

# Early Universe hypercharge breaking & neutrino mass generation

Álvaro Lozano Onrubia

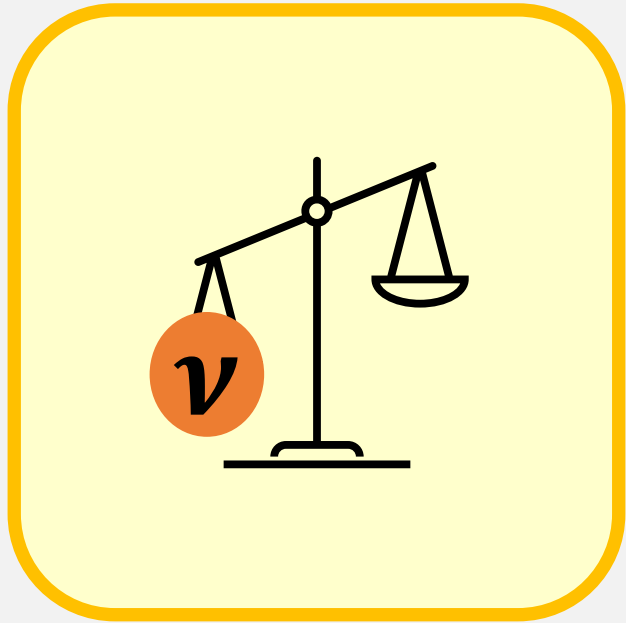
Based on arXiv:2308.09206 [hep-ph]

in collaboration with

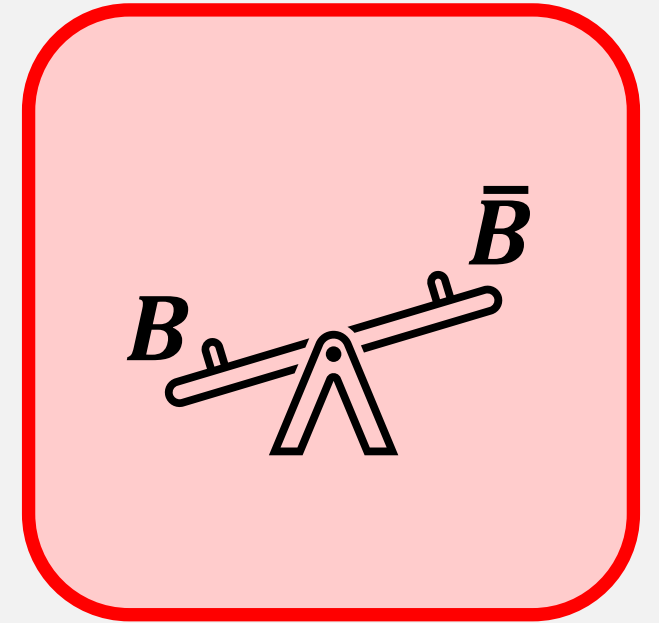
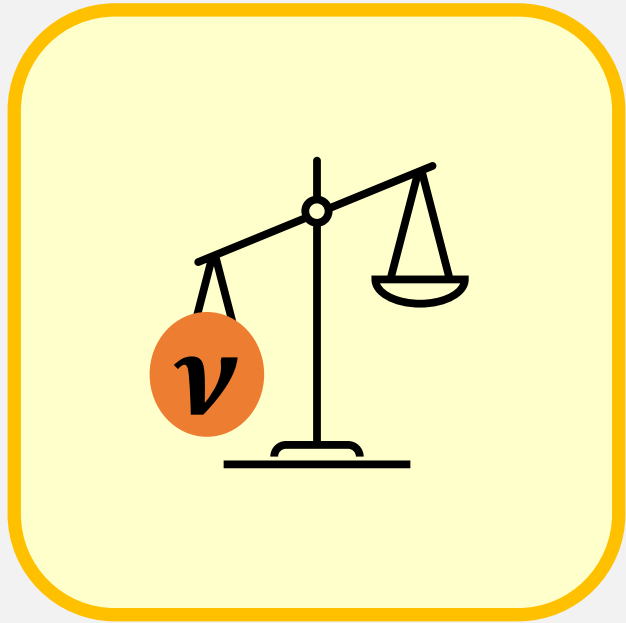
S. López Zurdo, L. Merlo, J. M. No

Invisibles23 Workshop, 29/08/2023

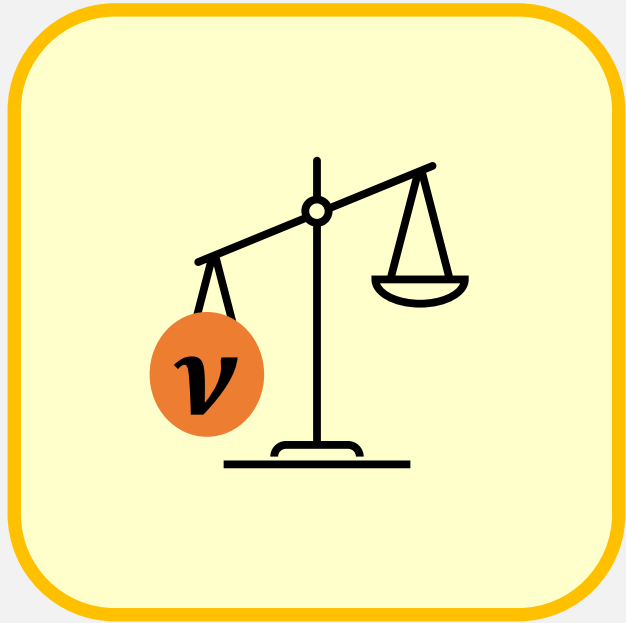




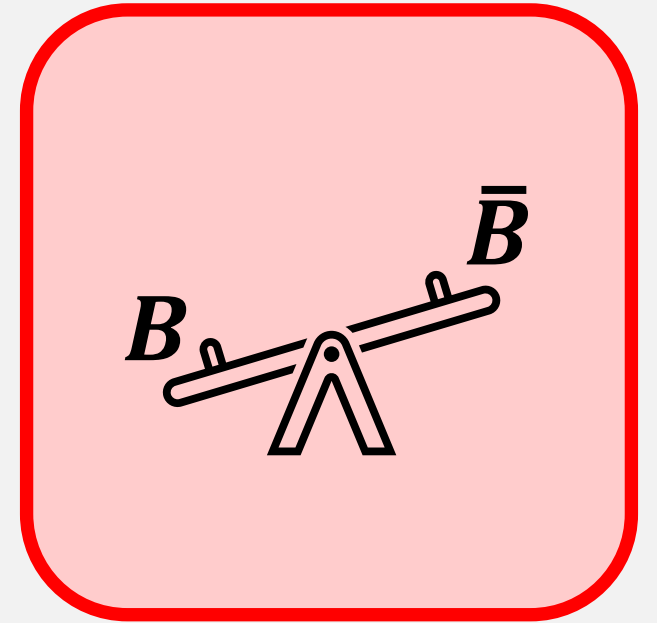
**Neutrino masses**



**Baryon asymmetry**

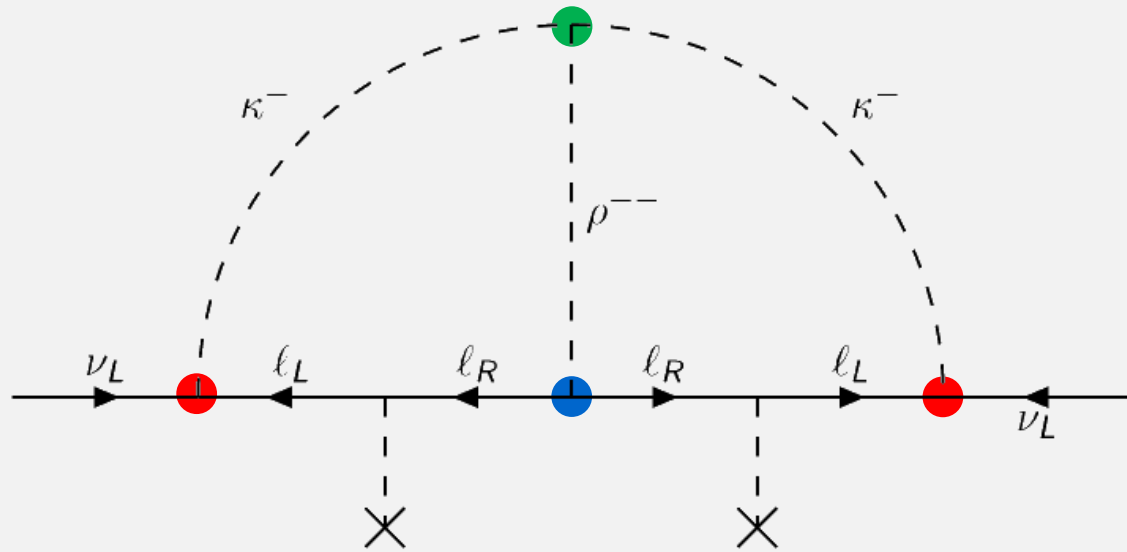


Exotic pheno





# Zee-Babu (ZB) model

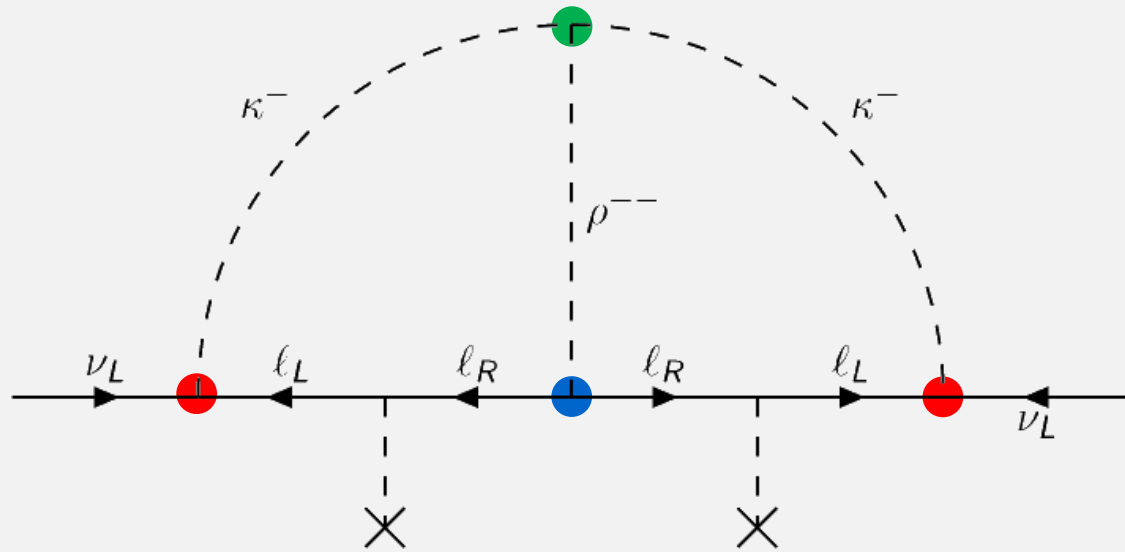


**Fig. 1:** Feynman diagram generating the neutrino masses in the ZB model [1, 2].

- Canonical 2-loop **radiative  $\nu$  mass** model [1, 2]
- Some features:
  - scalars  $\kappa^+ \sim (1_C, 1_L, \mathbf{2}_Y)$  and  $\rho^{++} \sim (1_C, 1_L, \mathbf{4}_Y)$
  - $\mathcal{L}_{ZB} \supset \overline{\widetilde{L}}_L \mathbf{f} L_L \kappa^+ + \overline{l}_R^c \mathbf{g} l_R \rho^{++} + \mu \rho^{++} \kappa^- \kappa^- + \text{h.c.}$   
with  $\mathbf{f}$  antisymmetric and  $\mathbf{g}$  symmetric.
  - neutrino masses:  $M_\nu \sim \mu \mathbf{f} Y_l \mathbf{g}^+ Y_l \mathbf{f}^T$



# Zee-Babu (ZB) model



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- scalars  $\kappa^+ \sim (1_C, 1_L, 2_Y)$  and  $\rho^{++} \sim (1_C, 1_L, 4_Y)$

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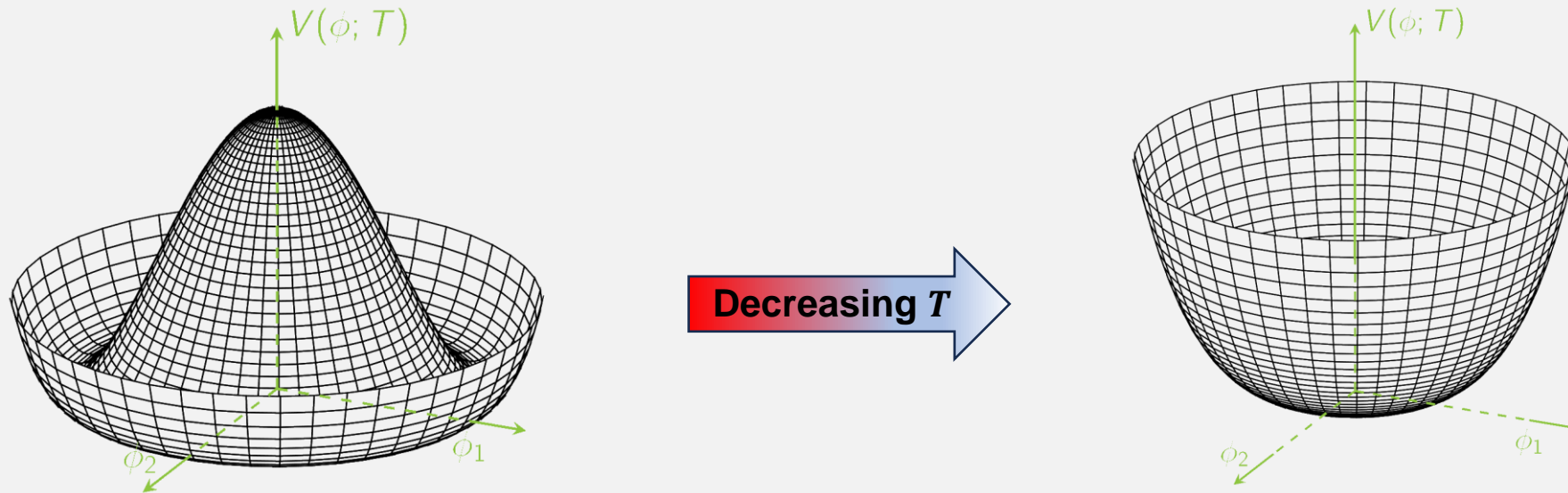
with  $f$  antisymmetric and  $g$  symmetric.

- neutrino masses:  $M_\nu \sim \mu f Y_l g^+ Y_l f^T$

- **Majorana mass terms** for  $L_L$  and  $l_R$  are interesting.



# Inverse high $T$ symmetry breaking

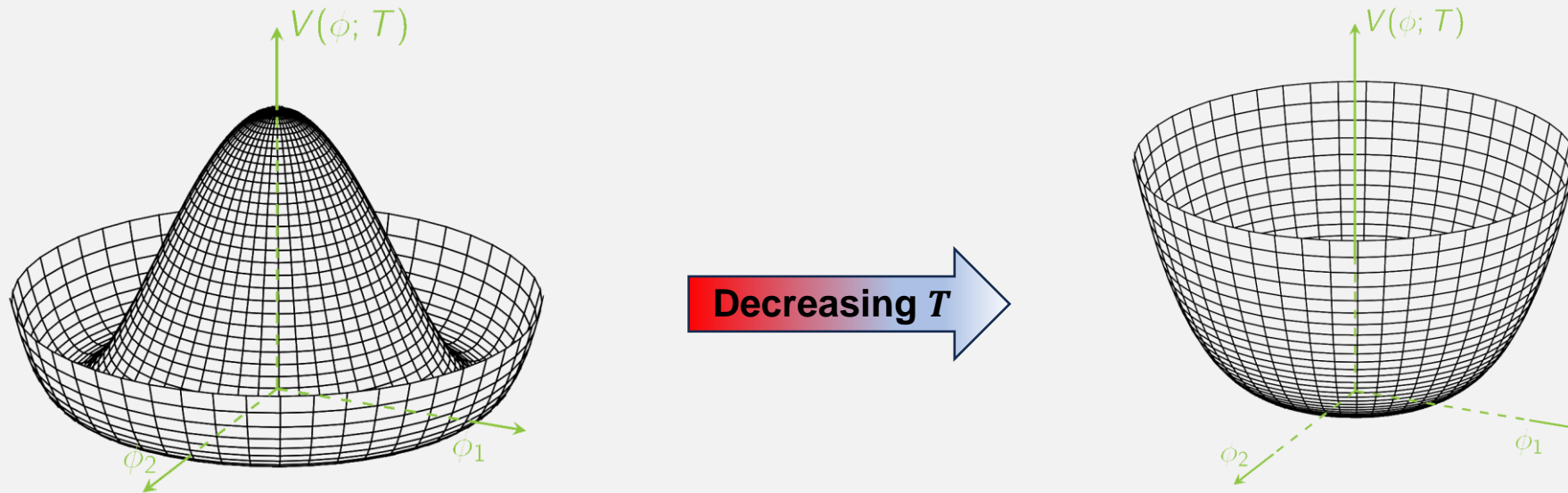


**Fig. 2:** Multi-scalar potential under high- $T$  symmetry breaking and low- $T$  symmetry restoration.

- To leading order in temperature  $T$  and 1-loop:  $V_{\mathbb{1}}^T \sim \sum_{i,j \neq i} [(m_i^2 + \mathbf{C}_{\phi_i} T^2) \phi_i^2 + \lambda_i \phi_i^4 + \lambda_{ij} \phi_i^2 \phi_j^2]$
- For  $\mathbf{C}_{\phi_k} < 0 \rightarrow \langle \phi_k \rangle \neq 0$  at high enough  $T$
- If  $\phi_k$  carries hypercharge: **SSB of  $U(1)_Y$**
- Caveat:  $\mathbf{C}_{\phi_k} < 0$  difficult



# Inverse high $T$ symmetry breaking



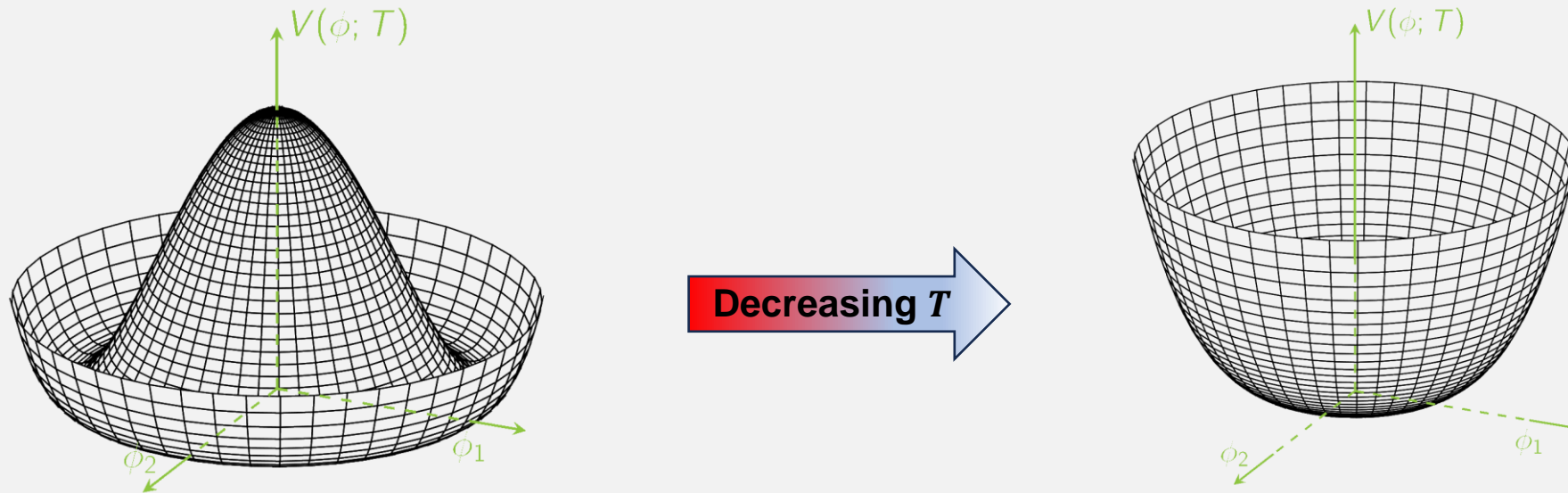
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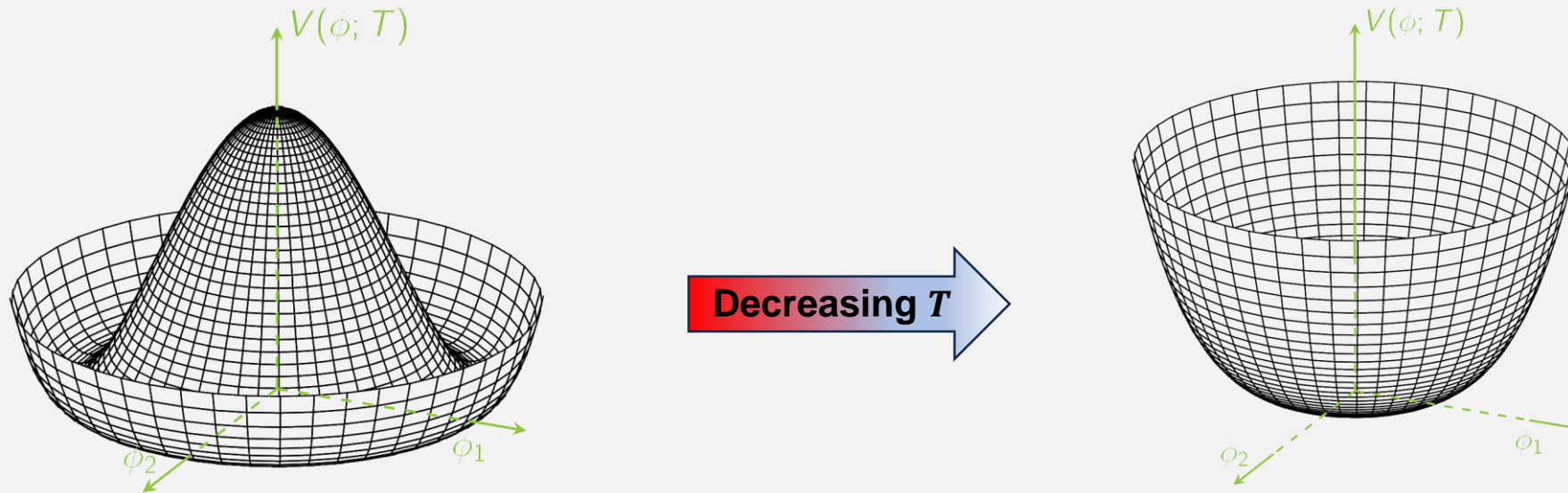


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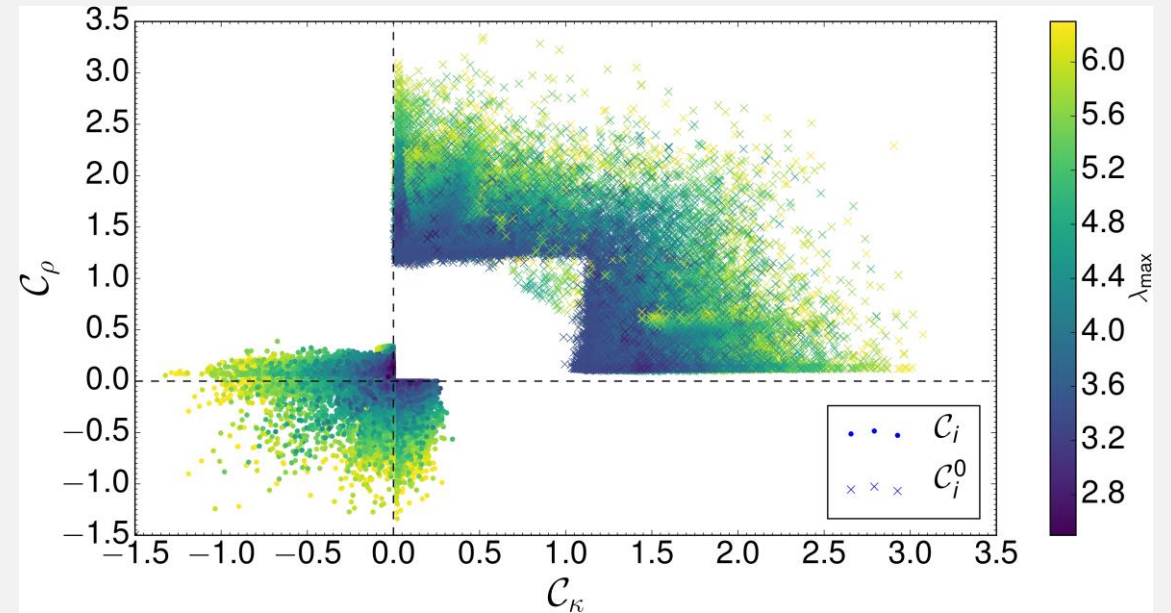


# High $T$ SSB of $U(1)_Y$ in ZB?

$$C_h = \frac{g'^2 + 3g^2}{32} + \frac{y_t^2}{8} + \frac{\lambda_h}{4} + \frac{\lambda_{h\kappa} + \lambda_{h\rho}}{24} + \Delta C_h$$

$$C_\kappa = \frac{g'^2}{4} + \frac{4\lambda_\kappa + 2\lambda_{h\kappa} + \lambda_{\kappa\rho}}{12} + \frac{1}{24} \sum_{j \neq \kappa} |f_{jk}|^2 + \Delta C_\kappa$$

$$C_\rho = g'^2 + \frac{4\lambda_\rho + 2\lambda_{h\rho} + \lambda_{\kappa\rho}}{12} + \frac{1}{24} \sum_{j,k} |g_{jk}|^2 + \Delta C_\rho$$



**Fig. 3:** Values of  $C_\kappa$ ,  $C_\rho$  (circles) and  $C_\kappa^0$ ,  $C_\rho^0$  (crosses) for a parameter scan of the quartic couplings in the ZB model. The color scheme encodes  $\lambda_{max} = \max\{\lambda_i\}$ . Both sets correspond to the same  $\lambda_i$ .



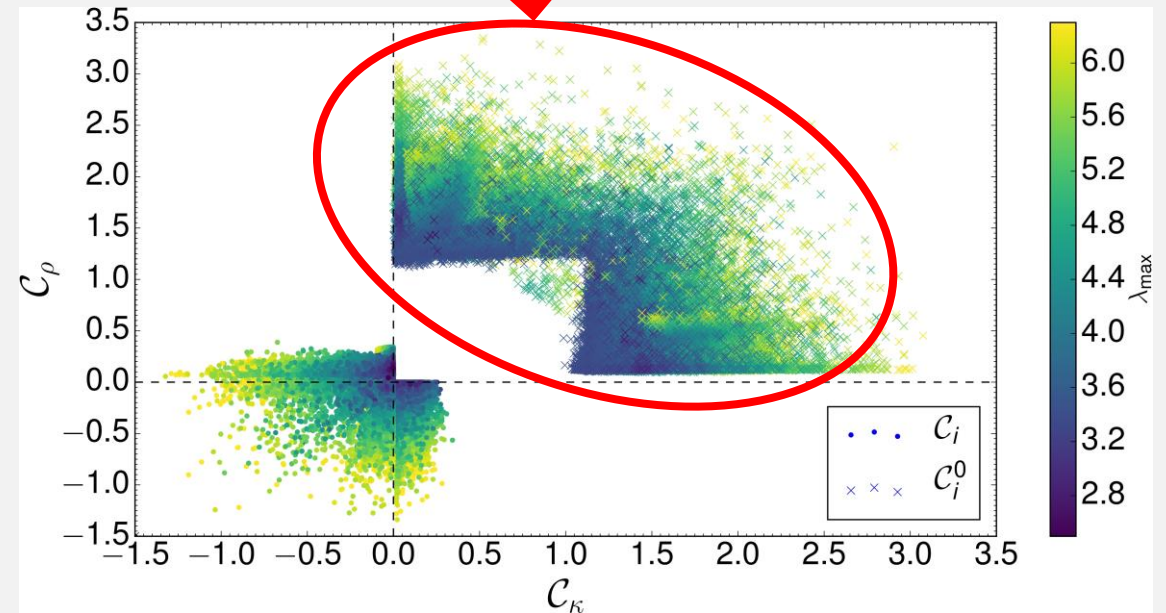
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naive calculation



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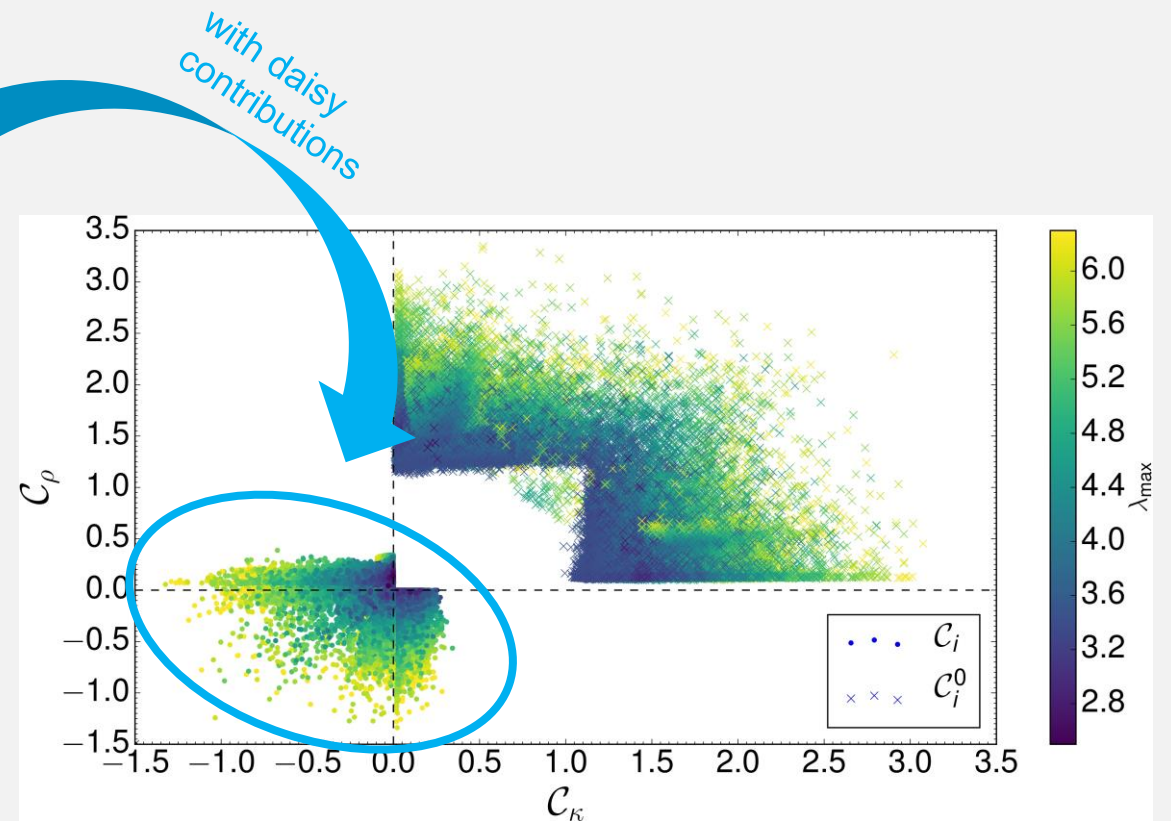


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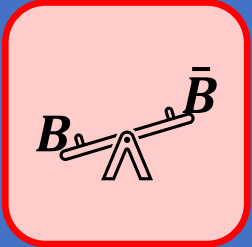
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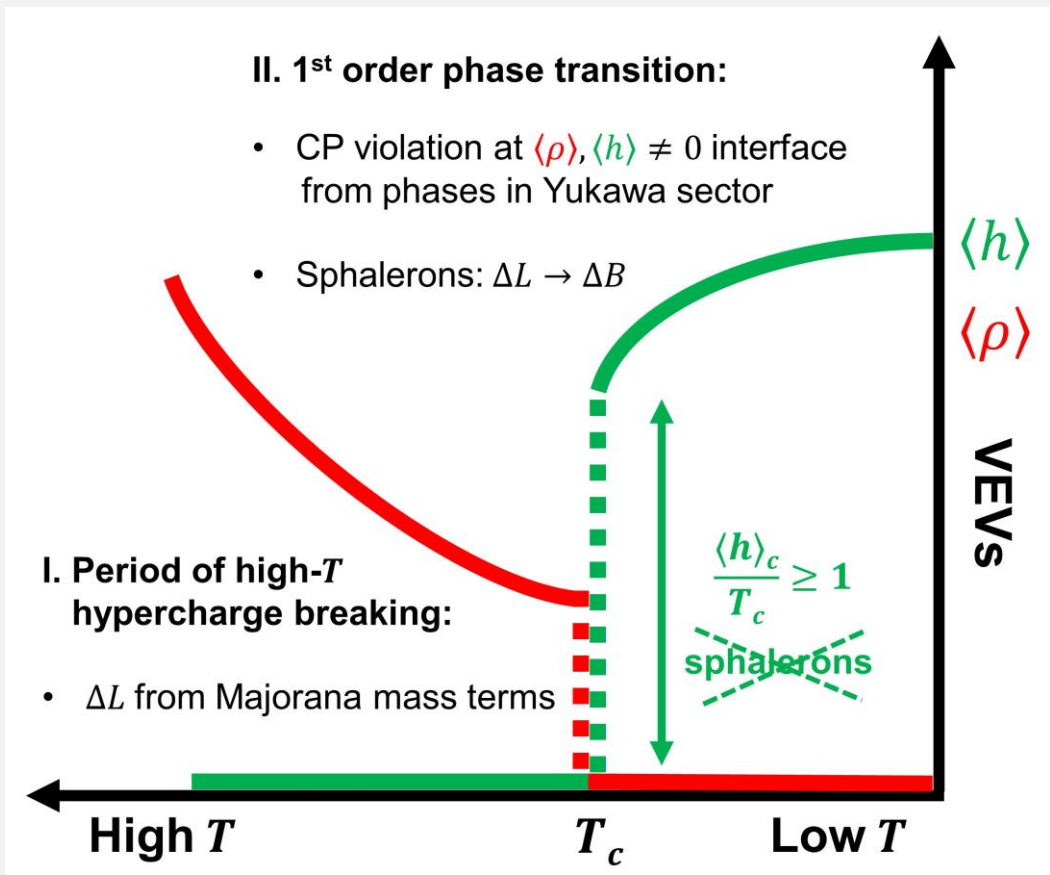
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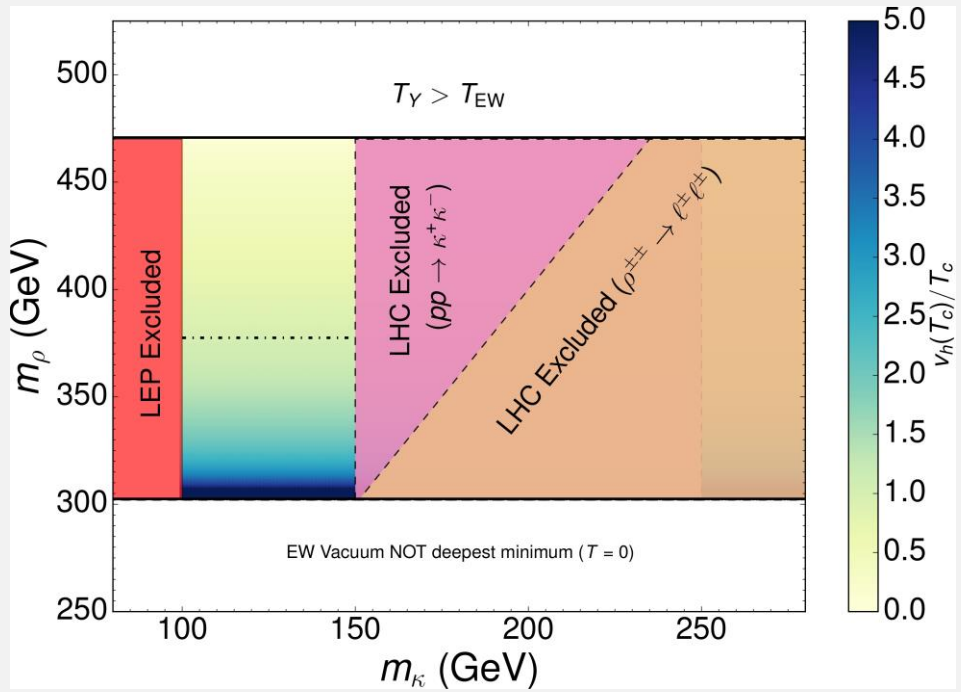


# Baryogenesis

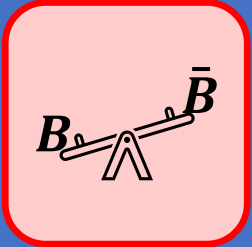


**Table 1: Benchmarks**

	$\lambda_\kappa$	$\lambda_\rho$	$\lambda_{h\kappa}$	$\lambda_{h\rho}$	$\lambda_{\kappa\rho}$	$C_h$	$C_\kappa$	$C_\rho$
BM1	0.118	5.44	4.70	-0.097	-0.052	0.042	0.048	-0.85
BM2	4.394	0.811	5.134	-0.537	-0.142	0.048	-0.529	0.192



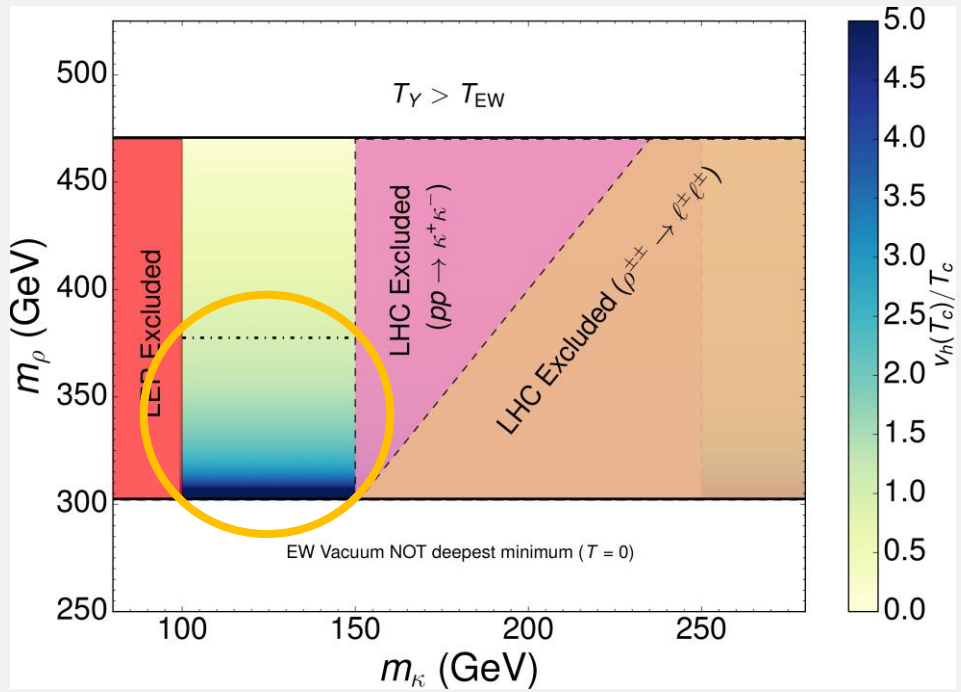
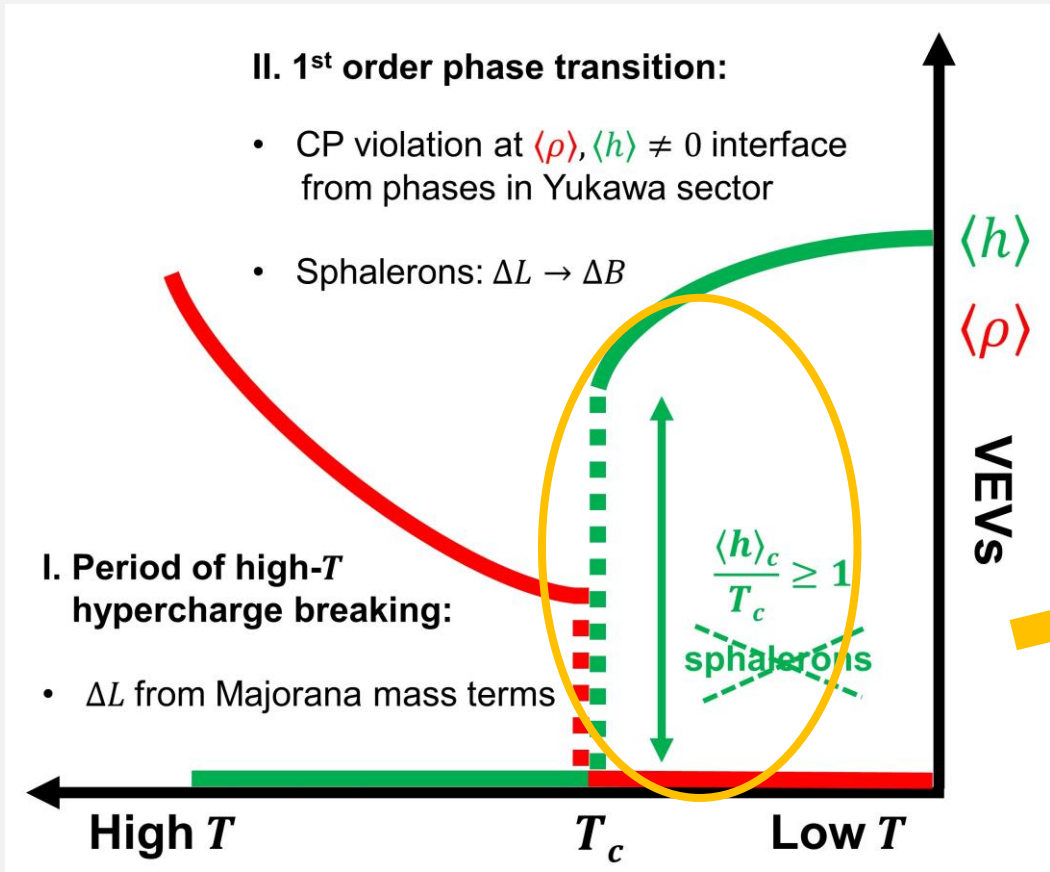
**Fig. 4: Viable masses ( $m_\kappa, m_\rho$ ) for baryogenesis in BM1.**



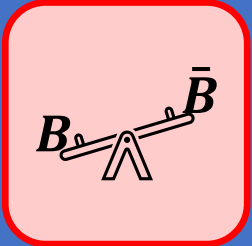
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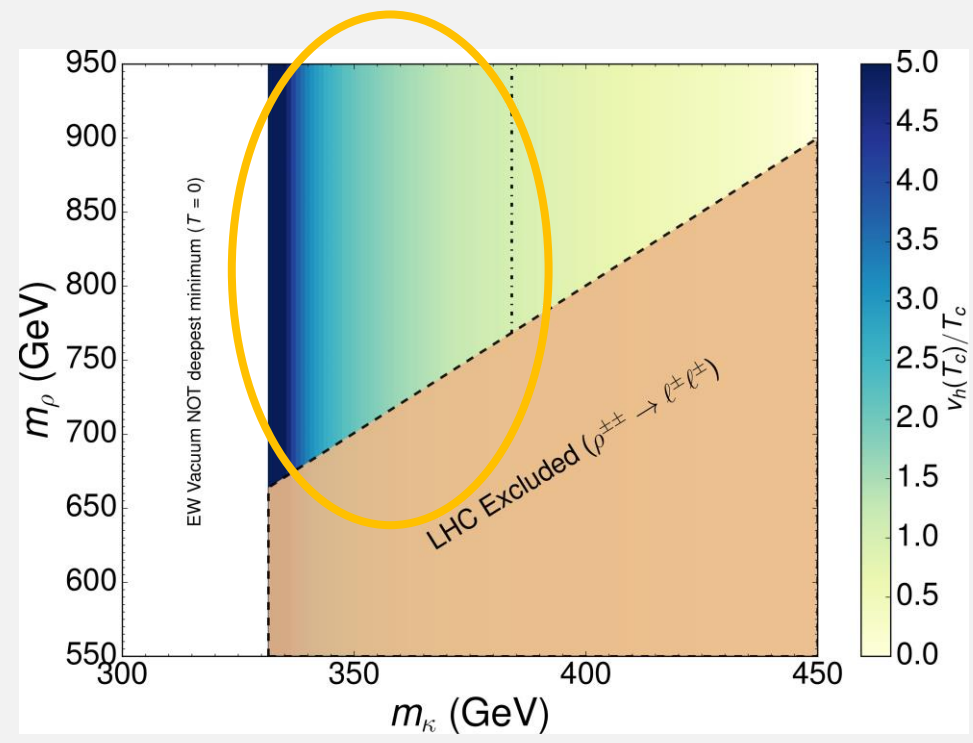
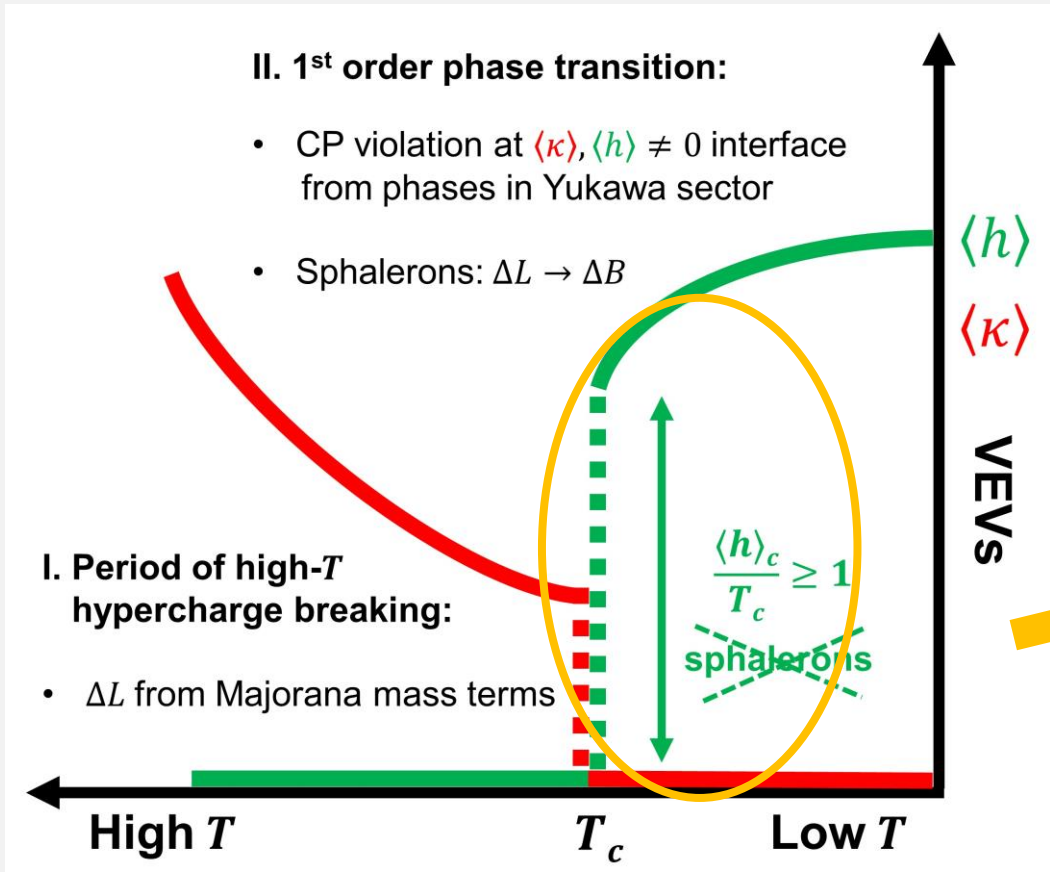
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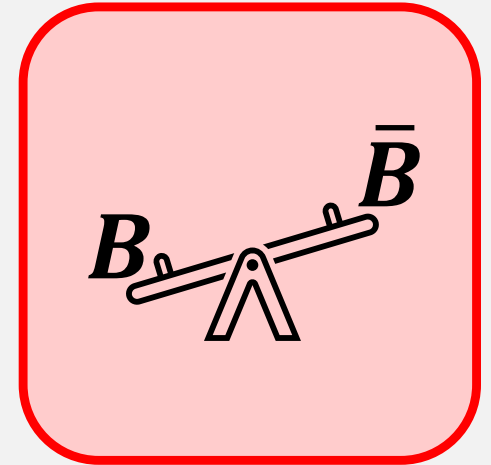
**Fig. 5: Viable masses ( $m_\kappa, m_\rho$ ) for baryogenesis in BM2.**



# Takeaways



$\emptyset$



- **ZB possesses the ingredients** for exotic early Universe phenomenology.
- How **generic to radiative models** are these features?

**Stay tuned!**



# Early Universe hypercharge breaking and neutrino mass generation

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Based on arXiv:2308.09206 [hep-ph]

## 1. Motivation

- We still do not know how neutrinos acquire mass.
- Radiative models of neutrino mass are very popular.
- They typically rely on **extended scalar sectors** which we exploit here for **exotic phenomenology**.

## 2. Zee-Babu model

- The **Zee-Babu (ZB)** model is a canonical and well-studied model that generates neutrino masses at 2-loop [1, 2]



Fig. 1: Feynman diagram generating the neutrino masses in the ZB model.

- It features:
  - New scalars  $\kappa^+ \sim (1_C, 1_U, 2_Y)$  and  $\rho^{++} \sim (1_C, 1_U, 4_Y)$
  - $\mathcal{L}_{ZB} \supset \bar{L}_i L_j \kappa^+ + \bar{L}_i^c L_j^c \rho^{++} + \mu \rho^{++} \kappa^- \kappa^- + \text{h.c.}$  with  $f$  antisymmetric and  $g$  symmetric.
- Majorana terms for charged leptons are interesting...

## 3. Inverse symmetry breaking

- Thermal effects** significantly modify scalar potentials [3].
- To leading order in temperature and 1-loop:

$$V^T_{11} = \sum_{i,j=1}^3 [(\bar{m}_i^2 + C_{\phi_i} T^2) \phi_i^\dagger \phi_i + \lambda_{ij} \phi_i^\dagger \phi_j^2]$$

- For  $C_{\phi_i} < 0$  a non-vanishing vacuum expectation value (vev) ( $\phi_i$ ) is induced at high temperature.
- If  $\phi_i$  carries hypercharge, the vev breaks  $U(1)_Y$  spontaneously.
- Caveat:  $C_{\phi_i}$  depend on constrained  $\lambda_i$ ,  $C_{\phi_i} < 0$  difficult.



Fig. 2: Scalar potential under high-T symmetry breaking and low-T symmetry restoration.

## 4. Early Universe $U(1)_Y$ breaking

$$C_h = \frac{g'^2 + 3g^2}{32} + \frac{\gamma^2}{8} + \frac{\lambda_h}{4} + \frac{\lambda_{\kappa} + \lambda_{\rho}}{24} + \Delta C_h$$

$$C_e = \frac{g'^2}{4} + \frac{4\lambda_e + 2\lambda_{\kappa} + \lambda_{\rho}}{12} + \frac{1}{24} \sum_{j=1}^3 |f_j|^2 + \Delta C_e$$

$$C_\nu = \frac{g'^2}{4} + \frac{4\lambda_\nu + 2\lambda_{\kappa} + \lambda_{\rho}}{12} + \frac{1}{24} \sum_{j=1}^3 |g_j|^2 + \Delta C_\nu$$

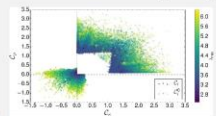
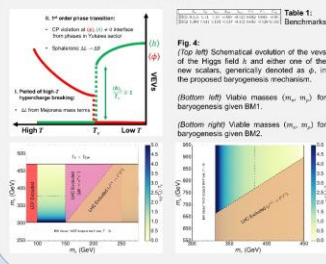


Fig. 3: Values of  $C_h$ ,  $C_e$  (circles) and  $C_\nu$ ,  $C_n$  (crosses) for a parameter scan of the quartic couplings in the ZB model. The color scheme indicates  $\lambda_{\text{min}} = \max(\lambda_i)$ . Both sets correspond to the same  $\lambda_i$ .

## 5. Baryogenesis



## 6. Conclusions

- The ZB model **possesses the ingredients** for very exotic early Universe phenomenology.
- This looks like a more **general feature** of radiative neutrino mass models – stay tuned for further work!

## 7. References

[1] A. Zee, Quantum Numbers of Majorana Neutrino Masses, Nucl. Phys. B 264, 99 (1986).  
 [2] K. S. Babu, Model of Calculable Majorana Neutrino Masses, Phys. Lett. B 203, 132 (1988).  
 [3] S. Weinberg, Gauge and Global Symmetries at High Temperature, Phys. Rev. D 9, 337 (1974).

# Thank you!

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# References

[1] A. Zee, Quantum Numbers of Majorana Neutrino Masses, Nucl. Phys. B 264, 99 (1986).

[2] K. S. Babu, Model of 'Calculable' Majorana Neutrino Masses, Phys. Lett. B 203, 132 (1988).