Minimal Electroweak Baryogenesis: from Elementary to Composite

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Technische Universität München

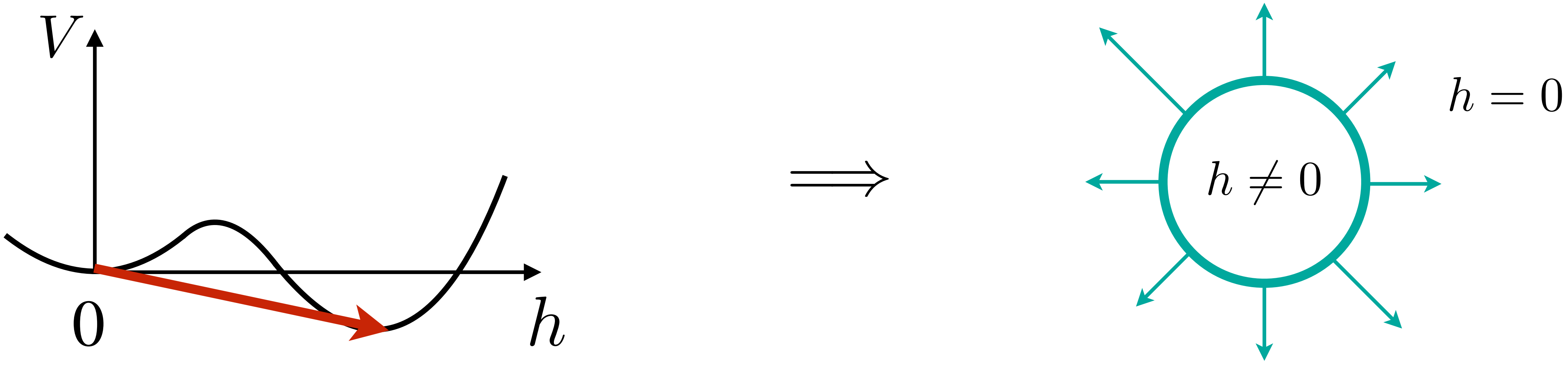
ORIGINS Excellence Cluster

Extended Scalar Sectors, CERN, 2024

Intro:
Standard EWBG

Electroweak Baryogenesis

First order EW phase transition proceeds through bubble nucleation:



Shaposhnikov ‘87

Cohen,Kaplan,Nelson ‘91

Electroweak Baryogenesis

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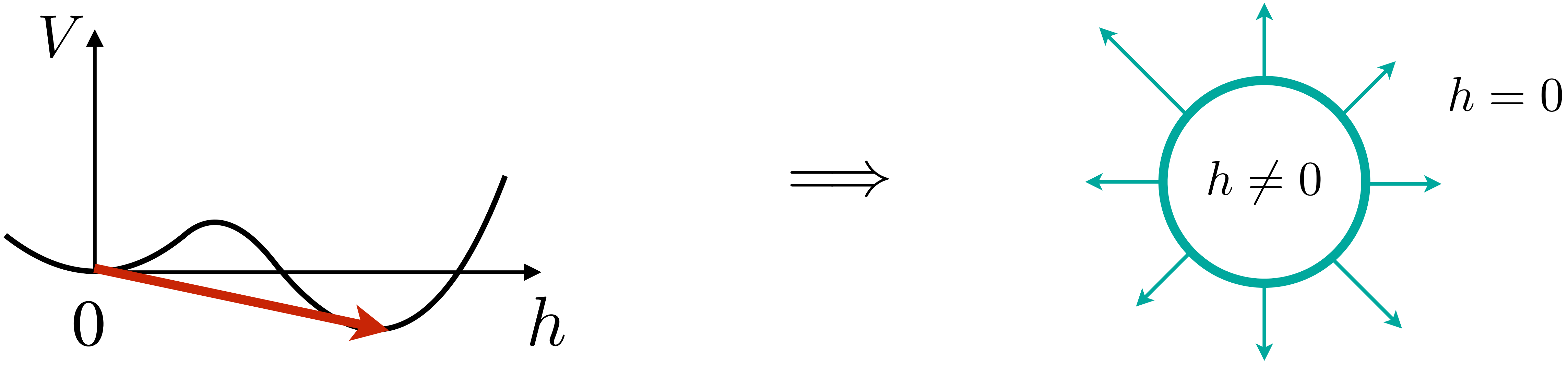
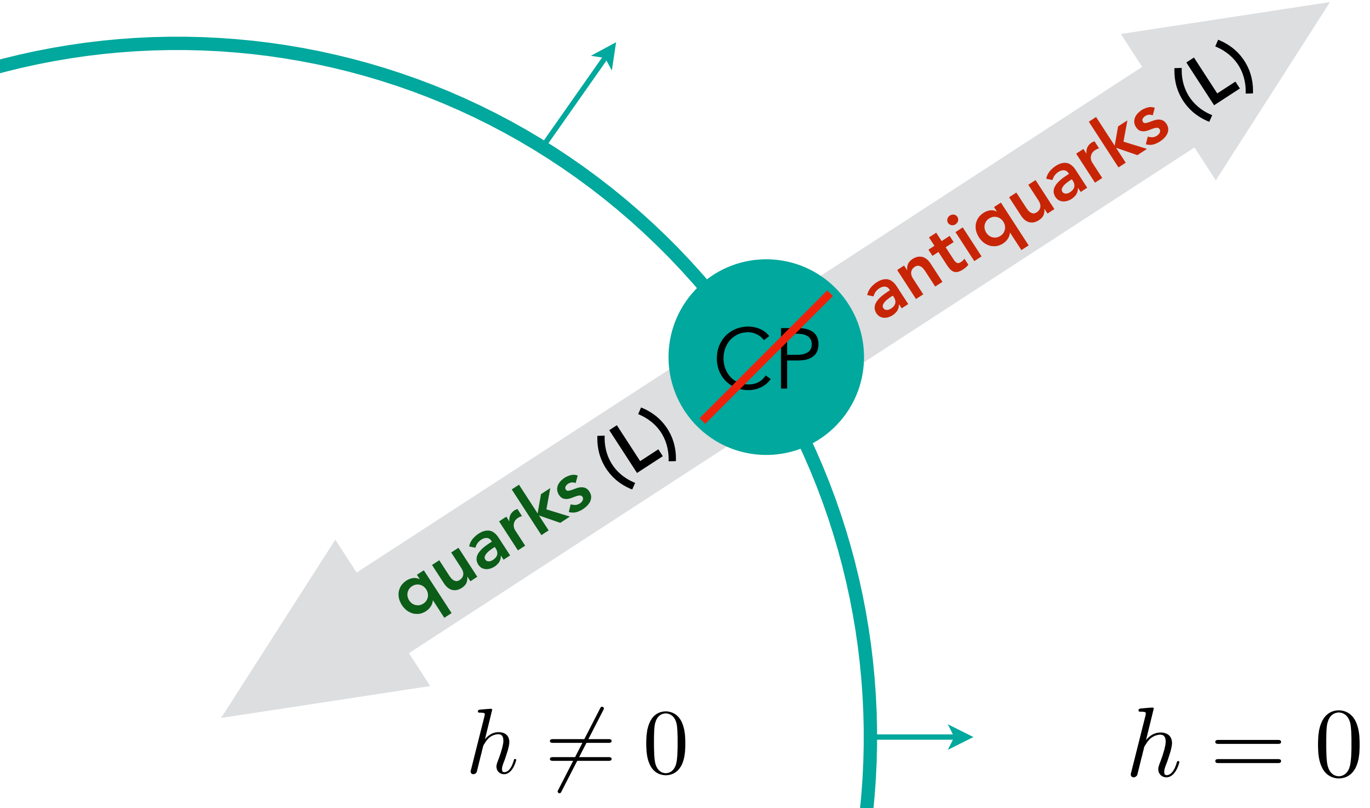


Baryon asymmetry is created close to bubble walls:



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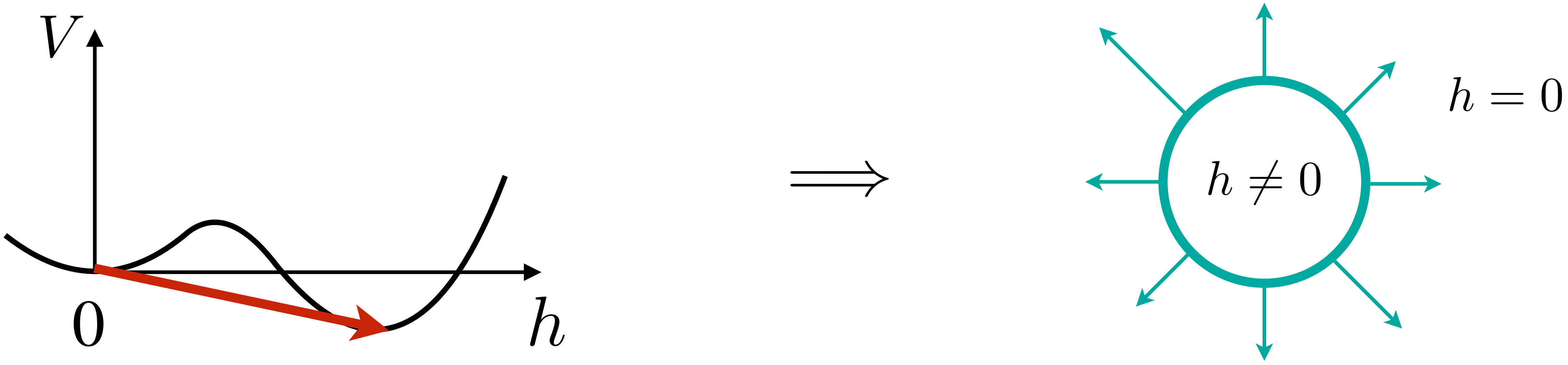

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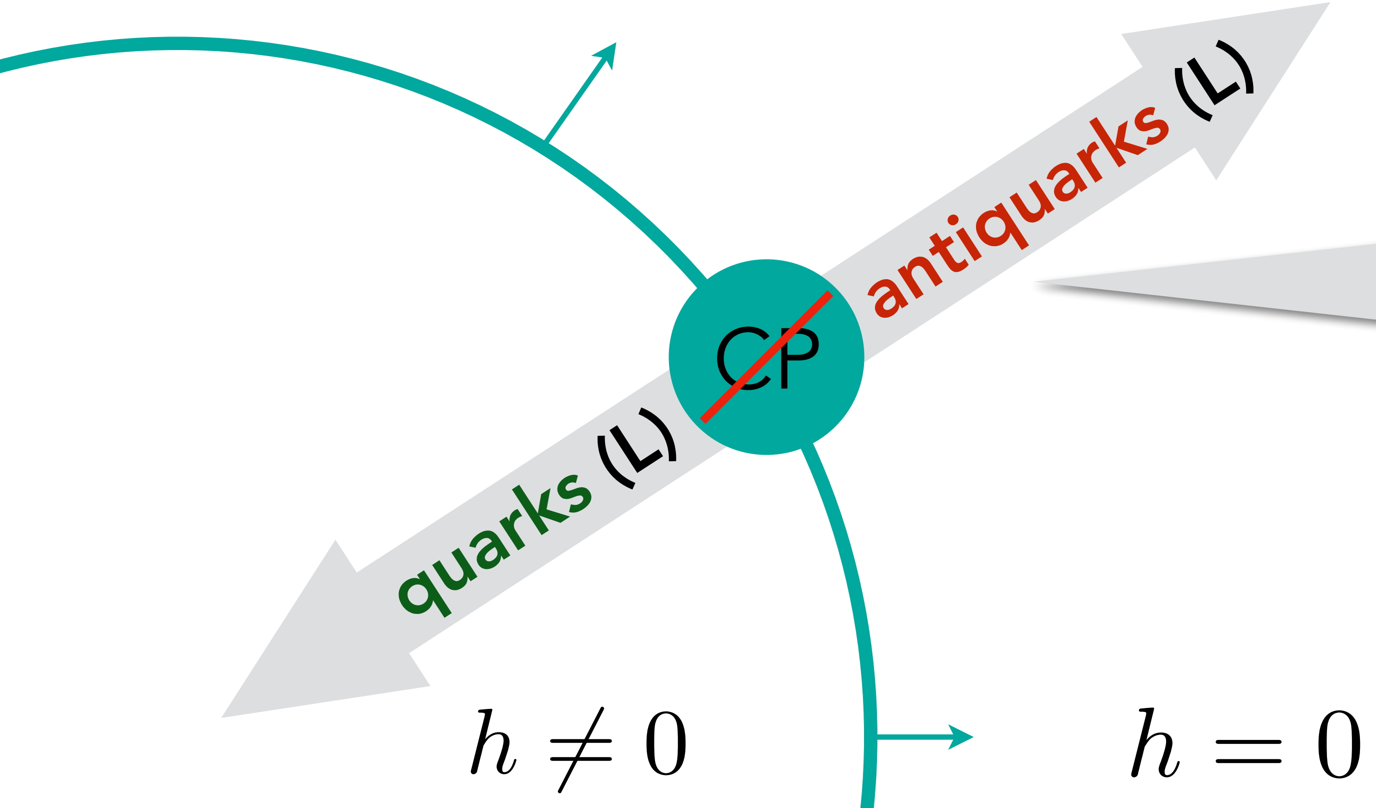

EW sphalerons:

B+L violation:

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_l = $$
$$= n_f \left(\frac{g^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \right)$$

Electroweak Baryogenesis

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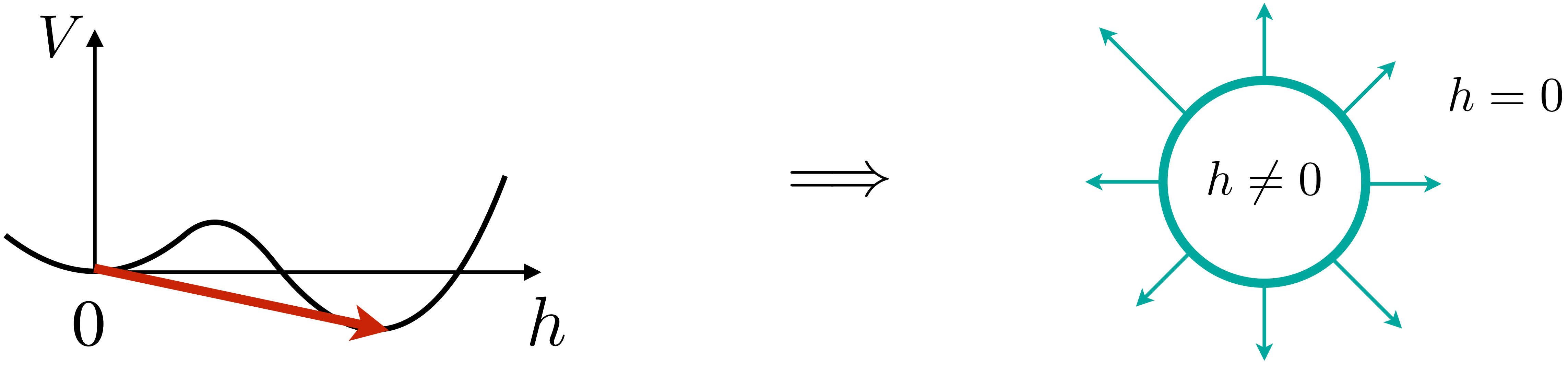

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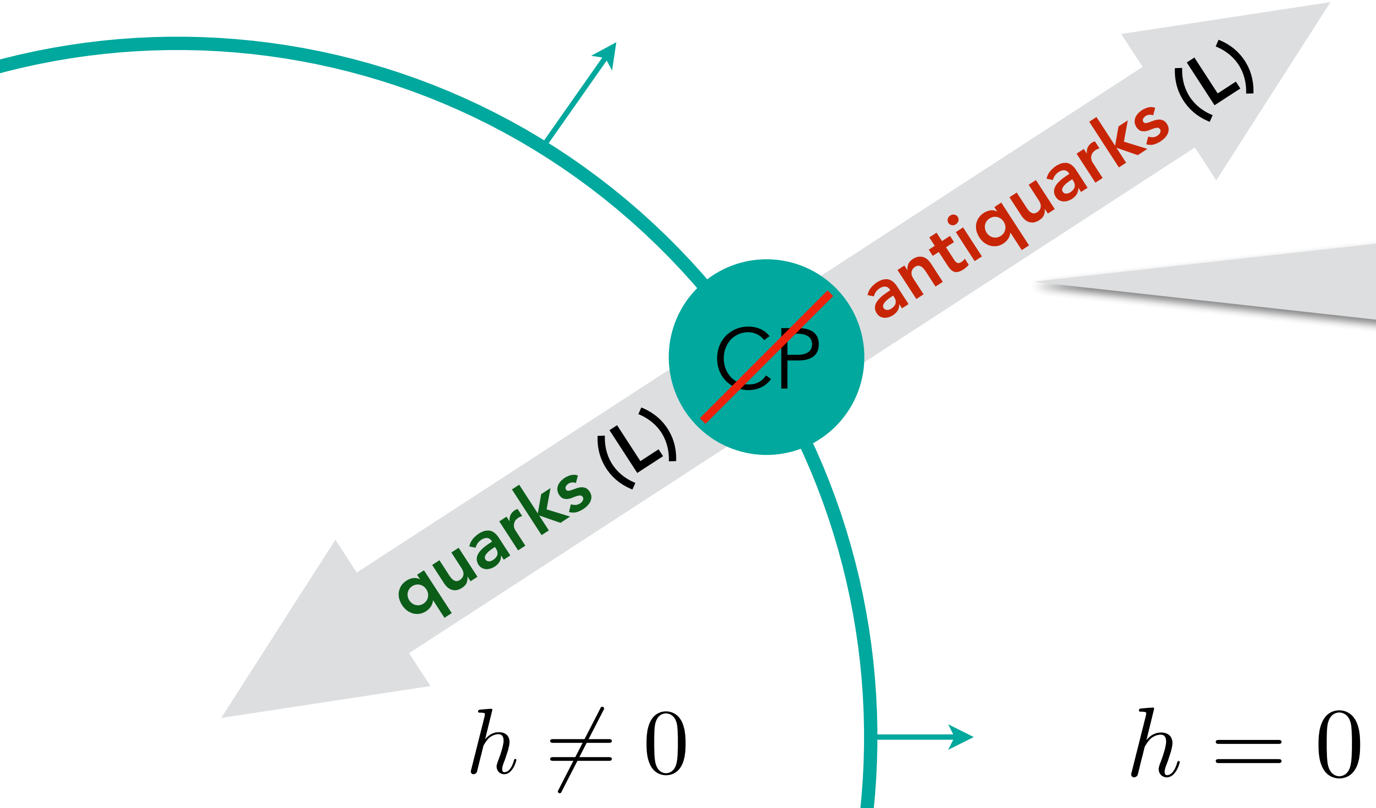

<u>EW sphalerons:</u>

rate $\sim \exp\left[-E_{\mathrm{sph}}/T\right] \sim \exp\left[-h/T\right]$

$\Rightarrow$ convert -B into L at $\mathbf{h/T < 1}$

Electroweak Baryogenesis

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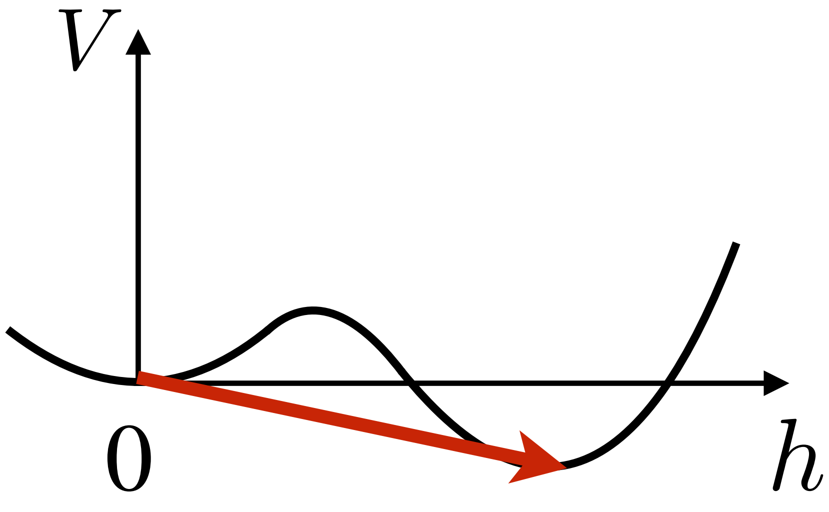
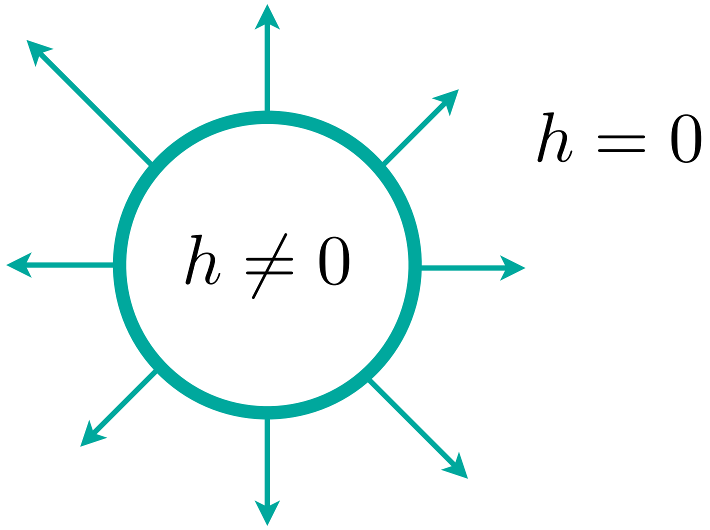


$\Longrightarrow$



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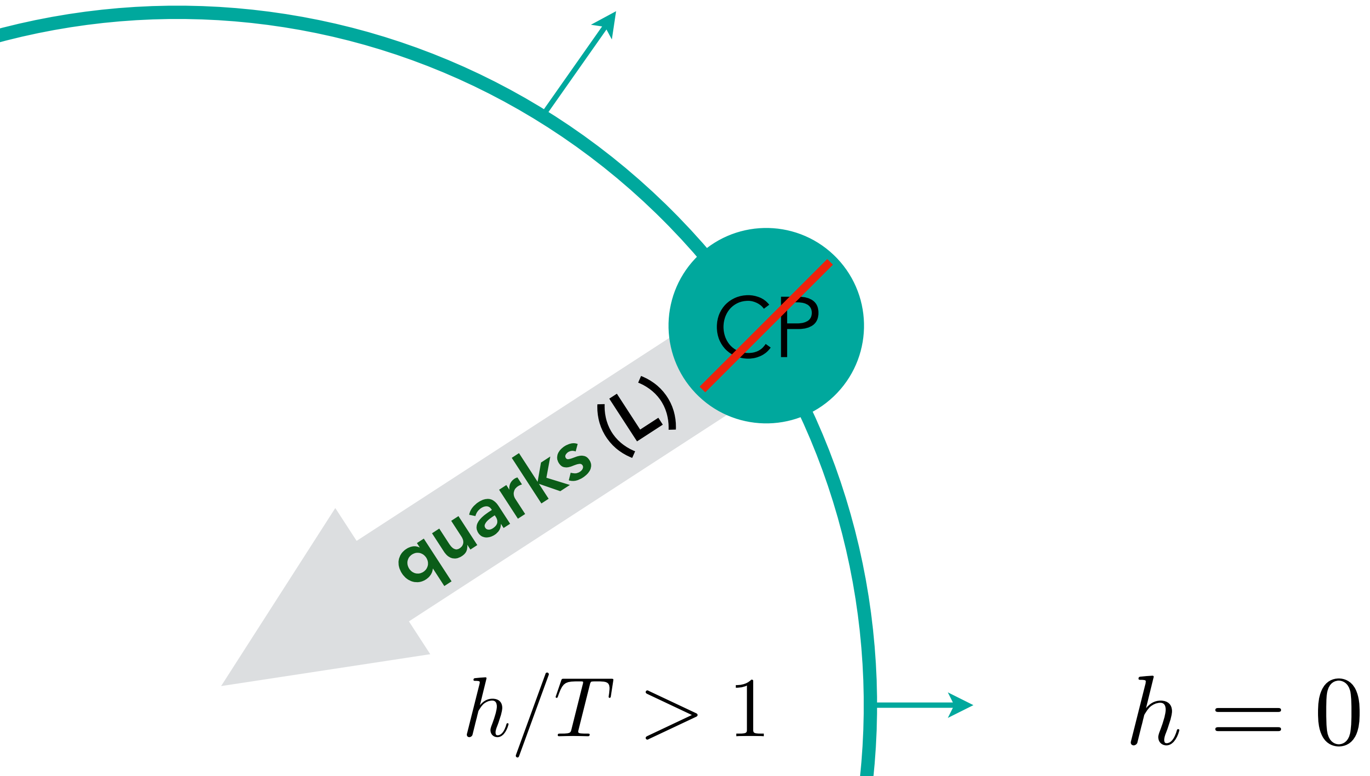

Electroweak Baryogenesis

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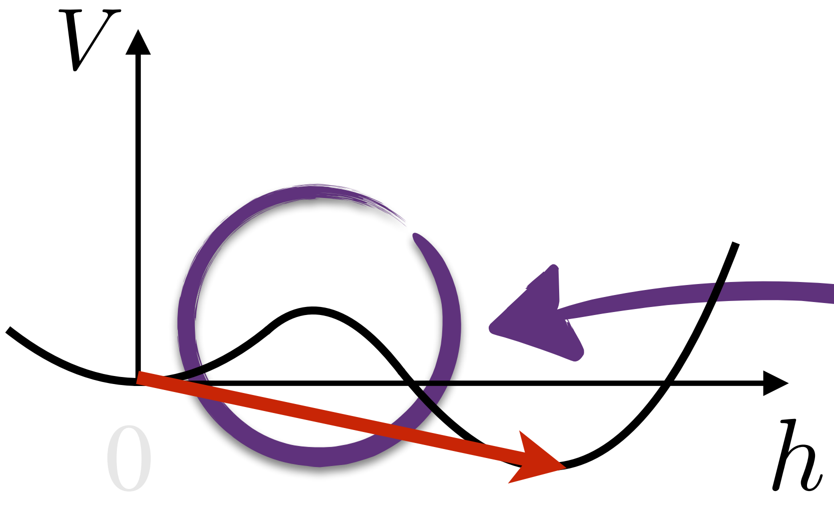

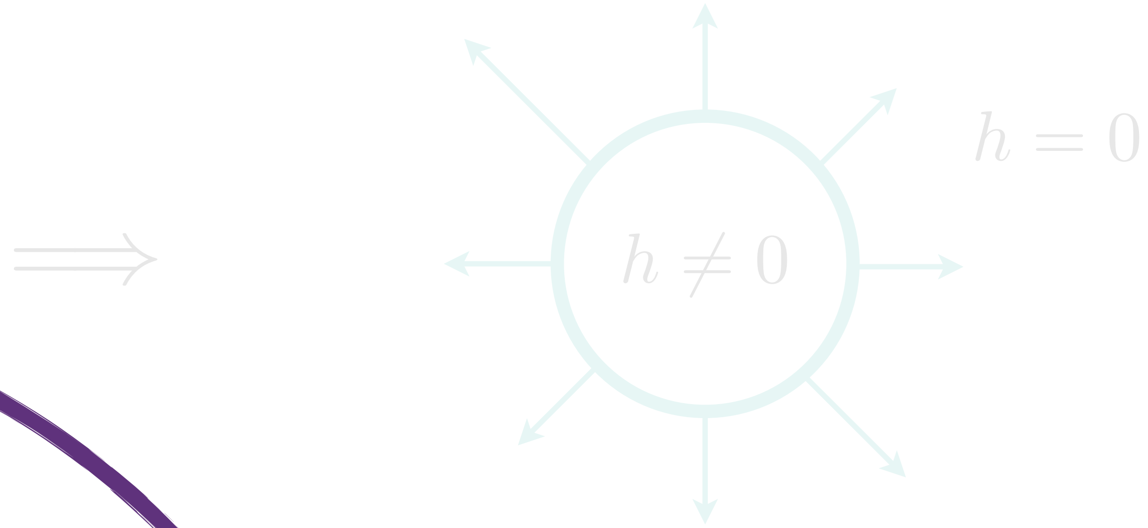

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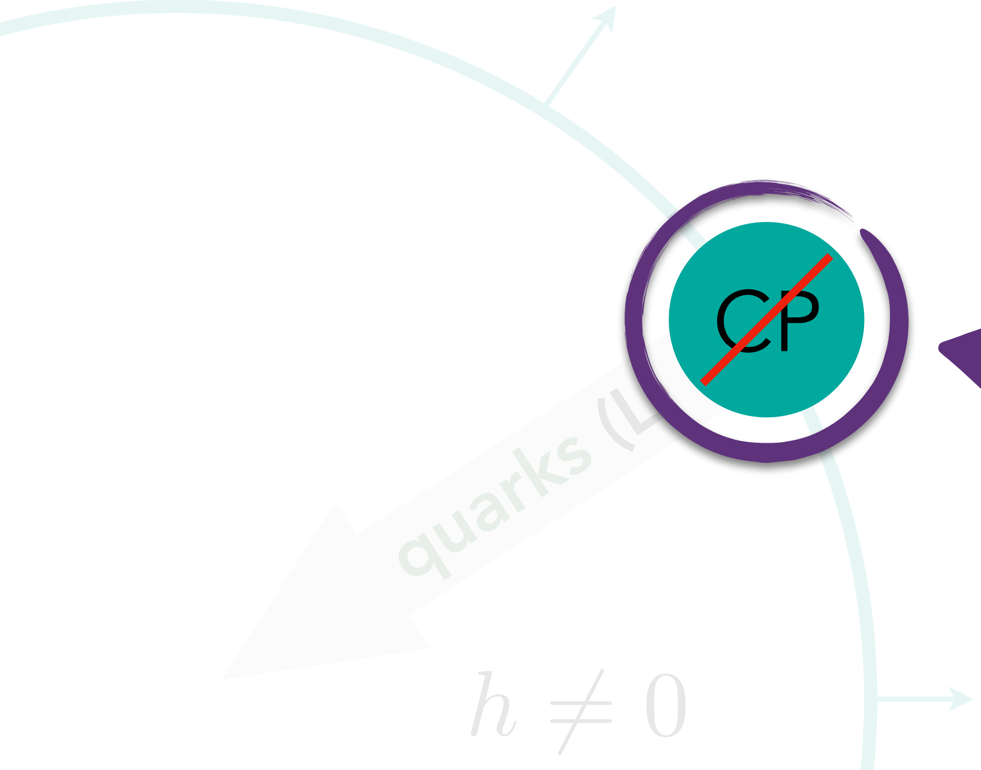
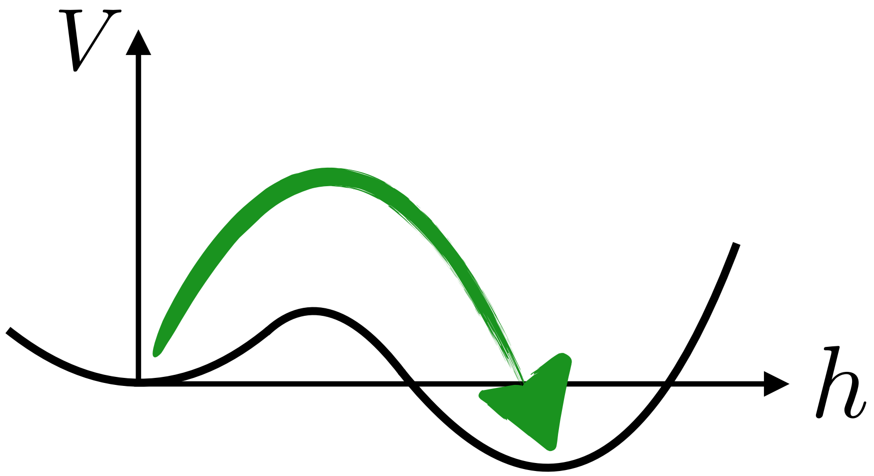


not provided by SM

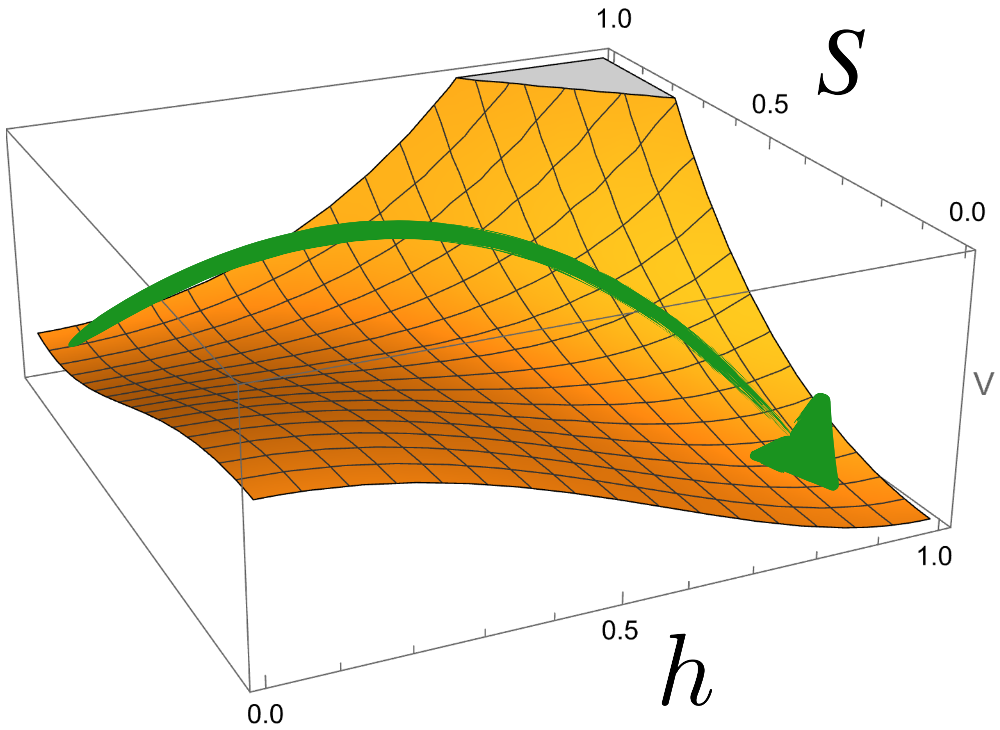
How to get first-order EWPT?

How to get first-order EWPT?

- New particles s.t. thermal/quantum corrections modify SM Higgs potential



- New field directions



The Minimal EWBG Model

SM + Singlet

$$V_{\rm tree}(h,S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$$

- Only an extremely small explicit $S \to -S$ breaking is needed to get B asymmetry and remove domain walls.

e.g. Espinosa et al, 1110.2876

- Consider the case with $S \to -S$ respected by the today's minimum

SM + Singlet

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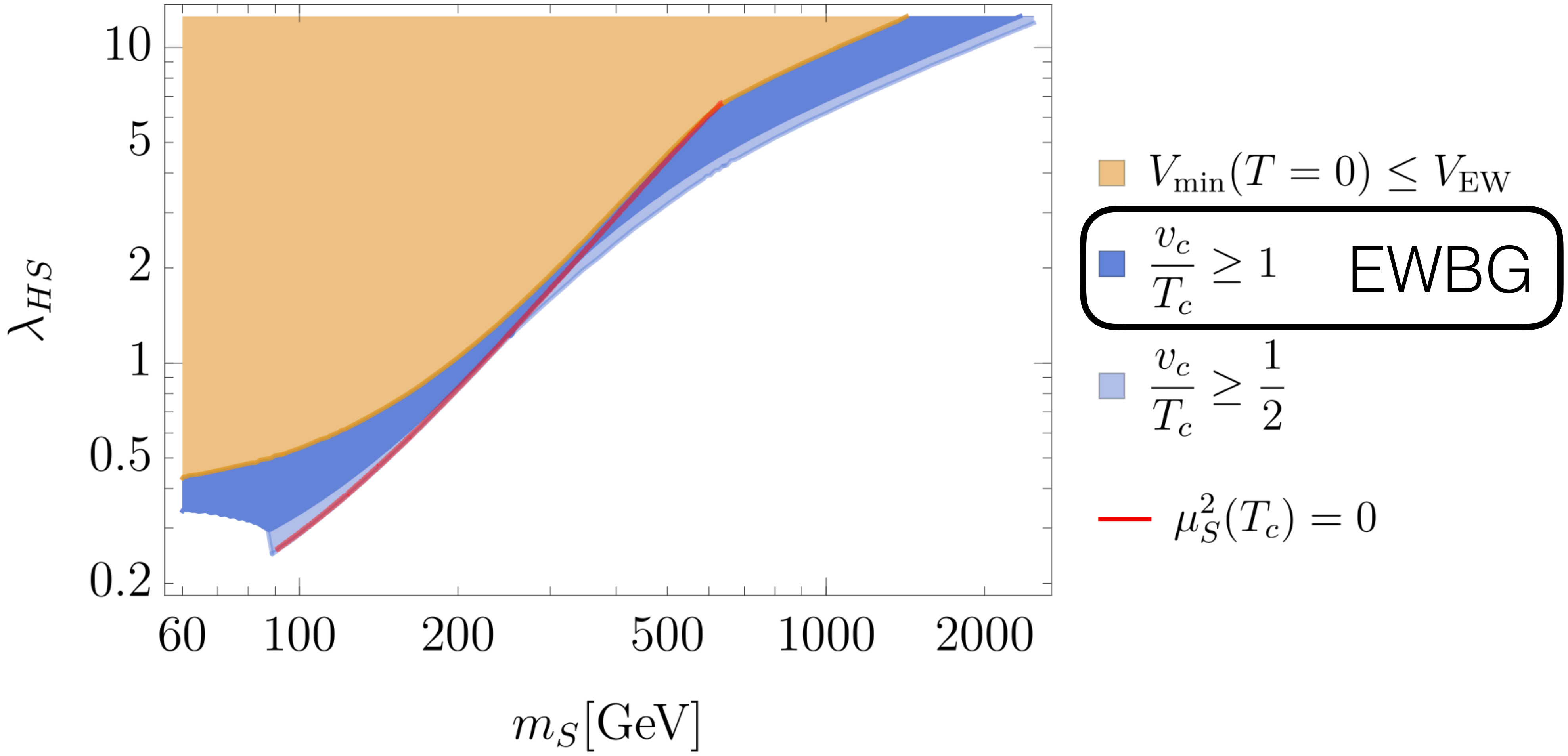

A.Benival et al, 1702.06124

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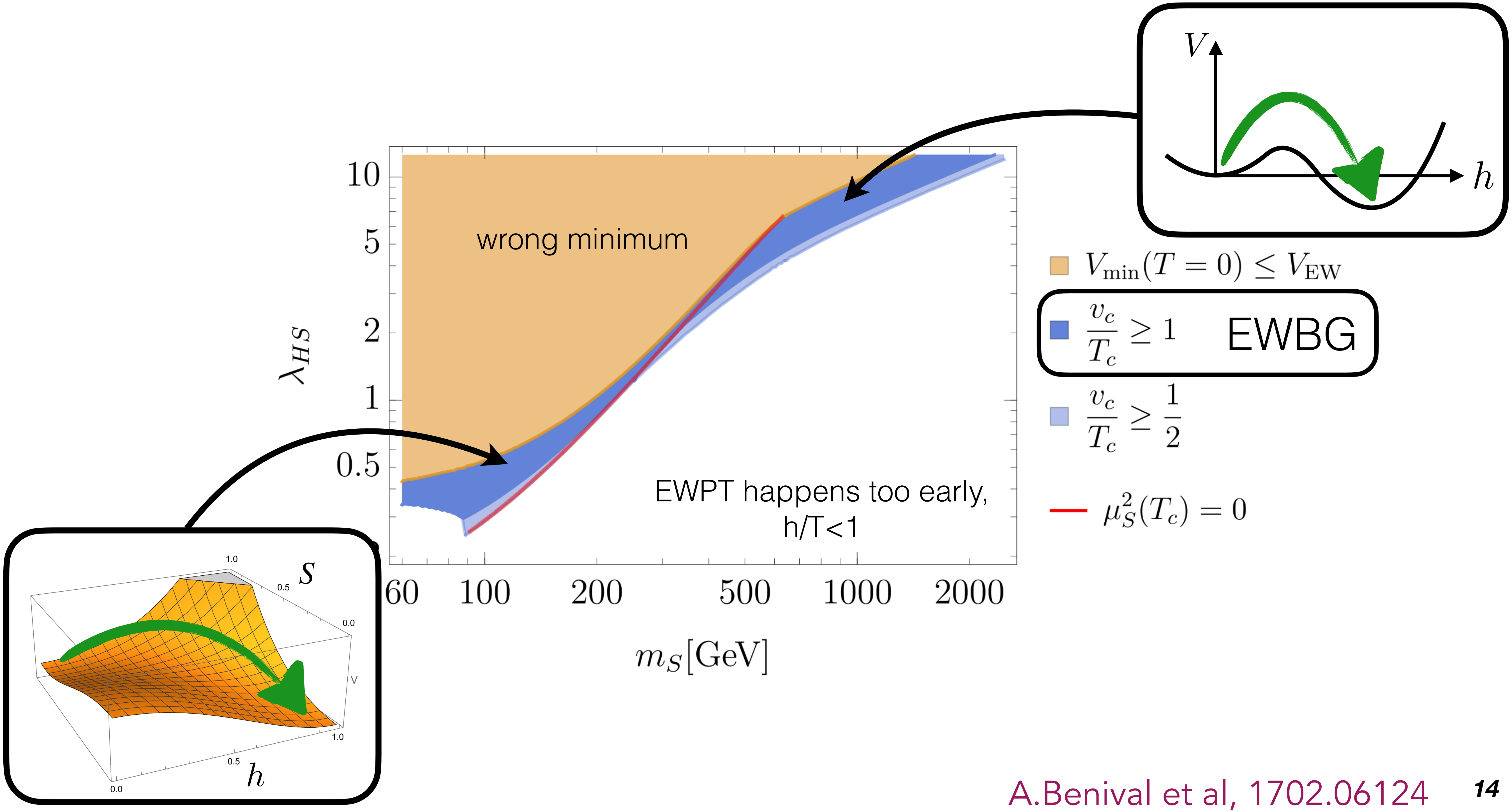

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SM + Singlet

Pheno: S-h mixing

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- $S \to -S$ symmetry:

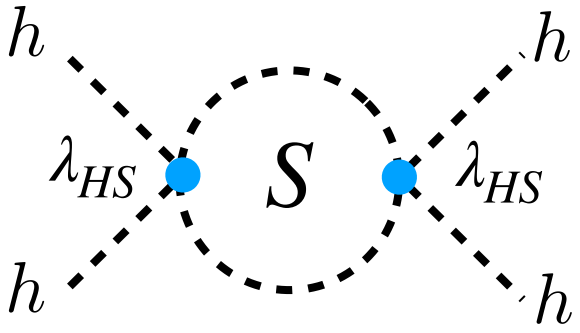
$\Rightarrow$ no sizeable Higgs-S mixing

$$\sin\theta \propto \lambda_{HS} \langle h \rangle \langle S \rangle$$

$\Rightarrow$ loop-induced effects of λ_{HS}

SM + Singlet

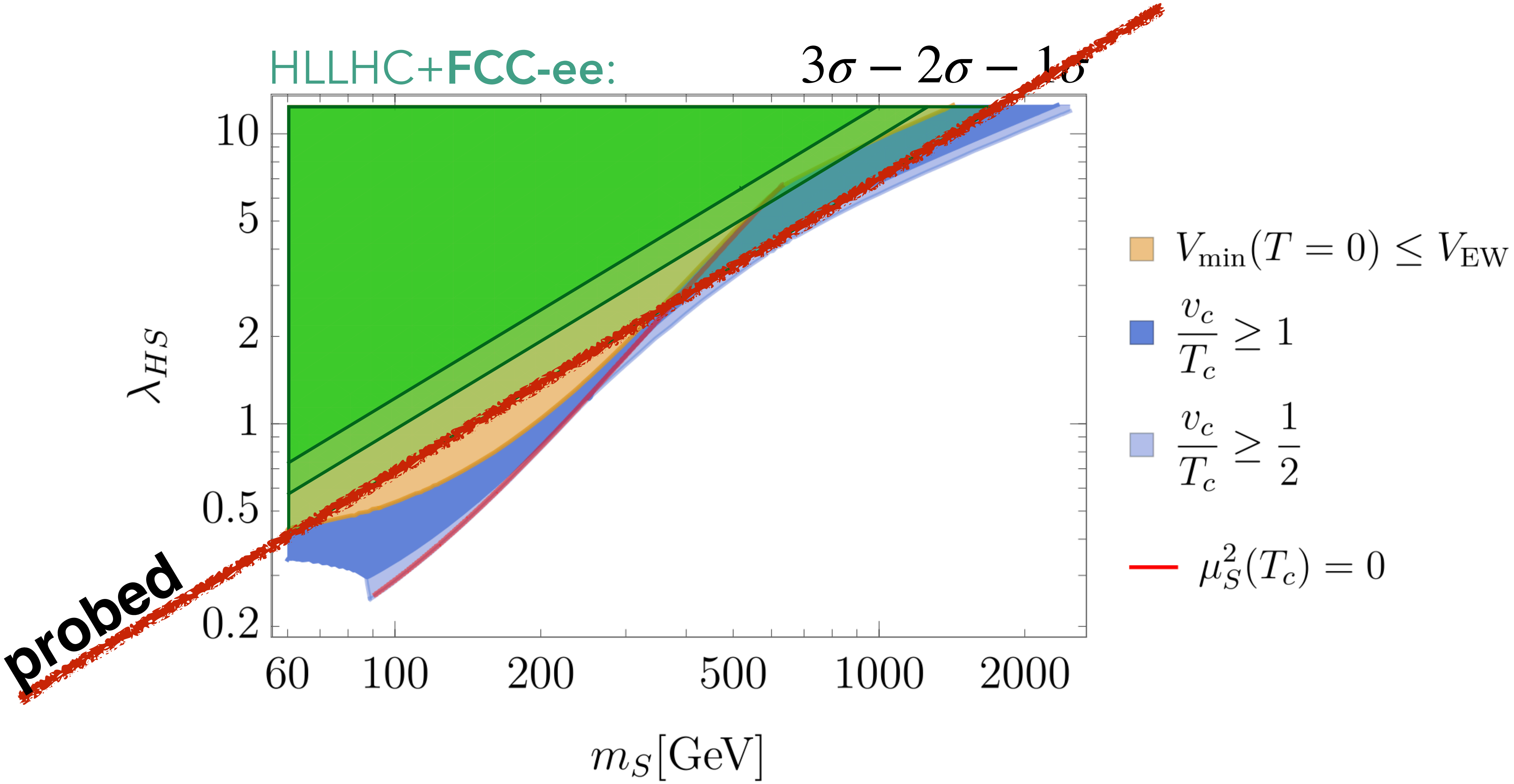
Pheno: c_H



$$\mathcal{O}_H = \frac{1}{2}(\partial_\mu |H|^2)^2$$

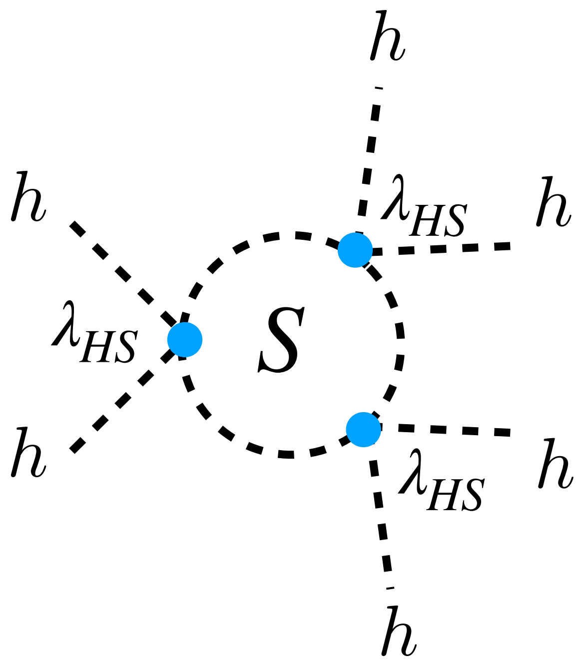
$$\frac{c_H}{\Lambda^2} = \frac{\lambda_{HS}^2}{48\pi^2}\frac{1}{m_S^2}$$

M.Carena et al, 2104.00638



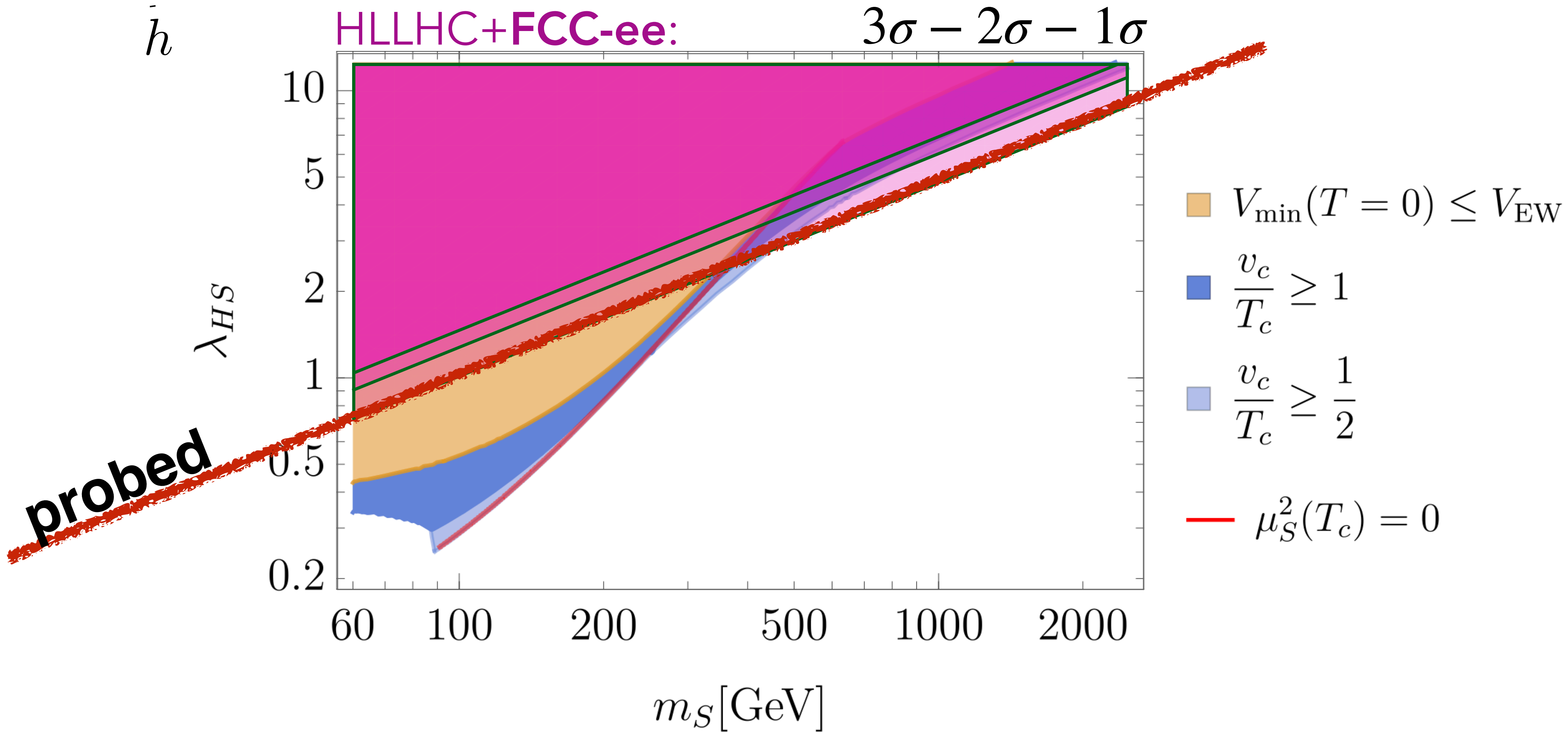
SM + Singlet

Pheno: h^3



$$\lambda_3 = \frac{1}{6}\frac{\partial^3 V(h,S=0,T=0)}{\partial h^3}\bigg|_{h=v_0} \approx \frac{m_h^2}{2v_0} + \frac{\lambda_{HS}^3 v_0^3}{24\pi^2 m_S^2}$$

A.Benival et al, 1702.06124



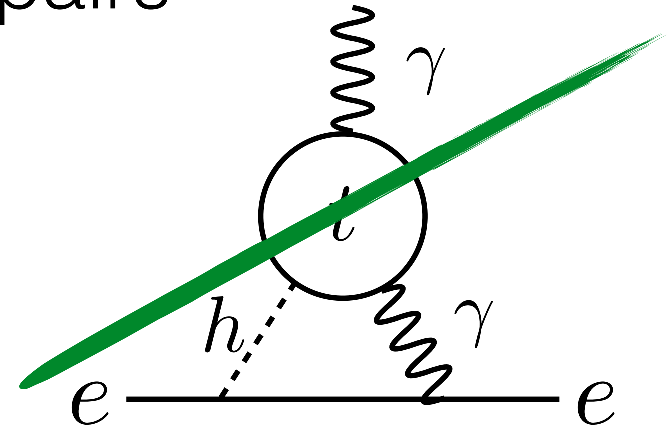
SM + Singlet: CPV

- CPV from varying top quark phase

$$\mathscr{L} \supset -y_t/\sqrt{2}\,\bar{t}th\left(1+iS/f\right)$$

$$\Rightarrow \quad S_{\rm CPV} \propto {\rm Im}\left[\underbrace{\left(\frac{\partial^2}{\partial z^2} m_t^\dagger\right)}_{\text{CPV when S varies}} m_t\right]$$

- For unbroken Z2 internal S always comes in pairs
  ⇒ protection from EDMs



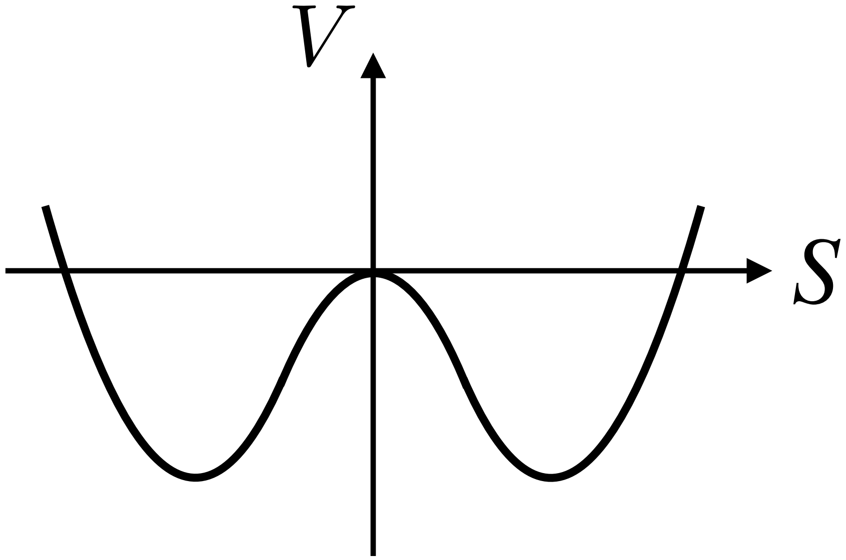
The Minimal
Defect-Mediated EWBG Model

SM + Singlet: EWBG on Defects

J.Azzola,OM,A.Weiler
work in progress

see also talk by M.Younes Sassi

discrete symmetry of vacuum manifold



$$S = v_S \tanh \frac{m_S z}{2}$$

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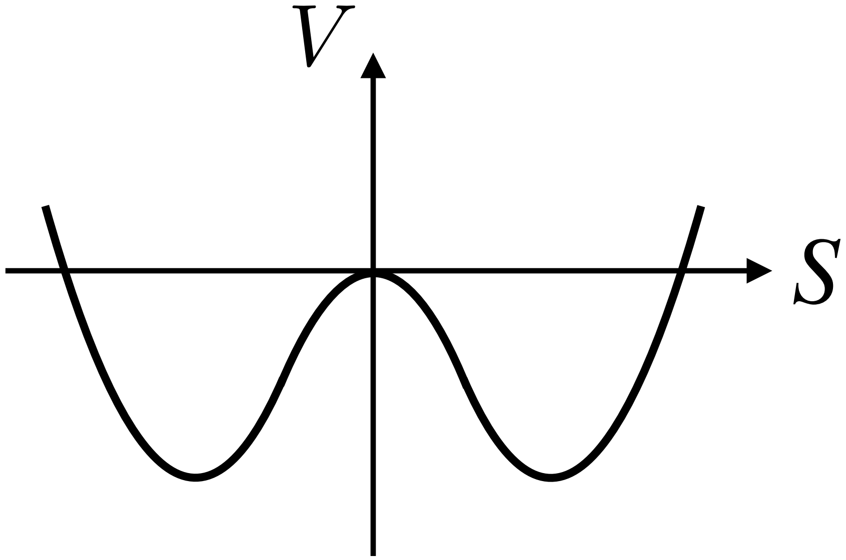
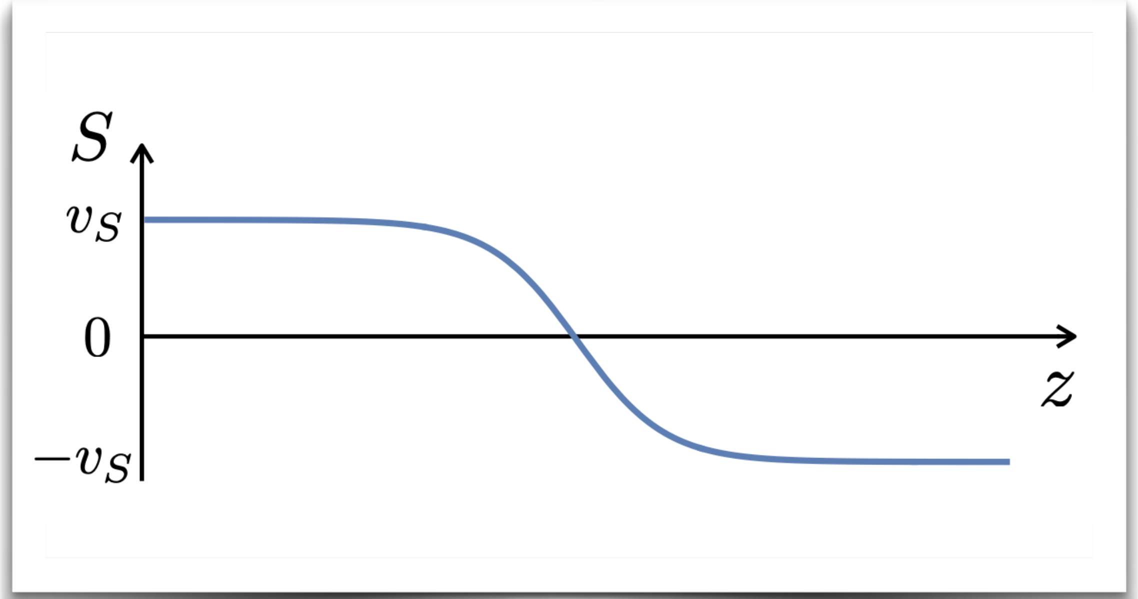


$\Rightarrow$



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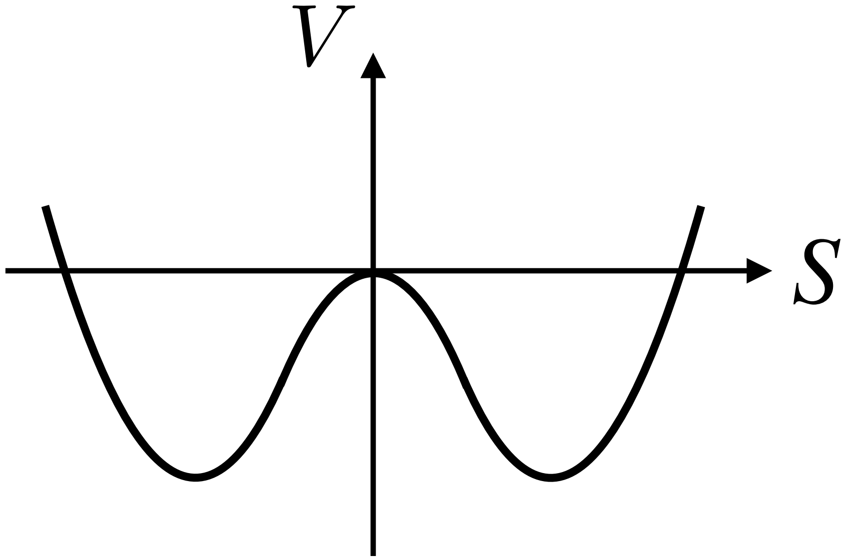

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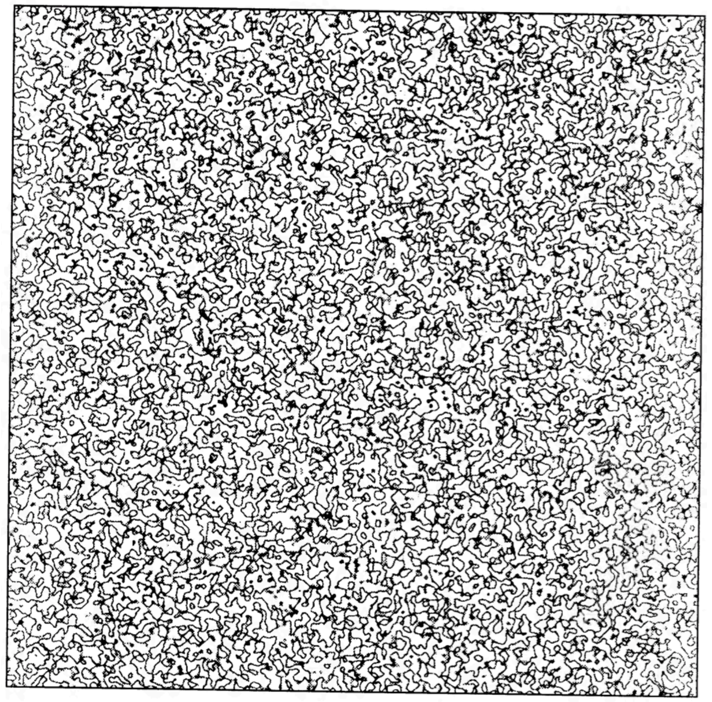
$\Rightarrow$

domain walls can be formed

in Z2 breaking phase transition



Press,Ryden,Spergel,
Astrophys.J. 347 (1989)

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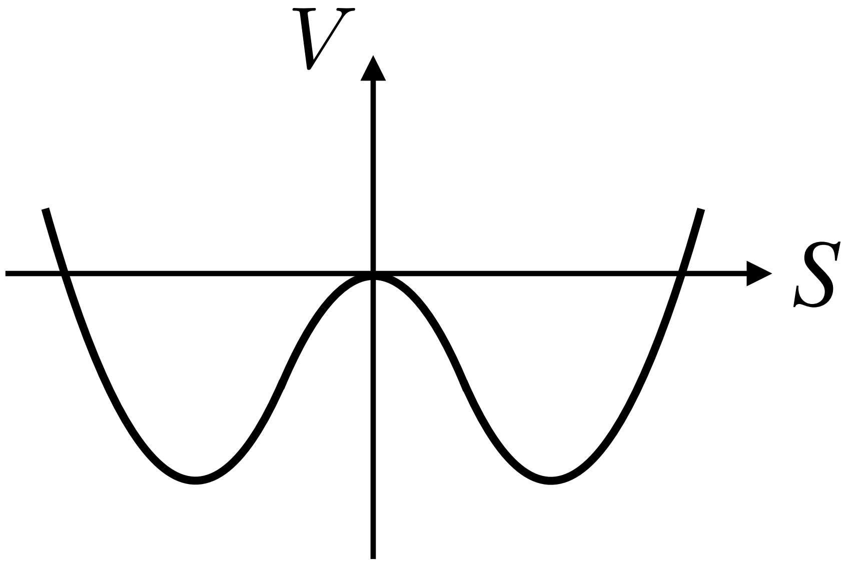

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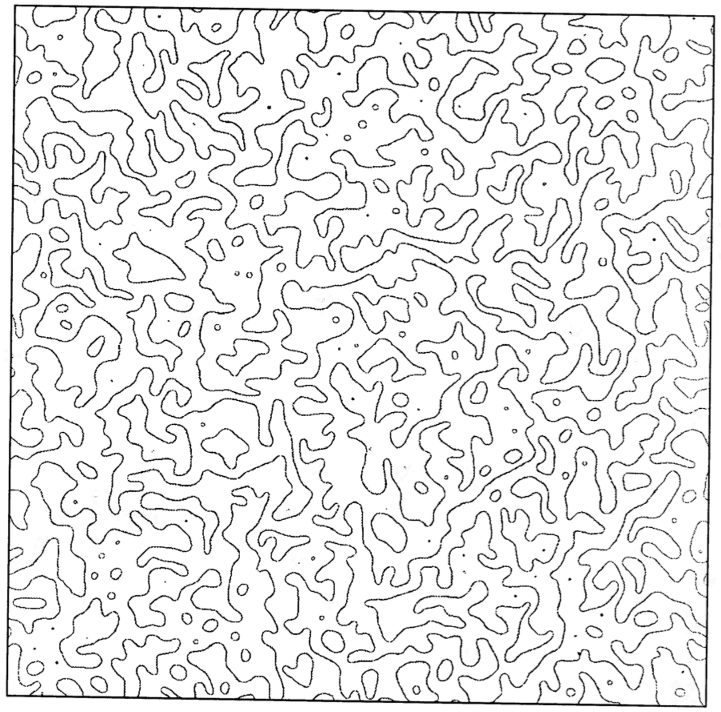

Press,Ryden,Spergel, Astrophys.J. 347 (1989)

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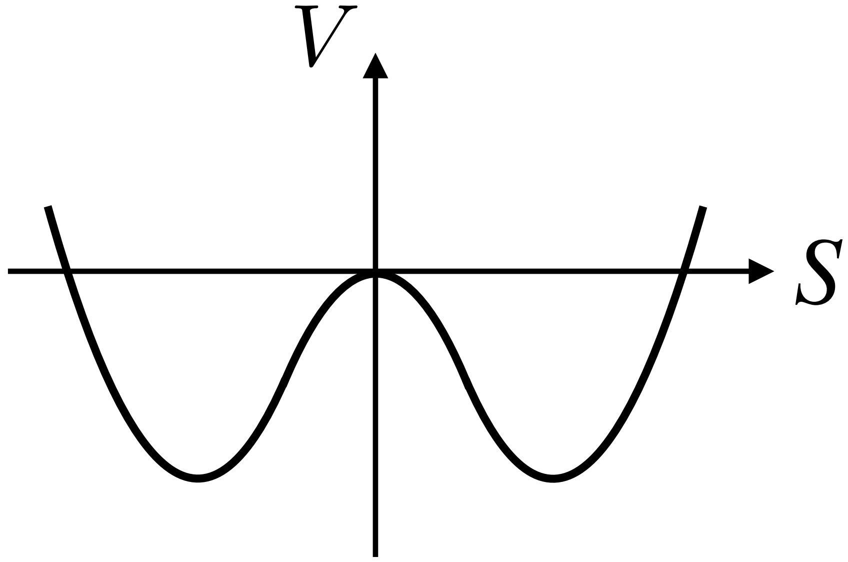

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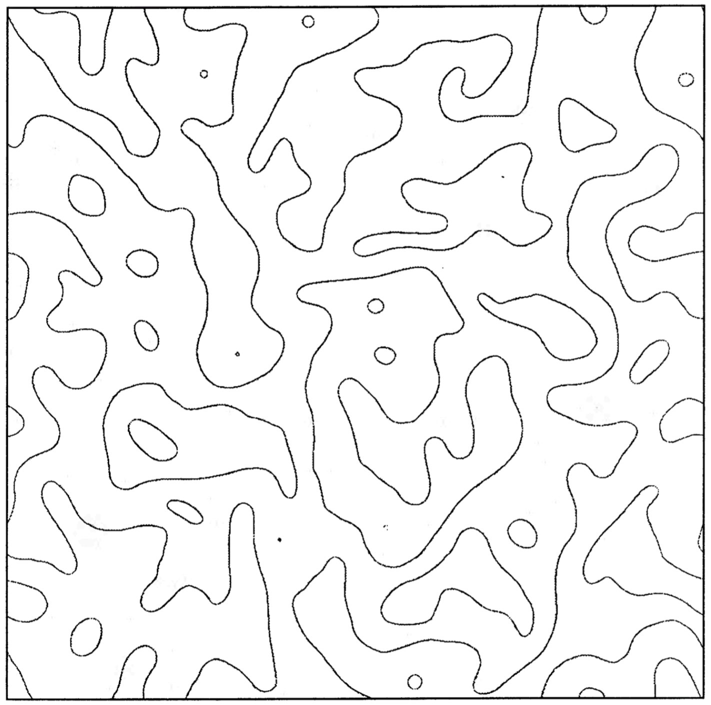
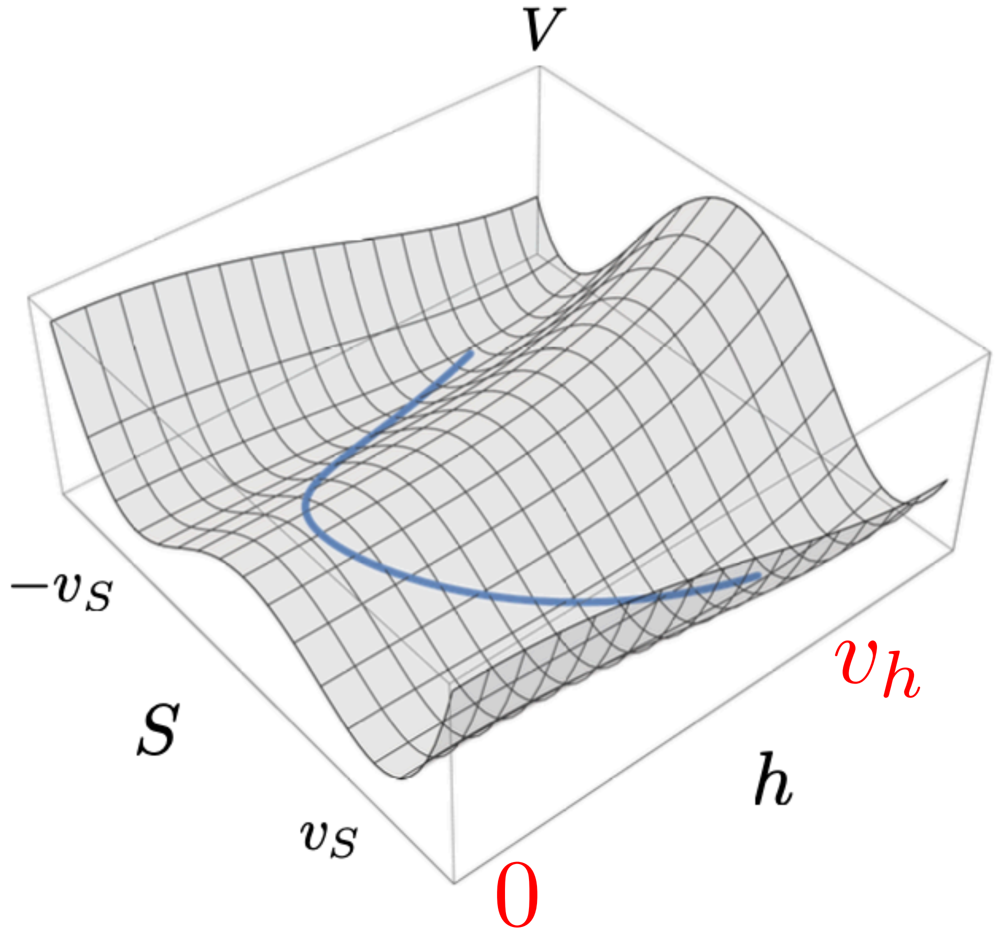


Press,Ryden,Spergel, Astrophys.J. 347 (1989)

SM + Singlet: EWBG on Defects

- h-S trajectory curved towards h=0

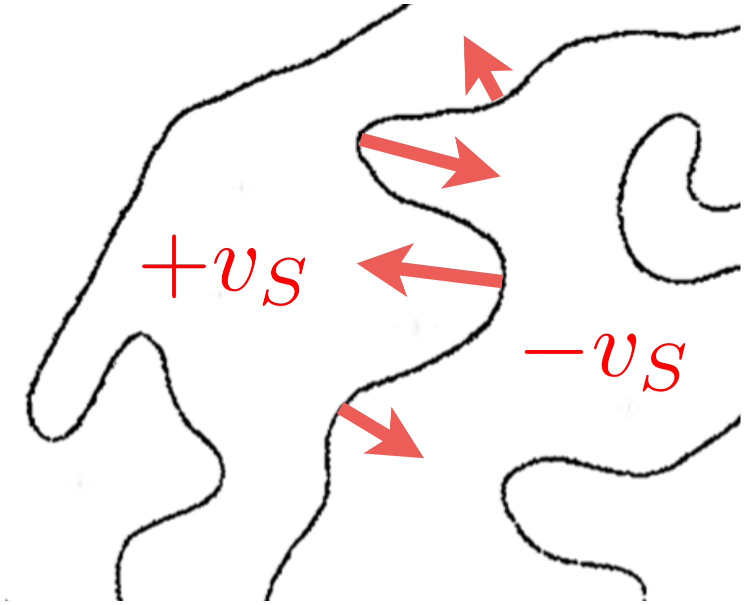
$$\mathscr{L} \supset -\frac{1}{2}|\lambda_{HS}||H|^2 S^2$$



SM + Singlet: EWBG on Defects

- CPV similar to the minimal EWBG

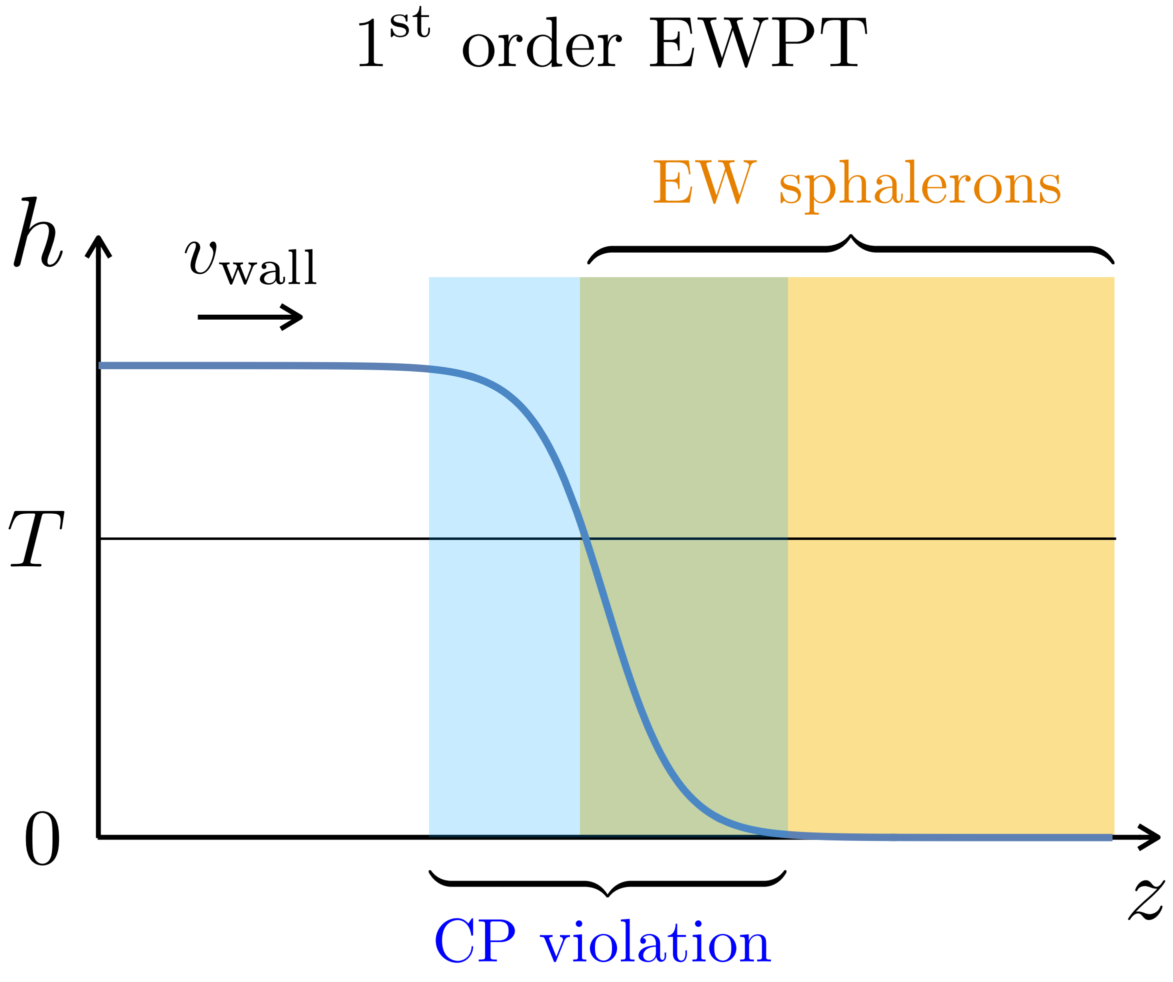
$$\mathscr{L} \supset - y_t/\sqrt{2}\, \bar{t}th\, (1 + \underbrace{i\, S^2/f^2}_{\text{insensitive to S sign}})$$

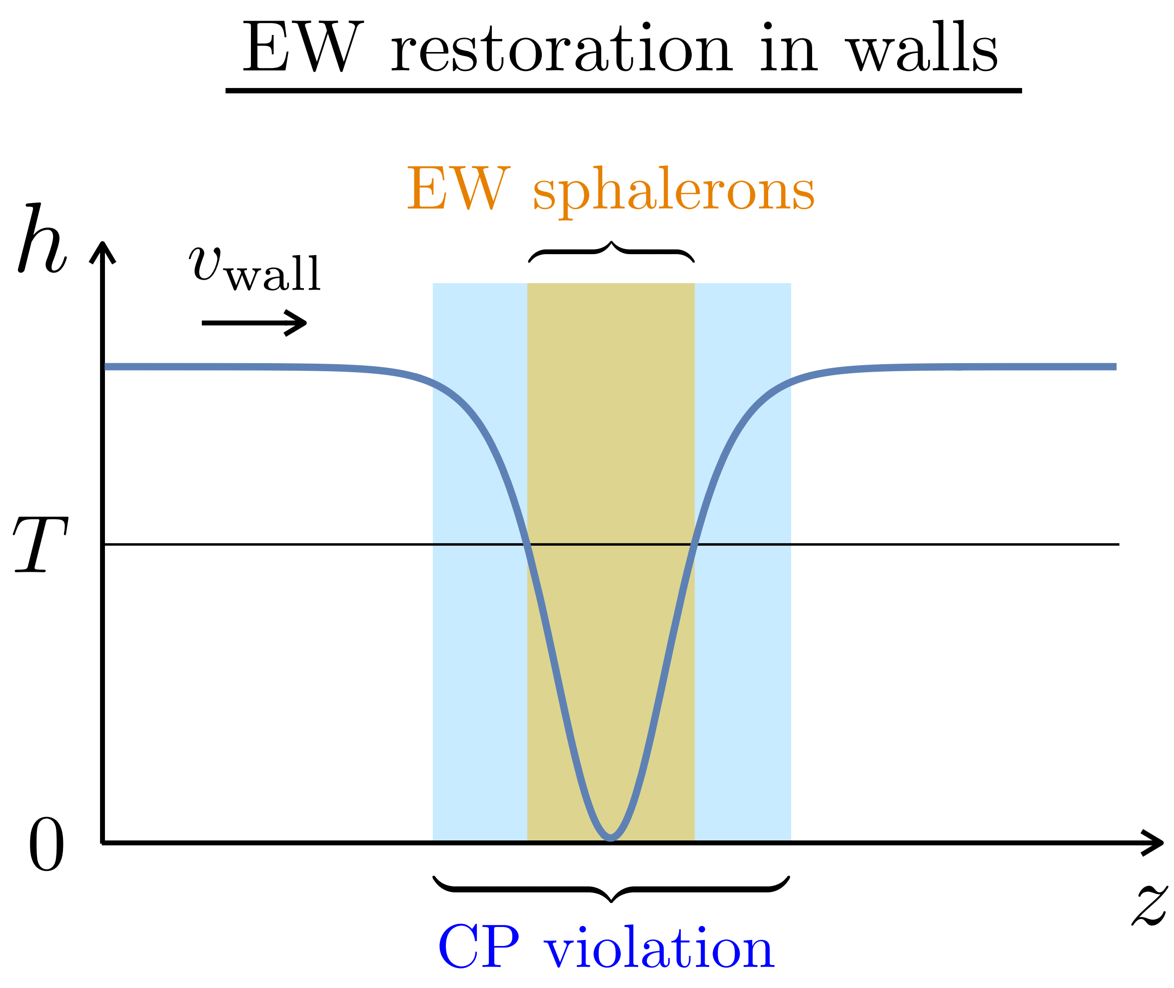


* domain walls in the scaling regime have an appropriate velocity for EWBG

SM + Singlet: EWBG on Defects

Brandenberger, Davis, Prokopec, Trodden
Phys. Rev. D 53 (1996) 4257–4266

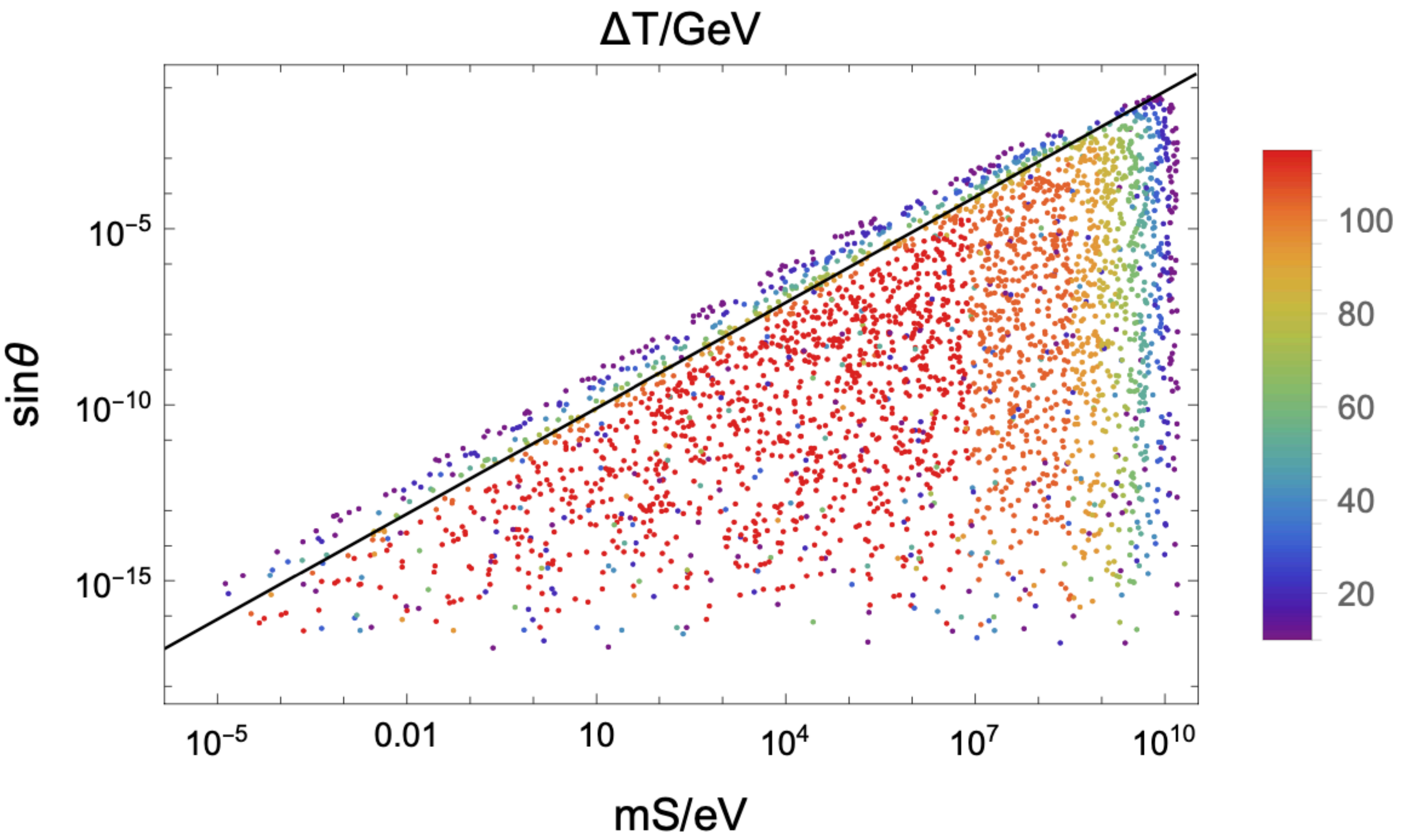




SM + Singlet: EWBG on Defects

[preliminary]

J.Azzola,OM,A.Weiler
work in progress



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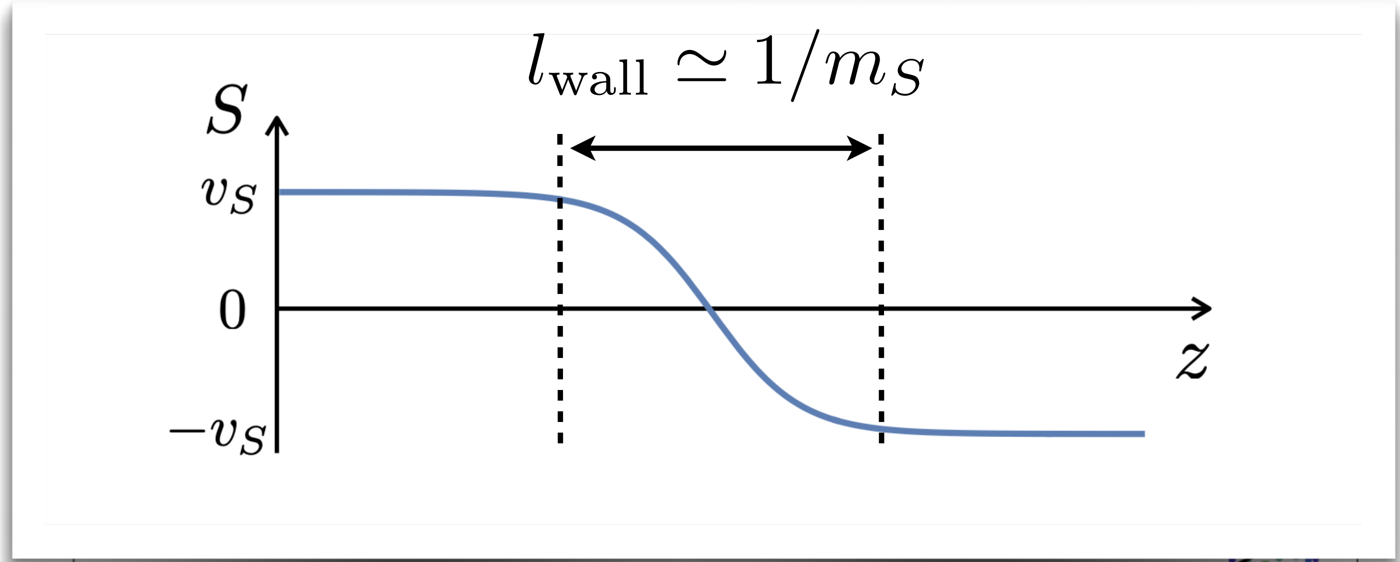

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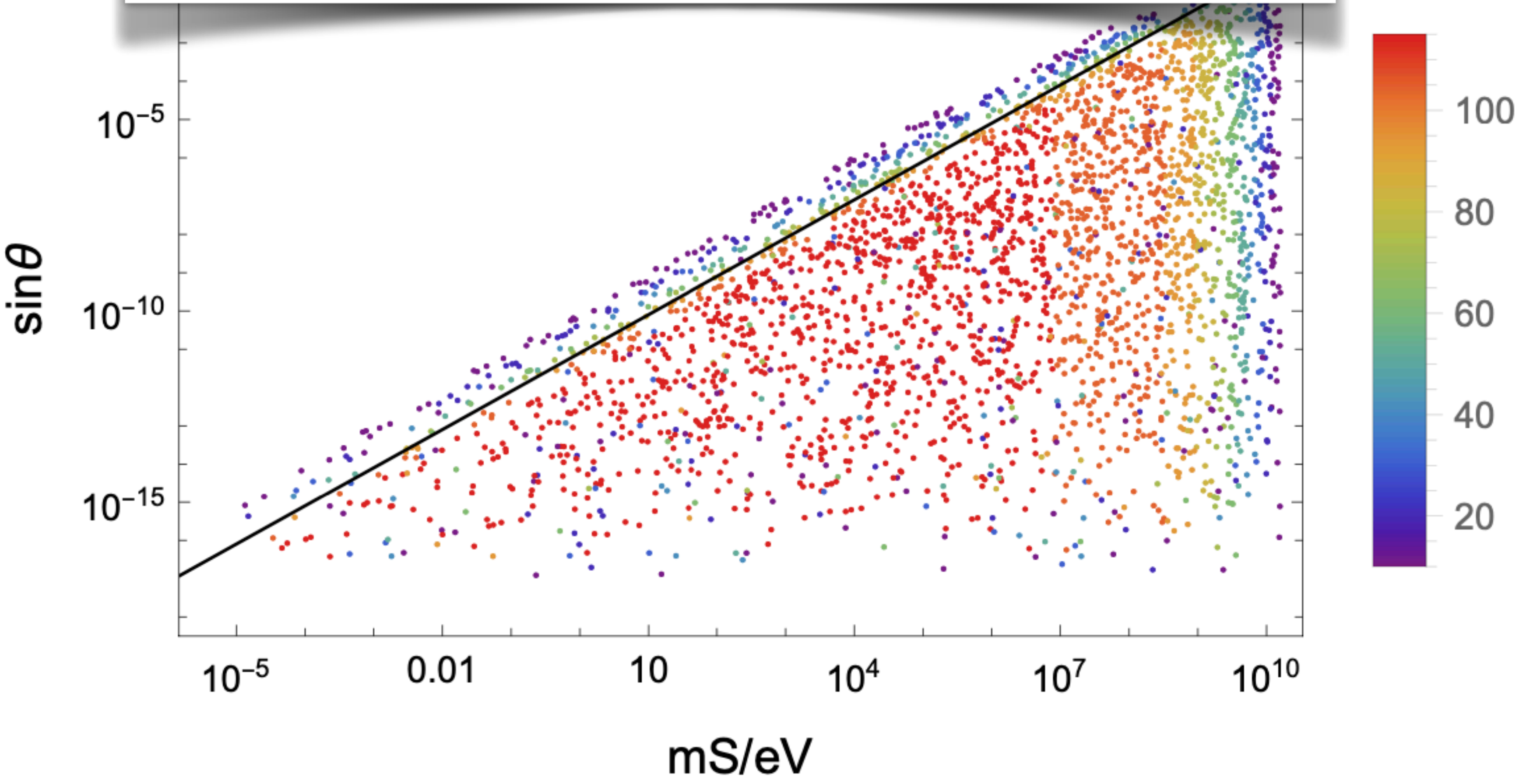

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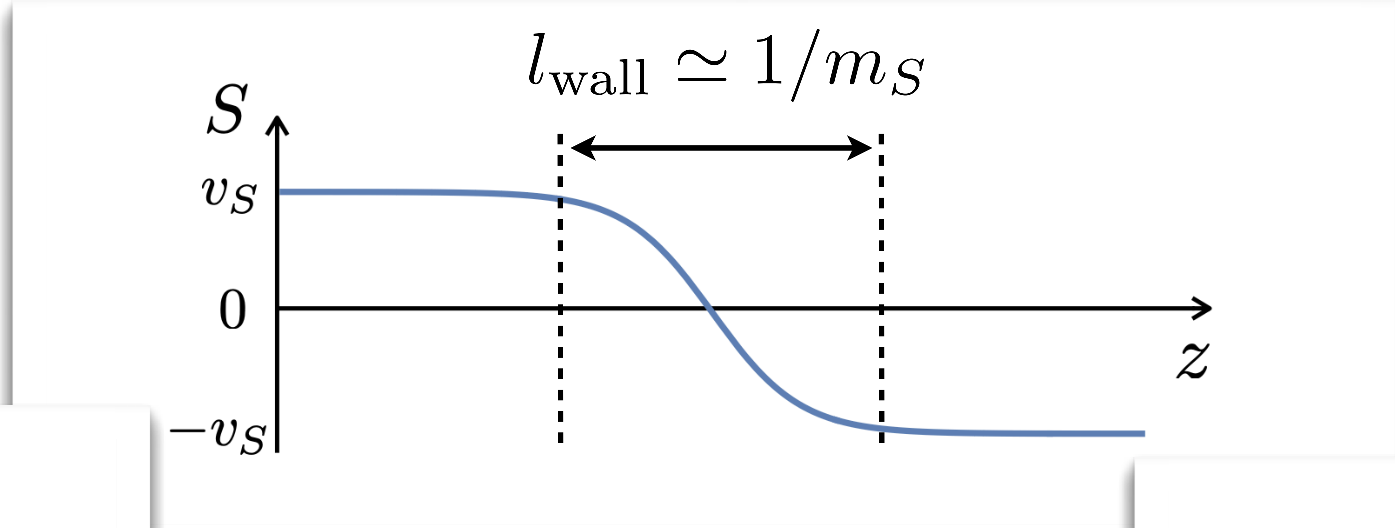
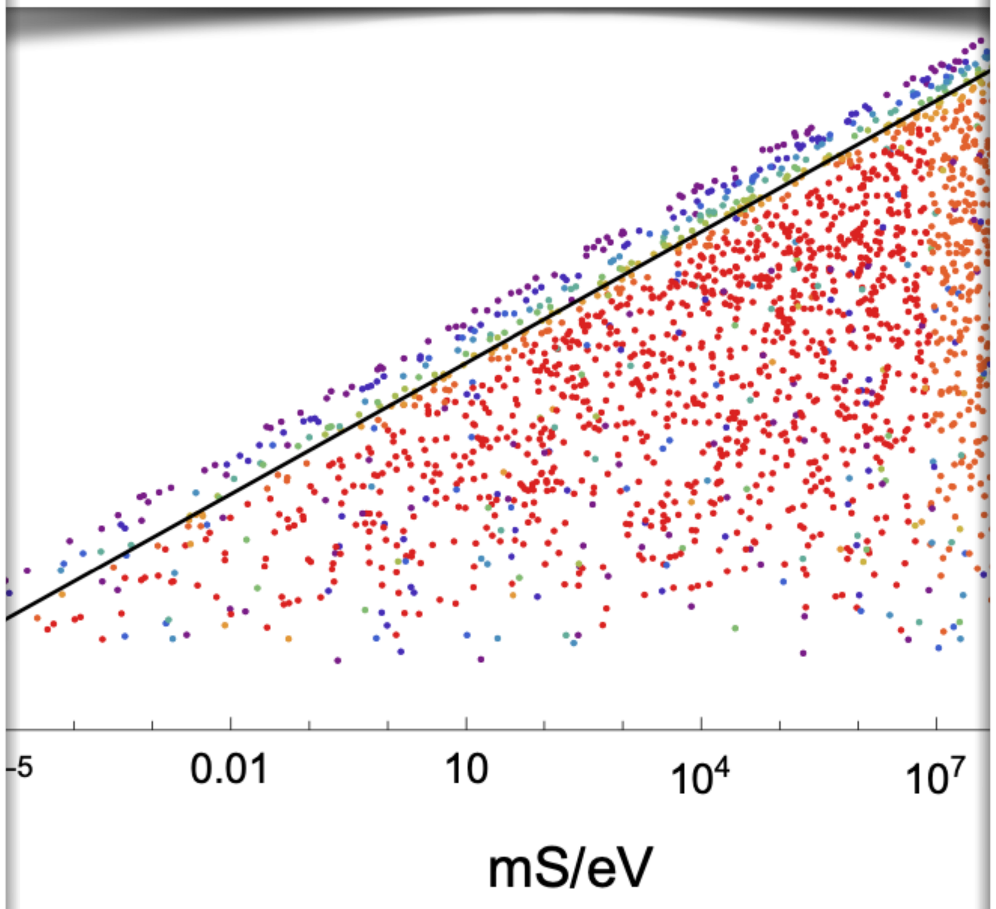


J.Azzola,OM,A.Weiler
work in progress

$m_S < H$

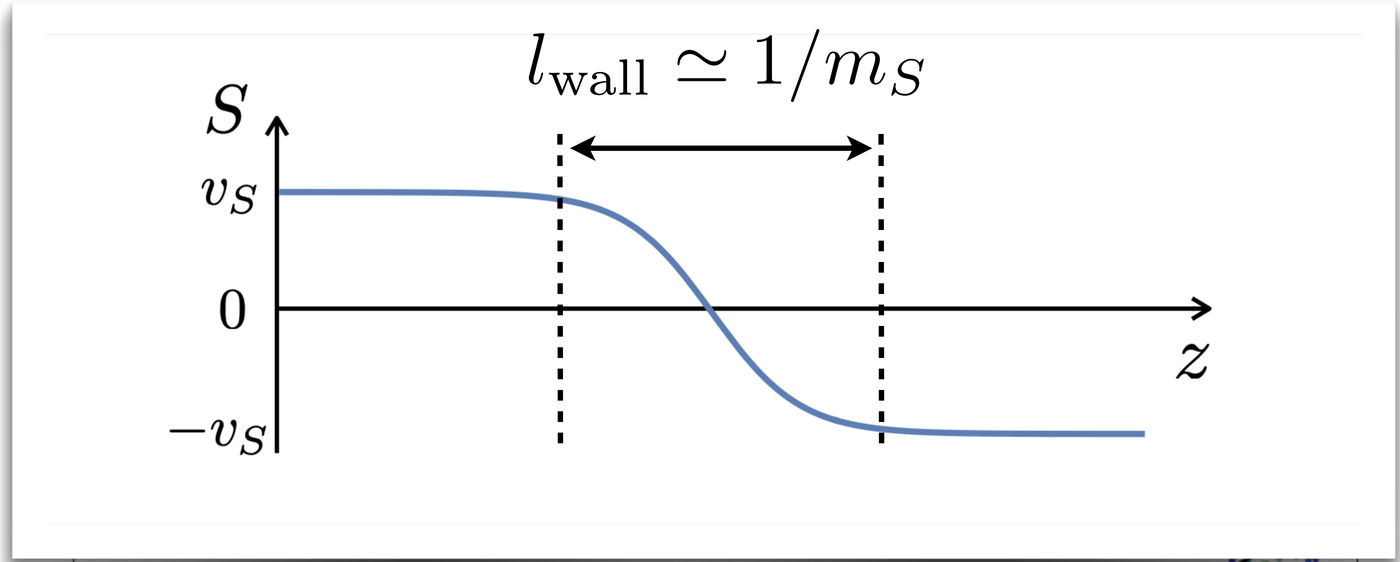
- no walls to talk about
- S is frozen because of Hubble friction



$l_{\text{wall}} < l_{\text{sphaleron}}$

- walls are too thin to allow for efficient production of B
- $l_{\text{sphaleron}} \sim \left(\frac{g^2}{4\pi} T\right)^{-1}$

SM + Singlet: EWBG on Defects



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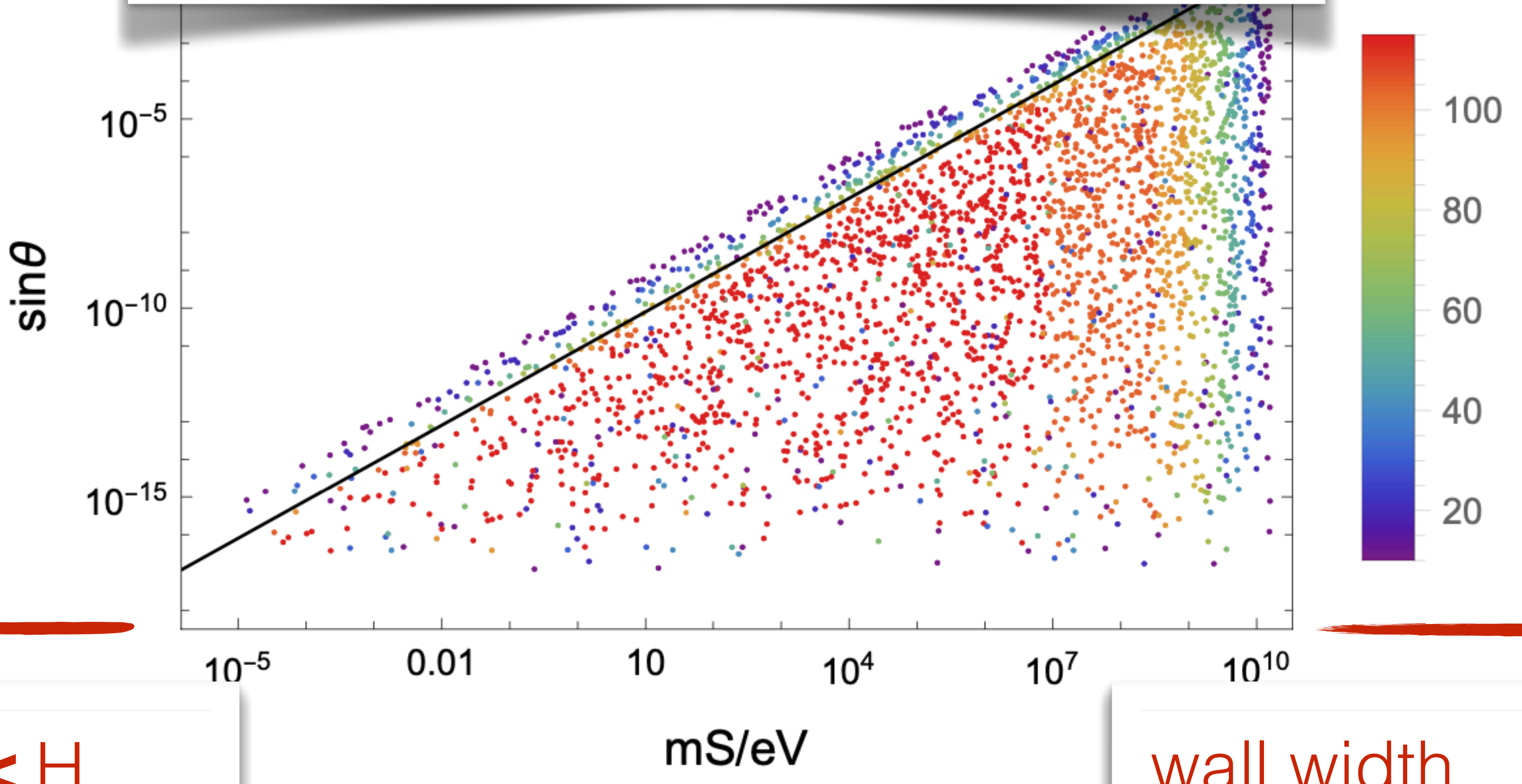

mS < H
@ T=100 GeV

wall width
~ 1/mS
<
EW
sphaleron

SM + Singlet: EWBG on Defects

J.Azzola,OM,A.Weiler
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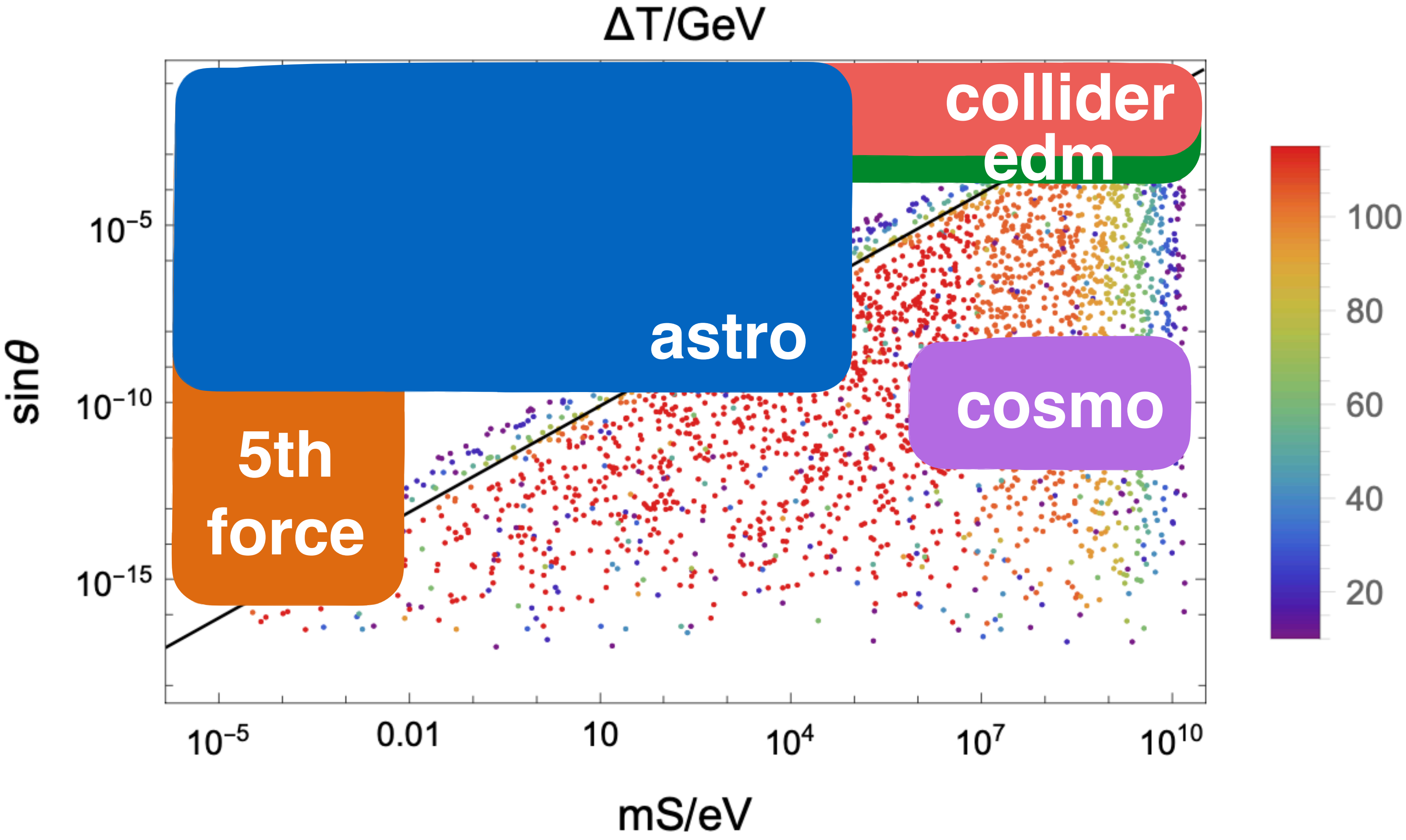
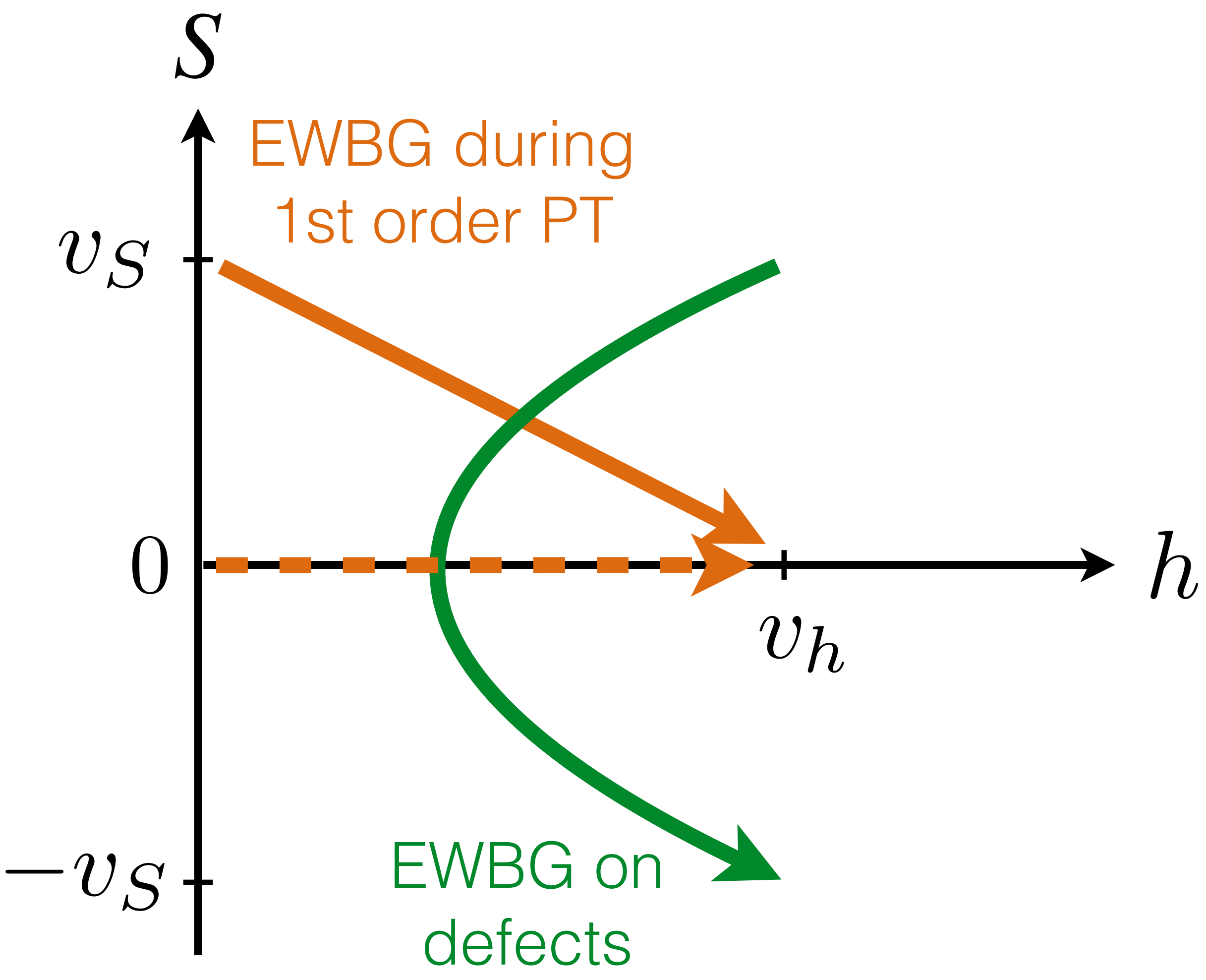


a wide range of experimental probes

SM + Singlet: Summary



Further Models

Where and Why to Extend?

- The nature doesn’t have to be minimal, and if it is, the question of minimality depends on the perspective and sometimes needs more information than we have.

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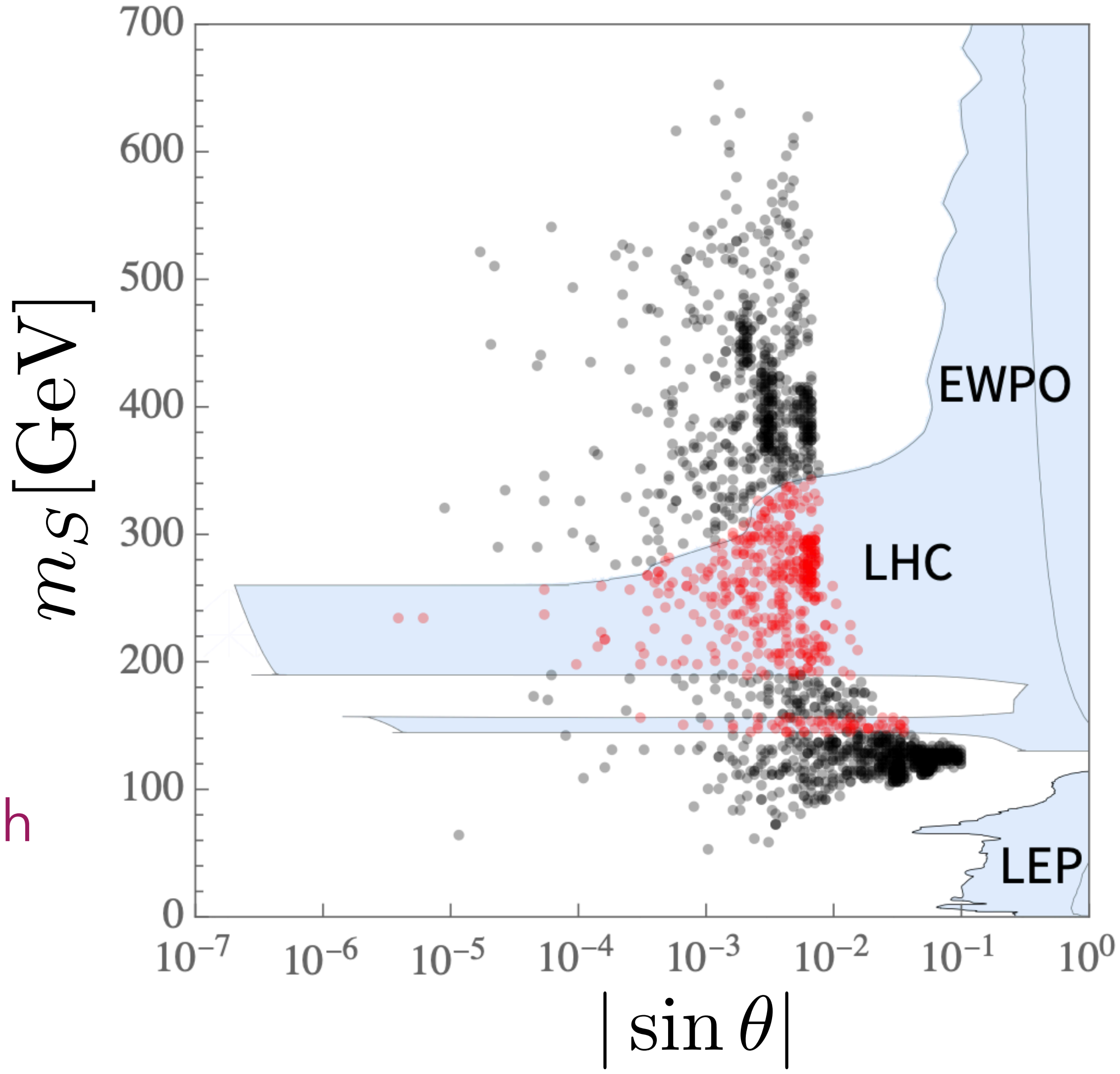
  - sizeable Z_2 breaking



J Ellis, M Lewicki, M Merchand, J M No, M Zych
2210.16305

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- EWBG models can be arbitrarily more complex:
  - sizeable Z_2 breaking
  - extra EW multiplets (2HDM, …)
  - shift part of EWBG to the dark sectors
  - embedding in more "complete" models

Where and Why to Extend?

- If there is anything at a scale very close to the EW scale, it's tempting to assume that there is some fundamental reason for that.

  Such as EW scale Naturalness.

  Note that even the "Minimal EWBG" requires higher-dimensional operators to get CPV, such as

  $$\mathscr{L} \supset -y_t/\sqrt{2}\,\bar{t}th\left(1+i\,S/f\right)$$

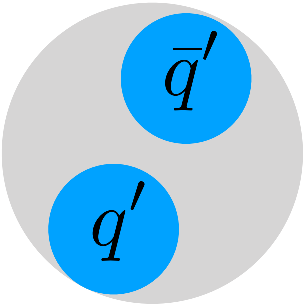
  with yet another physics scale f (on top of mS) not far from EW scale.

EWBG with Composite Higgs

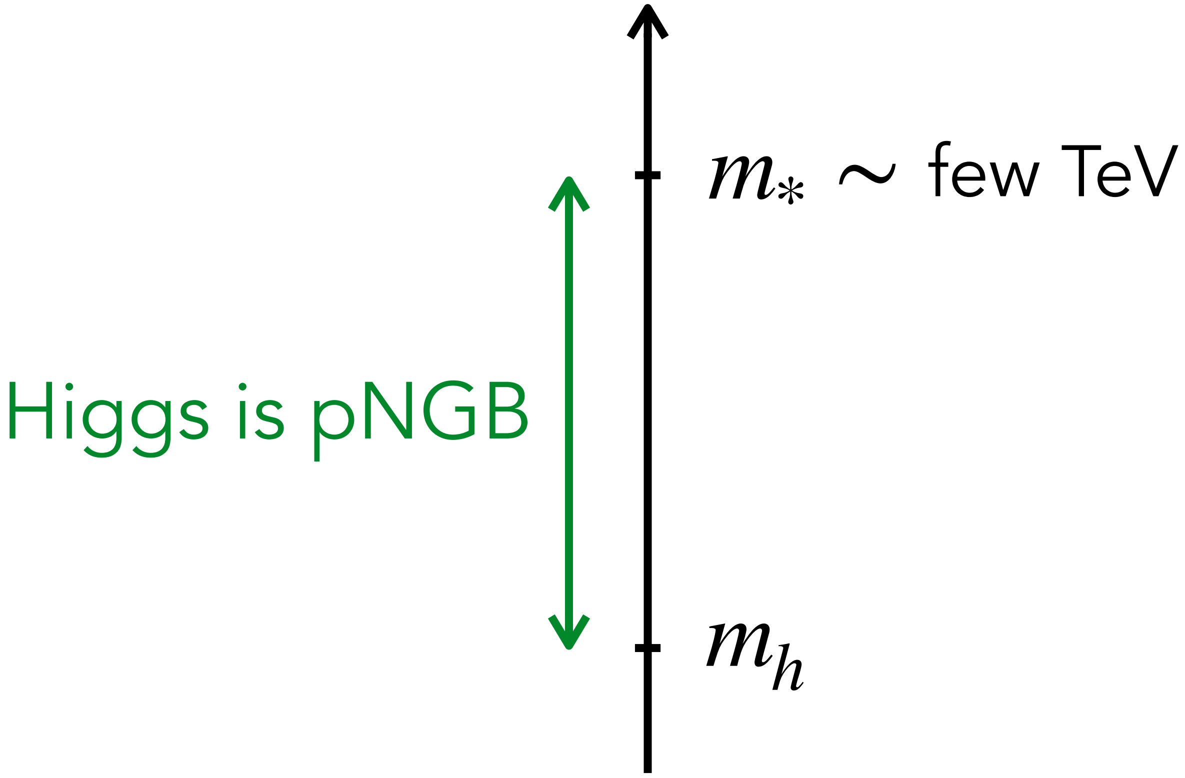
Composite Higgs

- Higgs is a bound state of new strong interactions confining at $f \sim 1\text{TeV}$

$h =$



spectrum:



$m_* \sim$ few TeV

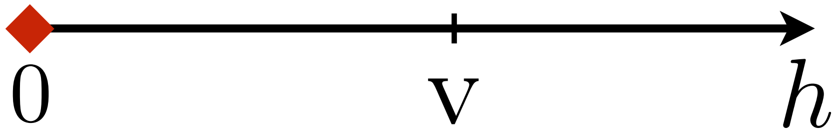
Higgs is pNGB

m_h

Kaplan,Georgi '84

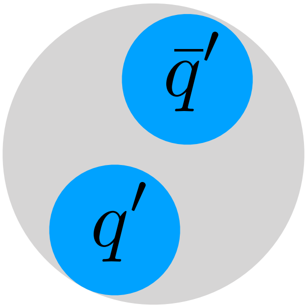
Agashe,Contino,Pomarol '04

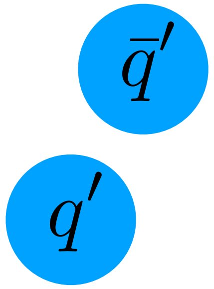
Phase Transitions in CH models

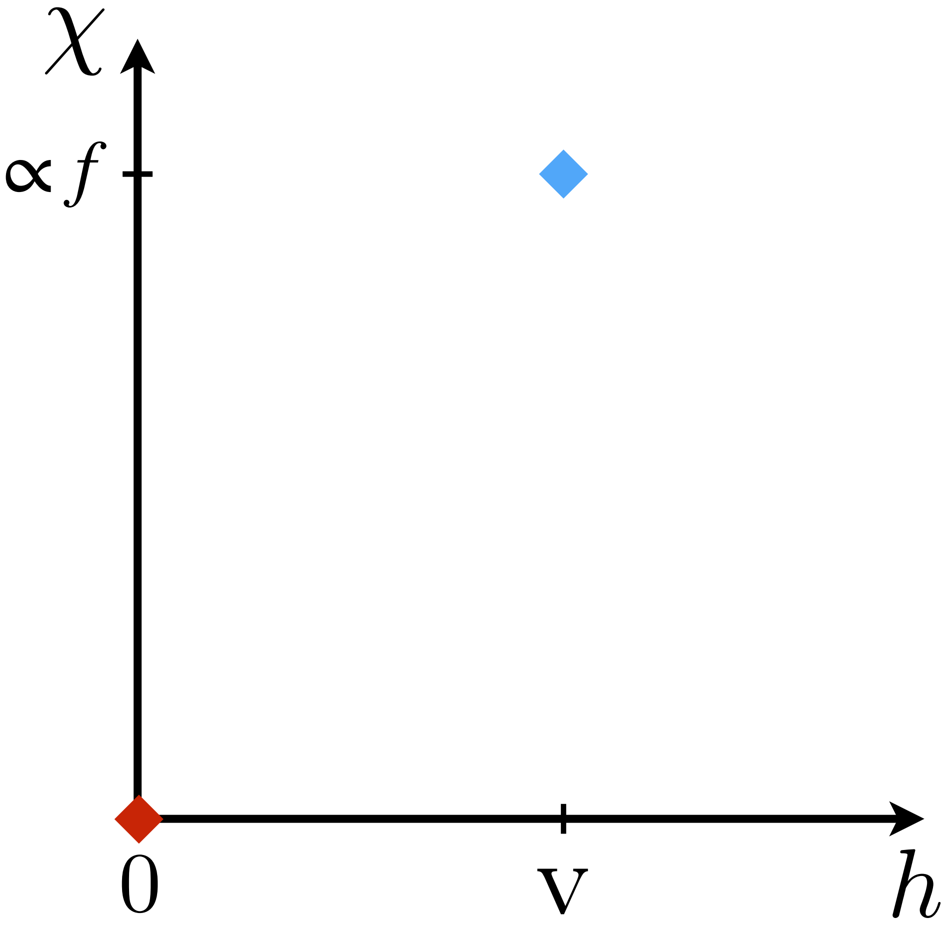


Phase Transitions in CH models

$h =$

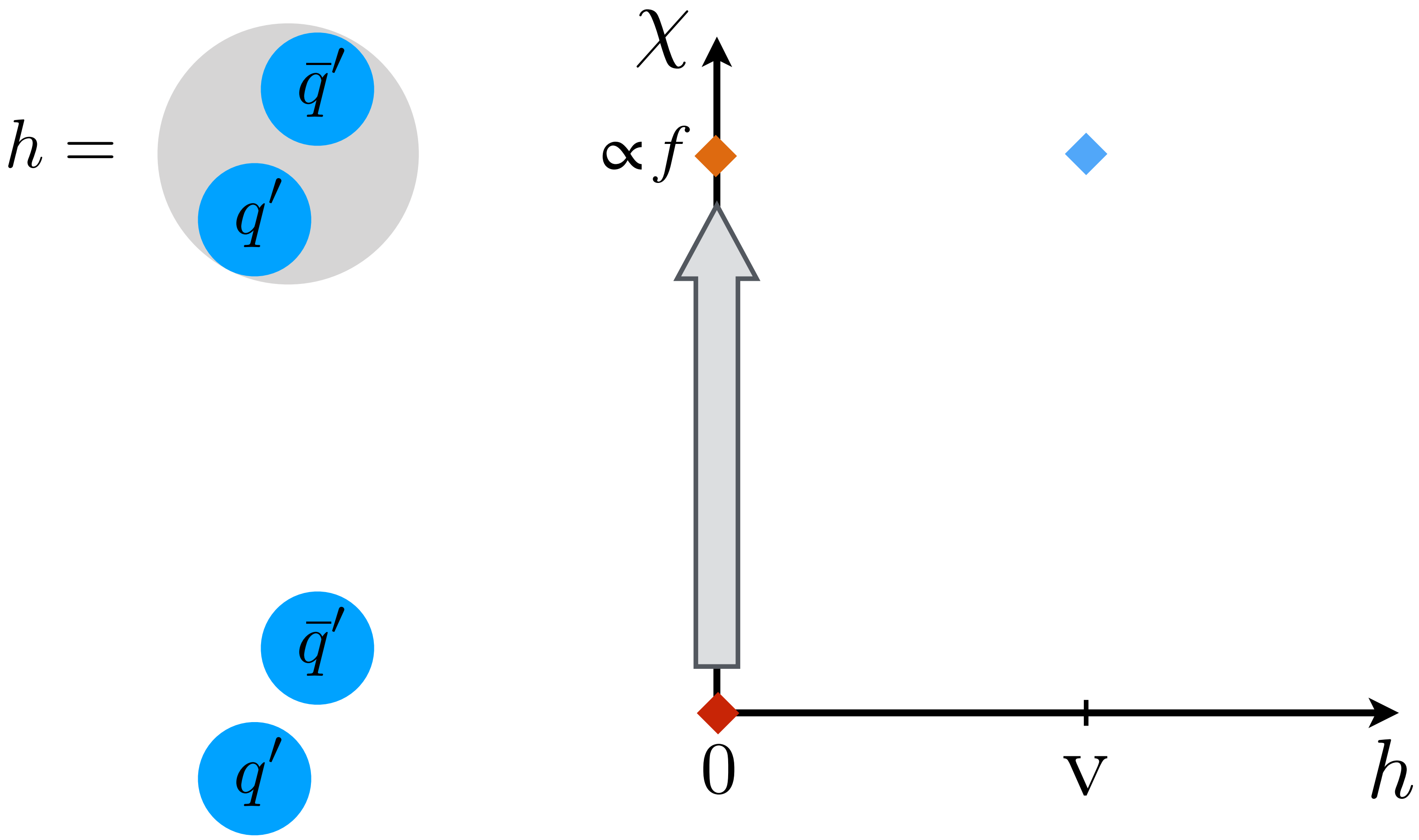






Phase Transitions in CH models

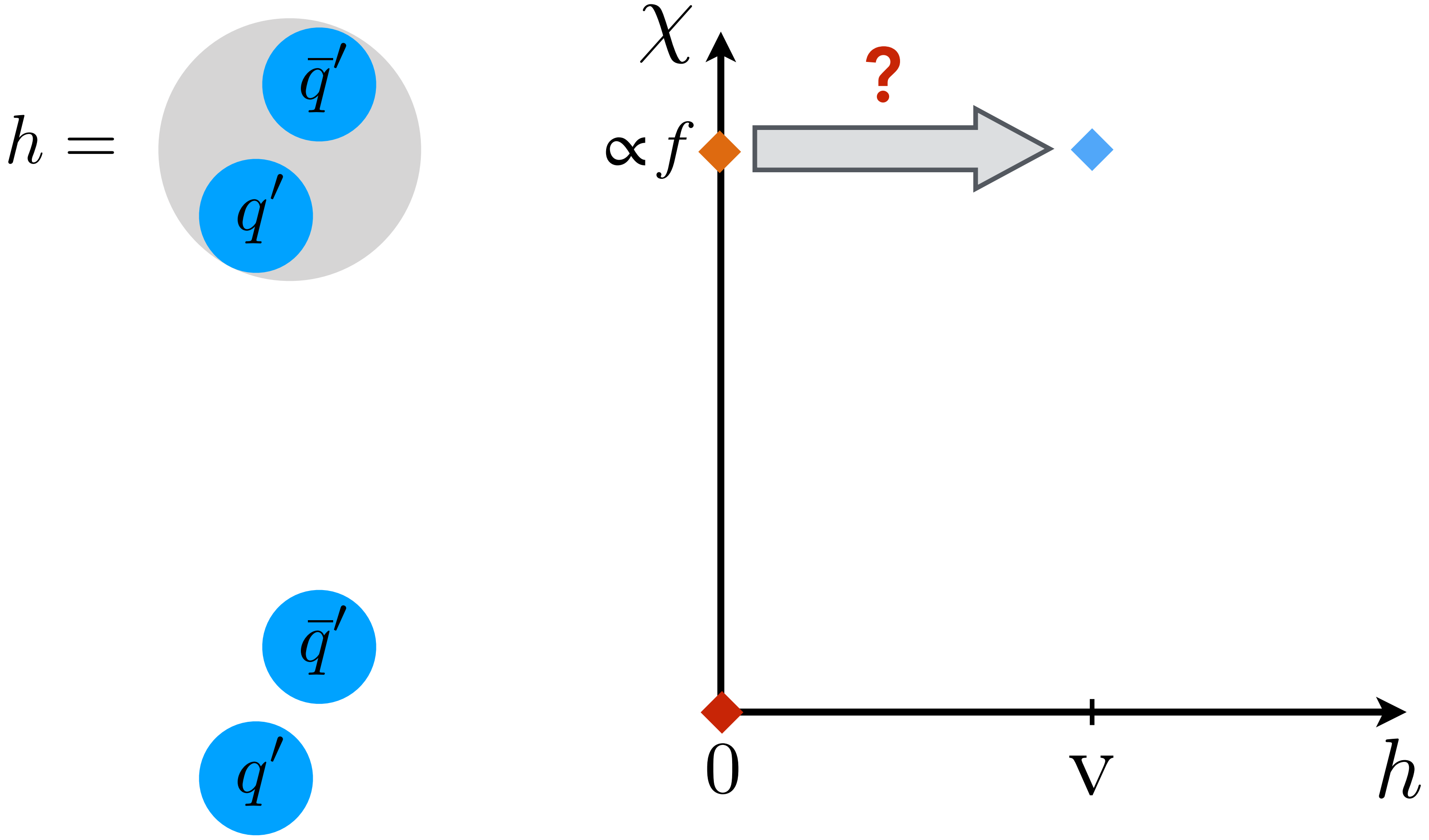
Two-Step Transition



Confinement happens before EW phase transition

Phase Transitions in CH models

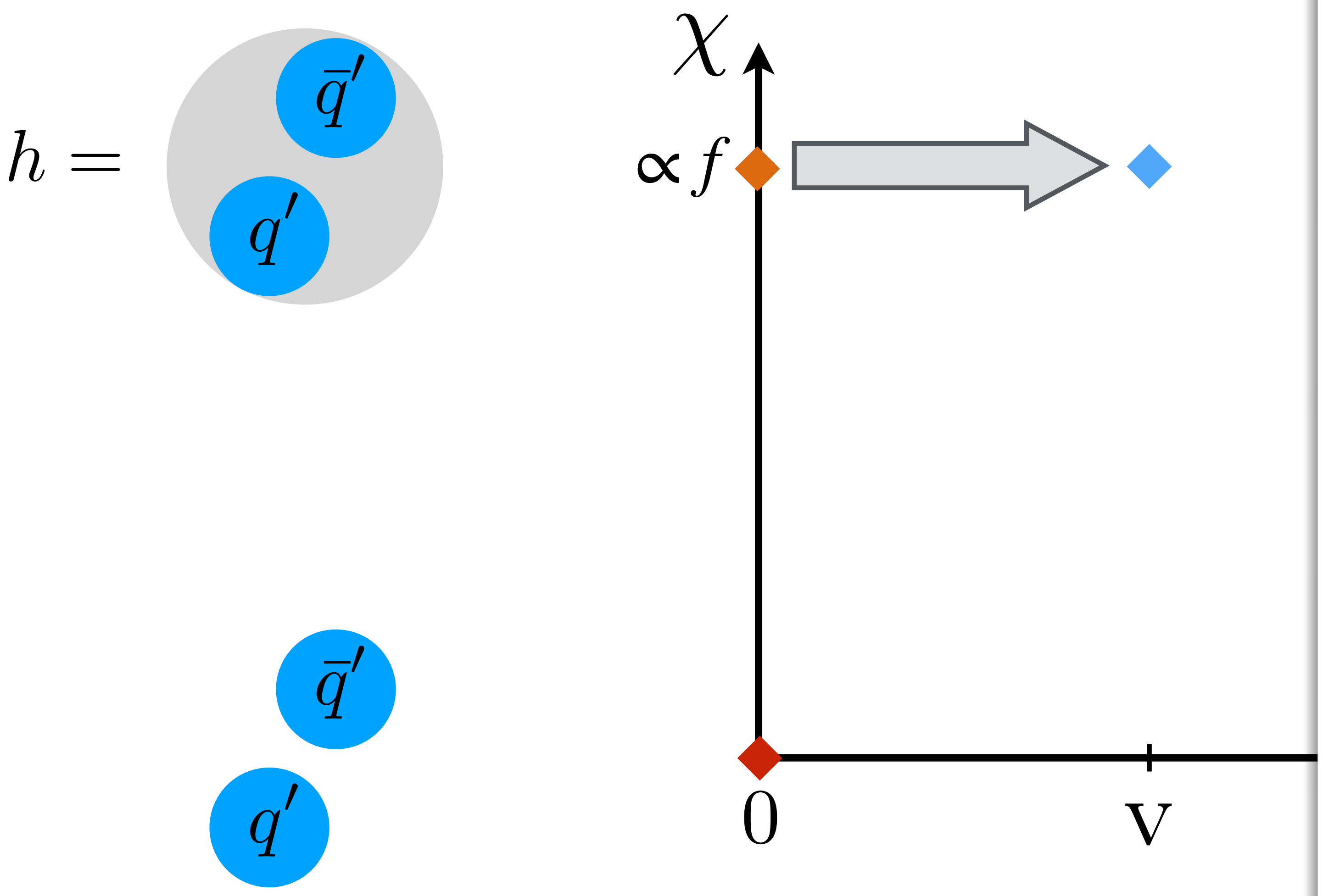
Two-Step Transition



At this point the lightest scalar is the SM-like Higgs, hence no first-order PT unless extra physics is added

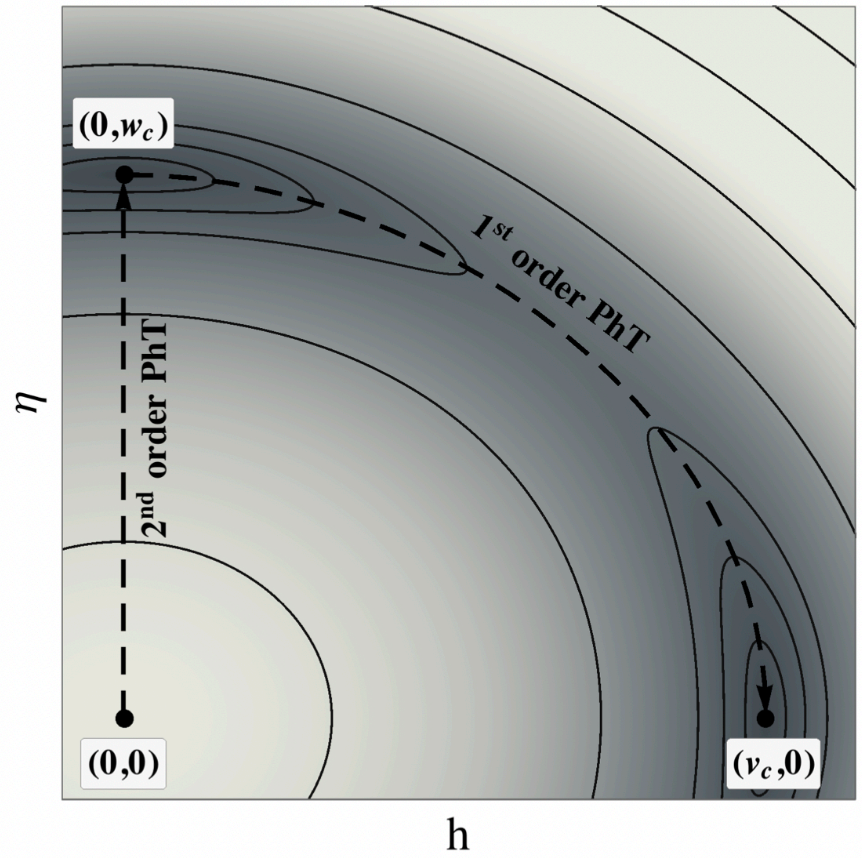
Phase Transitions in CH models

Two-Step Transition with a Singlet



1st order PT from an extra composite scalar η

SO(6)/SO(5) gives H and a singlet



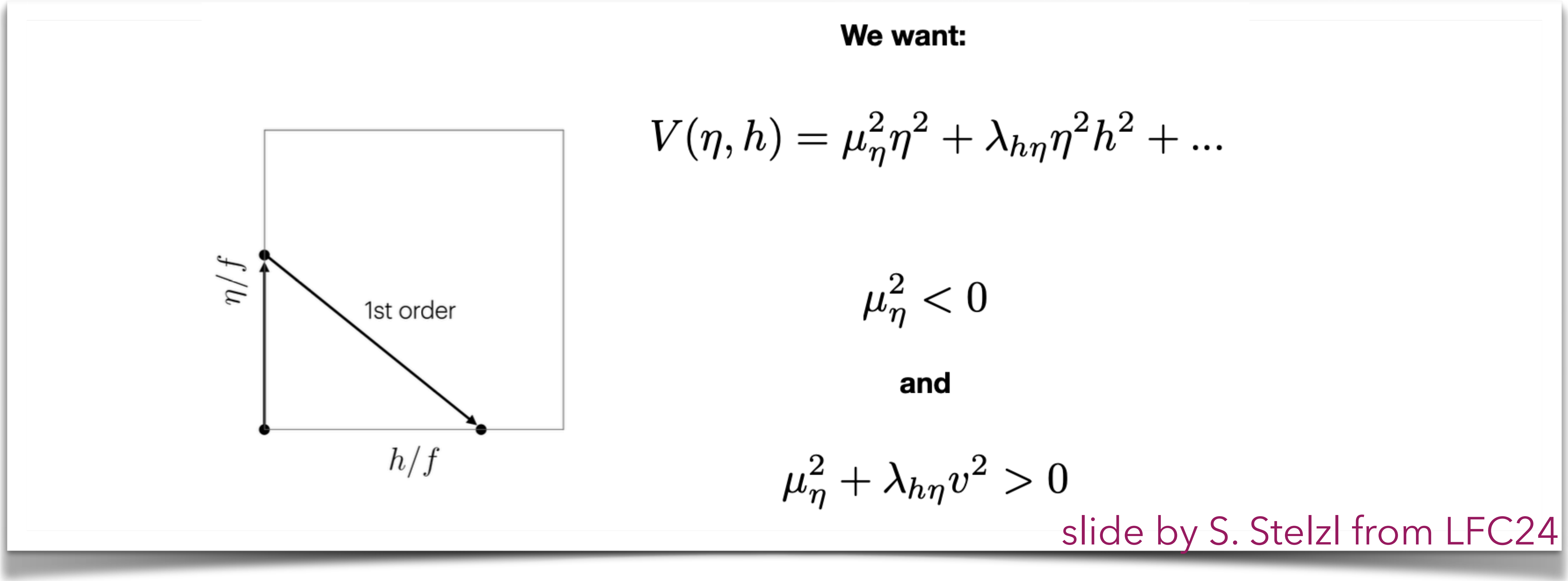
De Curtis, Delle Rose, Panico [1909.07894]

Phase Transitions in CH models

Two-Step Transition with a Singlet

Ekhterachian, Le Dorze, Rattazzi, Stelzl
to appear soon

However:



We want:

$$V(\eta, h) = \mu_\eta^2 \eta^2 + \lambda_{h\eta} \eta^2 h^2 + \ldots$$

$$\mu_\eta^2 < 0$$

and

$$\mu_\eta^2 + \lambda_{h\eta} v^2 > 0$$

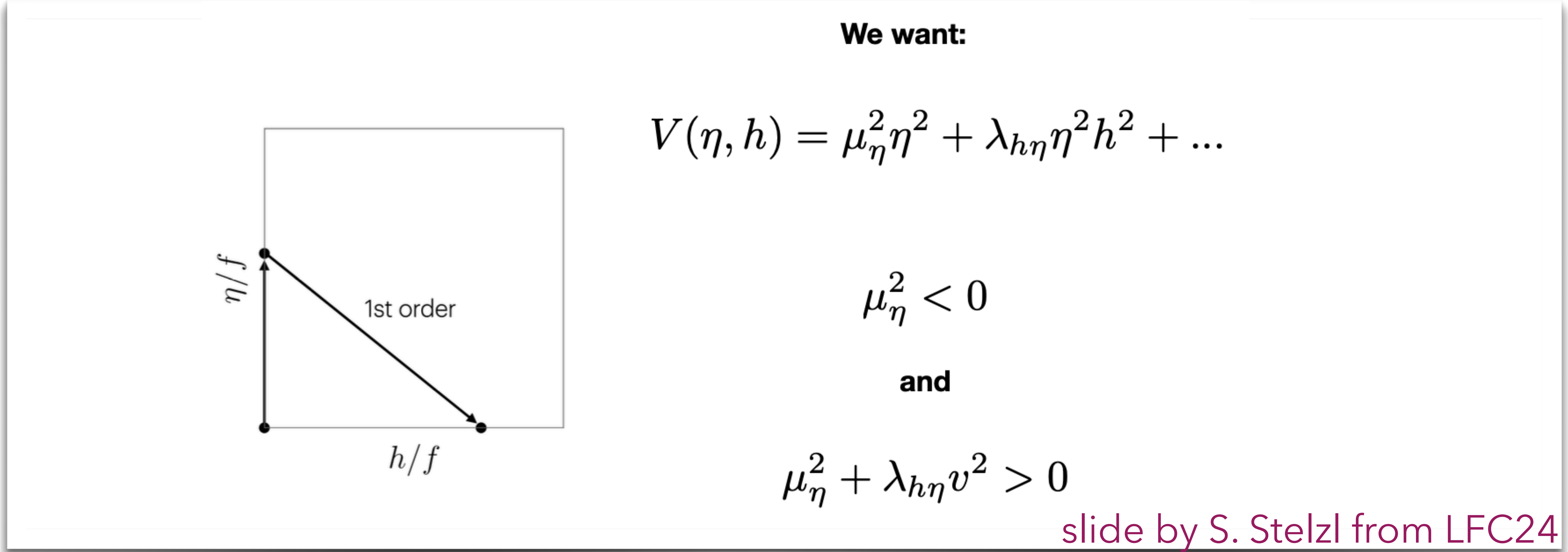
slide by S. Stelzl from LFC24

Phase Transitions in CH models

Two-Step Transition with a Singlet

However:

Ekhterachian, Le Dorze, Rattazzi, Stelzl
to appear soon



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$$\mu_\eta^2 < 0$$

and

$$\mu_\eta^2 + \lambda_{h\eta}v^2 > 0$$

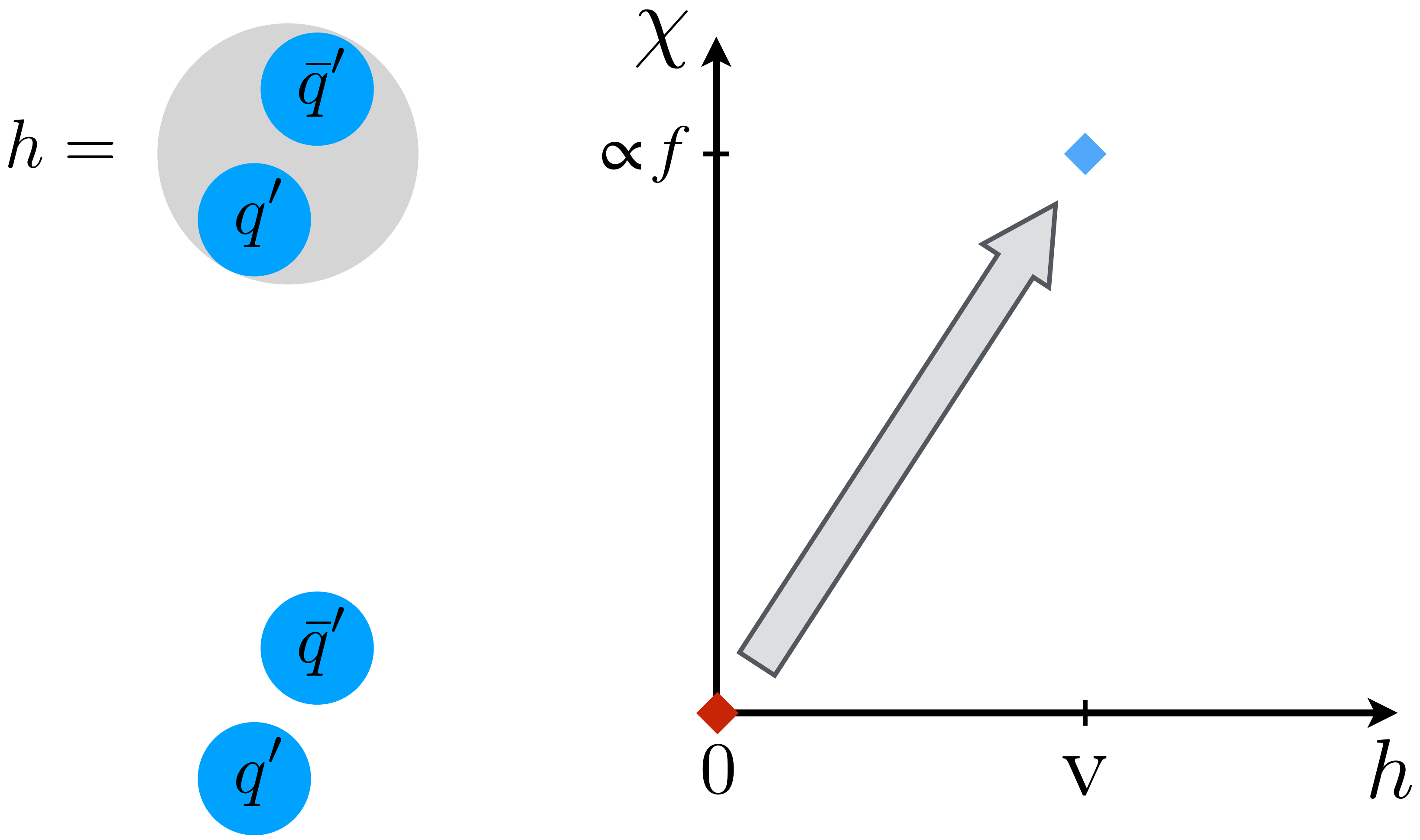
slide by S. Stelzl from LFC24

$\Rightarrow \lambda_{h\eta}v^2/|\mu_\eta^2| \gtrsim 1$ but in practice: $\sim v^2/f^2 \lesssim 0.1$

fine-tune, or go less minimal.

Phase Transitions in CH models

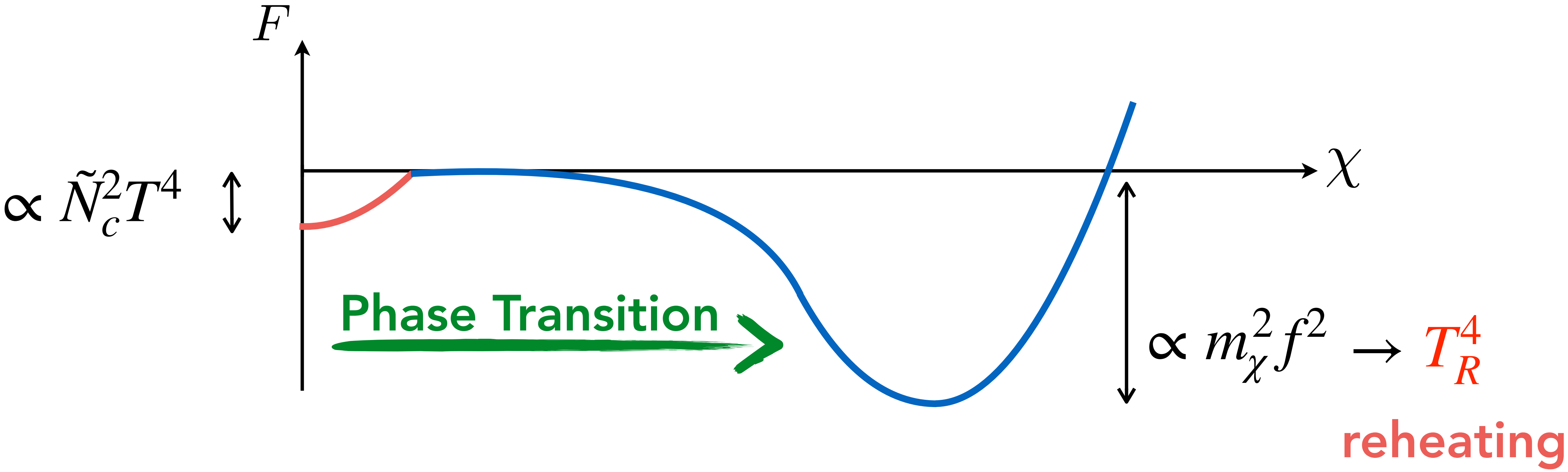
One-Step Transition



1-step: if T(confinement) < T(EWSB)

$h \propto \chi$ and EWPT is 1st order if confinement PT is

Confinement Phase Transition



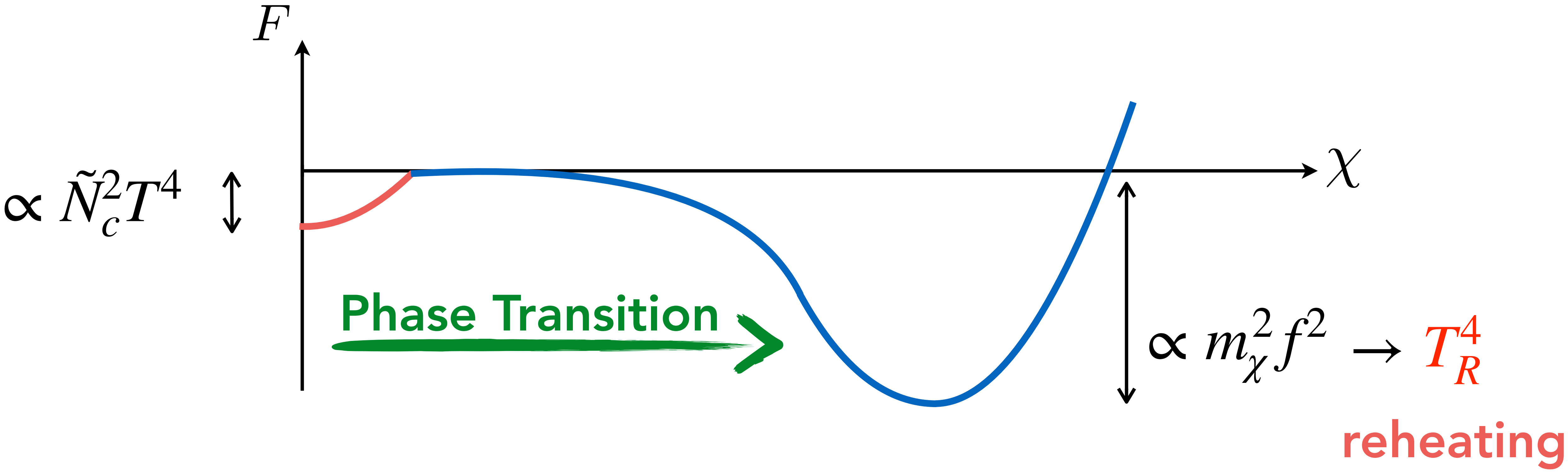
$\propto \tilde{N}_c^2 T^4$

Phase Transition

$\propto m_\chi^2 f^2 \to T_R^4$

reheating

Confinement Phase Transition



- If $T_R > 130\,GeV$ the EW symmetry is ~restored again (EW sphalerons are on)

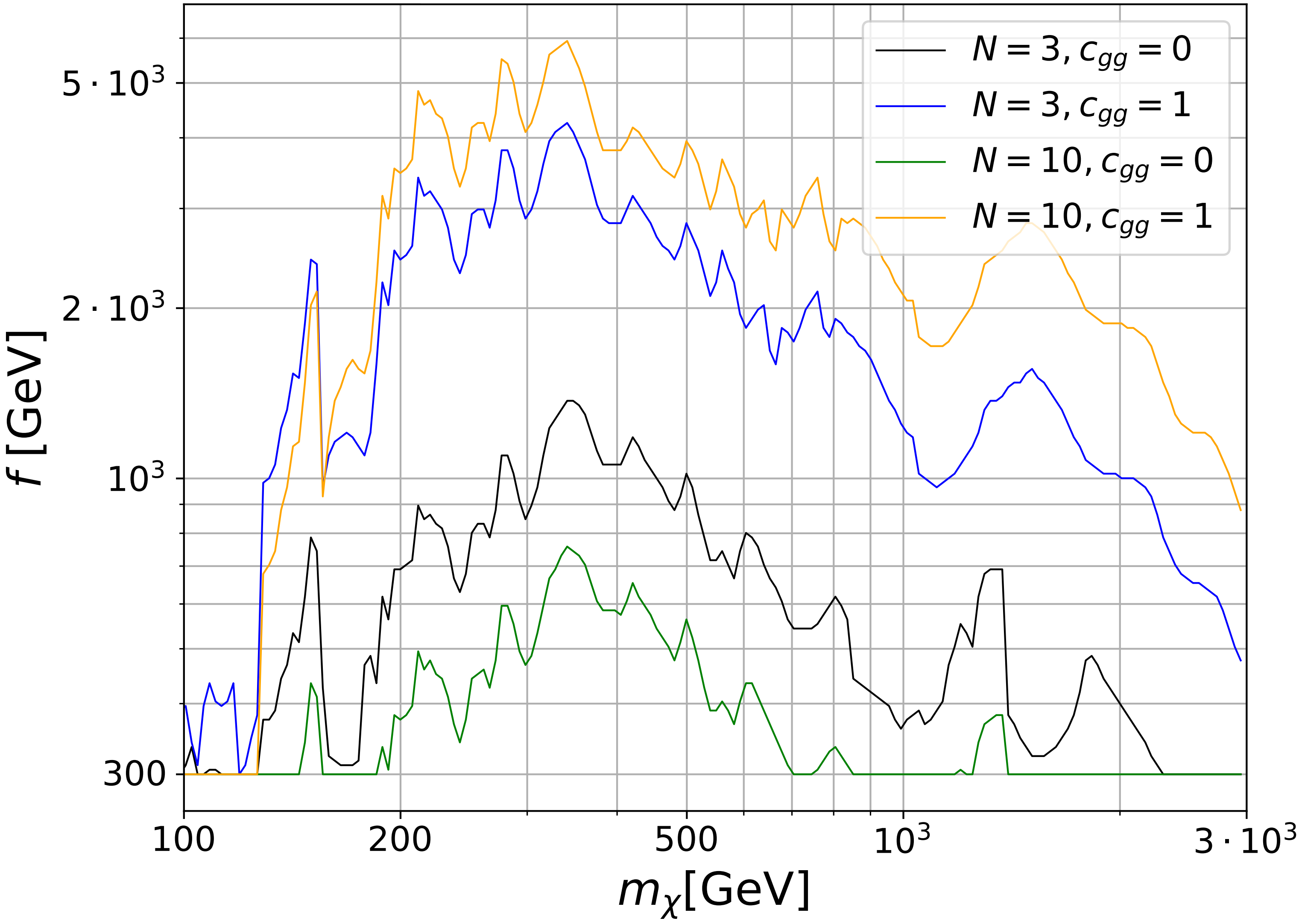
- To keep EWBG results we need

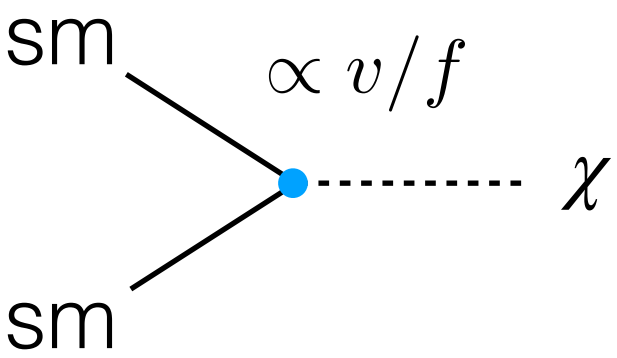
$$T_R \lesssim 130\,GeV \quad \Rightarrow \quad m_\chi \lesssim 500\,GeV \times \frac{800\,GeV}{f} \frac{1}{\tilde{N}_c^{1/2}}$$

LHC bounds

using HiggsBounds

Bruggisser,vonHarling,OM,Servant,2212.00056





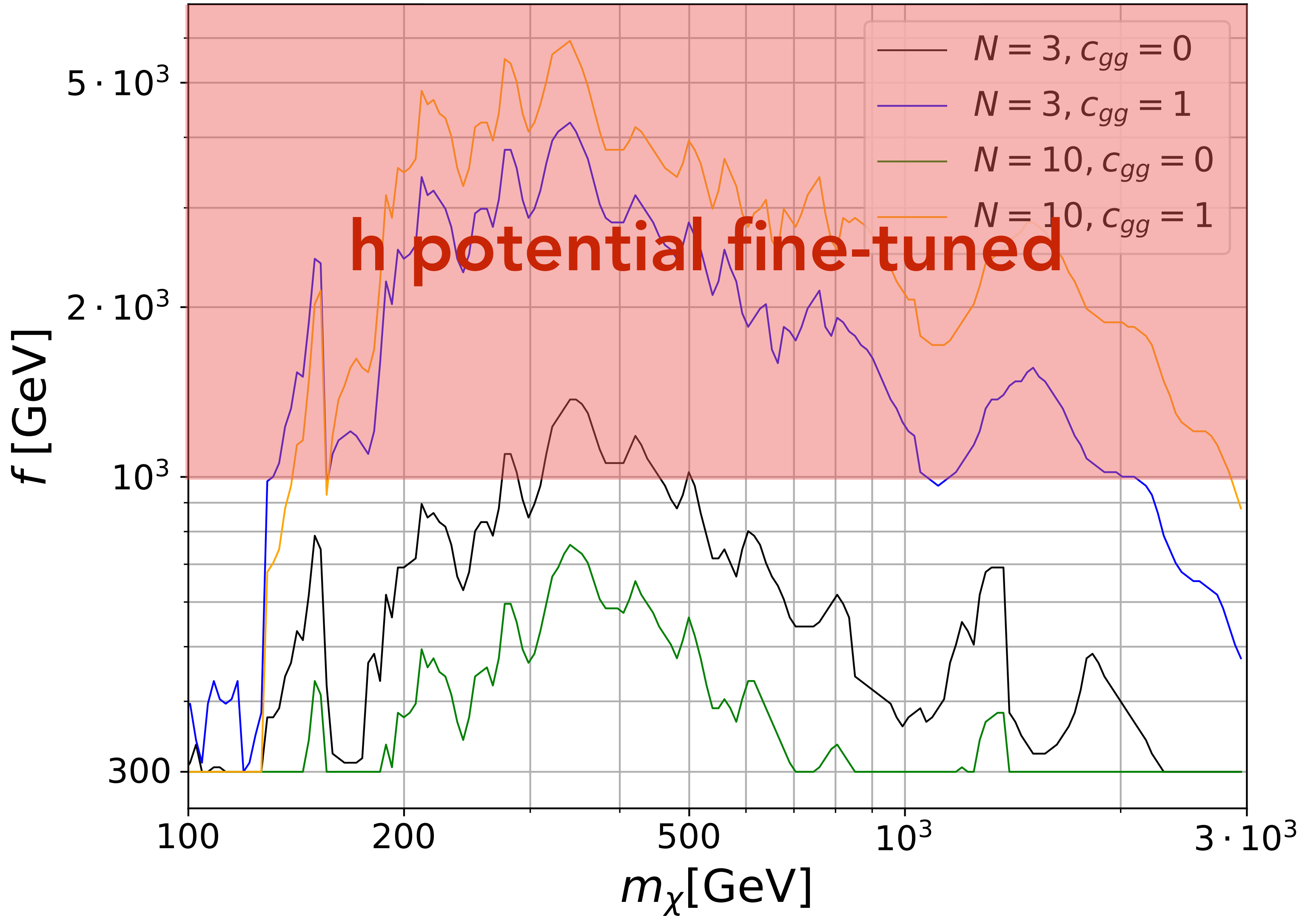
* extra N for $gg\chi$

* in fact $\propto v/\chi_0$

LHC bounds

using HiggsBounds

Bruggisser,vonHarling,OM,Servant,2212.00056



LHC bounds

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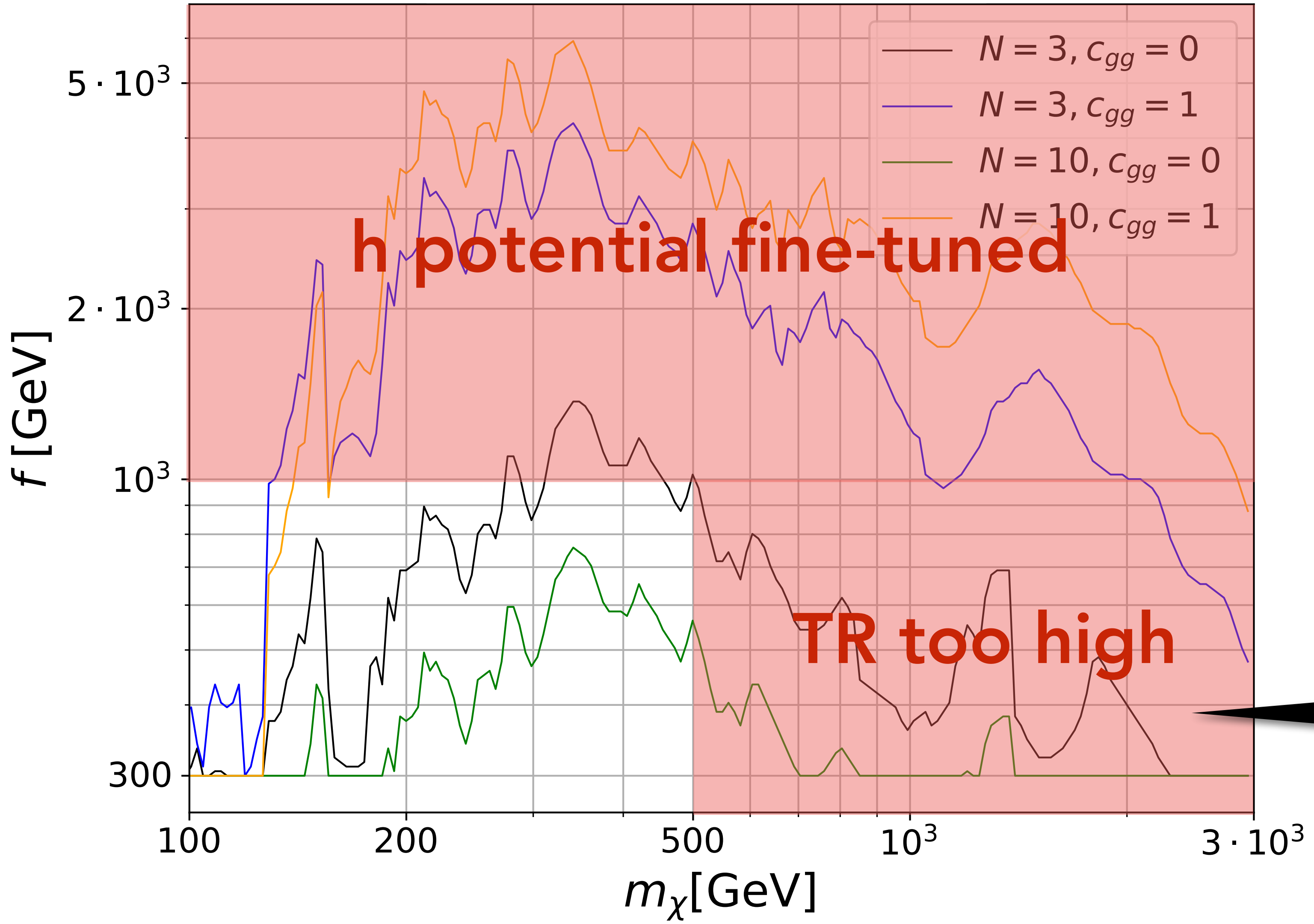
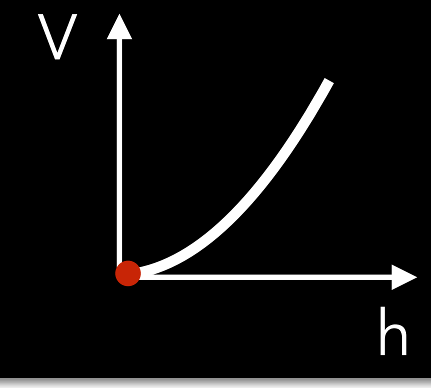
Bruggisser,vonHarling,OM,Servant,2212.00056



A small portion of parameter space survives in the minimal case.

T corrections to V(h)

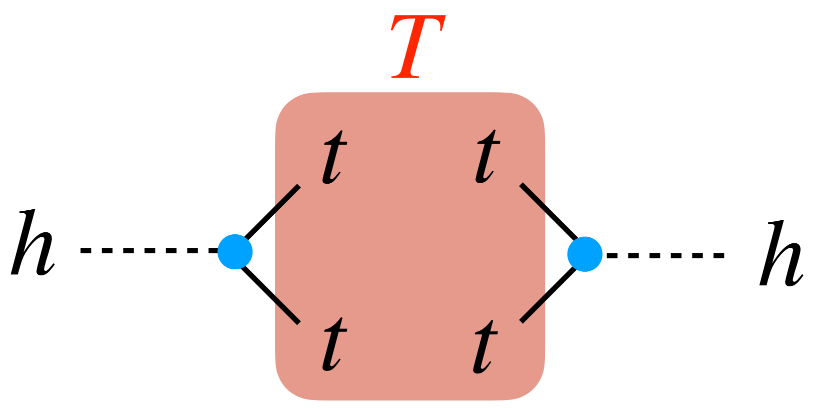


High-T EWBG

Electroweak Symmetry Non-Restoration at High T

- **SM states**

$$\frac{\lambda_t}{\sqrt{2}}\,\bar{t}th \quad \Rightarrow$$



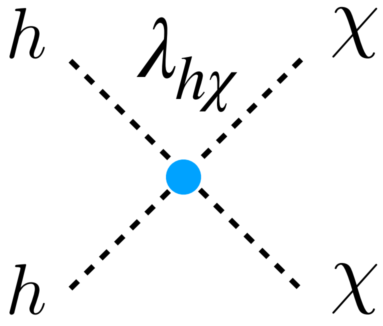
$$\Rightarrow \quad \delta V_h = \frac{1}{8}\lambda_t^2\, T^2\, h^2$$

⇒ positive thermal mass &
restoration at $T \simeq 160\,\mathrm{GeV}$

Electroweak Symmetry Non-Restoration at High T

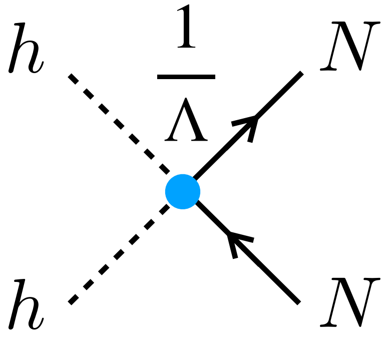
- **new light scalars**

  Weinberg '74 (toy model)
  Meade, Ramani, 1807.07578
  Baldes, Servant, 1807.08770
  Glioti, Rattazzi, Vecchi, 1811.11740



- **new light fermions**

  OM, Servant, 2020.05174



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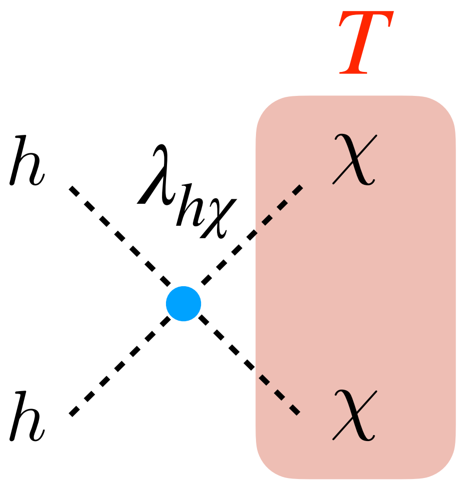

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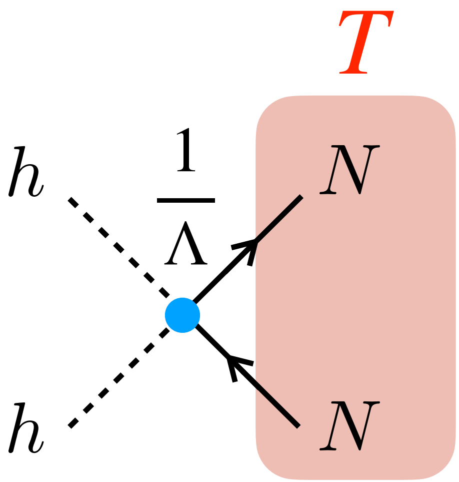

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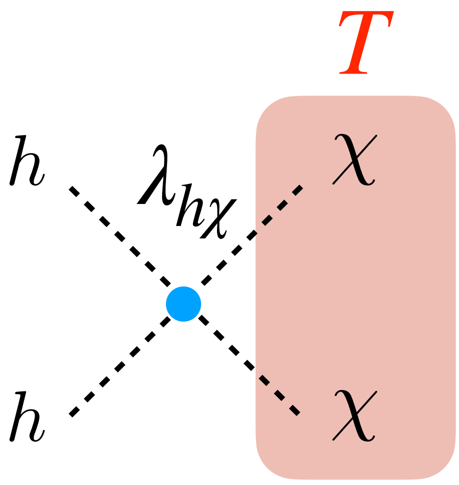
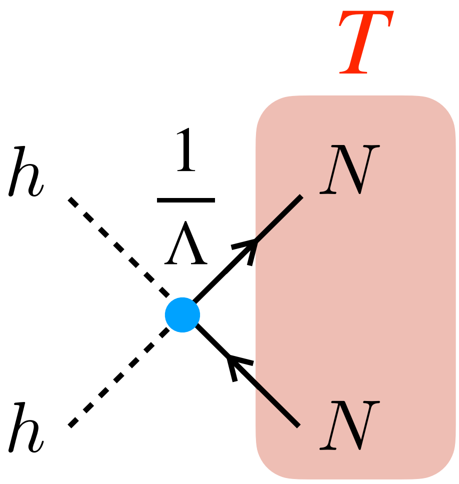


$$\Rightarrow \quad \delta V_h \sim \lambda_{h\chi} T^2 h^2$$

- **new light fermions**

  OM, Servant, 2020.05174



$$\Rightarrow \quad \delta V_h \sim \frac{m_N}{\Lambda} T^2 h^2$$

Electroweak Symmetry Non-Restoration at High T

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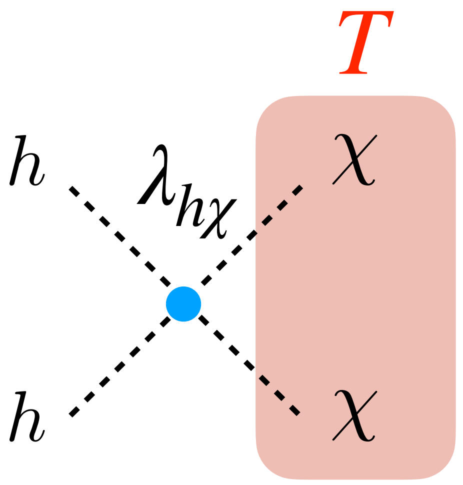

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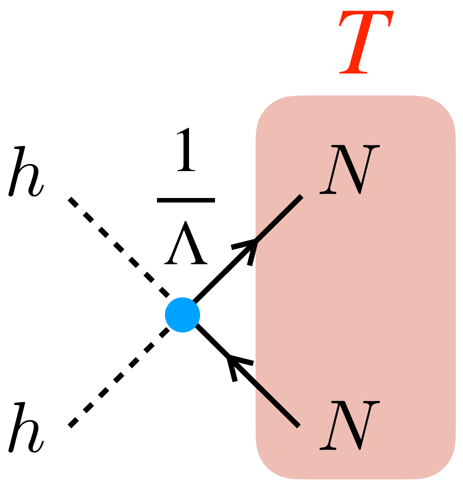


$$\Rightarrow \quad \delta V_h \sim \frac{m_N}{\Lambda} T^2 h^2$$

can be < 0

High-T EWSB vs Naturalness

SNR & Naturalness

- Can SNR be motivated by, or at least compatible with EW naturalness-motivated physics?

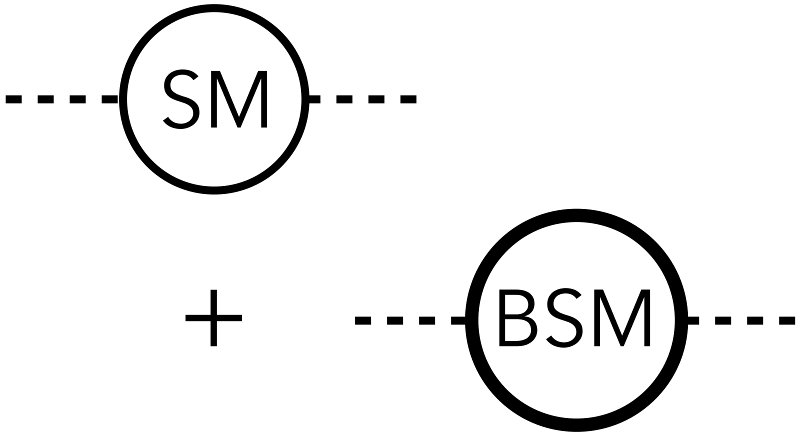
SNR & Naturalness

- no quadratic UV sensitivity of Higgs mass

$\Rightarrow$

add new d.o.f. such that

$$\delta V_{1loop} \propto \Lambda^2 \,\mathbf{STr}[M^2] \neq f[h]$$



SNR & Naturalness

- no quadratic UV sensitivity of Higgs mass

$$\textbf{STr}M^2 = \textbf{Tr}[M_0^2 - 2|M_{1/2}|^2 + 3M_1^2] \neq f[h]$$

SNR & Naturalness

- no quadratic UV sensitivity of Higgs mass

$$\mathbf{STr}M^2 = \mathbf{Tr}[M_0^2 - 2\,|M_{1/2}|^2 + 3M_1^2] \neq f[h]$$

- thermal potential (high-T)

$$\delta V_T \supset \frac{1}{24}T^2\mathbf{Tr}[M_0^2 + |M_{1/2}|^2 + 3M_1^2]$$

SNR & Naturalness

- **different-spin** naturalness (SUSY)

e.g. chiral superfield

- no quadratic UV sensitivity of Higgs mass

$$\mathbf{STr}M^2 = \mathbf{Tr}[\boxed{M_0^2 - 2|M_{1/2}|^2} + 3M_1^2] \neq f[h]$$

- thermal potential (high-T)

$$\delta V_T \supset \frac{1}{24}T^2\mathbf{Tr}[M_0^2 + \overset{\times 3}{\curvearrowright}|M_{1/2}|^2 + 3M_1^2]$$

$$\supset \frac{1}{8}T^2\mathbf{Tr}|M_{1/2}|^2$$

H.E.Haber ‘82
M.Mangano ‘84

SNR & Naturalness

- **different-spin** naturalness (SUSY)

e.g. chiral superfield

- no quadratic UV sensitivity of Higgs mass

$$\mathbf{STr}M^2 = \mathbf{Tr}\left[\boxed{M_0^2 - 2|M_{1/2}|^2} + 3M_1^2\right] \neq f[h]$$

$\times 3$

- thermal potential (high-T)

$$\delta V_T \supset \frac{1}{24}T^2\mathbf{Tr}[M_0^2 + |M_{1/2}|^2 + 3M_1^2]$$

$$\supset \frac{1}{8}T^2\mathbf{Tr}|M_{1/2}|^2$$

- way around, e.g. additional superfields with non-renormalizable interactions and large-n

Dvali, Tamvakis '96
Bajc, Melfo, Senjanovic '96
OM, Unwin, Wang 2211.09147

SNR & Naturalness

- **same-spin** naturalness (e.g. Goldstone Higgs)

- no quadratic UV sensitivity of Higgs mass

$$\mathbf{STr}M^2 = \mathbf{Tr}[\underset{\neq f[h]}{\boxed{M_0^2}} \;,\; \underset{\neq f[h]}{\boxed{2\,|M_{1/2}|^2}} \;,\; \underset{\neq f[h]}{\boxed{3M_1^2}}]$$

- thermal potential (high-T)

$$\delta V_T \supset \frac{1}{24} T^2 \mathbf{Tr}[M_0^2 \;,\; |M_{1/2}|^2 \;,\; 3M_1^2] \neq f[h]$$

e.g. top effect $\delta V_h = \frac{1}{8}\lambda_t^2 T^2 h^2$ is cancelled ⇒ potential SNR

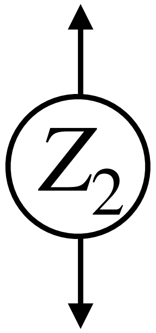
SNR & Naturalness

➤ **same-spin** naturalness (e.g. Goldstone Higgs)

● Twin Higgs

Chacko et al, hep-ph/0506256

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



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

SNR & Naturalness

- **same-spin** naturalness (e.g. Goldstone Higgs)

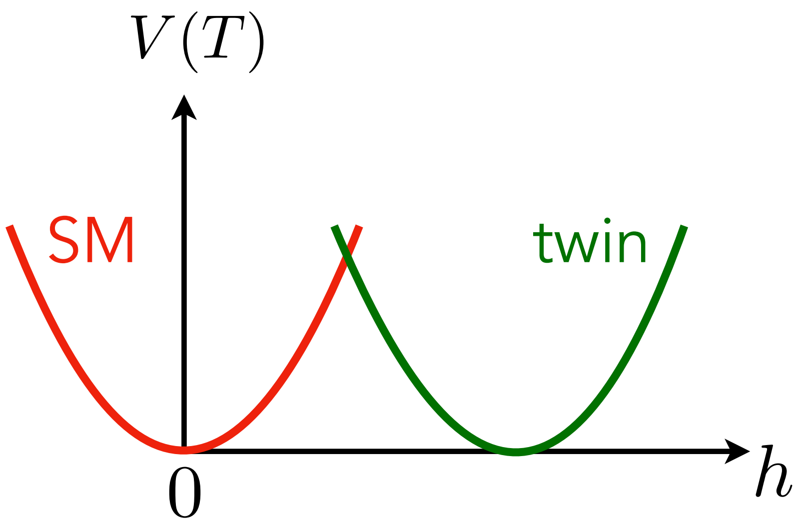
- Twin Higgs

Chacko et al, hep-ph/0506256

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

SM contribution

Twin contribution



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Chacko et al, hep-ph/0506256

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SM contribution

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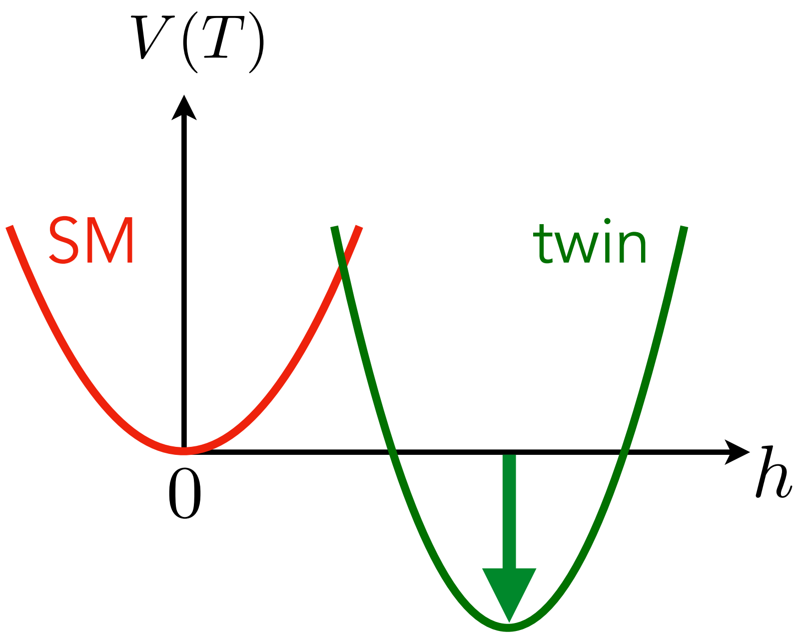


Z_2 breaking by light quark/ lepton Yukawas

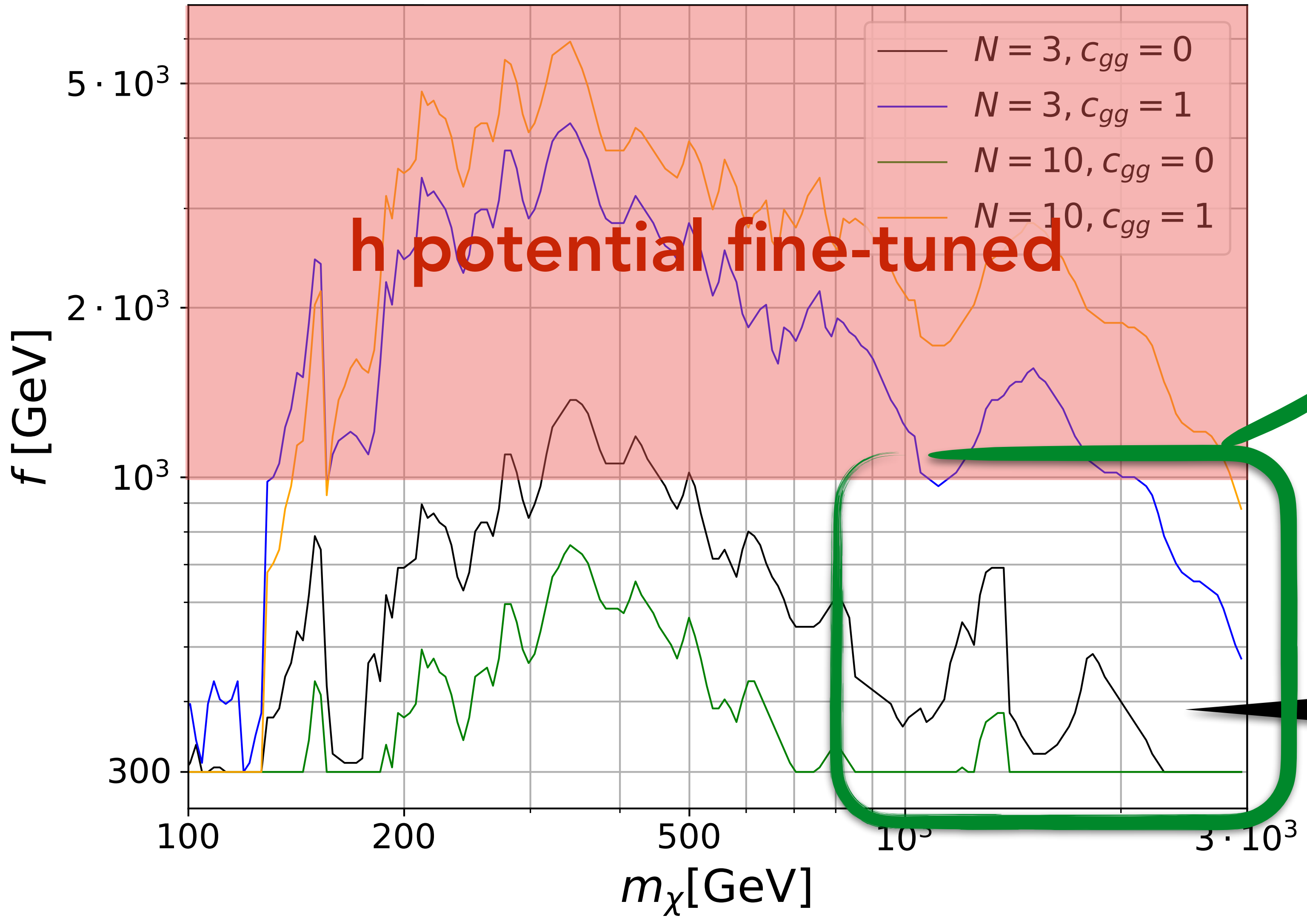
$$\tilde{\lambda}_q\, f\bar{q}q\, \cos h/f$$

OM, 2008.13725

LHC bounds

vonHarling,OM,Servant,2307.14426

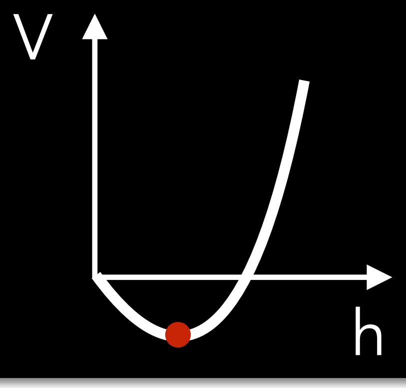
Bruggisser,vonHarling,OM,Servant,2212.00056



Search for heavy dilaton

Assume twin Higgs structure

High-T EWSB



Summary

- EWBG necessarily predicts $\lesssim$ TeV scale new physics, providing an important target for future colliders and other experiments
- Large variety of implementations with various signatures
- Combined explanation with EW naturalness may require extra assumptions about the model structure

Thank you!

Backup slides

SM + Singlet: EWBG on Defects

EDM bounds

J.Azzola,OM,A.Weiler
work in progress

parametric estimate for Barr-Zee:

$$d_e/e \sim \#16\frac{\alpha_{EM}}{(4\pi)^3}\sqrt{2}G_F m_e\,\{\sin\theta_{hS} v/f\}$$

to get h<T in the core:

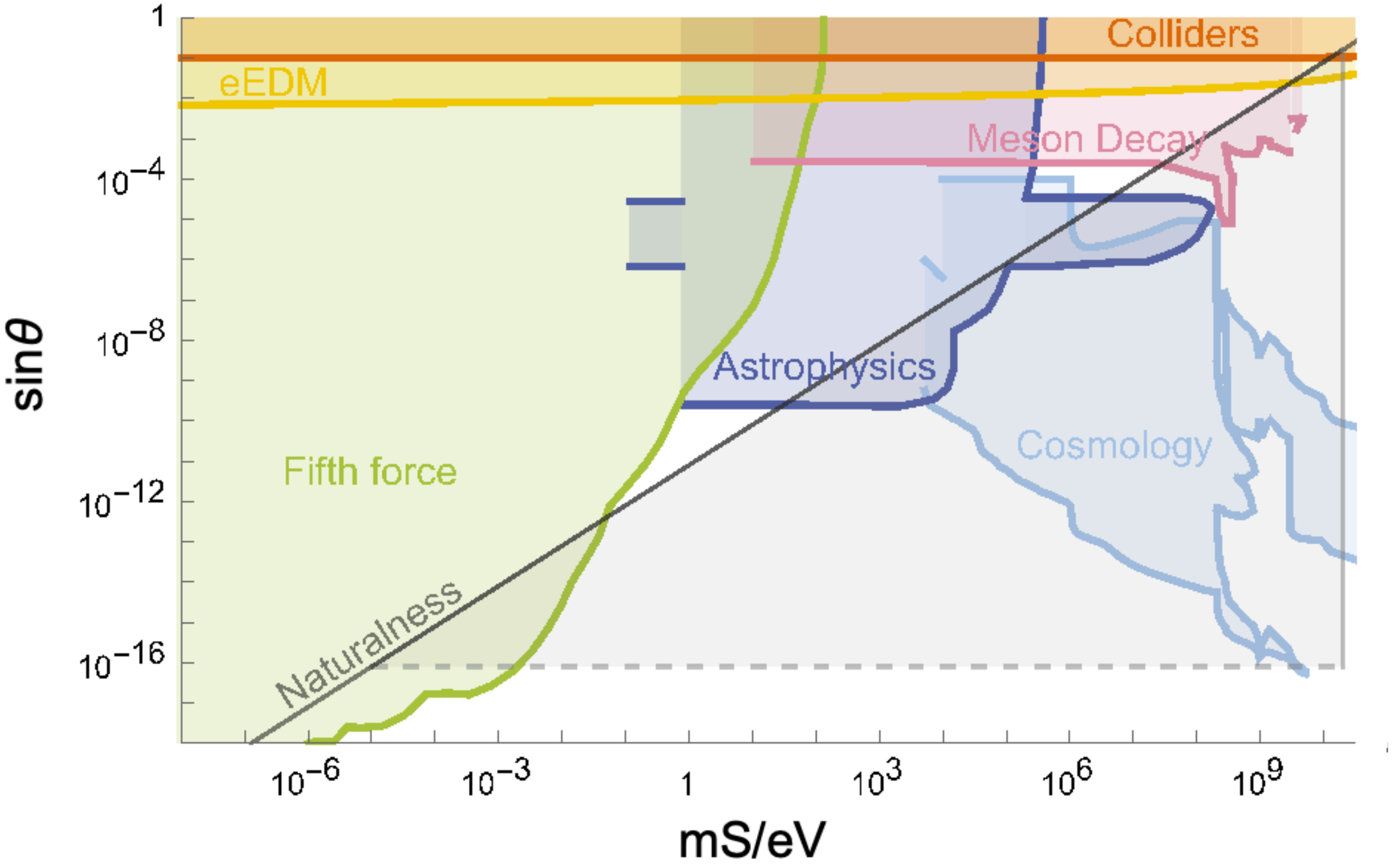
$$v/f \sim v/\langle S\rangle < \sin\theta_{hS}$$

bound (in GeV):

$$d_e/e \sim 5\times 10^{-12} s_\theta^2 < 6\times 10^{-16}$$

SM + Singlet: EWBG on Defects

J.Azzola,OM,A.Weiler
work in progress



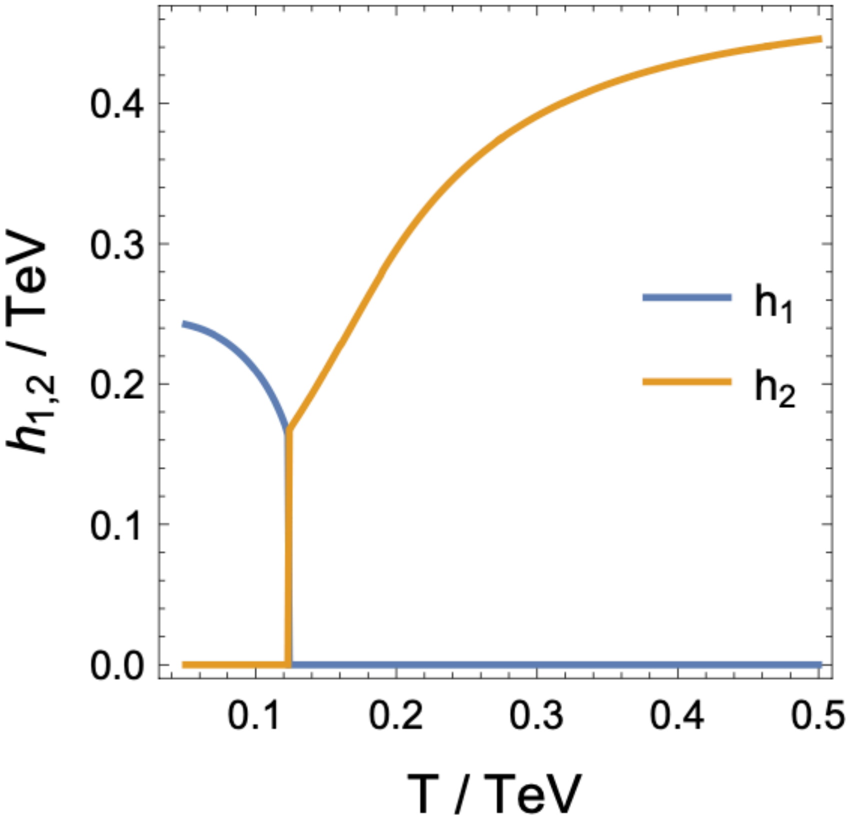
SNR: # of new d.o.f.

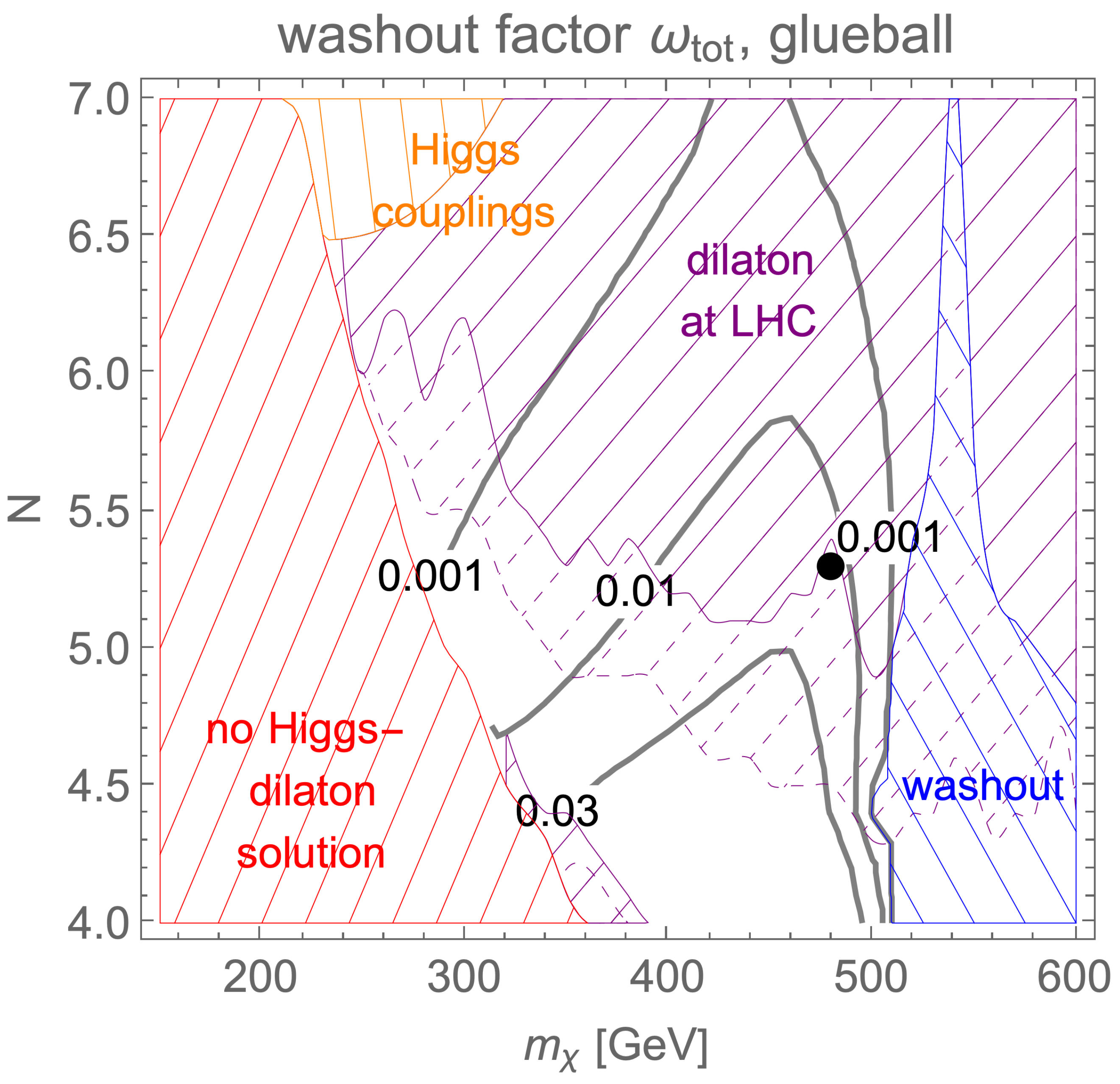
- large multiplets needed for perturbativity:
  - $\mathcal{O}(10)$ Dirac **fermions** for T < 1 TeV $(T_{\rm SNR}^{\rm max} \sim \sqrt{n}\, m_N)$
  - $\mathcal{O}(100)$ **scalars**
- In 2HDM: ~5 less d.o.f. and **DM candidate**

M.Carena,C.Krause,Z.Liu,Y.Wang 2104.00638

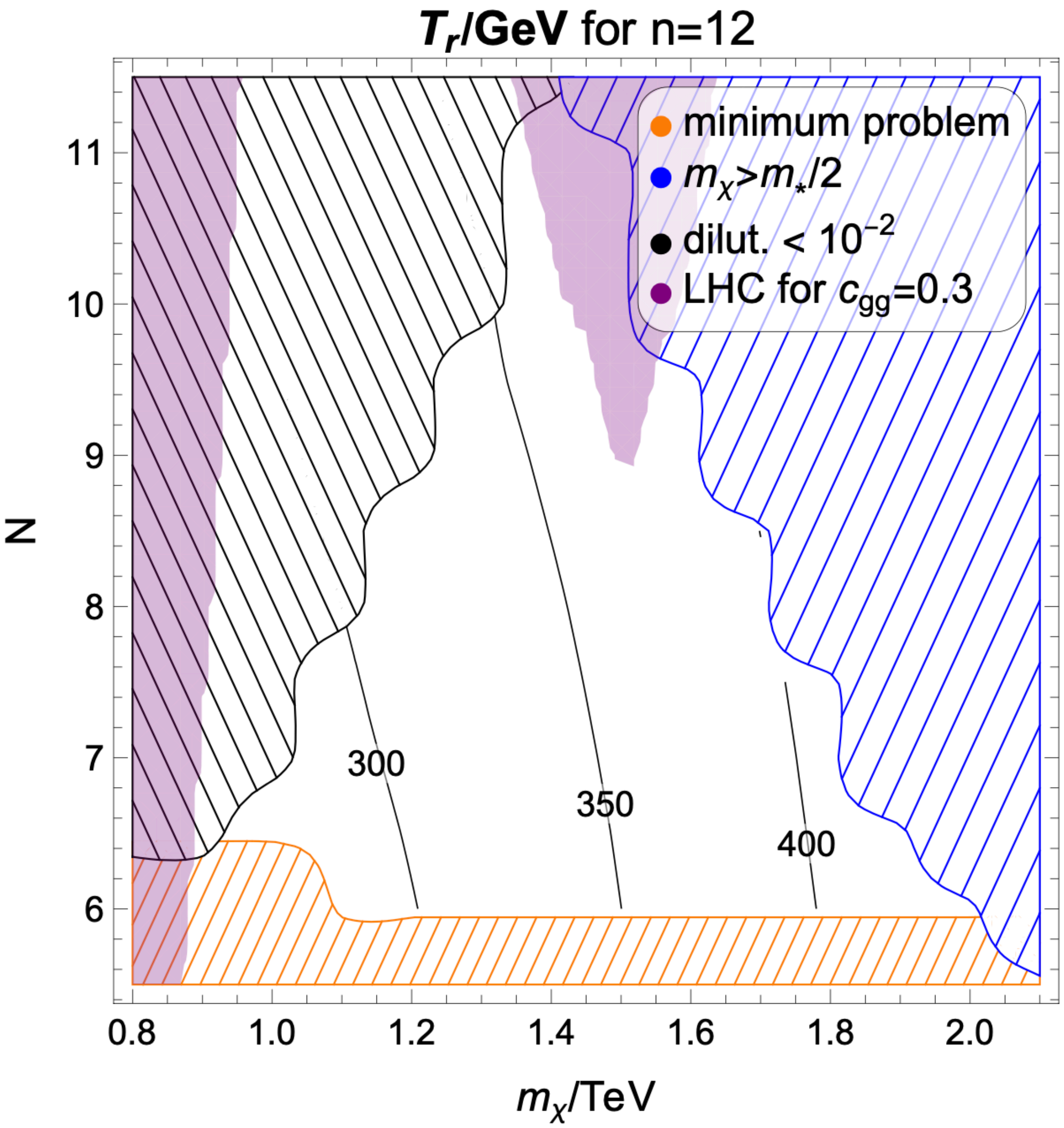
OM,J.Unwin,Q.Wang 2107.07560

$$\xcancel{\frac{\lambda_t}{\sqrt{2}}\bar{t}th_2}$$





Bruggisser,vonHarling,OM,Servant,2212.11953



vonHarling,OM,Servant

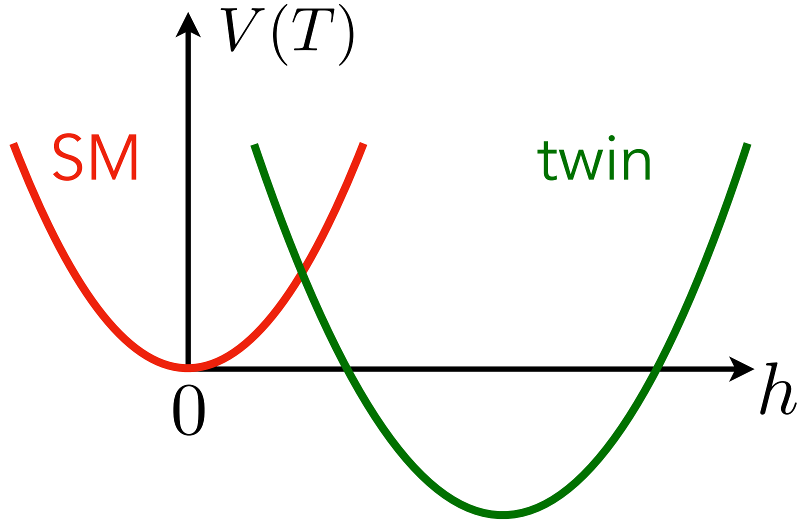
SNR: Twin Higgs

- 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

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

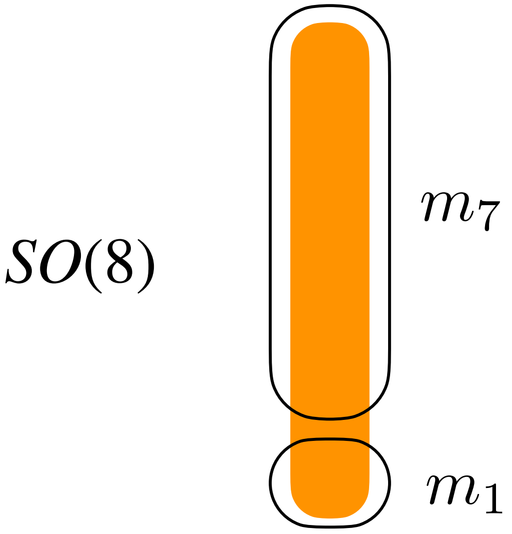


- This also spoils the cancellation of T=0 quadratic divergences to the Higgs mass: $\delta m_h^2 \sim (\tilde{\lambda}_q^2/16\pi^2)\Lambda^2$

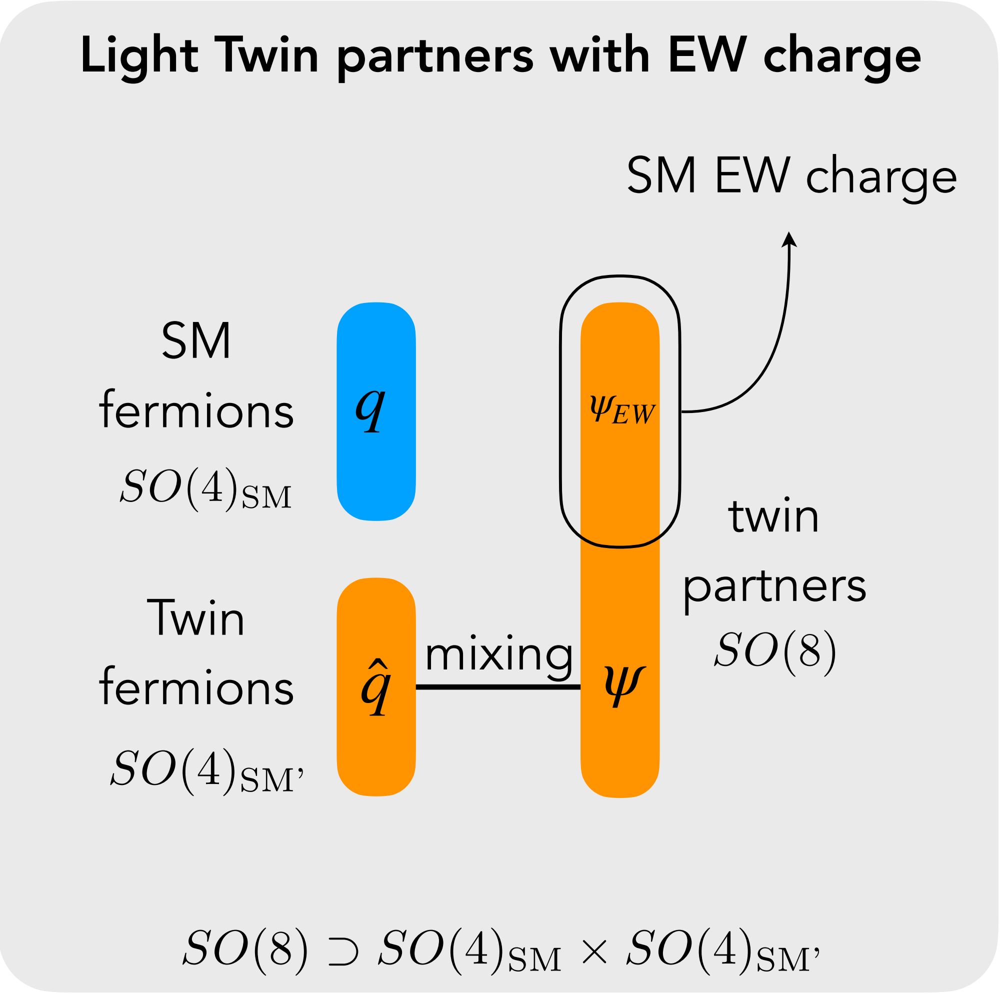
$\Rightarrow$ take a lower cutoff Λ in the twin light quark sector $\Rightarrow$ light **twin partners** (no SM QCD charge)

SNR: Twin Higgs

- To not spoil the Higgs mass, we need:

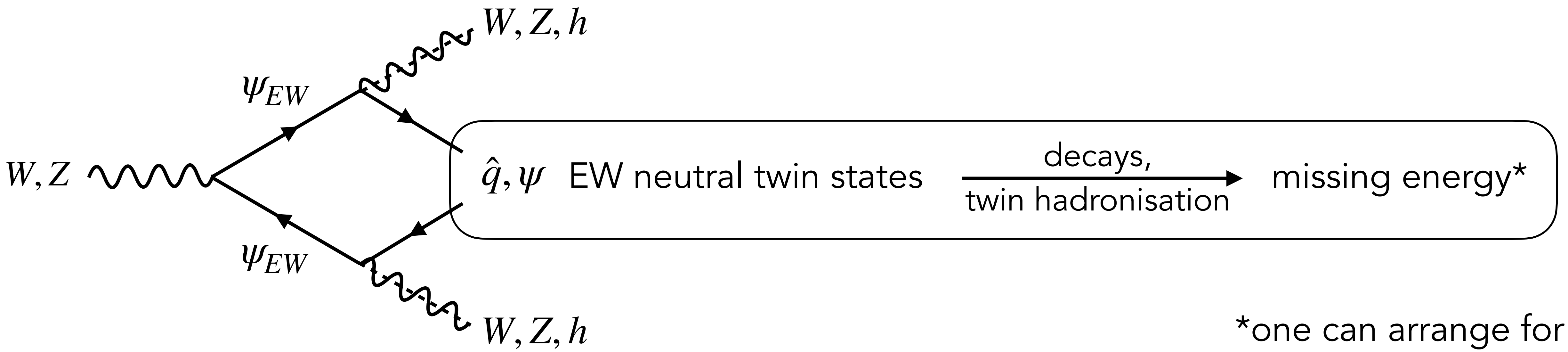


$$m_7^2 - m_1^2 \lesssim 1\,\mathrm{TeV}^2$$


Light Twin partners with EW charge

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

- Collider signal:



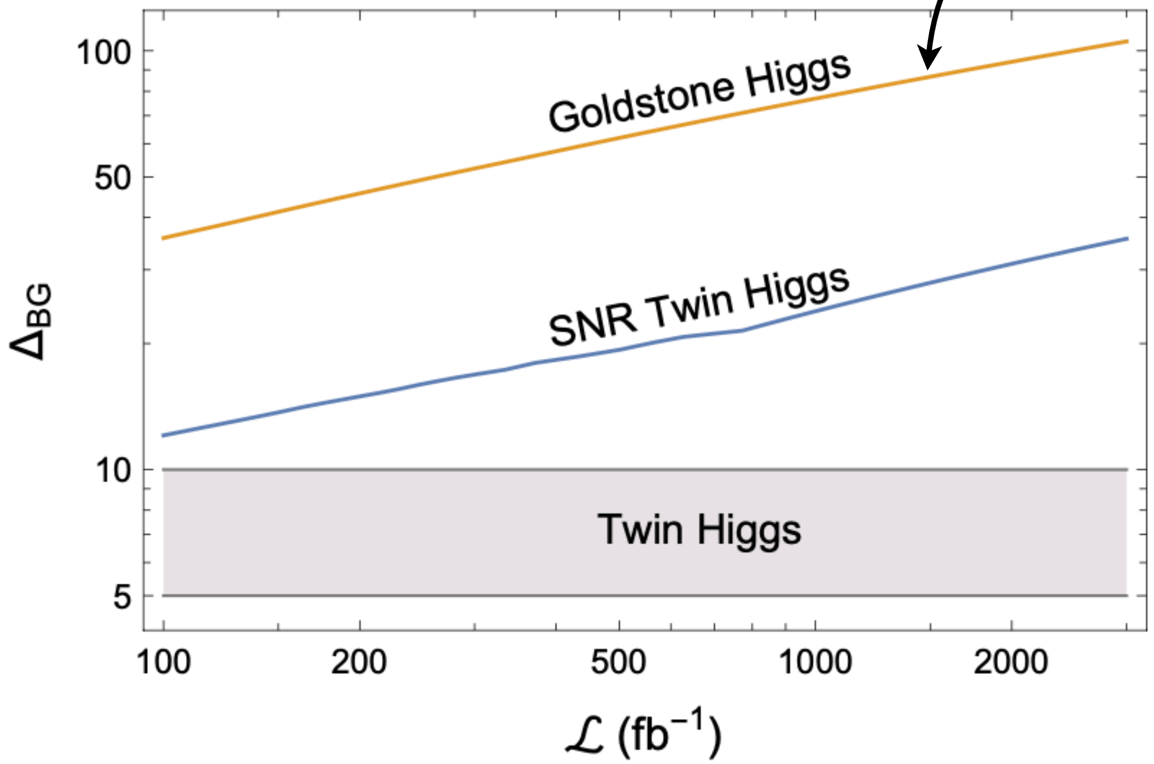
$\hat{q}, \psi$ EW neutral twin states $\xrightarrow[\text{twin hadronisation}]{\text{decays,}}$ missing energy*

*one can arrange for visible signatures too

SNR: Twin Higgs

- fine-tuning

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



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

SNR & Naturalness

- **different-spin** naturalness (SUSY)

H.E.Haber ‘82
M.Mangano ‘84

$$\delta V_T \supset \frac{1}{8} T^2 \mathbf{Tr}\, |M_{1/2}|^2$$

in **renormalizable** theories $M_{1/2\,ij} = const$ **or** h , hence

$$\mathbf{Tr}\, |M_{1/2}|^2 = \underbrace{\sum |M_{1/2\,ij}|^2}_{\geq 0} = c_1 + \underbrace{c_2}_{\geq 0} h^2$$

↑

positive thermal mass

SNR & Naturalness

- **different-spin** naturalness (SUSY)

Dvali,Tamvakis ‘96
Bajc, Melfo, Senjanovic ‘96
OM,Unwin,Wang 2211.09147

$$\delta V_T \supset \frac{1}{8} T^2 \mathbf{Tr}\,|M_{1/2}|^2$$

in **nonrenormalizable** theories $M_{1/2\,ij} = const,\, h,\, h^2, \ldots$, hence

$$\mathbf{Tr}\,|M_{1/2}|^2 = \underbrace{\sum |M_{1/2\,ij}|^2}_{\geq 0} = c_1 + \underbrace{c_2}_{\uparrow} h^2 + \underbrace{c_3}_{\geq 0} h^4$$

unconstrained thermal mass

SNR & SUSY

- assume large n

OM,Unwin,Wang
2211.09147

$$W = \mu_\chi(\chi_1.\chi_2) + \frac{c_{\chi h}}{\Lambda}(H_u.H_d)\,(\chi_1\overset{U(n)}{\overset{\frown}{.}}\chi_2)$$

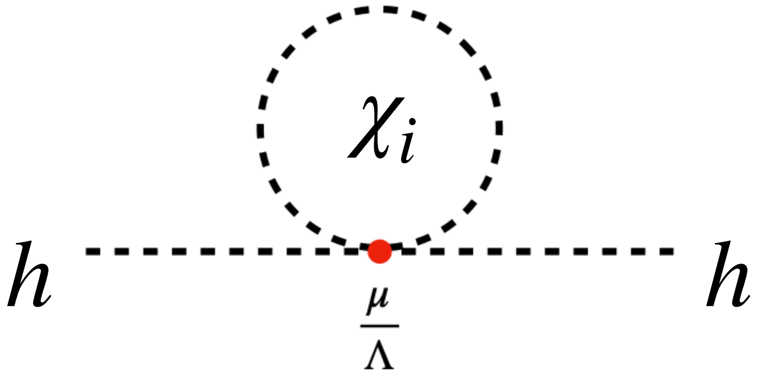
$$\begin{aligned} V = \;& \mu_\chi^2(|\chi_1|^2+|\chi_2|^2) + \tfrac{1}{\Lambda}c_{\chi h}\mu_\chi(|\chi_1|^2+|\chi_2|^2)(H_u.H_d + \text{h.c.}) \\ &+\tfrac{c_{\chi h}^2}{\Lambda^2}\left\{(|H_u|^2+|H_d|^2)|\chi_1.\chi_2|^2 + (|\chi_1|^2+|\chi_2|^2)|H_u.H_d|^2\right\} \end{aligned}$$

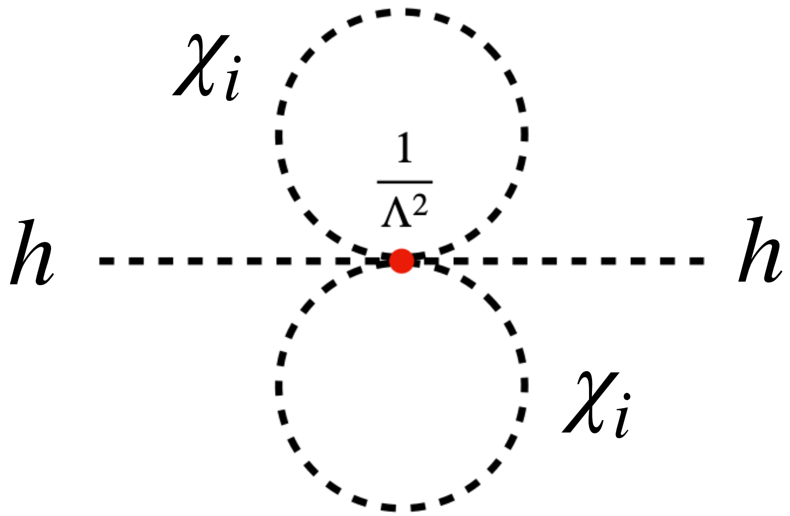
SNR & SUSY

- assume large n

OM,Unwin,Wang
2211.09147

$$W = \mu_\chi(\chi_1 \cdot \chi_2) + \frac{c_{\chi h}}{\Lambda}(H_u.H_d)\,(\chi_1 \overset{\overset{U(n)}{\frown}}{\cdot} \chi_2)$$





unconstrained thermal mass

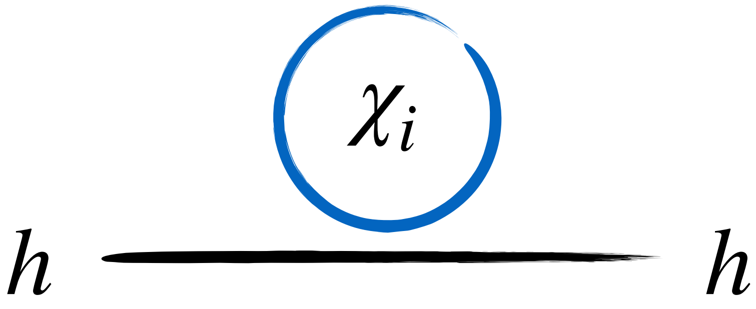
positive thermal mass

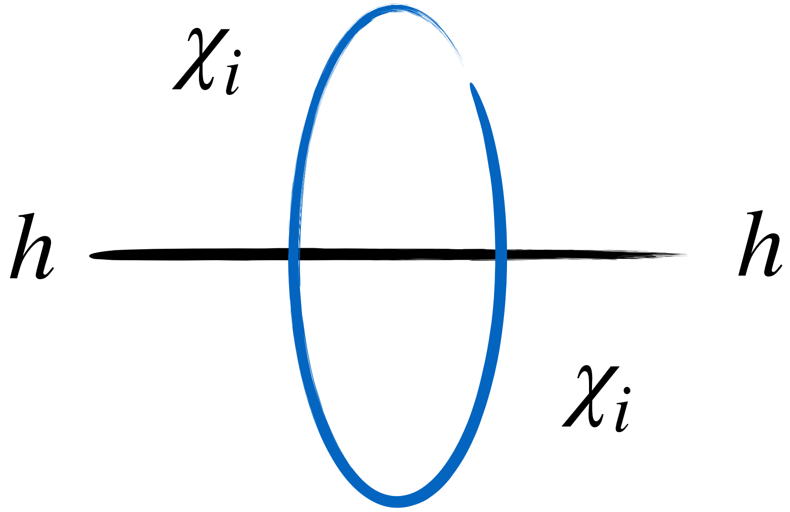
SNR & SUSY

- ➔ assume large n

OM,Unwin,Wang
2211.09147

$$W = \mu_\chi(\chi_1.\chi_2) + \frac{c_{\chi h}}{\Lambda}(H_u.H_d)\,\overset{U(n)}{\overgroup{(\chi_1.\chi_2)}}$$





unconstrained thermal mass

$$\propto n\frac{\mu_\chi}{\Lambda} \equiv \alpha$$

positive thermal mass

$$\propto n\frac{T^2}{\Lambda^2} = \frac{1}{n}\frac{\alpha^2 T^2}{\mu^2}$$