Baryo/Leptogenesis from Axion Inflation

Kyohei Mukaida

KEK

Based on **1905.13318**, **2011.09347**, 21xx.xxxxx

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

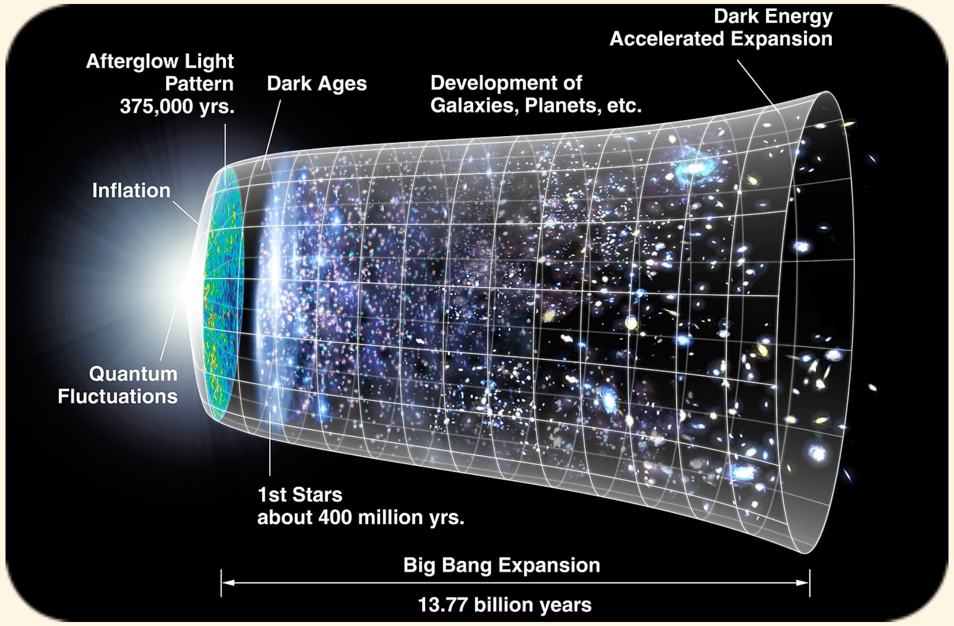
1.

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 baryons**.



NASA

- **Baryogenesis** after inflation
  - Baryon to photon ratio → $\eta = \dfrac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$

➡ Baryogenesis from Inflation?

- Reheating requires couplings btw inflaton and the SM particles.

Inflaton ϕ ⟷ **Baryogenesis ?** ⟷ **SM** particles

Introduction

Axion(-Like Particle) as Inflaton

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{\frac{\phi}{4\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

Inflaton U(1) **CS** coupling

$\propto \phi \partial \cdot h$

- **Flat** potential protected by shift sym: $\phi \mapsto \phi + c$

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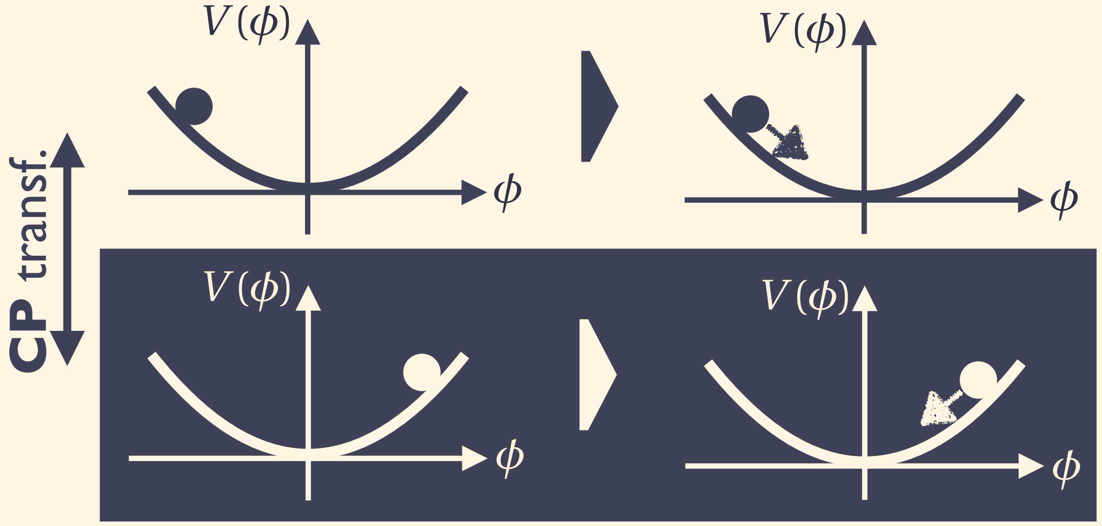

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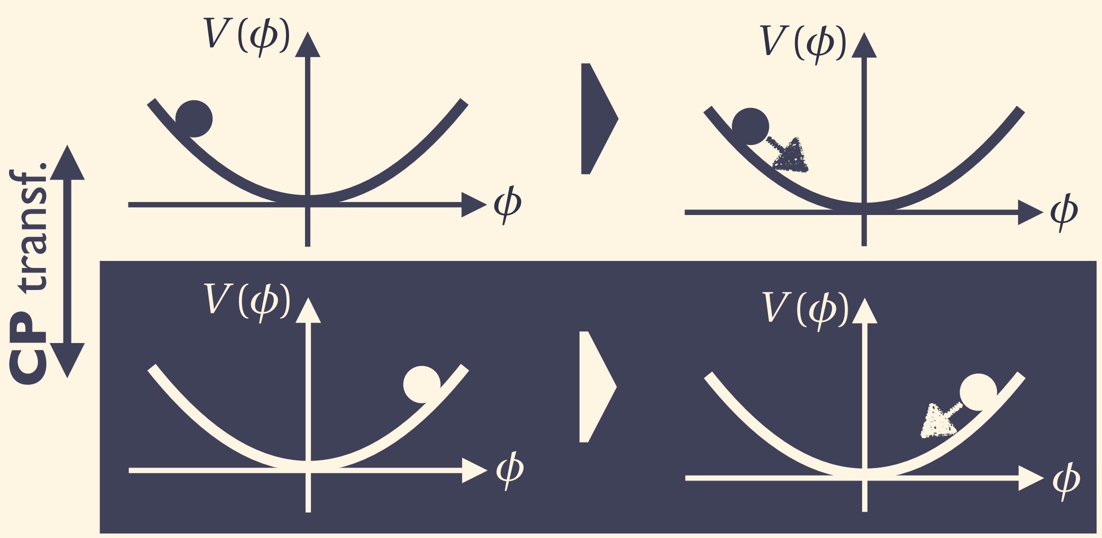


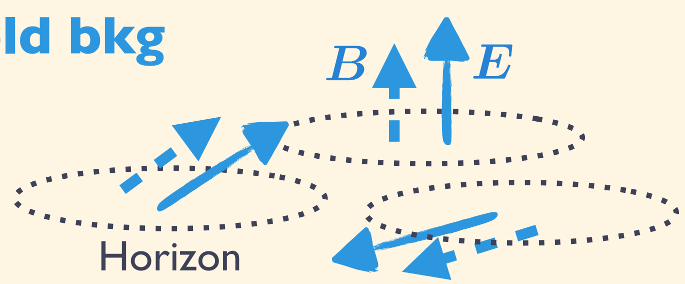
- Tachyonic growth in **one polarization**

$$0 = \left[\partial_\eta^2 + k(k \pm 2\xi aH)\right] A_\pm(\eta, k) \quad \text{where} \quad \xi \equiv \frac{\dot\phi}{2\Lambda H}$$

- **CP-violating gauge field bkg**

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

CP odd for $\dot\phi \gtrless 0$



Introduction

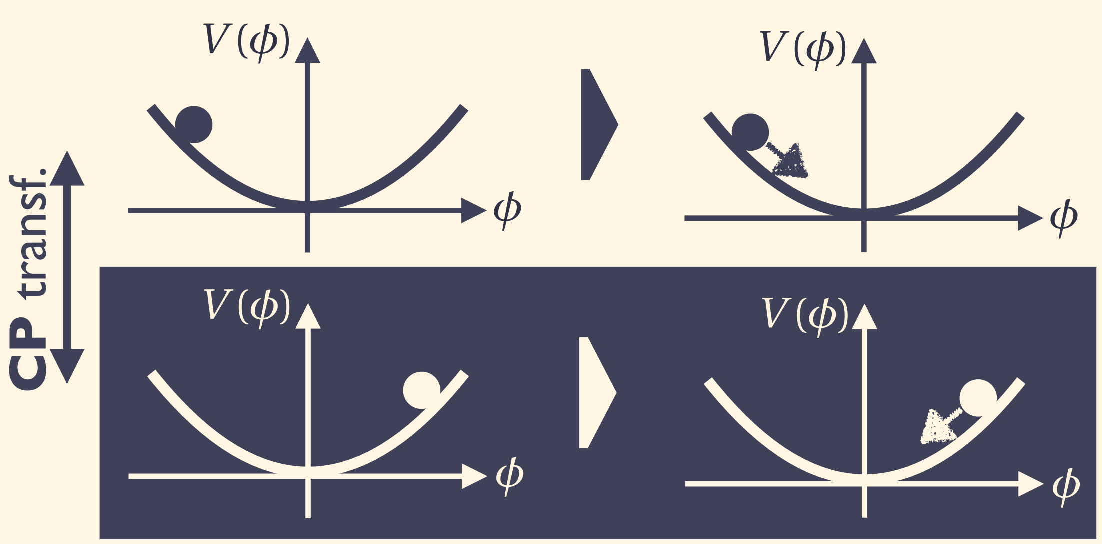
Axion(-Like Particle) as Inflaton

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} + \frac{\phi}{4\Lambda}Y_{\mu\nu}\tilde{Y}^{\mu\nu} + \sum_\alpha \psi_\alpha^\dagger iD\cdot\sigma\psi_\alpha + \cdots$$

Inflaton — $\mathrm{U(1)_Y}$ — **CS** coupling $\propto \phi\partial\cdot h_Y$ — **Charged** fermions

- **Chiral anomaly**
- **Backreaction**

- **Flat** potential protected by shift sym: $\phi \mapsto \phi + c$
- CP-violation from its **coherent motion** (cf. Spontaneous BG, Affleck-Dine BG)



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

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

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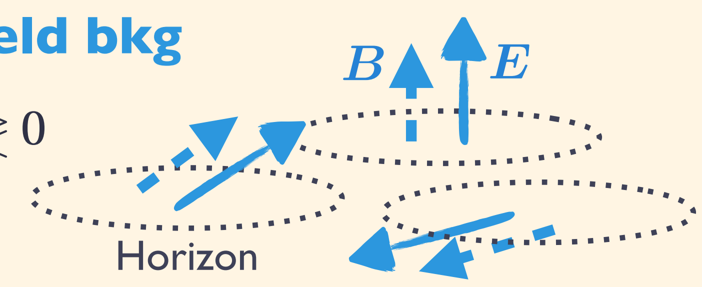


- **B+L asym. is generated!**

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

Outline

Baryo/Leptogenesis 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

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

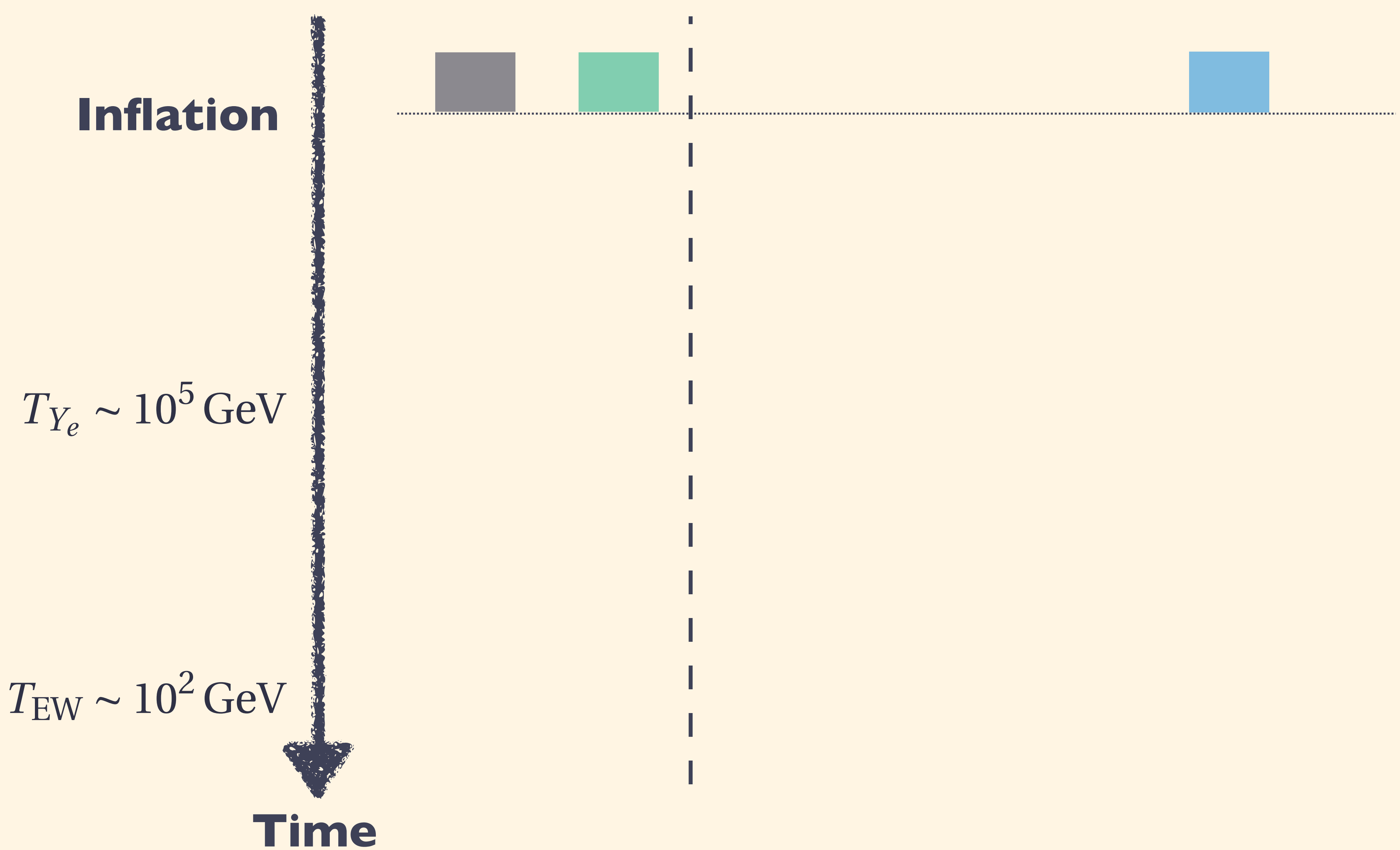
$T_{\mathrm{EW}} \sim 10^2\,\mathrm{GeV}$

Time

Outline

Baryo/Leptogenesis from B+L asymmetry?

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



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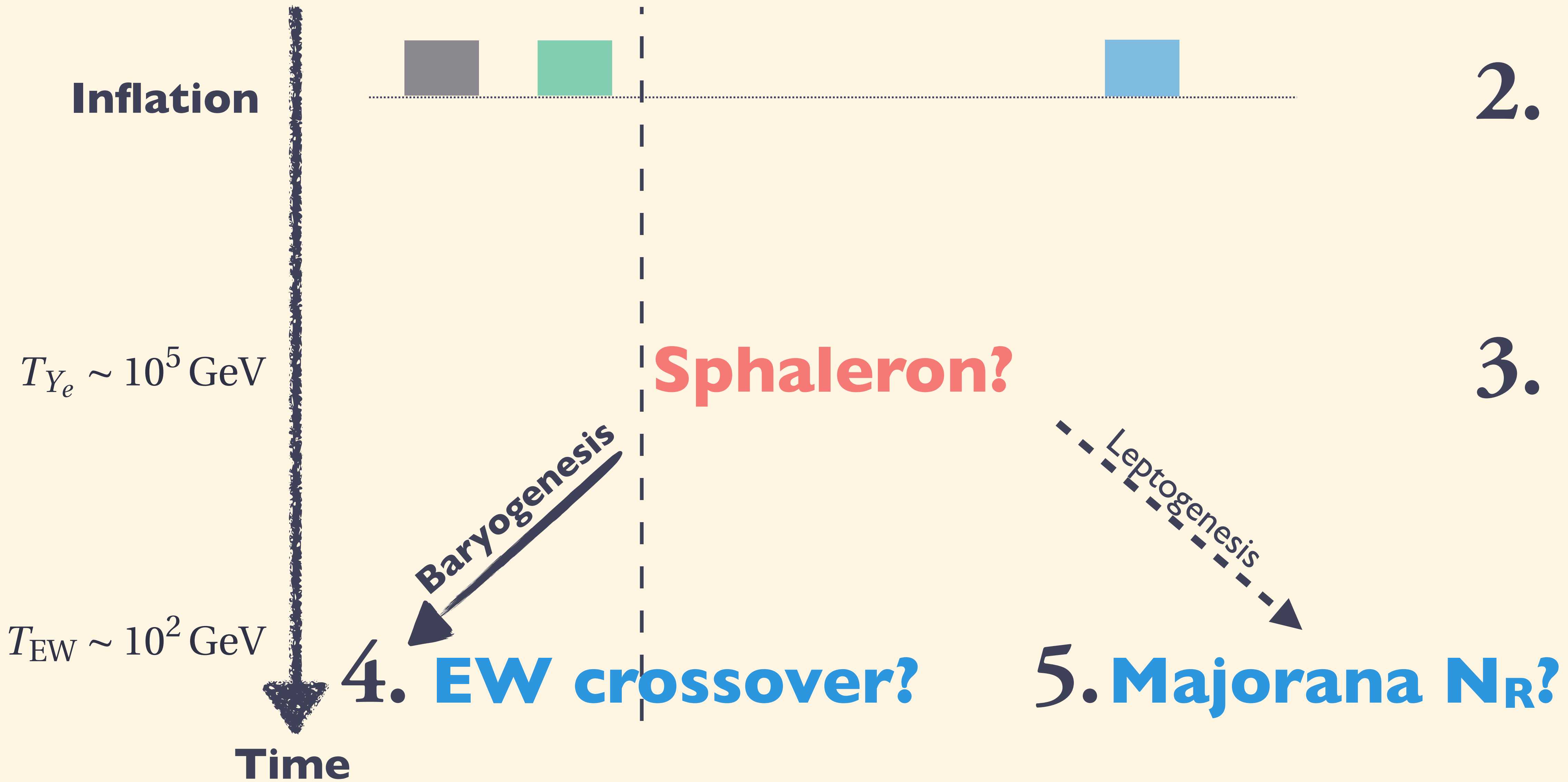


2.

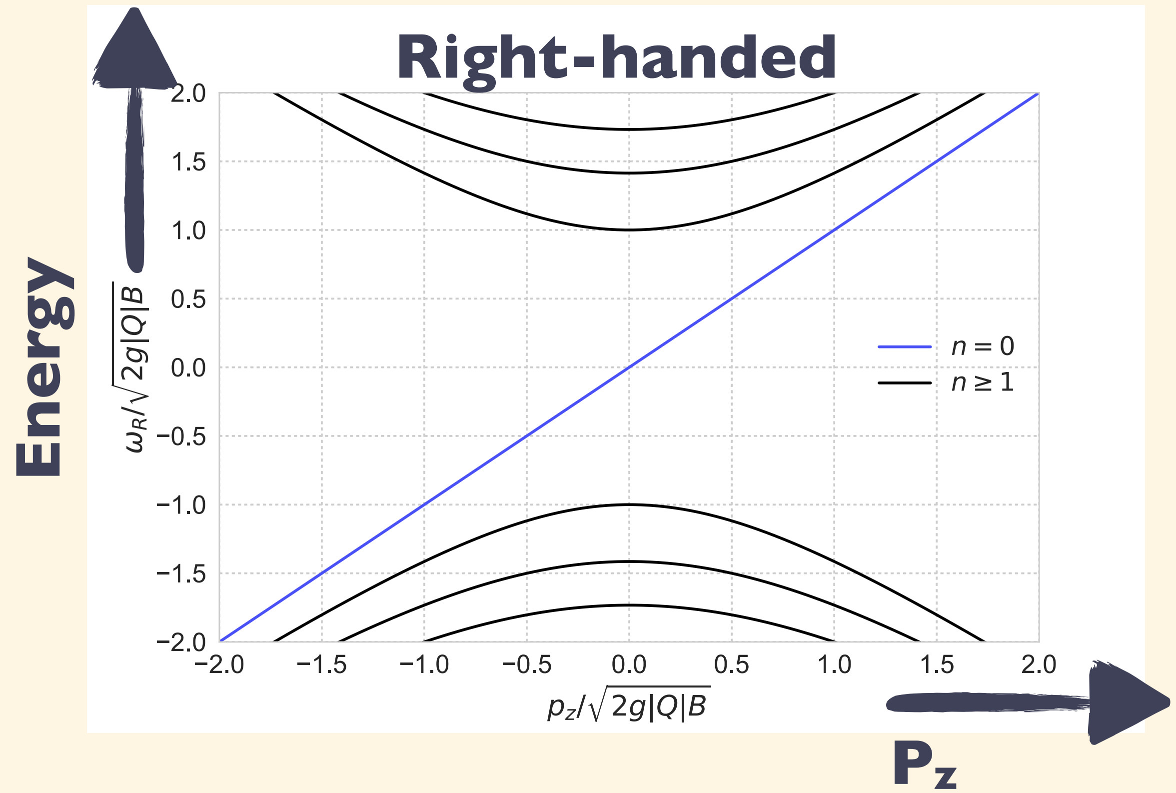
Production of

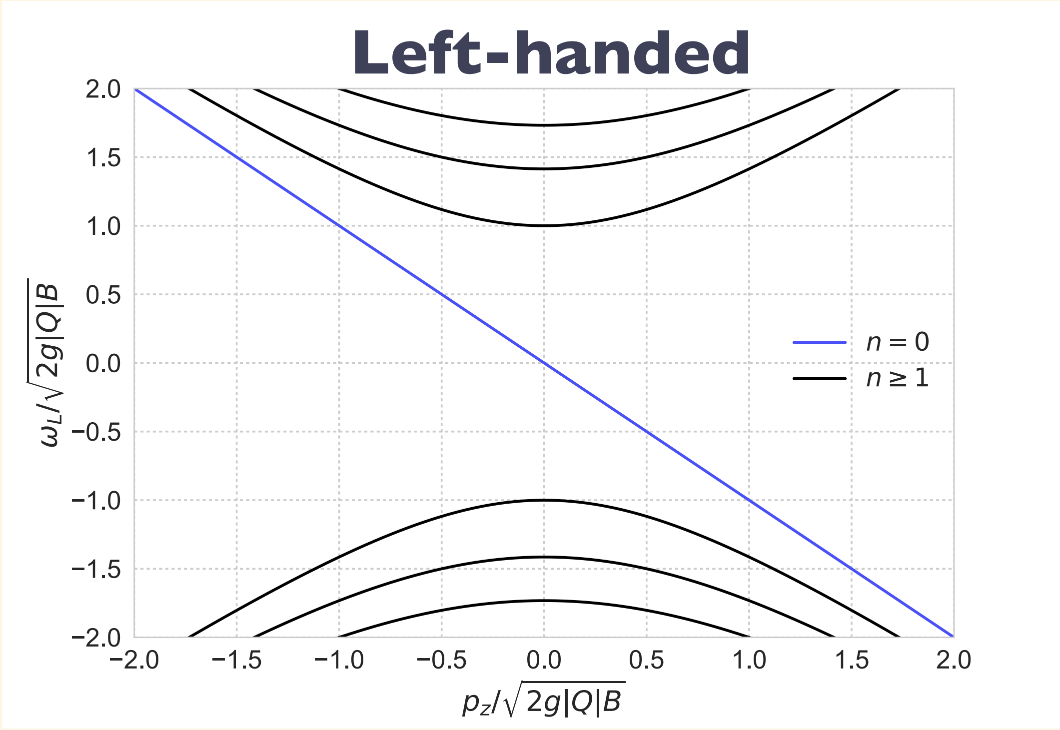
Helical gauge & **Chiral** fermion

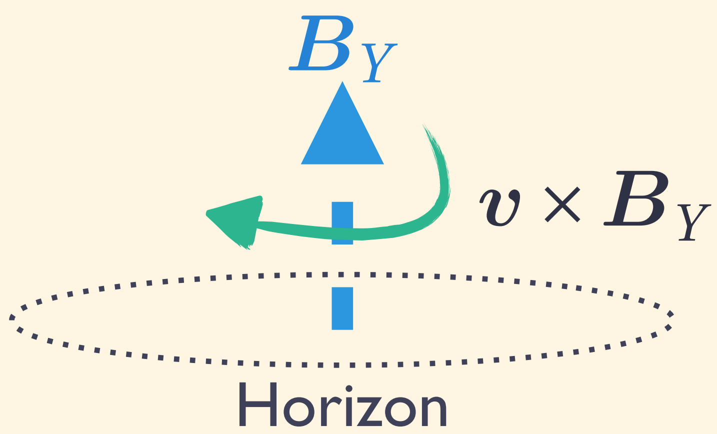
Fermion Production

Landau Levels

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





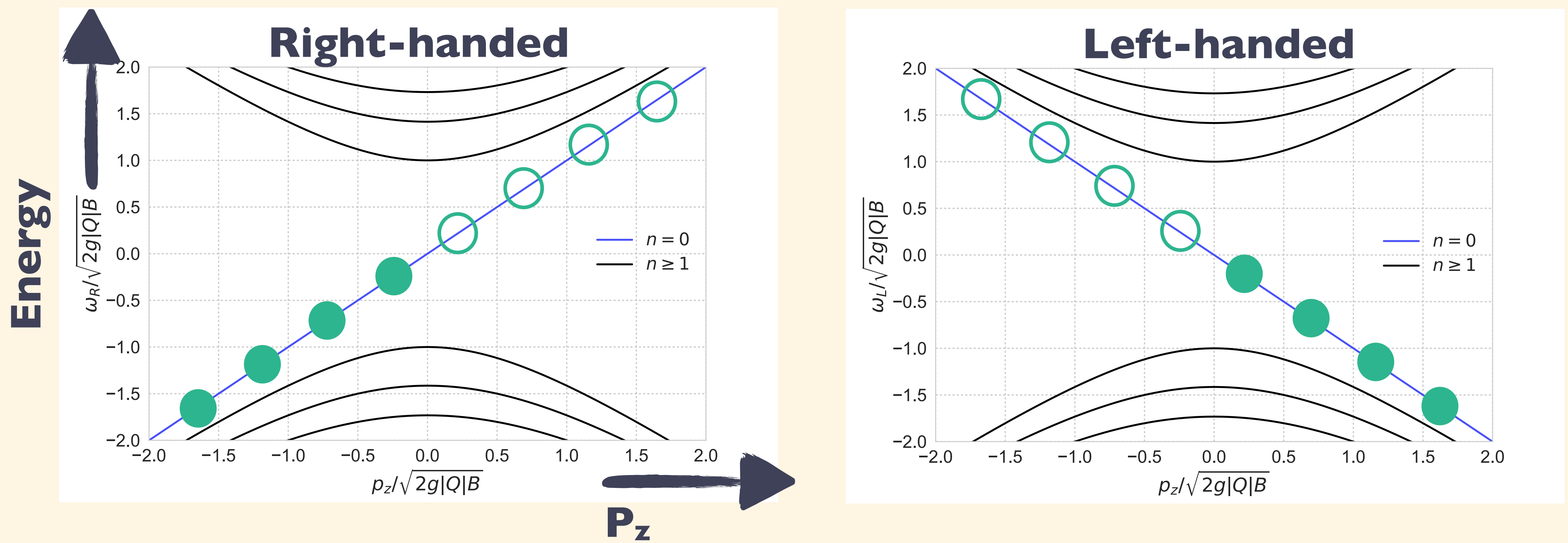


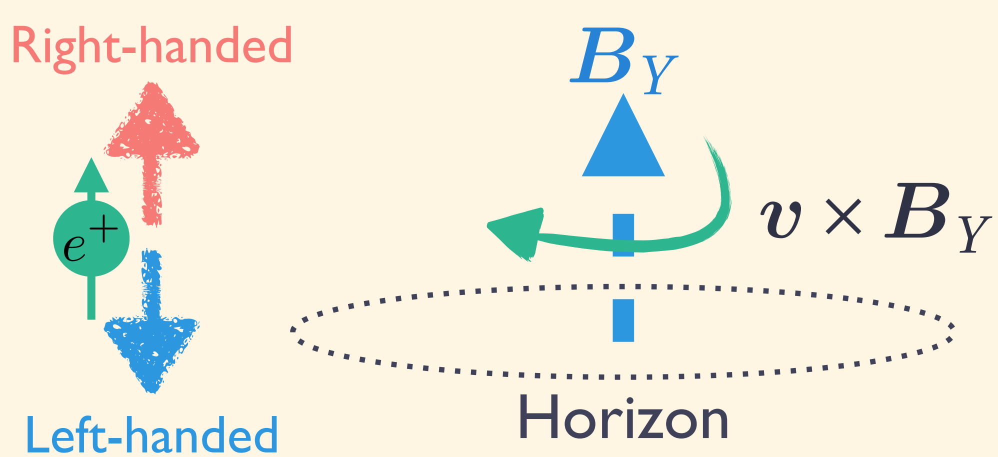
- **Landau level n** : transverse motion
- $\mathbf{P_z}$: parallel motion

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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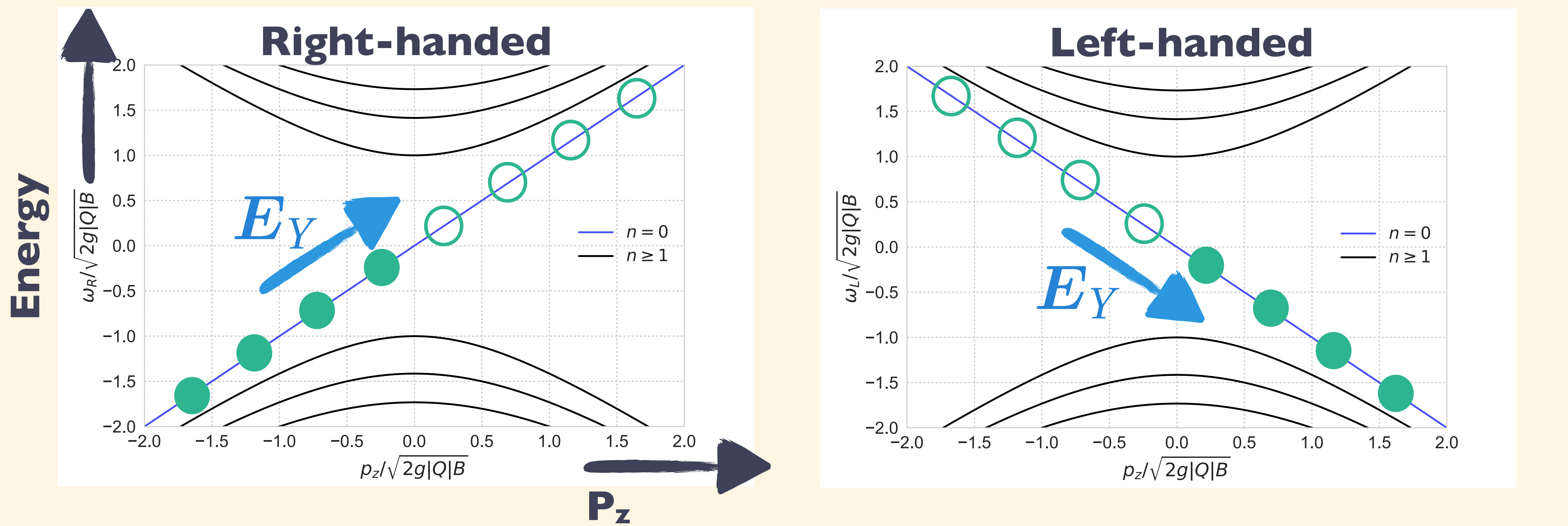

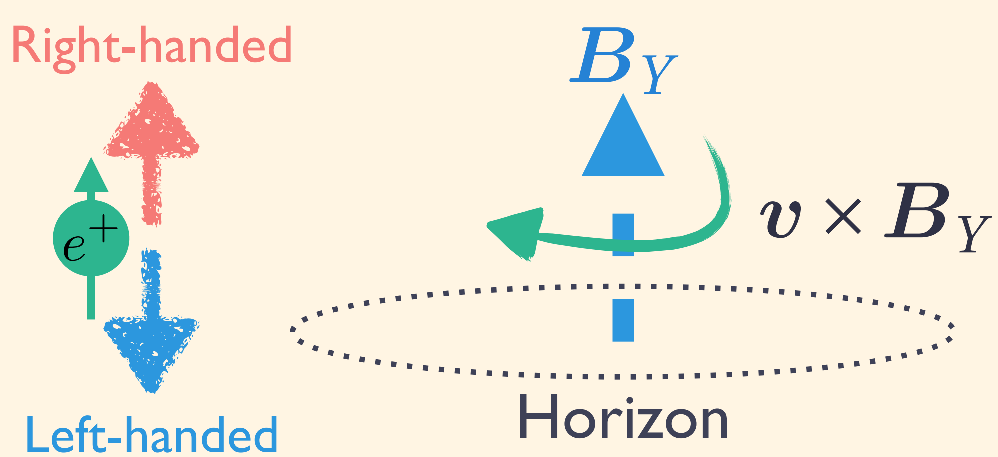

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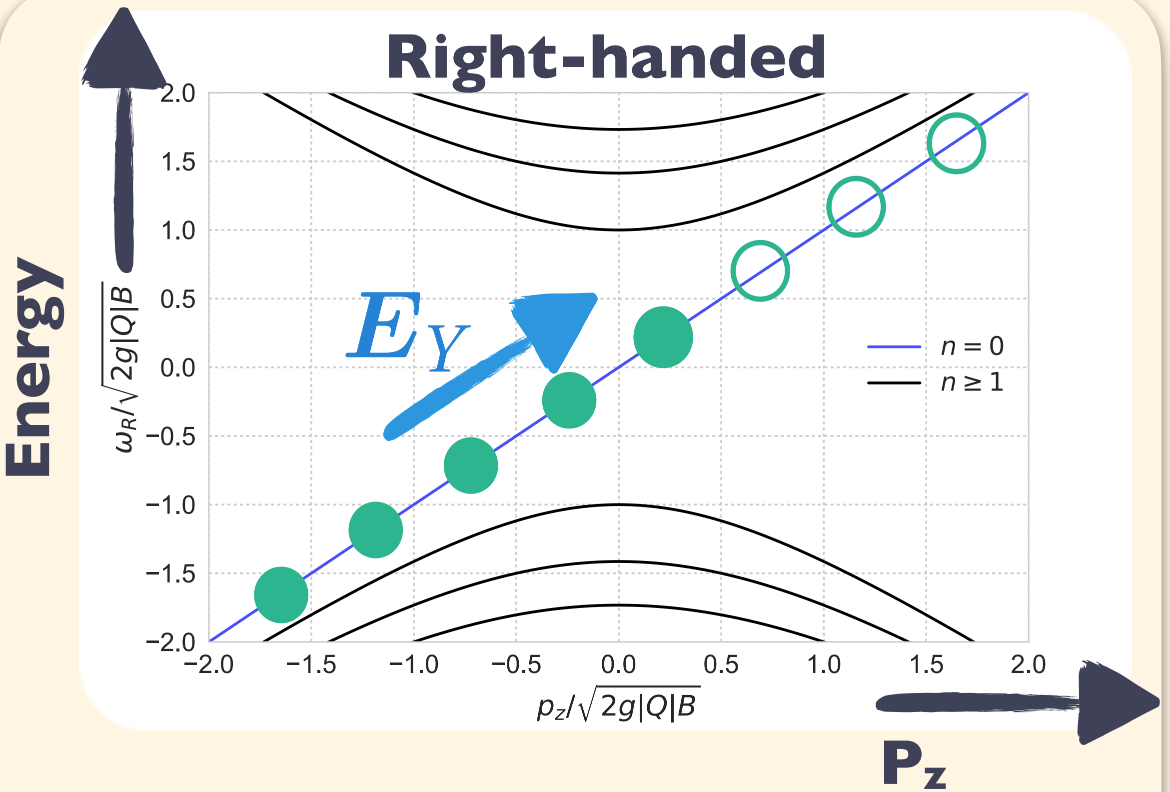
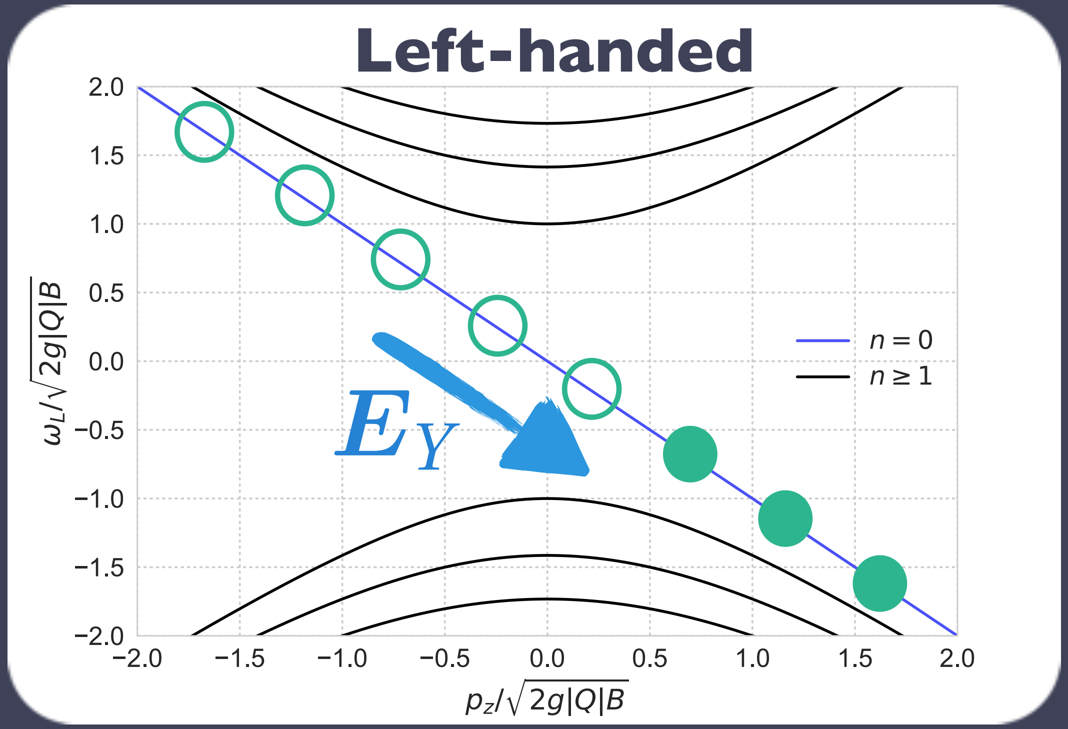


Particle production



Anti-particle production

➡ Reproduce chiral anomaly!

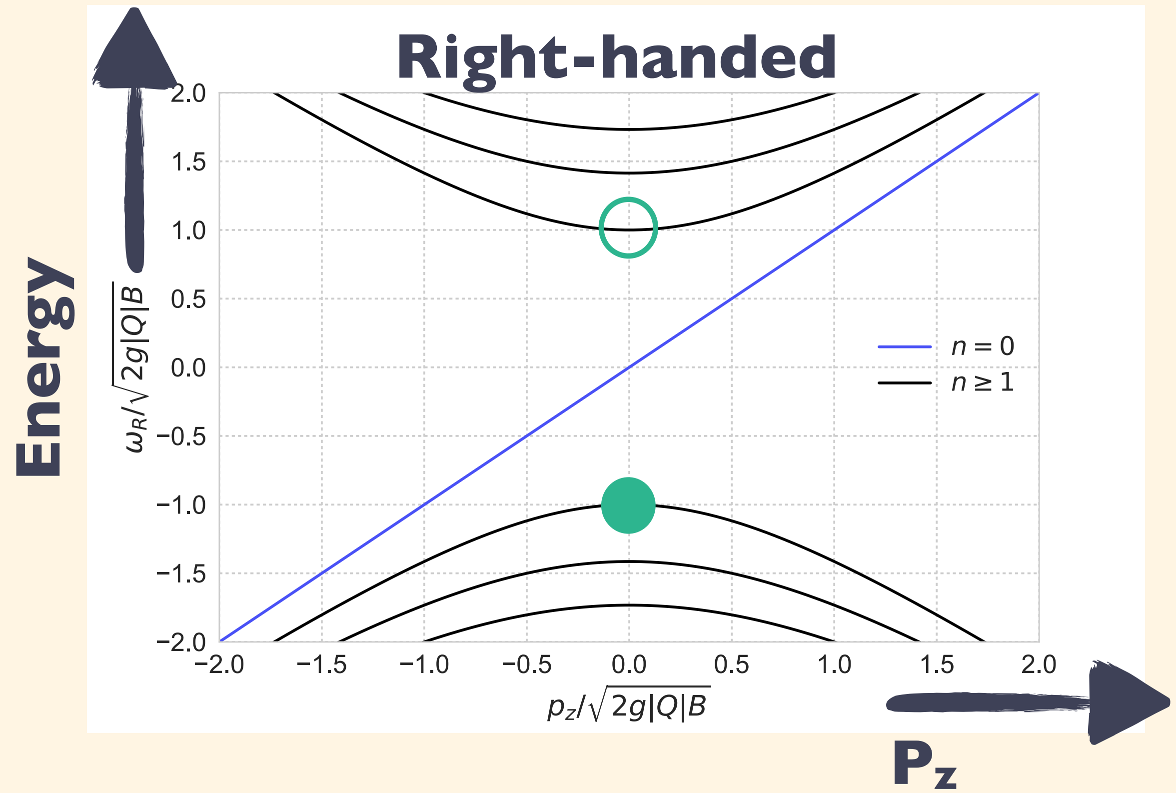
$$\dot{q}_{\mathrm{R/L}} = \dot{n}_{\mathrm{R/L}} - \dot{\bar{n}}_{\mathrm{R/L}} = \pm \frac{g_Y^2 Q_Y^2}{4\pi^2} E_Y B_Y = \mp \frac{g_Y^2 Q_Y^2}{16\pi^2} Y^{\mu\nu} \tilde{Y}_{\mu\nu}$$

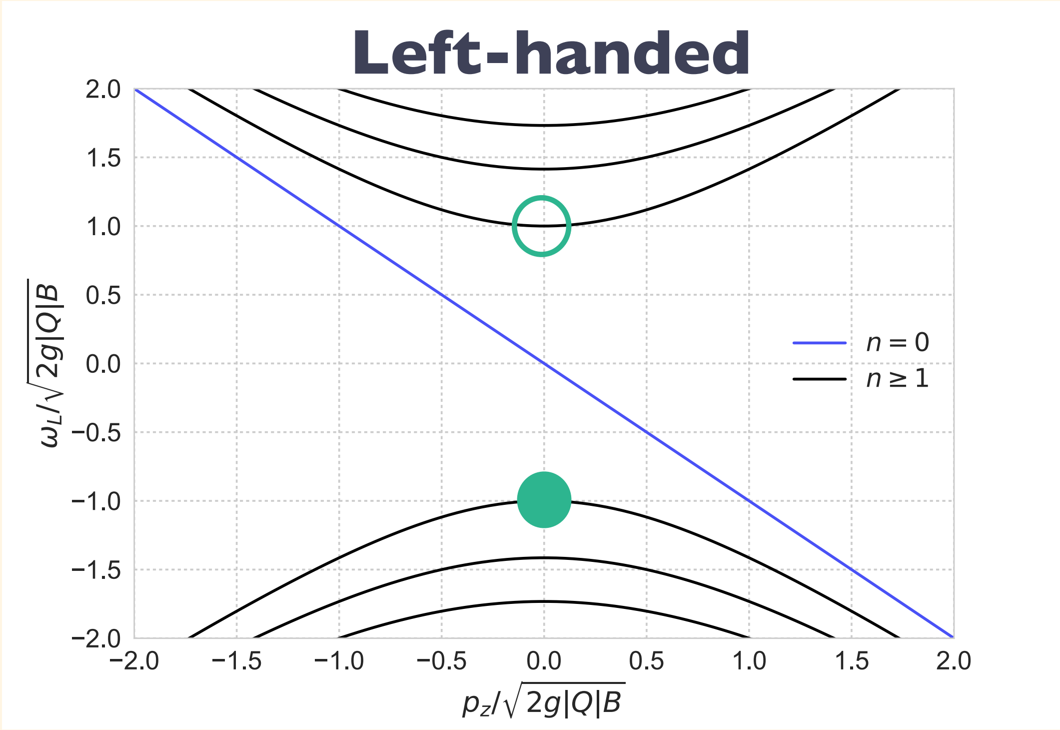
Fermion Production

Higher Landau Levels (n≧1) & Pair Production

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

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





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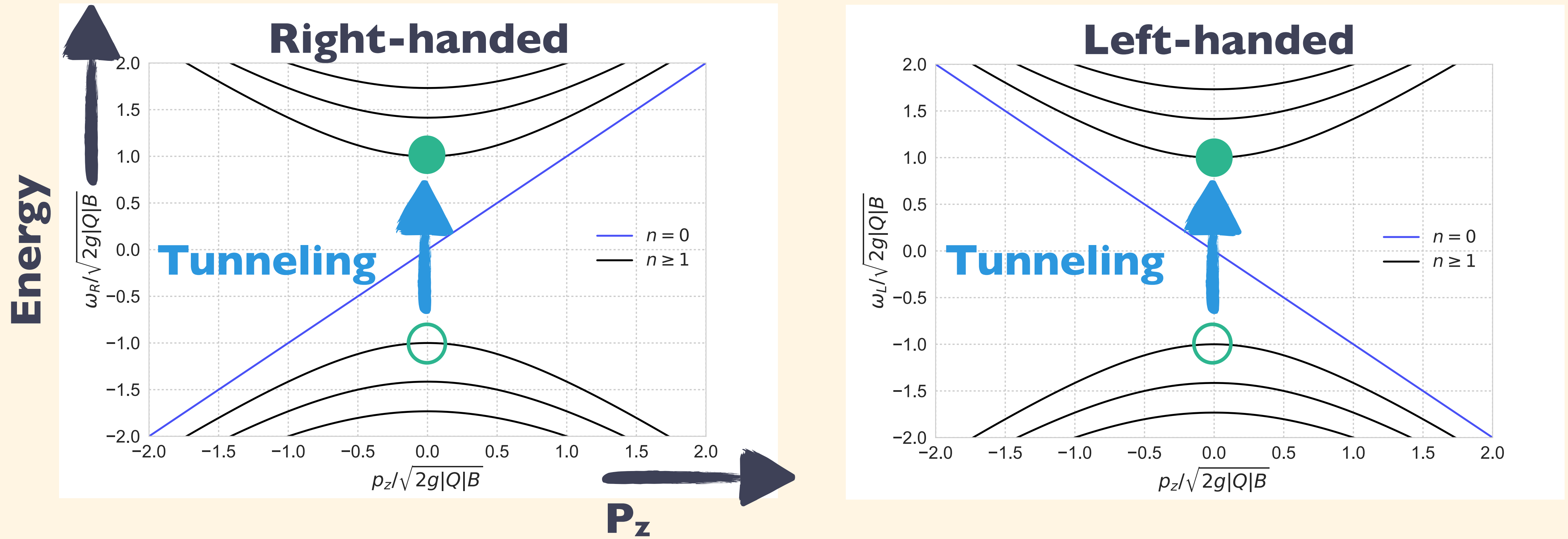

➡ Pair-production via Schwinger effect

$$\dot{n}^{(n)}_{\mathrm{R/L}} = \dot{\bar{n}}^{(n)}_{\mathrm{R/L}} = \frac{g_Y^2 Q_Y^2}{4\pi^2} E_Y B_Y e^{-\frac{2\pi n B_Y}{E_Y}}$$

- Never contribute to asymmetries!

Fermion Production

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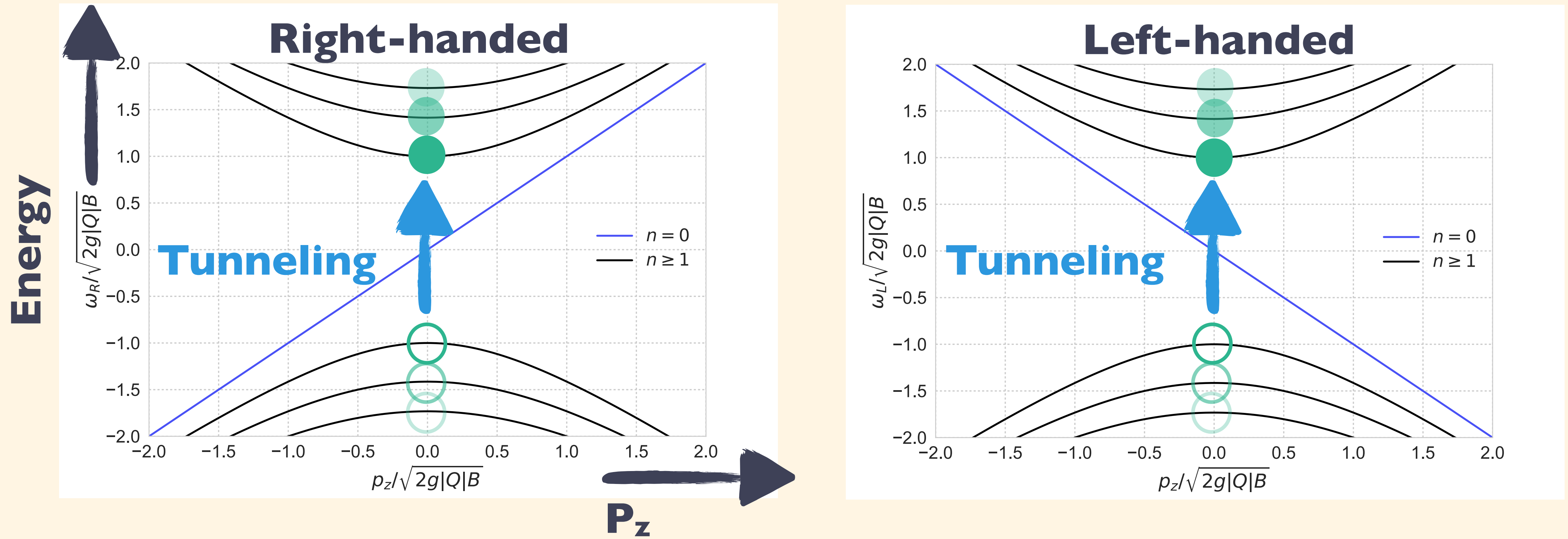

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See e.g., Cohen+ 0807.1117

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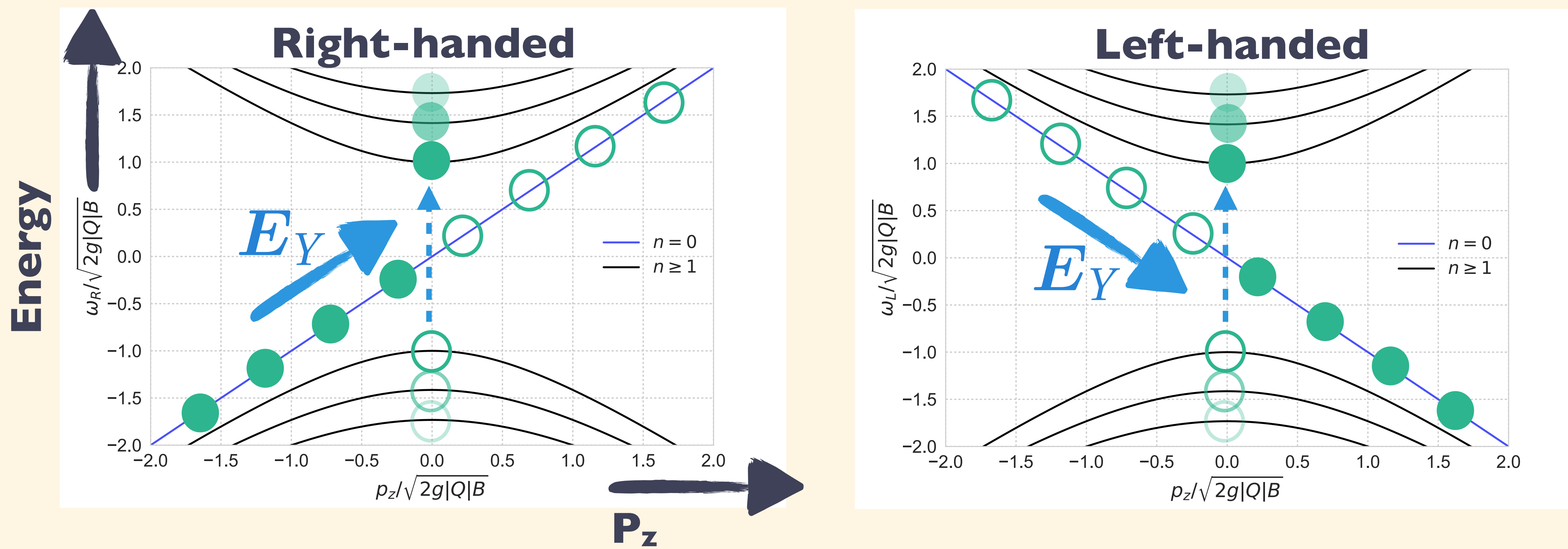
- Never contribute to asymmetries!

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

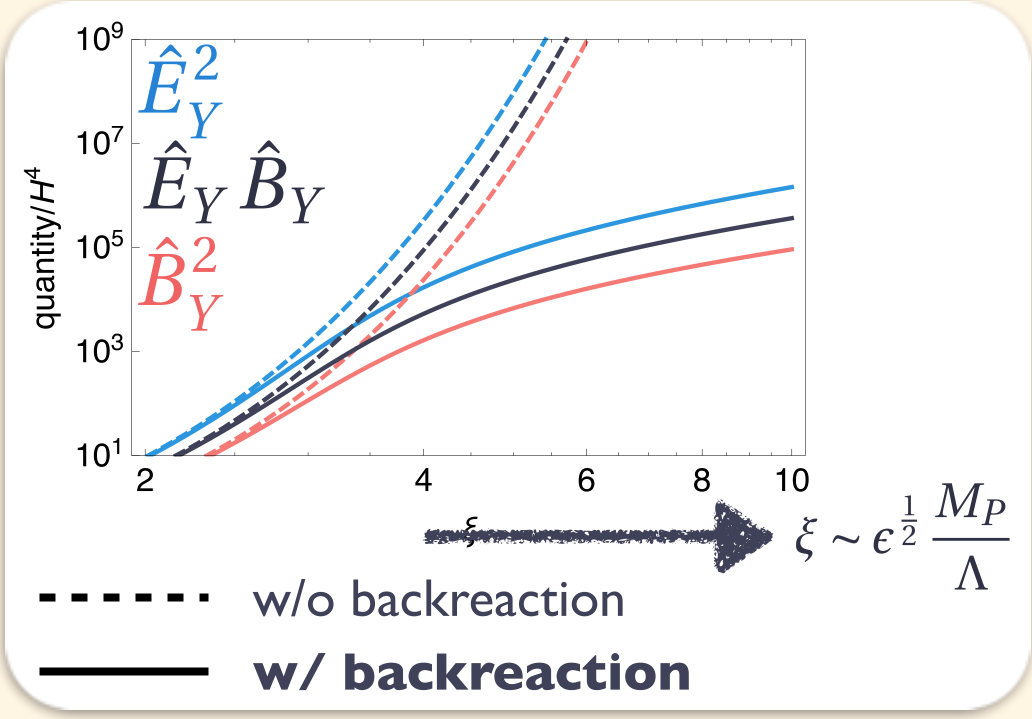
V.Domcke and **KM** 1806.08769

- **Backreaction** suppresses gauge field

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

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

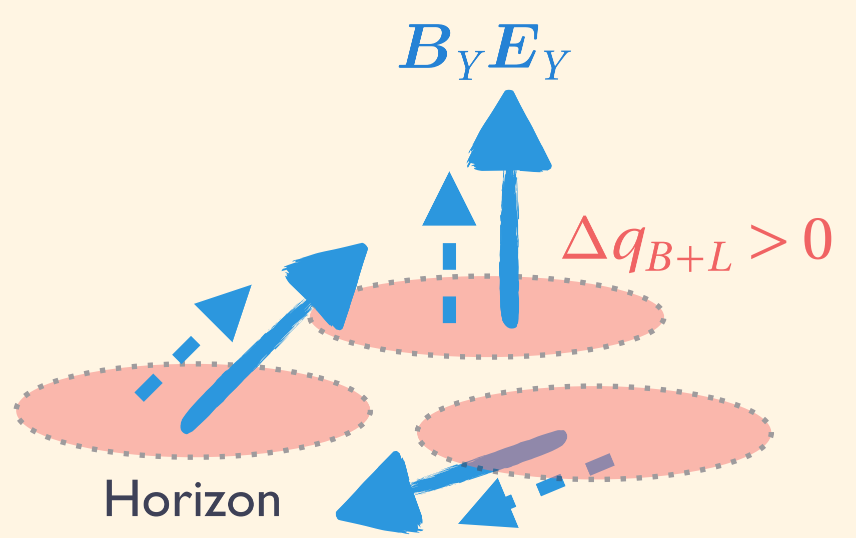
See e.g., Dunne 0406216, Warringa 1205.5679



- **Primordial B+L asymmetry**

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

$$\left.\frac{\Delta q_{B+L}}{s}\right|_{\rm rh} \sim 10^{-9} \left(\frac{H_{\rm rh}}{10^{12}\,\mathrm{GeV}} \right)^{\frac{3}{2}} \left(\frac{\langle \hat{\boldsymbol{E}}_Y \cdot \hat{\boldsymbol{B}}_Y \rangle_{\rm rh} / H_{\rm rh}^4}{10^4} \right)$$



3.

Survival of
Helical Gauge Field

Outline

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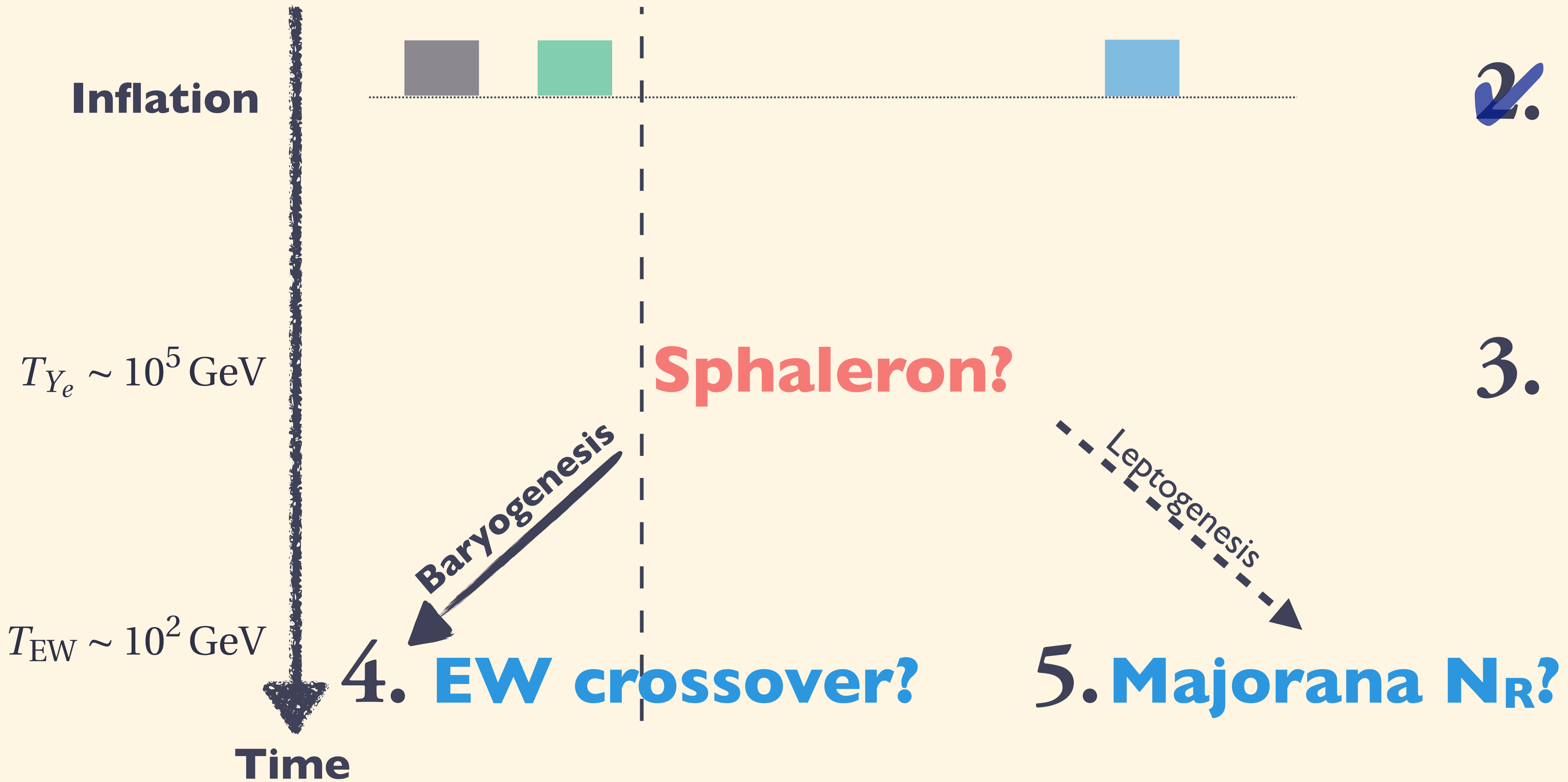

Survival of Helical Gauge Field

Avoid complete annihilation

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

- **Annihilation** v.s. **Sphaleron + Yukawa**

$\dot{\phi} h_Y$

$\dot{\phi} = 0$

Pair creation

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

q_e

Electron
Yukawa

q_{L_e}

Sphaleron
washout

Pair annihilation
via chiral plasma instability

- Chiral plasma instability occurs @

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

Joyce, Shaposhnikov 9703005, Akamatsu, Yamamoto 1302.2125,…

- Electron Yukawa is equilibrated @

$$T_{y_e} \sim 10^5 \text{ GeV}$$

Campbell, Davidson, Ellis, Olive 9302221

➡ Helical gauge field survives if $\left(\frac{H_{\rm rh}}{10^{14}\text{GeV}} \right)^3 \left(\frac{\langle \hat{E}_Y \cdot \hat{B}_Y \rangle_{\rm rh} / H_{\rm rh}^4}{10^5} \right)^2 < 1\,.$

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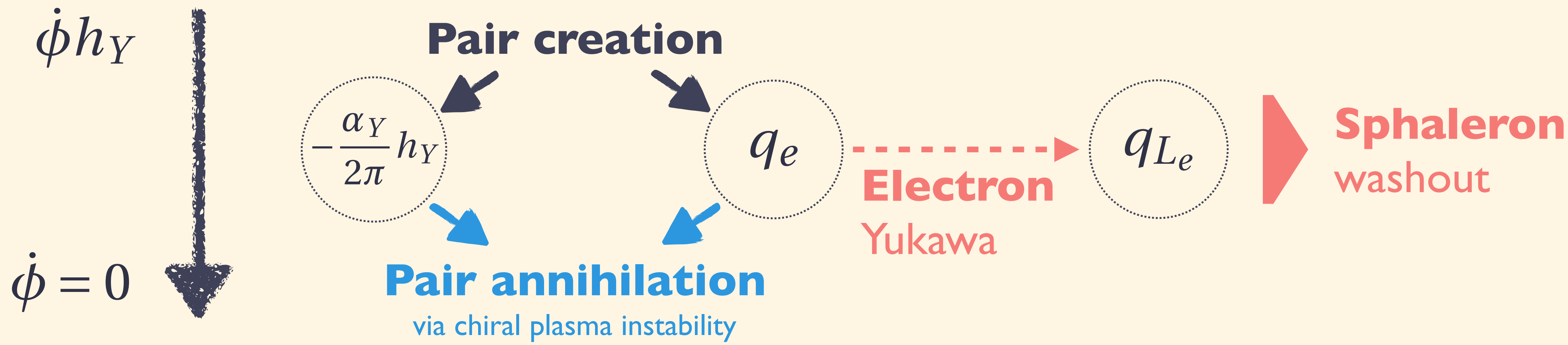

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- Electron Yukawa is equilibrated @

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Avoid Magnetic Diffusion

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

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

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

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

Avoid Magnetic Diffusion

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

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

Chiral Plasma Instability

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

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

Magnetic Diffusion $T_{\rm diff} \sim \frac{\alpha_Y \ln \alpha_Y^{-1}}{5} H_{\rm rh}$ $<$ **Inverse** cascade $T_{\rm ic} \sim v_{\rm rh} T_{\rm rh}$

- Drive h_Y to be zero.

- Approximate conservation of h_Y.

See e.g., Durrer and Neronov 1303.7121, Brandenburg+ 1212.0596

➡ Helical gauge field survives if $T_{\rm ic} > T_{\rm diff} \leftrightarrow R_m \equiv \sigma_Y L_{\rm rh} v_{\rm rh} > 1$

$$1 < R_m \lesssim 6 \times \left(\frac{\alpha_Y}{0.01}\right)^{-1}\left(\frac{H_{\rm rh}}{10^{12}\,{\rm GeV}}\right)^{1/2}\left(\frac{\langle \hat{B}_Y^2\rangle_{\rm rh}/H_{\rm rh}^4}{10^5}\right)^{1/2}$$

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

Chiral Plasma Instability

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

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

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See e.g., Durrer and Neronov 1303.7121, Brandenburg+ 1212.0596

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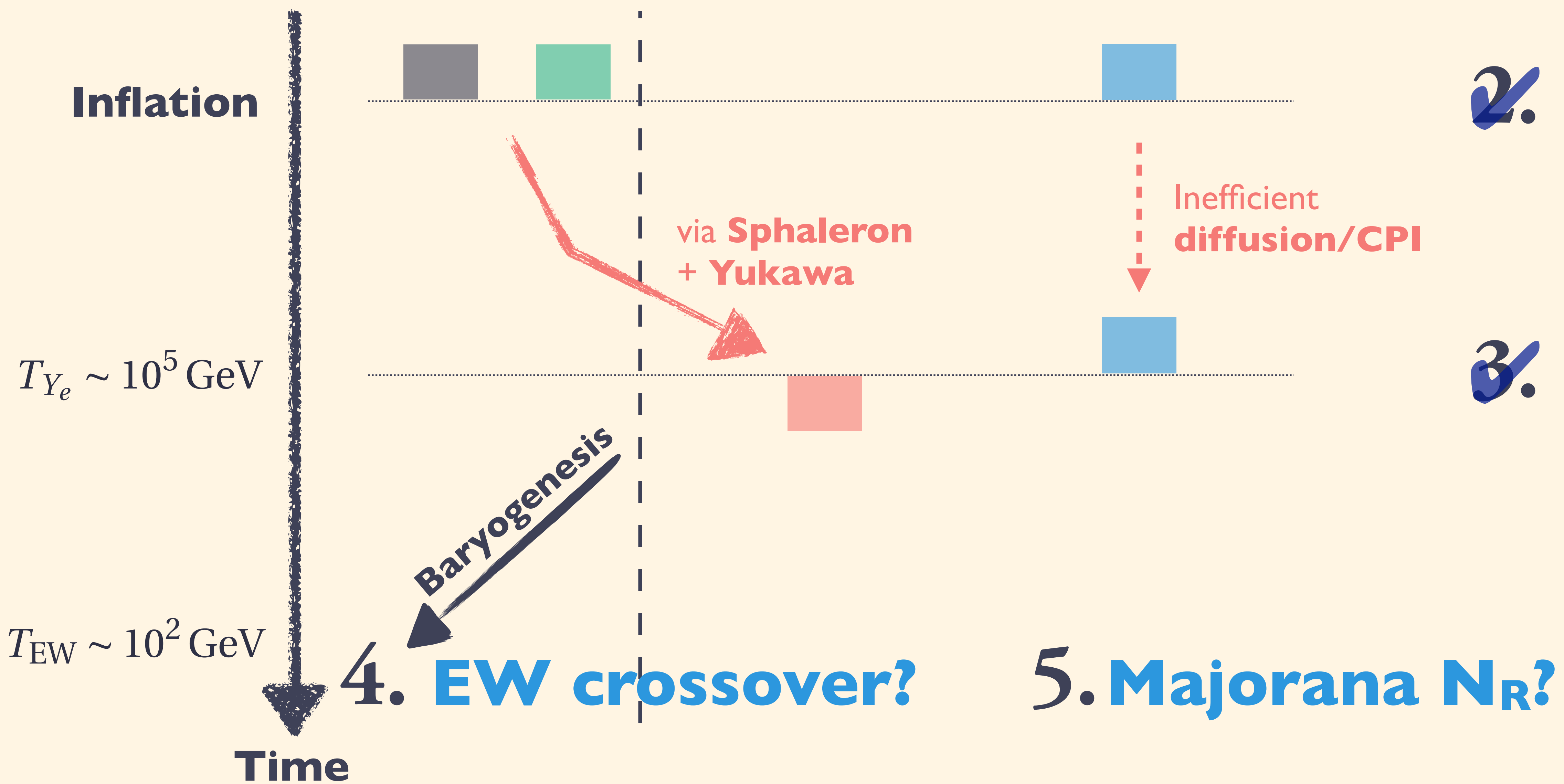
$$1 < R_m \lesssim 6 \times \left(\frac{\alpha_Y}{0.01} \right)^{-1} \left(\frac{H_{\rm rh}}{10^{12}\,{\rm GeV}} \right)^{1/2} \left(\frac{\langle \hat{B}_Y^2 \rangle_{\rm rh} / H_{\rm rh}^4}{10^5} \right)^{1/2}$$

Outline

Baryo/Leptogenesis from B+L asymmetry?

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



4.

Regeneration of Baryon Asymmetry

Regeneration of Baryon Asym.

Baryogenesis from Decaying Helicity

Fujita, Kamada 1602.02109
Kamada, Long 1610.03074

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

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

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

Regeneration of Baryon Asym.

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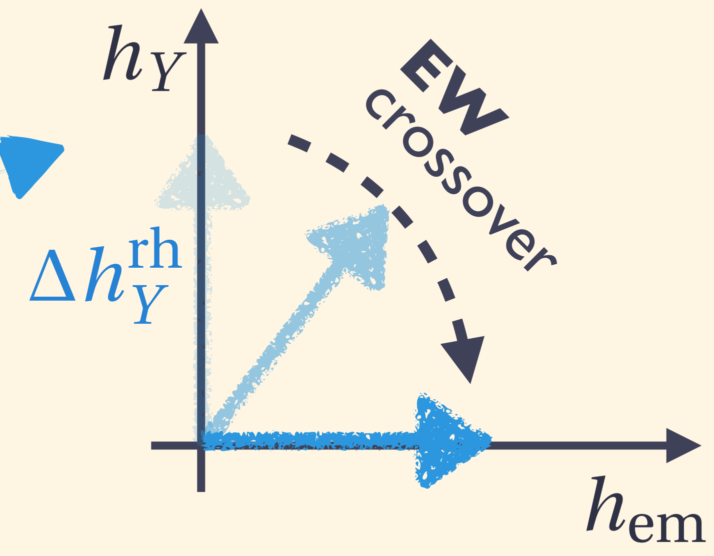

  - EW sphaleron washout v.s. Decaying helicity

$$\eta_B = \frac{q_B}{s} \simeq \epsilon \times \left.\frac{3\alpha_Y}{4\pi}\frac{\Delta h_Y}{s}\right|_{\mathrm{rh}} \qquad \Delta h_Y^{\mathrm{rh}} = -\frac{2}{3H_{\mathrm{rh}}}\left\langle \hat{E}_Y\cdot\hat{B}_Y\right\rangle_{\mathrm{rh}}$$

Sphaleron washout factor

✓ Huge uncertainty…

$$\epsilon \equiv \left[\frac{34}{111}\left(1+\frac{\alpha_2}{\alpha_Y}\right)\frac{H}{\Gamma_{W,\mathrm{sph}}} f(\theta,T)\right]_{T_{\mathrm{EW}}} \qquad \text{w/} \quad f(\theta,T) = -T\frac{\mathrm{d}\theta}{\mathrm{d}T}\sin(2\theta)$$

Regeneration of Baryon Asym.

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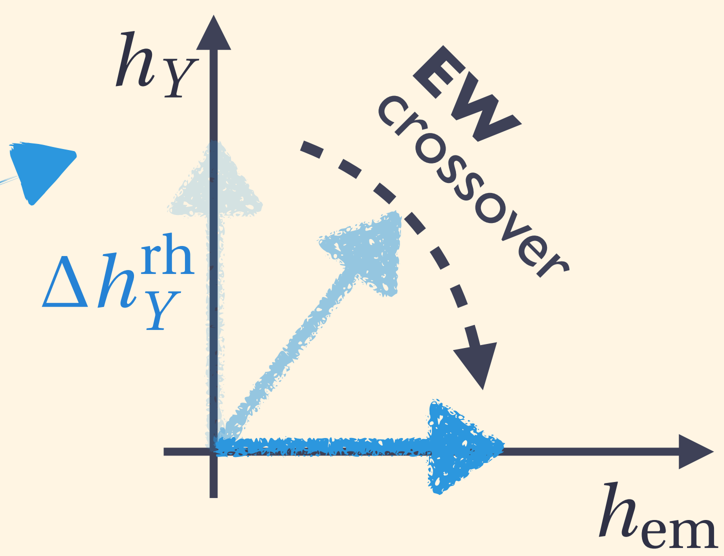

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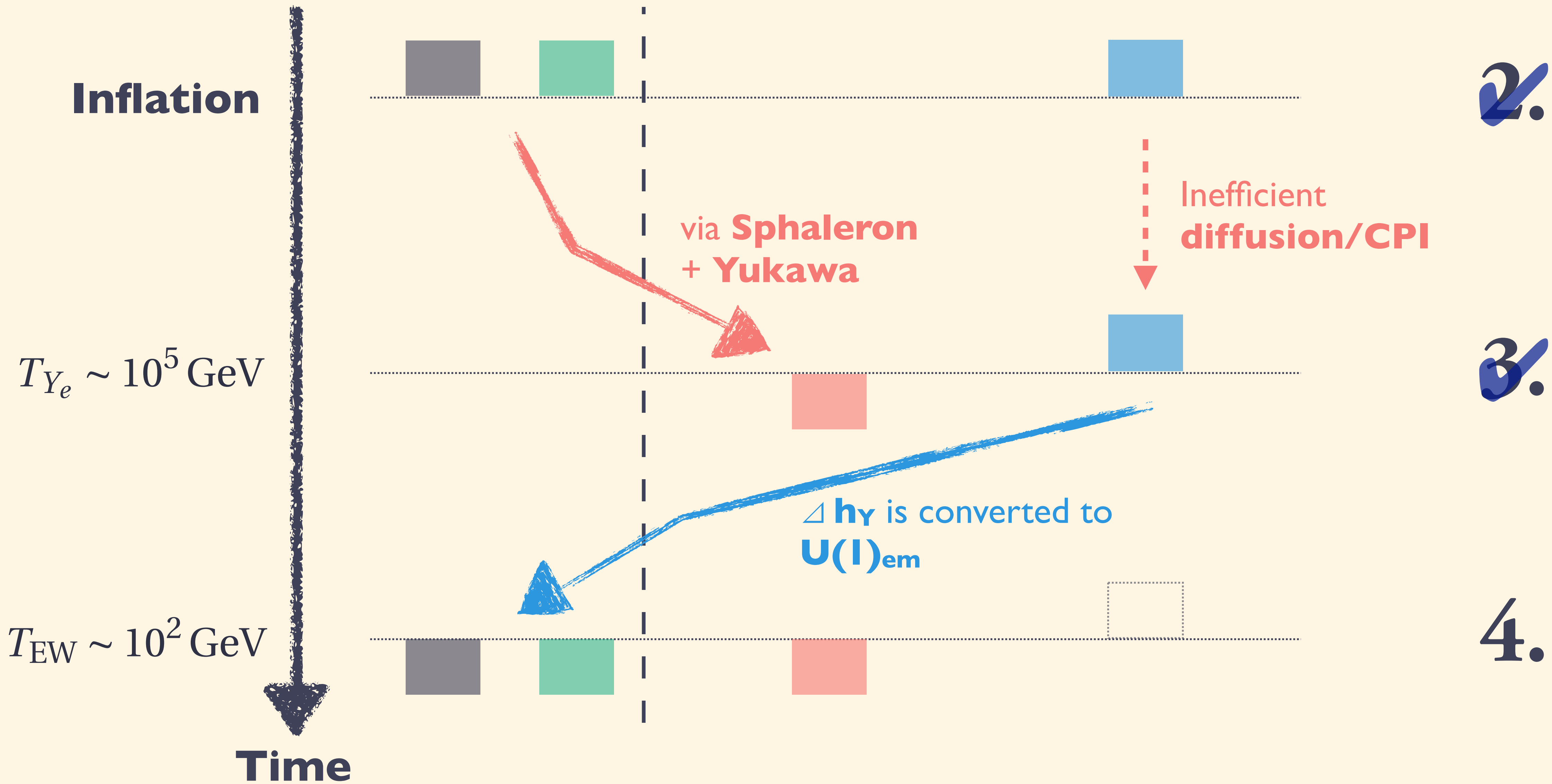

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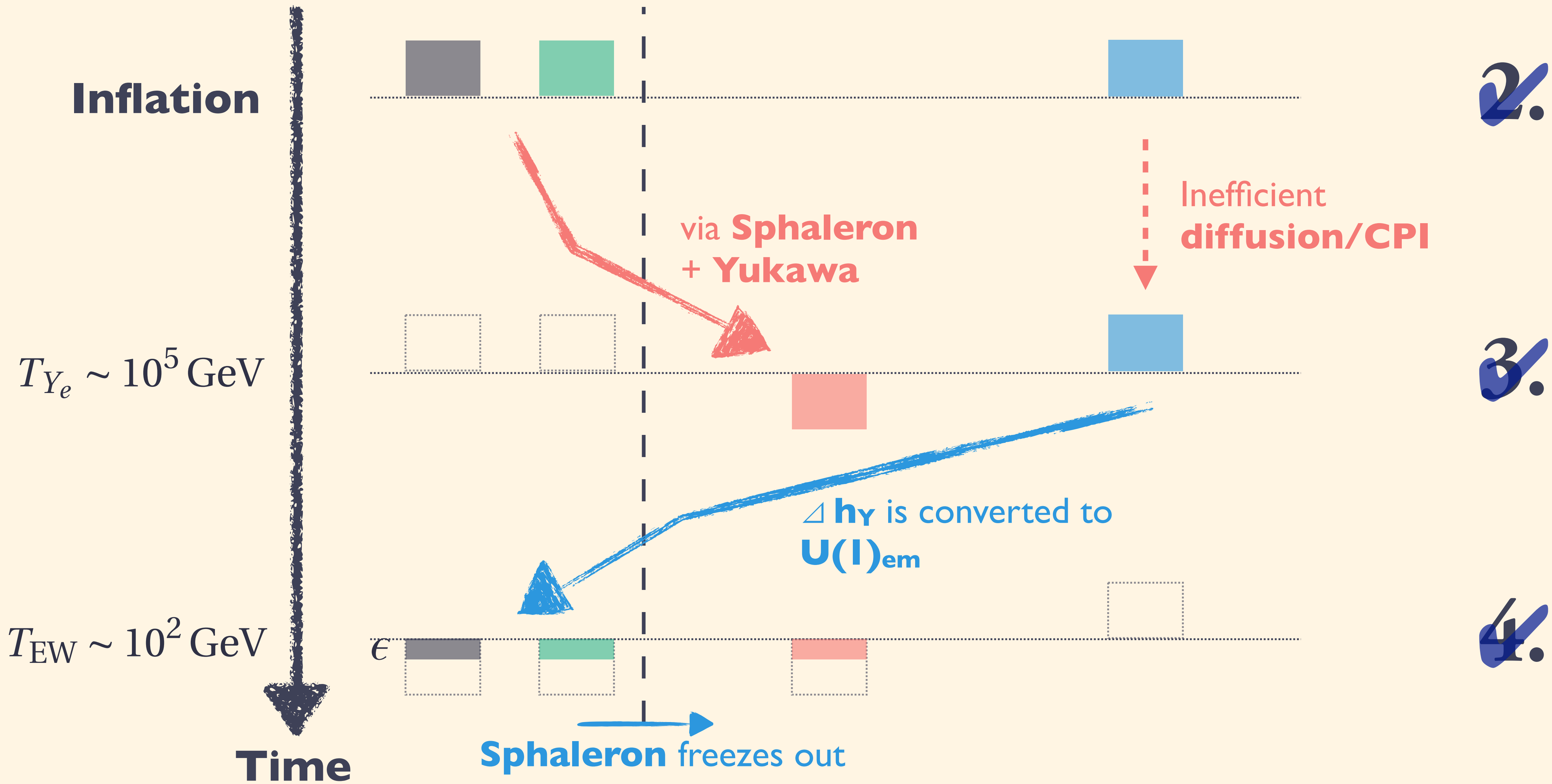
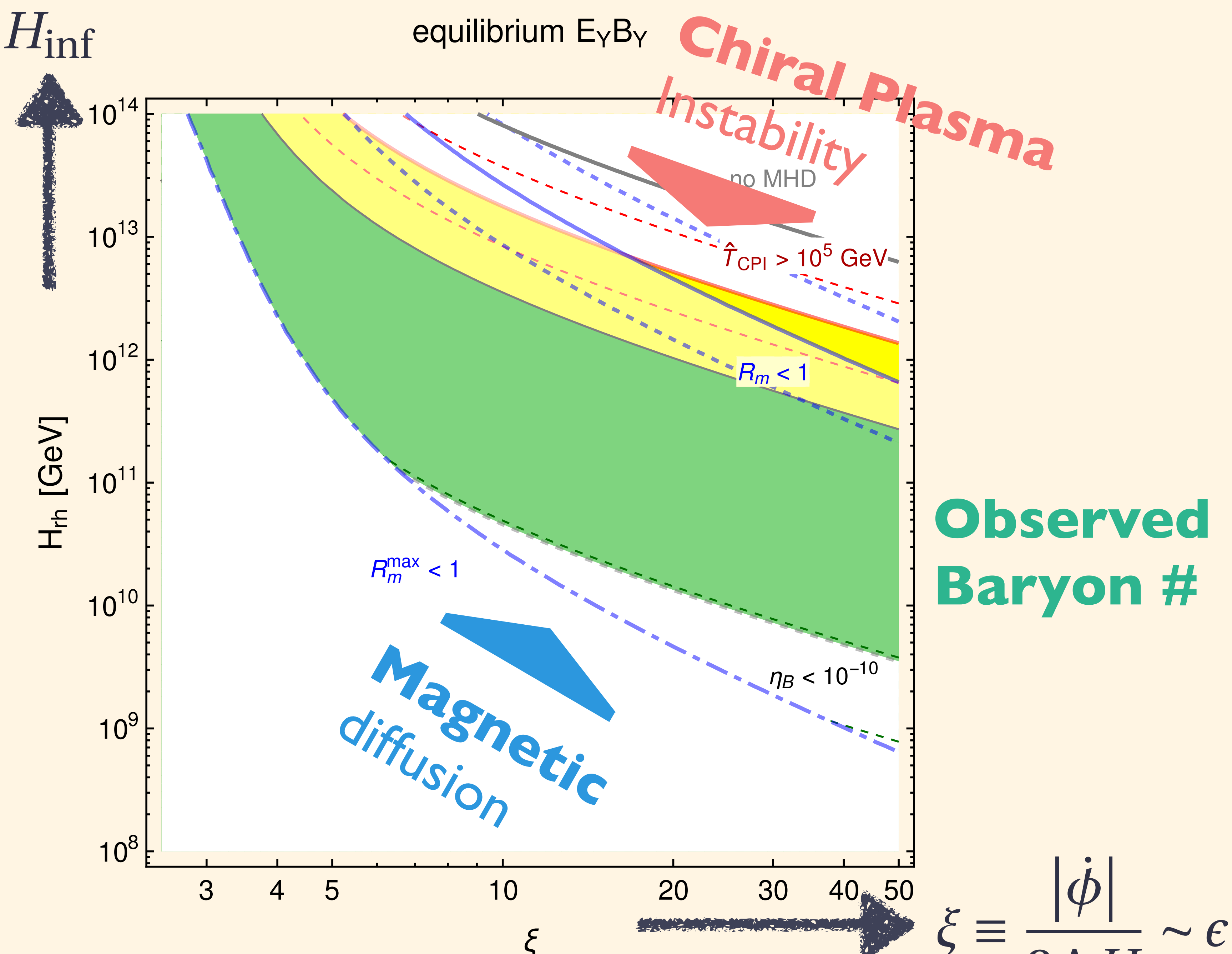


Viable parameters for Baryogenesis



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

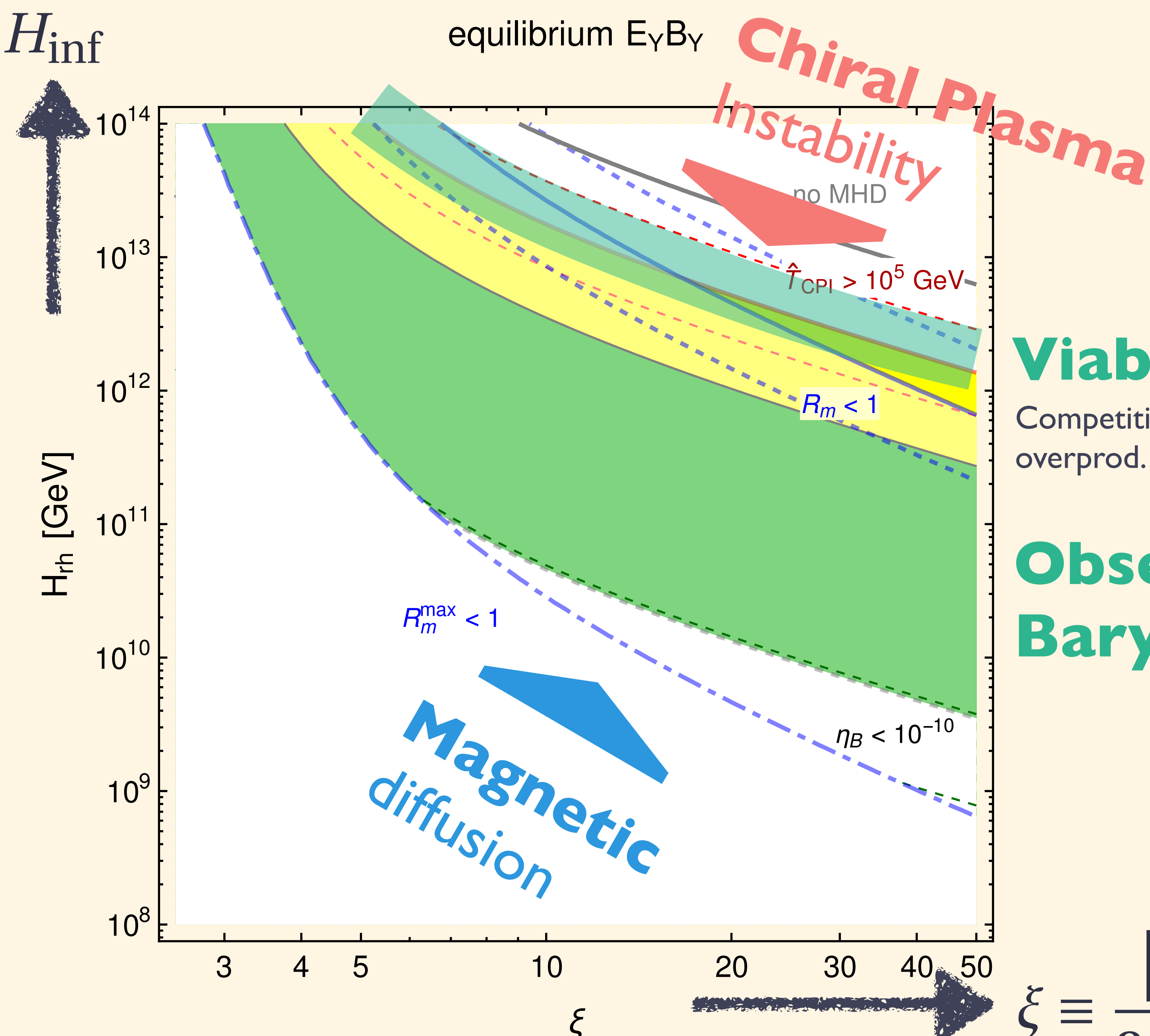
- Successful baryogenesis **only with SM + inflaton**
- ChMHD puts **lower**/**upper** bounds.
- **Mild dependence** on the Chern-Simons coupling

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

See also earlier attempts in K.Schmitz+1707.07943

Baryogenesis from axion inflation

Viable parameters for Baryogenesis



Viable?

Competition btw overprod. and CPI.

Observed Baryon #

- 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

See also earlier attempts in K.Schmitz+1707.07943

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

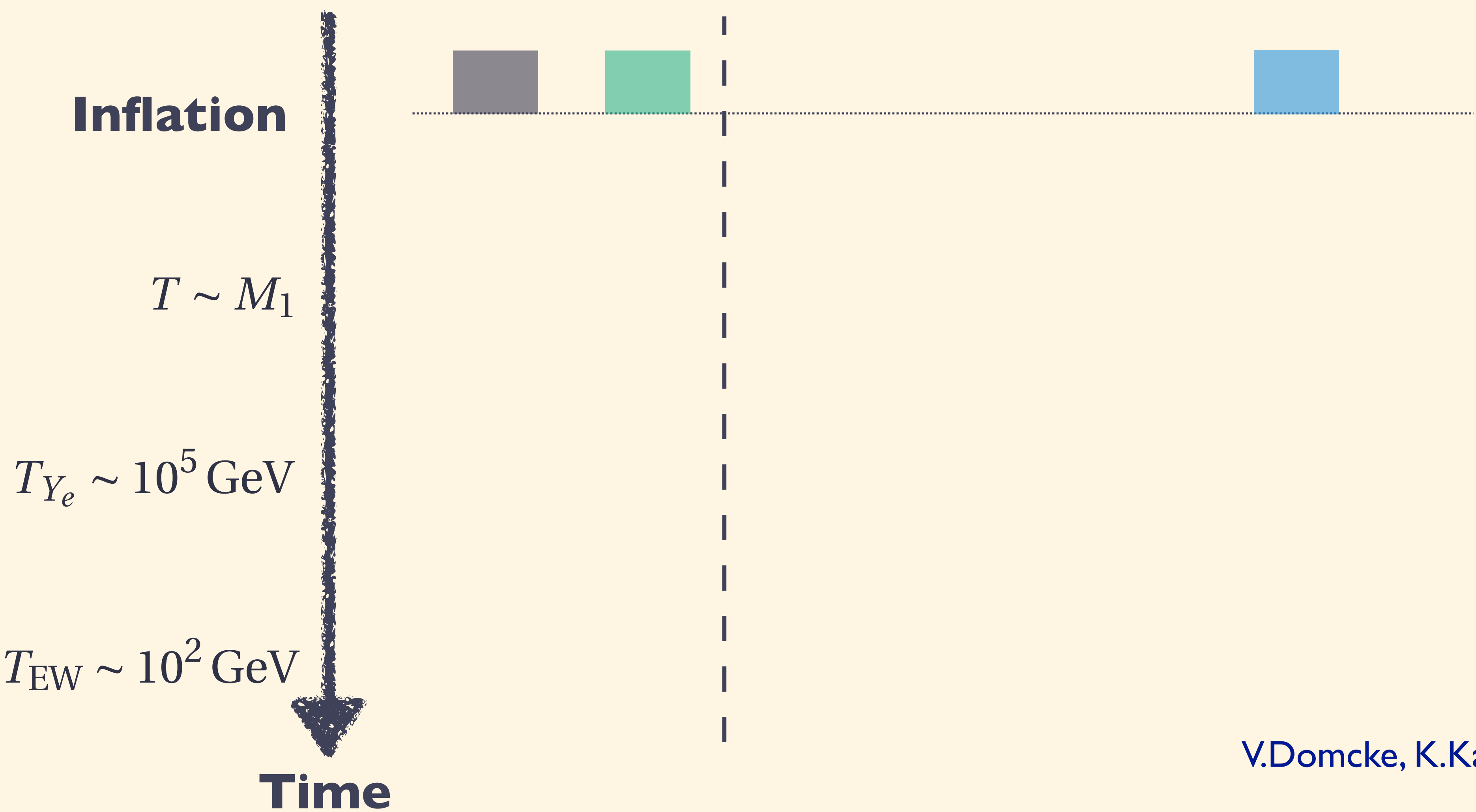
5.

Leptogenesis from axion inflation

Leptogenesis

Axion Inflation + Majorana RHν

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



V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
2011.09347, 21xx.xxxxx

Leptogenesis

Axion Inflation + Majorana RHν

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

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L-violation

Inflation

$T \sim M_1$

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

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

Time

V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
2011.09347, 21xx.xxxxx

Leptogenesis

Axion Inflation + Majorana RHν

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

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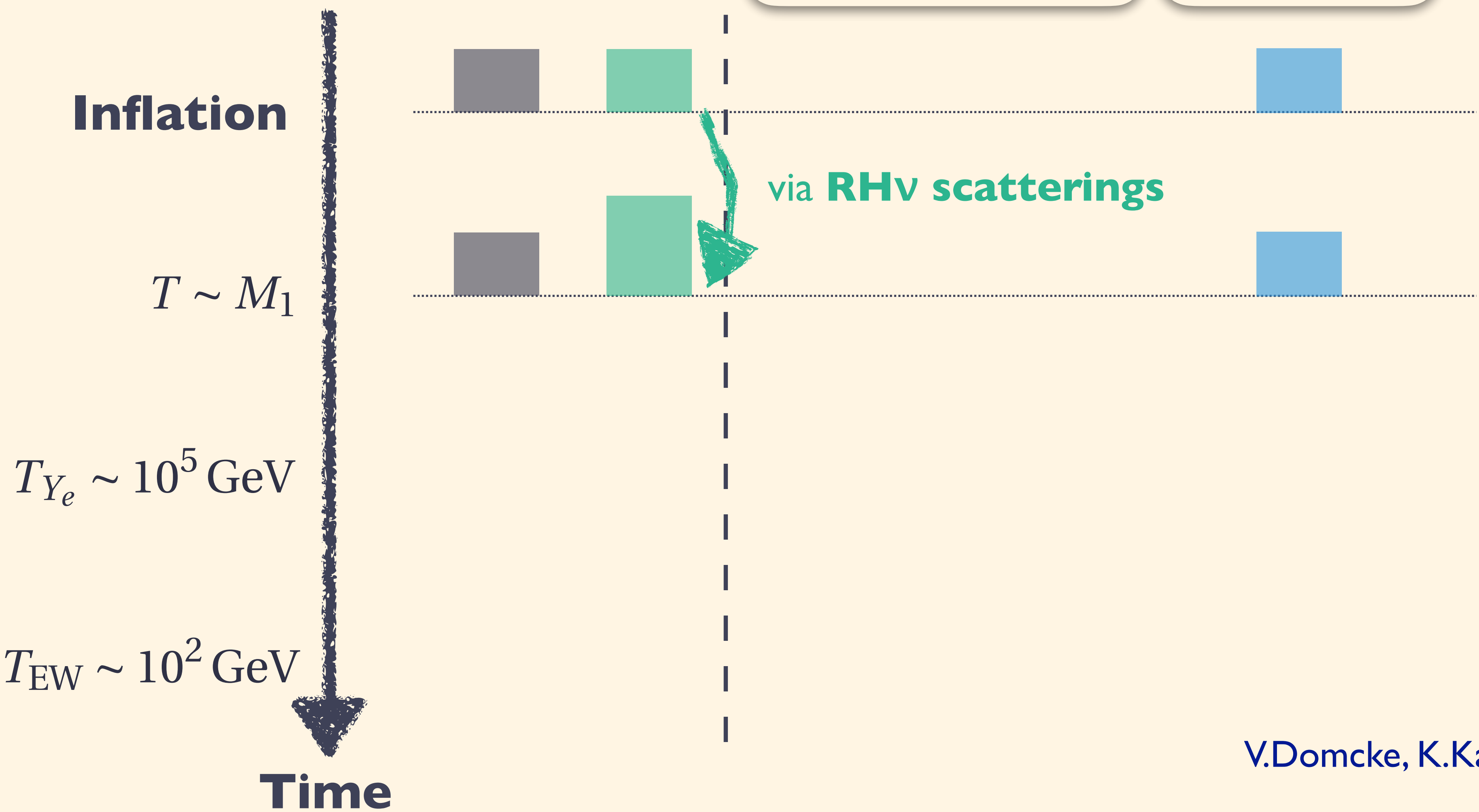

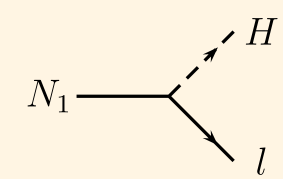

- **Works even if**
  - **No** CP violation in ν-Yukawa
  - **Strong** washout

V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
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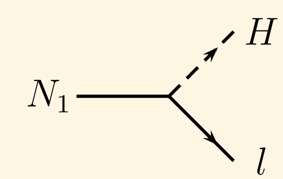

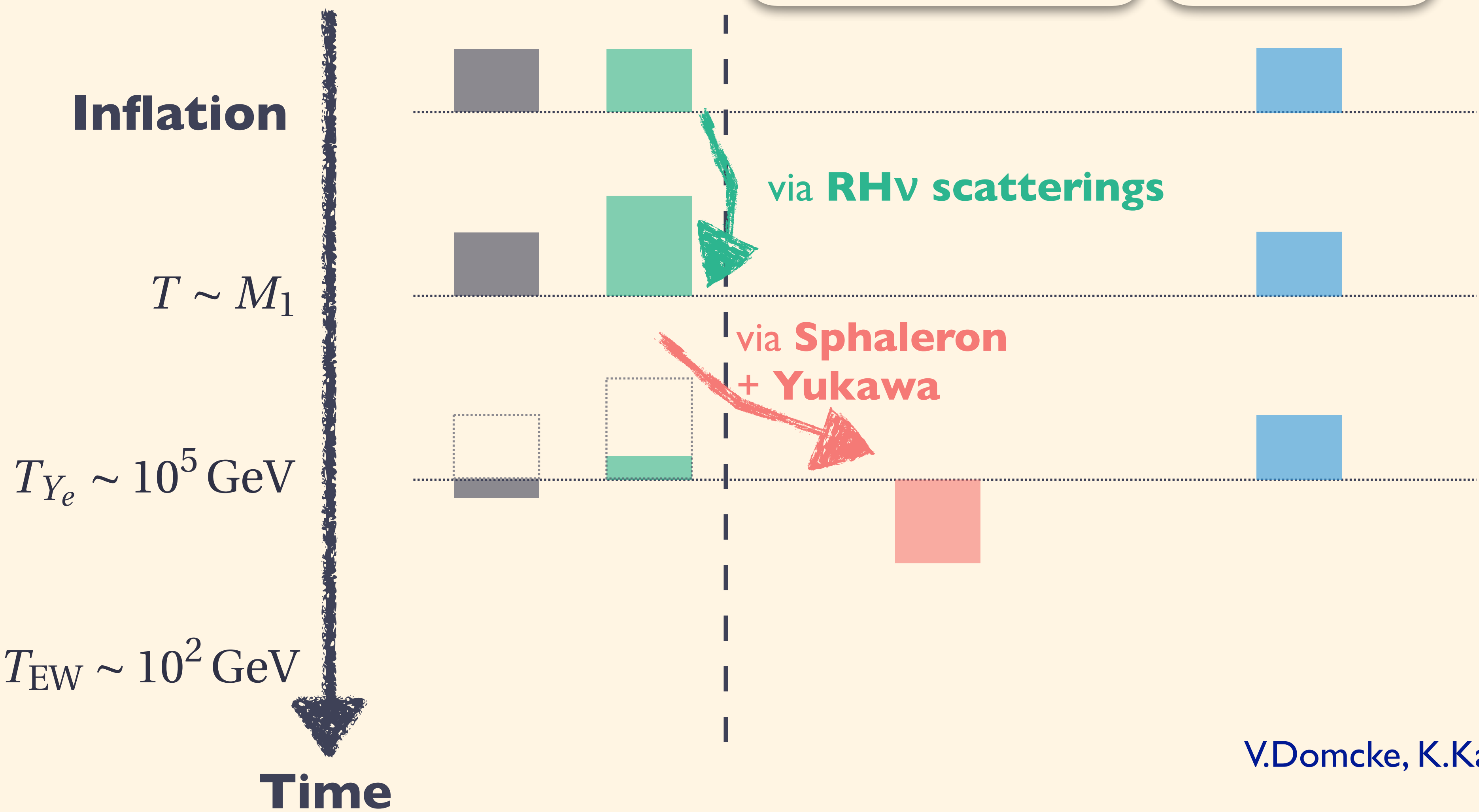

- Works even if

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V.Domcke, K.Kamada, **KM**, K.Schmitz, M.Yamada
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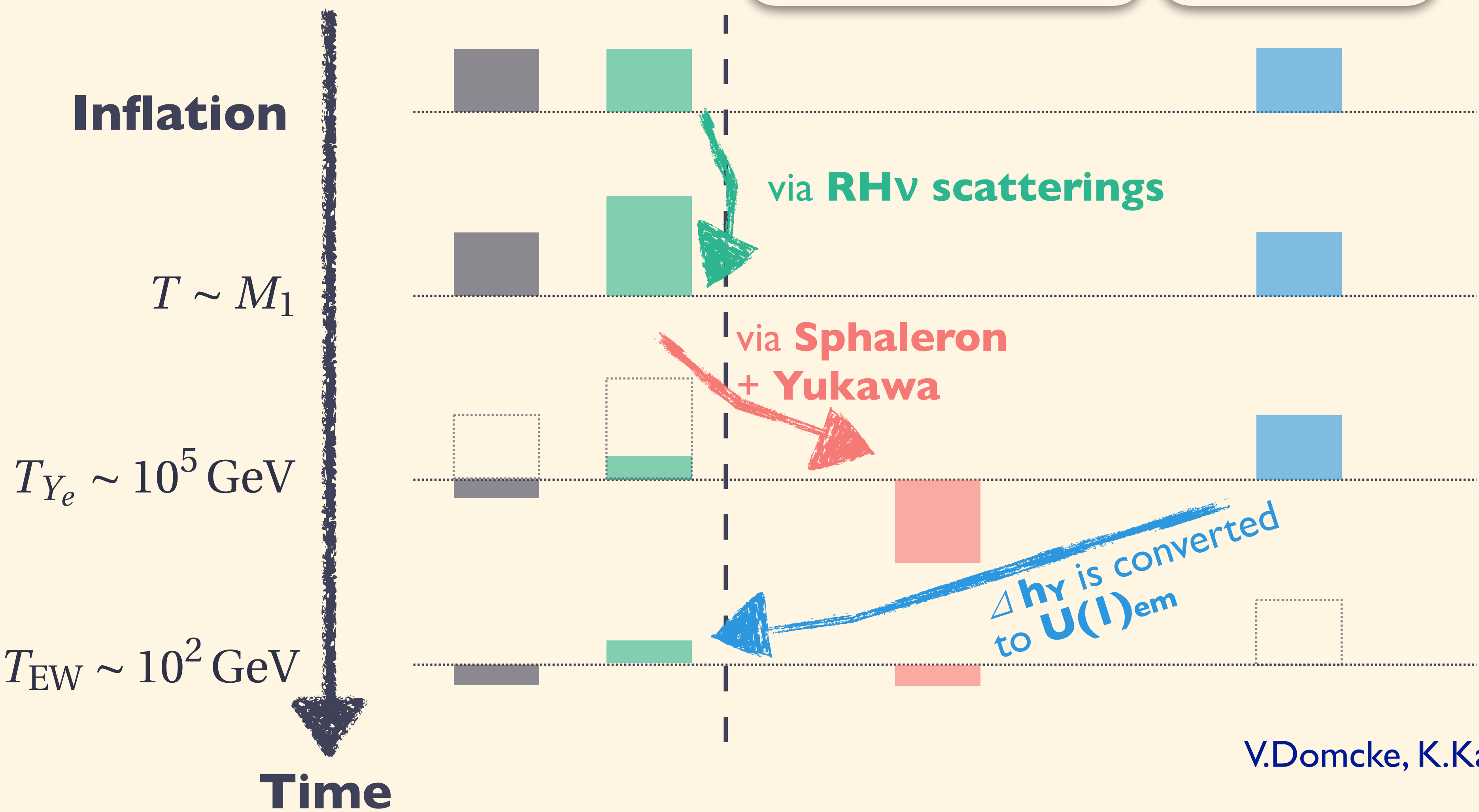

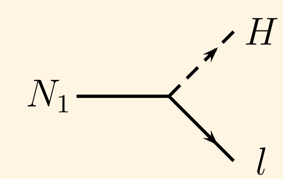

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Summary

SM (+ RHν) + Inflaton w/ U(1)$_Y$ CS coupling

- Dual production of **B+L asymmetry** & **helical U(1)$_Y$**

$$\left.\frac{\Delta q_{B+L}}{s}\right|_{\rm rh} = -\frac{3\alpha_Y}{2\pi}\left.\frac{\Delta h_Y}{s}\right|_{\rm rh} \sim 10^{-9}\left(\frac{H_{\rm rh}}{10^{12}\,{\rm GeV}}\right)^{\frac{3}{2}}\left(\frac{\langle \hat{\boldsymbol{E}}_Y\cdot\hat{\boldsymbol{B}}_Y\rangle_{\rm rh}/H_{\rm rh}^4}{10^4}\right)$$ @ the end of inflation