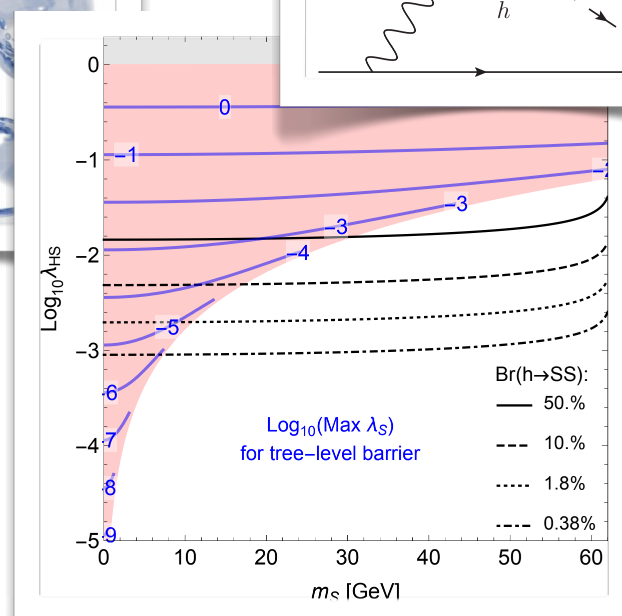
Probing Electroweak Baryogenesis with Exotic Higgs Decays

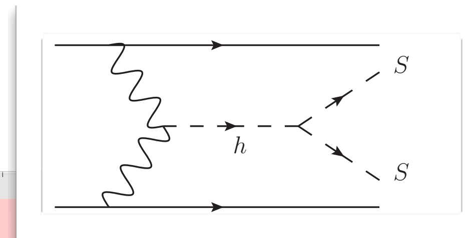
HXSWG Exotic Higgs Decays Meeting
Fermilab

22 May 2015

David Curtin
Maryland Center for Fundamental Physics
University of Maryland

Partially based on 1409.0005 (DC, Patrick Meade, Tien-Tien Yu)





Introduction

— Where do we (baryonic matter) come from? —

Electroweak baryogenesis (EWBG) is one of the only mechanisms of baryogenesis that is, in principal, ***testable.***

As a BG mechanism, EWBG relies on the *electroweak phase transition*, enhanced by BSM effects. However, even without BSM, probing the **electroweak phase transition** (PT) is cosmologically interesting.

Testing EWBG $\Rrightarrow$ detailed study of the Higgs $\Rrightarrow$ **future colliders**

Exotic Higgs decays are an important observable that constrain or exclude many EWBG theories that involve light particles.

This Talk

1/3 Reviewing EWBG Mechanism

1/3 How to probe EWBG (general)

1/3 Exotic Higgs Decays

Electroweak Baryogenesis

Higgs at High Temperatures

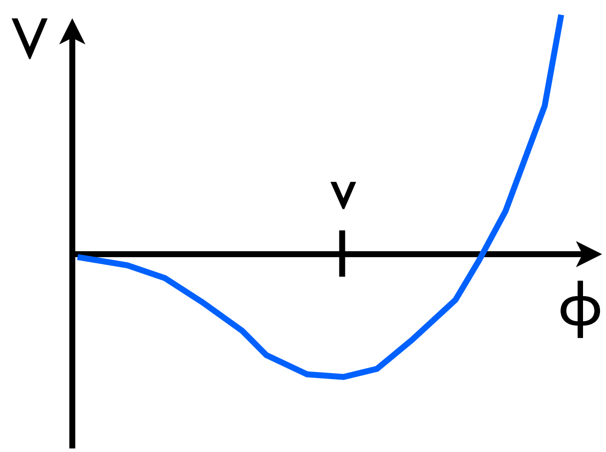
At finite temperature, the higgs potential receives new contribution from its interaction with the plasma.

Many reviews, e.g. Quiros hep-ph/9901312

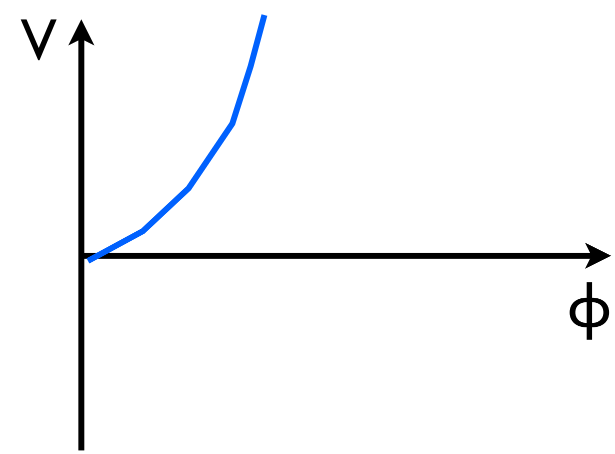
At high temperature, the higgs is stabilized at the origin.

→ The early universe was SU(2) symmetric!

T = 0

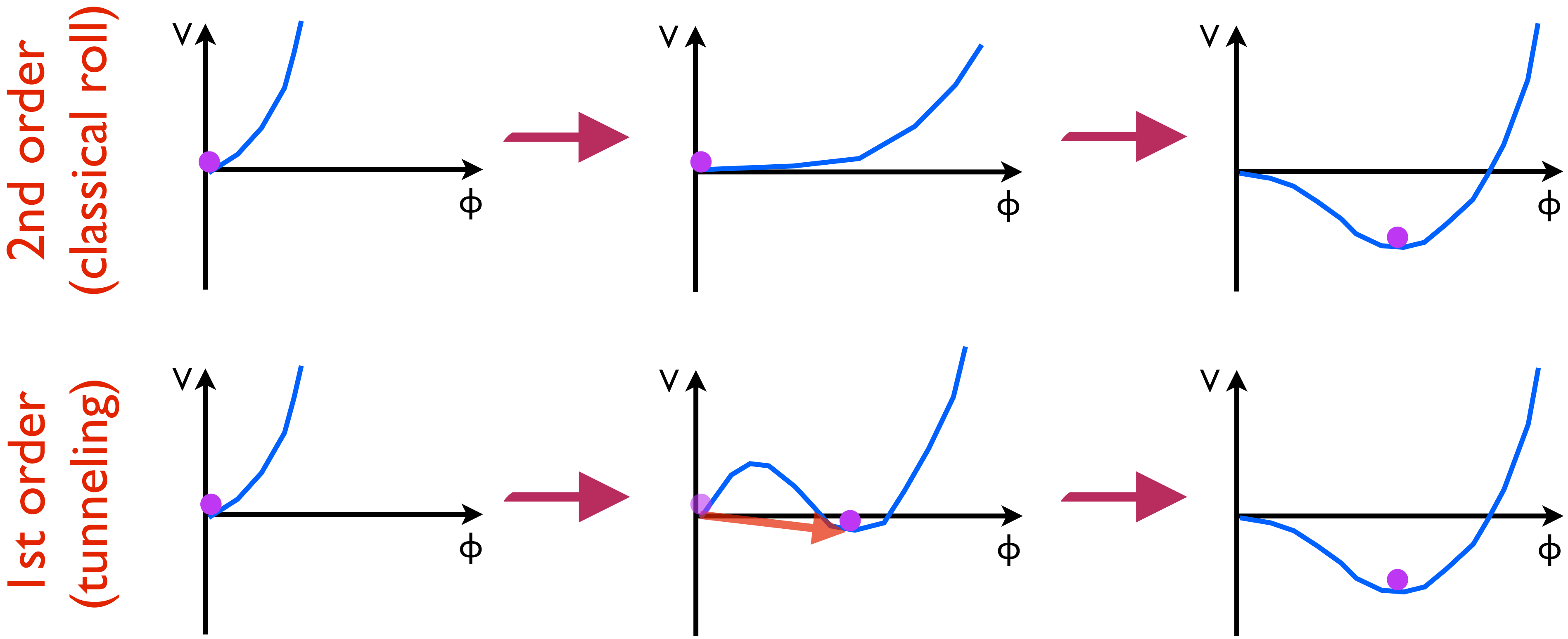


T ≫ 100 GeV



Higgs at High Temperatures

As the universe cools, the higgs undergoes a **phase transition (PT)** from zero to nonzero VEV.



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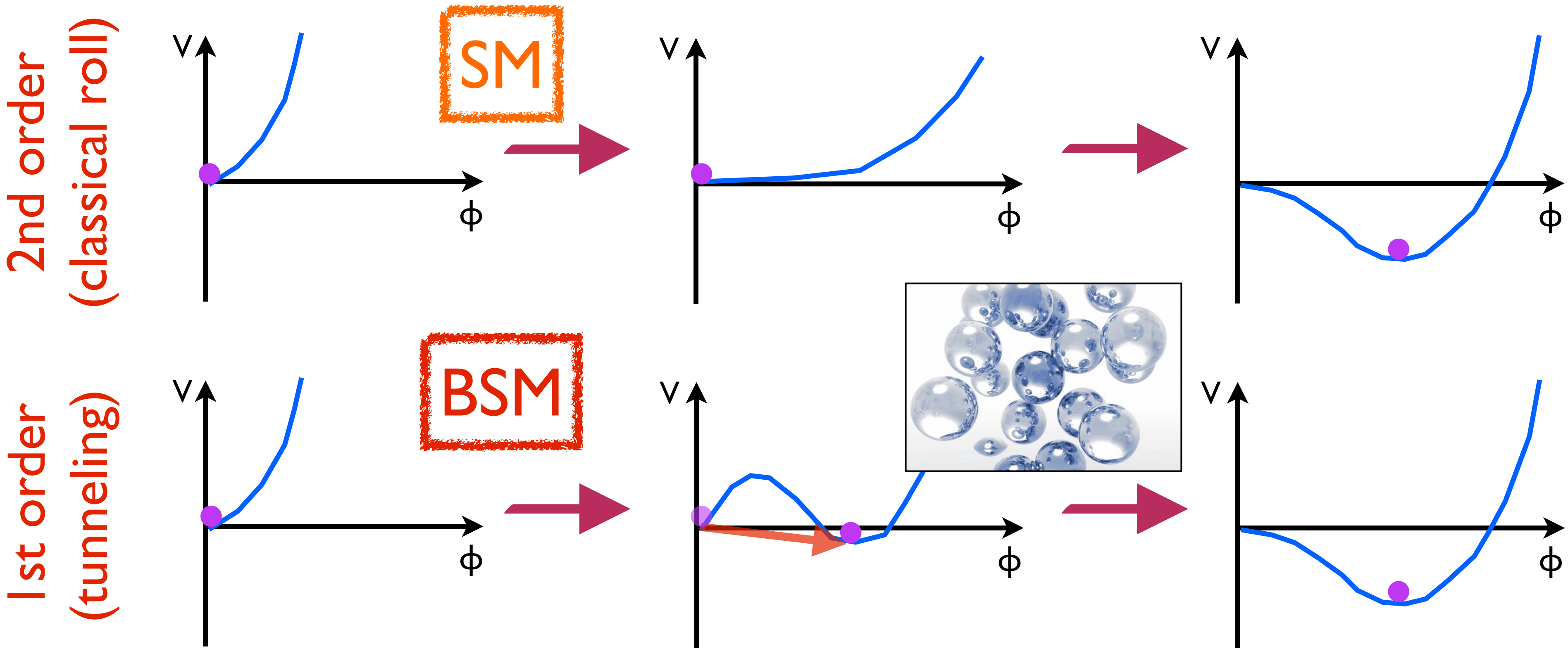


1st order phase transition gives rise to bubble nucleation!

This could create baryons...

$$\frac{n_B}{s} \sim 10^{-10}$$ Why?

To dynamically create Baryon Number Asymmetry, the three Sakharov conditions must be satisfied.

1. **B** Number Violation
2. **CP** Violation
3. **Departure from thermal equillibrium** ("**T** violation")

Most Baryogenesis mechanisms (Affleck–Dine, Leptogenesis,...) rely on very high-scale physics.

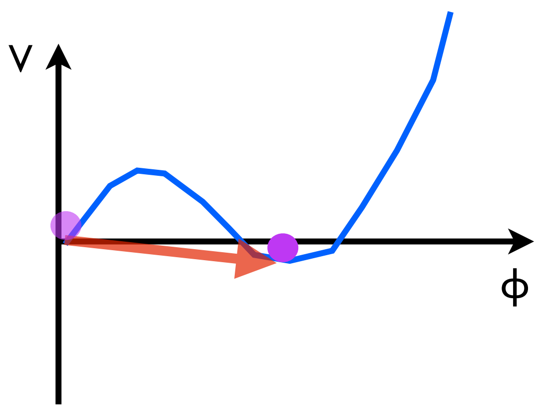
Electroweak Baryogenesis is all weak scale $\Rrightarrow$ testable mechanism!

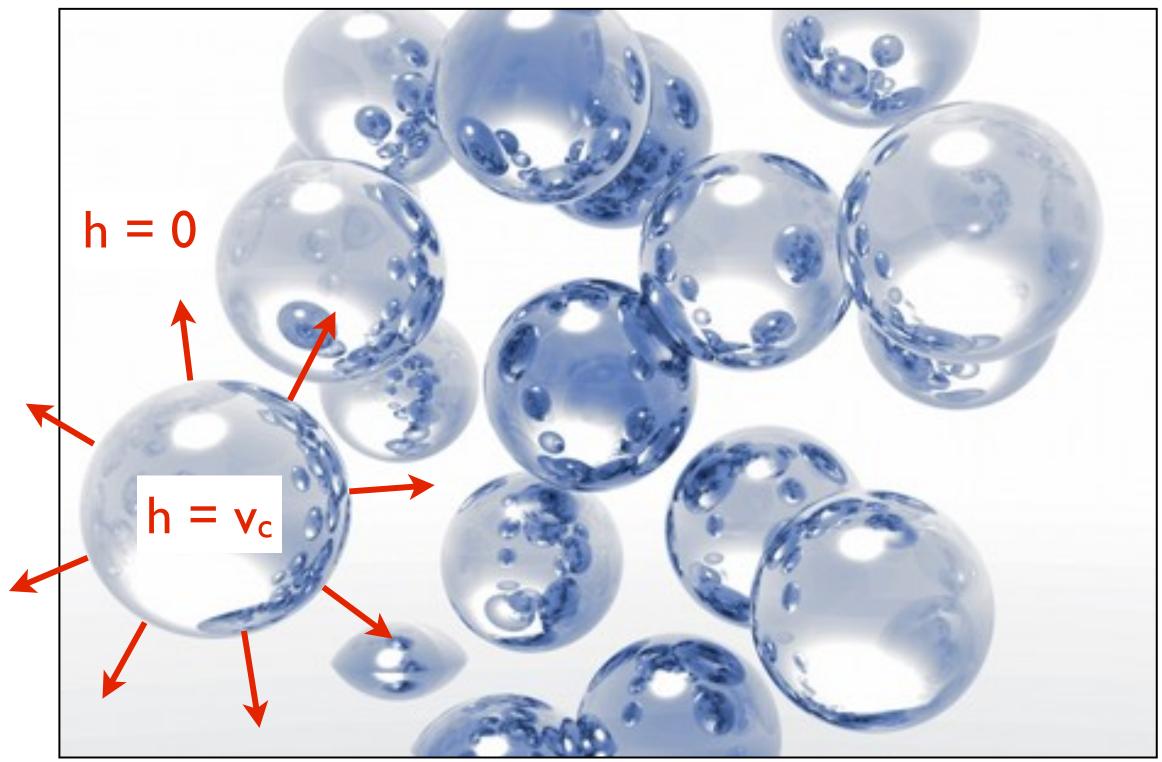
Kuzmin, Rubakov, Shaposhnikov 1985
Klinkhamer, Manton 1984
...

Electroweak Baryogenesis

say the electroweak phase transition was strongly 1st order....

At some critical temperature, bubbles of true vacuum **$h = v_c$** form, and grow into the false vacuum surroundings where **$h = 0$**.





Electroweak Baryogenesis

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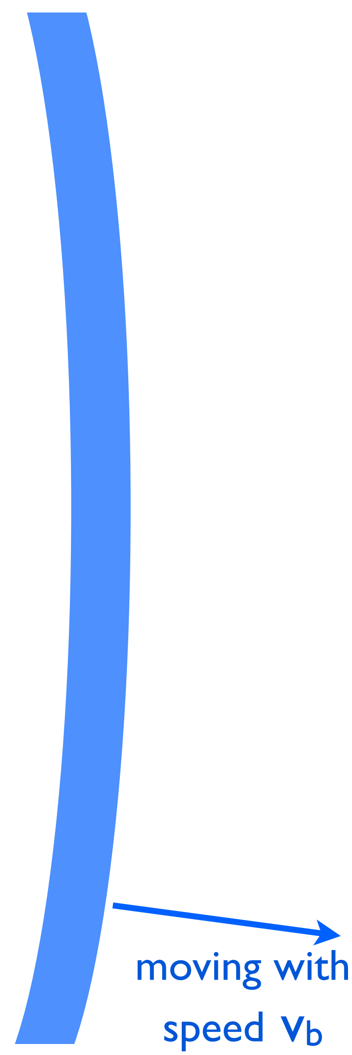

Electroweak Baryogenesis

say the electroweak phase transition was strongly 1st order....

bubble wall

True Vacuum
$\langle h \rangle = v_c$

~~Sphaleron~~

strongly suppressed in
SU(2) broken phase
$\Gamma_{sph} \sim \mathrm{Exp}(A\ h/T)$

False Vacuum
$\langle h \rangle = 0$

SM process that can
convert **chiral** asymmetry
to **Baryon** asymmetry

Sphaleron

$T \cong T_c \sim 100$ GeV

Electroweak Baryogenesis

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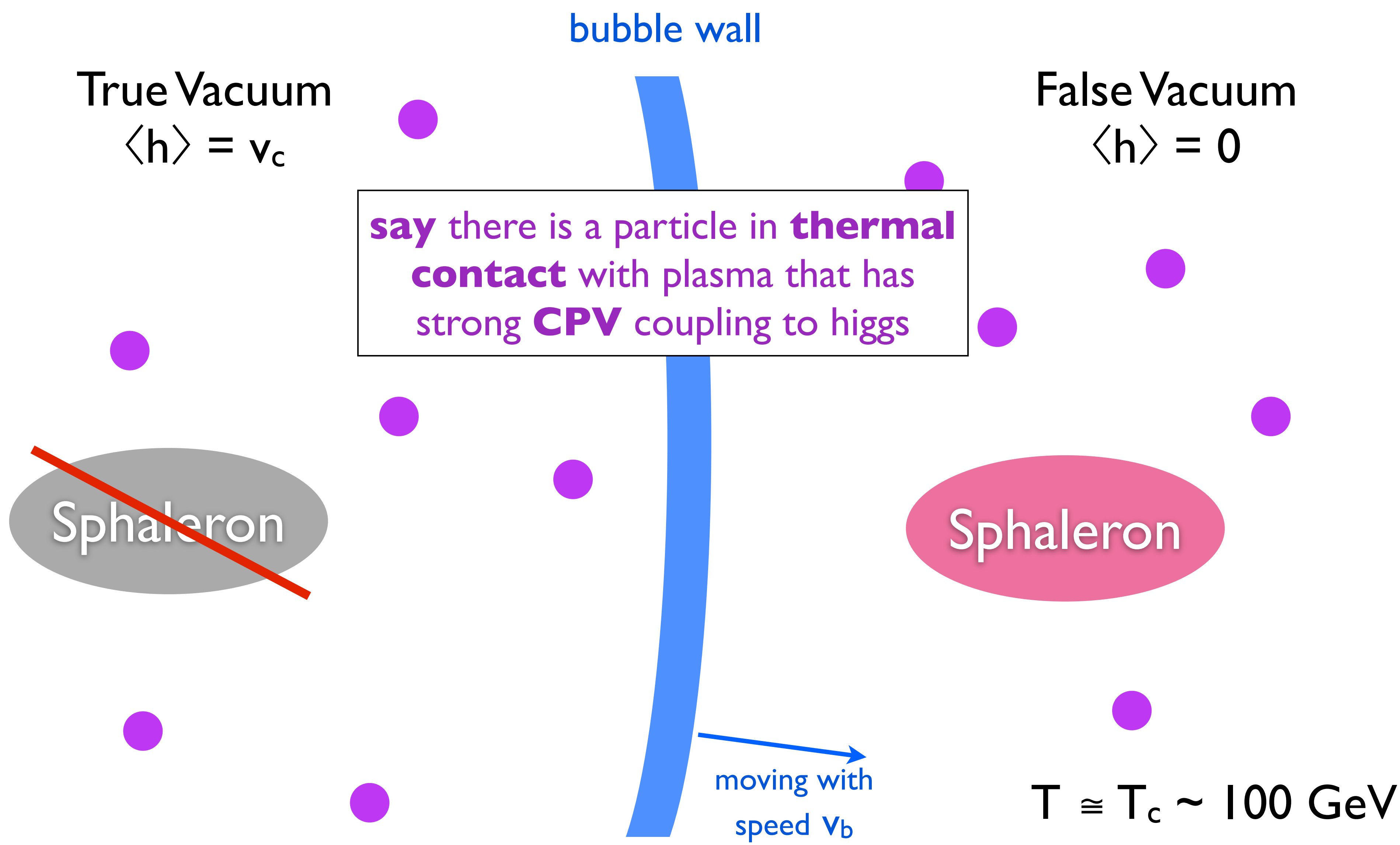

Electroweak Baryogenesis

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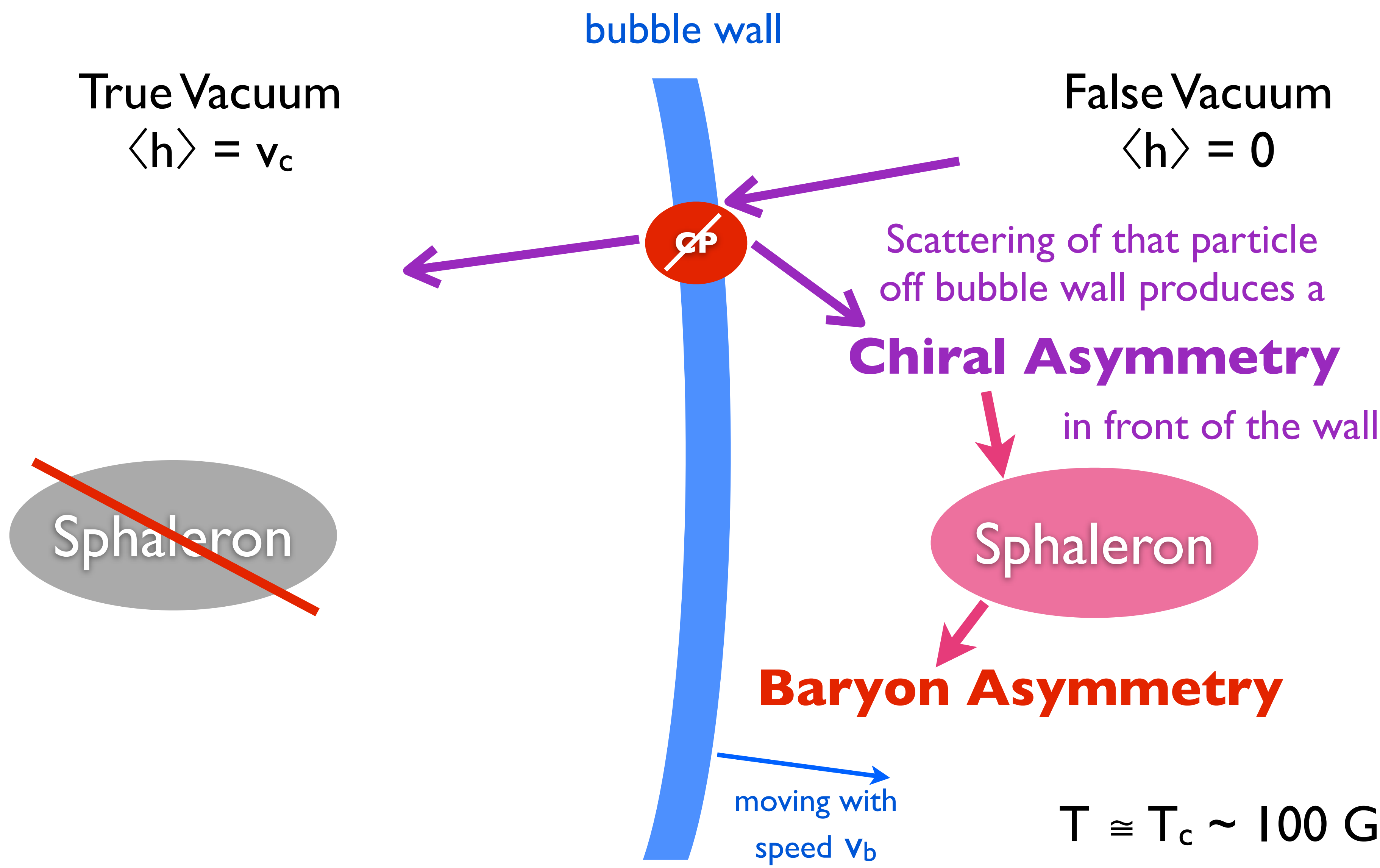

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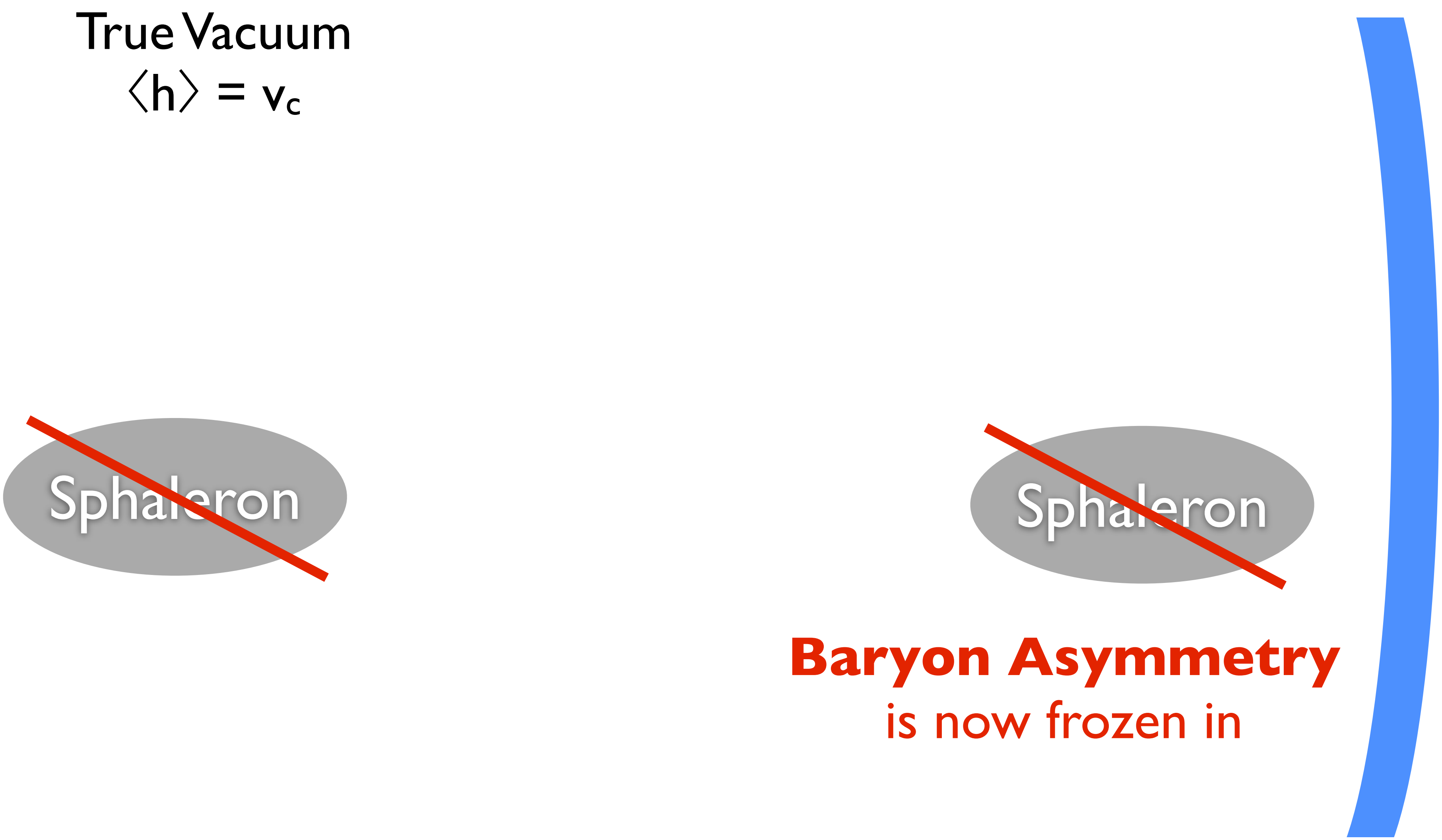
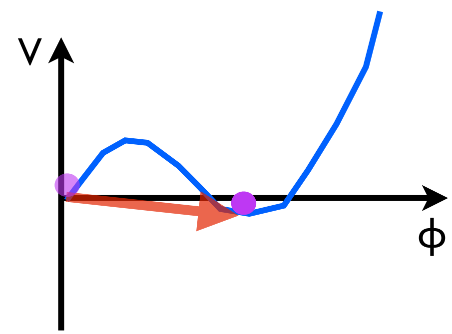


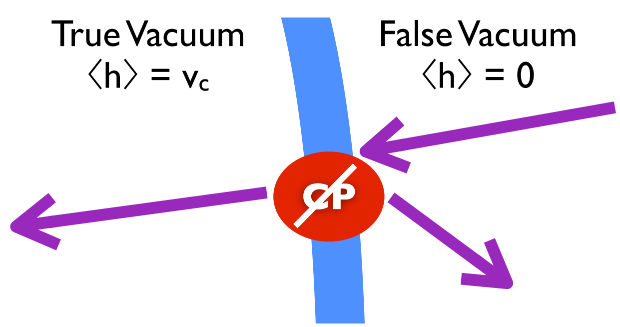
Electroweak Baryogenesis

EWBG requires two BSM ingredients:

1. Modified higgs potential to make phase transition 1st order



2. Sizable CPV coupling between higgs and another particle (BSM or SM) that is thermally active in the plasma ($M \lesssim T$)



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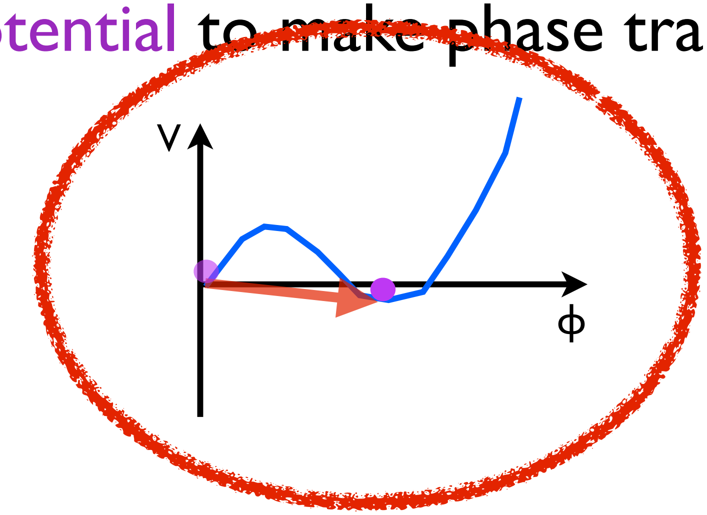
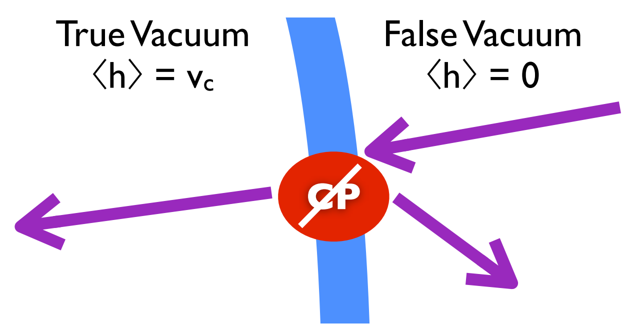


Try and exclude this

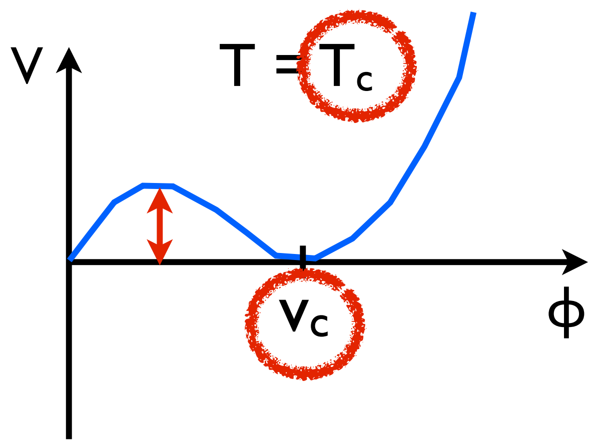
2. Sizable CPV coupling between higgs and another particle (BSM or SM) that is thermally active in the plasma ($M \lesssim T$)

(complicated...)



How to exclude discover? a strong electroweak phase transition?

Strong Phase Transition



The phase transition has to be strong enough to suppress sphaleron washout of the generated baryon number in the broken phase.

$$\frac{v_c}{T_c} > 0.6 - 1.6$$

Normally given as ~1, this more accurate figure is from Patel, Ramsey-Musolf, 1101.4665

Very simple criterion to determine if EWBG is at least *possible* with a given higgs potential.

Achieving a strong PT

How can you modify the SM higgs potential to get $v_c/T_c \gtrsim 1$?

$$V_{\text{eff}}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T)$$

tree-level potential | loop correction | finite temperature corrections

Achieving a strong PT

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tree-level potential | loop correction | finite temperature corrections

1. Thermal Effects
   add new BOSONS to the plasma to generate barrier (analogous to W and Z contributions)
2. Loop Effects
   add particles whose loops reduce the 'depth of the higgs potential well', so W and Z contributions can make a barrier.
3. Tree Effects
   add scalars to modify tree-level higgs potential and create a barrier
4. add non-renormalizable operators
   really a general way of parameterizing (2) and (3) ← a little subtle....

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New bosons have to be < 200 GeV
and will modify higgs couplings
⇛ **we'll find it! (or already excluded)**

Cohen, Morrissey, Pierce 1203.2924,
DC, Jaiswal, Meade 1203.2932
Carena, Nardini, Quiros, Wagner 1207.6330
Katz, Perelstein 1401.1827

Achieving a strong PT

How can you modify the SM higgs potential to get $v_c/T_c \gtrsim 1$?

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tree-level potential — loop correction — finite temperature corrections

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Do not require *very* light new particles.
Explore with simple scalar extensions of the SM.

Tree and Loop-driven PT

Consider SM + single real scalar

$$V_0^{T=0}(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

In generality, this scalar mixes with the higgs after EWSB.

$\Rrightarrow$
- direct production in (heavy) higgs searches
- exotic higgs decays h→ss (if light enough)
- EWPO constraints
- higgs precision coupling measurement constraints
- modifications to higgs self-couplings
- modification to Zh coupling

future lepton collider

100 TeV pp collider

A lot of handles for discovery using all future colliders!

e.g. Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342

But the model still has many parameters. Can EWBG be completely excluded?

Full exploration of parameter space needed!

Tree and Loop-driven PT

Need a simpler model to investigate these strong phase transitions....

DC, Patrick Meade, Tien-Tien Yu 1409.0005

Build a 'maximally stealthy' model to implement these mechanisms, then see how to exclude that model.

SM + *unmixed* Singlet:
A `simplified model' of stealthy electroweak baryogenesis!

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

heavy Higgs (sibling) production | Exotic Higgs Decays | EWPO | Higgs Couplings

Higgs portal production | h^3 measurement | $\sigma(Zh)$ measurement

Tree and Loop-driven PT

Need a simpler model to investigate these strong phase transitions....

DC, Patrick Meade, Tien-Tien Yu 1409.0005

Build a 'maximally ste
see how to exclude t

Let's first understand this model in the regime without Exotic Higgs Decays (no light singlet).

Come back to study in light singlet regime.

A simplified model of stealthy electroweak baryogenesis!

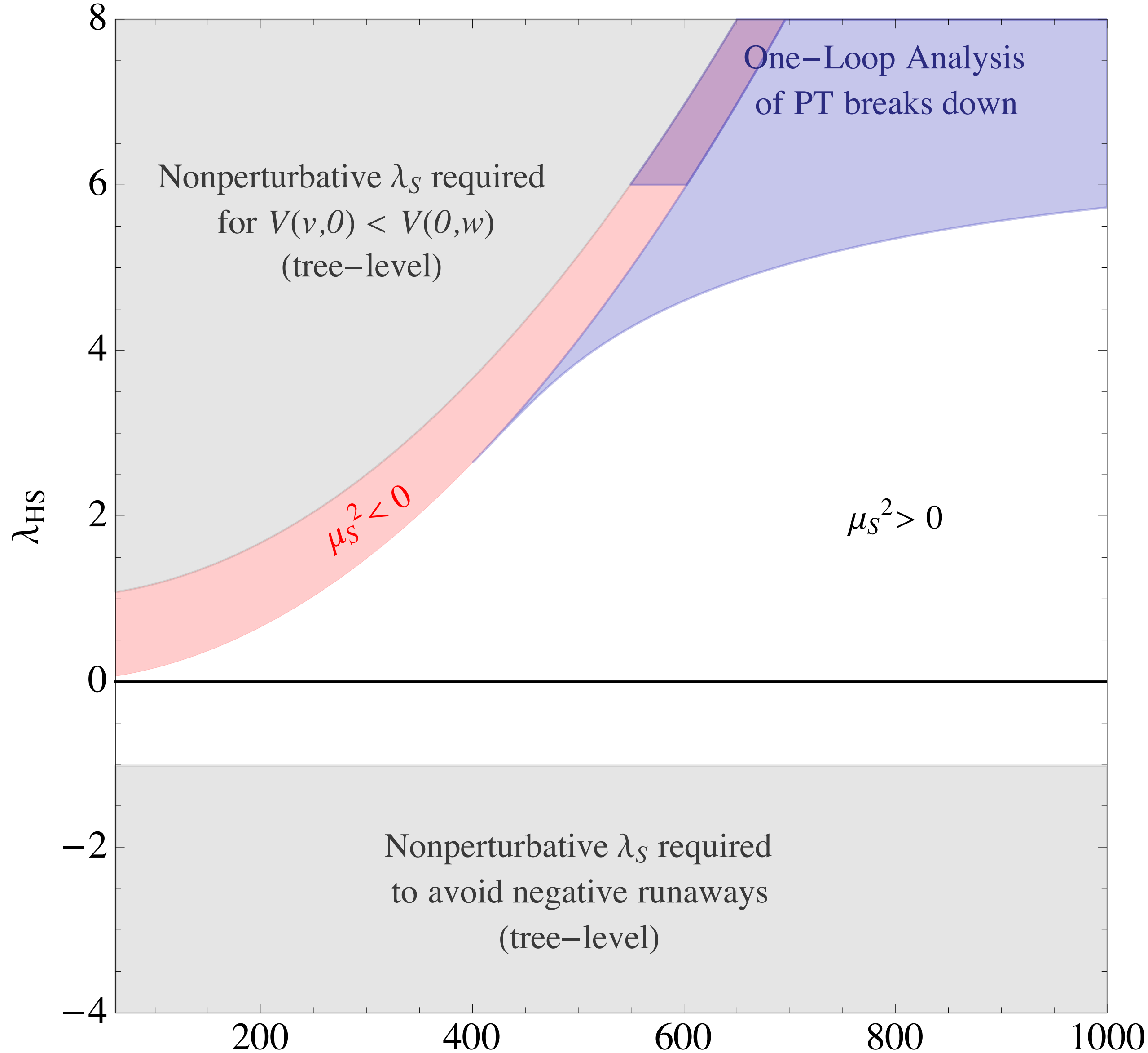
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

heavy Higgs (sibling) production | ~~Exotic Higgs Decays~~ | EWPO | Higgs Couplings

Higgs portal production | h^3 measurement | $\sigma(Zh)$ measurement

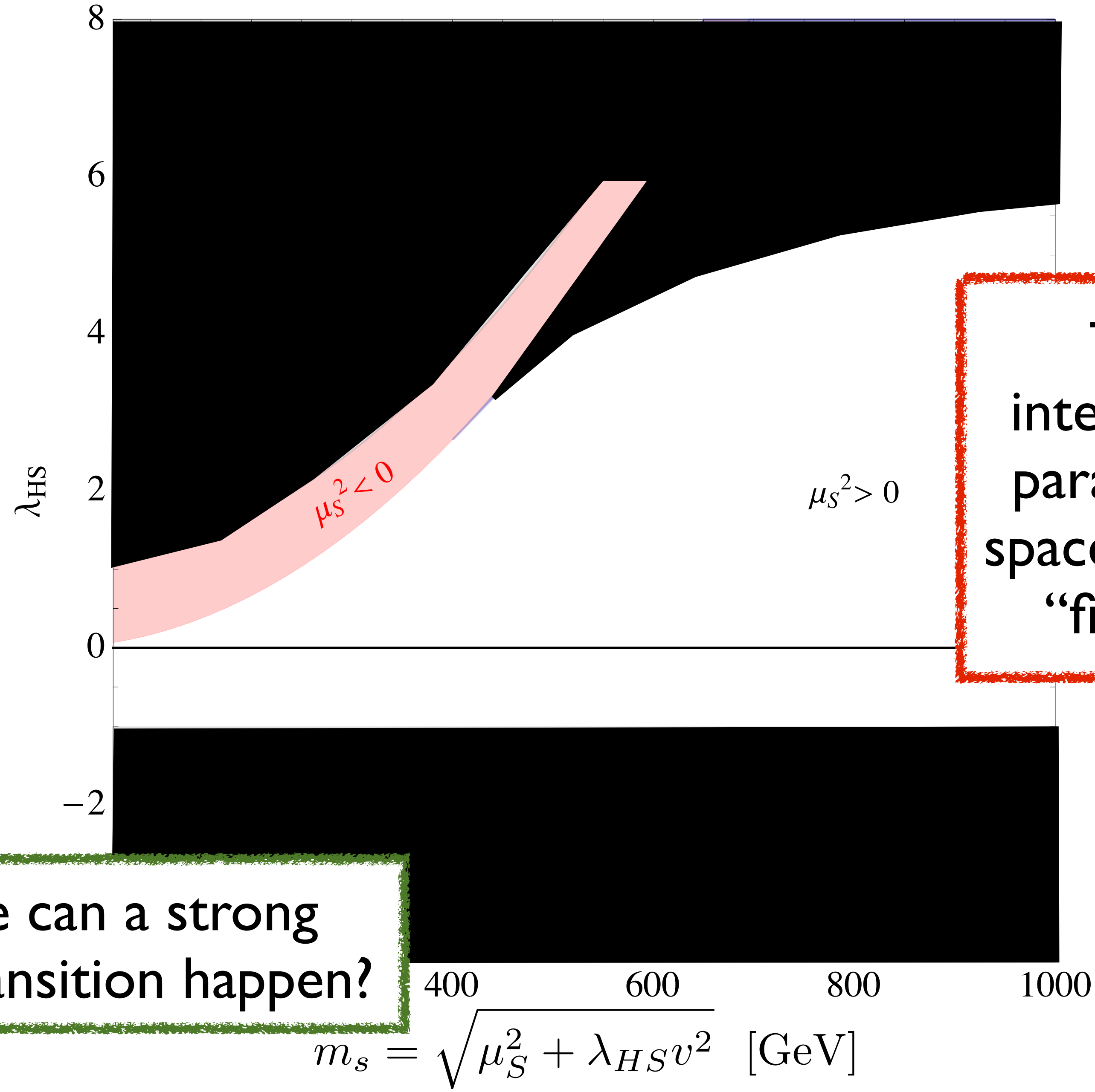
The (m_S, λ_{HS}) Plane

singlet-higgs coupling



singlet mass in our vacuum $m_s = \sqrt{\mu_S^2 + \lambda_{HS} v^2}$ [GeV]

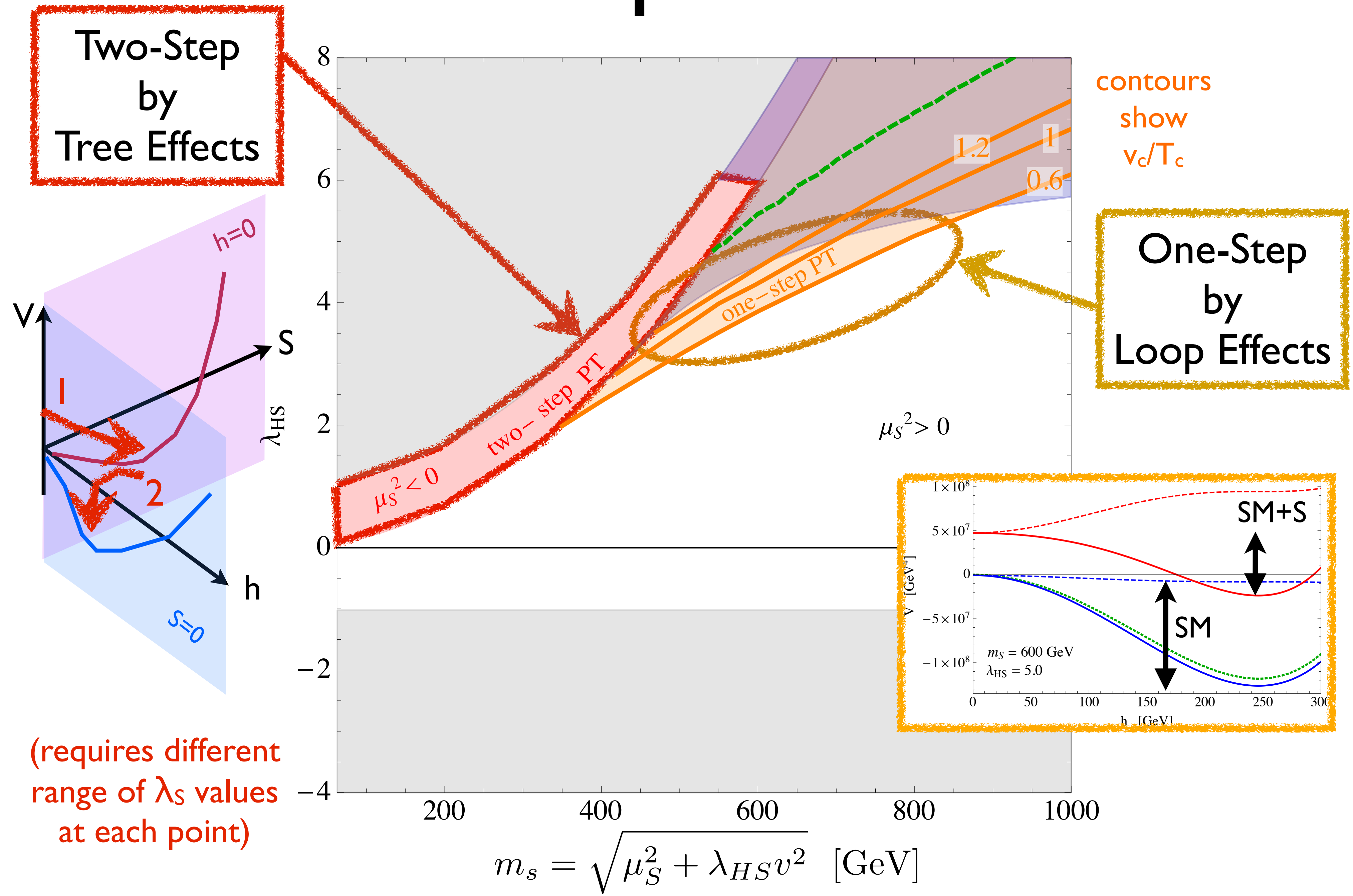
The (m_S, λ_{HS}) Plane



The interesting parameter space is very "finite".

Where can a strong phase transition happen?

Two* kinds of phase transitions



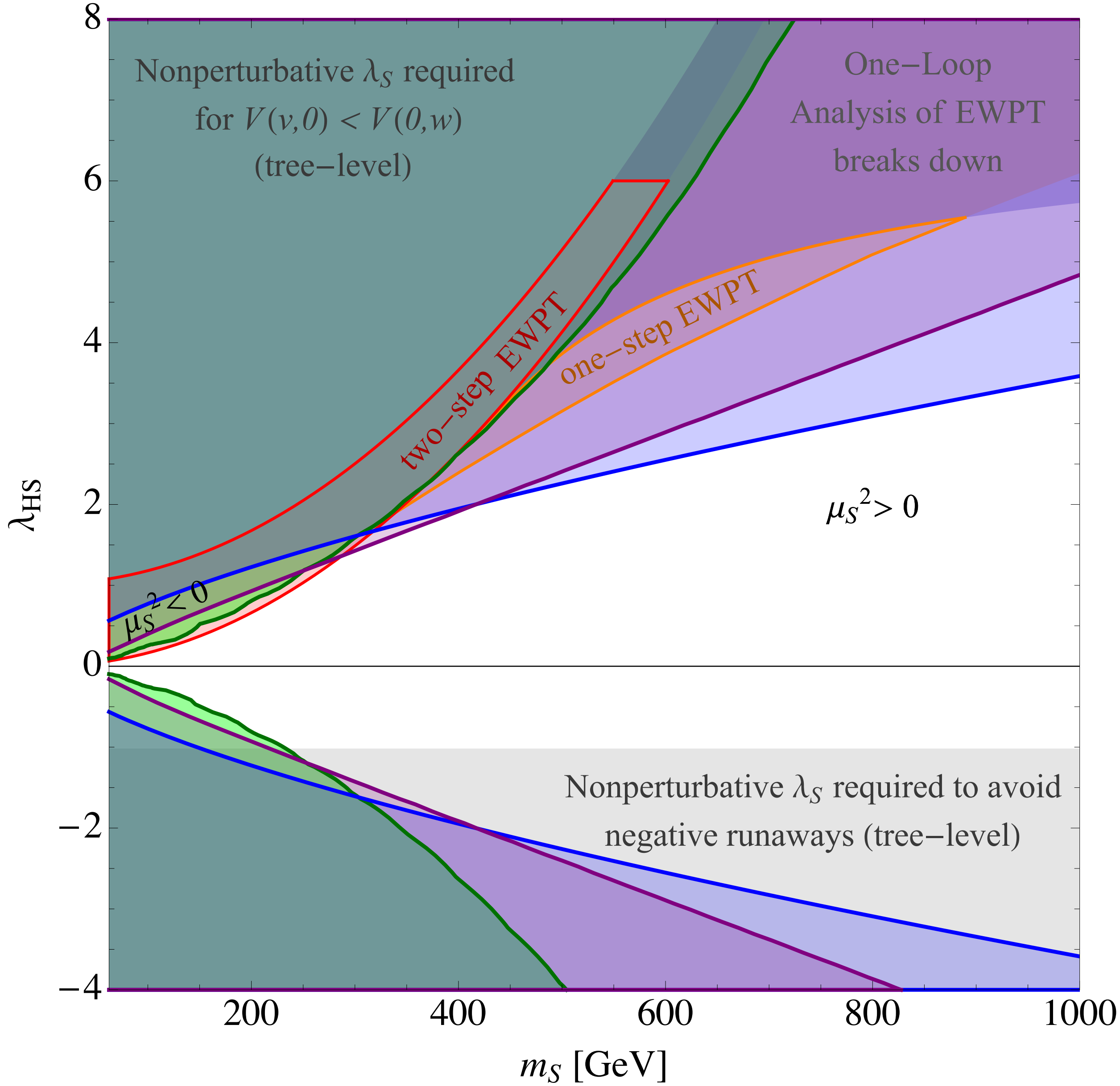
(requires different range of λ_S values at each point)

So can we exclude EWBG in this model?

Yes!*

*(depends on future collider capabilities)

2 σ exclusions



100 TeV Collider, 30/ab

triple-Higgs coupling measurement (> 10%)

Direct detection of VBF h* → SS
(S/√B > 2)

TLEP

$\delta\sigma_{Zh}$ measurement (> 0.3%)

100 TeV collider could cover *entire* parameter space.

TLEP can cover *almost all* of parameter space.

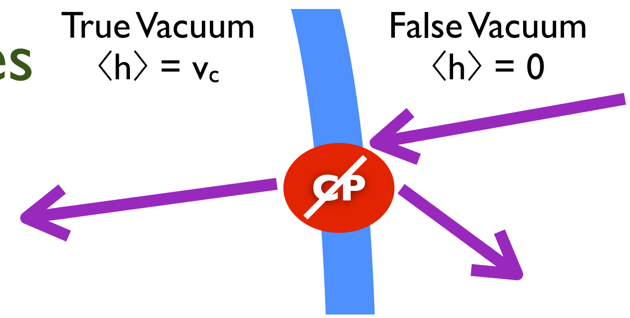
Potential complimentarily!

Exotic Higgs Decays

Exotic Higgs Decays

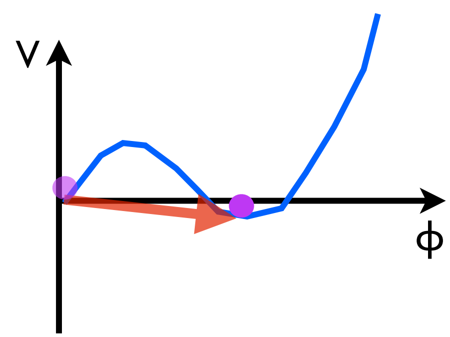
Light particles coupled to the Higgs could arise (separately) due to the physics of the strong phase transition (PT) or the creation of baryon asymmetry (BAU) during the PT.

BAU creation requires O(100 GeV) particles with sizable CPV couplings to higgs.



This particle could be < 63 GeV, but then
- in many cases, SM gauge charged → *excluded by LEP limits*
- if SM neutral, still require O(0.1) Higgs couplings
  → exotic Higgs decays already exclude this, or will soon...

What about the physics of the strong Phase Transition?



Exotic Higgs Decays

— Thermally driven PT —

Need O(1) couplings of new bosons to Higgs

If $m < 63$ GeV, will overwhelm SM Higgs decay modes.

Already inconsistent with data!

Exotic Higgs Decays

— Tree or Loop driven PT —

Again, explore in context of simple scalar extensions.

SM+S, 2HDM+S, with S-H mixing:

Big parameter space again makes it difficult to come up with exact statements.

If m_S < 63 GeV, mixing effects to give rise to $h \to 2s \to 4b, 4\tau$, etc

Should have access to Br ~ $10^{-4 \text{ or } 5} \leftrightarrow s_\theta \sim 10^{-2}$ at lepton colliders

Explicit studies needed!

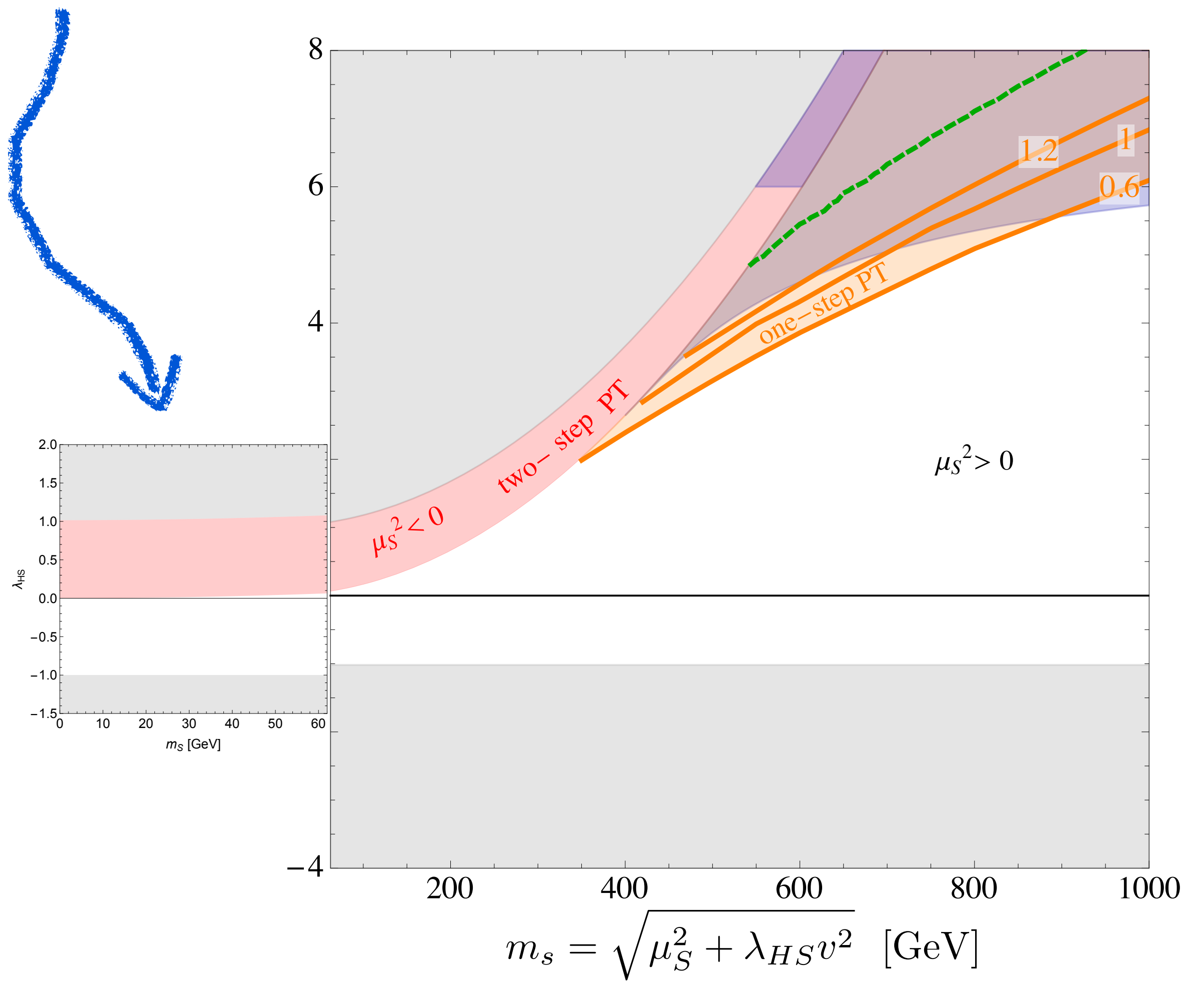
Certain cases are already excluded by data if scalar is light, e.g. exotic two-step transition.

1504.05195 Blinov, Kozaczuk, Morrissey, Tamarit

Unmixed SM+S

Let's go back to our simplified model of the strong PT to make some quantitative statements about exotic Higgs decays.

Explore the unmixed SM+S model in the regime where $m_S < m_h/2$



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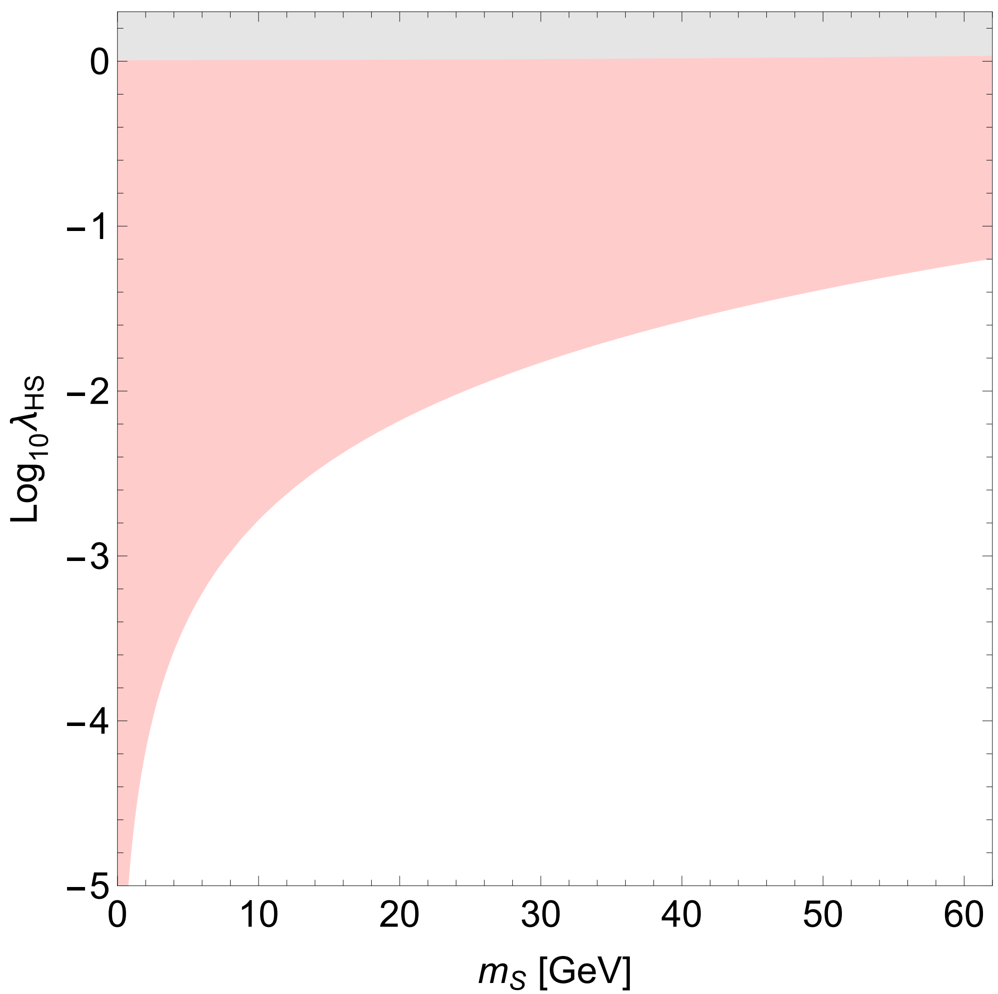

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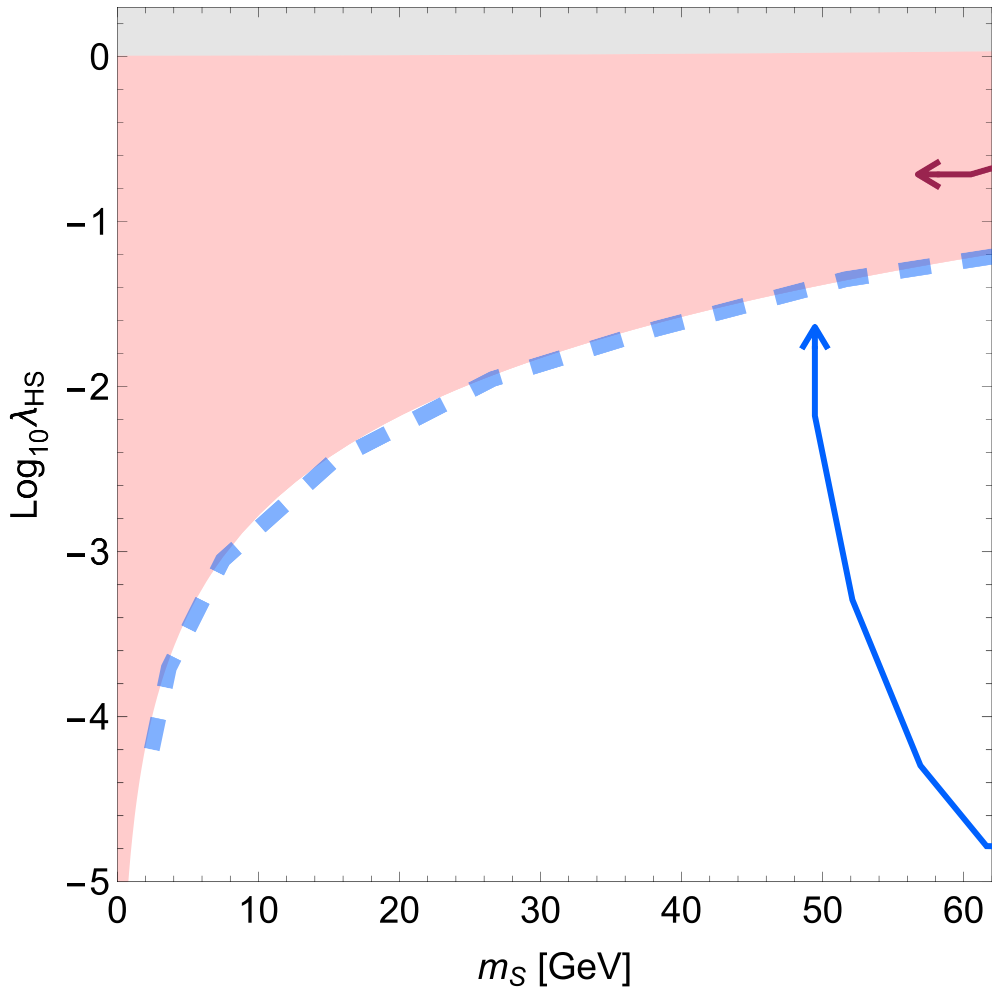


$\mu_S^2 < 0$

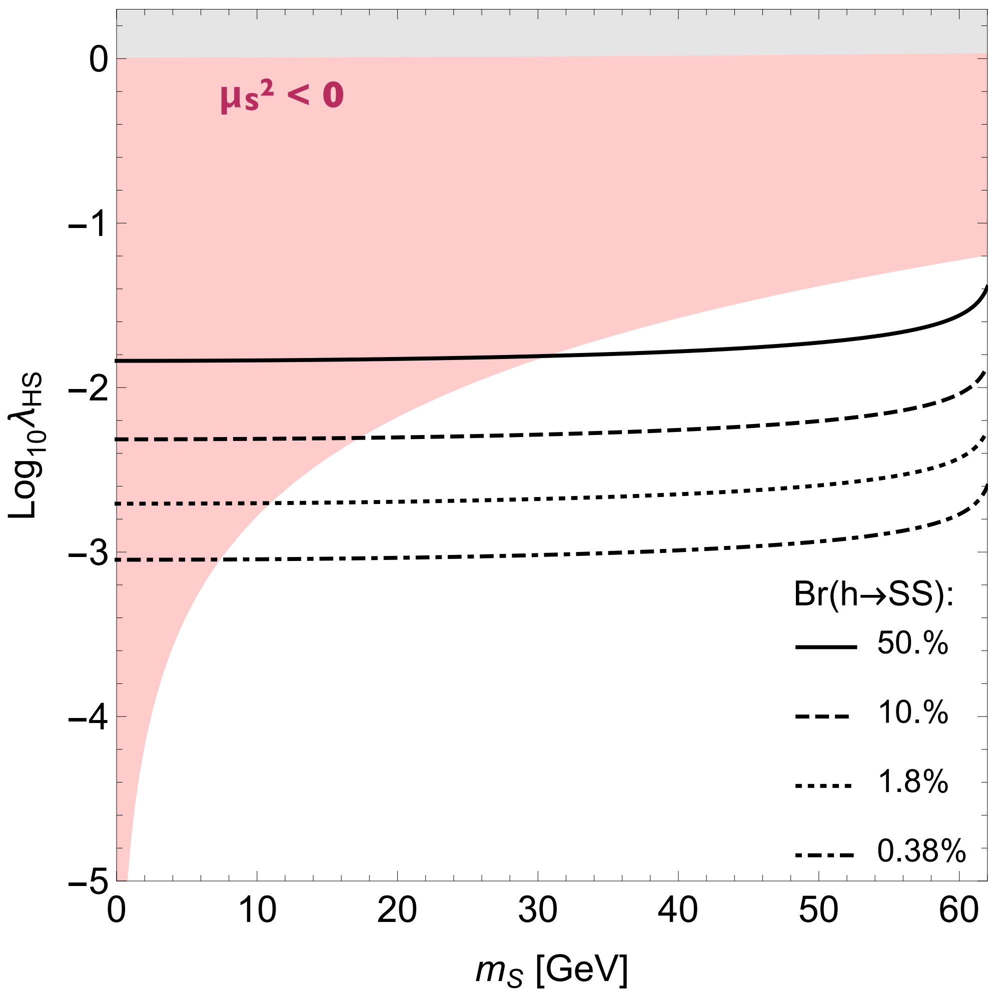
Two-step PT possible for certain choices of λ_S.

Loop-driven transitions are probably impossible for such low m_S

....

but if they happen they live along *very* thin band of $\mu_S^2 \sim 0$

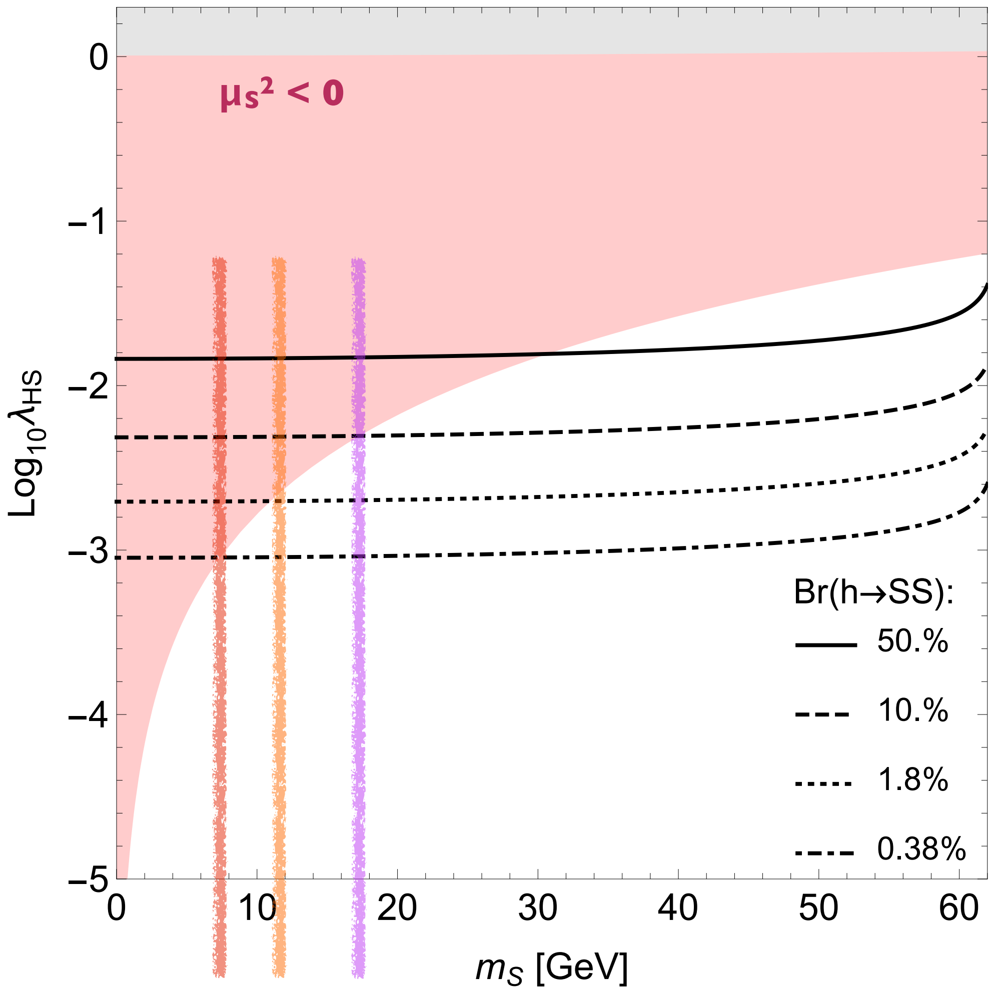
Unmixed SM+S



Compute

Br(h→SS) = Br(h→invis)

Unmixed SM+S



Compute
Br(h→SS) = Br(h→invis)

2σ reach

~ LHC

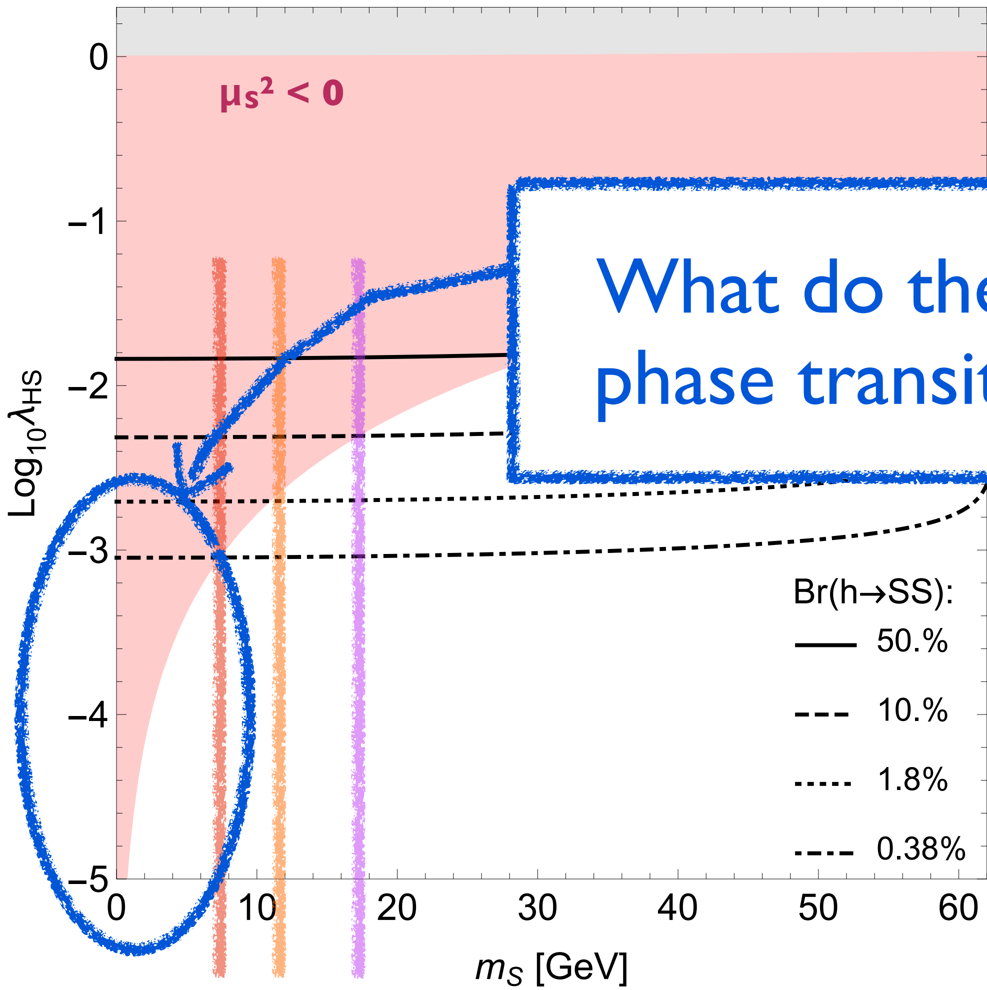
~ ILC

~ TLEP

LHC will exclude strong PT for $m_S \lesssim$ 20 GV

Lepton colliders can go down to ~ 7 GeV

Unmixed SM+S



What do the "unprobable" phase transitions look like?

Compute

Br(h→SS) = Br(h→invis)

2σ reach

~ LHC

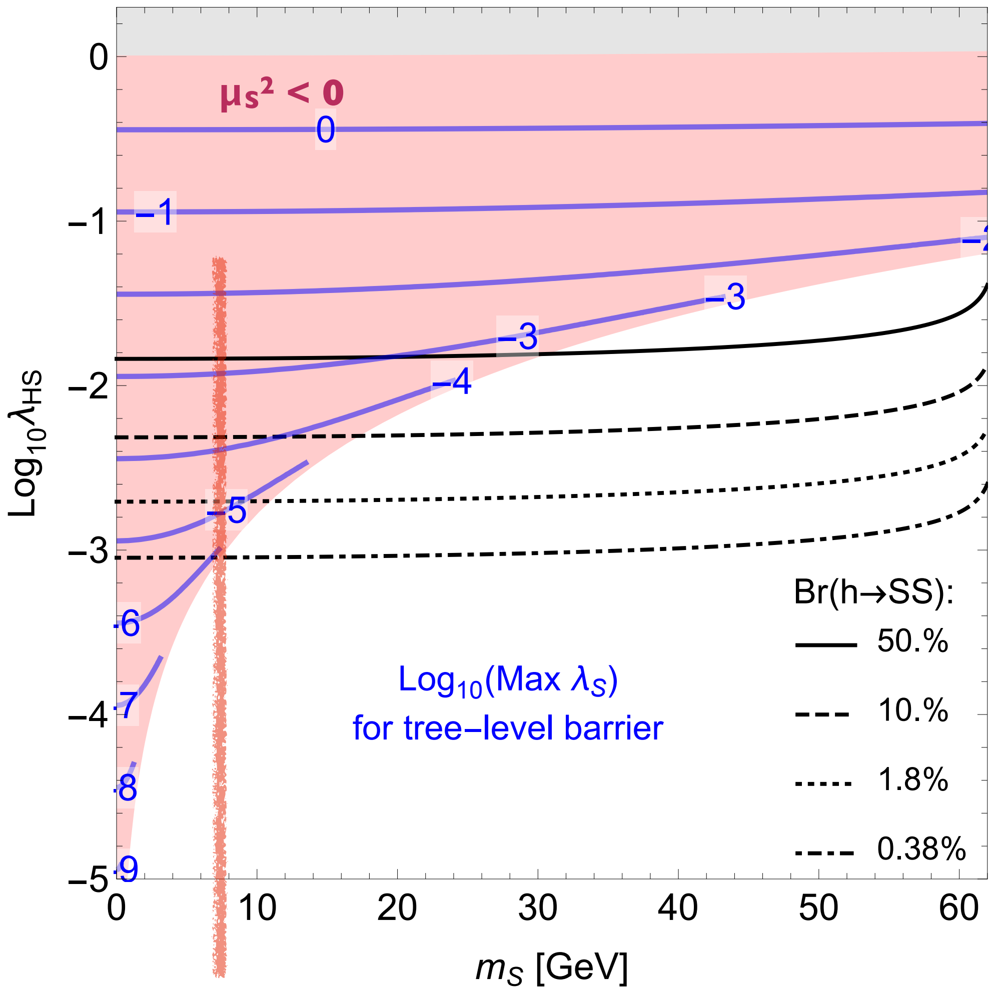
~ ILC

~ TLEP

exclude strong PT for $m_S \lesssim$ 20 GV

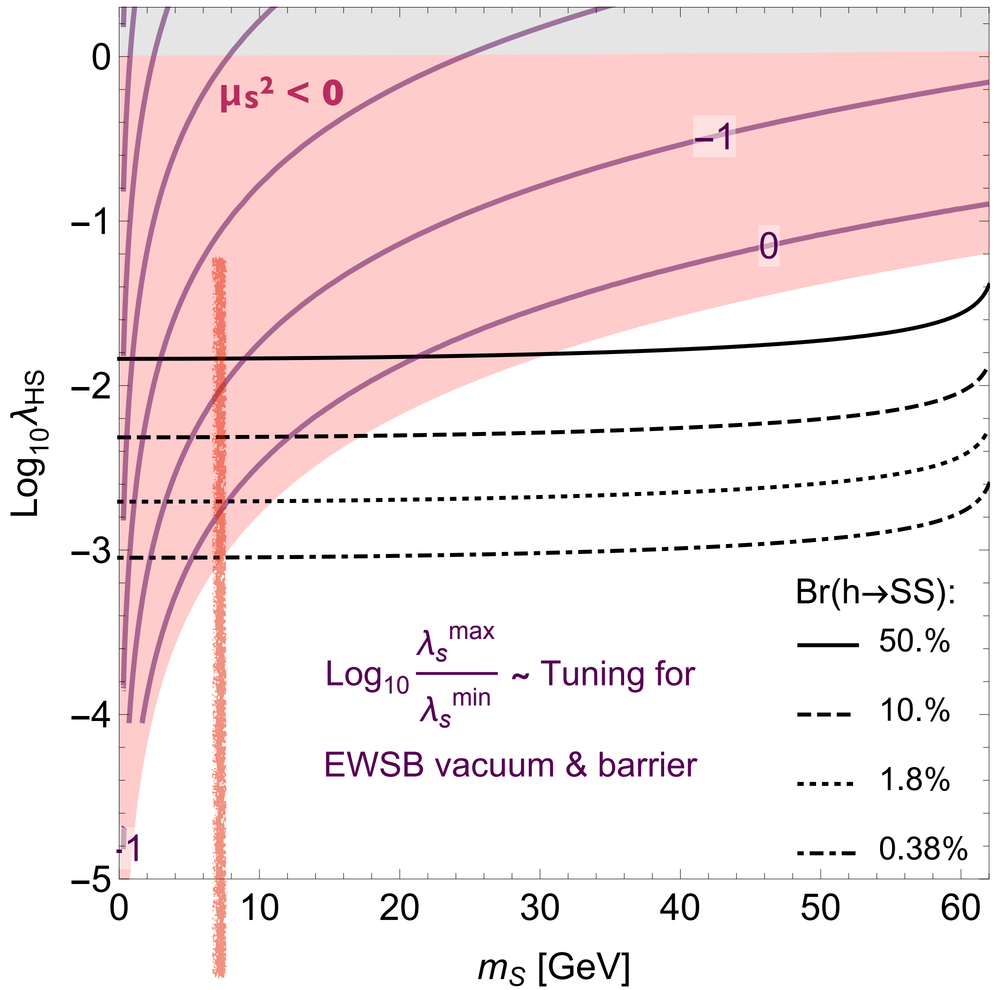
Lepton colliders can go down to ~ 7 GeV

Unmixed SM+S



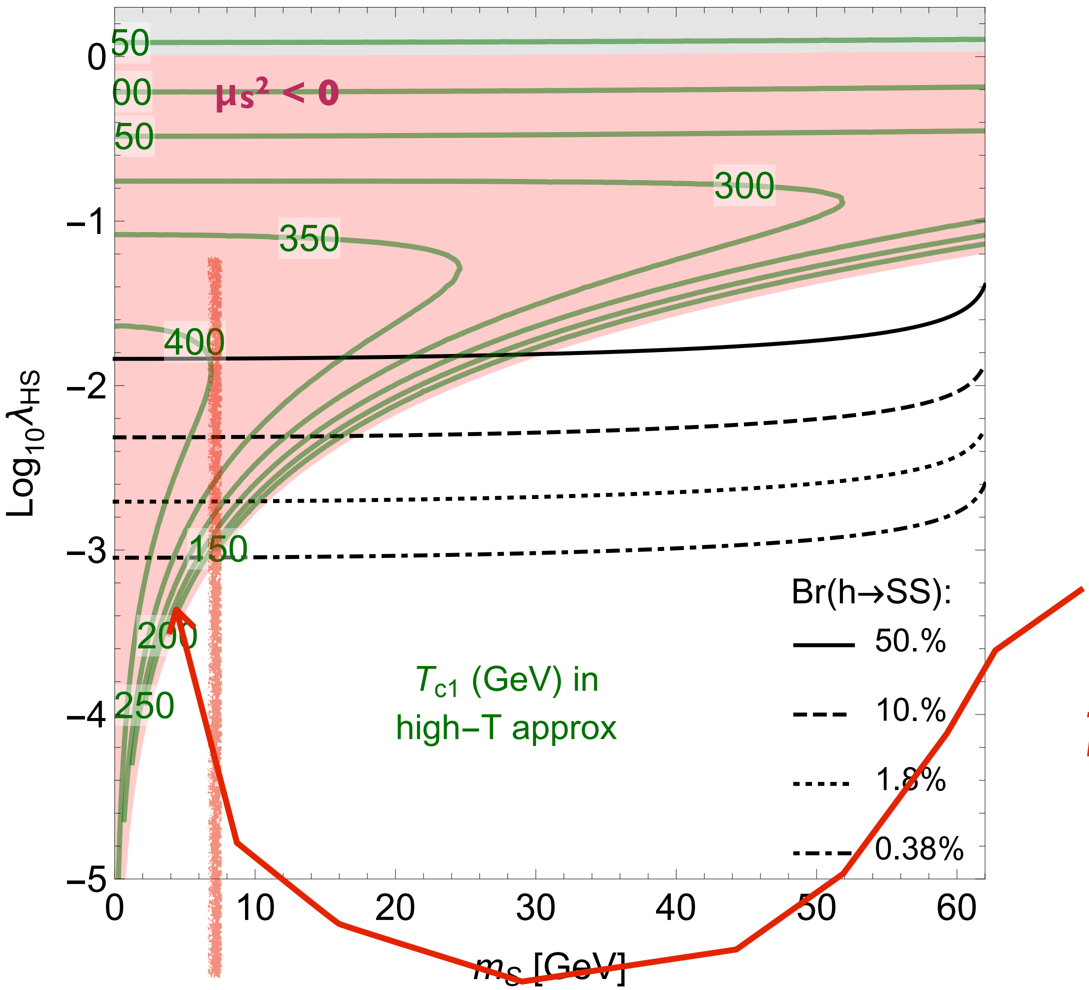
“Unprobable” two-step PT requires $\lambda_S < 10^{-5}$

Unmixed SM+S



Quartic Tuning & Radiative Stability: a priori OK

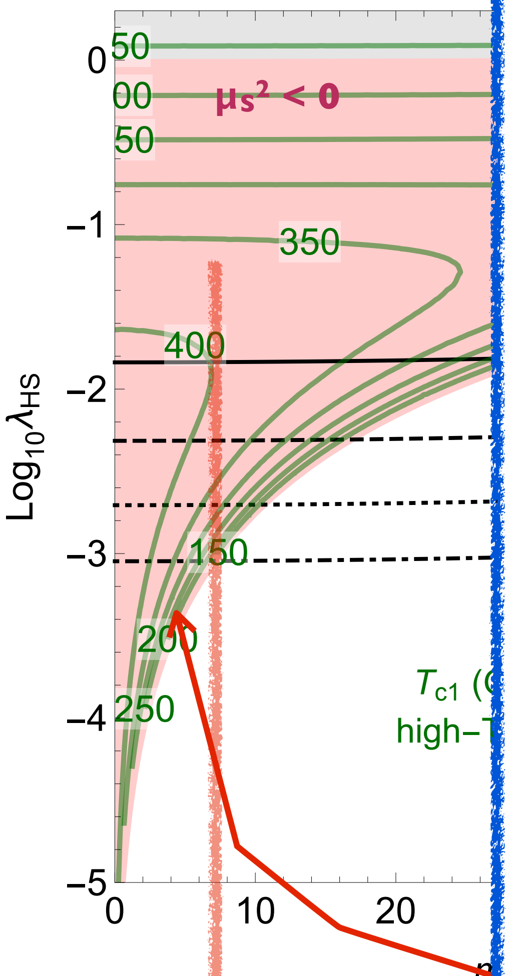
Unmixed SM+S



Reasonable values for T_{c1}, where singlet transitions from 0 to [large] vev.

Explicit spot-check: *two-step PT works as expected in full finite-T quantum calculation*

But are there other reasons this might fail?



Moral of the story:

You'll never exclude

*!!****everything****!!*

....

But for light scalars giving strong PT, evading exotic Higgs decay bounds certainly requires a very strange world....

alues for T_{c1},
transitions
arge] vev.

-check: *two-*
s expected in
tum calculation

ther reasons
ht fail?

Conclusions

Conclusions

EWBG can be probed at current colliders, and maybe excluded at future colliders (without exotic Higgs decays) by looking for signs of strong phase transition.

Exotic Higgs Decays are a powerful probe of EWBG if the physics of the strong PT or BAU creation involves particles below 63 GeV.

Basically excludes such light particles facilitating BAU creation

Basically excludes such light particles causing thermally driven PT

For tree/loop driven PT in scalar extensions **with** H-mixing, SM+S or 2HDM+S inspired decays $h \to 2a \to 4f$ (Yukawa ordered) are powerful probes, especially at lepton colliders. Make this more quantitative?

For tree/loop driven PT in scalar extensions **without** H-mixing, lepton collider bounds on $h \to$ invis exclude all but *very light particles with peculiarly tiny couplings*. Other ways to probe?