ELECTROWEAK PHASE TRANSITION**S** AND HIGGS COUPLINGS

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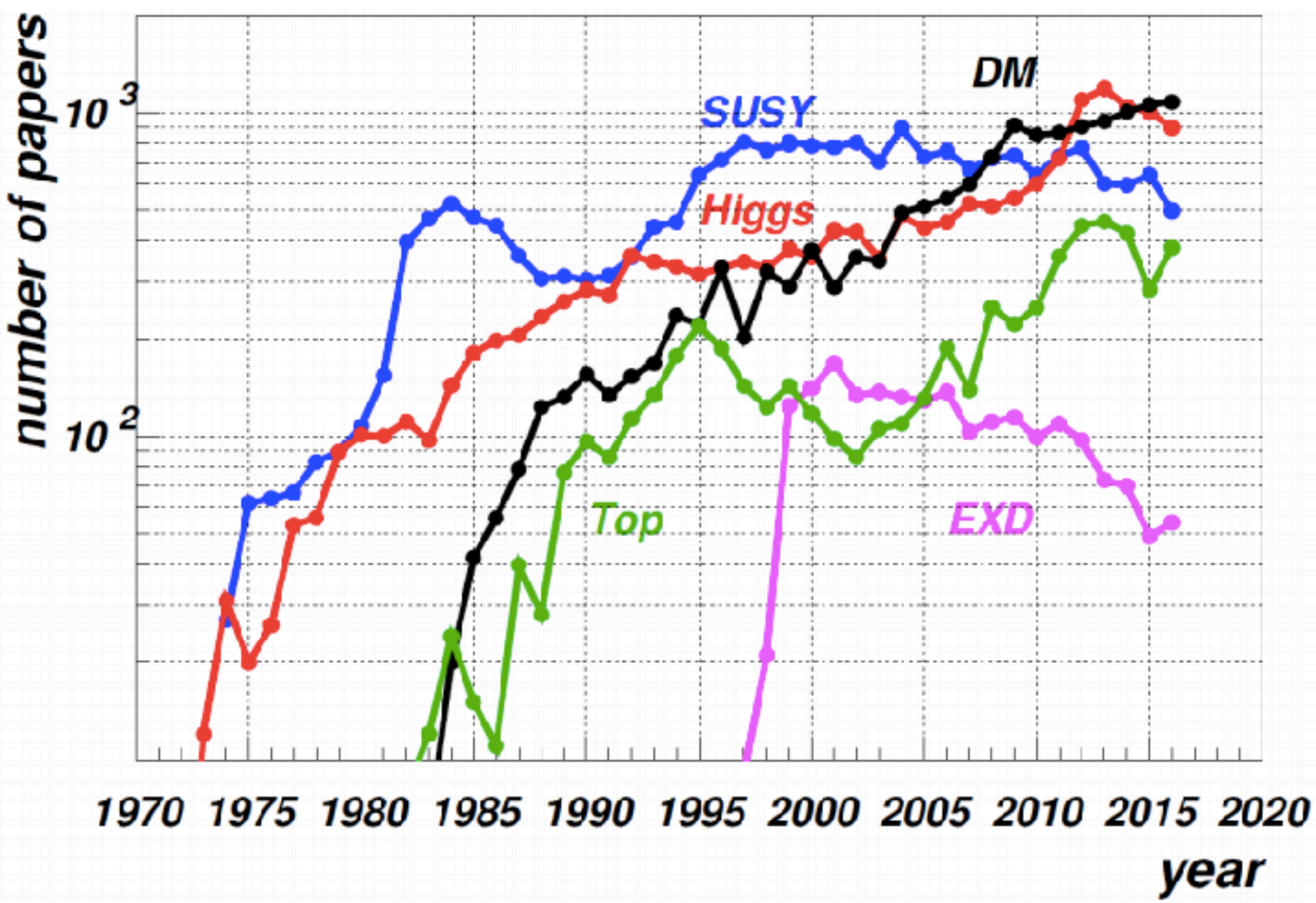
Based mostly on
PM, H. Ramani 1807.07578
PM. S. Homiller 1808/9.xxxxx
David Curtin, PM, H. Ramani 1612.00466

MOTIVATION…

Why do I care about the early universe and the Higgs and not DM for instance?

MOTIVATION...

Why we are so keen to study DM?

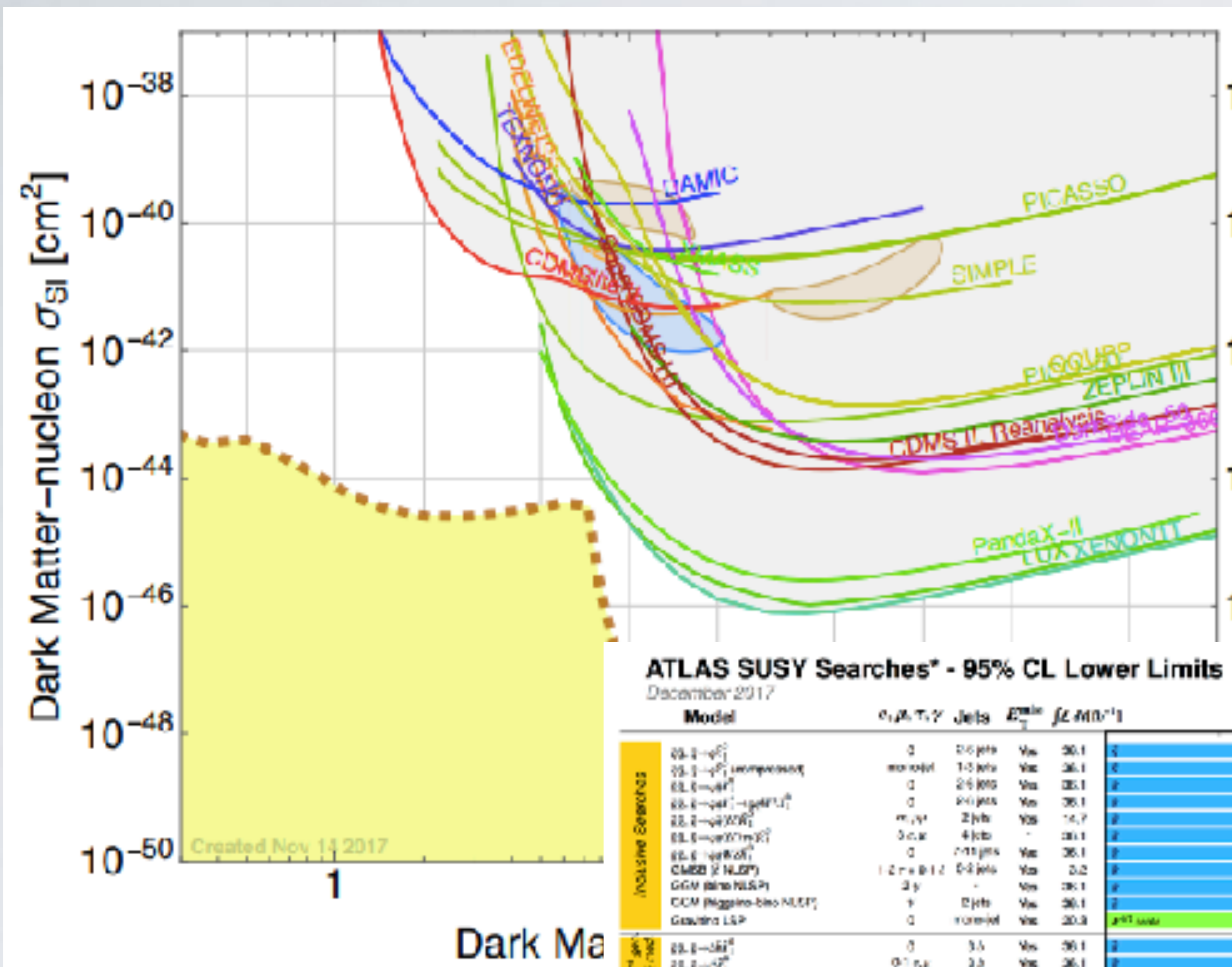


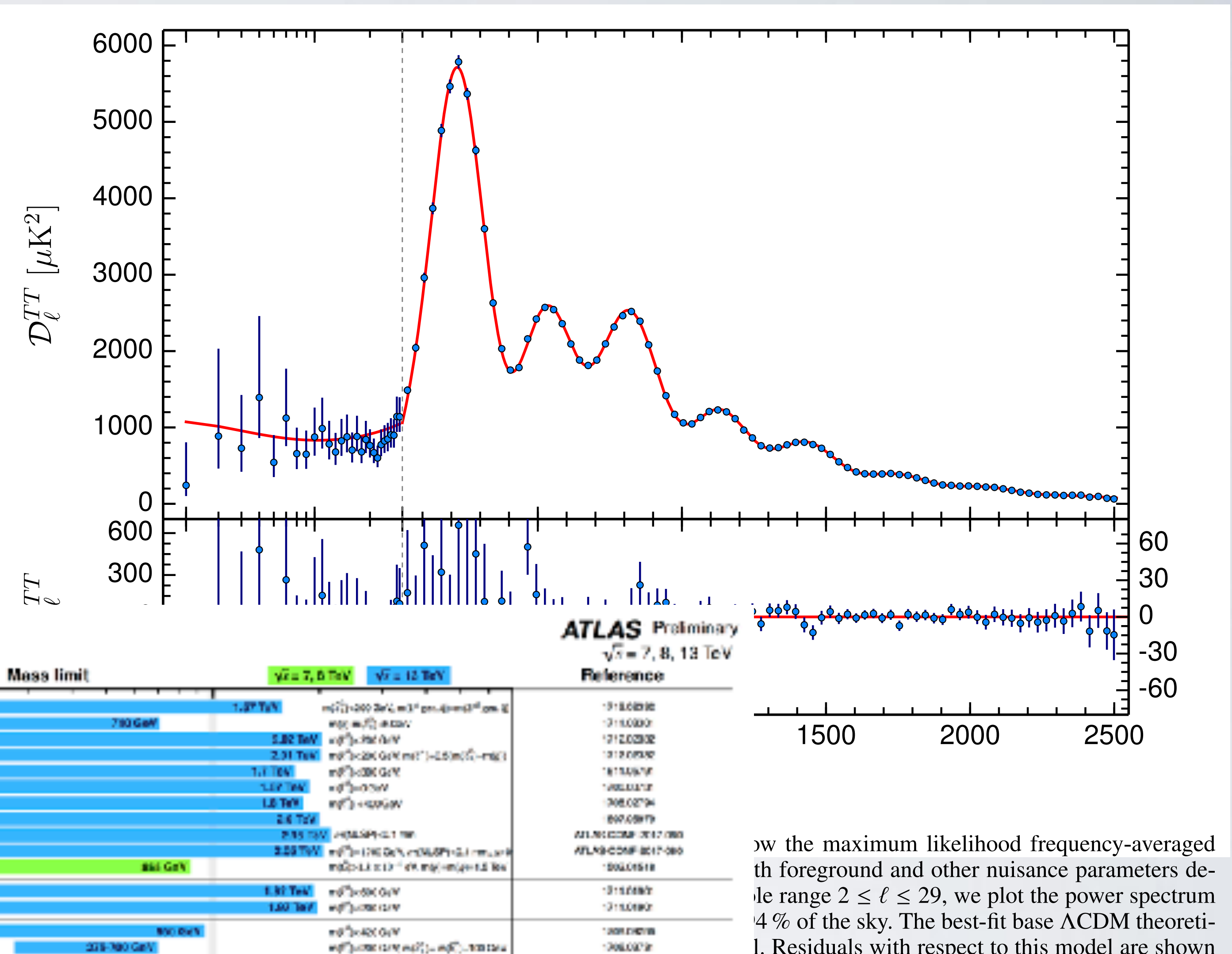
MOTIVATION…

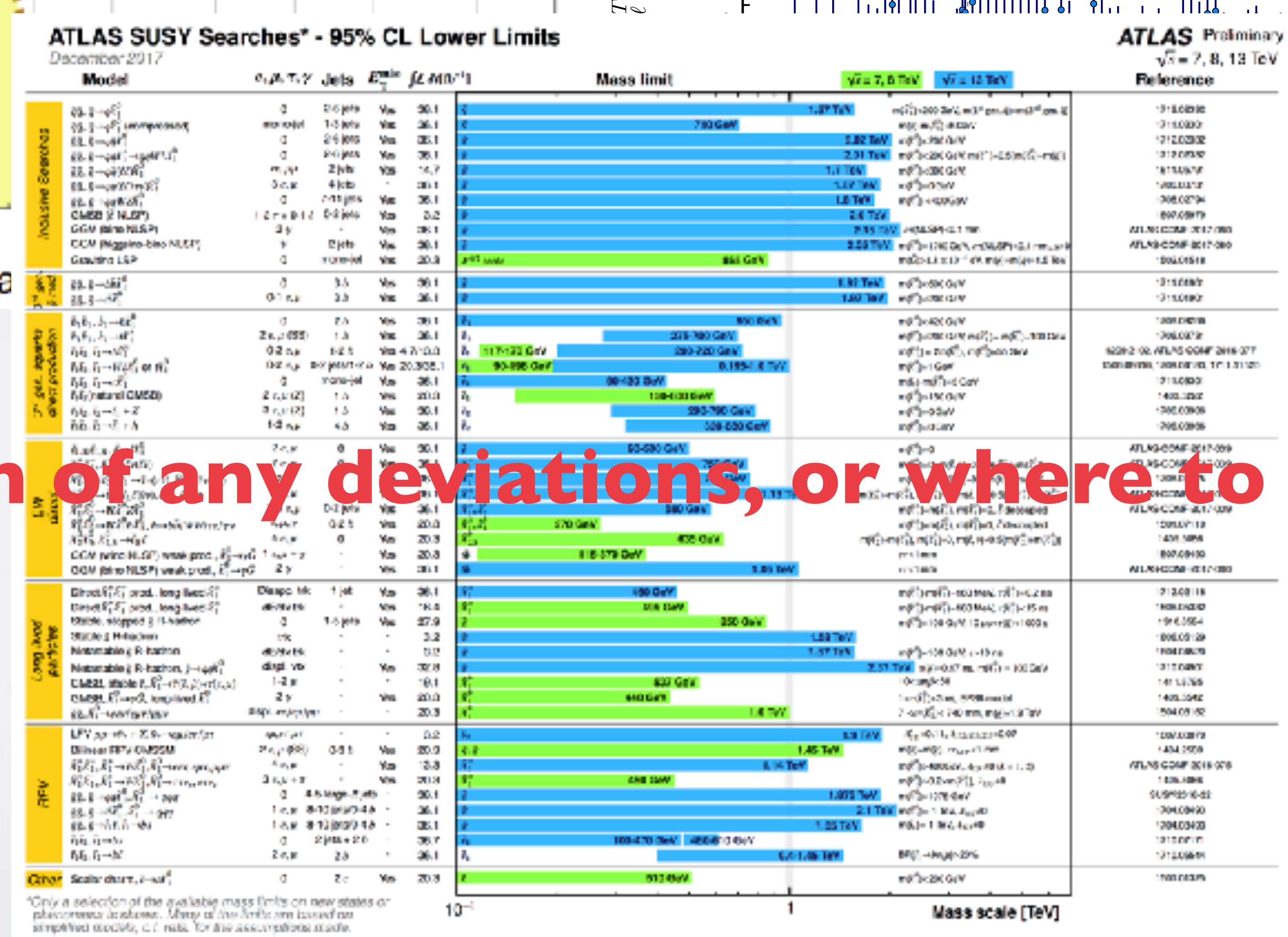
"It doesn't seem like there's anything interesting in pheno lately. Maybe Neutrinos?" L. Alvarez-Gaume (Simons Center for Geometry & Physics director at Stony Brook)

my atavistic pheno impulse is to give a panglossian view of our field:
"X, Y, and Z are being done, amazing new possibilities"

DATA/REALITY DRIVEN VIEW:







No clear sign of any deviations, or where to even test??

BY AND LARGE WE STILL HAVE ALL THE SAME PROBLEMS WE'VE HAD FOR DECADES

- 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

EXPERIMENT TO THE RESCUE?

THERE IS PROGRESS EXPERIMENTALLY!

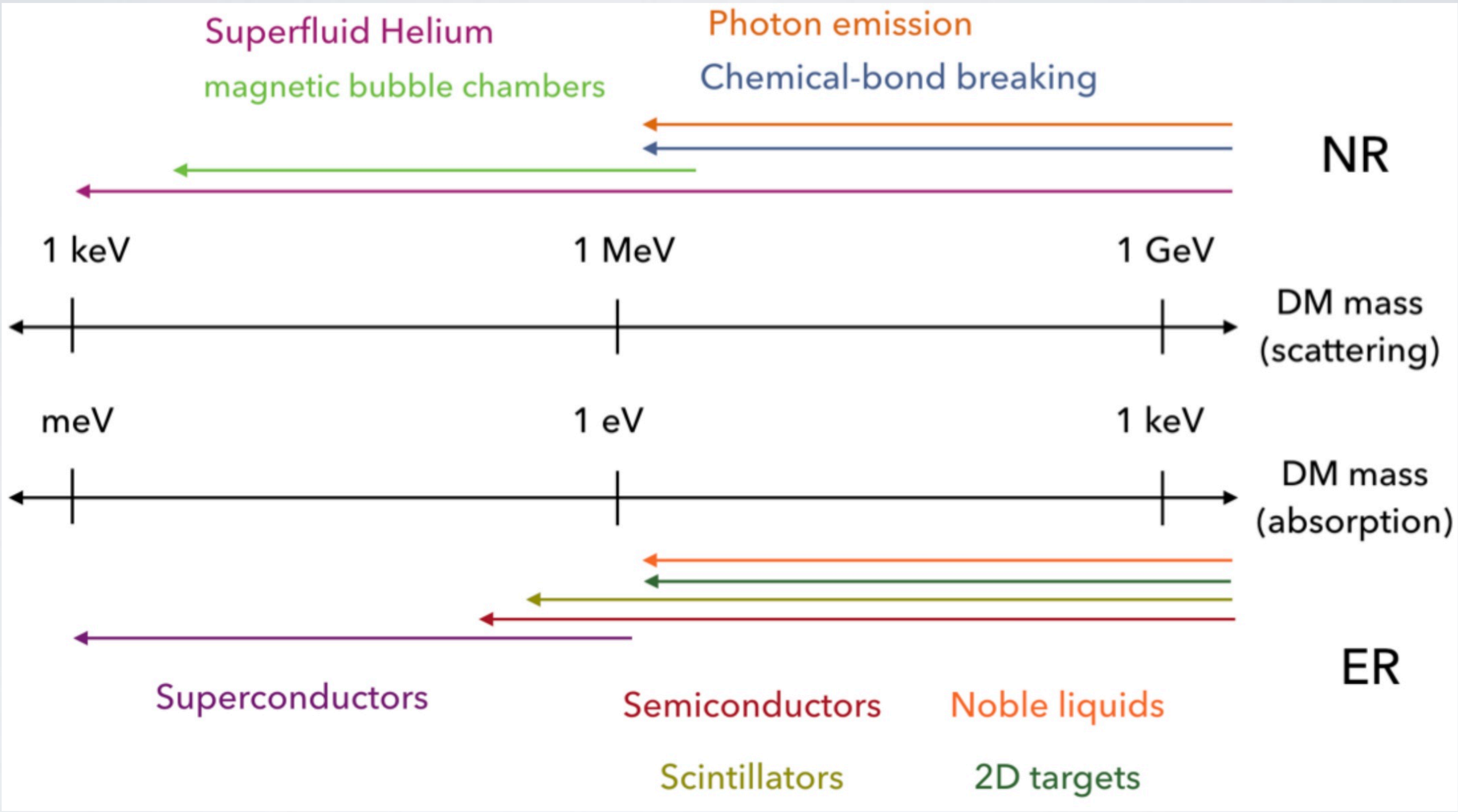


FIG. 4: Ideas to probe low-mass DM via scattering off, or absorption by, nuclei (NR) or electrons (ER).

"Dark Sectors" abound… just ask Howie

UN?FORTUNATELY WITH EXPERIMENTAL PROGRESS THERE IS ***ALSO*** THEORETICAL PROGRESS…

Wise professor tells entering graduate student 2002:

WIMPs are very motivated so it's likely: $m_{DM} \sim m_{weak}$

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Wise professor tells entering graduate student 2018:

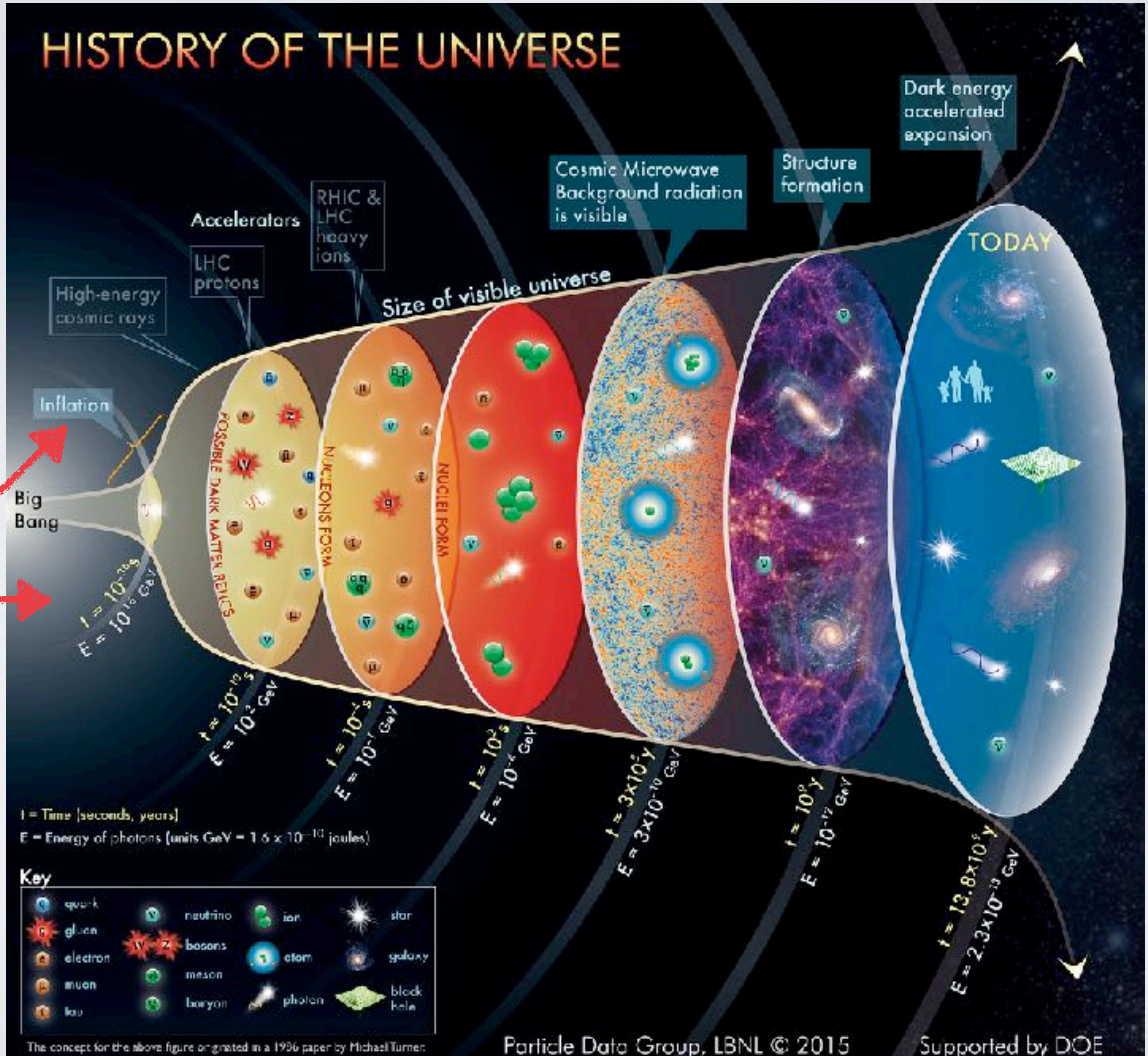
could be $m_{DM} \sim 10^{-22}\,\mathrm{eV}$

but… also could be **50** to **90** orders of magnitude heavier depending on assumptions of course

LAMPPOST EFFECT

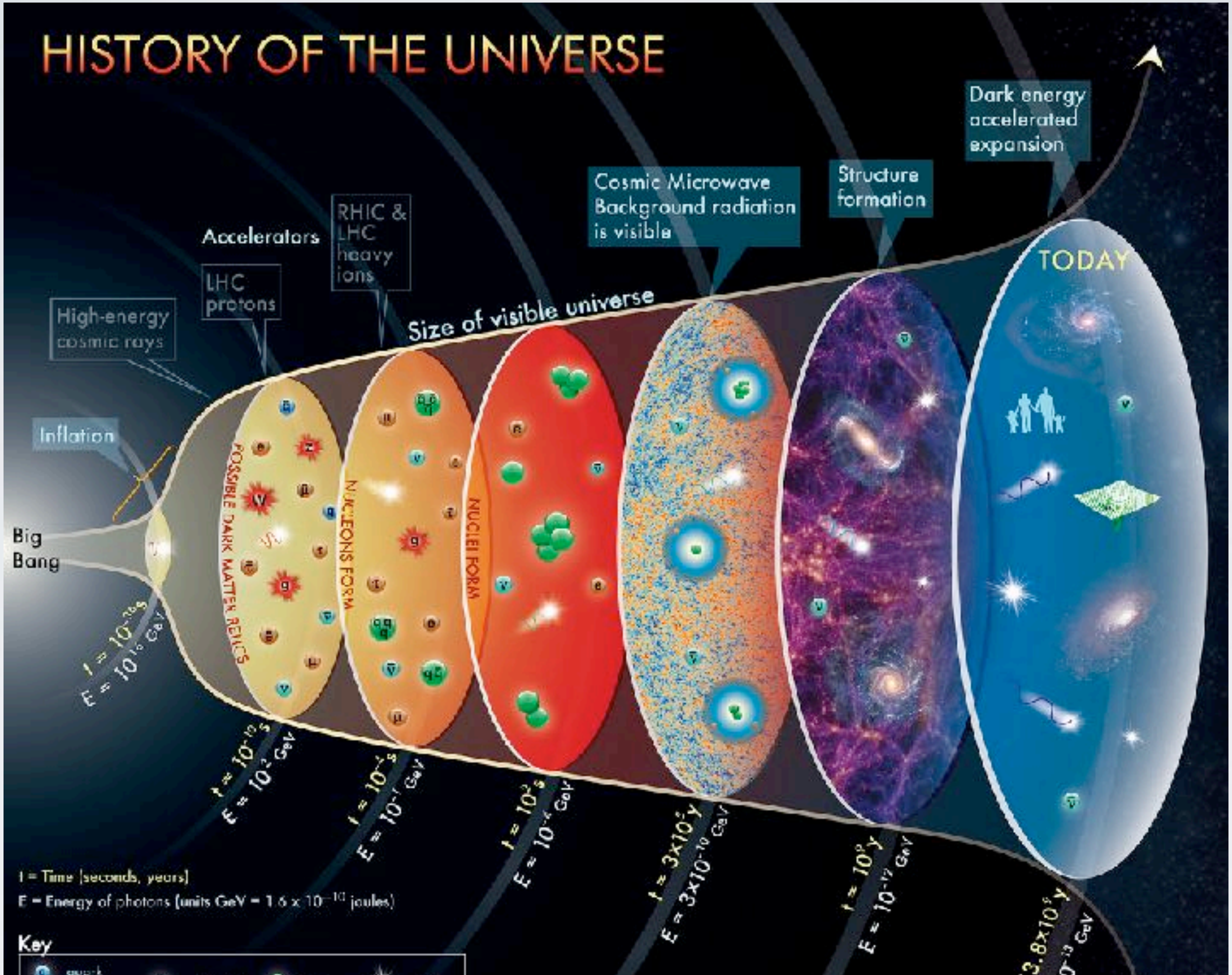
Not just limited to Dark Matter of course

WHY NO NOBEL FOR INFLATION?



Inflation!

WHY NO NOBEL FOR INFLATION?



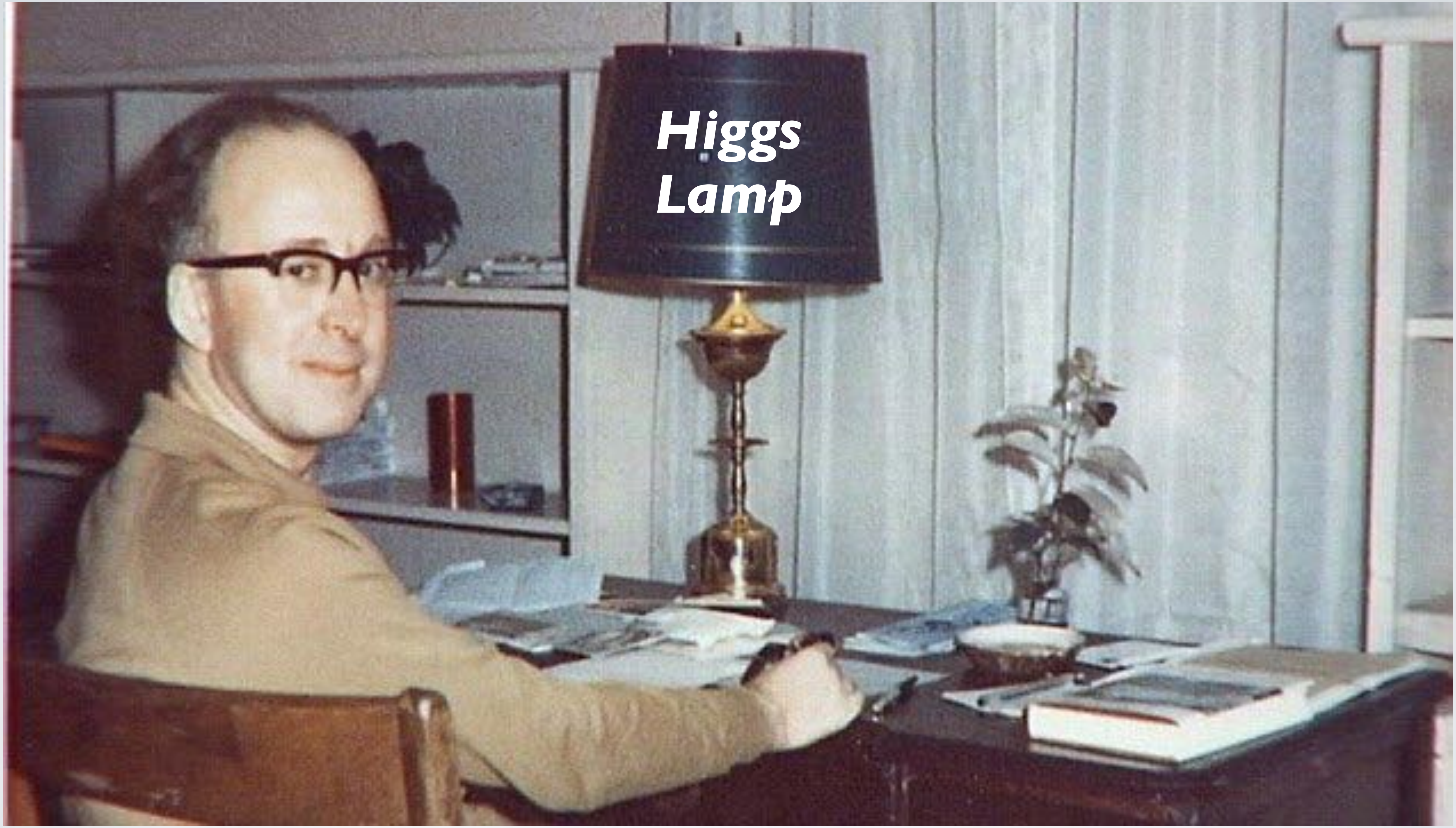
We don't know ***when*** it happened to better than ~15 orders of magnitude!!!

LAMPPOST EFFECT

I'm not a wise professor nor lucky, so…

LAMPPOST EFFECT

Is there a confluence of a *lamppost* **and** a *theory motivation*?


Higgs
Lamp

HIGGS LAMPPOST

- Naturalness
- Higgs Potential
- Higgs Portal to other sectors
- Cosmological History
- …

THIS LAMPPOST IS LESS BRIGHT FOR SOME QUESTIONS

***Example:* Colored** *Naturalness*

Essig, PM, Ramani, Zhong 1707.03399

Have to get "lucky" or...

THIS IS JUST ANOTHER LAMPPOST IN THE USUAL SENSE…

$$m_h^2 \sim \Lambda^2$$

$\Lambda \sim$ ~~100~~ GeV

~~200~~ GeV

~~300~~ GeV

~~500~~ GeV

~~1000~~ GeV

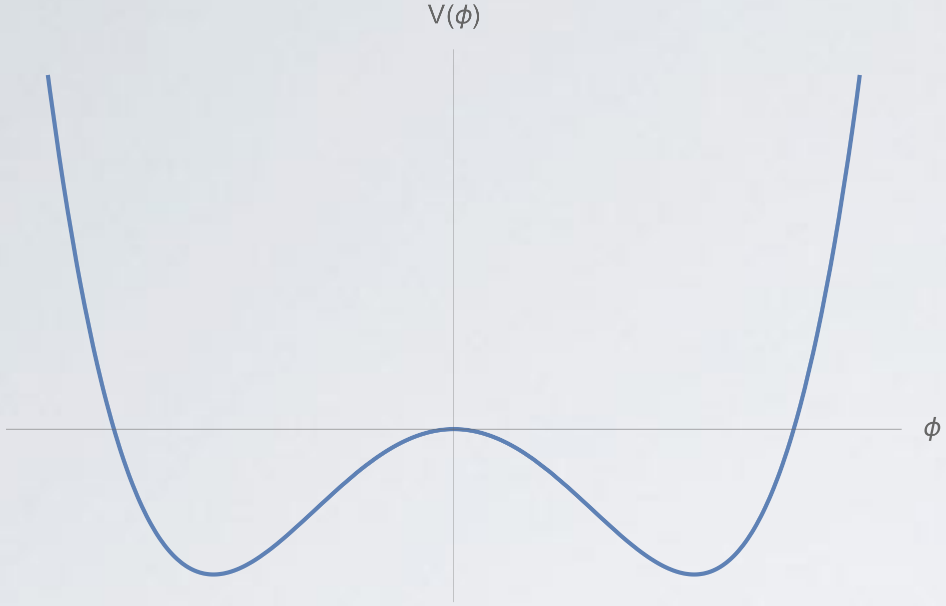
5000 GeV ????

We certainly learn something,
but ***what*** it is telling us isn't as clear

HIGGS POTENTIAL AND COSMOLOGICAL HISTORY

Here there is a chance where
***quantitative** measurements*
*can yield **qualitative** differences!*

HIGGS POTENTIAL



Higgs self interactions

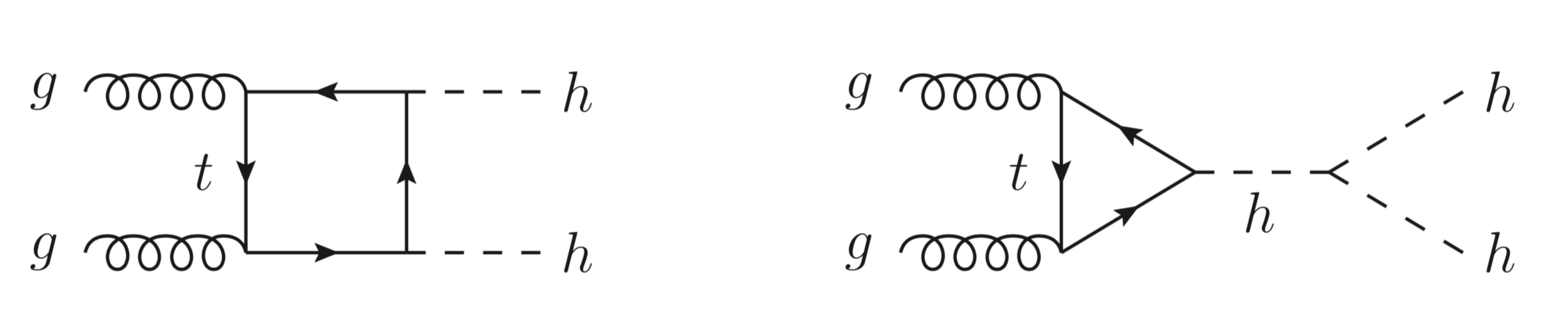
OR

$$\frac{\partial V(\phi)}{\partial \phi}\Big|_{\phi=v} = 0$$

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

VEV and mass
are *sufficient*
for Higgs potential, but BSM?

NEXT UP IS THE TRIPLE HIGGS COUPLING IN THE SM…



Unfortunately it's very difficult and it interferes with itself

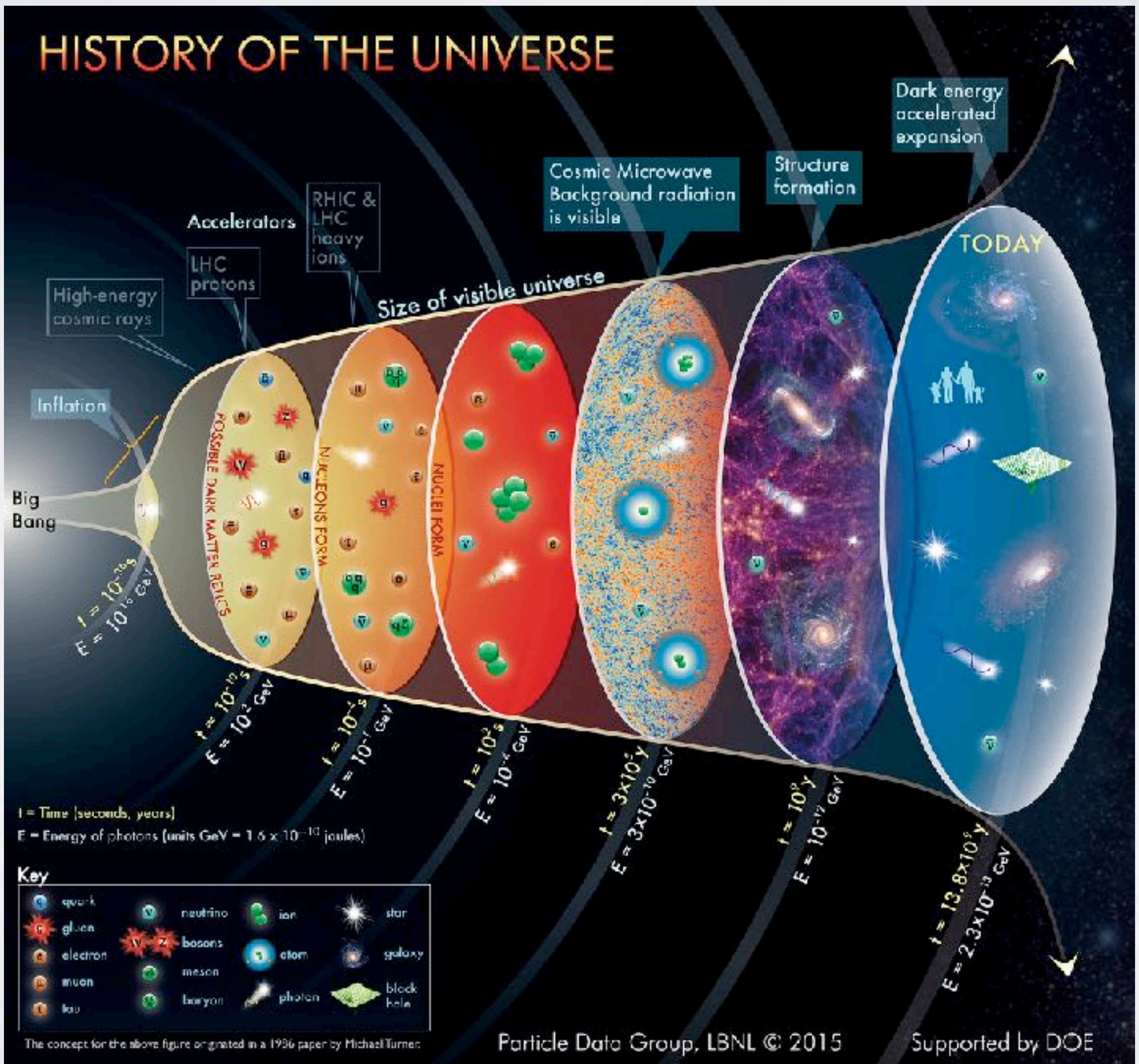
However, just measuring the SM value would be seeing something qualitatively new!

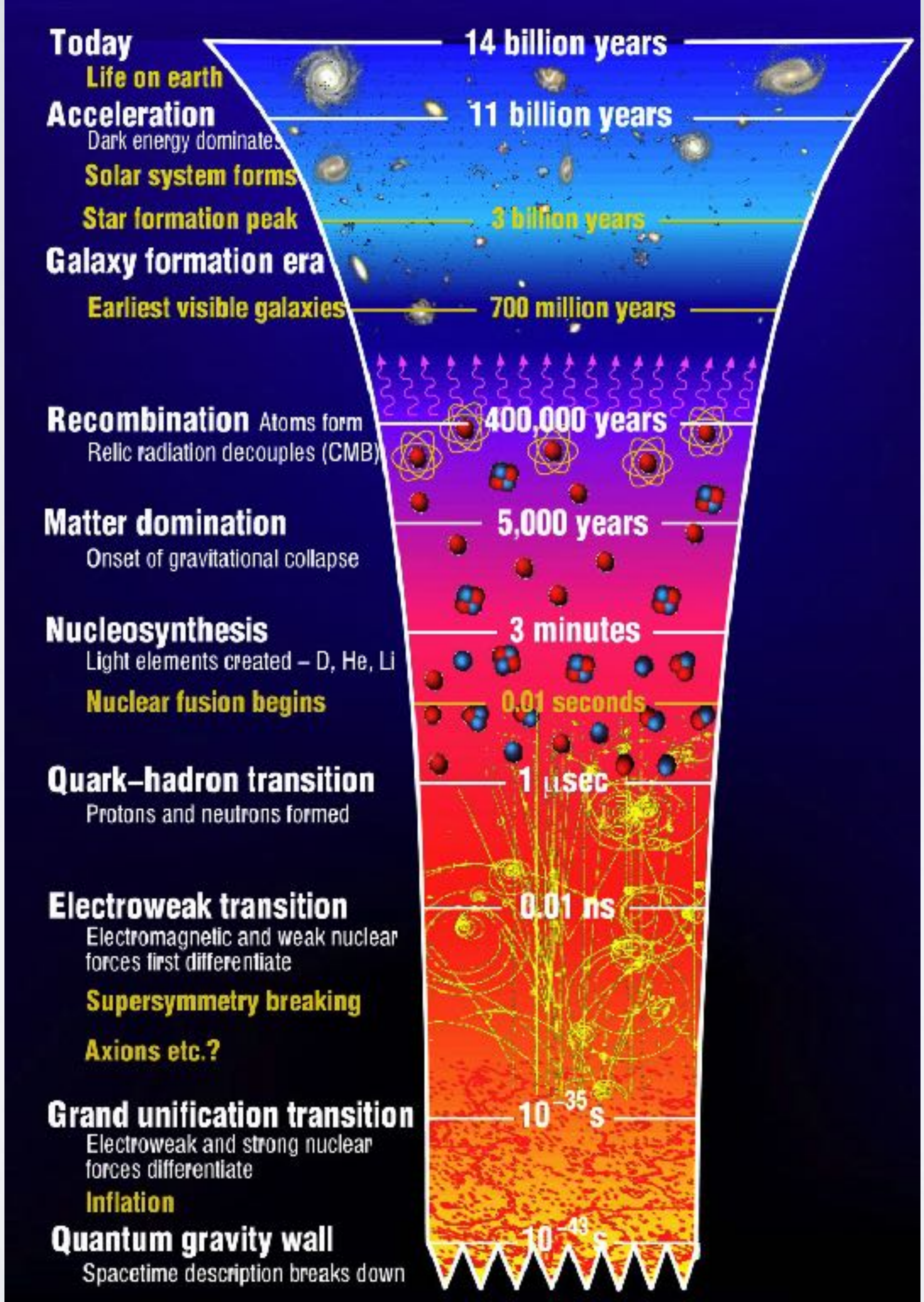
To go beyond though, is it *just* another lamppost?

Can be huge deviations…

How precisely do we *need* to measure it?

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





Cosmology stuck here

Need particle physics to go further!

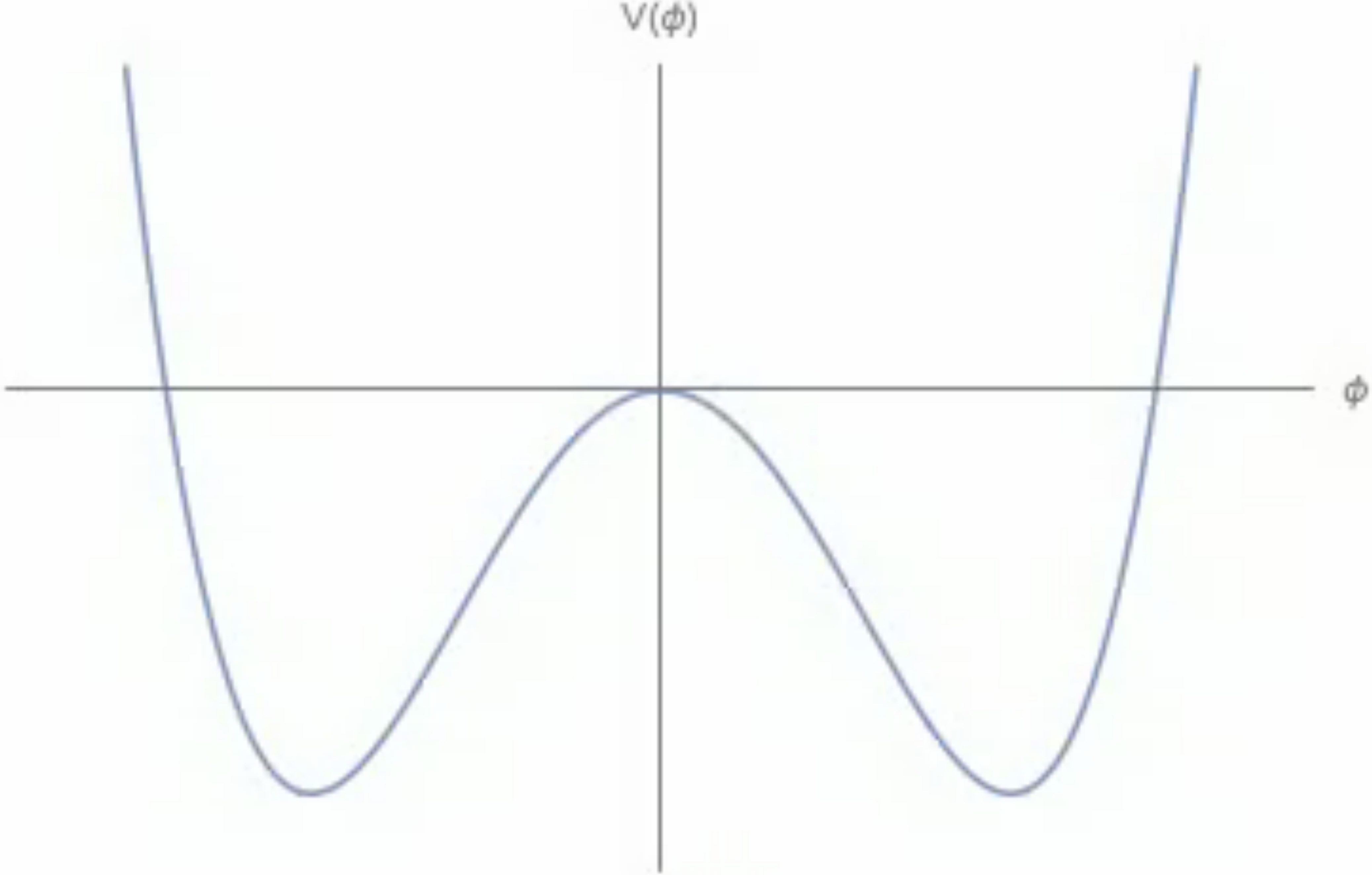
ELECTROWEAK PHASE TRANSITION

This heuristic picture of the cosmological history comes from analyzing a scalar potential at finite temperature which has been around for awhile…

FINITE TEMPERATURE FIELD THEORY STARTS WITH SOME RUSSIANS IN 1972…

IF YOU HEAT UP A SYSTEM WITH A BROKEN SYMMETRY DOES THE SYMMETRY GET RESTORED?

WHAT'S THE CURIE TEMPERATURE OF THE UNIVERSE?



0. = T

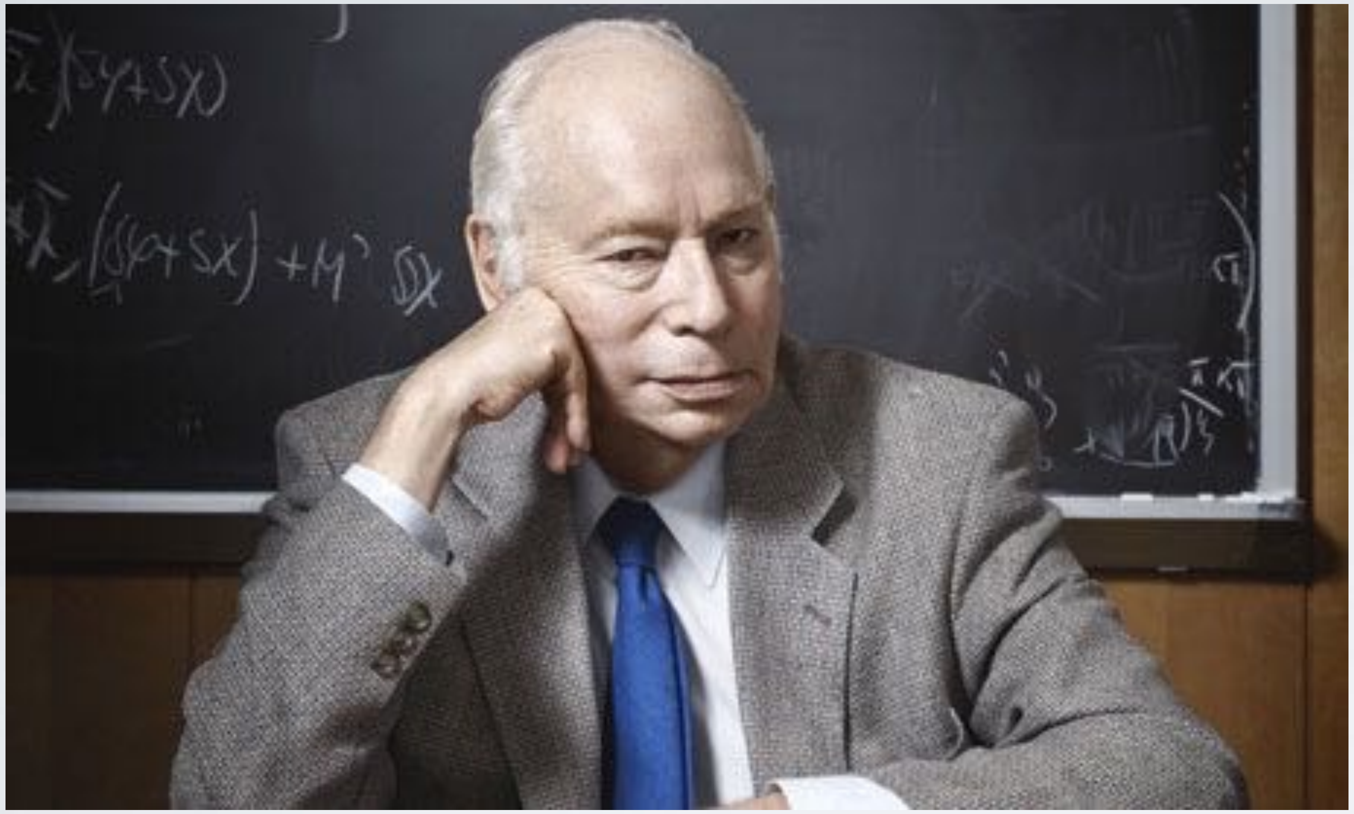
IF YOU HEAT UP A SYSTEM WITH A BROKEN SYMMETRY DOES THE SYMMETRY GET RESTORED?

WHAT'S THE CURIE TEMPERATURE OF THE UNIVERSE?

ANSWERS: YES, HMM…

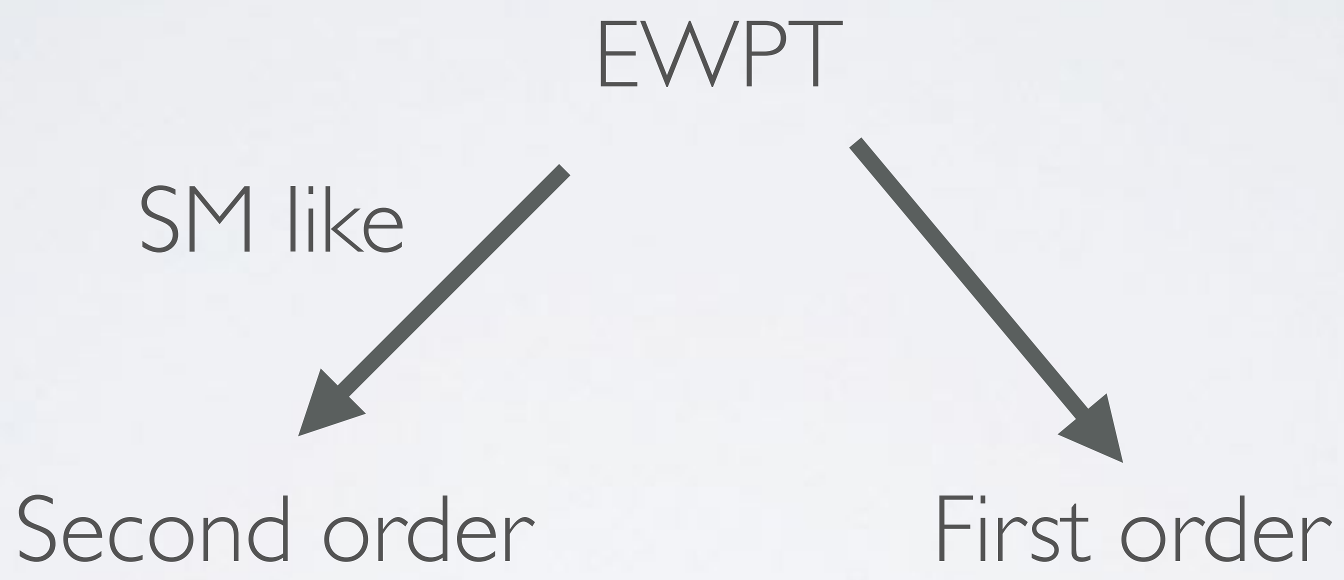

There's no place like home, There's no place like home, There's no place like home…


Weinberg,
Weinberg,
Weinberg…



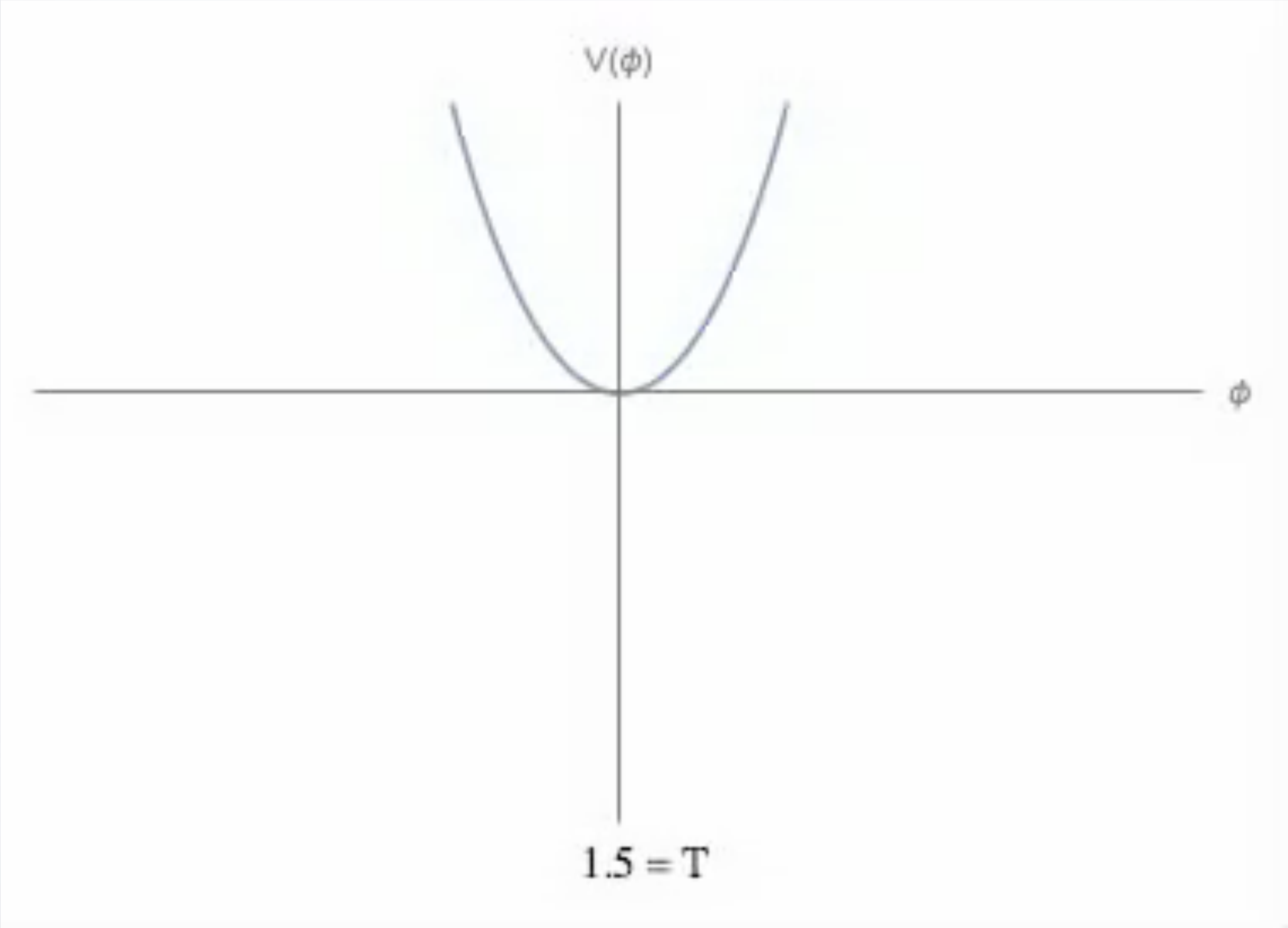
"A recent paper by Kirzhnits and Linde suggests that this is indeed the case. **However, although their title refers to a gauge theory, their analysis deals only with ordinary theories with broken global symmetries. Also, they estimate but do not actually calculate the critical temperature at which a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

IF THERE'S AN EWPT HOW DO WE QUALITATIVELY DISTINGUISH?



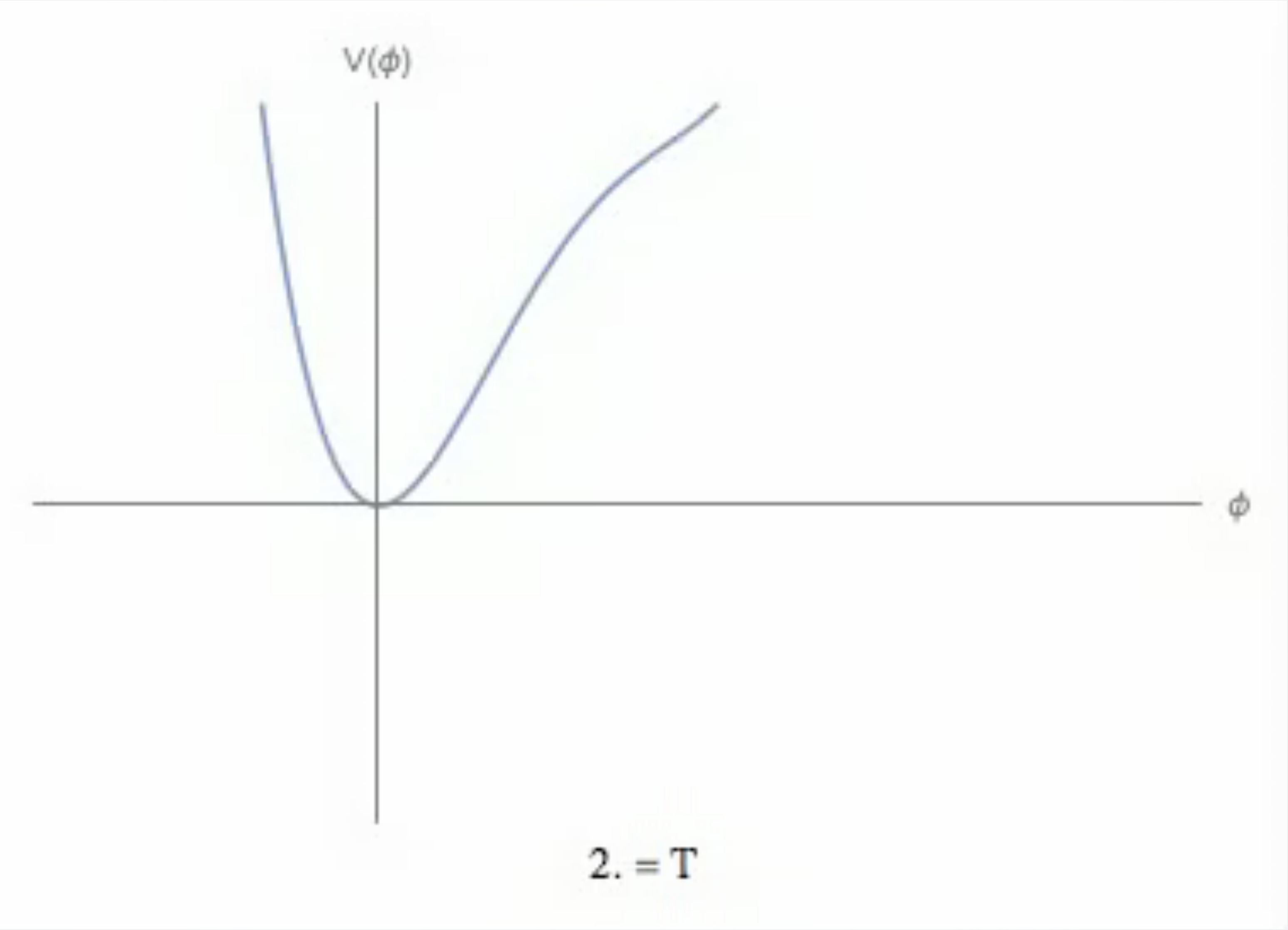
2ND ORDER PHASE TRANSITION

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



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!

IF THERE'S AN EWPT HOW DO WE QUALITATIVELY DISTINGUISH?

EWPT

Second order | First order

The qualitative difference is an effective cubic at finite temperature!

Why is this so useful? Thermal Decoupling! $e^{-\frac{m}{T}}$

HIGGS POTENTIAL AND COSMOLOGICAL HISTORY

Triple Higgs + EWPT

There ***could*** be a very large contribution and a FO EWPT - get lucky

There also ***could*** be a minimum contribution
within experimental reach

HIGGS POTENTIAL AND COSMOLOGICAL HISTORY

Triple Higgs + EWPT

There ***could*** be a very large contribution and a FO EWPT - get lucky

There also ***could*** be a minimum contribution ***within*** experimental reach

WHY?

- Has to couple to the Higgs strongly enough to affect potential
- Mass must not be too far away from EW scale!

"No-Lose"

Can make this even sharper if you connect to Electroweak Baryogenesis

THEORETICAL MINIMUM

SM + SINGLET

This model 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

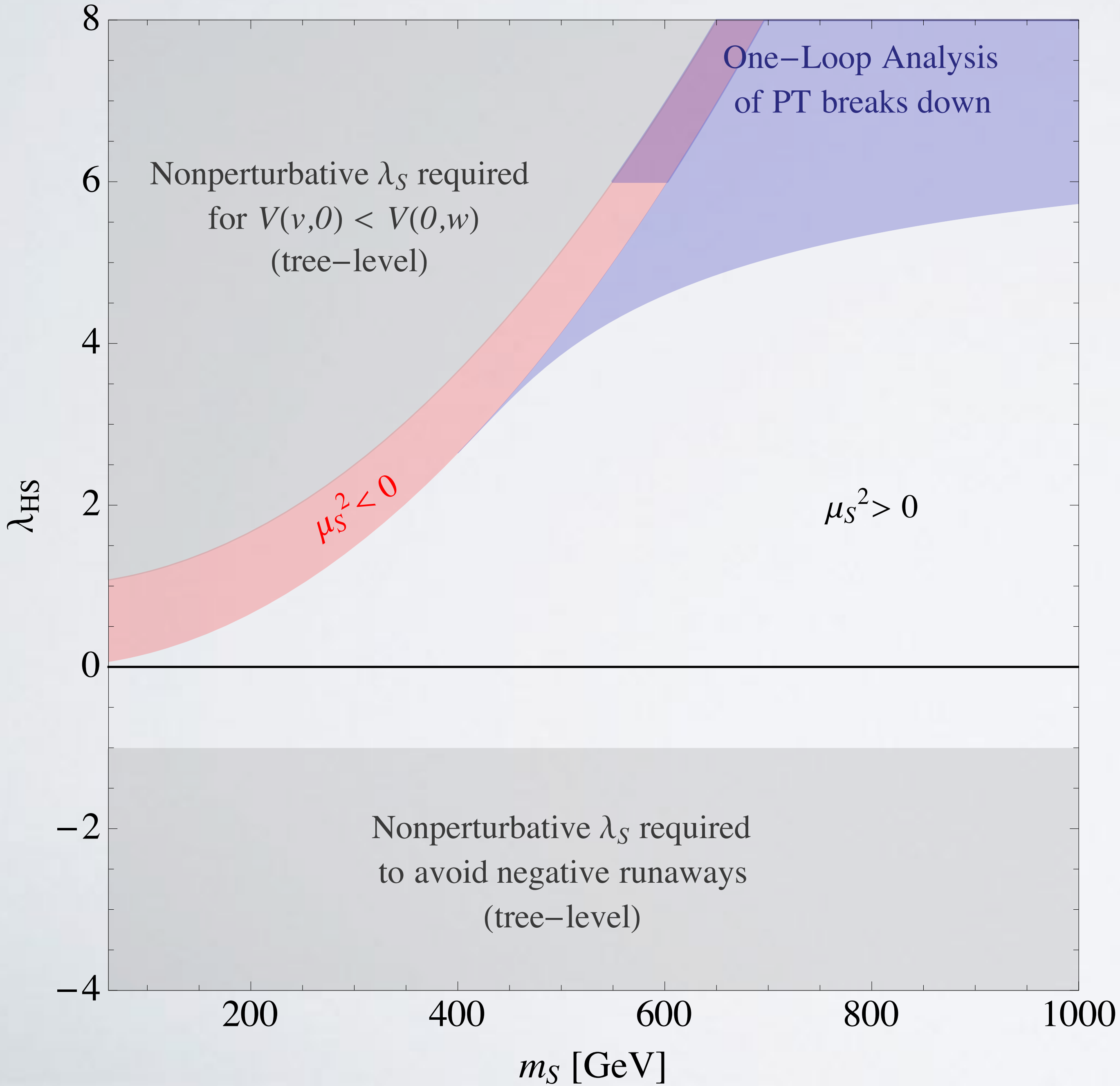
If the Singlet DOESN'T mix **but** its mass is less than half the Higgs mass you can see it in decays easily…

What if the singlet doesn't mix with the Higgs ***and*** is heavy?

SM + SINGLET "NIGHTMARE SCENARIO"

D. Curtin, PM, T. Yu 1409.0005

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



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

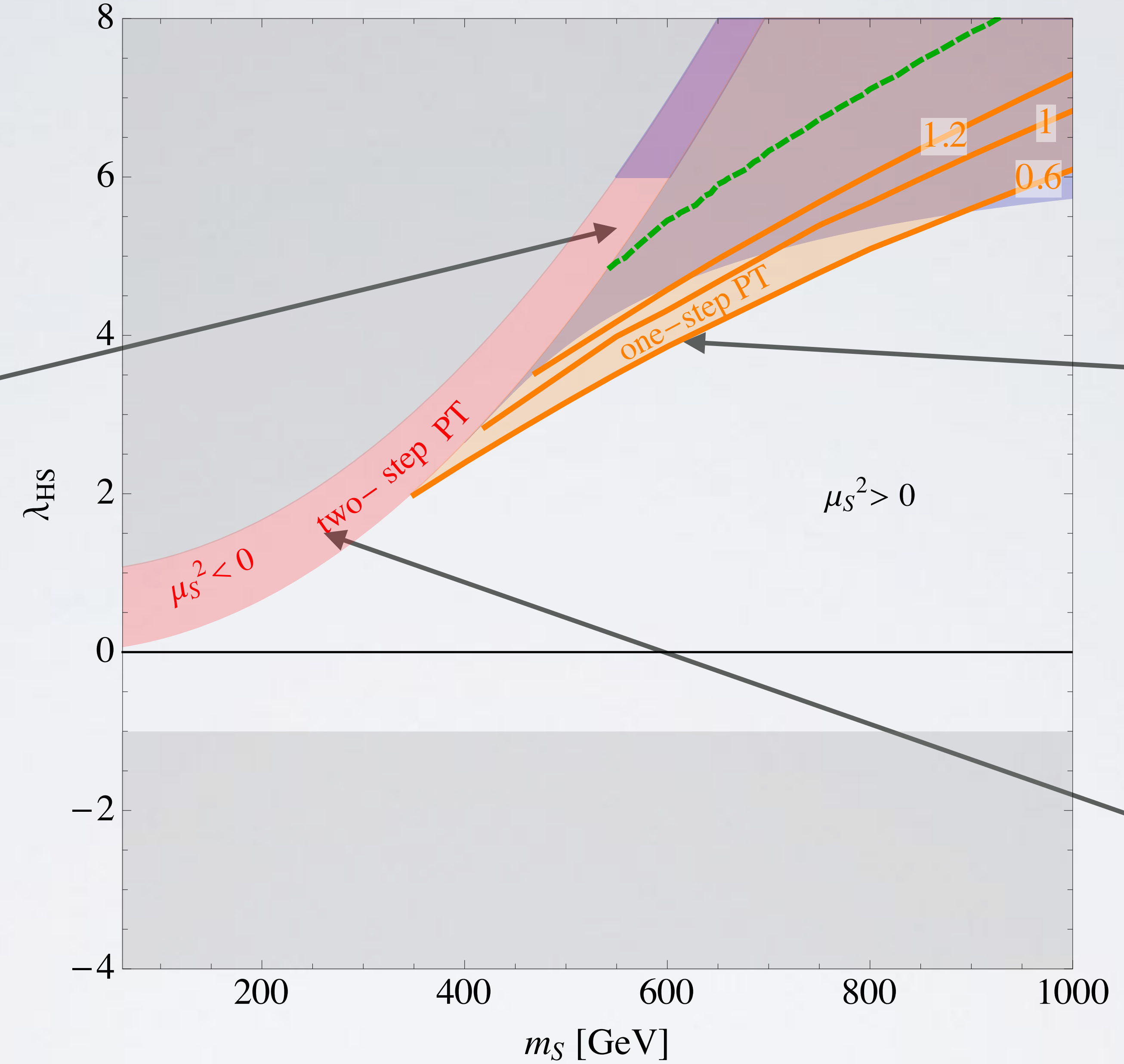
Phenomenological parameter space depends only on

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

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

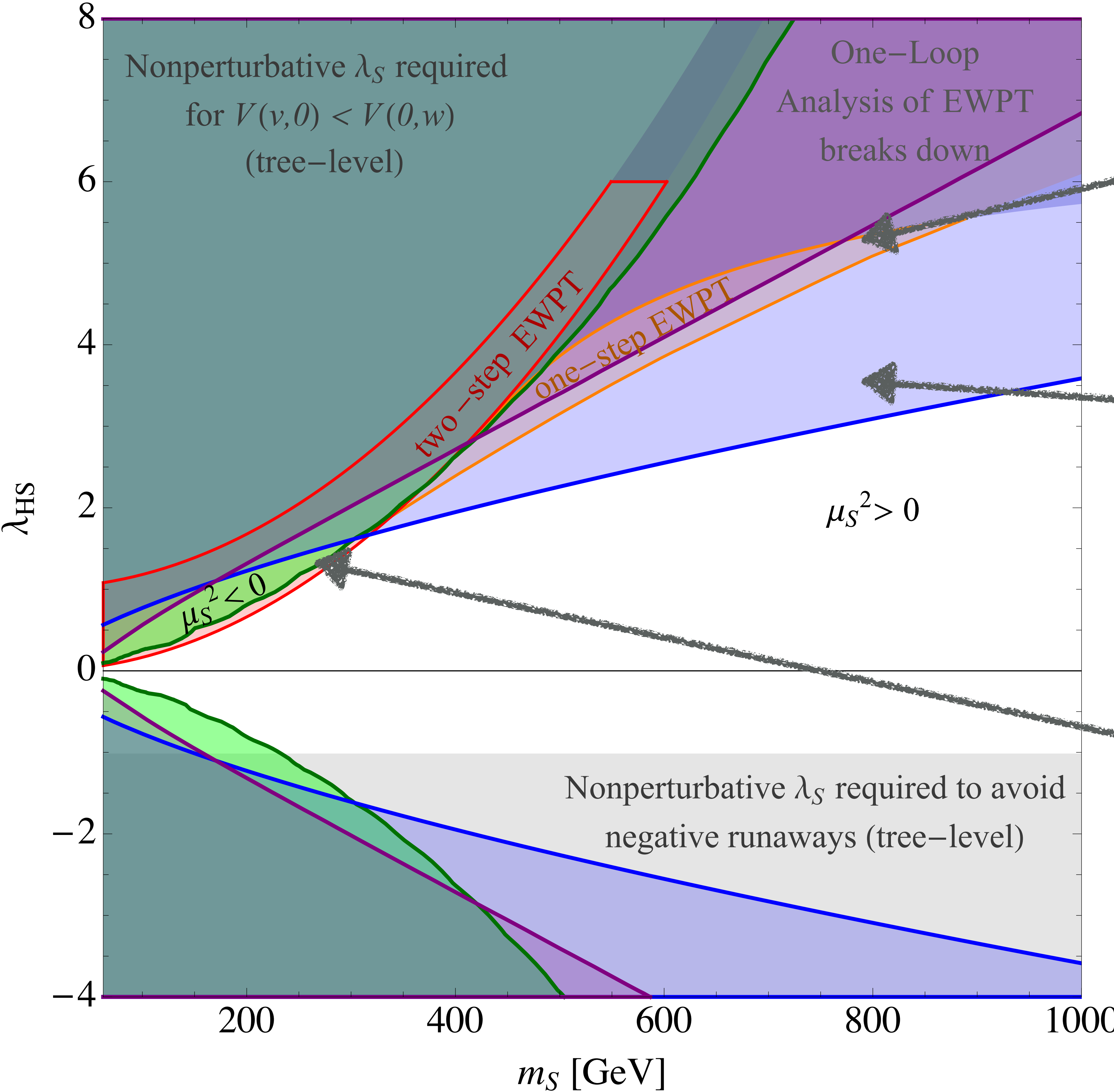


1-step PT
zero T
loops

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.

A "NO-LOSE" THEOREM



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

TRIPLE HIGGS

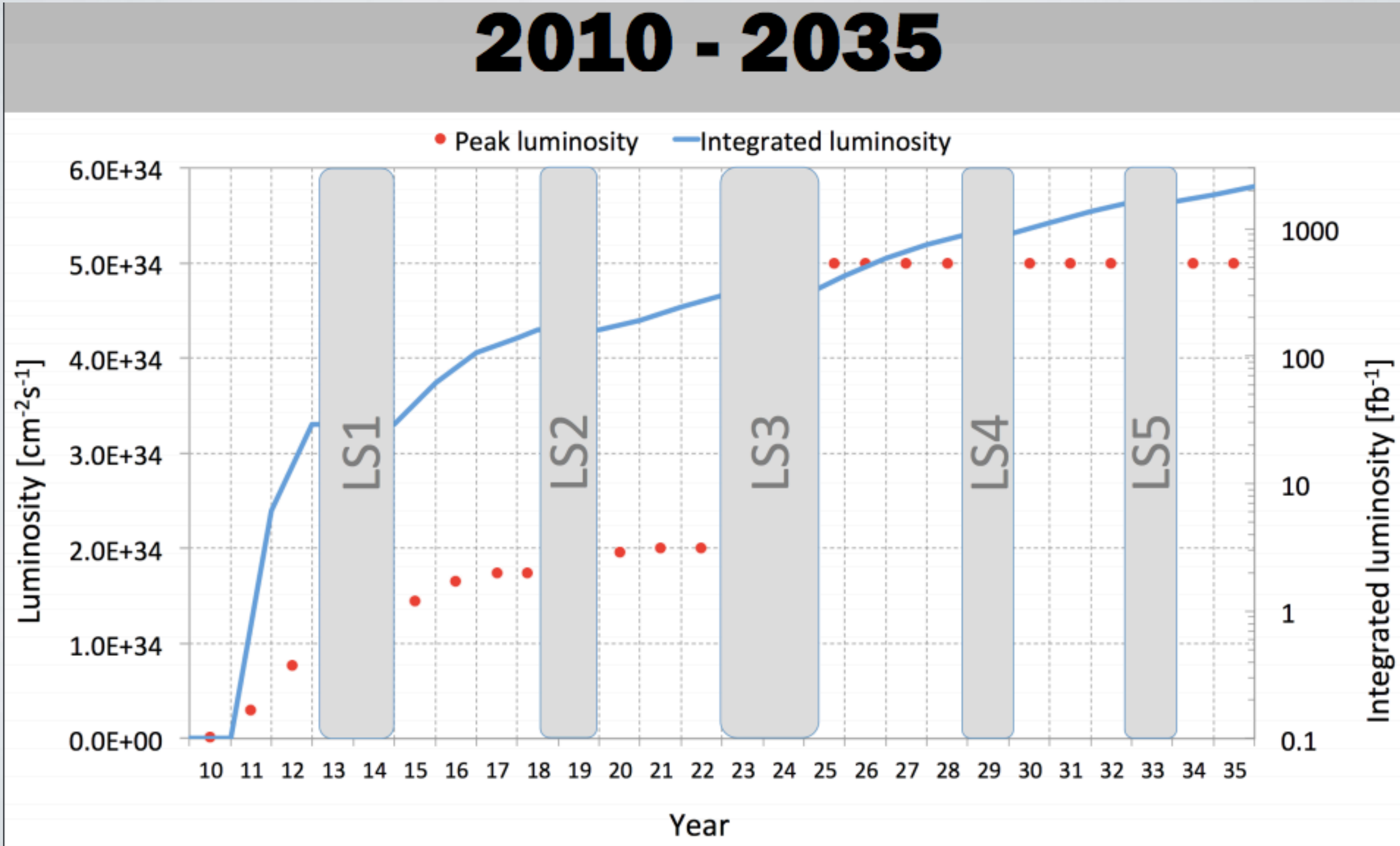
- Experimentally there are a number of different probes but the triple Higgs coupling does the heavy lifting

- In that study we used an assumed sensitivity of 10% on triple Higgs with 30/ab @ 100 TeV

- Strong FO EWPT typically naively has a 20-30% shift in this scenario

- A 100 TeV collider is a lot of money and a lot of time, what are the other possibilities?

TRIPLE HIGGS MEASUREMENTS



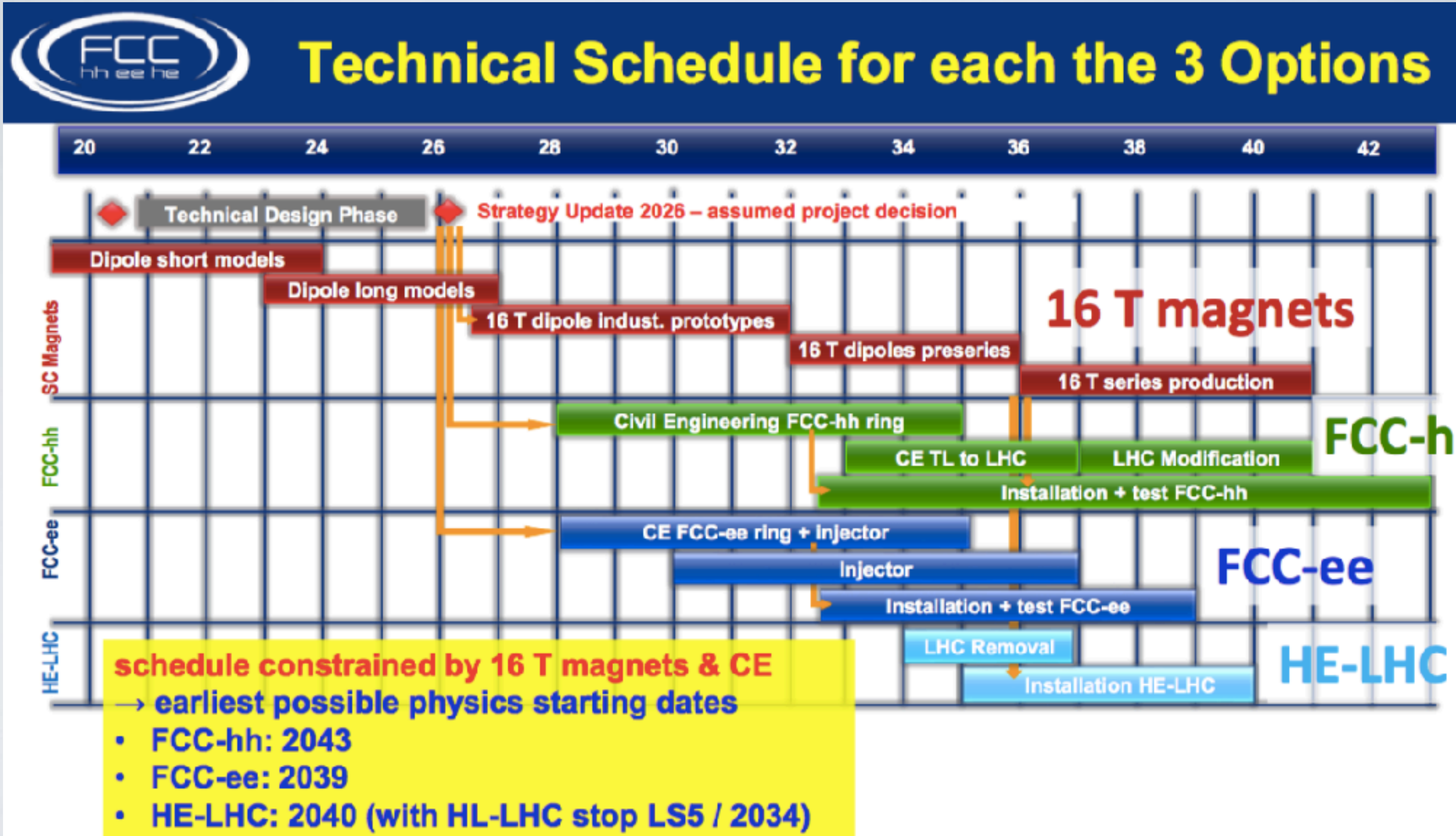
TRIPLE HIGGS MEASUREMENTS

- By 2035 we won't be able to tell the triple Higgs coupling compared to the SM better than

$$-0.8 < \lambda_3 < 7.7 \text{ at } 95\% \text{ C.L.}$$

Ugh…

TRIPLE HIGGS MEASUREMENTS



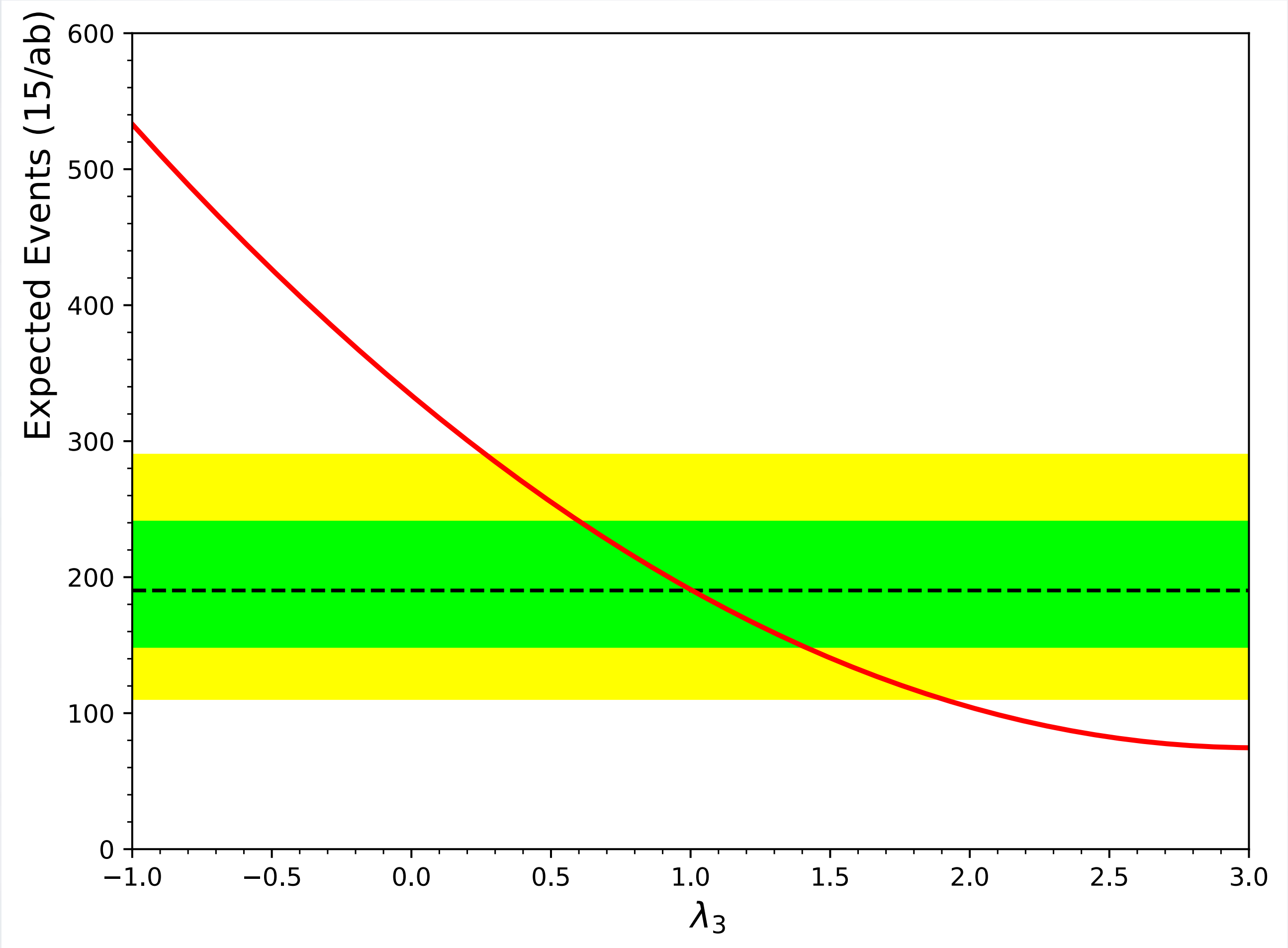
Chinese can't be faster?? although maybe politically more feasible…

TRIPLE HIGGS MEASUREMENTS

- Refined studies show that FCC-hh could get to 1.6%-few% precision, but these are missing some backgrounds and need some work
- What about HE-LHC?

HE-TRIPLE HIGGS MEASUREMENTS

- Han & Plehn et al claim you can get 5 sigma significance and a precision of 30%



Nevertheless HE-LHC does have a lot to say!

Homiller, PM to appear: a little more conservative results

Most non-experimental studies have left out key backgrounds

NICE SIMPLE STORY…
MEASURE TRIPLE HIGGS WELL ENOUGH YOU KNOW THE HISTORY OF THE UNIVERSE TO AN EARLIER TIME…

NICE SIMPLE STORY…
MEASURE TRIPLE HIGGS WELL ENOUGH YOU KNOW THE HISTORY OF THE UNIVERSE TO AN EARLIER TIME…

NO, NOT THAT SIMPLE!

THEORETICAL PROGRESS!

EXPERIMENTAL TESTS OF COSMOLOGICAL HISTORY

EWPT

SM like

Second order

First order

third possibility

The EWSB was never restored or it was delayed, or there were multiple EW phase transitions!!

Symmetry Non-Restoration

SNR phase

PM, Ramani 1807.07578

SYMMETRY-NON RESTORATION

- Weinberg in his original finite-T paper noted counter examples
  - Rochelle salts
  - O(N)xO(M) model
- Since been verified on the lattice and with various other methods!

VERY SIMPLE TO SEE WHERE IT COMES FROM…

$$V \sim (T^2 - \mu^2)\phi^2 + \lambda\phi^4$$

This comes from a term

$$V \supset \Pi_\phi \phi^2 \qquad \Pi_\phi \sim \lambda T^2$$

In a more general theory, e.g. for the Higgs

$$\Pi_h = T^2 \left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} \right)$$

NOW LET'S TAKE OUR SIMPLE SINGLET MODEL…

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

$$\Pi_h = T^2 \left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + \frac{\lambda_{HS}}{12} \right)$$

and flip a sign…

$$\Pi_h = T^2 \left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} - \frac{\lambda_{HS}}{12} \right)$$

IF THE SINGLET DOMINATES WE HAVE A QUALITATIVELY DIFFERENT PICTURE…

$$V \sim -(\mu^2 + T^2)h^2 + \lambda h^4$$

The VEV ***increases*** with temperature!

$$\langle h \rangle \sim T$$

The EW symmetry is **never** restored in the early universe

HOW WAS THIS MISSED?

- It's not quite so trivial, as you still have to make sure your calculation is under control and you have a good vacuum

$$\lambda_{HS}^2 \leq \lambda_s \lambda$$

So to satisfy this and dominate the thermal mass you run into non-peturbativity very quickly with the s quartic

$$\Pi_h = T^2 \left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} - \frac{\lambda_{HS}}{12} \right)$$

SIMPLE TRICK - SWITCH TO O(N) SINGLET

$$\Pi_h = T^2 \left(\frac{\lambda_t^2}{4} + \frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} - N_s \frac{\lambda_{HS}}{12} \right)$$

$$\Pi_s = T^2 \left((N_s + 2) \frac{\lambda_s}{12} - \frac{\lambda_{HS}}{3} \right)$$

Now it can dominate the thermal mass but keep the potential stable for small λ_{HS}

A rough estimate yields $\lambda_{HS} N_s \geq 4.8$

$$\lambda_{HS}^c \equiv \lambda_{HS} N_s$$

UNDER CONTROL…

You don't run into issues with the pure singlet quartic

$$\lambda_s \geq \left(\frac{\lambda_{HS}^c}{N_s} \right)^2 \frac{1}{\lambda}$$

β function running of the couplings stable to high scales

DOING THIS MORE CAREFULLY

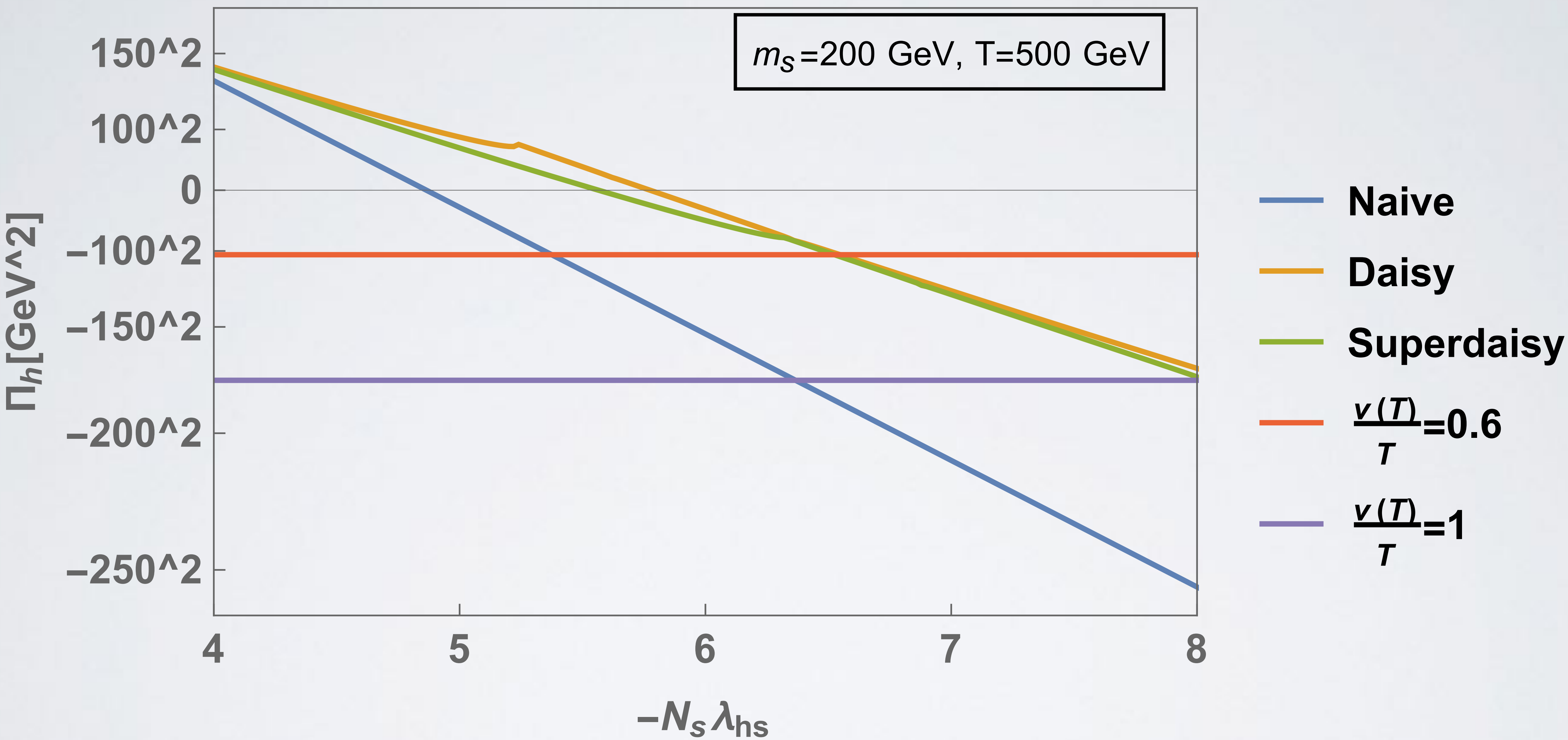
- Must take into account resummation and finite mass effects correctly - Optimized Partial Dressing

D. Curtin, PM, H. Ramani 1612.00466

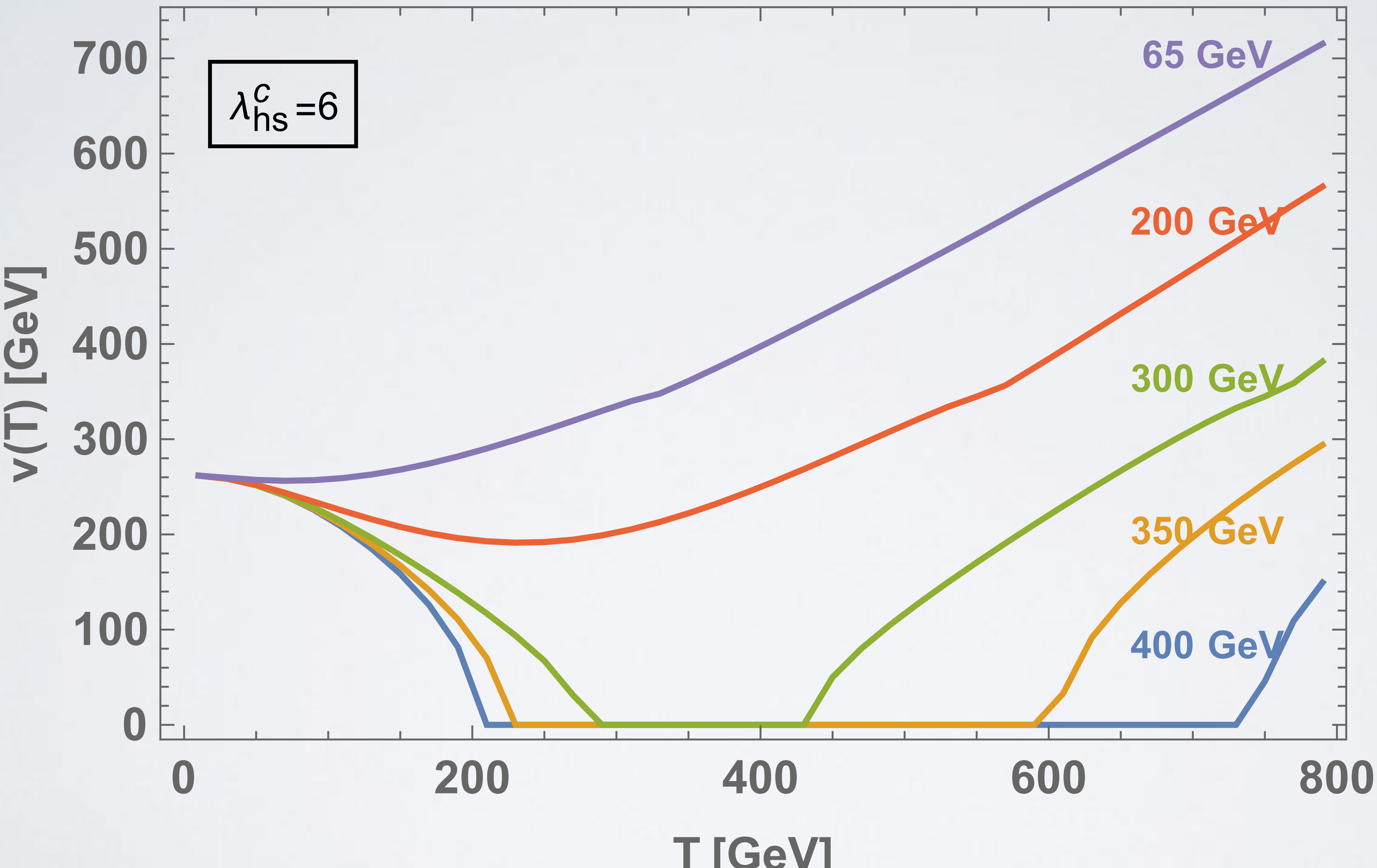
"Unfortunately, despite the fact that one is dealing with a weakly coupled theory, many aspects of the phase transition are surprisingly complicated. Indeed, the literature contains contradictory claims and statements on almost every important question."

'92 Dine, Leigh, Huet, Linde ,Linde

HIGHER ORDER EFFECTS



VERY COOL EARLY UNIVERSE POSSIBILITIES



Depending on the Singlet Mass you can get SNR-R-SNR

COSMOLOGICAL CHANGES

- Sphalerons are controlled by $\frac{v(T)}{T} \equiv \kappa$
  - for $\kappa \sim 1$ sphalerons are turned off
  - "GUT" Baryogenesis can work- Maximons
  - Models that use sphalerons would be dead (EWBG, some Leptogenesis) - can look SM like at low energies

Can also just postpone EWBG:
see Baldes, Servant and Rattazzi, Vecchio

COSMOLOGICAL CHANGES

- Avoid defects if you avoid phase transitions…

- Is decoupling any different? In principle yes

$$m(T) \sim g\kappa T$$

- For very large kappa, particles are non-relativistic instead of relativistic

$$\kappa \sim \frac{\sqrt{\Pi_h/\lambda}}{T}$$

Can enhance with running λ

Even more interesting you can get exotic equations of state!

LARGE N SCALING CHANGES COLLIDER OBSERVABLES AS WELL

However, let's look at the scaling for collider observables…

$$\delta_{Zh} \sim N_s \lambda_{HS}^2 \quad \sigma_{h^* \to ss} \sim N_s \lambda_{HS}^2 \quad \delta_{h^3} \sim N_s \lambda_{HS}^3$$

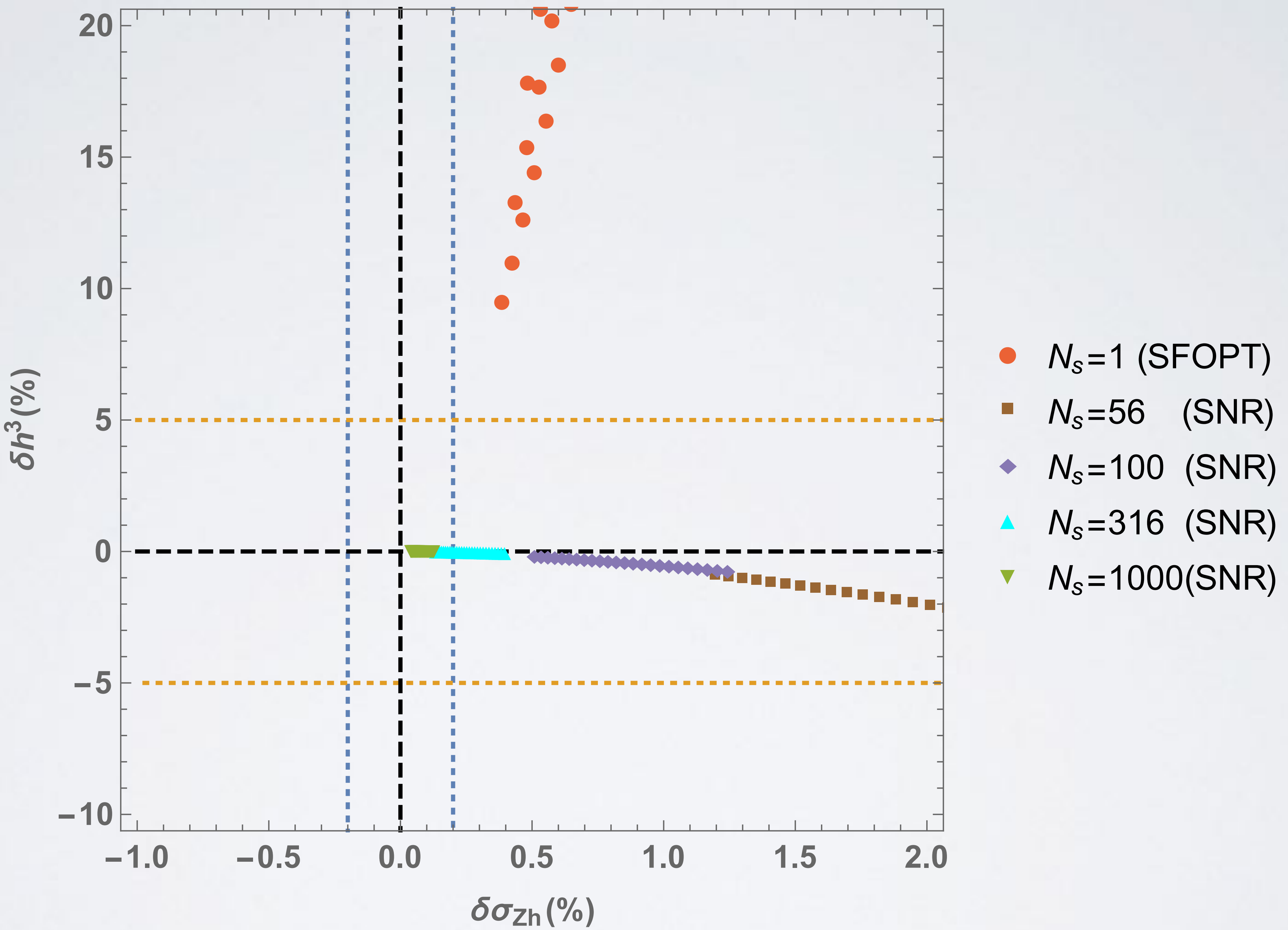
If we fix $\lambda_{HS} N_s = \lambda_{HS}^c$

$$\delta_{Zh} \sim \frac{(\lambda_{HS}^c)^2}{N_s} \quad \sigma_{h^* \to ss} \sim \frac{(\lambda_{HS}^c)^2}{N_s} \quad \delta_{h^3} \sim \frac{(\lambda_{HS}^c)^3}{N_s^2}$$

In the scaling limit the effects disappear!

Can we tell whether or not the early universe was in a SNR phase?

ANOTHER INTERESTING COMPLICATION



Can you confuse SNR with a strong FOPT? yes, up to triple higgs
One would have a strong gravitational wave signal, the other wouldn't

CONCLUSIONS

- Lots of interesting physics under the Higgs lamppost

- Need a ***new*** flowchart for thinking about triple Higgs couplings, but it is likely the most important measurement for understanding qualitative differences about our universe from particle perspective