מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

# High-temperature EW symmetry breaking: Reassessing the window for EW baryogenesis in Composite Higgs models

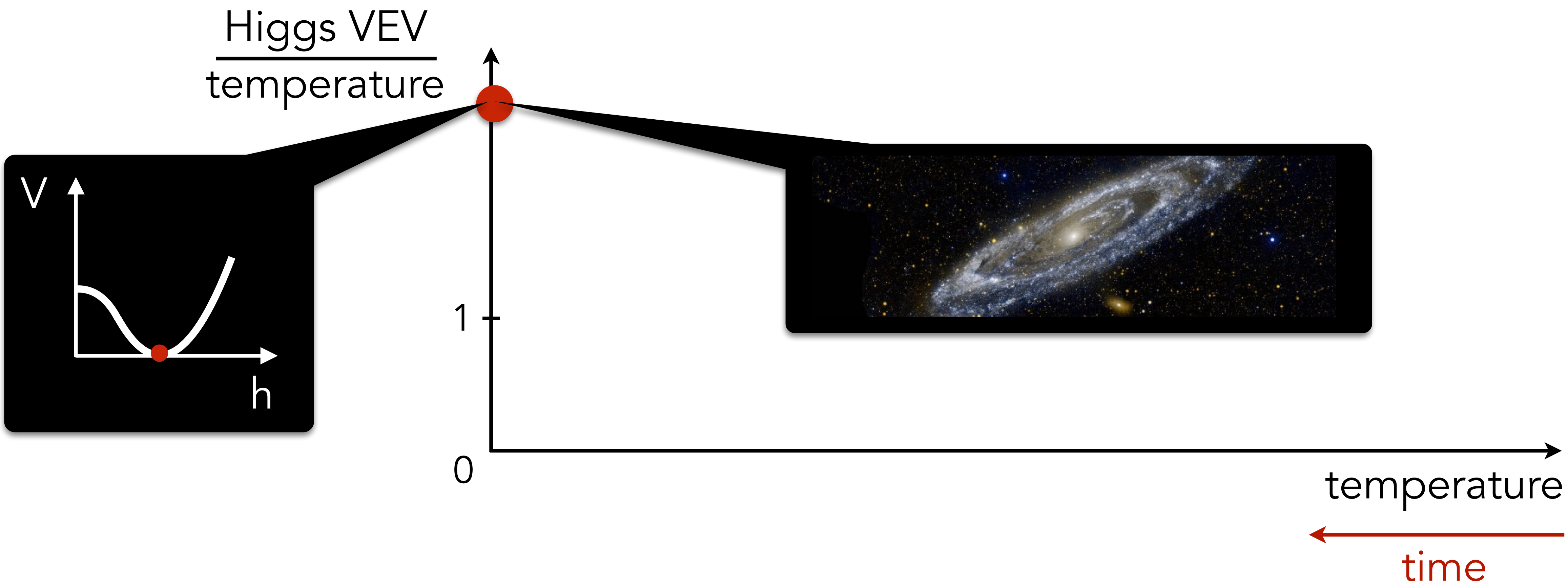
Oleksii Matsedonskyi

*HPNP 2021*

# Motivation

# Electroweak symmetry in the early Universe

# Electroweak symmetry in the early Universe



# Electroweak symmetry in the early Universe

**in Standard Model: high-T symmetry restoration**

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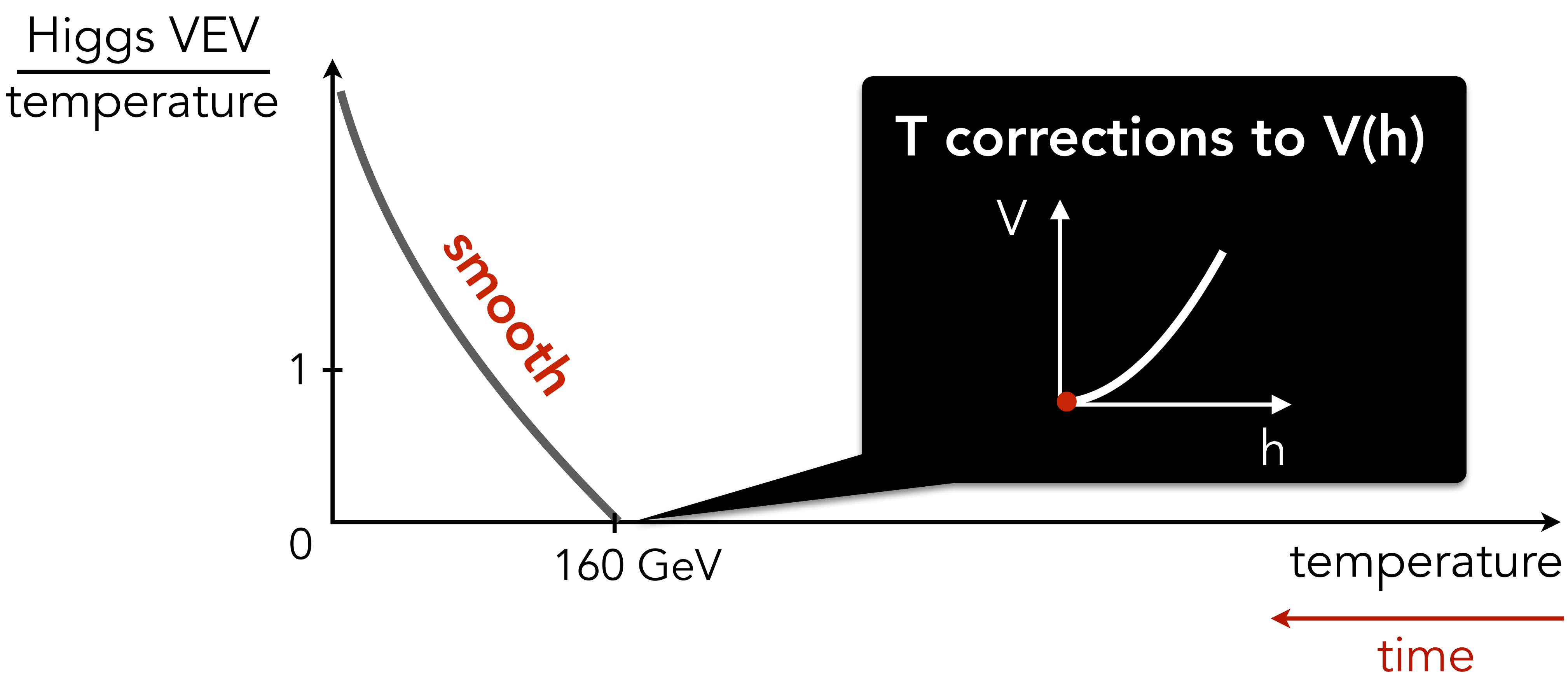
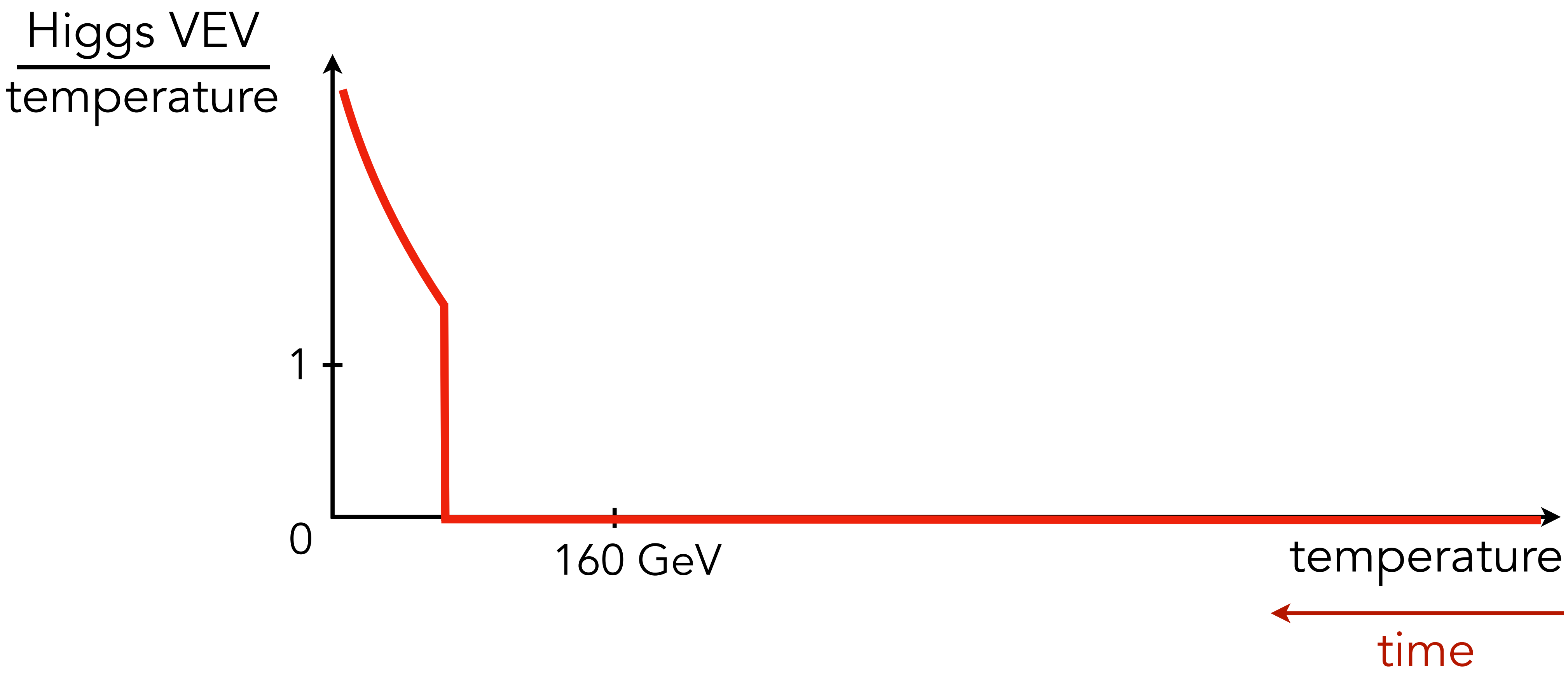


# Electroweak symmetry in the early Universe

**in Electroweak Baryogenesis scenarios**



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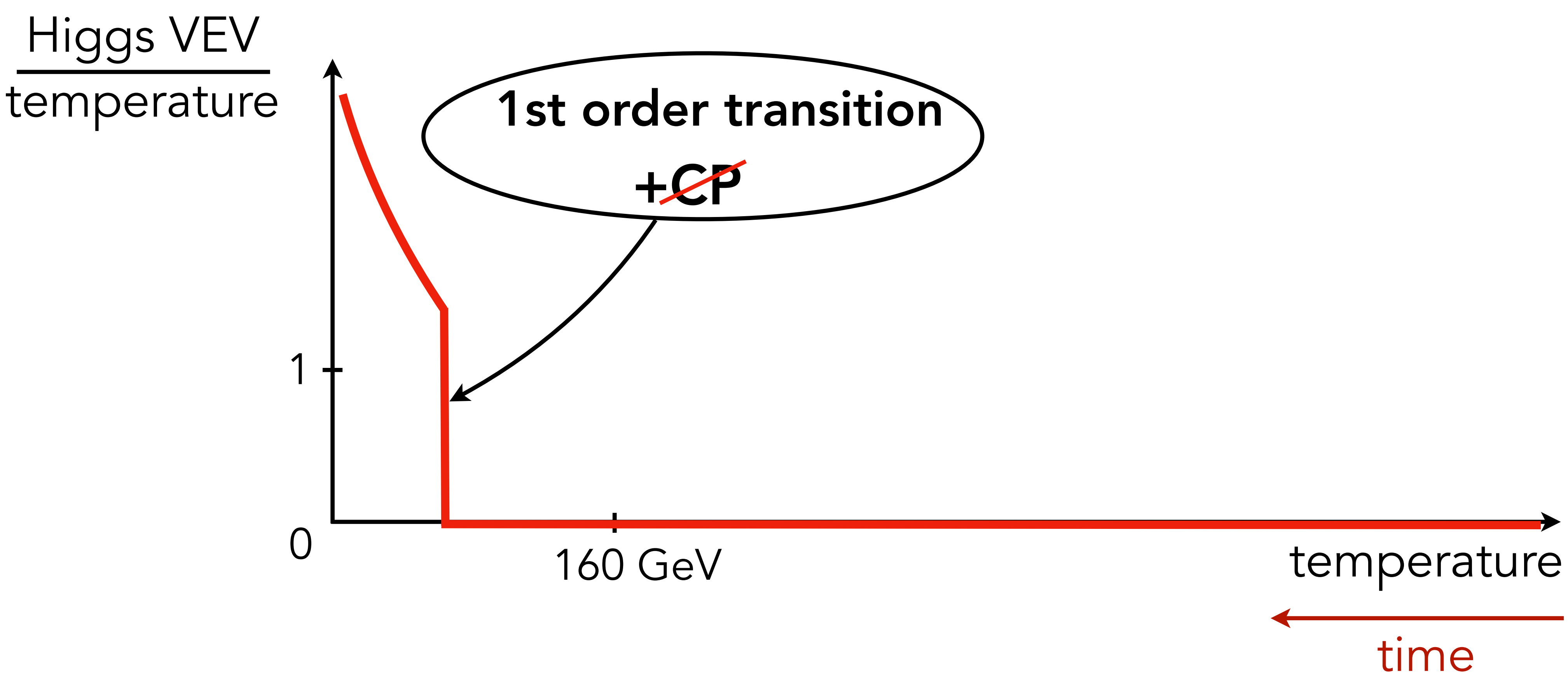

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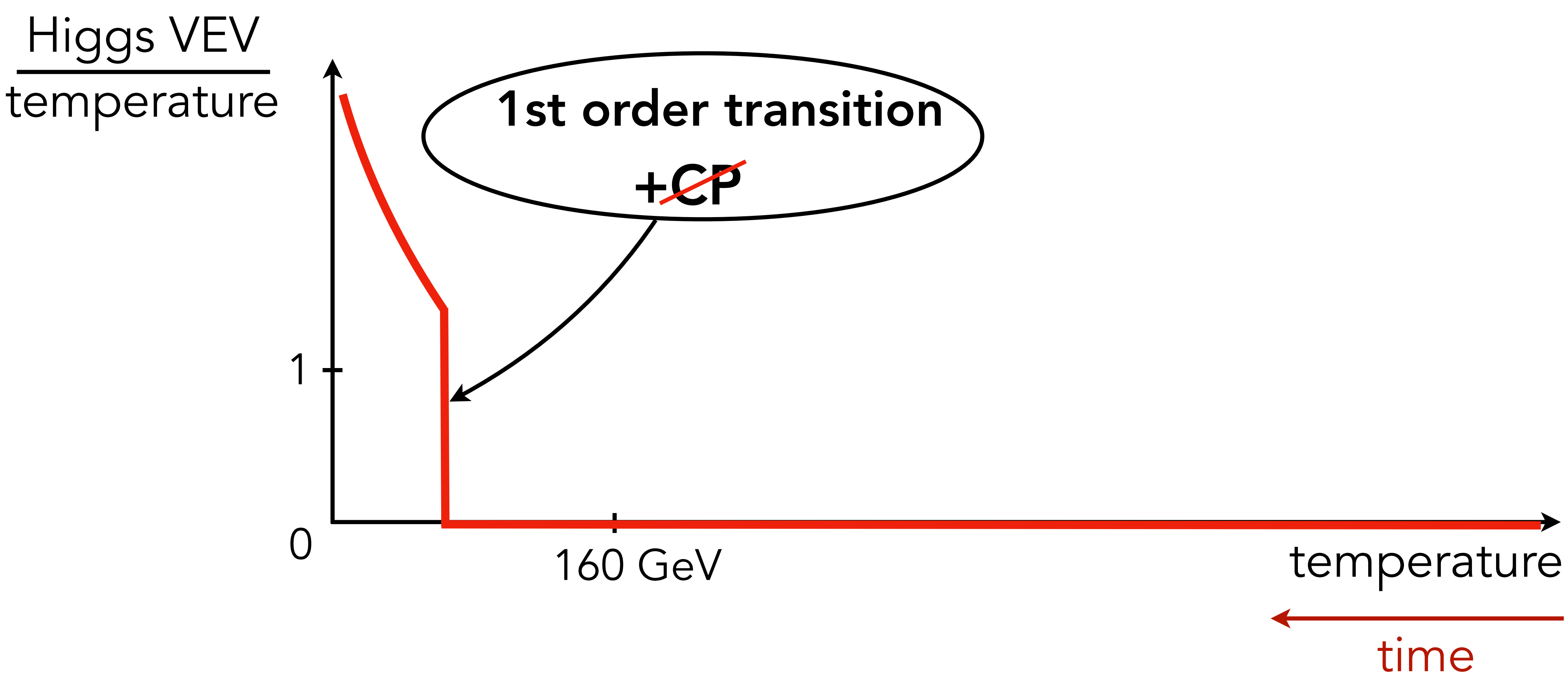
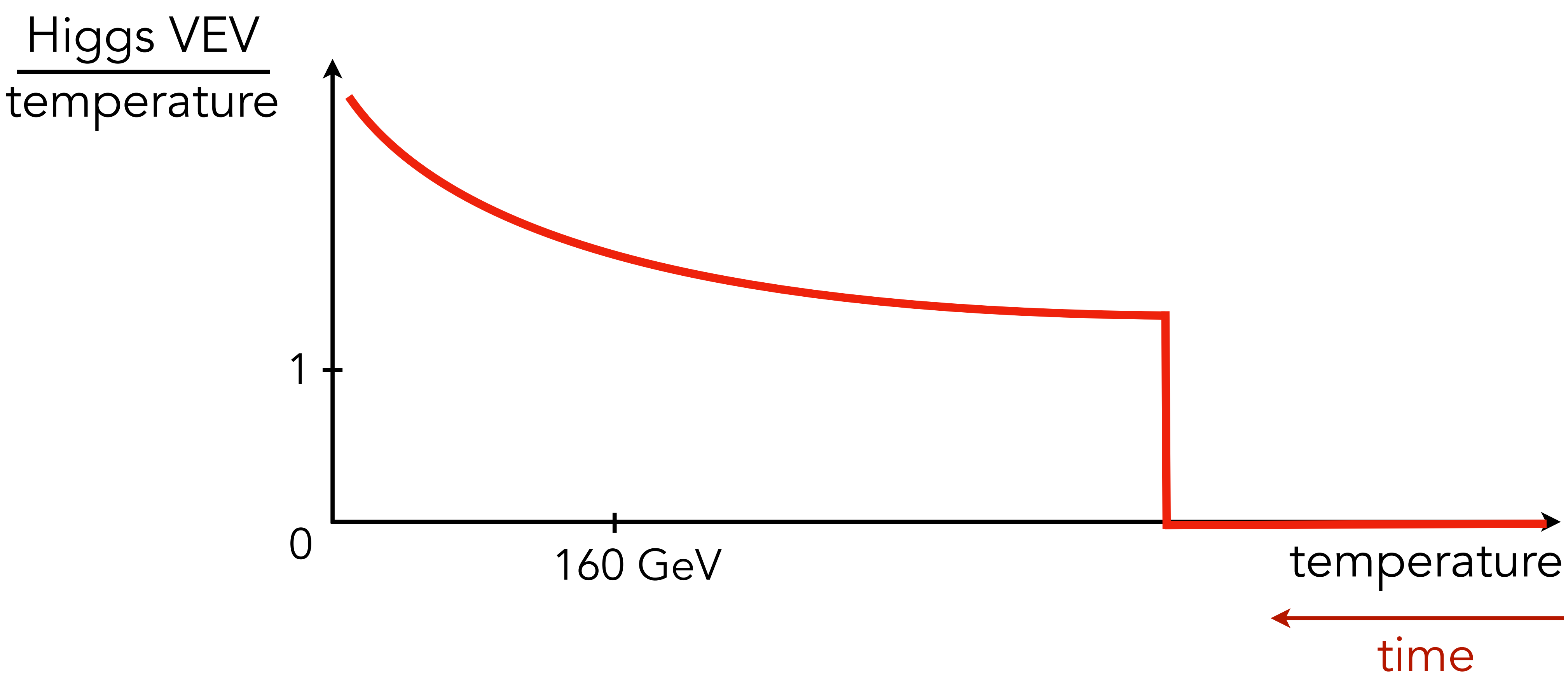



➔ new physics responsible for CP violation and first-order phase transition is at a few 100 GeV scale

➔ **good** because testable, **bad** (for some models) because overconstrained

**What if?**



# Electroweak symmetry in the early Universe

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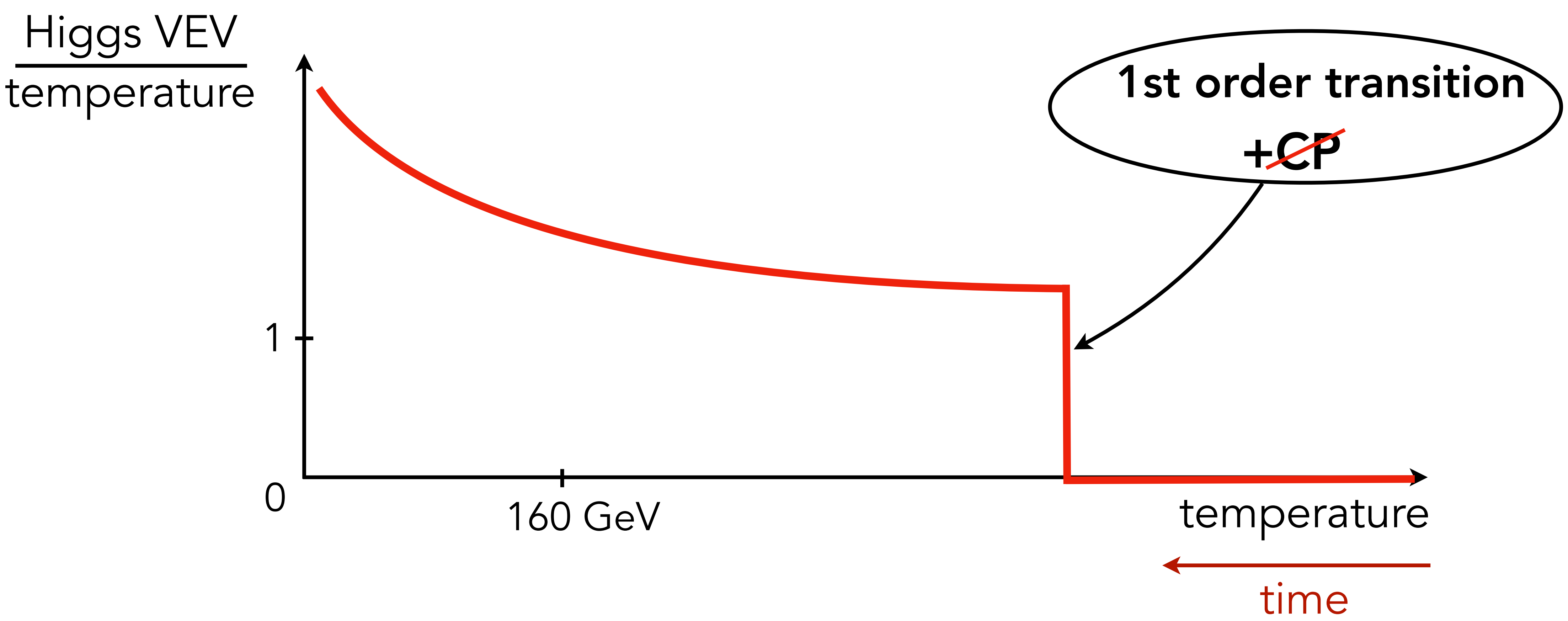
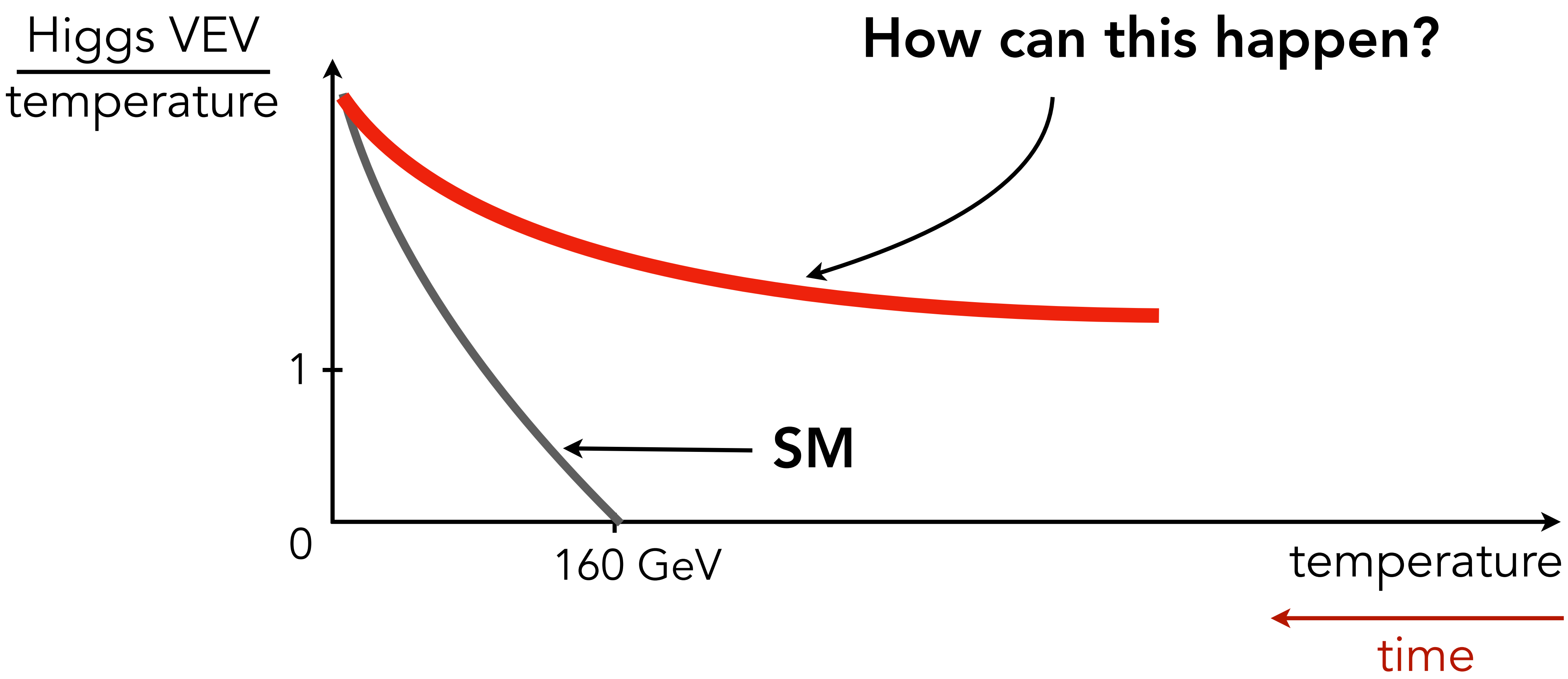



➔ new physics responsible for CP violation and first-order phase transition is **far above** 100 GeV scale

➔ **new phenomenology**

# Electroweak symmetry in the early Universe



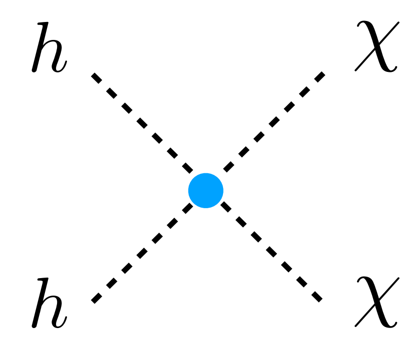
# EW Symmetry Breaking at High T

# Electroweak Symmetry Non-Restoration at High T

- EW SNR was first proposed in:

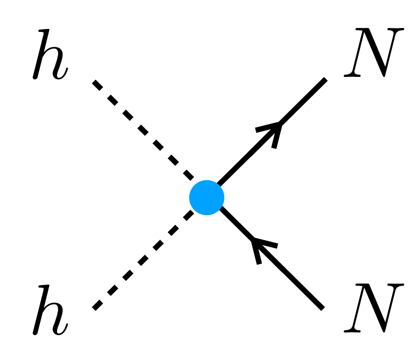
  Meade, Ramani, 1807.07578
  Baldes, Servant, 1807.08770
  Glioti, Rattazzi, Vecchi, 1811.11740

  with **new light scalars**



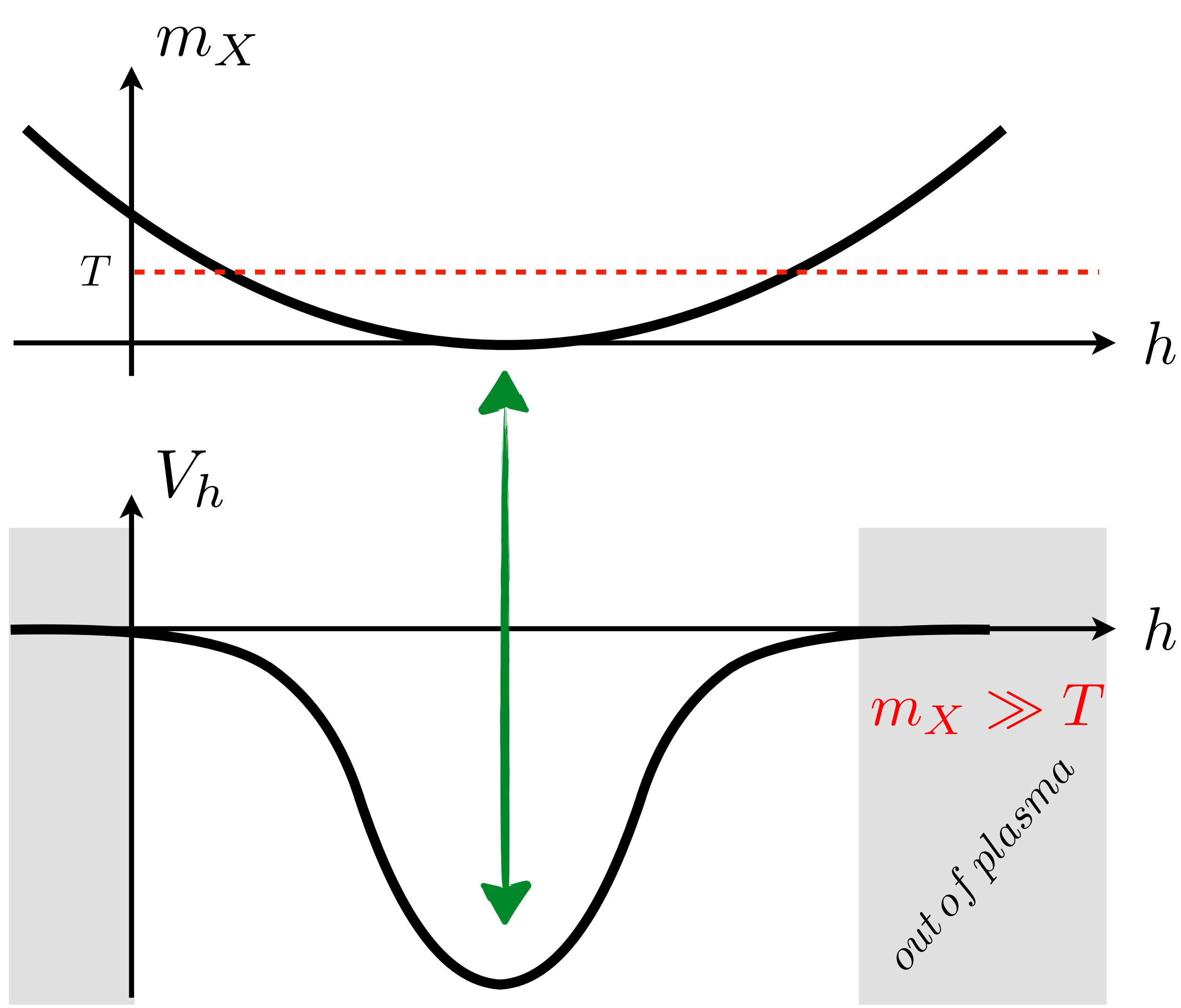

- We showed how can be done with **new fermions**

  OM, Servant, 2020.05174



# Electroweak Symmetry Non-Restoration at High T

- If h potential is induced by plasma of particles with h-dependent mass:



# SNR with fermions

OM, Servant, 2020.05174

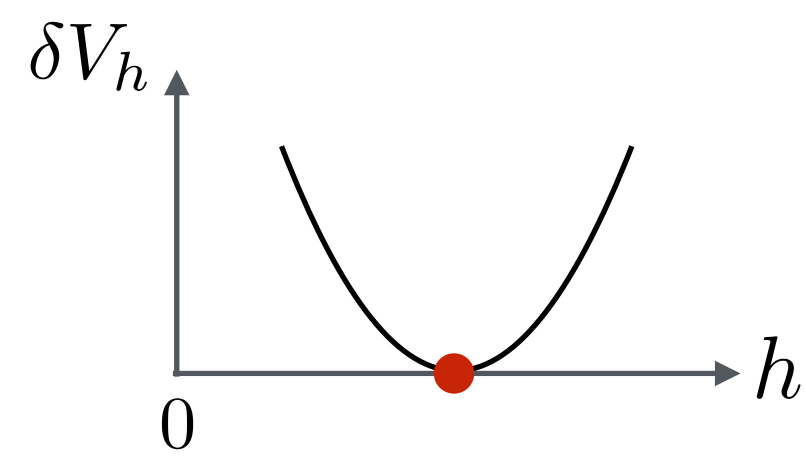
- Add $n$ copies of new SM singlet Dirac fermion $N$

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

- $N$ mass is minimized at large $h$

$$m_N(h) = m_N - \lambda_N h^2/\Lambda = 0$$

$$\longrightarrow \; h^2 = m_N \Lambda/\lambda_N$$



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**cutoff**

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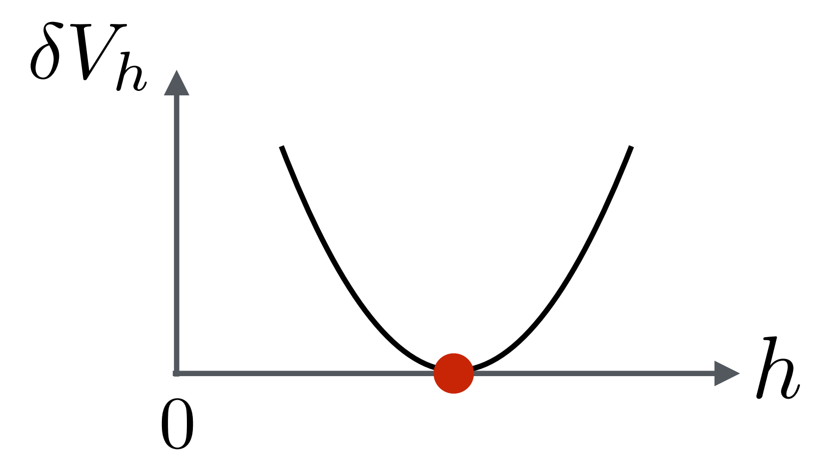

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**why not 1?**

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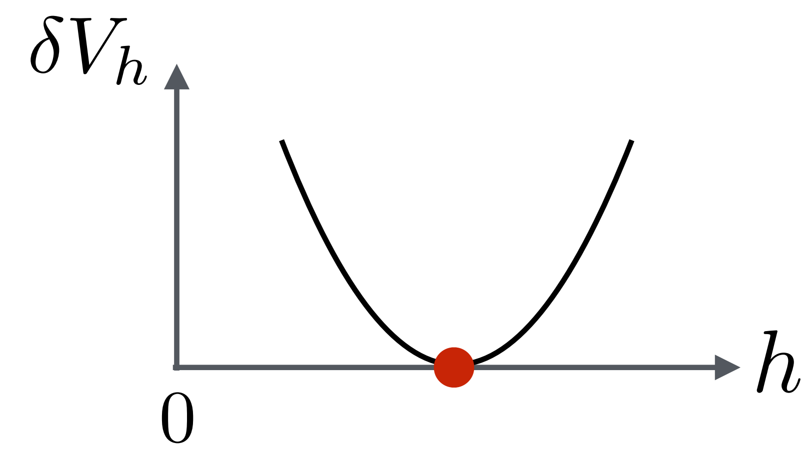
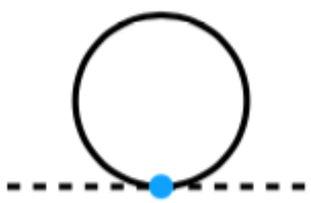


# SNR with fermions

OM, Servant, 2020.05174

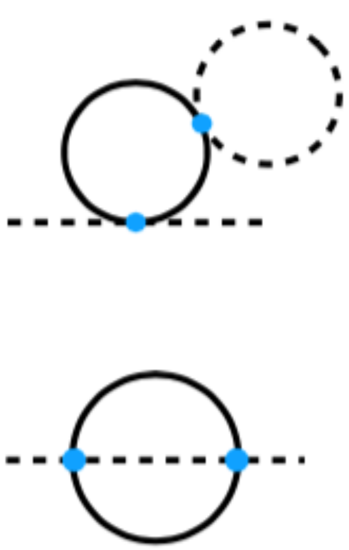
→ High-T perturbativity implies $T_{\rm SNR}^{\rm max} \sim \sqrt{n}\, m_N$

calculable 1-loop (negative mass):

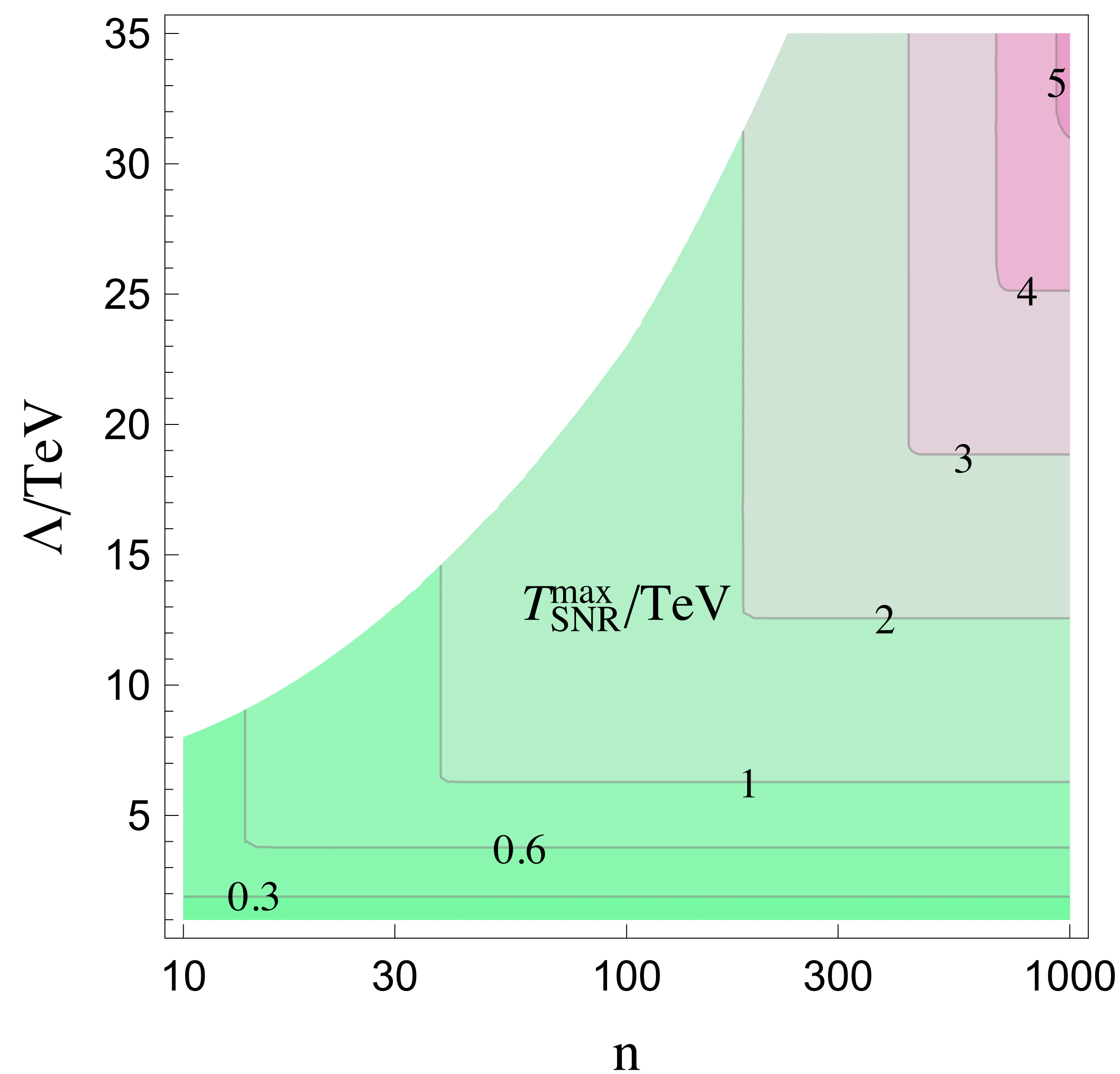


$$\propto n\lambda_N \frac{m_N}{\Lambda} \simeq 1$$

higher loops (out of control):



$$\beta = n\lambda_N^2 \frac{T^2}{\Lambda^2} \ll 1$$

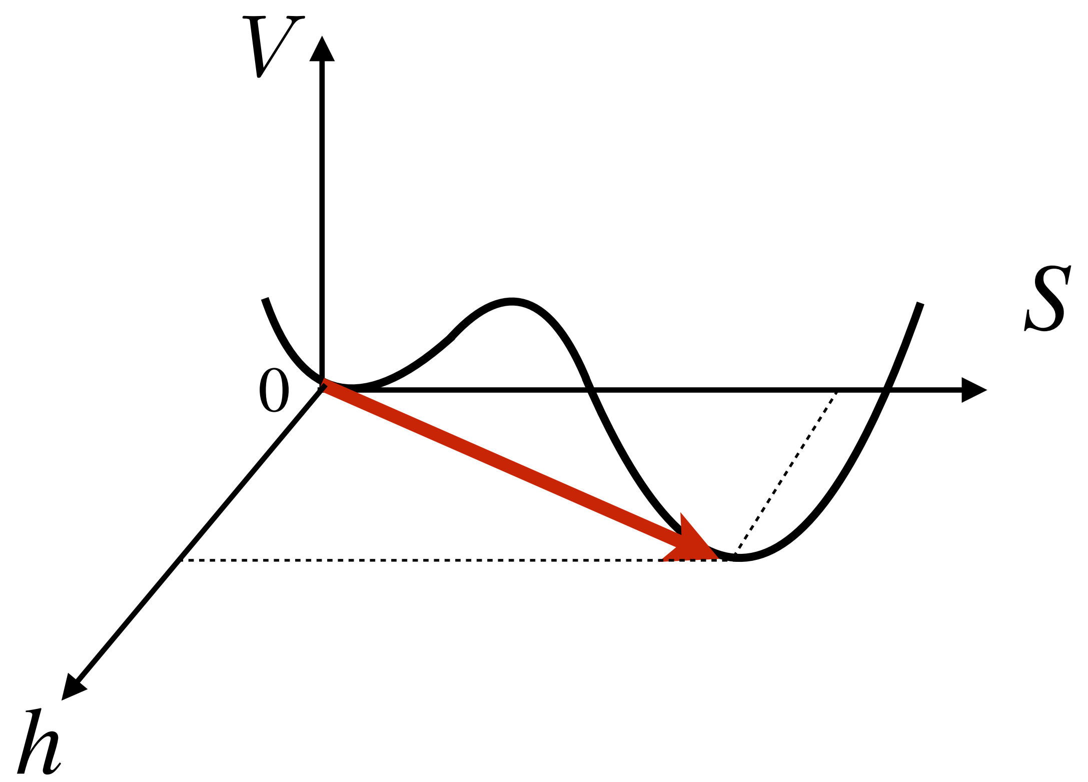


# Phenomenological Impact

# Phase Transition Temperature

work in progress
Bruggisser,VonHarling,OM,Servant

➔ Usual way to get 1st order EW phase transition: add a new scalar S




➔ EWBG needs T < T of EW restoration

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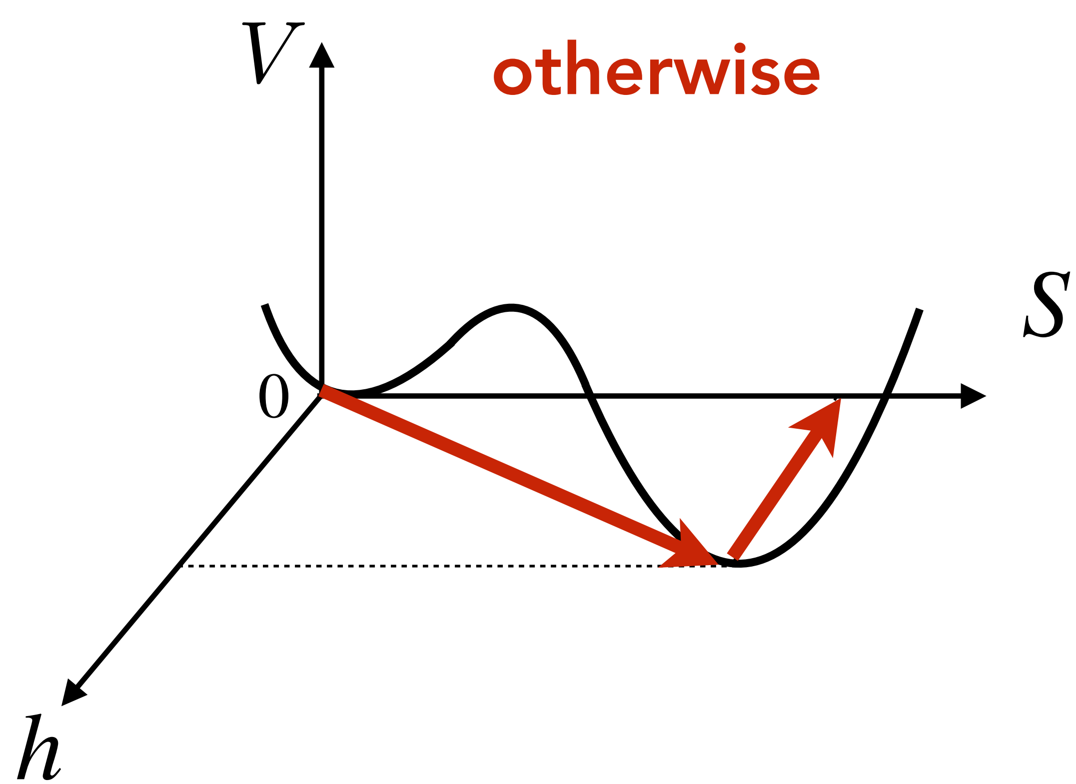


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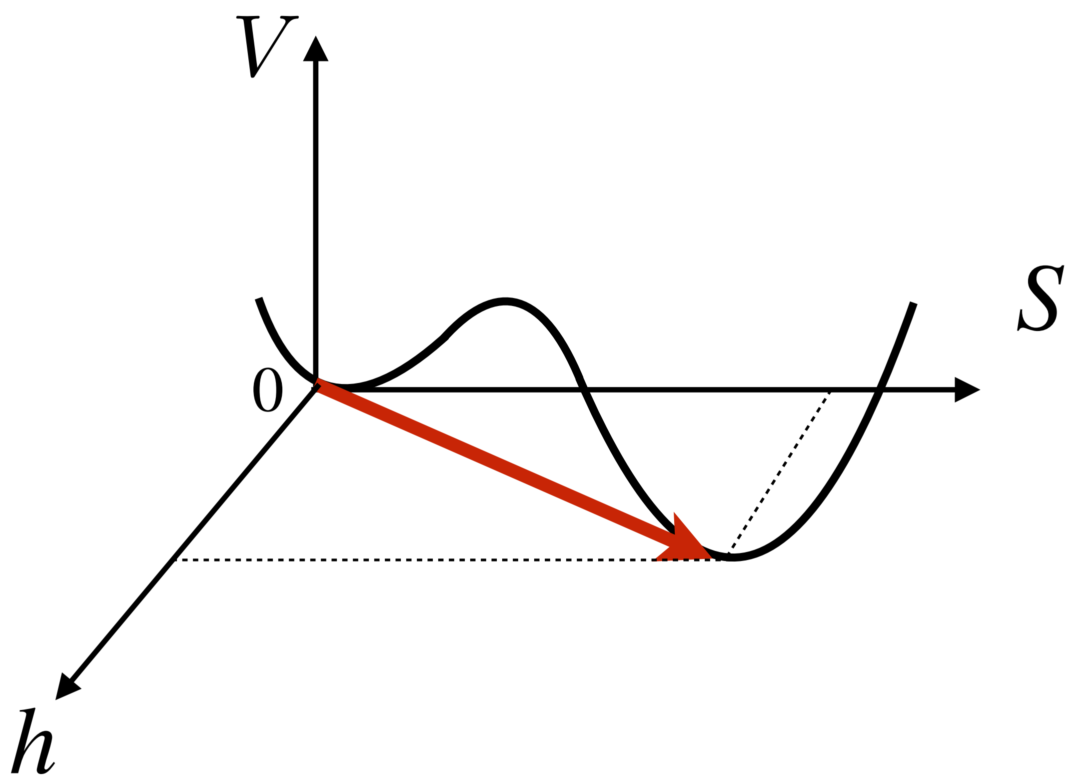


- EWBG needs T < T of EW restoration

- S phase transition releases latent heat

$$T^4 \propto m_S^2$$

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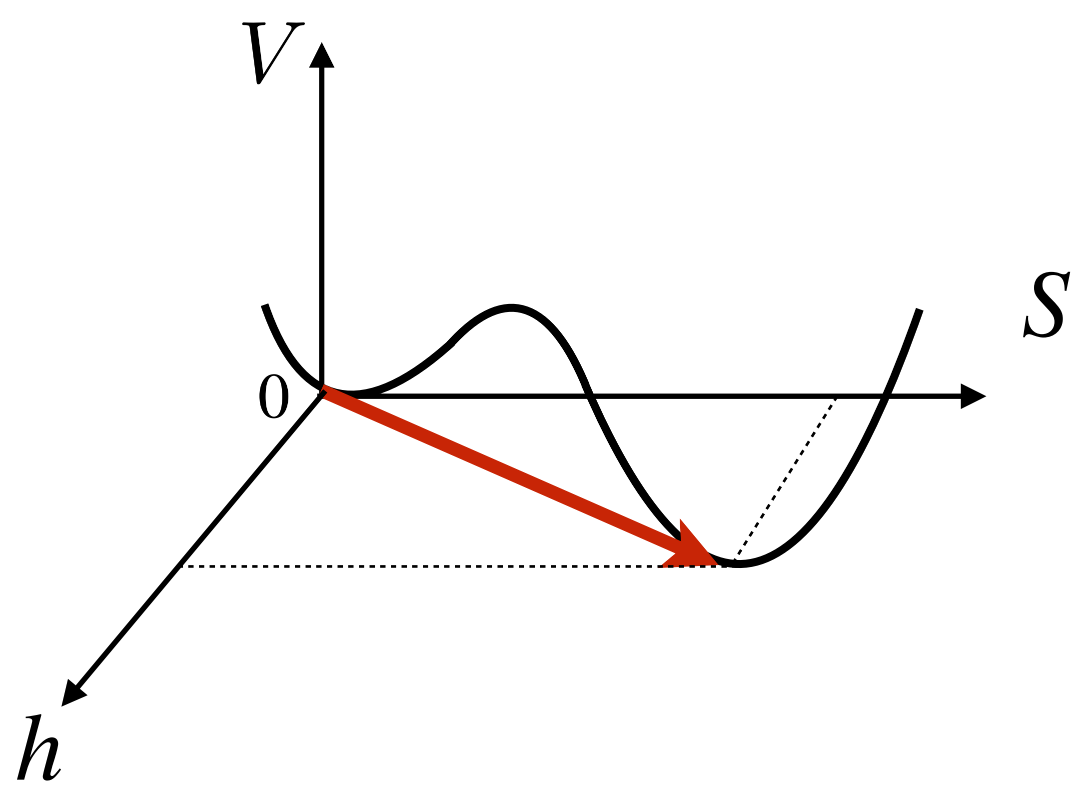


- EWBG needs T < T of EW restoration
- S phase transition releases latent heat

$$T^4 \propto m_S^2$$

$\Rightarrow$ for T restoration ~130 GeV

$m_S \lesssim$ O(100 GeV)

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work in progress
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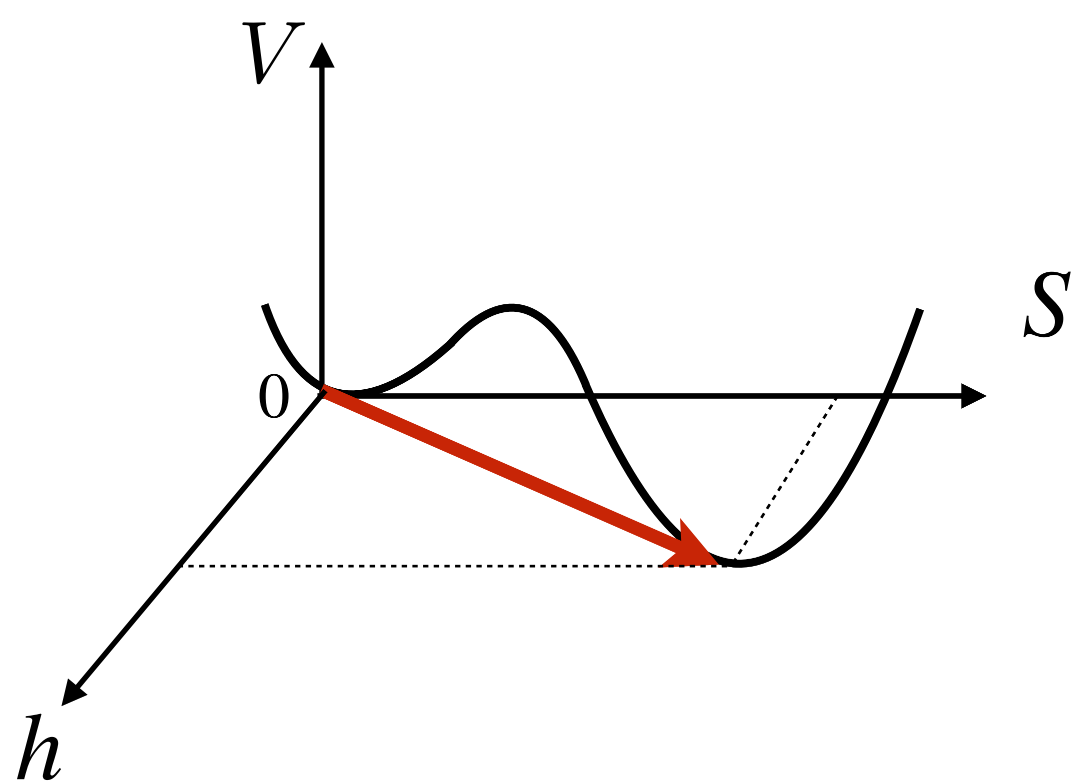



➔ EWBG needs T < T of EW restoration

➔ S phase transition releases latent heat

$$T^4 \propto m_S^2$$

$\Rightarrow$ for T restoration ~1 TeV

$m_S \lesssim$ O(few TeV)

# Concrete Example: EWBG in Composite Higgs

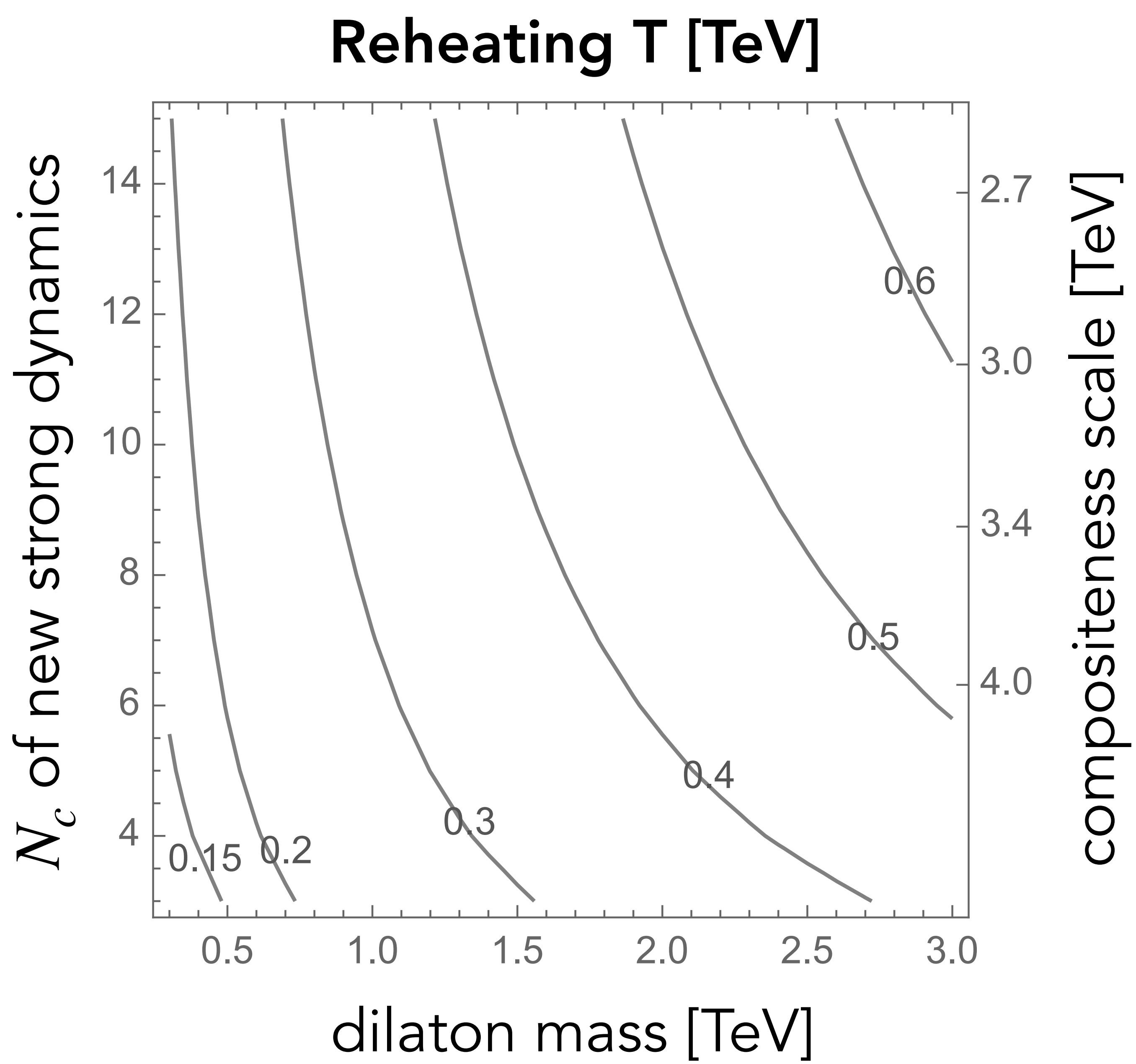
work in progress
Bruggisser,VonHarling,OM,Servant

➔ Higgs is a bound state of new strong interactions

➔ New scalar triggering the first order phase transition
- dilaton (PNGB of approximate conformal invariance)

# Concrete Example: EWBG in Composite Higgs

work in progress
Bruggisser,VonHarling,OM,Servant



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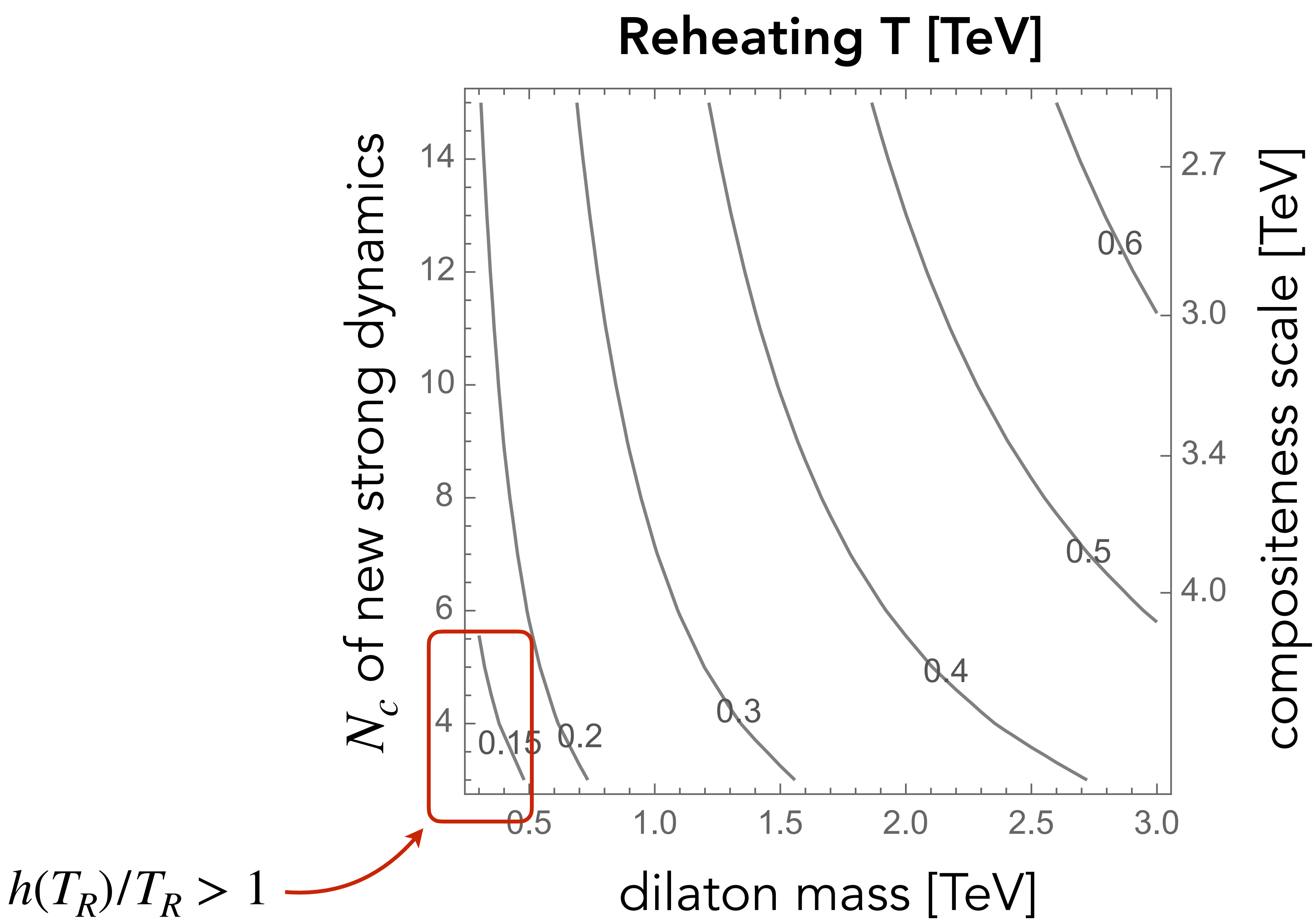
Bruggisser,VonHarling,OM,Servant




**tension with collider searches**

# Concrete Example: EWBG in Composite Higgs

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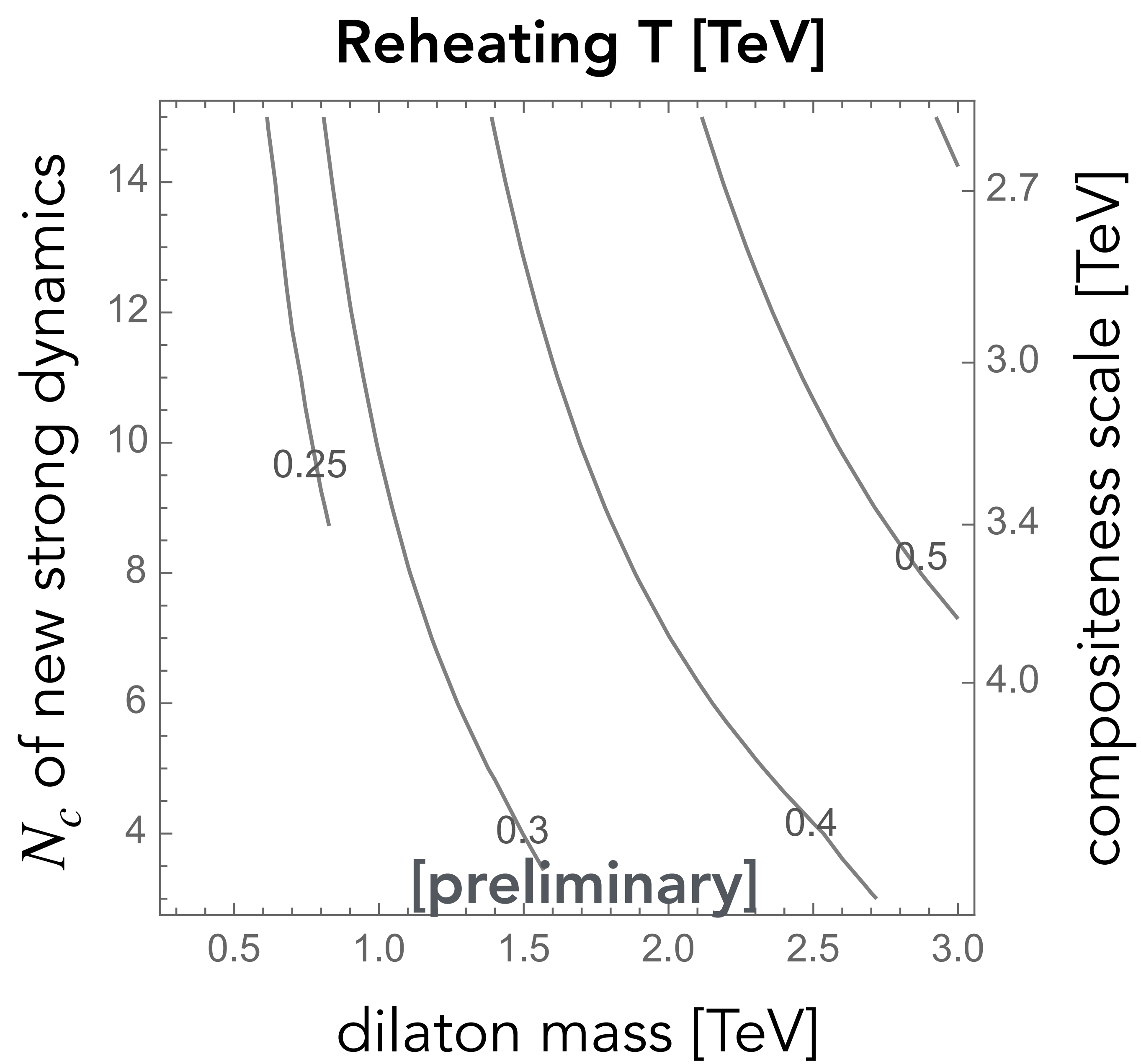
Bruggisser,VonHarling,OM,Servant

**+ 10 SNR fermions**



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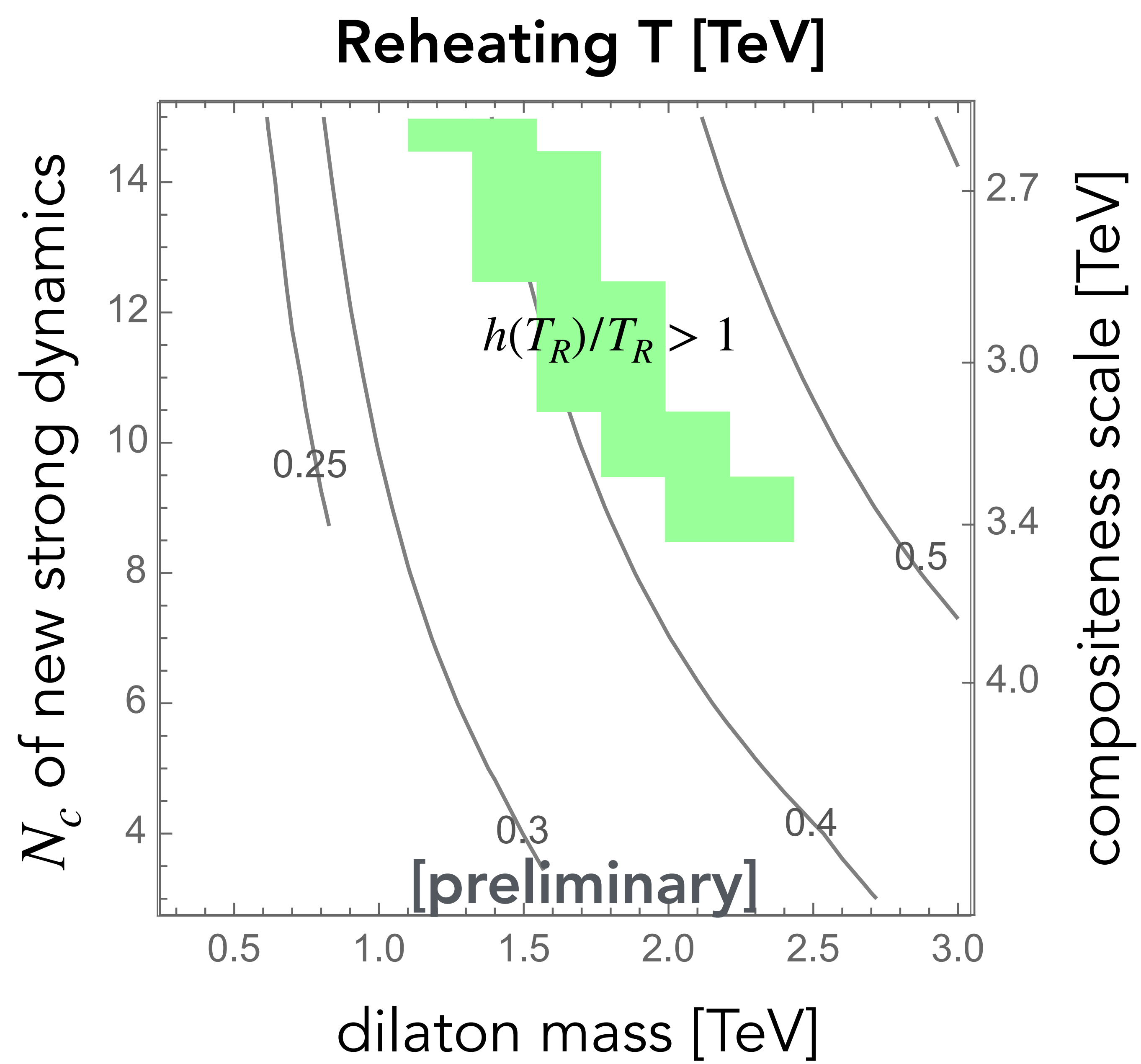

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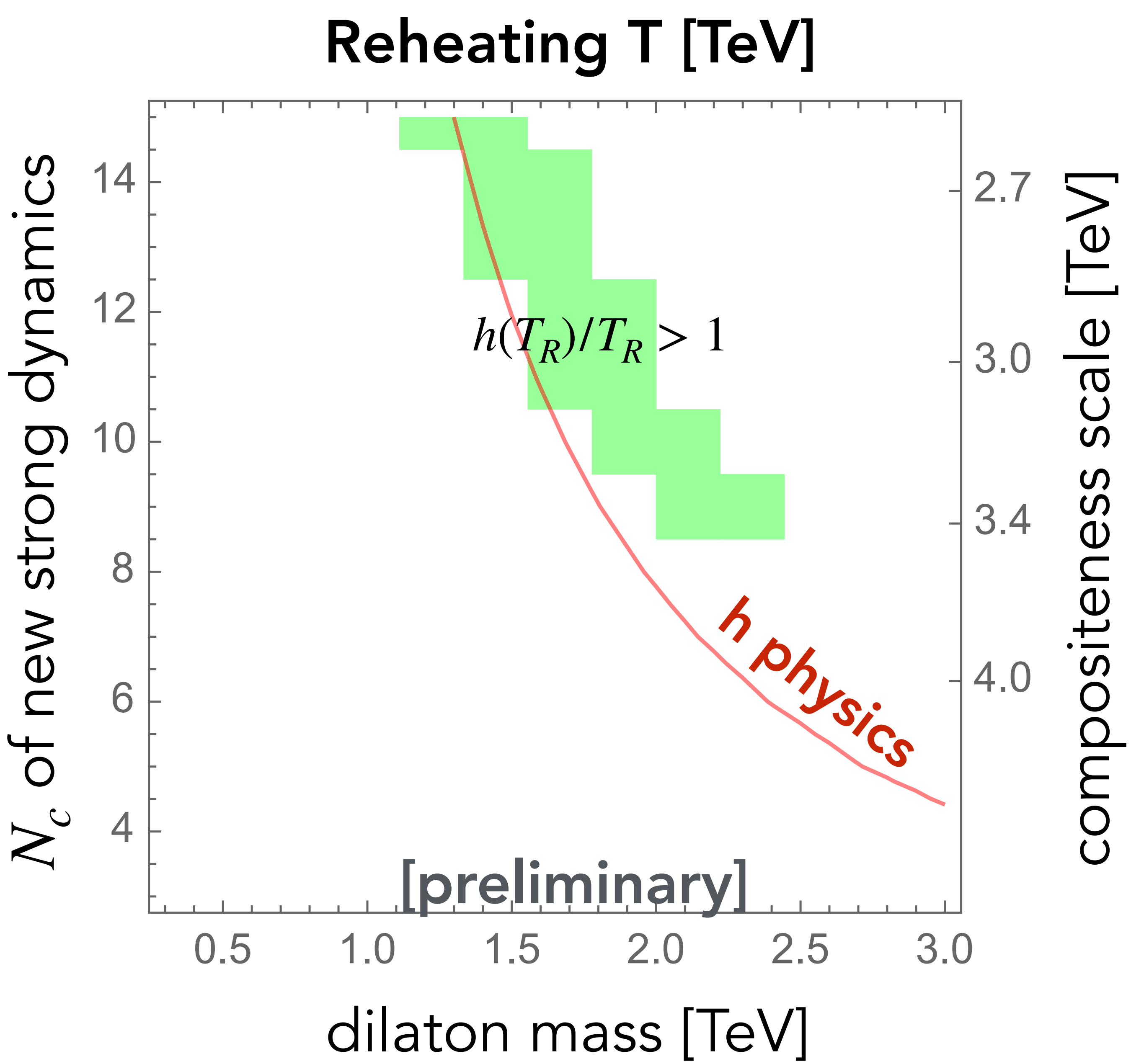

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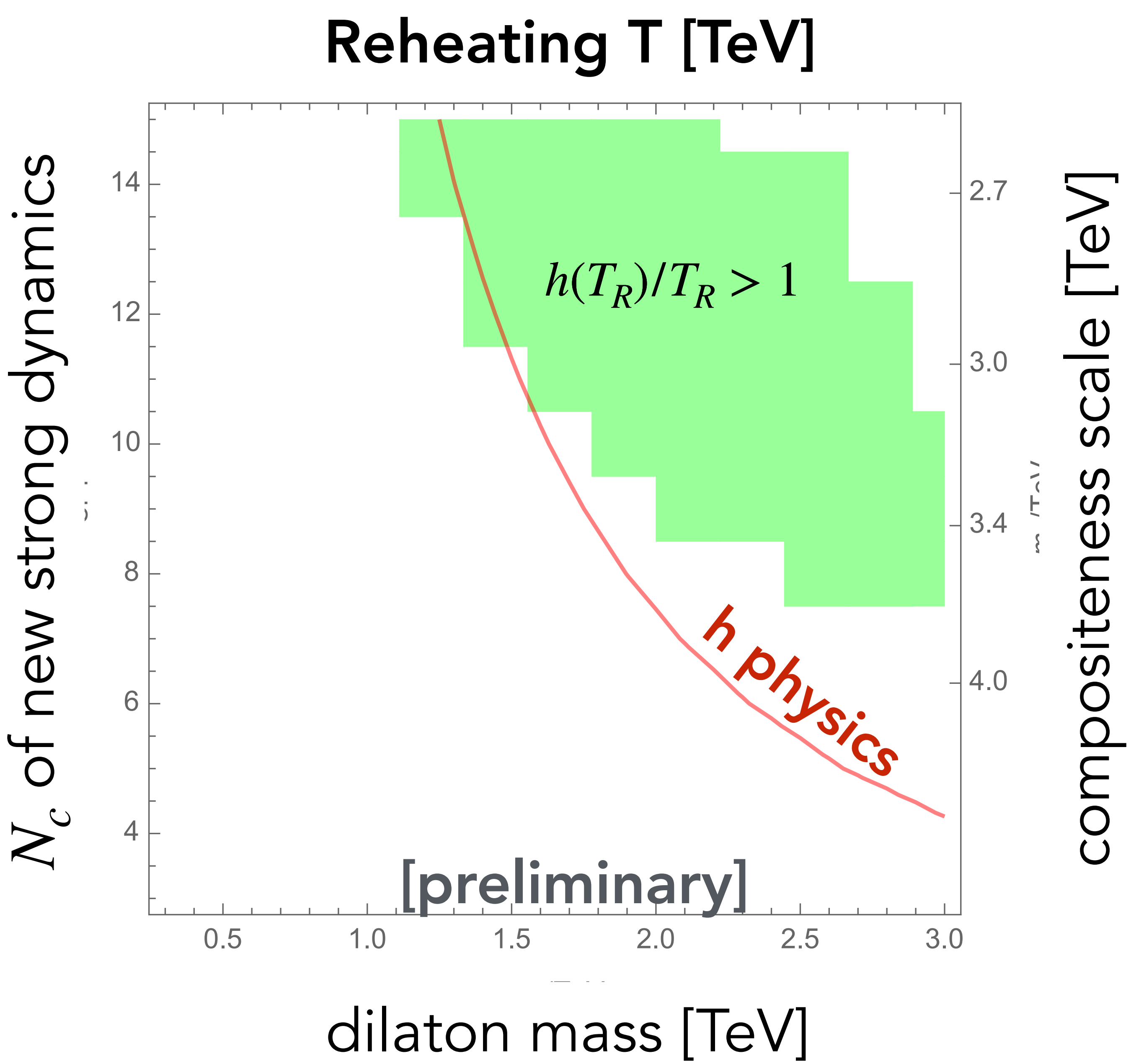
**+ 12 SNR fermions**



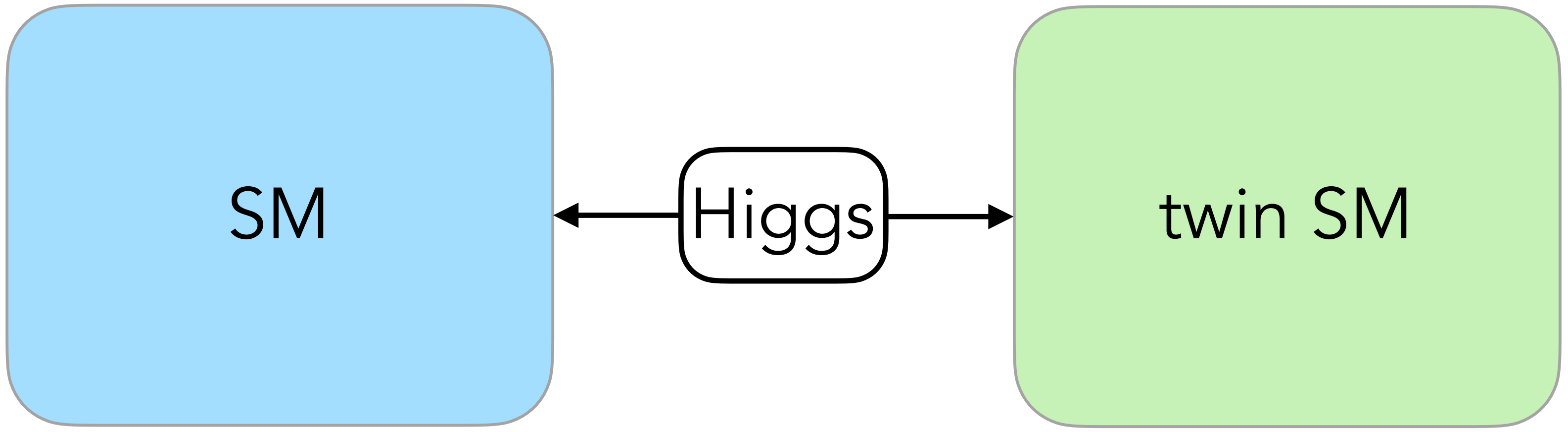
# “Automatic” Realizations

# Automatic SNR

➔ **Are there scenarios where the new SNR states appear automatically?**

First suspect - Twin Higgs models (Chacko et al, hep-ph/0506256)

Constructed to **solve the Higgs mass naturalness** problem.



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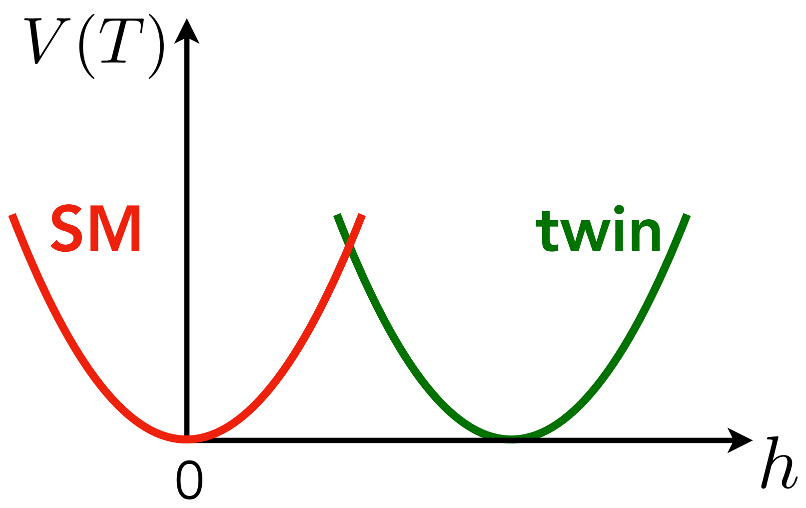

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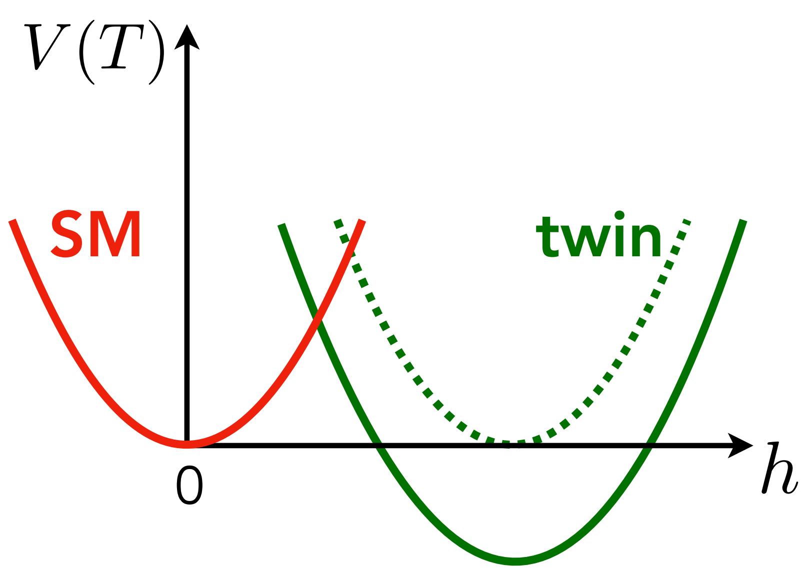


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(OM, 2008.13725)

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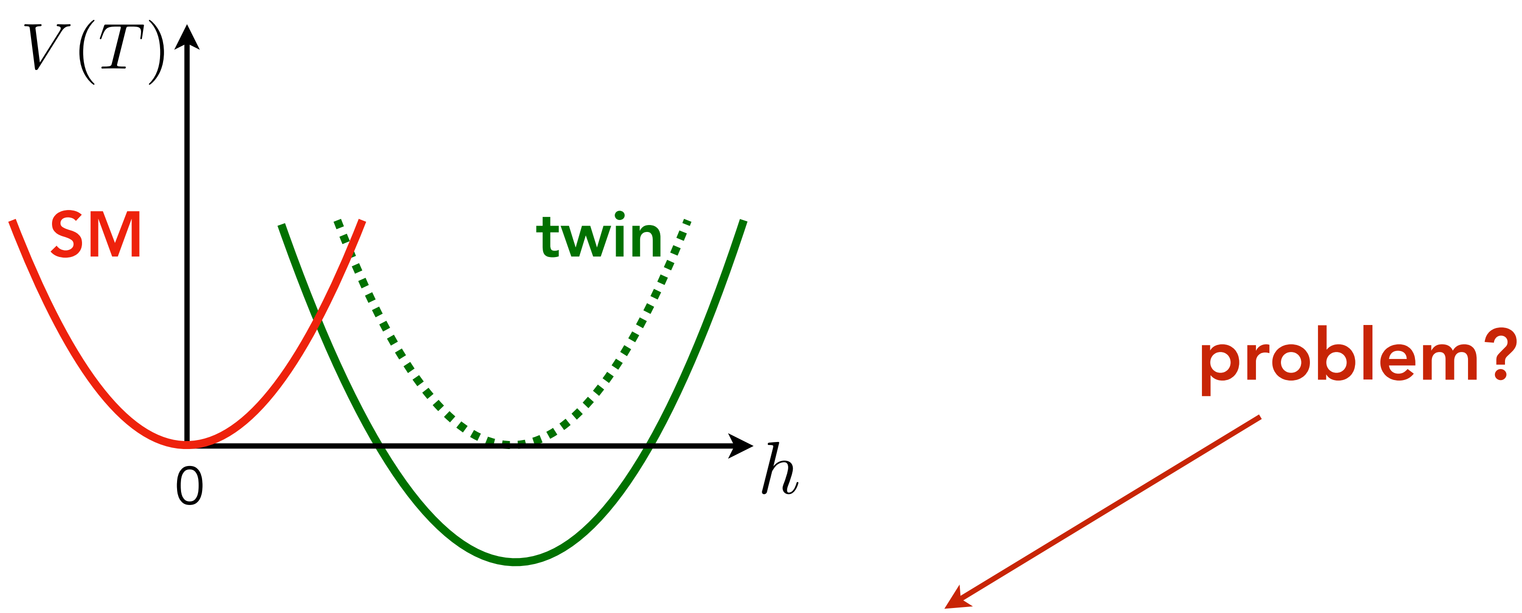


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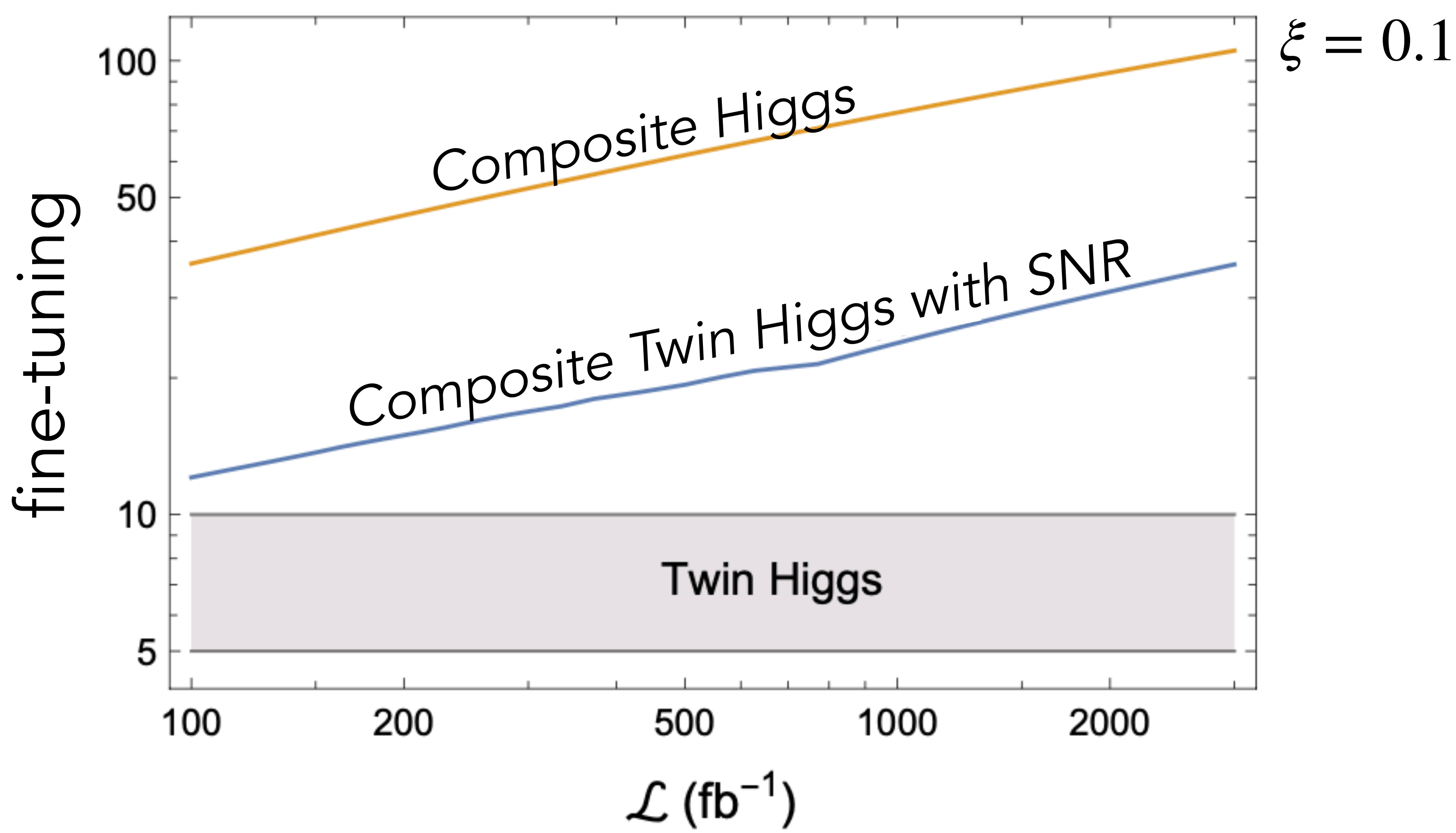
➔ Higgs potential **fine-tuning** in Composite Twin Higgs scenario with SNR




LHC luminosity projection

# Summary

- ➔ The typical energy scales associated with EW baryogenesis can change substantially in the presence of new physics triggering high-T EW symmetry non-restoration.

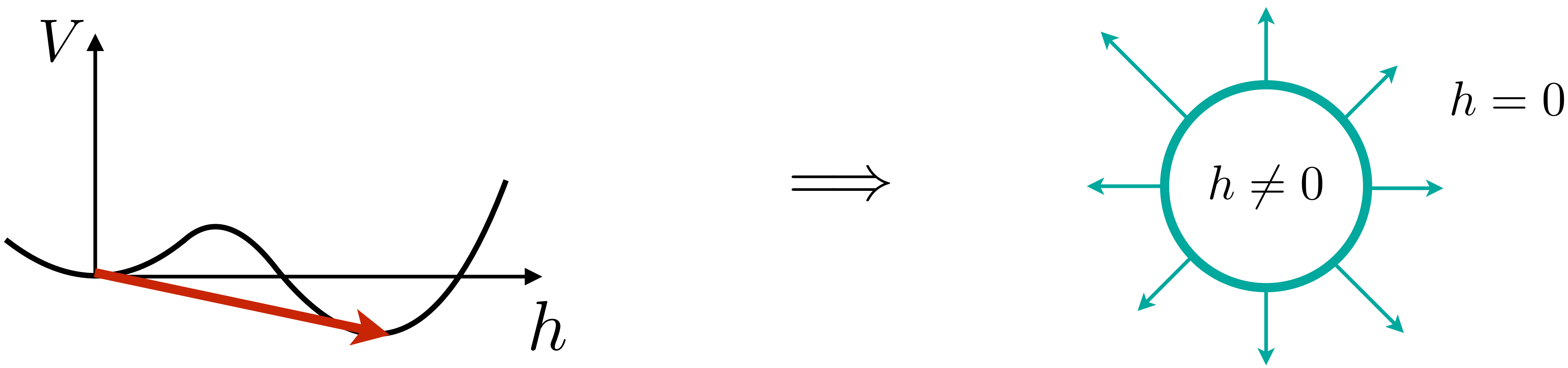
- ➔ From the collider physics point of view, this opens up a broad parameter space to search for EWBG traces.

- ➔ Perturbative models with EW SNR require a sizeable number of new states. One example of new physics scenarios which provides them "naturally" is the Twin Higgs models.

Thank you!

# Backup slides

**First order EW phase transition proceeds through bubble nucleation:**



# Electroweak Baryogenesis

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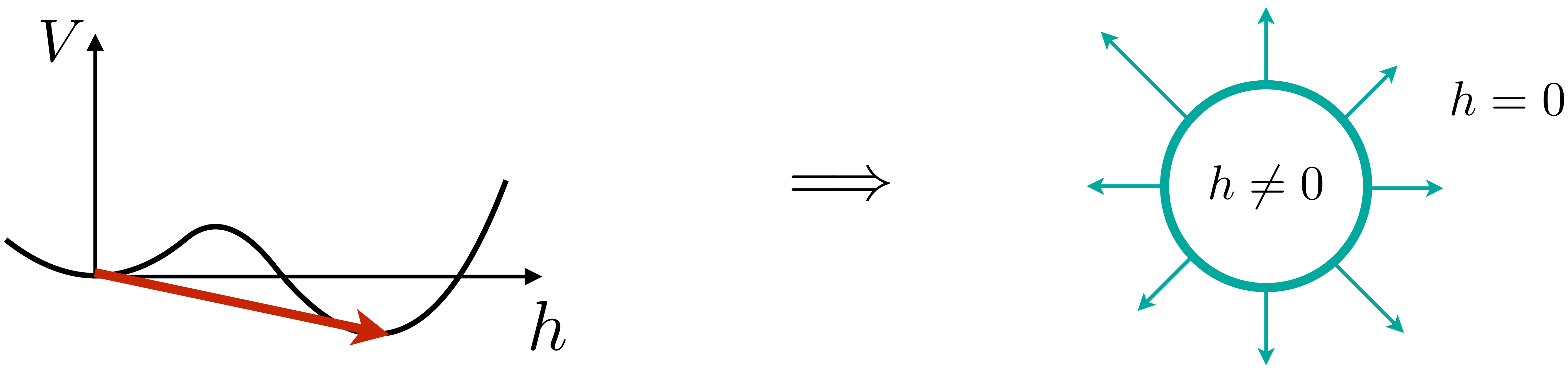
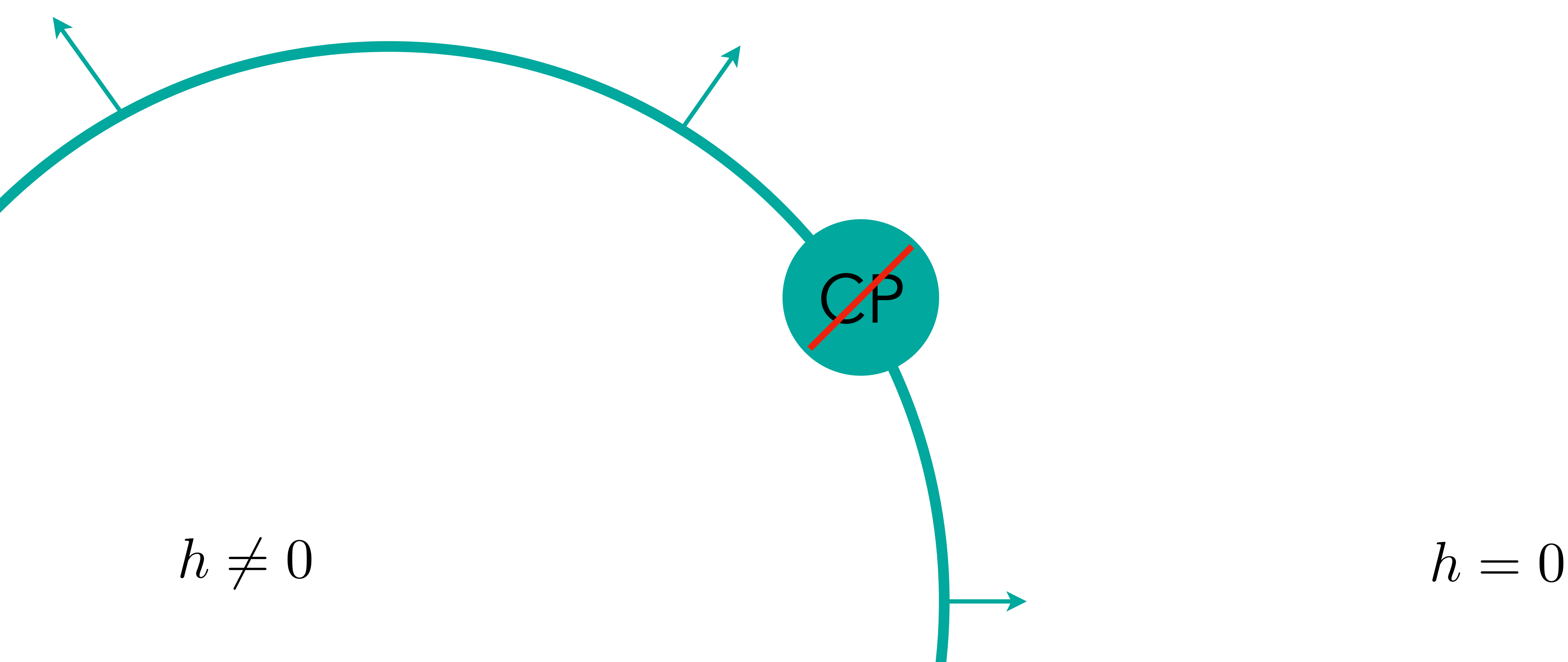



**Baryon asymmetry is created close to bubble walls:**



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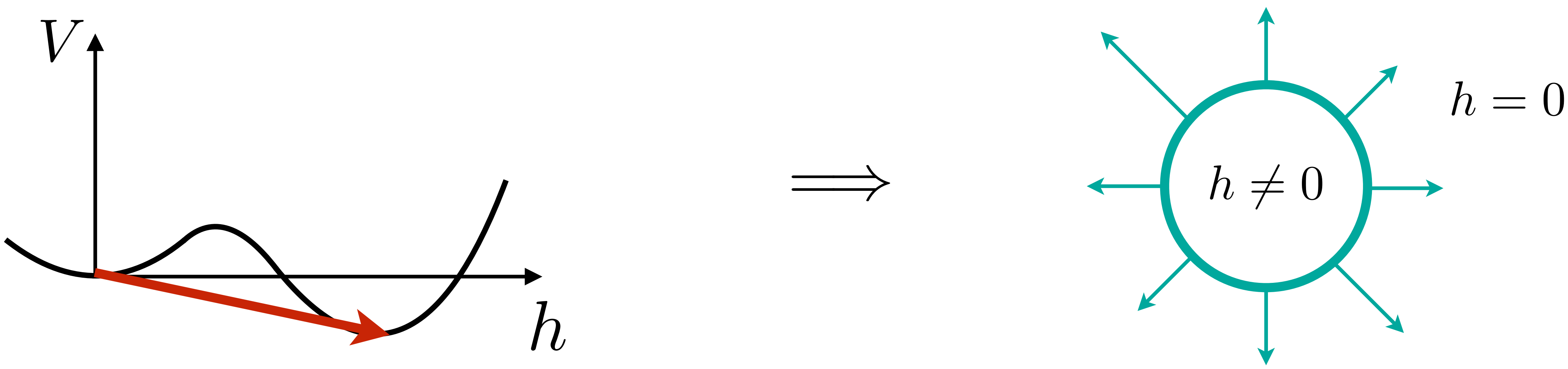


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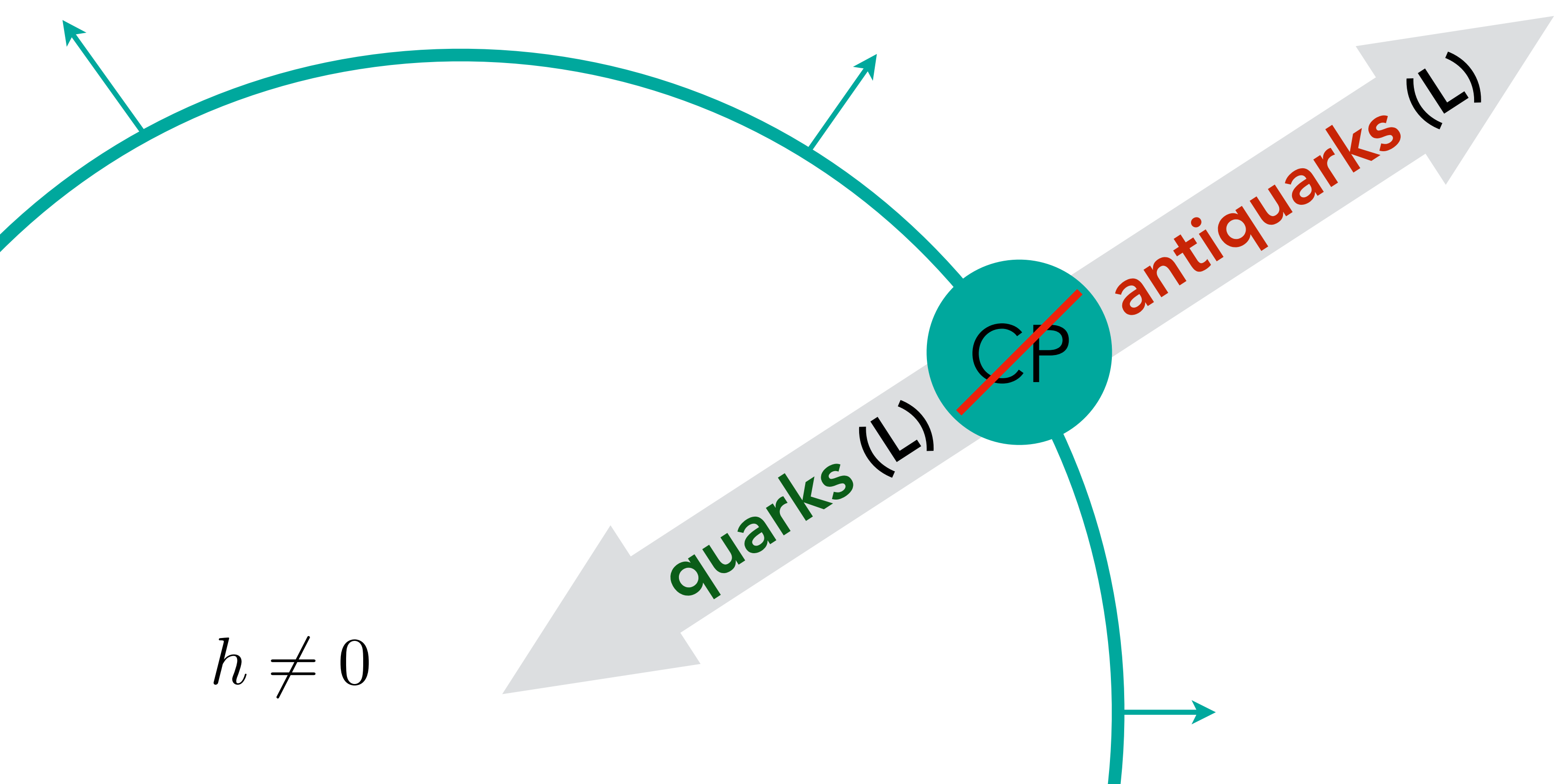

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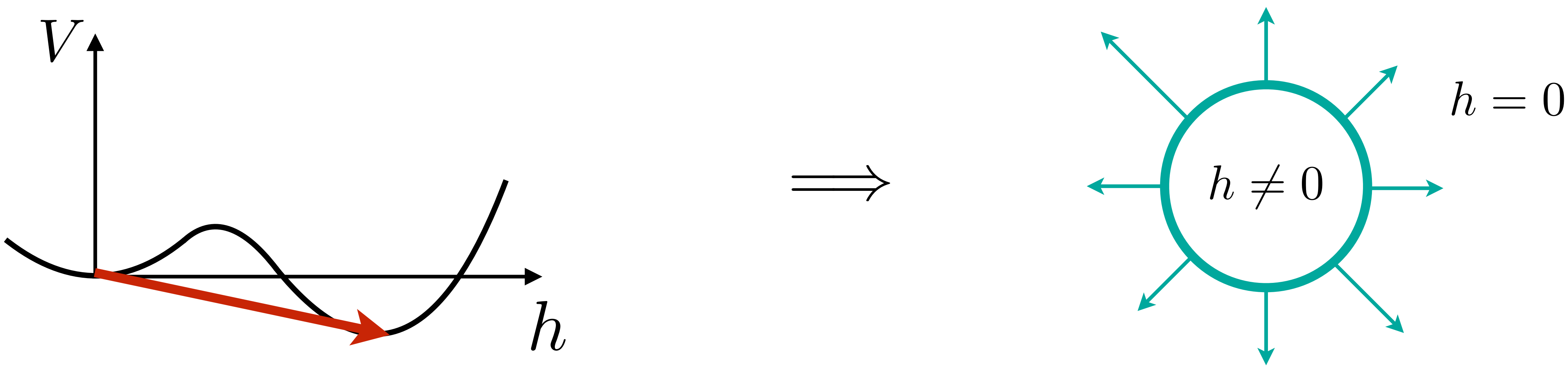


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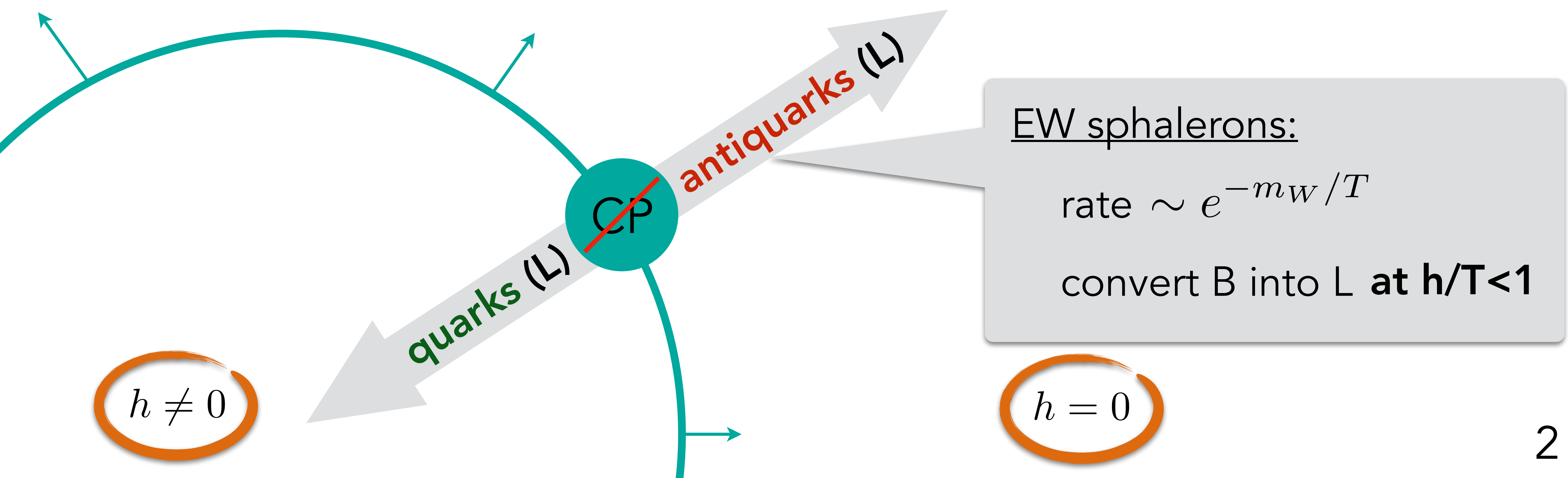

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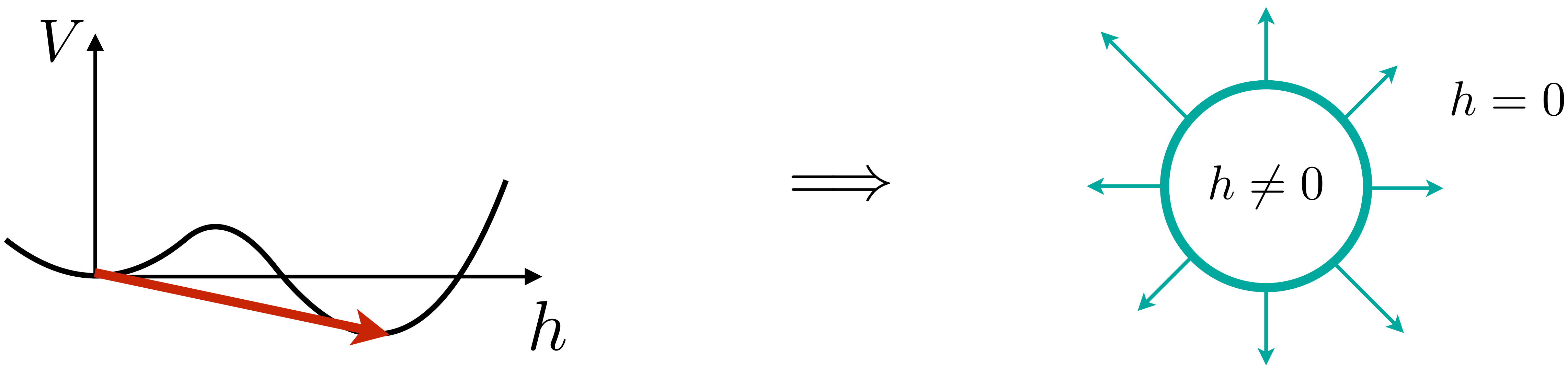


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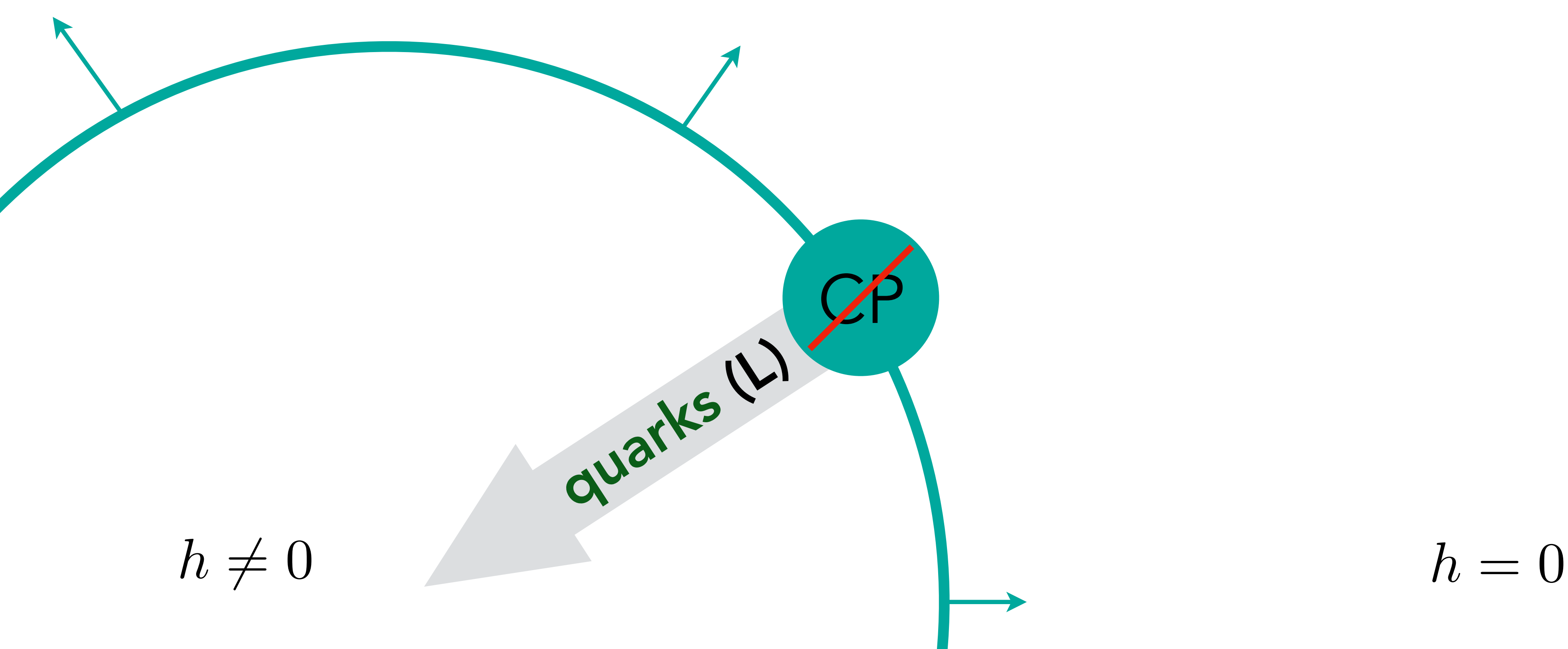

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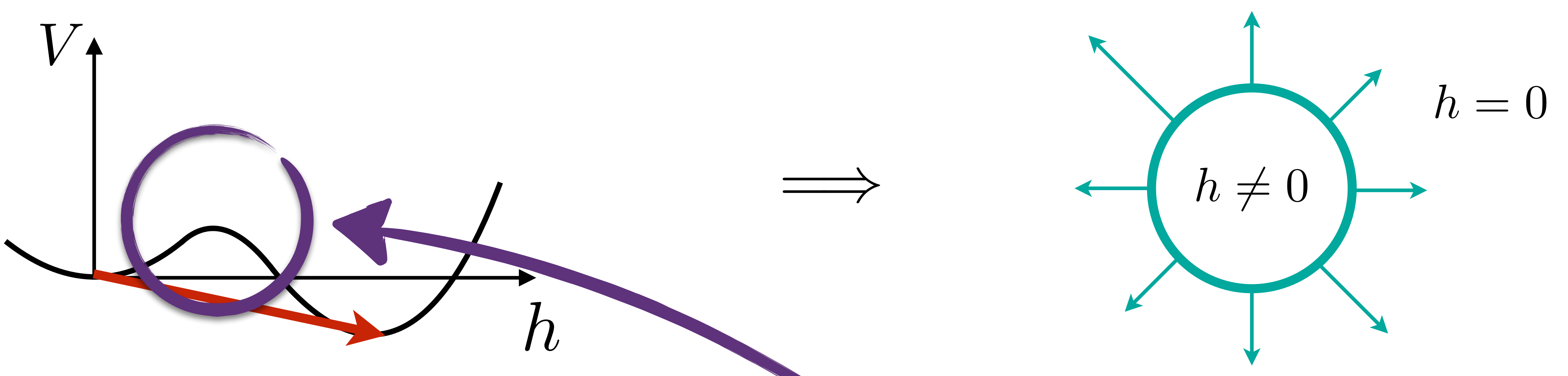


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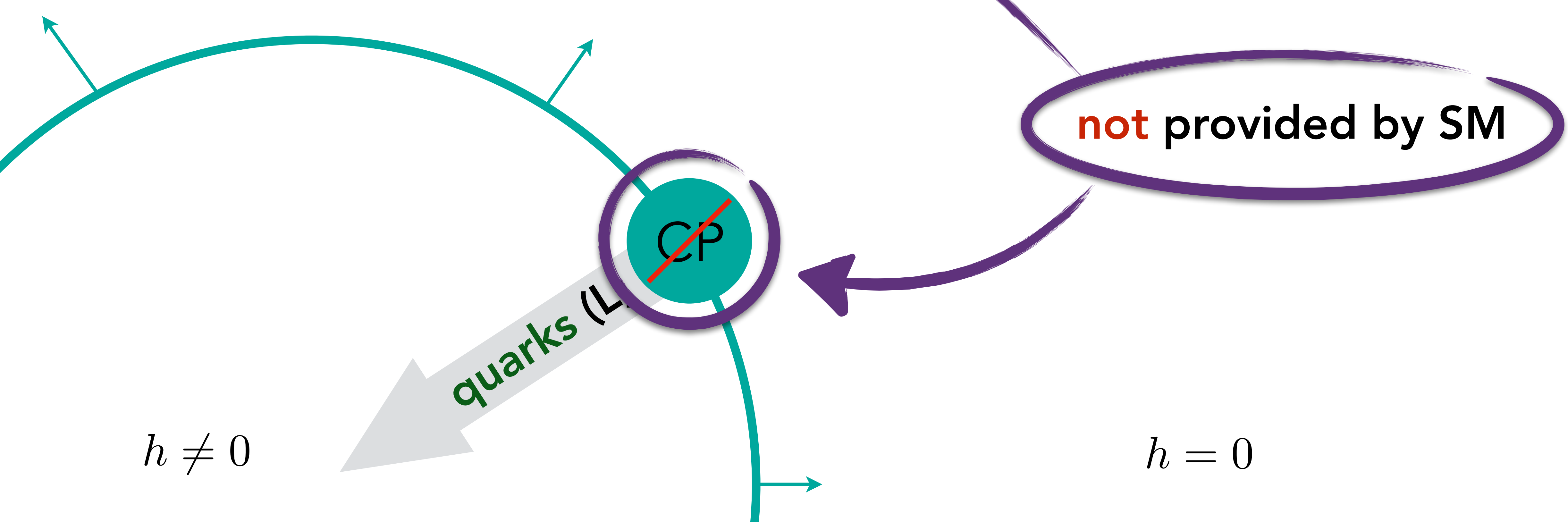

# SNR with fermions

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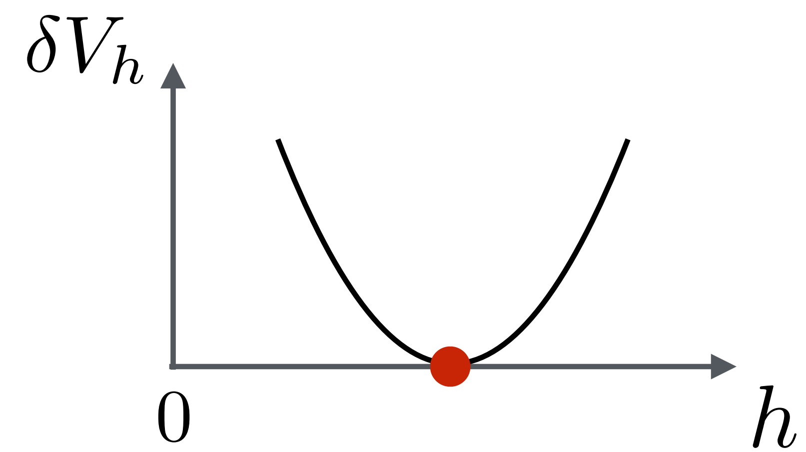



- can't be done with renormalizeable interactions:

$$\delta V_h \propto \sum_i m_i^2 = \mathrm{Tr}[\mathcal{M}^\dagger \mathcal{M}] = \sum_{i,j} |\mathcal{M}_{ij}|^2$$

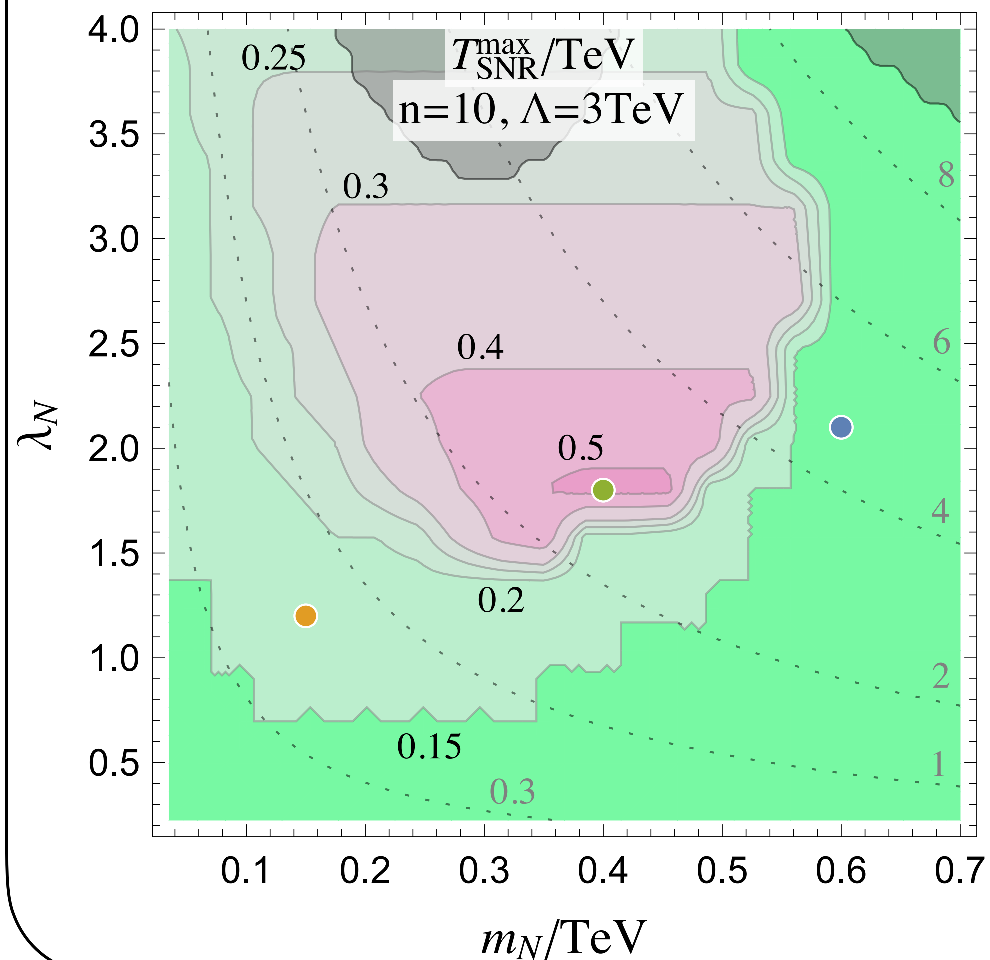
- in **renorm.** theories $|\mathcal{M}_{ij}|$ are h-independent *or* linear in h

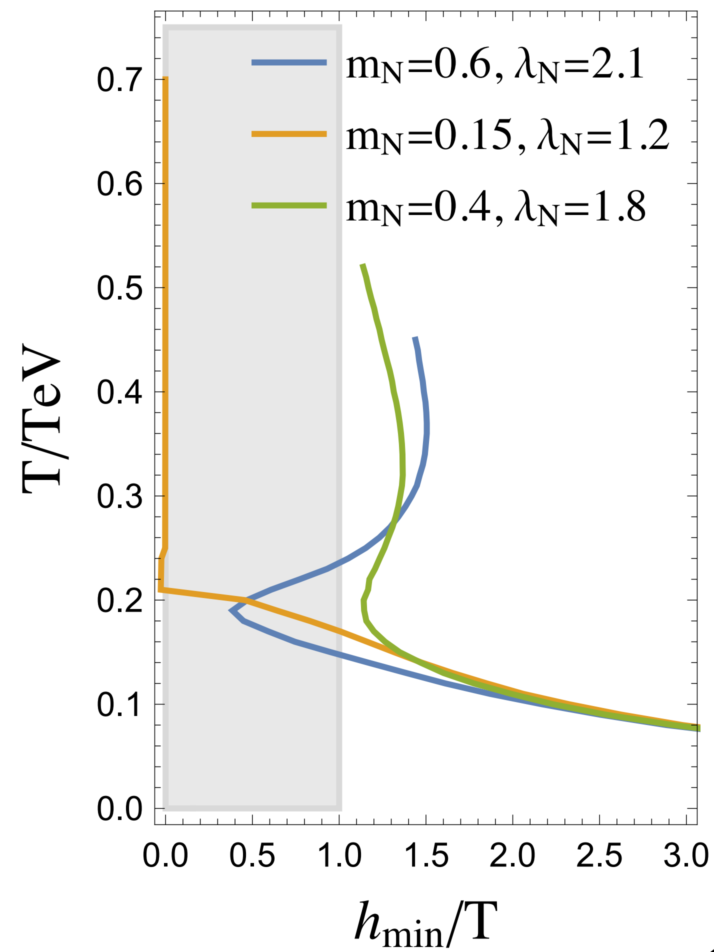
$$\sum_{i,j} |\mathcal{M}_{ij}| = const_1^2 + const_2^2\, h^2 \quad \Longrightarrow$$ **min at h=0**

# SNR with fermions

- minimal and "natural" SM deformation:

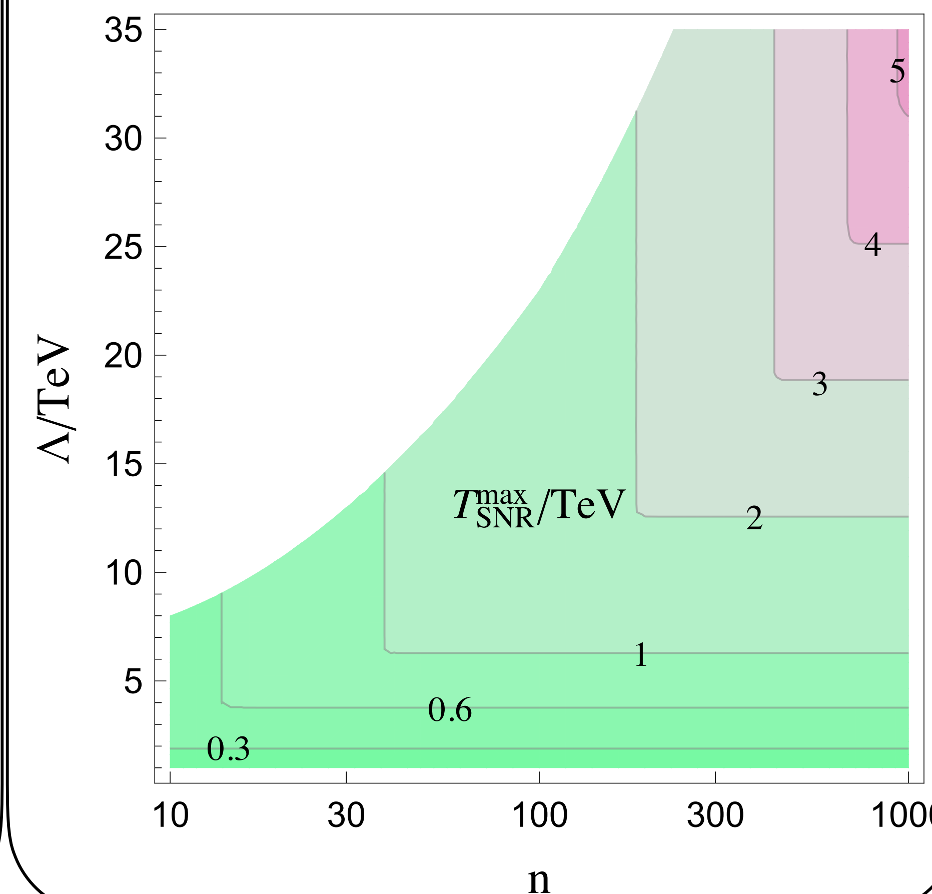
  $n = 10,\ \Lambda = 3TeV$




- going to higher temperatures

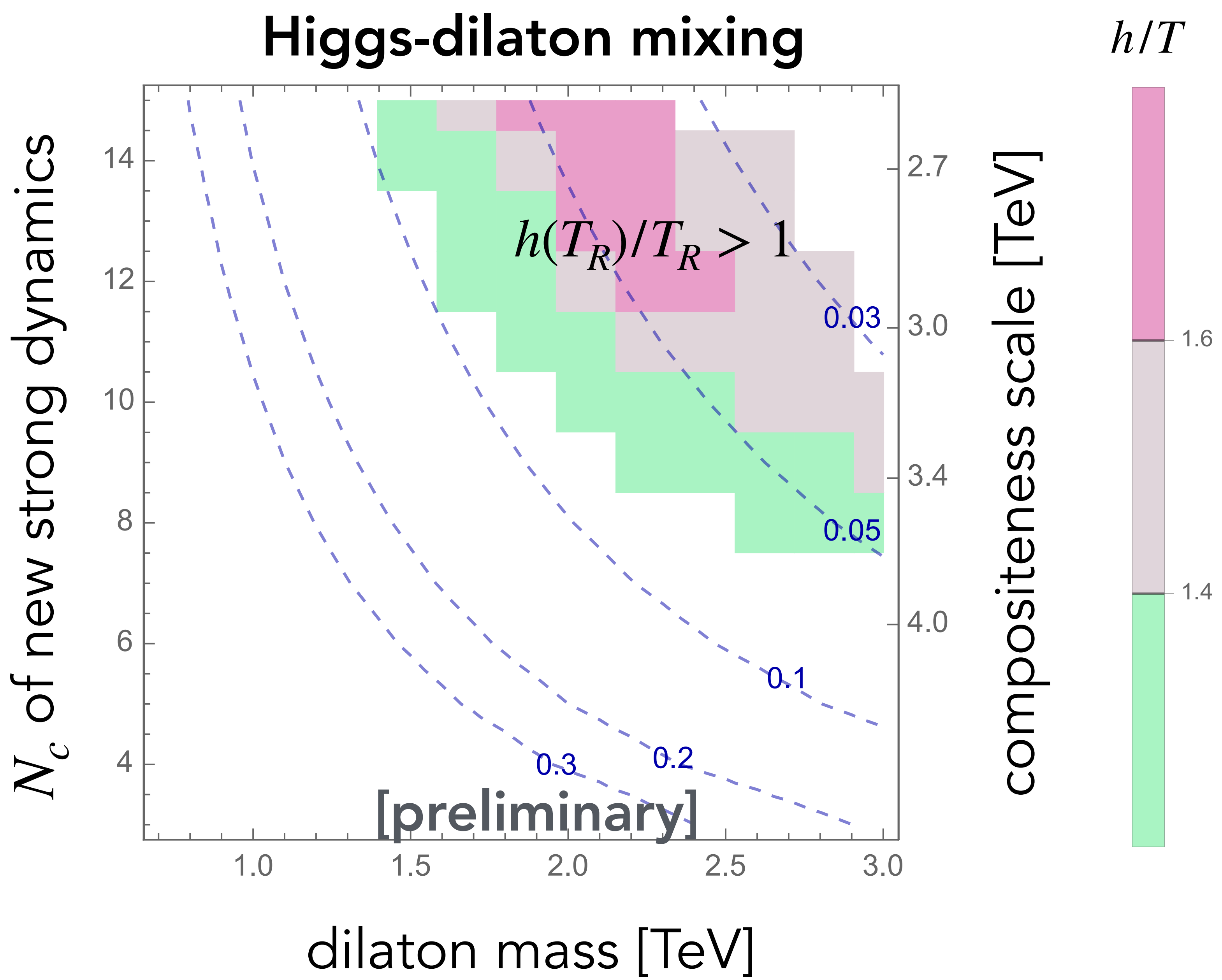
$$T^{max}_{SNR} \sim \sqrt{n}\, m_N$$



# Concrete Example: EWBG in Composite Higgs

work in progress
Bruggisser,VonHarling,OM,Servant

**+ 12 SNR fermions**



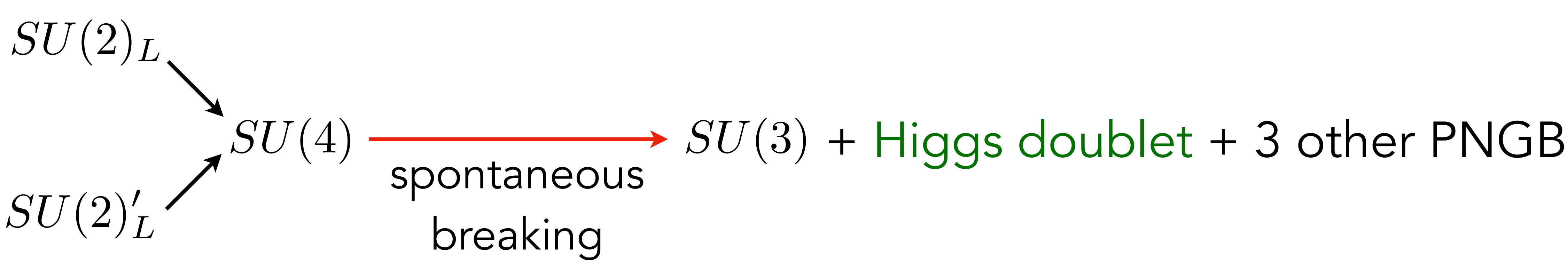
# SNR: Twin Higgs

- proposed in Chacko,Goh,Harnic, hep-ph/0506256
  provides a **solution to the Higgs mass naturalness problem** with **no QCD-charged new physics** up to ~10 TeV

- Assumes a twin sector - an approximate $Z_2$ copy of SM

- Higgs is a pseudo-Nambu-Goldstone boson of a large symmetry, which accommodates both SM and Twin $SU(2)_L$

  *example:*



# SNR: Twin Higgs

- SM states couplings to the Higgs $\propto \sin h/f$

  Twin states couplings to the Higgs $\propto \cos h/f$

- Quadratic divergences $\propto \Lambda^2$ in the Higgs mass cancel

$$V \sim f^2\Lambda^2(\sin^2 h/f + \cos^2 h/f) = f^2\Lambda^2$$

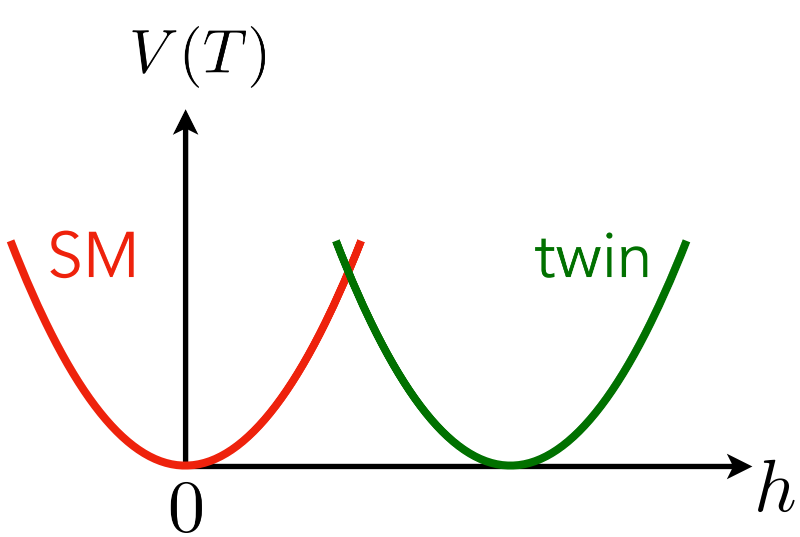
no Higgs dependence

no contribution to the Higgs mass $\propto \Lambda^2$

SM contribution ($\sin^2 h/f$)

Twin contribution ($\cos^2 h/f$)

- The EW symmetry-restoring high-T SM correction is also canceled (balanced)




The resulting position of the minimum depends on weak $Z_2$ breaking

→ analyze which type of $\not{Z}_2$ can tilt high-T potential to SNR minimum

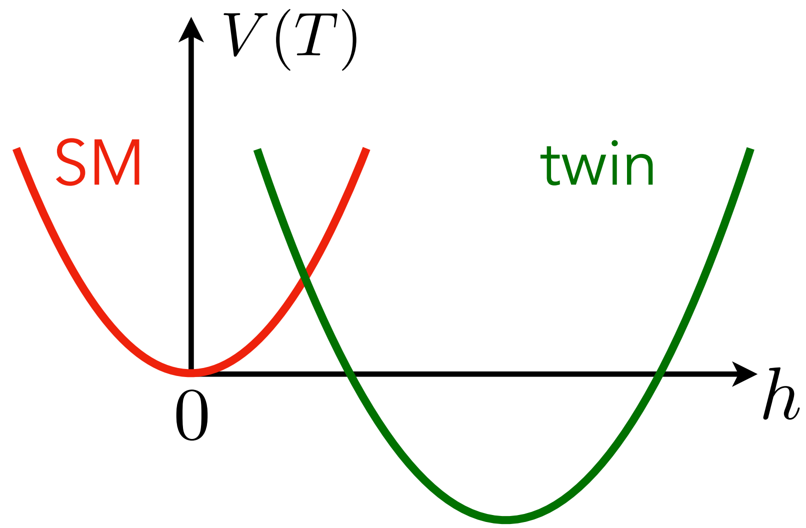
# SNR: Twin Higgs

- Sources of $\not{Z}_2$

<u>necessarily</u> broken in the light fermion sector: eg twin neutrinos cannot be light.

simplest realization: larger Yukawas $\tilde{\lambda}_q$ for light twin fermions

$$\tilde{\lambda}_q \, f \bar{q} q \, \cos h/f$$

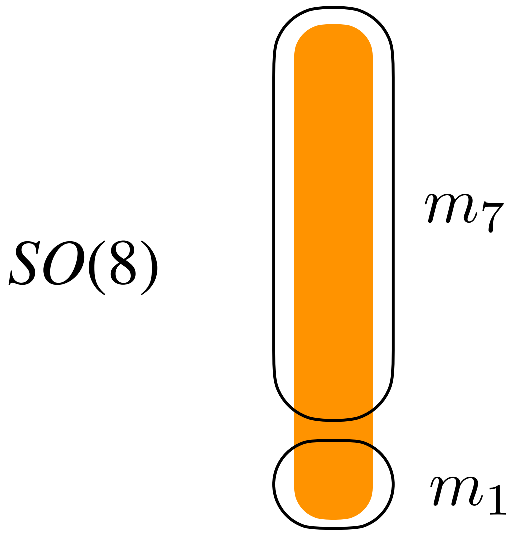



- This also spoils the cancellation of T=0 quadratic divergences to the Higgs mass: $\delta m_h^2 \sim (\tilde{\lambda}_q^2/16\pi^2)\Lambda^2$

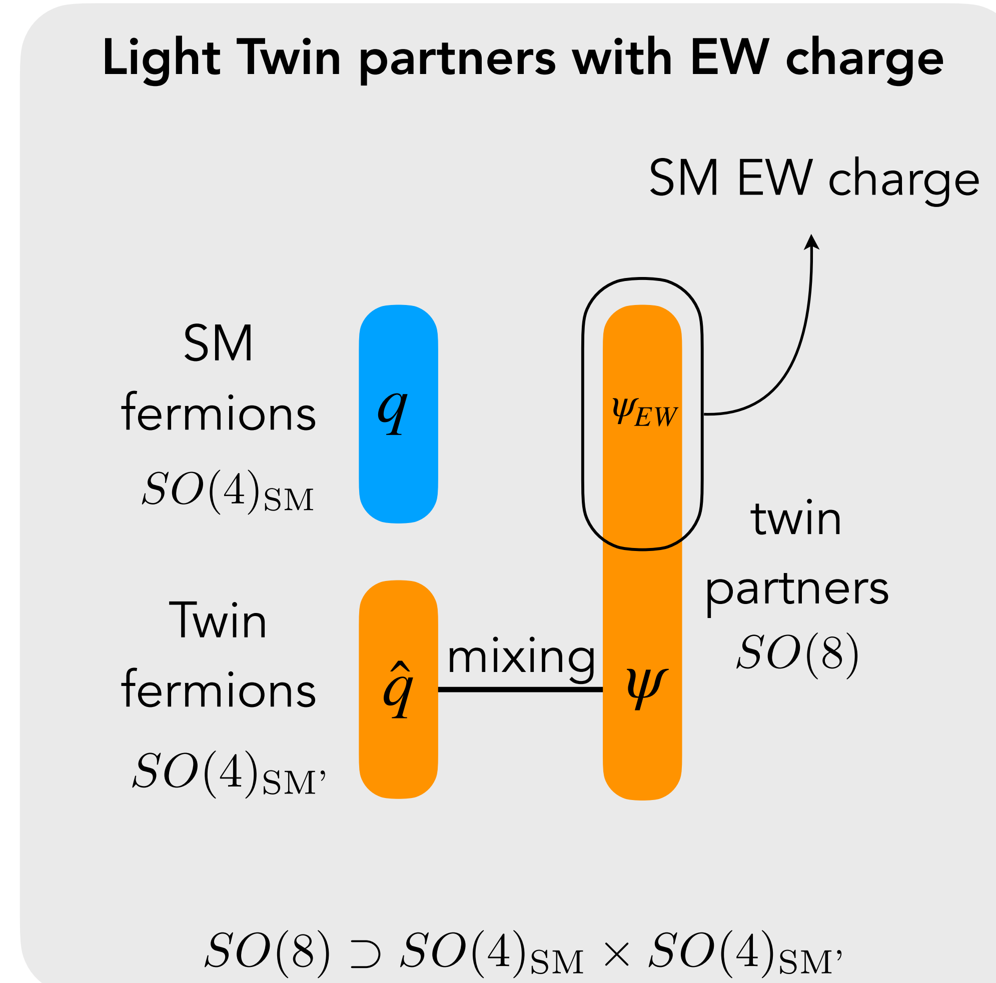
$\Rightarrow$ take a lower cutoff $\Lambda$ in the twin light quark sector $\Rightarrow$ light **twin partners** (no SM QCD charge)

# SNR: Twin Higgs

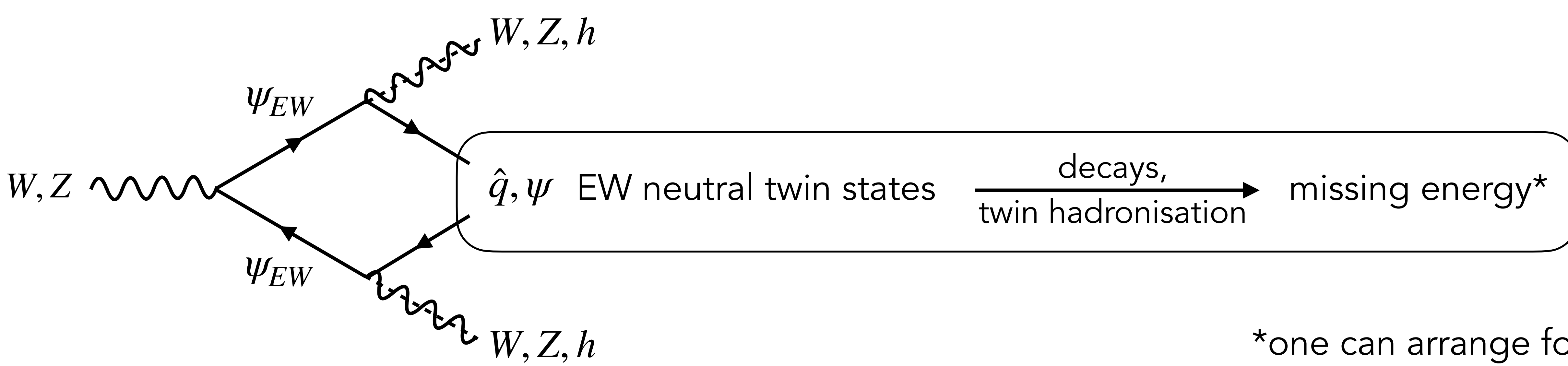
- To not spoil the Higgs mass, we need:




$$m_7^2 - m_1^2 \lesssim 1\,\mathrm{TeV}^2$$



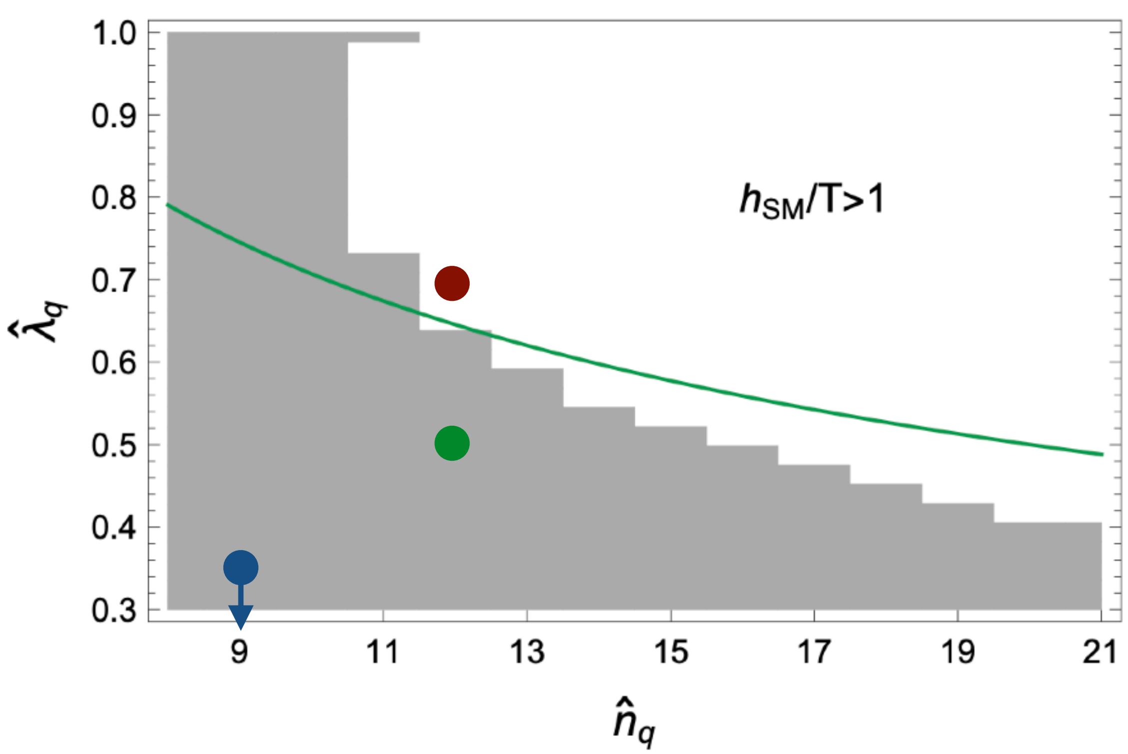

- Collider signal:




*one can arrange for visible signatures too

# SNR: Twin Higgs

- numerical results



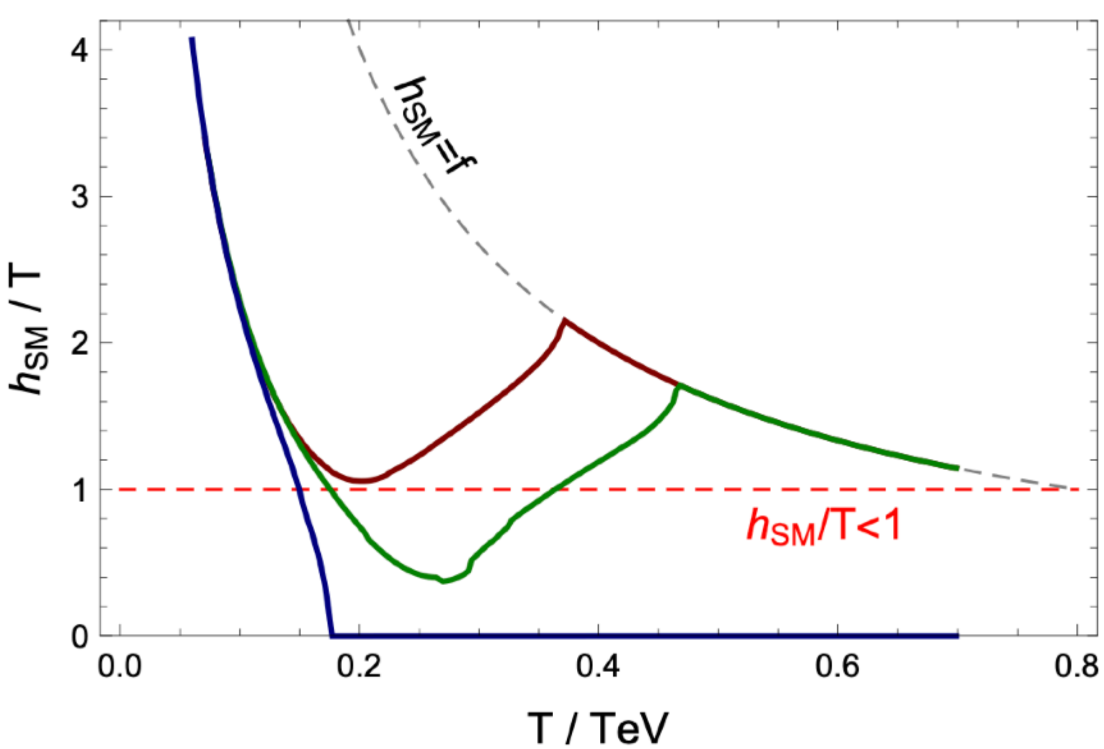




Figure 2: *Solid lines show the evolution of $h_{SM}/T$ in the minimum of the Higgs potential depending on the temperature, for three choices of parameters:* $\hat{\lambda}_q = 0.2, \hat{n}_q = 9$ *(blue),* $\hat{\lambda}_q = 0.5, \hat{n}_q = 12$ *(green), and* $\hat{\lambda}_q = 0.7, \hat{n}_q = 12$ *(red).*

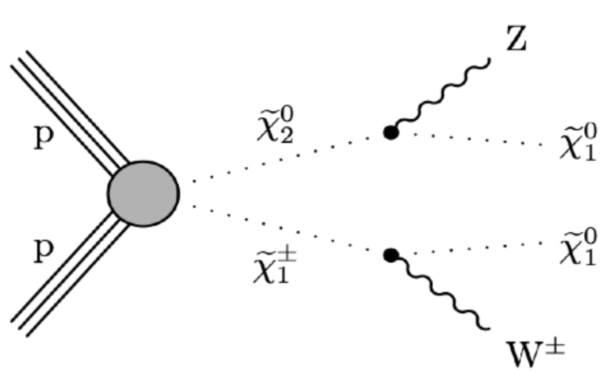
# Automatic SNR

- $Z_2$ breaking leads to additional contributions to the Higgs mass

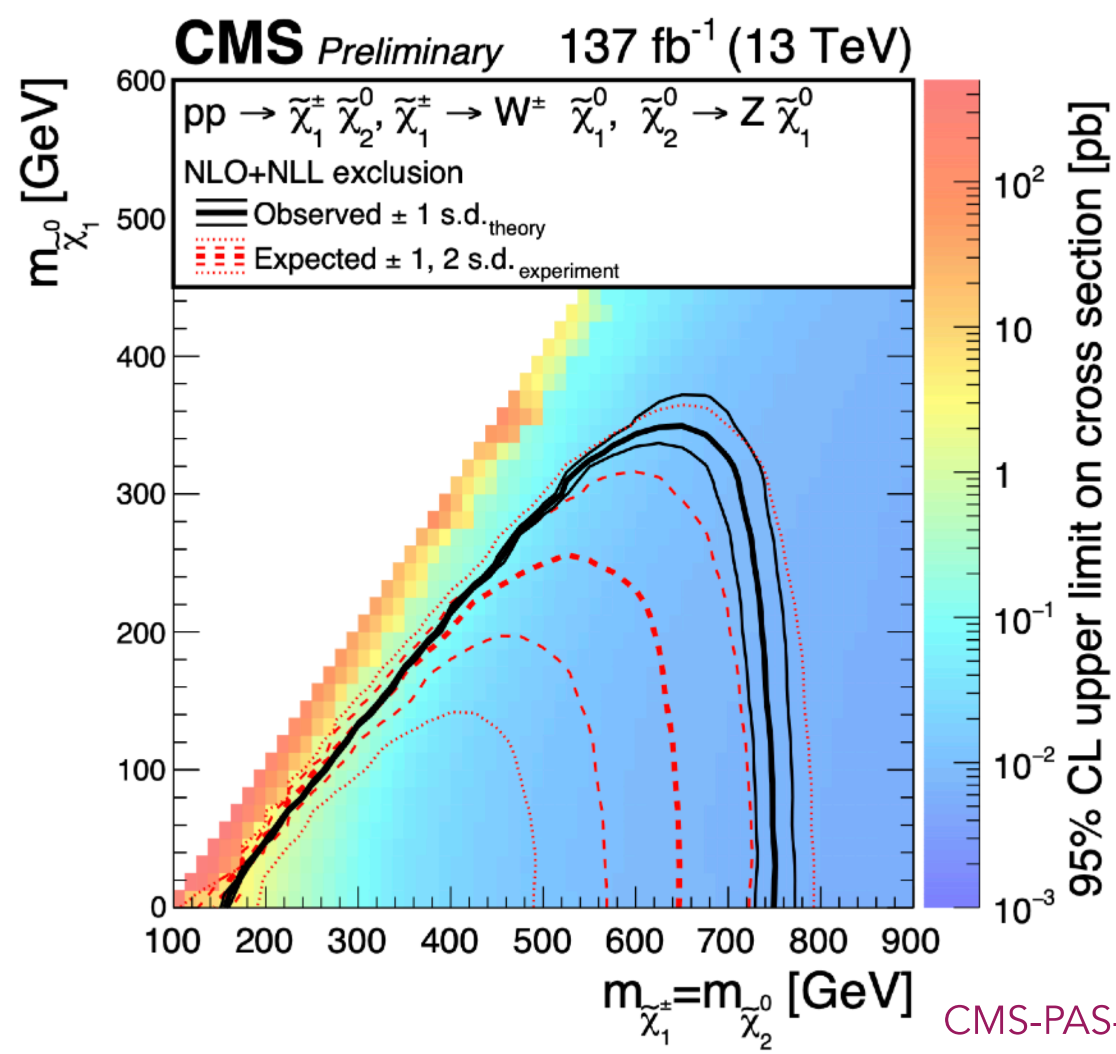
$$\delta m_h^2 \propto n_q \lambda_q^2 \boxed{\Lambda^2}$$

← mass of EW-charged twin partners

- chargino/neutralino-like signal




for twin hadron decays see: Craig,Katz,Strassler,Sundrum 1501.05310

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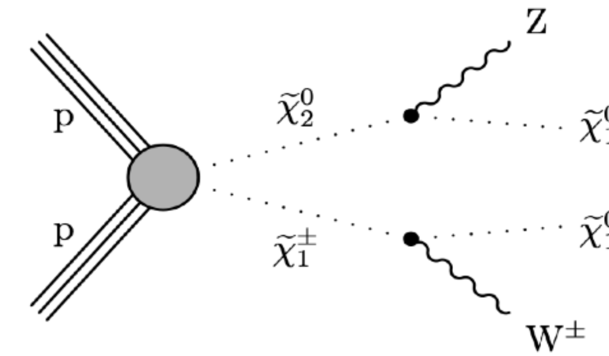
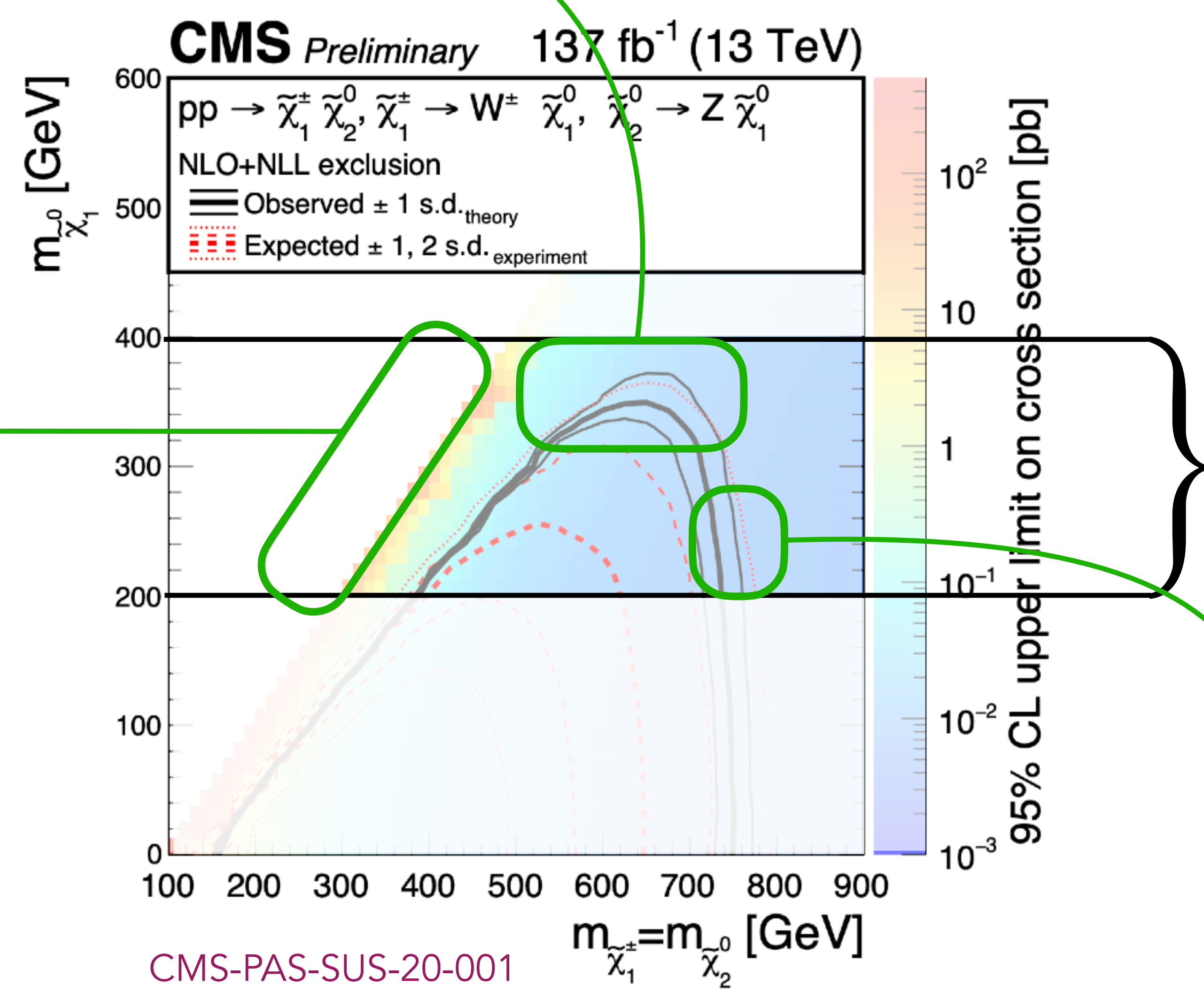
# SNR: Twin Higgs

➔ experimental bounds on EW-charged twin partners

chargino/neutralino pair production with a decay to a W,Z,h and neutralino (missing Et)




bounds significantly depend on kinematical distributions

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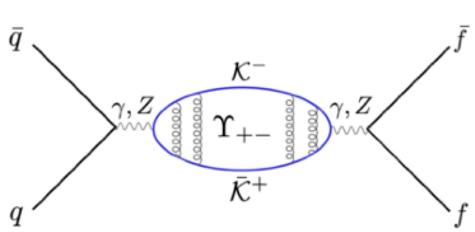
if charged under twin QCD, partners hadronise, and decay back into SM

optimal mass of twin fermions $\hat{q}$

**eventually used for the derivation of bounds**



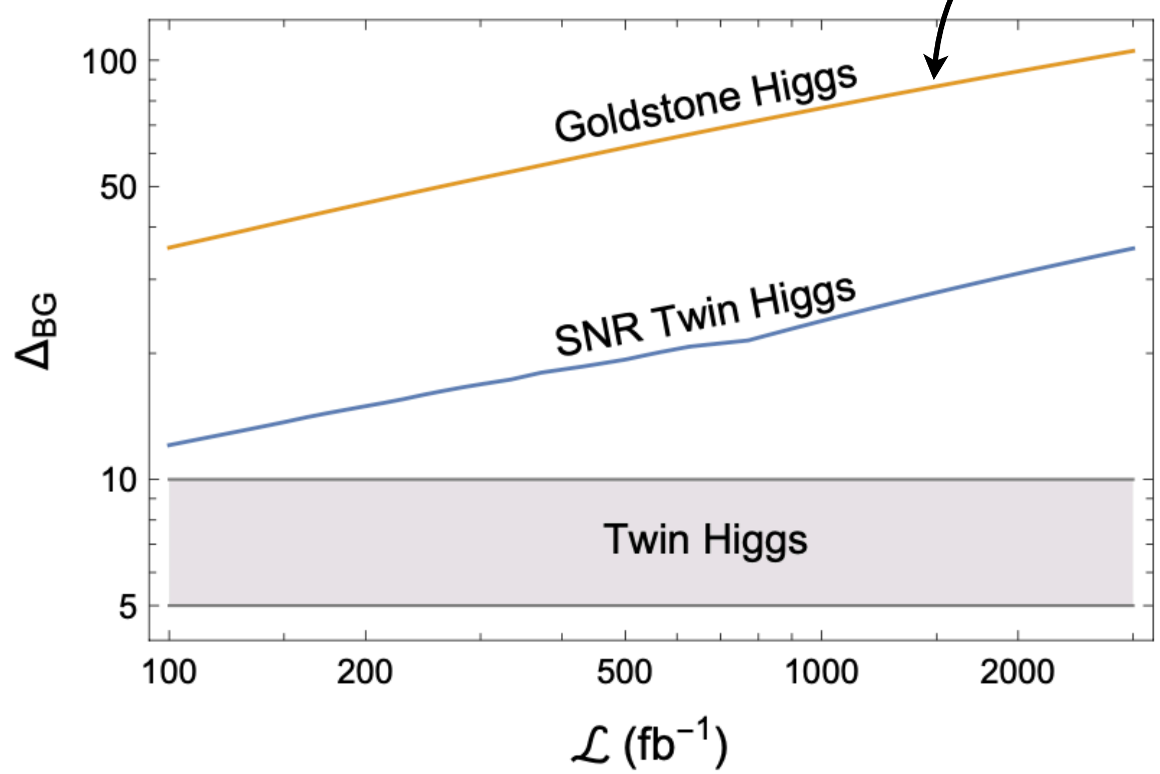

Cheng,Salvioni,Tsai
1612.03176

# SNR: Twin Higgs

- fine-tuning

$$\Delta_{\rm BG} = \frac{\hat{n}_q y_L^2 m_7^2 \cos^2 v/f}{2\pi^2 m_h^2}$$

lower bound from a pair production of one top partner,
does not include single production or pile-up from several partners



# SNR: thermal corrections

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

bosons:

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

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

fermions:

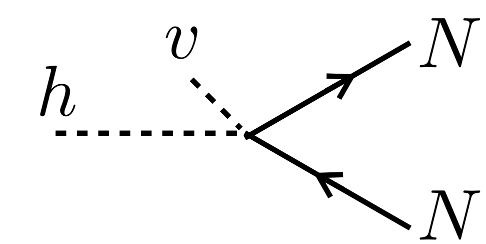
$$\Delta V_f^T = -\frac{2T^4}{\pi^2} J_f[m^2/T^2]$$

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

# SNR: collider pheno

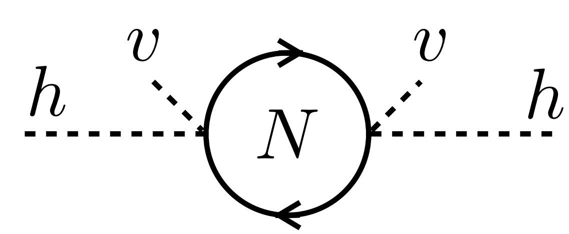
- invisible Higgs decays

$$\mathrm{BR}_{h\to NN} \sim \frac{1}{n}\left(n\lambda_N \frac{m_N}{\Lambda}\right)^2 \frac{v_{\mathrm{SM}}^2}{m_h \Gamma_h} \quad \text{where} \quad \Gamma_h \simeq 6\,\mathrm{MeV}$$




requires either $n \gtrsim 10^6$ or $m_N > m_h/2$

- Universal Higgs couplings modification




from Higgs wave function renormalization

$$\delta Z_h \sim \frac{1}{(4\pi)^2}\frac{1}{n}\left(\frac{n\lambda_N m_N}{\Lambda}\right)^2 \frac{v^2}{m_N^2} \longrightarrow$$ future lepton colliders?

- Production via off-shell Higgs

D.Curtin et al 1409.0005

if no decay within detector, may be testable at 100TeV collider
for low $m_N$ and $n$