# A Tight Scrutiny Of Electroweak Phase Transitions 

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Based on $1510 \pm 1 . x x x x x$ with David Curtin \& Patrick Meade

## Baryogenesis problem

- Fact:The universe around us has excess matter over antimatter
- Baryon-Antibaryon asymmetry with symmetric initial conditions.
- Sakharov Conditions:

1. $\mathrm{C} \mathrm{\& CP}$ violation
2. B violating processes
3. Thermal inequilibrium

## Finite Temperature Effective Potential

- Need Effective Potential V to talk about vev as its minimum.
- Tree level V gets corrections at 1-loop
-Captured by Coleman-Weinberg calculation
-Finite temperature:virtual interactions with plasma
- Imaginary Time formalism to modify potential


## 10 second crash course in FTFT

$$
\begin{array}{rc}
V_{C W}=\frac{1}{2} \int \frac{d^{4} k}{(2 \pi)^{4}} \log \left[k_{E}^{2}+M^{2}\right] & \text { Good old CW potential } \\
\int \frac{d k_{4}}{2 \pi} f\left(k_{4}\right) \rightarrow T \sum_{n} f\left(k_{4}=i \omega_{n}\right), \omega_{n}=2 \pi n T & \text { Imaginary time formalism } \\
\text { replacement }
\end{array}
$$

$$
V_{C W}=V_{C W}^{T=0}+V_{C W}^{T \neq 0} \quad \text { Splits neatly into T-dependent }
$$ and T-independent parts

$$
V_{C W}^{T \neq 0}=\frac{T}{2 \pi^{2}} \int d p p^{2} \log \left[1-\exp \left[-\beta \sqrt{p^{2}+M^{2}}\right]\right]
$$

## Break down of P.T :Conventional wisdom

$$
V_{C W}^{T \neq 0}=\frac{T^{4}}{2 \pi^{2}} J_{B}\left(\frac{M^{2}}{T^{2}}\right)
$$

In the high T limit,

$$
\Pi_{1}(T)=\frac{d^{2} V_{C W}^{T \neq 0}}{d h^{2}}=\frac{\lambda}{4} T^{2}
$$



- the one loop generated thermal mass is much larger than the tree level mass.
- Break down in P.T.
- WIDLTB


## If you like it you shoulda put a ring on it



- contributions from all orders(called Daisy diagrams).
- to resum Daisies,replace $M^{2} \rightarrow M^{2}+\Pi$



## Incapable standard model

- Not enough CP violation
- Could EWSB(h=0 -> h=v) provide thermal in-equilibrium?
- Phase transition required to be first order to prevent Baryon washout
- Standard model provides only second order phase transition


## Cooling Down



1st order Phase Transition


2nd order Phase Transition

Left is good, further $\mathrm{v}_{\mathrm{c}} / \mathrm{T}_{\mathrm{c}}>1$

## Extensions to Higgs



## Why is Type 1 special?



- only type where Temperature produces the cubic coupling.
- All other types affect the Higgs tri-linear coupling
- Requires precision thermal field theory.


## High temperature approximation Ring induced phase transition

- add new singlet: $\Delta L=-\frac{1}{2} \mu_{s}^{2} s^{2}+\frac{1}{2} \lambda_{h s} h^{2} s^{2}+\frac{1}{4} \lambda_{s} s^{4}$
- now, at high T, $\quad V_{C W}^{T \neq 0}=-\frac{T^{4}}{90}+\frac{T^{4}}{24} \frac{M^{2}}{T^{2}}-\sqrt{\frac{T^{4}}{12 \pi}\left(\frac{M^{3}}{T^{3}}\right)}$
- replacing, $M^{2} \rightarrow M^{2}+\Pi$ for an extra singlet coupled to the Higgs,
- you get $\left(M_{s}^{2}+\Pi\right)^{3 / 2}=\left(-\mu_{s}^{2}+\lambda_{h s} h^{2}+\Pi\right)^{3 / 2}$
- and then $\left(M_{s}^{2}+\Pi\right)^{3 / 2}=\left(-/ M_{s}^{2}+\lambda_{h s} h^{2}+\lambda /()^{3 / 2}=\lambda_{h s}^{(3 / 2)} h^{3}\right.$


## Wait What?

- How is high T limit valid? T~EW scale and so are all masses
- In fact typically the extra scalar is more massive
- Mass is h dependent.
- regions where M is small:approximation valid
- regions where $\mathrm{M} \sim \mathrm{T}$, thermal mass small for small coupling

$$
\Pi=\frac{\lambda_{h s}}{2} T^{2}
$$

## Problems with

$$
\Pi=\frac{\lambda_{h s}}{2} T^{2}
$$

- Thermal mass doesn't decouple as Ms becomes massive
- Thermal mass seems to be h independent
- Super-Daisy terms not taken into account.



## What we did

- Computed thermal mass accurately.(no highT expansion)
- How about new thermal mass after substitution?

$$
\Pi_{\text {super }}=\frac{d V_{T}^{\prime}}{d h}\left[M^{2} \rightarrow M^{2}+\Pi_{\text {super }}\right]
$$

- Solved iteratively to take into account superdaisy


## RESULTS

## Old vs New Thermal Mass



## Procedure

- Account for accurate thermal mass in potential
- Cool down to find critical temperature
- is S still stable?, i.e. $M_{s}^{2}+\Pi_{s}>0$
- is $\mathrm{V}_{\mathrm{c}} / \mathrm{T}_{\mathrm{c}}>1$


## RESULTS

Parameter space where ring induced 1st-order phase transition feasible

$$
\mathrm{M}_{\mathrm{s}}=270 \mathrm{GeV}
$$



## RESULTS-IDM

Parameter space where ring induced 1st-order phase transition feasible

|  | $M_{H}$ | $M_{A}$ | $M_{H^{+}}$ | $\lambda_{L}$ | $\lambda_{T}$ | $v_{c} / T_{c}($ old $)$ | $v_{d} / T_{c}(n e w)$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| BM1 | 66 | 300 | 300 | 0.01 | 0.01 | 1.5 | 1.1 |
| BM2 | 200 | 400 | 400 | 0.01 | 0.01 | 1.5 | 1.2 |
| BM3 | 5 | 265 | 265 | -0.006 | 0.01 | 1.3 | 1.0 |

## Summary

- FTFT required to handle EWPT
- in some regimes high T approx not valid
- Full iteration based computation the way out
- Leads to drastically reduced parameter space for thermally induced phase transition

The Ring has awoken, its heard its masters call


