Electroweak Baryogenesis above the Weak Scale

Based on 1811.11740 (JHEP)
with A. Glioti, R. Rattazzi

Luca Vecchi

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

24th Rencontres Itzykson, Saclay (2019)

Electroweak Phase Transition above the Weak Scale

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Plan

- **Introduction**
  - Higgs potential, electroweak phase transition
  - EW phase transition: 3 options
- **Option 3: no electroweak phase transition?**
  - A simple O(N) model, large N
  - Application: Electroweak Baryogenesis
- **Conclusions**

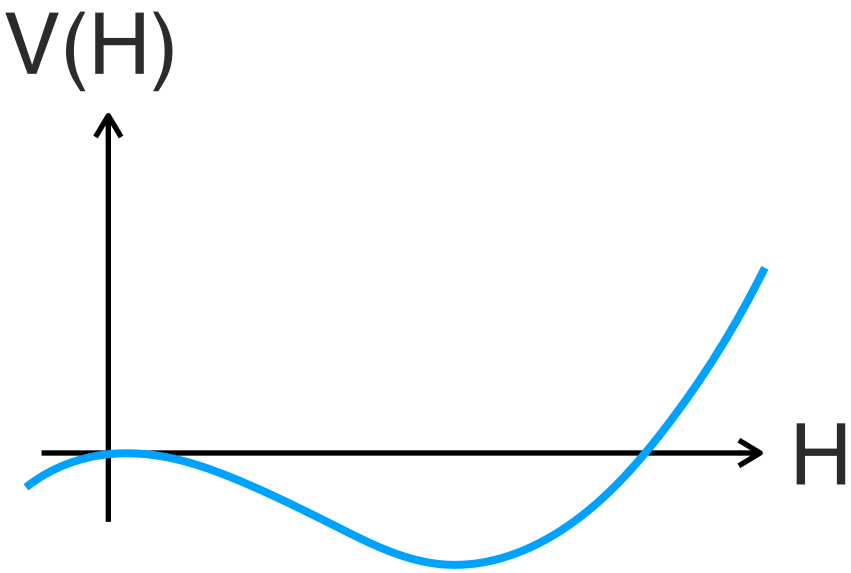
The Higgs:
What we know

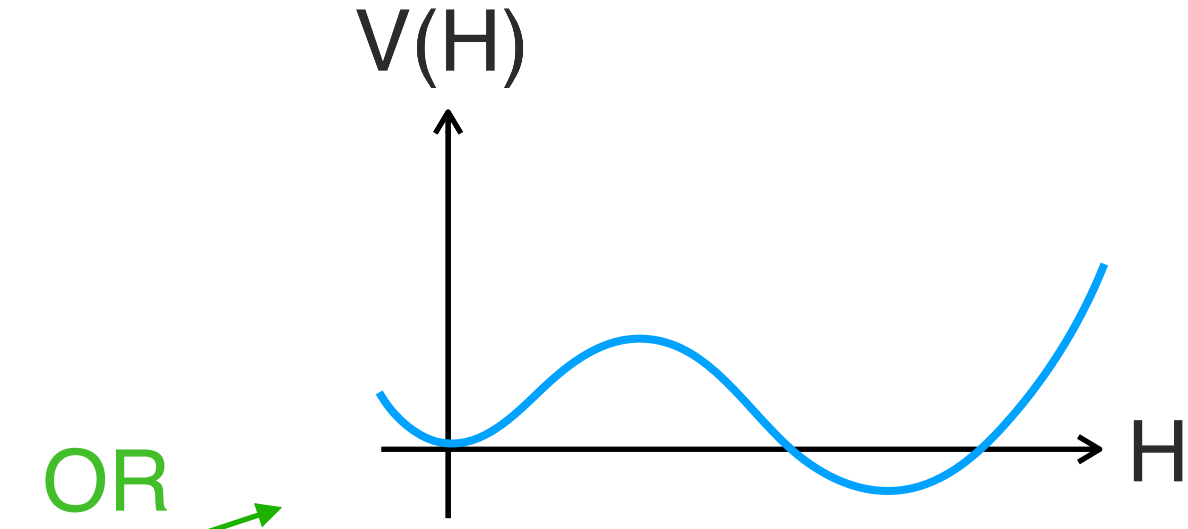
$$\mathcal{L}_{\rm SM} \supset |DH|^2 - [y\psi\psi' H + {\rm hc}] - V(|H|^2) + \cdots$$

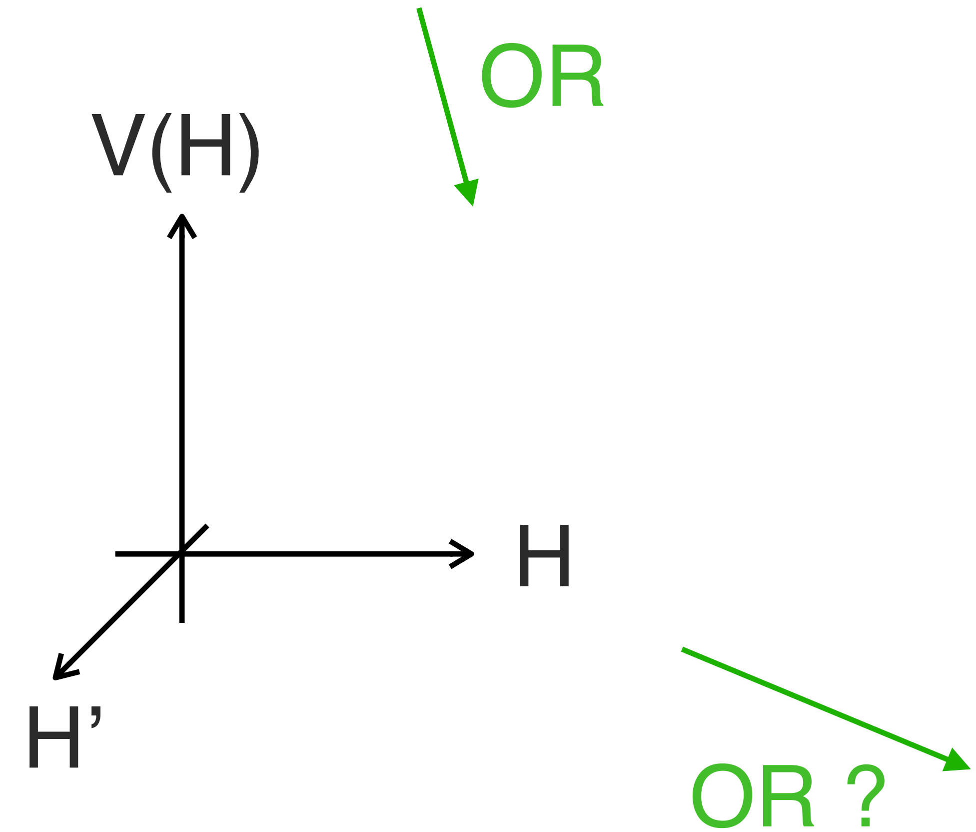
10%

Vev & mass
self-couplings O(1-10) (HL-LHC)

We do not know V(H):







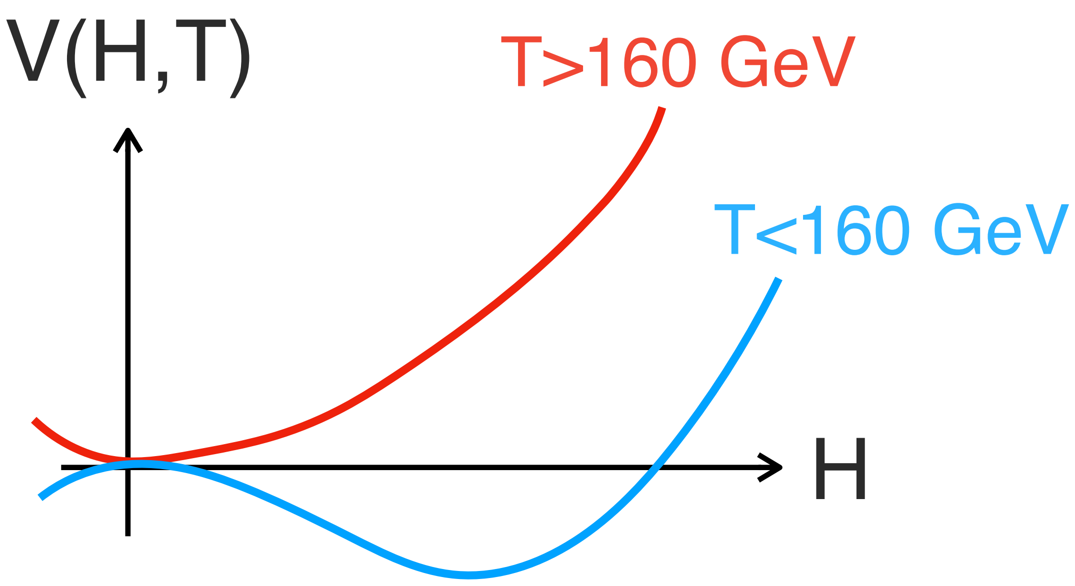
What happens at finite T?
What phase transition?

Why do we care?
— We are curious
— Understand T>100 GeV?
— First order transition and grav. waves?
— Baryogenesis?
— …

Electroweak (EW) phase transition:

1) **Continuous** (ex: Standard Model)
2) **Discontinuous** (Standard Model + <u>what</u>?)
3) **No transition** (Standard Model + <u>what</u>?)

Continuous: Standard Model + nothing



$$m_H^2(T) \sim m_H^2 + \left[\frac{1}{2}\lambda_H + \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2\right]T^2$$

Discontinuous: Standard Model + <u>what</u>?

Example:
Everybody's model: a scalar singlet S

$$V = m^2|H|^2 + \lambda|H|^4$$

$$+m_*^2 S^2 + g_* m_* S^3 + g_*^2 S^4$$

$$+c|H|^2 \left[g_* m_* S + g_*^2 S^2\right]$$

Grojean-Servant-Wells (2005)

Heavy S (ε<1)

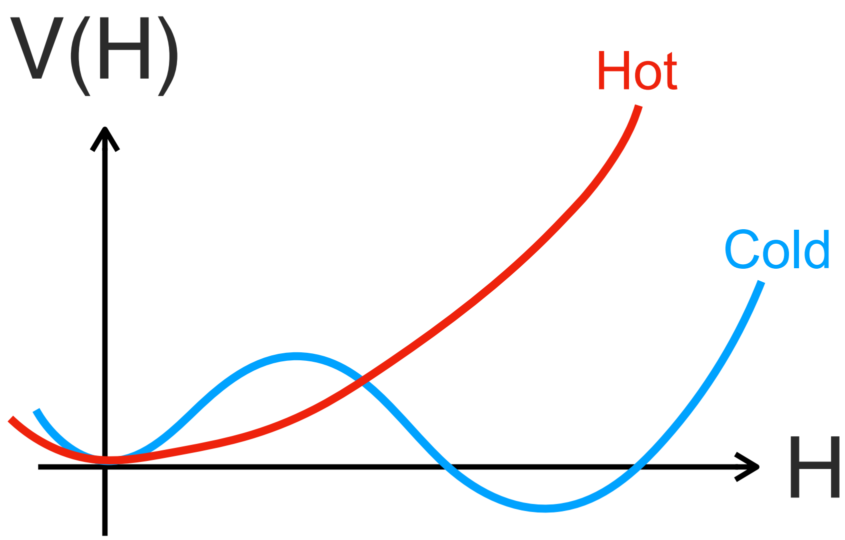
$$\lambda_H = \lambda + c^2 g_*^2$$

$$\mathcal{L}_{\rm EFT} = |DH|^2 - m_H^2 |H|^2 - \lambda_H |H|^4$$
$$+ \frac{c_H}{v^2}(\partial|H|^2)(\partial|H|^2) + \frac{c_6 \lambda_H}{v^2}|H|^6 + \cdots$$

$$\epsilon = \frac{c g_*^2 v^2}{m_*^2} = \frac{V_{H^{2n+2}}}{V_{H^{2n}}} \ll 1$$

$$c_H = c\epsilon \ll 1$$

$$c_6 = \epsilon \frac{c^2 g_*^2}{\lambda_H}$$



mH^2>0 & λH<0 & c6>0 & c6~1
→ <u>1st order</u>

$$c_6 \sim 1 \iff \frac{c^2 g_*^2}{\lambda_H} \sim \frac{1}{\epsilon} \gg 1$$

Fine tuning of quartic (+mass) is necessary

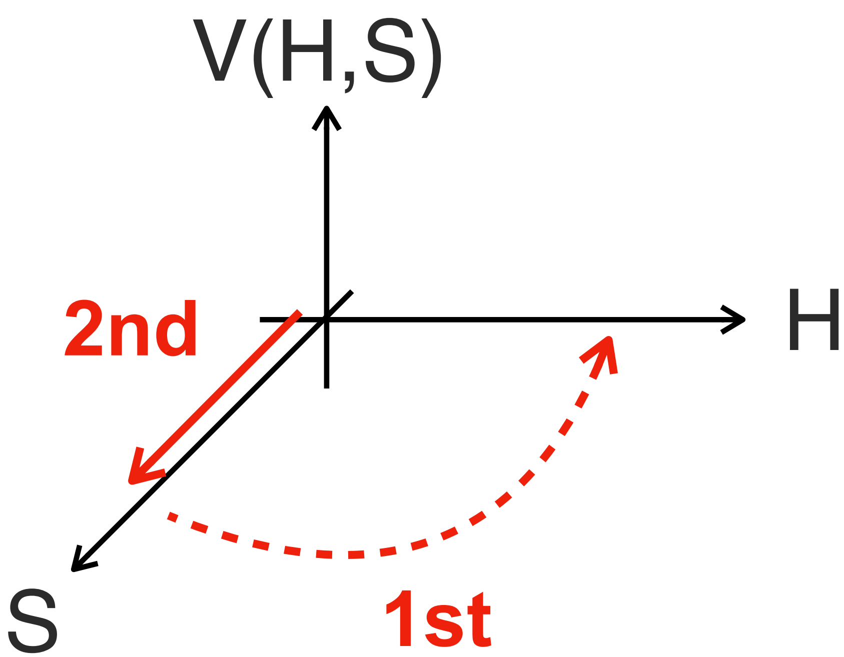
Anderson-Hall (1992)
Espinosa-Quiros (1993)
Choi-Volkas (1993)
…

Light S (ε>1)

Z2 symmetry

$$V = m^2|H|^2 + \lambda|H|^4$$
$$+ m_*^2 S^2 + \xcancel{g_* m_* S^3} + g_*^2 S^4$$
$$+ c|H|^2 \left[\xcancel{g_* m_* S} + g_*^2 S^2\right]$$

$$\epsilon = \frac{c g_*^2 v^2}{|m_*^2|} > 1$$



$$m_*^2 < 0, \quad c > 0$$

2-step transition at finite T → <u>1st order</u>

No tuning of quartic necessary

Small corrections to Higgs couplings

(Collider Bounds: H→SS)

Electroweak (EW) phase transition:

1) **Continuous** (ex: Standard Model, or SM + S) ✔
2) **Discontinuous** (ex: SM + higher-dim., SM + S) ✔
3) **No transition?**

Toy model: Linear O(N), Light S

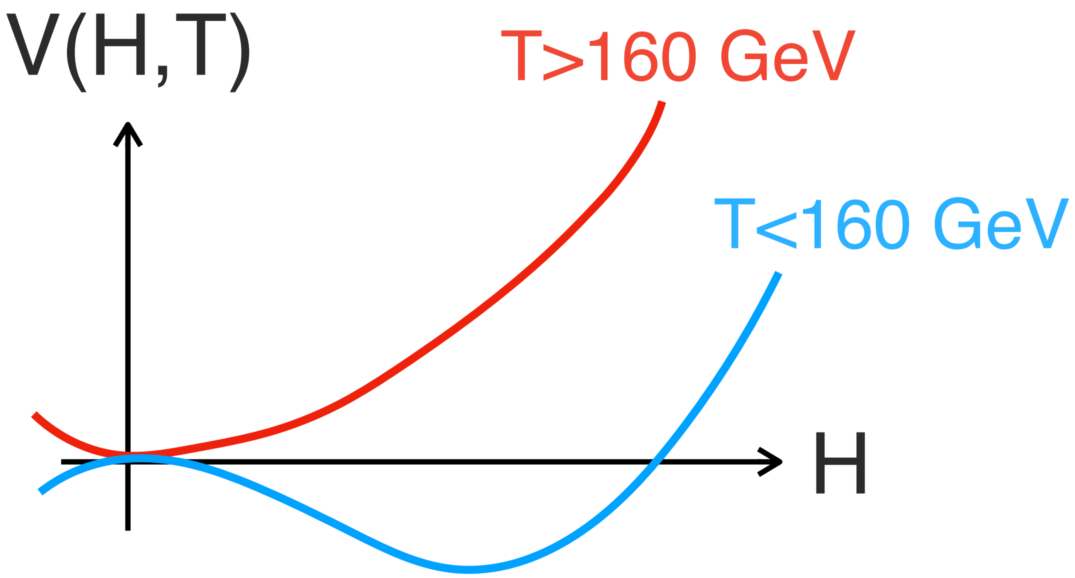
Large N <u>necessary</u> and <u>welcome</u>…

$$V = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4}(S^2)^2 + \lambda_{HS} S^2 H^\dagger H$$

$$-\sqrt{\lambda_S \lambda_H} < \lambda_{HS} < 0$$

Weinberg (1974)
Meade-Ramani (2018)
Baldes-Servant (2018)
Glioti, Rattazzi, LV (2018)

As a rough first approximation:
V(H,S) with 1-loop thermal masses and couplings at T



$$m_H^2(T) \sim \left[\boxed{\left(\frac{1}{2}\lambda_H + \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2 \right)} + \boxed{\frac{1}{12}N\lambda_{HS}} \right] T^2$$

Many dof with >

Many dof with <

Negative H mass mass $|\lambda_{HS}|N \gtrsim 4.5$

Stability $\frac{\lambda_{HS}^2}{\lambda_H \lambda_S} < 1$

$$\Longrightarrow \quad \langle h^2(T)\rangle \sim \frac{|m_H^2(T)|}{\lambda_H(T)} \qquad \langle S^2(T)\rangle = 0$$

$$N > \frac{(N\lambda_{HS})^2}{\lambda_H(N\lambda_S)} \gtrsim \left(\frac{\lambda_S N}{16\pi^2}\right)^{-1}$$

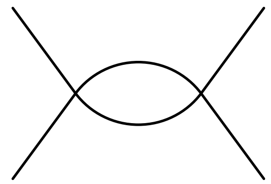
Qualitative…

Large N necessary

Glioti, Rattazzi, LV (2018)

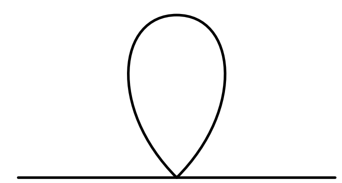
A curious scaling

Perturbation theory:



$$\epsilon_H \equiv \frac{\lambda_H}{16\pi^2} \ll 1, \quad \epsilon_S \equiv \frac{\lambda_S N}{16\pi^2} \ll 1, \quad \boxed{\epsilon_{HS} \equiv \frac{|\lambda_{HS}|\sqrt{N}}{16\pi^2} \ll 1}$$

Thermal H mass (leading order):



$$\delta m_H^2 \sim \frac{\lambda_{HS} N}{12} T^2 \sim \boxed{\epsilon_{HS}\sqrt{N}(\pi T)^2}$$

$$\sqrt{N} \gg \frac{1}{\epsilon} \gg 1$$

Sizable finite T effects (in particular symmetry non-restoration) even if the theory is weakly-coupled in vacuum!

$$\sqrt{N} \gg \frac{1}{\epsilon} \gg 1$$

Generalizes to any large N theory coupled to |H|^2: $\delta\mathcal{L} = \frac{\epsilon}{\sqrt{N}} H^\dagger H O$

— All non-linear effects are small at ε<<1
— N>>1 thermalized states → large thermal Higgs mass
— Large Higgs VEV → <u>top, Higgs, W, Z might decouple…</u>

Towards a refined approximation: **what expansion parameter?**

EFT: Calculation of the effective potential is effectively 3D.

$$m_{\rm Heavy} = \frac{4\pi T}{\hbar}$$

$$\frac{m_{\rm Light}}{\hbar} = \frac{g\sqrt{N}\sqrt{\hbar}}{4\pi} m_{\rm Heavy} = \frac{g\sqrt{N}T}{\sqrt{\hbar}}$$

— 3D couplings are relevant $g_3^2 = g^2 T$
— Poorer convergence of perturbative series.

$$\epsilon_{3,\rm Heavy} = \frac{g^2 N T}{4\pi m_{\rm Heavy}} = \frac{g^2 N \hbar}{(4\pi)^2} = \epsilon_4$$

$$\epsilon_{3,\rm Light} = \frac{g^2 N T}{4\pi m_{\rm Light}} = \frac{g\sqrt{N}\sqrt{\hbar}}{4\pi} = \sqrt{\epsilon_4}$$

Large N welcome:
— re-sums all √ε (auxiliary field)
— tell us which diagrams dominate

Auxiliary field

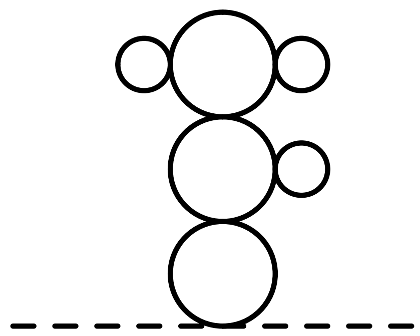
$$\mathcal{L} = D_\mu H^\dagger D^\mu H - \left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma\right) H^\dagger H - \lambda_H \left(1 - \frac{\lambda_{HS}^2}{\lambda_H \lambda_S}\right)(H^\dagger H)^2 + \frac{1}{4\lambda_S}\sigma^2 + N\Gamma[m_S^2 + \sigma, \partial]$$

$$V_{\rm eff}(h,\sigma_c) = \frac{1}{2}\left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma_c\right) h^2 + \frac{\lambda_H}{4}\left(1 - \frac{\lambda_{HS}^2}{\lambda_H\lambda_S}\right) h^4 - \frac{1}{4\lambda_S}\sigma_c^2 + N V_0(m_S^2 + \sigma_c)$$
$$+ V_0\left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma_c + \lambda_H\left(3 - \frac{\lambda_{HS}^2}{\lambda_H\lambda_S}\right) h^2\right)$$
$$+ 3V_0\left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma_c + \lambda_H\left(1 - \frac{\lambda_{HS}^2}{\lambda_H\lambda_S}\right) h^2\right)$$
$$+ 6V_1\left(\frac{g^2}{4}h^2\right) + 3V_1\left(\frac{g^2 + g'^2}{4}h^2\right) + 12 V_{1/2}\left(\frac{y_t^2}{2}h^2\right)$$

"Tree"

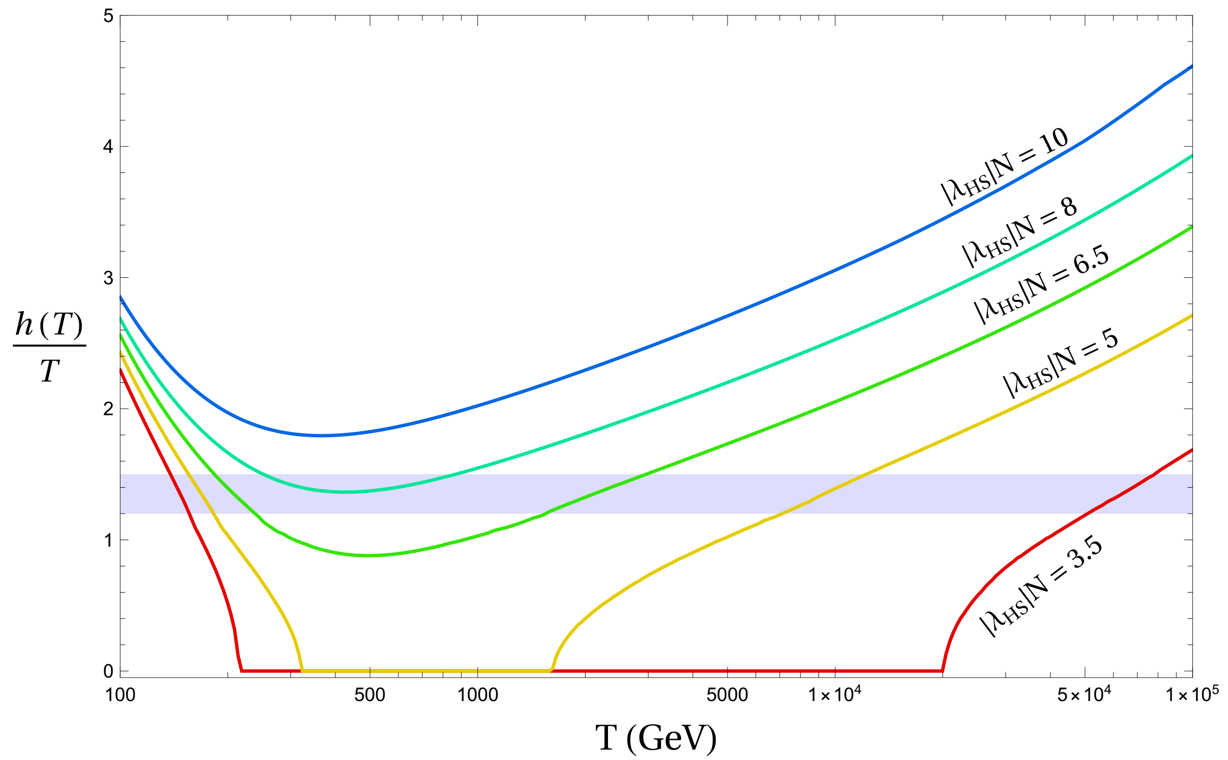
Higgs (NGB) loop

gauge+top



Includes main effects (systematically improvable):
O(1/N), all orders in Nλ_S, all orders in Nλ_HS, but neglects 2-loop SM

$$V_j(M^2) = (-)^{2j}\frac{1}{64\pi^2}(M^2)^2[\ln(M^2/\mu^2) - c_j] + (-)^{2j} T \int \frac{d\vec{p}}{(2\pi)^3} \ln\left[1 - (-)^{2j}\exp\left(-\frac{1}{T}\sqrt{\vec{p}^2 + M^2}\right)\right]$$



1/N calculation "confirms" that N>>1 is required (self-consistency?):

Constrained at low T

$$N > \frac{(N\lambda_{HS}(m_t))^2}{\lambda_H(\Lambda)(N\lambda_S)} \geq \mathcal{O}(50)\left(\frac{0.07}{\epsilon_S}\right)$$

Sizable NLO effects

$$\epsilon_S = \frac{\lambda_S N}{16\pi^2}$$

Gets small fast at high RG scales (T)

1) Top Yukawa is large at T=100 GeV
2) RG effects (top) makes λH much smaller at μ>>weak (here Λ=100 TeV)
3) Large √ε effects (for ε~0.01-0.07) help a bit

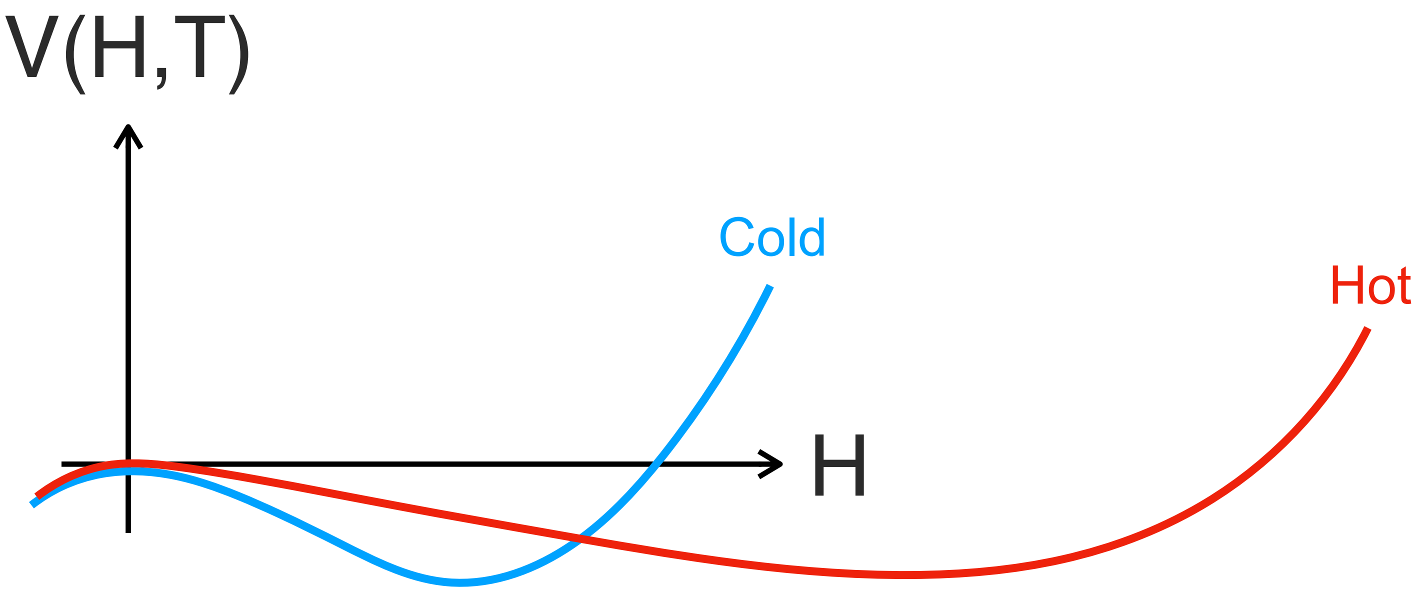
How large N?

Depends on:

(1) How large UV cutoff? → N decreases if the UV cutoff is lower
(2) Absolute stability? → N~20-30 if vacuum is metastable (long-lived)
(3) SM neutrality? → N~20-30 if Higgs replaced by other EW scalars

(Ex: S~Adj of SU(5) has N=24)

OK, we may have EW symmetry non-restoration.
What is it good for?!



EW Baryogenesis…

Sakharov (1967)

Dimopoulos, Susskind (1978)
Kuzmin et al. (1985)
Cohen et al. (1990)

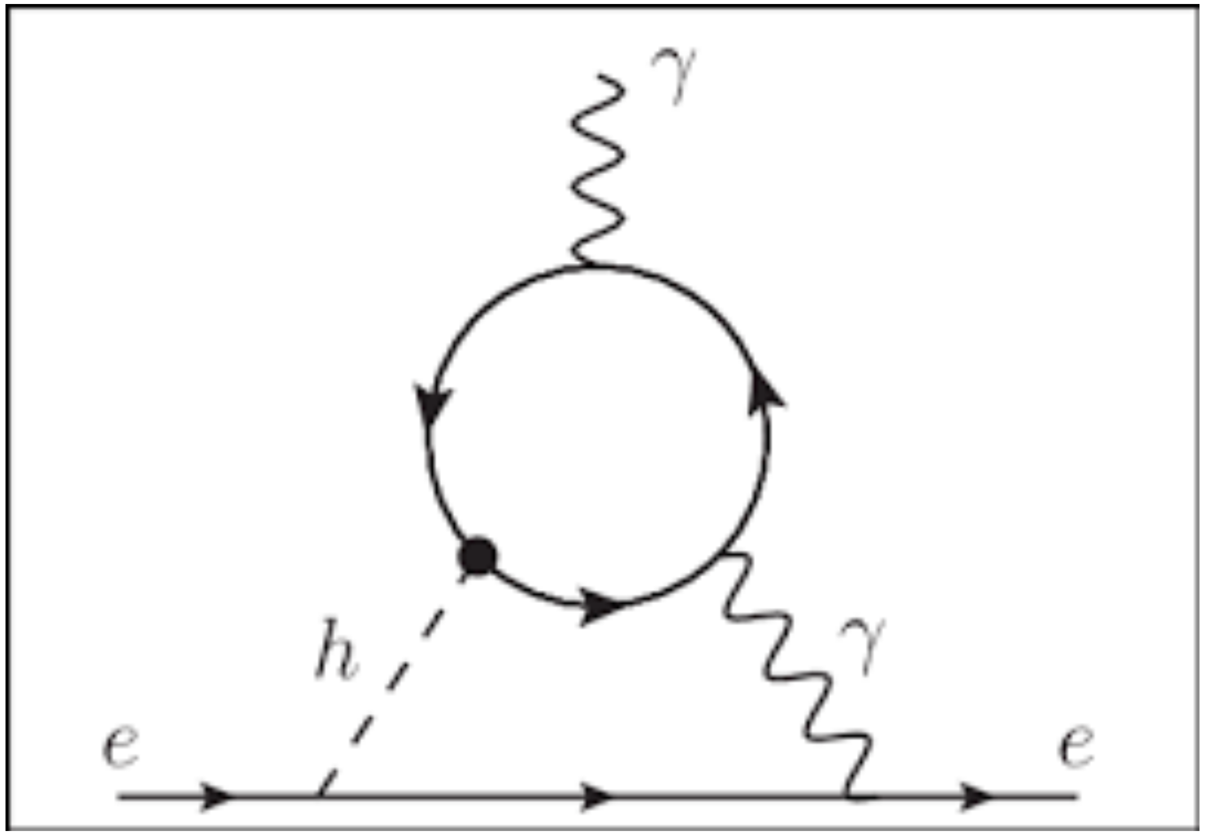
Electroweak Baryogenesis

1) No equilibrium → 1st order EW transition ✔
2) B violation → Sphalerons (B+L) ✔
3) C violation → Gauge ✔
4) CP violation → New physics at $m_* \sim c_{\not{C}\not{P}}\, g_* T_{\rm EW}$?

$$m_* \sim c_{\not{CP}}\, g_* T_{\rm EW}$$
$$T_{\rm EW} \sim 100 \text{ GeV}$$

Problem!!!

— Colliders: EW (colored) m_*>300 (1000) GeV
— Flavor violation: m_*>> 100 GeV
— Electric dipole moments: m_*> TeV (Barr-Zee)



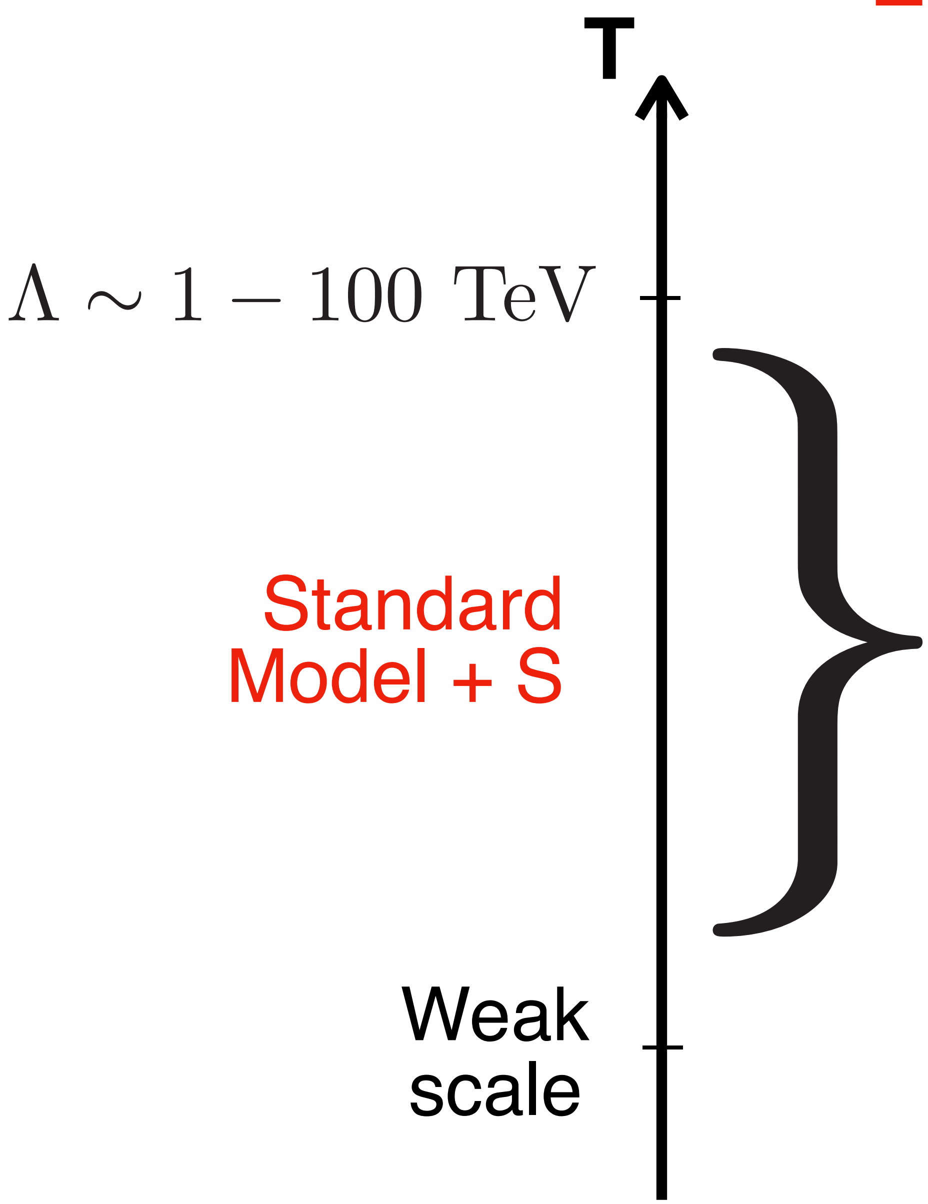
$$\frac{d_e}{e} \sim \frac{g^2}{16\pi^2}\frac{c_{\not{CP}}^2 g_*^2}{16\pi^2}\frac{m_e}{m_*^2}$$
$$\sim 10^{-29}\text{cm}\left(\frac{4 \text{ TeV}}{m_*/c_{\not{CP}}\, g_*}\right)^2$$

Glioti, Rattazzi, LV (2018)

Bounds structurally relaxed if $T_{\rm EW} \sim \Lambda \gg {\rm TeV}$

$\Updownarrow$

EW symmetry non-restoration

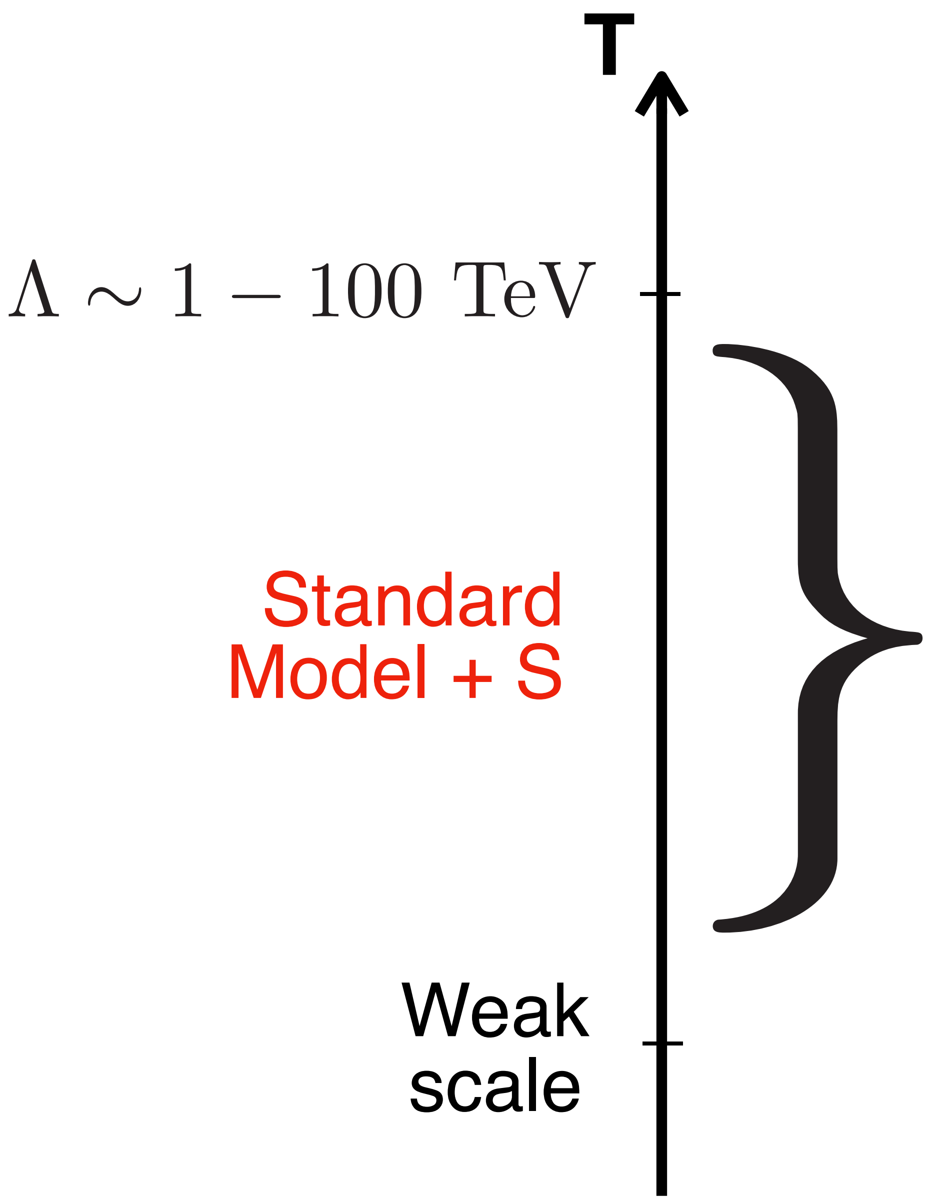


$$\frac{d\eta_B}{dt} = -\Gamma_{\rm sph}\eta_B + S_{C\!\!\!/P}$$

1st order transition
+<u>CP violation</u>

$$\frac{d\eta_B}{dt} = -\Gamma_{\rm sph}\eta_B$$

Must avoid washout



$$\frac{d\eta_B}{dt} = -\Gamma_{\rm sph}\eta_B + S_{\not{CP}}$$

1st order transition
+CP violation

$$\frac{d\eta_B}{dt} = -\Gamma_{\rm sph}\eta_B$$

Must avoid washout

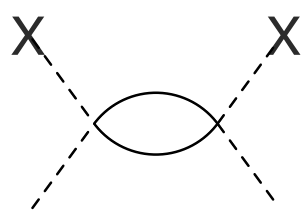
$$\Gamma_{\rm sph} \sim T e^{-\frac{4\pi h}{gT}} \ll H(T)$$

$$\Longrightarrow \quad h(T)/T \gtrsim 1$$

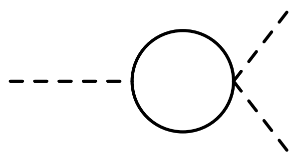
N>>1

Colliders:

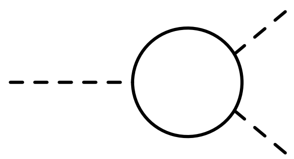
— S must be at the EW scale mS<<TeV
— H→SS must be kinematically forbidden mS>63 GeV
— <u>All signatures suppressed by 1/N</u>



$$\delta Z_H \sim \frac{\lambda_{HS}^2 N v^2}{16\pi^2 m^2} \sim \frac{1}{N}$$



$$\frac{\delta\lambda_3}{\lambda_3} \sim \frac{\lambda_{HS}^2 N v}{16\pi^2 \lambda_H v} \sim \delta Z_H$$



$$\frac{\delta\lambda_3}{\lambda_3} \sim \frac{\lambda_{HS}^2 N v^2}{16\pi^2 m^2}\frac{\lambda_{HS}}{\lambda_H} \sim \delta Z_H \frac{100}{N}$$

$$d\sigma(pp \to SS + X) \propto \lambda_{HS}^2 N \sim \frac{1}{N}$$

Testable at 100 TeV pp collider
(Curtin-Meade-Yu, 2014)

Astrophysics with N>>1

S stable on cosmological scales
→ Excluded by direct detection (abundance N times larger than N=1)

Cross section for N=1

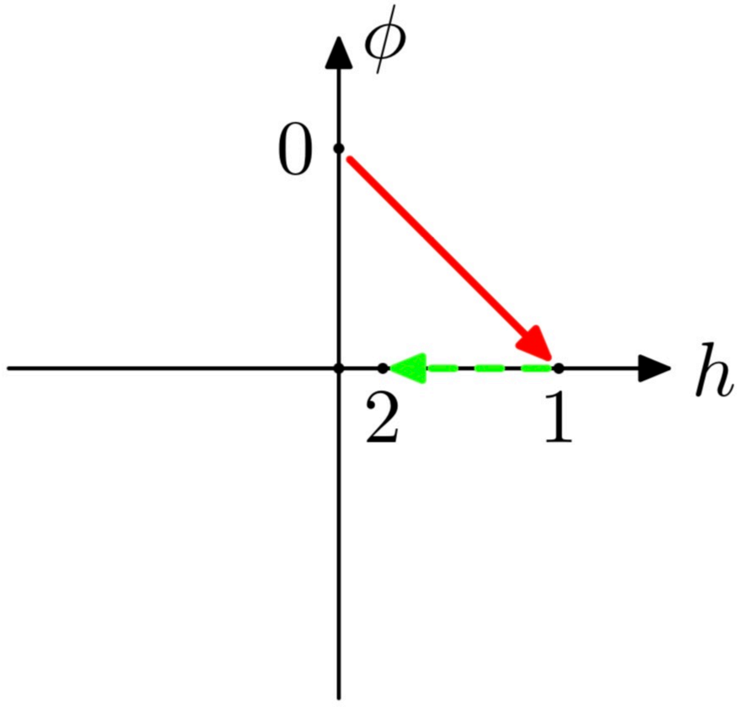
$$\frac{dn_{\rm tot}}{dt} + 3H(T)n_{\rm tot} \approx -\frac{\langle \sigma_{\rm ann} v \rangle}{N}[(n_{\rm tot})^2 - (n_{\rm tot}^{\rm eq})^2],$$

Solutions

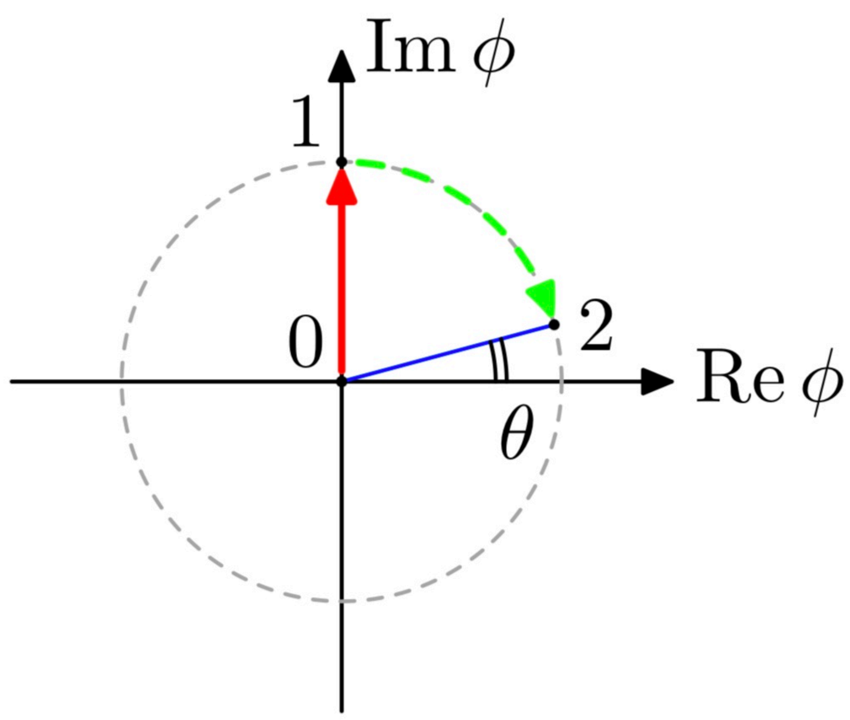
— Keep O(N) and add lighter particles to play the role of dark matter
— Break O(N) via soft terms (peculiar collider signatures)
— Break O(N) via gauging (peculiar large N meson phenomenology)

1st order transition at Λ>>100 GeV: many options

No obstruction from S.



2 scalars
(weak coupling)



Composite Higgs
(strong coupling)

Conclusions

* **Nature of the electroweak phase transition? 3 Options:**
  - Opt1. Continuous (Ex: Standard Model!)
  - Opt2. Discontinuous. Price: new light (colliders) or heavy (fine-tuned) d.o.f.
  - Opt3. No (or early) transition?
* **Opt3: no (or early) transition**
  - Proved it is possible: peculiar $\sqrt{N}>1/\varepsilon>1$ scaling
  - Price: N>>1 light scalars (collider and astro signatures)
  - Models with N~20-30 exist (details need to be worked out)
* **EW Baryogenesis remains main new physics motivation for Op2, Op3**
  - Opt2 (1st order transition at 100 GeV) under significant pressure
  - Tension structurally relaxed with Opt3. Is the price N>>1 worth it?

Thank You