THE ELECTROWEAK PHASE TRANSITION

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Based mostly on
PM, H. Ramani work in progress
David Curtin, PM, H. Ramani 1612.00466
David Curtin, PM, Tien-Tien Yu 1409.0005

WHERE ARE WE GOING IN HEP?

MANY REASONS FOR BSM PHYSICS

- Hierarchy Problem
- Dark Matter
- Matter anti-Matter asymmetry
- Neutrino Mass origin
- Strong CP problem
- Flavor
- Number of generations
- Apparent Unification of Coupling Constants
- Inflation
- Reheating
- Unification with Gravity
- Cosmological Constant Problem

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Experimental difficulty...
We don't know the scales!!!

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No big deal, experimental science is for discovery not just validation!

ARE THERE QUESTIONS WHICH ARE BOTH THEORETICALLY MEANINGFUL AND EXPERIMENTALLY ACCESSIBLE?

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Yes! The nature of EWSB

SOME WAYS TO UNDERSTAND EWSB

- Higgs couplings to other particles
- Higgs potential itself
- Cosmological history of EWSB

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- Higgs potential itself ***HL-LHC and future colliders***
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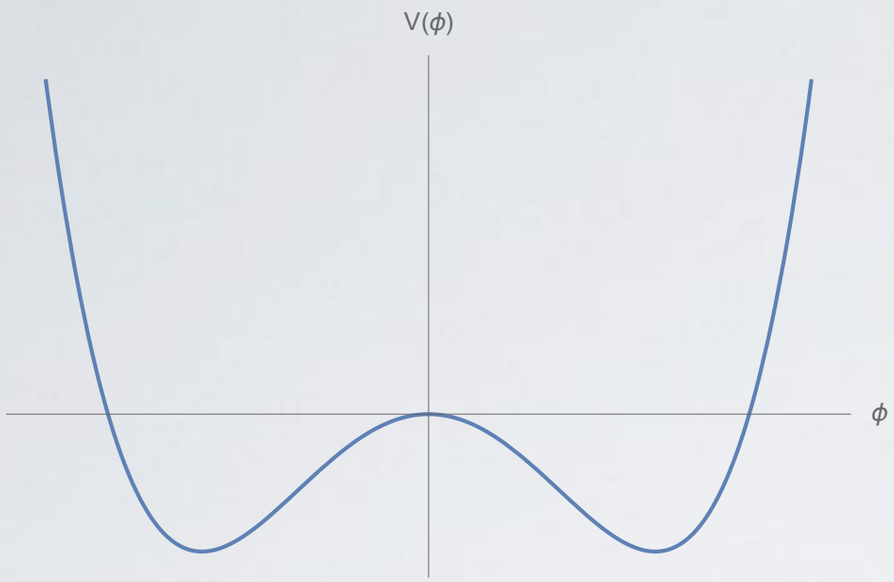
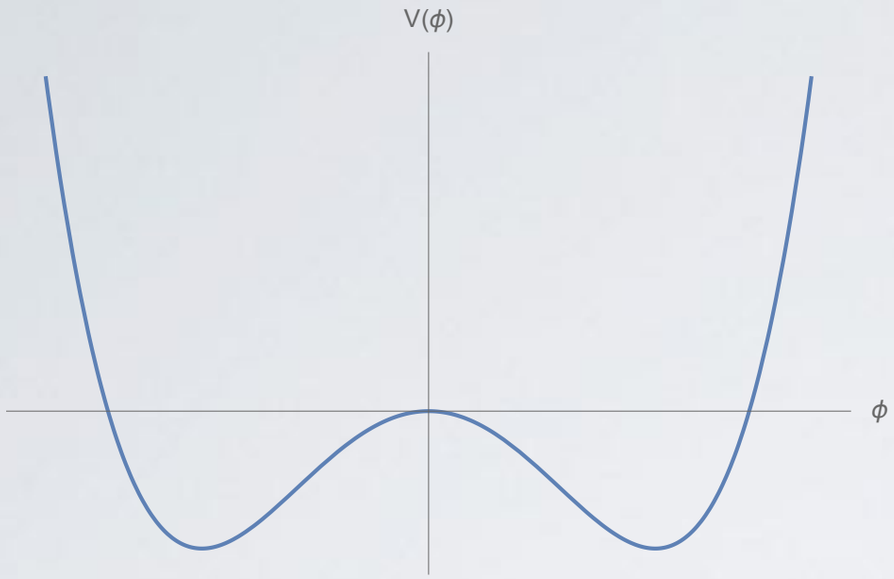


$$\left.\frac{\partial V(\phi)}{\partial \phi}\right|_{\phi=v} = 0$$

$$\left.\frac{\partial^2 V(\phi)}{\partial \phi^2}\right|_{\phi=v} = m_h^2$$

VEV and mass
are sufficient
for Higgs potential



OR

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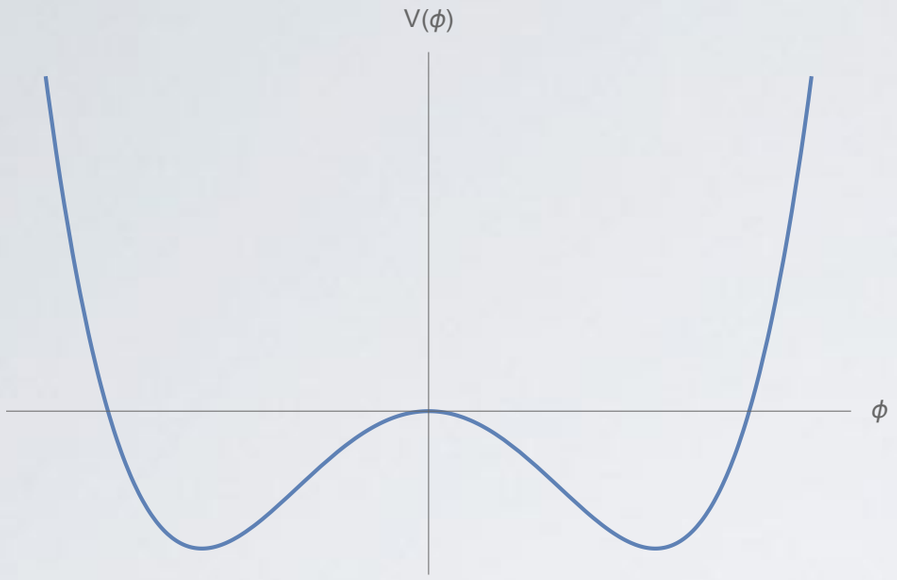

Higgs self interactions

OR

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HL-LHC and future colliders and focus of this talk

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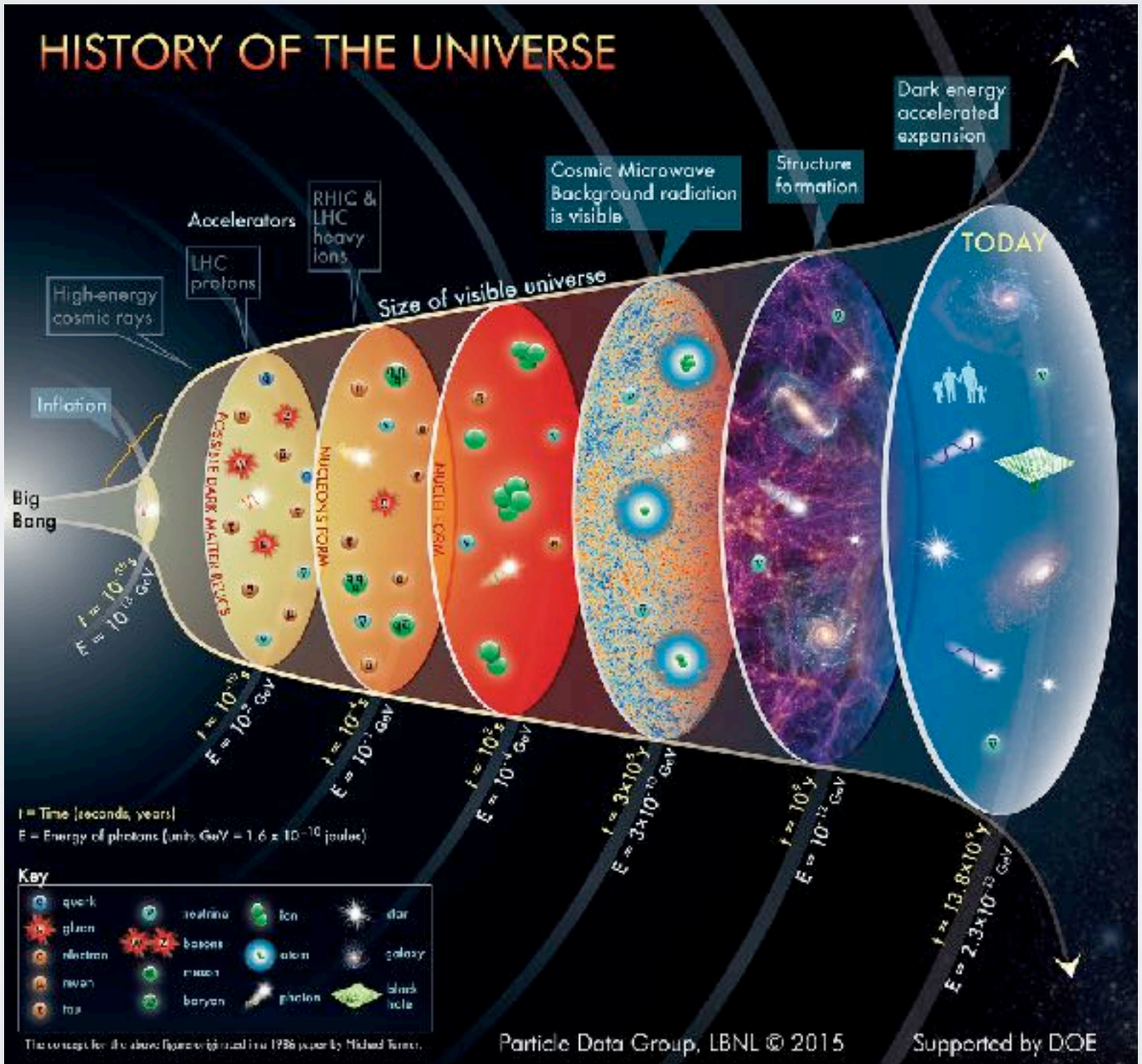
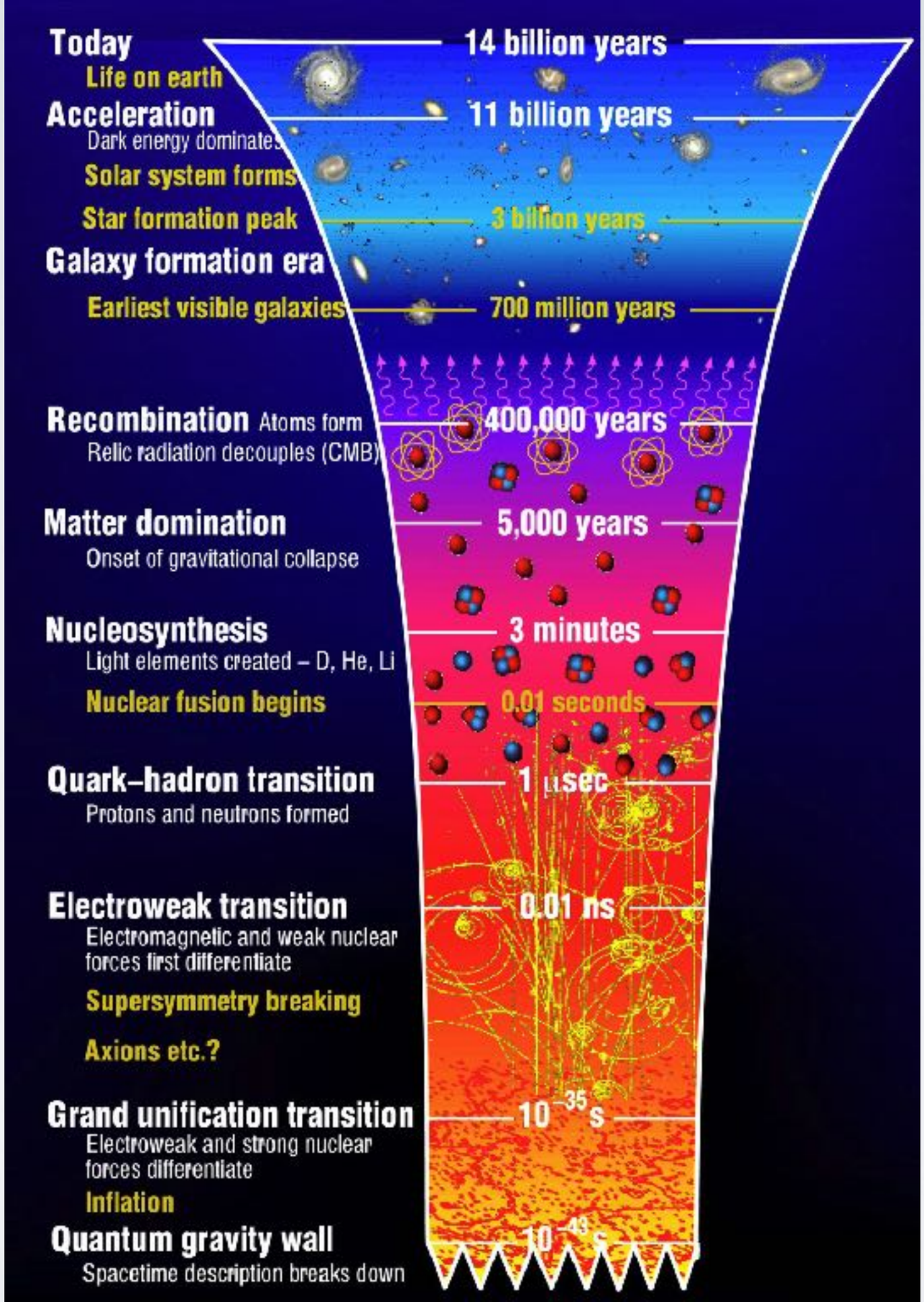
What we're really interested in is when can quantitative measurements distinguish qualitative pictures

WHAT IS OUR QUALITATIVE PICTURE OF THE COSMOLOGICAL HISTORY OF EWSB??





Cosmology stuck here

Need particle physics to go further!

WHERE DOES THIS QUALITATIVE PICTURE COME FROM?

IT ALL STARTED WITH SOME RUSSIANS…

IT ALL STARTED WITH SOME RUSSIANS IN 1972…

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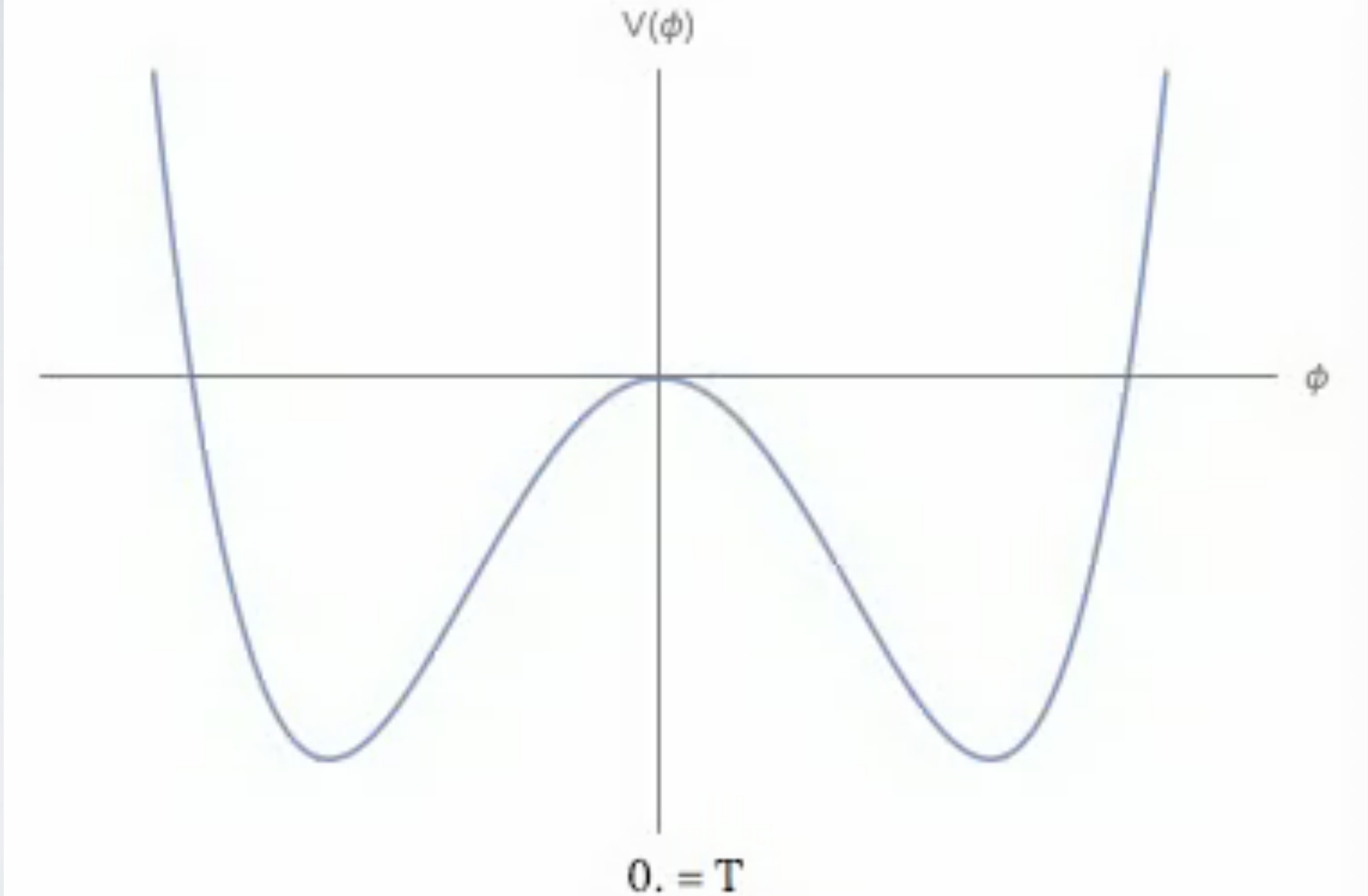
IF YOU HEAT UP A GAUGE THEORY WITH A SPONTANEOUSLY BROKEN SYMMETRY DOES THE SYMMETRY GET RESTORED?

WHAT'S THE CURIE TEMPERATURE OF THE UNIVERSE?


V(ϕ)
ϕ
0. = T

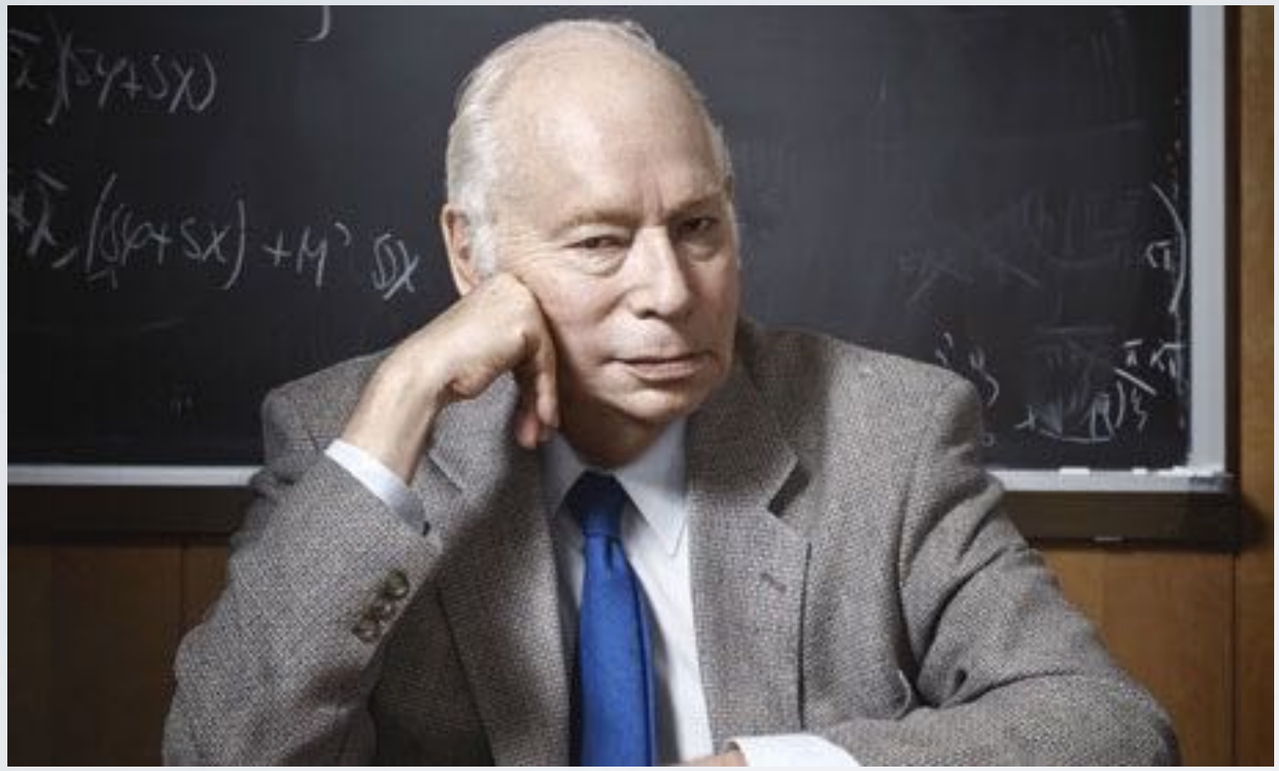
IF YOU HEAT UP A GAUGE THEORY WITH A SPONTANEOUSLY BROKEN SYMMETRY DOES THE SYMMETRY GET RESTORED?

WHAT'S THE CURIE TEMPERATURE OF THE UNIVERSE?

ANSWERS: YES, HMM…


There's no place
like home,
There's no place like home,
There's no place like
home…


Weinberg,
Weinberg,
Weinberg…



"A recent paper by Kirzhnits and Linde suggests that this is indeed the case. However, although their title refers to a gauge theory, their analysis deals only with ordinary theories with broken global symmetries. Also, they estimate but do not actually calculate the critical temperature at which a broken symmetry is restored."

THERMAL PHASE TRANSITIONS A LONG ROAD

’74 Weinberg, Dolan, Jackiw
’72 Kirzhnits, Linde

MANY INGREDIENTS AND APPLICATIONS

- Many different types of physics that enter in to calculating any of this… ridiculously complicated if you have to go into all of it simultaneously

- Thermal inflation, Gravitational Waves, Baryogenesis, Leptogenesis, Dark Matter, etc etc

THERMAL PHASE TRANSITIONS A LONG ROAD

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"Unfortunately, despite the fact that one is dealing with a weakly coupled theory, many aspects of the phase transition are surprisingly complicated. Indeed, the literature contains **contradictory claims and statements on almost every important question**."

'92 Dine, Leigh, Huet, Linde ,Linde

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Recently with Curtin and Ramani we think we have established the correct way to calculate for BSM theories

HOW DOES THIS STORY RELATE TO FUTURE COLLIDERS AND ANSWER OUR COSMOLOGICAL QUESTIONS…

A lot of details of thermal QFT go into this but I'll try to offer a heuristic set of pictures for what happens when

$$V(h) \to V(h, T)$$

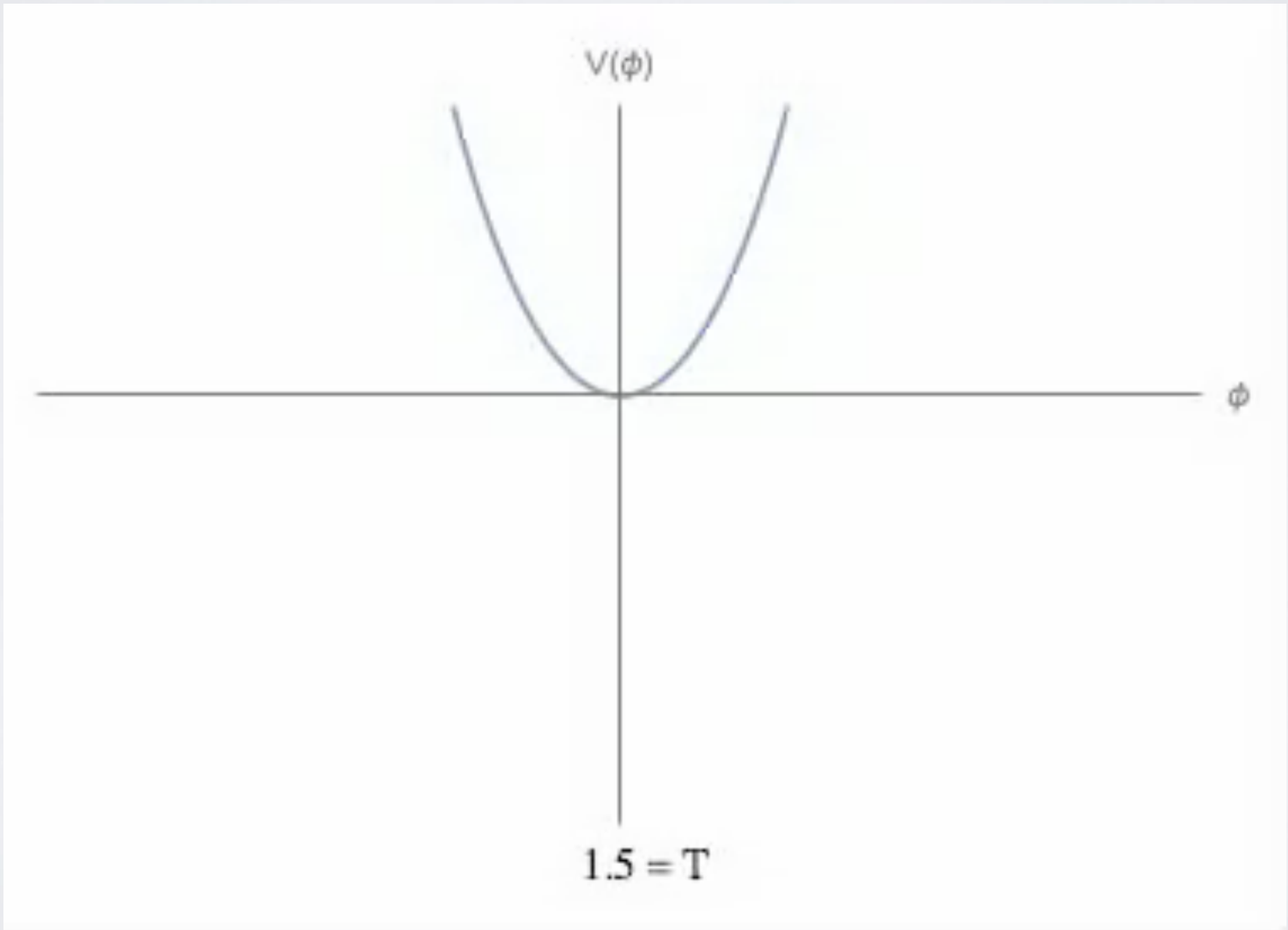
MANTRA - ALL HIGGSED THEORIES HAVE SYMMETRIES RESTORED AT HIGH-T

Interesting fact… but what's it useful for?

The universe supposedly went through at least an EW phase transition, it's interesting to study it and understand its nature e.g. 1st order vs 2nd order

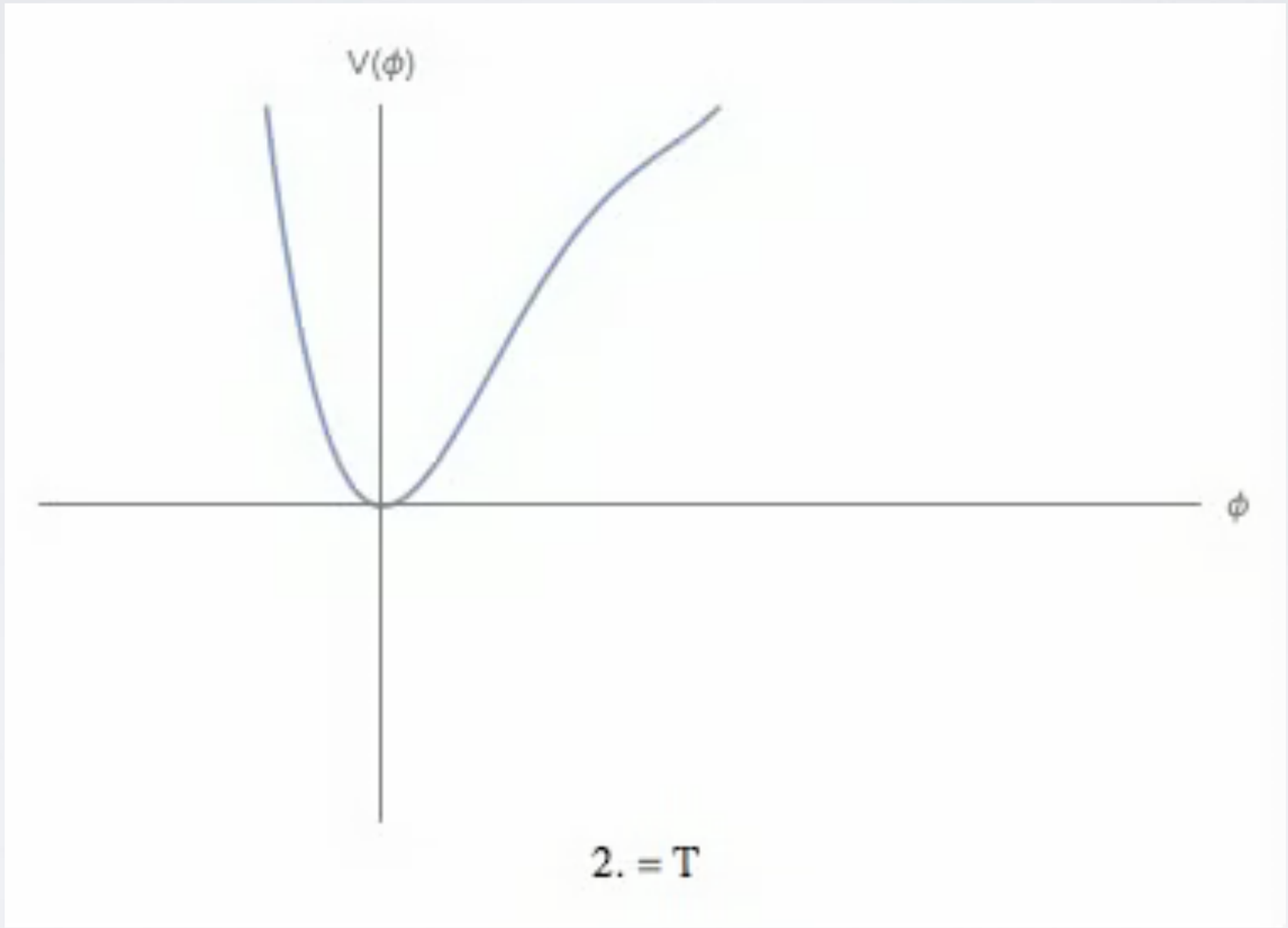
2ND ORDER PHASE TRANSITION

$$V(\phi, T) = D(T^2 - T_o^2)\phi^2 + \frac{\lambda(T)}{4}\phi^4$$



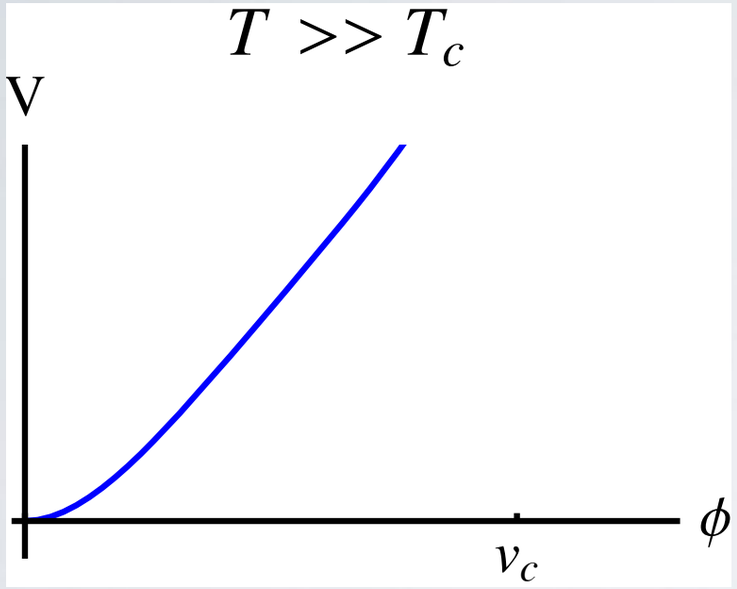
1ST ORDER PHASE TRANSITION

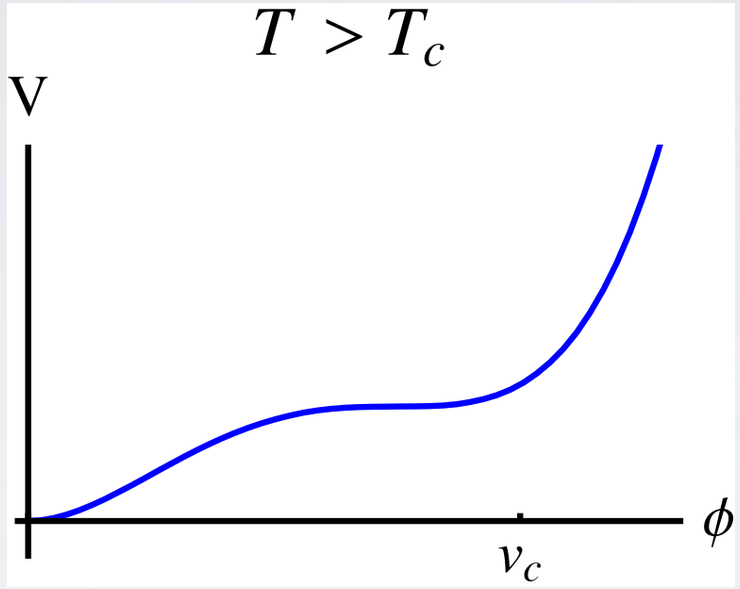
$$V(\phi, T) = D(T^2 - T_o^2)\phi^2 - ET\phi^3 + \frac{\lambda(T)}{4}\phi^4$$



A second minimum separated by a barrier!

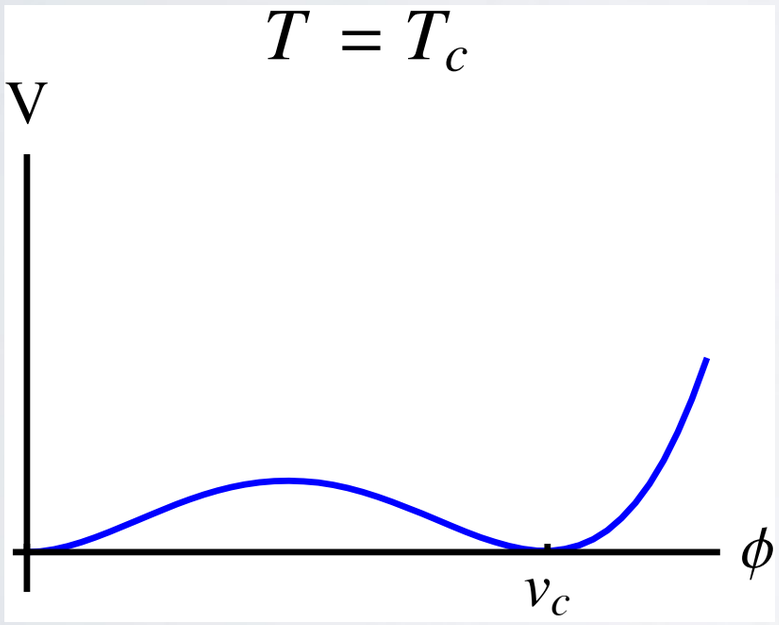
EW PHASE TRANSITION

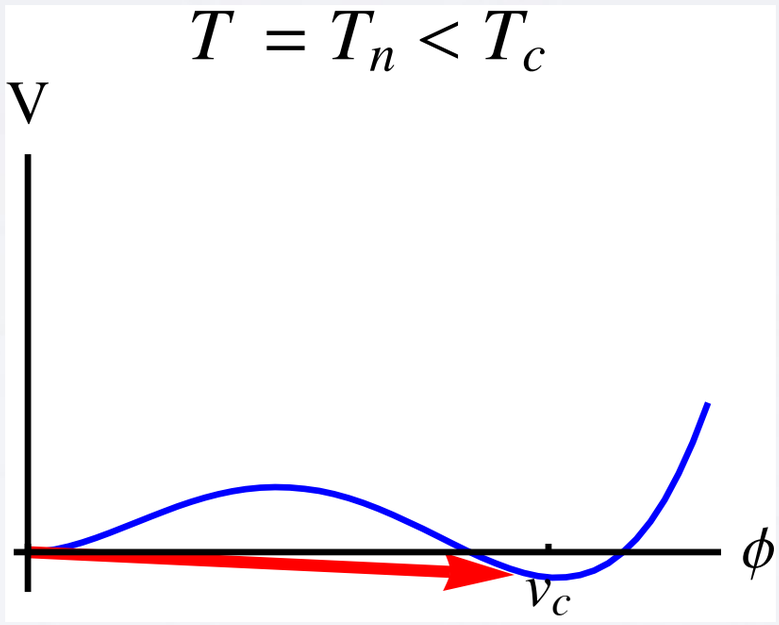




To have a strong 1st order phase transition

$$\frac{\langle\phi\rangle}{T_c} \sim 1$$





This translates in the Higgs potential to

$$\frac{\langle\phi\rangle}{T_c} \sim \frac{cubic}{quartic}$$

This is the basis for why it connects to future colliders

IF WE TAKE THE SM ALONE

- Not a 1st order phase transition because the Higgs is too heavy

- **Could** be 1st order and it depends on couplings we haven't measured yet!

RECENT PROGRESS

- Can future colliders test the entire range of models that can generate a 1st order EW phase transition?
- Are we theoretically under control for BSM models?
- Did we have to have an EW phase transition?

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- Are we theoretically under control for BSM models? YES David Curtin, PM, H. Ramani 1612.00466

- Did we have to have an EW phase transition?

  NO!!! PM, H. Ramani WORK IN PROGRESS

HOW TO TEST POTENTIAL OF FUTURE COLLIDERS TO TEST EW PHASE TRANSITION?

FIND A SCENARIO THAT GIVES A 1ST ORDER PHASE TRANSITION, BUT IS A "NIGHTMARE" TO SEE WITH COLLIDERS

Not a no-lose theorem, but a big step along the road and illustrates important theoretical difficulties we have improved on

SM + SINGLET

This scenario has been studied
numerous times for a variety of reason….

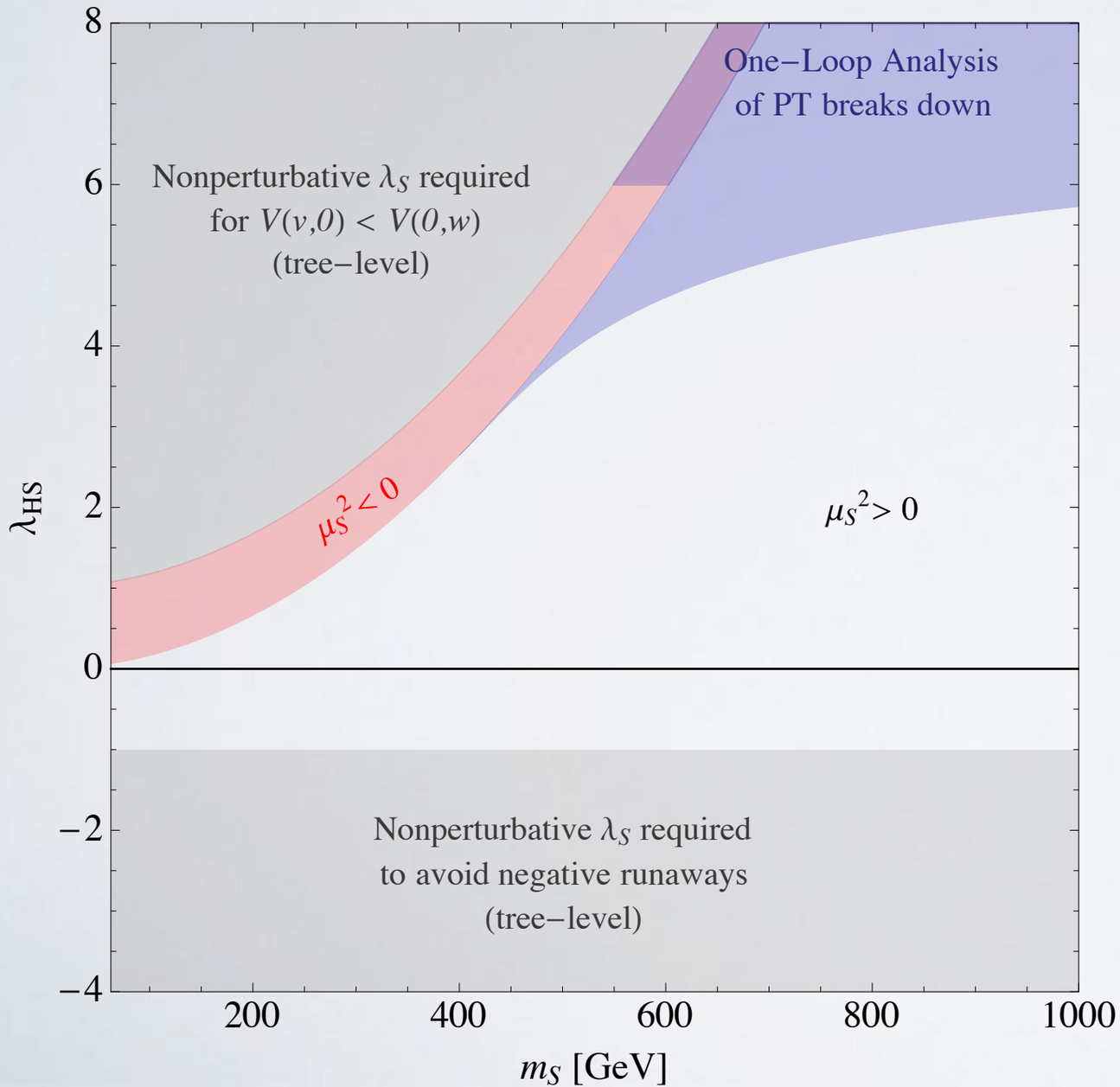
If the Singlet mixes with the Higgs you can see it easily via Higgs properties and has been studied quite a bit

If the Singlet DOESN'T mix but its mass is less than half the Higgs mass you can see it in decays easily…

What if the singlet doesn't mix with the Higgs and is heavier than half the Higgs mass?

SM + SINGLET NIGHTMARE SCENARIO

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



$$m_S^2 = \mu_S^2 + \lambda_{HS} v^2 > 0$$

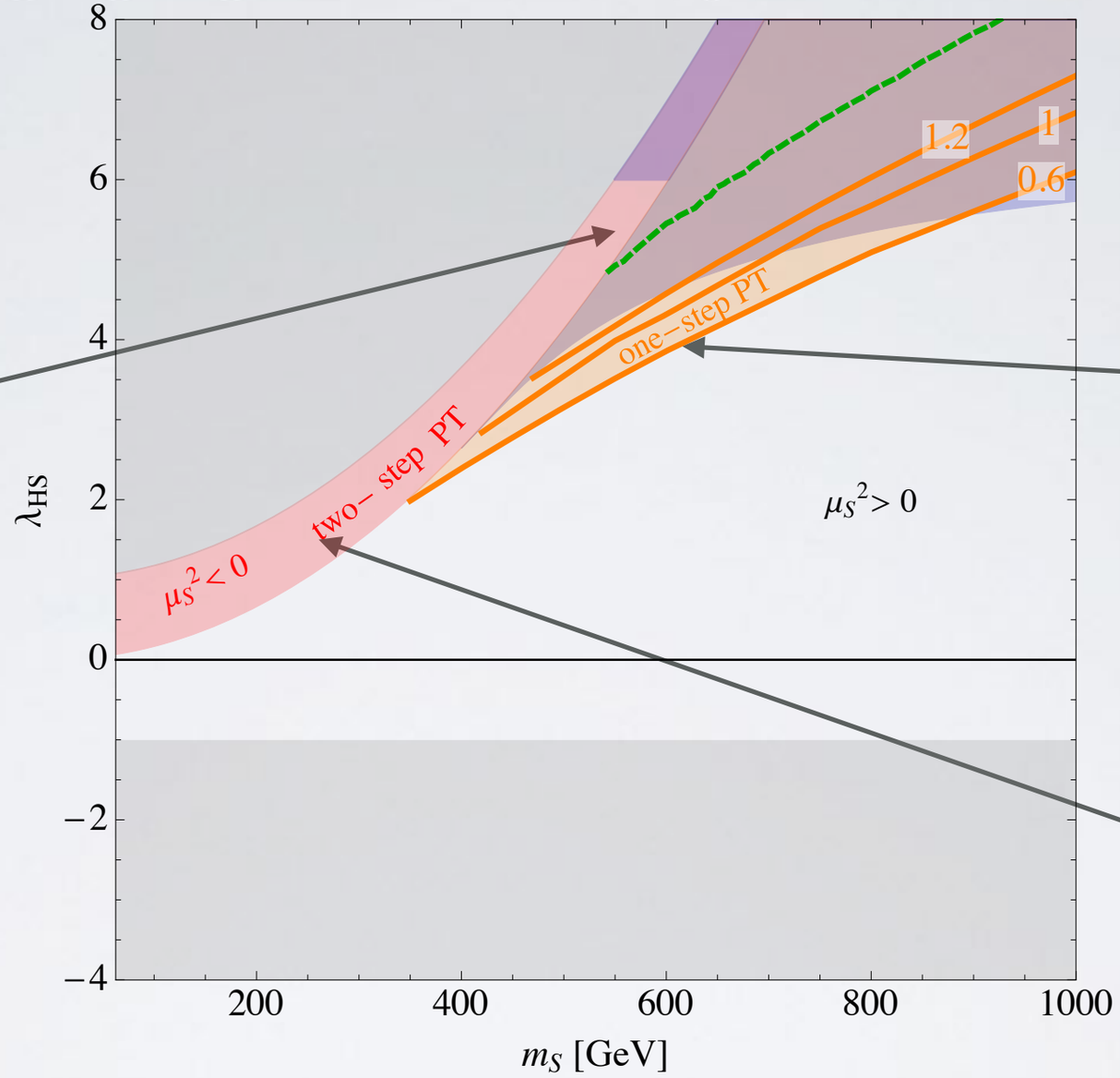
Phenomenological parameter space depends only on

$$(m_S, \lambda_{HS})$$

There are two qualitatively different regions depending on the sign of μ_S^2

WHERE IN THE PARAMETER SPACE IS THERE A GOOD PHASE TRANSITION?

thermal 1-step PT

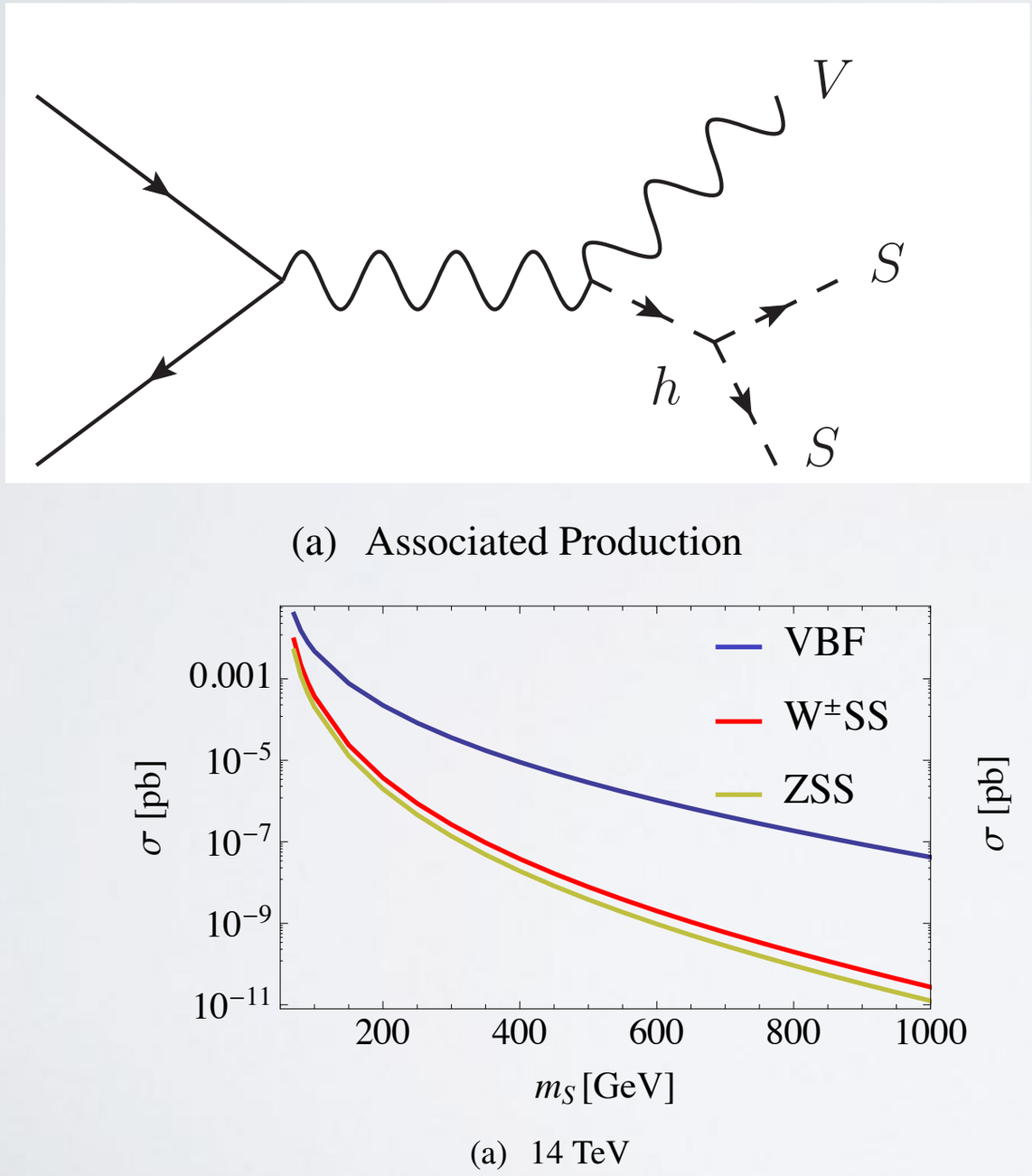


1-step PT zero T loops

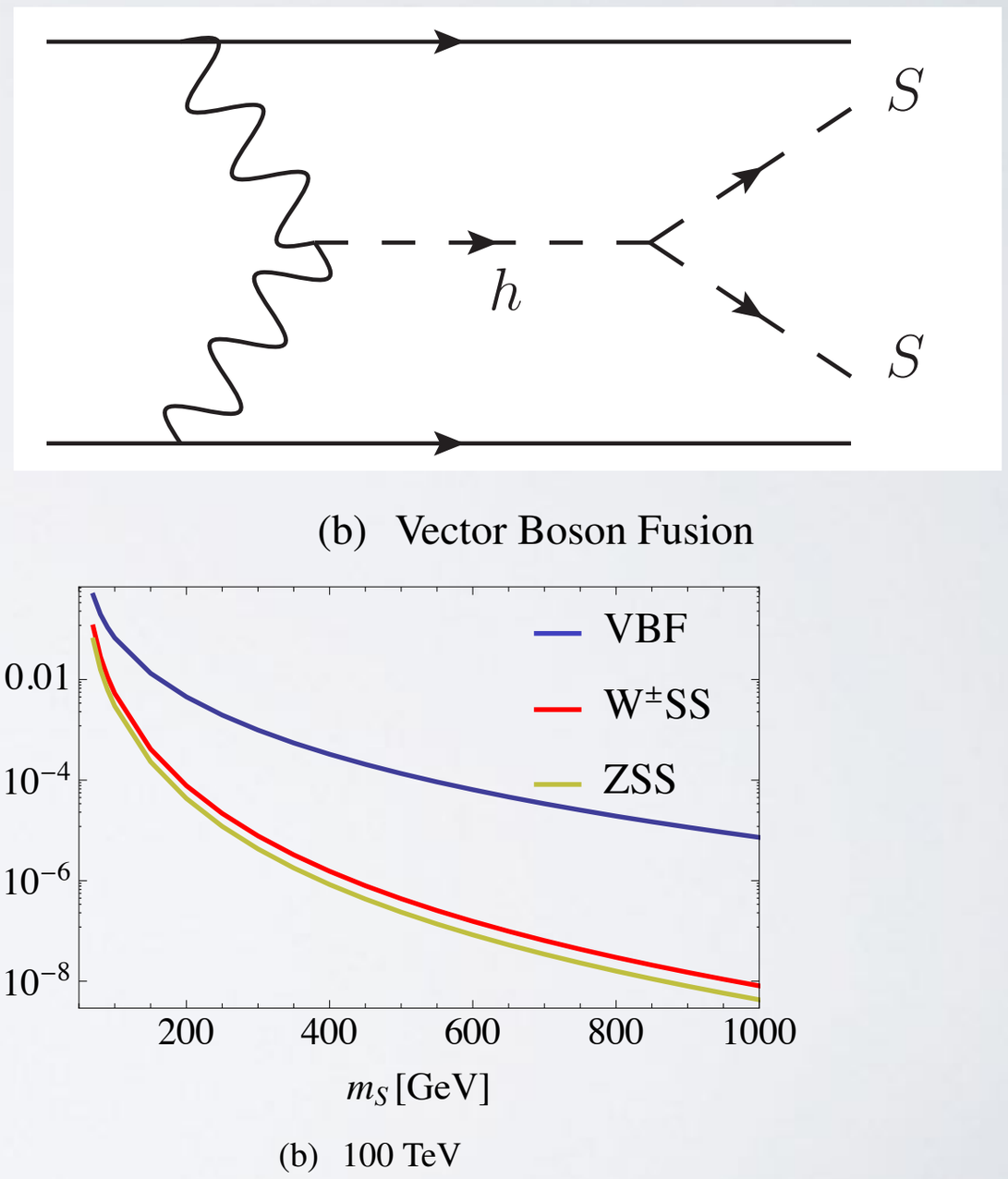
2-step PT transition

Figure 3. Regions in the (m_S, λ_{HS}) plane with viable EWBG. Red shaded region: for $\mu_S^2 < 0$ it is possible to choose λ_S such that EWBG proceeds via a tree-induced strong two-step electroweak phase transition. Orange contours: value of v_c/T_c for $\mu_S^2 > 0$. The orange shaded region indicates $v_c/T_c > 0.6$, where EWBG occurs via a loop-induced strong one-step phase transition. Above the green dashed line, singlet loop corrections generate a barrier between $h = 0$ and $h = v$ even at $T = 0$, but results in the dark shaded region might not be reliable, see Section 3.1.3.

DIRECT PRODUCTION OF SINGLETS



(a) Associated Production



(b) Vector Boson Fusion

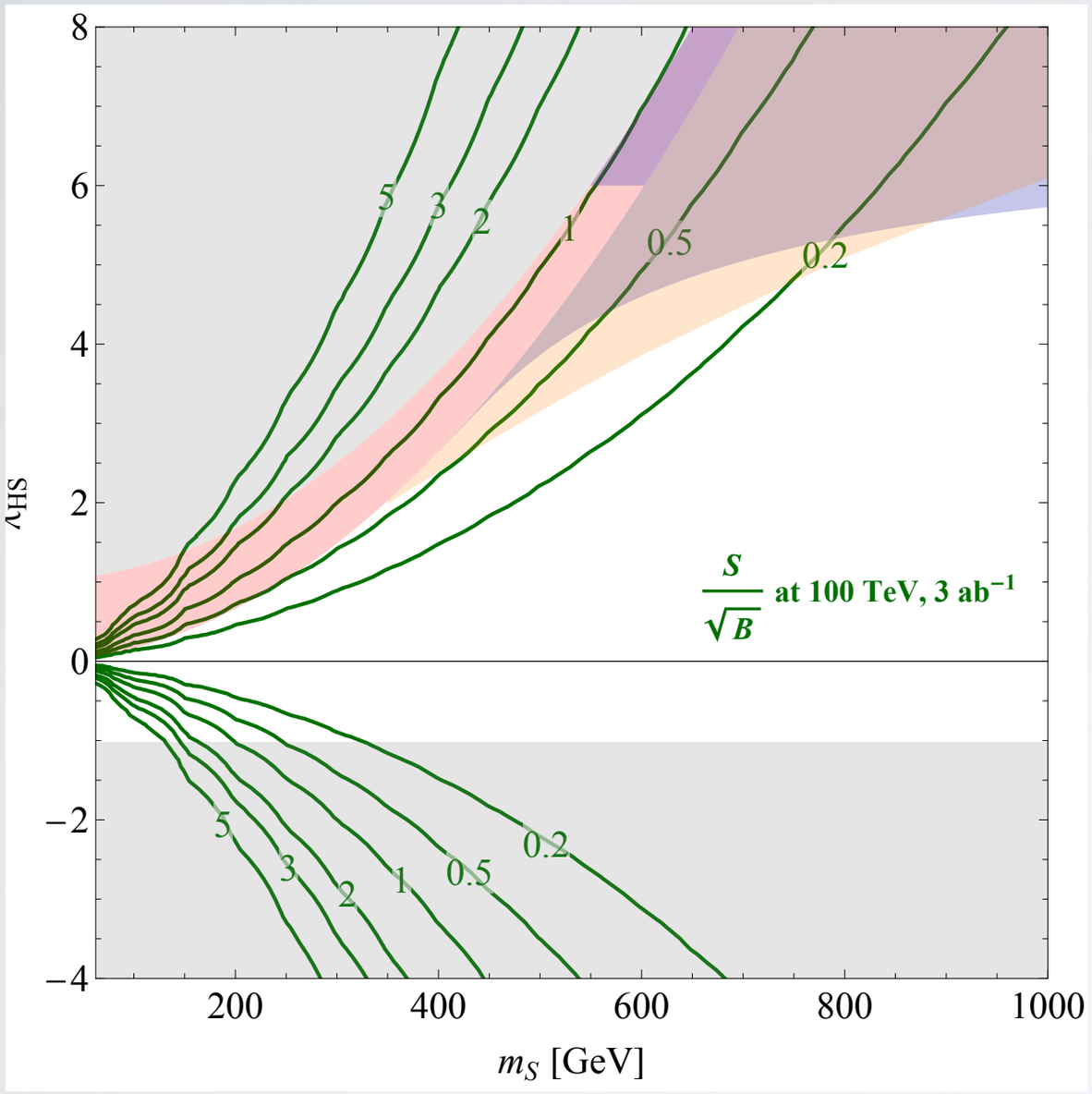
(a) 14 TeV

(b) 100 TeV

Figure 7. Production cross-sections at hadron colliders for various modes of singlet production with $\lambda_{HS} = 2$. These calculations were computed at LO with MadGraph5 [84]

POTENTIAL REACH…

Toy VBF study, using Snowmass backgrounds and detectors



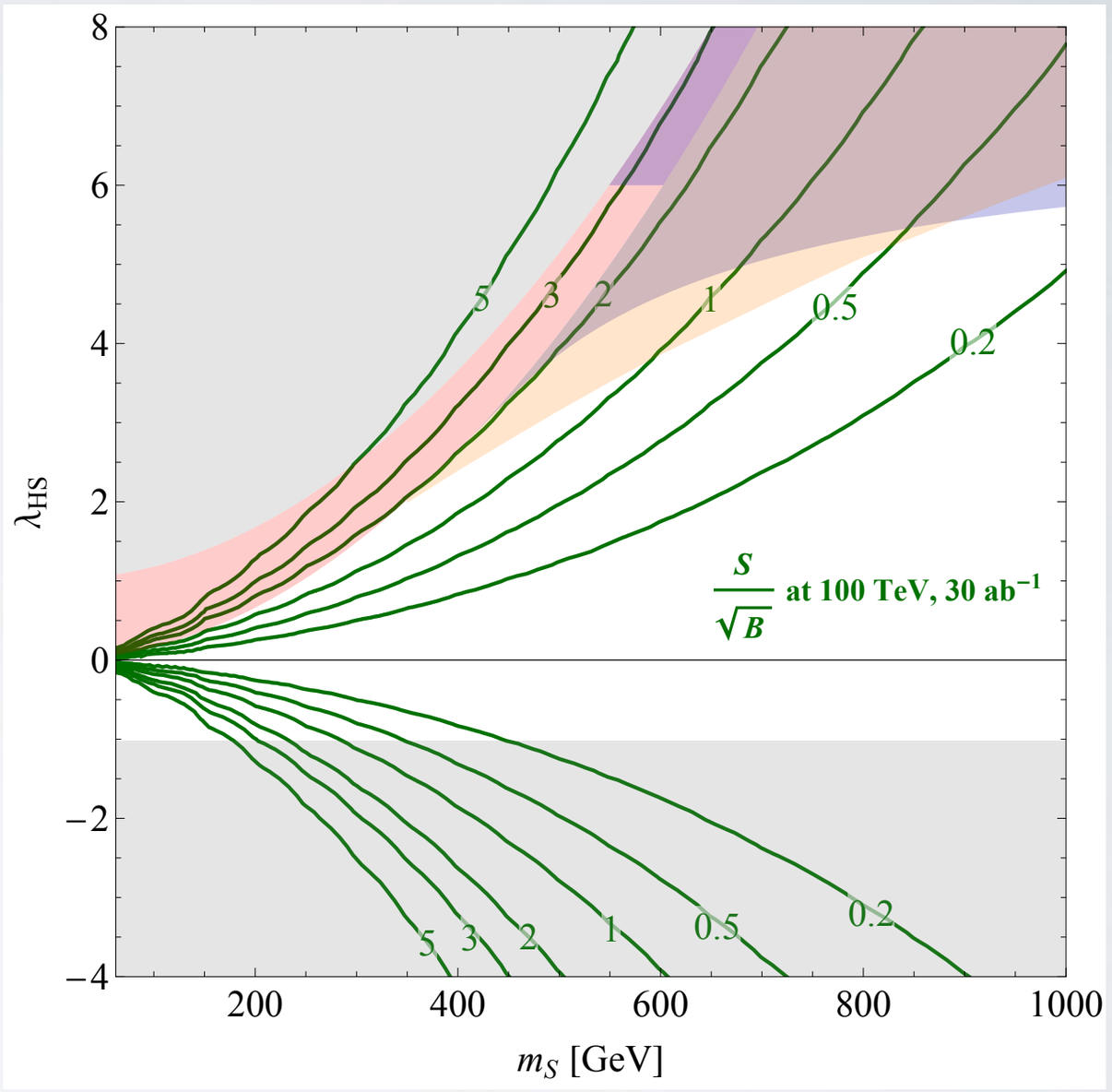
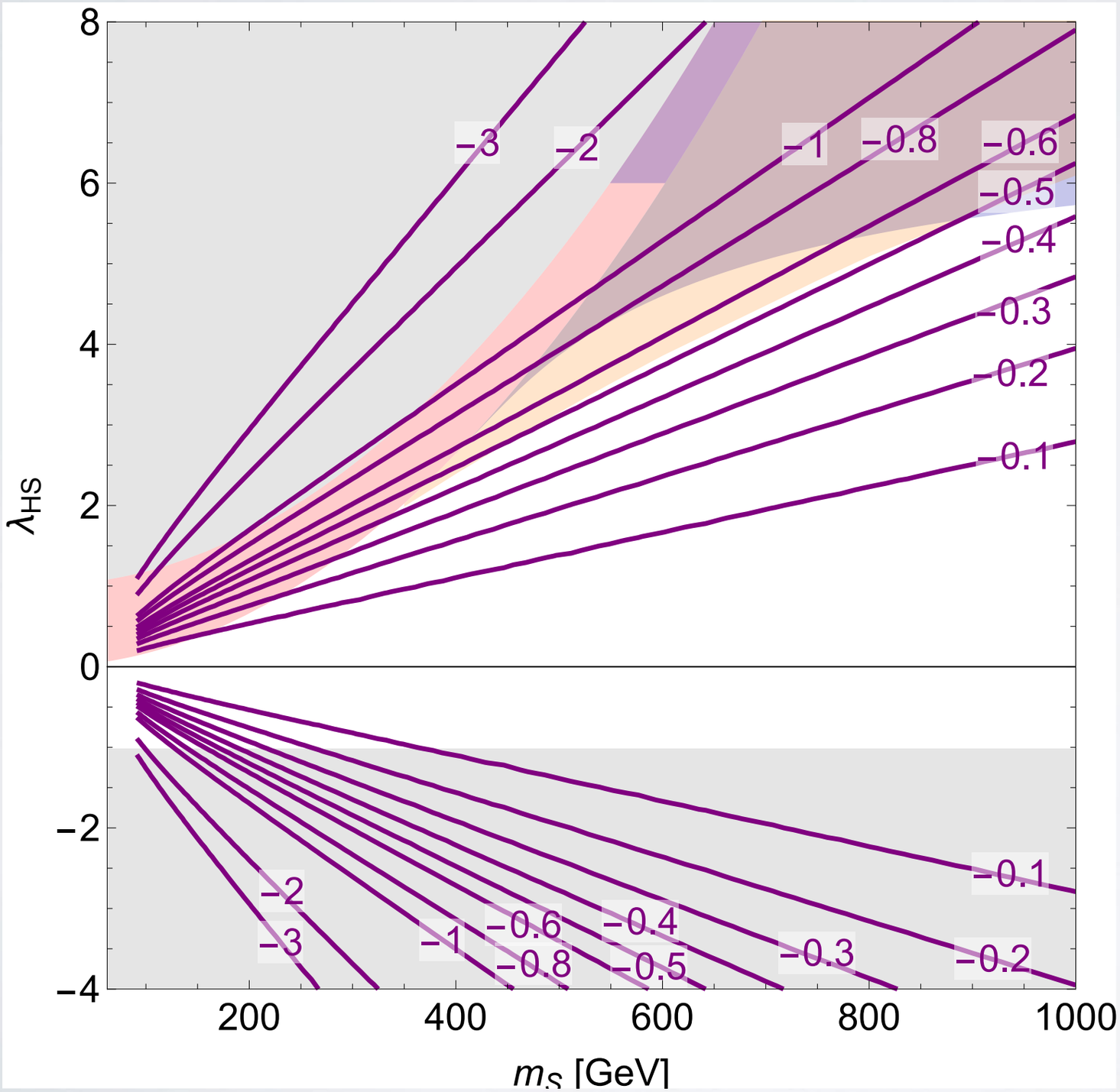


Figure 6. Green contours show $S/\sqrt{B}$ for VBF production of the $SSqq$ signal vs main background, $(Z \to \nu\bar{\nu}) + jj$, for a 100 TeV pp collider with 3 ab^{-1} (left) and 30 ab^{-1} (right) of data. VBF selection criteria and a $\not{E}_T > 150$ GeV requirement were used to cut down on QCD background. Shading identical to Figs. 2 and 4.

ZH TRIPLE HIGGS PROBES

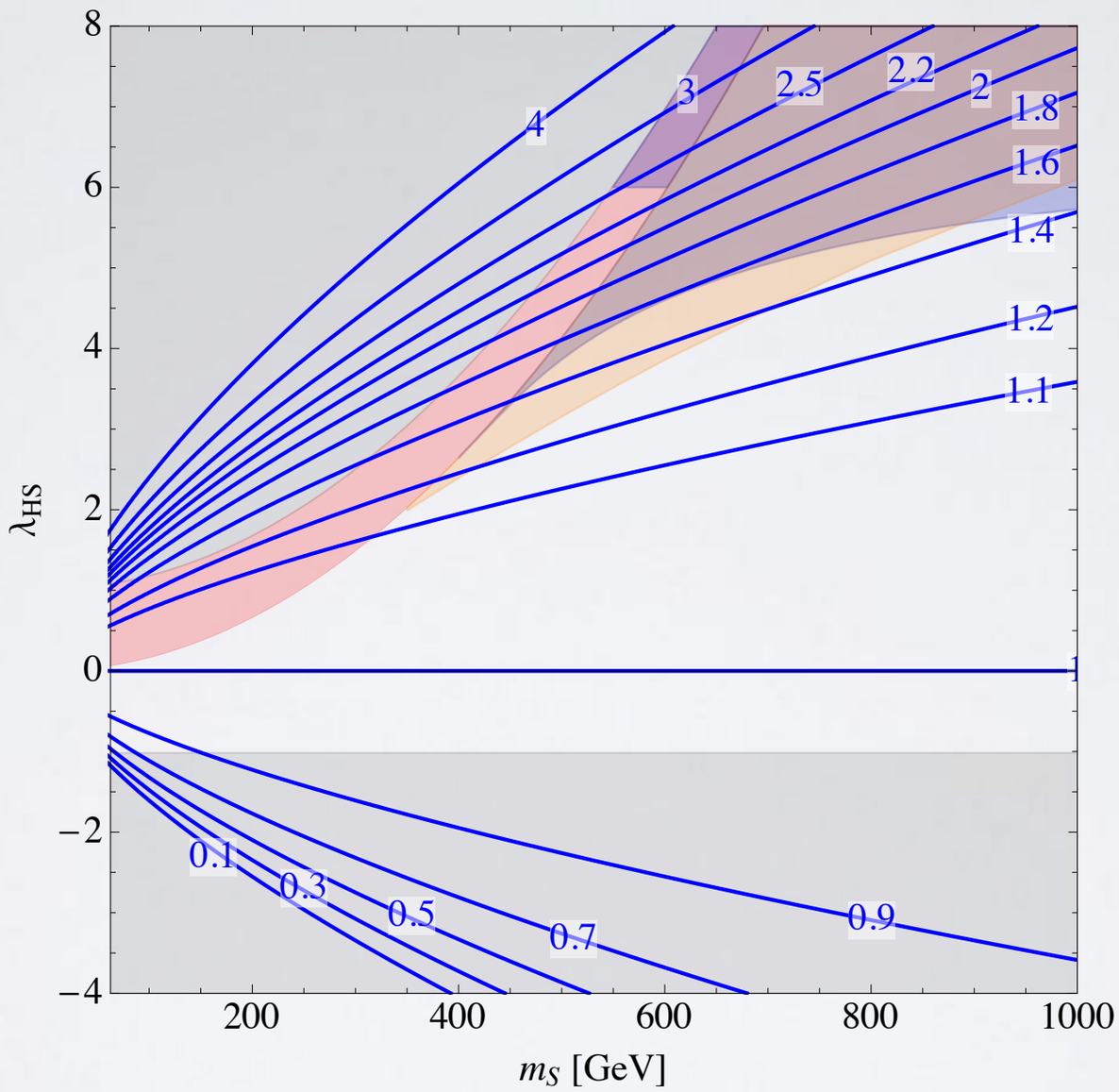
e.g. similar to N. Craig, C. Englert, M. McCullough 1305.525



Recent studies suggest a measurement to O(.6)% so it doesn't compete with di-Higgs measurement of triple Higgs shifts

Statistics limit is .15 %

TRIPLE HIGGS COUPLING PROBES

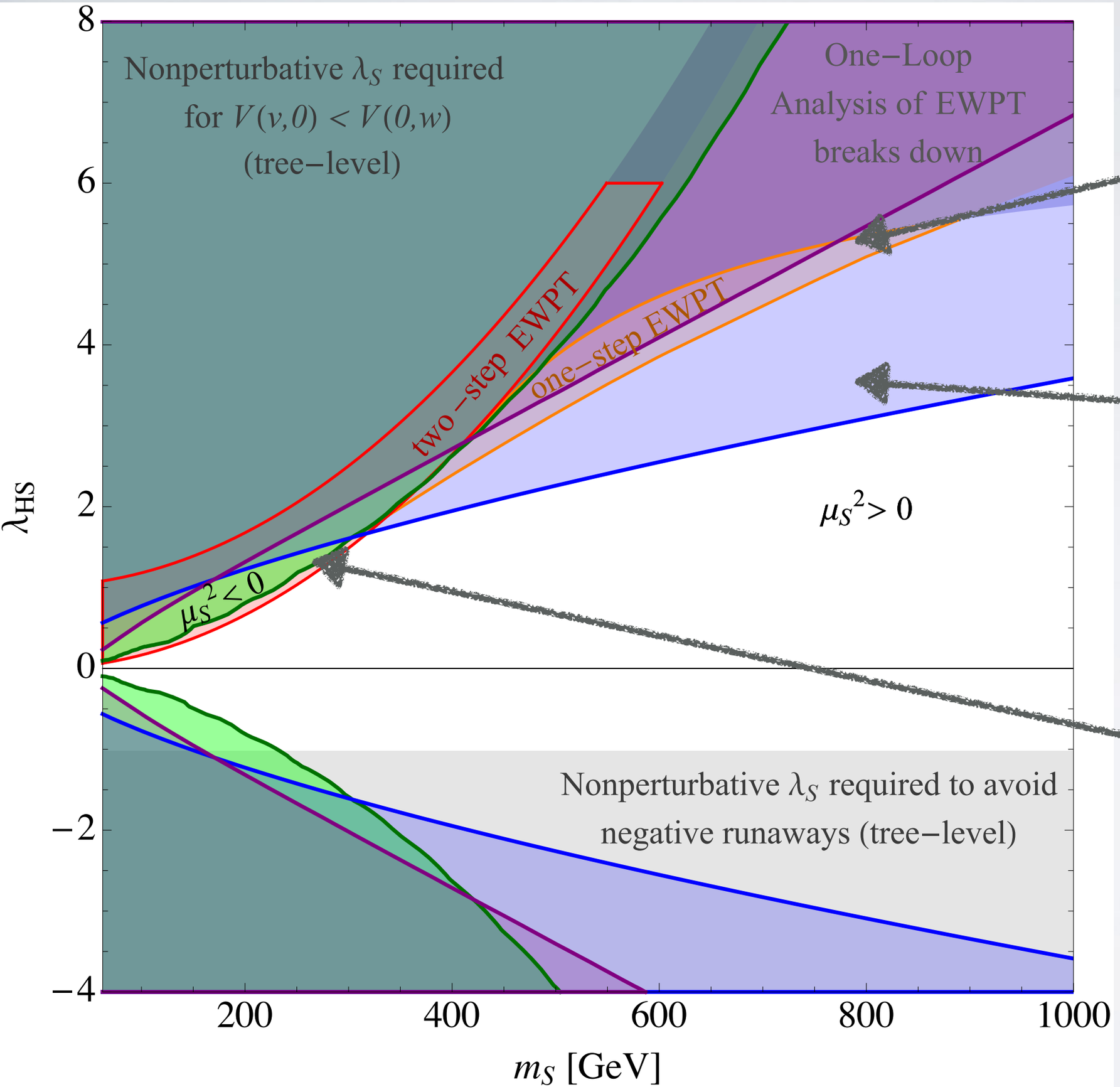


Triple Higgs probes are ***extremely*** important!!!!

We must get these estimates correct and double checked for any future collider

Figure 7. Blue contours show $\lambda_3/\lambda_3^{\rm SM}$. Measuring λ_3 with a precision of 30%, 20%, and 8% can be achieved at 14 TeV, 33 TeV, and 100 TeV hadron colliders with 3 ab^{-1} of data, respectively. A 1000 GeV ILC with 2.5 ab^{-1} could achieve a precision of 13%. See text for details.

SUMMARY OF REGIONS



TLEP exclusion with Zh shift

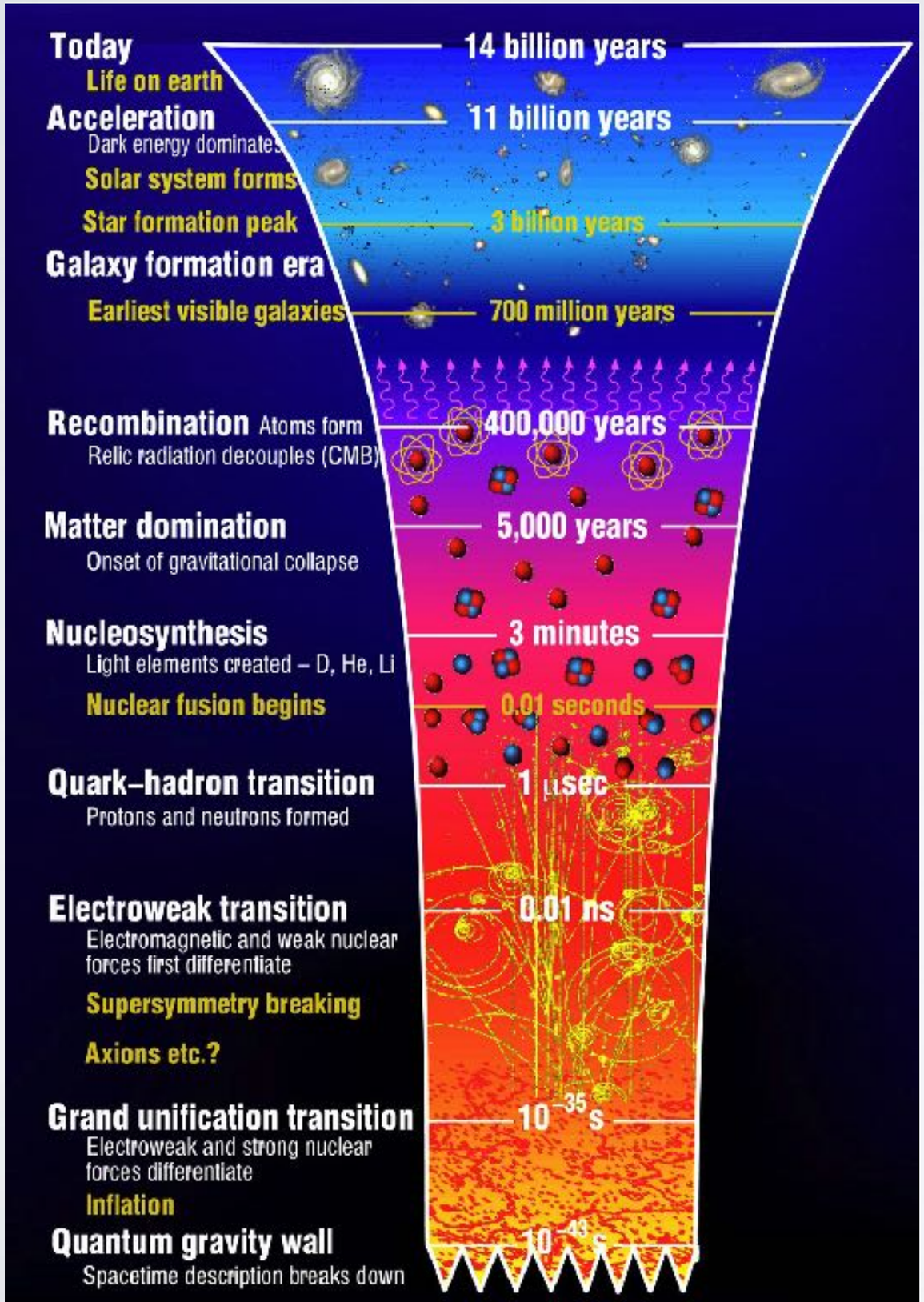
2 Sigma Exclusion with triple Higgs at 100 TeV

Collider

$$\frac{S}{\sqrt{B}} \geq 2$$

for 100 TeV 30/ab

WHAT IF ALL THIS IS WRONG?



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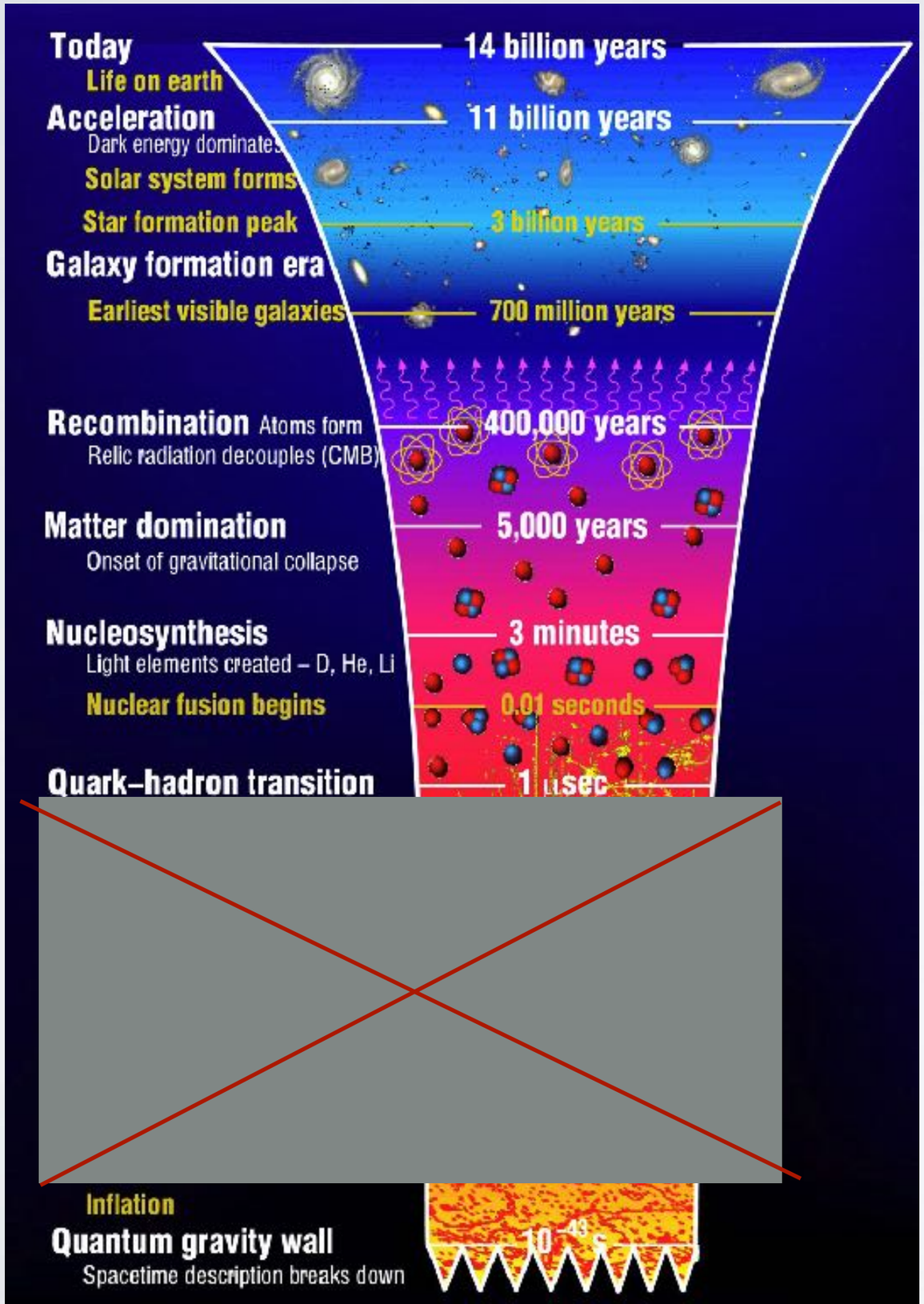
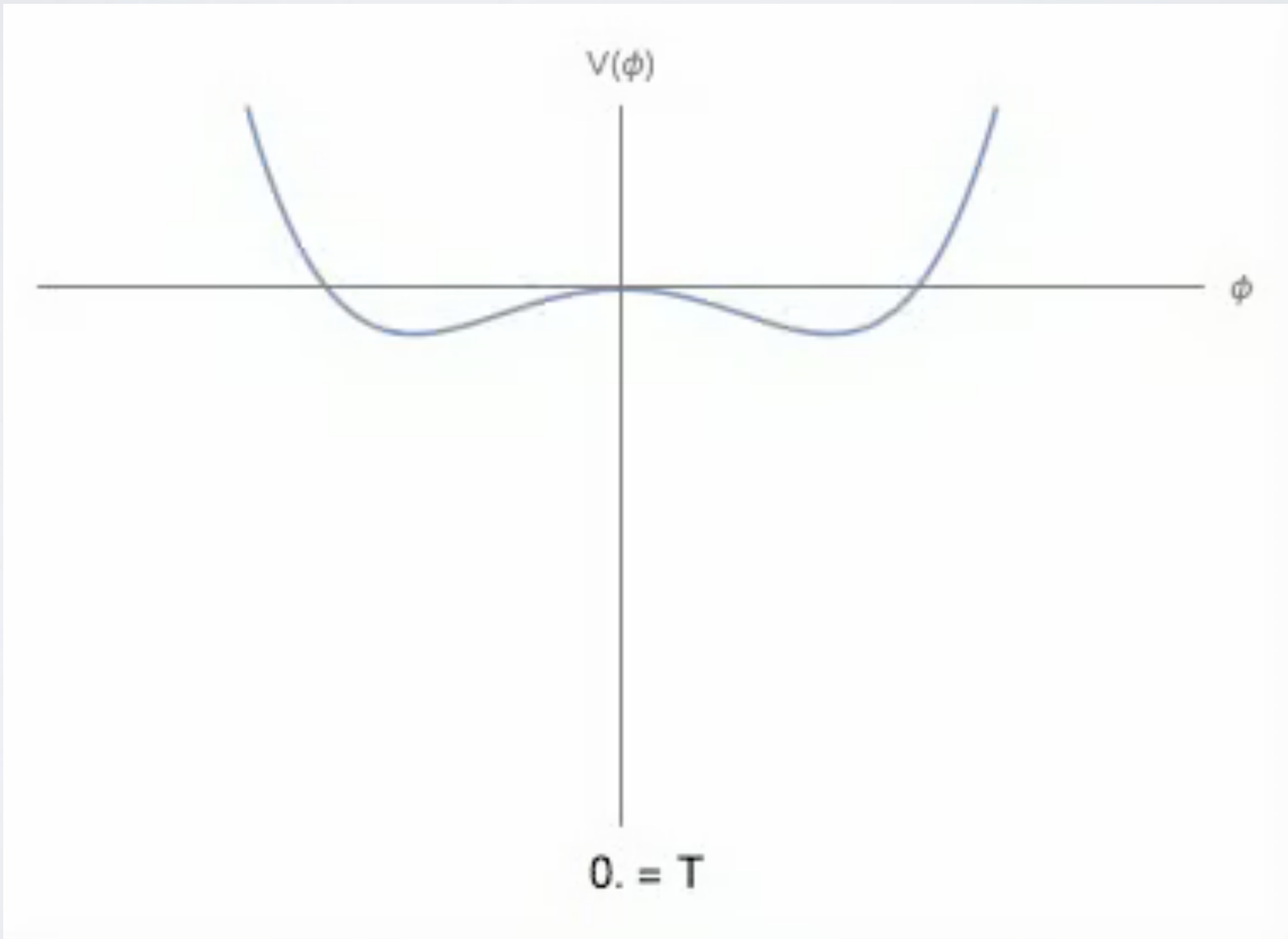


What if the EW symmetry was never unbroken????

SIMPLE SINGLET MODEL AGAIN…

Flip the sign of λ_{HS}



THEORY WITH ALWAYS BROKEN EW SYMMETRY?

- Contradicts our whole cosmological picture, but nevertheless is technically allowed and under control… new picture of our universe

- EW Baryogengesis and Leptogenesis don't work but GUT baryogengesis can!

- avoids difficulties with strings/domain walls

CONCLUSIONS

- With future colliders we may finally have a chance to unravel the cosmological history of our universe to the earliest times
- Triple Higgs coupling is an important window
  - can get theories which give huge deviations - in principle LHC
  - can also be confronted with things that need 100 TeV (no lose?)
- Complementary probes with gravitational waves
- New theoretical techniques need to be used to update predictions
- There may be a fundamentally new picture of the universe out there so we have to be careful not to go down the rabbit hole over over-hyping