מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

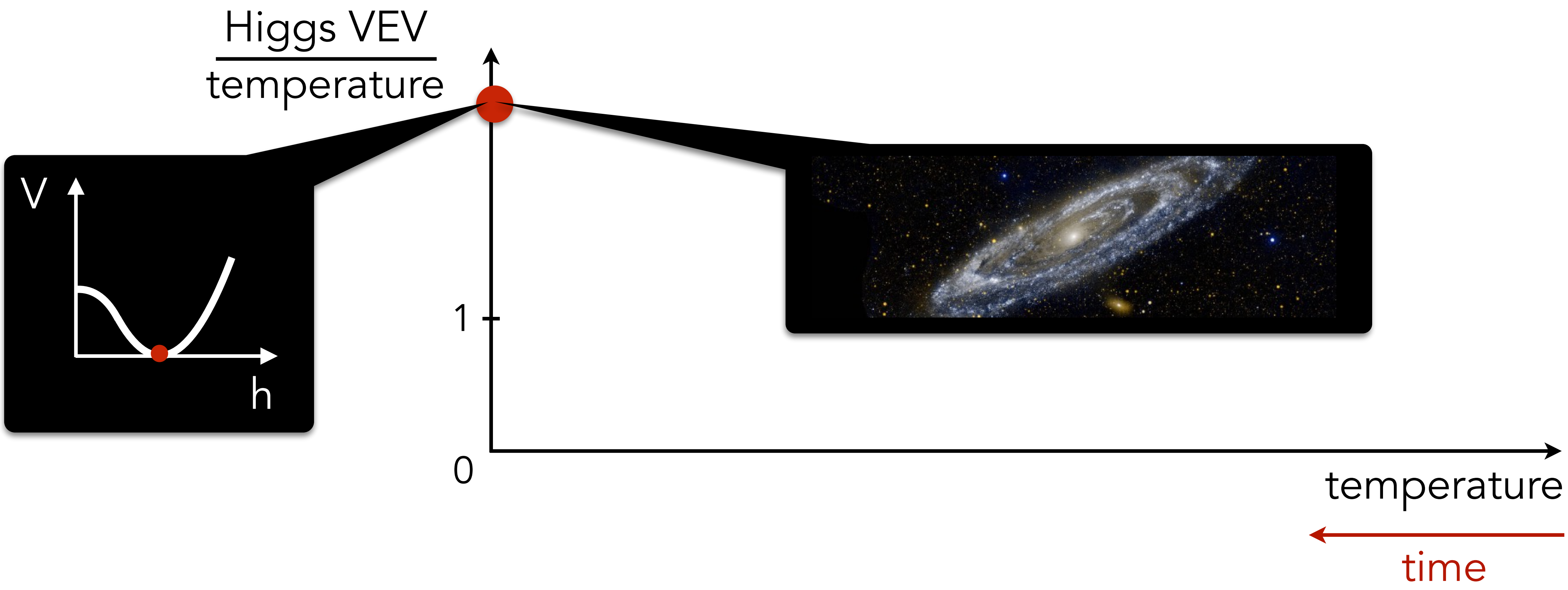
New Paths for Electroweak Baryogenesis

Oleksii Matsedonskyi

Motivation

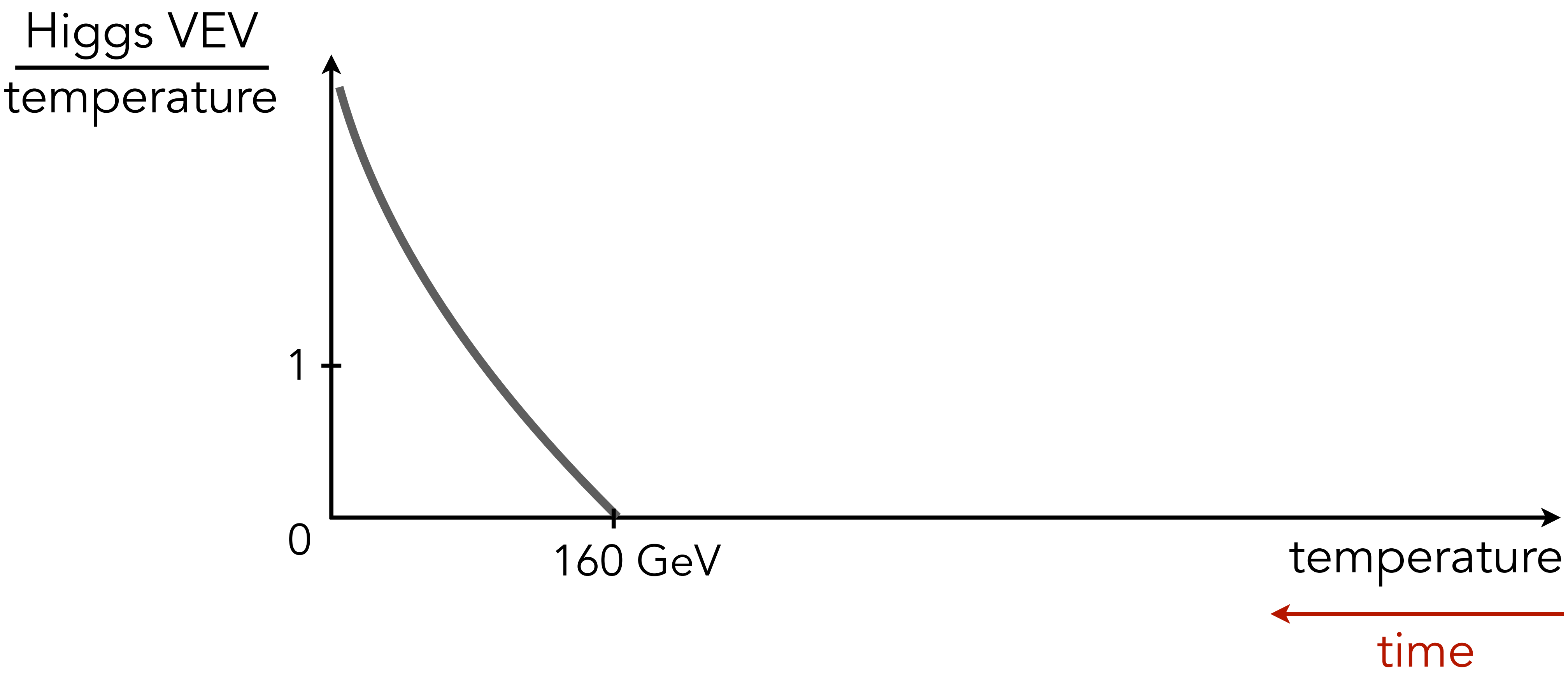
Electroweak symmetry in the early Universe

Electroweak symmetry in the early Universe



Electroweak symmetry in the early Universe

in Standard Model: high-T symmetry restoration



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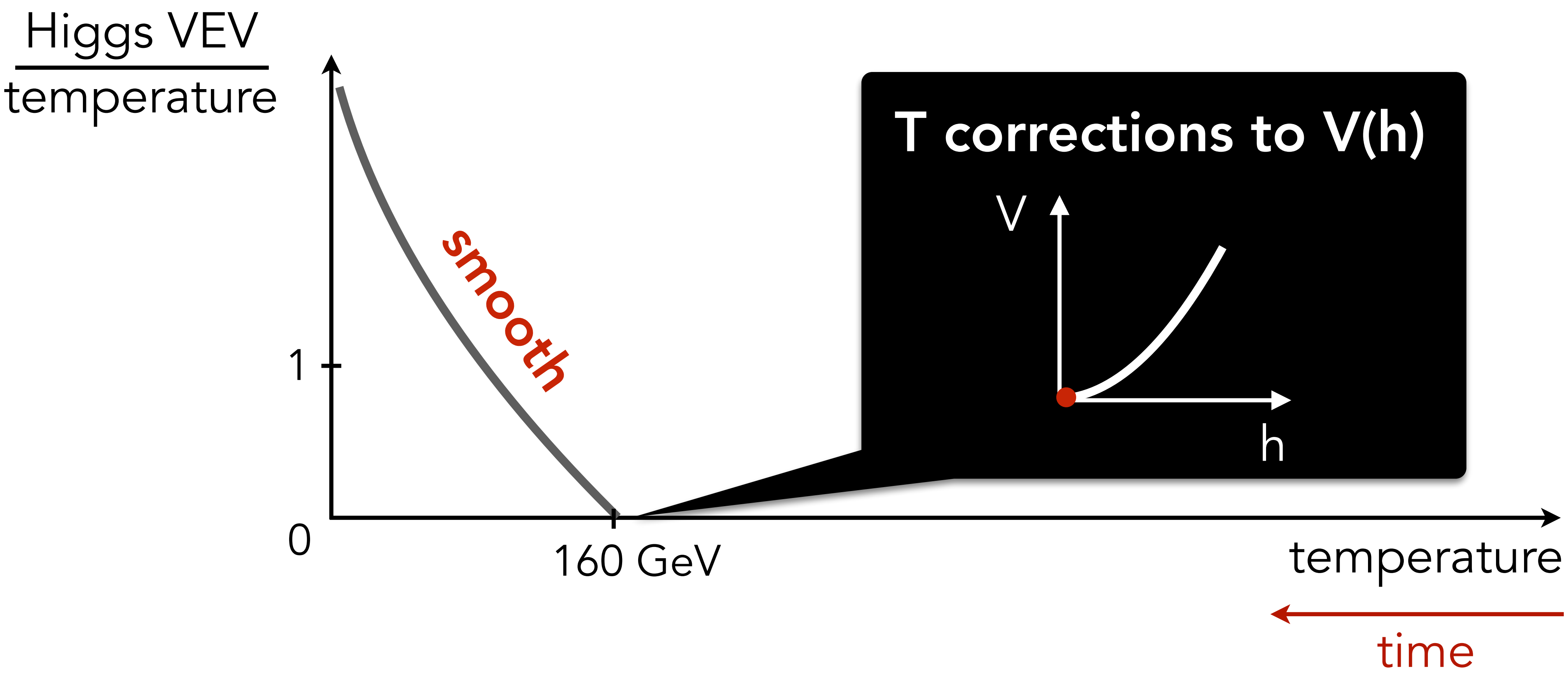
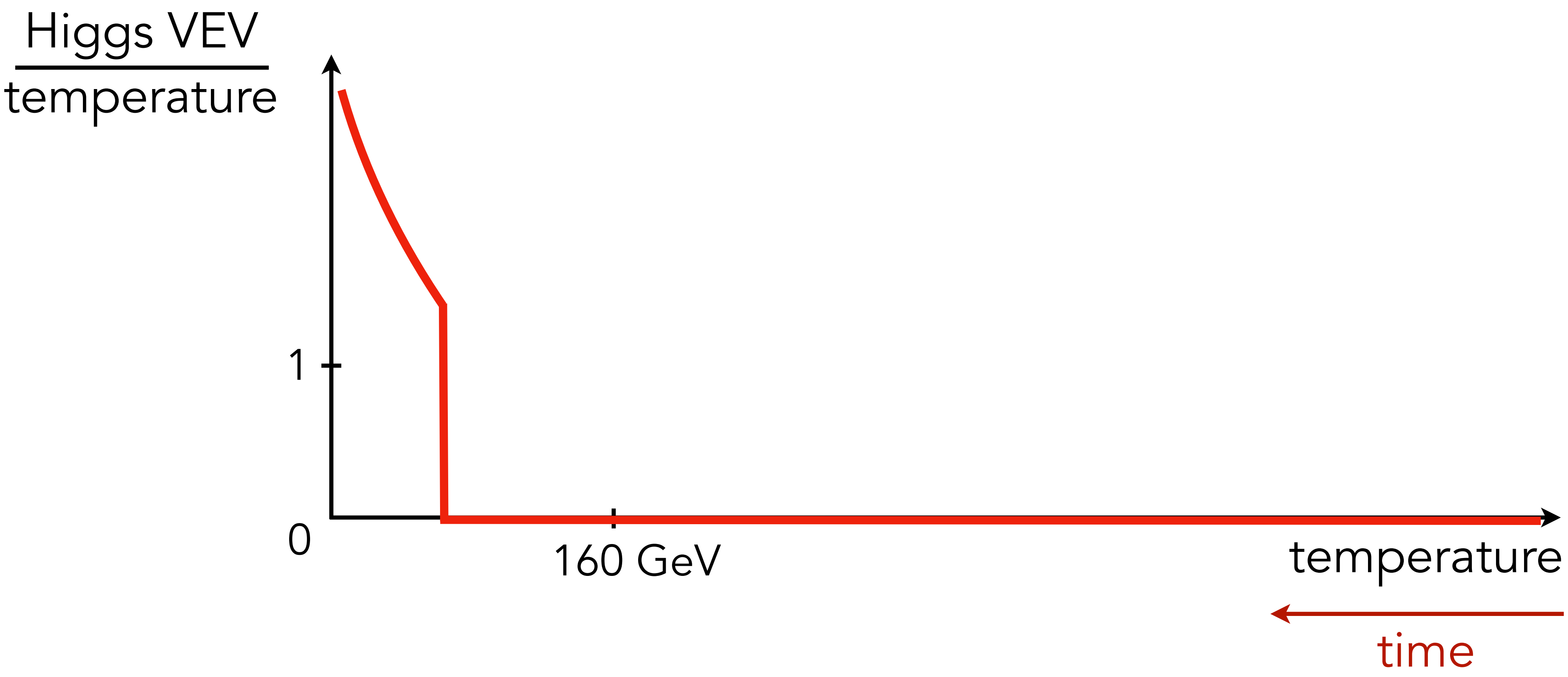


Electroweak symmetry in the early Universe

in Electroweak Baryogenesis scenarios



Electroweak symmetry in the early Universe

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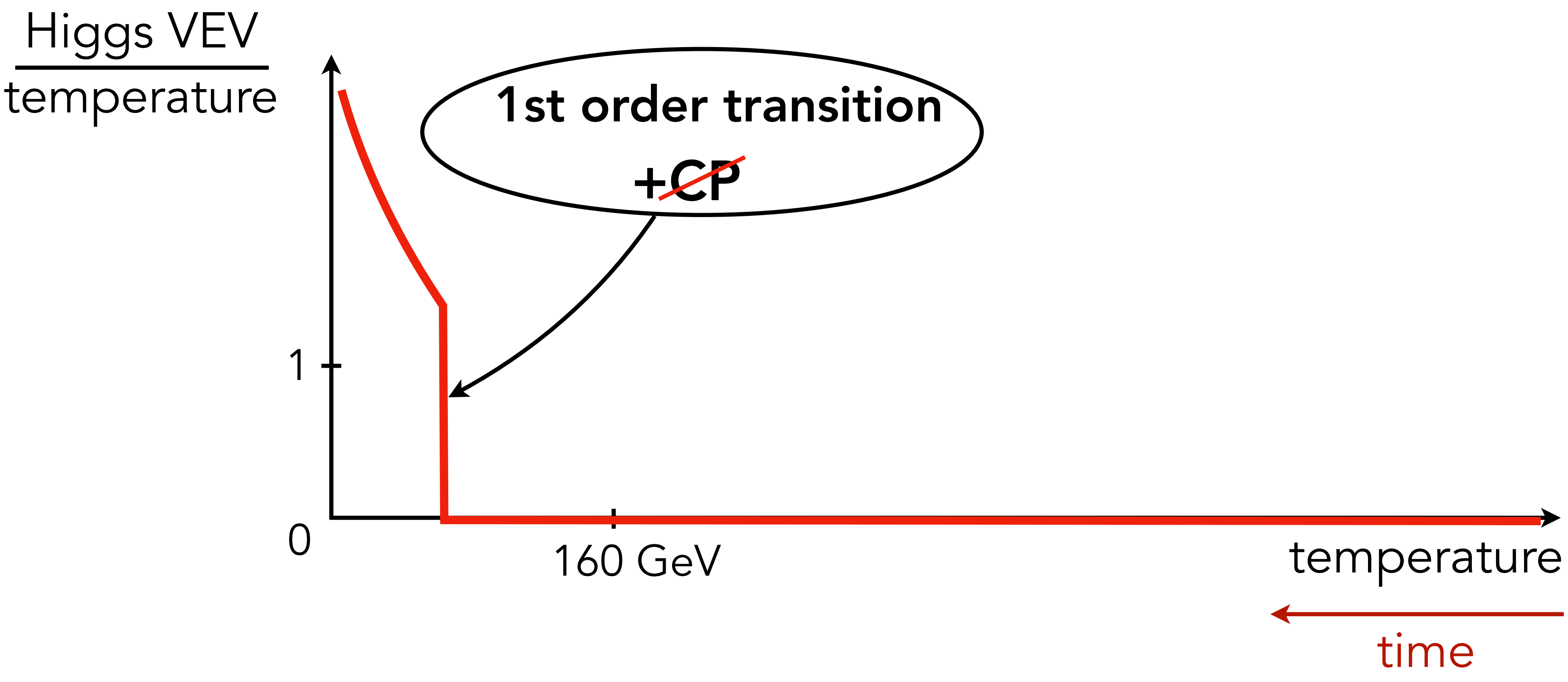
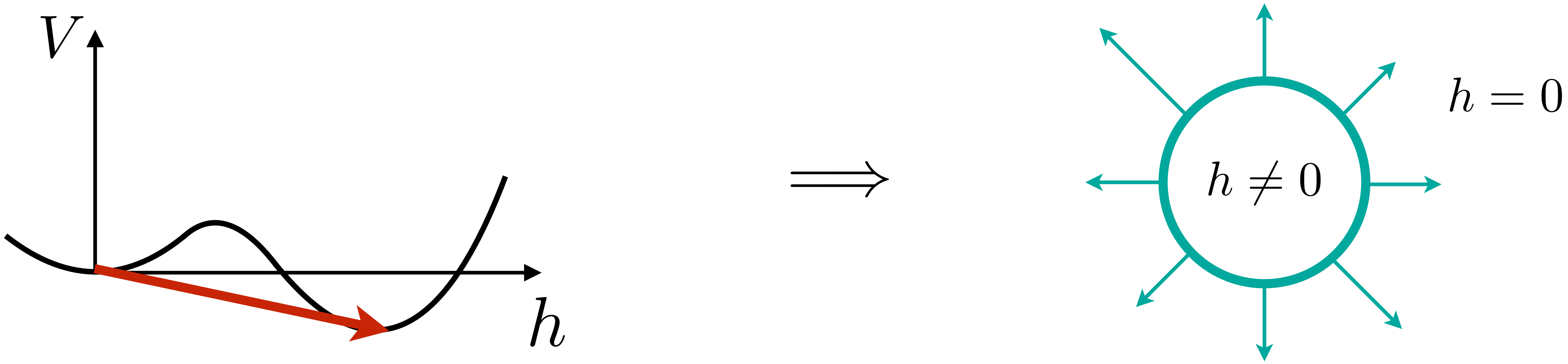


Electroweak Baryogenesis

First order EW phase transition proceeds through bubble nucleation:



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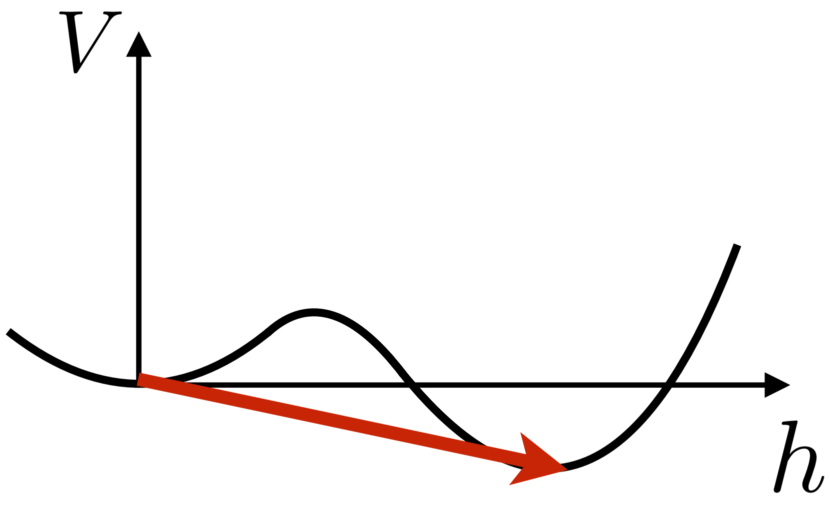
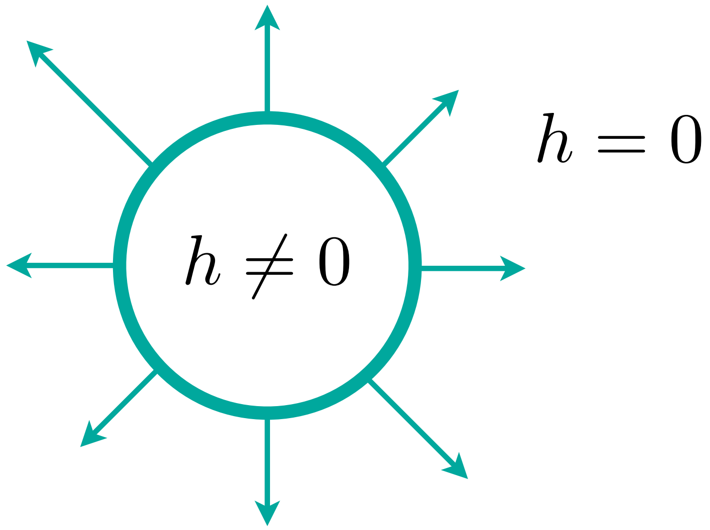
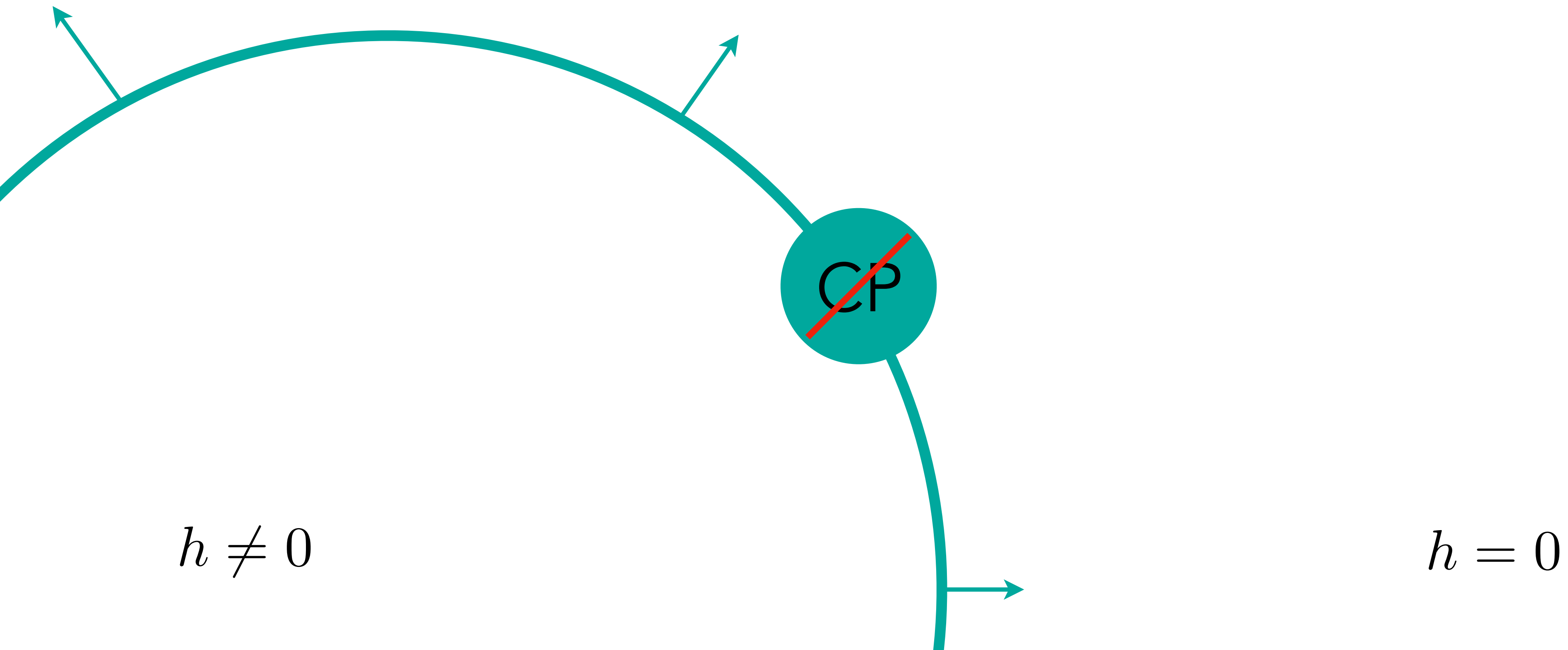


$\Longrightarrow$



Baryon asymmetry is created close to bubble walls:



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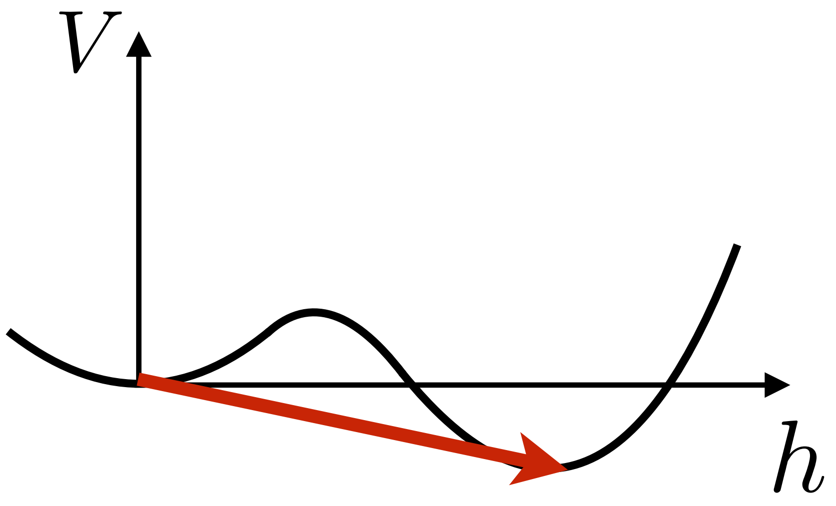

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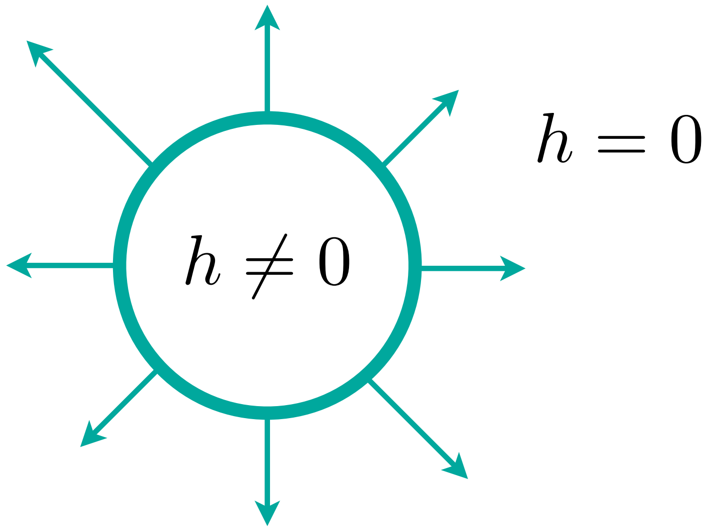

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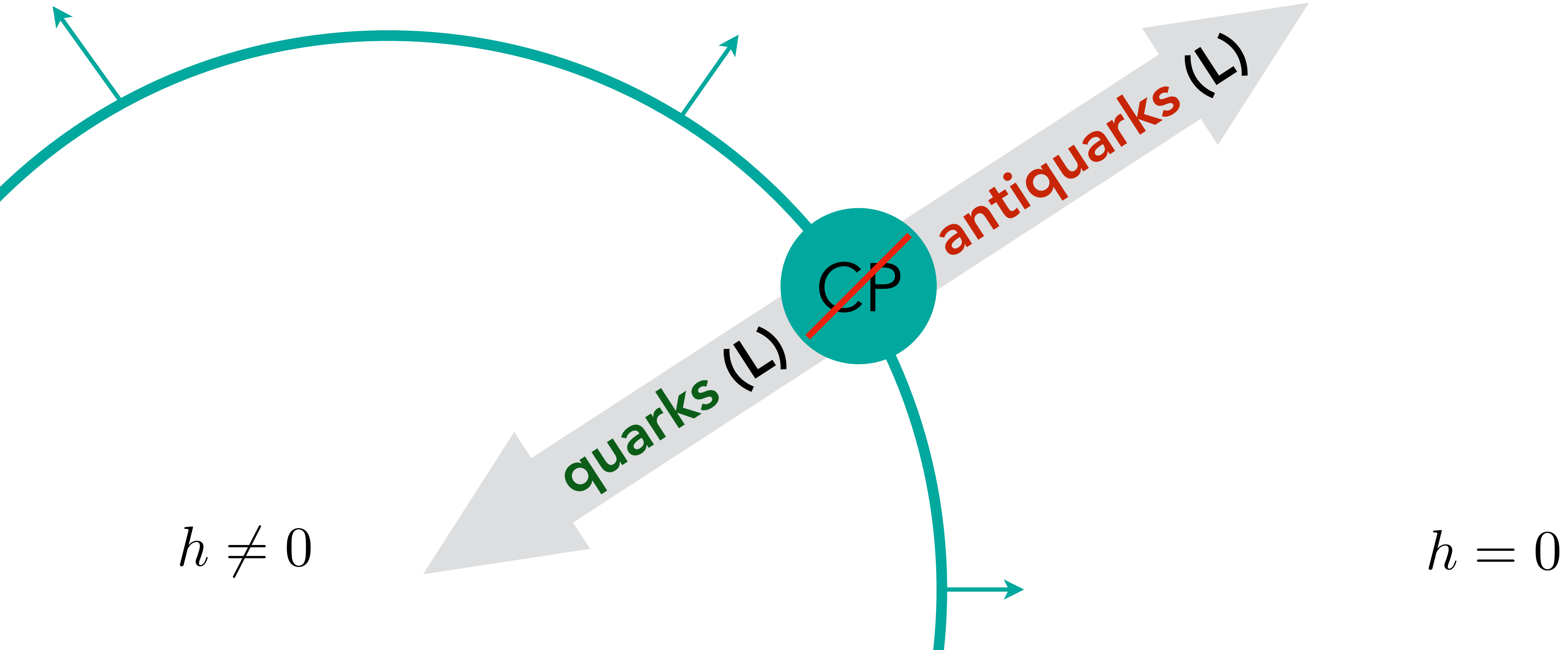

Electroweak Baryogenesis

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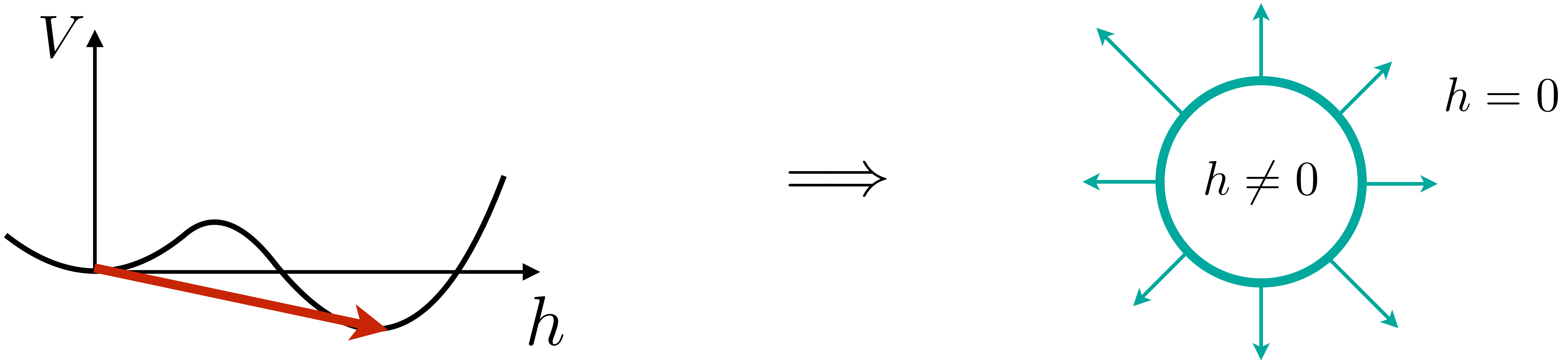

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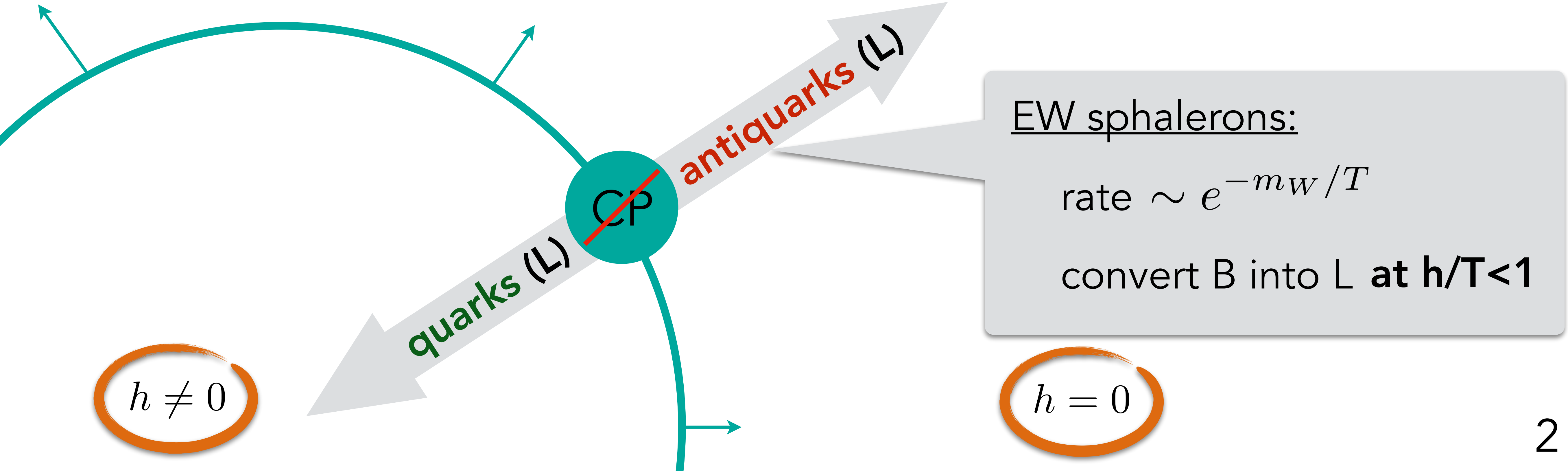

EW sphalerons:

rate $\sim e^{-m_W/T}$

convert B into L **at h/T<1**

Electroweak Baryogenesis

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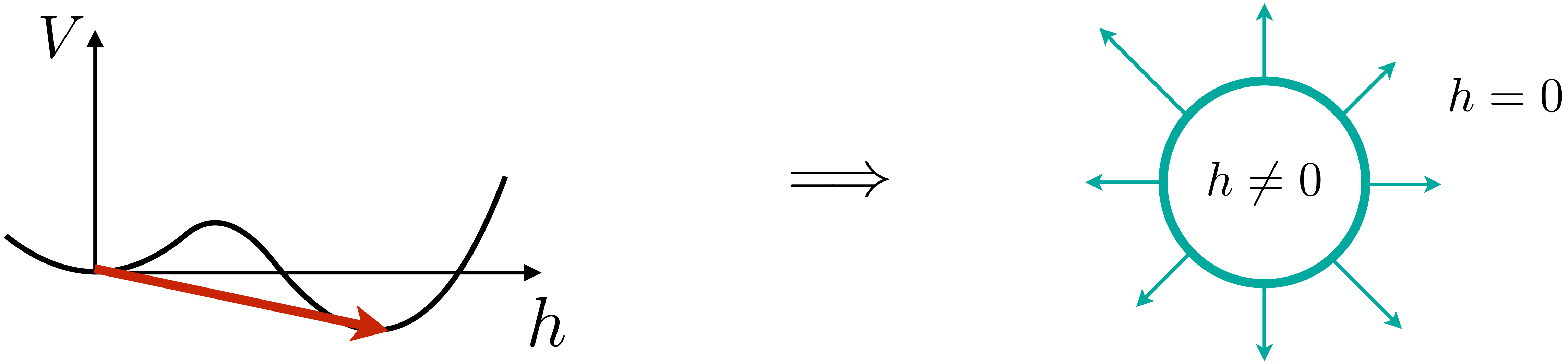

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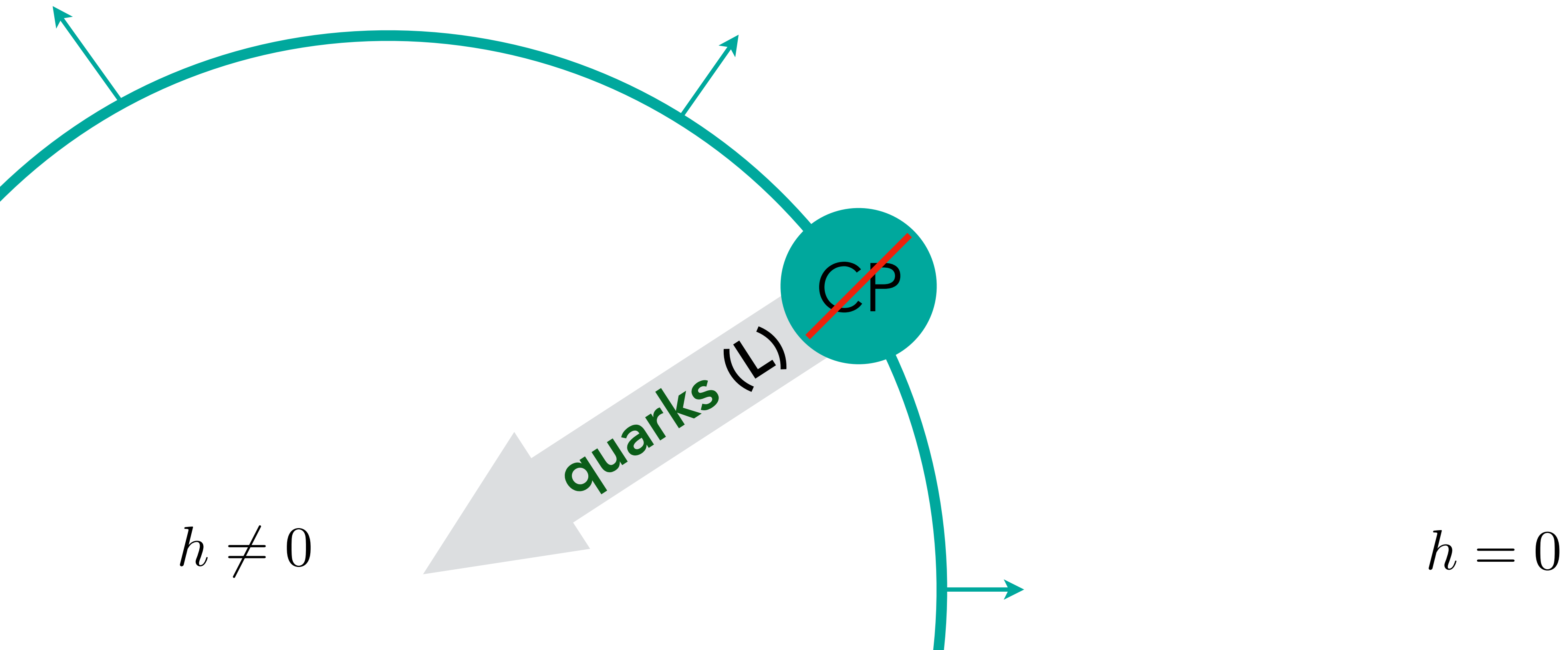

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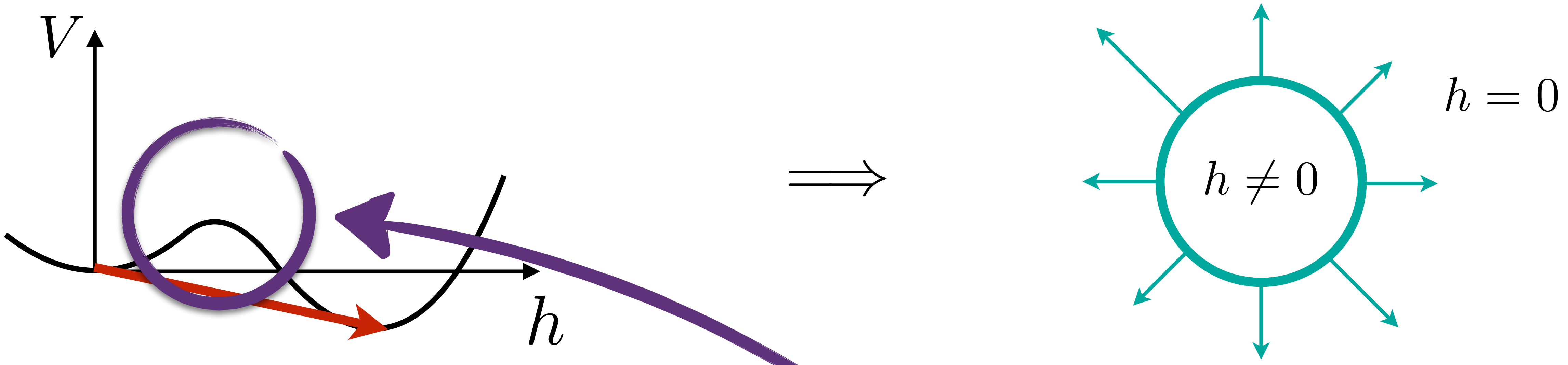

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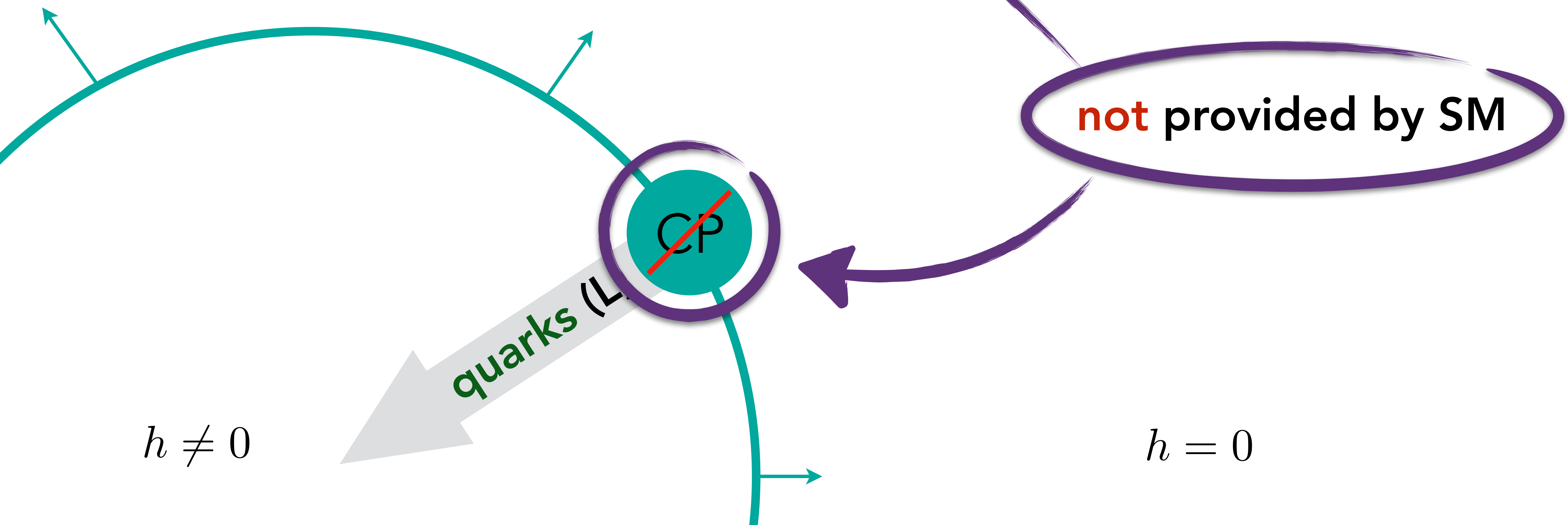
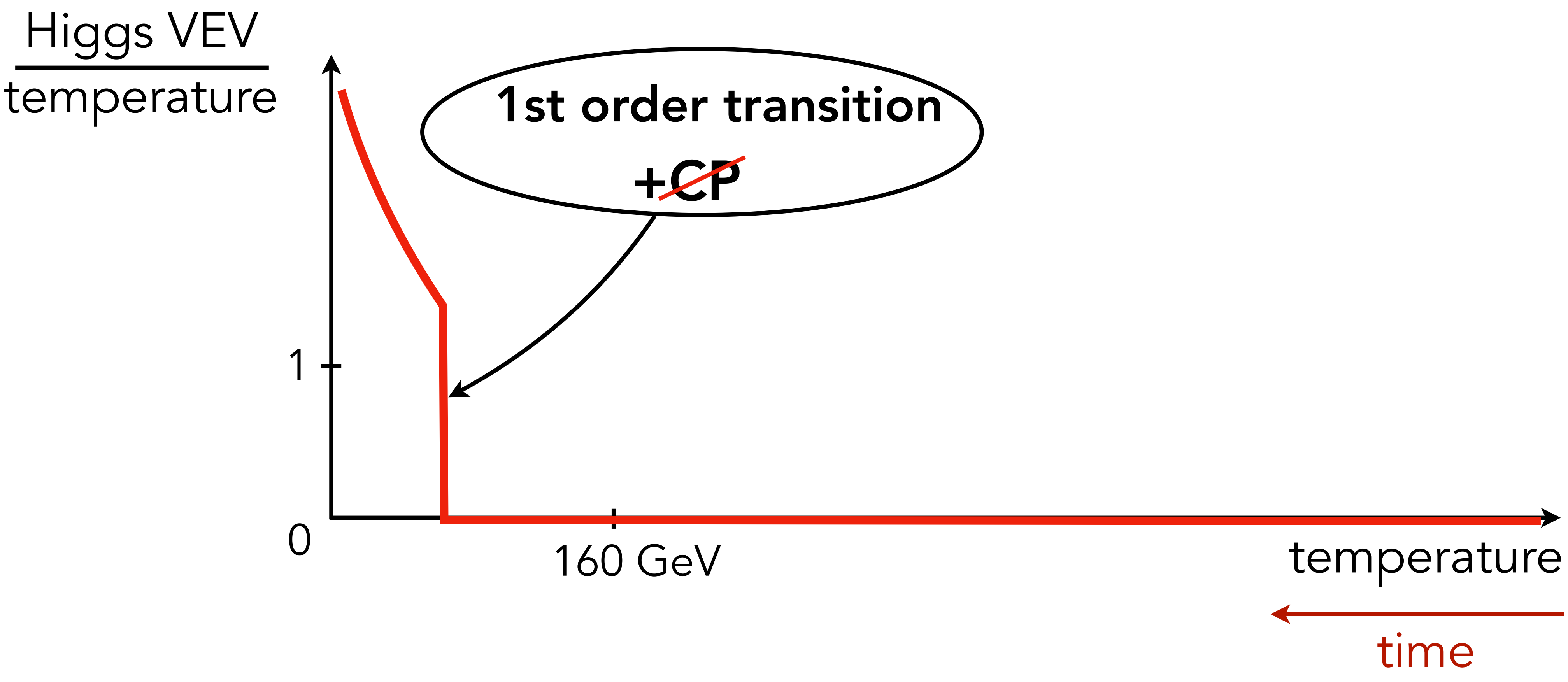


not provided by SM

Electroweak symmetry in the early Universe

in Electroweak Baryogenesis scenarios

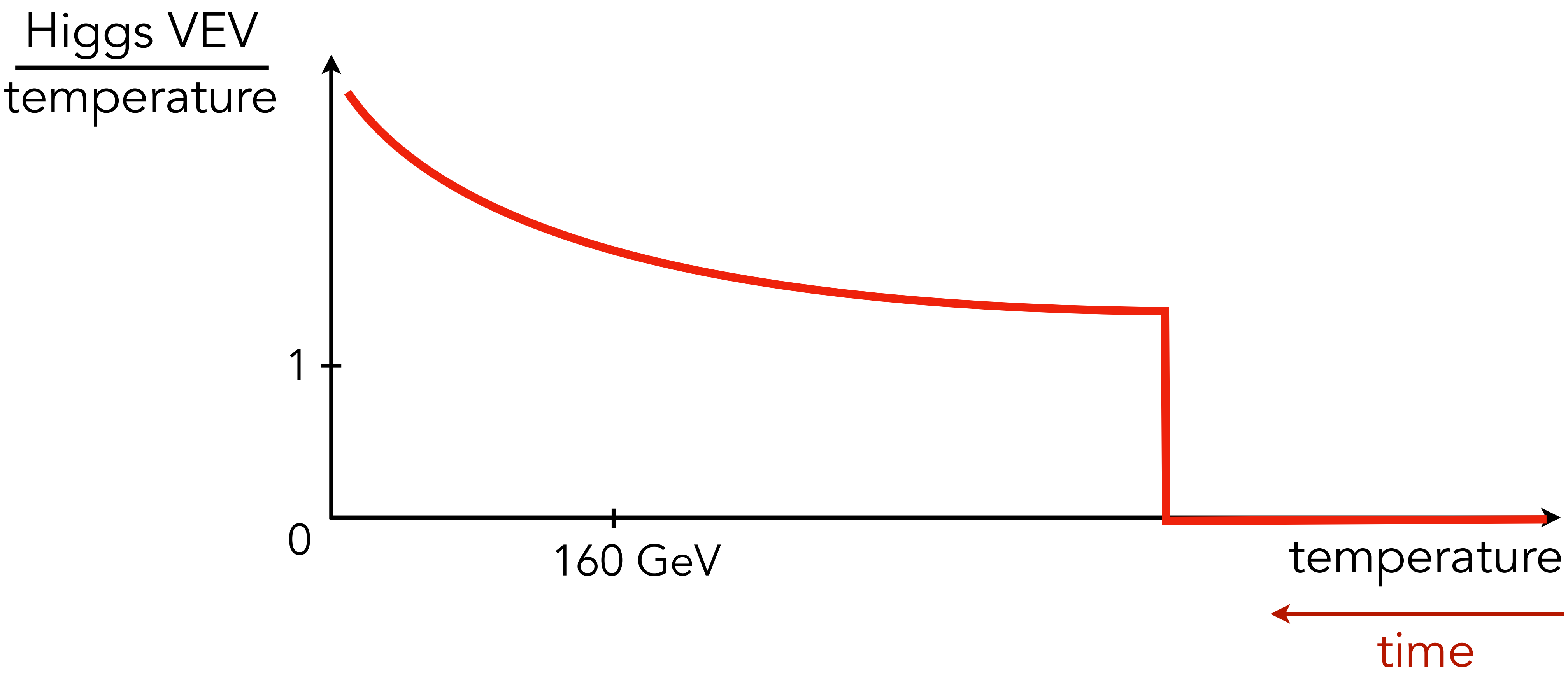


- ➔ new physics responsible for CP violation and first-order phase transition is at a few 100 GeV scale

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

Electroweak symmetry in the early Universe

What if?



Electroweak symmetry in the early Universe

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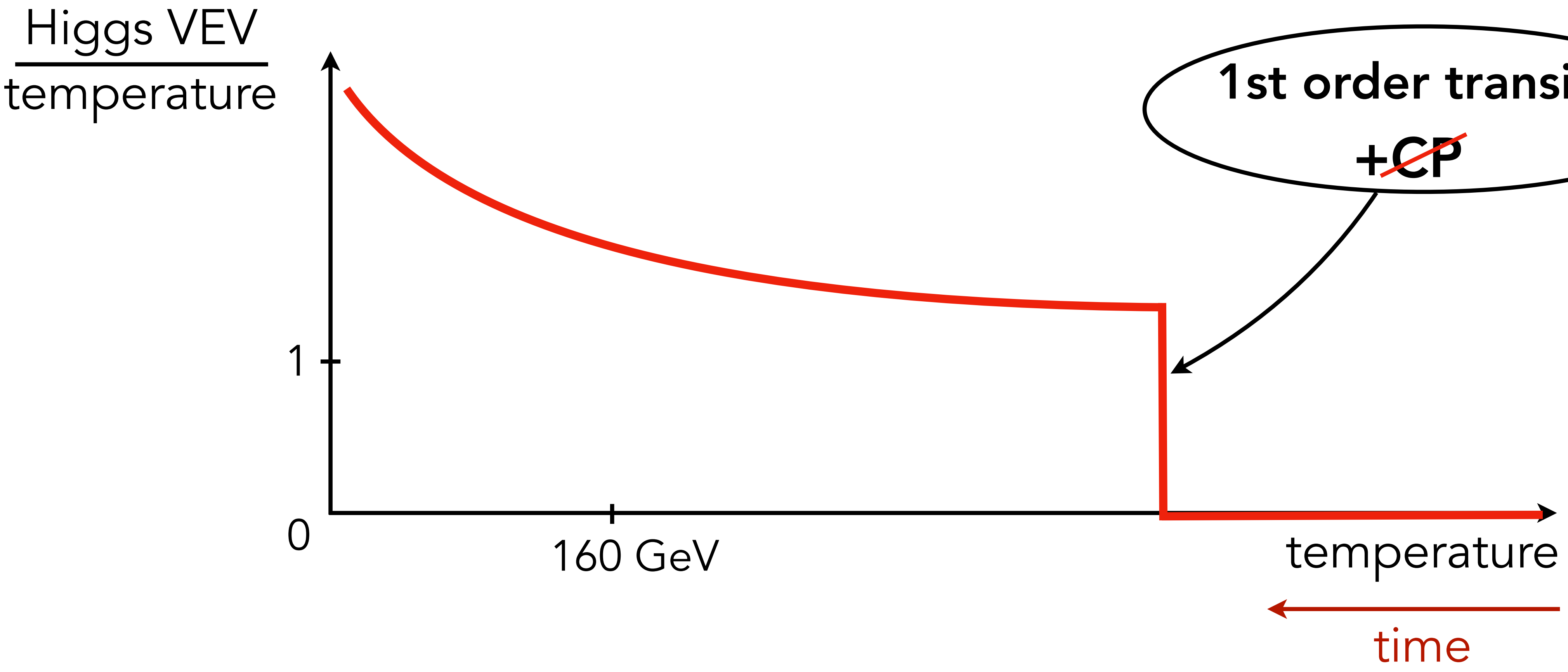
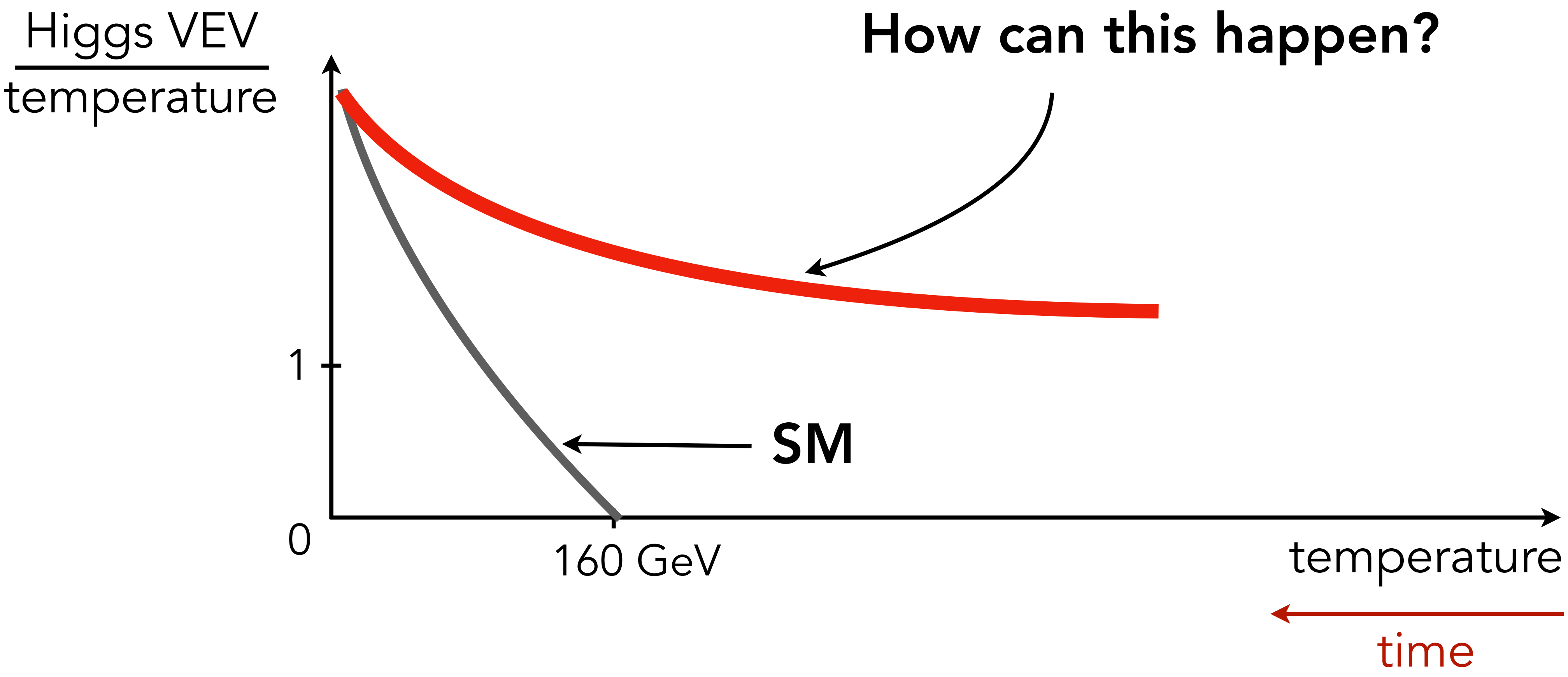


- ➔ new physics responsible for CP violation and first-order phase transition is **far above** 100 GeV scale

- ➔ **new phenomenology**

Electroweak symmetry in the early Universe



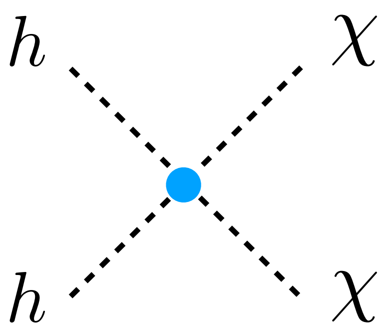
EW Symmetry Breaking at High T

Electroweak Symmetry Non-Restoration at High T

- ➔ EW SNR was first proposed ~2 years ago in:

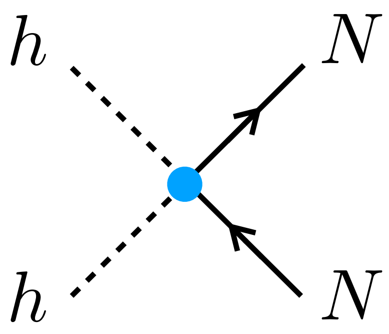
  Meade, Ramani, 1807.07578
  Baldes, Servant, 1807.08770
  Glioti, Rattazzi, Vecchi, 1811.11740

  with **new light scalars**



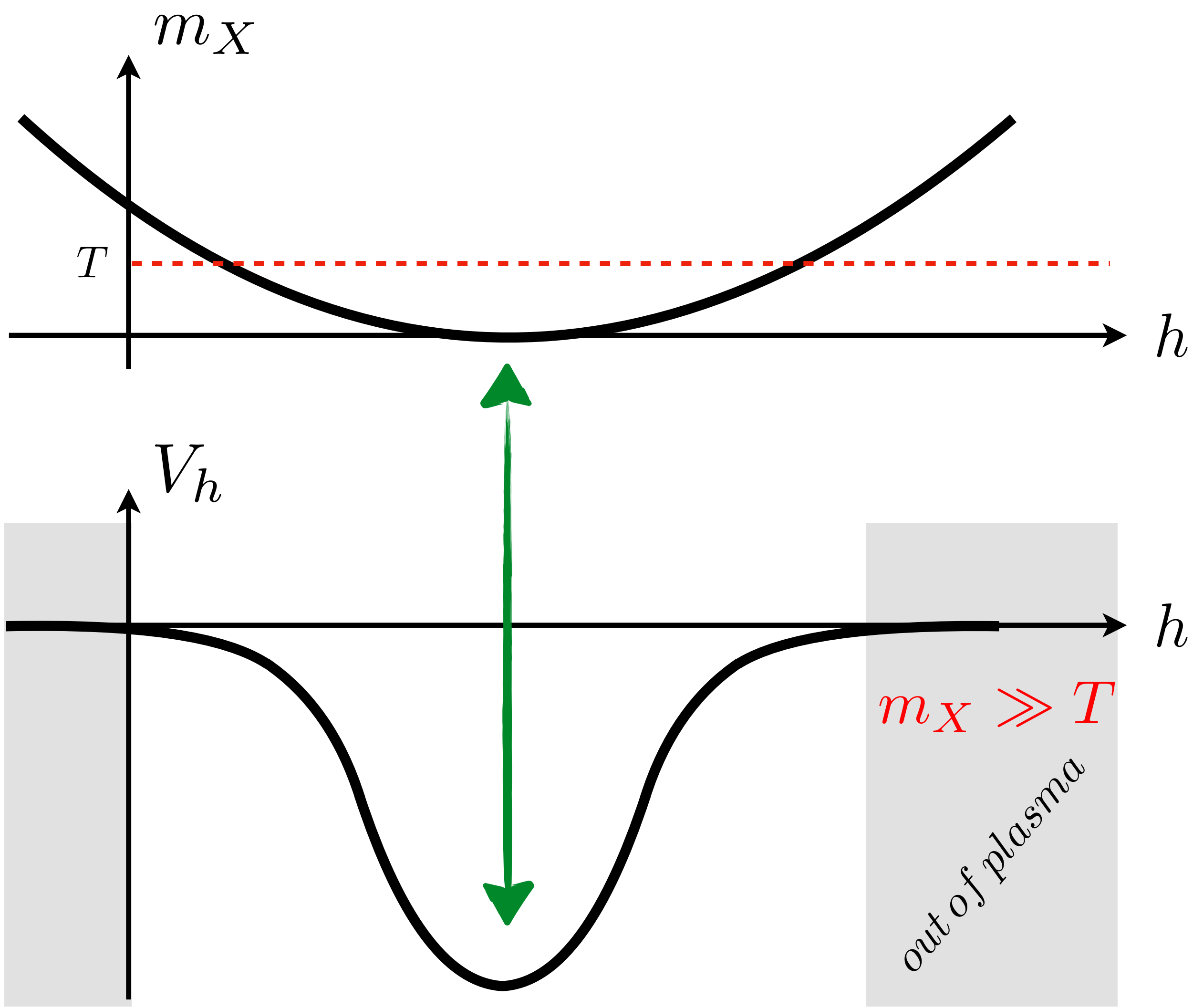
- ➔ We showed how can be done with **new fermions**

  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

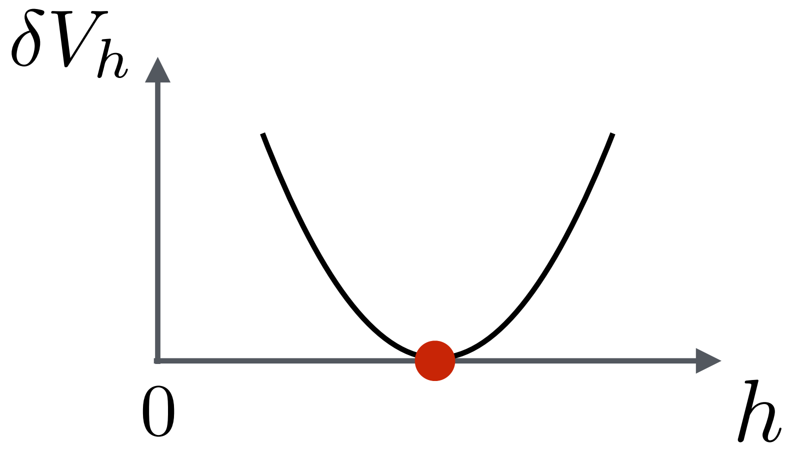
- ➔ Add n copies of new SM singlet Dirac fermion N

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

- ➔ N mass is minimized at large h

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

$$\longrightarrow \quad h^2 = m_N^{(0)}\Lambda/\lambda_N$$

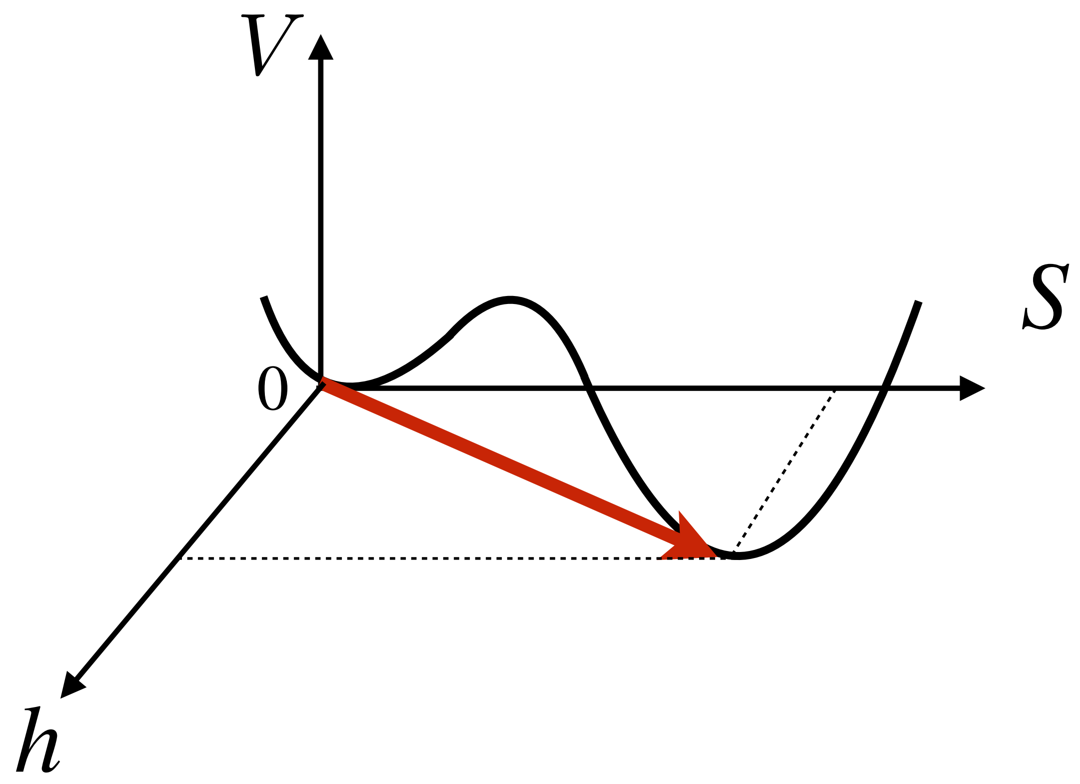


Phenomenology

New Pheno: Example

work in progress
Bruggisser,VonHarling,OM,Servant

- Usual way to get 1st order EW phase transition: add a new scalar S (eg dilaton)



- only works if T < T of EW restoration

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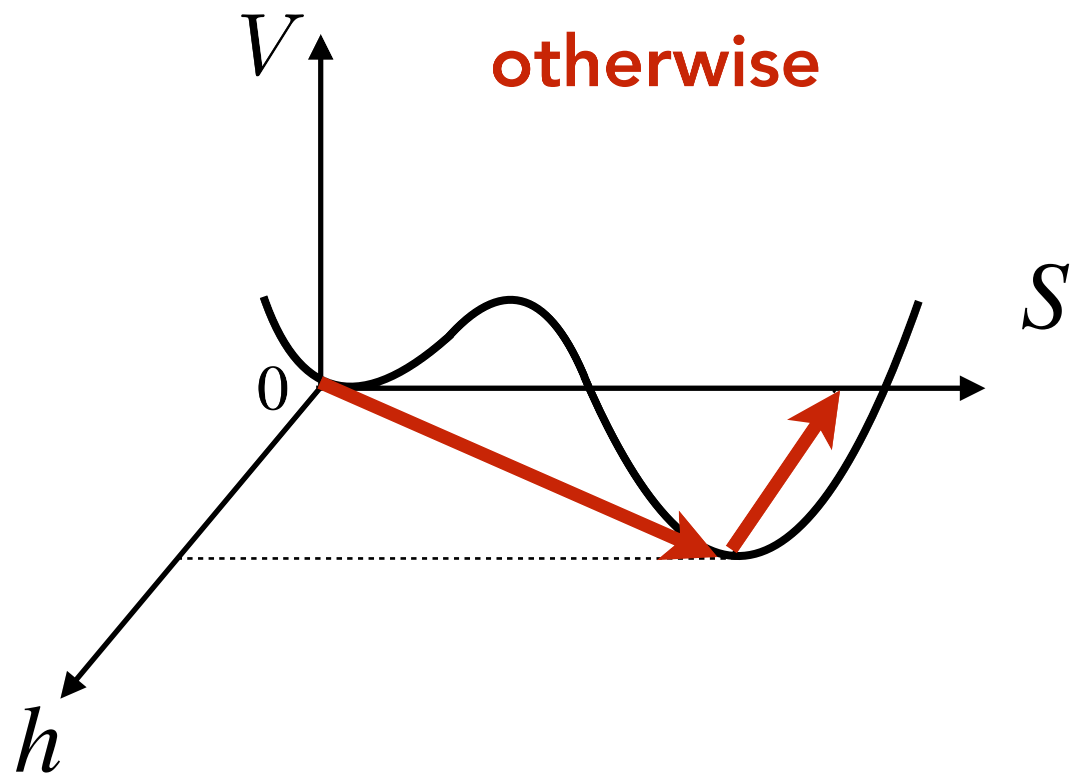

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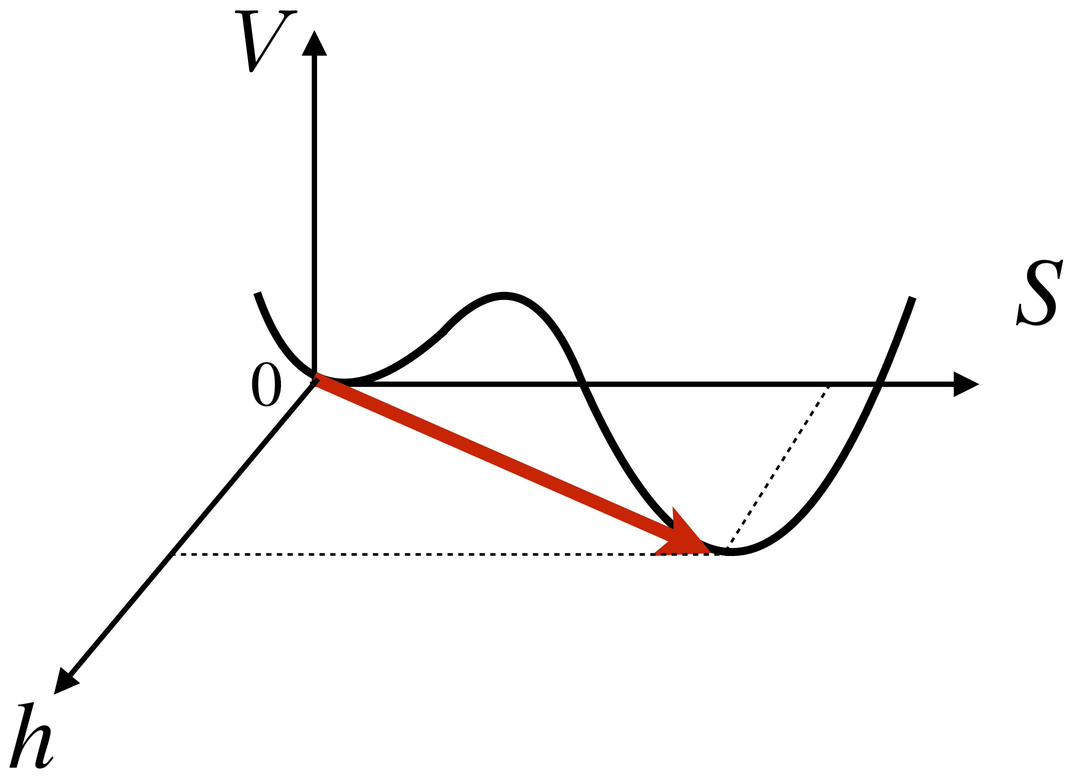

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- ➔ S phase transition releases latent heat

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

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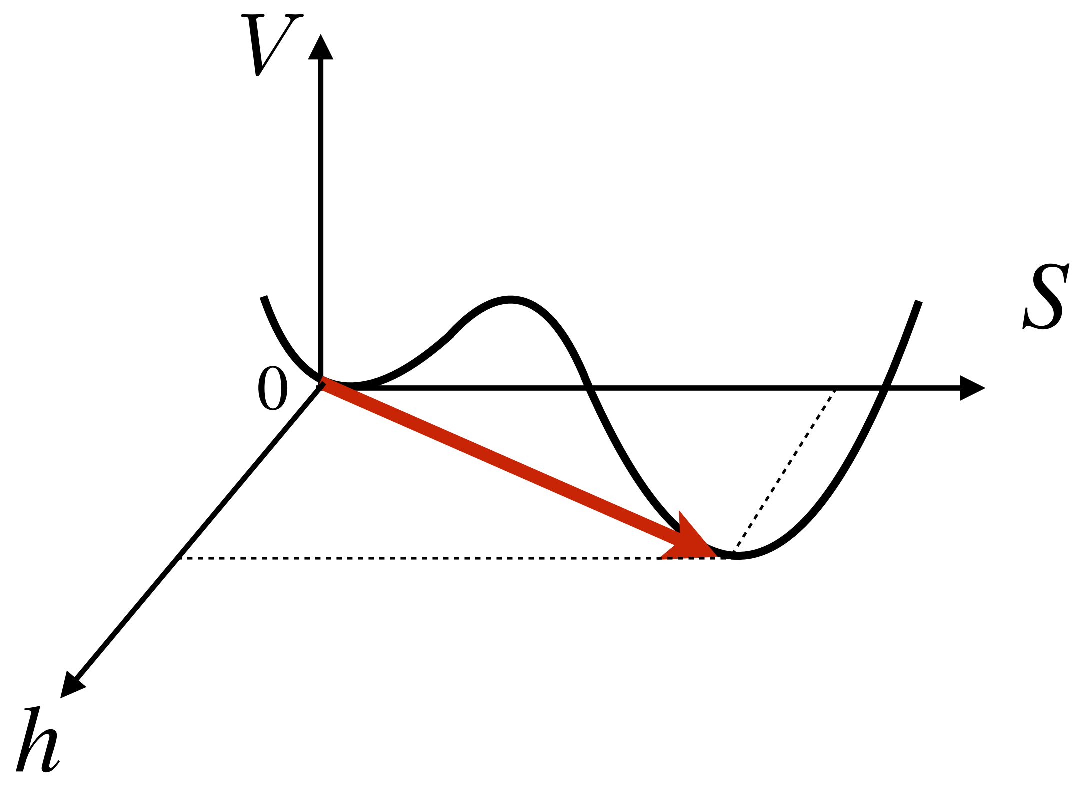

➔ only works if T < T of EW restoration

➔ S phase transition releases latent heat

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

$\Rightarrow$ for T restoration ~130 GeV

$m_S \lesssim$ O(100 GeV)

New Pheno: Example

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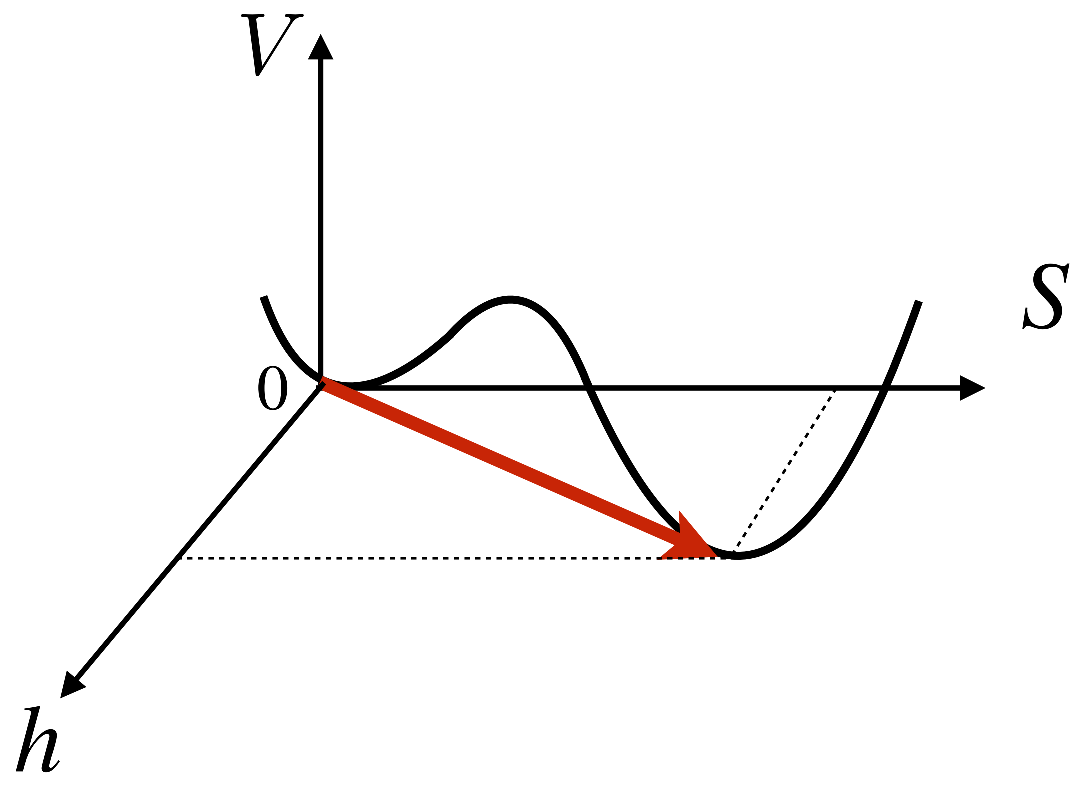

- ➔ only works if T < T of EW restoration
- ➔ S phase transition releases latent heat

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

⇒ for T restoration ~1 TeV

$m_S \lesssim$ O(few TeV)

“Automatic” Realizations

Automatic SNR

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

Automatic SNR

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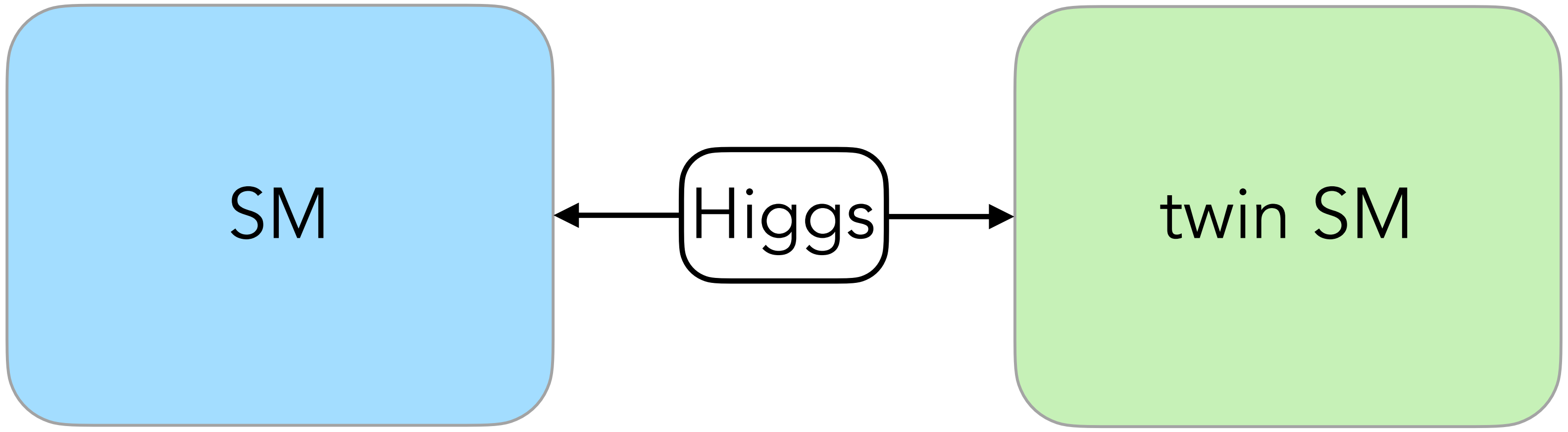
First suspect - Twin Higgs models (Chacko et al, hep-ph/0506256)

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



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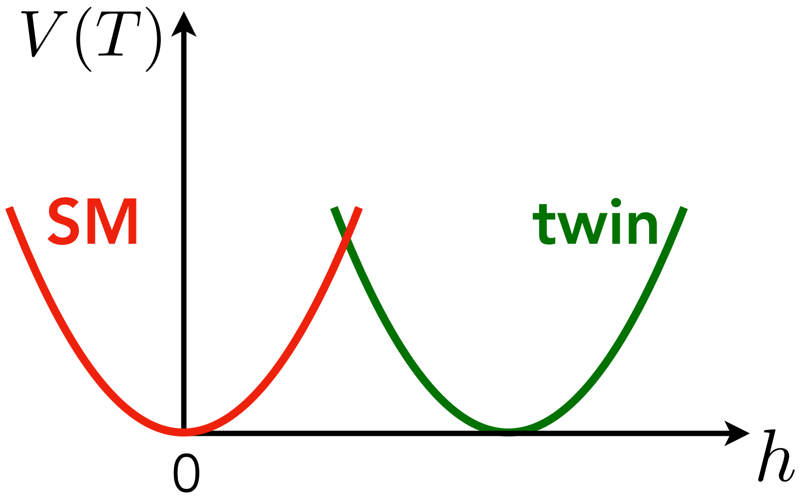

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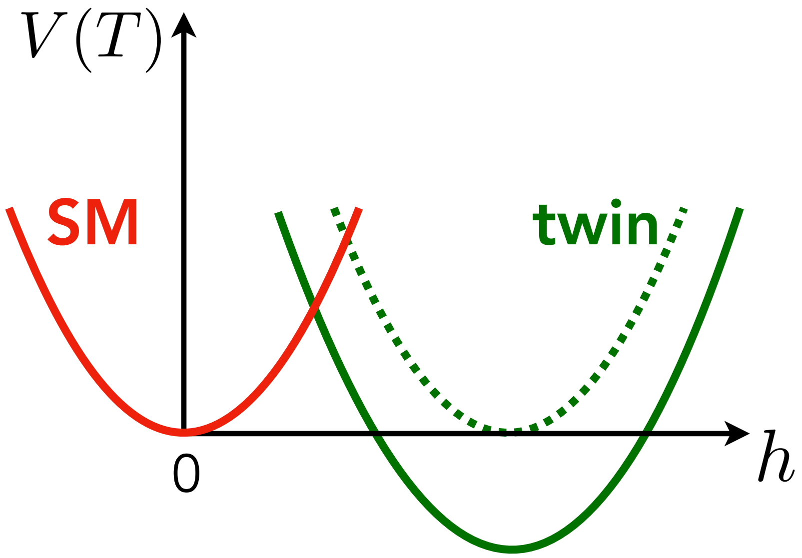

The (anyway necessary) Twin symmetry breaking by light quarks and/or leptons can tip the balance to the non-restoration.

(OM, 2008.13725)

Thank you!

Backup slides

SNR with fermions

- Add n copies of new SM singlet Dirac fermion N

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

- N mass is minimized at large h

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

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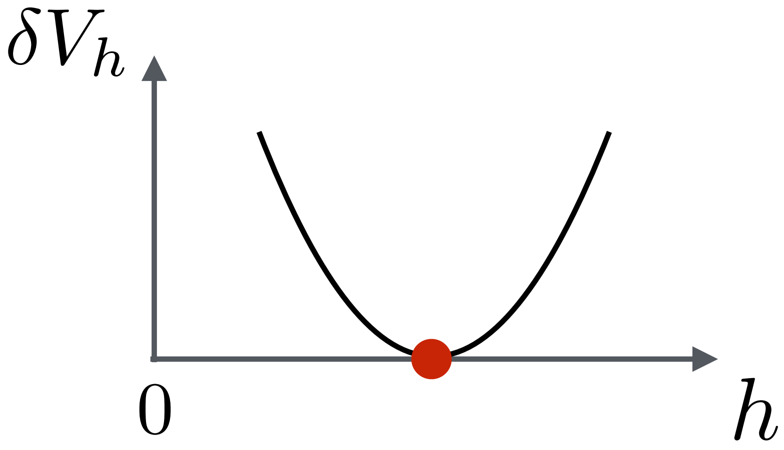


- can't be done with renormalizeable interactions:

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

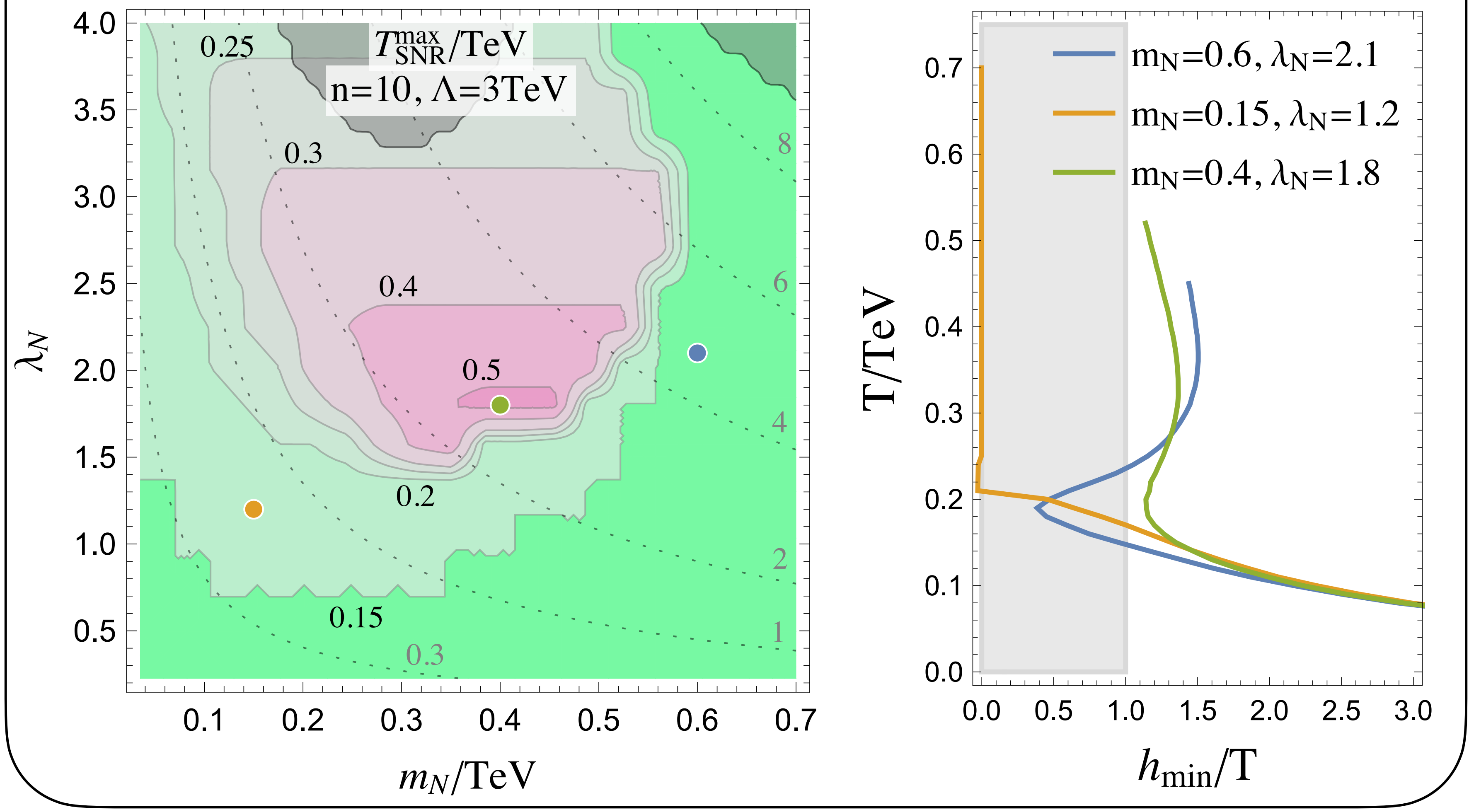
- in **renorm.** theories $|\mathcal{M}_{ij}|$ are h-independent *or* linear in h

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

SNR with fermions

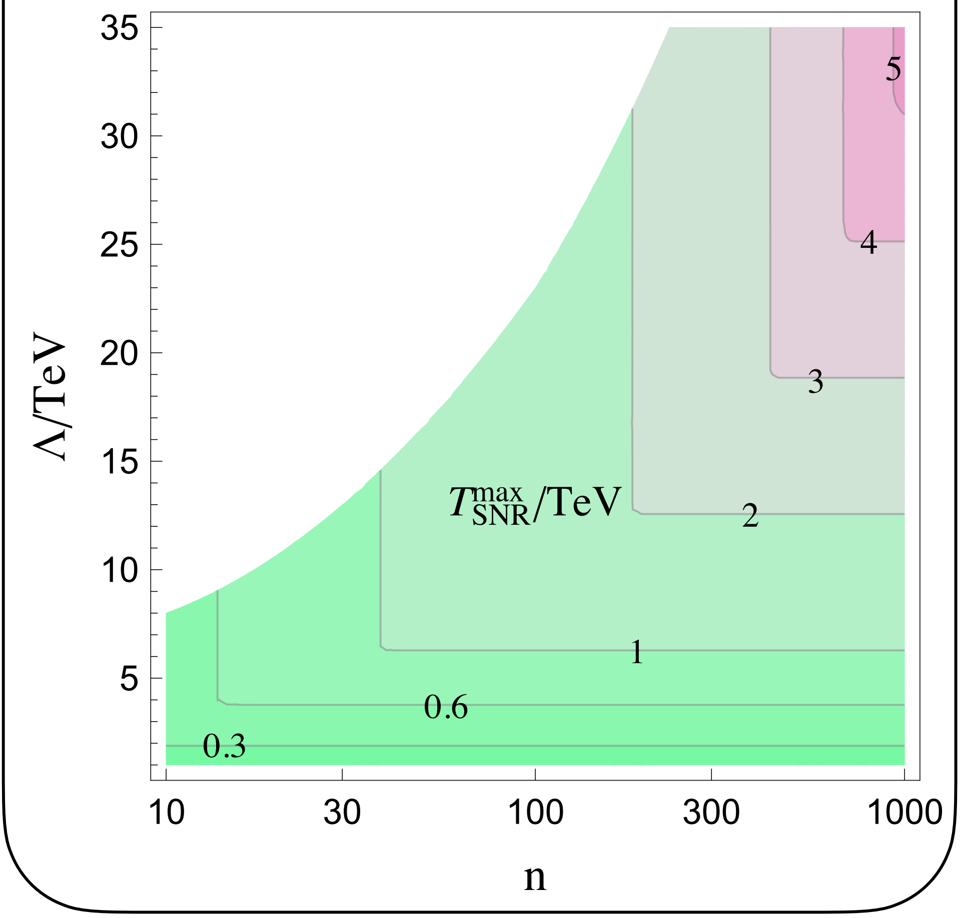
- minimal and "natural" SM deformation:

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



- going to higher temperatures

$$T_{\rm SNR}^{\rm max} \sim \sqrt{n}\, m_N$$



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-Goldtone boson of a large symmetry, which accommodates both SM and Twin $SU(2)_L$

example:

$$\begin{tikzcd}
SU(2)_L \arrow[dr] & & \\
 & SU(4) \arrow[r, "\text{spontaneous breaking}"'] & SU(3) + \text{Higgs doublet} + \text{3 other PNGB} \\
SU(2)'_L \arrow[ur] & &
\end{tikzcd}$$

SNR: Twin Higgs

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

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

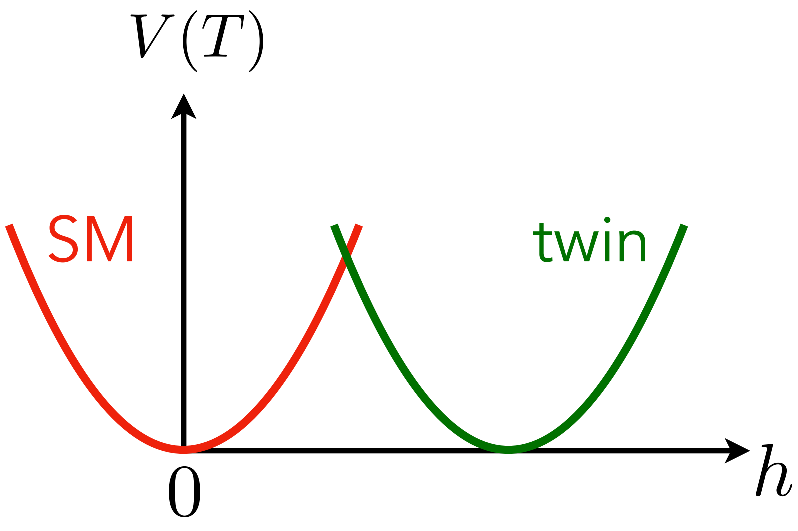
- Quadratic divergences $\propto \Lambda^2$ in the Higgs mass cancel

$$V \sim f^2\Lambda^2(\underset{\substack{\uparrow \\ \text{SM contribution}}}{\sin^2 h/f} + \underset{\substack{\uparrow \\ \text{Twin contribution}}}{\cos^2 h/f}) = f^2\Lambda^2$$

no Higgs dependence

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

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



The resulting position of the minimum depends on weak Z_2 breaking

→ analyse which type of $\cancel{Z}_2$ can tilt high-T potential to SNR minimum

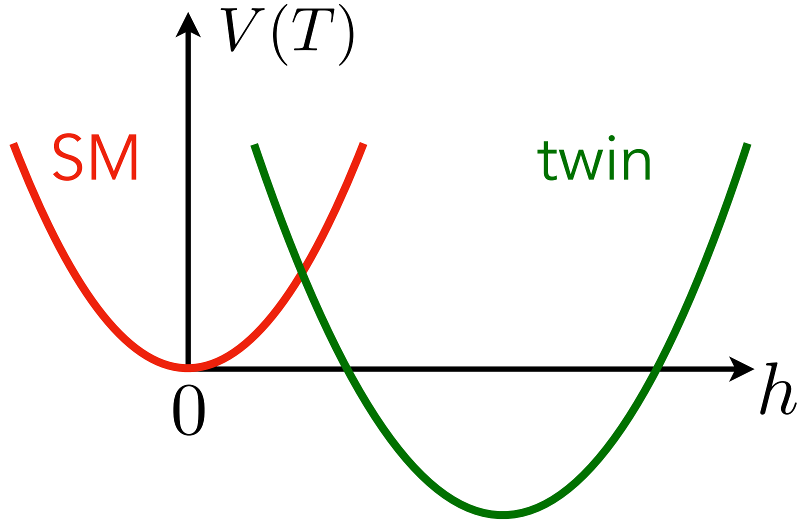
SNR: Twin Higgs

- ➔ Sources of $\cancel{Z}_2$

necessarily broken in the light fermion sector: eg twin neutrinos cannot be light.

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

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

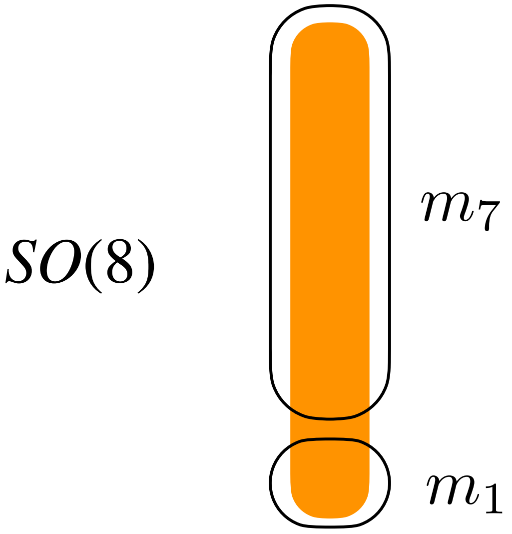


- ➔ This also spoils the cancellation of T=0 quadratic divergences to the Higgs mass: $\delta m_h^2 \sim (\tilde{\lambda}_q^2/16\pi^2)\Lambda^2$

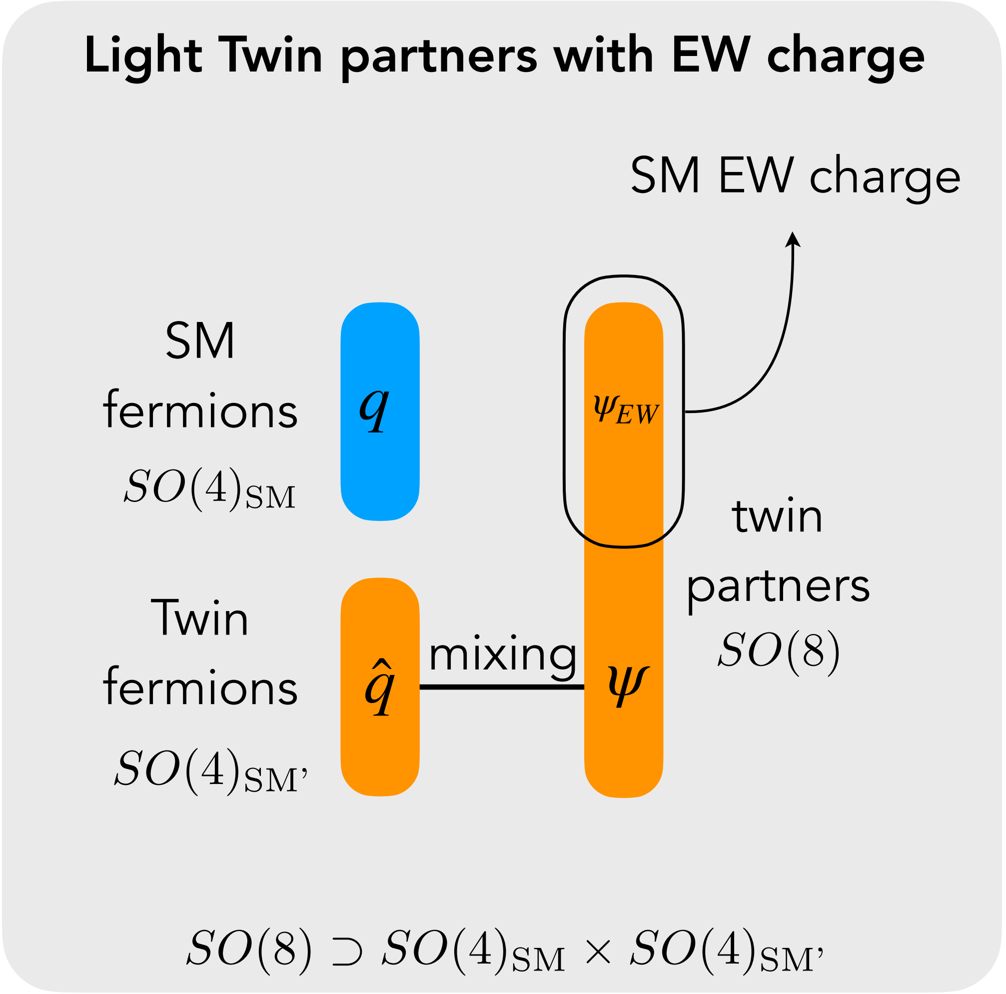
$\Rightarrow$ take a lower cutoff Λ in the twin light quark sector $\Rightarrow$ light **twin partners** (no SM QCD charge)

SNR: Twin Higgs

- To not spoil the Higgs mass, we need:



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



Light Twin partners with EW charge

SM EW charge

SM fermions $SO(4)_{\text{SM}}$ — q

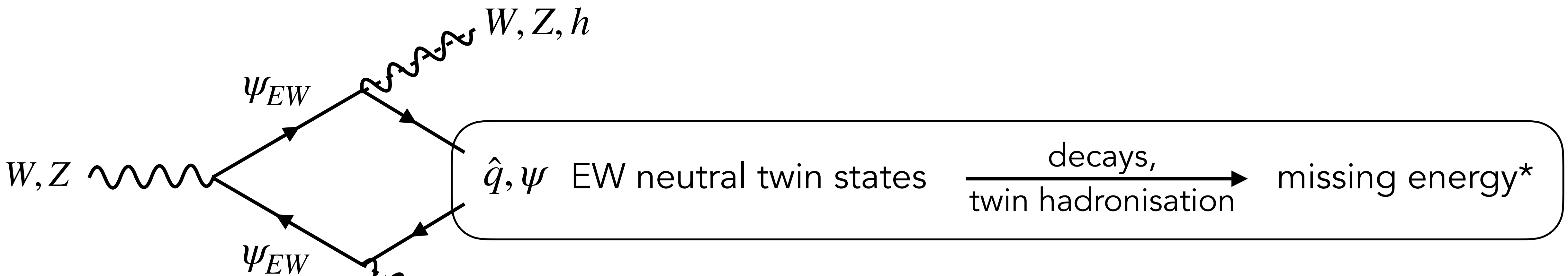
ψ_{EW}

twin partners $SO(8)$

Twin fermions $SO(4)_{\text{SM'}}$ — $\hat{q}$ — mixing — ψ

$$SO(8) \supset SO(4)_{\text{SM}} \times SO(4)_{\text{SM'}}$$

- Collider signal:

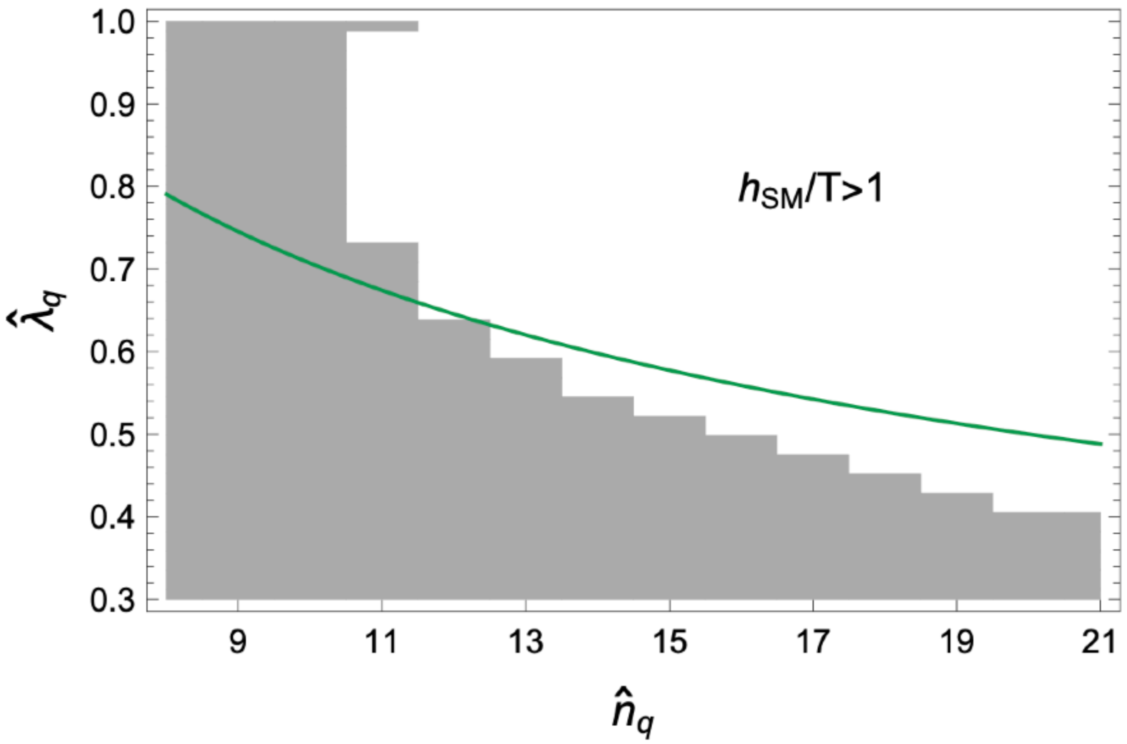


$\hat{q}, \psi$ EW neutral twin states $\xrightarrow[\text{twin hadronisation}]{\text{decays,}}$ missing energy*

*one can arrange for visible signatures too

SNR: Twin Higgs

- ➔ numerical results



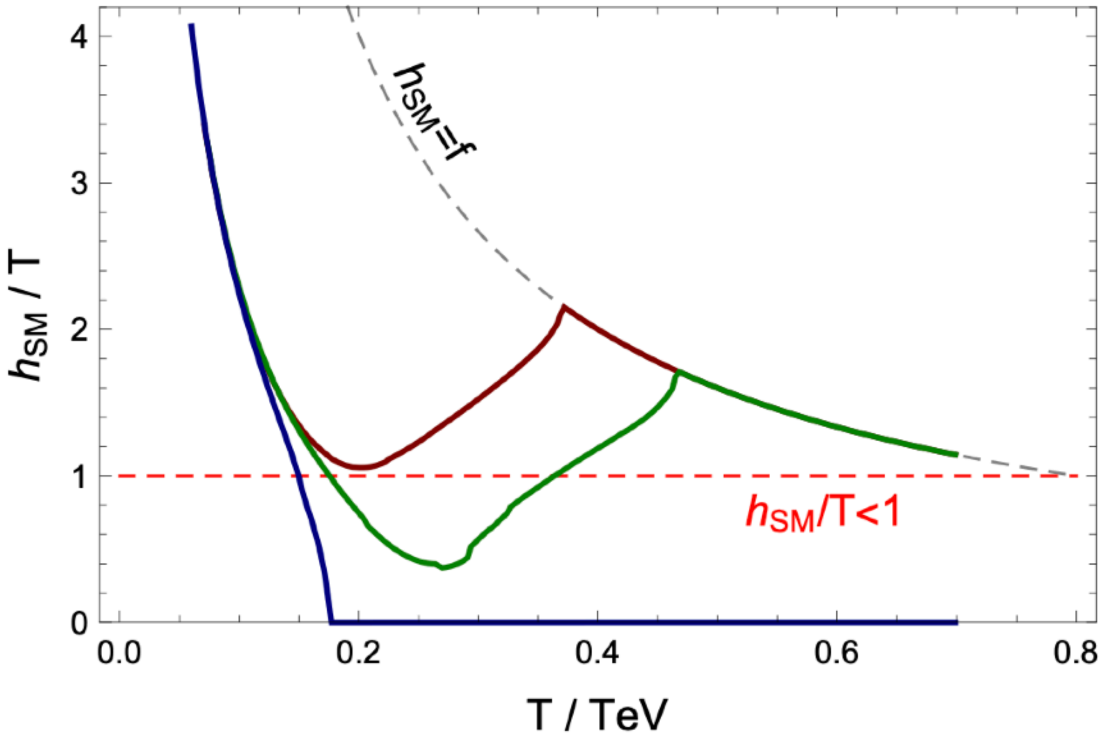
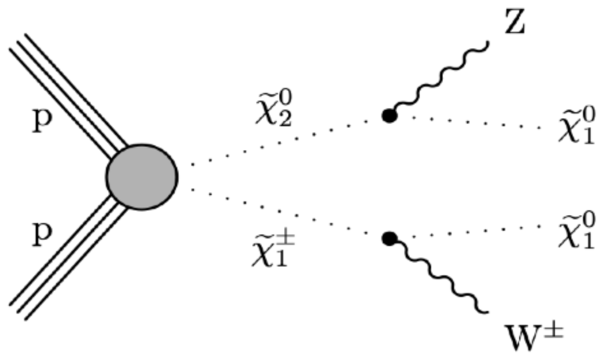


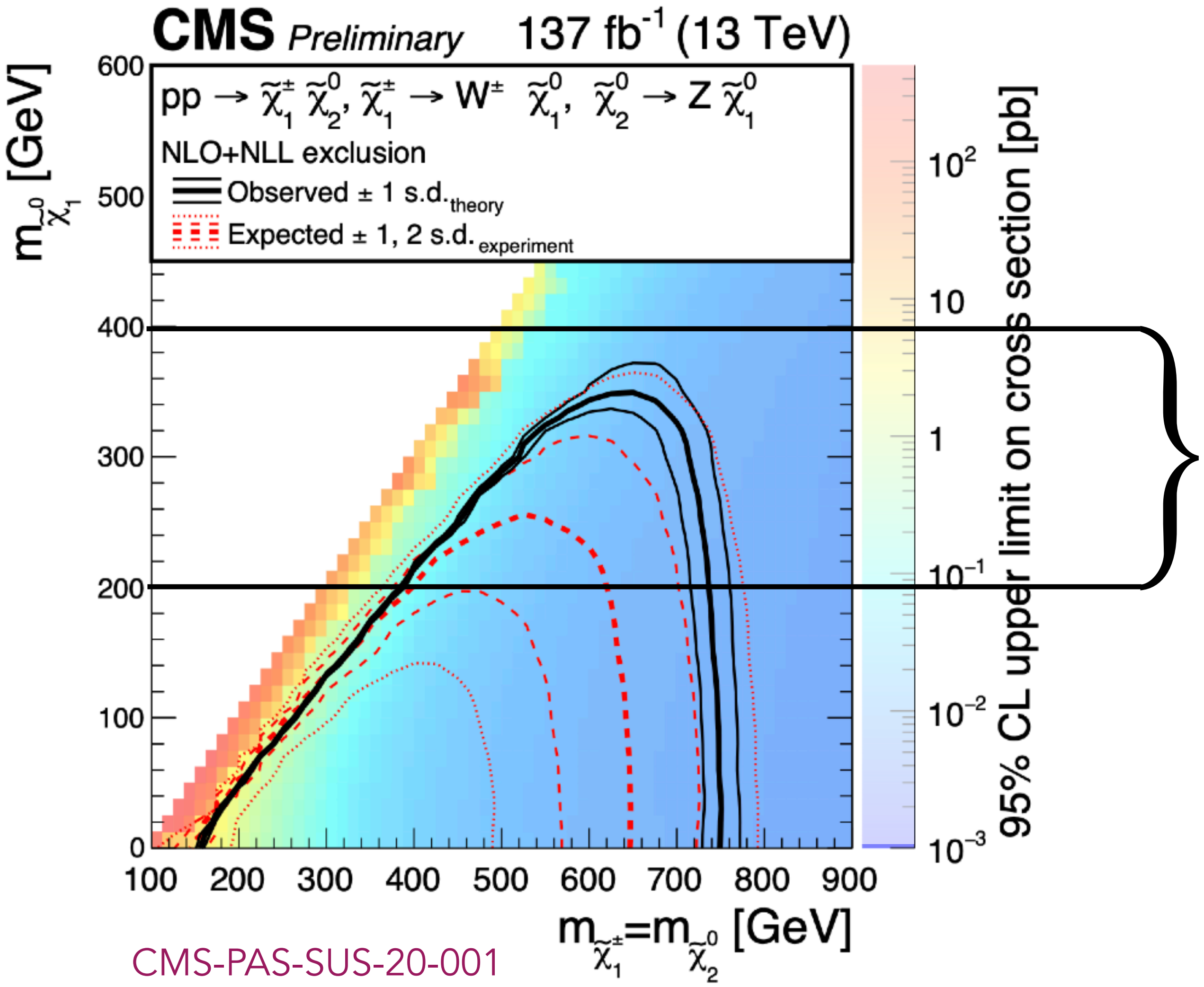
Figure 2: *Solid lines show the evolution of* h_{SM}/T *in the minimum of the Higgs potential depending on the temperature, for three choices of parameters:* $\hat{\lambda}_q = 0.2, \hat{n}_q = 9$ *(blue),* $\hat{\lambda}_q = 0.5, \hat{n}_q = 12$ *(green), and* $\hat{\lambda}_q = 0.7, \hat{n}_q = 12$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

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)





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

CMS-PAS-SUS-20-001

SNR: Twin Higgs

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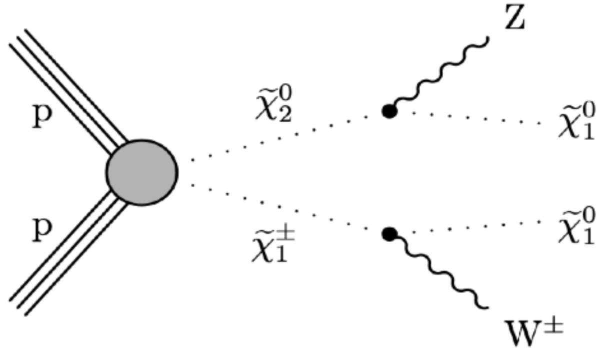
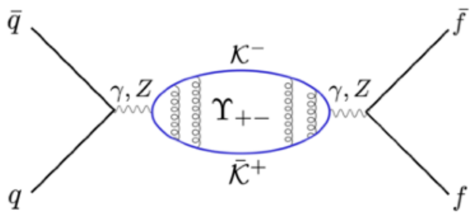
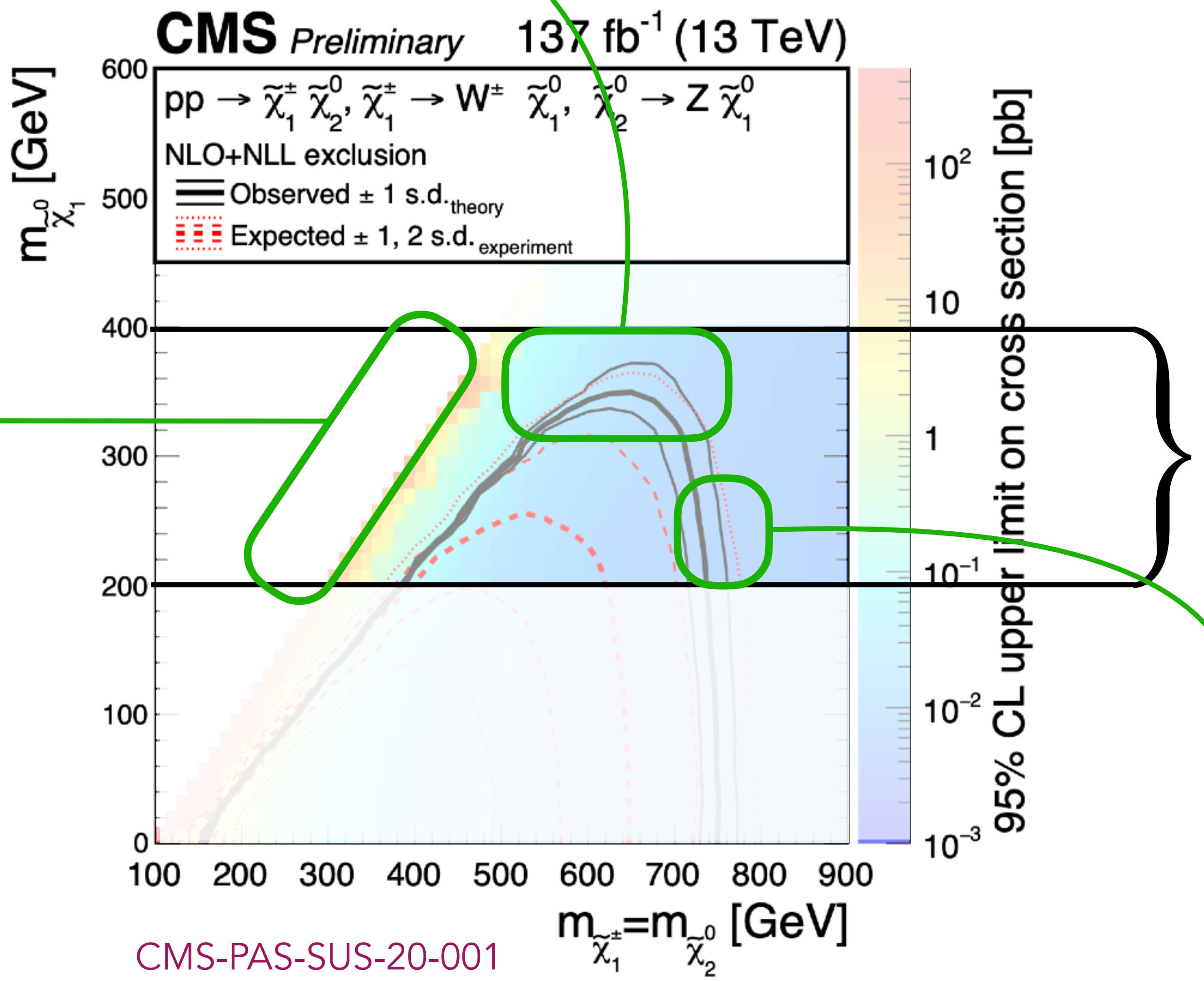


bounds significantly depend on kinematical distributions

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



Cheng,Salvioni,Tsai
1612.03176



CMS-PAS-SUS-20-001

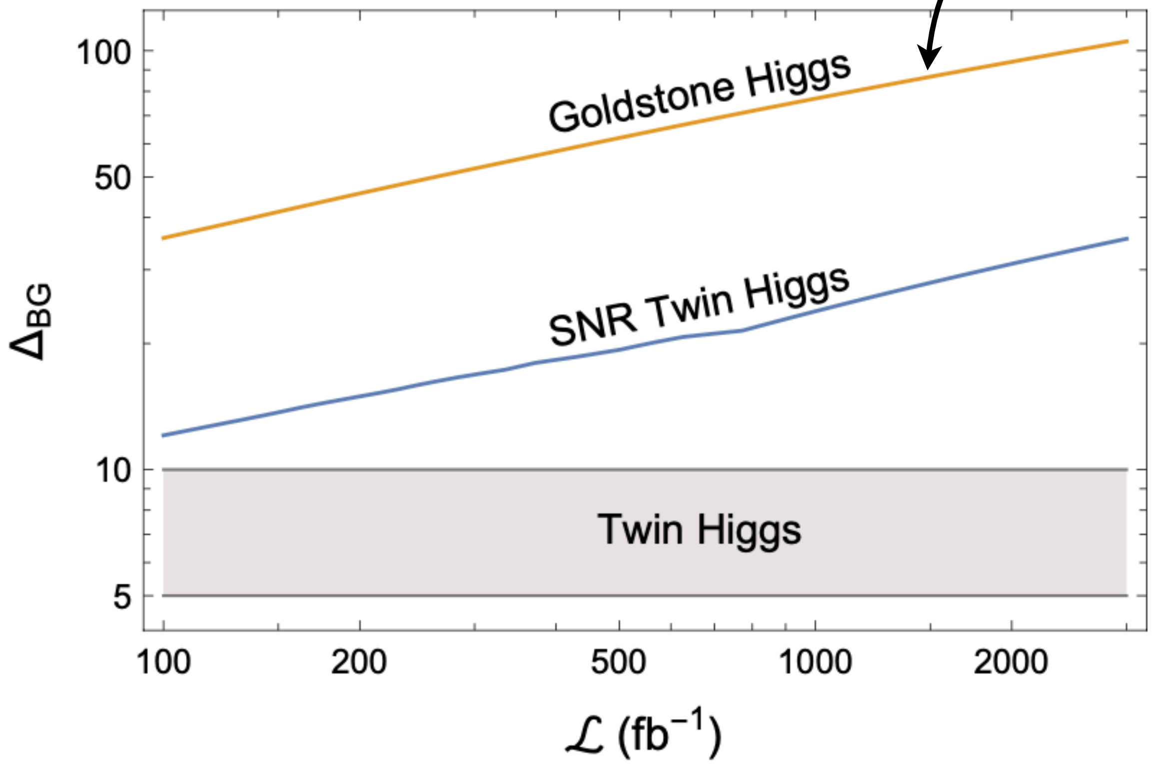
optimal mass of twin fermions $\hat{q}$

eventually used for the derivation of bounds

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:

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

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

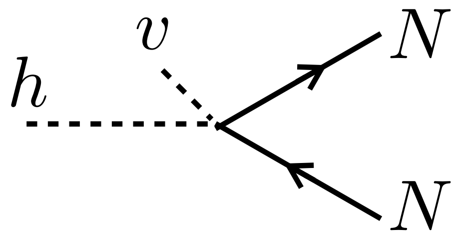
fermions:

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

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

SNR: collider pheno

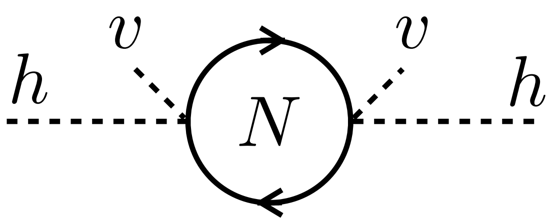
- invisible Higgs decays



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

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

- Universal Higgs couplings modification



from Higgs wave function renormalization

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