ElectroWeak Baryogenesis above the Weak Scale

Riccardo Rattazzi, EPFL

- Alfredo Glioti, RR, Luca Vecchi, to appear
- Meade, Ramani 2018
- Baldes, Servant 2018

Problems vs Mysteries

- Dark Matter
- Baryogenesis
- Strong CP
- Fermion masses & mixings

Plausible EFT-solutions exist

- Cosmological Constant
- EW hierarchy
- BH information paradox

Challenge EFT paradigm

Problems

- Dark Matter
- Baryogenesis
- Strong CP
- Fermion masses
  & mixings

Inflation → $\rho_{DM}, \frac{n_B}{s}$ need mechanism operating during Big Bang before BBN

▲ B from high-T mechanism $\sim$ boundary condition

possible because
- B-L is conserved in SM at $T \lesssim T_{B-L}$
- B+L violated by SM sphaleron processes

Ex.
- leptogenesis
- Affleck-Dine mechanism

▲ EW Baryogenesis: primordial B-L = 0

n_B generated by sphalerons at EW phase transition, below which B and L well defined q-numbers (≡conserved)

EW-Baryogenesis in principle testable in experiment

▲ SM could have realized it, but it failed quantitatively

- B+L violated by sphalerons
- $m_h \simeq 125\,\mathrm{GeV}$ phase transition is a smooth crossover
- $J_{CP} \sim 10^{-5}$ too small in any case

▲ New Physics at 100's GeVneeded to ensure

- 1st order phase transition
- enough CP violation

... and still not easy to pass constraints from direct and indirect searches (ex. edms)

Ex: MSSM and its variants

Phase transition: ~~light stops~~ or NMSSM

direct searches &
Higgs couplings

Katz, Perelstein, Ramsey-Musolf, Winslow 2016

CP phases: ~~$A_{\tilde{f}}^* B$~~ with resonant sfermions

ruled out by
d_{Hg} and d_e

Kozaczuk, Profumo, Ramsey-Musolf, Wainwright 2012

$M_{1/2}^* B$ via Higgsino-gaugino mixing

only higgsino-bino with non-universal phase survives with $d_e \gtrsim 10^{-29} e\,\mathrm{cm}$

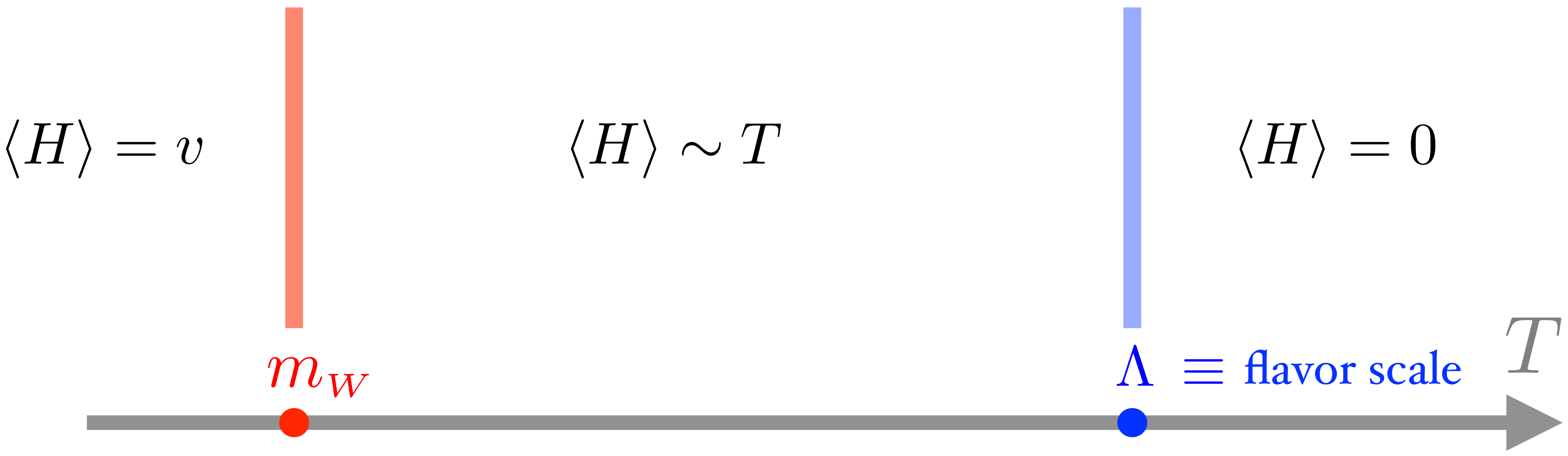
Cirigliano, Li, Profumo, Ramsey-Musolf 2010

No big surprise: Flavor and CP violation have long nagged natural approaches to Hierarchy Problem

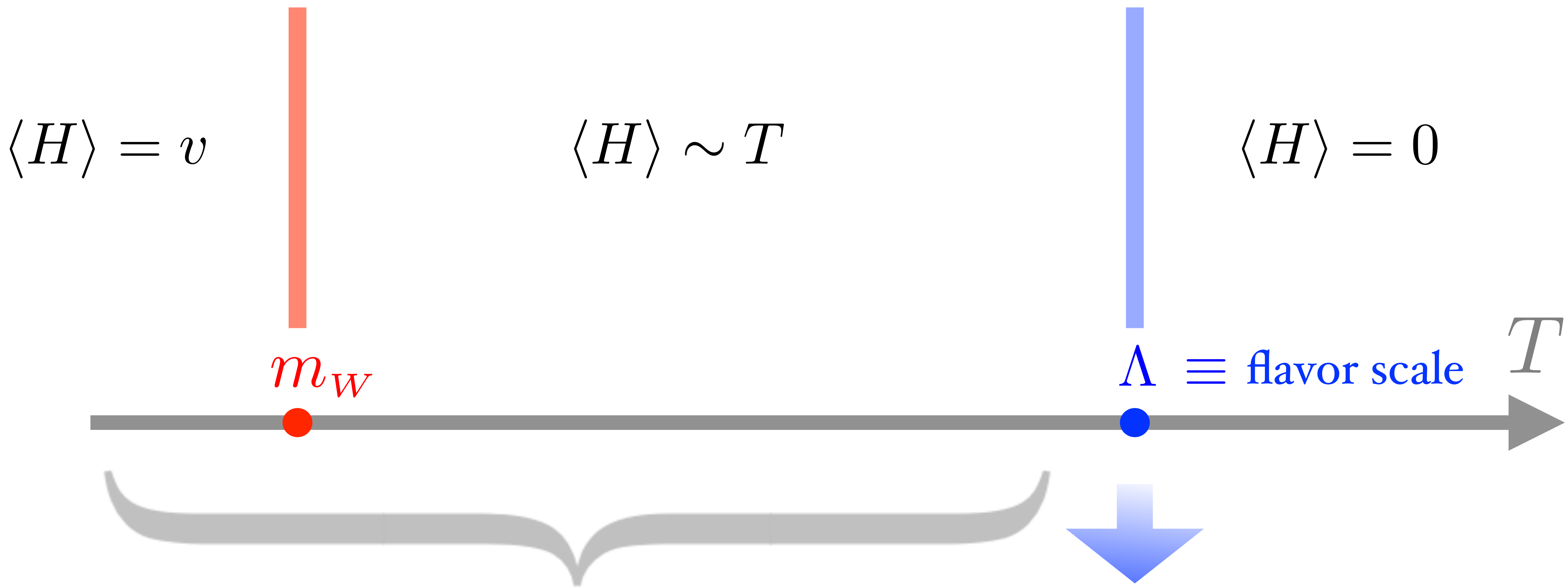
There however exist(ed) very special scenarios cleverly doing away with all Flavor & CP effects at weak scale (ex: Gauge Mediated Supersymmetry Breaking)

Is there a way to realize EW-baryogenesis without introducing any new sources of CP violation at the Fermi scale?

Scenario


$\langle H \rangle = v$
$\langle H \rangle \sim T$
$\langle H \rangle = 0$
T
m_W
$\Lambda \equiv$ flavor scale

Scenario



$\frac{\langle H \rangle}{T} \gtrsim 1$

- sphalerons suppressed
- n_B/s preserved

- 1st order PT + CP viol.
- n_B/s from sphalerons

$\langle H \rangle = 0$ in SM at $T > 160\,\mathrm{GeV}$ → **Light New Physics**

The mechanism for ensuring $\langle H \rangle \neq 0$ at $T \gg m_h^2$
already appears in Weinberg's 1973 paper on finite T
but stressed to us by Meade

- Meade, Ramani 2018
- Baldes, Servant 2018
- Glioti, RR, Vecchi…still waiting

minimal communications, basically same model,
but some different perspectives

A model (below Λ)

SM + scalar in O(N) fund $\quad S_i \quad i = 1, \ldots, N \quad\quad S^2 \equiv S_i S_i$

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

$\lambda_h, \ \lambda_S > 0 \quad\quad -\sqrt{\lambda_h \lambda_S} < \lambda_{hS} < 0$ → **stability**

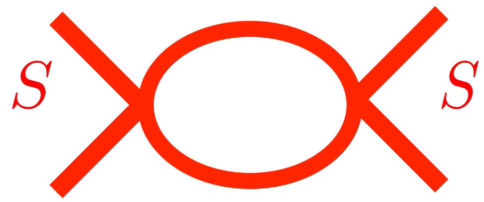
$$\lambda_{hS}^2 \leq \lambda_h \lambda_S$$

$m_H^2 < 0 \quad\quad m_S^2 > \dfrac{\lambda_{hS}}{\lambda_h} m_H^2$ → **minimum at**

$$\langle H \rangle \neq 0 \quad\quad \langle S \rangle = 0$$

Of Loops and Tadpoles

weakly coupled



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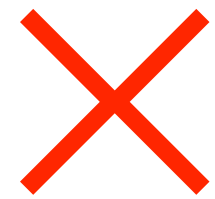
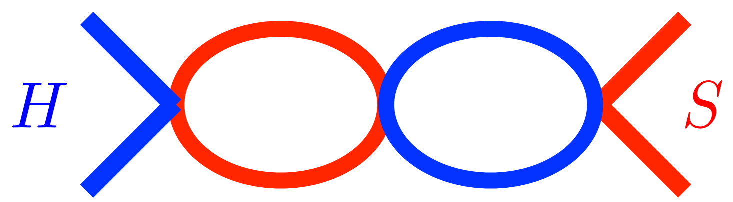


$$\epsilon_S \equiv \frac{\lambda_S N}{16\pi^2} \ll 1$$



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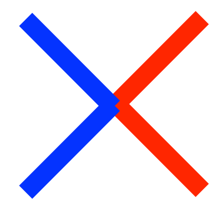
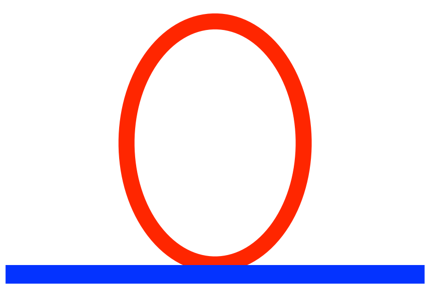


$$|\epsilon_{hS}| \equiv \frac{|\lambda_{hS}|\sqrt{N}}{16\pi^2} \ll 1$$

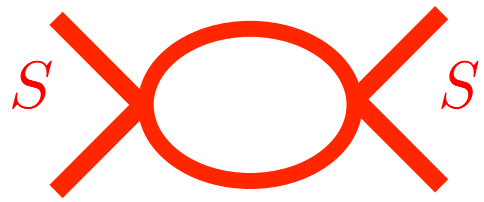
mass effects



$$\propto \quad \frac{\lambda_{hS} N}{16\pi^2}$$

Of Loops and Tadpoles

weakly coupled



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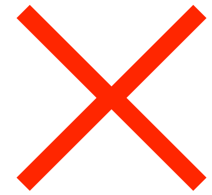

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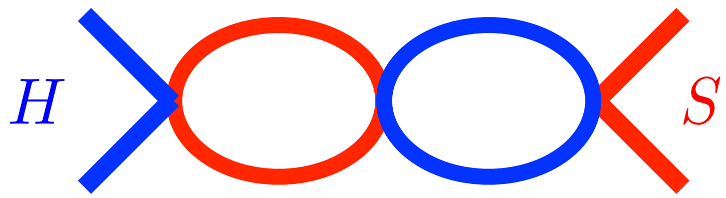

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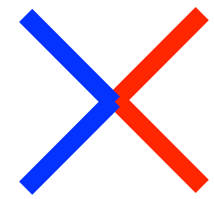
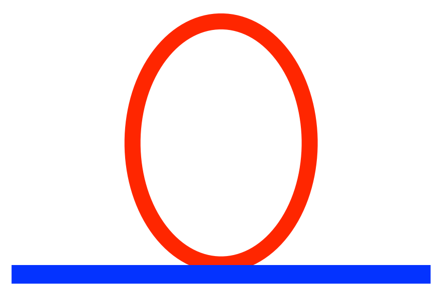


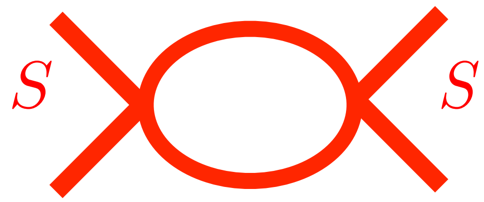
$$|\epsilon_{hS}| \equiv \frac{|\lambda_{hS}|\sqrt{N}}{16\pi^2} \ll 1$$

mass effects

δm_H^2

$$\propto \quad \frac{\lambda_{hS} N}{16\pi^2} M^2 \quad \sim \quad \epsilon_{hS}\sqrt{N}\, M^2$$

Of Loops and Tadpoles

weakly coupled



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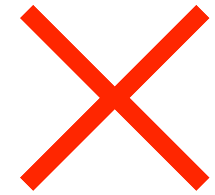
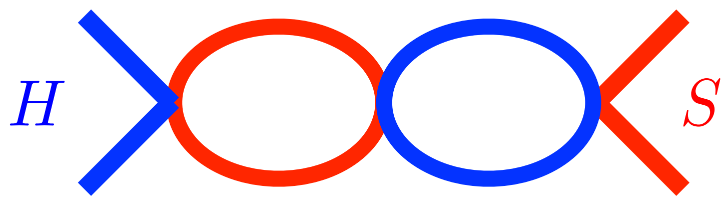


$$\epsilon_S \equiv \frac{\lambda_S N}{16\pi^2} \ll 1$$



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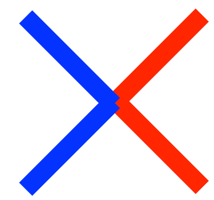
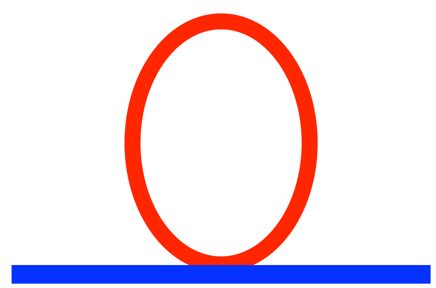


$$|\epsilon_{hS}| \equiv \frac{|\lambda_{hS}|\sqrt{N}}{16\pi^2} \ll 1$$

mass effects

δm_H^2



$$\propto \frac{\lambda_{hS} N}{16\pi^2} M^2 \sim \epsilon_{hS}\sqrt{N}\, M^2$$

Finite T: $M^2 \sim T^2$ → **thermal effects persist at** $N \to \infty, \ \epsilon_{hS} \to 0, \ \epsilon_{hS}\sqrt{N} = \text{fixed}$

Thermal vacuum dynamics in first approximation

$$\frac{h^2(T)}{T^2} = -\frac{m_H^2(T)}{T^2\lambda_h} \simeq -\left[\frac{N}{12}\lambda_{hS} + \frac{1}{2}\lambda_h + \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2\right]\frac{1}{\lambda_h} \equiv \frac{\frac{N}{12}|\lambda_{hS}(T)| - A(T)}{\lambda_h(T)}$$

sphalerons suppressed

$$\lambda_{hS}N \gtrsim 12\left[A(T) + (1.2)^2\lambda_h(T)\right] \gtrsim 7$$

stability

$$N \geq \frac{[N\lambda_{hS}(\mu)]^2}{\lambda_h(\mu)[N\lambda_S(\mu)]}$$

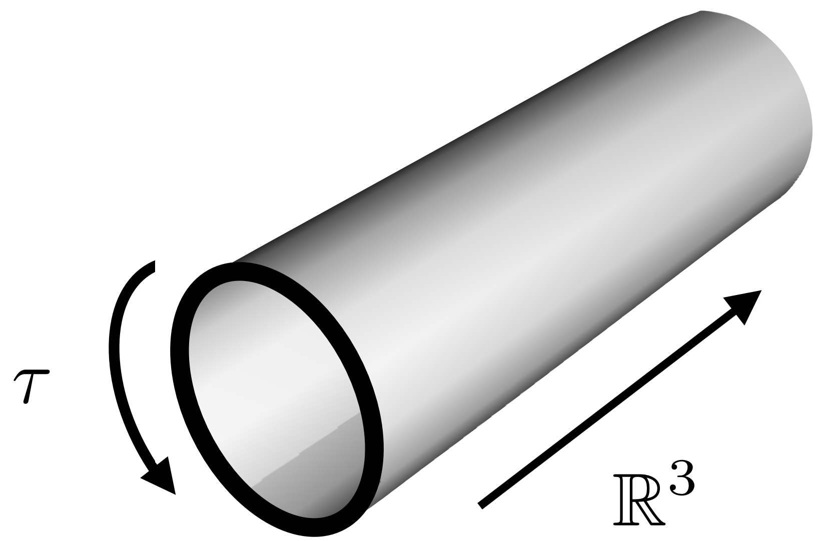
$$N \gtrsim 800\left(\frac{0.01}{\epsilon_S(\Lambda)}\right)$$

Refinements

ϵ_S preferred large → resumm leading series in $1/N$

$\dfrac{h}{T} \gtrsim 1$ → account for Boltzmann suppression

A reminder about thermal loops



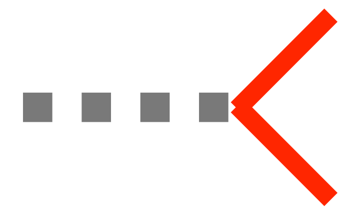
IR enhancement of interaction strength

Ex $\quad \lambda\varphi^4 \xrightarrow{3D} \lambda T\varphi^4 \equiv \lambda_{3D}\varphi^4$

loop-expansion in 3D controlled by $\quad \epsilon_{3D} \equiv \frac{3\lambda T}{8\pi m_\varphi(T)} \xrightarrow{\text{high } T} \frac{3\sqrt{\lambda}}{4\pi} \equiv \sqrt{\epsilon_{4D}}$

same story at large N: $\quad \epsilon_S^{\text{3D}} \sim \sqrt{\epsilon_S}$

ϵ_S effects 'resummed' in $1/N$ expansion $\left[\begin{array}{l} N \to \infty \\ \lambda_S N, \ \lambda_{hS}\sqrt{N} \ = \ \text{fixed} \end{array} \right.$

introduce auxiliary mediator σ 

$$V \quad \to \quad \frac{1}{2}(m_S^2+\sigma)S^2 + \frac{1}{4\lambda_S}\sigma^2 + \left(m_H^2 + \frac{\lambda_{hS}}{\lambda_S}\sigma\right) H^\dagger H - \lambda_h \left(1 - \frac{\lambda_{hS}^2}{\lambda_h \lambda_S}\right)(H^\dagger H)^2$$

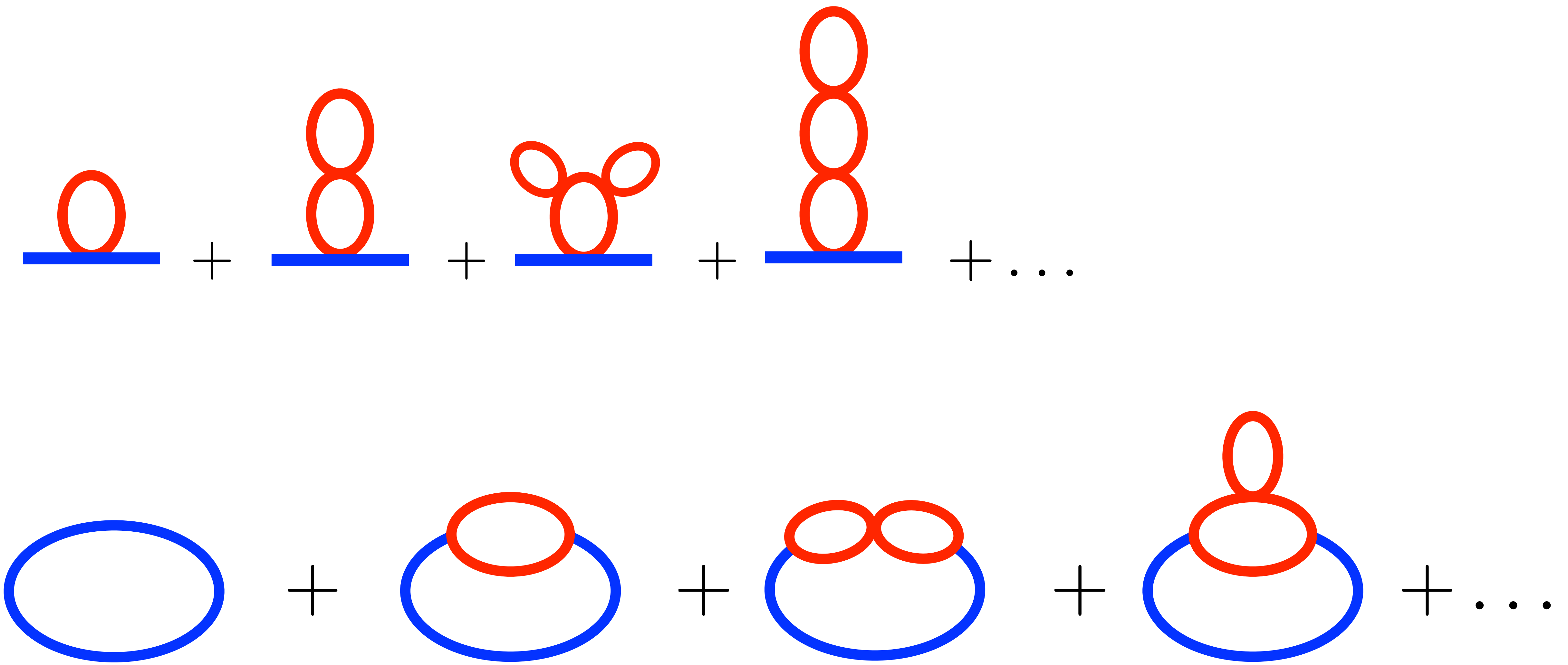
$$\mathcal{L}_{eff} \quad = \quad \mathcal{L}_{SM} + \left(m_H^2 + \frac{\lambda_{hS}}{\lambda_S}\sigma\right) H^\dagger H \ - \ \lambda_h \left(1 - \frac{\lambda_{hS}^2}{\lambda_h \lambda_S}\right)(H^\dagger H)^2$$

$$+ \quad \frac{1}{4\lambda_S}\sigma^2 + N\Gamma[m_S^2 + \sigma, \partial]$$

σ-loops $= \ (1/N)^\ell$

Compute V_{eff} at 1-loop neglecting σ-loops

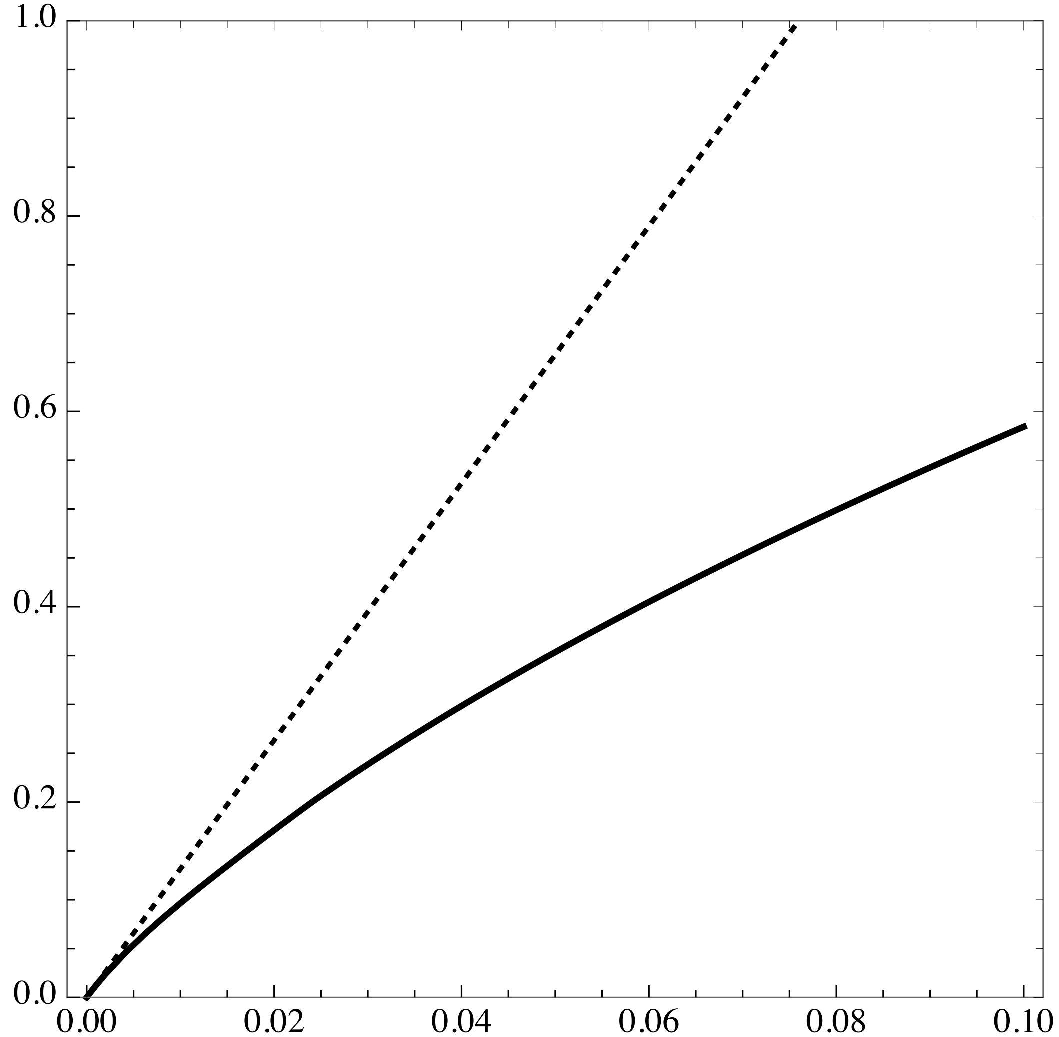
Diagrammatically



Captures

- analytic terms from 4D UV $\qquad (\lambda_S N)^\ell \propto \epsilon_S^\ell$
- non-analytic terms from 3D IR

$\langle\sigma\rangle \equiv \lambda_S \langle S^2 \rangle$

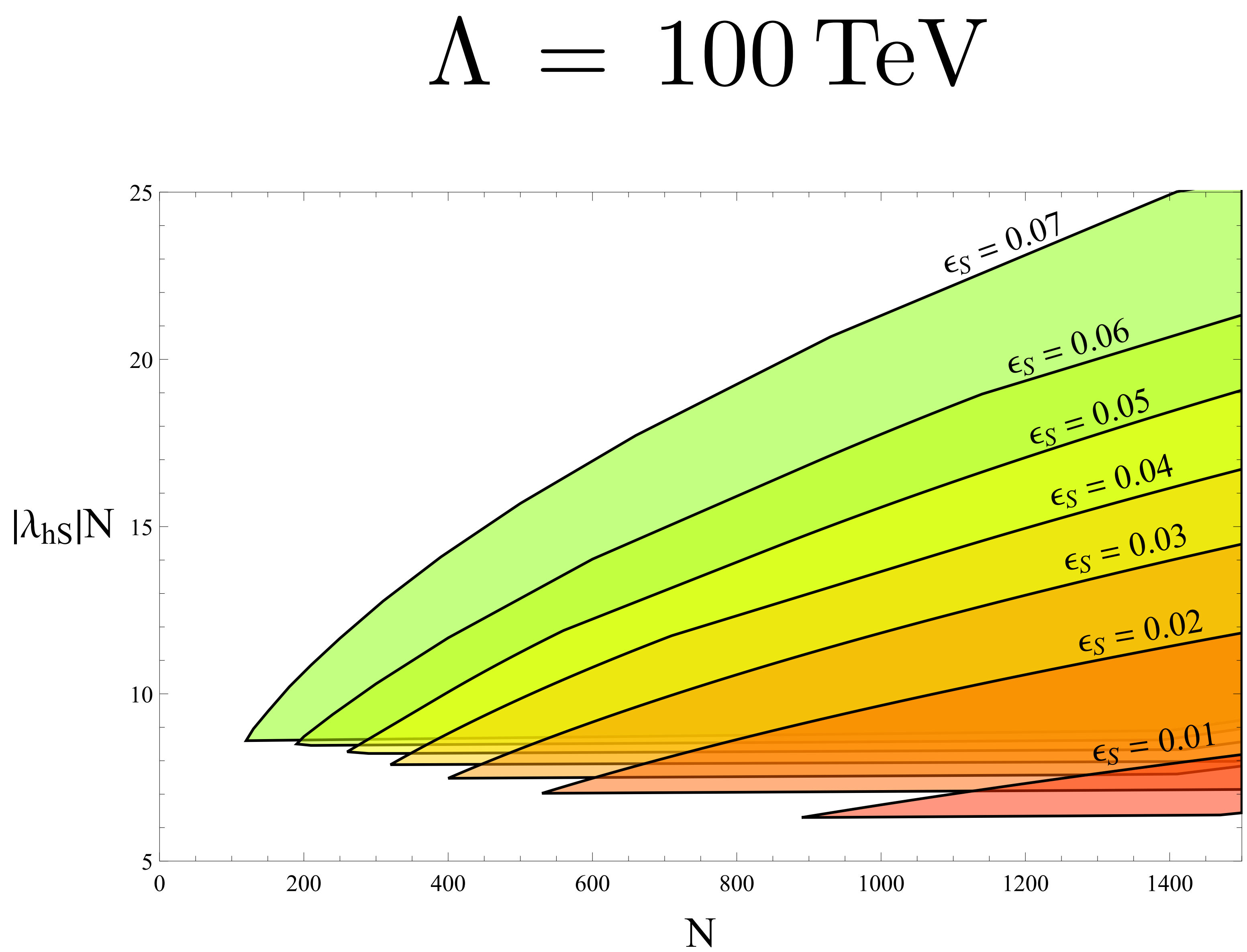


ϵ_S

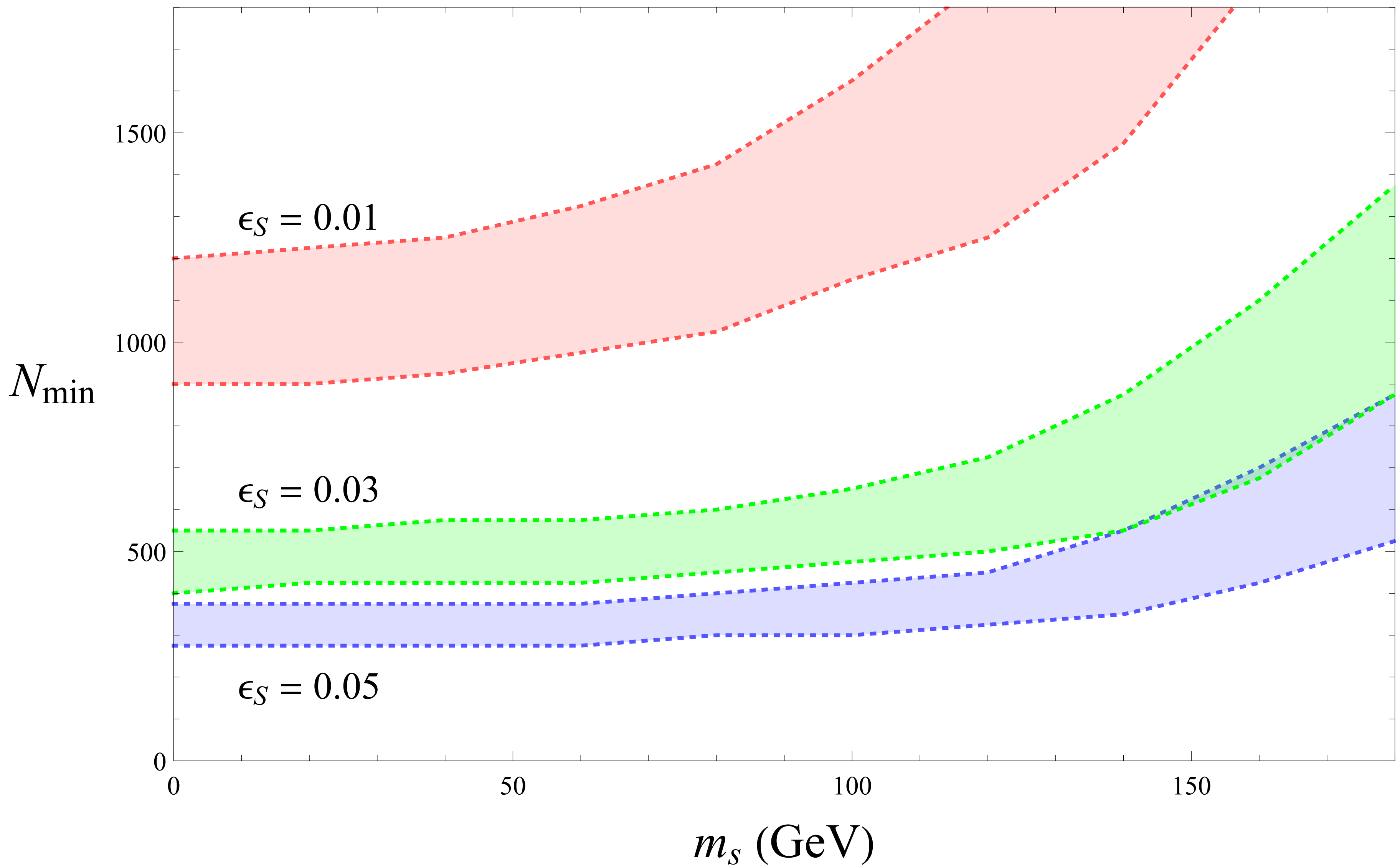
1-loop $= \dfrac{\lambda_S N T^2}{12}$

resummed

As expected 3D effects can be sizeable at weak 4D coupling

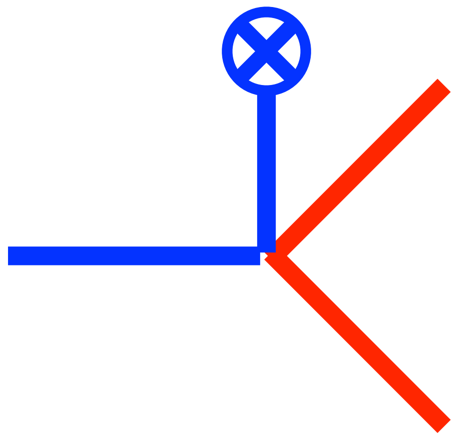


Λ = 100 TeV
|λhS|N
N
ϵS = 0.07
ϵS = 0.06
ϵS = 0.05
ϵS = 0.04
ϵS = 0.03
ϵS = 0.02
ϵS = 0.01
25
20
15
10
5
0
200
400
600
800
1000
1200
1400



$\epsilon_S = 0.01$
$\epsilon_S = 0.03$
$\epsilon_S = 0.05$
$N_{\rm min}$
m_s (GeV)
0
500
1000
1500
0
50
100
150

Collider Phenomenology



$$\mathrm{B}R(h \to \mathrm{inv}) \sim 0.1 \left(\frac{10^6}{N}\right) \longrightarrow m_S > m_h/2$$

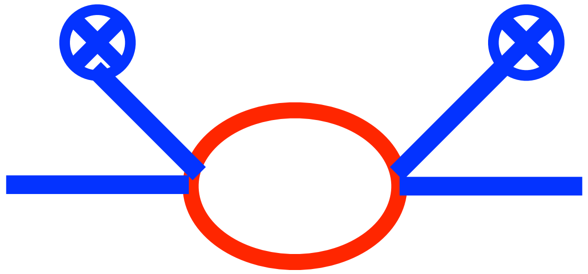
direct 

$$q\bar{q} \to SSV$$

$$qq \to SSqq$$

$$\longrightarrow N \lesssim 10^3$$ sensitivity at 100 TeV

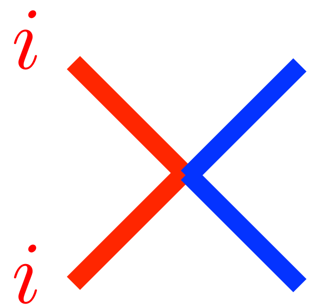
Curtin, Meade, Yu 2014

indirect 

$$\frac{\delta g_h}{g_h} \simeq \frac{(\lambda_{hS} N)^2 v^2}{96\pi^2 m_S^2} \sim \frac{1}{N}$$

Relic Density and Dark Matter

$$n_i = \frac{n_{tot}}{N}$$



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

$$\frac{\rho_S}{\rho_{\rm DM}} \sim \left(\frac{N}{50}\right)^3 \left(\frac{m_S}{100\ {\rm GeV}}\right)^2 \left(\frac{10}{\lambda_{hS} N}\right)^2$$

- assume $\frac{\rho_S}{\rho_{DM}} = 1$ by some other means

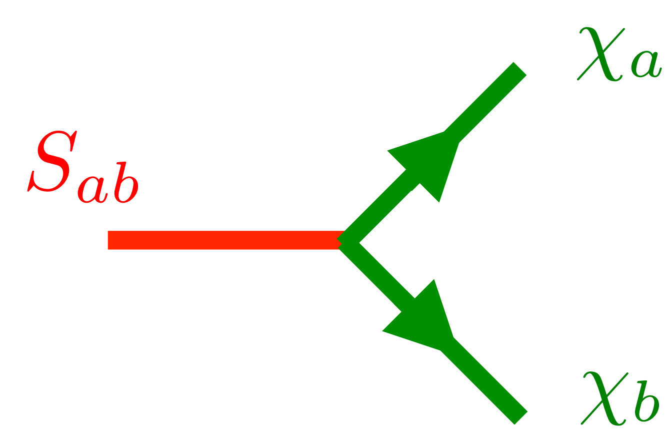
direct detection $\quad \sigma_{\rm DD} \simeq 0.1 \frac{\lambda_{hS}^2}{\pi m_S^2} \frac{\mu_{nS}^2 m_n^2}{m_h^4}$ → $N \gtrsim 2 \times 10^3$

‘Cheap Fixes’: make S decay

- Break SO(N)

$$\delta V_{\rm soft} = a_i \frac{\mu^3}{g} S_i + b_{ij} \frac{\mu^2}{2} S_i S_j + c_{ijk} g\mu S_i S_j S_k + d_i g\mu S_i |H|^2$$

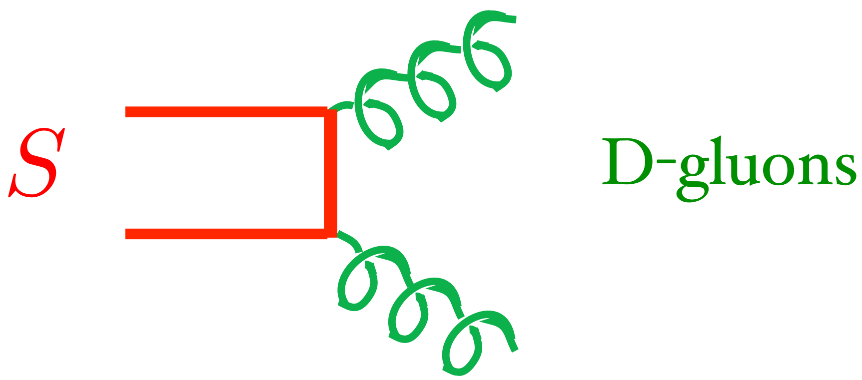
- $S_i \to S_{ab} \qquad a, b = 1, \ldots, n \qquad n^2 \sim N$



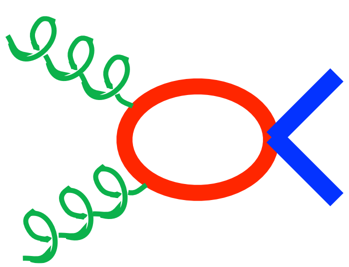
- $m_\chi = m_S \dfrac{\rho_{DM}}{\rho_S}$
- $4\pi\sqrt{g_*}\dfrac{T^2_{\rm BBN}}{m_S M_{\rm Pl}} \lesssim y^2 \lesssim 4\pi\sqrt{g_*}\dfrac{N}{\epsilon_S^2}\dfrac{m_S}{M_{\rm Pl}}$

correct DM density & BBN ok

Less cheap: gauge global $SO(n) \sim SO(\sqrt{N})$ (DQCD)



$g_D^2 \sim 10^{-2}$ ⟷ $\rho_S = \rho_{DM}$



$\tau_{Dglueballs} < \tau_{BBN}$

$G^D_{\mu\nu} G^{D\mu\nu} H^\dagger H$ ⟶ $\Lambda_{DQCD} \gtrsim 1\,\text{GeV}$, $g_D^2 n \gtrsim 1$

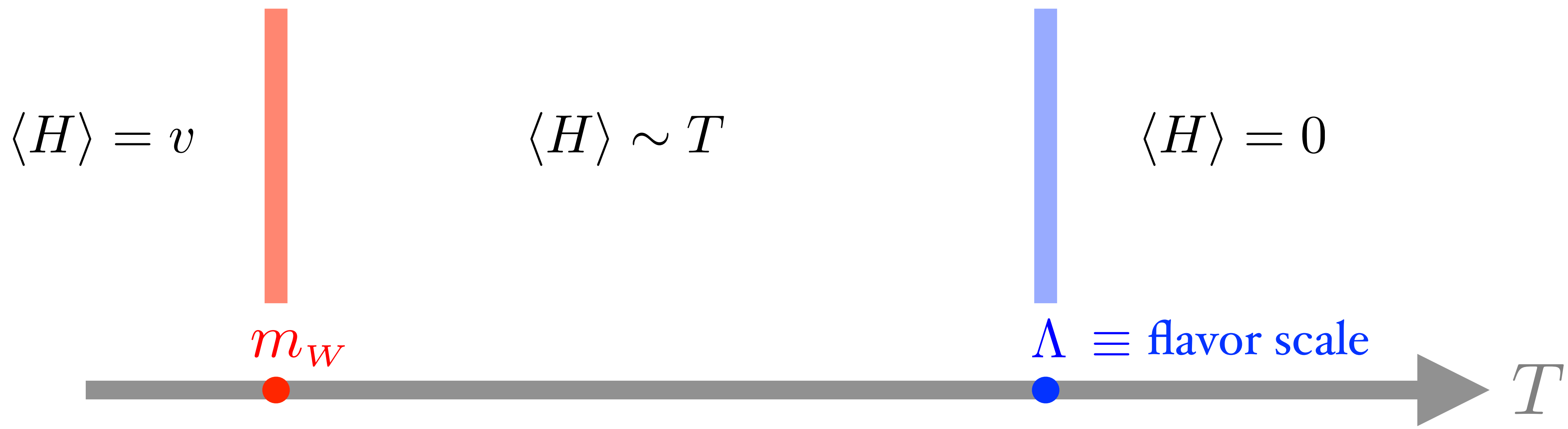
$n \sim \sqrt{N} \sim 50 - 100$

- ☑ DM density
- ☑ BBN
- ☑ direct detection
- ☑ indirect detection
- ☑ suppressed sphalerons

] need detailed computation (indirect detection, suppressed sphalerons)

Summary

Higgs dynamics is relevant for baryogesis, even in the absence of new sources of CP violation at the weak scale



- Weak scale sector with $N \gtrsim 200$ scalars required for $\Lambda \sim 10^2 - 10^3$ TeV
- N seems crazy, but structure of model quite simple
- In principle testable at future colliders for $N \lesssim 10^3$
- Dark sector could provide DM in various ways
- $m_H \sim m_S \ll \Lambda$ un-natural, but crucial for the world as we see it...