NATIONAL SCIENCE CENTRE
POLAND

Naturalness-guided Search for the Origins of Matter

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University of Warsaw
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Based on:
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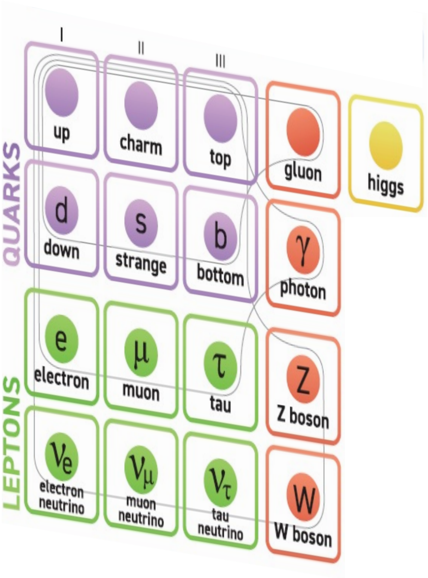
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Scalar potential

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- Higgs mechanism requires $U(4)$ to be the approximate symmetry
$|\kappa|,\ |\sigma|,\ |\rho| < \lambda.$

One-loop effective potential

$$V_{\text{eff}}(h_A, h_B, T) = V_{\text{tree}}(h_A, h_B) + {\color{blue}V_{\text{CW}}(h_A, h_B)} + {\color{red}V_{\text{therm}}(h_A, h_B, T)},$$

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- $V_{\text{CW}} =$
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- $V_{\text{therm}} = \frac{T^4}{2\pi^2}\sum_{i\in\text{bosons}} n_i \text{J}_-(\frac{m_i^2}{T^2}) - \frac{T^4}{2\pi^2}\sum_{j\in\text{fermions}} n_j \text{J}_+(\frac{m_i^2}{T^2})$

  $J_\pm(x) \equiv \int_0^\infty dk\, k^2 \log[1 \pm \exp(-\sqrt{k^2 + x})]$

One-loop effective potential

$$V_{\rm eff}(h_A,h_B,T)=V_{\rm tree}(h_A,h_B)+V_{\rm CW}(h_A,h_B)+V_{\rm therm}(h_A,h_B,T),$$

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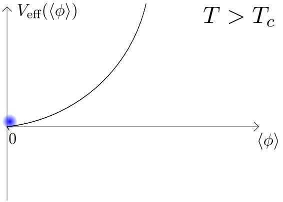
- Daisy diagrams resummation: $m_i^2\to\bar{m}_i^2=m_i^2+\Pi^2(T)$ in $V_{\rm CW}$ and $V_{\rm therm}$.

Phase transition types



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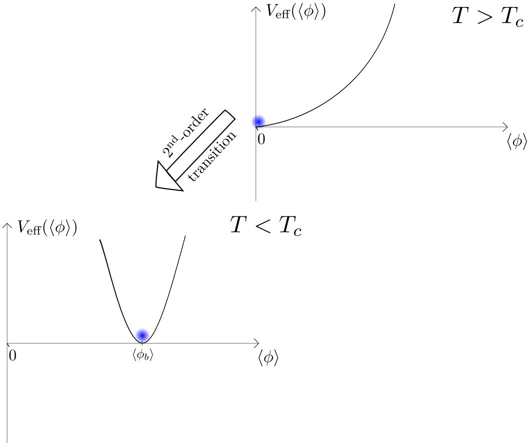

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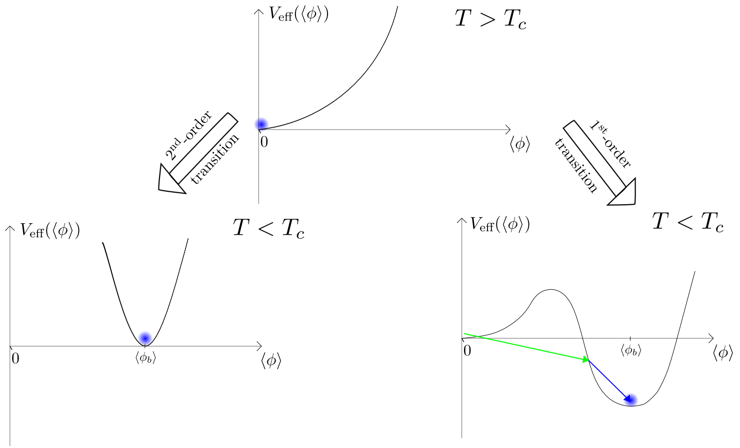
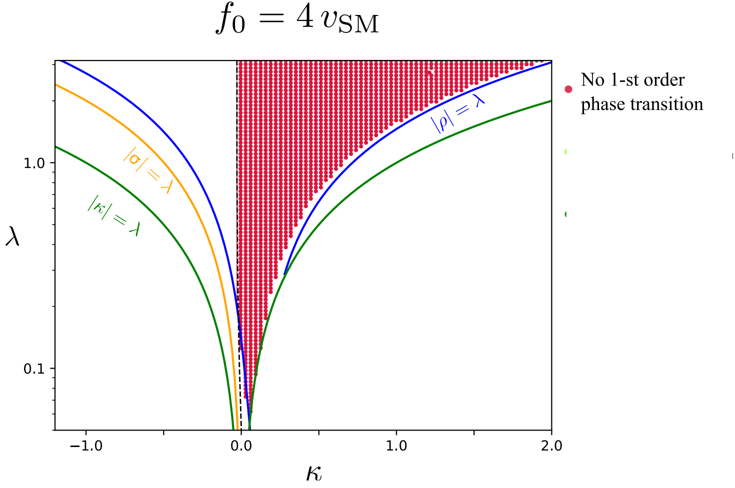


Phase transitions in TH



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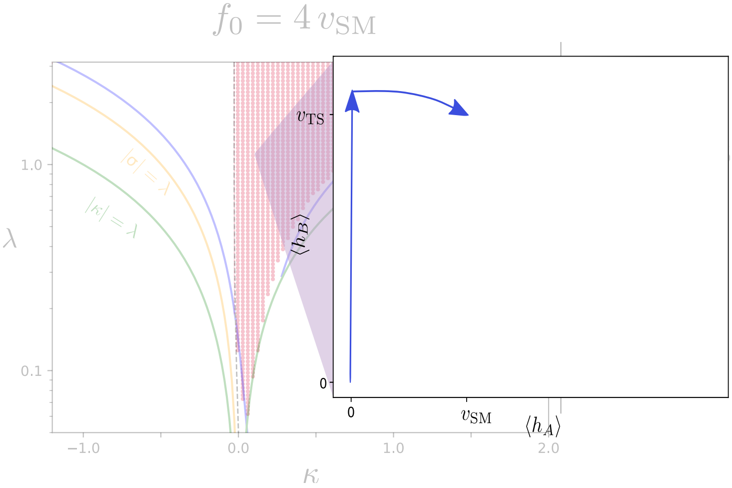

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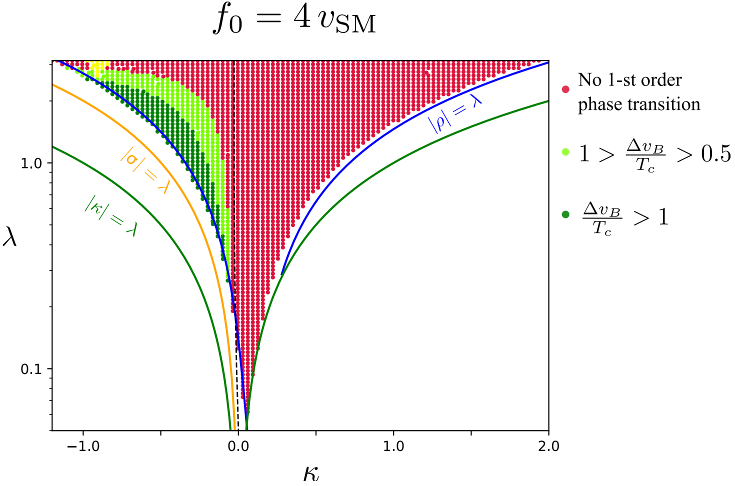
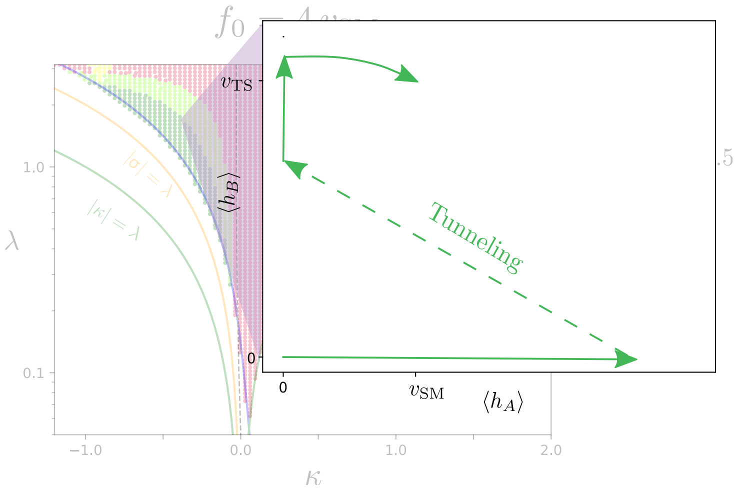
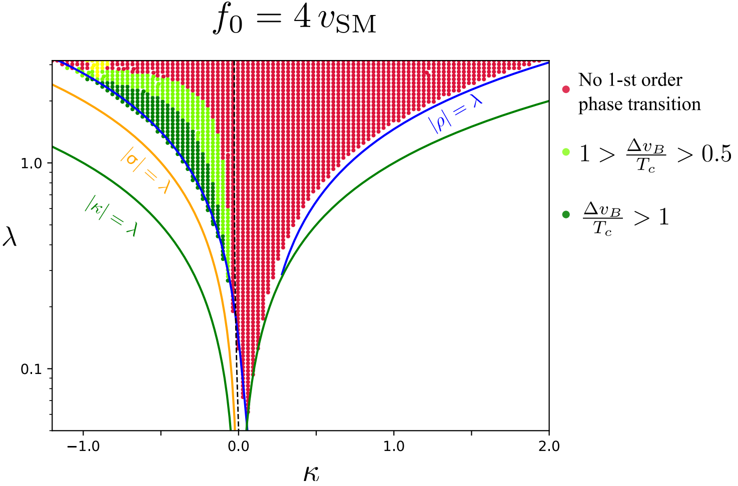



$f_0 = \Lambda v_{SM}$
v_{TS}
0
$\langle h_B \rangle$
Tunneling
0
v_{SM}
$\langle h_A \rangle$
1.0
0.1
λ
$|\sigma| = \lambda$
$|\kappa| = \lambda$
−1.0
0.0
1.0
2.0
κ

Phase transitions in TH



$\mathbb{Z}_2$-breaking and phase transition

At $T \sim f_0$ global minimum rests at $h_A = h_B = 0$.

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$\mathbb{Z}_2$-breaking in twin lepton Yukawas

- Enhancment of the twin Yukawa couplings makes $\zeta_{\mathsf{TS}} > \zeta_{\mathsf{SM}}$ in $\sqrt{\frac{\zeta_{\mathsf{TS}}}{\zeta_{\mathsf{SM}}}\left(1 - \frac{\sigma}{\lambda}\right)}$ and thus allow for $T_{\mathsf{SM}} > T_{\mathsf{TS}}$, even for *positive* σ.

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We consider two variants:

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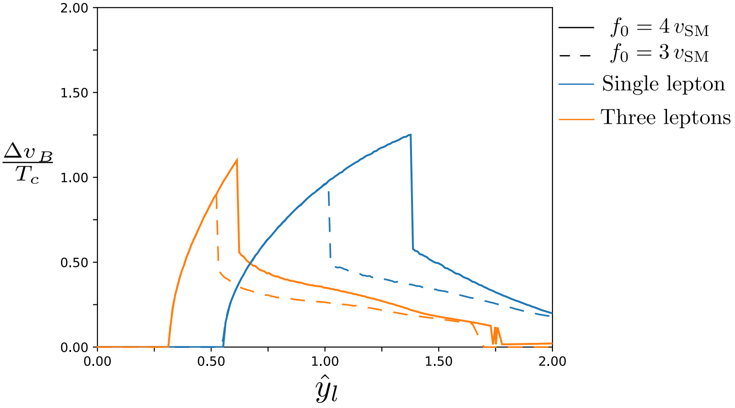
1. **The UV agnostic TH with enhanced lepton Yukawas $\hat{y}_l \gg y_l$.**
2. **The MSSM*-like extension with scalar lepton partners**

$$\hat{m}^2_{\mathrm{sl}\ R} = \hat{\mu}^2_R + \frac{1}{2}\tilde{y}^2_l h^2_B \cos^2\beta - \frac{1}{4}g'^2 h^2_B \cos(2\beta),$$
$$\hat{m}^2_{\mathrm{sl}\ L} = \hat{\mu}^2_L + \frac{1}{2}\tilde{y}^2_l h^2_B \cos^2\beta - \frac{1}{8}(g^2 - g'^2) h^2_B \cos(2\beta).$$

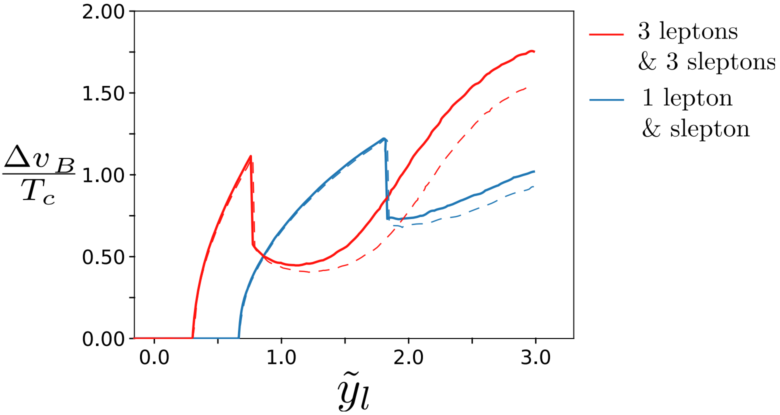
*MSSM-Minimal Supesymmetric Standsrd Model

UV agnostic TH with enhanced twin lepton Yukawas



$$\lambda = 1, \quad \rho = 0$$

MSSM-like TH



$$\lambda = 1, \quad \rho = 0, \quad \tan\beta = 2$$

Solid lines $\hat{\mu}_{\text{sl}}^2 = (90\ \text{GeV})^2$, Dashed lines $\hat{\mu}_{\text{sl}}^2 = (290\ \text{GeV})^2$

Recipe for baryon asymmetry

Ingredients (aka Sakharov Conditions)

1. Baryon number violating process.

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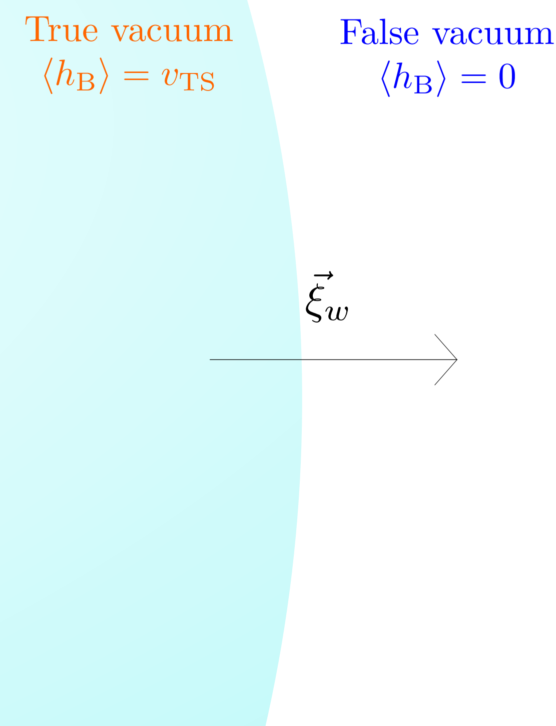
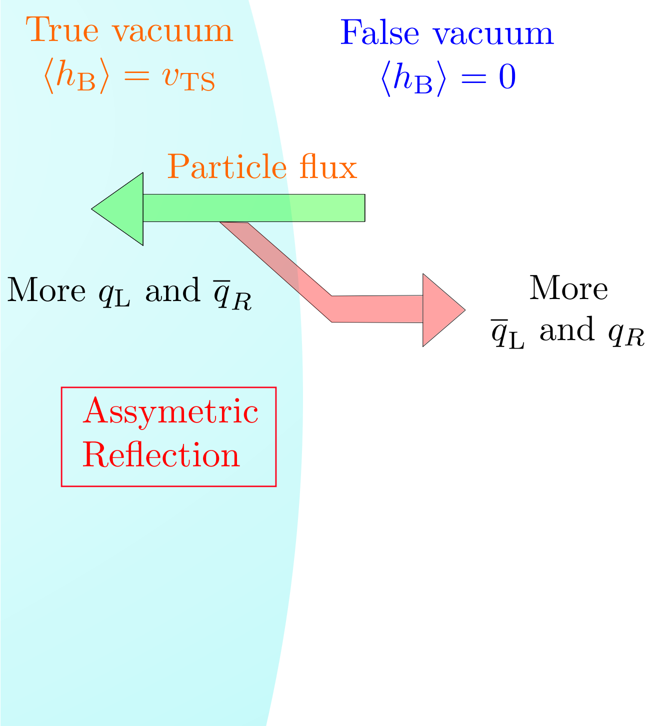

True vacuum
$\langle h_{\rm B}\rangle = v_{\rm TS}$
False vacuum
$\langle h_{\rm B}\rangle = 0$
$\vec{\xi}_w$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Particle flux
More q_L and $\overline{q}_R$
More
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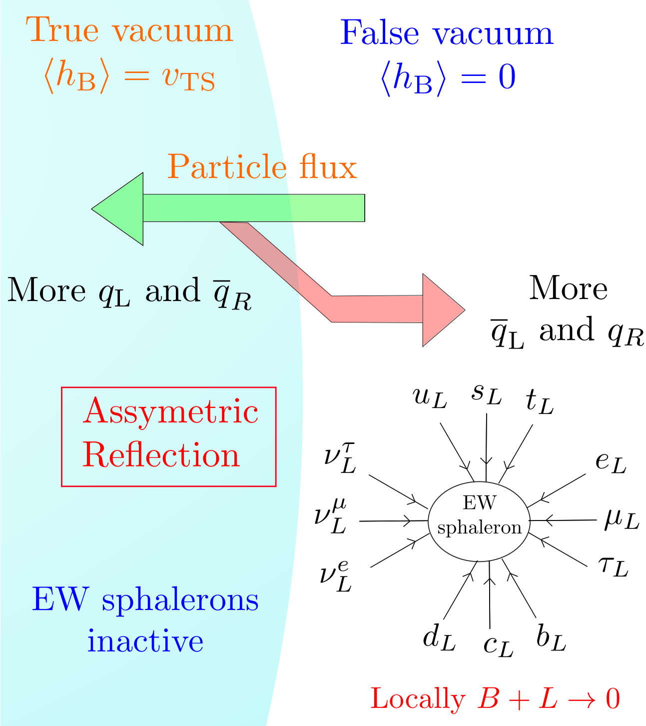
Assymetric
Reflection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u_L s_L t_L
ν_L^τ e_L
ν_L^μ μ_L
ν_L^e τ_L
EW
sphaleron
d_L c_L b_L
EW sphalerons
inactive
Locally $B + L \to 0$

TH and Darkogenesis

Idea – Baryon asymmetry forms in the twin sector and later is reprocessed to the SM baryon number.

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Necessary ingredients

- Source of the *twin CP* violation – in SUSY TH one can introduce complex phase in the lepton threelinear term. The impact of this *CP* phase on the SM dipole moments would be strongly suppressed.

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- Transport operator – there are many suitable options, for instance neutron operator

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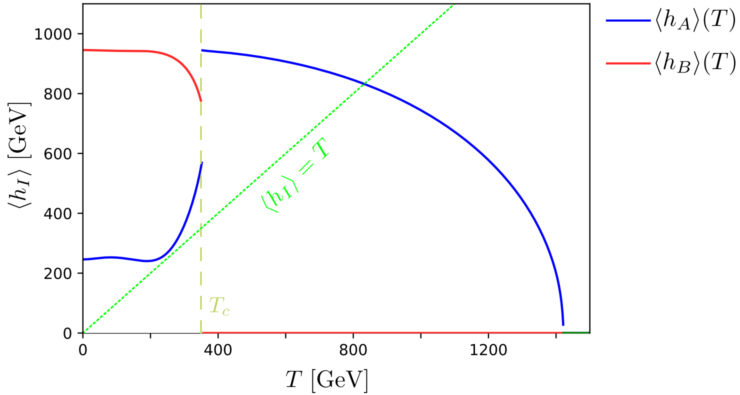
Washout?

After FOPT ends	$\hat{B} = X, \;\; B = 0$
$\mathcal{O}_n$ **in equilibrium**	$\hat{B} \approx \frac{X}{2}, \;\; B \approx \frac{X}{2}$
$\mathcal{O}_n$ **decoupled, SM sphaleros active**	$B + L = 0, \;\; B - L \approx B \approx \frac{X}{4}$

More accurate computation in equilibrium approximation yields $B \approx 0.24X$.

Symmetry non-restoration



$$f_0 = 1 \text{ TeV}$$

$$\lambda = 1, \quad \rho = 0, \quad \tan\beta = 0.8, \quad \tilde{y}_I = 2.7$$

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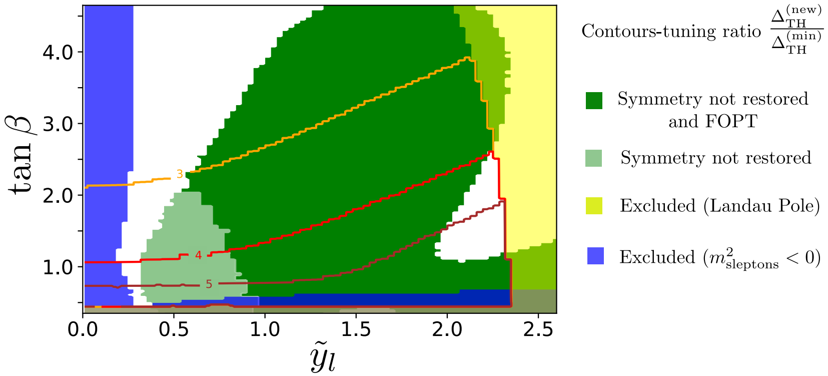
Condition for the symmetry non-restoration in TH

$$\sum_{j \in \text{fermions}} \frac{n_j}{4}(\hat{y}_j^2 - y_j^2) \geq 5,$$

[2] O. Matsedonskyi, "High-Temperature Electroweak Symmetry Breaking by SM Twins", JHEP, 10.1007 (2021): 4-36.

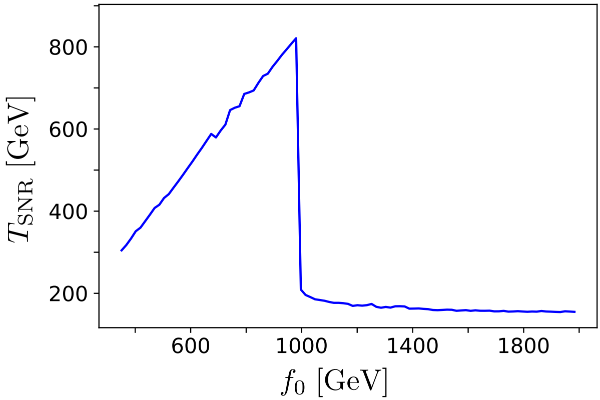
Twin leptons, quarks and scalar partners



$$\lambda = 1, \ \rho = 0,$$

$$\tilde{y}_\nu = 0.9, \quad \hat{y}_u = \hat{y}_c = 0.4, \quad \hat{y}_s = \hat{y}_b = 0.3$$

Temperature of EW symmetry breaking



$$\tilde{y}_\nu = \tilde{y}_l = 1$$

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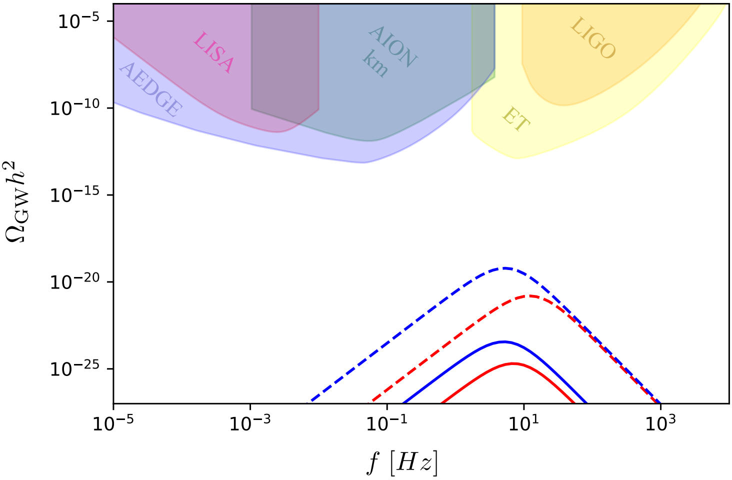
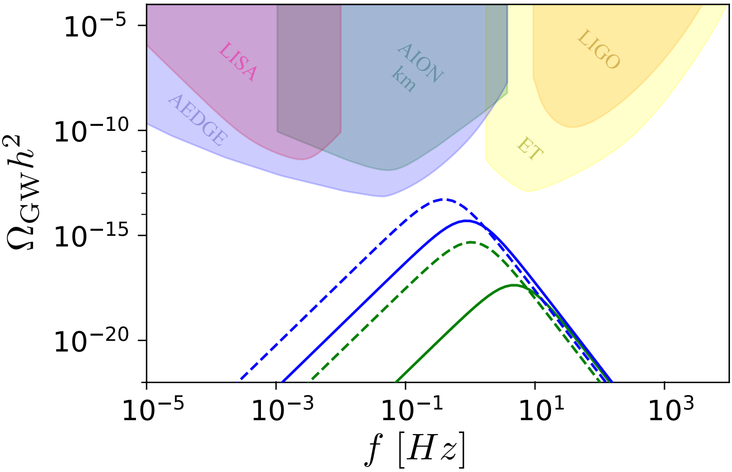
- The new generation of GW detectors will partially probe the range at which gravitational signal from scalar FOPTs is expected.

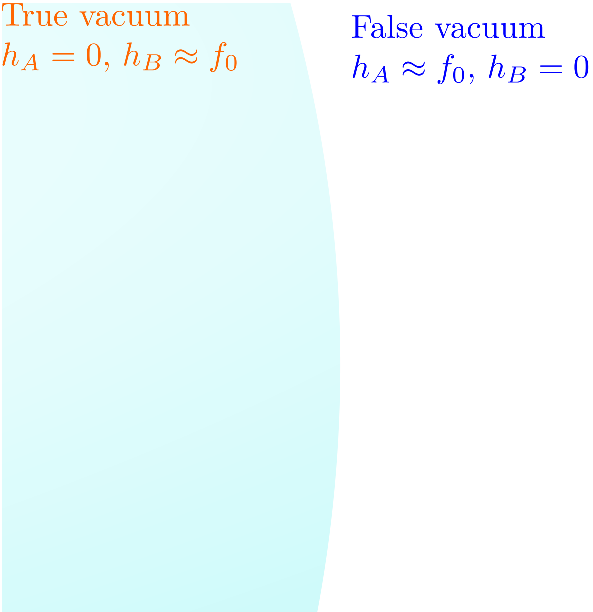
Gravitational waves in UV agnostic TH



Gravitational waves in SUSY TH



Non-equilibrium effects



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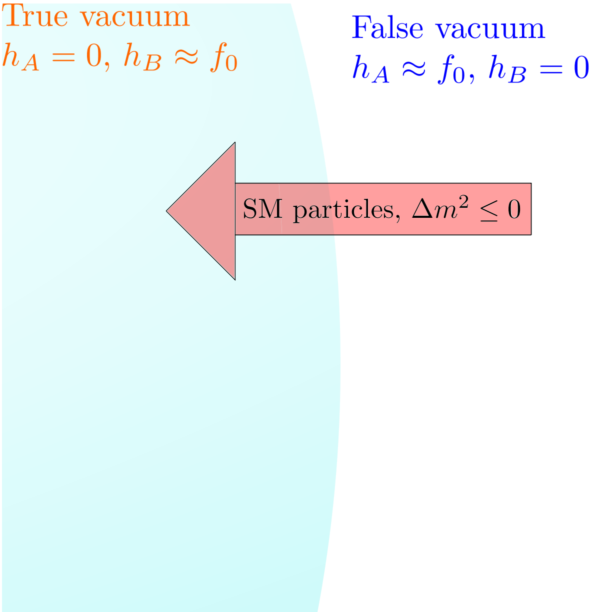

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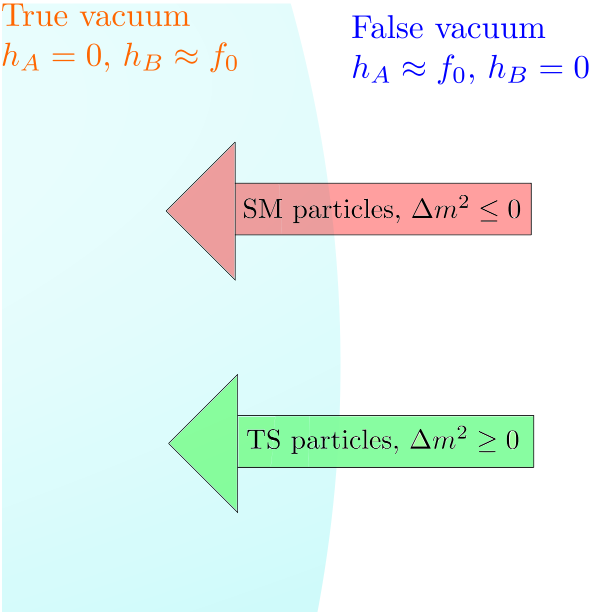

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- In supersymmetric TH extensions the emission of detectable gravitational signal is not excluded.