Early Universe hypercharge breaking & neutrino mass generation

SUSY 2024

Madrid
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Álvaro Lozano Onrubia

Based on arXiv:2308.09206 [hep-ph]

with S. López Zurdo, L. Merlo, J. M. No

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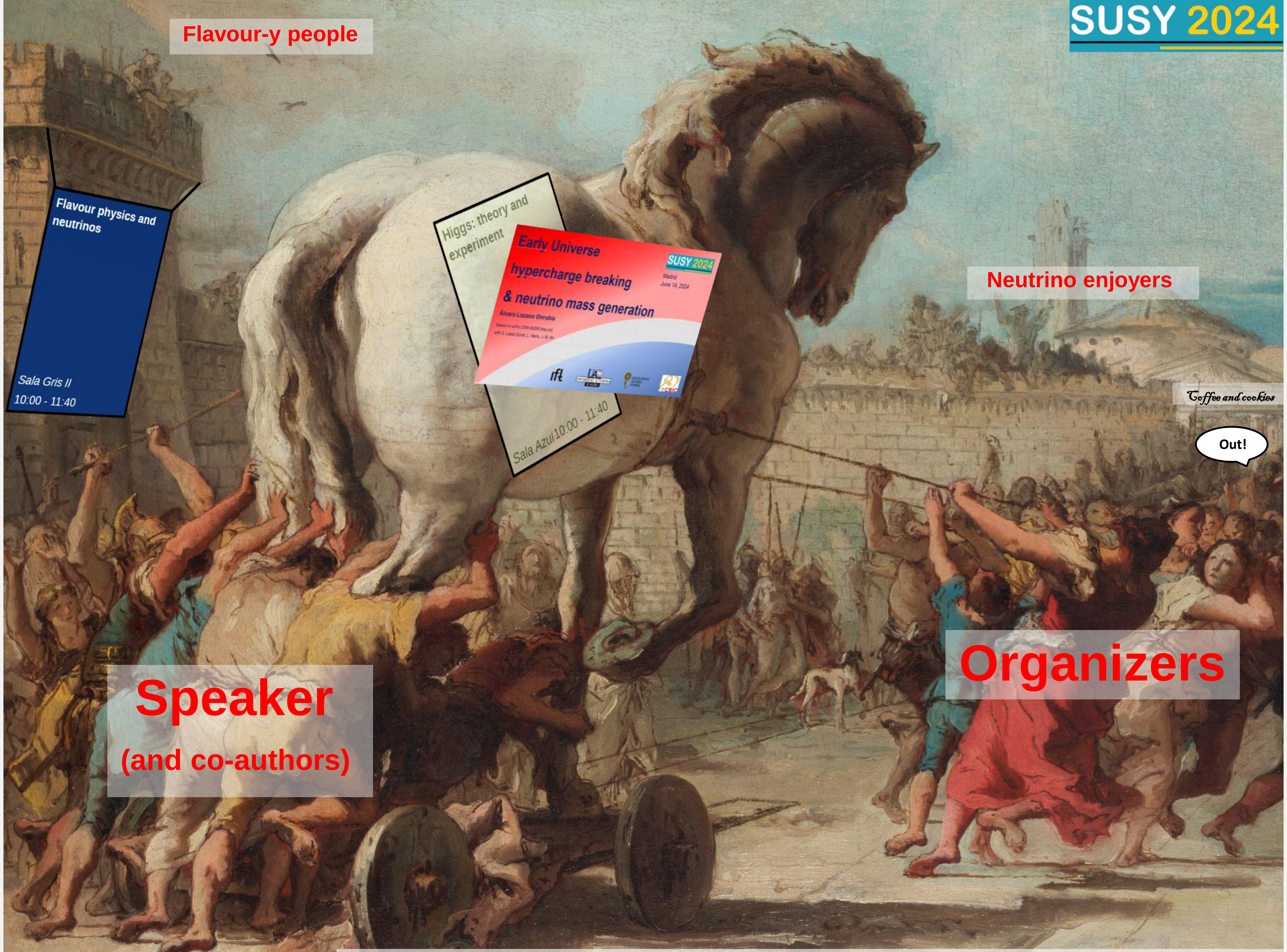
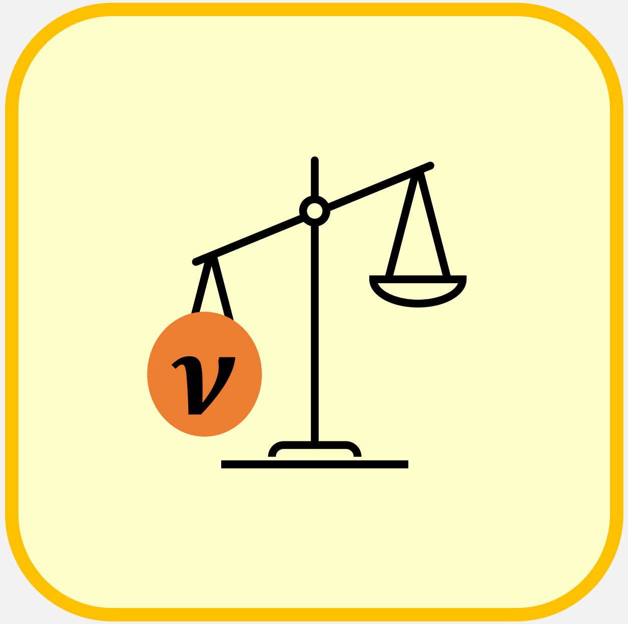
UNIVERSIDAD AUTONOMA DE MADRID
EXCELENCIA SEVERO OCHOA
CSIC

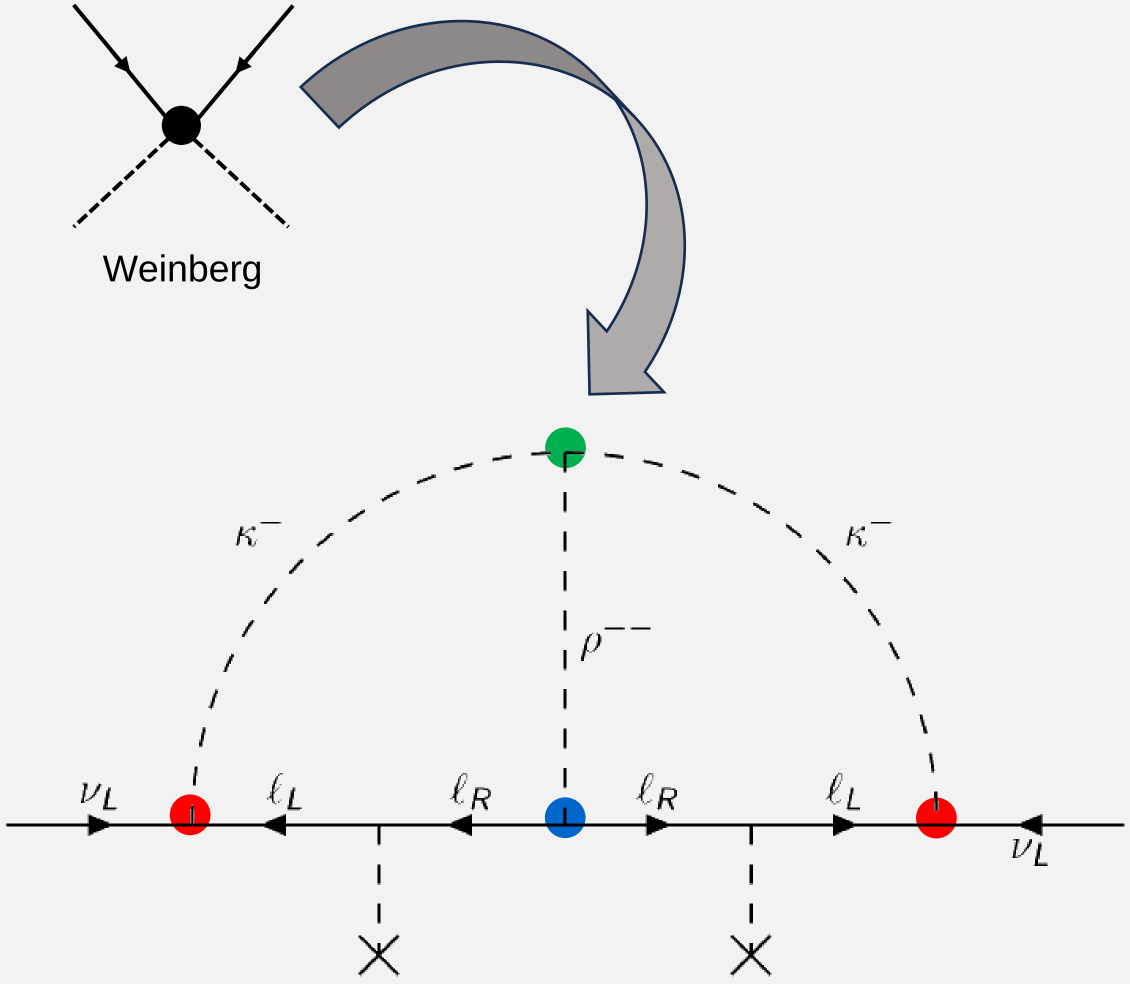


The Procession of the Trojan Horse in Troy (cropped and adapted) by Giovanni Domenico Tiepolo – see Wikipedia



Neutrino masses

Case study: Zee-Babu model



- Canonical 2-loop **radiative $\boldsymbol{\nu}$ mass** model
  - A. Zee, Quantum Numbers of Majorana Neutrino Masses, Nucl. Phys. B 264, 99 (1986).
  - K. S. Babu, Model of 'Calculable' Majorana Neutrino Masses, Phys. Lett. B 203, 132 (1988).

- Some features:
  - scalars $\kappa^+ \sim (1_C, 1_L, \mathbf{2_Y})$ and $\rho^{++} \sim (1_C, 1_L, \mathbf{4_Y})$
  - $\mathcal{L}_{ZB} \supset \overline{\widetilde{L_L}} \boldsymbol{f} L_L \kappa^+ + \overline{l_R^c}\, \boldsymbol{g}\, l_R \rho^{++} + \boldsymbol{\mu}\, \rho^{++}\kappa^-\kappa^- + \text{h.c.}$
    with $\boldsymbol{f}$ antisymmetric, $\boldsymbol{g}$ symmetric and $\widetilde{L_L} = i\sigma_2 L^c{}_L$.
  - neutrino masses: $M_\nu \sim \mu\, f\, Y_l\, g^\dagger\, Y_l\, f^T$

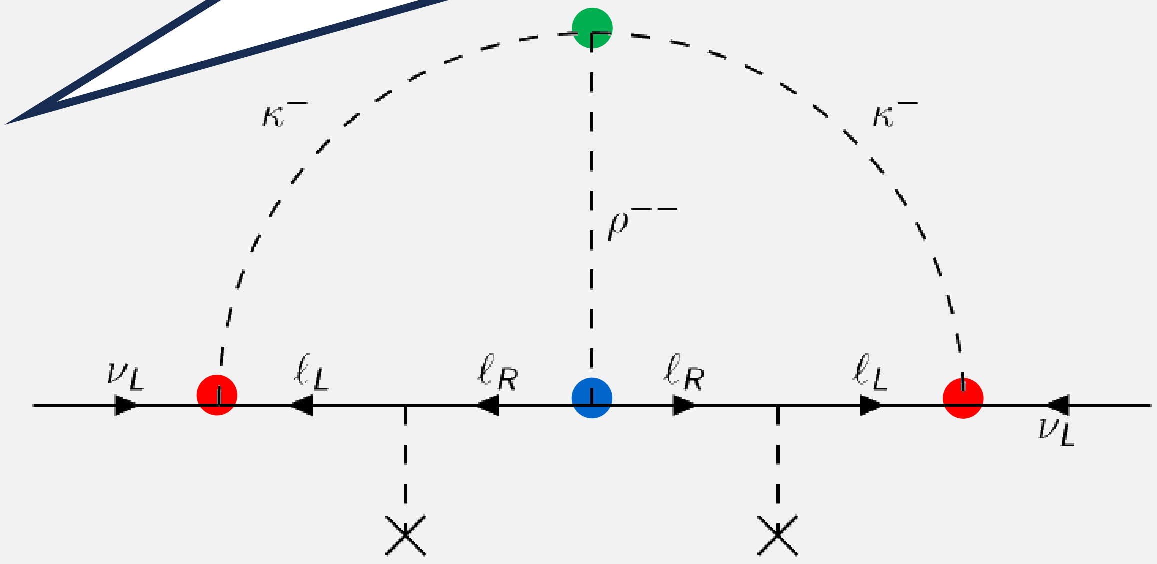
Case study: Zee-Babu model

Charged VEVs?

Majorana masses?

Lepton number violation?

Baryogenesis?



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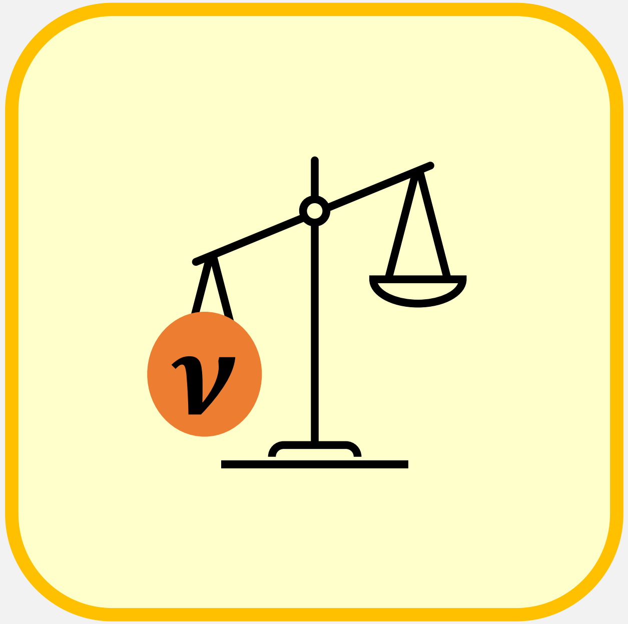
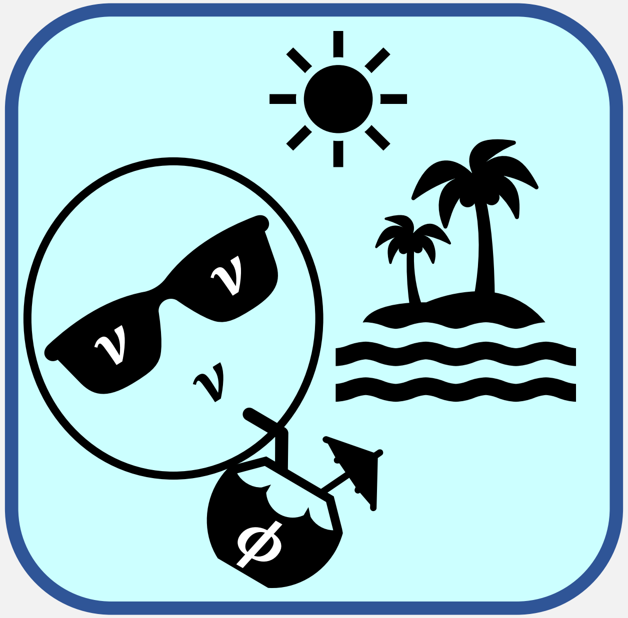
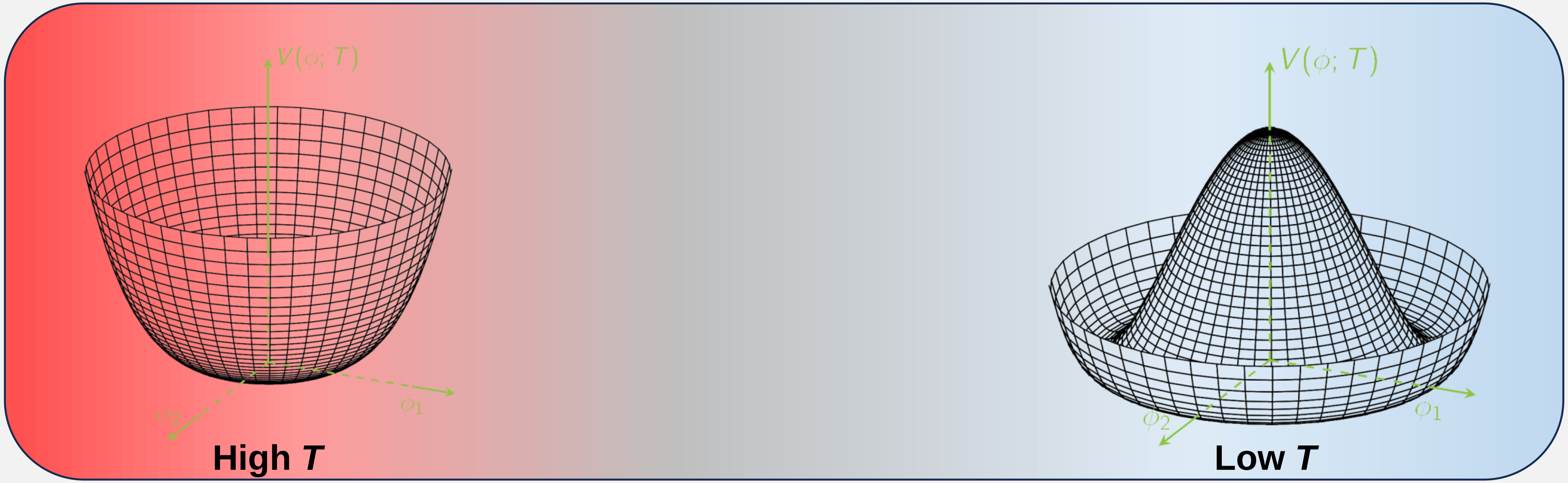




Exotic pheno

Standard picture of cosmological SSB



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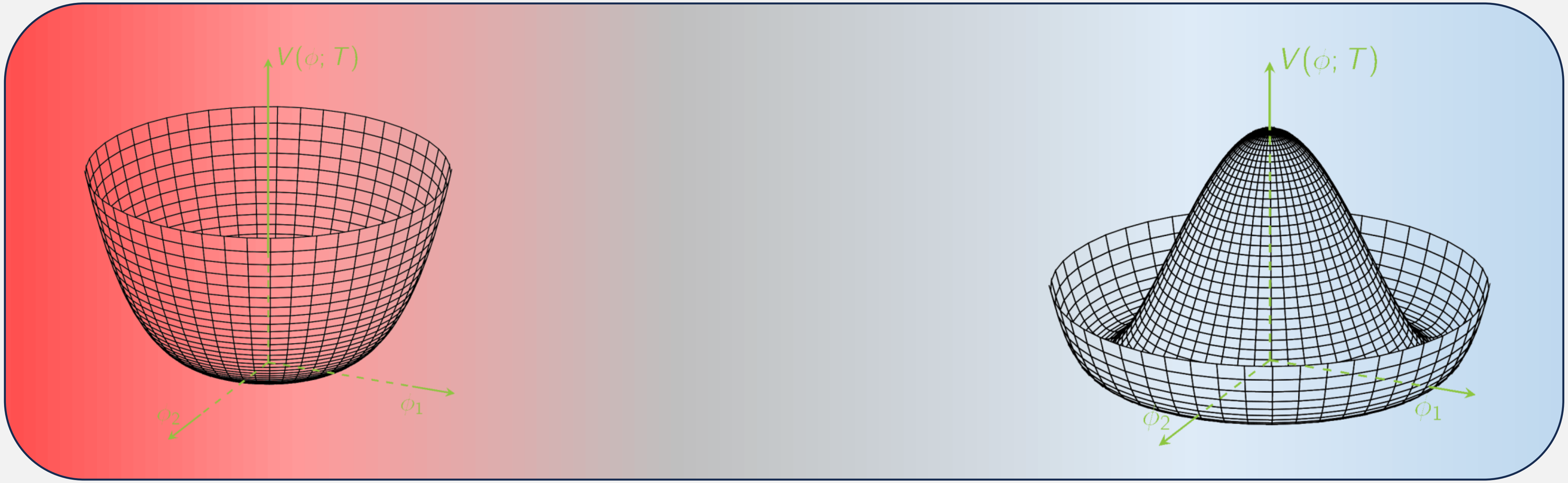

To leading order in temperature T and 1-loop:

$$V_1^{T\neq 0}(\phi;T) \supset \frac{T^4}{2\pi^2}\left[\sum_b n_b \left(\#_1 \cdot \frac{m_b(\phi)^2}{T^2} - \#_2 \cdot \left(\frac{m_b(\phi)^2}{T^2}\right)^{3/2} \right) + \sum_f n_f \#_3 \cdot \frac{m_f(\phi)^2}{T^2}\right]$$

SPOILER ALERT!

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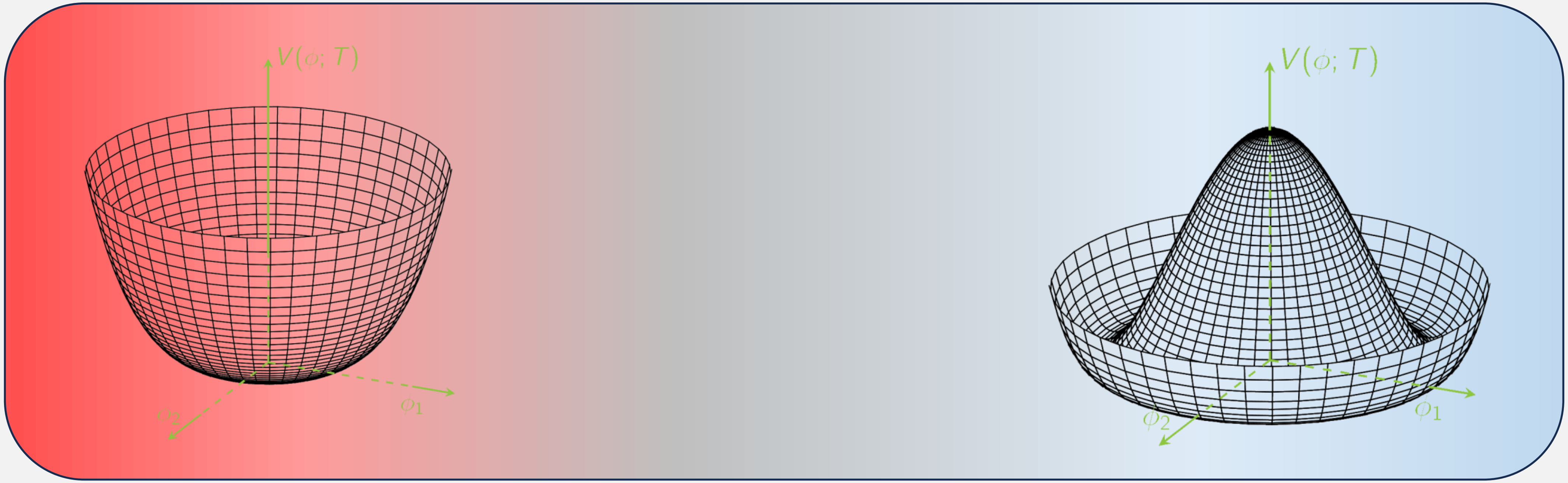
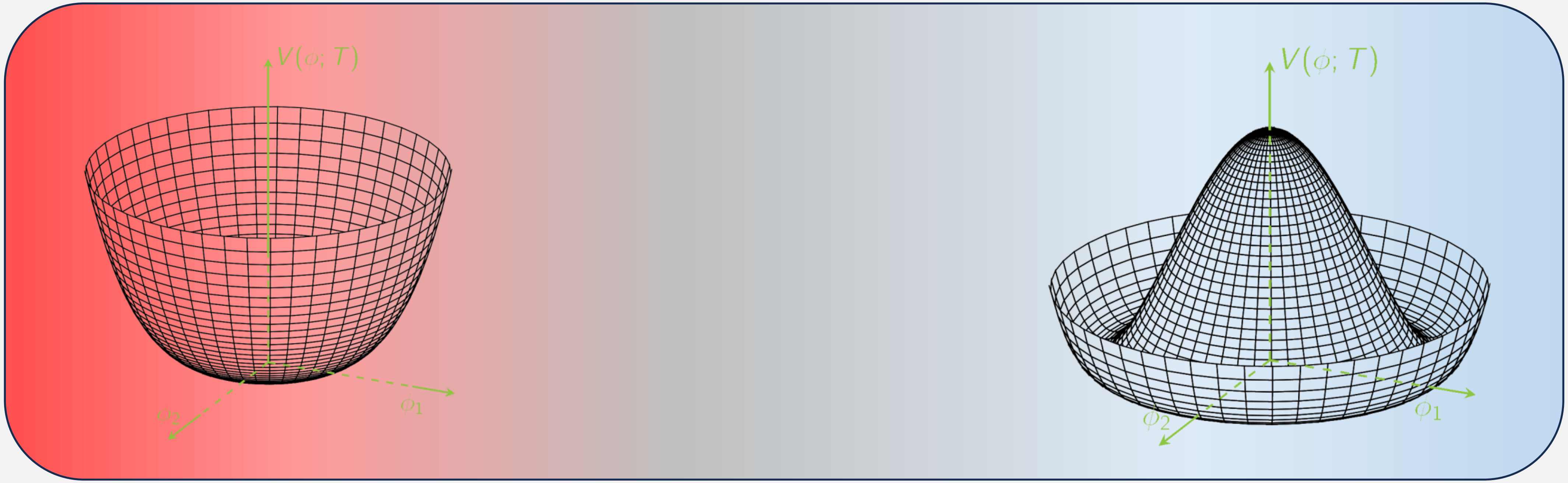


To leading order in temperature T and 1-loop:

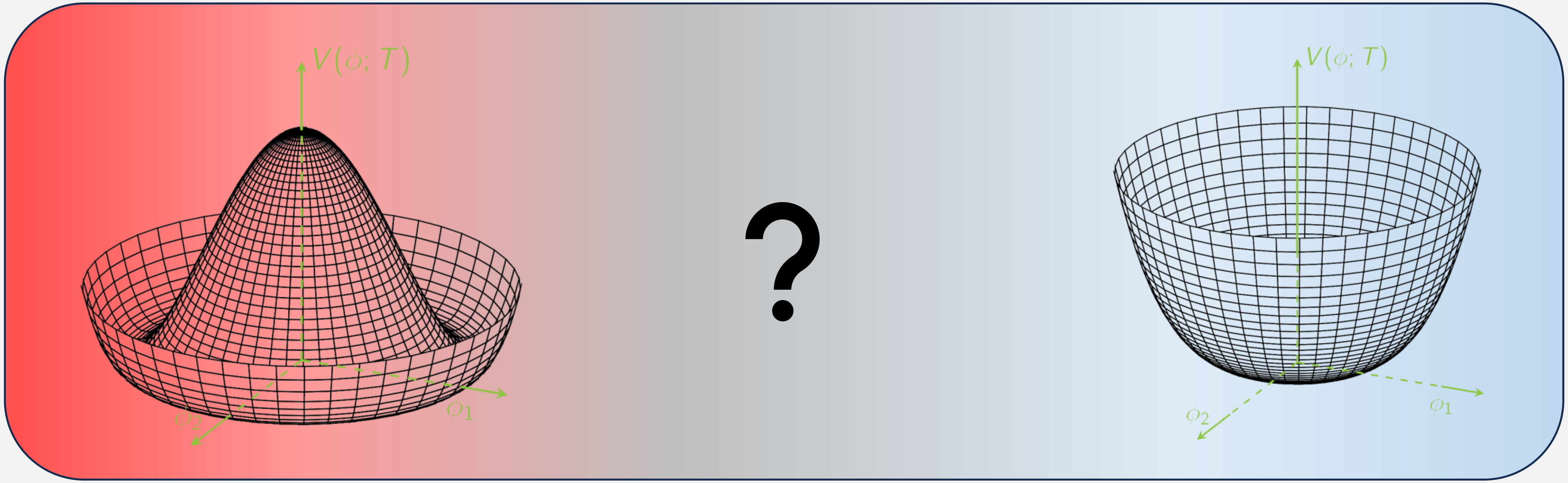
$$\Longrightarrow \quad V_1^{T\neq 0}(\phi;T) \sim \mathcal{C}_\phi^0 T^2 \phi^2 \quad \text{with} \quad \underline{\mathcal{C}_\phi^0 = \mathcal{C}_\phi^0(\lambda)}$$

Standard picture of cosmological SSB



$$V(\phi; T) = \frac{1}{2}(\underbrace{\overline{m}^2}_{\text{negative}} + \underbrace{\mathcal{C}}_{\text{positive}} T^2)\phi^2 + \frac{1}{4}\lambda\phi^4$$

Inverse high T symmetry breaking?



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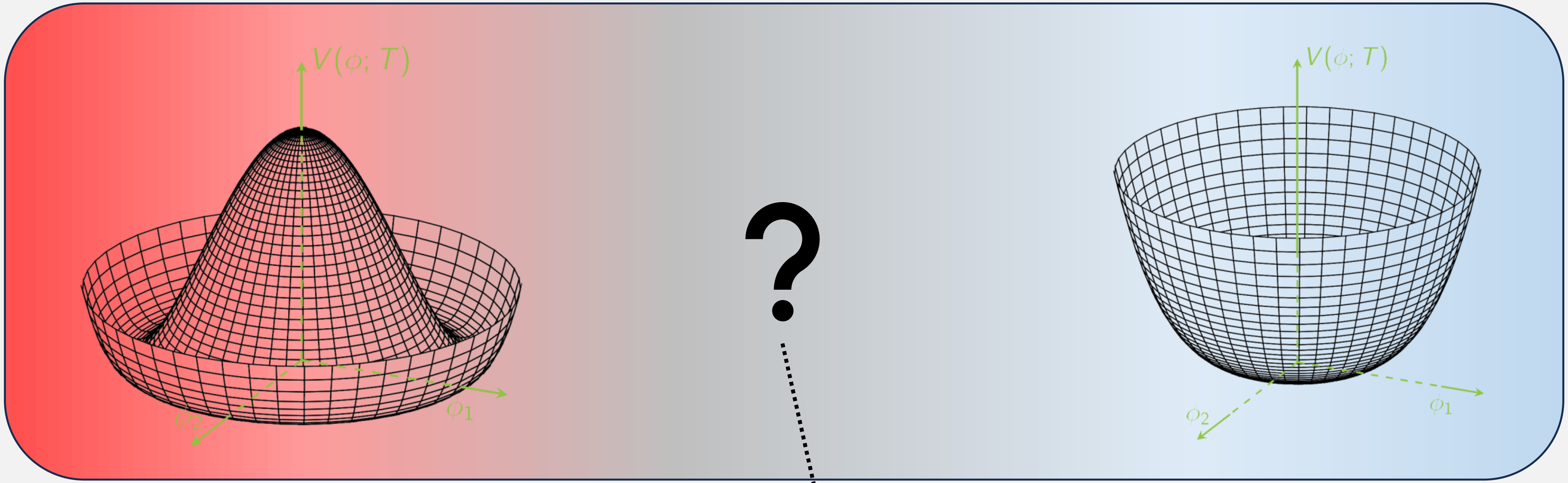

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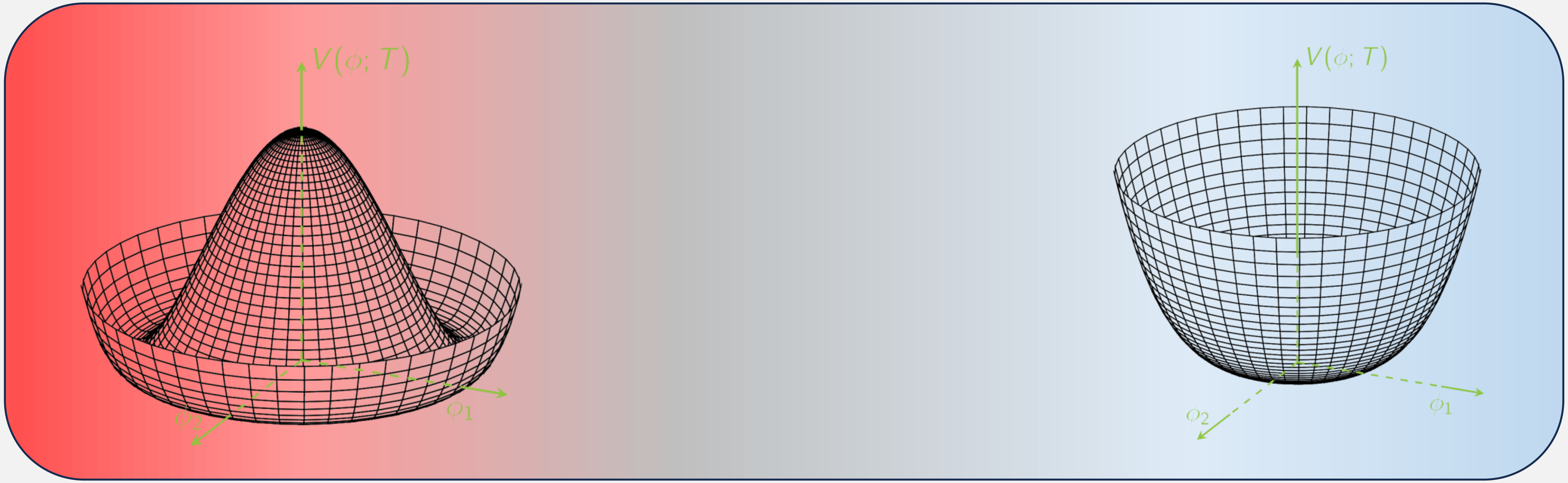
Inverse high T symmetry breaking?

- So far, mostly studied in **perturbation theory**:
  - Weinberg, S. (1974). Gauge and global symmetries at high temperature. *Physical Review D*, *9*(12), 3357.
  - Mohapatra, R. N., & Senjanović, G. (1979). Broken symmetries at high temperature. *Physical Review D*, *20*(12), 3390.
  - Orloff, J. (1997). The UV price for symmetry non-restoration. *Physics Letters B*, *403*(3-4), 309-315.
  - Dvali, G., Melfo, A., & Senjanović, G. (1996). Nonrestoration of spontaneously broken P and CP at high temperature. *Physical Review D*, *54*(12), 7857.
  - **Baldes, I., & Servant, G. (2018). High scale electroweak phase transition: baryogenesis & symmetry non-restoration. *Journal of high energy physics*, *2018*(10), 1-25.**
  - **Bahl, H., Carena, M., Ireland, A., & Wagner, C. E. (2024). Improved Thermal Resummation for Multi-Field Potentials. *arXiv preprint arXiv:2404.12439*.**

- **Non-perturbative studies** (lattice, FRG…) of simple models support viability*:
  - .
  - Roos, T. G. (1996). Wilson renormalization group study of inverse symmetry breaking. *Physical Review D*, *54*(4), 2944.
  - Jansen, K., & Laine, M. (1998). Inverse symmetry breaking with 4D lattice simulations. *Physics Letters B*, *435*(1-2), 166-174

*(after some debate in the 1990s)

Inverse high T symmetry breaking?



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

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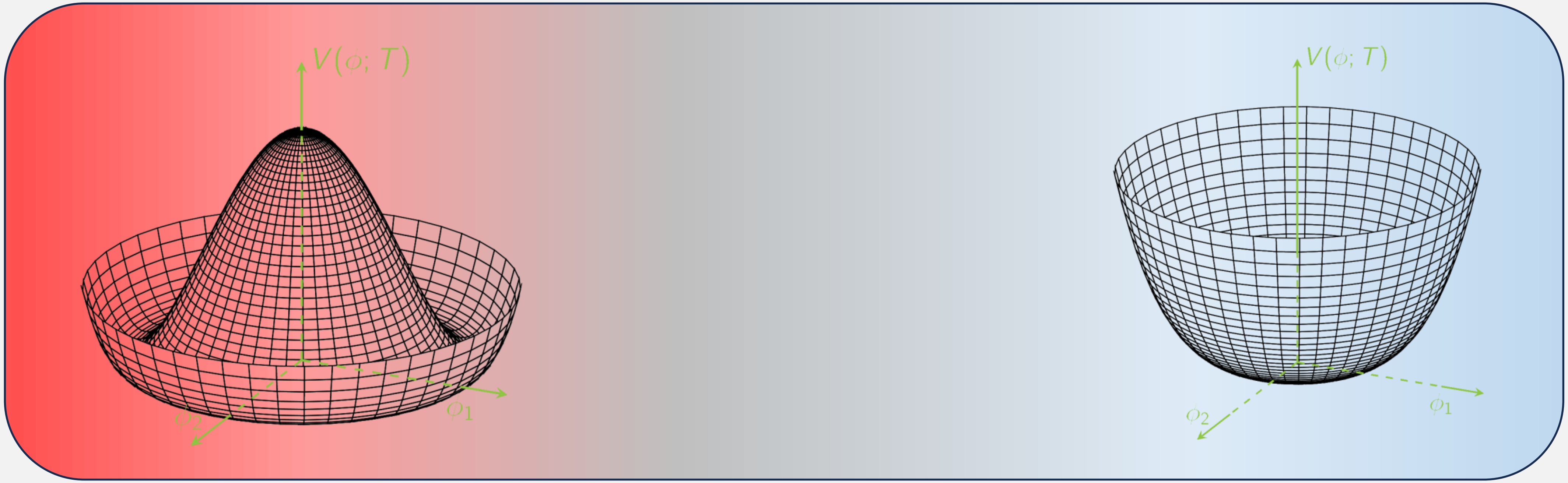

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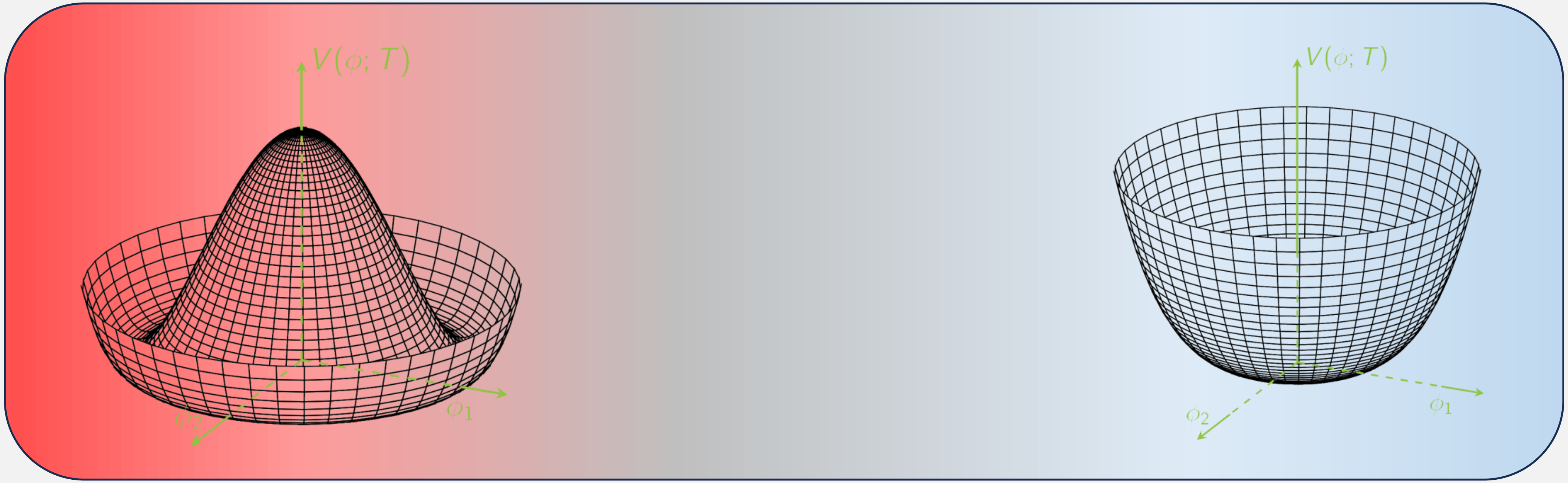

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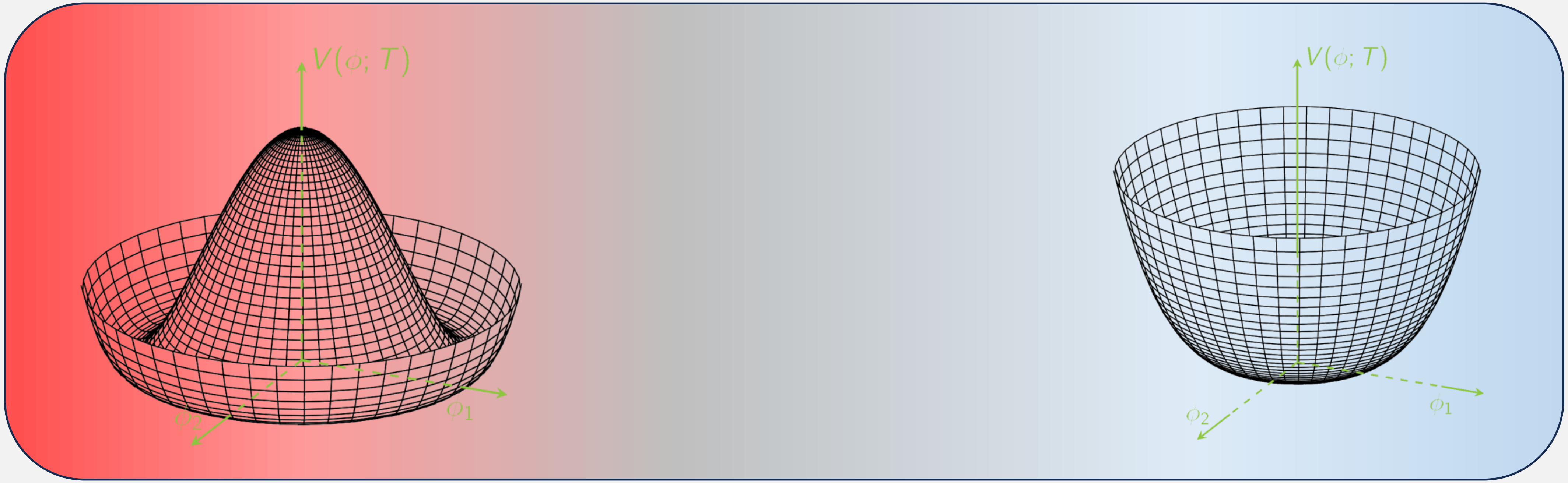

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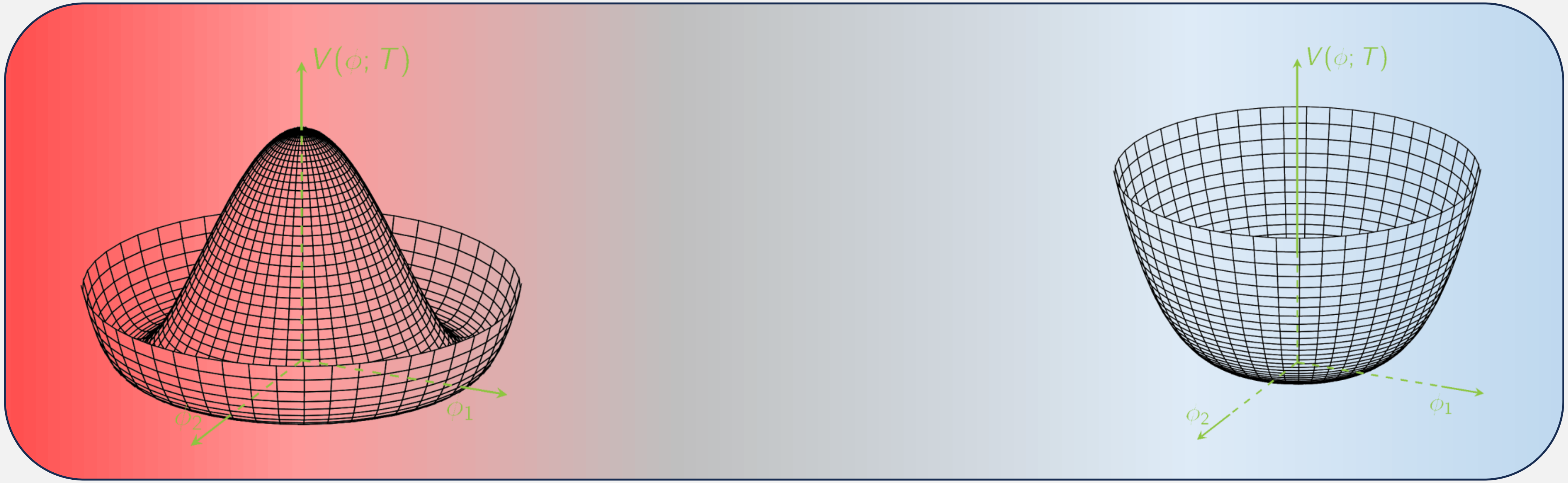

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SPOILER ALERT!

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Inverse high T symmetry breaking?

Theoretical constraints

- Vacuum stability:

  Kannike, K. (2012). The European Physical Journal C, 72(7), 2093.

$$\lambda_a \geq 0$$

$$\lambda_{ab} + \sqrt{\lambda_a \lambda_b} \equiv \Lambda_{ab} \geq 0$$

$$\sqrt{\lambda_h \lambda_\kappa \lambda_\rho} + \lambda_{h\kappa}\sqrt{\lambda_\rho} + \lambda_{h\rho}\sqrt{\lambda_\kappa} + \lambda_{\kappa\rho}\sqrt{\lambda_h} + \sqrt{2\,\Lambda_{h\kappa}\Lambda_{\kappa\rho}\Lambda_{h\rho}} \geq 0$$

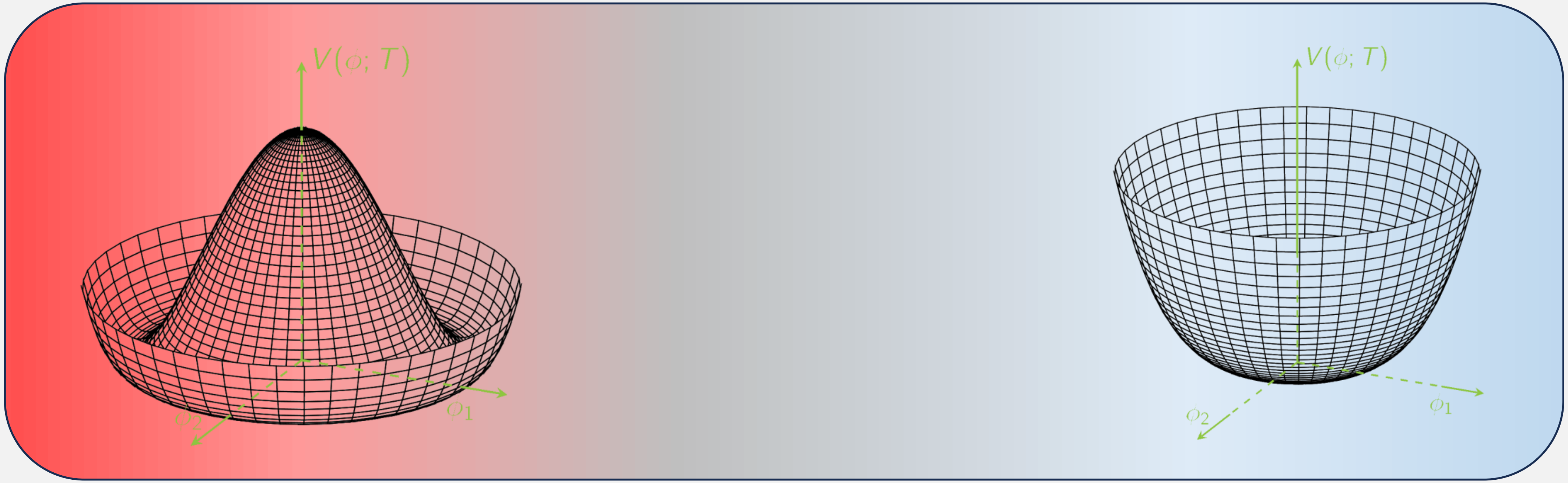
- Perturbativity:

$$\lambda_a \in [0, 4\pi]$$

$$\lambda_{ab} \in [-2\sqrt{\lambda_a \lambda_b}, 4\pi]$$

for $a, b \in \{h, \kappa, \rho\}$

Inverse high T symmetry breaking?



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Inverse high T symmetry breaking?

Daisy resummation: curse turned blessing?

$$V_1^{T\neq 0}(\phi; T) \supset \frac{T^4}{2\pi^2}\left[\sum_b n_b \left(\#_1 \cdot \frac{m_b(\phi)^2}{T^2} - \#_2 \cdot \left(\frac{m_b(\phi)^2}{T^2}\right)^{3/2}\right) + \sum_f n_f \#_3 \cdot \frac{m_f(\phi)^2}{T^2}\right]$$

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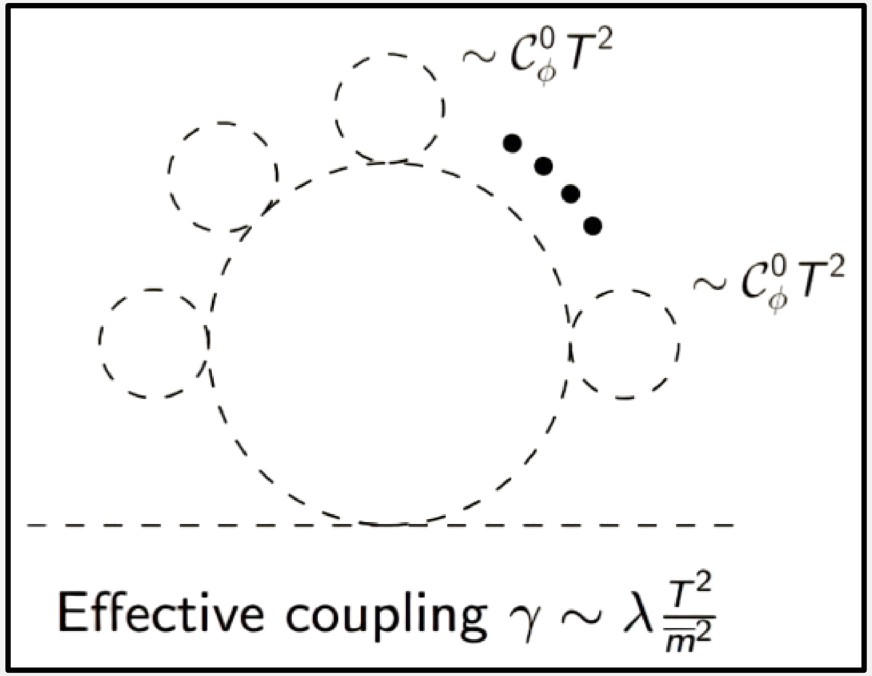

Arnold, P., Espinosa, O. (1993). Physical Review D, 47(8), 3546.

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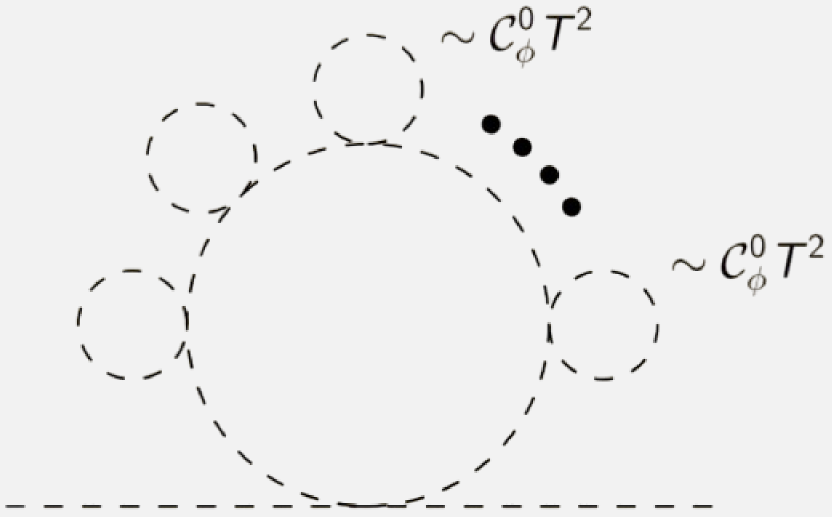


Effective coupling $\gamma \sim \lambda \frac{T^2}{m^2}$

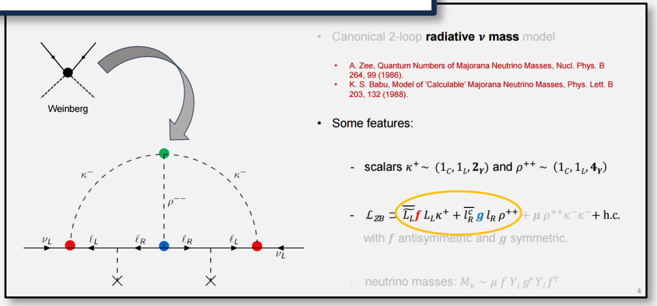
$$m_b(\phi)^2 \to m_b(\phi)^2 + \mathcal{C}_\phi^0 T^2$$

$$\mathcal{C}_\phi^0 \to \mathcal{C}_\phi^0 - \sqrt{\mathcal{C}_\phi^0 \lambda}$$

Arnold, P., Espinosa, O. (1993). Physical Review D, 47(8), 3546.

Back to Zee-Babu…

$$
\begin{aligned}
V(H,\kappa,\rho;T) = {} & \left(\overline{m}_h^2 + C_h T^2\right)|H|^2 + \left(\overline{m}_\kappa^2 + C_\kappa T^2\right)|\kappa|^2 + \left(\overline{m}_\rho^2 + C_\rho T^2\right)|\rho|^2 \\
& + \lambda_h |H|^4 + \lambda_\kappa |\kappa|^4 + \lambda_\rho |\rho|^4 + \lambda_{\kappa\rho}|\kappa|^2|\rho|^2 + \lambda_{h\kappa}|\kappa|^2|H|^2 + \lambda_{h\rho}|\rho|^2|H|^2 \\
& + \mu\,\rho^{++}\kappa^-\kappa^- + \text{h.c.}
\end{aligned}
$$



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

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

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

Back to Zee-Babu…

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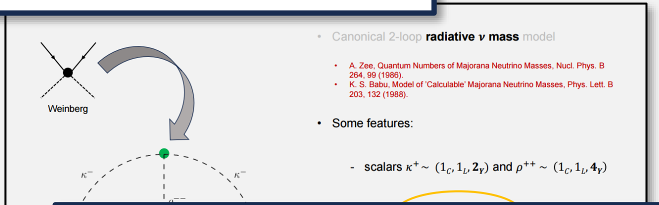

- Herrero-Garcia, J., Nebot, M., Rius, N., & Santamaria, A. (2014). The Zee–Babu model revisited in the light of new data. *Nuclear Physics B*, *885*, 542-570.
- …

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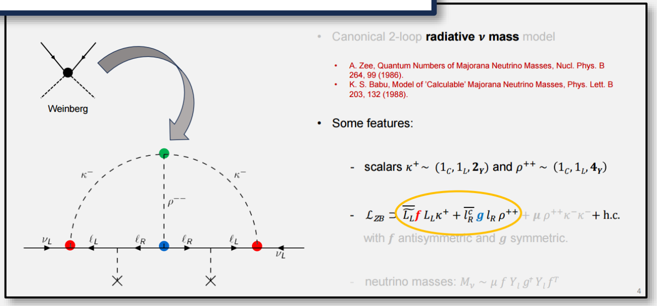

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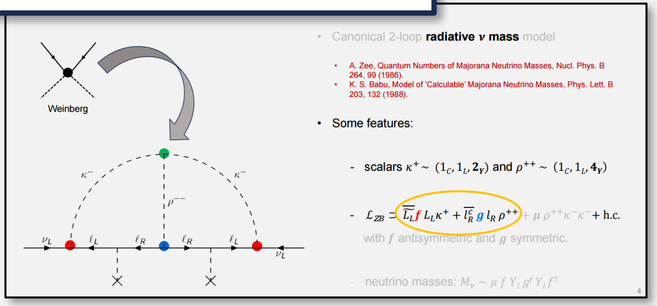

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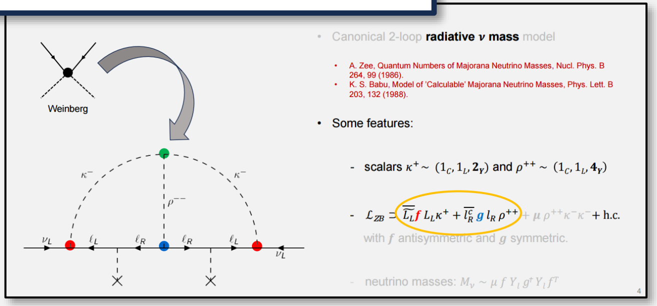

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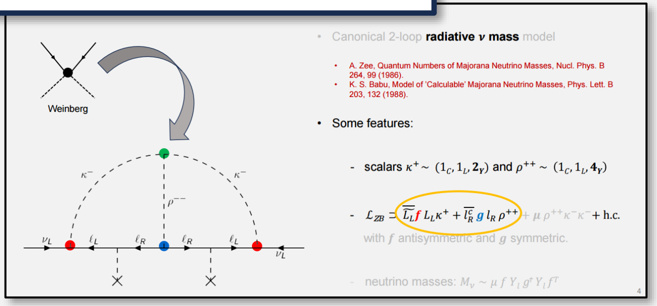
$$0 > \quad C_\rho = g'^2 + \frac{4\lambda_\rho + 2\lambda_{h\rho} + \lambda_{\kappa\rho}}{12} + \frac{1}{24}\sum_{j,k}|g_{jk}|^2 + \Delta C_\rho$$

Back to Zee-Babu…

$$V(H,\kappa,\rho;T) = \left(\overline{m}_h^2 + C_h T^2\right)|H|^2 + \left(\overline{m}_\kappa^2 + C_\kappa T^2\right)|\kappa|^2 + \left(\overline{m}_\rho^2 + C_\rho T^2\right)|\rho|^2$$
$$+ \lambda_h|H|^4 + \lambda_\kappa|\kappa|^4 + \lambda_\rho|\rho|^4 + \lambda_{\kappa\rho}|\kappa|^2|\rho|^2 + \lambda_{h\kappa}|\kappa|^2|H|^2 + \lambda_{h\rho}|\rho|^2|H|^2$$
$$+ \mu\,\rho^{++}\kappa^-\kappa^- + \text{h.c.}$$



$$C_h = \frac{g'^2 + 3g^2}{32} + \frac{y_t^2}{8} + \frac{\lambda_h}{4} + \frac{\lambda_{h\kappa} + \lambda_{h\rho}}{24} + \Delta C_h \quad > 0$$

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

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

High T SSB of $U(1)_Y$ in Zee-Babu?

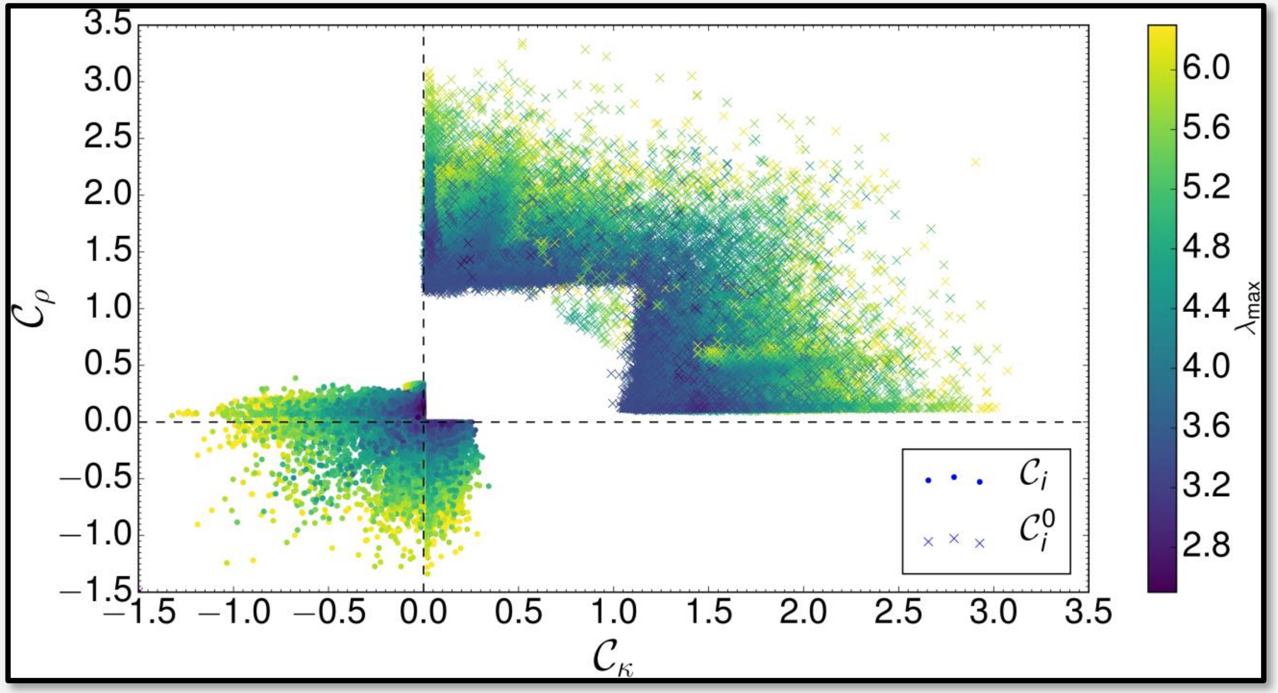
Pure 1-loop

Daisies

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

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

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



High T SSB of $U(1)_Y$ in Zee-Babu?

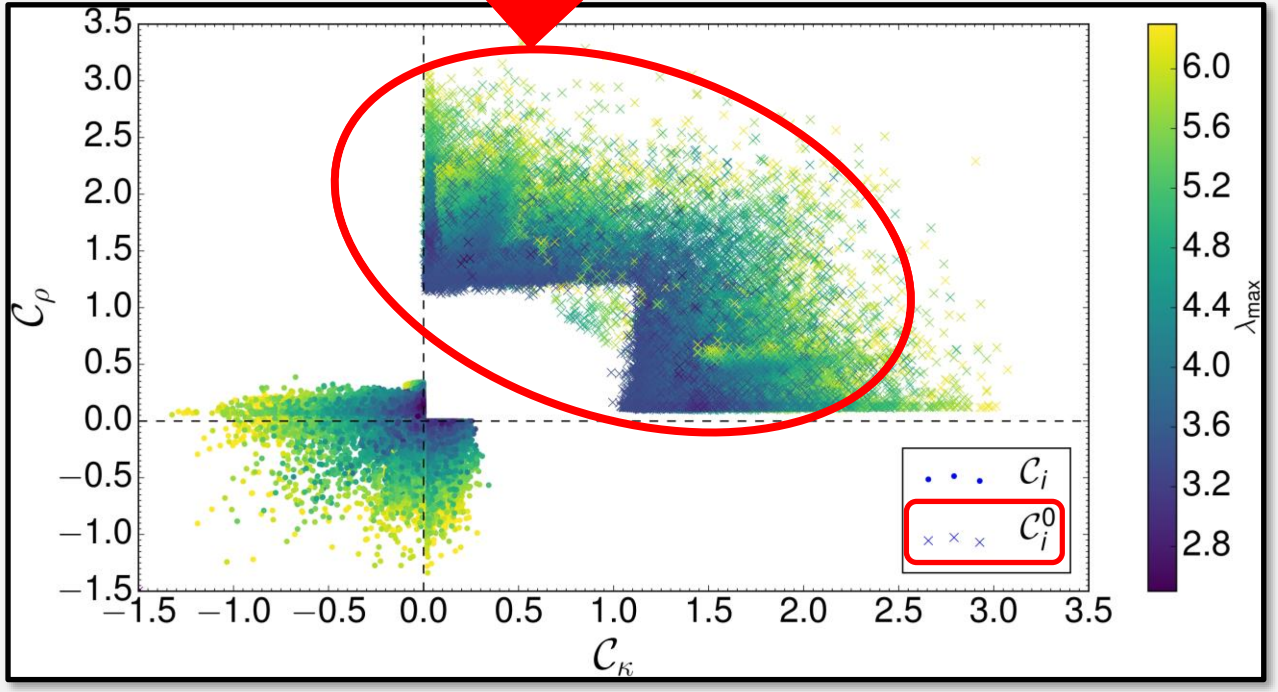
Pure 1-loop

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

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

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

naive calculation



High T SSB of $U(1)_Y$ in Zee-Babu?

Pure 1-loop

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

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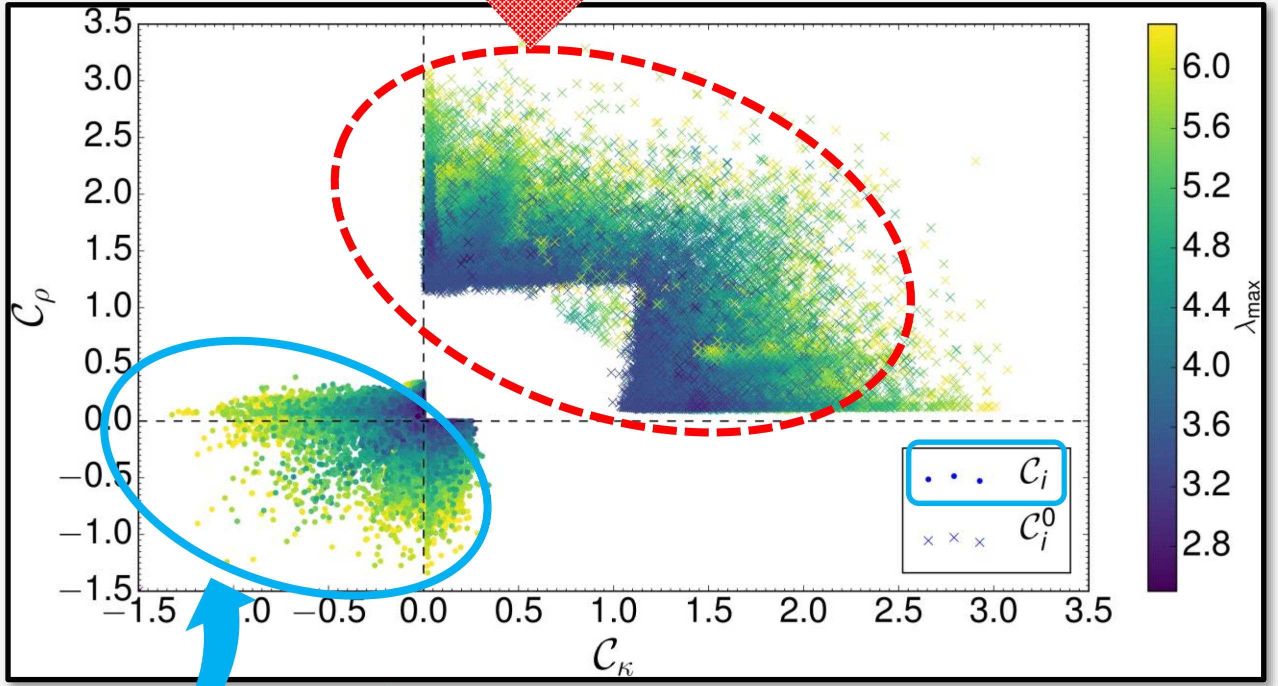
naive calculation



with daisy contributions

High T SSB of $U(1)_Y$ in Zee-Babu?

Pure 1-loop

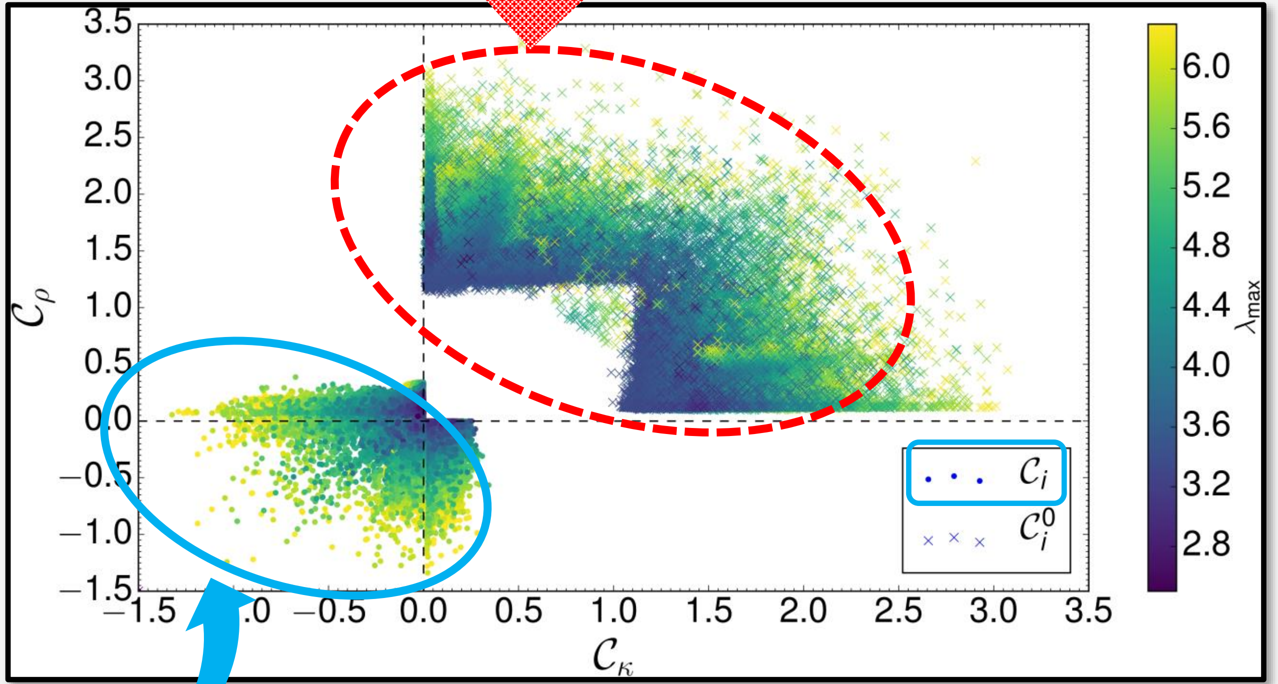
$$C_h = \frac{g'^2 + 3g^2}{32} + \frac{y_t^2}{8} + \frac{\lambda_h}{4} + \frac{\lambda_{h\kappa} + \lambda_{h\rho}}{24} \cdots + \Delta C_h$$

$$C_\kappa = \frac{g'^2}{4} + \frac{4\lambda \cdots}{} \cdots \sum_{j\neq k} |f_{jk}|^2 + \Delta C_\kappa$$

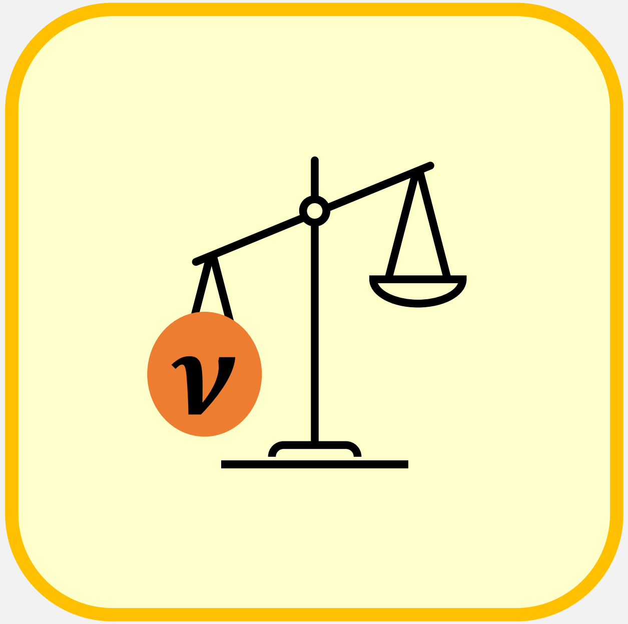
$$C_\rho = g'^2 + \frac{\cdots\lambda_\rho + 2\lambda_{h\rho} + \lambda_{\kappa\rho}}{12} + \frac{1}{24}\sum_{j,k} |g_{jk}|^2 + \Delta C_\rho$$

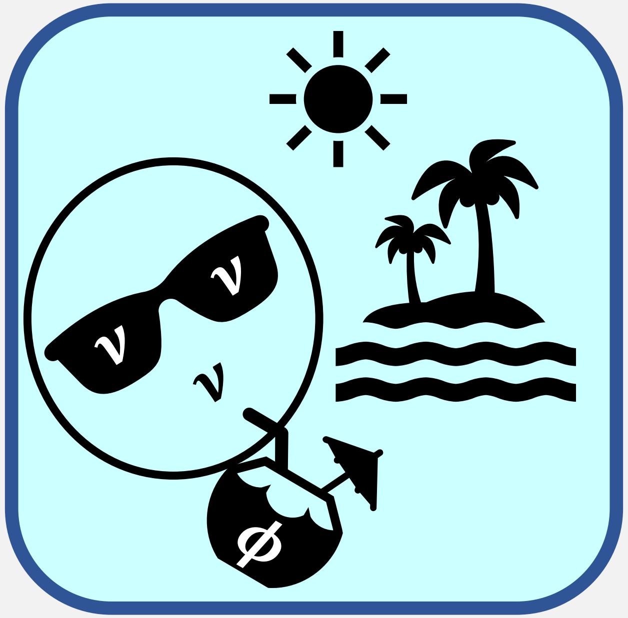
Same sets of model parameters!

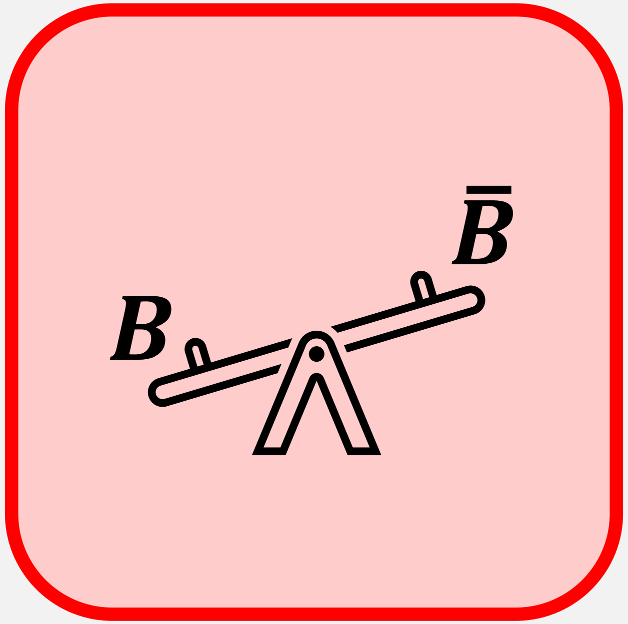
naive calculation



with daisy contributions







Baryon asymmetry

Baryogenesis

Sakharov conditions

- Baryon number violation

- *C* & *CP* violation

- Out-of-equilibrium conditions

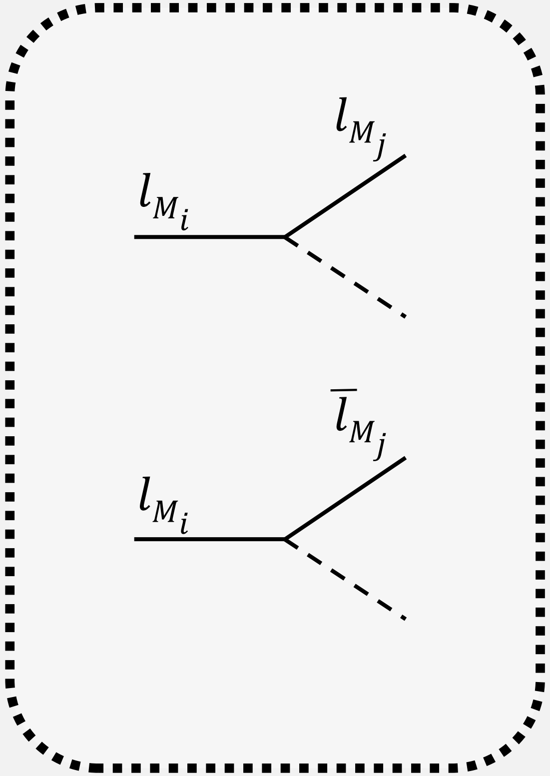
Baryogenesis

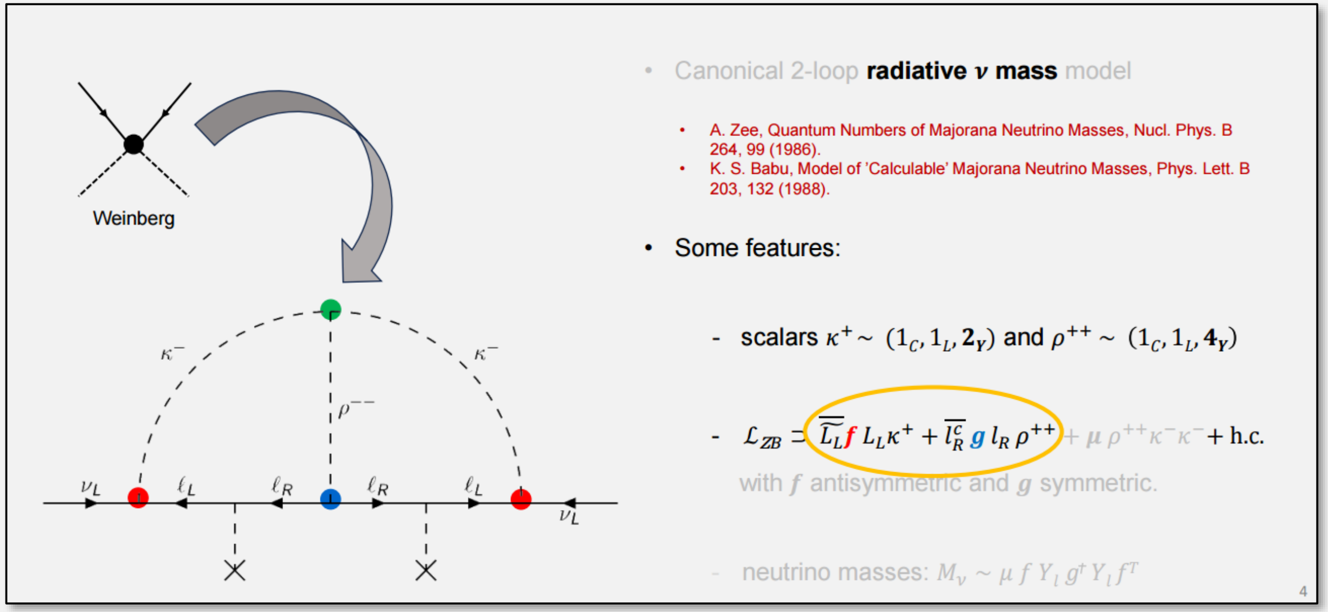
Sakharov conditions… in the SM?

- Baryon number violation (✓)
- *C* & *CP* violation ✗
- Out-of-equilibrium conditions ✗

À la Type-1 seesaw leptogenesis?

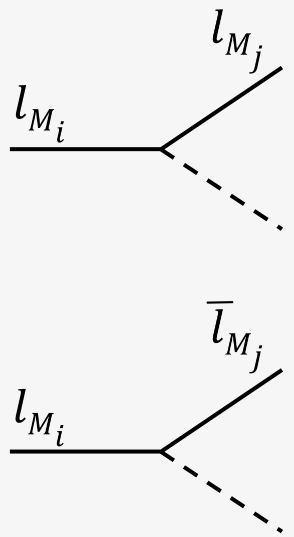
Decays out of termal equilibrium



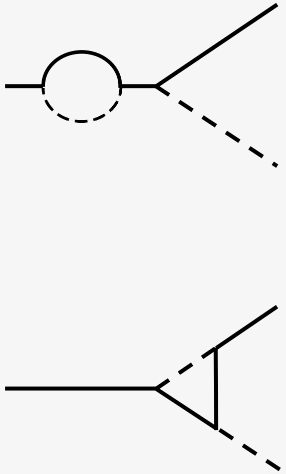


À la Type-1 seesaw leptogenesis?

Decays out of termal equilibrium



***C* & *CP* violation**



Baryon number violation

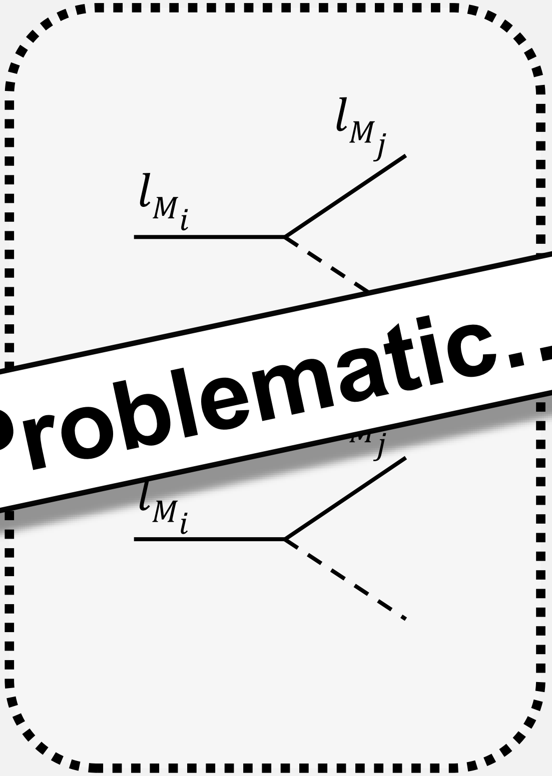
$$\Delta L \rightarrow \Delta B$$

Lepton number violation

ΔL

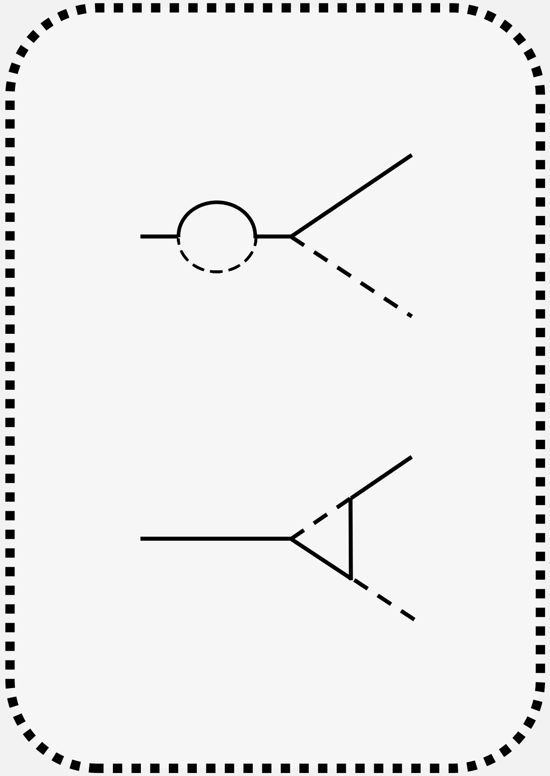
À la Type-1 seesaw leptogenesis?

Decays <u>out of termal equilibrium</u>



Problematic…

_C_ & _CP_ violation



Baryon number violation

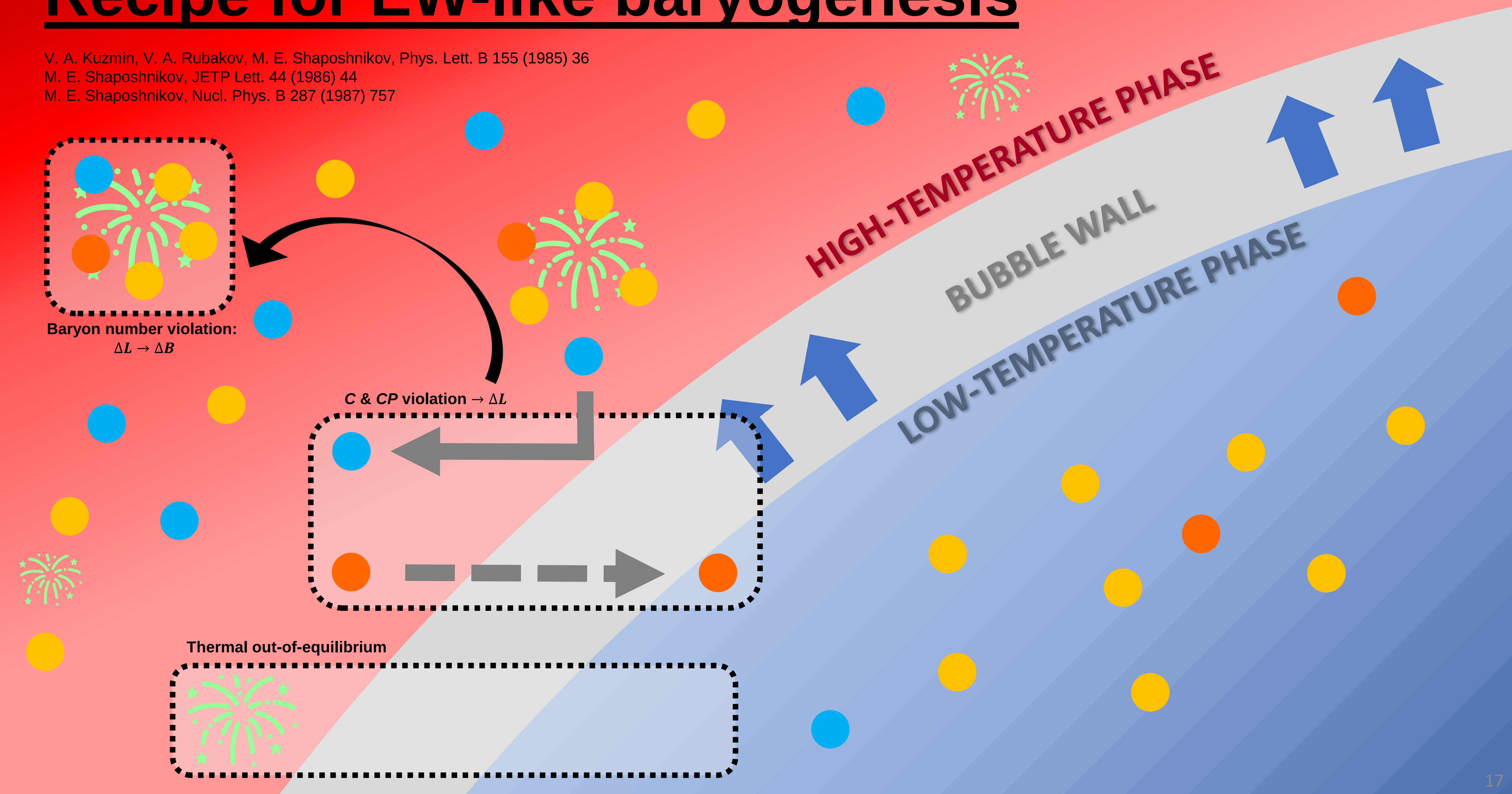
$$\Delta L \rightarrow \Delta B$$

Lepton number violation

ΔL

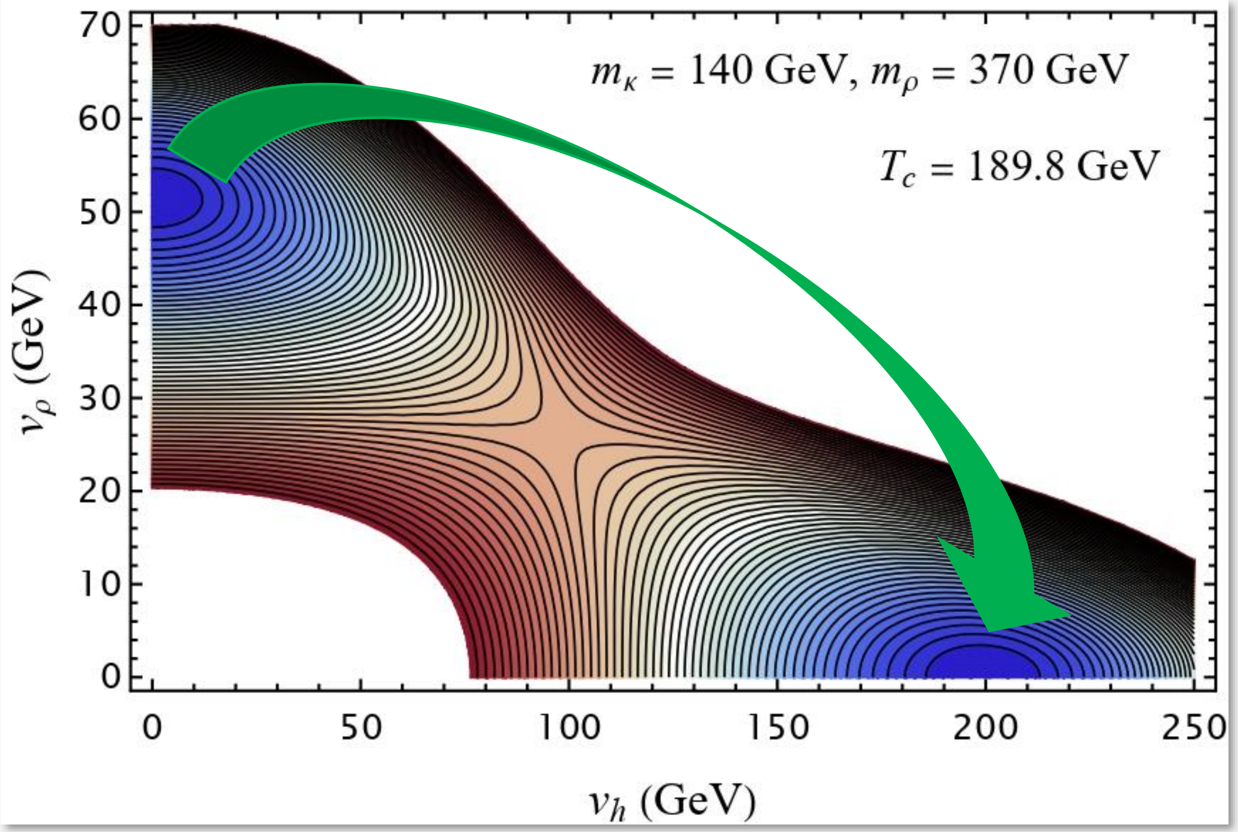
Recipe for EW-like baryogenesis

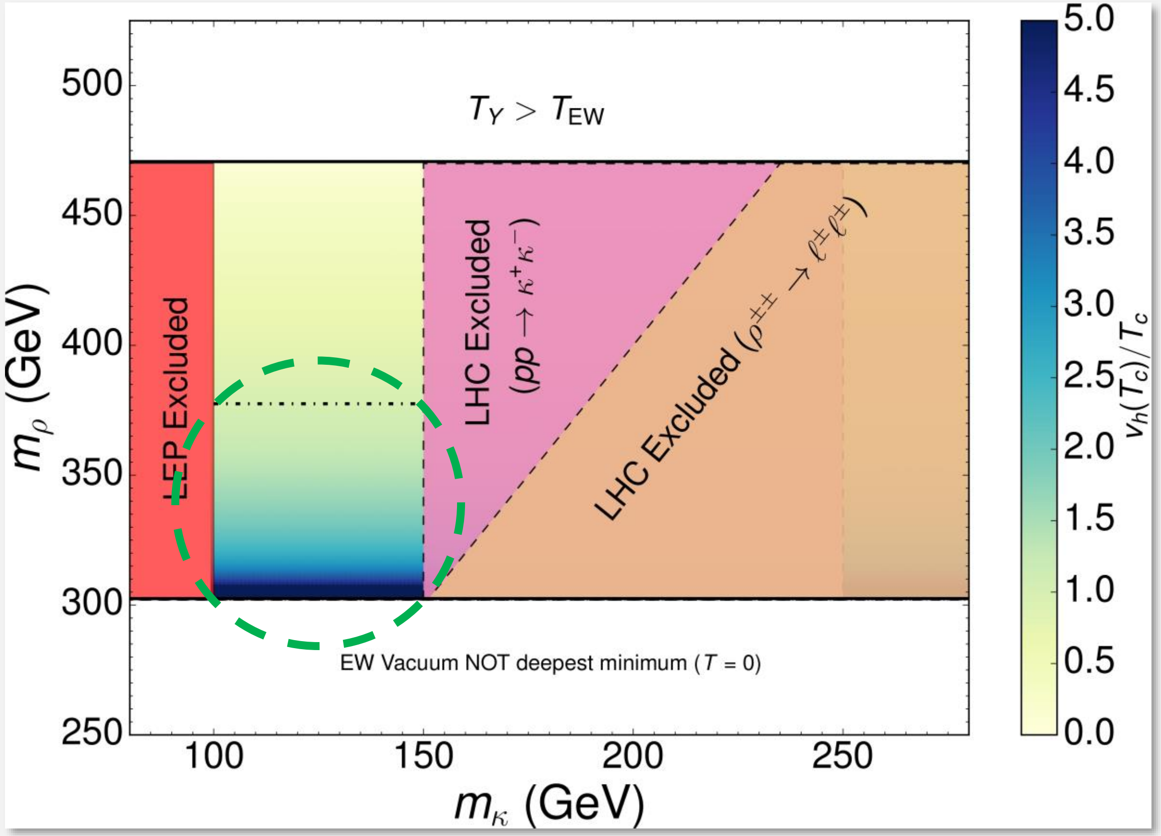
V. A. Kuzmin, V. A. Rubakov, M. E. Shaposhnikov, Phys. Lett. B 155 (1985) 36
M. E. Shaposhnikov, JETP Lett. 44 (1986) 44
M. E. Shaposhnikov, Nucl. Phys. B 287 (1987) 757



EW-like baryogenesis

	λ_κ	λ_ρ	$\lambda_{h\kappa}$	$\lambda_{h\rho}$	$\lambda_{\kappa\rho}$	C_h	C_κ	C_ρ
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





EW-like baryogenesis

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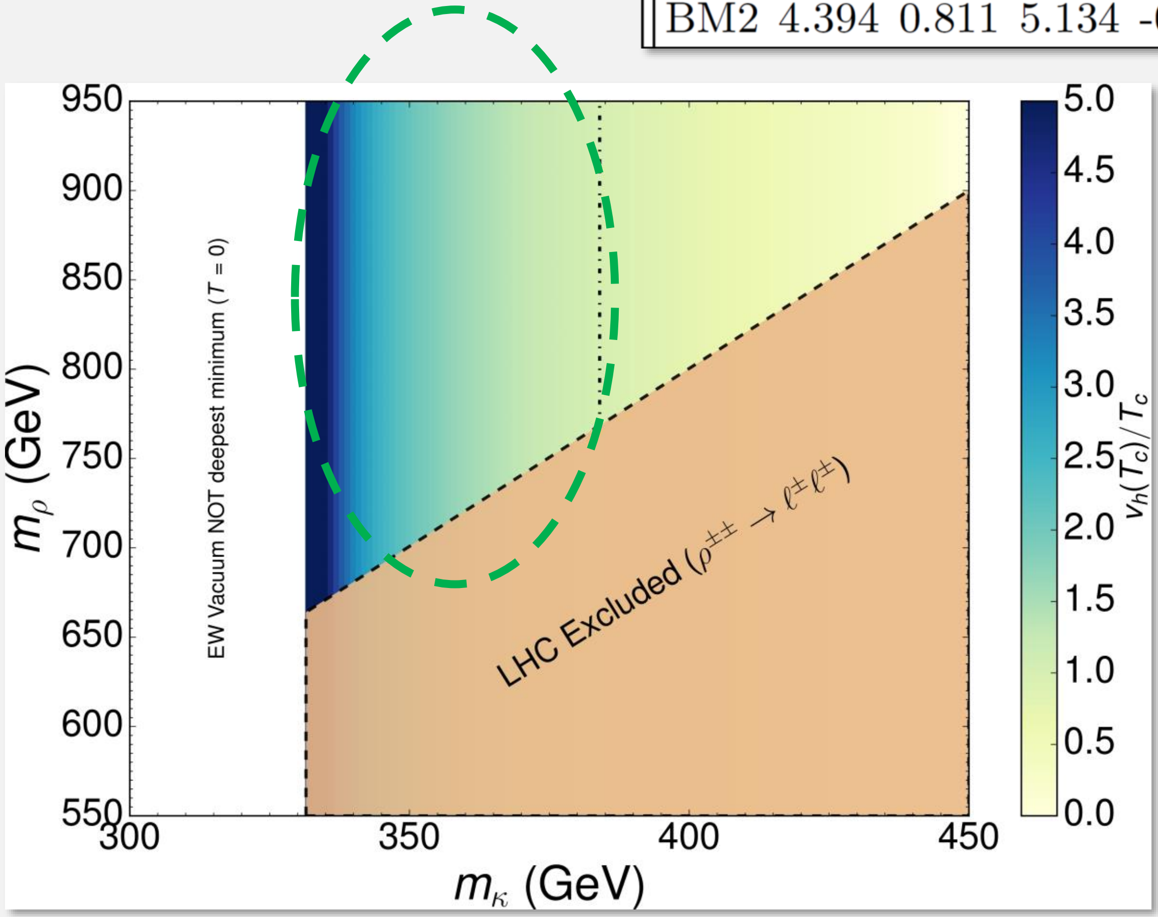
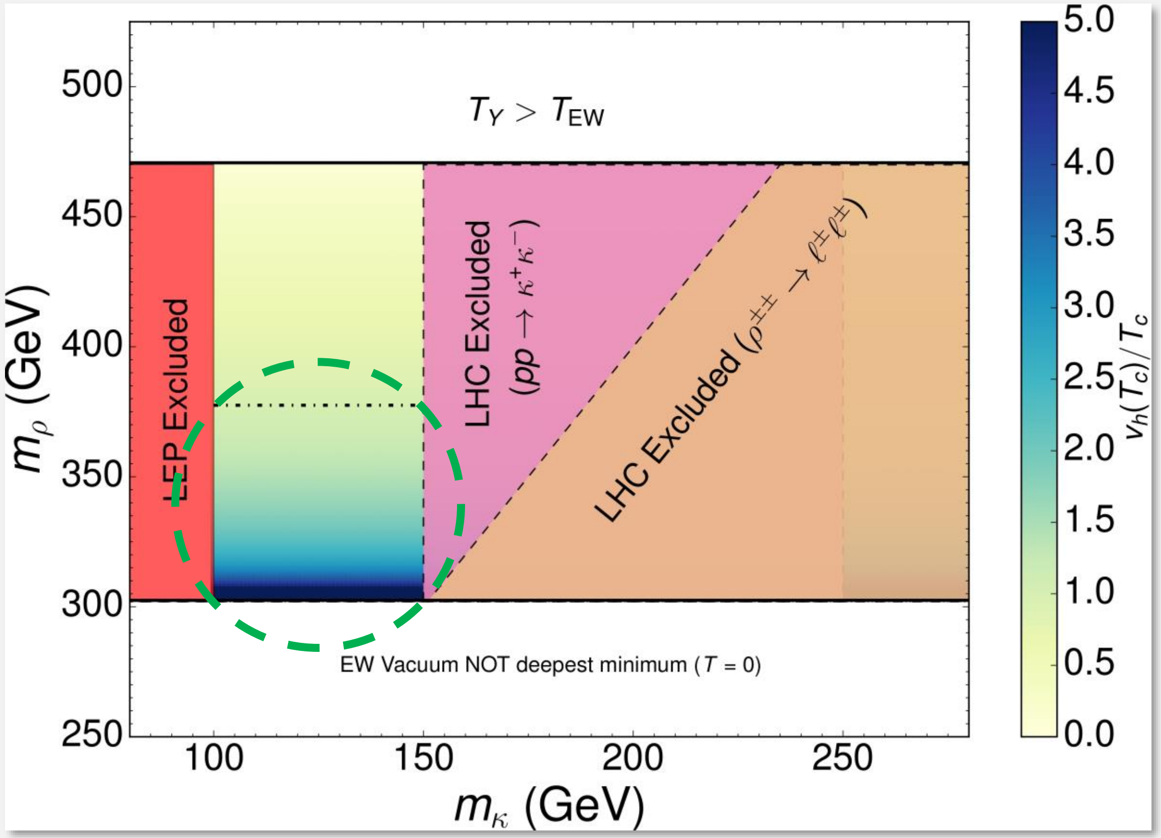
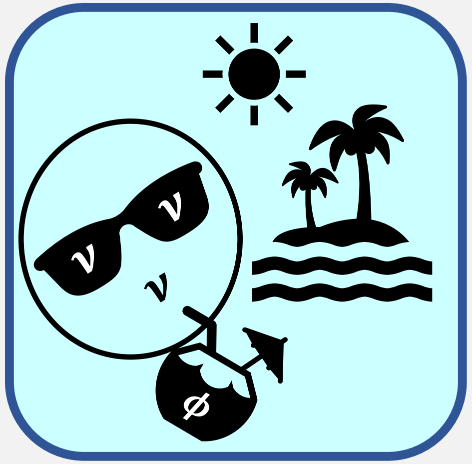
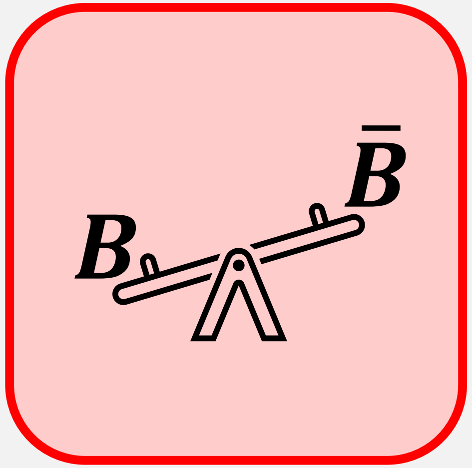




Takeaways





- ZB possesses the ingredients for **exotic early Universe** phenomenology.
- How generic to **radiative models** are these features?
- Can we generate the correct **baryon asymmetry**?

Stay tuned!

Contact: alvaro.lozano.onrubia@csic.es

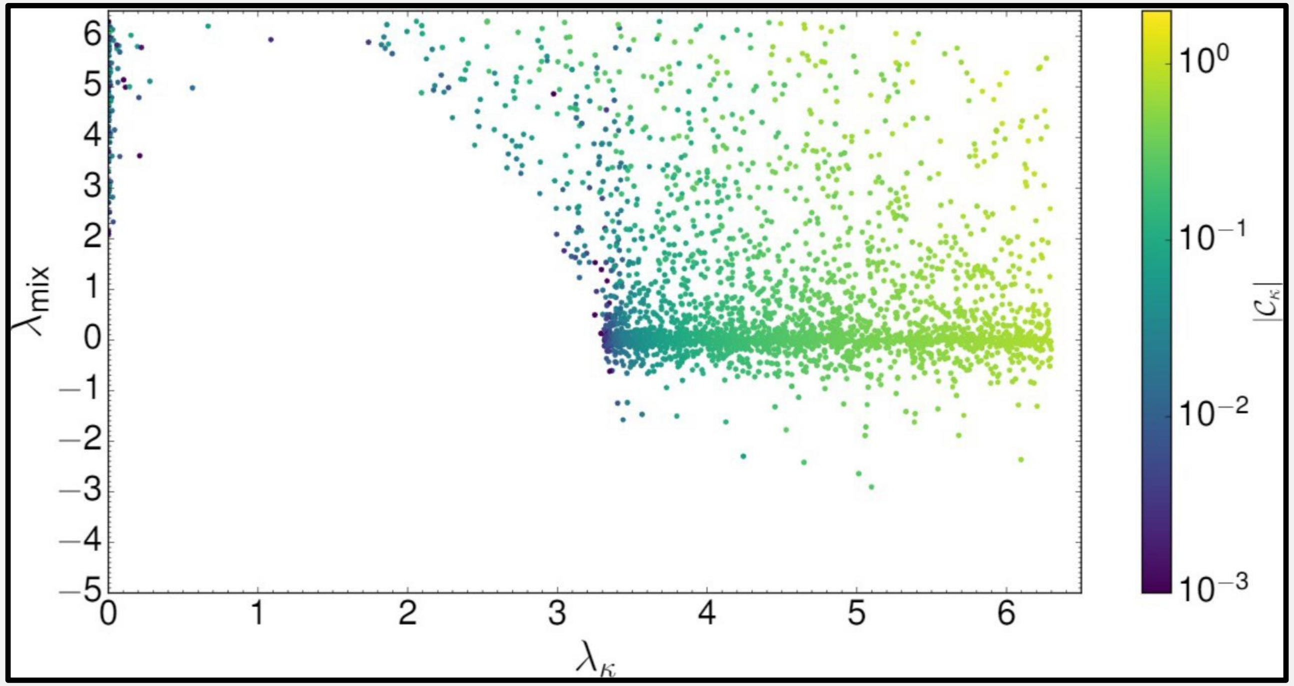
Backup

High T SSB of $U(1)_Y$ in Zee-Babu?

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

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

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



Bounds on exotic Zee-Babu Yukawas

Taken and adapted from:
Herrero-Garcia, J., Nebot, M., Rius, N., & Santamaria, A. (2014). The Zee–Babu model revisited in the light of new data. *Nuclear Physics B*, *885*, 542-570.

Process	Experiment (90% CL)	Bound (90% CL)
$\mu^- \to e^+ e^- e^-$	BR$< 1.0 \times 10^{-12}$	$\lvert g_{e\mu} g^*_{ee}\rvert < 2.3 \times 10^{-5} \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to e^+ e^- e^-$	BR$< 2.7 \times 10^{-8}$	$\lvert g_{e\tau} g^*_{ee}\rvert < 0.009 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to e^+ e^- \mu^-$	BR$< 1.8 \times 10^{-8}$	$\lvert g_{e\tau} g^*_{e\mu}\rvert < 0.005 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to e^+ \mu^- \mu^-$	BR$< 1.7 \times 10^{-8}$	$\lvert g_{e\tau} g^*_{\mu\mu}\rvert < 0.007 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to \mu^+ e^- e^-$	BR$< 1.5 \times 10^{-8}$	$\lvert g_{\mu\tau} g^*_{ee}\rvert < 0.007 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to \mu^+ e^- \mu^-$	BR$< 2.7 \times 10^{-8}$	$\lvert g_{\mu\tau} g^*_{e\mu}\rvert < 0.007 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to \mu^+ \mu^- \mu^-$	BR$< 2.1 \times 10^{-8}$	$\lvert g_{\mu\tau} g^*_{\mu\mu}\rvert < 0.008 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\mu^+ e^- \to \mu^- e^+$	$G_{M\bar{M}} < 0.003 G_F$	$\lvert g_{ee} g^*_{\mu\mu}\rvert < 0.2 \left(\frac{m_k}{\text{TeV}}\right)^2$

Table 1: Constraints from tree-level lepton flavour violation [1].

SM Test	Experiment	Bound (90%CL)
lept./hadr. univ.	$\sum_{q=d,s,b} \lvert V^{exp}_{uq}\rvert^2 = 0.9999 \pm 0.0006$	$\lvert f_{e\mu}\rvert^2 < 0.007 \left(\frac{m_h}{\text{TeV}}\right)^2$
μ/e universality	$\frac{G^{exp}_\mu}{G^{exp}_e} = 1.0010 \pm 0.0009$	$\lvert \lvert f_{\mu\tau}\rvert^2 - \lvert f_{e\tau}\rvert^2 \rvert < 0.024 \left(\frac{m_h}{\text{TeV}}\right)^2$
τ/μ universality	$\frac{G^{exp}_\tau}{G^{exp}_\mu} = 0.9998 \pm 0.0013$	$\lvert \lvert f_{e\tau}\rvert^2 - \lvert f_{e\mu}\rvert^2 \rvert < 0.035 \left(\frac{m_h}{\text{TeV}}\right)^2$
τ/e universality	$\frac{G^{exp}_\tau}{G^{exp}_e} = 1.0034 \pm 0.0015$	$\lvert \lvert f_{\mu\tau}\rvert^2 - \lvert f_{e\mu}\rvert^2 \rvert < 0.04 \left(\frac{m_h}{\text{TeV}}\right)^2$

Table 2: Constraints from universality of charged currents obtained combining the experimental results compiled in table 2 of [2].

Experiment	Bound (90%CL)
$\delta a_e = (12 \pm 10) \times 10^{-12}$	$r\left(\lvert f_{e\mu}\rvert^2 + \lvert f_{e\tau}\rvert^2\right) + 4\left(\lvert g_{ee}\rvert^2 + \lvert g_{e\mu}\rvert^2 + \lvert g_{e\tau}\rvert^2\right) < 5.5 \times 10^3\,(m_k/\text{TeV})^2$
$\delta a_\mu = (21 \pm 10) \times 10^{-10}$	$r\left(\lvert f_{e\mu}\rvert^2 + \lvert f_{\mu\tau}\rvert^2\right) + 4\left(\lvert g_{e\mu}\rvert^2 + \lvert g_{\mu\mu}\rvert^2 + \lvert g_{\mu\tau}\rvert^2\right) < 7.9\,(m_k/\text{TeV})^2$
$BR(\mu \to e\gamma) < 5.7 \times 10^{-13}$	$r^2 \lvert f^*_{e\tau} f_{\mu\tau}\rvert^2 + 16 \lvert g^*_{ee} g_{e\mu} + g^*_{e\mu} g_{\mu\mu} + g^*_{e\tau} g_{\mu\tau}\rvert^2 < 1.6 \times 10^{-6}\,(m_k/\text{TeV})^4$
$BR(\tau \to e\gamma) < 3.3 \times 10^{-8}$	$r^2 \lvert f^*_{e\mu} f_{\mu\tau}\rvert^2 + 16 \lvert g^*_{ee} g_{e\tau} + g^*_{e\mu} g_{\mu\tau} + g^*_{e\tau} g_{\tau\tau}\rvert^2 < 0.52\,(m_k/\text{TeV})^4$
$BR(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$	$r^2 \lvert f^*_{e\mu} f_{e\tau}\rvert^2 + 16 \lvert g^*_{e\mu} g_{e\tau} + g^*_{\mu\mu} g_{\mu\tau} + g^*_{\mu\tau} g_{\tau\tau}\rvert^2 < 0.7\,(m_k/\text{TeV})^4$

Table 3: Constraints from loop-level lepton flavour violating interactions and anomalous magnetic moments [1,3].

[1] Beringer, J., Arguin, J. F., Barnett, R. M., Copic, K., Dahl, O., Groom, D. E., ... & Shaevitz, M. H. (2012). Review of particle physics. *Physical Review D*, *86*(1).

[2] Pich, A. (2014). Precision tau physics. *Progress in Particle and Nuclear Physics*, *75*, 41-85.

[3] Adam, J., Bai, X., Baldini, A. M., Baracchini, E., Bemporad, C., Boca, G., ... & MEG Collaboration. (2013). New constraint on the existence of the μ+→ e+ γ decay. *Physical review letters*, *110*(20), 201801.