Cosmological Modifications of QCD

…and the baryon asymmetry of the Universe…

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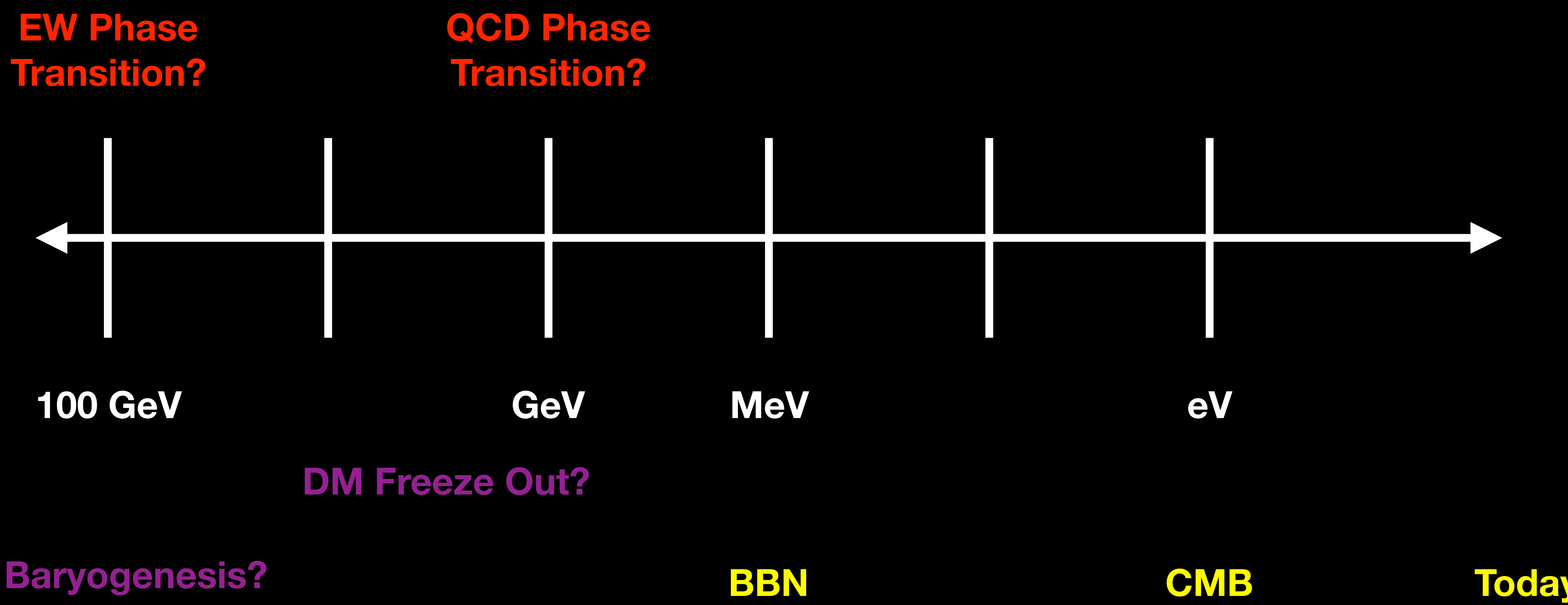
arXiv:1811.00559 & PRL

MPI Kernphysik
July 21, 2019

Invitation



Before BBN, most of what we know about the physics in the early Universe is an extrapolation based on the Standard Model + ingredients such as dark matter.

Features such as inflation, dark matter, primordial gravitational waves, and the existence of a baryon asymmetry are all handles on earlier times…

Outline

- The Baryon Asymmetry of the Universe
- The SM and Challenges for Weak scale solutions
- Baryon asymmetry and the strong CP problem
- The QCD Phase Transition at 1 TeV
- Outlook & Future Directions

The Matter-Anti-matter Asymmetry

- Experiments show that:

# of baryons - # anti-baryons

$$\eta_B \equiv \frac{n_B}{s} = 9.2^{+0.6}_{-0.4} \times 10^{-11}$$

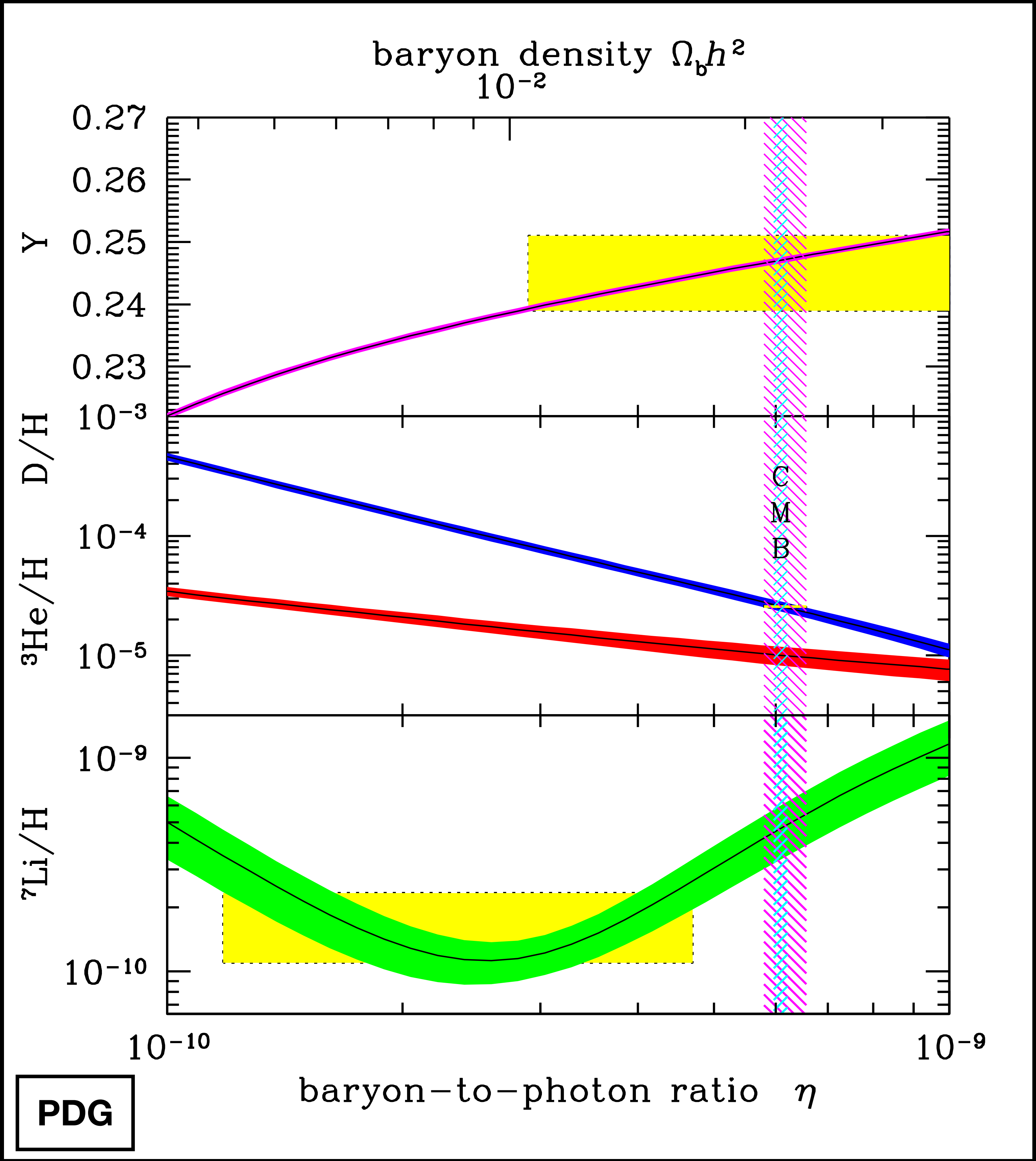
Entropy density

- Cosmic rays contain: $\frac{\bar{p}}{p} \sim 10^{-4}$
- Density of hadrons in the Universe: If there had been equal baryons and anti-baryons, they would have annihilated and frozen out to a much smaller density:

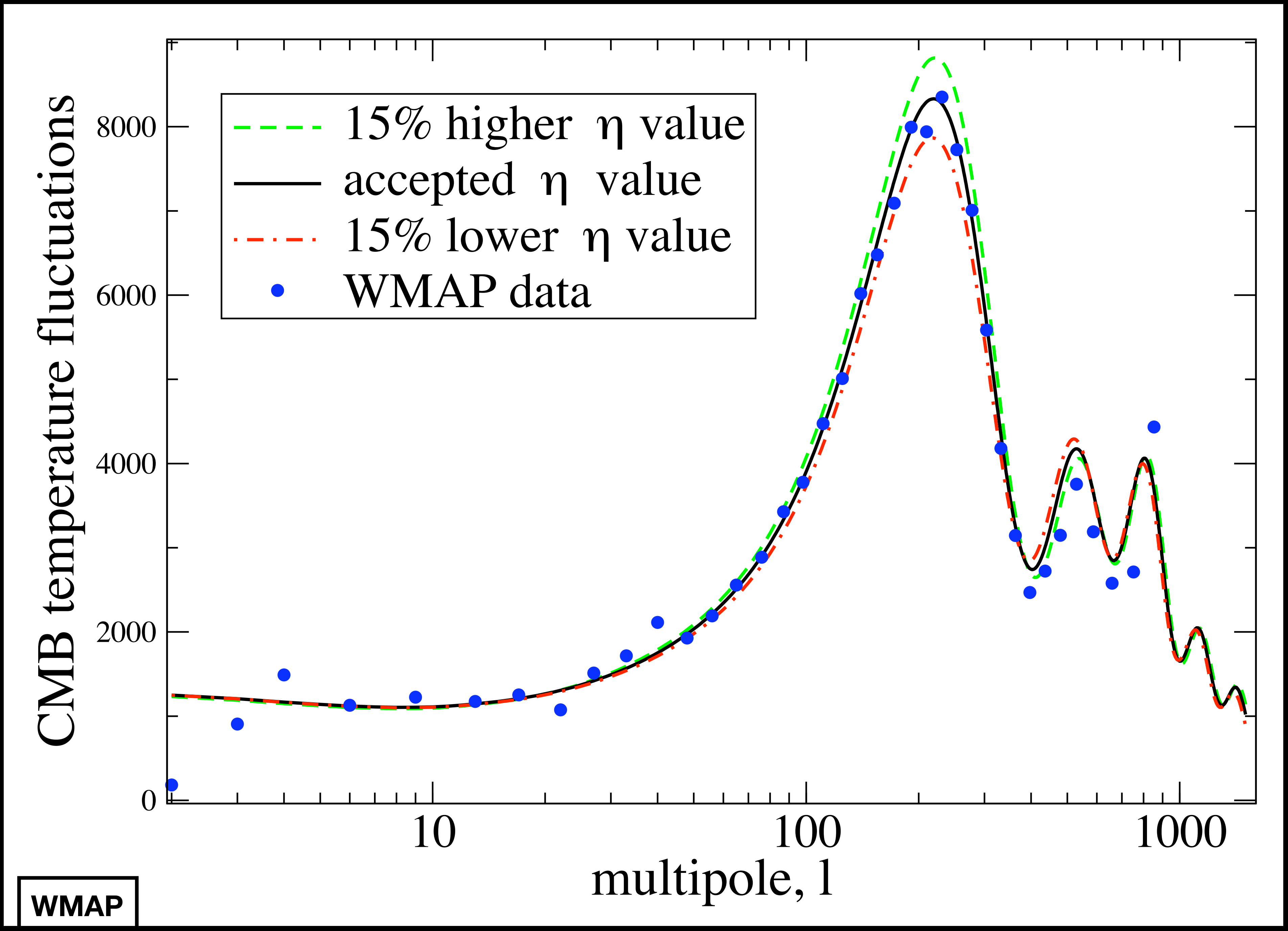
$$\frac{n_B}{s} = \frac{n_{\bar{B}}}{s} \sim 10^{-20}$$

Big Bang Nucleosynthesis

- The ratios of the primordial elements are also sensitive to the baryon asymmetry.
- Y is more or less equivalent to the fraction of ^{4}He.
- The ^{7}Li abundance is marginally inconsistent with the most accurate determinations from deuterium and Helium.
- The best fit value agrees with CMB determinations.



Cosmic Microwave Background



- The sizes of the doppler peaks of the CMB are sensitive to the number of baryons in the Universe.

Hu, Dodelson Ann.Rev.Astron.Astrophys.40, 171 (2002)

Questions for Particle Physics

- It could be that the baryon asymmetry is an initial condition of our Universe. This would have been mysterious, but possible.

- However, it is hard to reconcile this idea with the evidence for inflation. Inflation erases all primordial abundances, and regenerates them thermally.

- As an input to nucleosynthesis, the baryon asymmetry must be generated by scales around a GeV. So it is a problem for particle physics to solve.

Sakharov Conditions

Requirements for baryogenesis from a baryon symmetric starting point:

1. **B Violation:** If we can't generate baryon number ("B") through some process, we are dead in the water.
2. **C and CP Violation:** Essentially, if we don't violate C and CP, the sum of all baryon-violating processes will still result in no net baryon number.
3. **Out of Equilibrium:** If the processes which violate B are in equilibrium, the reverse processes will cancel out the B generated.

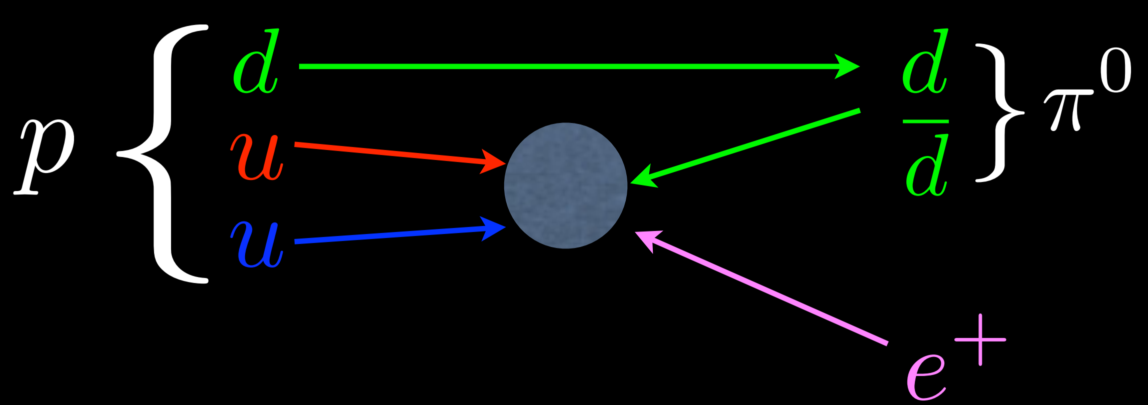
Realizing Baryogenesis

- The first question is: what scale is natural for baryogenesis? The answer is, we don’t really know.
  - Low scales would be attractive because they are testable and offer a strong connection to structure we think is likely to be there to explain EWSB and the hierarchy problem.
  - High scale models (such as Leptogenesis) are attractive because they are **less** testable and have **more indirect** connection to EW physics. (So not ruled out…)

B Violation at Low Scales

- At first glance, weak scale baryogenesis looks problematic. We need reasonably strong B violation, but we look for such things at low energies, mediated by irrelevant operators, and see no signs:
  - ΔB=1: Proton decay: $\Lambda >$ around 10^{16} GeV

$$\frac{1}{\Lambda^2}(\bar{u}d)(\bar{u}e)$$



$$\tau \sim \frac{\Lambda^4}{m_p^5} \gtrsim 10^{30} \text{ years}$$

  - ΔB=2: n-nbar oscillation: $\Lambda >$ around 10^{12} GeV

- So it seems that any B-violating interaction should be highly suppressed at the weak scale.

SM Baryogenesis?

- Actually, not only can the SM explain the mismatch between low energy and EW scale B violation, it could have satisfied all three Sakharov conditions.

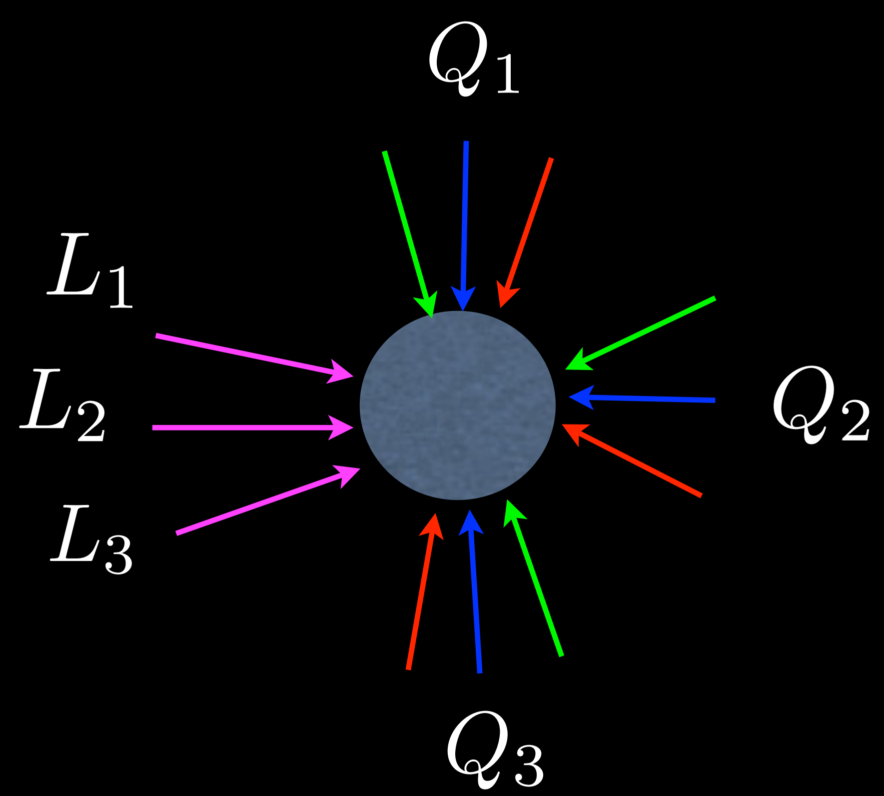
- C and CP violation are the hallmarks of the electroweak force.

- Non-perturbative EW processes violate baryon number.

- At a temperature of T ~ 100 GeV, the Universe transitions from an EW symmetric to an EW non-symmetric state. The transition could have been a non-equilibrium process which shuts off the baryon number violation in the broken phase.

B Violaton

- The electroweak instantons of the SM violate baryon and lepton number.
- Perturbatively, weak interactions preserve B and L, but non-perturbatively, there is a triangle anomaly between B+L and the SU(2) interaction.



$$Q_1 = \begin{bmatrix} u_L \\ d_L \end{bmatrix} \quad L_1 = \begin{bmatrix} \nu_e \\ e_L \end{bmatrix}$$

$$Q_2 = \begin{bmatrix} c_L \\ s_L \end{bmatrix} \quad L_2 = \begin{bmatrix} \nu_\mu \\ \mu_L \end{bmatrix}$$

$$Q_3 = \begin{bmatrix} t_L \\ b_L \end{bmatrix} \quad L_3 = \begin{bmatrix} \nu_\tau \\ \tau_L \end{bmatrix}$$

- The sphalerons destroy 3 quarks of each family and one lepton of each family. They preserve B-L. (Actually, over-all B-L_i for each lepton family i is effectively preserved).

Sphaleron Rates

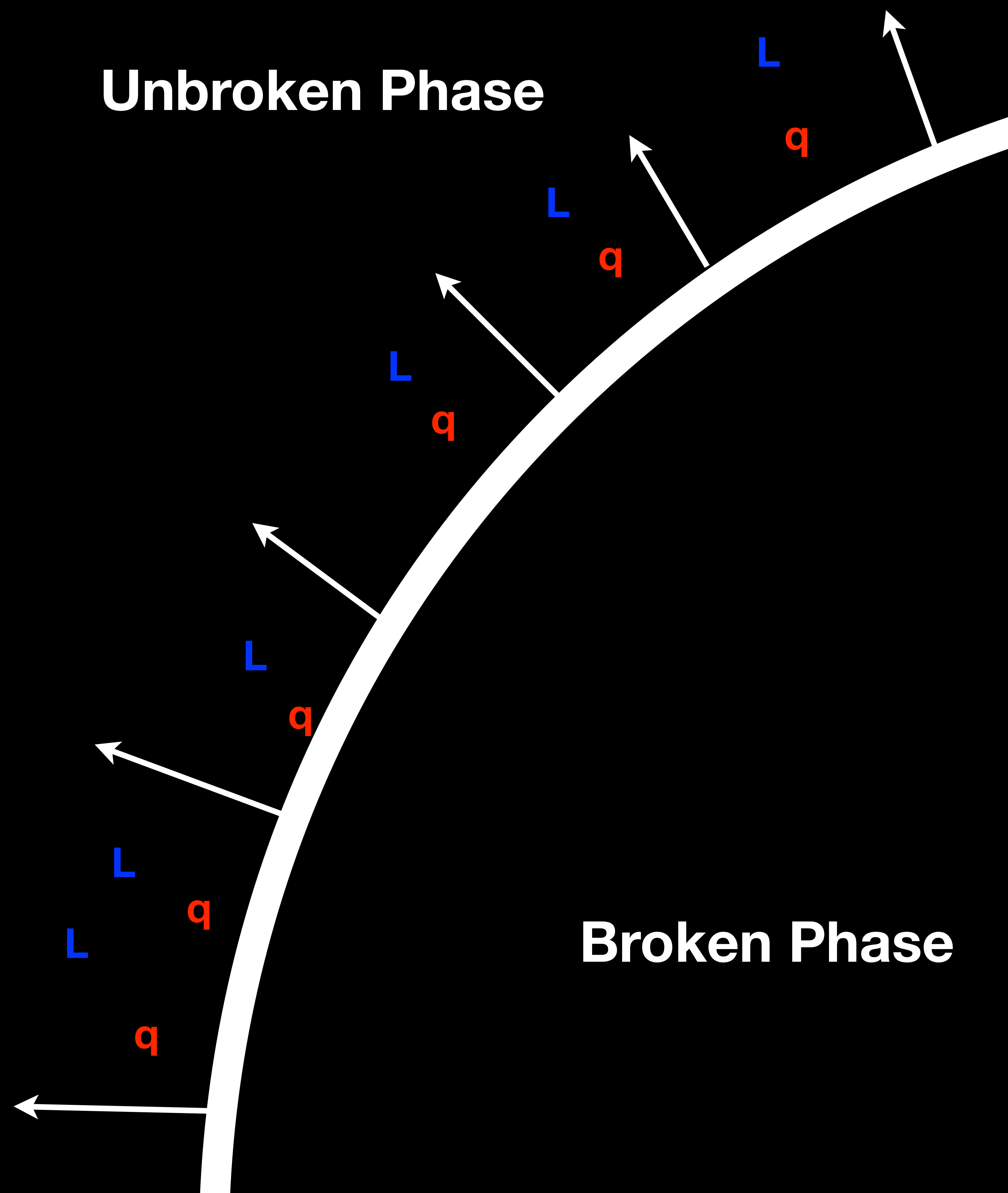
- The sphalerons can also naturally explain the paradox of strong baryon-number violation at temperatures around 100 GeV, but very small rates in low energy tests.
- At low temperatures, when the Electroweak symmetry is broken, the masses for the W and Z fields imply that it costs energy to form the sphaleron configuration. The sphaleron rate is proportional to:

$$\Gamma \sim e^{-E_{sph}/T} \qquad E_{sph} \simeq \frac{8\pi v}{g}$$

- At high temperatures, the electroweak symmetry is restored. The sphalerons become completely unhindered by electroweak symmetry-breaking masses, and proceed very rapidly.

EWBG: Basic Picture

- At the critical temperature, a bubble of true vacuum nucleates, and expands.
- CP violation, combined with the EW sphalerons, induces an asymmetry between matter and anti-matter at the surface of the bubble.
- The quarks fall into the bubble. Once inside sphaleron processes are switched off, and quarks can't be processed away.



It Almost Works!

- There is a strong connection between Higgs physics and the EW phase transition.

- The connection comes through the thermal corrections to the Higgs potential from the plasma of SM fields:

$$V(H,T) = -m^2|H|^2 + \lambda|H|^4 + T\sum_i \left(\pm \int_0^\infty \frac{d^3p}{(2\pi)^3} \log\left[1 \mp e^{-\beta\sqrt{p^2+m_i^2(H)}}\right]\right)$$

- In order to get a first order phase transition, one must have a small Higgs quartic, such that:

$$m_H < 50 \ \ \mathrm{GeV}$$

(Recall: $m_h^2 = \lambda v^2$)

- This is close enough to working that theories that do nothing more than add fields coupling strongly to the Higgs can be enough to make it viable. The MSSM is a famous example.

CP Violation

- The SM also doesn't have enough CP violation to explain the magnitude of the baryon asymmetry.
- The weak CP-violating phase enters physical observables as the Jarlskog invariant:

$$\prod_q y_q^2 \sim 10^{-20}$$

- This is suppressed because of the small first and second generation quark masses, and would lead to a baryon asymmetry far smaller than the one that we observe (assuming the problem with the first order phase transition were to be solved in some other way).

Strong CP?

- An interesting idea is to invoke a strong CP phase as the source of CP violation.

Kuzmin, Shaposhnikov, Tkachev PRD45, 466 (1992)

$$\frac{\alpha_S}{8\pi}\overline{\theta}\; G^{\mu\nu}\widetilde{G}_{\mu\nu} \qquad\qquad \overline{\theta} \equiv \theta + \mathrm{Arg\ Det} M_q$$

- Of course, in the SM we know that the neutron EDM requires

$$\overline{\theta} \lesssim 10^{-10}$$

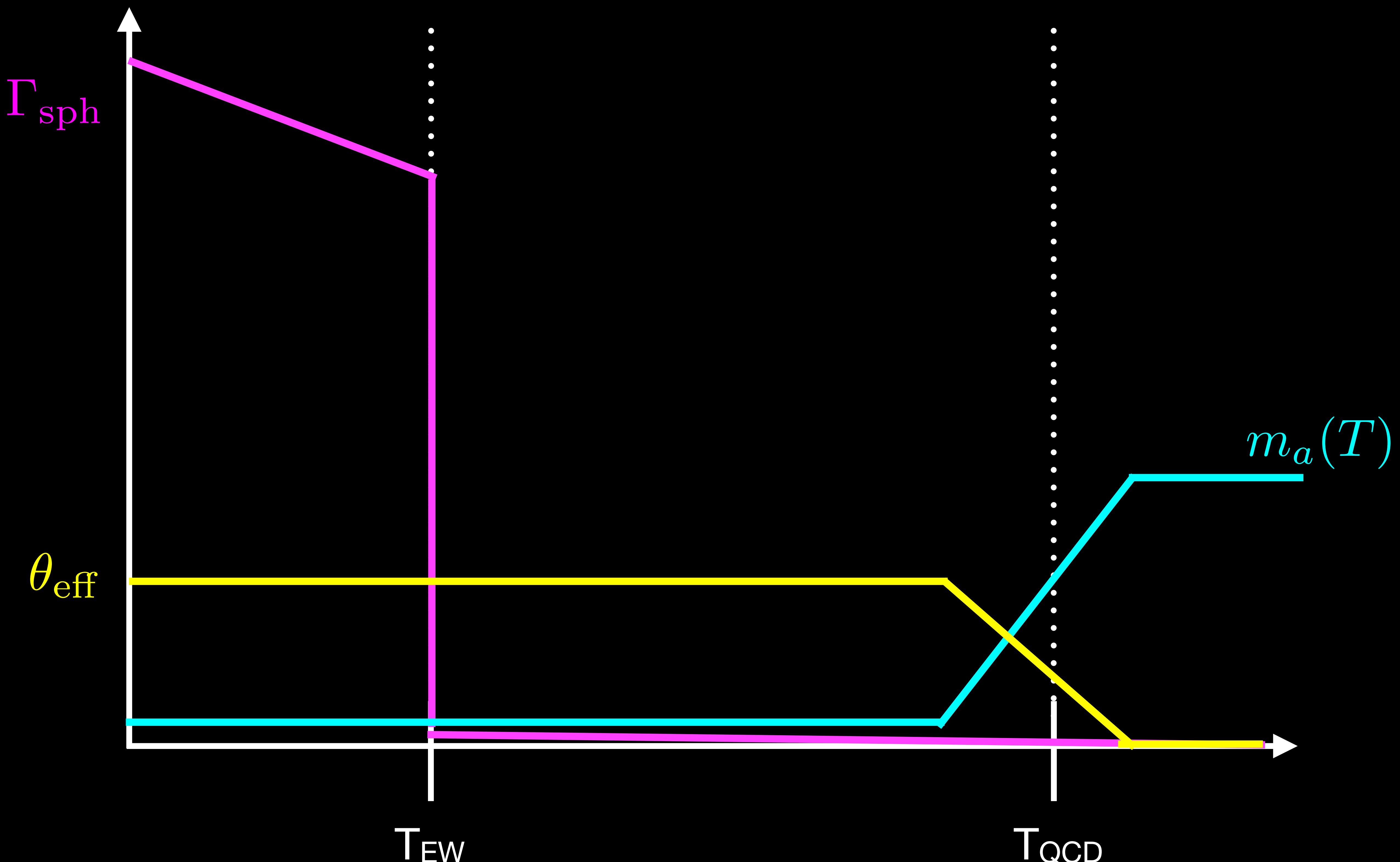
…so it's irrelevant…

- But if there is a dynamical solution to the strong CP problem such as the axion, the effective phase could be different in the early Universe before the axion reaches the minimum of its potential.

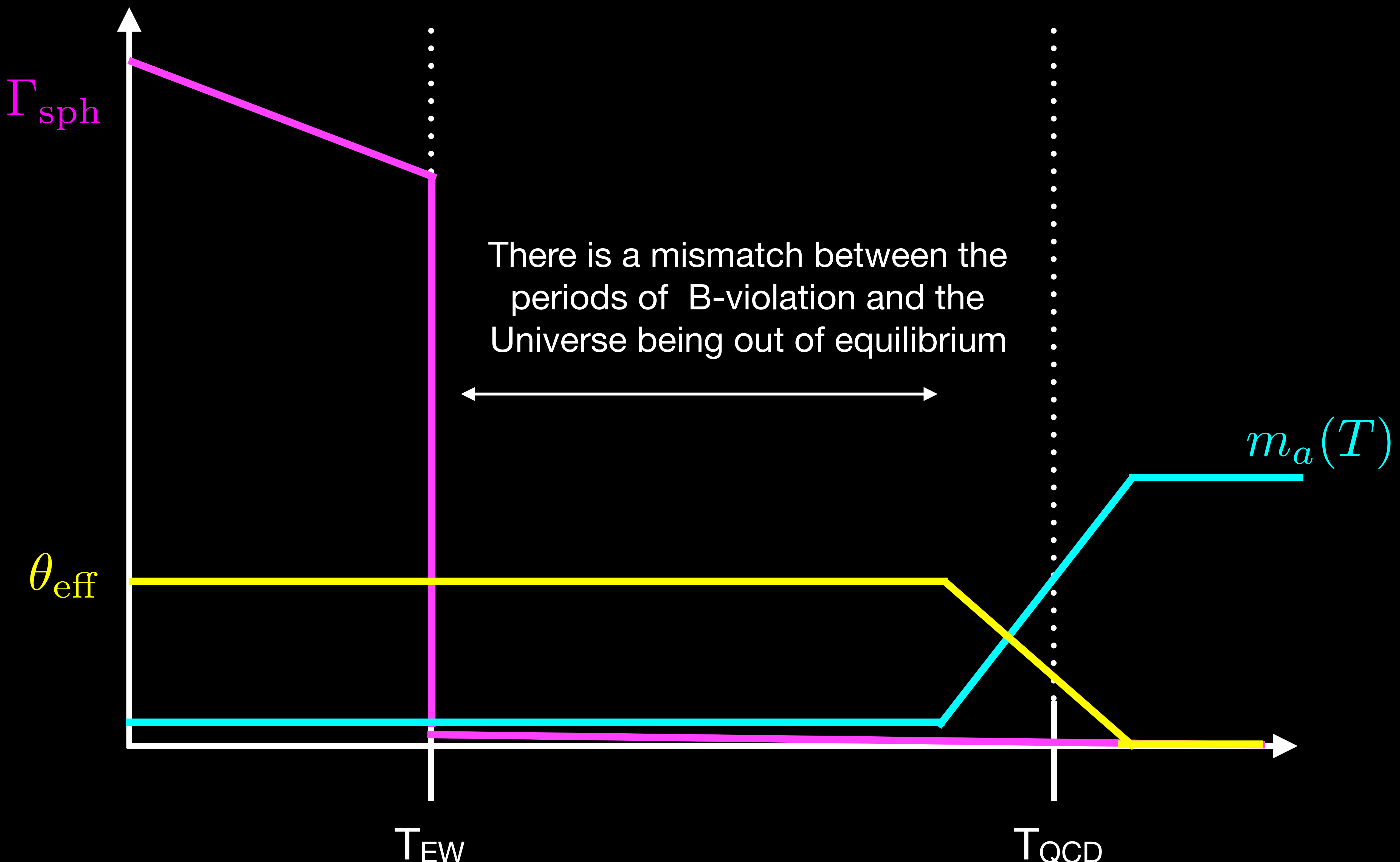
$$\frac{\alpha_S}{8\pi}\left[\overline{\theta} + \frac{a(x)}{f_a}\right]\; G^{\mu\nu}\widetilde{G}_{\mu\nu}$$

Peccei, Quinn PRL38, 1140 (1997)
Wilczek PRL40, 279 (1978)
Weinberg, PRL40 223 (1978)

Thermal History

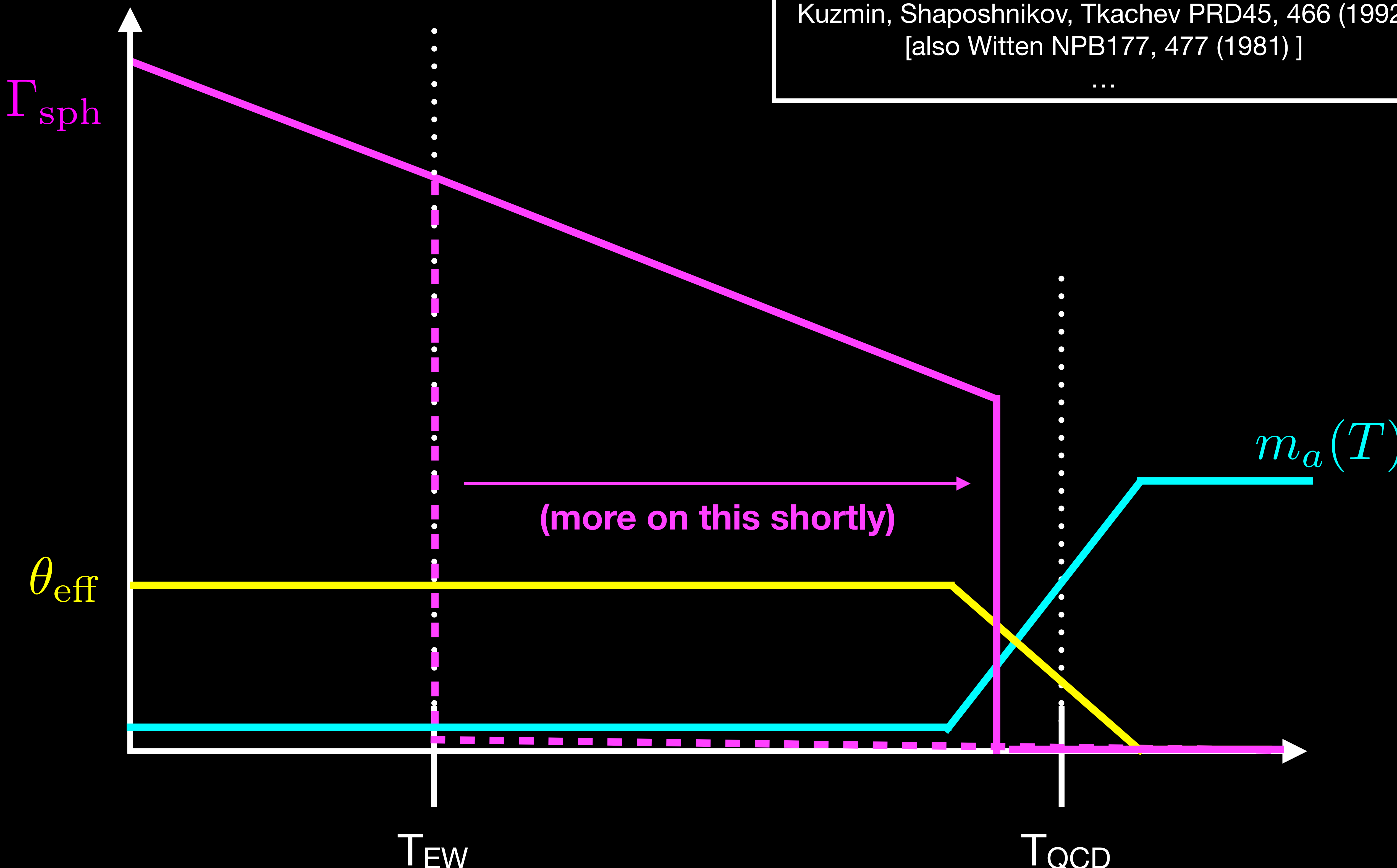


The Challenge



Supercooled EW Transition

Kuzmin, Shaposhnikov, Tkachev PRD45, 466 (1992)
[also Witten NPB177, 477 (1981)]
...



Spontaneous Baryogenesis

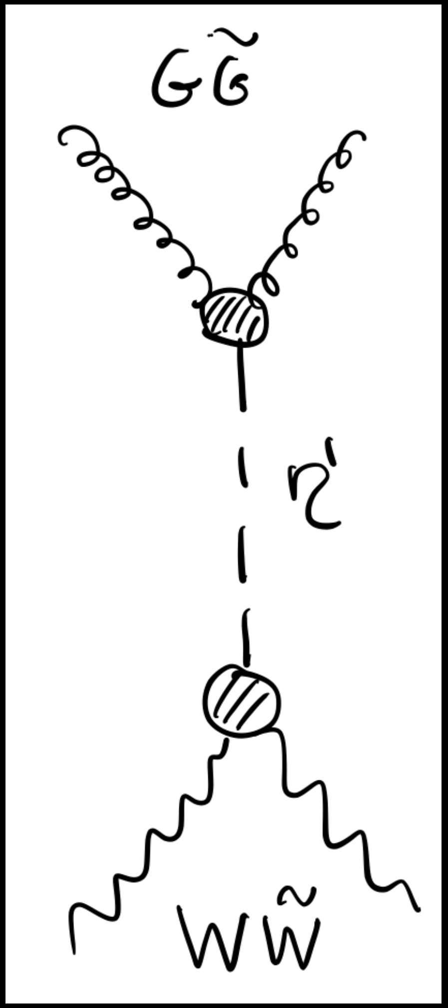
- The non-zero θ_{eff} looks like a tadpole for $G\widetilde{G}$:

$$\frac{\alpha_S}{8\pi}\,\langle G\widetilde{G}\rangle = f_a^2 m_a^2\,\sin\theta_{\text{eff}}$$

- Which in turn sources a tadpole for $W\widetilde{W}$:

$$\mathcal{L}_{\text{eff}} = \frac{10}{f_\pi^2\, m_{\eta'}^2}\frac{\alpha_S}{8\pi}\frac{\alpha_W}{8\pi}\,G\widetilde{G}\,W\widetilde{W}$$

$$\rightarrow \underbrace{\frac{10}{f_\pi^2\, m_{\eta'}^2} f_a^2 m_a^2 \sin\theta_{\text{eff}}}_{\equiv\,\chi(T)}\;\underbrace{\frac{\alpha_W}{8\pi} W\widetilde{W}}_{\partial_\mu j_B^\mu}$$



Spontaneous Baryogenesis

- Integrating by parts, this is a term in the action representing a chemical potential for baryons:

$$\mu_{\text{eff}} = \frac{d\chi(T)}{dt} = \frac{10}{f_\pi^2 m_{\eta'}^2} f_a^2 \frac{d}{dt}\left[m_a^2(T)\sin\theta_{\text{eff}}(T)\right]$$

- Which leads to baryon production:

$$n_B = \int dt \frac{\Gamma_{\text{sph}}(T)}{T}\mu_{\text{eff}}(T)$$

$$= \frac{10}{f_\pi^2 m_{\eta'}^2} f_a^2 \int dt \frac{\Gamma_{\text{sph}}(T)}{T}\frac{d}{dt}\left[m_a^2(T)\sin\theta_{\text{eff}}(T)\right]$$

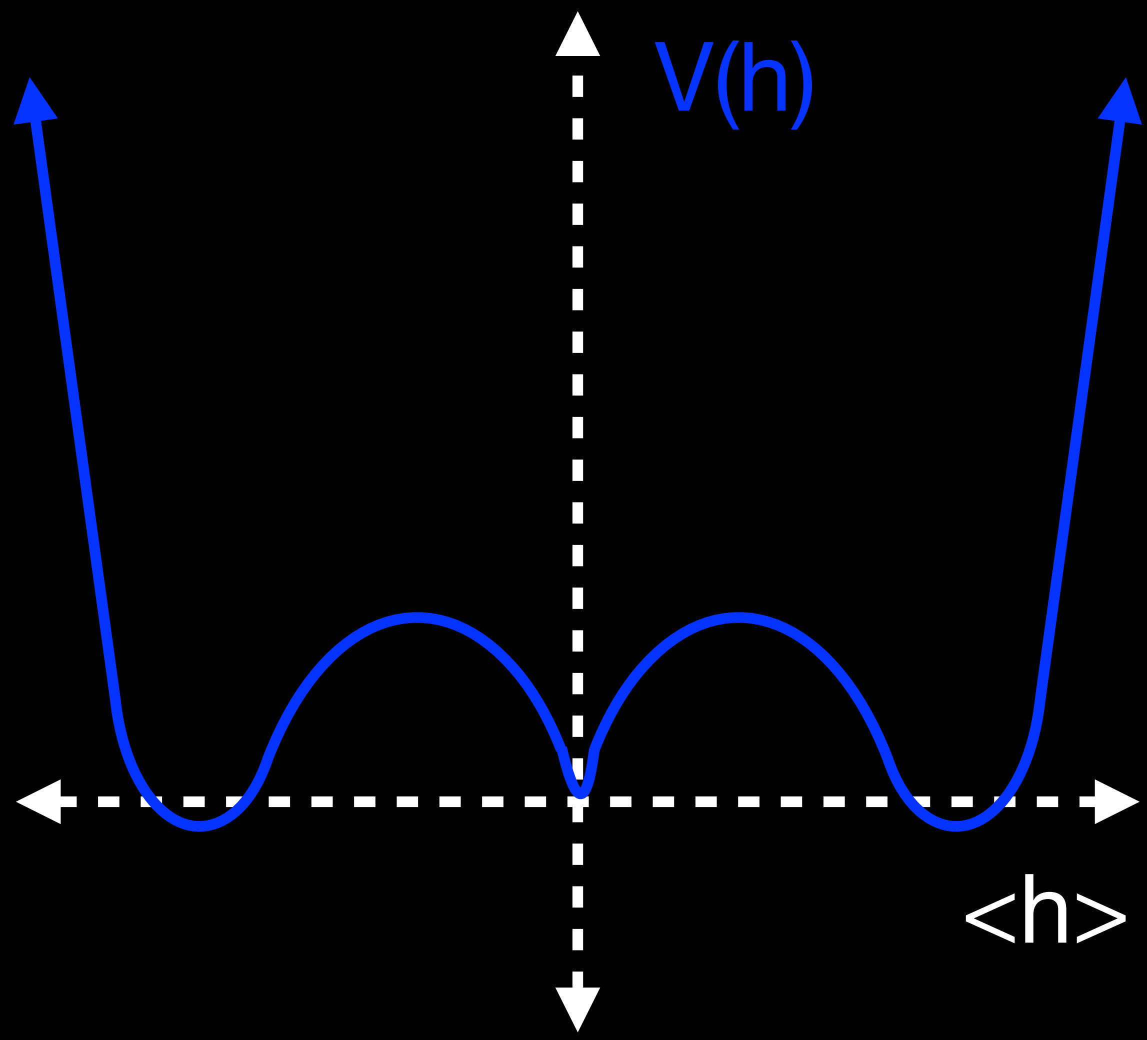
$$\Gamma_{\text{sph}}(T) \sim (\alpha_W T)^4$$

$$m_a^2(T) \sim m_\pi^2 \frac{f_\pi^2}{f_a^2}\left(\frac{\Lambda}{T}\right)^7$$

Phase Transition

- Kuzmin et al engineer the super-cooled EW phase transition by invoking a Coleman-Weinberg potential for the Higgs.
    - (That was still an option in 1992…)
    - Today, one can arrive at something appropriate with a modified Higgs sector.

e.g. in a RS composite Higgs model:
von Harling, Servant JHEP1801, 159 (2018)



- For that choice, the barrier between the symmetric and broken phases is hefty enough that around T_{QCD}, there wouldn't have been enough time to tunnel.

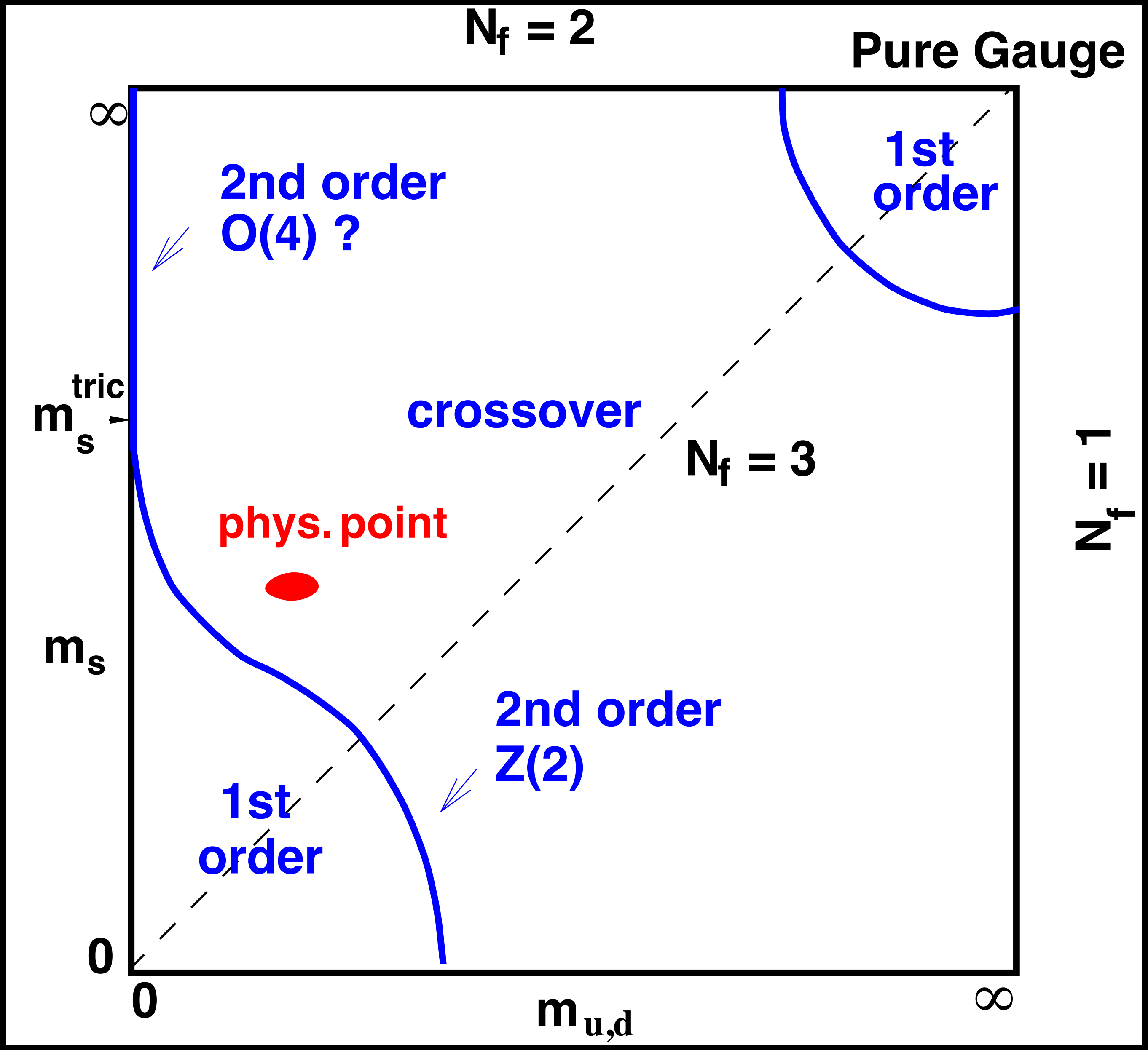
QCD Phase Transition

- However, the QCD phase transition breaks chiral symmetry, inducing a quark condensate.
  - For $n_f = 6$ massless flavors, this is expected to be a first order transition.

Pisarski, Wilczek, PRD29, 338 (1984)

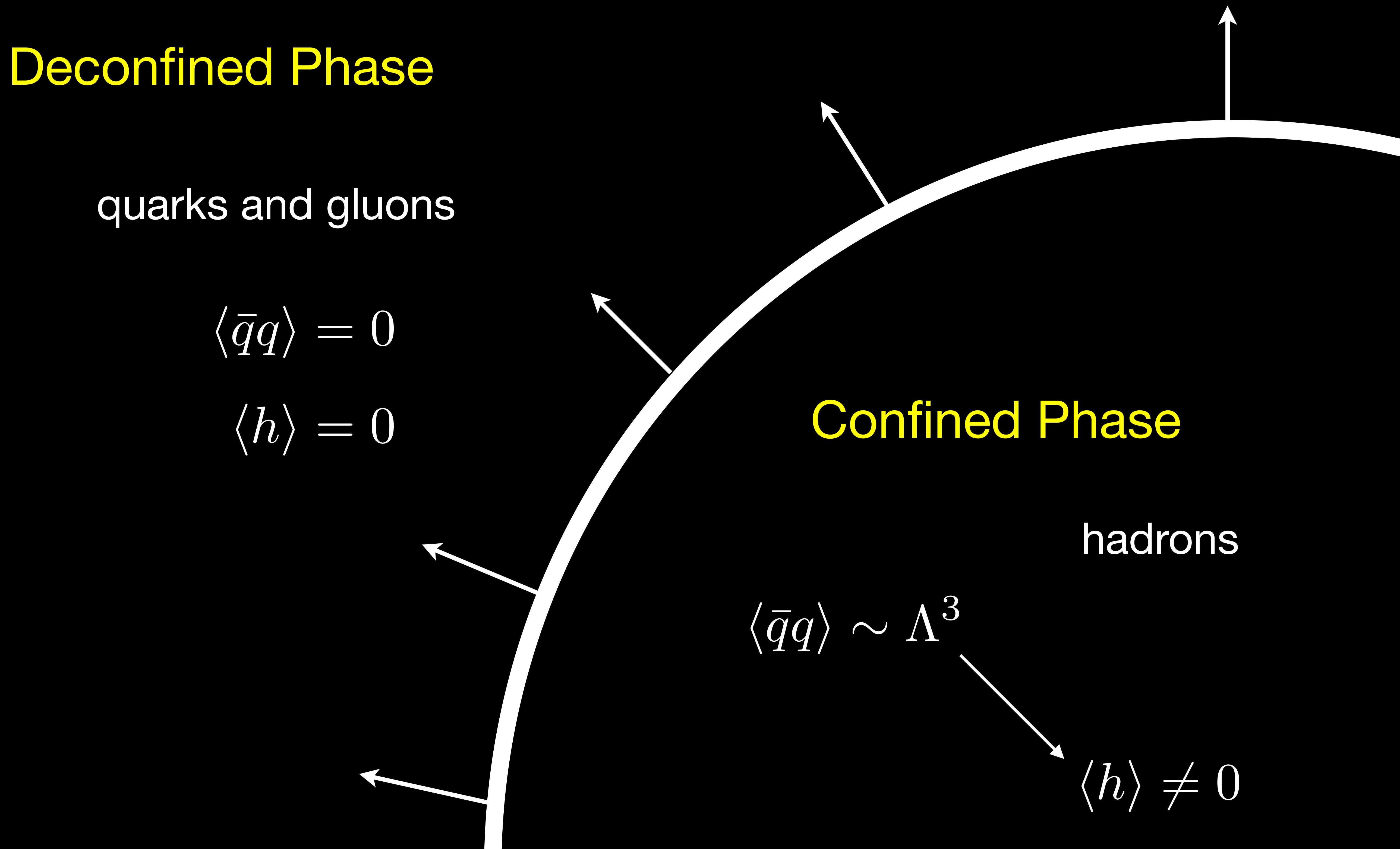
- That already breaks the electroweak symmetry.

- It also looks like a tadpole for the Higgs, which triggers quark masses.



Review by Schaefer & Wagner 0812.2855

QCD Phase Transition



Baryon Asymmetry

- The resulting baryon asymmetry is:

$$n_B \simeq 5 \ \frac{m_\pi^2}{m_{\eta'}^2} \ \alpha_W^4 T_{\rm QCD}^3 \ \cos\theta_{\rm eff} \left(\frac{\Lambda}{T_{\rm QCD}}\right)^7$$

- Allowing for entropy production after the phase transition:

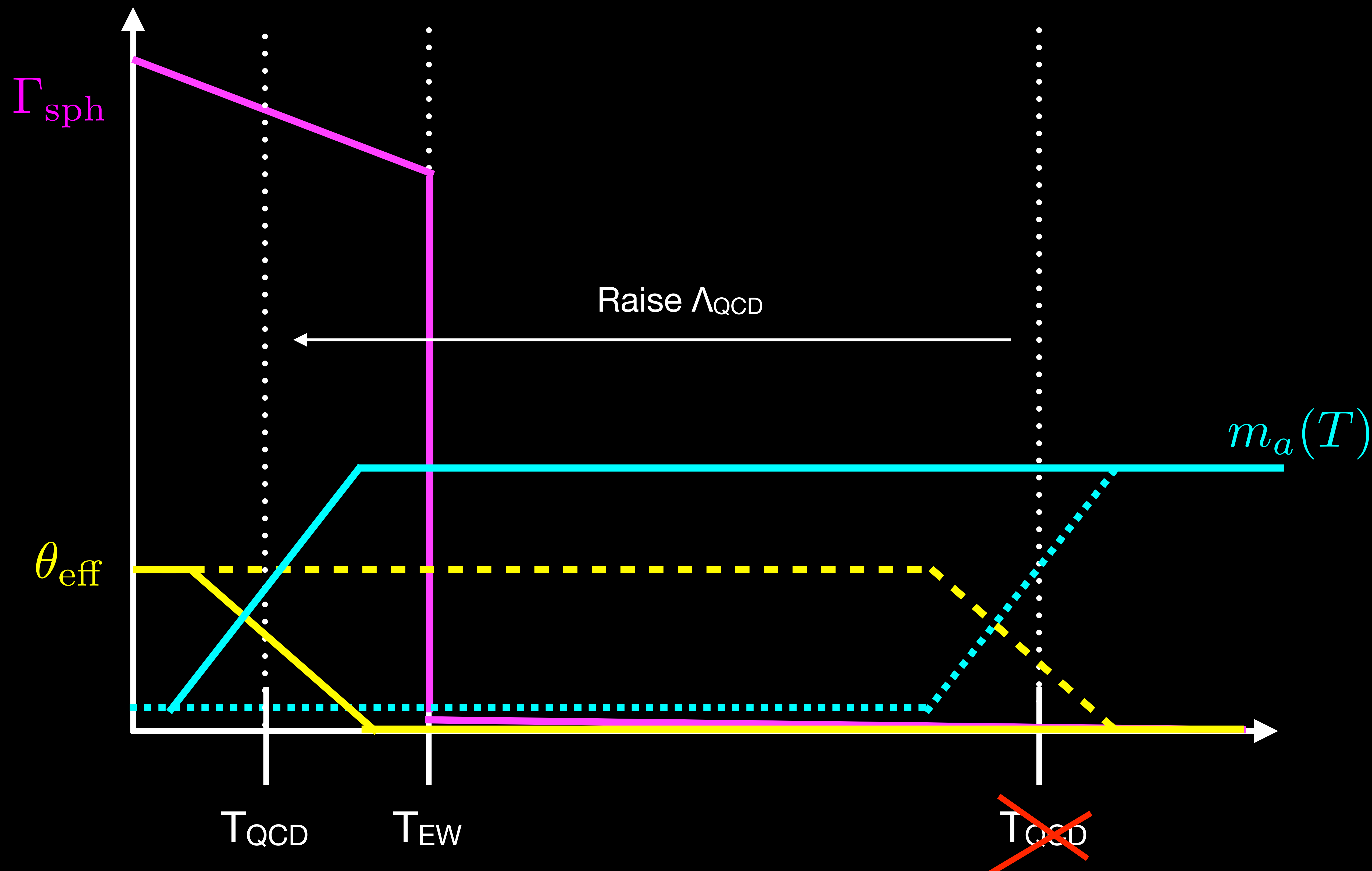
$$\eta \equiv \frac{n_B}{s} \simeq \frac{225}{2\pi^2 g_*} \ \frac{m_\pi^2}{m_{\eta'}^2} \ \alpha_W^4 \cos\theta_{\rm eff} \ \left(\frac{T_{\rm QCD}}{T_{RH}}\right)^3 \left(\frac{\Lambda}{T_{\rm QCD}}\right)^7$$

$$\simeq 5 \times 10^{-9} \left(\frac{T_{\rm QCD}}{T_{RH}}\right)^3$$

- This leads to a new problem. The weak bosons get masses of order 100 GeV once the EW symmetry is fully broken. Their decays instantly produce too much entropy, which dilutes the baryon asymmetry by about 10^{-9}.

Strategy #2

Ipek, TMPT 1811.00559



Baryon Asymmetry

- From here, the baryogenesis story is essentially the same as before, with the important distinction that $T_{RH} \sim T_{QCD} \sim$ TeV.

$$\eta \equiv \frac{n_B}{s} \simeq \frac{225}{2\pi^2 g_*} \frac{m_\pi^2}{m_{\eta'}^2} \alpha_W^4 \cos\theta_{\rm eff} \left(\frac{T_{\rm QCD}}{T_{RH}}\right)^3 \left(\frac{\Lambda}{T_{\rm QCD}}\right)^7$$

$$\simeq 5 \times 10^{-9} \left(\frac{T_{\rm QCD}}{T_{RH}}\right)^3$$

- To get the observed baryon asymmetry, we need to live in a patch where θ ~ 0.1, or there needs to be a small amount of extra dilution.

- Of course, there is plenty we need to think about how to make it happen…

Λ_{QCD} at ~1 TeV

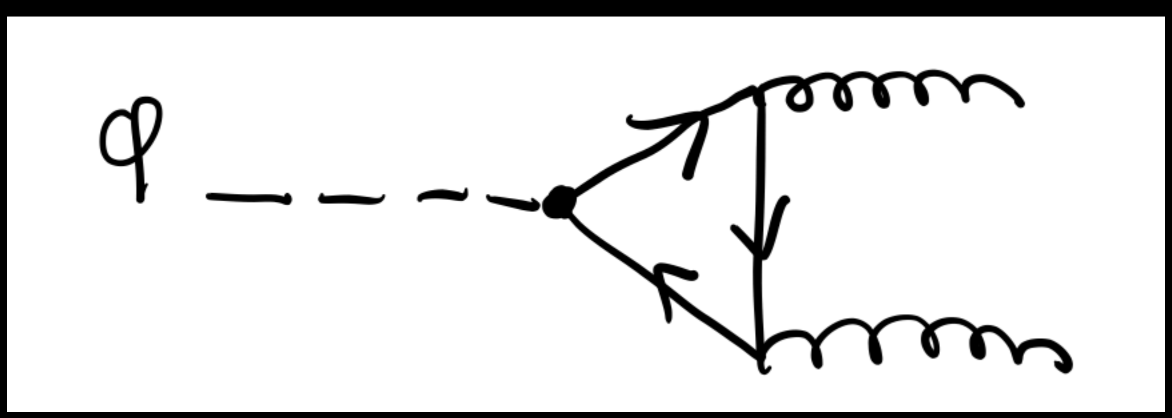
- We envision something like the following:
  - The strong coupling is promoted (at least in part) to a field of some kind.
  - The parameters are such that above T_{EW}, QCD confines.
    - This triggers EW breaking (including a Higgs VEV), and generates a baryon asymmetry at high temperatures.
    - Dilution is negligible, because everything happens around the EW scale.
  - Below the usual T_{EW} (and well before BBN), the field adjusts itself to the usual strong coupling we measure at low temperatures.

Strong Coupling

- We can model the strong coupling as:

$$-\frac{1}{4}\left(\frac{1}{g_0^2}+\frac{\phi}{M_*}\right)G^{\mu\nu}G_{\mu\nu} \qquad g_{\rm eff}^2\left(\langle\phi\rangle\right)=\frac{g_0^2}{1+g_0^2\frac{\langle\phi\rangle}{M_*}}$$

- Φ could be something like a dilation, or a radion in a theory with extra dimensions. It could also have a coupling induced radiatively.



(e.g. via vector-like quarks)

- g_0 is the strong coupling in the absence of a φ VEV. It runs just like in ordinary QCD.

Strong Coupling

- At one loop:

$$\frac{1}{\alpha_{\rm eff}} = \frac{1}{\alpha_0} + \frac{33 - 2n_f}{12\pi} \ln\left(\frac{\mu^2}{\mu_0^2}\right) + 4\pi \frac{\langle\phi\rangle}{M_*}$$

- The scale at which QCD gets strong is about:

$$\Lambda \simeq \Lambda_0 \times {\rm Exp}\left(\frac{24\pi^2}{2n_f - 33}\frac{\langle\phi\rangle}{M_*}\right)$$

- For $n_f = 6$, to get $\Lambda \sim$ TeV, we would like:

$$\frac{\Delta\langle\phi\rangle}{M_*} \simeq -0.8$$

- This is pushing the EFT, but not so much that it is clearly problematic. If induced radiatively, this would require ~10 vector-like quarks at M_*.

Φ Potential

- I'll stay pretty agnostic about where the ϕ potential comes from. Writing down something generic characterized by a single mass scale obviously provides a VEV around that scale.

$$V(\phi) = \alpha_1 m^3 \phi + \alpha_2 m^2 \phi^2 + \alpha_3 m \phi^3 + \alpha_4 \phi^4 + ... + \frac{\phi}{M_*} \langle GG \rangle$$

- For choices of α_i of O(1) and m ~ $M_*/10$, one can get $\langle \phi \rangle \sim M_*$ without much tuning.

- Once QCD gets strong, it will also induce corrections of $O(\Lambda_{QCD})$, which is likely to be a fairly large corrections to the VEV unless m >> Λ.

Thermal Corrections

- To “fix” QCD after the electroweak transition, there need to be appropriate thermal corrections to the ϕ potential.

- That could be as simple as some states with O(1) couplings to ϕ and masses around the ~TeV scale so that they decouple around 100 GeV.

- They don’t need to be colored or electroweak-charged, so LHC bounds on them are probably not very strong.

    - Dark matter?

- Of course, they could be important for the ϕ phenomenology and play an important role in its decays, etc.

Phase Transition

- The phase transition is a little complicated in this case, because the Higgs VEV is induced via the chiral condensate through the Yukawa interactions.

- Naively this is dominated by the top quark, but wasn't initially clear to us that the induced VEV isn't so large that the top just decouples from the picture.

- We model the chiral symmetry breaking and Higgs VEV using a linear sigma model with SU(6)xSU(6) symmetry:

$$\mathcal{L}_\Pi = \text{Tr}\left[\partial^\mu \Pi^\dagger \partial_\mu \Pi\right] + \mu^2 \ \text{Tr}\left[\Pi^\dagger \Pi\right] - \lambda_1 \ \text{Tr}\left[\Pi^\dagger \Pi \Pi^\dagger \Pi\right] - \lambda_2 \ \text{Tr}\left[\Pi^\dagger \Pi\right]^2 .$$

- Neglecting the Higgs, NDA would suggest: $f_\pi \sim \frac{\mu}{\lambda} \sim \frac{\bar{\Lambda}}{4\pi}$ ← χPT Cut-off

Phase Transition

- We include the Higgs and Yukawas as a SU(6)xSU(6) breaking spurion:

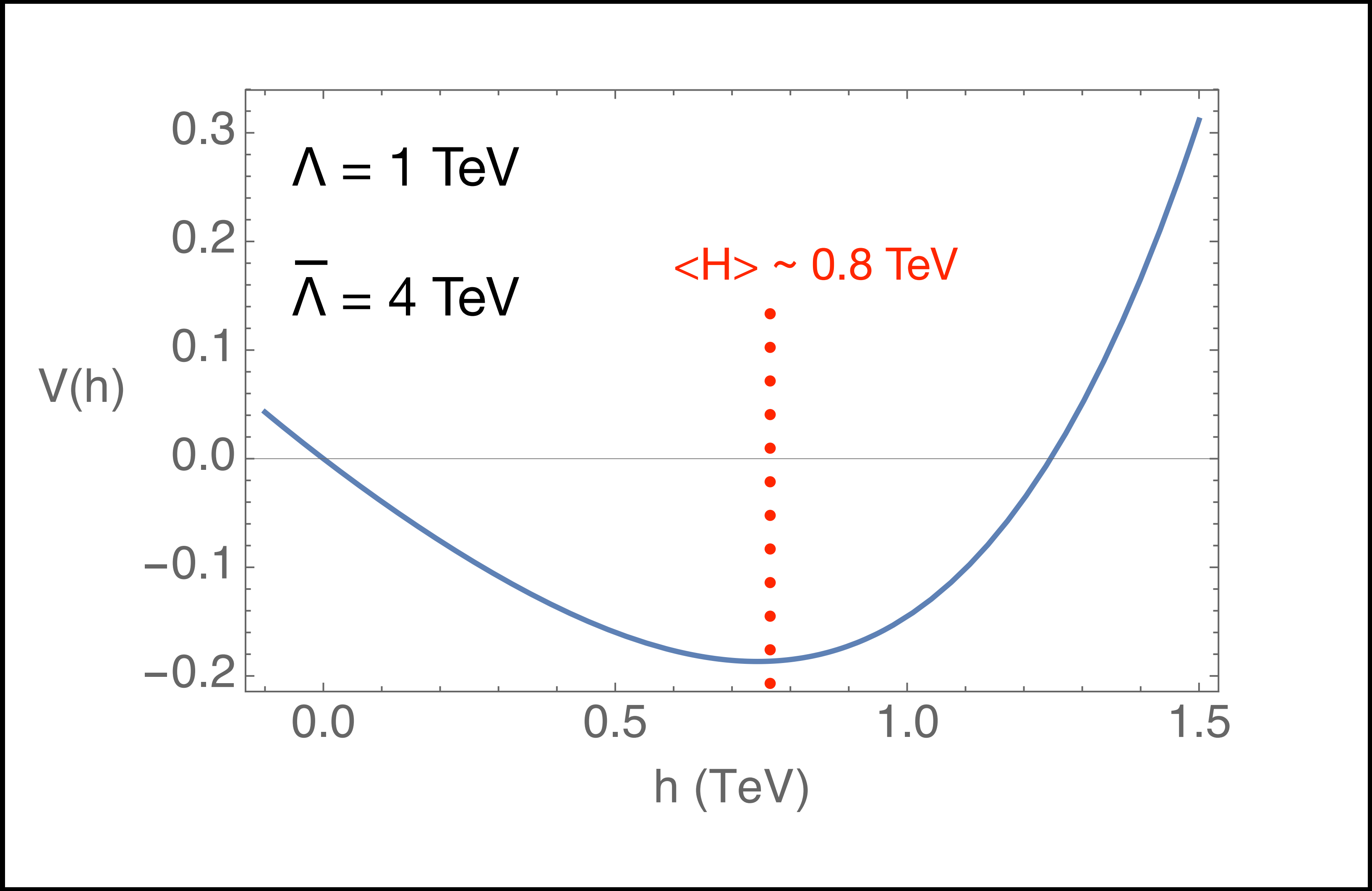
$$\mathcal{L}_Y = \tilde{m}^2 \ \mathrm{Tr}\left[\Pi^\dagger Y\right] - \tilde{\lambda}_1 \mathrm{Tr}\left[\Pi^\dagger Y \Pi^\dagger Y\right] - \tilde{\lambda}_2 \mathrm{Tr}\left[\Pi^\dagger Y Y^\dagger \Pi\right] - \tilde{\lambda}_3 \mathrm{Tr}\left[\Pi Y^\dagger Y \Pi^\dagger\right]$$

- (where Y has diagonal entries given by y_i H).

- If we continue to estimate the coefficients a la NDA, the induced Higgs VEV is a little smaller than Λ.

- That implies that the top mass is itself O(Λ). Probably there is an O(1) impact on <H>, but the results are probably trustworthy at the order of magnitude level.

Phase Transition



- This seems to be borne out by more careful simulations, but of course this is all fuzzy at the level of O(1) NDA coefficients anyway.
- It might be fun (but computationally expensive) to look at on the lattice.

Outlook

- The idea that QCD may have undergone a period of confinement in the early universe is an interesting question that highlights our general ignorance of the universe at times before BBN.

- I played with a theory that adjusts the coupling such that confinement occurs at around 1 TeV, and later relaxes to ~ 1 GeV after the electroweak phase transition.

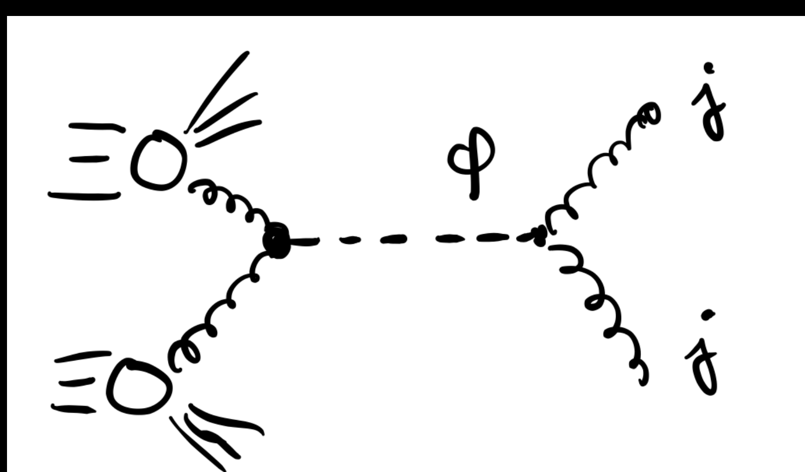
- In a theory in which the axion is invoked to solve the strong CP problem, it appears to offer a viable baryogenesis option in which the CP violation originates from the QCD phase, before it is cancelled by the low temperature axion VEV.

Outlook

- Still many questions remain…
  - Naively, the axion could possibly end up with the right relic density to be dark matter, if fa is adjusted appropriately to match the preferred θ_0.
  - But it goes through a period in which it has a much larger mass! It could be that most of the axions decay during that period… (Probably not important unless $\Lambda > 10^8$ GeV or so)
  - If there is a separate dark matter candidate which couples to quarks, it may freeze-out in a period of time in which baryons are very heavy and pions are the accessible final states.
  - This could influence both the freeze-out dynamics and the entropy scaling.

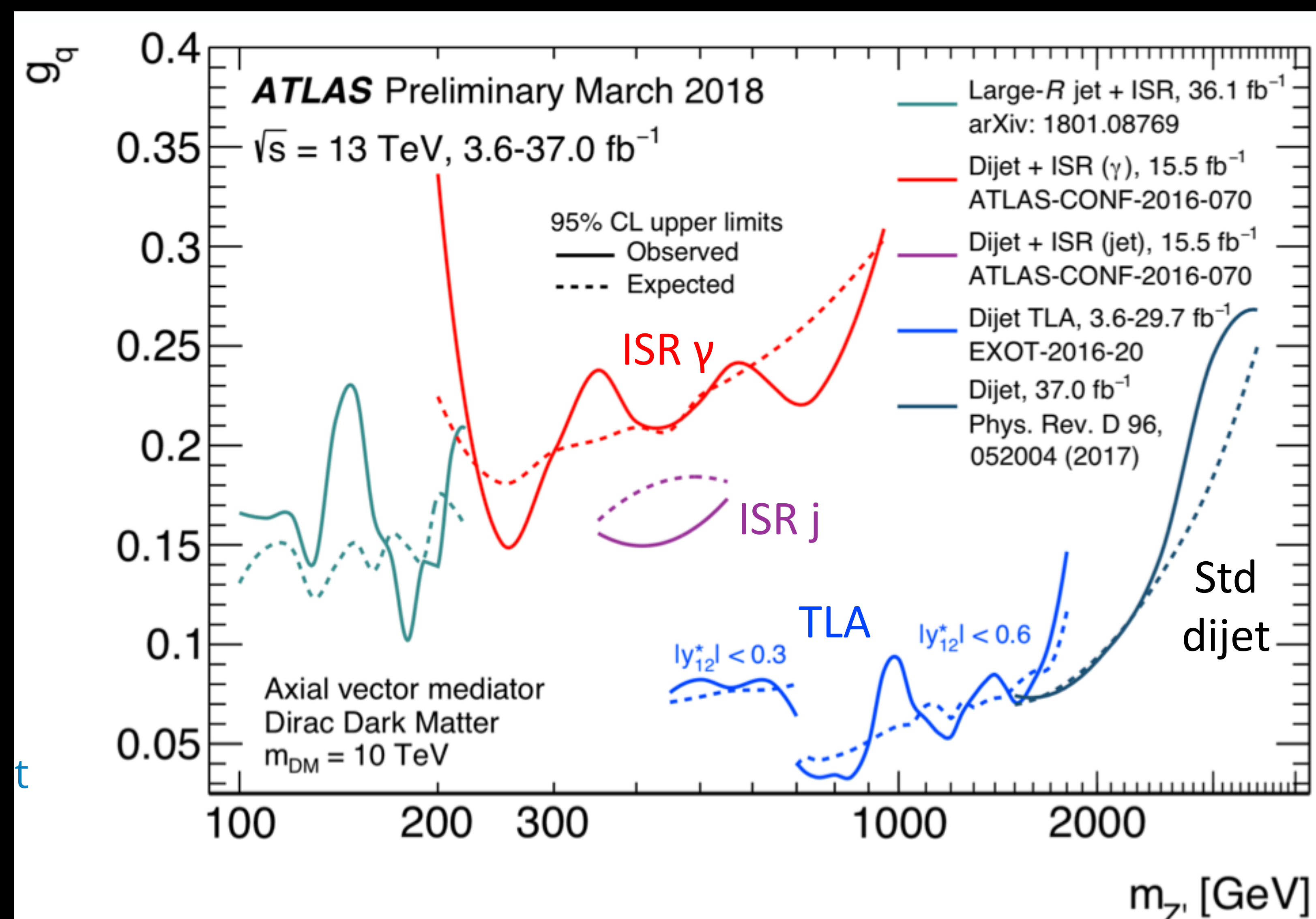
Outlook

- The true hallmark of these dynamics is the ϕ.
  - Minimally, it couples to gluons. So it can be produced at the LHC and appear as a resonance in dijets.



$$g \sim \frac{m_\phi}{M_*}$$

(Should be gluon, not quark PDFs)



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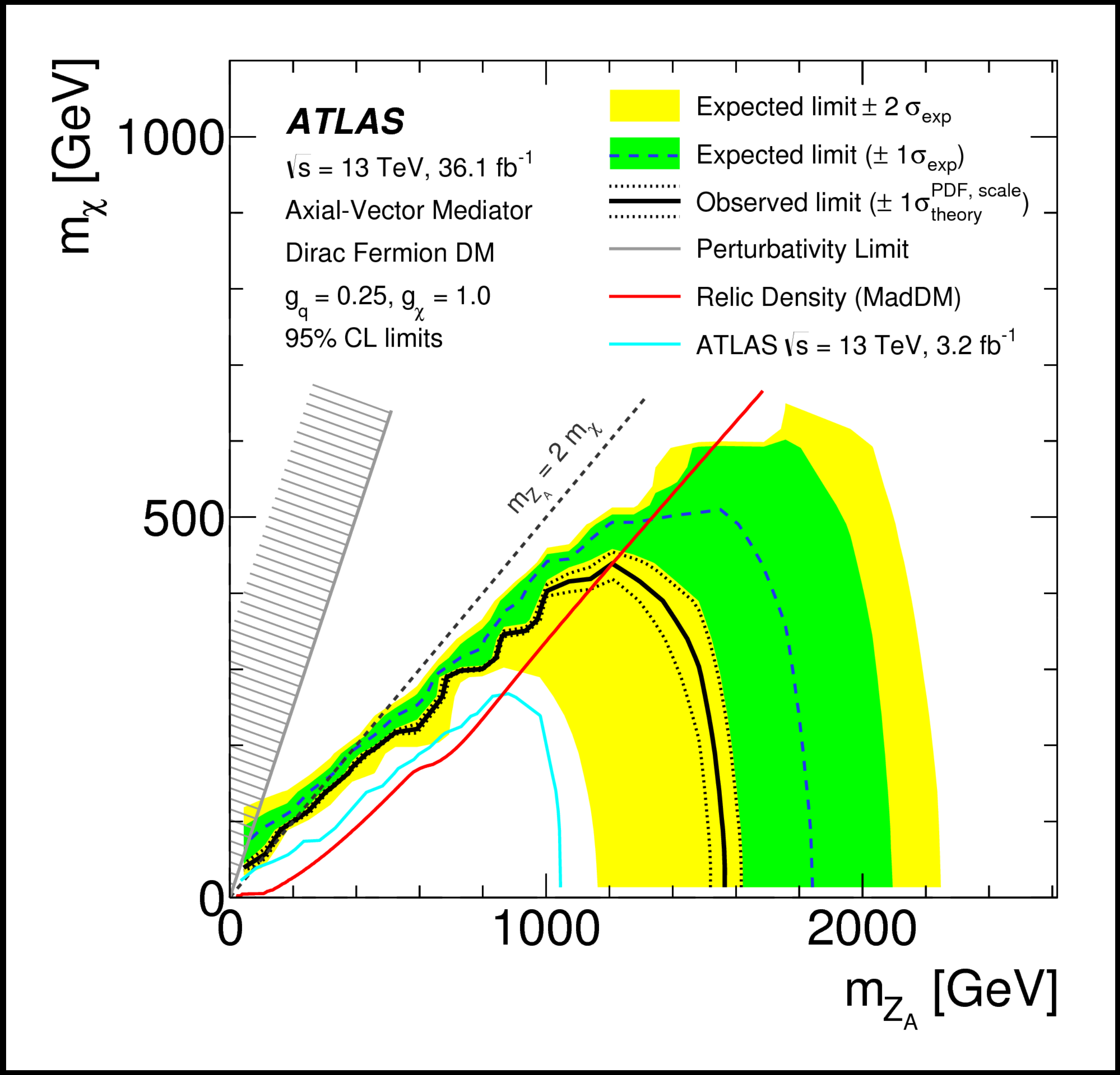
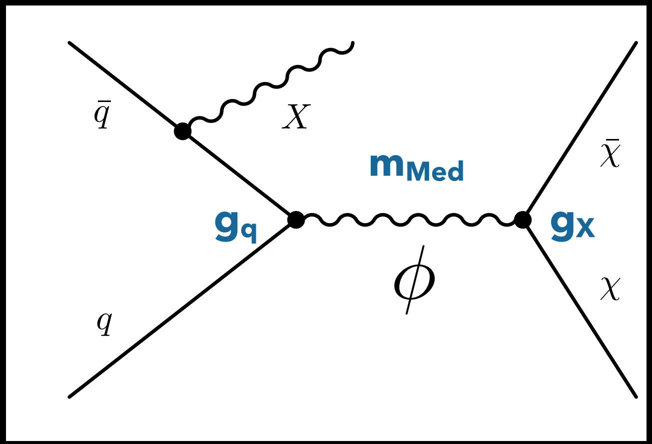
Outlook

- We imagined its dynamics are TeV scale, but it could also be a bit higher, perhaps out of the reach of the LHC.

- The need to have something interesting happen to its potential around the EW scale argues for new states that it couples to with masses that are probably within the LHC's reach. They may be important φ decay modes.

- These could be missing momentum, and might play the role of WIMP dark matter.



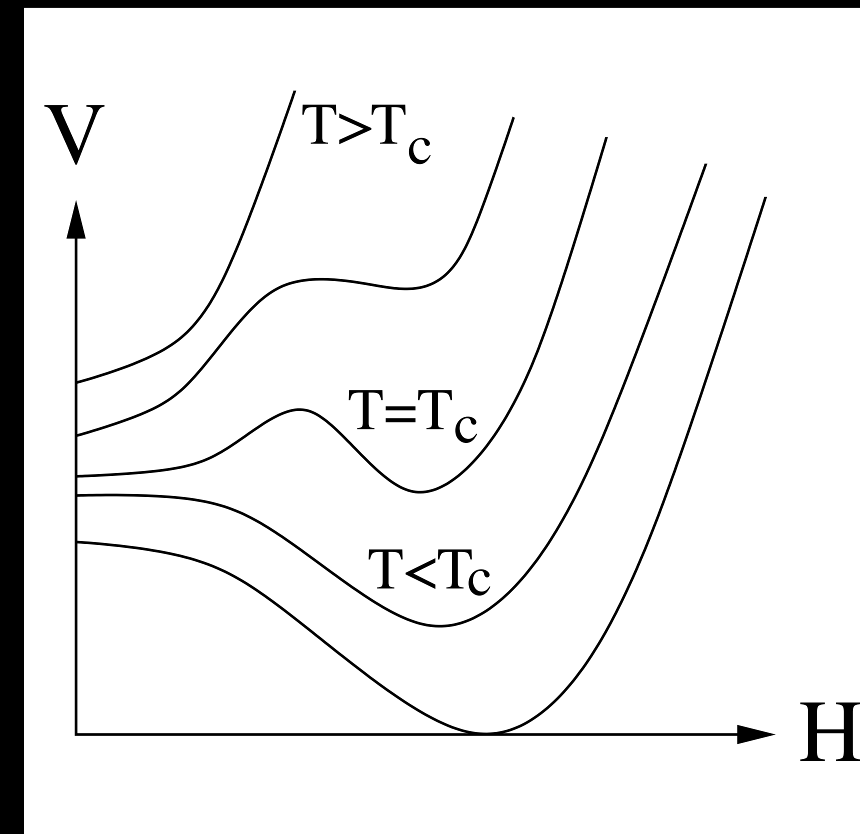


Thank you!

Out of Equilibrium

- The SM also has a problem with the out-of-equilibrium condition.
- The EW phase transition needs to be strongly first order, or the sphalerons will stay in equilibrium and erase any baryon asymmetry that is generated.

1st Order



2nd Order