THE ELECTROWEAK PHASE TRANSITION, BEYOND THE STANDARD MODEL

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Based (in part) on:

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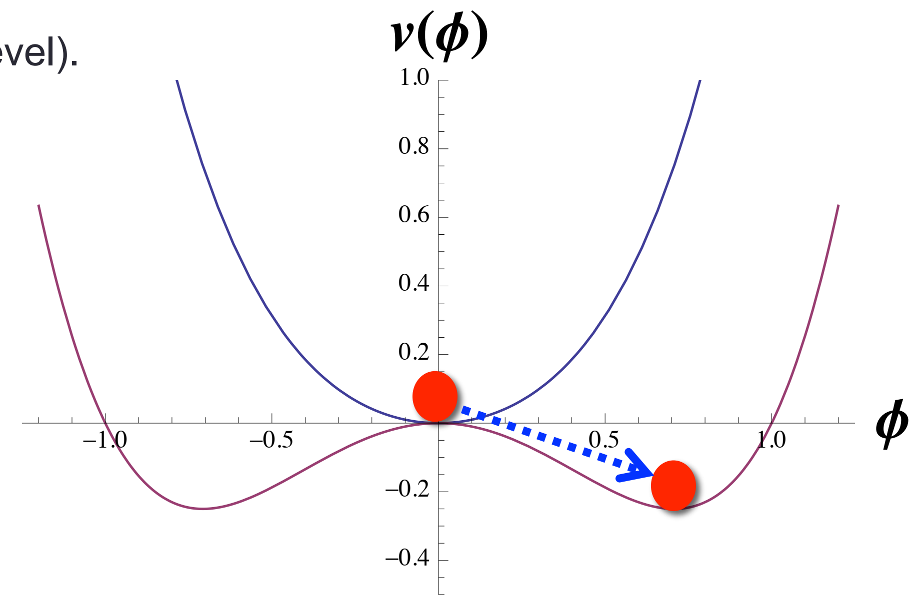
Electroweak phases

- The Higgs (effective) potential has a global minimum…
  - At ”low” T: non-zero field value, v = 246 GeV.
    - Fermions have mass.
    - Gauge boson W, Z have mass.
    - Higgs has mass.
  - At ”high” T: zero field value, v = 0.
    - Fermions are massless (at tree level).
    - Gauge bosons are massless (at tree level).

Phase transition at
some ”intermediate” T.
Context:
After the Big Bang → ”high” T.
Expansion → cool down → ”low” T.
Phase transition in time, T(t)!



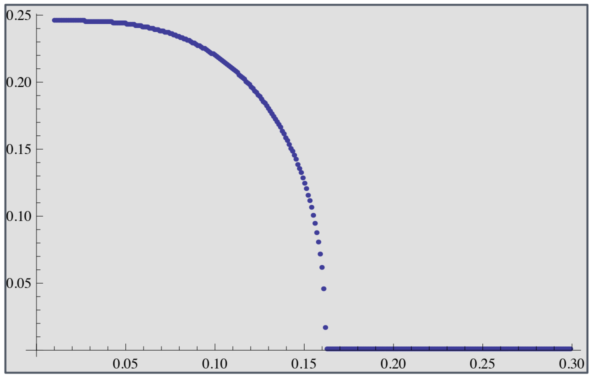
Finite temperature phase transitions

- The thermodynamic equilibrium system is described by a finite temperature effective potential (the free energy).
- A function of an "order" parameter.
- The value of the order parameter corresponds to the minimum of the free energy.

If the minimum evolves continuously as a function of T → 2. order phase transition. (Or higher…)

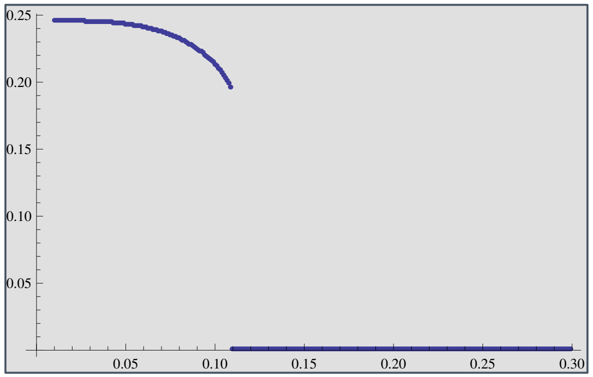
If the minimum evolves discontinuously as a function of T → 1. order phase transition.

V(T)/TeV



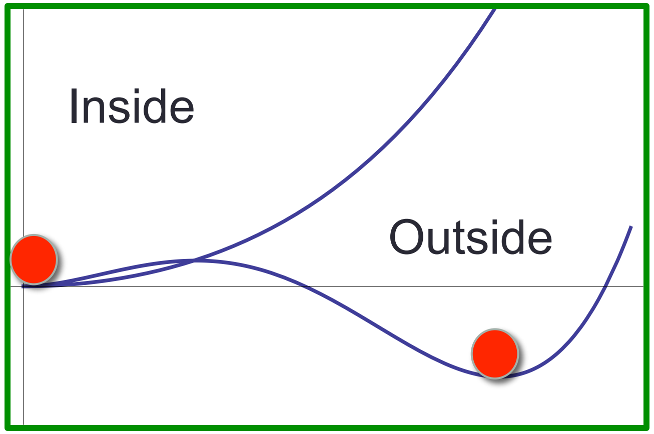
T/TeV

V(T)/TeV



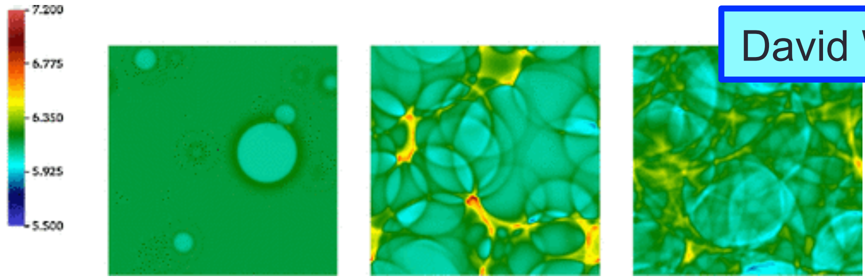
T/TeV

What do I need a first order transition for?



If 1. order → nucleation of vacuum bubbles.

- Outside: high-T phase, v = 0.
- Inside: low-T phase, v > 0.
- Bubbles expand at up to the speed of light.



David Weir

If particle physics model has:
- C- and CP-violation (like in the Standard Model)
- Baryon number violation (like in the Standard Model)

→ A baryon asymmetry is created as the bubble walls sweep through the plasma.

→ Electroweak Baryogenesis

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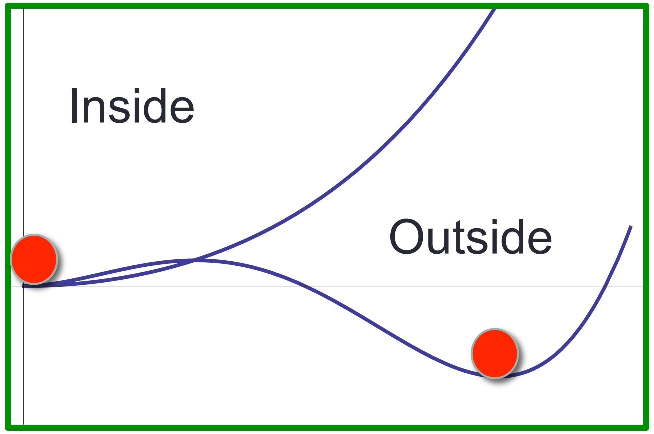

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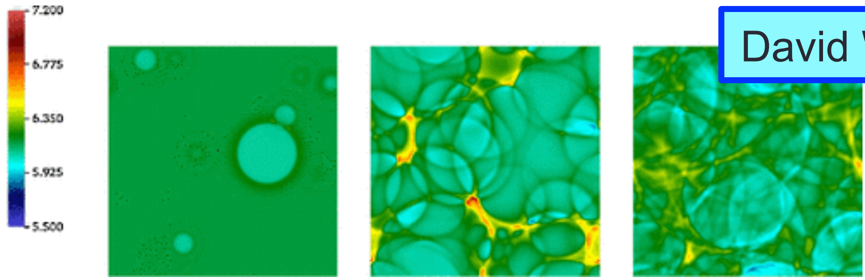
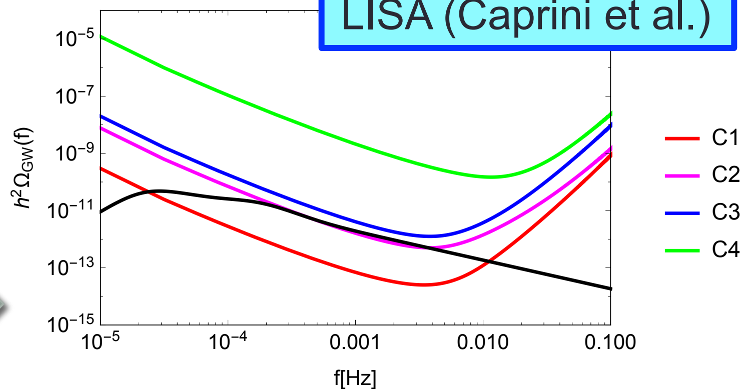


David Weir

- As the bubble walls push around the plasma
- → gravitational waves are created.
- As the bubble walls collide
- → gravitational waves are created.

Gravitational waves



LISA (Caprini et al.)

How to compute it…perturbatively?

$$V_{\rm eff}(\phi,T) = V_{\rm tree}(\phi) + V_{\rm CW}(\phi) + V_{\rm c.t.}(\phi) + V_T^1(\phi,T) + V_T^2(\phi,T)$$

$$V_T^1(\phi,T) = \frac{T^4}{2\pi^2}\sum_i N_i \int_0^\infty dx\, x^2 \log\left[1 \pm e^{-\sqrt{x^2+\frac{M_i^2(\phi)}{T^2}}}\right]$$

$$V_T^2(\phi,T) = \frac{T}{12\pi}\sum_i N_i {\rm Tr}\left[M_i^3(\phi) - M_i^3(\phi,T)\right]$$

Procedure:

Scanning through your parameter space:

- Compute the 1-loop, daisy-resummed, finite temperature effective potential V(Φ,T).
- Find the minimum.
- Plot the minimum as a function of T.
- Does it go to zero continuously as T increases?
  - Yes? No bubbles → Game Over.
  - No? Bubbles → How big is the jump?

Lots and lots of people:
Carrington, Kainulainen, Cline, Huber, Seniuch, Konstandin, Servant, Kozaczuk, Laine, Nardini, Ramsey-Musolf, Damgaard, AT, Petersen. O'Connell, Haarr, Kvellestad, Dorsch, No, Harmann, Mimasu, Profumo, Shaughnessy, …

How to compute it…non-perturbatively?

→ Lattice Monte Carlo in full 4D (expensive).
→ Lattice Monte Carlo in effective 3D model (less expensive).

Procedure:

Scanning through your parameter space:

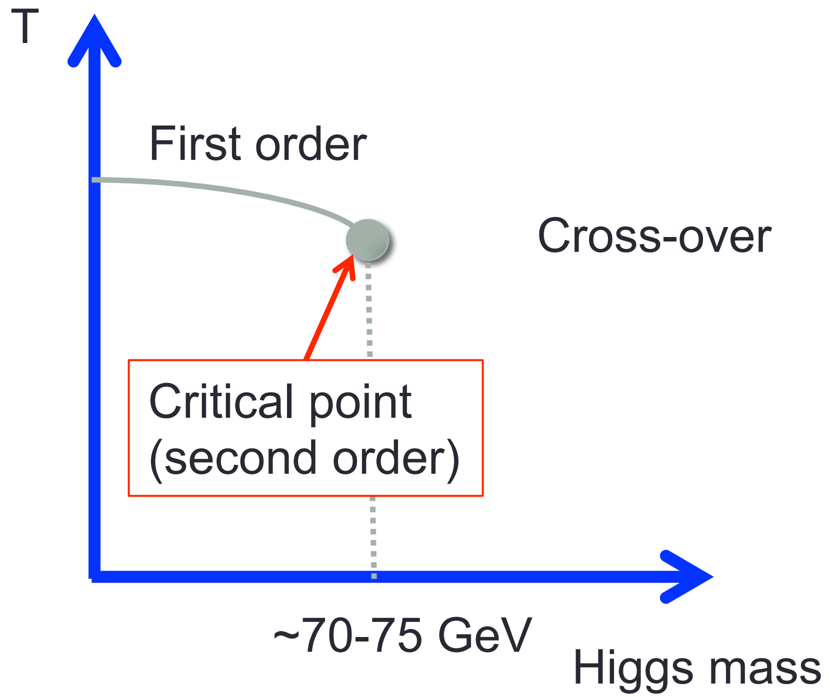
- Analytically, match your 4D theory to a 3D effective theory.
- In the 3D theory, numerically compute the full, nonperturbative effective potential as a function of T.
- Find the minimum.
- Plot the minimum as a function of T.
- Does it go to zero continuously as T increases?
  - Yes? No bubbles → Game Over.
  - No? Bubbles → How big is the jump?

Quite few people:
Appelquist, Pisarski, Kajantie, Laine, Rummukainen, Shaposhnikov, Farakos. Csikor, Fodor, Heitger.

The phase transition in the Standard Model

Higgs mass unknown in 1998.
Phase diagram and Tc as a function of mH.

4D-endpoint → 72 GeV.
3D-endpoint → ~80 GeV.

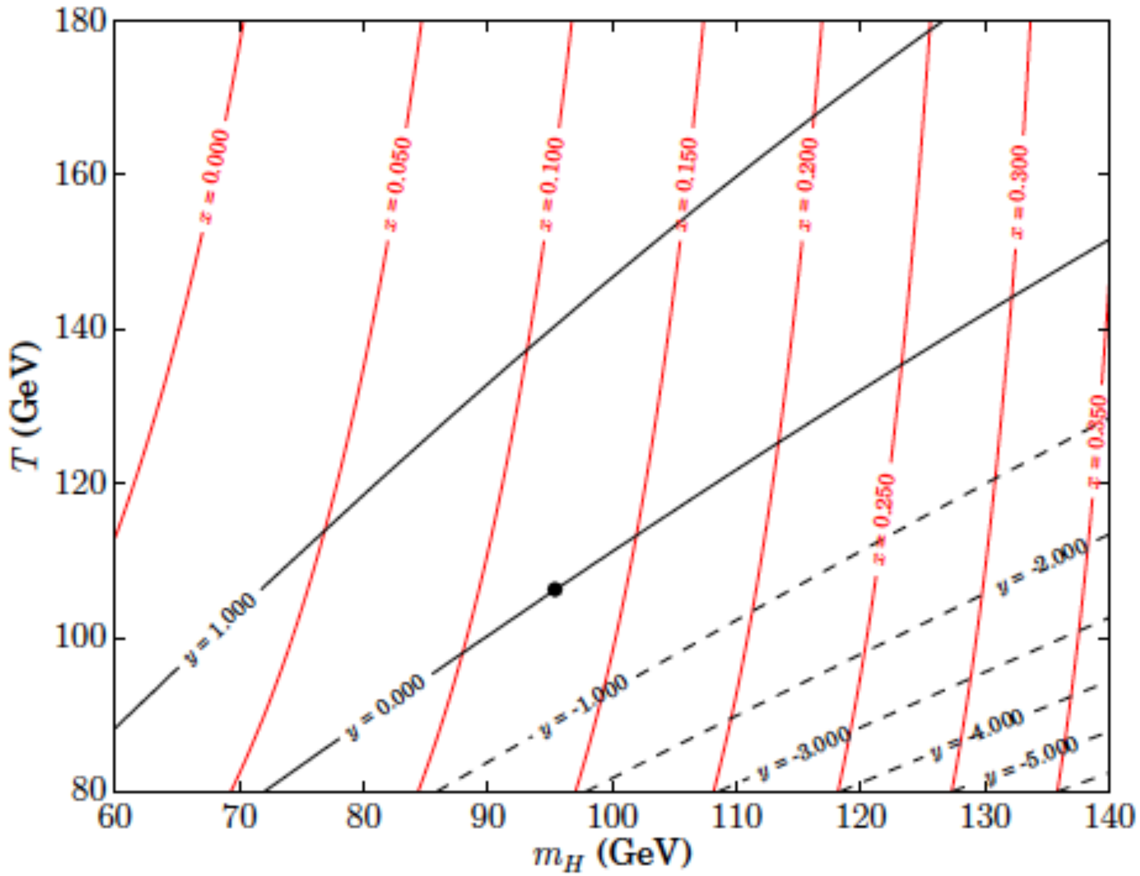


Higgs mass = 125 GeV!
No first order transition.
→ No bubbles.
→ Game over!
Our existence → proof of BSM physics.

Kajantie, Laine, Rummukainen, Shaposhnikov: 1995-8
Csikor, Fodor, Heitger: 1998

The phase transition in the Standard Model

3D-model: $$S = \int d^3x \left[\frac{1}{4} F^a_{ij} F^{ij,a} + (D_i\phi)^\dagger D^i\phi + m_3^2 \phi^\dagger\phi + \lambda_3 (\phi^\dagger\phi)^2 \right]$$



Redone at 1-loop level.
Different DimRed procedure.

$$x = \frac{\lambda_3}{g_3^2}, \quad y = \frac{m_3^2}{g_3^4}$$

Phase transition at y~0.
1. Order at x < xc = 1/8 .

Brauner, Tenkanen, AT, Vuorinen, Weir: 2017.

BSM: Add a scalar

Existence of matter requires BSM physics!

If electroweak baryogenesis is responsible, need 1. order phase transition.
→ Add new degrees of freedom: Try with a scalar coupled to the Higgs.

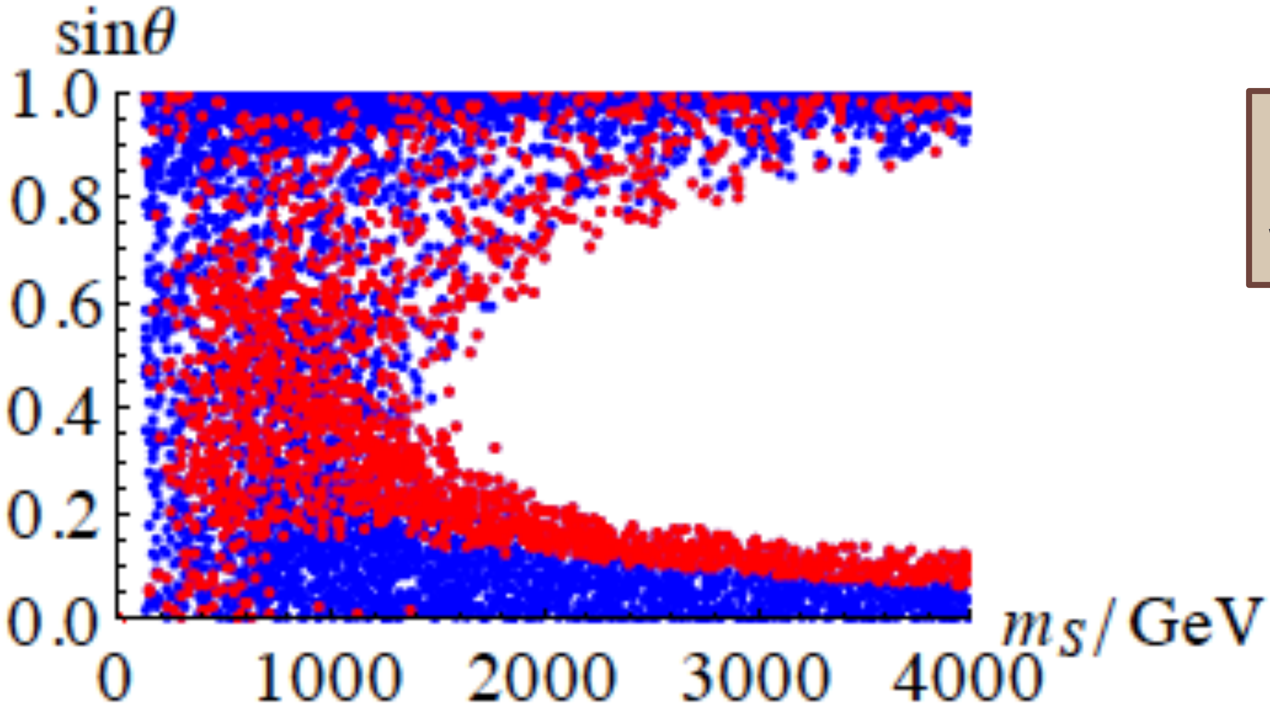
$$SM + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\mu_\sigma^2\sigma^2 + \mu_1\sigma + \frac{1}{3}\mu_3\sigma^3 + \frac{1}{4}\lambda_\sigma\sigma^4 + \frac{1}{2}\mu_m\sigma\phi^\dagger\phi + \frac{1}{2}\lambda_m\sigma^2\phi^\dagger\phi$$

Singlet

$$SM - Higgs + (D_\mu\phi_1)^\dagger D^\mu\phi_1 + (D_\mu\phi_2)^\dagger D^\mu\phi_2 + \frac{1}{2}m_{11}^2\phi_1^\dagger\phi_1 + \frac{1}{2}m_{22}^2\phi_2^\dagger\phi_2 + \frac{1}{2}m_{12}^2\phi_1^\dagger\phi_2 + \text{ h.c.} + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{ h.c.}$$

Doublet

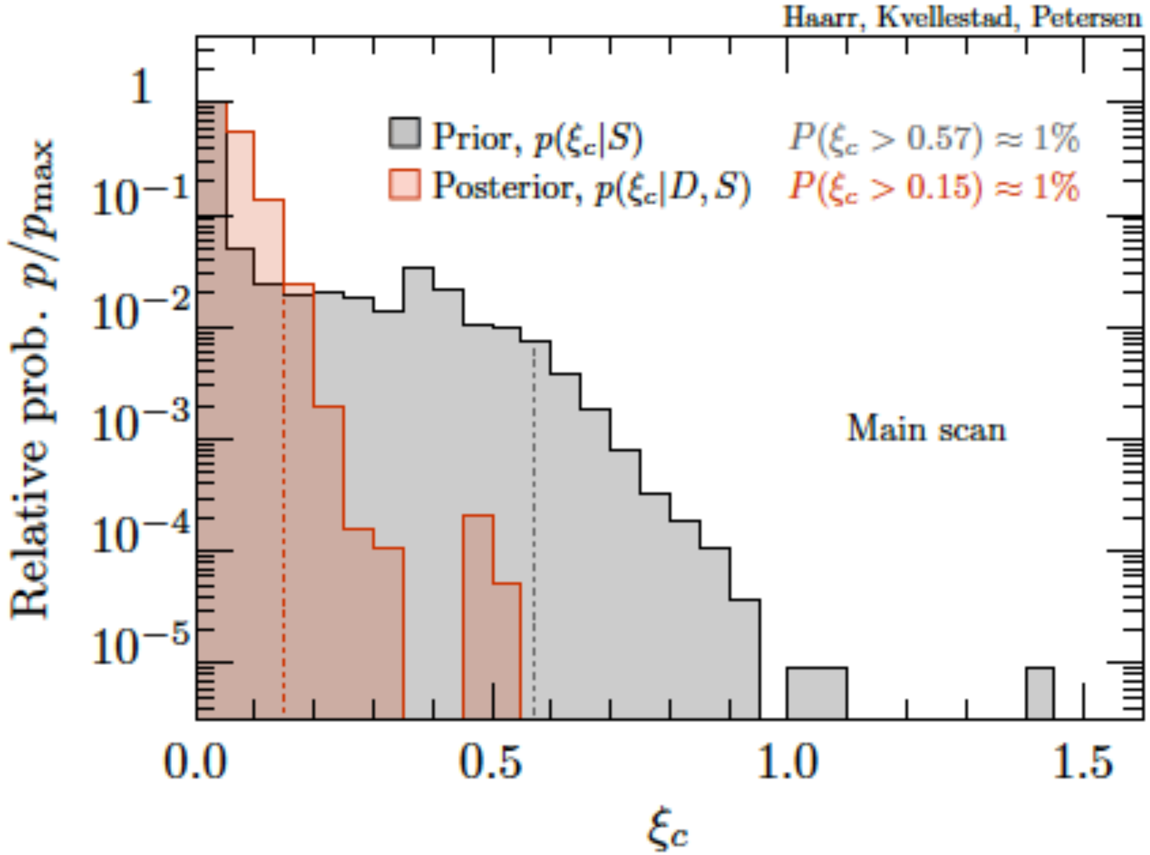
Perturbatively: SM + singlet



Blue = 2. order
Red = 1. order
White = Unstable

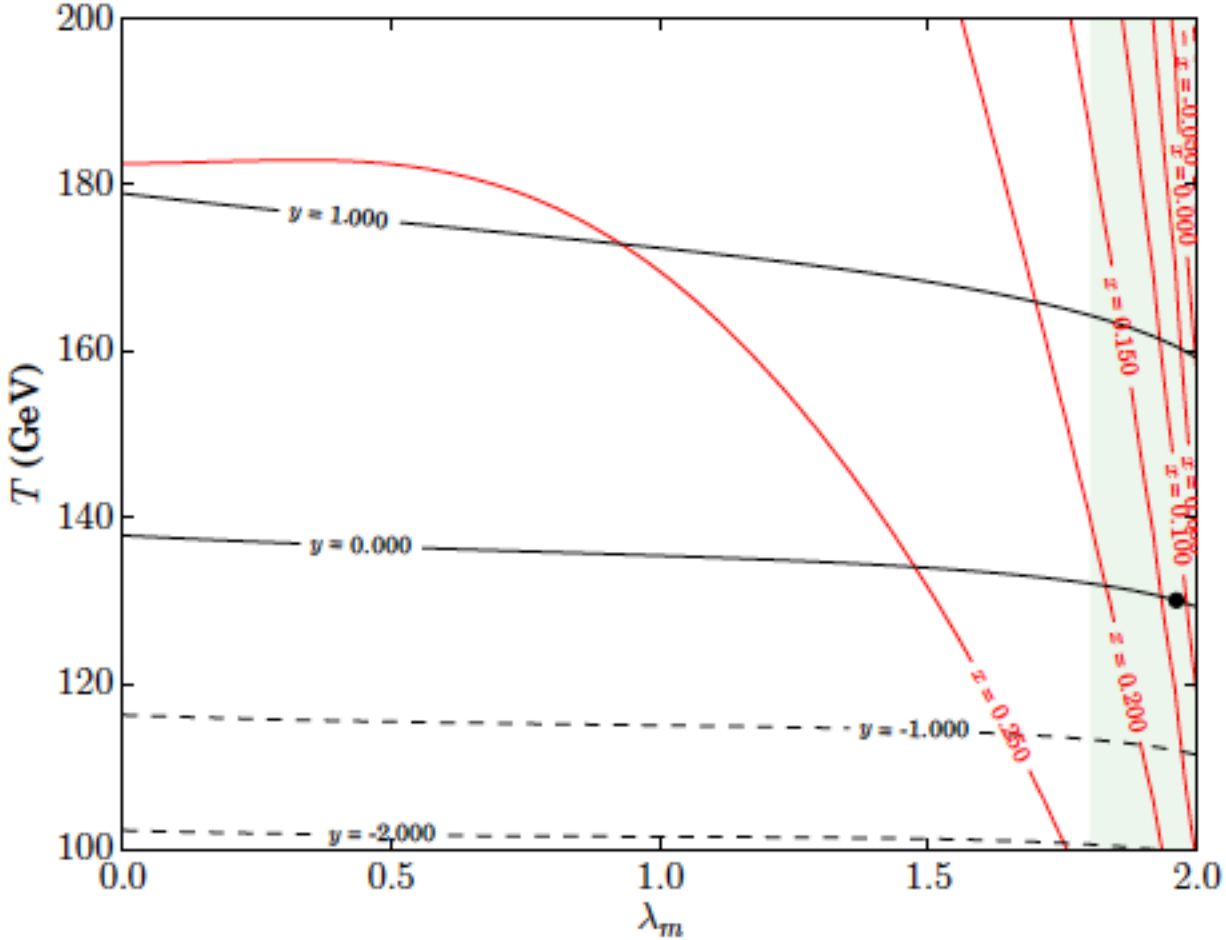
Absolutely biased selection: Example only!
Damgaard, Haarr, O'Connell, AT: 2015.

Perturbatively: SM + Doublet



Absolutely biased selection: Example only!
Haarr, Kvellestad, Petersen: 2017.

Non-perturbatively: SM + singlet

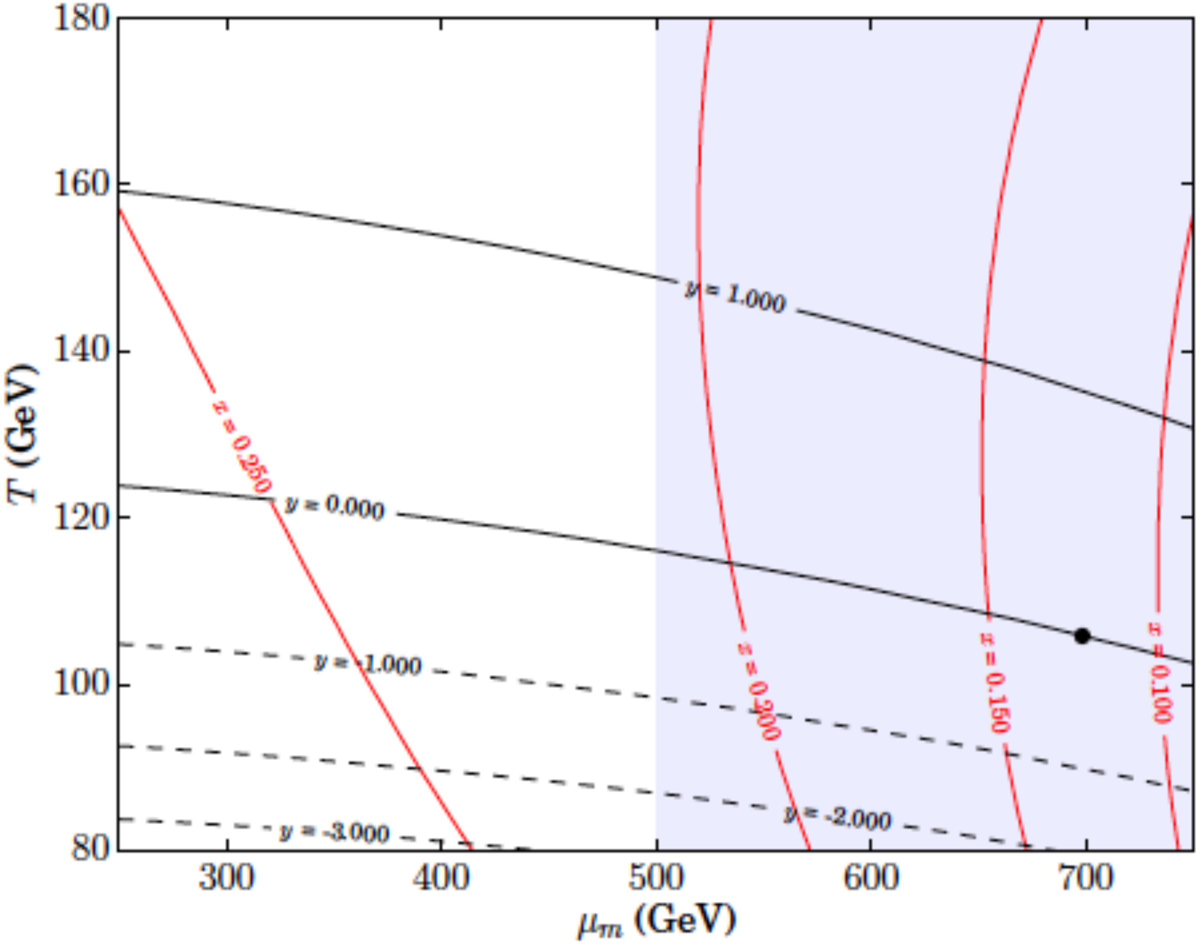


Brauner, Tenkanen, AT, Vuorinen, Weir: 2017

Singlet mass: 500 GeV

$$
\begin{aligned}
&SM \\
&+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\mu_\sigma^2\sigma^2 \\
&+\cancel{\mu_1\sigma} + \cancel{\frac{1}{3}\mu_3\sigma^3} + \frac{1}{4}\lambda_\sigma\sigma^4 \\
&+\cancel{\frac{1}{2}\mu_m}\sigma\phi^\dagger\phi + \frac{1}{2}\lambda_m\sigma^2\phi^\dagger\phi
\end{aligned}
$$

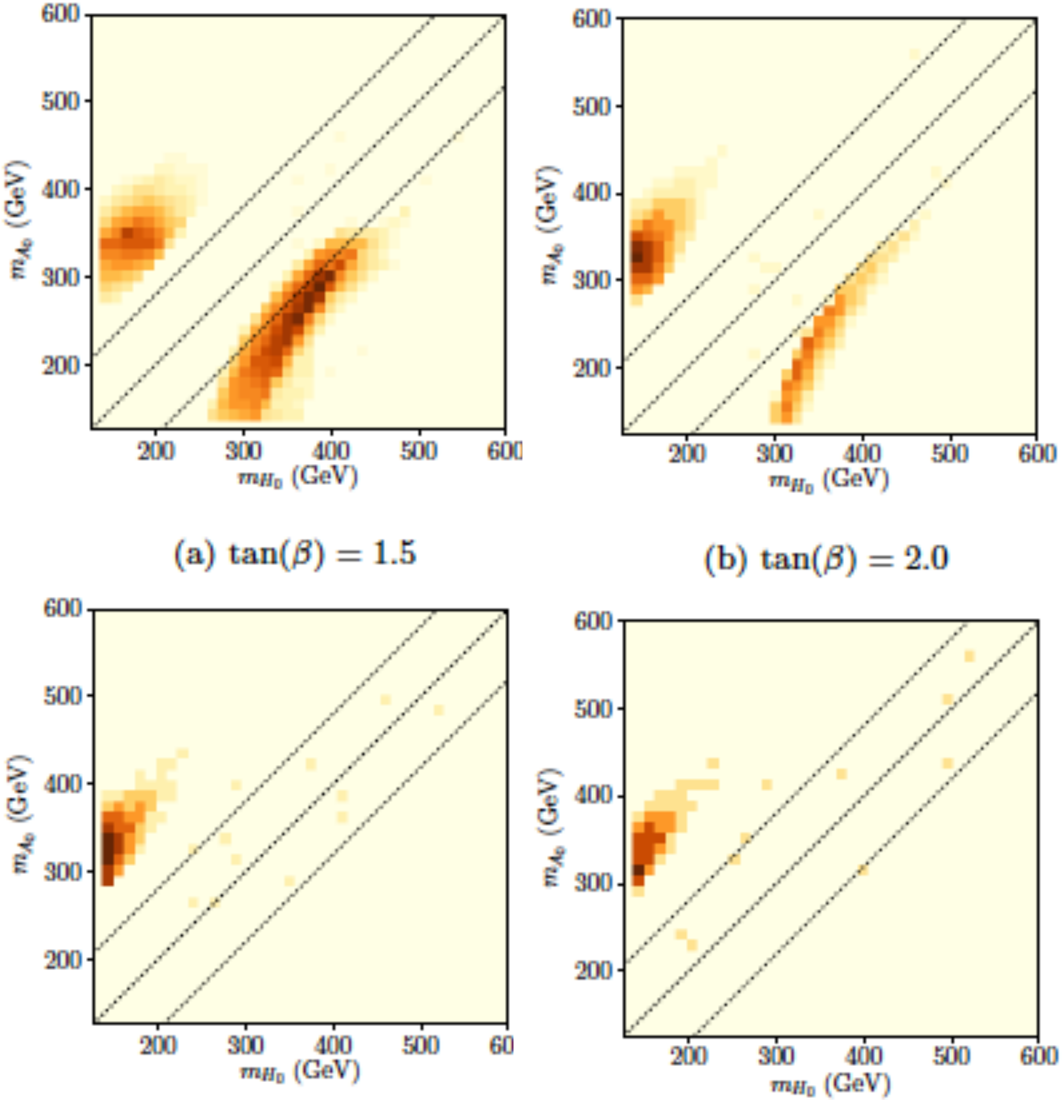
Non-perturbatively: SM + singlet



Singlet mass: 250 GeV

$$
\begin{aligned}
&SM\\
&+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma+\frac{1}{2}\mu_\sigma^2\sigma^2\\
&+\cancel{\mu_1\sigma}+\cancel{\frac{1}{3}\mu_3}\sigma^3+\frac{1}{4}\lambda_\sigma\sigma^4\\
&+\frac{1}{2}\mu_m\sigma\phi^\dagger\phi+\frac{1}{2}\cancel{\lambda_m}\sigma^2\phi^\dagger\phi
\end{aligned}
$$

Non-perturbatively: SM + doublet



(a) $\tan(\beta) = 1.5$ (b) $\tan(\beta) = 2.0$

(c) $\tan(\beta) = 2.5$ (d) $\tan(\beta) = 3.0$

$$
\begin{aligned}
& SM - Higgs \\
& +(D_\mu\phi_1)^\dagger D^\mu\phi_1 + (D_\mu\phi_2)^\dagger D^\mu\phi_2 + \\
& \frac{1}{2}m_{11}^2\phi_1^\dagger\phi_1 + \frac{1}{2}m_{22}^2\phi_2^\dagger\phi_2 + \\
& \frac{1}{2}m_{12}^2\phi_1^\dagger\phi_2 + \text{ h.c.} + \\
& \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \\
& \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \\
& \frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{ h.c.}
\end{aligned}
$$

$$m_{H^\pm} = m_{A_0},$$

$$\tan(\beta) = \frac{v_2}{v_1},\ v_1^2 + v_2^2 = (246\text{ GeV})^2$$

$$\cos(\beta - \alpha) = 0,$$

$$\mu_{12} < 400\text{ GeV},$$

All real $\rightarrow$ no CP-violation

Andersen, Gorda, Niemi, Weir, Tenkanen, AT, Vuorinen: 2017

Outlook

A first order electroweak phase transition would provide:

1. A viable baryognesis mechanism.
2. A detectable cosmological GW source.

Where the SM model fails, extended Higgs sectors may succeed:

Collider constraints are complementary:

- LHC suggests extensions give small corrections to SM.
- A 1. order phase transition requires large corrections to SM.

Combine theoretical computation, collider constraints, BG and measurements of GW to rule in or out TeV-scale extensions of the SM.

Perturbative computations allow broad parameter scans.
But non-perturbatively, transition may be weaker or go away!

To do: In parallel compute:

- Numerically, phase diagrams of more general 3D theories.
- Analytically, matching relations from 4D theories to those 3D theories.

Thank you!