Higgs and Baryogenesis

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So to do this topic justice we'll need to develop a good understanding of:

Cosmology

Finite Temperature Quantum Field Theory

Non perturbative Quantum Field Theory Methods

…


ALL IN 55 MINUTES
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So as per the organizer's instruction

"We hope that your lecture will provide a broad overview of the connection between baryogenesis and the Higgs boson (within, but also Beyond the Standard Model) - all with a rather broad brush."

My apologies if it seems more like this…

What I hope you come away with…

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Higgs

Baryogenesis

Why are they related?

What I hope you come away with…

Higgs **Baryogenesis**

If they are related

$\downarrow$

What experimental observables *matter*?

Why are they usually related?

Why are they usually related?

ON ANOMALOUS ELECTROWEAK BARYON-NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE

V.A. KUZMIN, V.A. RUBAKOV

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and

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Received 8 February 1985

We estimate the rate of the anomalous electroweak baryon-number non-conserving processes in the cosmic plasma and find that it exceeds the expansion rate of the universe at $T >$ (a few)$\times 10^2$ GeV We study whether these processes wash out the baryon asymmetry of the universe (BAU) generated at some earlier state (say, at GUT temperatures). We also discuss the possibility of BAU generation by the electroweak processes themselves and find that this does not take place if the electroweak phase transition is of second order No definite conclusion is made for the strongly first-order phase transition We point out that the BAU might be attributed to the anomalous decays of heavy ($M_F \geq M_W/\alpha_W$) fermions if these decays are unsuppressed

Why are they usually related?

Electroweak Baryogenesis

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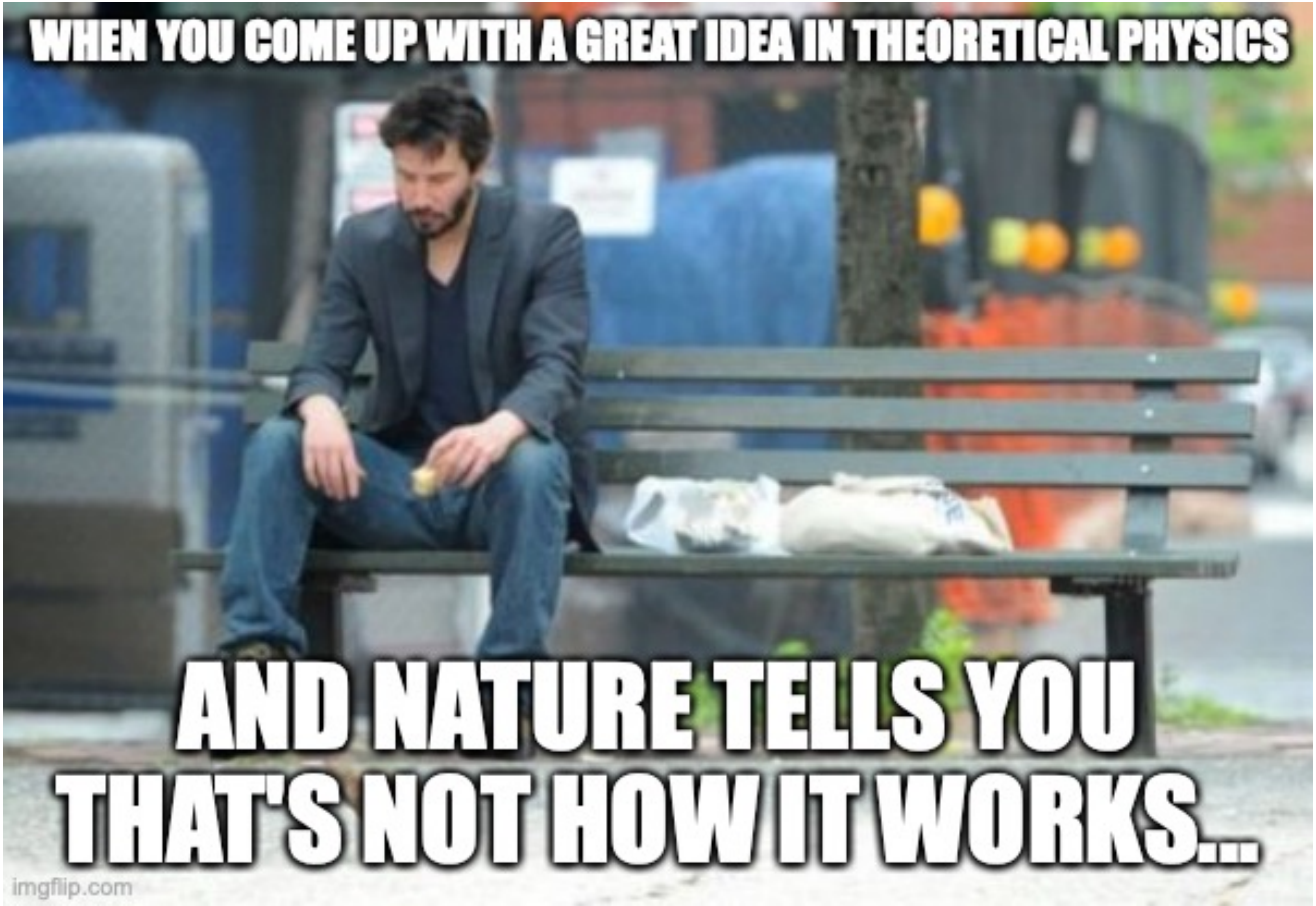
WHEN YOU COME UP WITH A GREAT IDEA IN THEORETICAL PHYSICS
AND NATURE TELLS YOU THAT'S NOT HOW IT WORKS...
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Nevertheless, it’s instructive to understand what are the ingredients that made this idea so compelling

First… because it’s cool!

Second, because so little is *known* about the Higgs and it’s properties can *easily* be changed by BSM physics as you’ve heard many times over during the SSI

Let’s start at the beginning

What is Baryogenesis (Baryosynthesis)?

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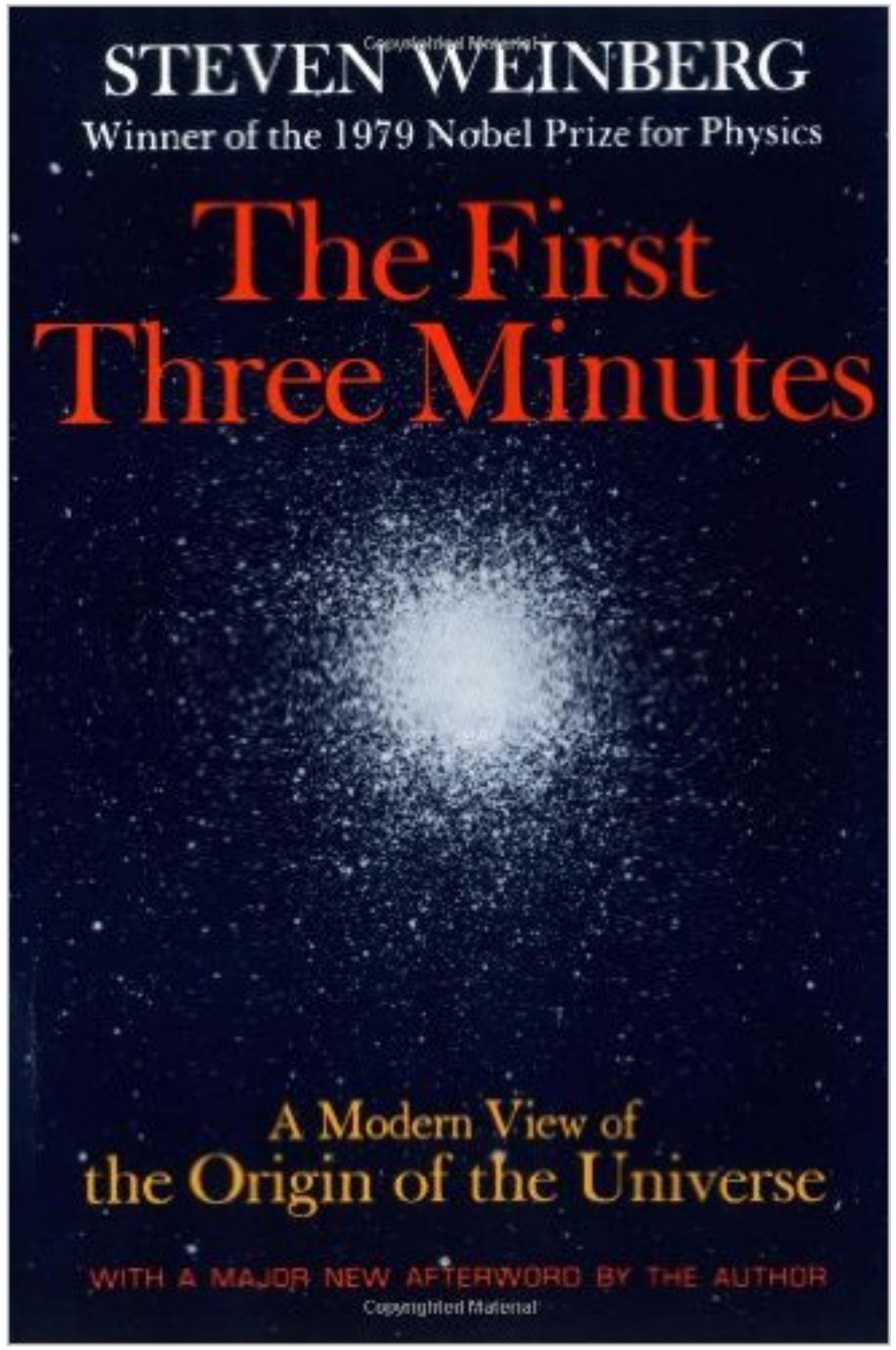
What is Baryogenesis (Baryosynthesis)?

The more poetic version… Why are we here?

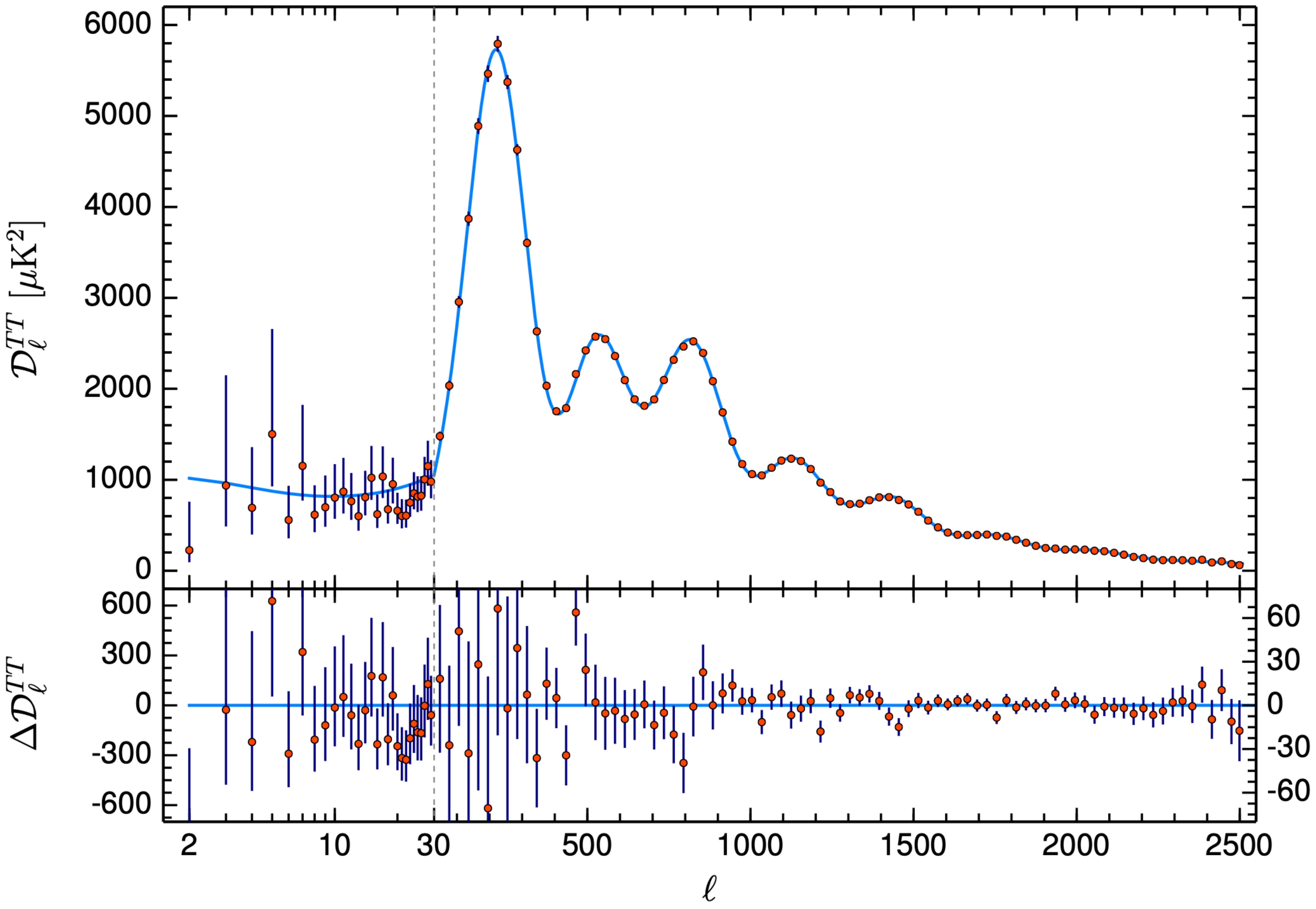
We have a beautiful understanding of the universe when we combine particle physics and cosmology



Quantitatively it's absolutely ridiculous…

e.g.

Planck Collaboration: Cosmological parameters



We're led to pictures like this

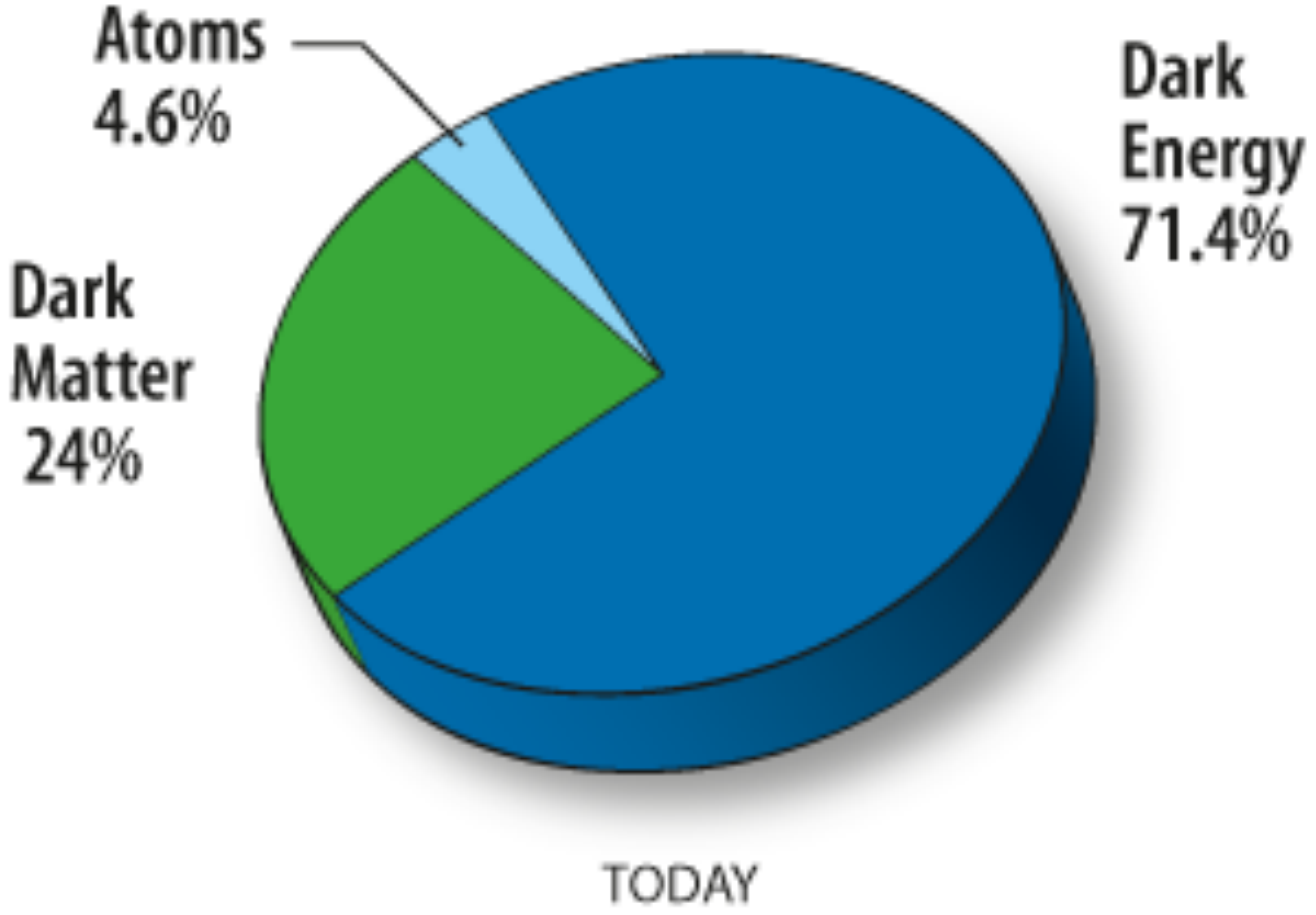
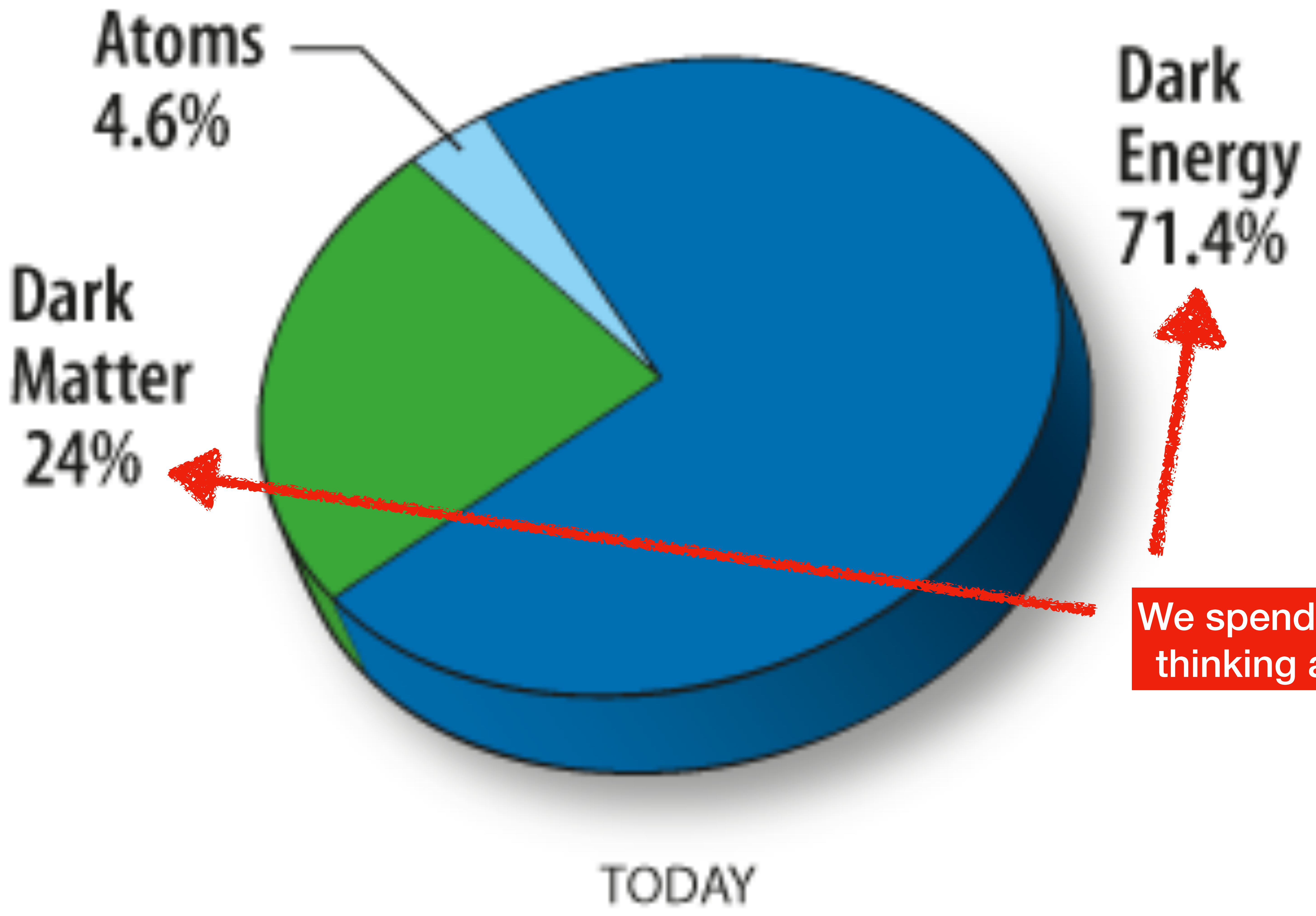


Figure from WMAP collaboration

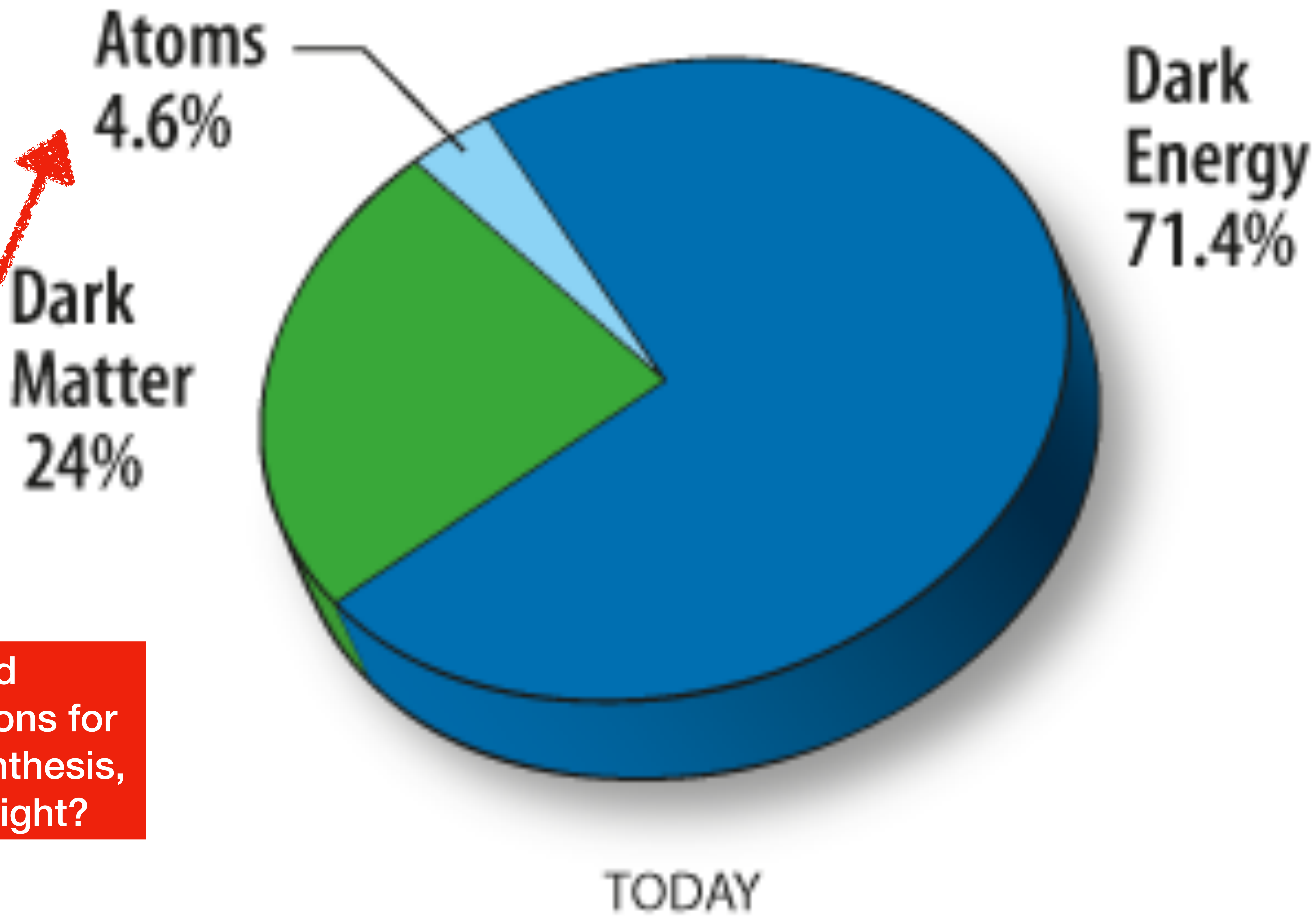
We're led to pictures like this



We spend a lot of time thinking about these

Figure from WMAP collaboration

We're led to pictures like this



We know this, and
Use it to make predictions for
the CMB and nucleosynthesis,
and everything else, right?

Figure from WMAP collaboration

There are really 2 questions we seek to answer, what sets the amount of "us" correctly, and why is there more matter than antimatter?

For Nucleosynthesis we need $\eta \equiv \frac{n_b - n_{\bar{b}}}{s} \sim 6 \times 10^{-10}$

This is because not only do we need enough of *us*… We seen no evidence of *"anti-us"* on the largest scales we can access

Cosmic ray anti-particles
Diffuse Gamma ray background vs Spatial Inhomogeneity

Dark matter and Dark Energy are certainly gigantic unsolved problems, but how far off are we from the lowly Baryons?

If you start from a symmetric universe in thermal equilibrium and follow your nose like for Dark Matter

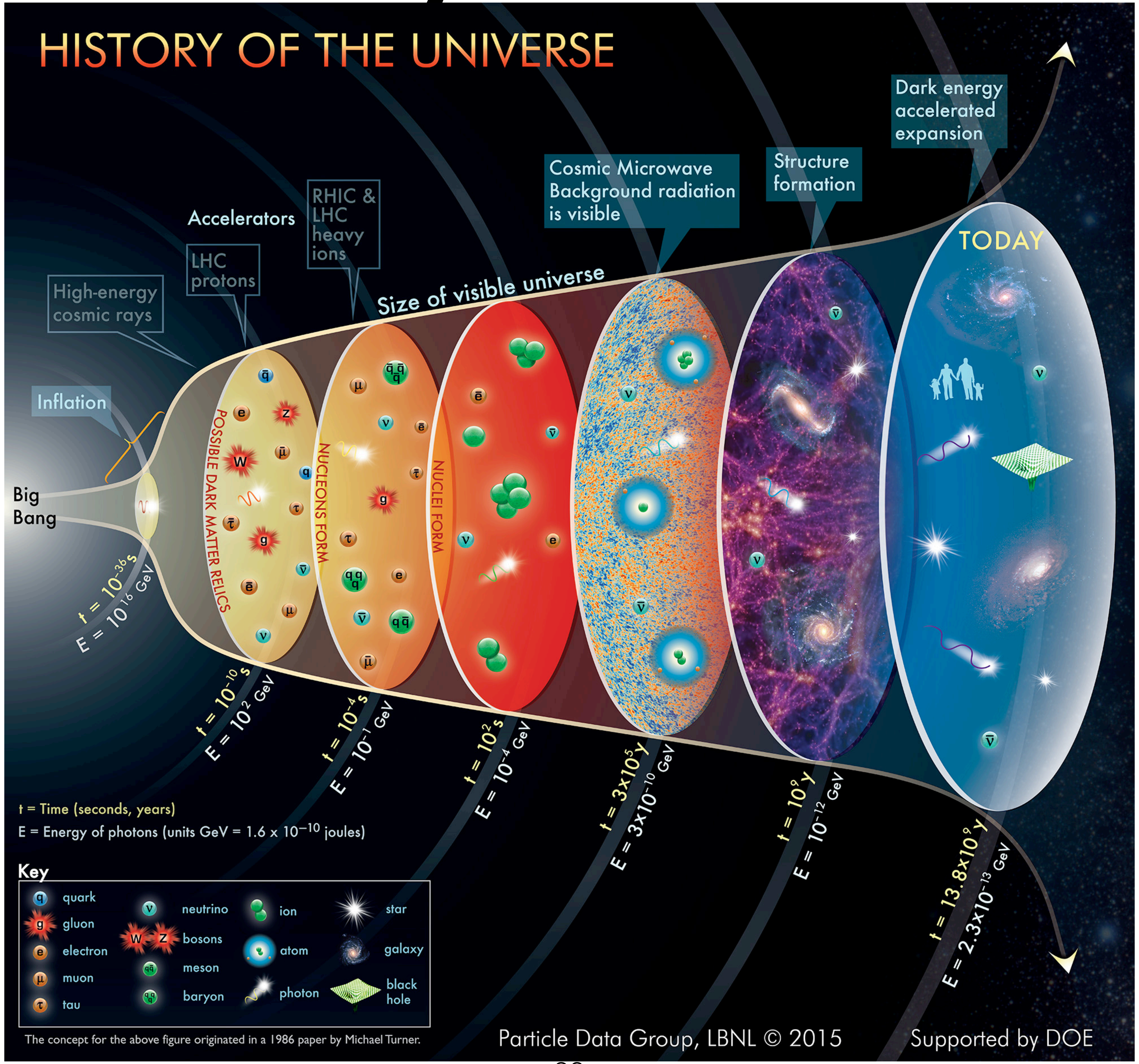
Recall Prof. Shelton's Higgs Portal lectures earlier!

$$\Gamma_{ann} = n\langle\sigma v\rangle \quad \textbf{vs.} \quad H$$

Stays symmetric and off by about 10 orders of magnitude for density

Couldn't this all just be fixed with some initial condition instead of some fancy sounding new idea like *BARYOGENESIS*?

Well we really like inflation too…



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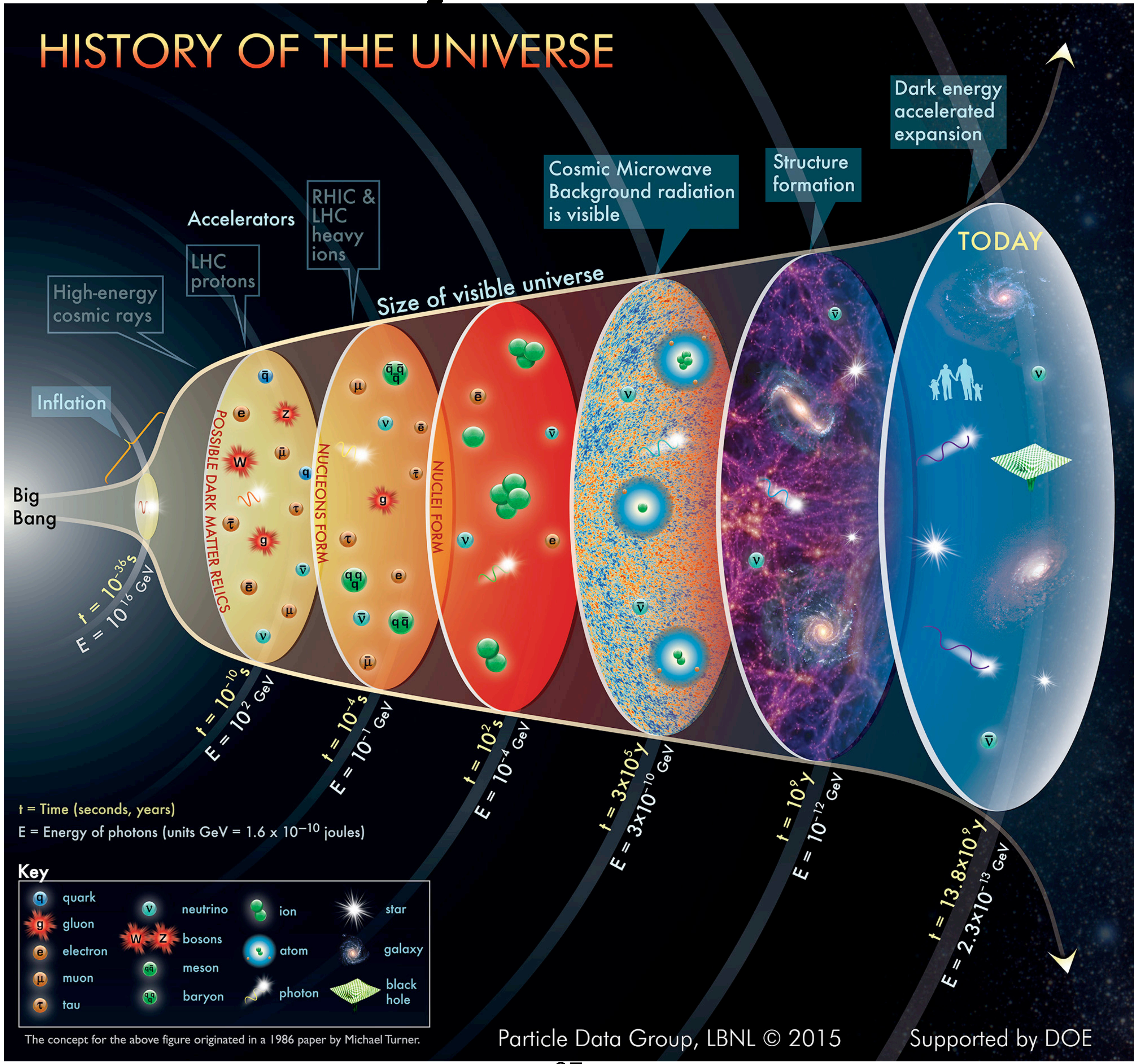
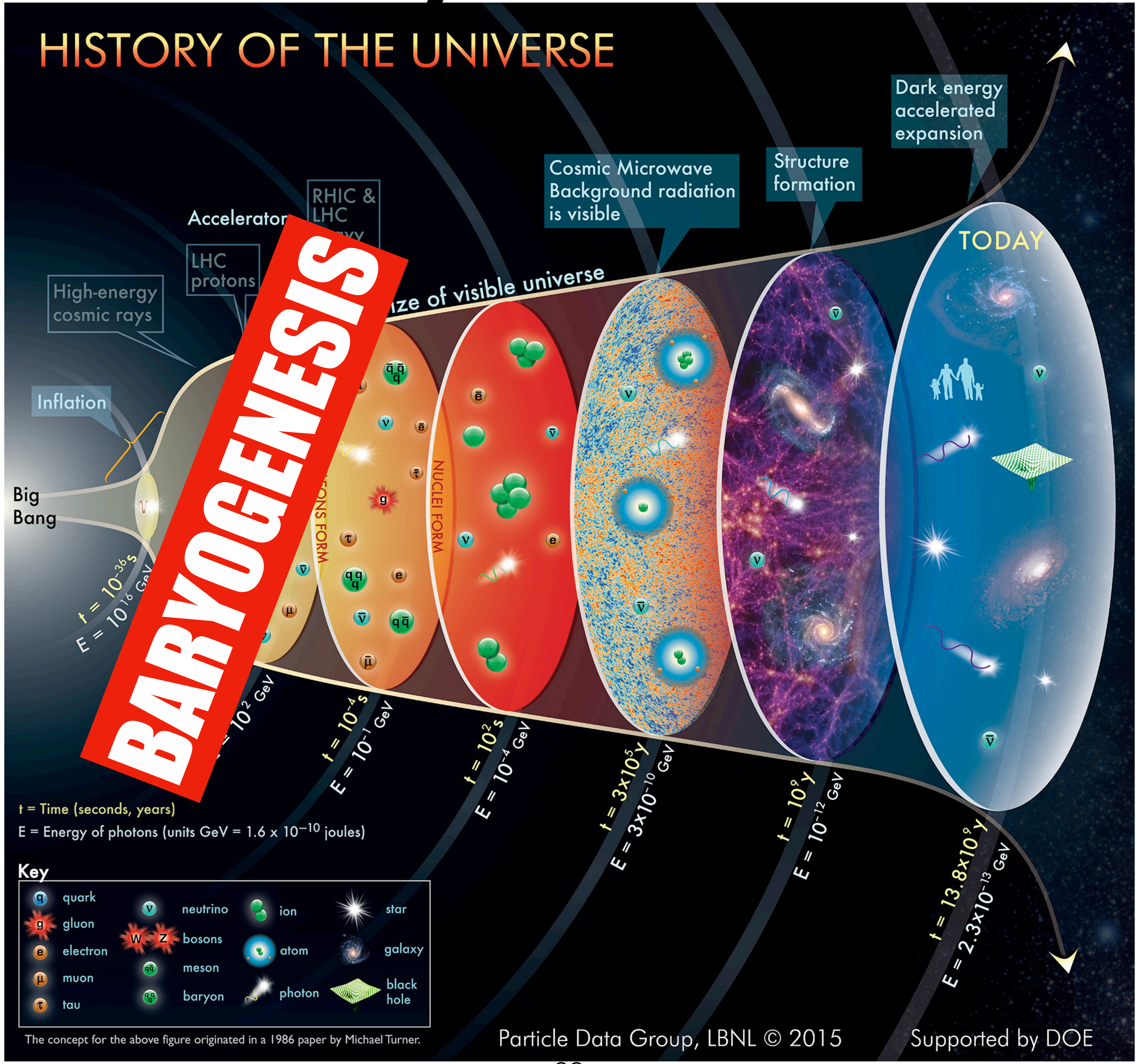


So initial conditions don't work

Well we really like inflation too…

So initial conditions don't work




BARYOGENESIS EXPLAINS
THE OBSERVED BARYON DENSITY
YOU KNOW THE MECHANISM RIGHT?
imgflip.com
YOU KNOW THE MECHANISM RIGHT?

Don’t know the mechanism and don’t know when it occurred…

After inflation, but I don’t know when that happened either

Before nucleosynthesis

Sakharov to the rescue…

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Sakharov Conditions

- Baryon number violating processes
- C and CP violation
- Thermal equilibrium departure

Many theories can satisfy the criteria

- GUT Baryogenesis
- Leptogenesis
- Affleck-Dine Baryogenesis
- Electroweak Baryogenesis
- (Insert your model here)
- ...

Qualitative features that satisfy Sakaharov criteria are different in this grouping (but shared sometimes)

GUT Baryogenesis

Grand Unified Theories in principle have all the needed ingredients…

GUT Baryogenesis

The devil is always in the details, not the arguments

Generically it runs into many other problems *IF* you want to explain the observed values

Many theories can satisfy the criteria

- GUT Baryogenesis
- Leptogenesis
- Affleck-Dine Baryogenesis
- Electroweak Baryogenesis
- (Insert your model here)
- …

Qualitative features that satisfy
Sakaharov criteria are different
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Why out of all these possibilities is the Higgs singled out?

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The SM when looked at in more detail actually *had* all the features to *potentially* dynamically explain Baryogenesis

- Baryon number violating processes (Sphalerons!)
- C and CP violation (experimentally seen!)
- Thermal equilibrium departure (EW phase transition)

It’s actually a quite intricate story that needs A good deal of background information so keep in mind…

What's a sphaleron?

The Standard Model has accidental global symmetries - like Baryon number!

't Hooft showed that non-perturbative processes (Instantons) could violate it!

$$B + L$$

Violated in SM

$$B - L$$

Conserved in SM

What's a sphaleron?

Unfortunately/Fortunately instantons are highly suppressed!

$$\sim e^{-\frac{16\pi^2}{g^2}}$$

What’s a sphaleron?

However, a related field configuration at finite temperature (the sphaleron) has a temperature dependence.

$$\sim e^{-\frac{M_W(T)}{T}}$$

What happens to the SM at high temperatures? (assuming we just have the SM)

Textbook cosmology…

PHASE TRANSITIONS

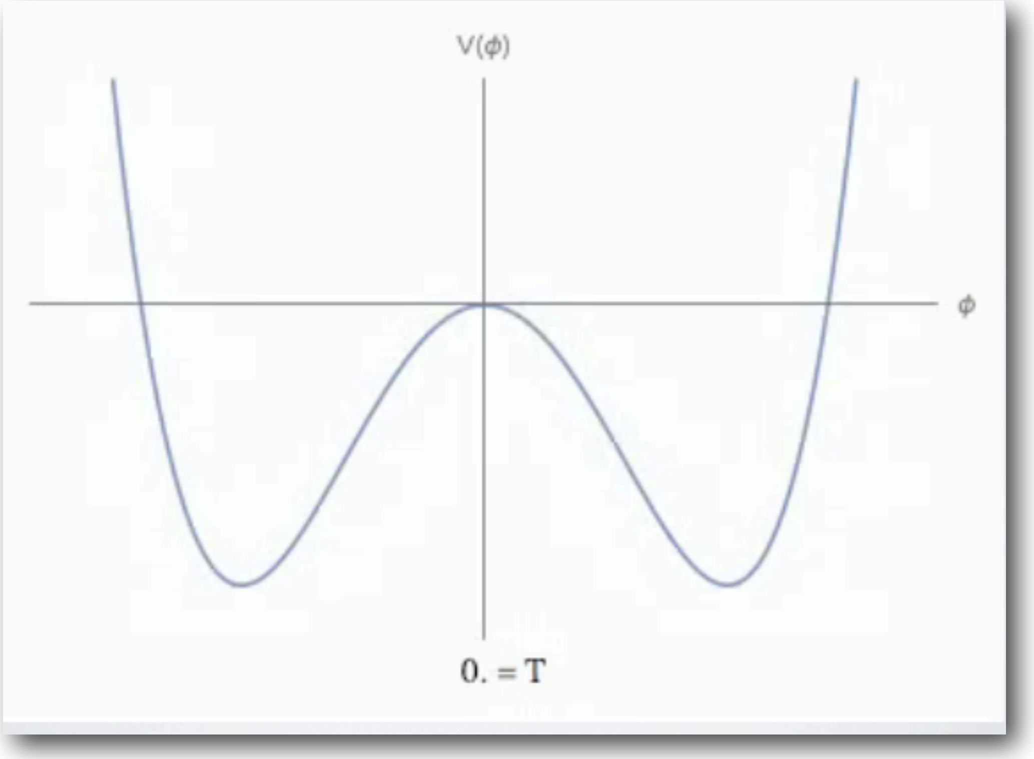
7.1 High-Temperature Symmetry Restoration

One of the most important concepts in modern particle theory is that of spontaneous symmetry breaking (SSB). The idea that there are underlying symmetries of Nature that are not manifest in the structure of the vacuum appears to play a crucial role in the unification of the forces. In all unified gauge theories—including the standard model of particle physics—the underlying gauge symmetry is larger than that of our vacuum, whose symmetry is that of $SU(3)_C \otimes U(1)_{EM}$. Of particular interest for cosmology is the theoretical expectation that at high temperatures, symmetries that are spontaneously broken today were restored [1], and that during the evolution of the Universe there were phase transitions, perhaps many, associated with the spontaneous breakdown of gauge (and perhaps global) symmetries. In particular, we can be reasonably confident that there was such a phase transistion at a temperature of order 300 GeV and a time of order 10^{-11} sec, associated with the breakdown of $SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$. Moreover, the vacuum structure in many spontaneously broken gauge theories is very rich: Topologically stable configurations of gauge and Higgs fields exist as domain walls, cosmic strings, and monopoles. In addition, classical configurations that are not topologically stable, so-called nontopological solitons, may exist and be stable for dynamical reasons. Interesting examples include soliton stars, Q-balls, nontopological cosmic strings, and so on [2].

The cosmological production, and subsequent implications, of such topological defects will occupy much of this Chapter. The possibility that the Universe undergoes inflation during a phase transition will be the subject of the next Chapter. Before discussing topological defects and their production in cosmological phase transitions, we will review some general

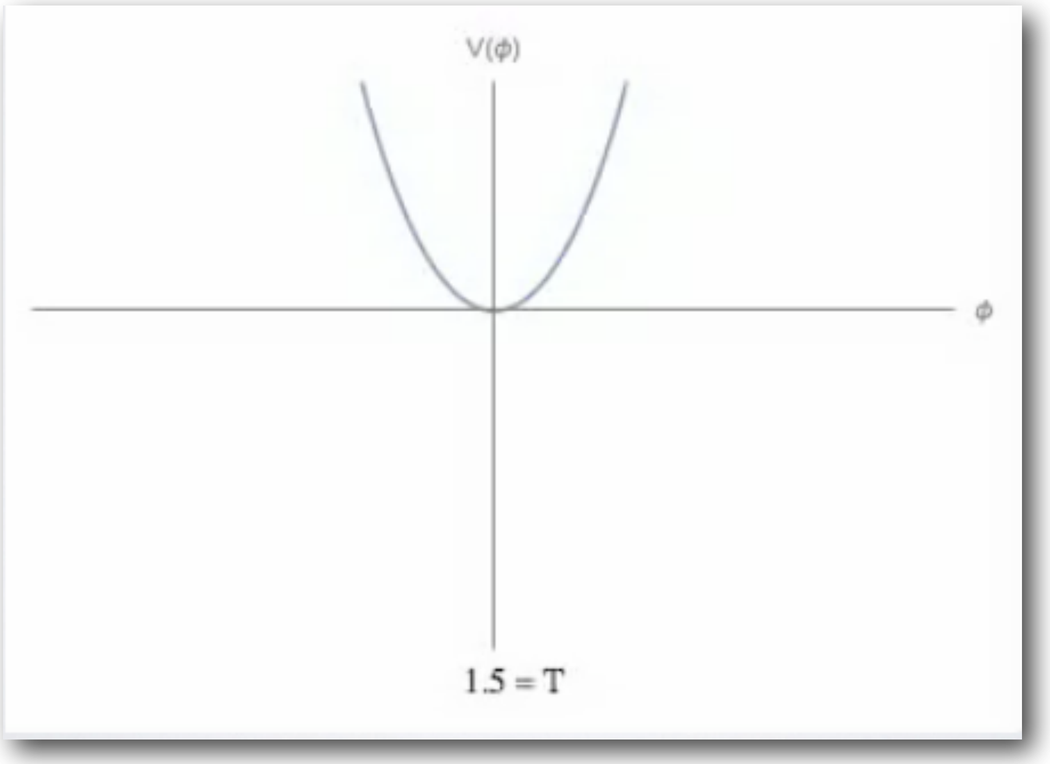
Kolb & Turner

Imperfect Analogy:



Universe now

Early universe
was hotter!



Early Universe

Sphalerons allow for unsuppressed B violation in SM for

$$T \gg T_{EW} \sim v$$

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$$T \gg T_{EW} \sim v$$

Sphalerons can allow for a potential SM only solution, but also are important for *any* BSM idea like GUT Baryogeneis, Leptogenesis, etc. that occurs at high T

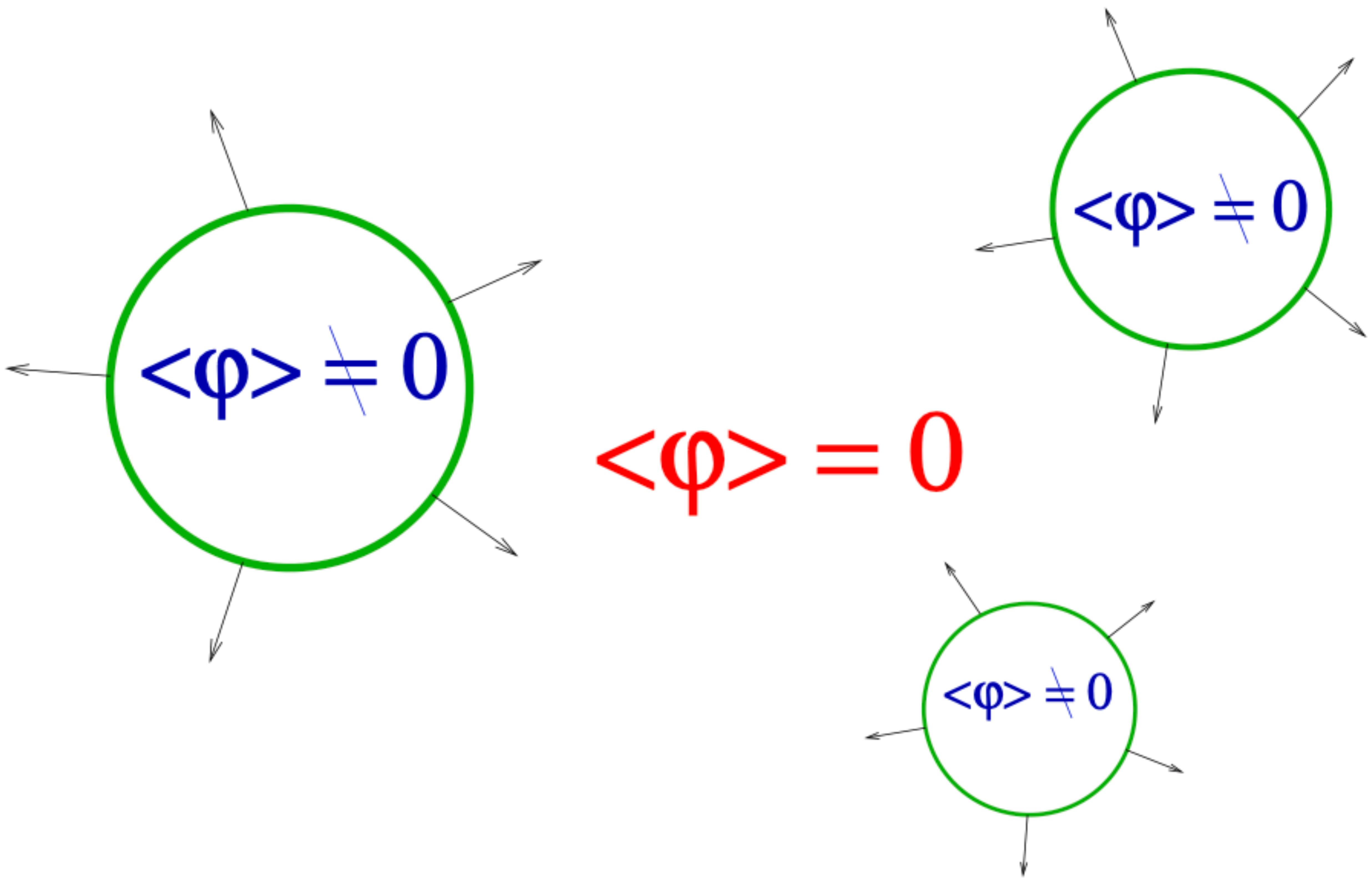
Can provide B violation, or convert asymmetries, can also washout asymmetries…

The SM when looked at in more detail actually *had* all the features to *potentially* dynamically explain Baryogenesis

- Baryon number violating processes (Sphalerons!)
- C and CP violation (experimentally seen!)
- Thermal equilibrium departure (EW phase transition)

What about these?

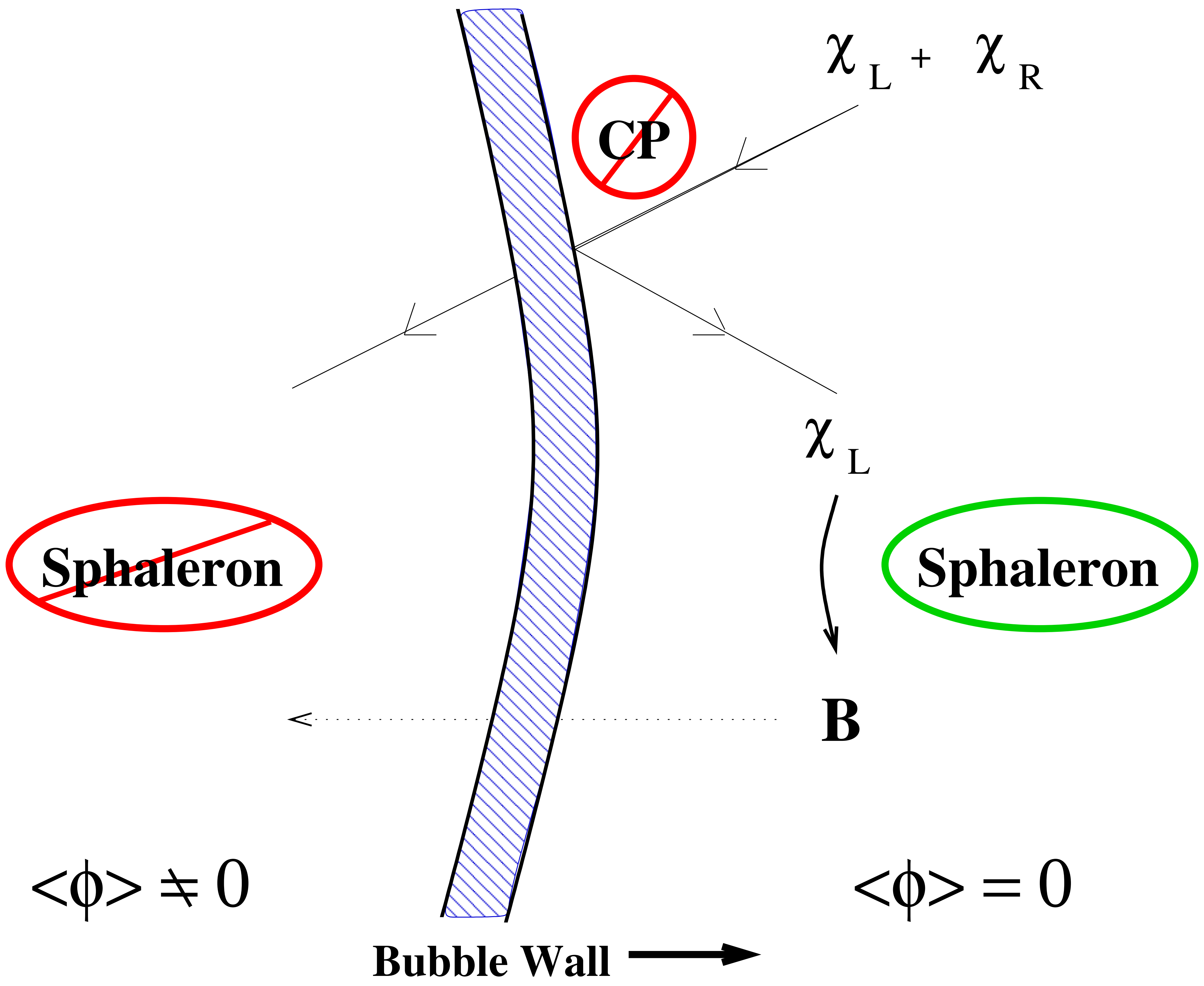
EWBG in pictures…



IF you had a first order EWPT

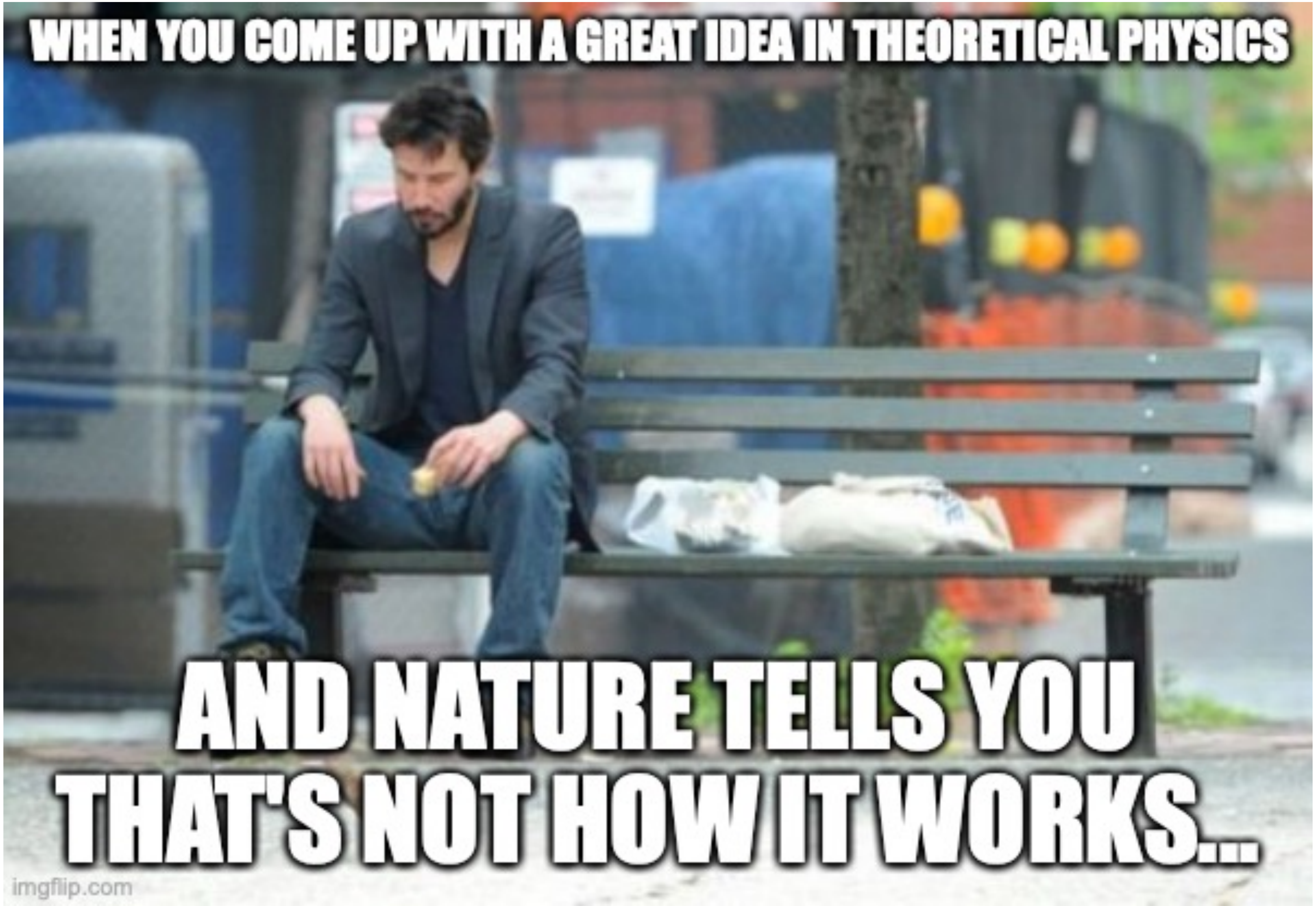
D. Morrissey, M. Ramsey-Musolf
1206.2942

EWBG in pictures…



D. Morrissey, M. Ramsey-Musolf
1206.2942

as I said earlier, lots of ingredients…


WHEN YOU COME UP WITH A GREAT IDEA IN THEORETICAL PHYSICS
AND NATURE TELLS YOU THAT'S NOT HOW IT WORKS...
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Alas in the SM…

- The EWPT is not first order(crossover)
- There is not enough CP violation

Baryogenesis

EWBG

Something else?

Baryogenesis

~~EWBG~~

Something else?

The end… or not yet?

The parts that are lacking for EWBG in the SM all have to do with the *Higgs*

- The EWPT is not first order(crossover)
- There is not enough CP violation

The properties of the Higgs can be modified easily as you’ve seen in numerous lectures so far…

The parts that are lacking for EWBG in the SM all have to do with the *Higgs*

- The EWPT is not first order(crossover)
- There is not enough CP violation

For EWBG you need both

The properties of the Higgs can be modified easily as you've seen in numerous lectures so far…

EWPT

- New particles that couple to Higgs
- Low energy - modify Higgs potential
- Modify Higgs couplings
- ***New particles can't be too heavy***
- ***Can search at LHC and future colliders, but also Gravitational Waves***

CPV

- New sources of CPV
- In SM Higgs is only substantial source!
- Need new couplings to SM w/ phases that can't be rotated away
- ***Can search at LHC and future colliders, but also EDMs, flavor etc***

EWPT

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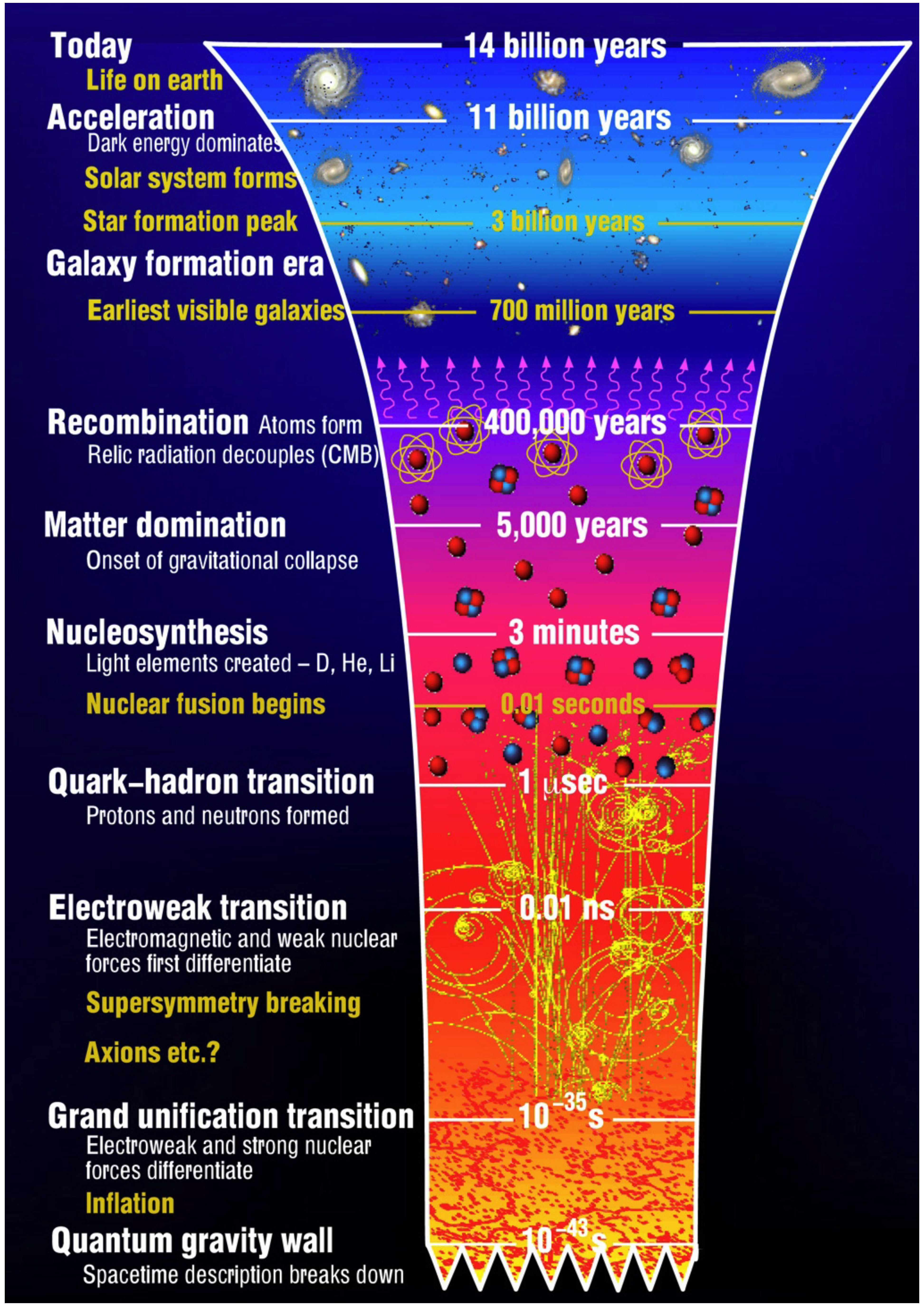
For example in the MSSM it added ingredients that would have fixed everything (but it doesn't really work either)

The nice thing is that even if Baryogenesis has nothing to do with the Higgs

EWPT

Studying this is crucial to understanding the history of our universe independently

CPV



We need particle physics to probe possibilities at hinger T

How can the EW phase transition be modified, and why does it need to be “around the corner”

For this we need Finite T - QFT

How can the EW phase transition be modified, and why does it need to be "around the corner"

For this w

ite T - QFT

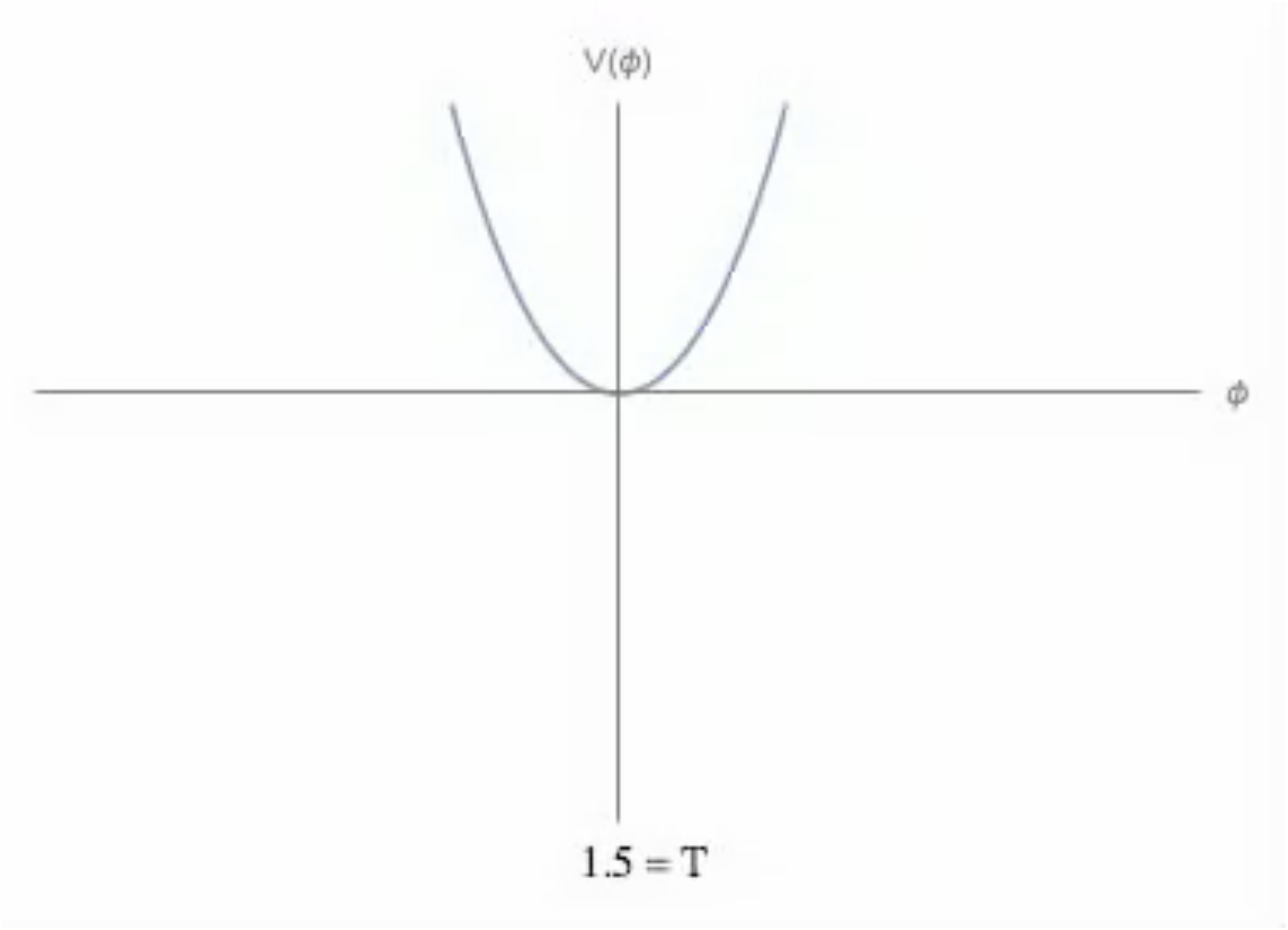
Calculating Thermal Potential for Higgs

Kind of like effective potential calculations…

If particles couple to Higgs then loops involving them generate T-dependent terms (including itself)

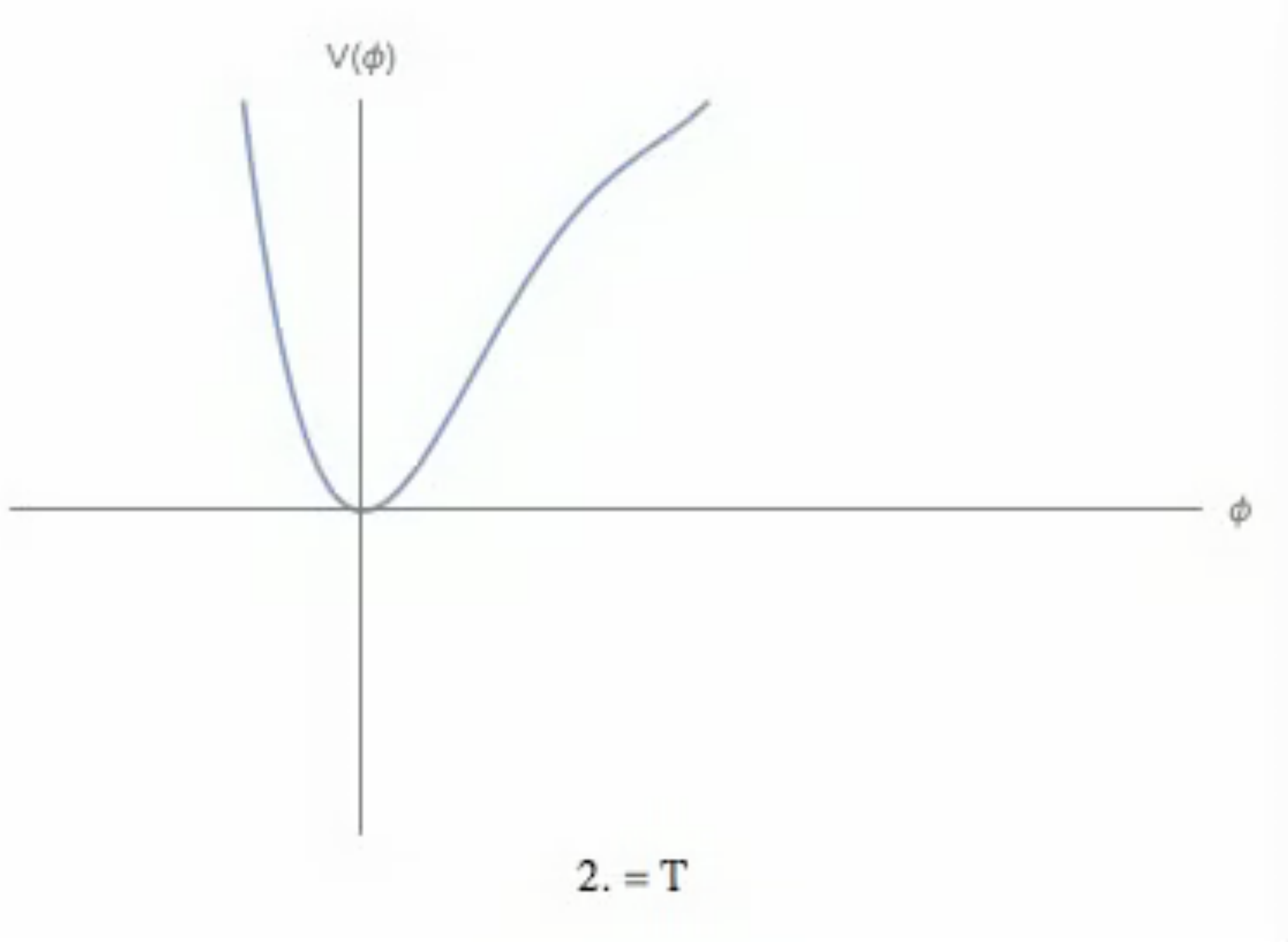
2ND ORDER PHASE TRANSITION

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



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

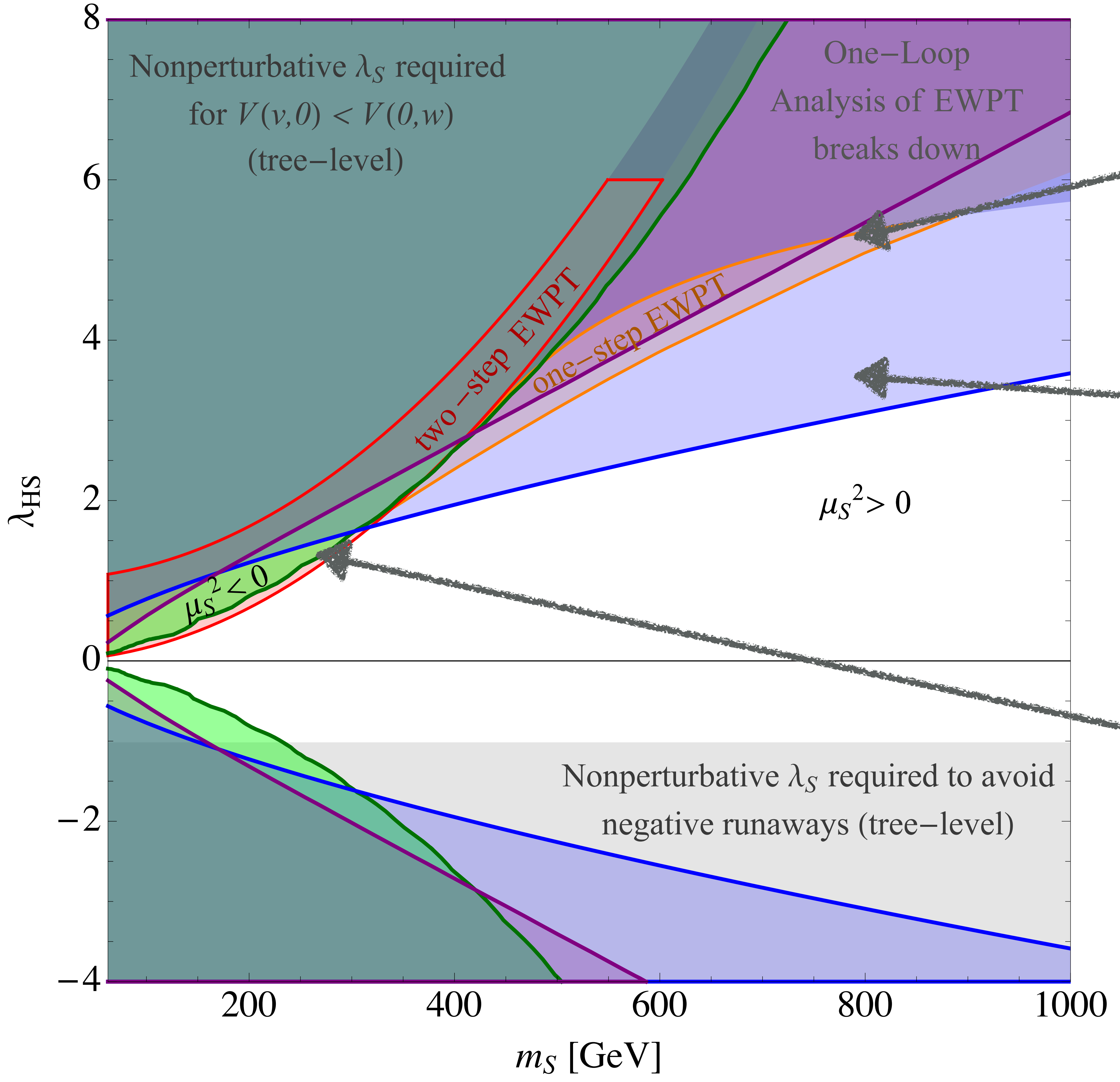
The qualitative difference is an effective cubic at finite temperature!

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

Anything that modifies Higgs potential significantly at finite T - must be right around the corner!

An example you saw earlier in Prof. Shelton's lectures

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



TLEP exclusion
with Zh shift

2 Sigma Exclusion
with triple Higgs at
100 TeV

Collider
100 TeV 30/ab

1409.0005 D. Curtin, PM, T.Yu

Connecting to Baryogenesis more difficult

EWPT

CPV

Typically not around the corner…

Strong CPV bounds

However, there are always new ideas that can generalize old ones or challenge initial assumptions

PHASE TRANSITIONS

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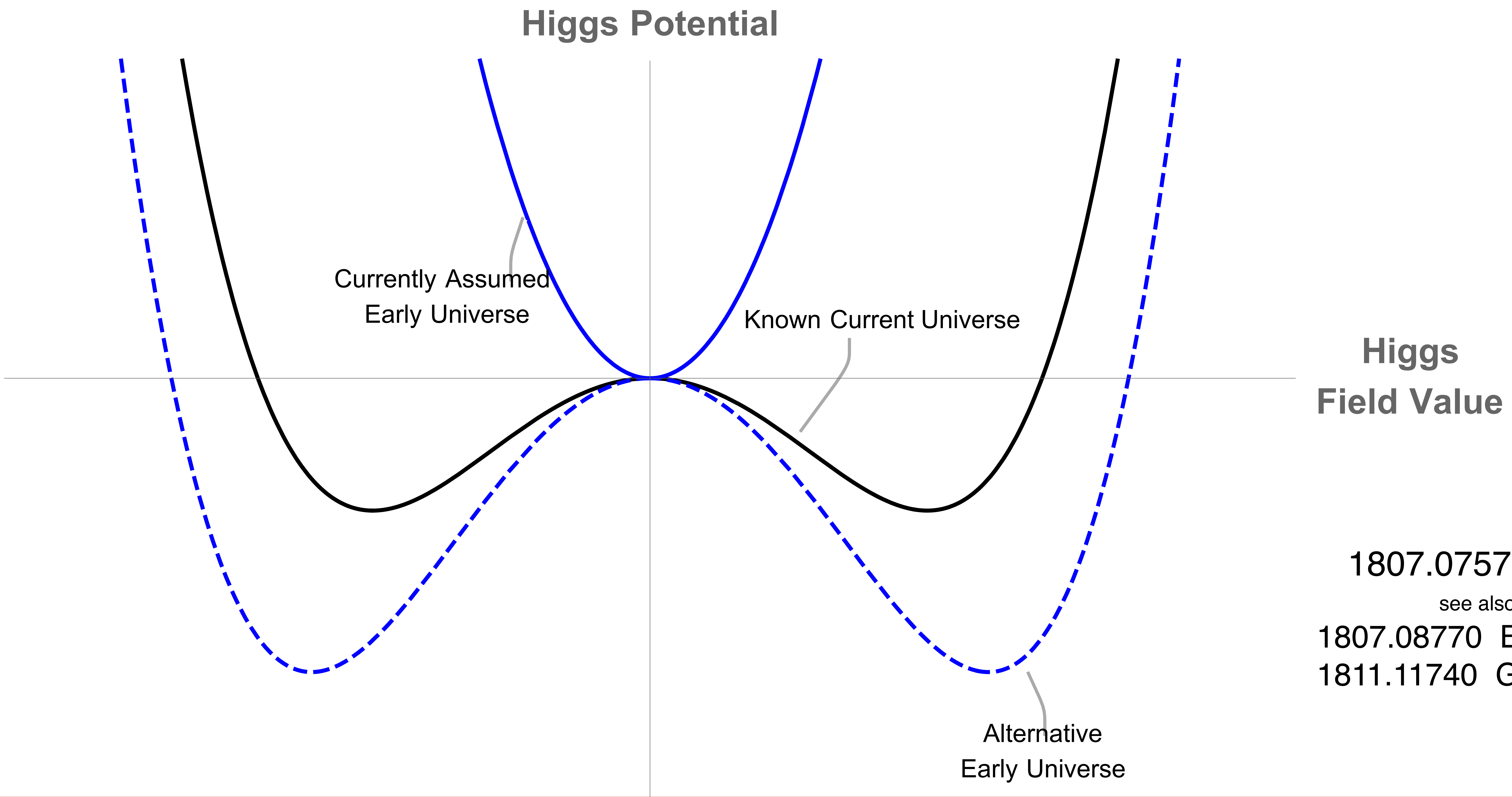
For example…

However, there are always new ideas that can generalize old ones or challenge initial assumptions

What if the EW Phase transition didn't happen at the EW scale???



1807.07578 PM, H. Ramani

see also

1807.08770 Baldes, Servant

1811.11740 Glioti, Rattazzi, Vecchi

Could delay EWPT to high scales where CPV is perfectly allowed - still need new particles at EW scale, and test through Higgs!

Many more possibilities but the Higgs is our next big particle physics key to unlocking the early universe!

Summary

- Baryogenesis is needed - don't know what the mechanism is or when it happened (physics is hard!)
- Higgs can be intimately connected to it through EWBG
    - Modifications to Higgs properties and CPV are the experimental targets
- Independent of Baryogenesis, the Electroweak Phase transition is an important target for particle physics - and modifications must be around corner in energy
- Come up with some new ideas, or find something new, and ask me if you have questions!

Lecture note references (not exhaustive)

- Theories of Baryogenesis, Riotto hep-ph/9807454
- Electroweak Baryogenesis, Morrissey and Ramsey-Musolf 1206.2942
- On the origin of matter in the universe, Di Bari 2107.13750