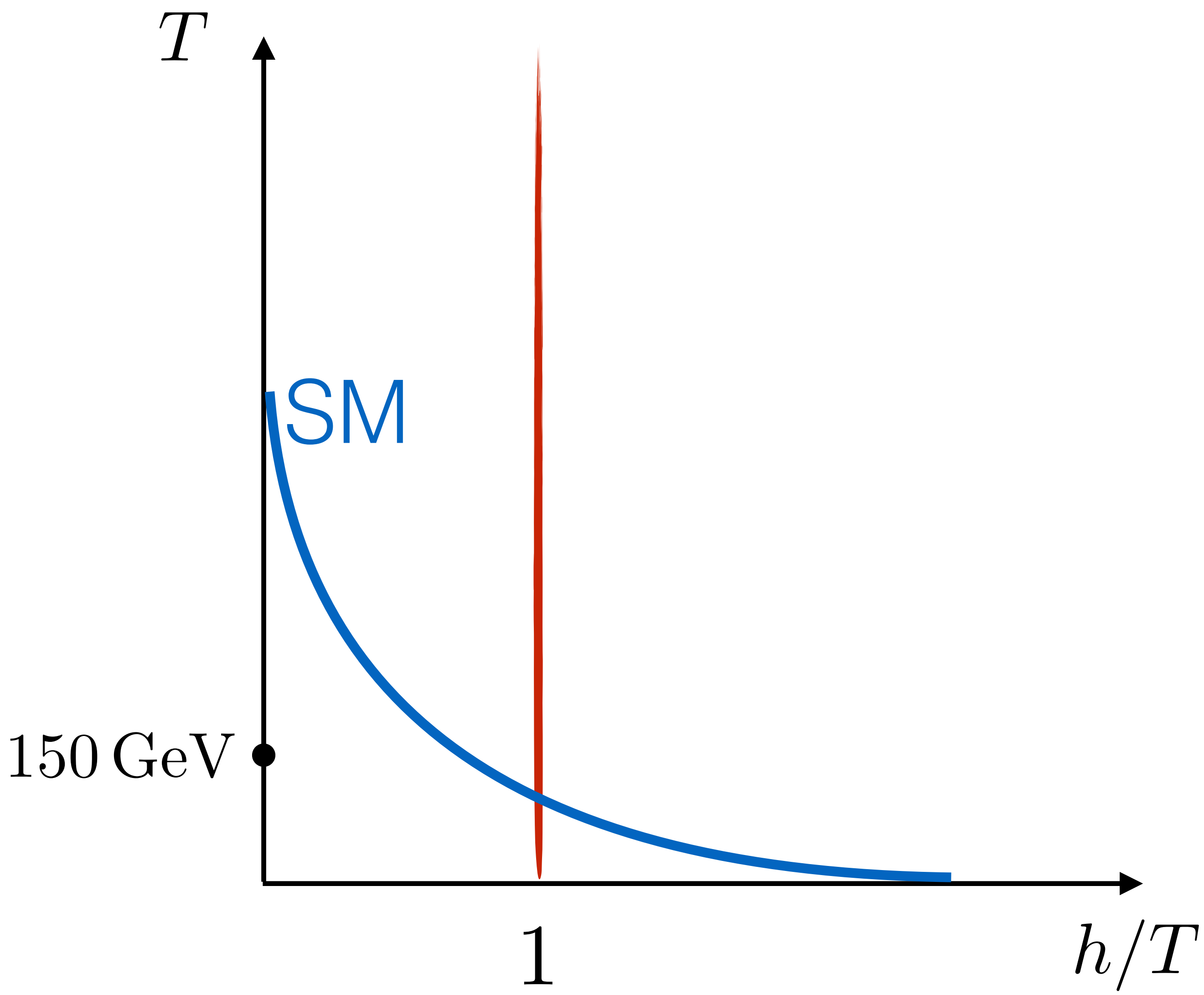
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

EW Symmetry Non-Restoration at High Temperature with New Fermions

Oleksii Matsedonskyi

in collaboration with G. Servant

Why Search for Non-Restoration?



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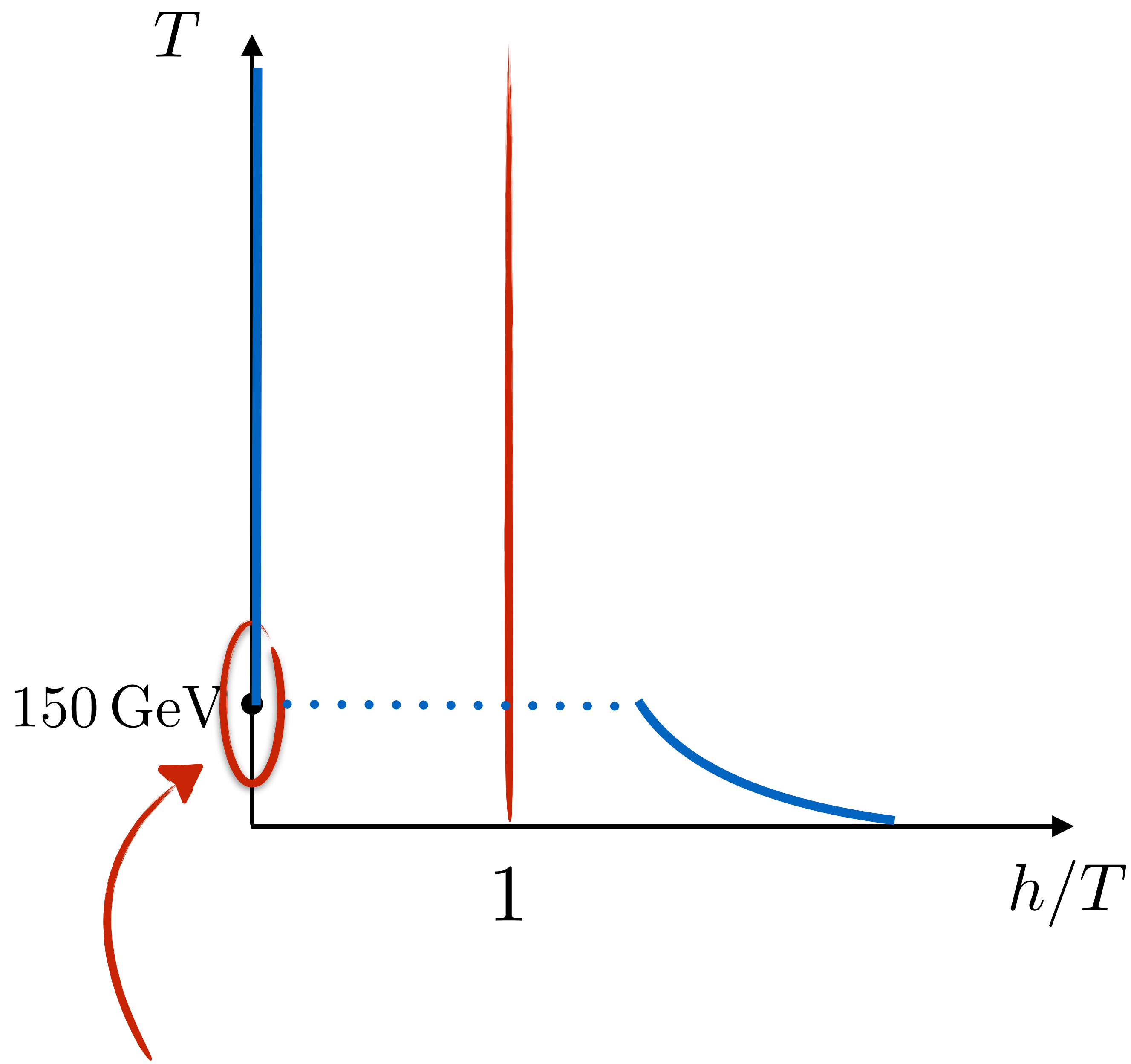

- <u>EW-scale new physics</u> for EW Baryogenesis
  - to produce first-order PT
  - CP-violating interaction

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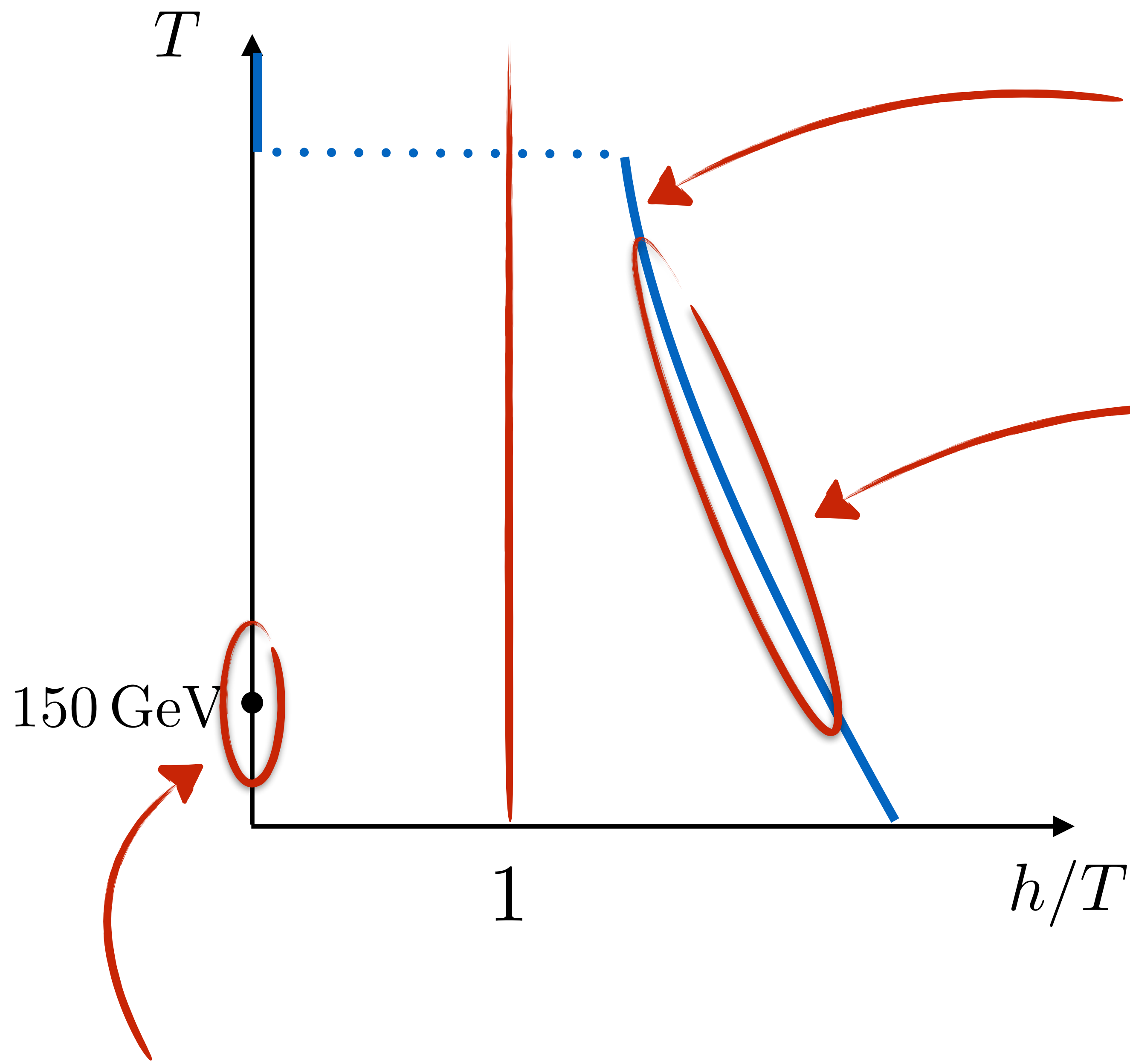

- SNR can allow for higher-T EWPT
- subject of this talk
- <u>EW-scale new physics</u> for EW Baryogenesis
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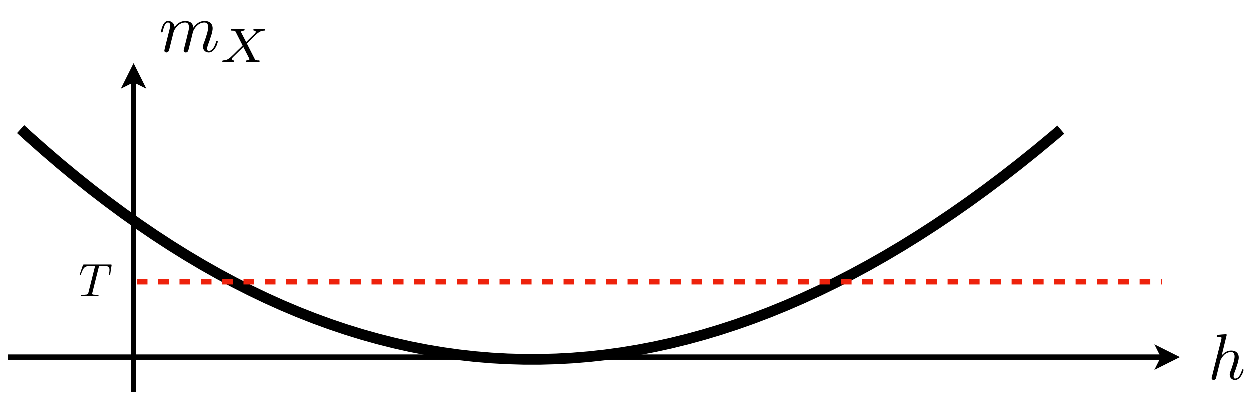
Thermal Corrections and EW symmetry

Thermal Corrections

- In thermal bath of X particles, what is the effect of interaction on the Higgs potential?



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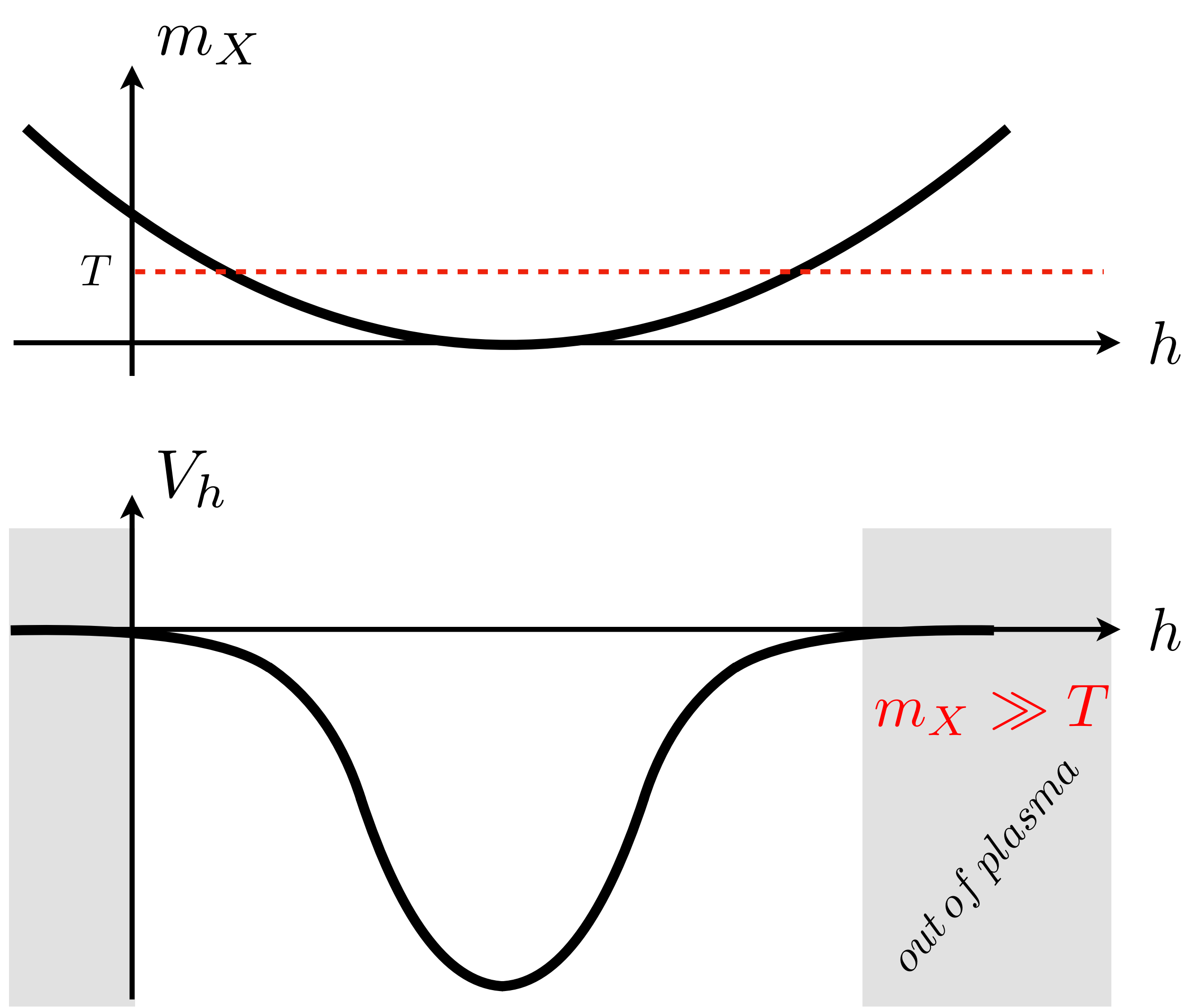

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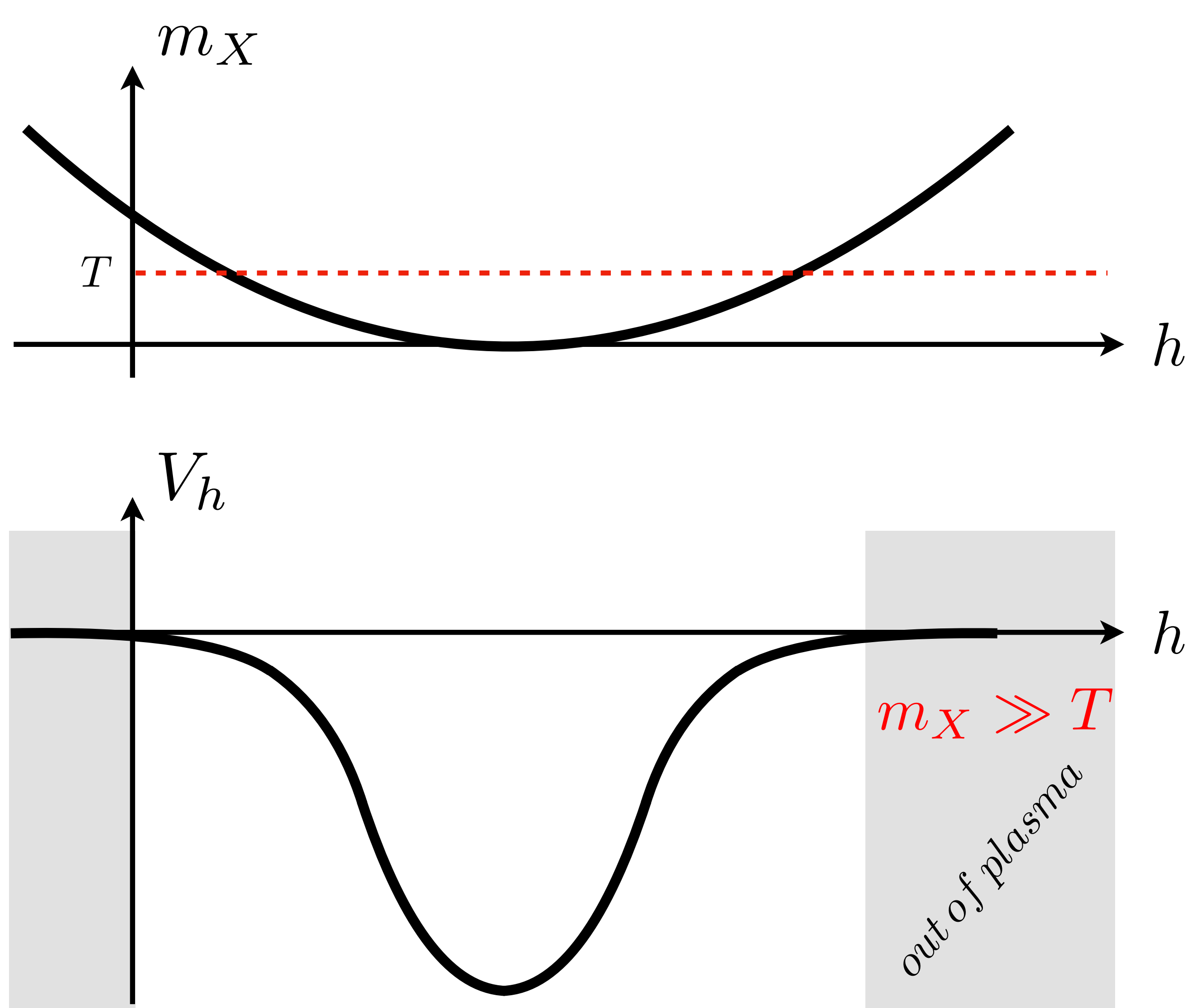

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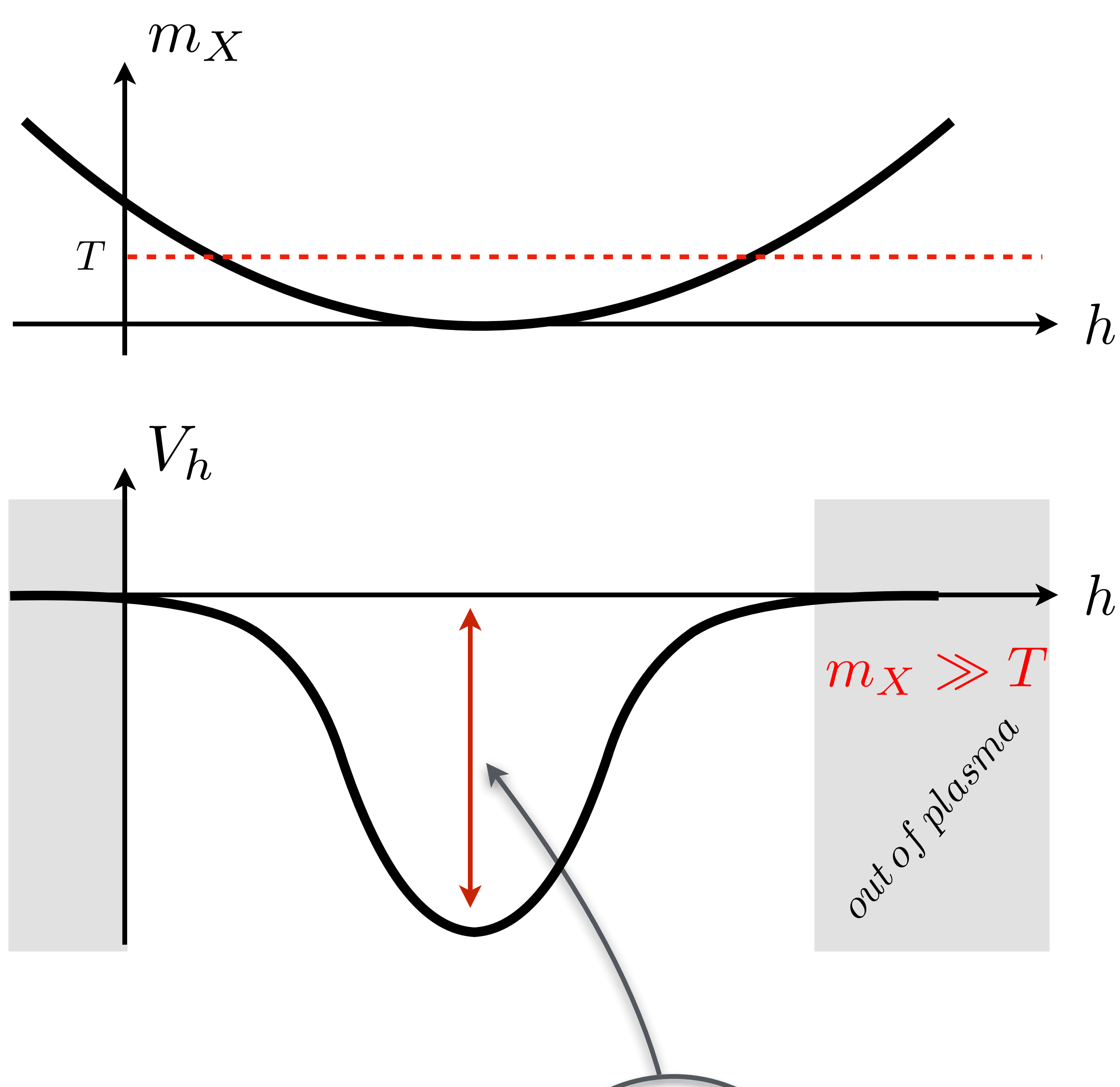

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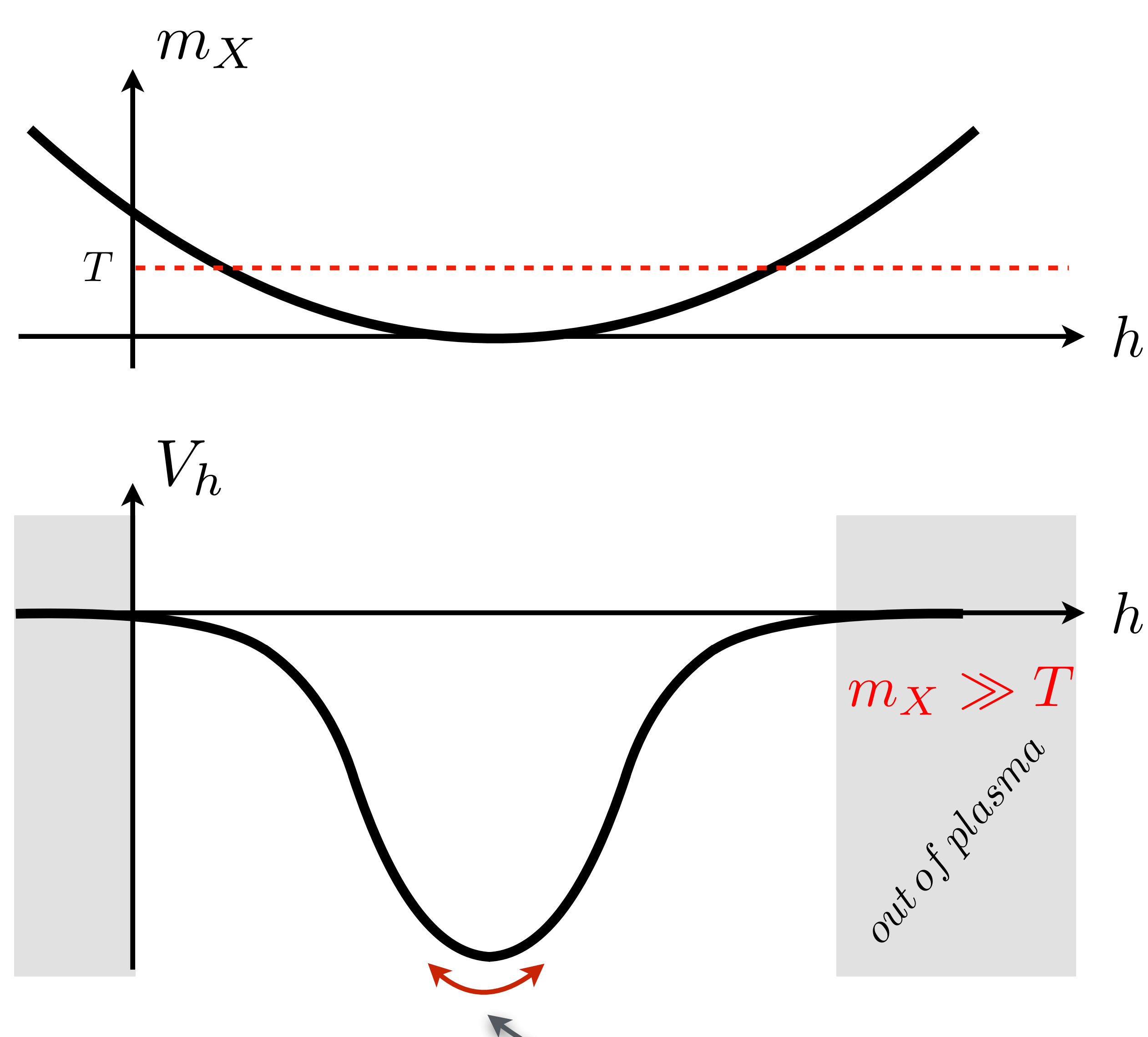

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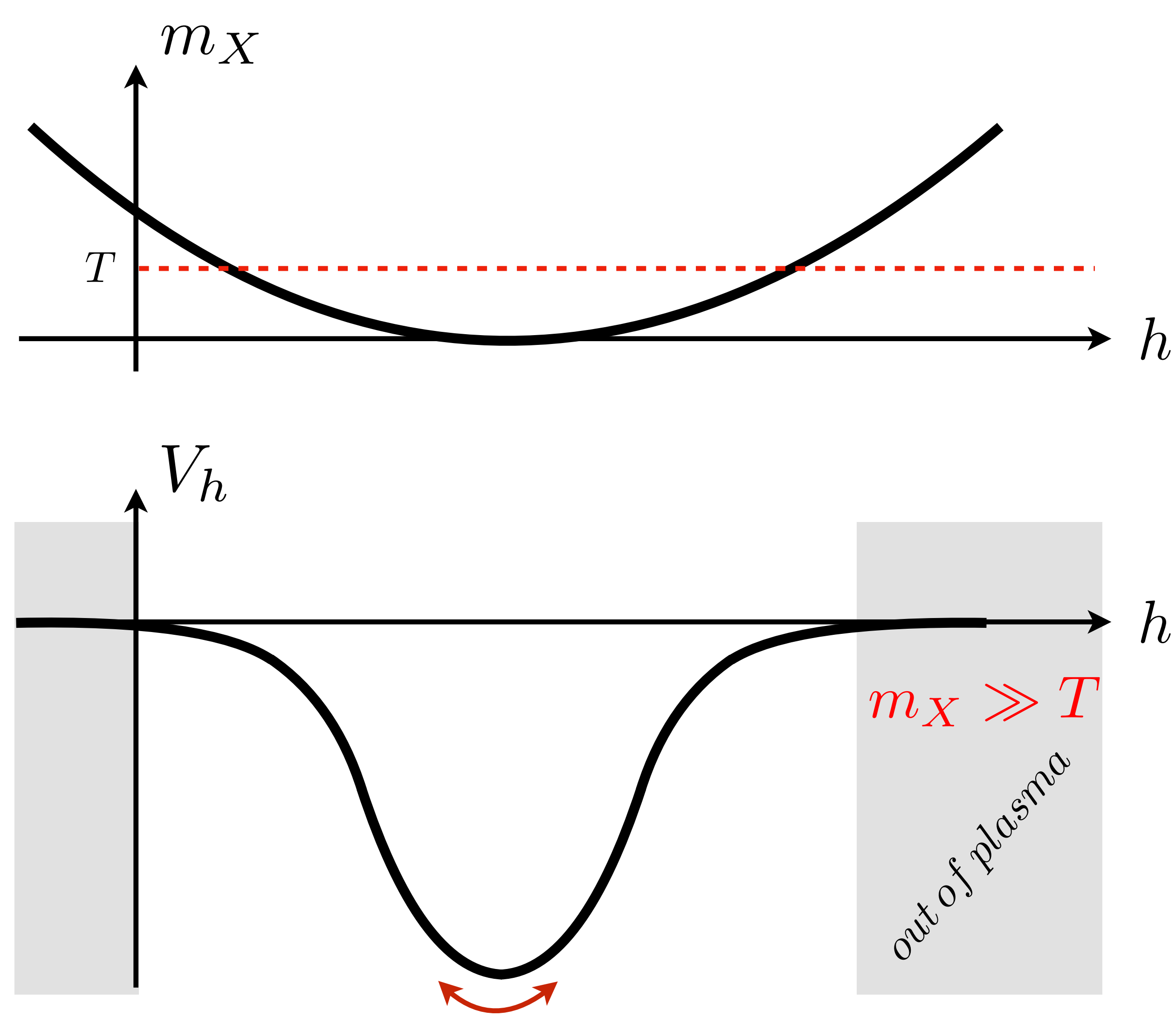
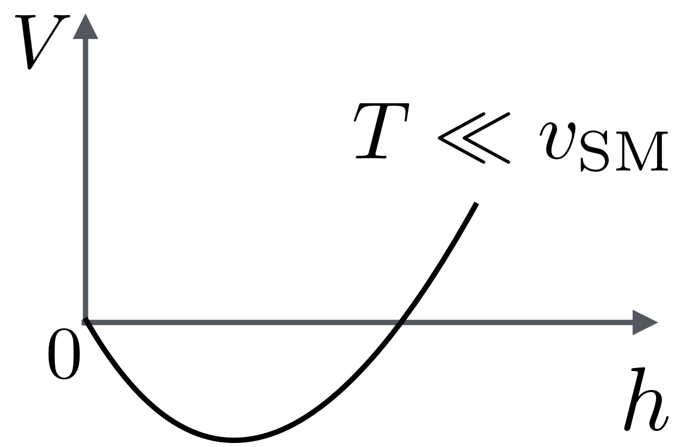


- in $m^2/T^2 \ll 1$ limit: $\delta m_h^2(T) \propto T^2 (m_X^2(h))''$

Thermal Corrections: SM

- SM at low T



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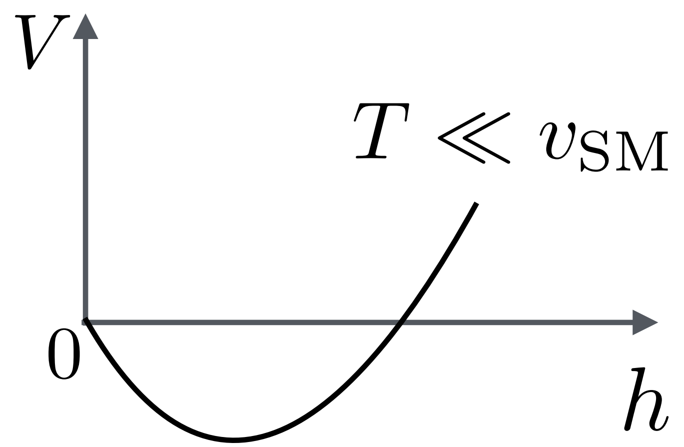

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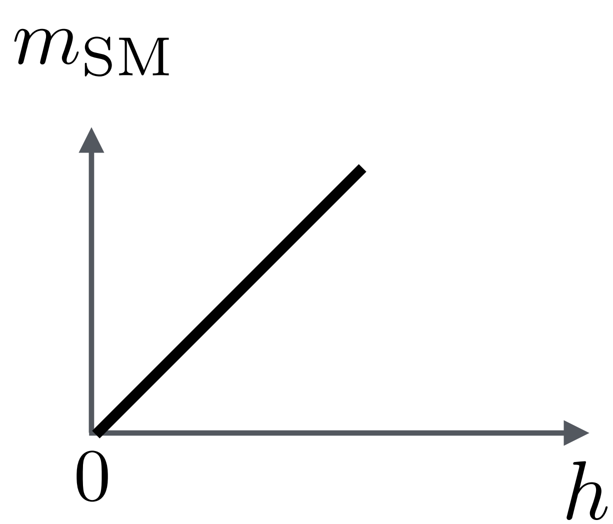

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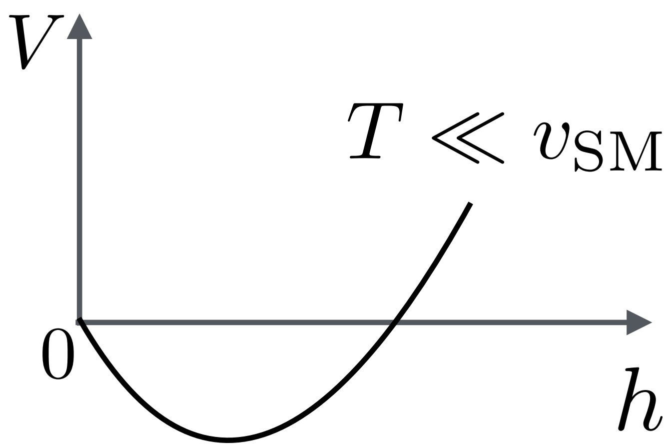

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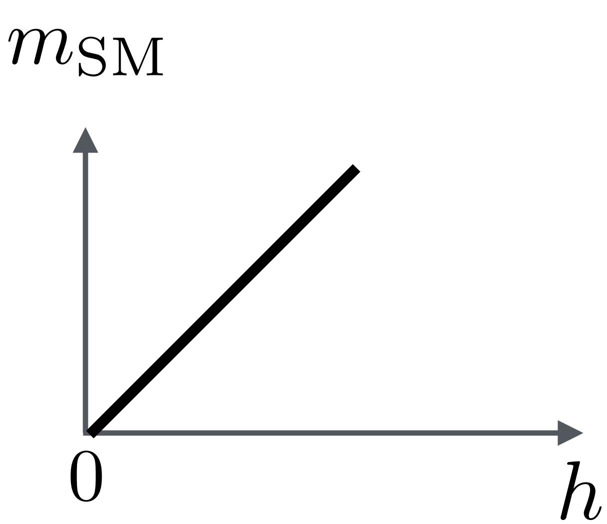
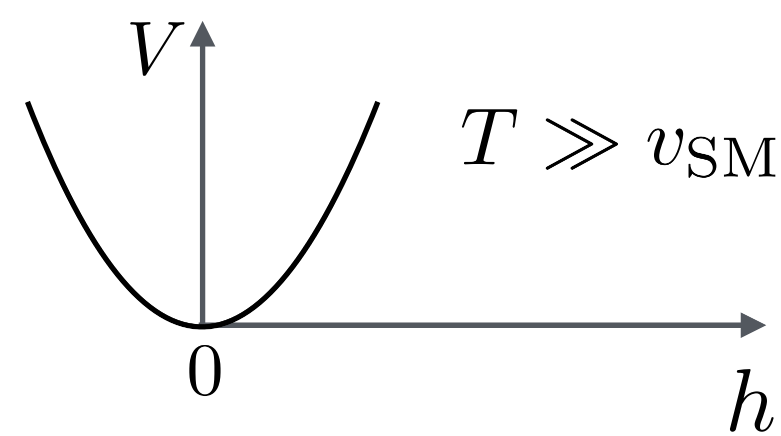


$\longrightarrow$



$$\delta m_h^2(T) \simeq T^2 \left[\frac{\lambda_t^2}{4} + \frac{\lambda}{2} + \frac{3g^2}{16} + \frac{g'^2}{16} \right]$$

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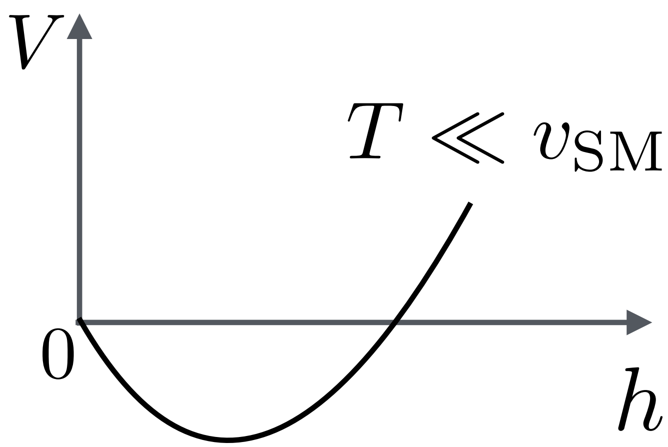

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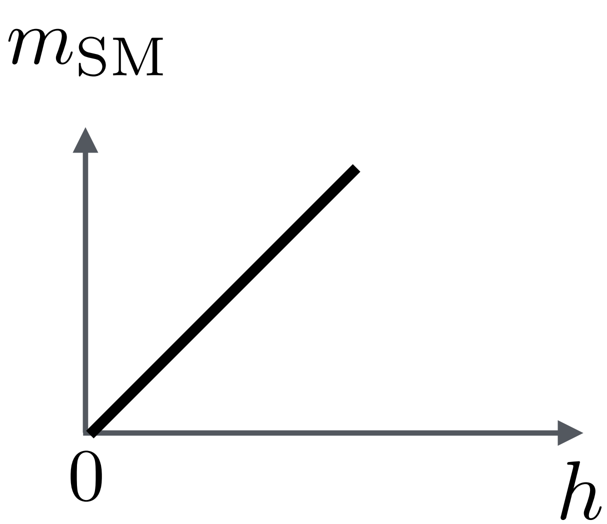

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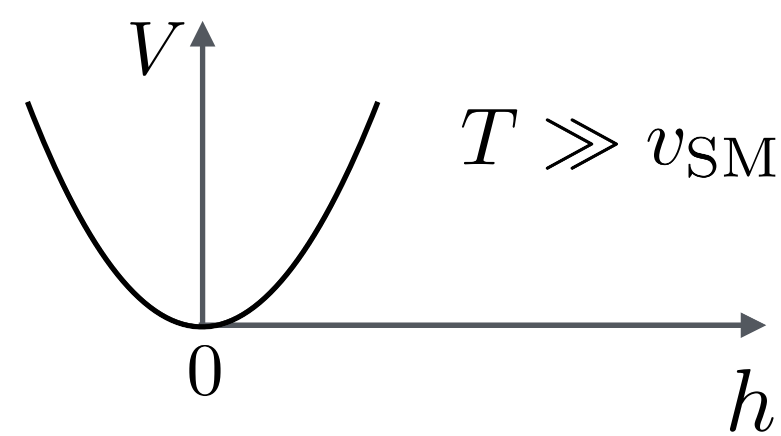

top Yukawa

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Symmetry NonRestoration with Scalars

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- EW SNR:
  - 1807.07578 Meade,Ramani — just SNR
  - 1807.08770 Baldes,Servant
  - 1811.11740 Glioti,Rattazzi,Vecchi

  } SNR+high-T EWPT+BG

Symmetry NonRestoration with Scalars

- Main ingredient: SM singlet field χ in n copies

$$\mathcal{L} \supset -\frac{m_\chi^2}{2}\sum_i \chi_i^2 + \frac{\lambda_{\chi h}}{2}\sum_i \chi_i^2 h^2 - \frac{\lambda_\chi}{4}\sum_{ij}\chi_i^2\chi_j^2$$

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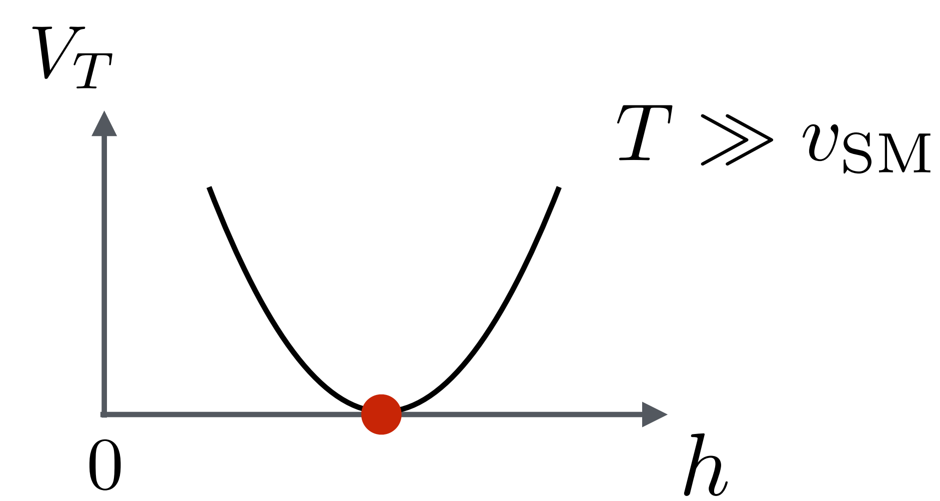

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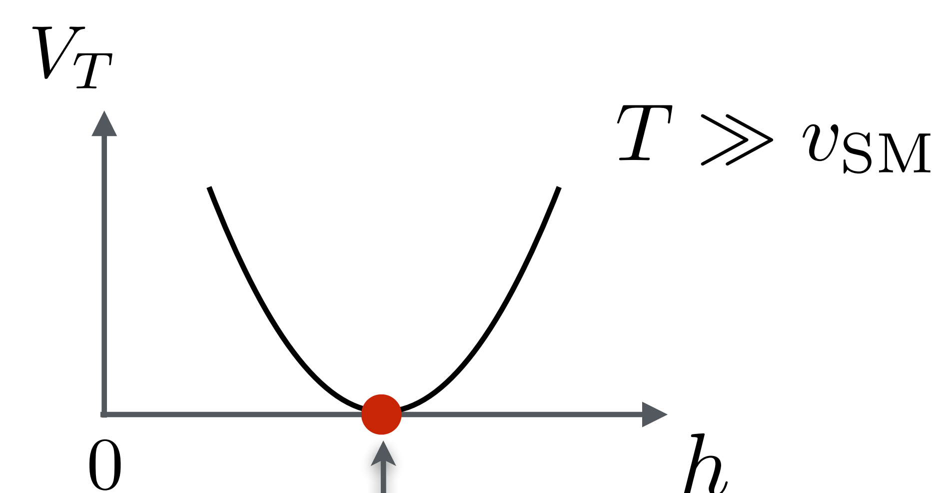


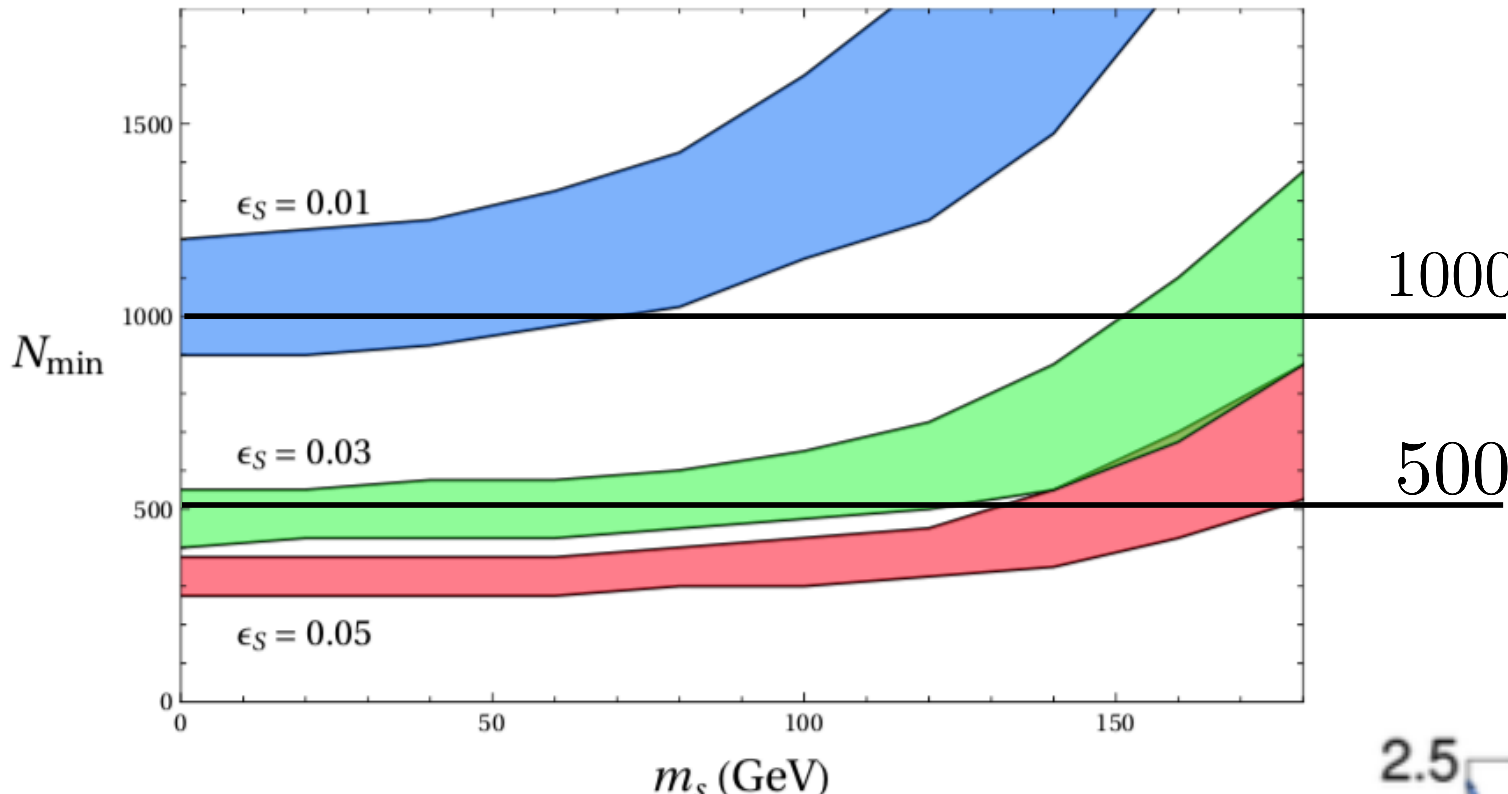
$$h^2 = m_\chi^2/\lambda_{\chi h}$$

(up to T corrections)

Symmetry NonRestoration with Scalars

- how large n needed?

1811.11740



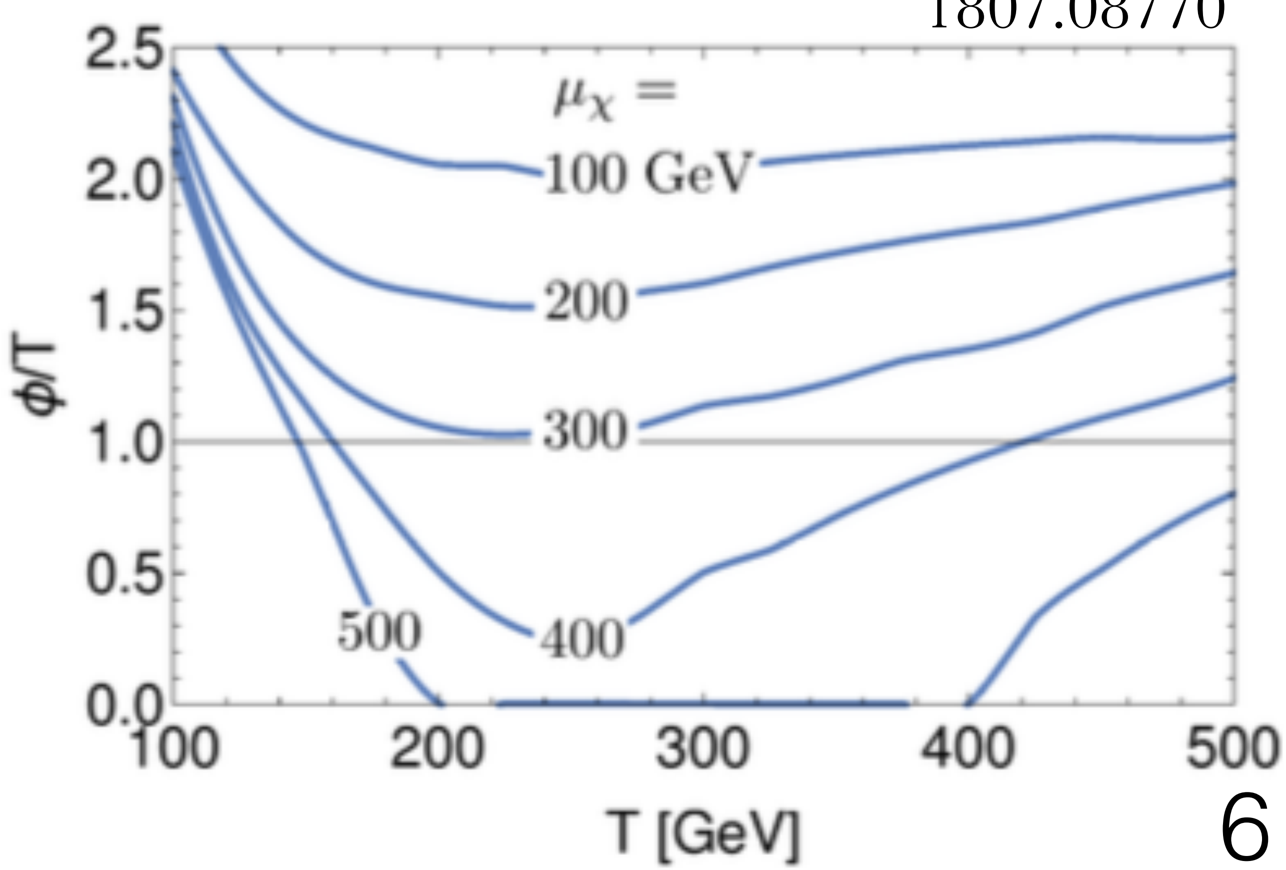
stability of tree-level potential
+
perturbativity of chi quartic

- how light should chi be?

$$m_\chi < 300\text{GeV}$$

extra naturalness problem

1807.08770



SNR with Fermions

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- Add n copies of new SM singlet Dirac fermion N

$$\mathcal{L}_N = -m_N^{(0)} \bar{N} N + \lambda_N \bar{N} N h^2 / \Lambda$$

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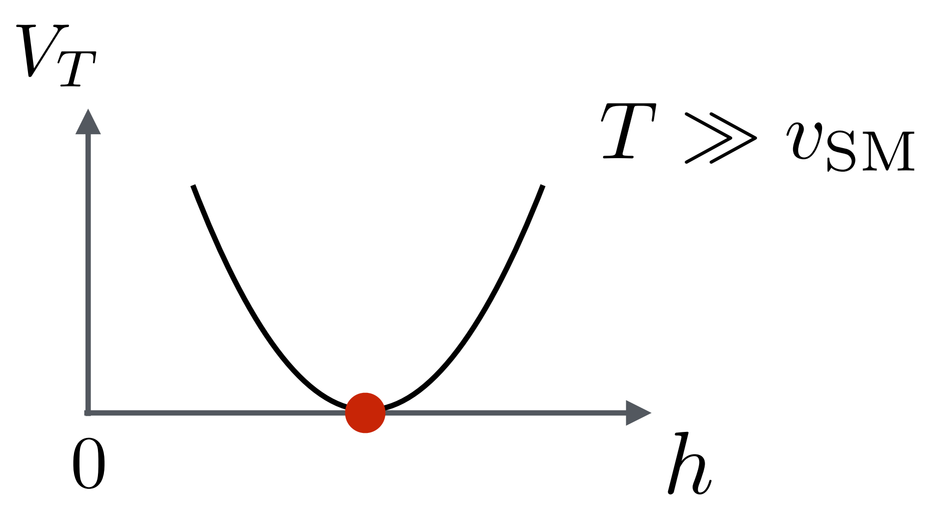
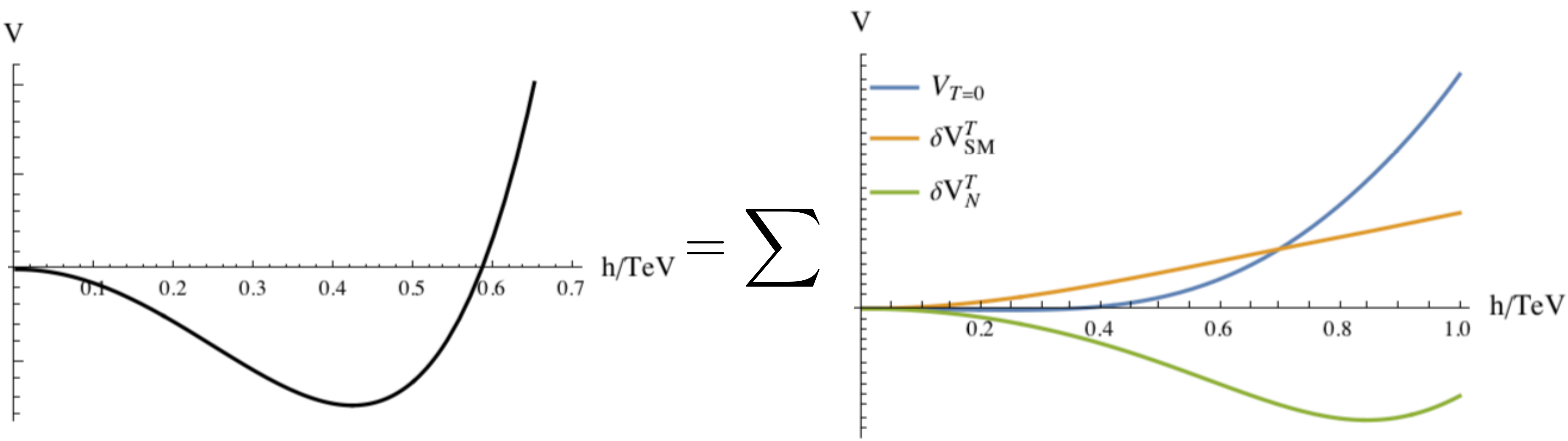
- thermal correction to the Higgs potential:



SNR with Fermions

- Resulting effective potential:



- Negative thermal mass

$$\delta m_h^2[T] \simeq n\frac{T^2}{12}(m_N^2(h))'' = -n\lambda_N\frac{m_N^{(0)}}{3\Lambda}T^2$$

- SNR condition

$$V''(h=0) < 0 \quad \longrightarrow \quad n\lambda_N \gtrsim 5\left(\frac{v_{SM}}{m_N}\right)\left(\frac{\Lambda}{\text{TeV}}\right)$$

Fermions vs Scalars

- No (tree-level) scalar potential stability constraint with fermions
- By default, less hierarchy problems

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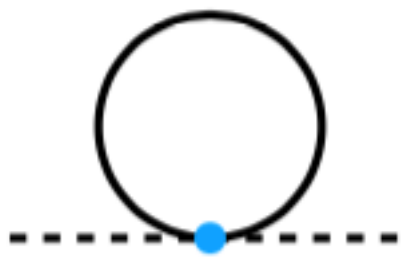
- No (tree-level) scalar potential stability constraint with fermions
- By default, less hierarchy problems
- Non-renormalizability of $\frac{\lambda_N}{\Lambda}\bar{N}Nh^2$ leads to:
  - high-T effects out of control above some $T_{\mathrm{max}} \propto \Lambda$
  - EFT breaks down at $\mu \gtrsim \Lambda$

SNR with Fermions: Higher Order T Effects

- main negative thermal mass effect:



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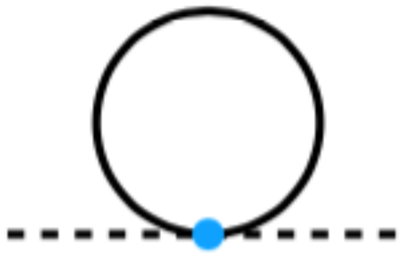

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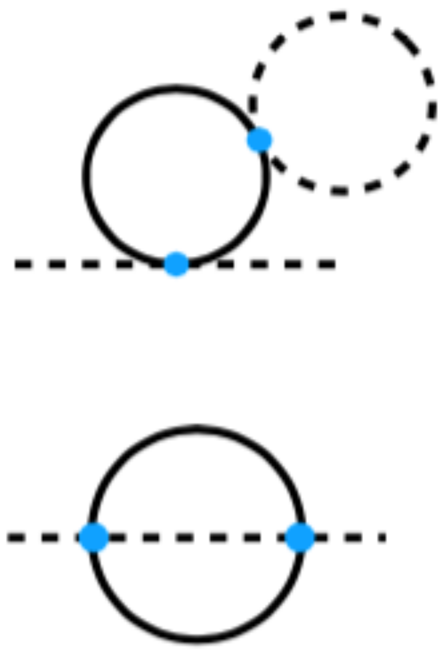
- higher loop corrections:



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- maximal temperature $$T_{\max} = \frac{\Lambda}{\sqrt{n}\lambda}$$

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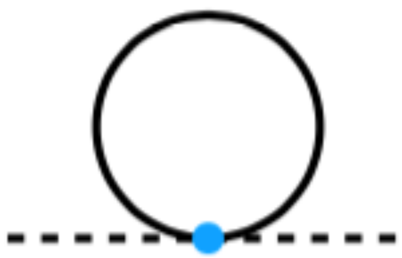

$$\propto n\lambda_N \frac{m_N}{\Lambda} \xrightarrow[\lambda_N \sim 1/n]{n \gg 1} const$$

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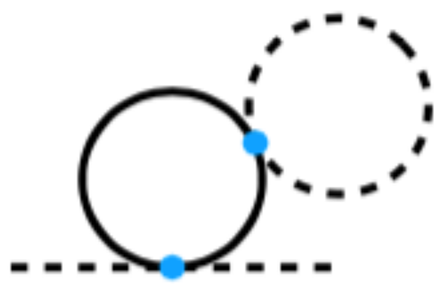
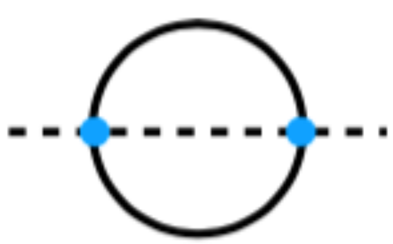


$$\propto n\lambda_N^2 \frac{T^2}{\Lambda^2} \longrightarrow 0$$



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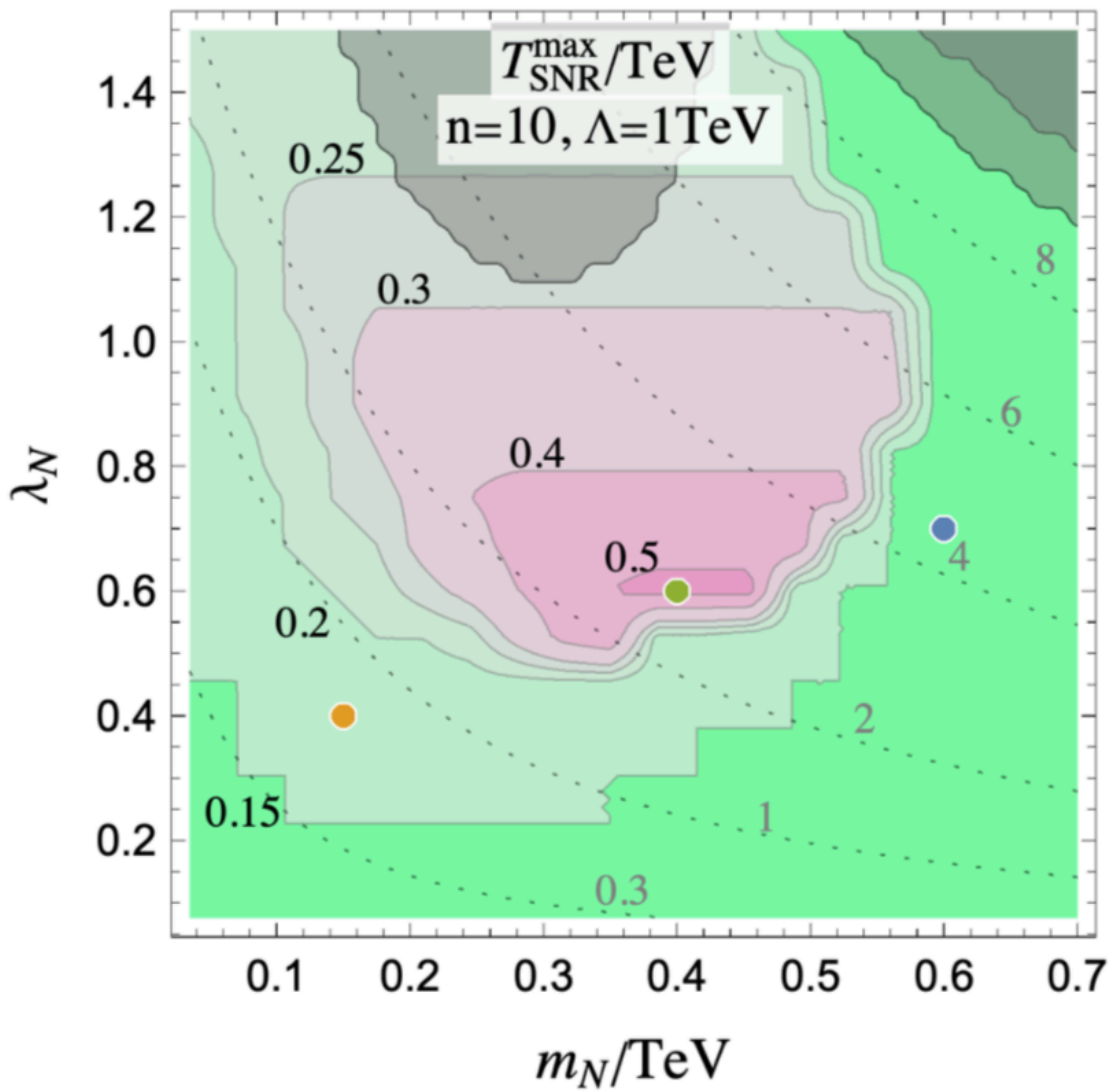
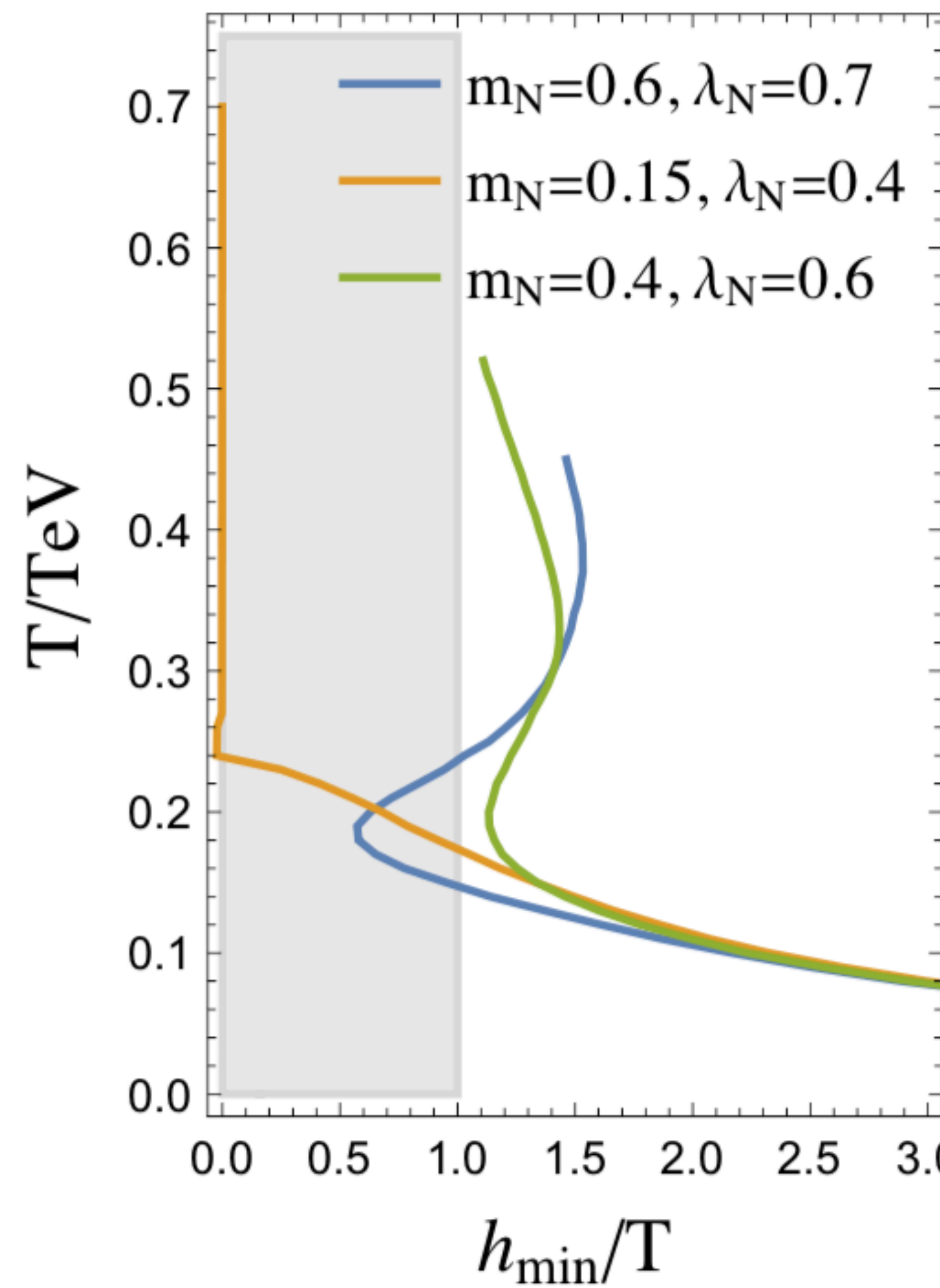
SNR with Fermions: Parameter Space

- minimal and “natural” SM deformation: $n = 10, \Lambda = 1\text{TeV}$





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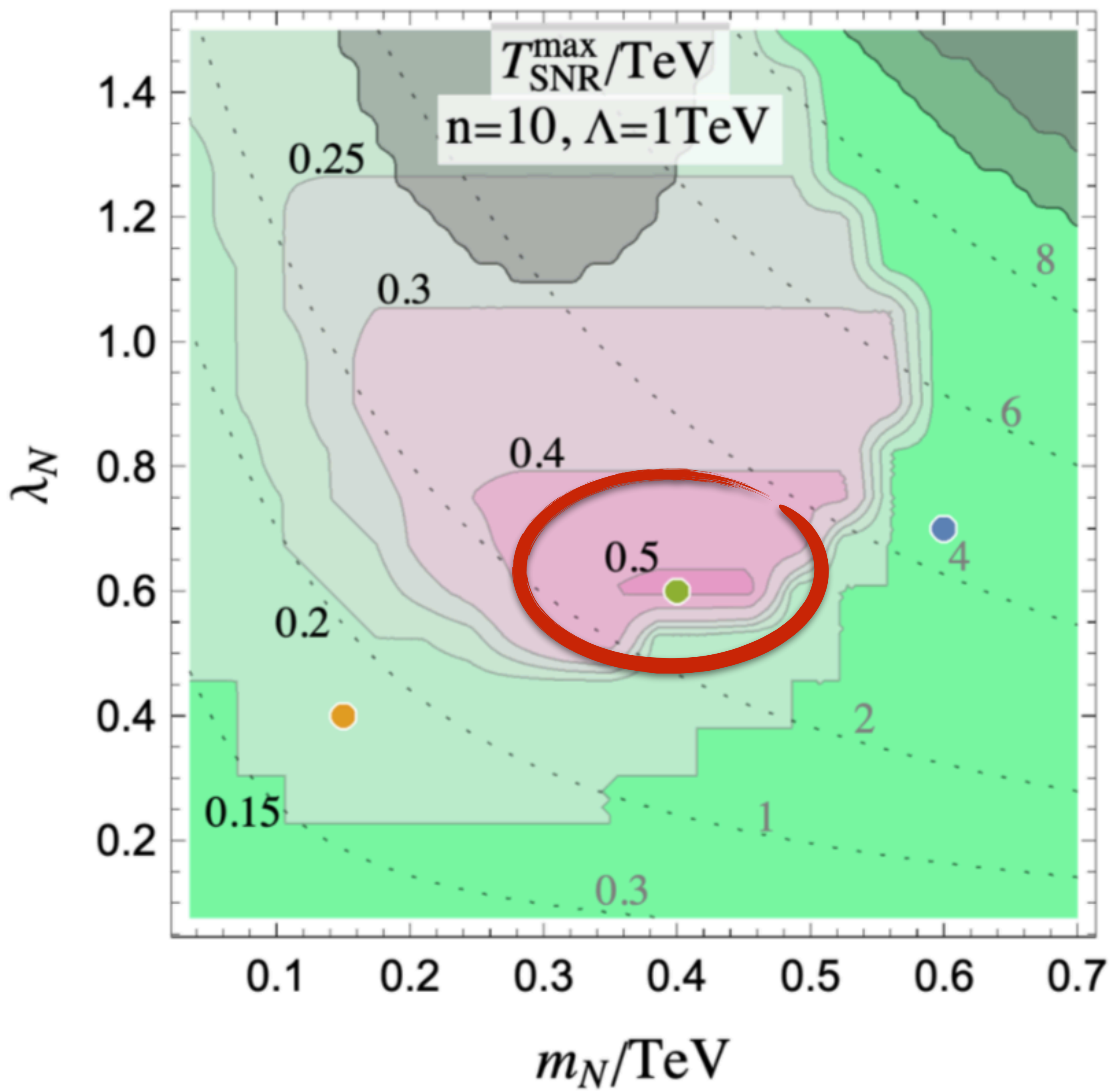

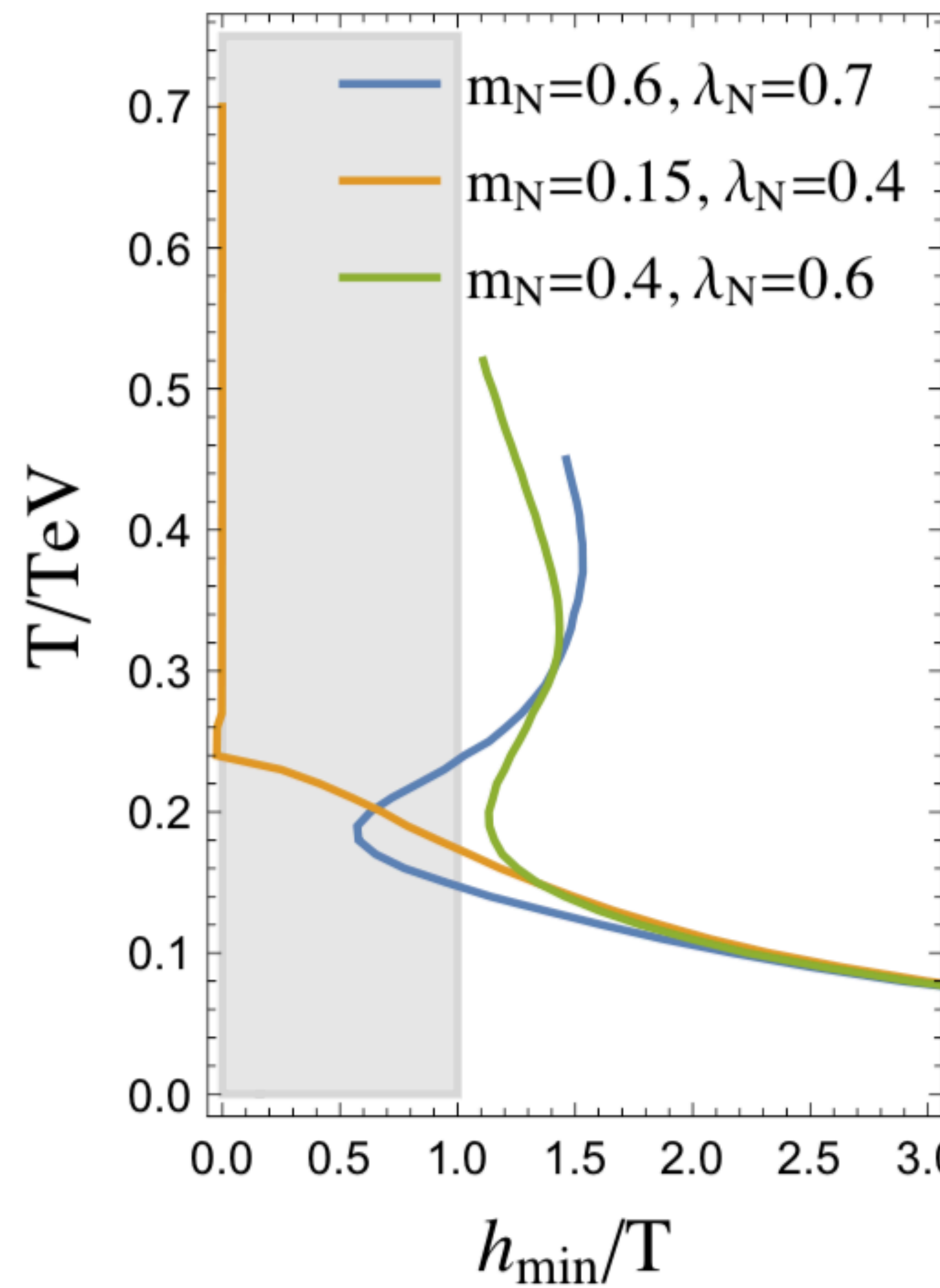

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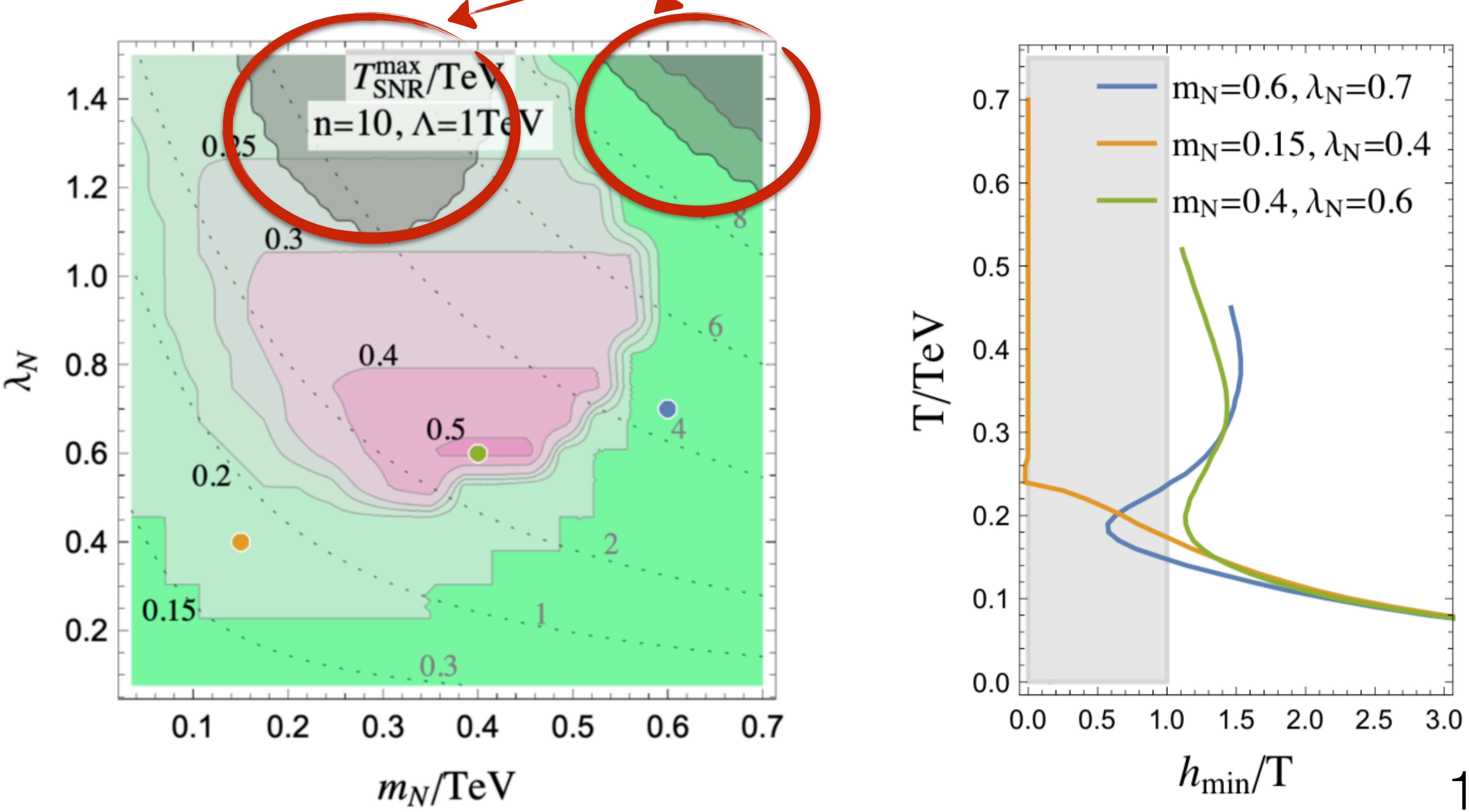
instab. at 1-loop level



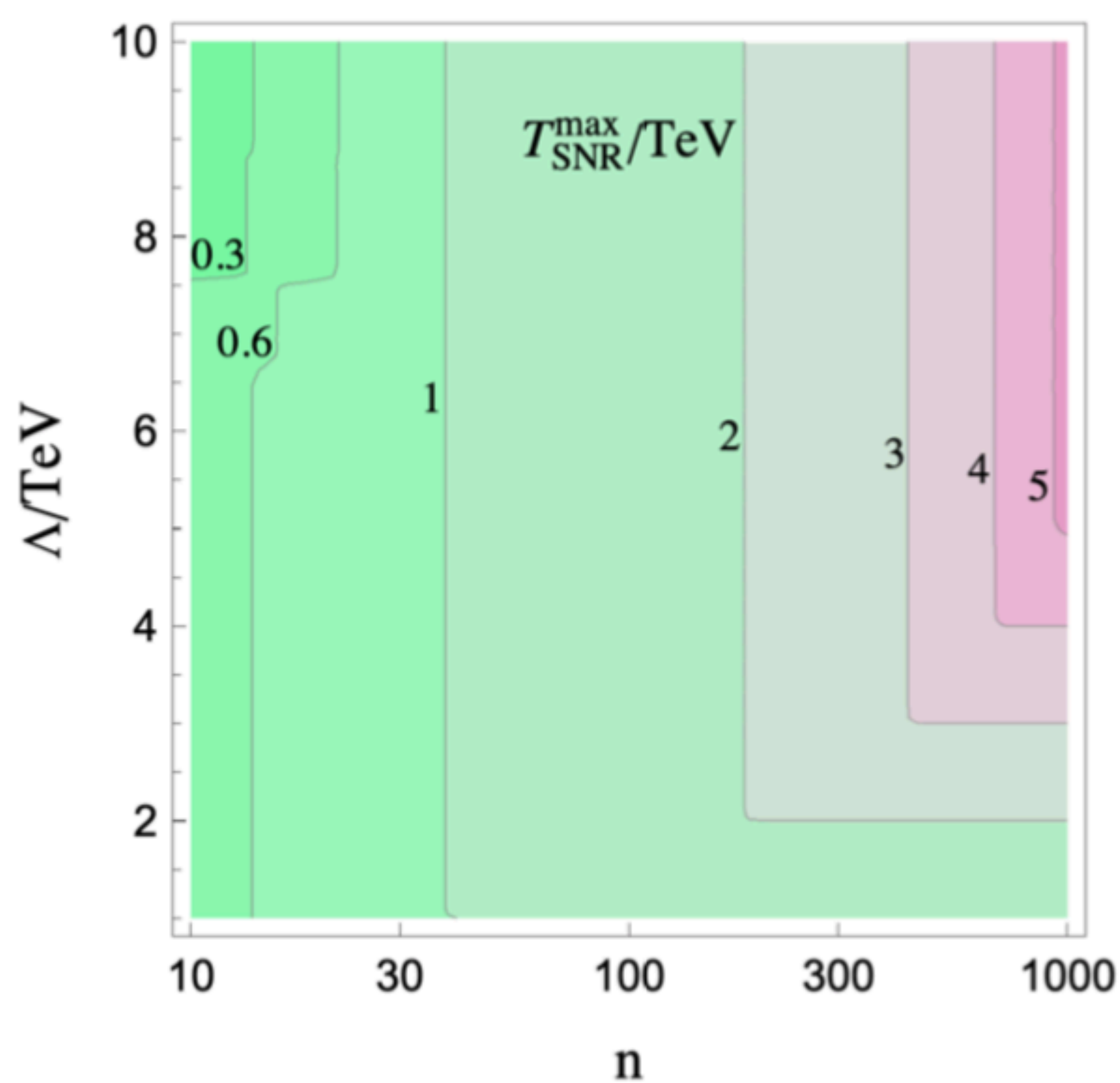
SNR with Fermions: Parameter Space

- Perturbativity bound + negative thermal mass condition

$$T_{\rm SNR} \lesssim \sqrt{n} m_N$$

- Continuous SNR requires

$$m_N \simeq 0.3 \ldots 0.5 \ \text{TeV}$$



UV Completions for $\bar{N}Nh^2$ Coupling

Explicit models: Goldstone Higgs

- Higgs is a PNGB: $\mathcal{L}$ [trigonometric functions of (h/f)]

- Assume partial-compositeness-like coupling between an elementary singlet N and its composite singlet partner ψ

$$\mathcal{L}_{\text{mass}} = f(y_L \bar{N}_L \psi_R + y_R \bar{N}_R \psi_L + h.c.) \cos h/f - m_\psi^0 \bar{\psi}\psi - \hat{m}_N^0 \bar{N} N$$

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- SNR coupling of N is reproduced at energies below $m_\psi \longleftrightarrow \Lambda$

$$\longrightarrow \quad \frac{y_L y_R f^2}{m_\psi} \bar{N} N \cos h/f \quad \underset{h \ll f}{\longrightarrow} \quad \frac{y_L y_R}{m_\psi} \bar{N} N h^2$$

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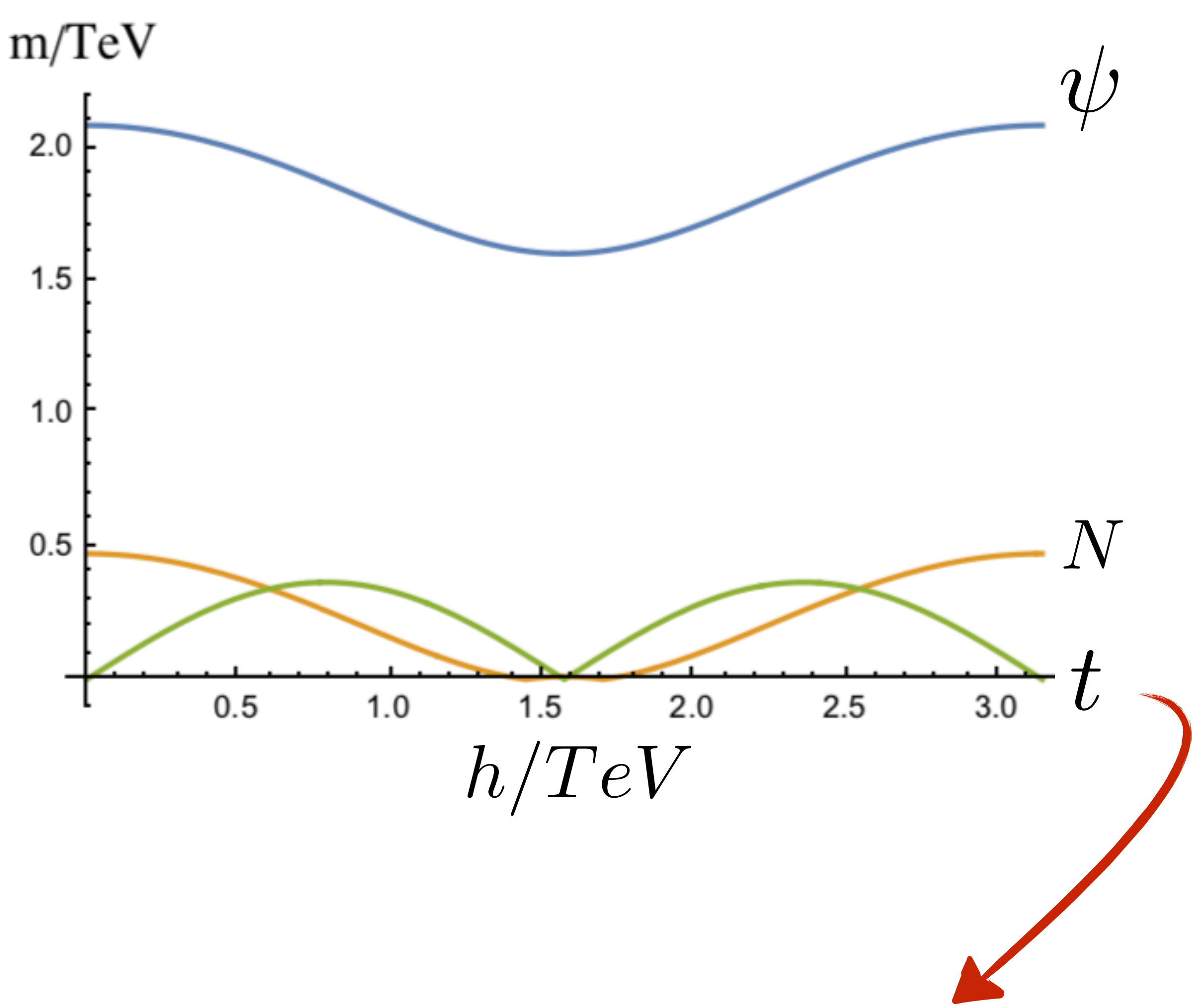
- in total 3 types of fermions with decreasing m at large h:



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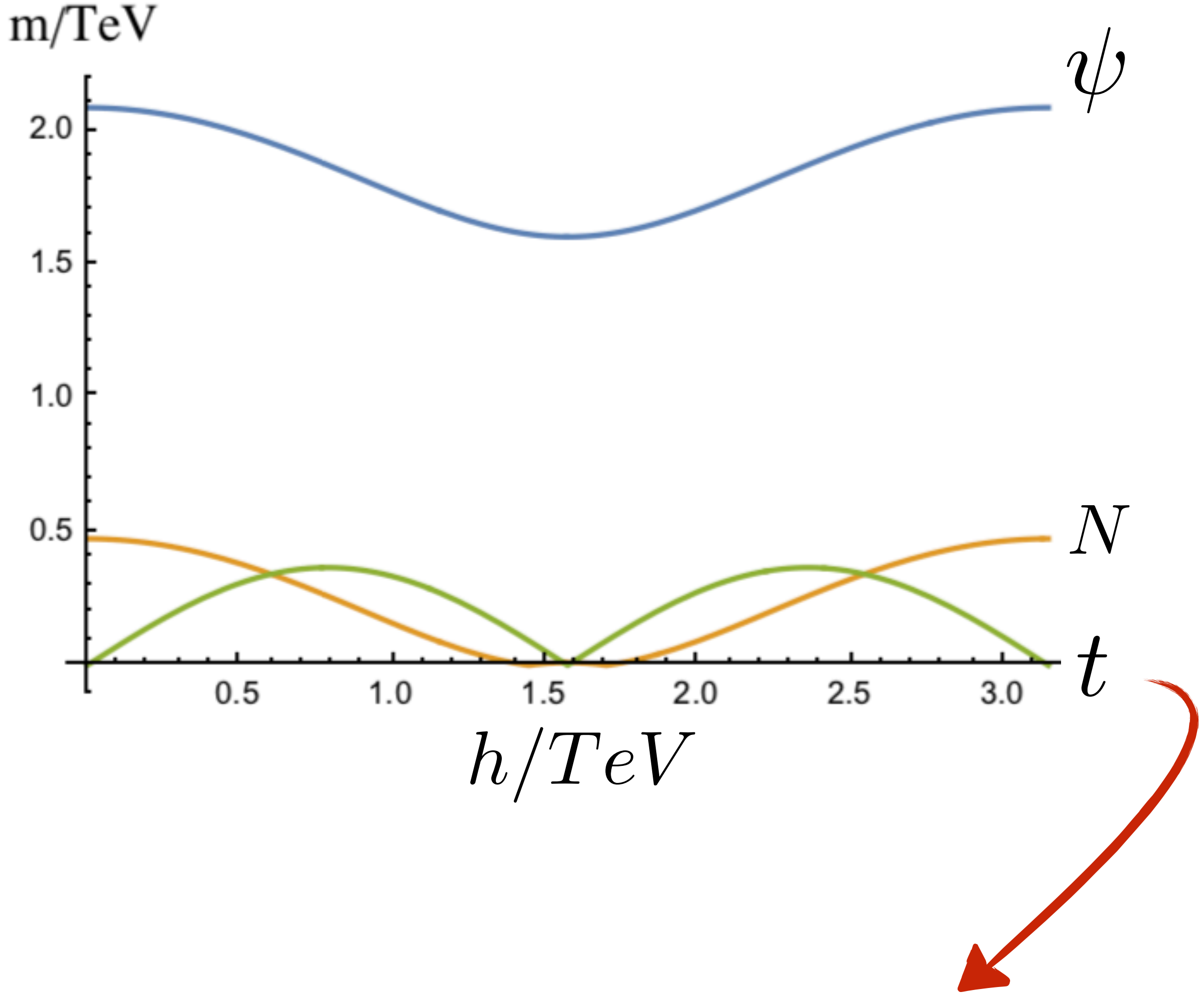

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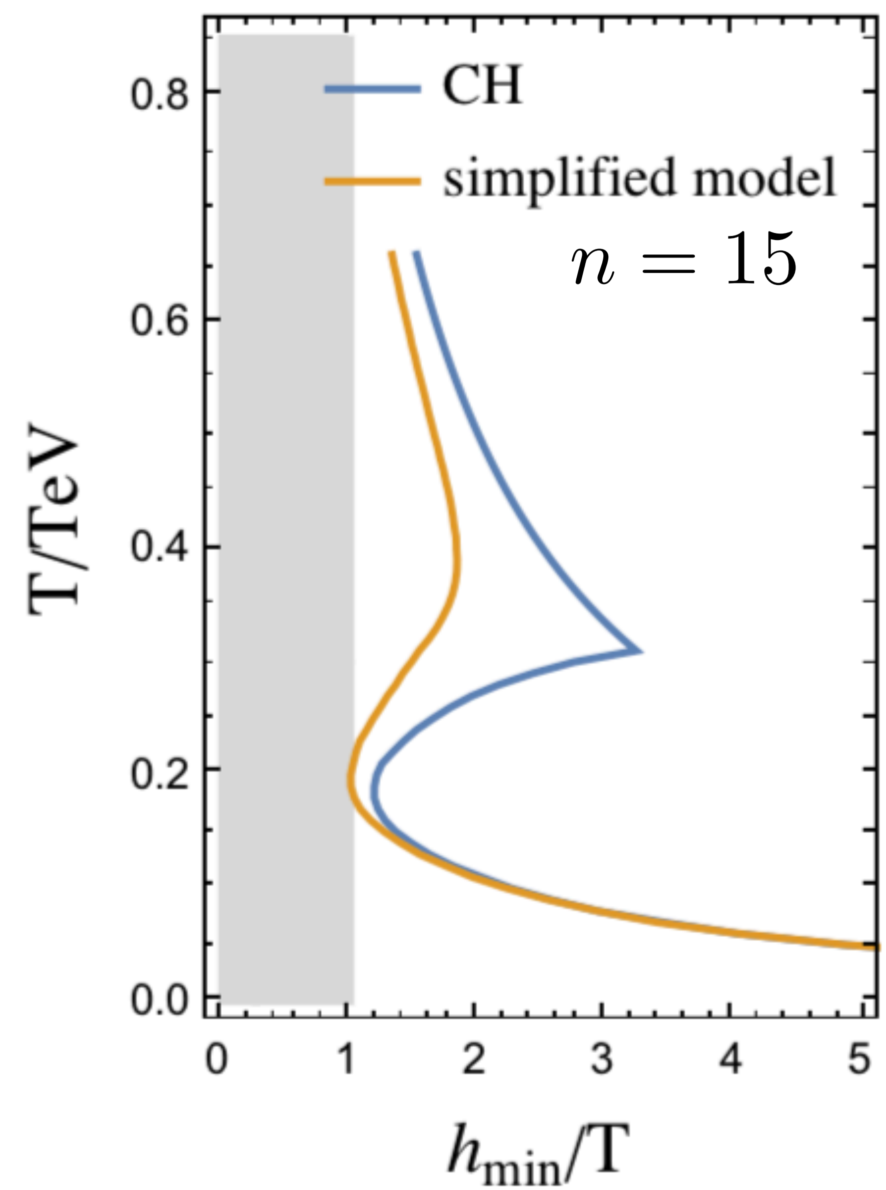

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- Renormalizeable completion:

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- dim-4 op. coupling fermions to the Higgs is allowed

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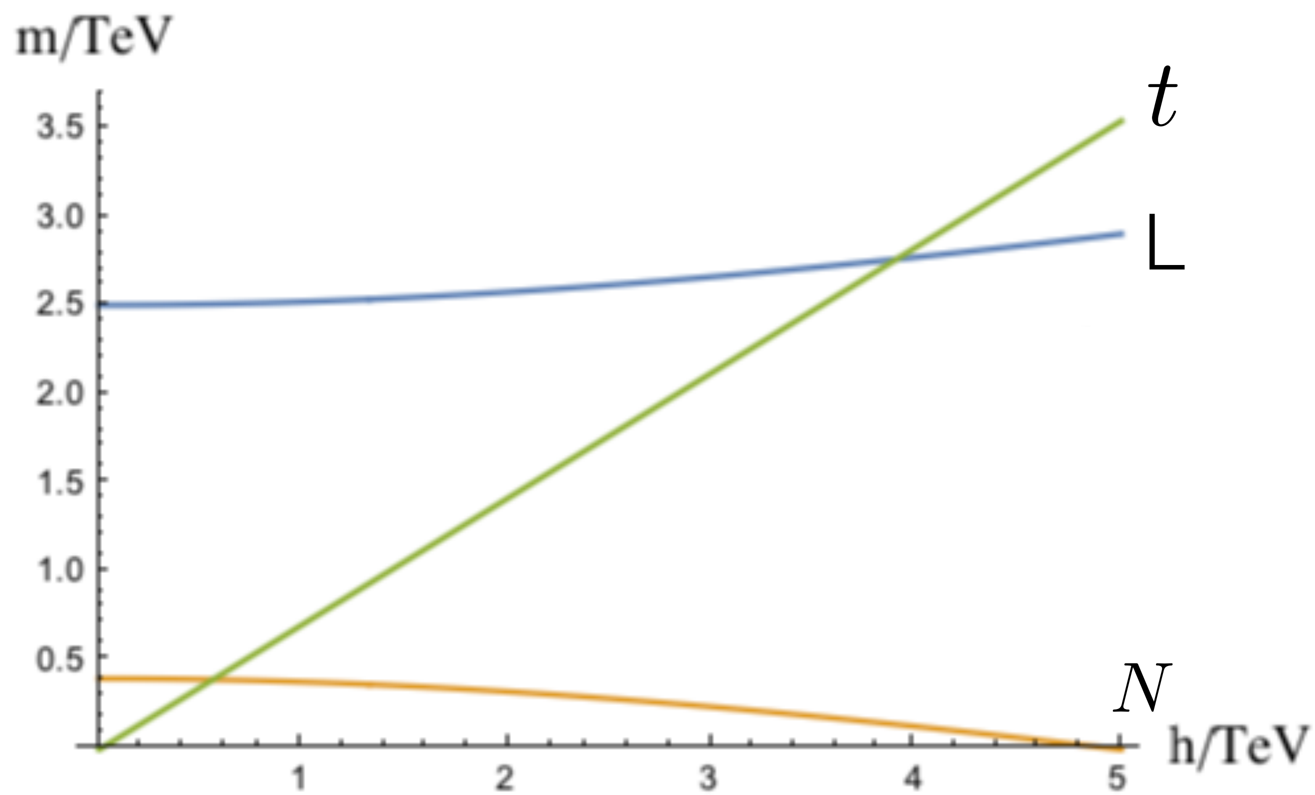
- dim-5 SNR operator produced at low T after integrating L out, with

  $m_L \longleftrightarrow \Lambda$

Explicit models: Singlet-Doublet Model

- Mass spectrum:



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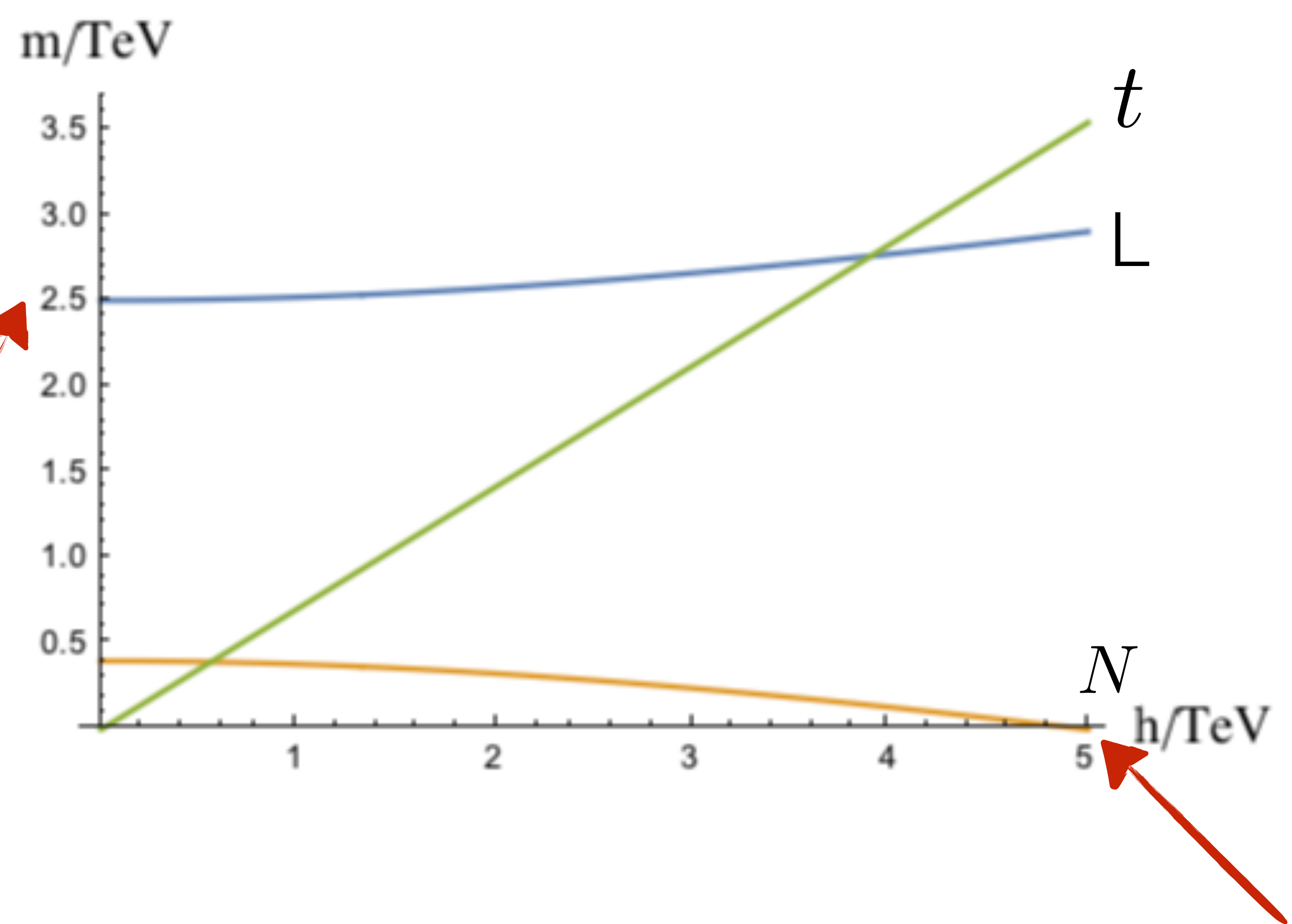


L mass minimized at $h = 0$

→ contributes to SR at $T > m_L/4$

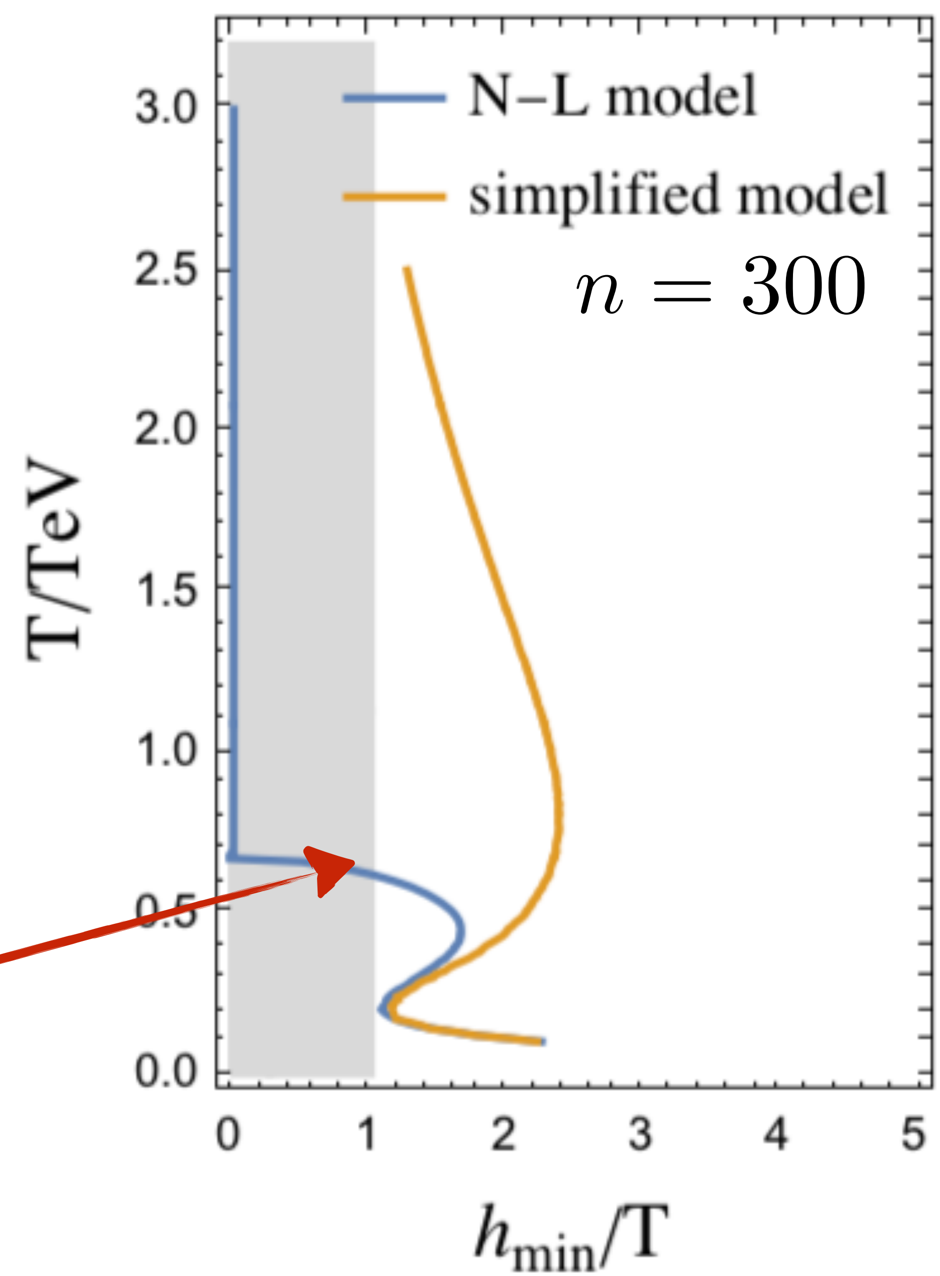
vanishing N mass at $h^2 = 2\frac{m_L^0 \hat{m}_N^0}{y_1 y_2}$

→ contributes to SNR

Explicit models: Singlet-Doublet Model

- lower SNR temperature because of the doublet component

$$T_{\rm SNR} \lesssim \frac{1}{5}\sqrt{n}\, m_N$$



effect of the doublet component

Conclusions

- We have shown an alternative way to have high-T SNR based on new fermionic d.o.f.
- Non-renormalizability is tightly related to SNR.
- Moderate number of fermions needed for SNR around 1 TeV, but becomes ~1000 for T~10TeV.
- Main predictions: at least ~10 new fermions with a mass 300-500 GeV coupled to the Higgs boson
- Opens new parameter space e.g. for EWBG
- Scenario is easy to realize in motivated models like CH

Back-up

Thermal Loops

$$\Delta V_b^T = \frac{T^4}{2\pi^2} J_b[m^2/T^2], \qquad \Delta V_f^T = -\frac{2T^4}{\pi^2} J_f[m^2/T^2]$$

$$J_b[x] = \int_0^\infty dk\, k^2 \log\left[1 - e^{-\sqrt{k^2+x}}\right], \qquad J_f[x] = \int_0^\infty dk\, k^2 \log\left[1 + e^{-\sqrt{k^2+x}}\right]$$

Symmetry NonRestoration with Scalars

- Negative mass correction competing with SM corrections:

$$\delta m_h^2(T) \simeq -\frac{n_\chi \lambda_{\chi h}}{12} T^2 \qquad \text{vs} \qquad \delta m_h^2(T) \simeq T^2 \left[\frac{\lambda_t^2}{4} + \frac{\lambda}{2} + \frac{3g^2}{16} + \frac{g'^2}{16} \right]$$

- For $\lambda_{\chi h} > 0$ stability of scalar potential requires

$$\lambda_{\chi h}^2 < \lambda_h \lambda_\chi \qquad \longrightarrow \qquad \lambda_\chi > \frac{\lambda_{\chi h}^2}{\lambda_h}$$

non-perturbative χ quartic for small n