



Cosmological Modifications of QCD

...and the baryon asymmetry of the Universe...

Tim M.P. Tait

University of California, Irvine

In collaboration with:

Seyda Ipek

arXiv:1811.00559 & PRL

Croon, Howard, Ipek

arXiv:1911.01432 & PRD

Berger, Ipek, Waterbury

arXiv:2004.06727

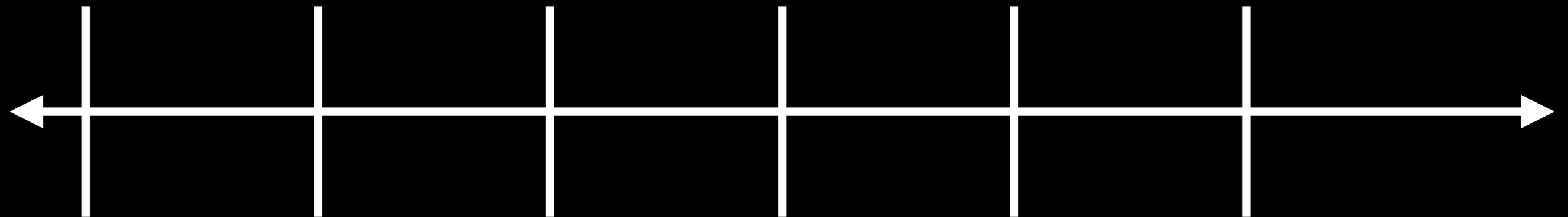


UC Davis
May 4, 2020

Invitation

**EW Phase
Transition?**

**QCD Phase
Transition?**



100 GeV

GeV

MeV

eV

DM Freeze Out?

Baryogenesis?

BBN

CMB

Today

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.

In this talk, I'll explore the idea that the QCD phase transition initially happened at a much higher temperature than \sim GeV.

Outline

- The Baryon Asymmetry of the Universe
- 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:

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

of baryons - # anti-baryons

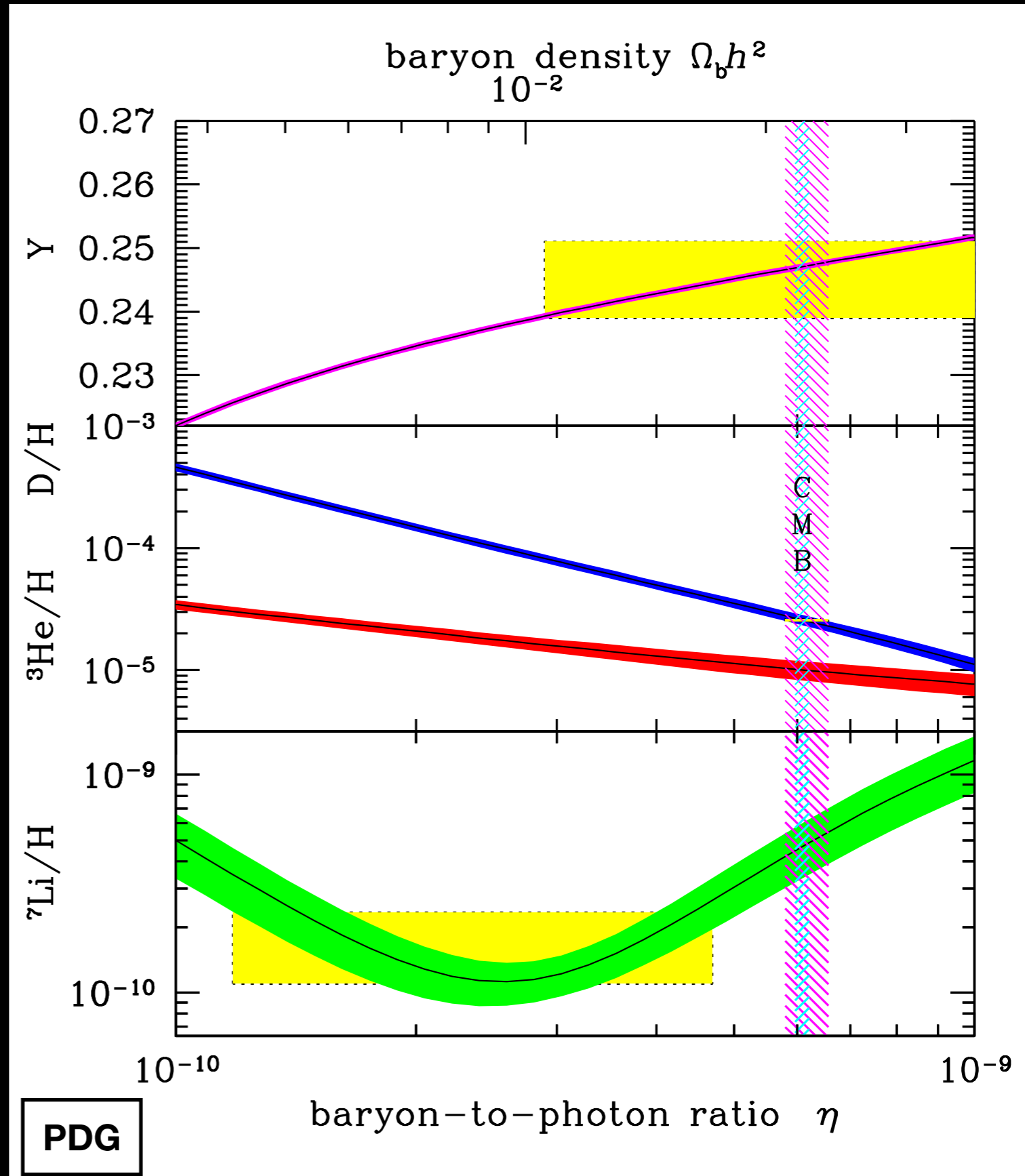
Entropy density

- 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:

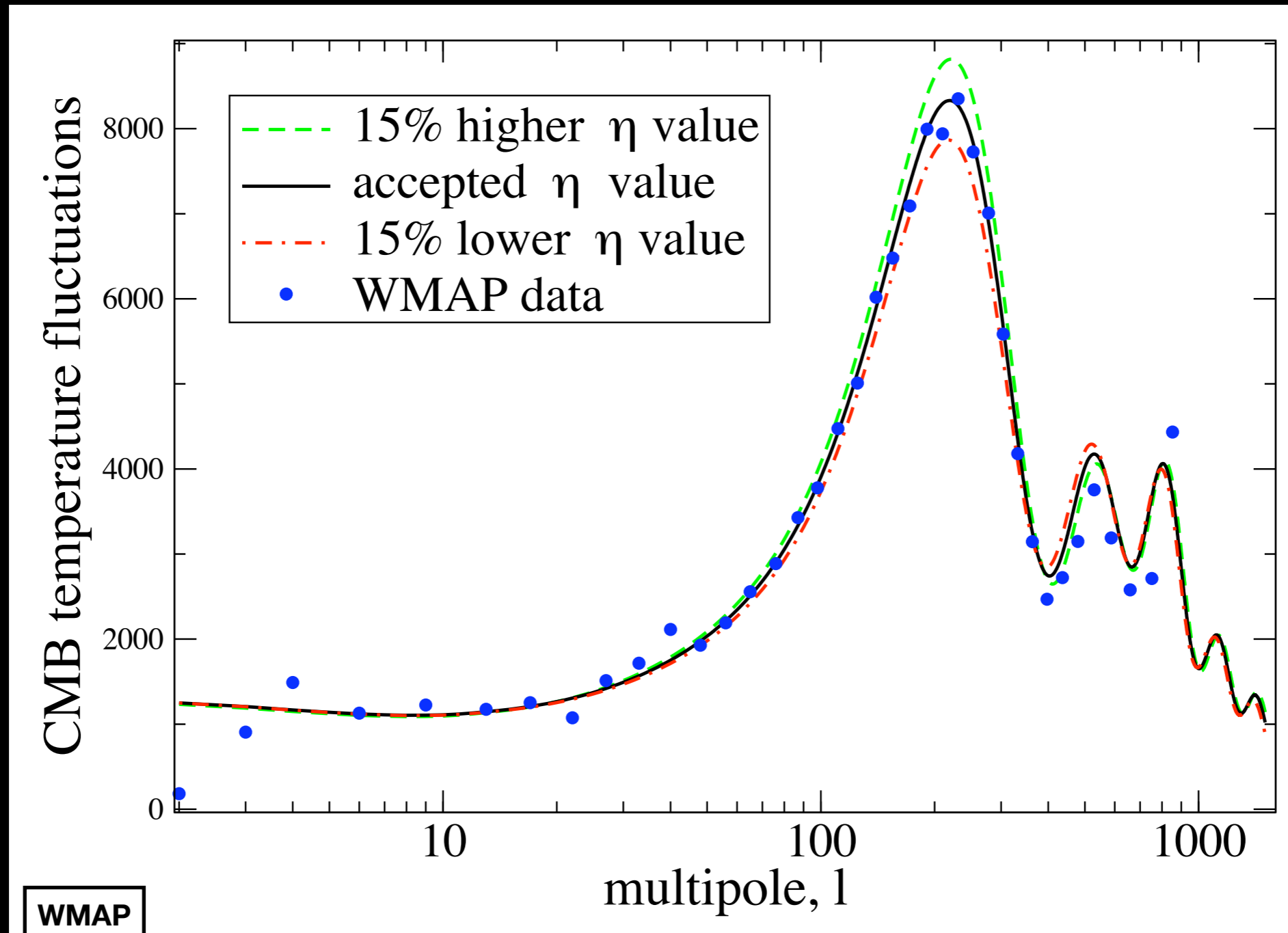
$$\frac{n_B}{s} = \frac{n_{\bar{B}}}{s} \sim 10^{-20}$$

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 ${}^4\text{He}$.
- The ${}^7\text{Li}$ 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.

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.

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:

- $\Delta B=1$: Proton decay: $\Lambda >$ around 10^{16} GeV

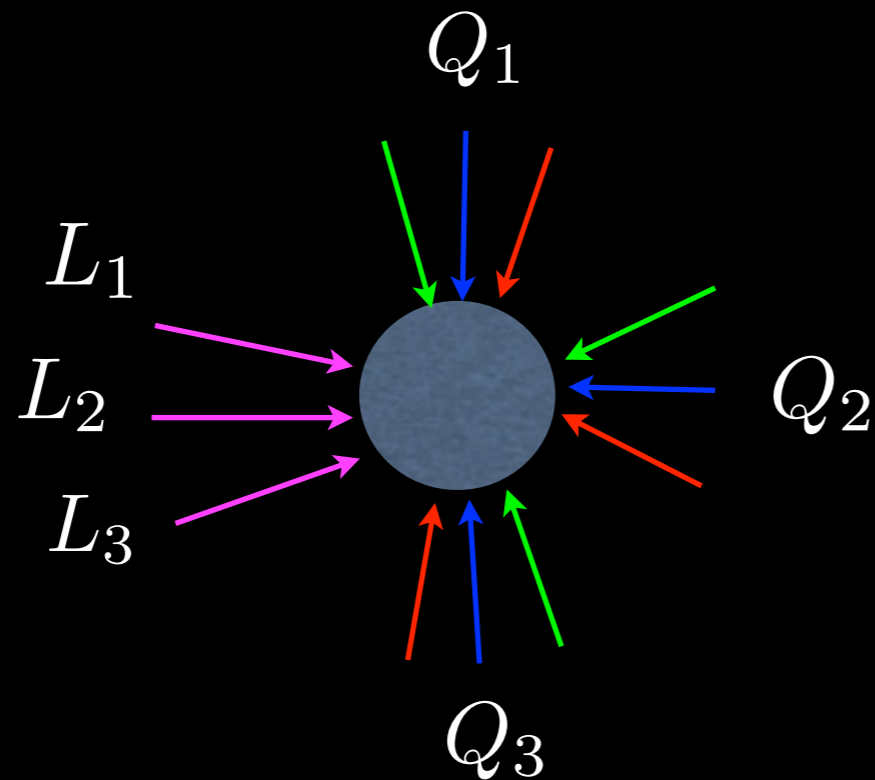
$$\frac{1}{\Lambda^2} (\bar{u}d)(\bar{u}e) \quad p \left\{ \begin{array}{l} d \longrightarrow d \\ u \longrightarrow \bar{d} \\ u \longrightarrow \bar{d} \end{array} \right\} \pi^0 \quad \tau \sim \frac{\Lambda^4}{m_p^5} \gtrsim 10^{30} \text{ years}$$

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

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

B Violation

- 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

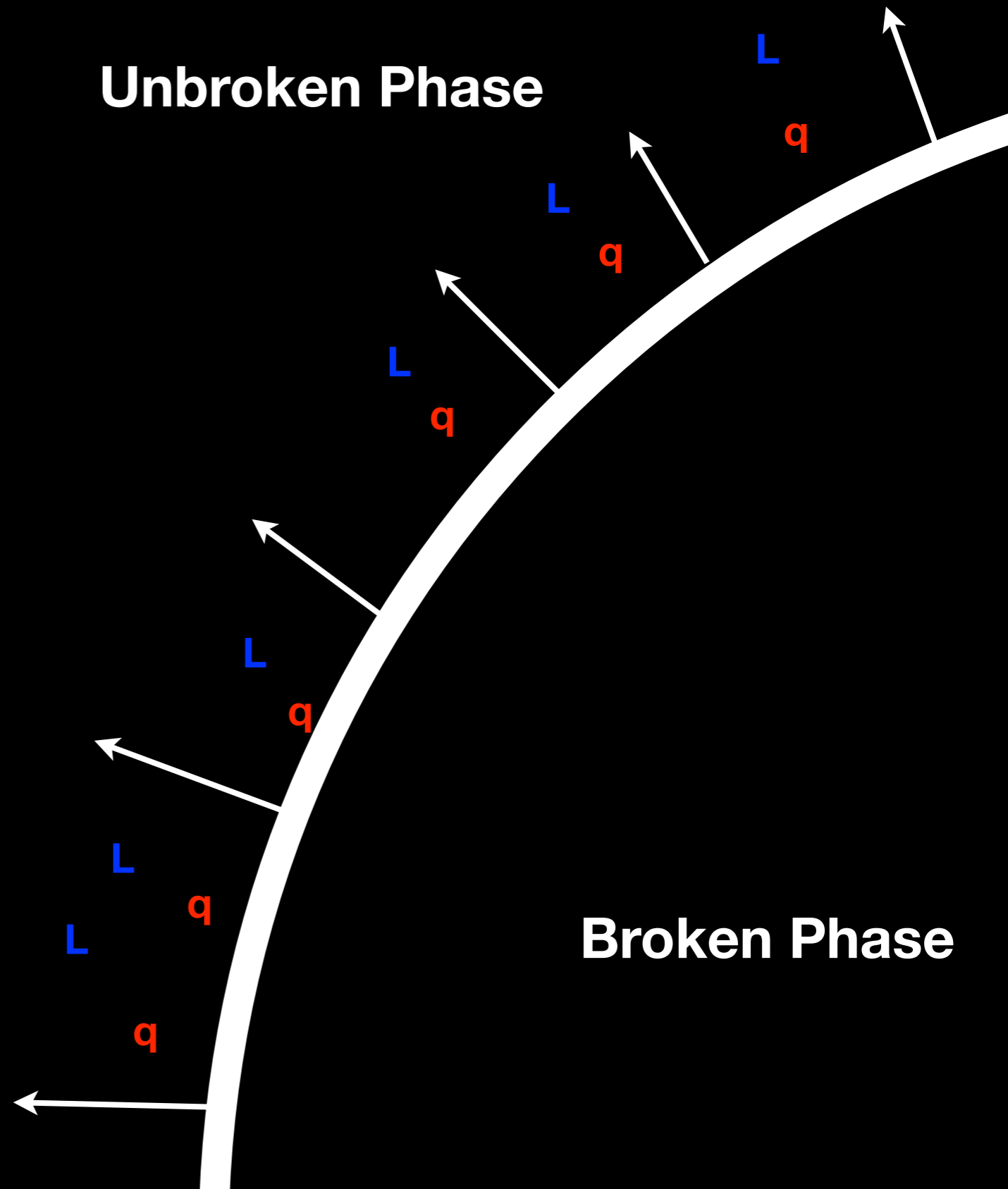
- The sphalerons can also naturally explain the paradox of strong baryon-number violation at temperatures around 100 GeV, but very small rates in low energy tests.
- At low temperatures, when the Electroweak symmetry is broken, the masses for the W and Z fields imply that it costs energy to form the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

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

- 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:

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

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

$$m_H < 50 \text{ GeV} \quad \text{(Recall: } m_h^2 = \lambda v^2 \text{)}$$

- 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.
- The SM also does not have enough effective CP violation in the CKM matrix.

Strong CP?

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

Kuzmin, Shaposhnikov, Tkachev PRD45, 466 (1992)

$$\frac{\alpha_S}{8\pi} \bar{\theta} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$\bar{\theta} \equiv \theta + \text{Arg Det} M_q$$

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

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

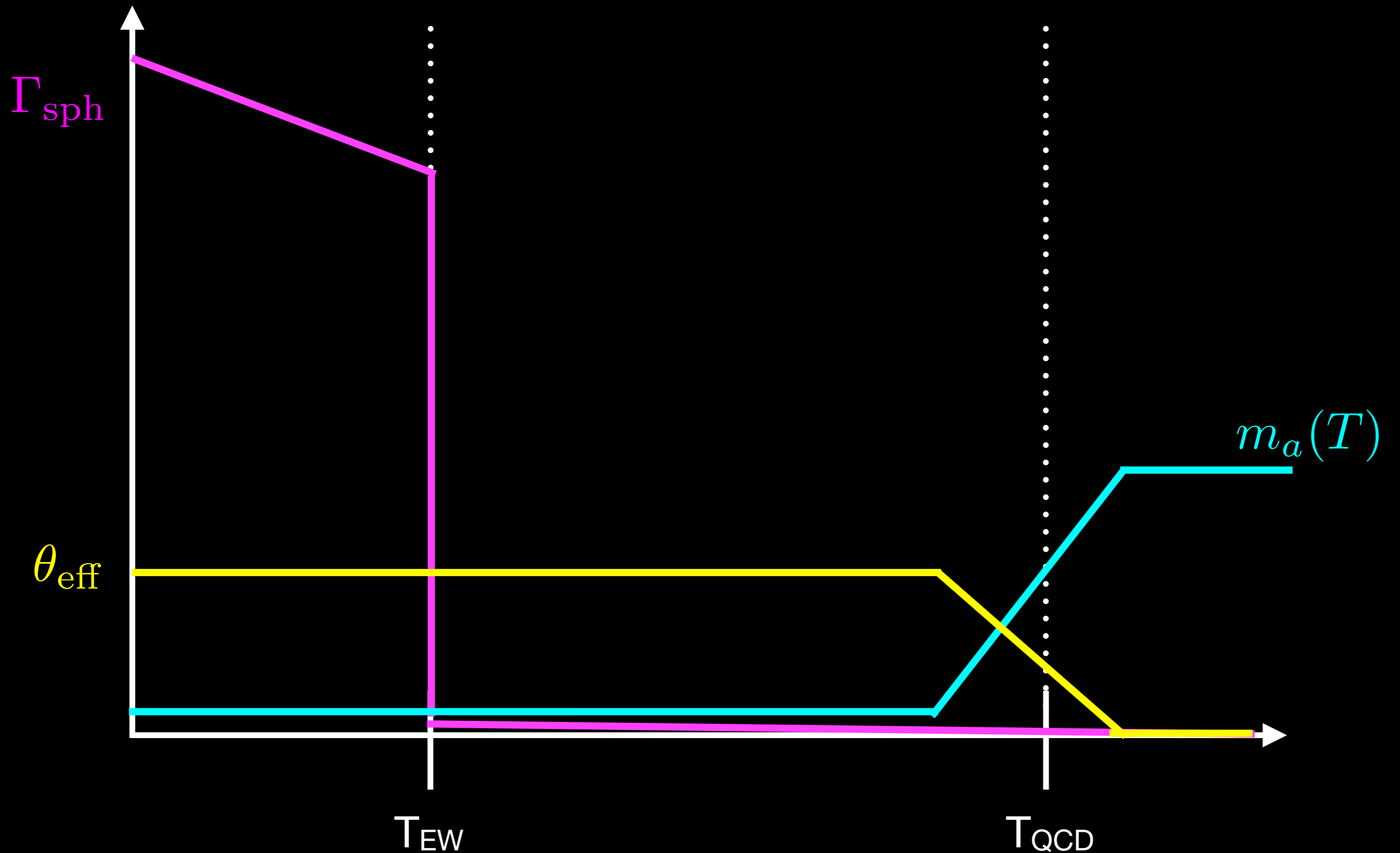
...so it's irrelevant...

- 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.

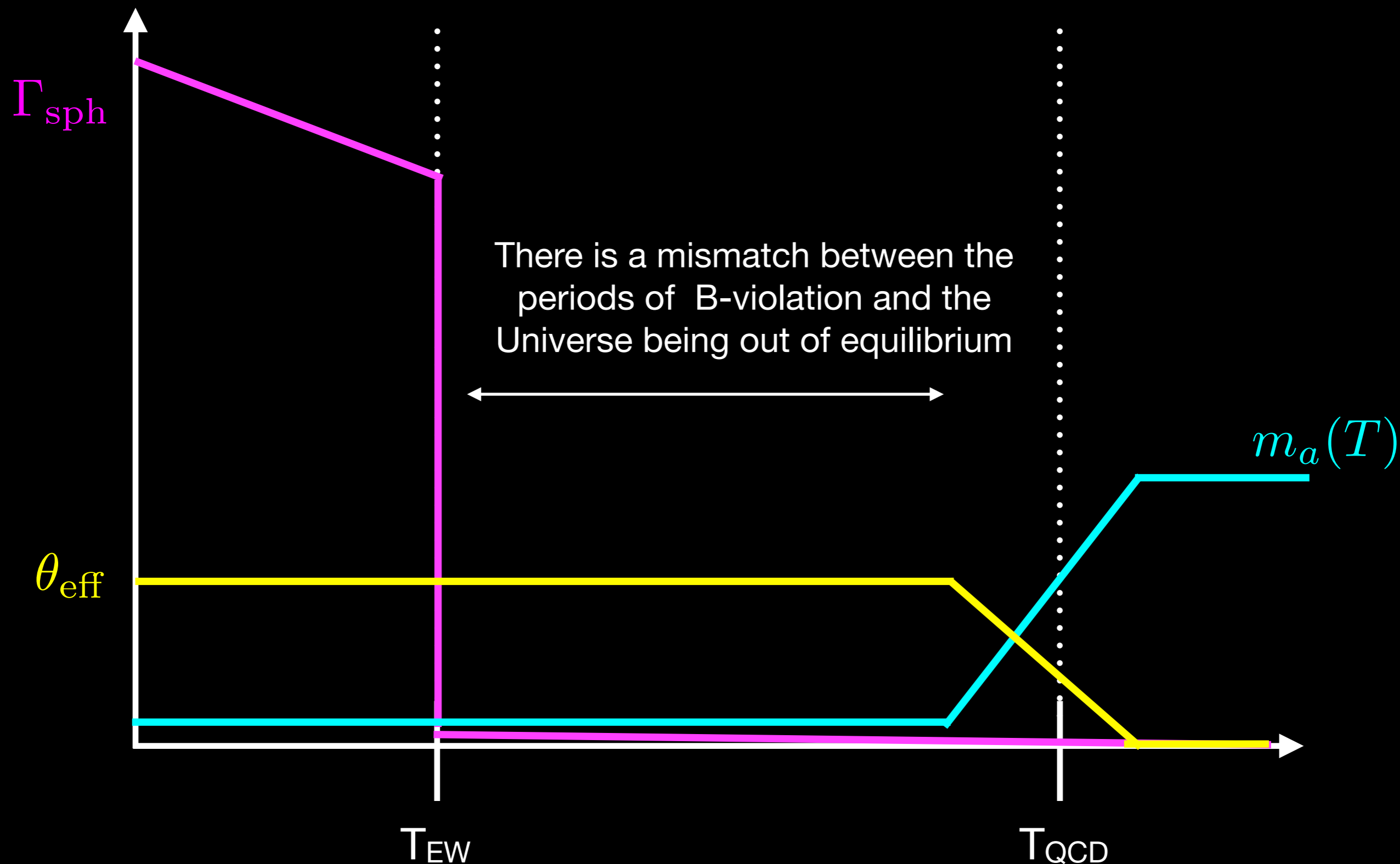
$$\frac{\alpha_S}{8\pi} \left[\bar{\theta} + \frac{a(x)}{f_a} \right] G^{\mu\nu} \tilde{G}_{\mu\nu}$$

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

Thermal History



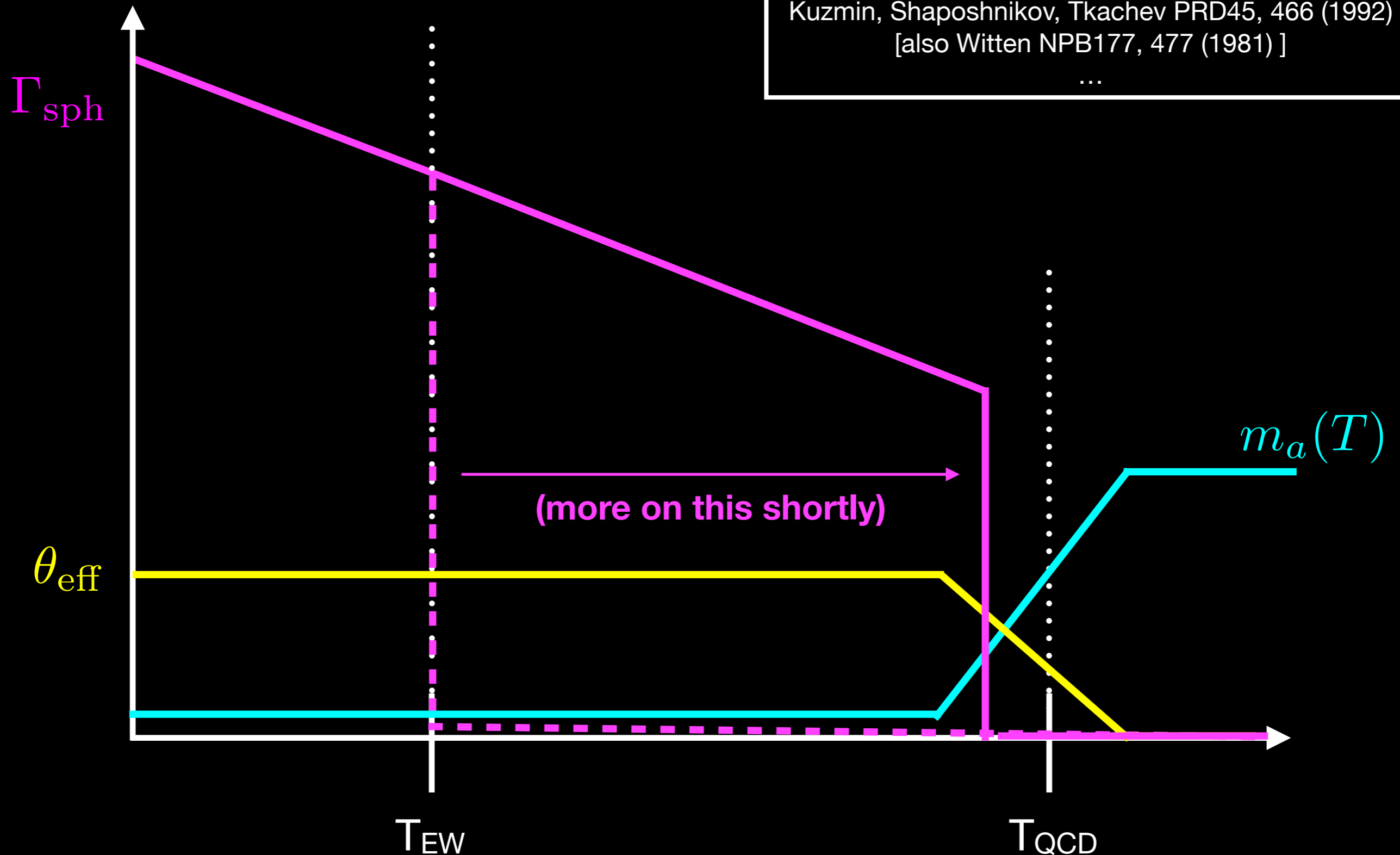
The Challenge



Supercooled EW Transition

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

...



Spontaneous Baryogenesis

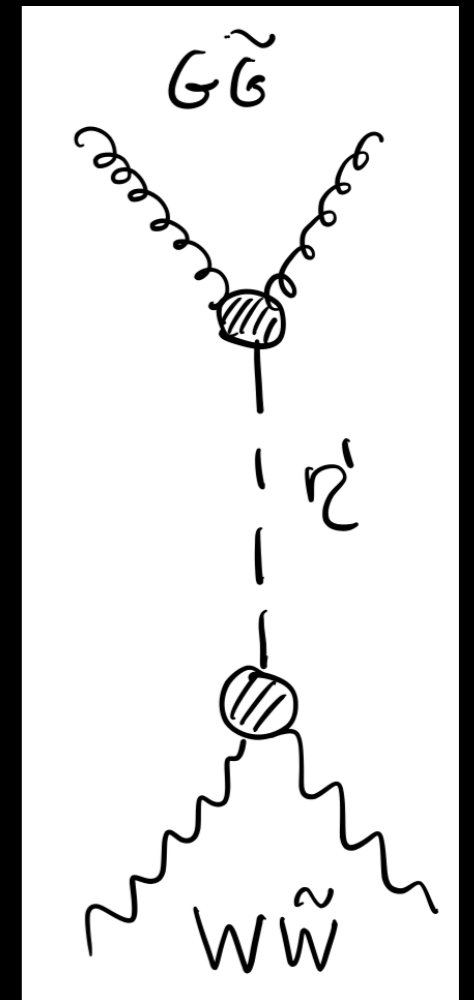
- The non-zero θ_{eff} looks like a tadpole for $G\tilde{G}$:

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

- Which in turn sources $W\tilde{W}$:

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

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



Spontaneous Baryogenesis

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

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

- Which leads to baryon production:

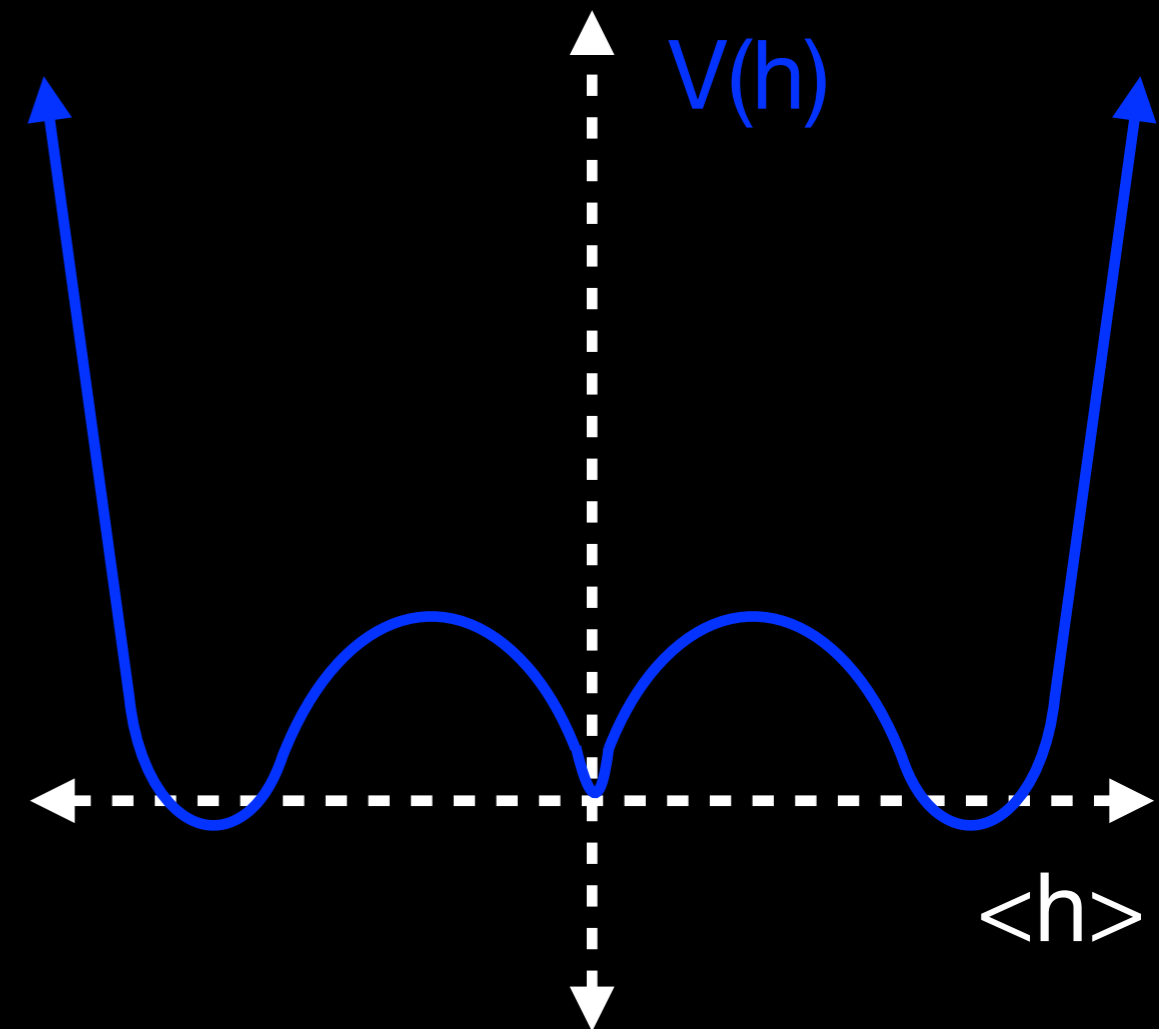
$$n_B = \int dt \frac{\Gamma_{\text{sph}}(T)}{T} \mu_{\text{eff}}(T)$$

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

$$\Gamma_{\text{sph}}(T) \sim (\alpha_W T)^4 \qquad m_a^2(T) \sim m_{\pi}^2 \frac{f_{\pi}^2}{f_a^2} \left(\frac{\Lambda}{T} \right)^7$$

Phase Transition

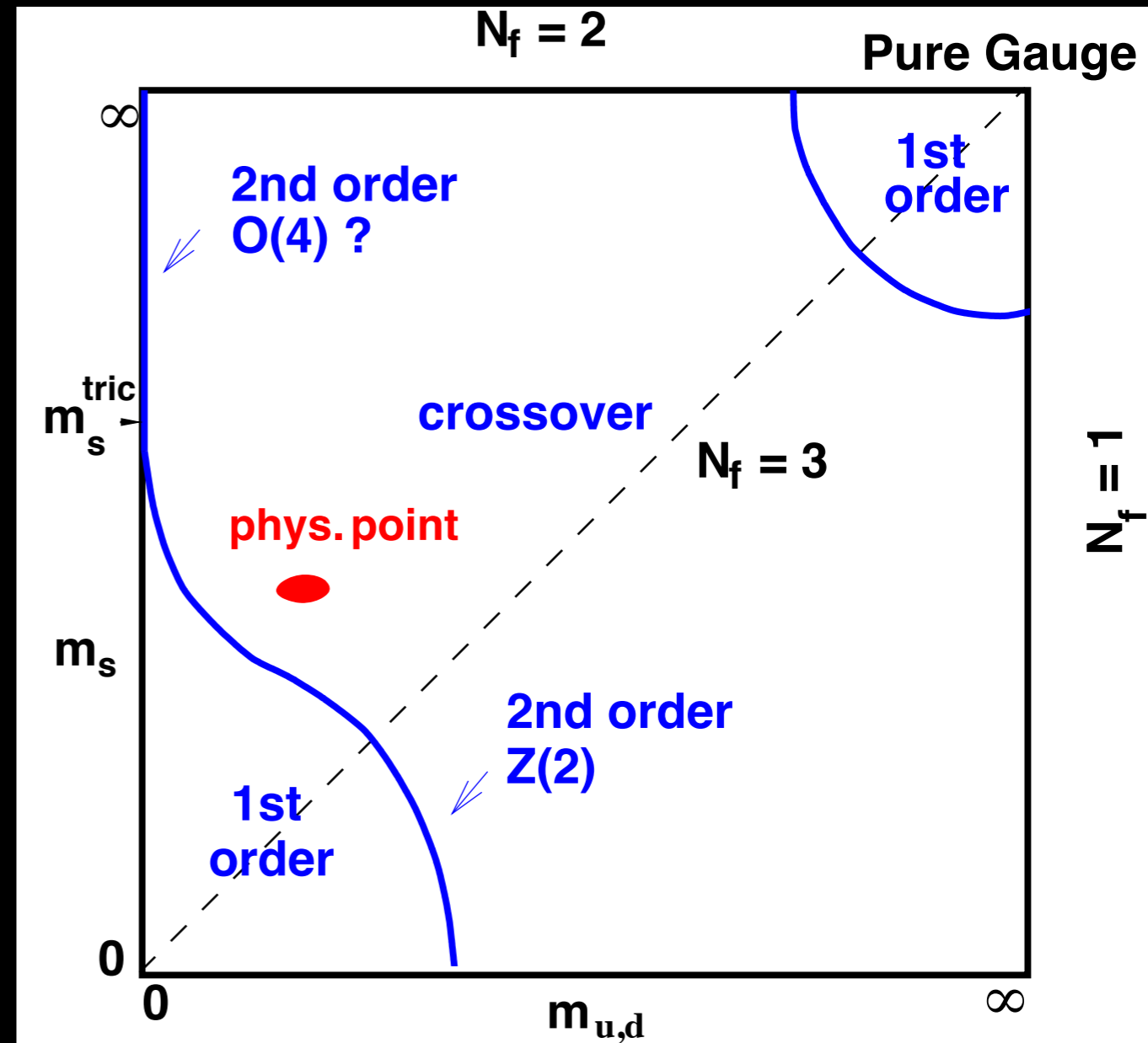
- Kuzmin et al engineer the super-cooled EW phase transition by invoking a Coleman-Weinberg potential for the Higgs.
 - (That was still an option in 1992...)
 - Today, one can arrive at something appropriate with a modified Higgs sector.
- e.g. in a RS composite Higgs model:
von Harling, Servant JHEP1801, 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.
- That already breaks the electroweak symmetry.
- It also looks like a tadpole for the Higgs, which triggers EWSB & quark masses.

Pisarski, Wilczek, PRD29, 338 (1984)



Review by Schaefer & Wagner 0812.2855

QCD Phase Transition

Deconfined Phase

quarks and gluons

$$\langle \bar{q}q \rangle = 0$$

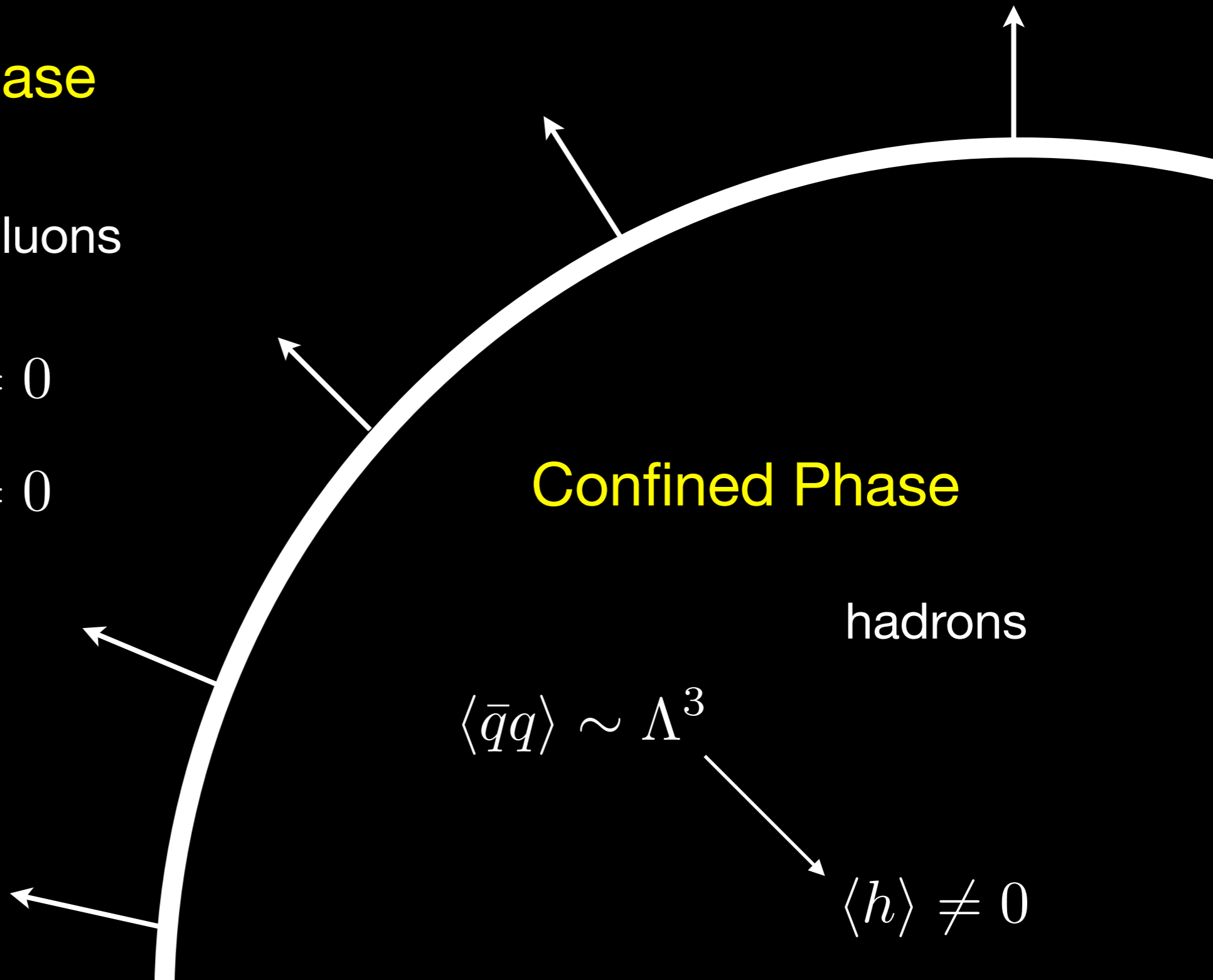
$$\langle h \rangle = 0$$

Confined Phase

hadrons

$$\langle \bar{q}q \rangle \sim \Lambda^3$$

$$\langle h \rangle \neq 0$$



Baryon Asymmetry

- The resulting baryon asymmetry is:

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

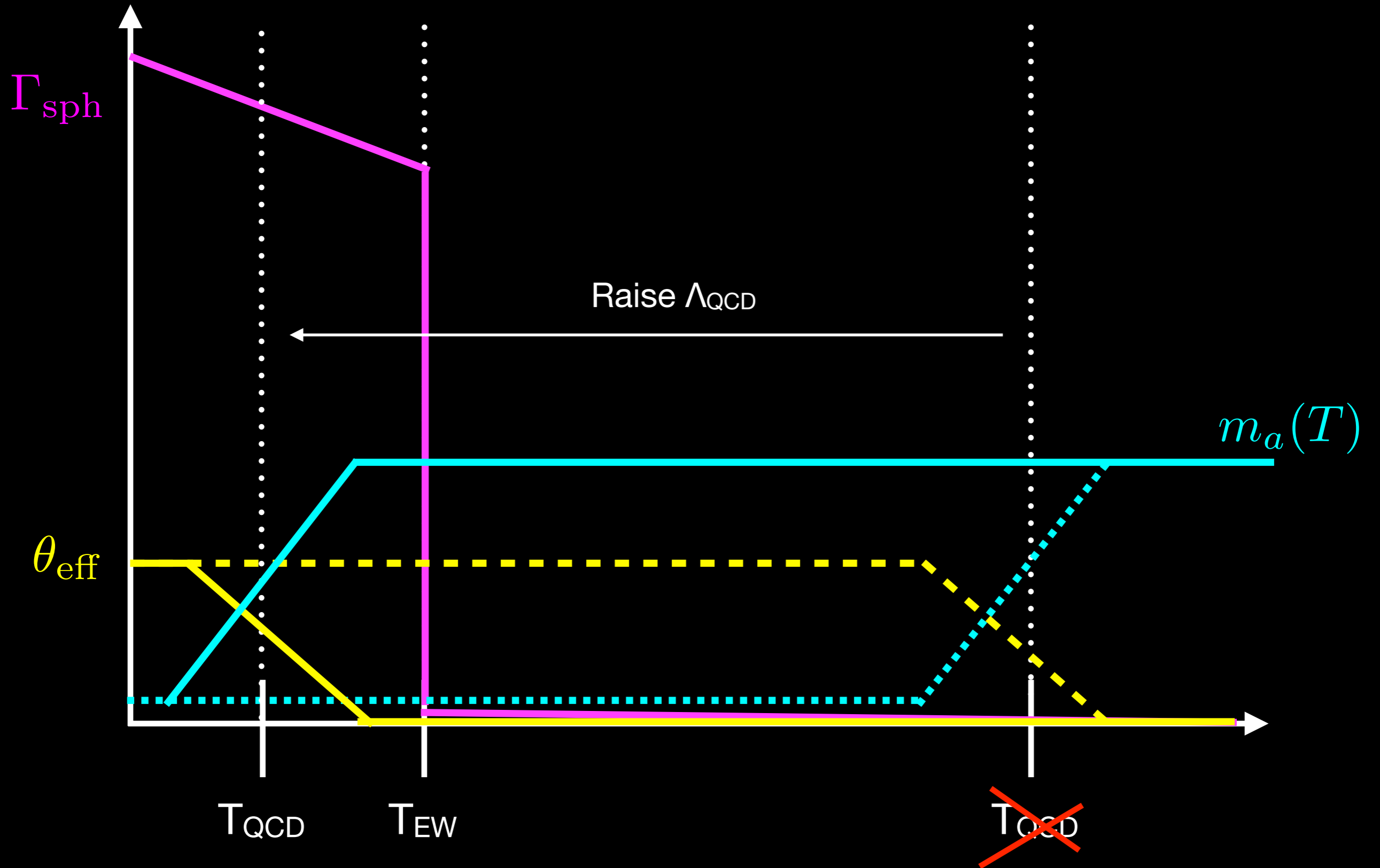
- Allowing for entropy production after the phase transition:

$$\eta \equiv \frac{n_B}{s} \simeq \frac{225}{2\pi^2 g_*} \frac{m_\pi^2}{m_{\eta'}^2} \alpha_W^4 \cos \theta_{\text{eff}} \left(\frac{T_{\text{QCD}}}{T_{RH}} \right)^3 \left(\frac{\Lambda}{T_{\text{QCD}}} \right)^7$$
$$\simeq 5 \times 10^{-9} \left(\frac{T_{\text{QCD}}}{T_{RH}} \right)^3$$

- 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 & PRL



Baryon Asymmetry

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

$$\eta \equiv \frac{n_B}{s} \simeq \frac{225}{2\pi^2 g_*} \frac{m_\pi^2}{m_{\eta'}^2} \alpha_W^4 \cos \theta_{\text{eff}} \left(\frac{T_{QCD}}{T_{RH}} \right)^3 \left(\frac{\Lambda}{T_{QCD}} \right)^7$$
$$\simeq 5 \times 10^{-9} \left(\frac{T_{QCD}}{T_{RH}} \right)^3$$

- To get the observed baryon asymmetry, we need to live in a patch where $\theta \sim 0.1$, 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

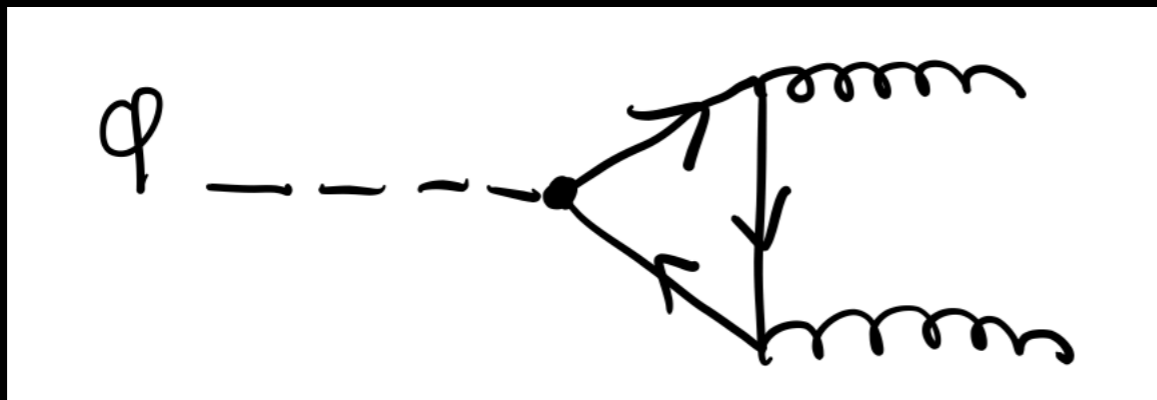
- We envision something like the following:
 - The strong coupling is promoted (at least in part) to a field of some kind.
 - The parameters are such that above T_{EW} , QCD confines.
 - This triggers EW breaking (including a Higgs VEV), and generates a baryon asymmetry at high temperatures.
 - Dilution 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:

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

- 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:

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

- The scale at which QCD gets strong is about:

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

- For $n_f = 6$, to get $\Lambda \sim \text{TeV}$, 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.

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

- For choices of α_i of $O(1)$ and $m \sim M_*/10$, one can get $\langle \phi \rangle \sim M_*$ without much tuning.
- Once QCD gets strong, it will also induce corrections of $O(\Lambda_{\text{QCD}})$, which is likely to be a fairly large corrections to the VEV unless $m \gg \Lambda$.


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 \sim 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.
- So we model the chiral symmetry breaking and Higgs VEV using a linear sigma model with $SU(6) \times SU(6)$ symmetry:

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

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

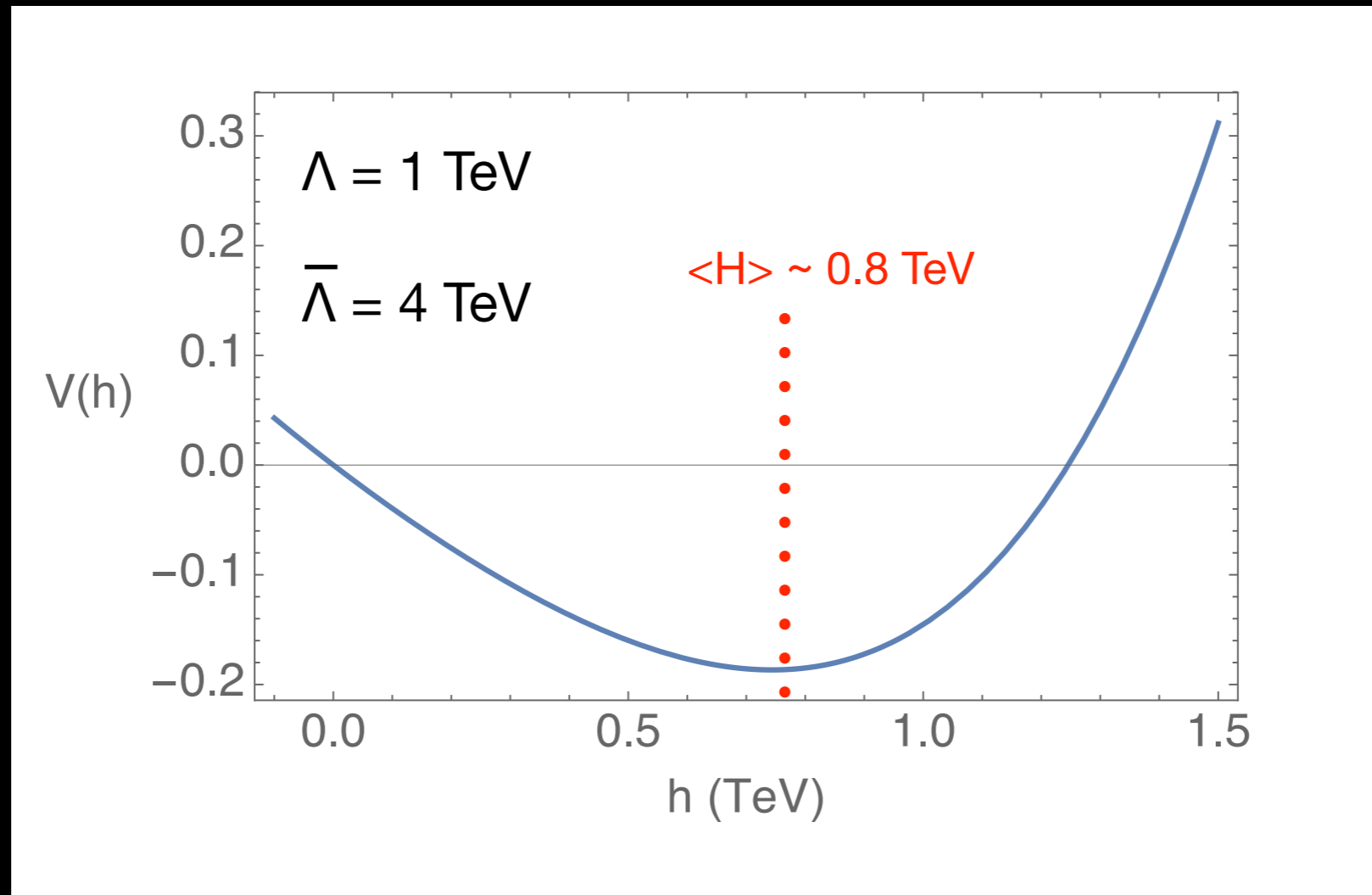
Phase Transition

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

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

- (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 $O(\Lambda)$. Probably there is an $O(1)$ impact on $\langle H \rangle$, but the results are probably trustworthy at the order of magnitude level.

Phase Transition



- This seems to be borne out by more careful estimates, 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.

Deconfinement

$$V(H) = -\mu^2 |H|^2 + \lambda_h |H|^4,$$

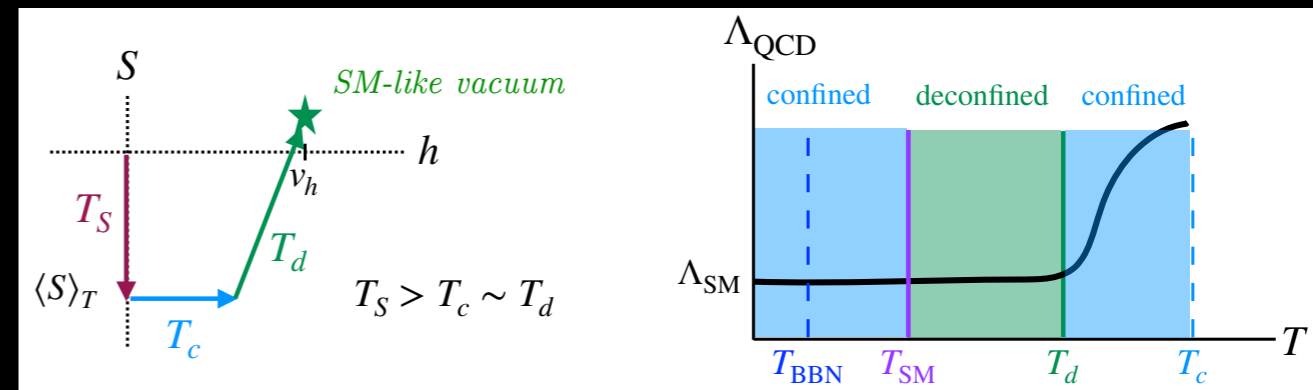
$$V(S) = a_2 (S - S_0)^2 + a_3 (S - S_0)^3 + a_4 (S - S_0)^4,$$

$$V(H, S) = -b_1 S |H|^2 + b_2 S^2 |H|^2.$$

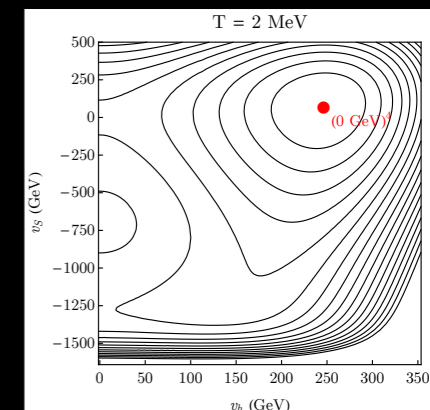
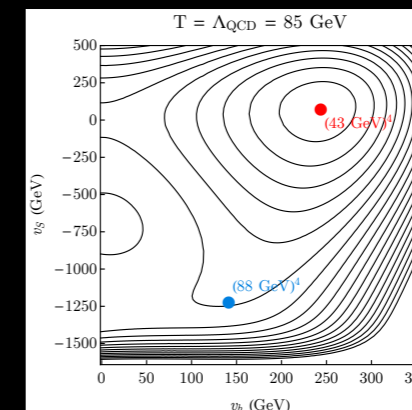
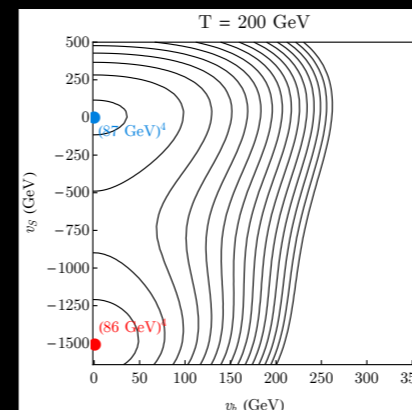
One possibility is to use the Higgs evolution with temperature as the trigger which causes the shift in ϕ which takes us to a SM-like vacuum.

The Temperature-dependent corrections to the Higgs potential contain terms from the EW bosons (standard), but the top contribution is modified during confined phases, and is dominated by top-flavored mesons.

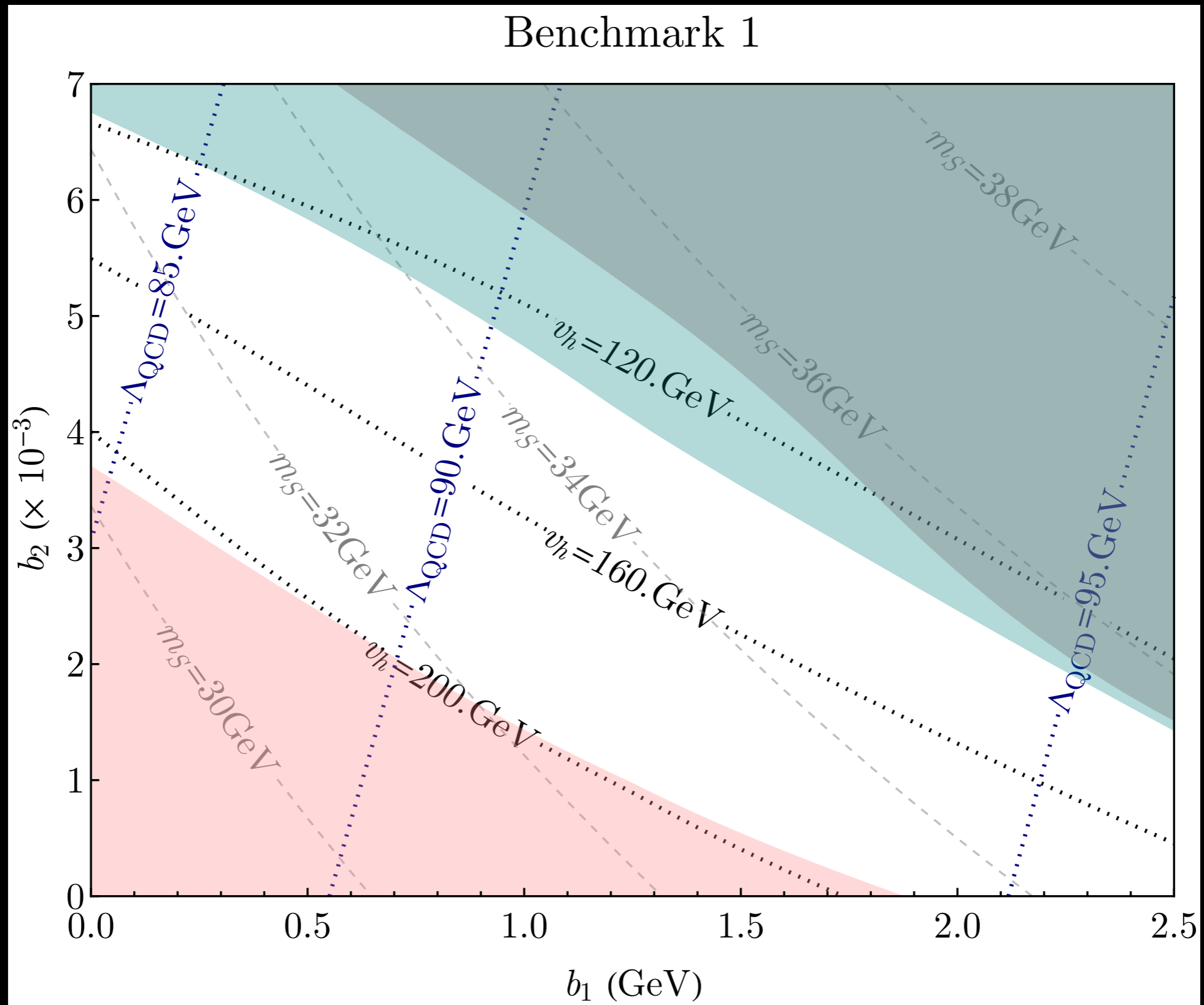
They're bosons!



Croon, Ipek, Howard, TMPT, arXiv:1911.01432



Parameters



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 toy theory that adjusts the coupling such that confinement occurs at around 1 TeV, and later relaxes to ~ 1 GeV after the electroweak phase transition.
- There could be primordial gravitational wave signatures associated with the first order phase transition of the early QCD confinement.
- In a theory in which the axion is invoked to solve the strong CP problem, it appears to offer a viable baryogenesis option.

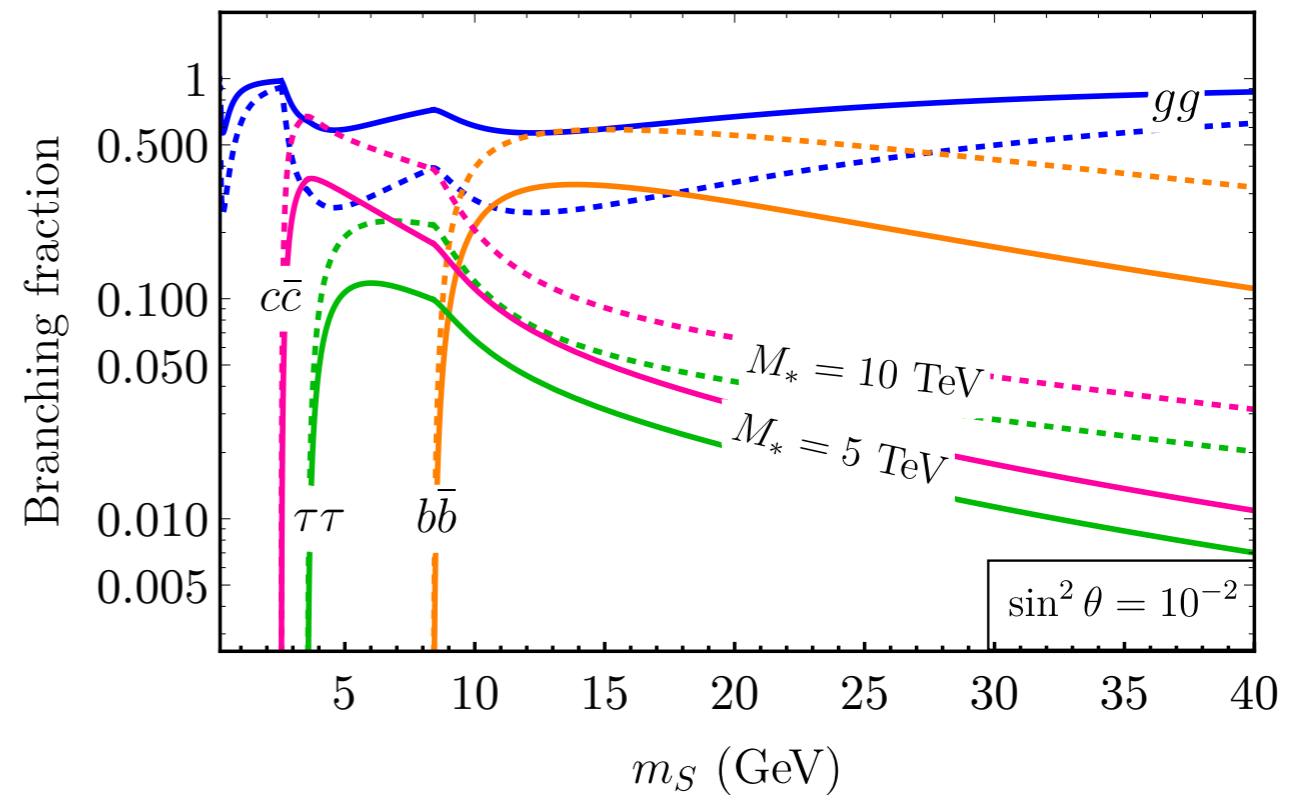
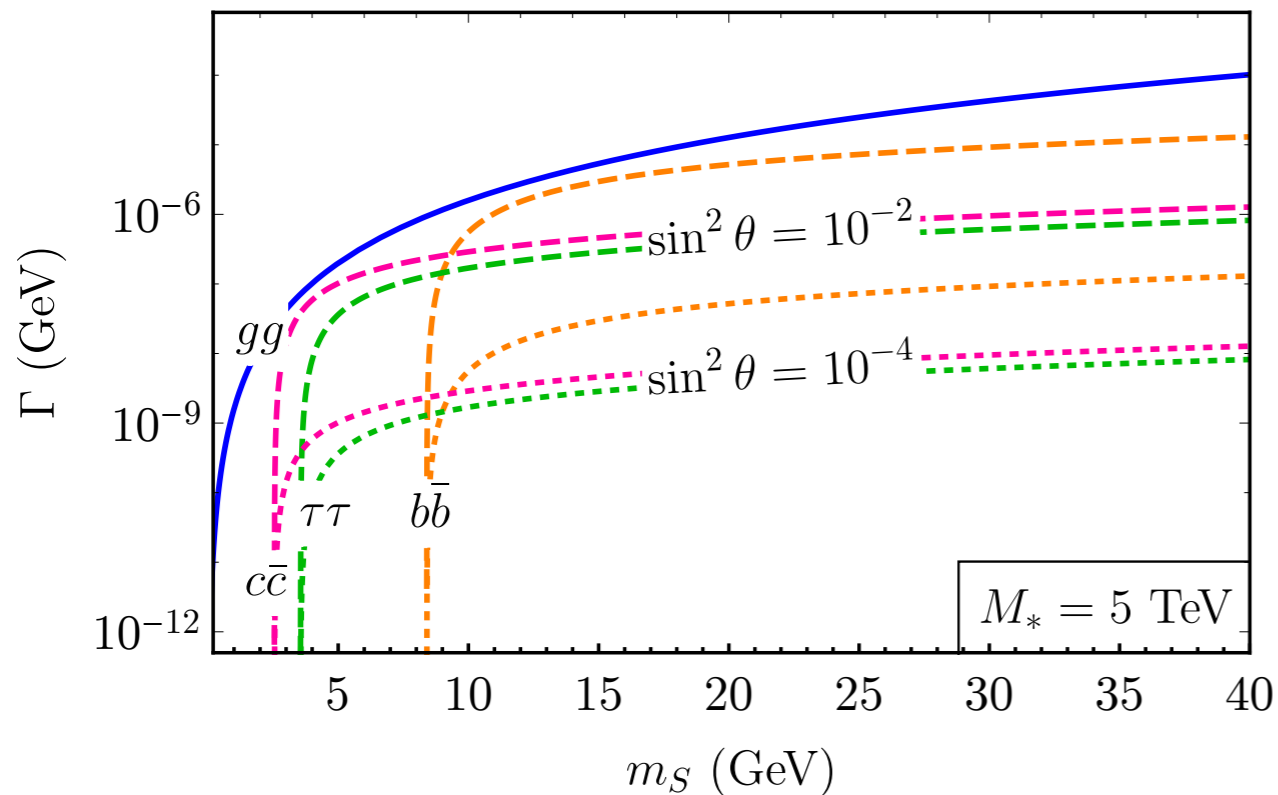
Outlook

- Still many questions remain...
 - Naively, the axion could possibly end up with the right relic density to be dark matter, if f_a 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...

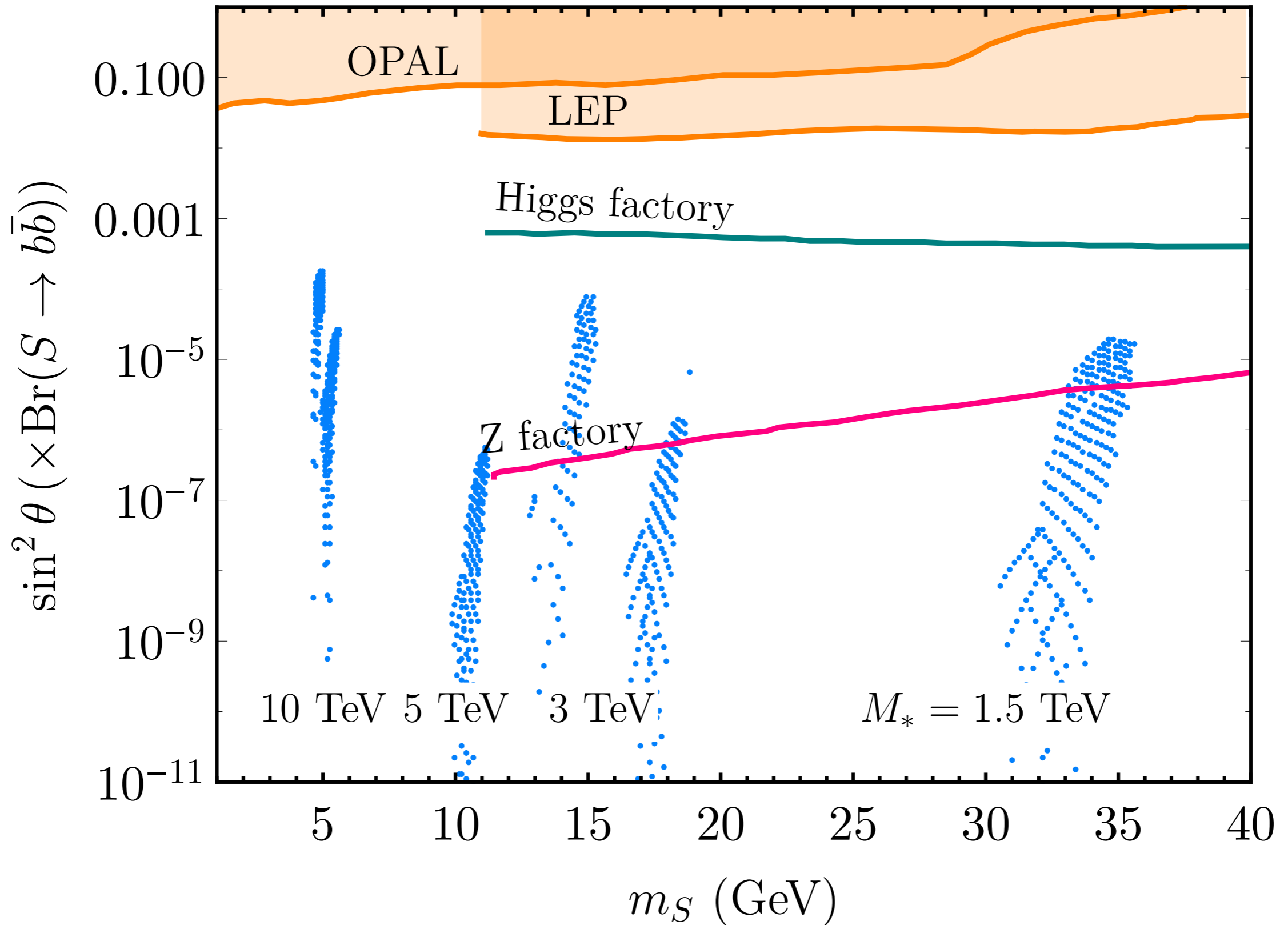
Requires $\Lambda > 10^9$ GeV or so...

Outlook

- The true hallmark of these dynamics is the ϕ .
- Minimally, it couples to gluons.
- Also has Higgs-like interactions through mixing (but in this parameter space, $\theta < 10^{-3}$ or so).

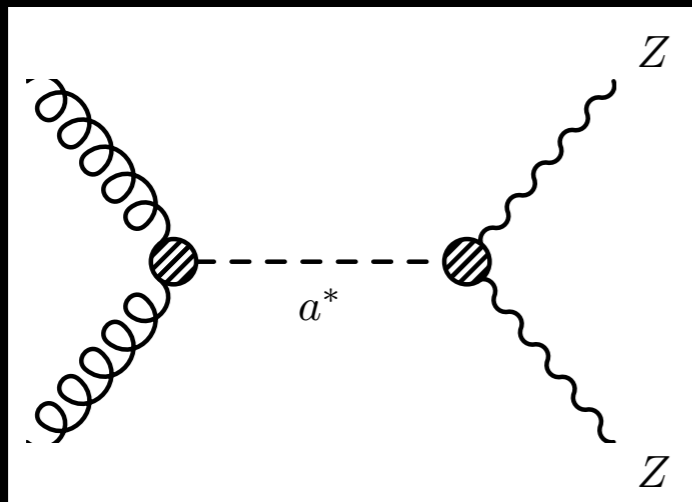


Outlook



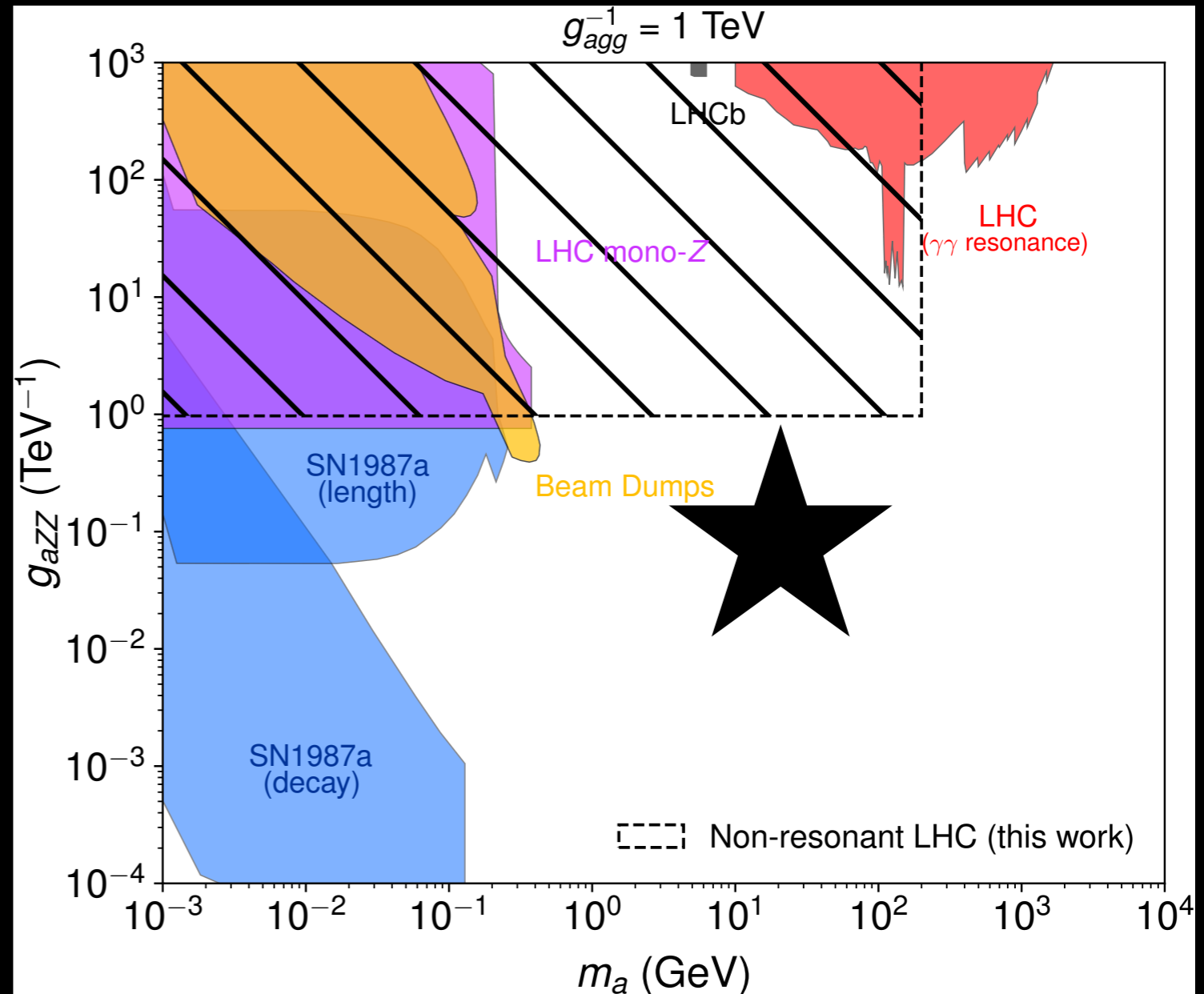
Outlook

- 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.
 - Studies by theorists suggest M^* greater than about 3 TeV (depending on the Higgs mixing).



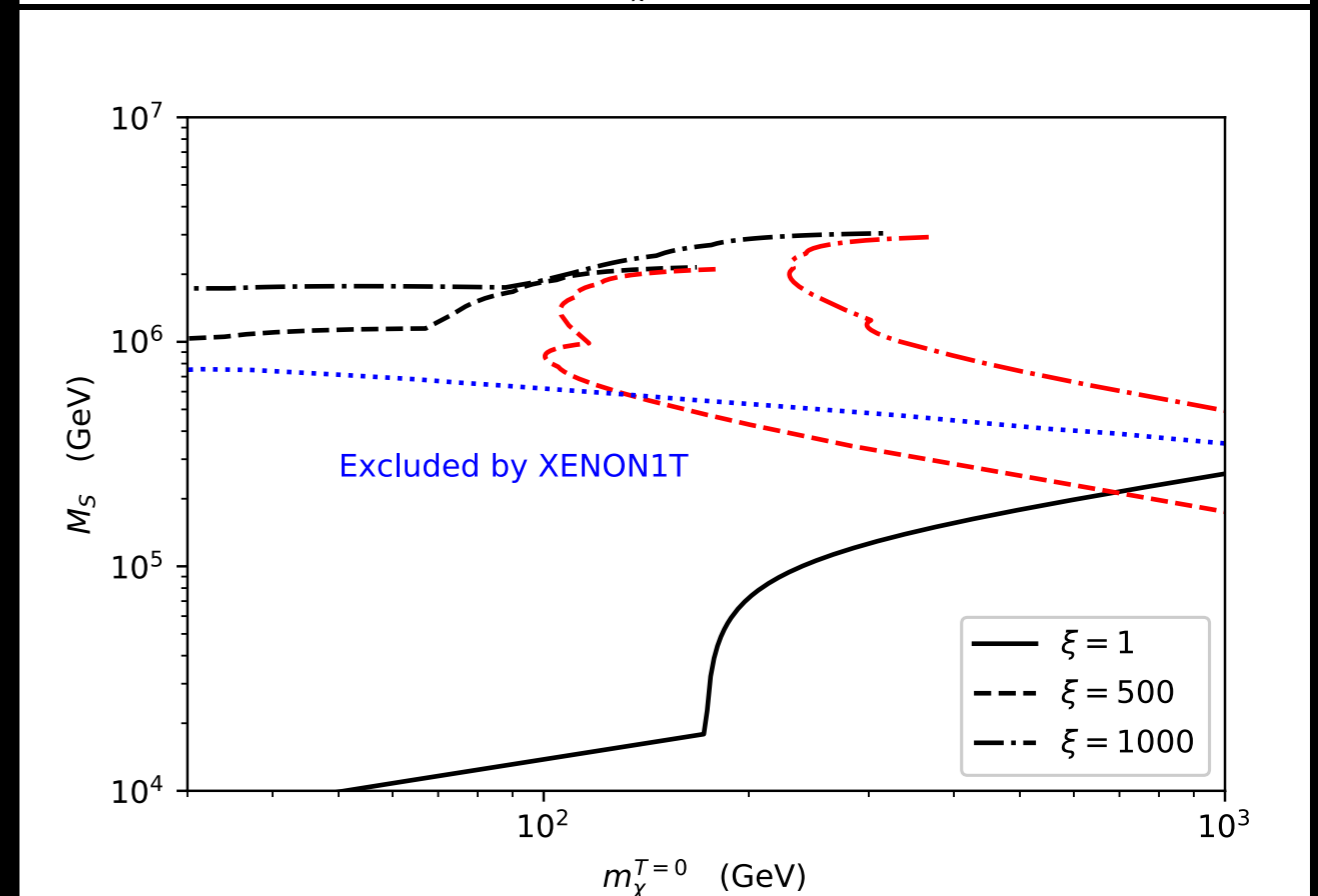
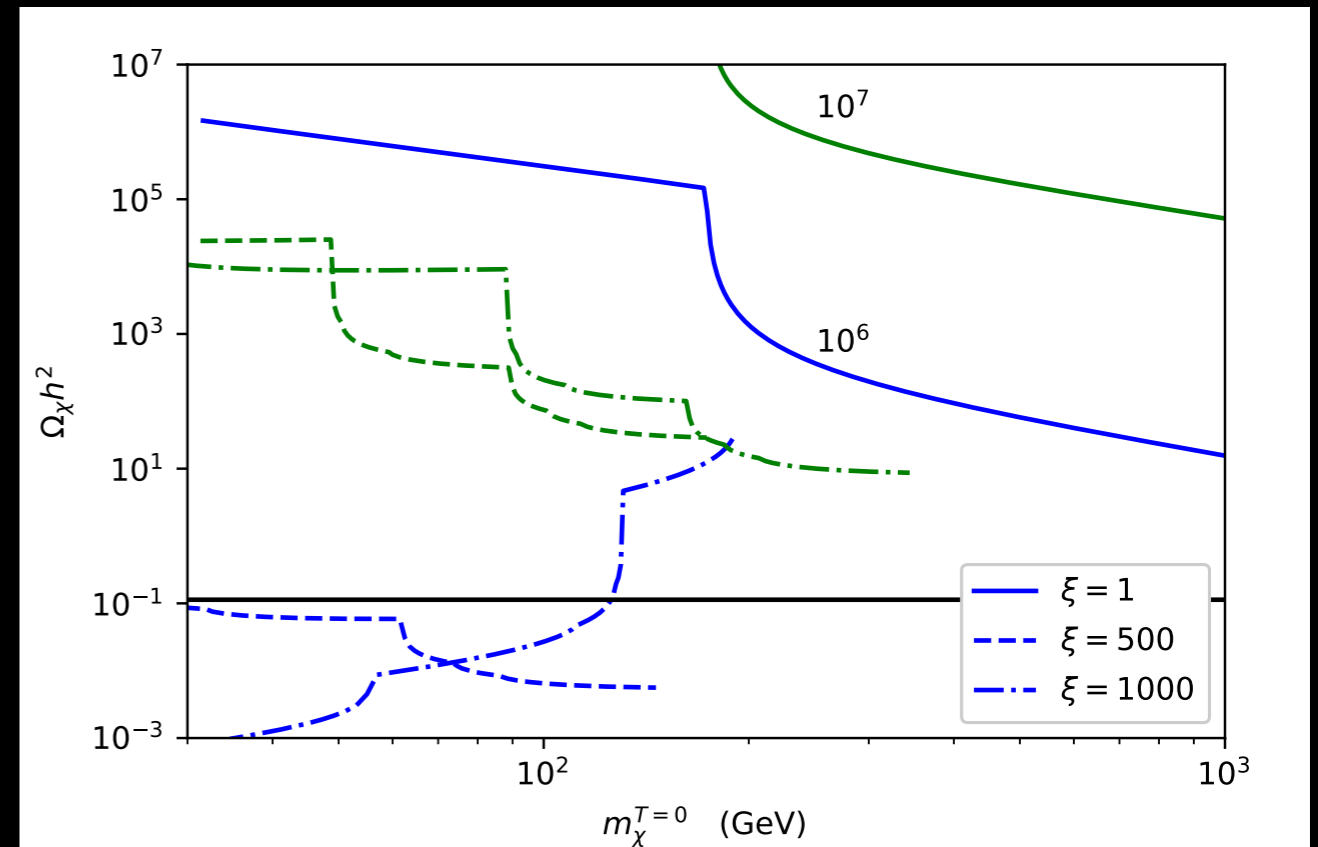
Gavela, No, Sanz, Troconiz 1905.12953

There could be other, possibly dark, important decay modes.



Outlook

- If there is WIMP dark matter coupled to quarks via a scalar portal (such as the ϕ itself), and it freezes out during a confined phase, the relic density can be very different from naive expectations.
- The freeze-out is into mesons rather than quarks.
- In that case, the DM mass is shifted by chiral symmetry breaking.
- Regions which naively look excluded by Xenon may be viable.

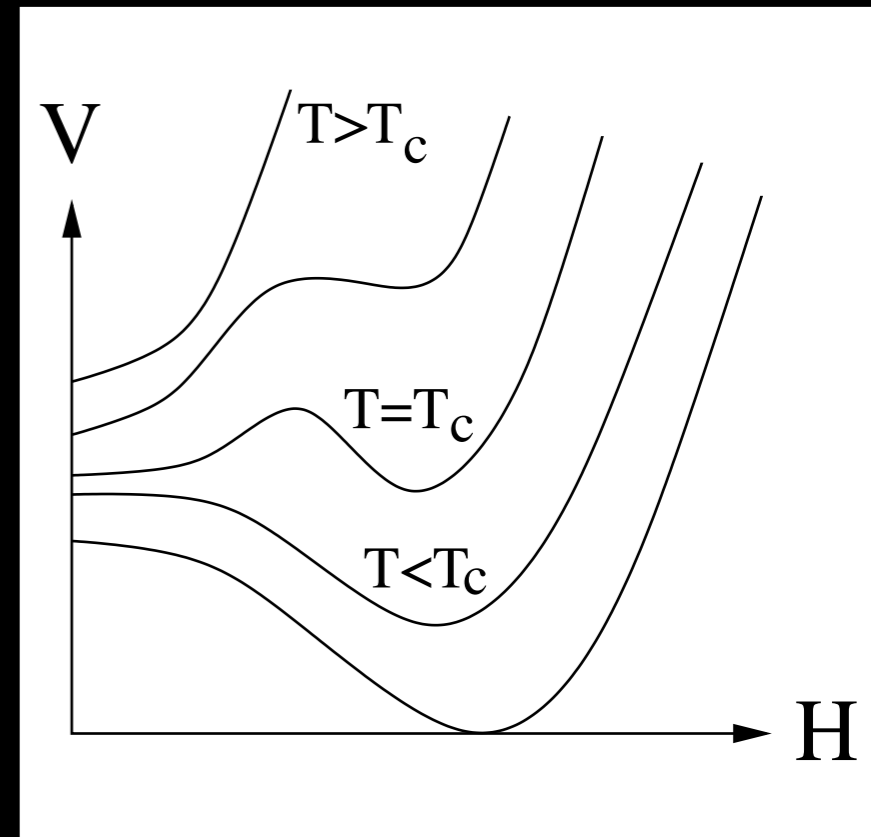


Thank you!

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

