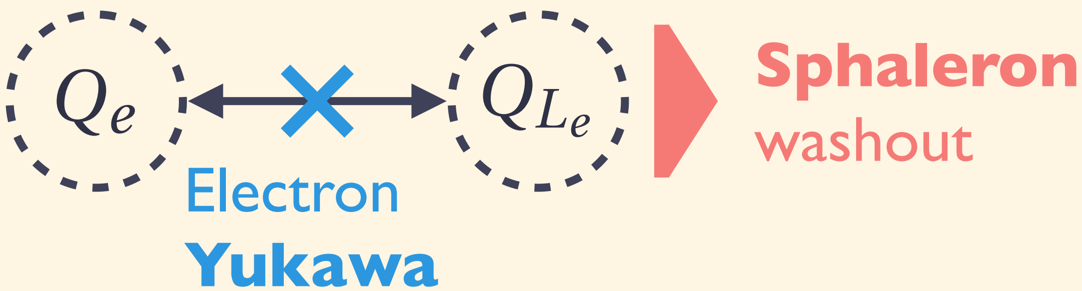

Electron Yukawa is **NOT** efficient till

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

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

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

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

	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

Avoid Chiral Plasma Instability

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** efficient till

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

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

	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

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

▼ **Sphaleron+Yukawa** washout

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

Survival of Helical Gauge Field

Avoid Chiral Plasma Instability

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

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

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

Chiral Plasma Instability

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

Survival of Helical Gauge Field

Avoid Magnetic Diffusion

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

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

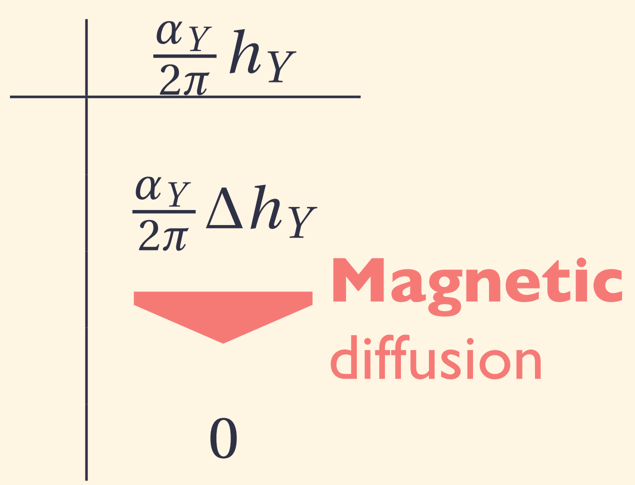
$$\frac{\partial B_Y}{\partial\eta} = \frac{\nabla^2}{\sigma_Y}B_Y + \nabla\times(v\times B_Y) + \frac{2\alpha_Y}{\pi}\frac{\mu_{Y,5}}{\sigma_Y}\nabla\times B_Y$$

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

Chiral Plasma Instability

Magnetic Diffusion

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



Survival of Helical Gauge Field

Avoid Magnetic Diffusion

V.Domcke, B.Harling, E.Morgante, **KM**
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$$\frac{\partial}{\partial \eta} v + v \cdot \nabla v = \nu \nabla^2 v + \frac{1}{\rho + P} \left(-\frac{1}{2} \nabla B_Y^2 + (B_Y \cdot \nabla) B_Y \right)$$

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

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

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

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

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

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

Magnetic diffusion

0

Inverse cascade

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

- 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?

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

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

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

2.

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

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

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

3.

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

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

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

Baryogenesis from Decaying Helicity

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

K.Kamada and A.Long 1610.03074

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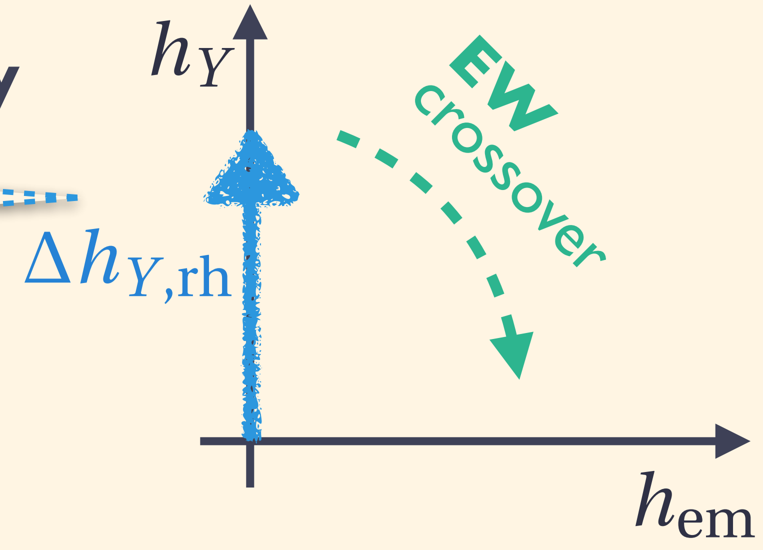
$\propto \partial_\eta h_Y$



Regeneration of Baryon Asym.

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K.Kamada and A.Long 1610.03074

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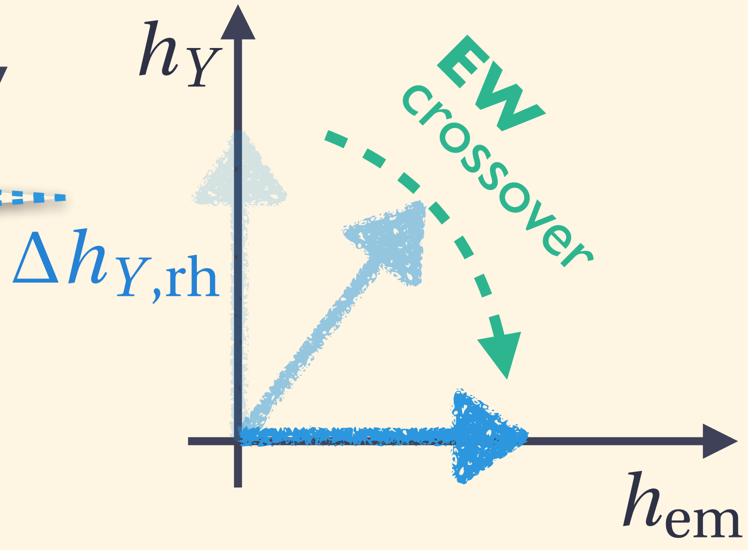

Regeneration of Baryon Asym.

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K.Kamada and A.Long 1610.03074

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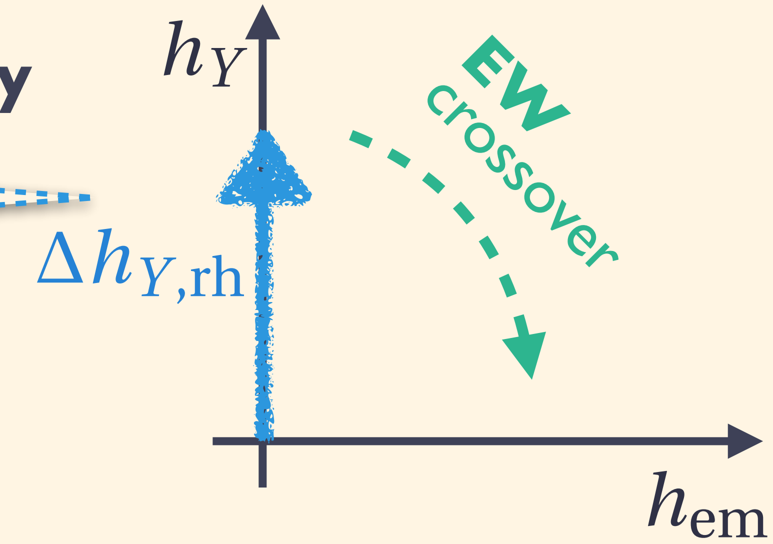
$$\begin{cases} \Gamma_{\mathrm{W,sph}} \propto e^{-\frac{M_{\mathrm{sph}}(T)}{T}} \\ M_{\mathrm{sph}}(T) \propto v(T) \end{cases} \qquad \propto \partial_\eta h_Y$$



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

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

EW sphaleron
Washout-factor

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

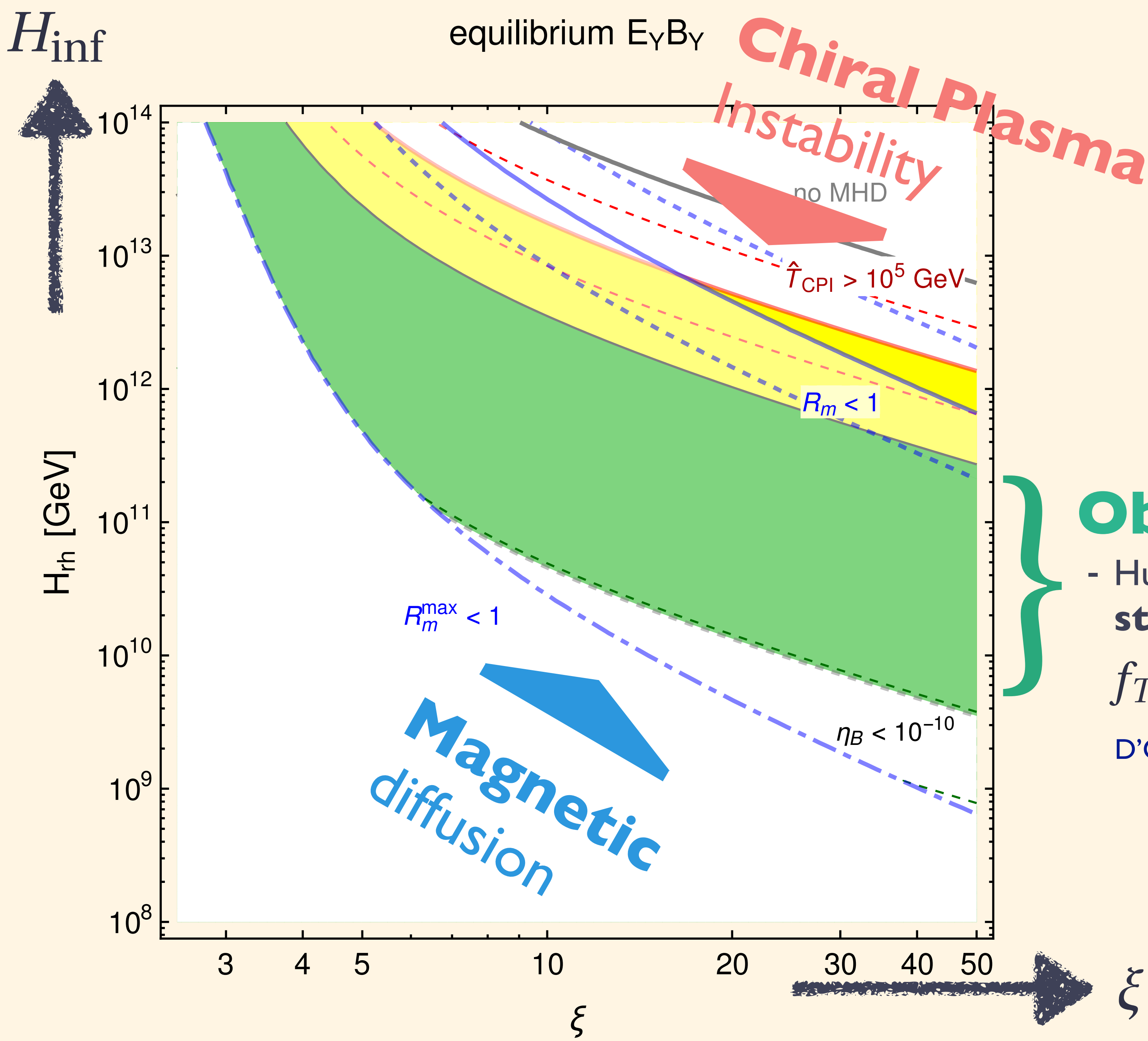
EW crossover
- Huge uncertainties…

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

D'Onofrio and Rummukainen 1508.07161

Viable parameters for Baryogenesis

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



Observed η_B

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

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

D'Onofrio and Rummukainen 1508.07161

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

Viable parameters for Baryogenesis

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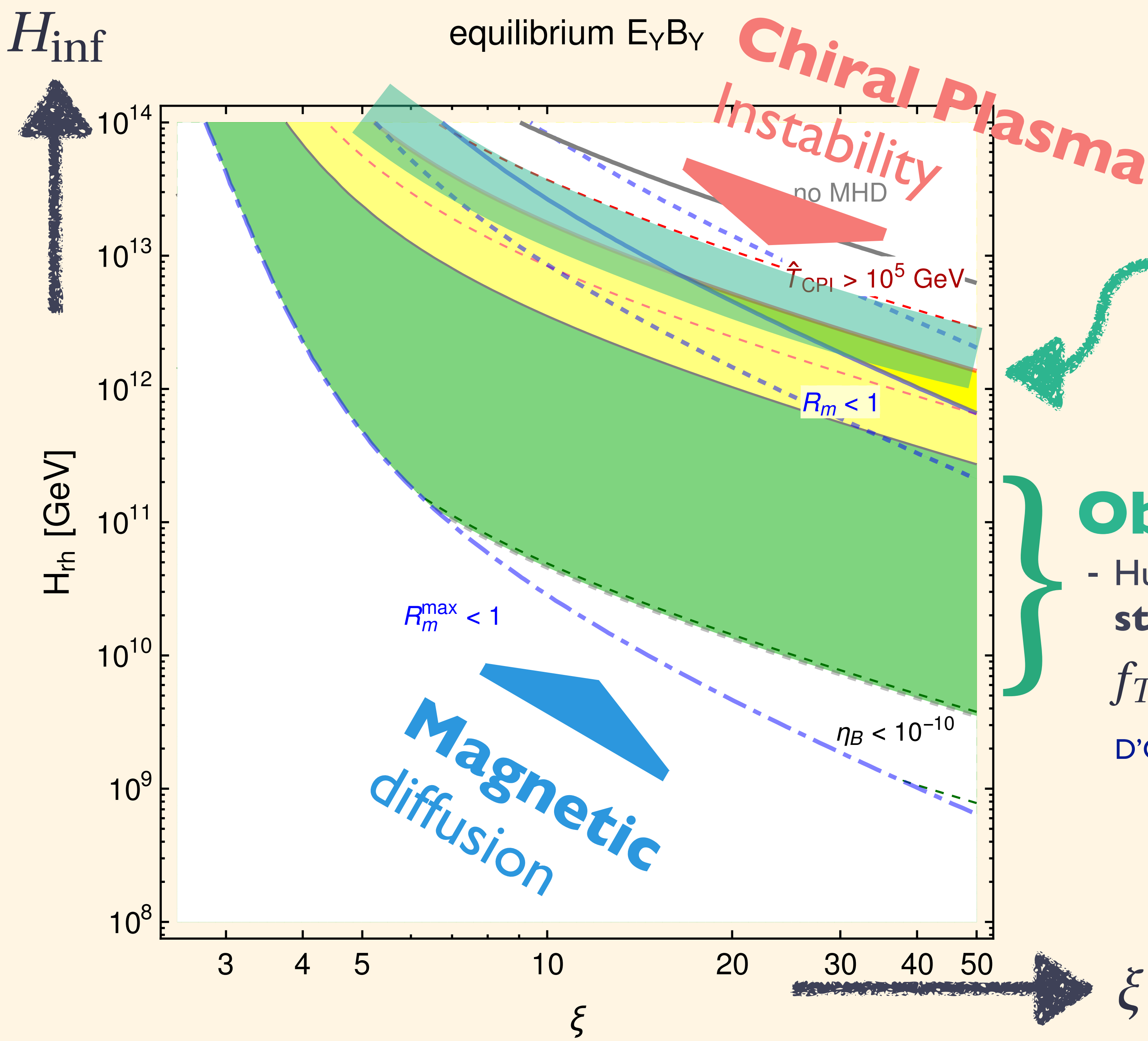


Viable prm???

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

Observed η_B

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

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

D'Onofrio and Rummukainen 1508.07161

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

Summary

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

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

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**

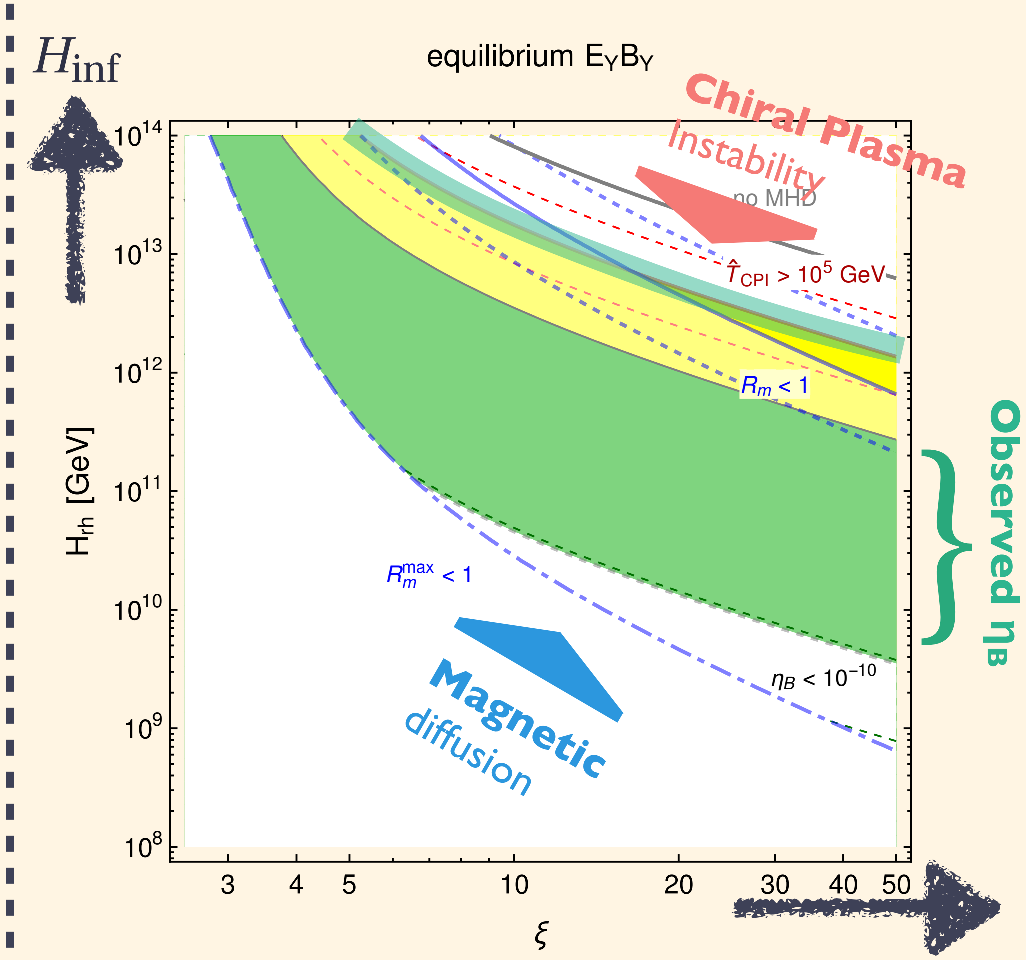
Inefficient **diffusion**
No **CPI**

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

⊿ **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



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

Back up

Backreaction

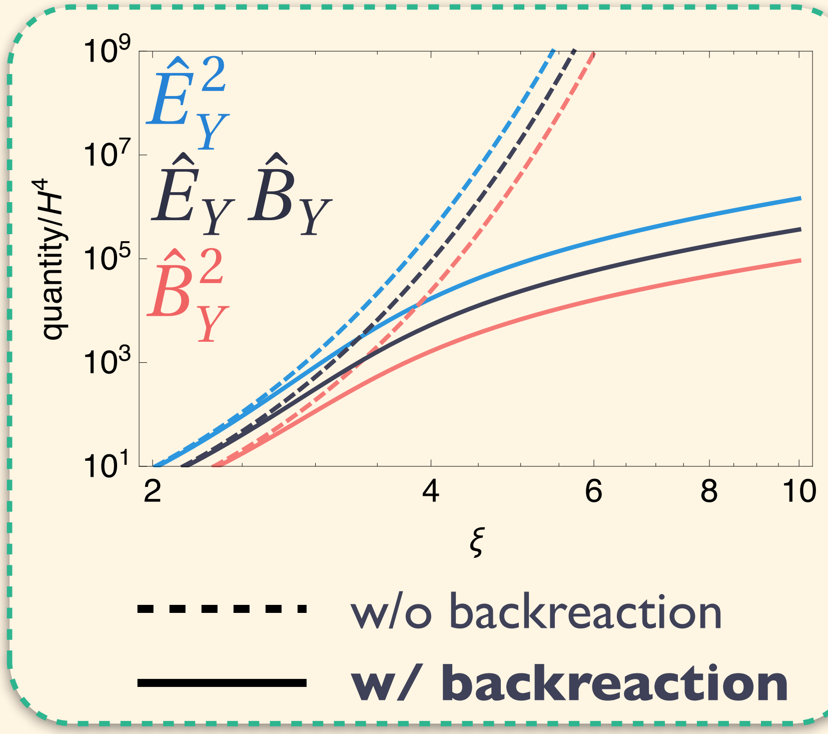
Implications on Axion Inflation

V.Domcke and **KM** 1806.08769

- **Backreaction** suppresses gauge field

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

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



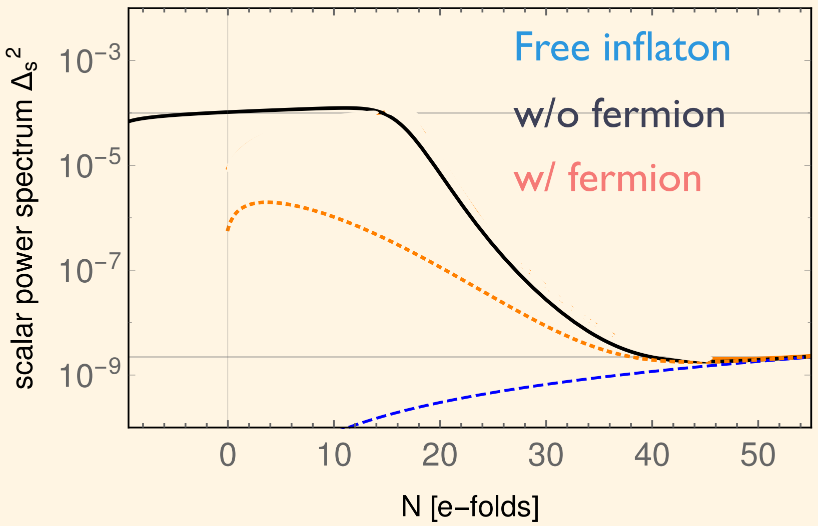
- **Sourced** curvature perturbation
  - Reduction of $\boldsymbol{\Delta_s}$ sourced by gauge field

$$\Delta_s^2 \simeq \left(\frac{H^2}{2\pi\dot\phi}\right)^2 + \left(\frac{\alpha\langle\hat{\boldsymbol{E}}\cdot\hat{\boldsymbol{B}}\rangle}{3\pi\beta H\dot\phi f_a}\right)^2 \text{ w/ } \beta = 1 + \frac{2\xi\alpha\langle\hat{\boldsymbol{E}}\cdot\hat{\boldsymbol{B}}\rangle}{3\pi H\dot\phi f_a}$$

A.Linde, S.Mooij, E.Pajer 1212.1693

  - Reduction of **GWs** sourced by gauge field (?)

Fermion contributions to GWs? Need further investigation…



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

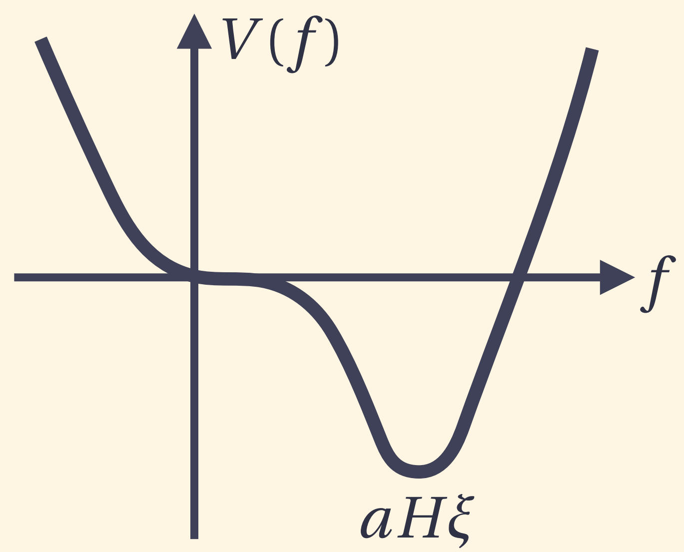
- "Lightness" protected by the shift symmetry (classically): $\phi \mapsto \phi + c$
- Efficient **helical-gauge field** production by $\dot{\phi} \neq 0$.

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

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

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

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



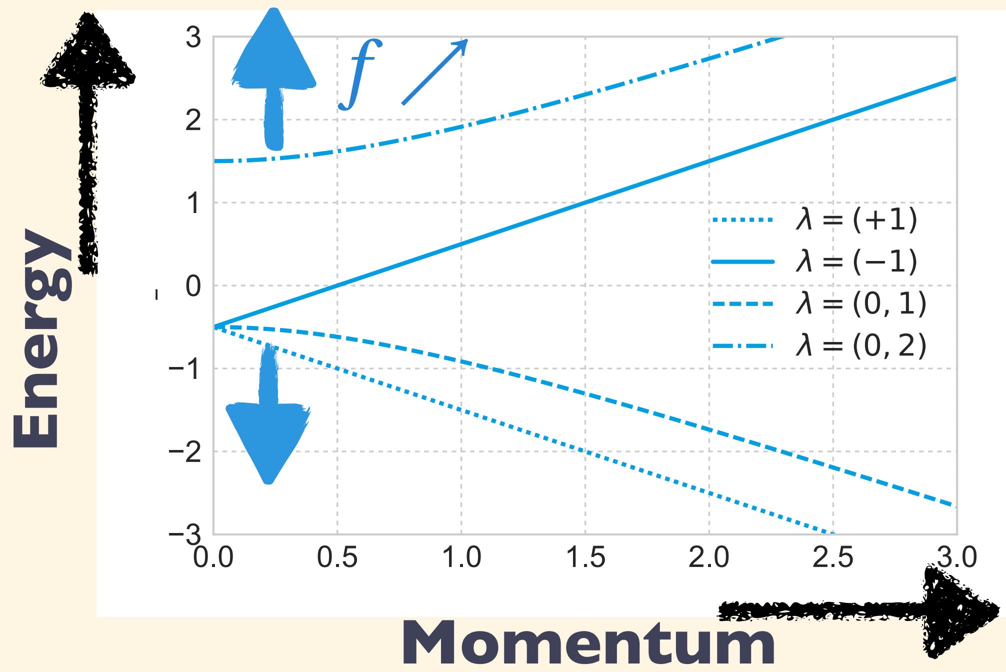
➡ **axion inflation, relaxion, chiral GWs, baryogenesis, magnetogenesis,...**

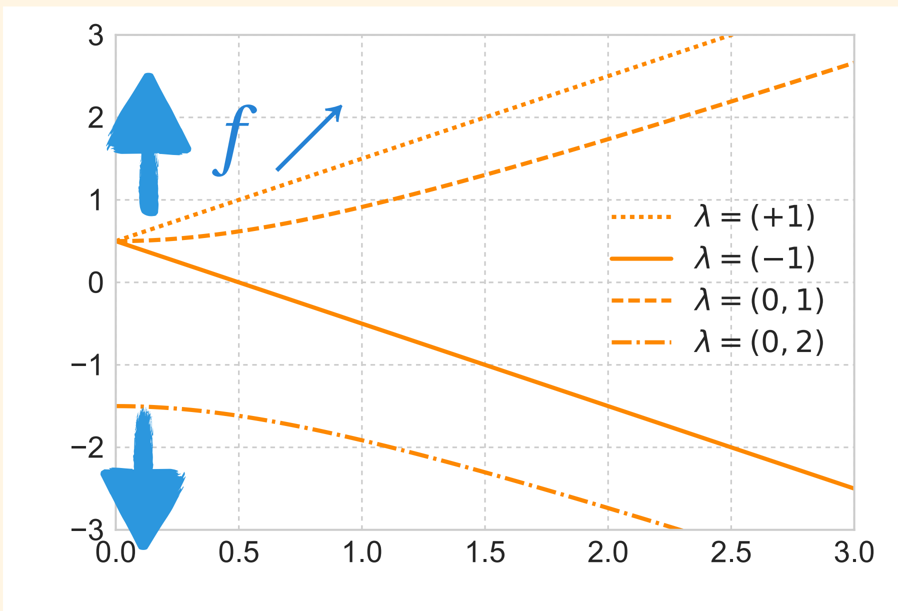
Fermion Production

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.

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

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

The eta-invariant; see Atiyah and Singer

Induced Current

How does Induced Current look like?

- **Weak** electromagnetic field in thermalized plasma

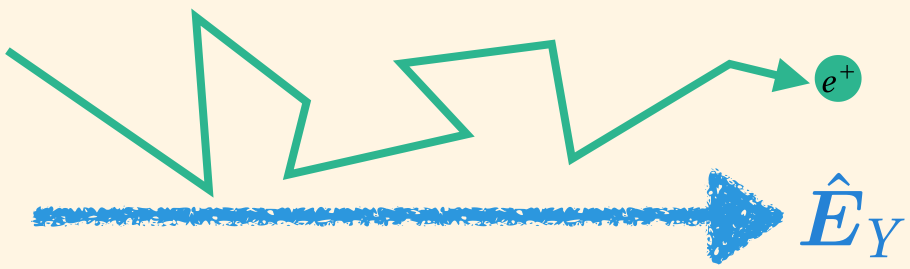
$$\hat{\boldsymbol{J}}_Y = \hat{\sigma}_Y \hat{\boldsymbol{E}}_Y + \frac{2\alpha_Y}{\pi} \hat{\mu}_{Y,5} \hat{\boldsymbol{B}}_Y$$ i.e., Generalized Ohm's law (neglecting velocity field)

  - **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**

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

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

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

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

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

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

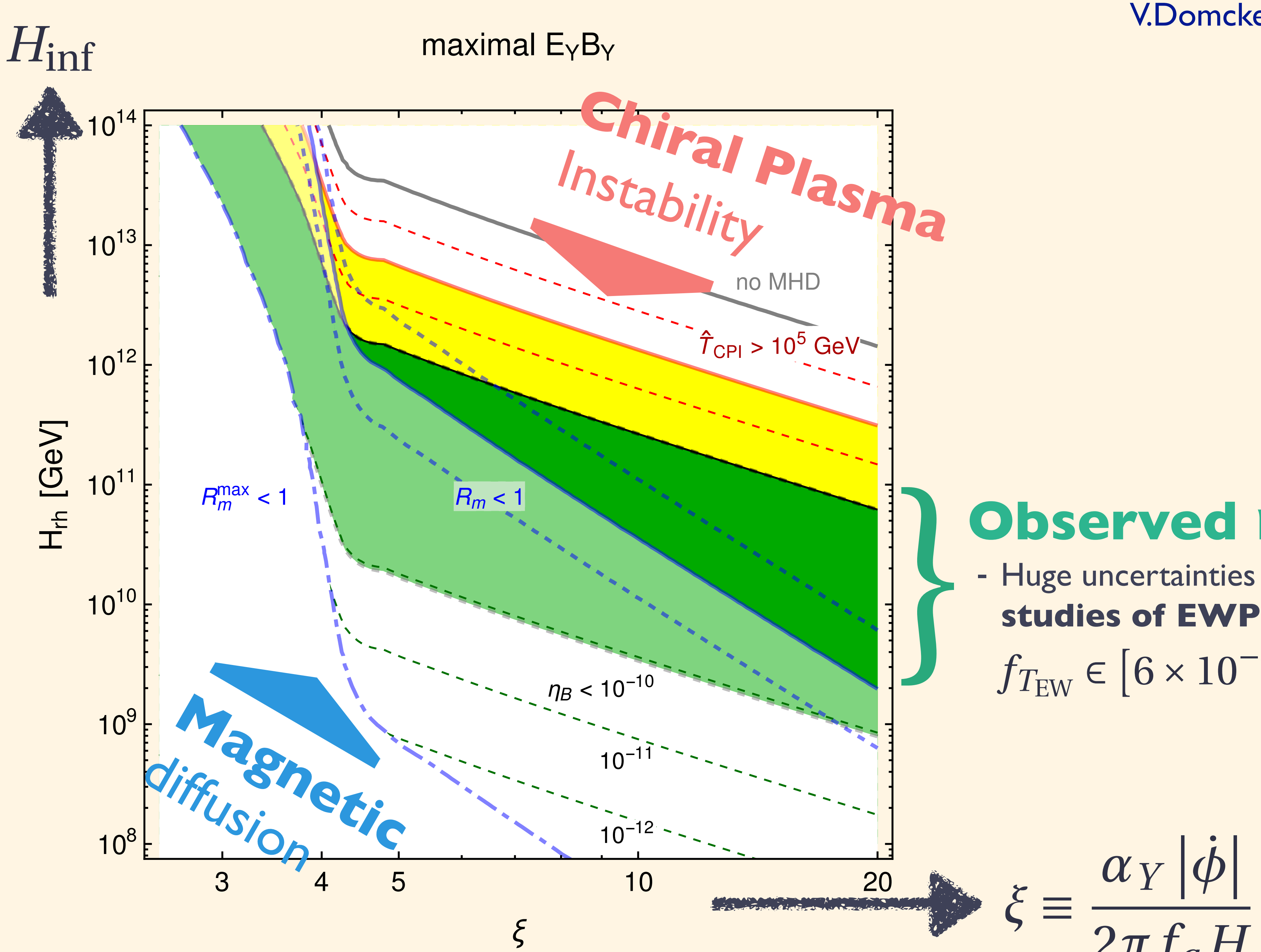
- **Viscous** regime: $R_m > 1 > R_e$

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

Result

Viable parameters for Baryogenesis

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



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

Observed η_B

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

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