Nikhef

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SOURCE TERMS IN ELECTROWEAK BARYOGENESIS

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CERN September 2024

with G. White & J. v/d Vis

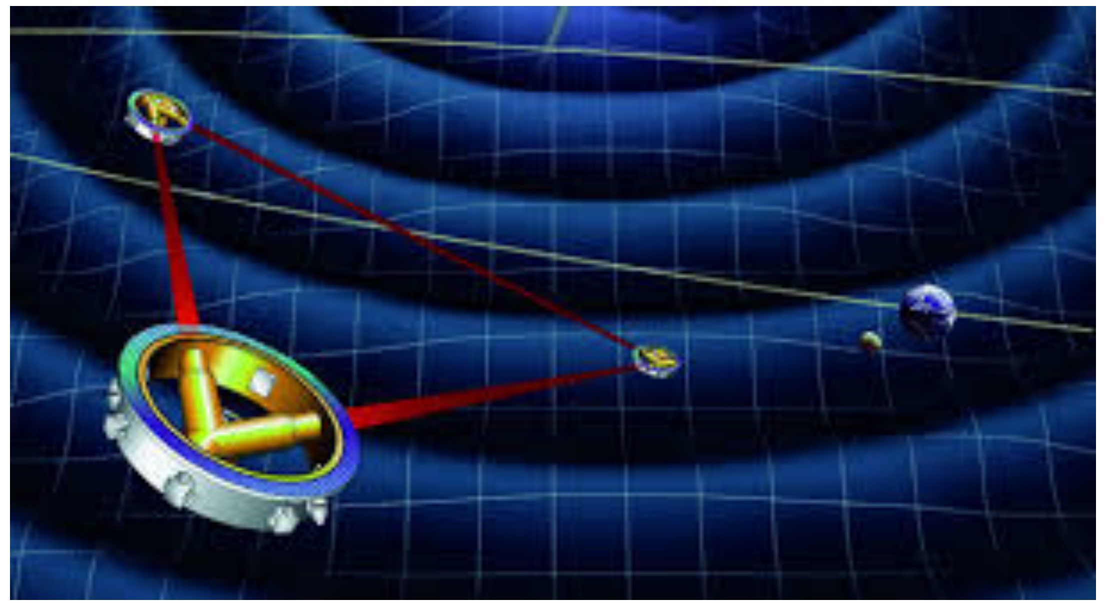
2107.05971, 2206.01120

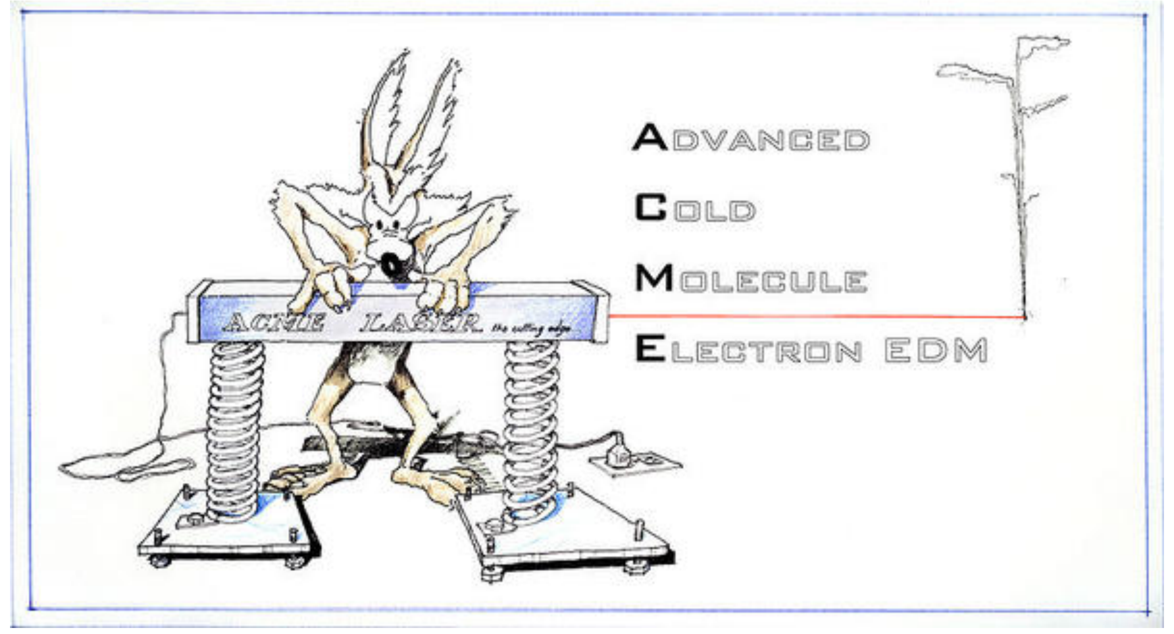
Why is everything made out of matter?

ELECTROWEAK BARYOGENESIS

new physics at the EW scale:

- $\not{CP}$ operators
- extended Higgs sector: 1st order EW phase transition





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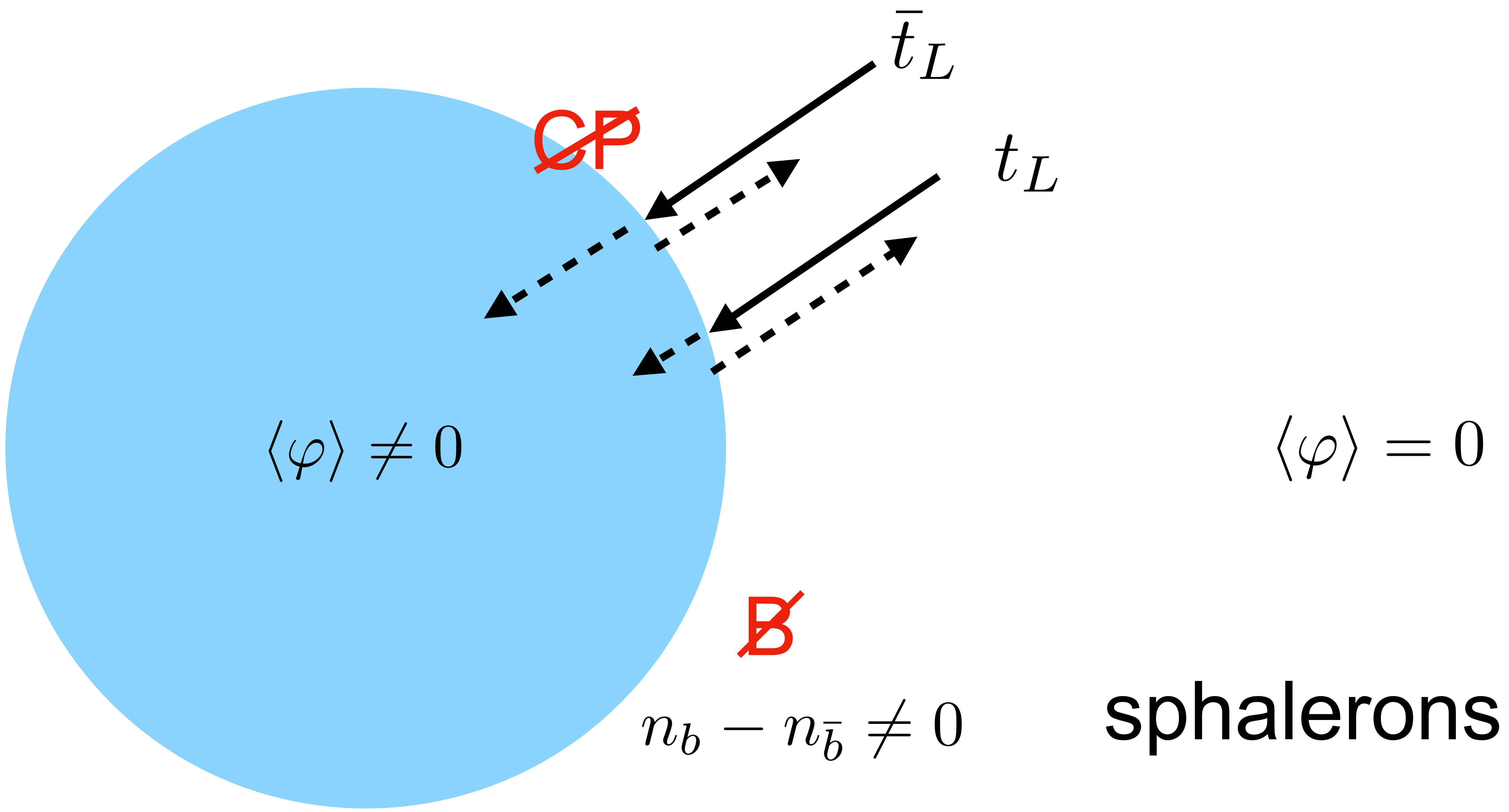
EW BARYOGENESIS IN A NUTSHELL

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

CP violation



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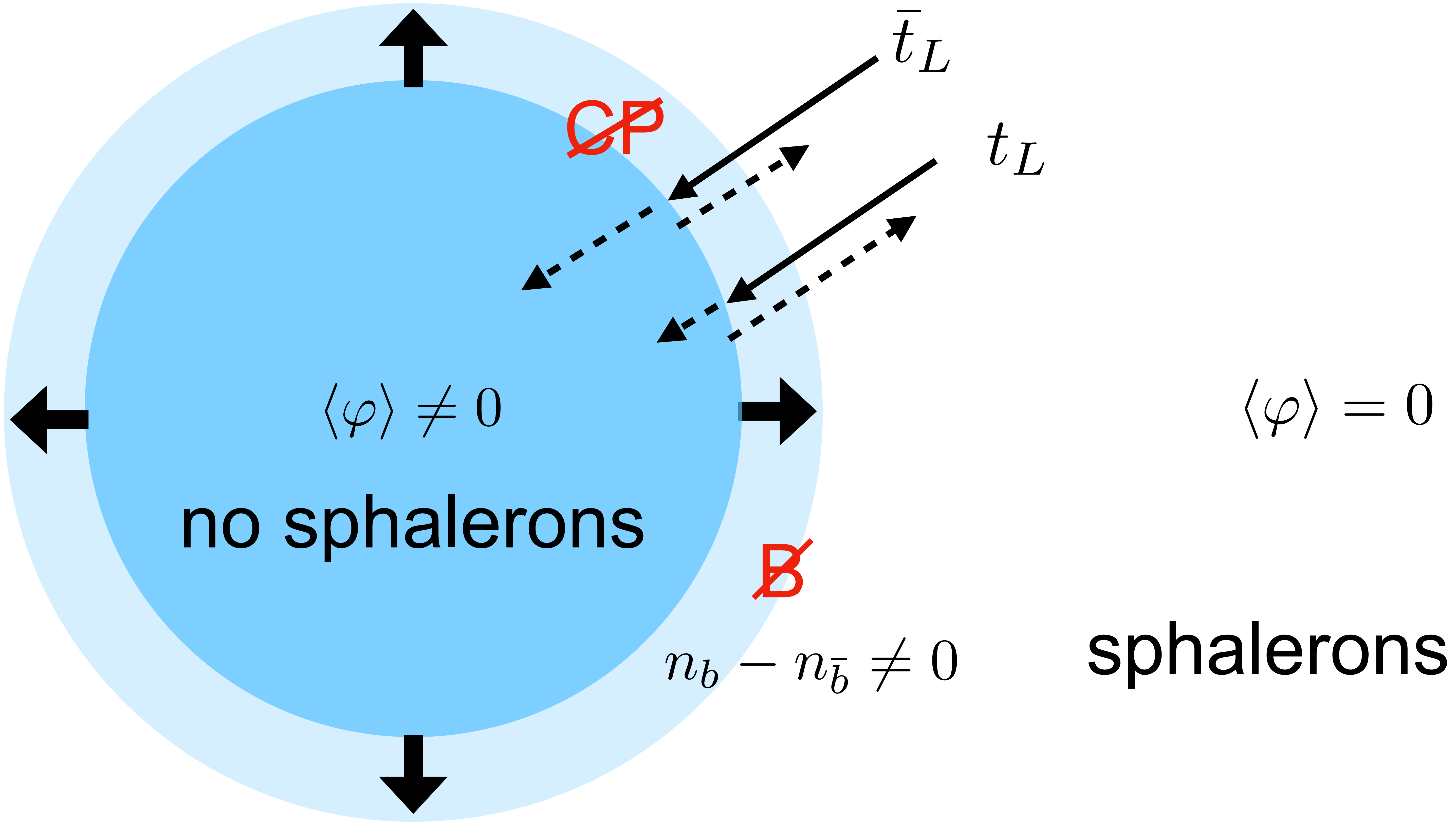


BOLTZMANN EQUATIONS

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

CP violation

Boltzmann eqs: $\partial f_i + \text{interactions} = \text{source}$

Source

1. semi-classical source
2. flavour source
3. vev-insertion-approximation (VIA)

Joyce, Cline, Prokopec, Kainulainen, Konstandin, Schmidt, Turok, Weinstock, …

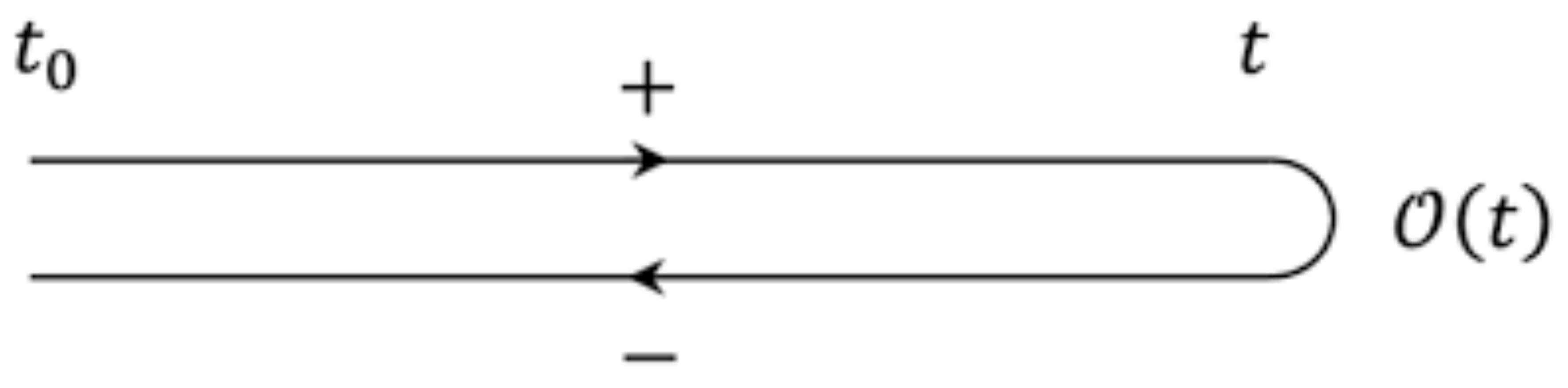
Cirigliano, Lee, Tulin, Ramsey-Musolf, Prokopec, Konstandin, Schmidt, Seco

Riotto, Cirigliano, Lee, Tulin, Ramsey-Musolf

Kainulainen ’21

INGREDIENTS OF THE CALCULATION

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



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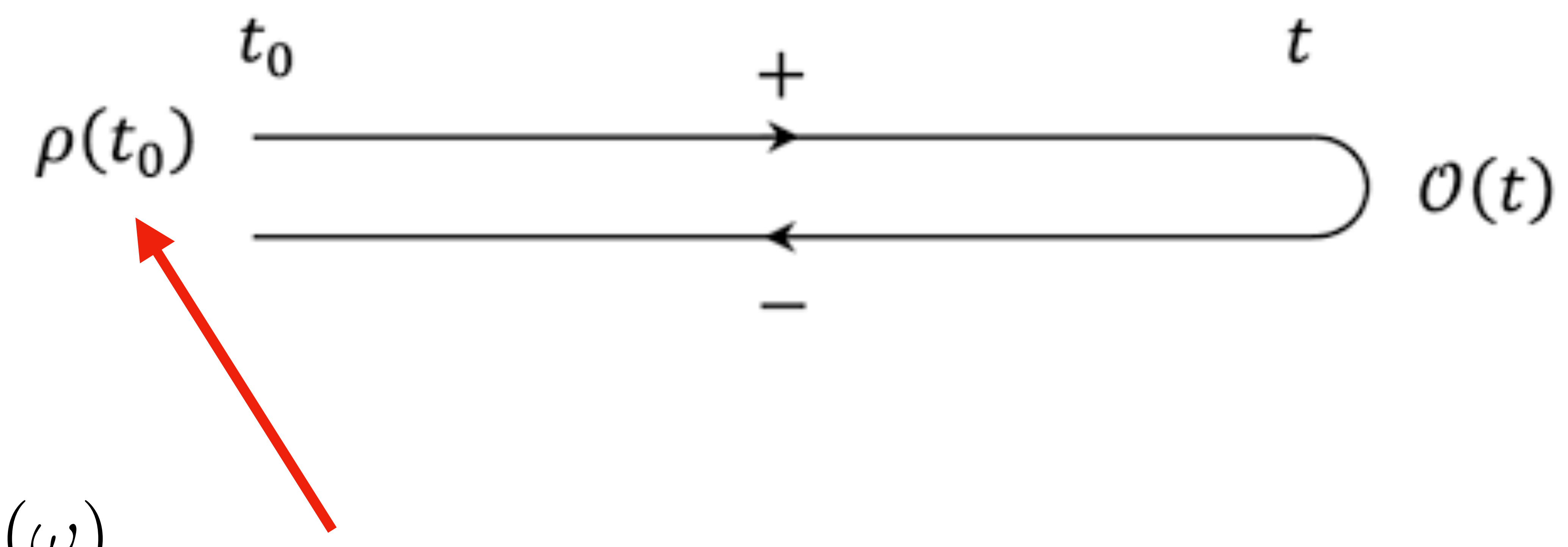

- finite temperature $\int_0^\infty \mathrm{d}k_0 (2k_0)(iG^<(k,x)) = f(\omega)$

$$x = \frac{1}{2}(u+v), \quad r = u - v$$

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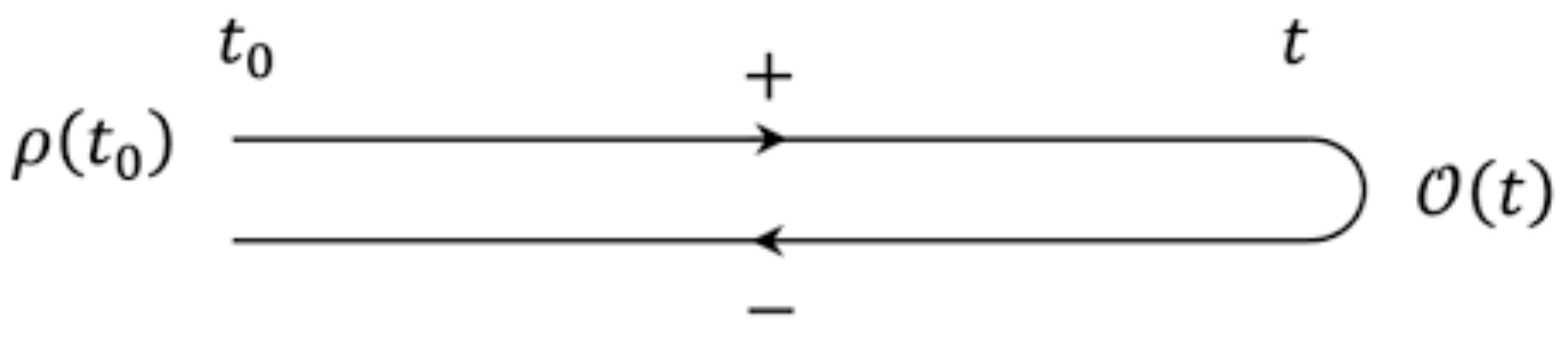

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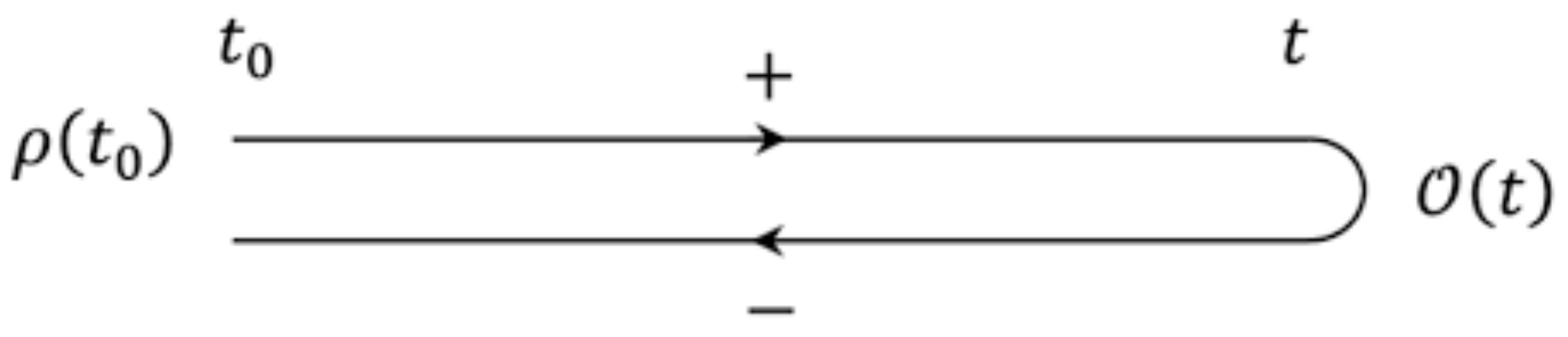

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INGREDIENTS OF THE CALCULATION

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

constraint eq

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

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

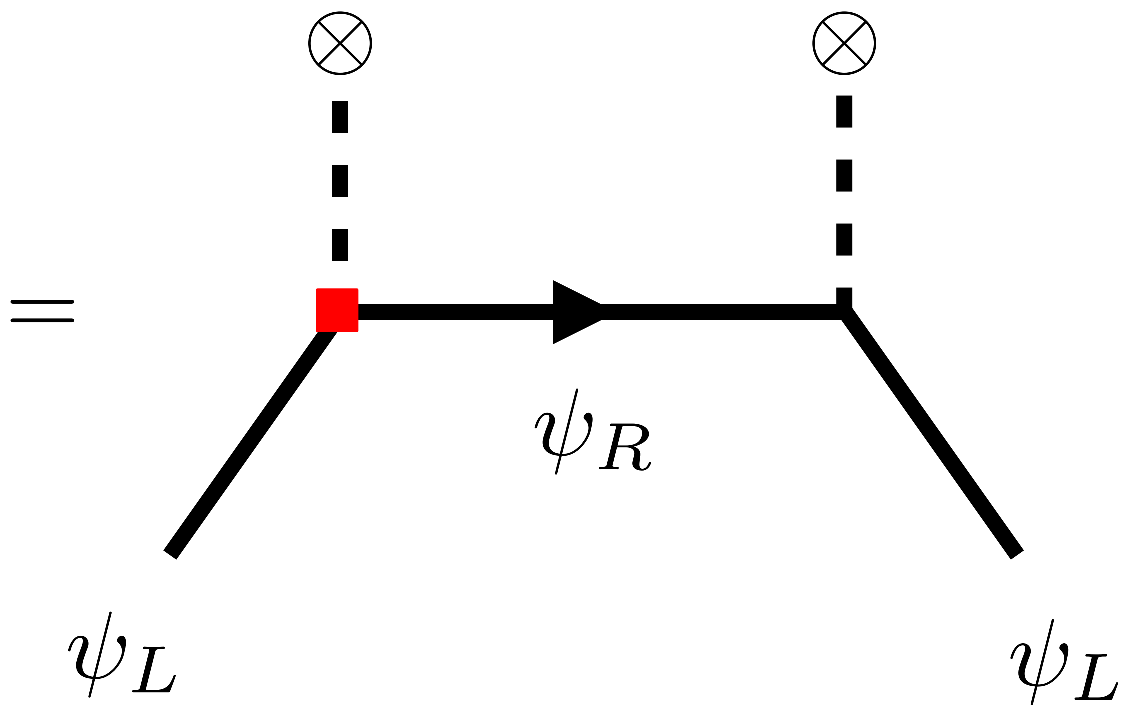
$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation

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

old calculation

$\Sigma_{LL} =$



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

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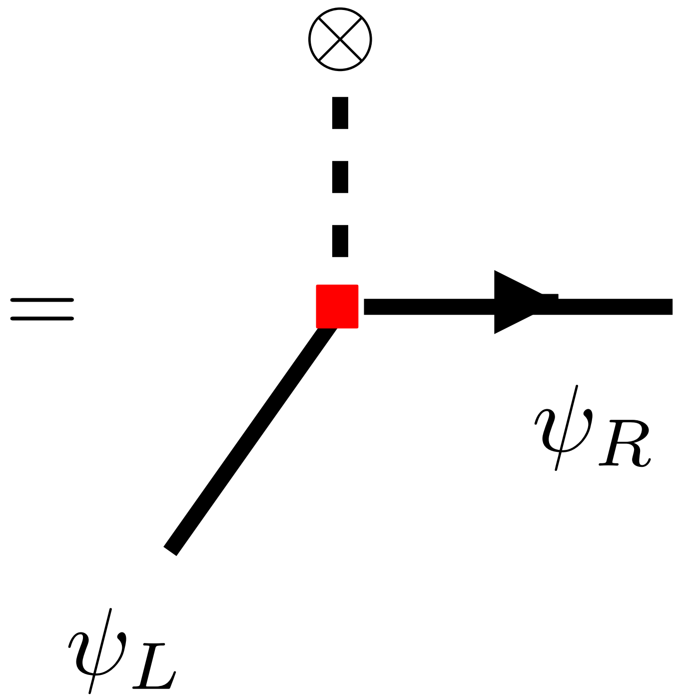

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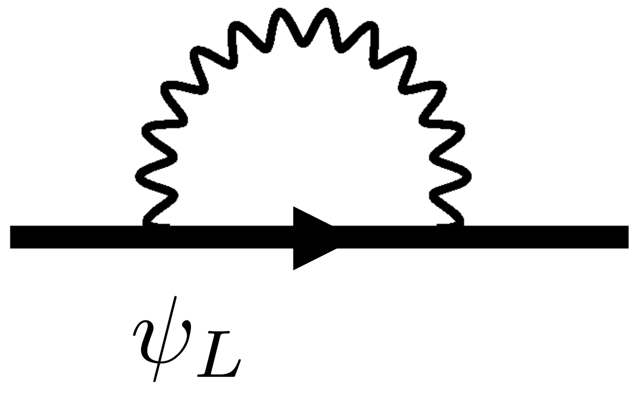

$+ \ldots$

1PI!

thermal corrections

RESULTS

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

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- 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

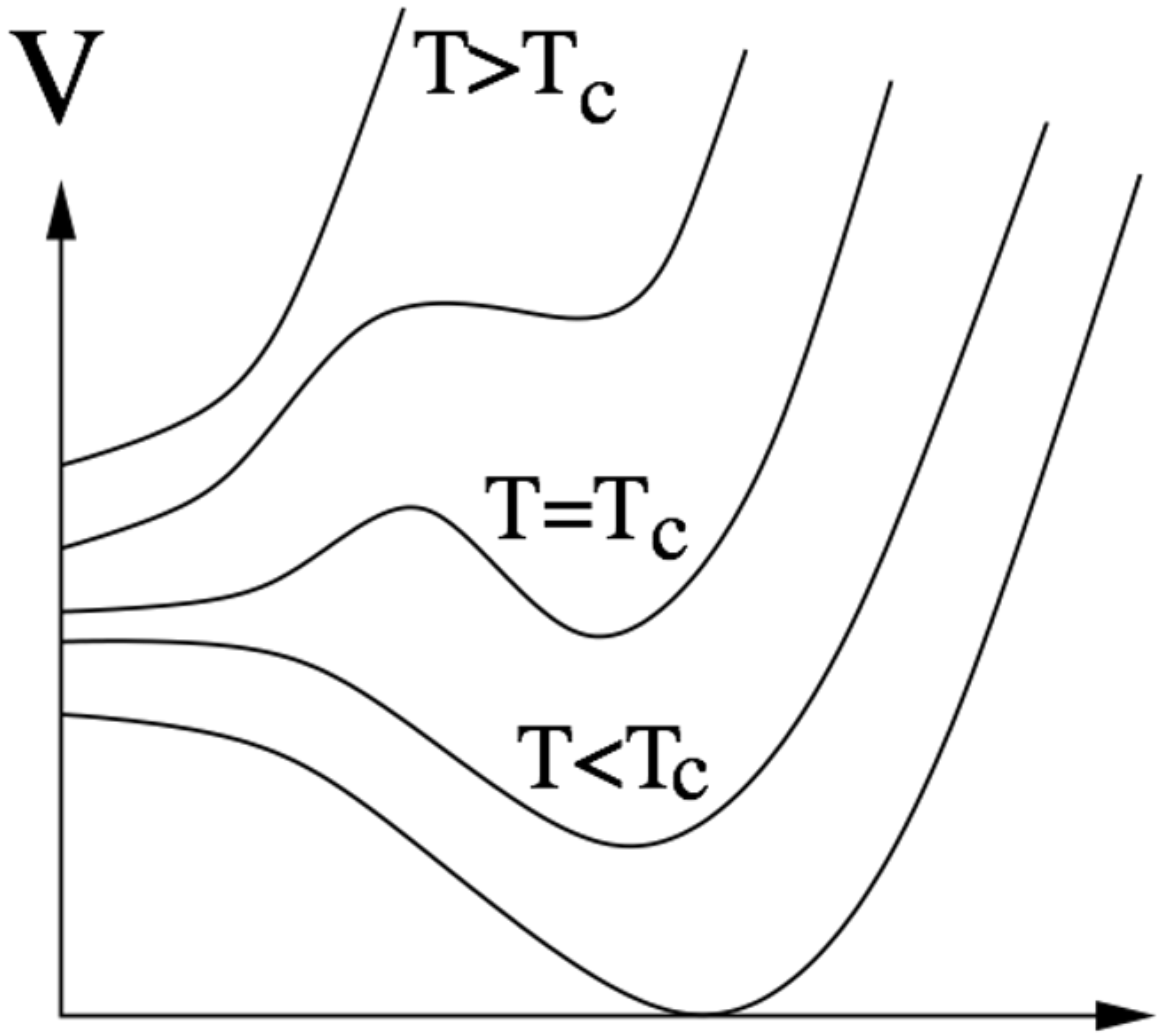
- EW baryogenesis is testable: precise theoretical predictions needed

- VIA source vanishes at leading order in gradient expansion

  generalizes Kainulainen '21 to chiral theories

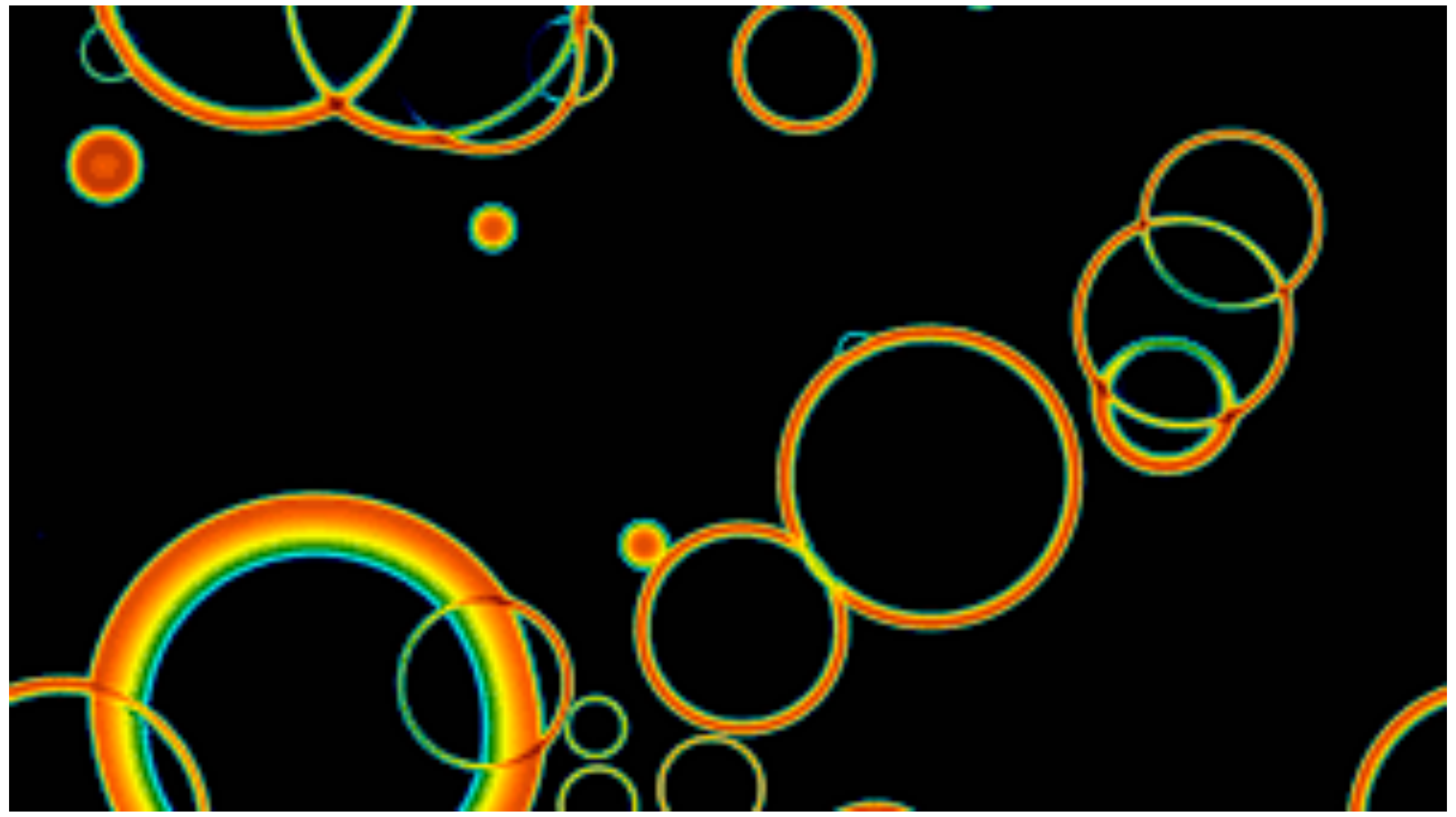
  To do: NLO (flavor source induced by thermal corrections)

EW PHASE TRANSITION



from Cline ’06

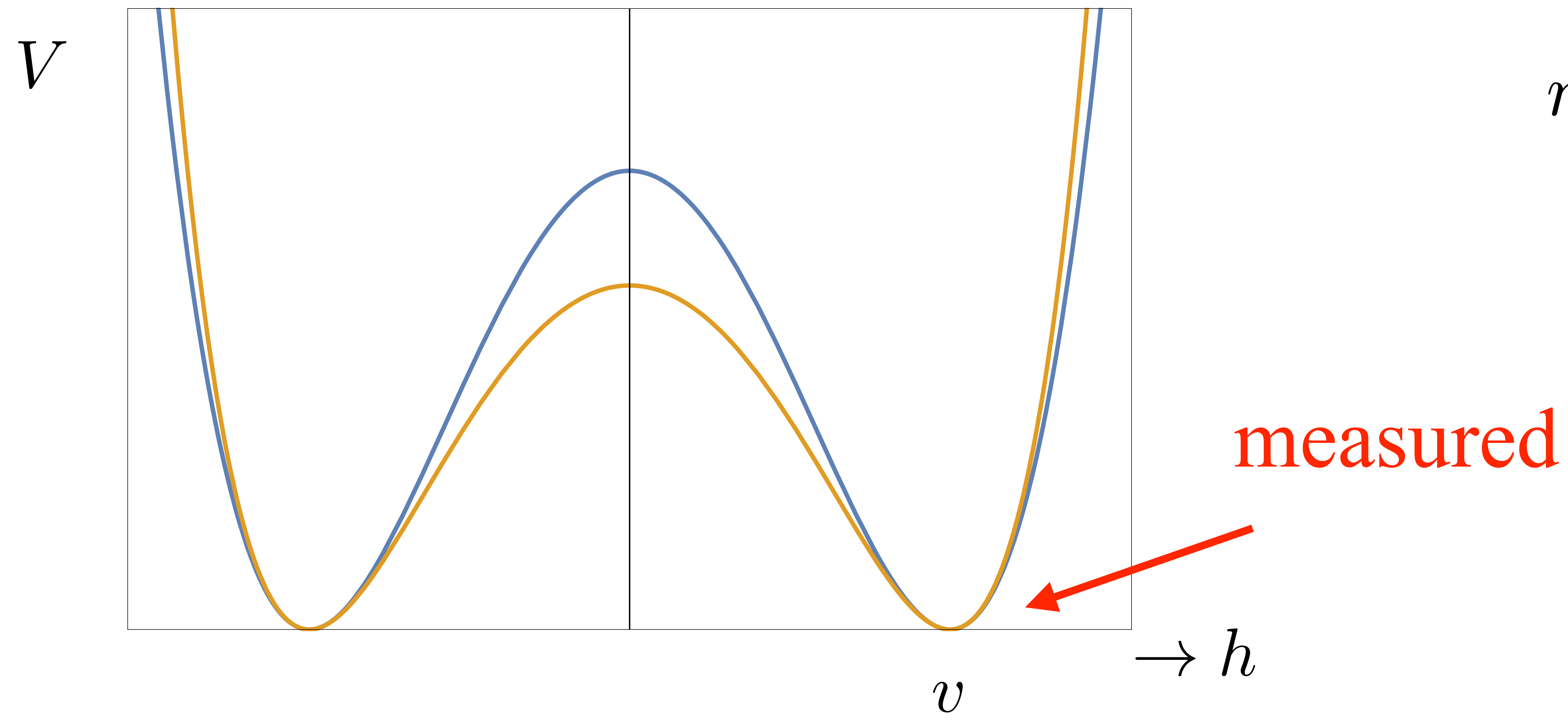
1st order



EW PHASE TRANSITION

how much room for new physics?

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



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

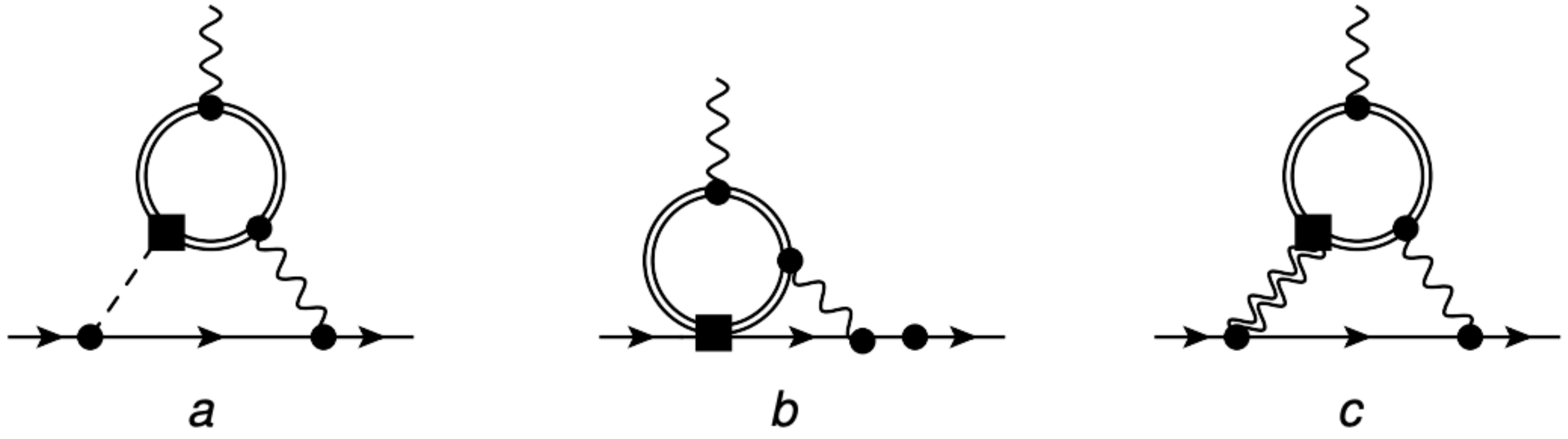
$$v = 246\,\mathrm{GeV}$$

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