Nikhef

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SOURCE TERMS IN ELECTROWEAK BARYOGENESIS

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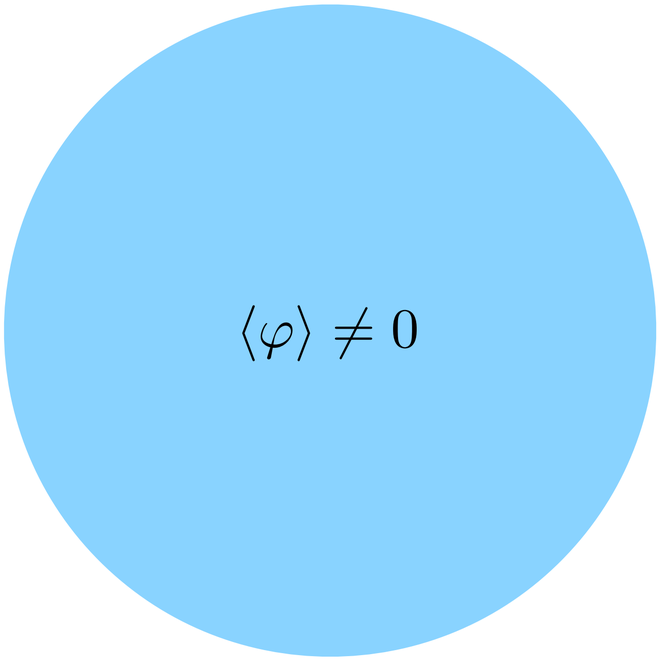
with G. White & J. v/d Vis
2107.05971, 2206.01120

Why is everything made out of matter?

BARYOGENESIS

leptogenesis, Affleck-Dine baryogenesis, pangenesis, mesongenesis, electroweak baryogenesis, Wimpy baryogenesis, GUT baryogenesis, darkogenesis, cogenesis, gravitational baryogenesis, wash-in leptogenesis, axiogenesis, scotogenesis, spontaneous baryogenesis, …

EW BARYOGENESIS IN A NUTSHELL



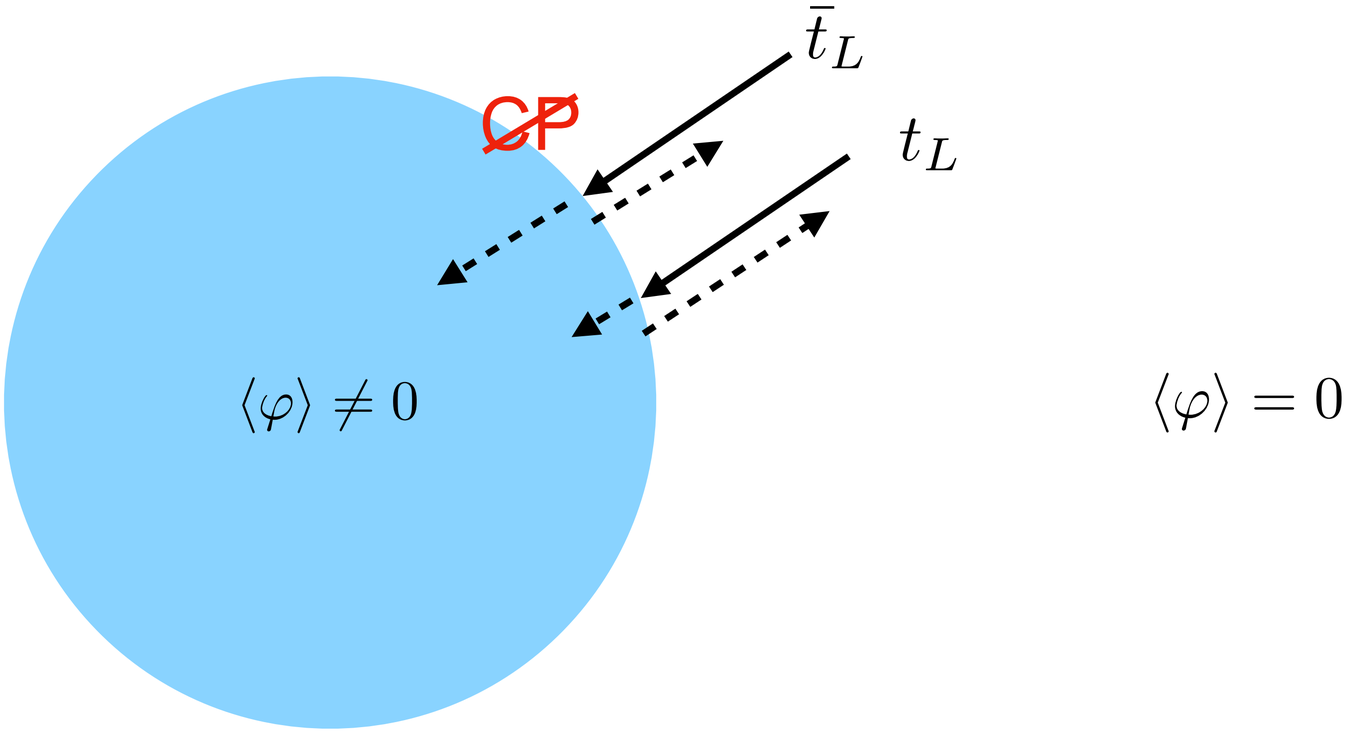
$\langle\varphi\rangle = 0$

1st order EW phase transition

EW BARYOGENESIS IN A NUTSHELL

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation



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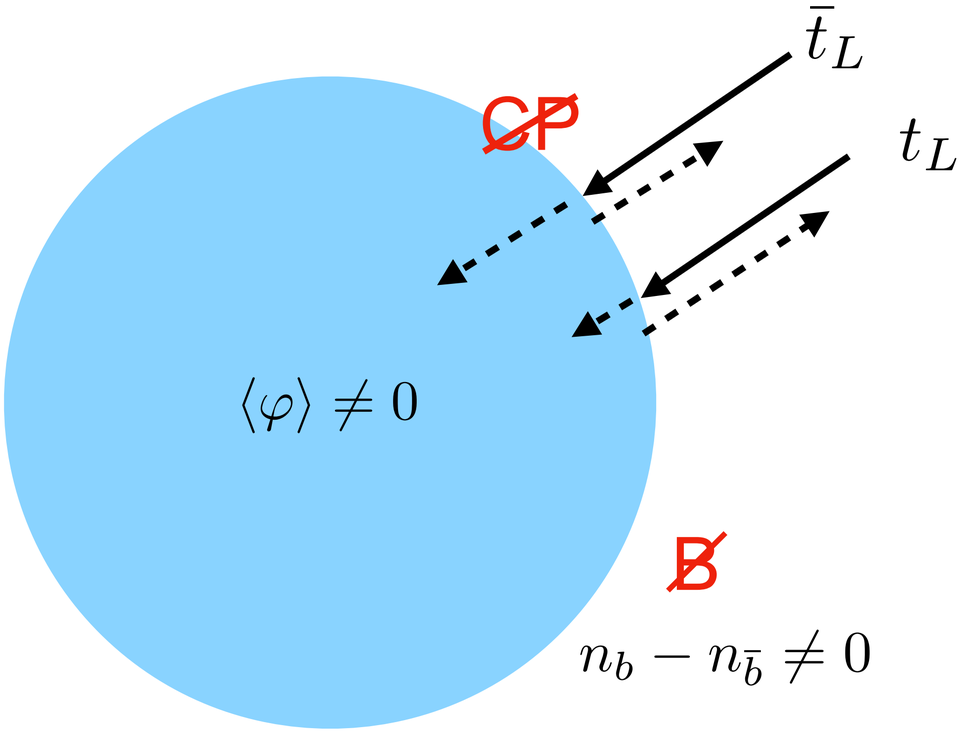

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B violation by sphalerons

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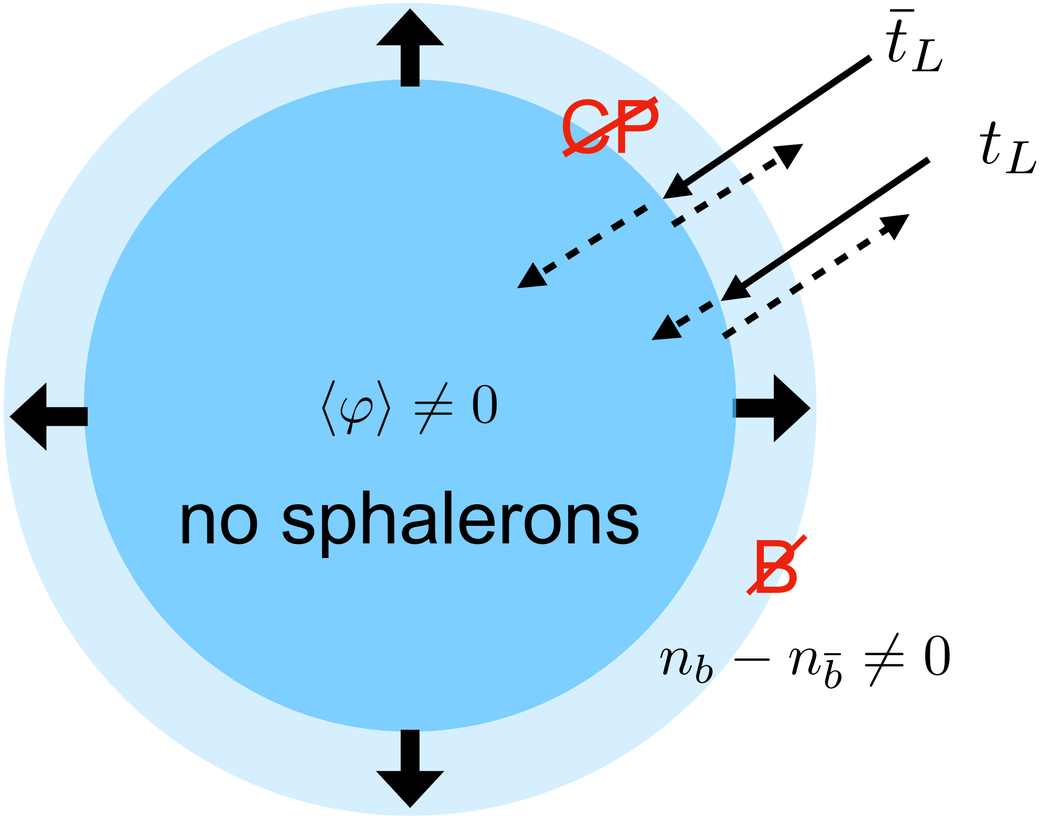


$\langle\varphi\rangle = 0$

B violation by sphalerons

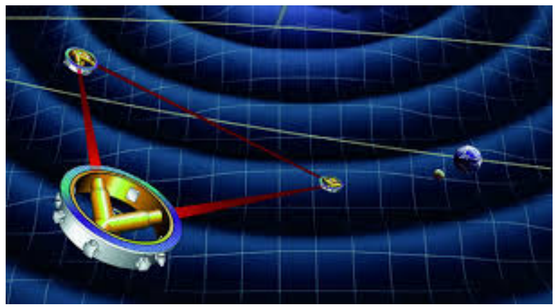
TESTING ELECTROWEAK BARYOGENESIS

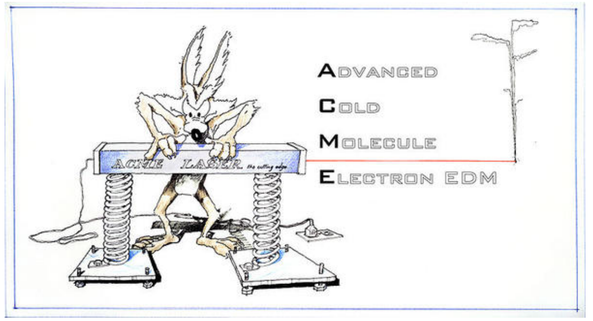
new physics at the EW scale:

- ~~CP~~ operators

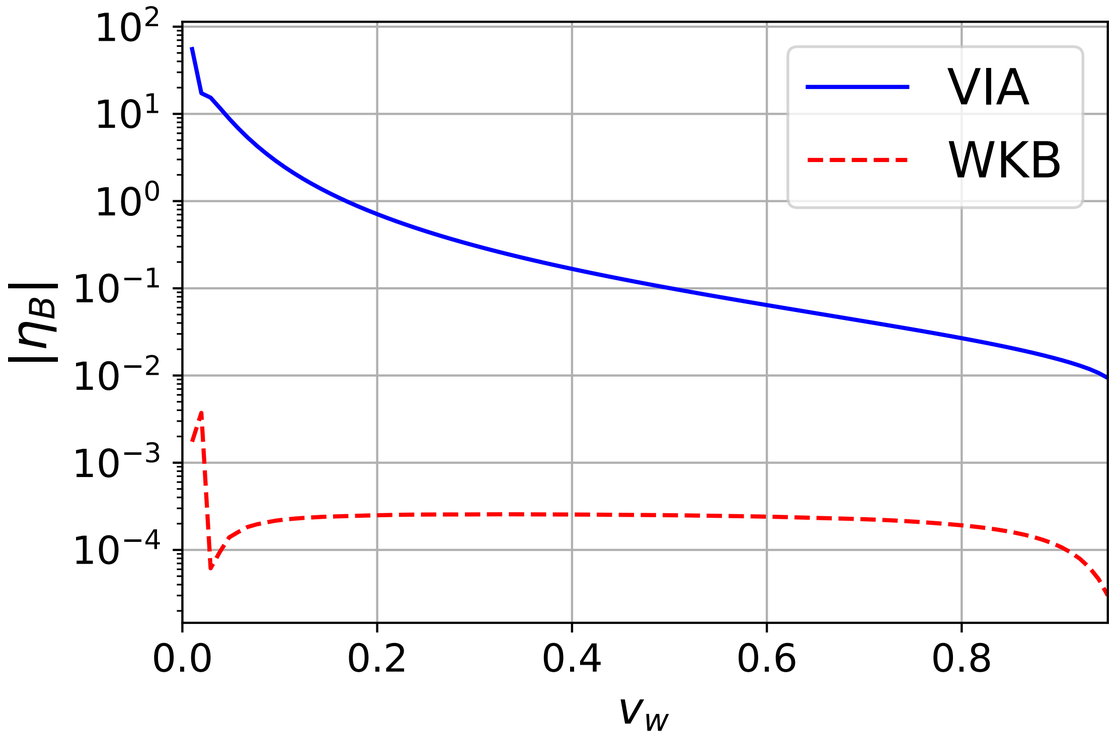
- extended Higgs sector: 1st order EW phase transition

see Lisa Biermann's talk





TESTING ELECTROWEAK BARYOGENESIS



Cline & Laurent ‘21

BOLTZMANN EQUATIONS

$$\partial f_i + \text{interactions} = \text{source}$$

BOLTZMANN EQUATIONS

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation

Source:

1. semi-classical / WKB source — Joyce, Cline, Prokopec, Kainulainen, Konstandin, Schmidt, Turok, Weinstock,…
2. flavour source — Cirigliano, Lee, Tulin, Ramsey-Musolf, Prokopec, Konstandin, Schmidt, Seco

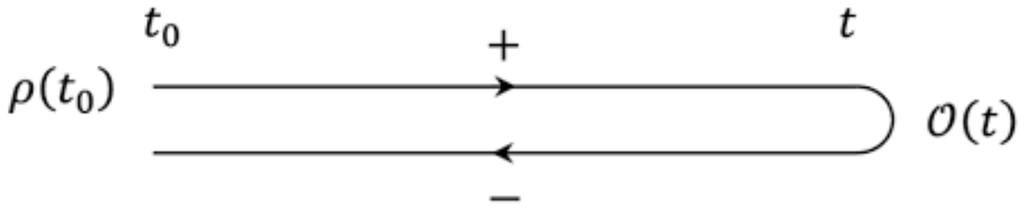
see Bahaa Ilyas' talk

3. vev-insertion-approximation (VIA) — Riotto, Cirigliano, Lee, Tulin, Ramsey-Musolf, Kainulainen

INGREDIENTS OF THE CALCULATION

CTP formalism

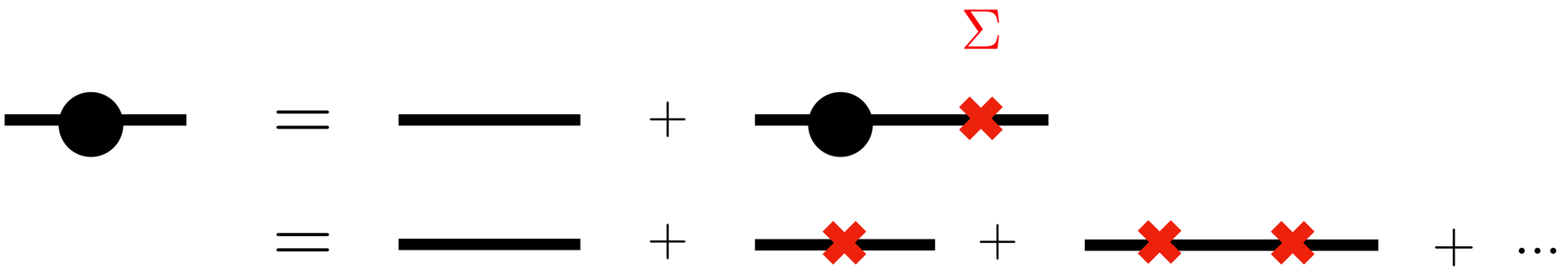
$$\langle \text{in}|\mathcal{O}(t)|\text{in}\rangle \sim$$



propagator $\quad iG = \langle \text{in}|T_{\mathcal{C}}(\psi(u)\bar{\psi}(v))|\text{in}\rangle$

INGREDIENTS OF THE CALCULATION

Schwinger-Dyson eq. $[i\not{\partial} - M]G = 1 + \Sigma \otimes G$



INGREDIENTS OF THE CALCULATION

Schwinger-Dyson eq. $[i\not{\partial} - M]G = 1 + \Sigma \otimes G$

finite temperature $\int \mathrm{d}k_0 \, G_{LL} \propto f_L$

INGREDIENTS OF THE CALCULATION

$$\{k, G^<\} = \mathrm{e}^{-i\diamond}\left(\{M, G^<\} + \{\Sigma^<, G^h\} + \frac{1}{2}([\Sigma^>, G^<] - [\Sigma^<, G^>])\right)$$

constraint eq

$$\frac{i}{2}\{\not{p}_x, G^<\} = \mathrm{e}^{-i\diamond}\left([M, G^<] + [\Sigma^<, G^h] + \frac{1}{2}(\{\Sigma^>, G^<\} - \{\Sigma^<, G^>\})\right)$$

kinetic eq

gradient expansion $\mathrm{e}^{-i\diamond} = 1 - i\diamond + \ldots$

$$\diamond(AB) = \frac{1}{2}\left(\partial_x A \cdot \partial_k B - \partial_k A \cdot \partial_x B\right)$$

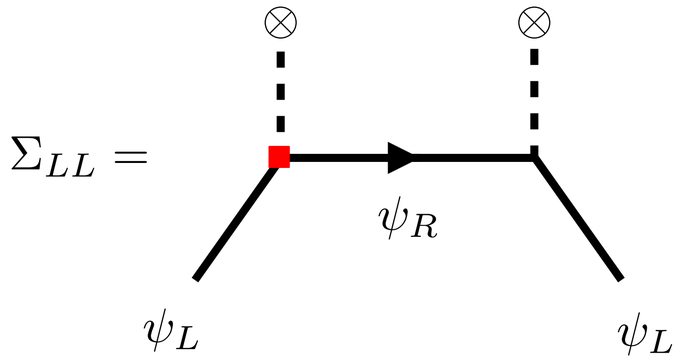
RESULTS

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation

$$S = [M, G_0^<] + [\Sigma^<, G_0^h] + \frac{1}{2}(\{\Sigma^>, G_0^<\} - \{\Sigma^<, G_0^>\})$$

old calculation



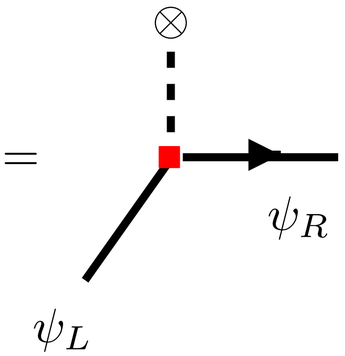
not 1PI!

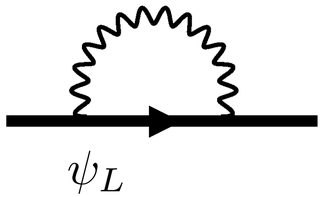
no thermal corrections

RESULTS

$$S = [M, G_0^<] + [\Sigma^<, G_0^h] + \frac{1}{2}(\{\Sigma^>, G_0^<\} - \{\Sigma^<, G_0^>\})$$

new calculation

$\Sigma_{LR} =$ 

$\Sigma_{LL} =$ 

$+\ldots$

1PI!

thermal corrections

RESULTS

$$S = [M, G_0^<] + [\Sigma^<, G_0^h] + \frac{1}{2}(\{\Sigma^>, G_0^<\} - \{\Sigma^<, G_0^>\}) = 0$$

RESULTS

$$S = [M, G_0^<] + [\Sigma^<, G_0^h] + \frac{1}{2}(\{\Sigma^>, G_0^<\} - \{\Sigma^<, G_0^>\}) = 0$$

- no need for VIA expansion (mass can be resummed)

- leading order in gradients $\sim$ constant background

- derivation in postion space, expansion is not gradient expansion

CONCLUSIONS

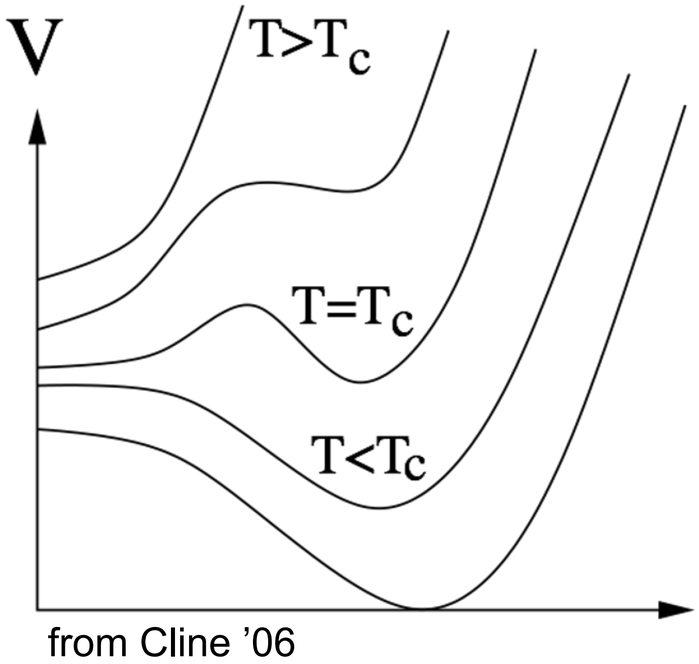
➤ EW baryogenesis is testable: precise theoretical predictions needed

➤ VIA source vanishes at leading order in gradient expansion

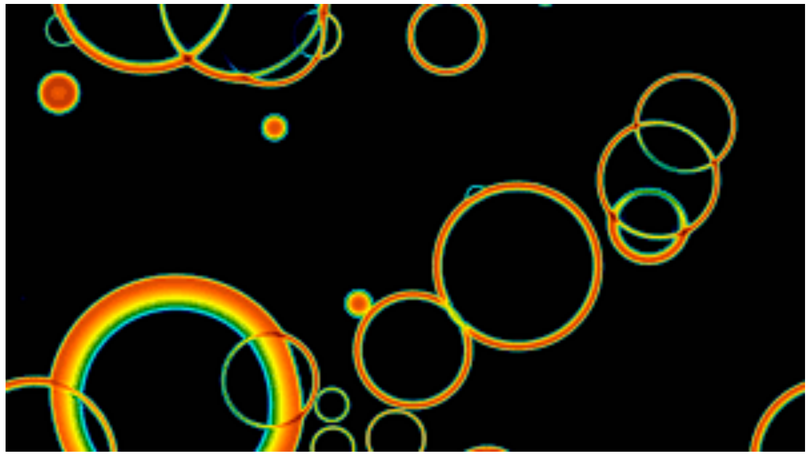
generalizes Kainulainen ’21 to chiral theories

To do: NLO (flavor source induced by thermal corrections)

EW PHASE TRANSITION



from Cline ’06

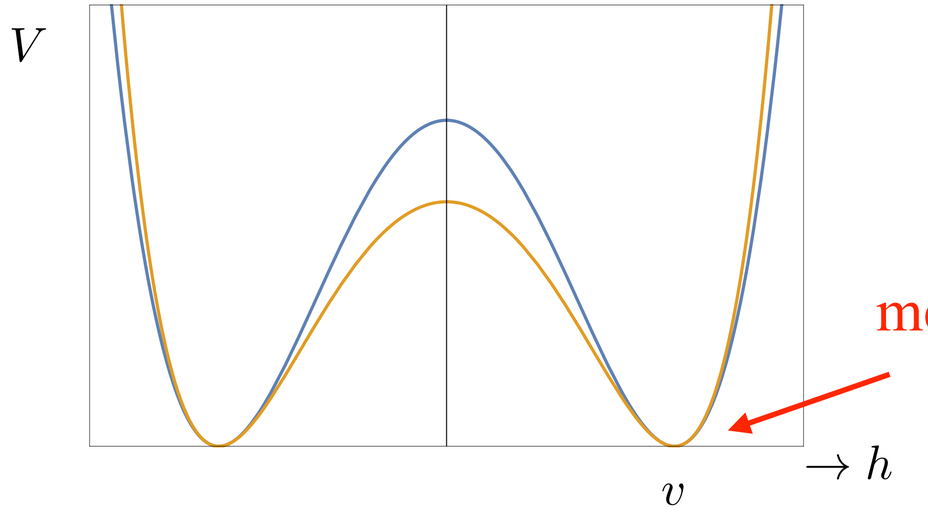


1st order

EW PHASE TRANSITION

how much room for new physics?

$$-1 \lesssim \frac{\lambda_{hhh}^{\text{BSM}}}{\lambda_{hhh}^{\text{SM}}} \lesssim 7$$



measured

$m_h = 125.3\,\text{GeV}$

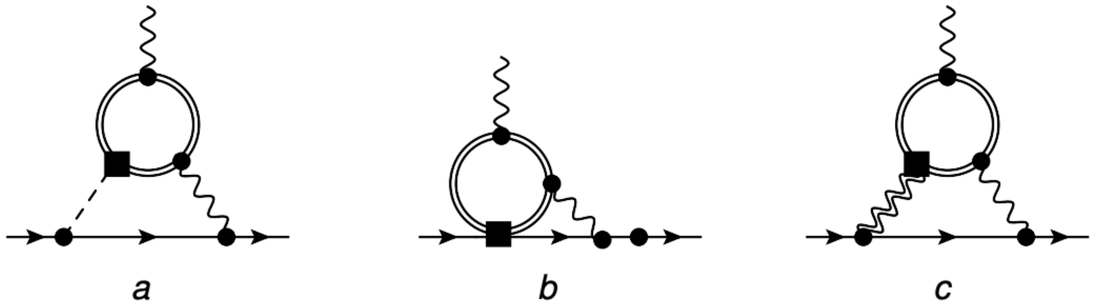
$v = 246\,\text{GeV}$

ELECTRIC DIPOLE MOMENT OF ELECTRON

measured $|d_e| \lesssim 4 \times 10^{-30}\, e\,\mathrm{cm}$

new physics $\mathcal{L} \supset \frac{y_t}{\sqrt{2}} \phi \left(1 + c\frac{\phi^2}{\Lambda^2}\right) \bar{t}_L t_R + \mathrm{h.c.}$

Rules out simplest scenarios



$\Lambda \gtrsim 10\,\mathrm{TeV}$

GRAVITATIONAL WAVES

- bubble collisions
- colliding sound waves
- turbulence