An Early Period of QCD Confinement

For Fun and Profit

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University of California, Irvine

BSM PANDEMIC
May 6, 2020

Based On:

Early Cosmological Period of QCD Confinement

Seyda Ipek (UCI), TMPT 1811.00559 & PRL

QCD Baryogengesis

Djuna Croon (TRIUMF), Jessica Howard (UCI),
Seyda Ipek (UCI), TMPT 1911.01432 & PRD

Dark Matter Freeze Out during an Early Period of QCD Confinement

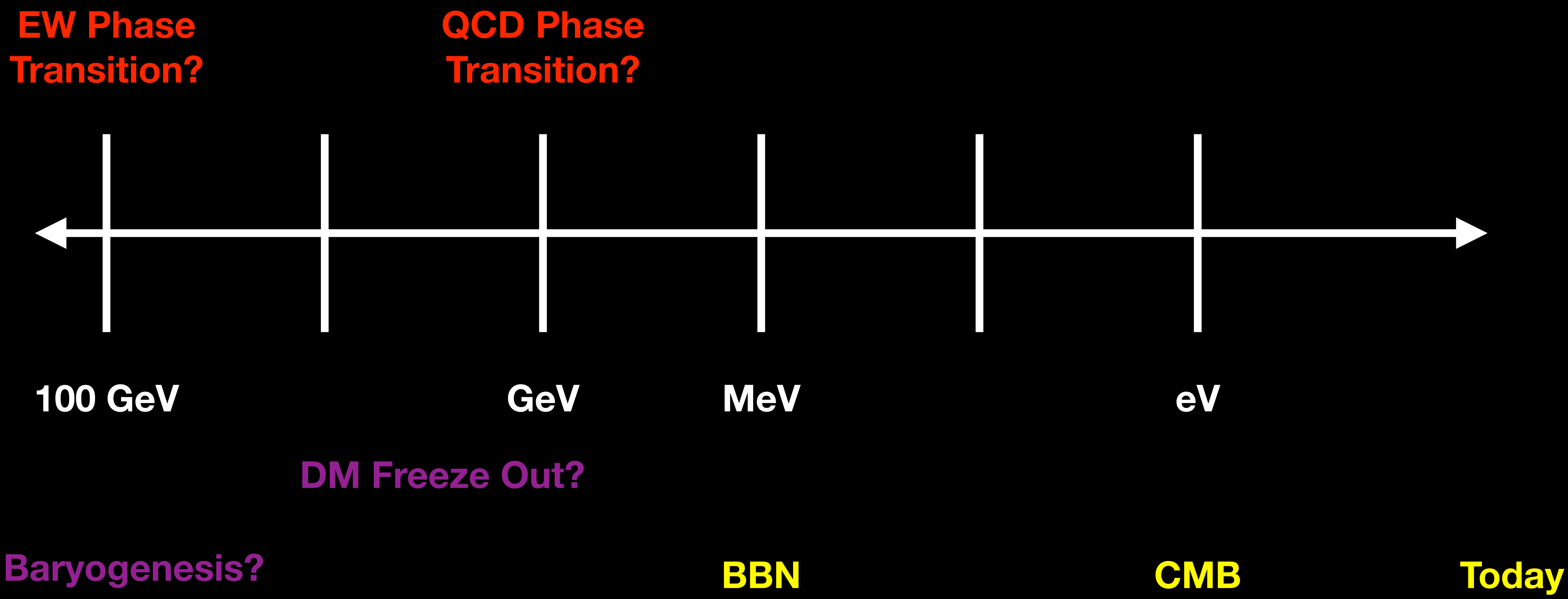
Dillon Berger, Seyda Ipek,
TMPT, Michael Waterbury (UCI)
2004.06727

Outline

- Motivation: Exploring novel cosmologies
- An Early Period of QCD Confinement
- Baryon Asymmetry
- Dark Matter Freeze-out
- Outlook

Introduction

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 ~GeV.

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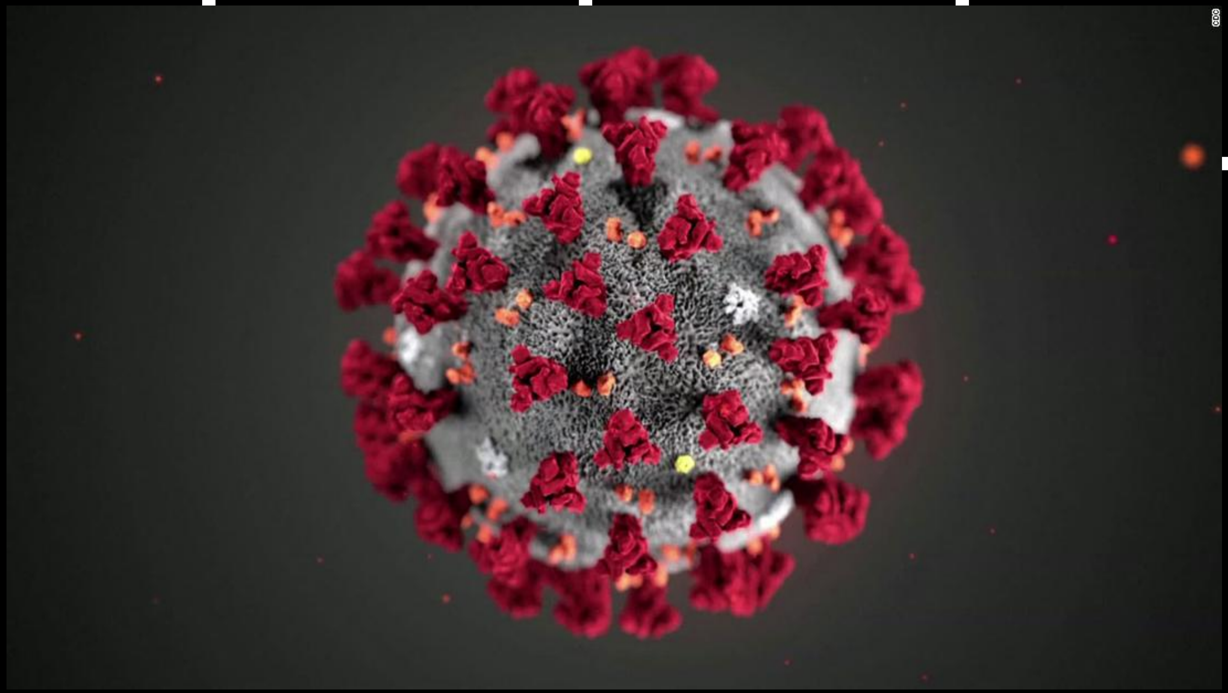

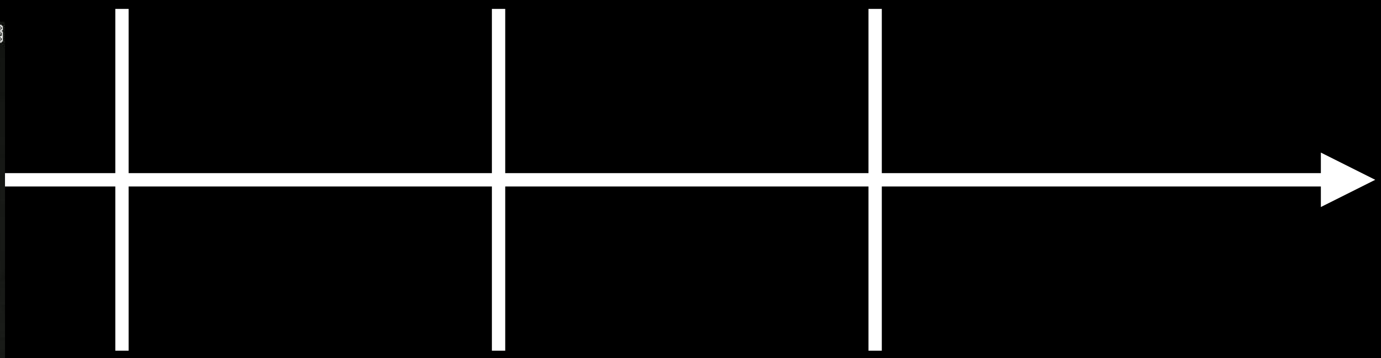

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Motivation

- If we’re hoping to learn about fundamental physics from early cosmological probes such as the abundances of dark matter or baryons, knowledge of the cosmological history of the Universe is essential.
- A non-standard picture, even at early times, could distort how we interpret these observations. We need to have some understanding of the space of possibilities to put them into context.
- The idea that coupling “constants” could have taken different values at different times is a familiar one. We have very good indications that at late times any such evolution was very slow.
- At times before BBN, there is still some room for a theoretical physicist to play.

Motivation

- I will focus on the rather radical idea that QCD has such a different coupling at some early epoch that it actually confines at that time with a much larger confinement scale than the Λ ~ 1 GeV of the Standard Model.
- Before BBN, it must relax back to something that looks a lot like the Standard Model with Λ ~ 1 GeV.
- Of course, more modest modifications are interesting and could even be considered more likely.

E.g. Electroweak Baryogenesis from Temperature-varying Couplings
S.A.R. Ellis, S. Ipek, G. White 1905.11994 & JHEP

- So why jump to the dramatic case first?
    - It does seem to recast old problems in a new light.
    - It's fun!
- One can play similar games with SU(2) Weak and get an even weirder Universe than the one I will describe…

Phases of Confined Electroweak Force in the Early Universe
J. Berger, A. Long, J. Turner 1906.05157 & PRD

A Period of Early Confinement

Strong Coupling

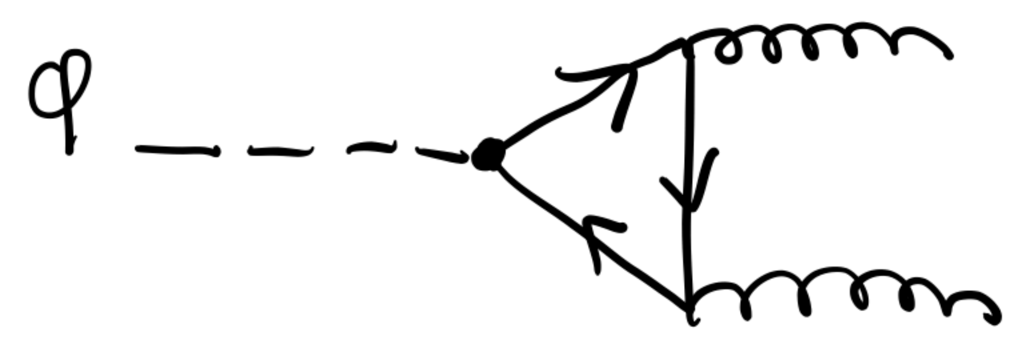
- We introduce dynamics promoting the strong coupling to a dynamical field (denoted by ϕ or S):

1811.00559

$$-\frac{1}{4}\left(\frac{1}{g_0^2}+\frac{\phi}{M_*}\right)G^{\mu\nu}G_{\mu\nu}$$

$$g_{\text{eff}}^2\left(\langle\phi\rangle\right)=\frac{g_0^2}{1+g_0^2\frac{\langle\phi\rangle}{M_*}}$$

- 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:

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

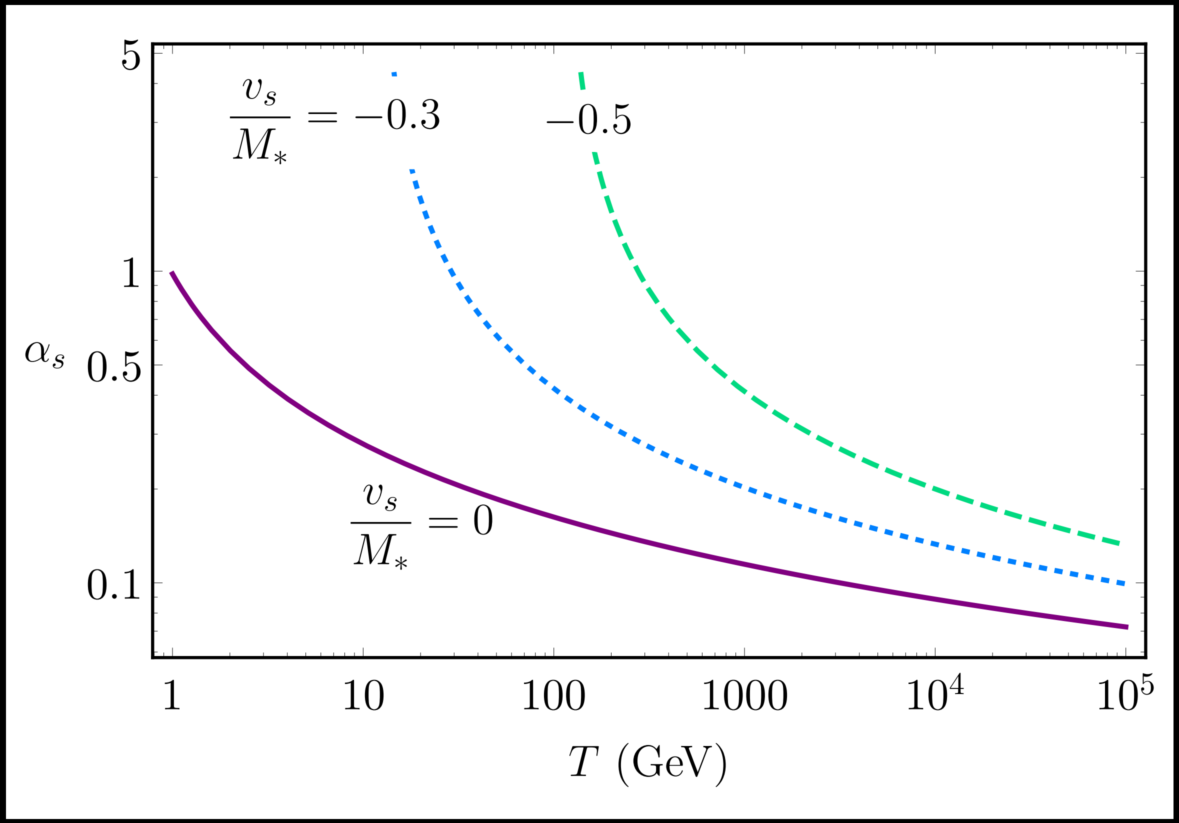
- The scale at which QCD gets strong is about:

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

- For $n_f = 6$, to get Λ ~ TeV:

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

- This is pushing the EFT. If induced radiatively, it would require ~10 vector-like quarks at M_*.



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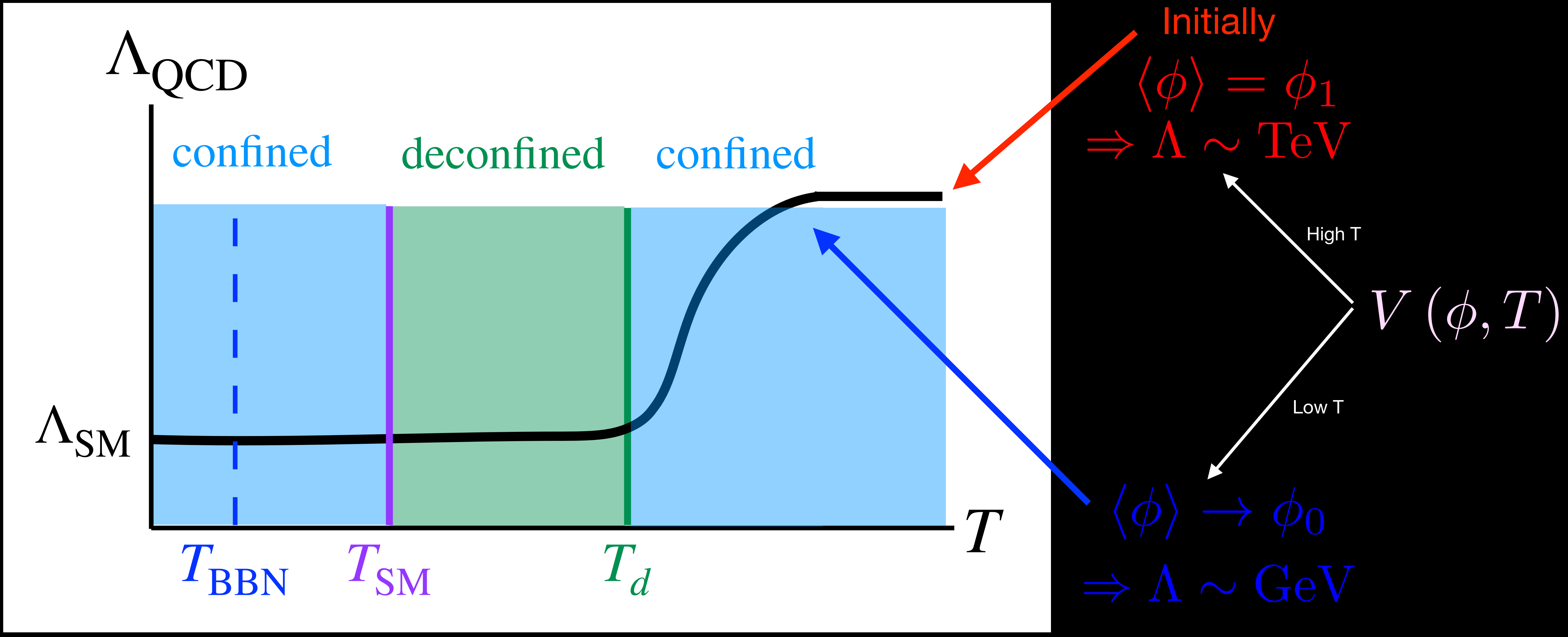
Φ Potential

- The potential for ϕ should receive temperature-dependent corrections such that <ϕ> shifts, moving from a value at high temperatures corresponding to a large Λ to a value at low temperatures matching on to Λ ~ 1 GeV.



Initially

$\langle \phi \rangle = \phi_1$

$\Rightarrow \Lambda \sim \text{TeV}$

$V(\phi, T)$

$\langle \phi \rangle \to \phi_0$

$\Rightarrow \Lambda \sim \text{GeV}$

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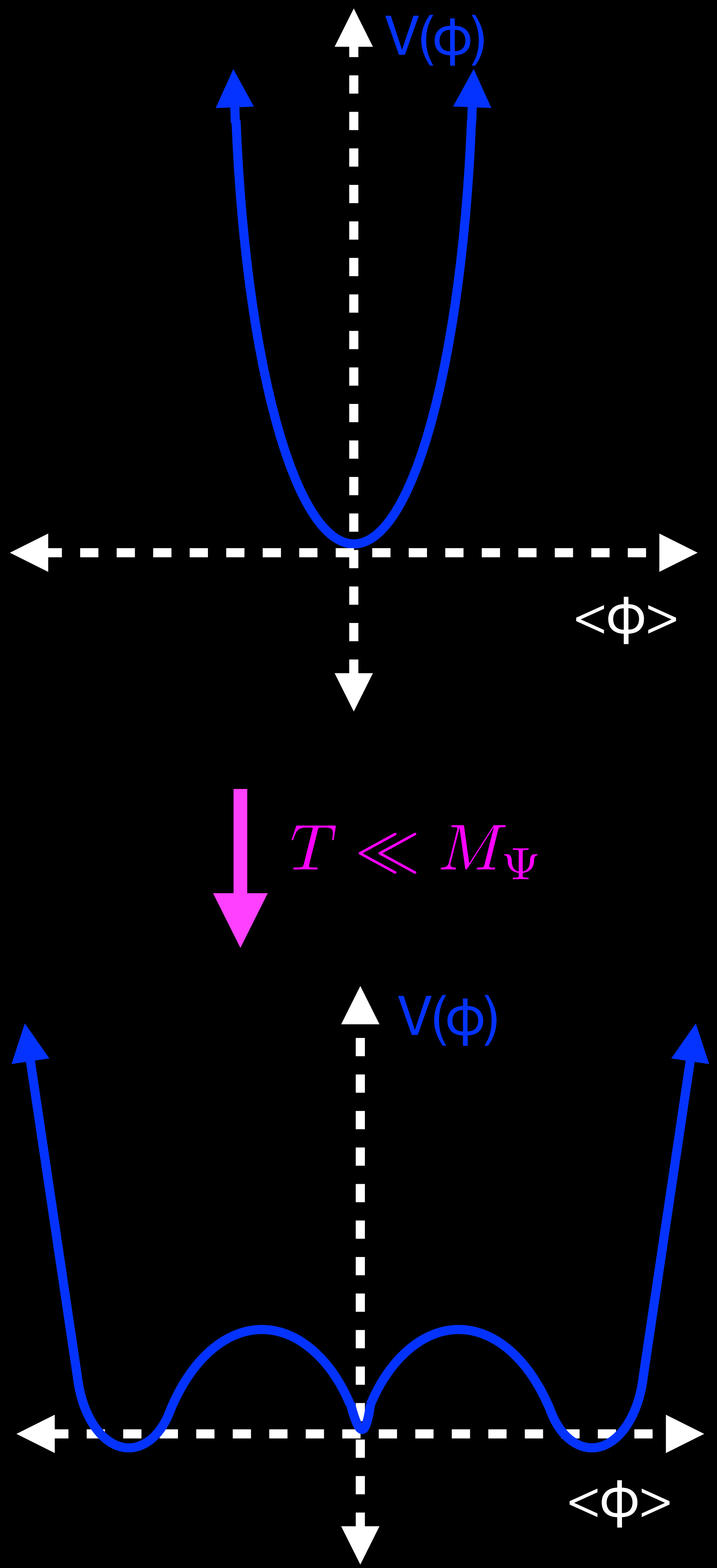
Thermal Corrections

- One could imagine different ways to obtain appropriate thermal corrections to the ϕ potential.
- For example, there could be some new fields Ψ with O(1) couplings to ϕ and masses around the ~TeV scale.
- At T~m, their corrections become exponentially suppressed.
- 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.



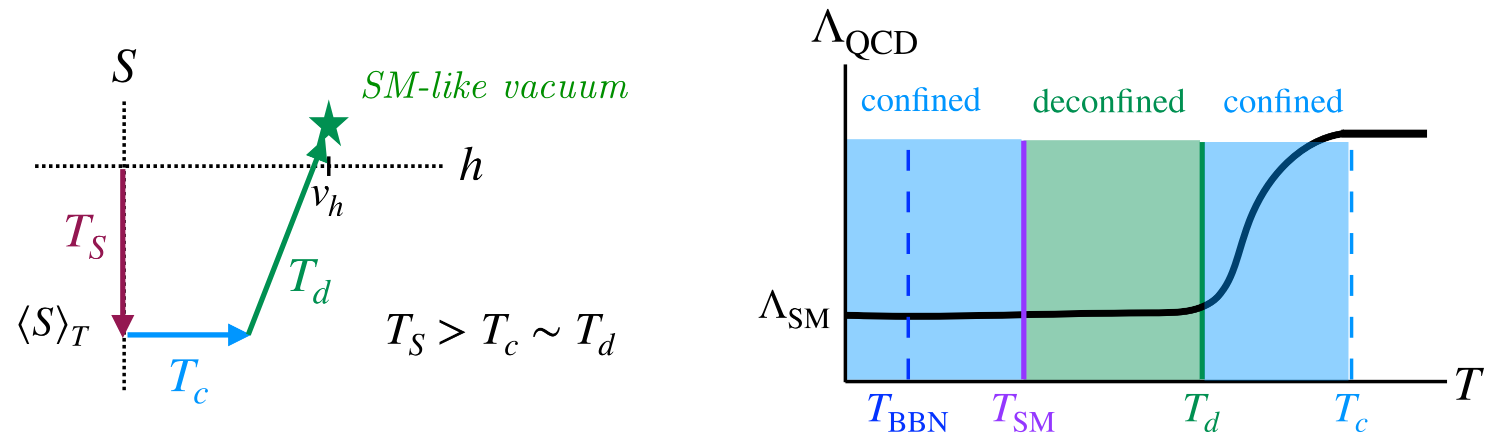
Higgs Interactions

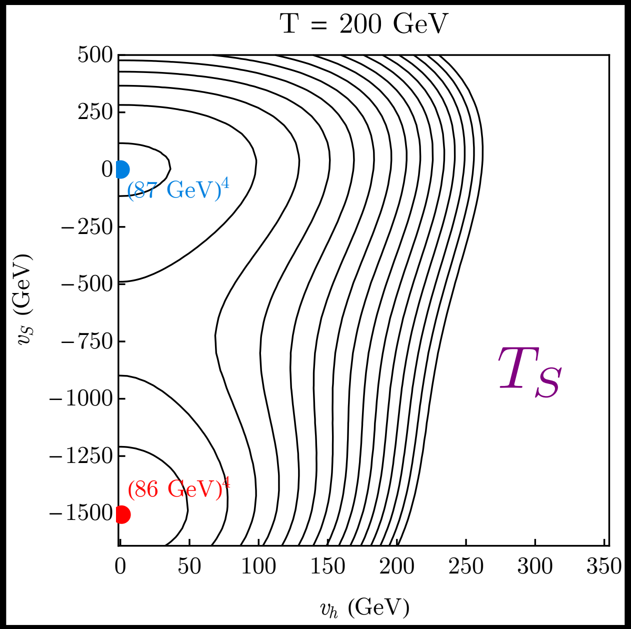
- Another option would be to make use of the (inevitable) cross interactions between the SM Higgs and the singlet.

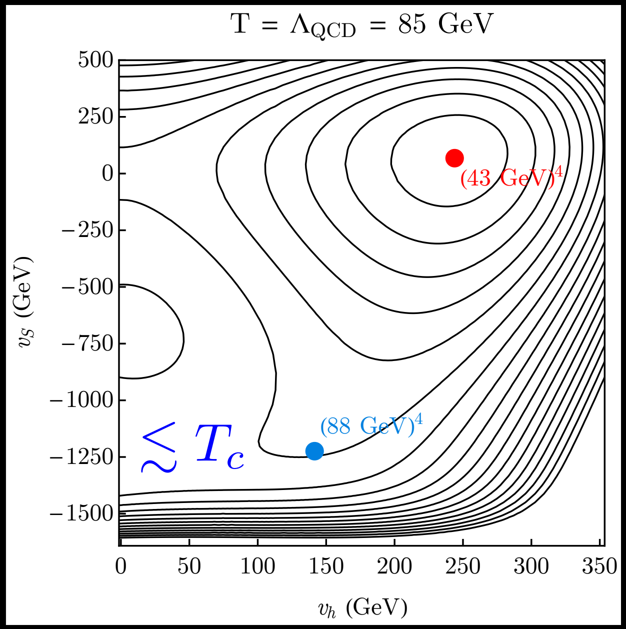
$$
\begin{aligned}
V(H) &= -\mu^2|H|^2 + \lambda_h|H|^4 \ , \\
V(S) &= a_2(S-S_0)^2 + a_3(S-S_0)^3 + a_4(S-S_0)^4 \ , \\
V(H,S) &= -b_1 S|H|^2 + b_2 S^2|H|^2 .
\end{aligned}
$$

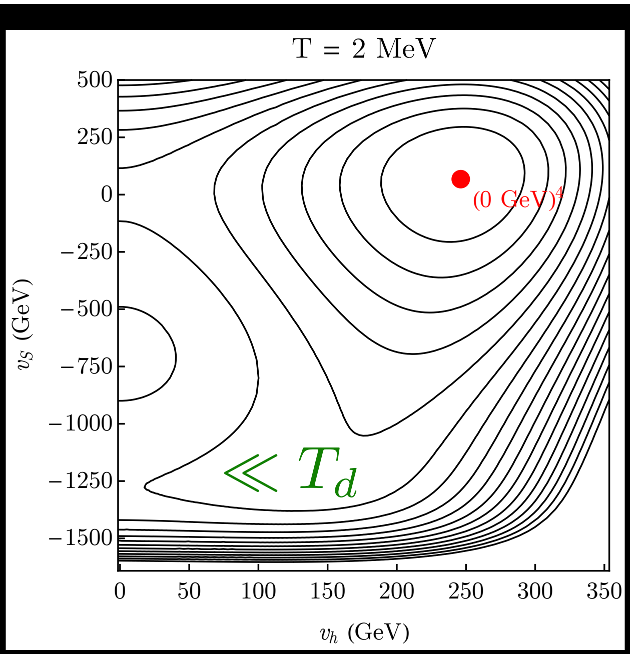
- The Higgs potential is also evolving with temperature, and its evolution could trigger a switch in the singlet potential to a new minimum.

- Since this picture requires balance between the singlet and Higgs potentials, it works effectively when the dynamics is close to the weak scale.




T = 200 GeV


T = $\Lambda_{\rm QCD}$ = 85 GeV


T = 2 MeV

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● Global Minimum

◆ Local Minimum

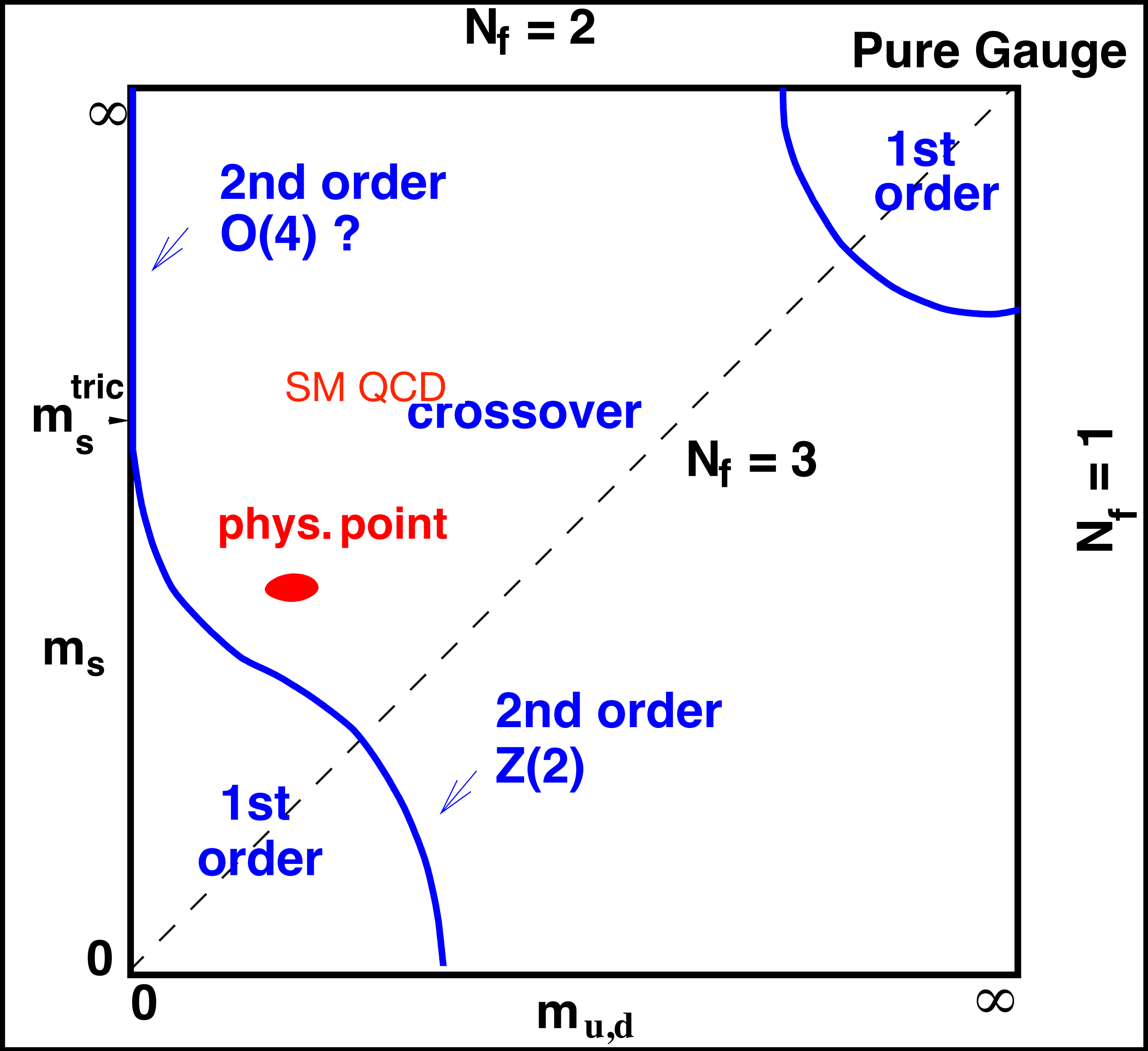
QCD Phase Transition

- The (first) QCD phase transition takes place at high temperatures, before the electroweak breaking, and thus with massless SM quarks.
    - For $n_F = 6$ massless flavors, this is expected to be a first order transition.

Pisarski, Wilczek, PRD29, 338 (1984)

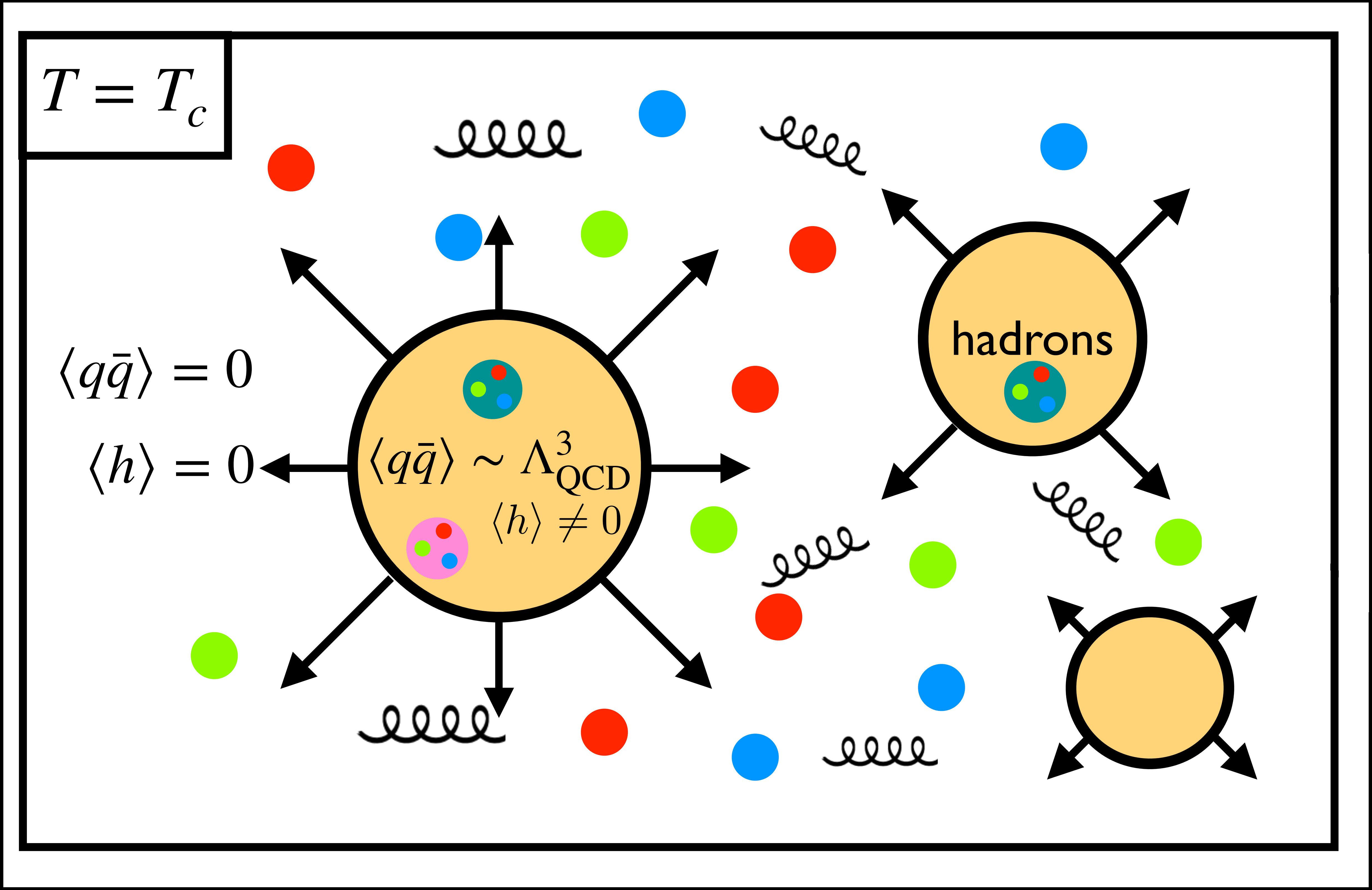
- The confined vacuum forms via bubble nucleation.
- After confinement, chiral symmetry breaking also breaks the electroweak symmetry, and the condensate acts as a tadpole for the Higgs, inducing a VEV for it.

2+1 Flavor QCD Phase Diagram



Review by Schaefer & Wagner 0812.2855

QCD Phase Transition



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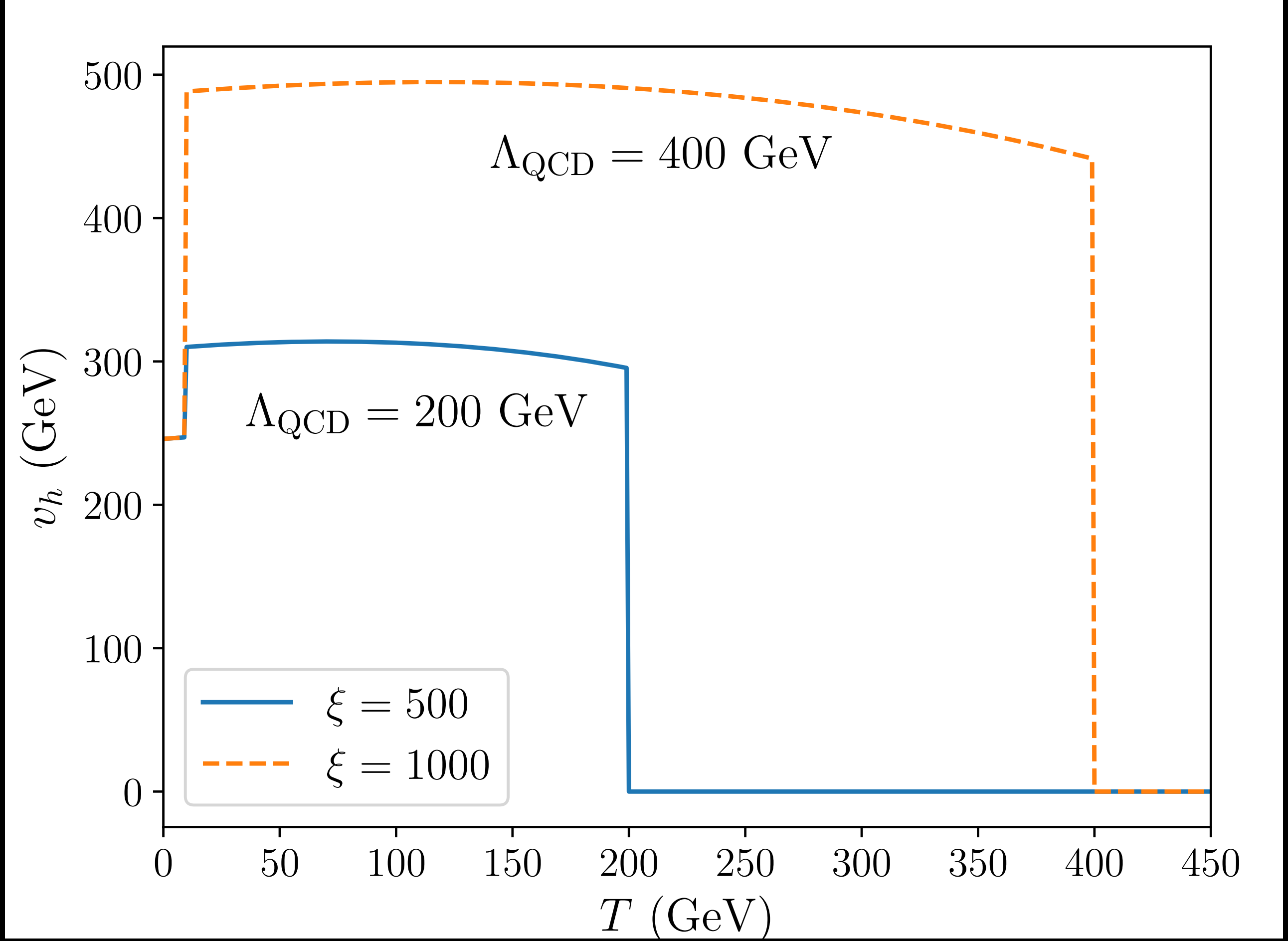
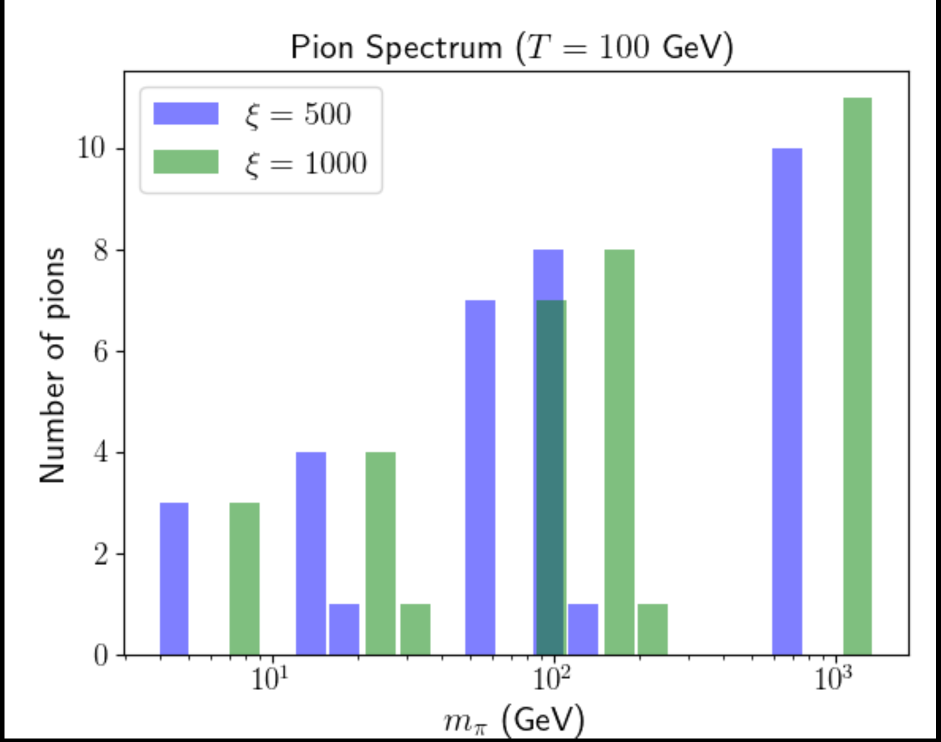
Confined Universe

- In the confined phase, the important active degrees of freedom are the ~35 pNGB mesons.
  - Their properties are described by chiral perturbation theory, with parameters matched to low energy QCD data, and dimensionful quantities scaled up to the high scale confinement scale.

$$\kappa \simeq (220\ \mathrm{MeV})^3\, \xi^3\ , \qquad f_\pi \simeq 94\ \mathrm{MeV}\, \xi, \qquad m_\pi^2 \simeq m_{\pi 0}^2\, \xi\, v_h / v_h^0,$$



- The thermal corrections to the Higgs potential are dominated by the top-flavored (or bottom-flavored) mesons rather than top/bottom quarks.



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- The chiral condensate acts as a tadpole for the Higgs doublet.

$$\kappa\ \mathrm{tr}(U M_q^\dagger + M_q U^\dagger) \longrightarrow \sqrt{2}\kappa\, y_t\, h - \frac{\kappa}{f_\pi^2}\, \mathrm{tr}[\{T^a, T^b\} M]\, \pi^a \pi^b\ ,$$

Spontaneous Baryogenesis

Strong CP Phase

- Famously, the Standard Model does not have sufficient CP violation in the CKM phase to generate a sufficient baryon asymmetry.

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

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

- 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.

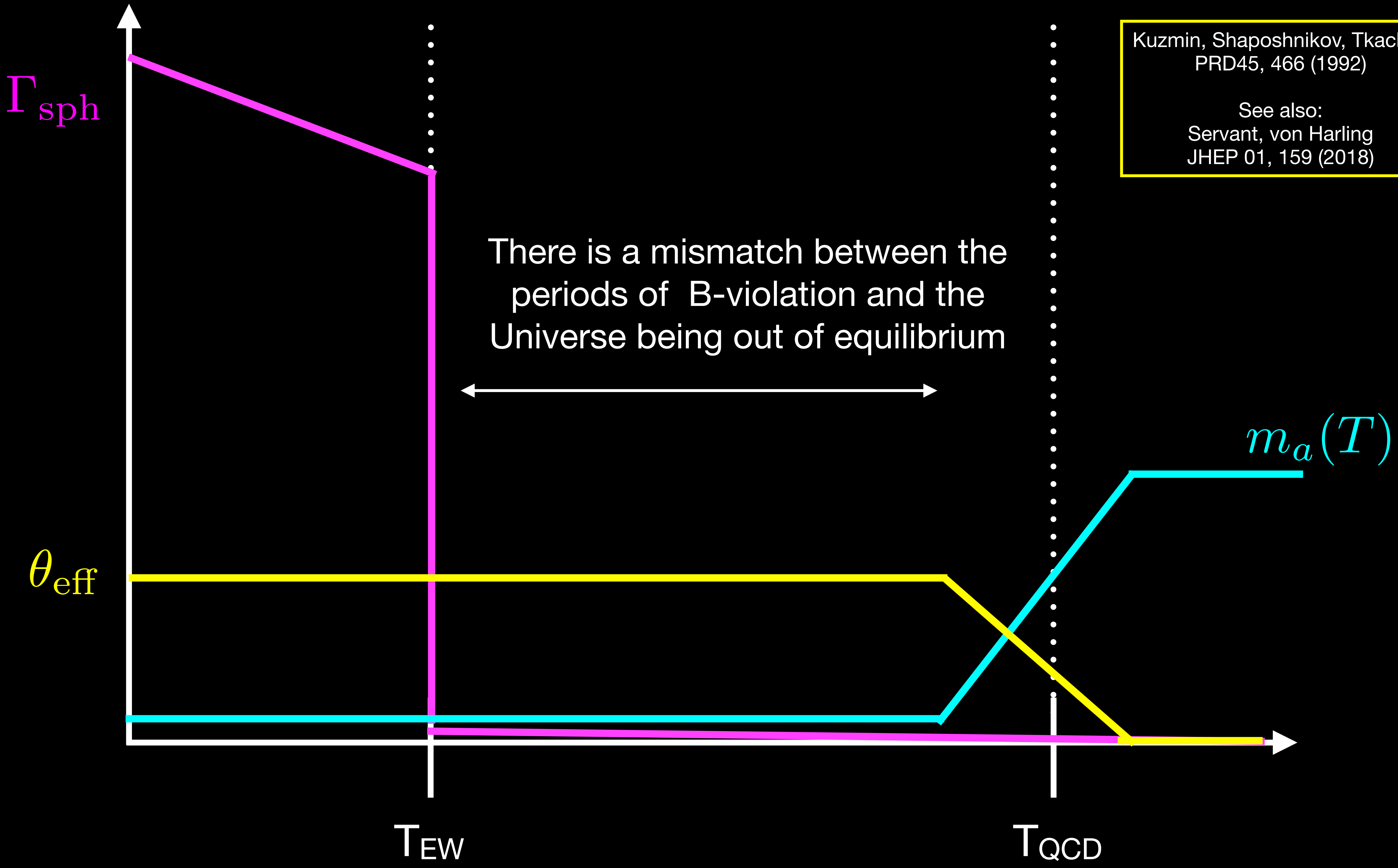
$$\frac{\alpha_S}{8\pi}\left[\bar{\theta} + \frac{a(x)}{f_a}\right]\; G^{\mu\nu}\widetilde{G}_{\mu\nu}$$

- In some sense, this is another way in which one imagines that the properties of the strong nuclear force are different in the early Universe than they are today for dynamical reasons.

- The rolling of the axion to its minimum also provides an out-of-equilibrium condition necessary to produce a net baryon asymmetry.

Kuzmin, Shaposhnikov, Tkachev PRD45, 466 (1992)

The Challenge



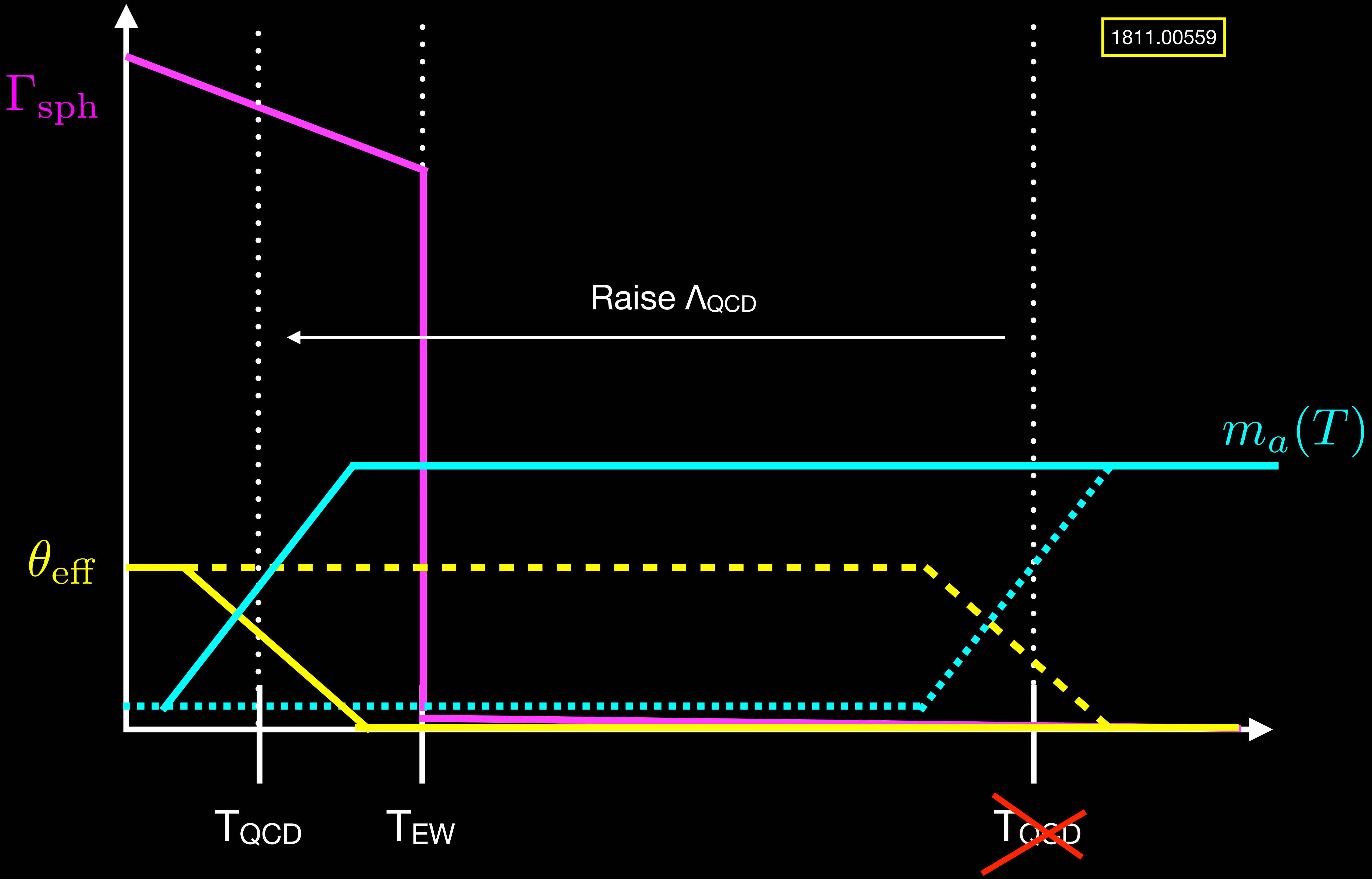
There is a mismatch between the periods of B-violation and the Universe being out of equilibrium

Kuzmin, Shaposhnikov, Tkachev
PRD45, 466 (1992)

See also:
Servant, von Harling
JHEP 01, 159 (2018)

(KST addressed this challenge by invoking a super-cooled electroweak phase transition.)

Early Confinement

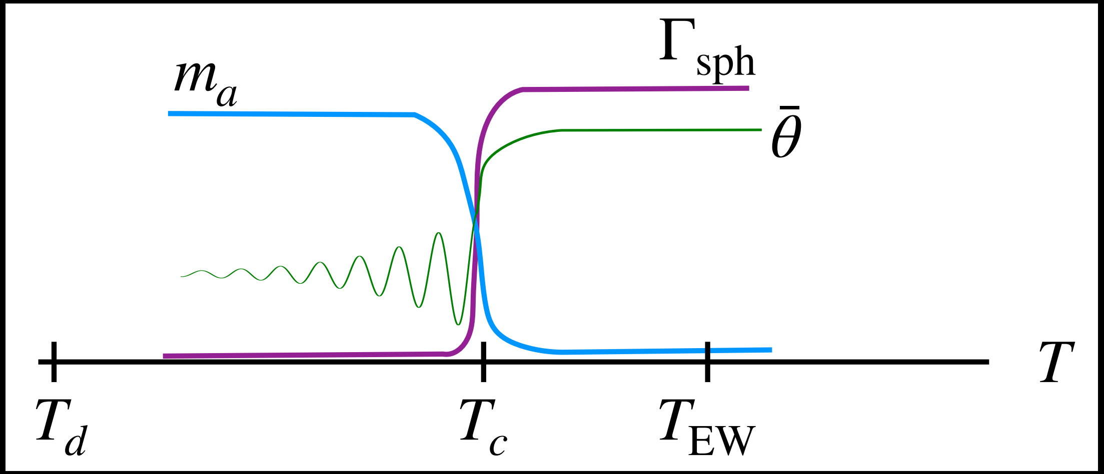


Spontaneous Baryogenesis

- 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 $W\widetilde{W}$:



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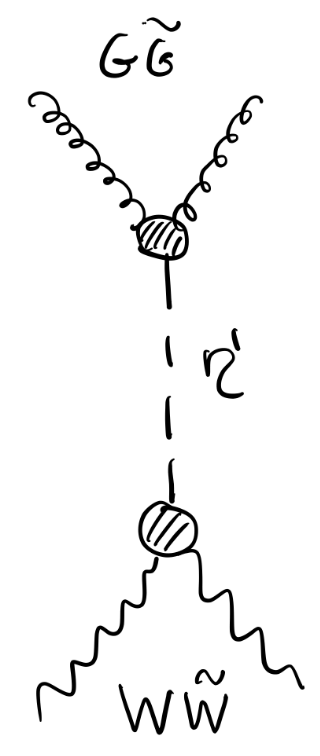
$$\mathcal{L}_{\text{eff}} = \frac{10}{f_\pi^2\ m_{\eta'}^2}\frac{\alpha_S}{8\pi}\frac{\alpha_W}{8\pi}\ G\widetilde{G}\ W\widetilde{W}$$

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



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:

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

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

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

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

Baryon Asymmetry

- The resulting baryon asymmetry is:

$$\eta = \frac{n_B}{s} \simeq \frac{45 \times 125}{2\pi^2 g_* \left(T_{\rm reh}\right)} \alpha_w^5 \sin\bar{\theta} \frac{\Delta \left[m_a^2(T) f_a^2\right]_{T_c}}{m_{\eta'}^2 f_\pi^2} \left(\frac{T_{\rm sph}}{T_{\rm reh}}\right)^3$$

$$\simeq 10^{-11} \sin\bar{\theta} \left(\frac{v_h}{\Lambda_{\rm QCD}}\right) \left(\frac{T_{\rm sph}}{T_{\rm reh}}\right)^3$$

- $T_{\rm sph}$ represents the temperature at which the sphalerons switch off.

- $T_{\rm reh}$ is the “reheat” temperature, and allows for the possibility additional entropy production during the phase transition.

(g* ~ 30 during confinement)

- Since the electroweak symmetry is strongly broken during the confined phase, as long as the deconfinement temperature is below the usual electroweak transition (so the sphalerons never switch back on), one expects $T_{\rm sph} \sim T_{\rm reh}$.

- This is the right ballpark provided that the initial misalignment of the axion is O(1) and the potential is such that the sphalerons switch off fast enough.

WIMP
Freeze Out

WIMP Dark Matter

- Let’s imagine that there is a WIMP-like particle which is a (SM singlet) Dirac fermion that likes to interact with quarks.
- If the mediators are heavy compared to the energies of interest, this can be parameterized by a dimension six operator.
- For simplicity, I will also imagine that this is a scalar interaction, and its flavor structure is minimal-flavor violating (MFV), matching the quark Yukawa interactions.
- (If the singlet field is heavy and has some mixing with the Higgs, this is the kind of low energy interaction it would mediate).
- If the WIMP further freezes out during the confined phase, its interactions are with mesons rather than quarks, which are enhanced by Λ.
- The chiral condensate can shift the DM mass by a non-trivial amount!

2004.06727

$$\frac{\beta_{ij}}{M_S^2}\bar{\chi}\chi\ \bar{q}_i q_j$$

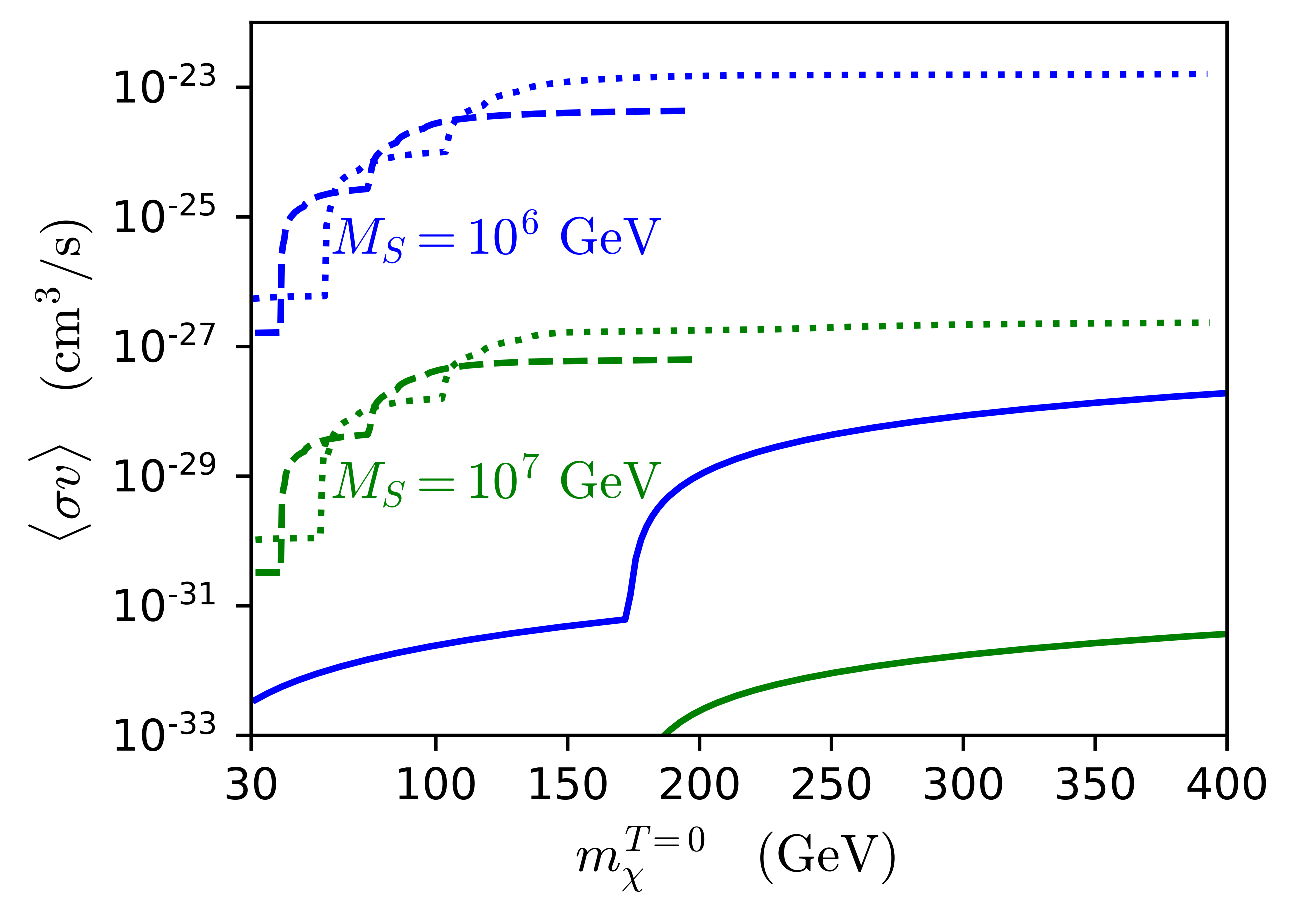
$$\beta_{ij} \equiv \pm\delta_{ij}\frac{y_i}{y_u}$$

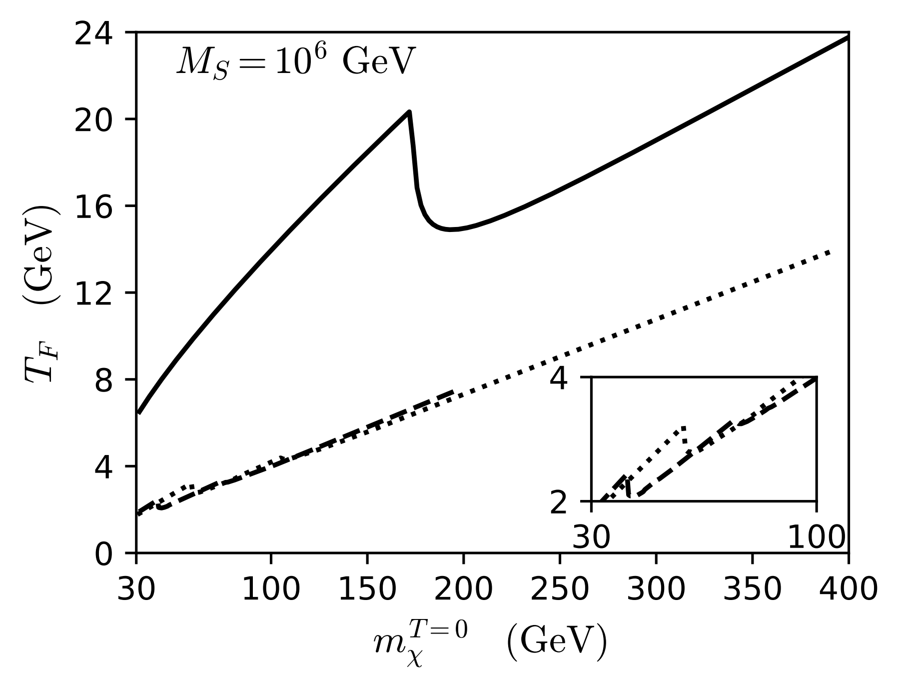
$$\frac{\kappa}{M_S^2}\ \bar{\chi}\chi\ \mathrm{tr}\left(U^\dagger\beta + U\beta^\dagger\right)$$

$$\frac{2\kappa\ \mathrm{tr}\left[\beta\right]}{M_S^2}\ \bar{\chi}\chi + \frac{2\kappa}{f_\pi^2}\frac{1}{M_S^2}\ \mathrm{tr}[T^aT^b\beta]\ \bar{\chi}\chi\pi^a\pi^b$$

$$m_\chi^{T=T_F} = m_\chi^{T=0} + \Delta m_\chi\ , \quad \text{where}\ \ \Delta m_\chi \simeq (2\ \text{eV})\,\xi^3\left(\frac{10^6\ \text{GeV}}{M_S}\right)^2$$

Freeze Out





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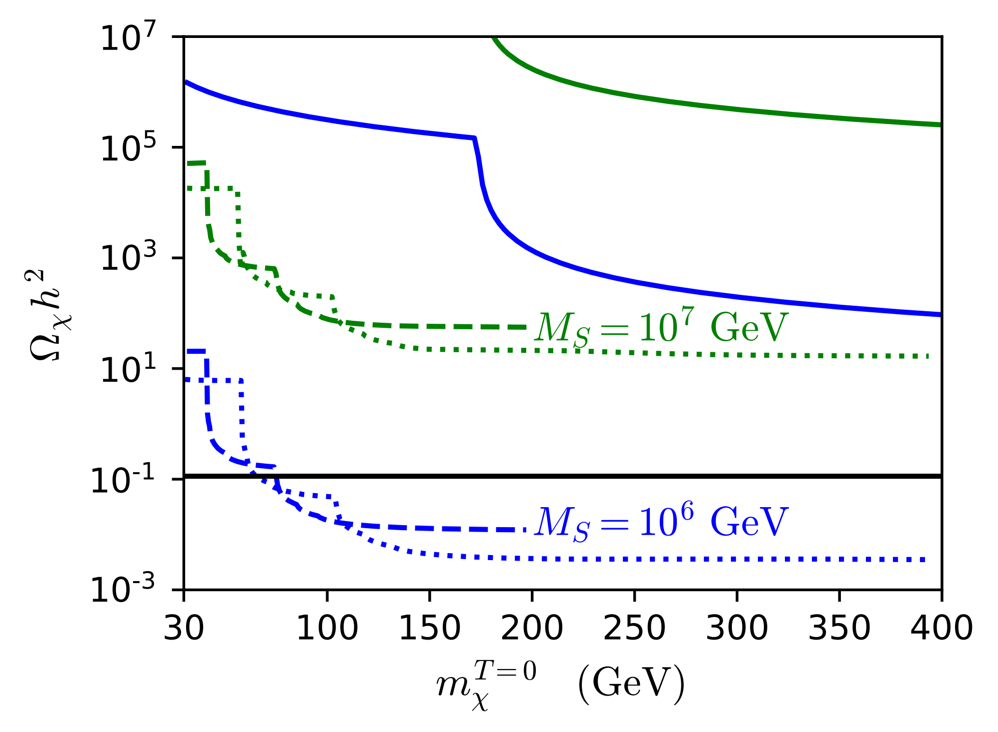
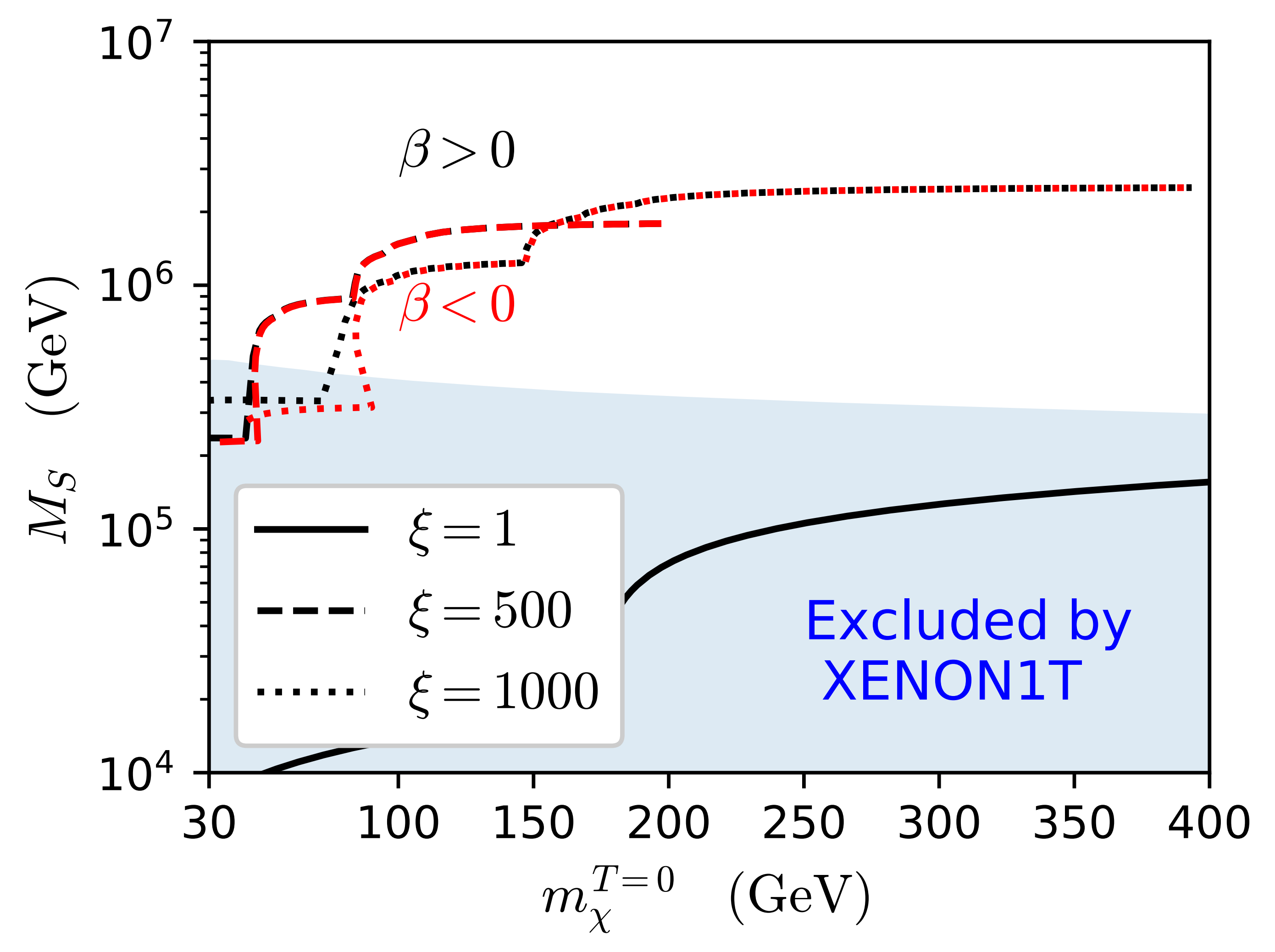
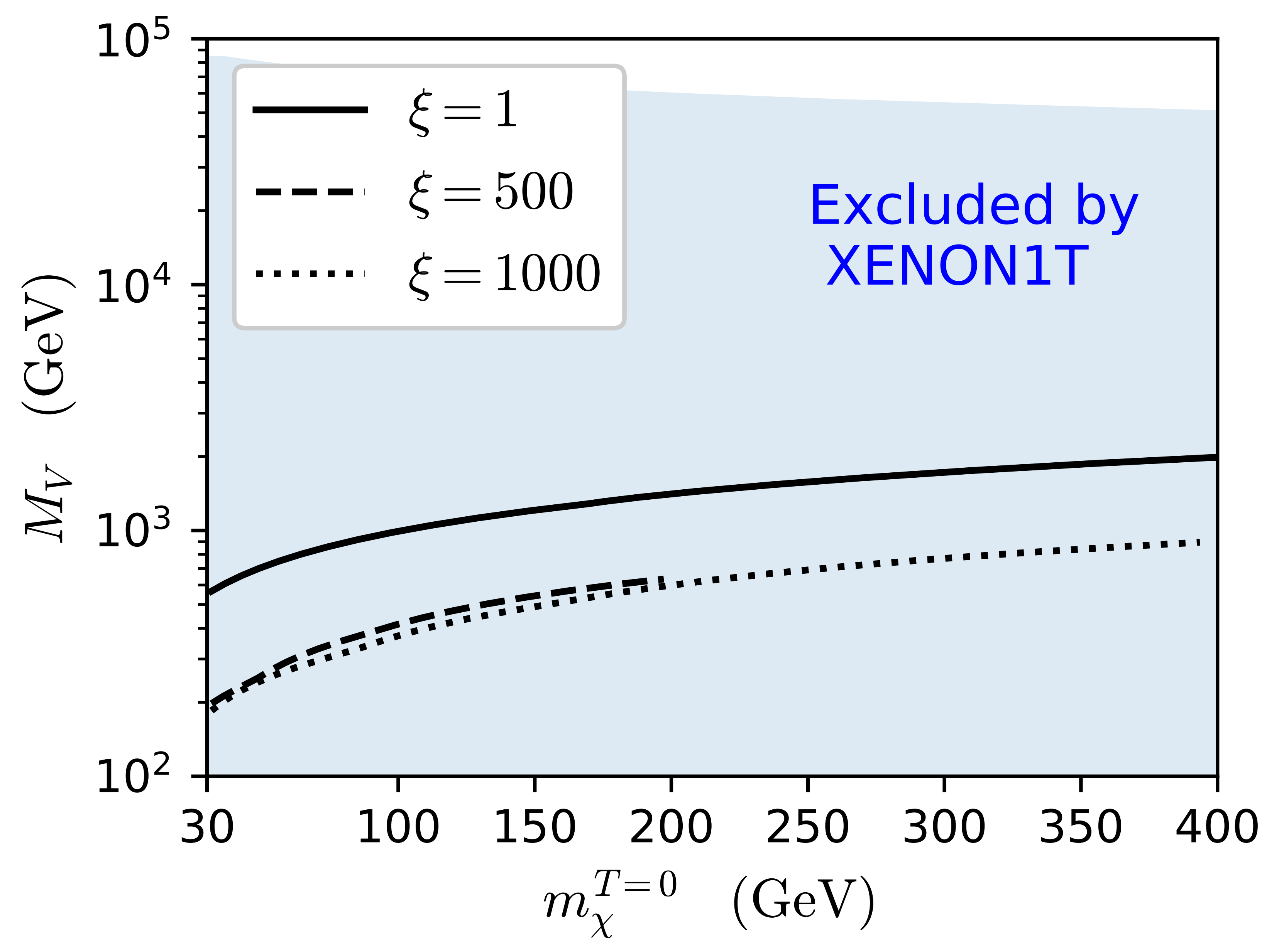




Freeze Out



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The situation is rather different for MFV vector interactions.

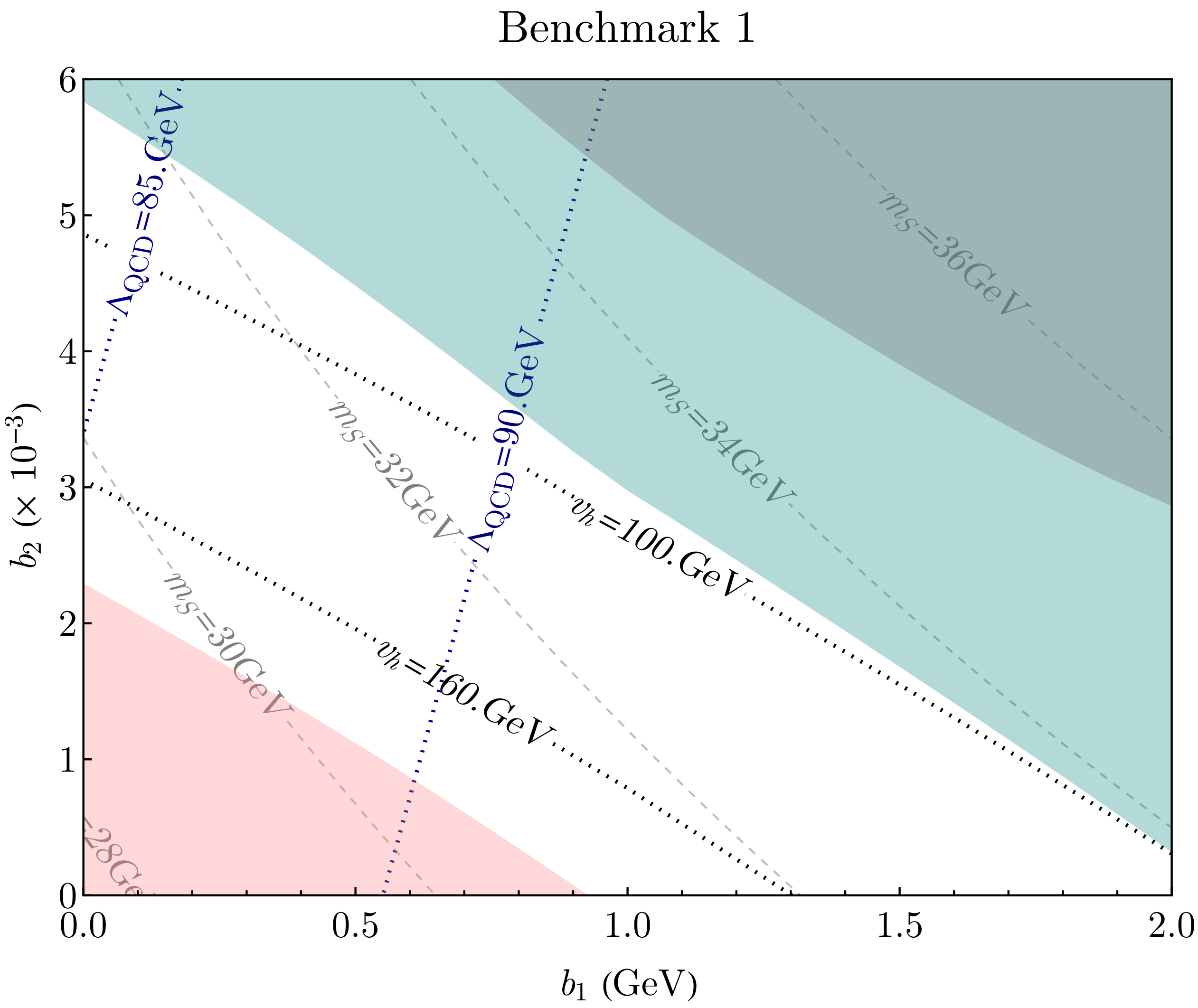
$$\frac{\lambda_{ij}}{M_V^2}\bar{\chi}\gamma^\mu\chi\ \bar{q}_i\gamma_\mu q_j$$

$$\lambda_{ij} \equiv \begin{cases} \delta_{ij}, & j = u, c, t \\ (1+\alpha)\delta_{ij}, & j = d, s, b \end{cases}$$

$$\frac{2i}{M_V^2} f^{abc}\ \mathrm{tr}[T^b\lambda]\ \bar{\chi}\gamma^\mu\chi\ \pi^a(\partial_\mu\pi^c)$$

Singlet Phenomenology

Parameters



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Higgs VEV switches on too slowly, allowing baryon asymmetry to be washed out by sphalerons.

Higgs VEV switches on too fast, and sphalerons are already inactive by the time the axion starts rolling.

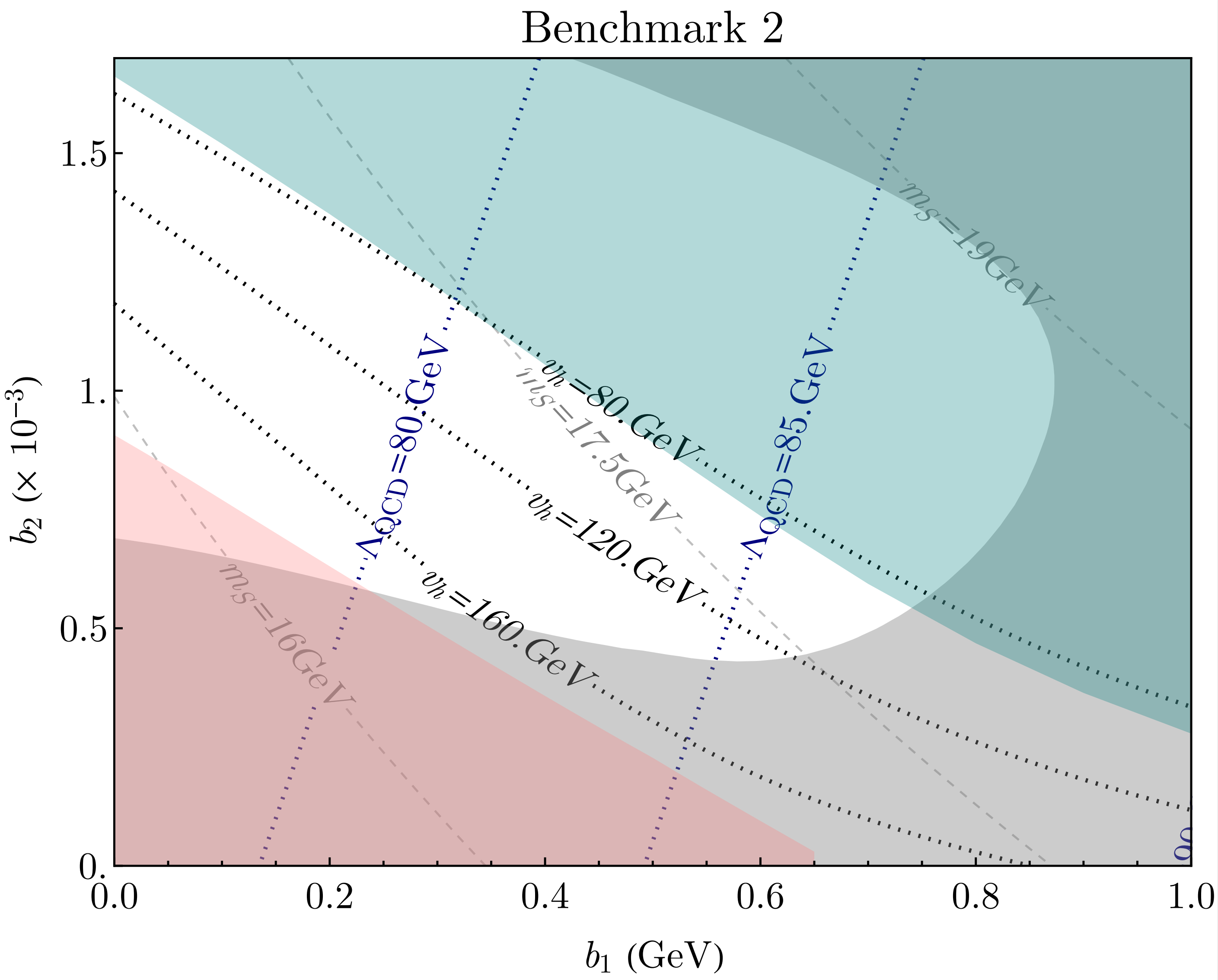
Tunneling to the SM-like vacuum is suppressed and occurs too late for BBN.

Example parameter space motivated by deconfinement triggered by the Higgs

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

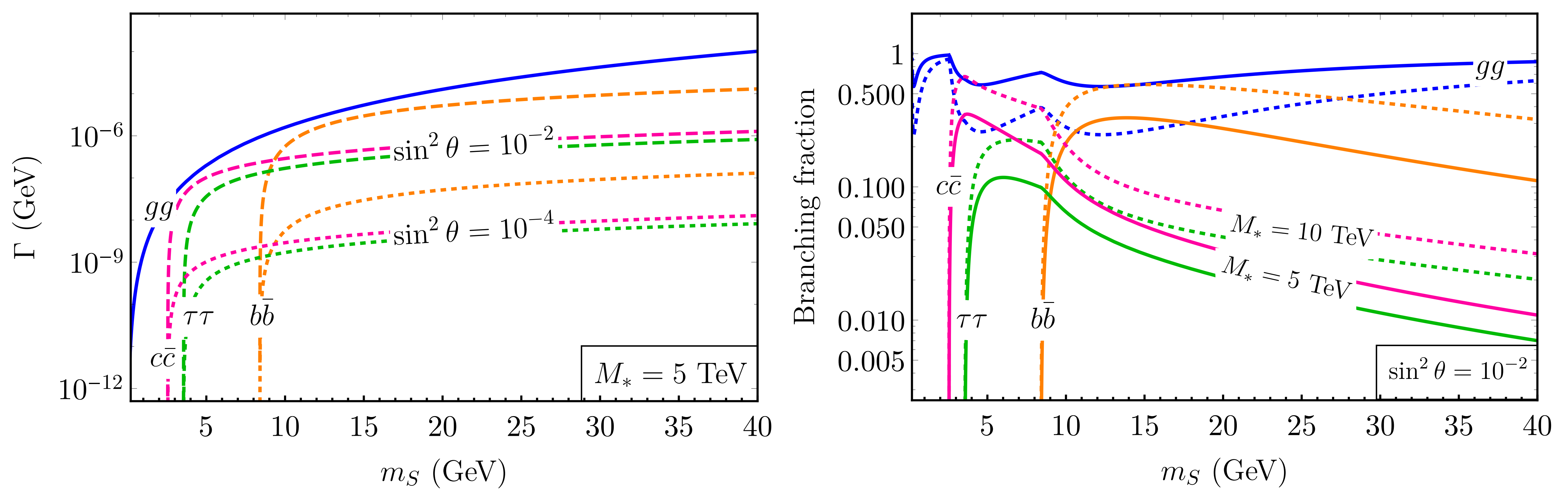
$$V(S) = a_2(S-S_0)^2 + a_3(S-S_0)^3 + a_4(S-S_0)^4 \ ,$$

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



Scalar Properties

- The true hallmark of these dynamics is the presence of the singlet scalar field.
  - It couples to gluons through the dimension 5 interaction characterized by scale M_*.
  - It also picks up scaled down Higgs interactions through mixing with the SM Higgs (but in this parameter space, the mixing $\theta < 10^{-3}$ or so).
  - This is too small for the LHC to see a deviation in the SM-like Higgs properties.
  - There could be additional dark decay modes.



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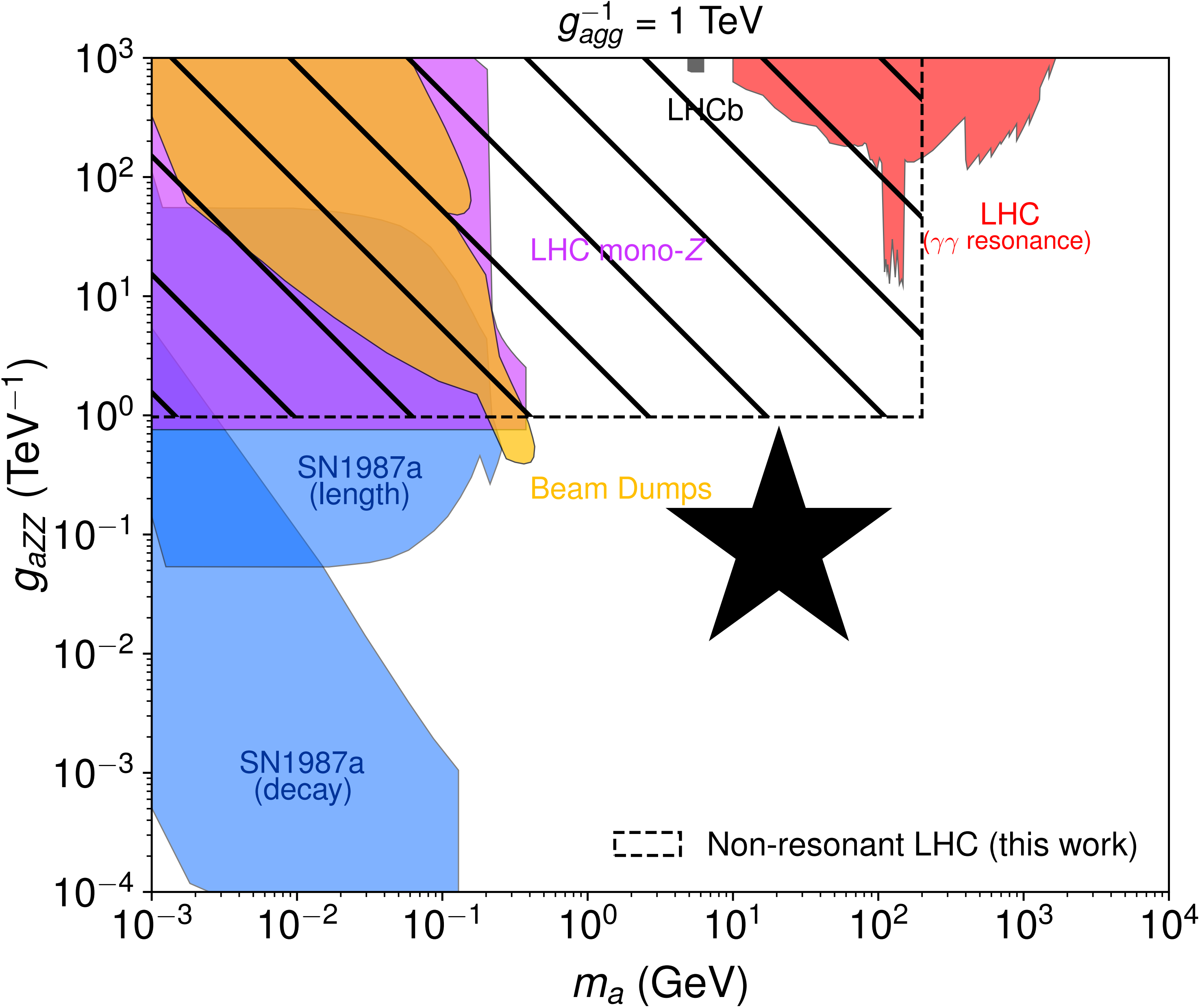
LHC Prospects

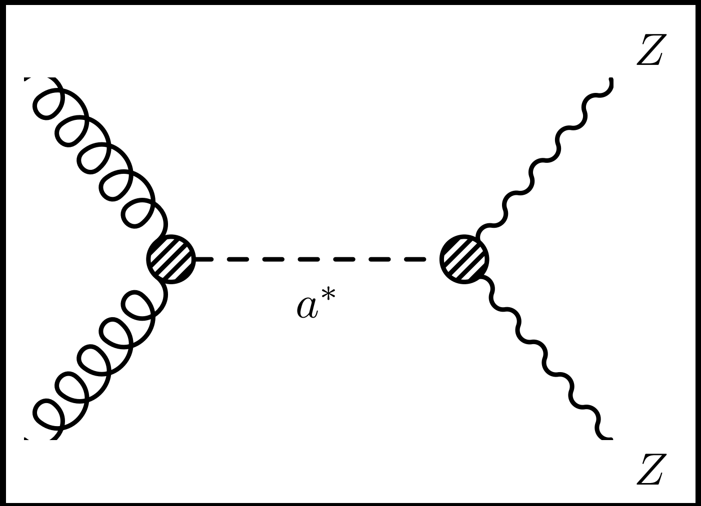
Gavela, No, Sanz, Troconiz 1905.12953

The scalar can be produced off-shell at the LHC through gluon fusion.

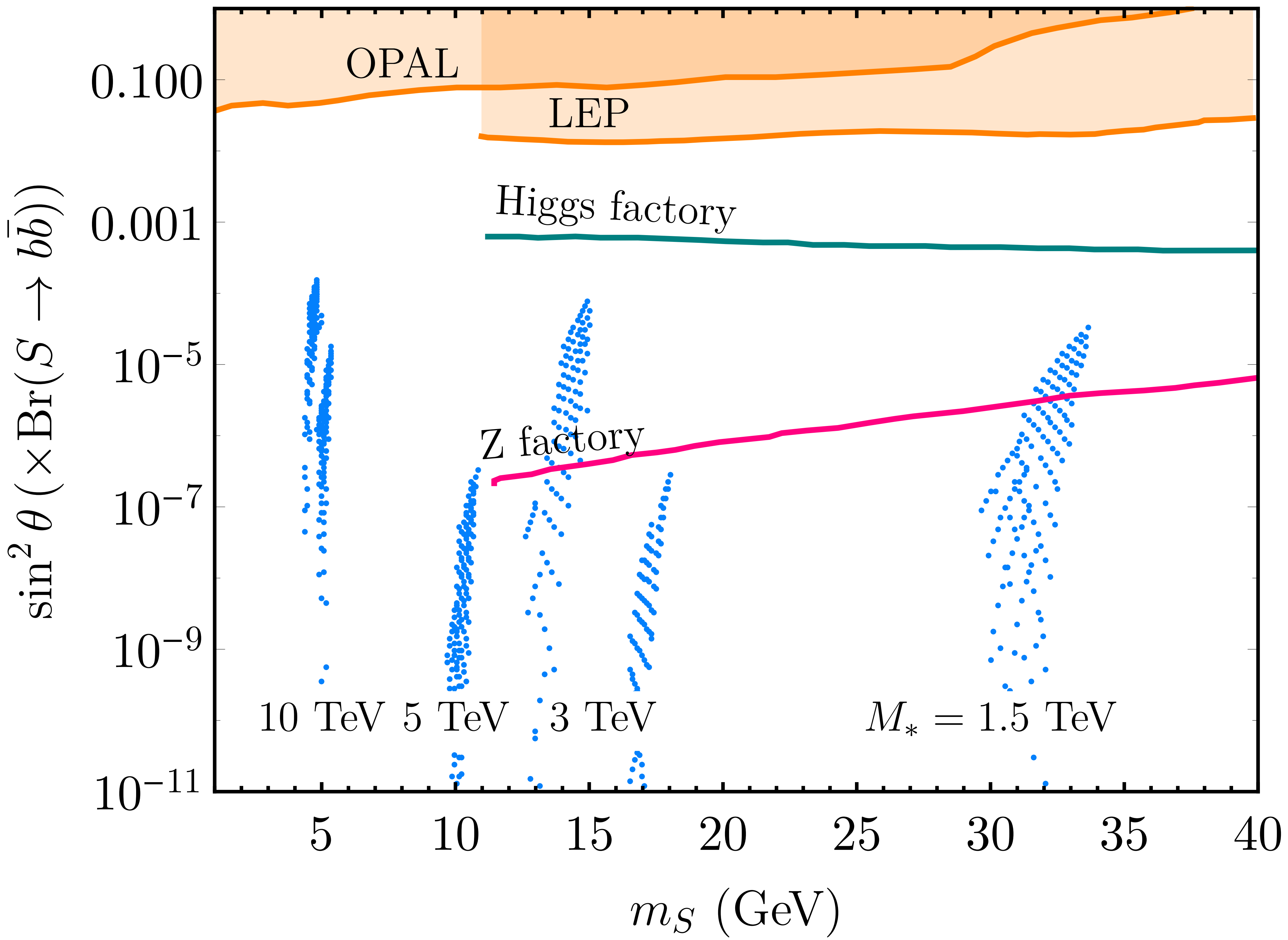
Usually it decays to dijets, which have large backgrounds.

Through mixing with the Higgs, it can also decay into more interesting signatures such as dibosons.





Future Colliders



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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.

- It's worth exploring as part of a general investigation into the possibility that physics may hold surprises in the high temperatures of the early Universe.

- I highlighted a few applications one could imagine related to realizing the baryon asymmetry or rescuing WIMP dark matter that would otherwise have been ruled out by direct searches.

- One could also imagine applications to axion cosmology.

Heurtier, Huang, TMPT, in progress

- I see this as part of a larger program in which we should strive to understand the space of what is possible in the early Universe, how to constrain the space of possibilities, and explore how they could cause us to rethink standard solutions to its mysteries.

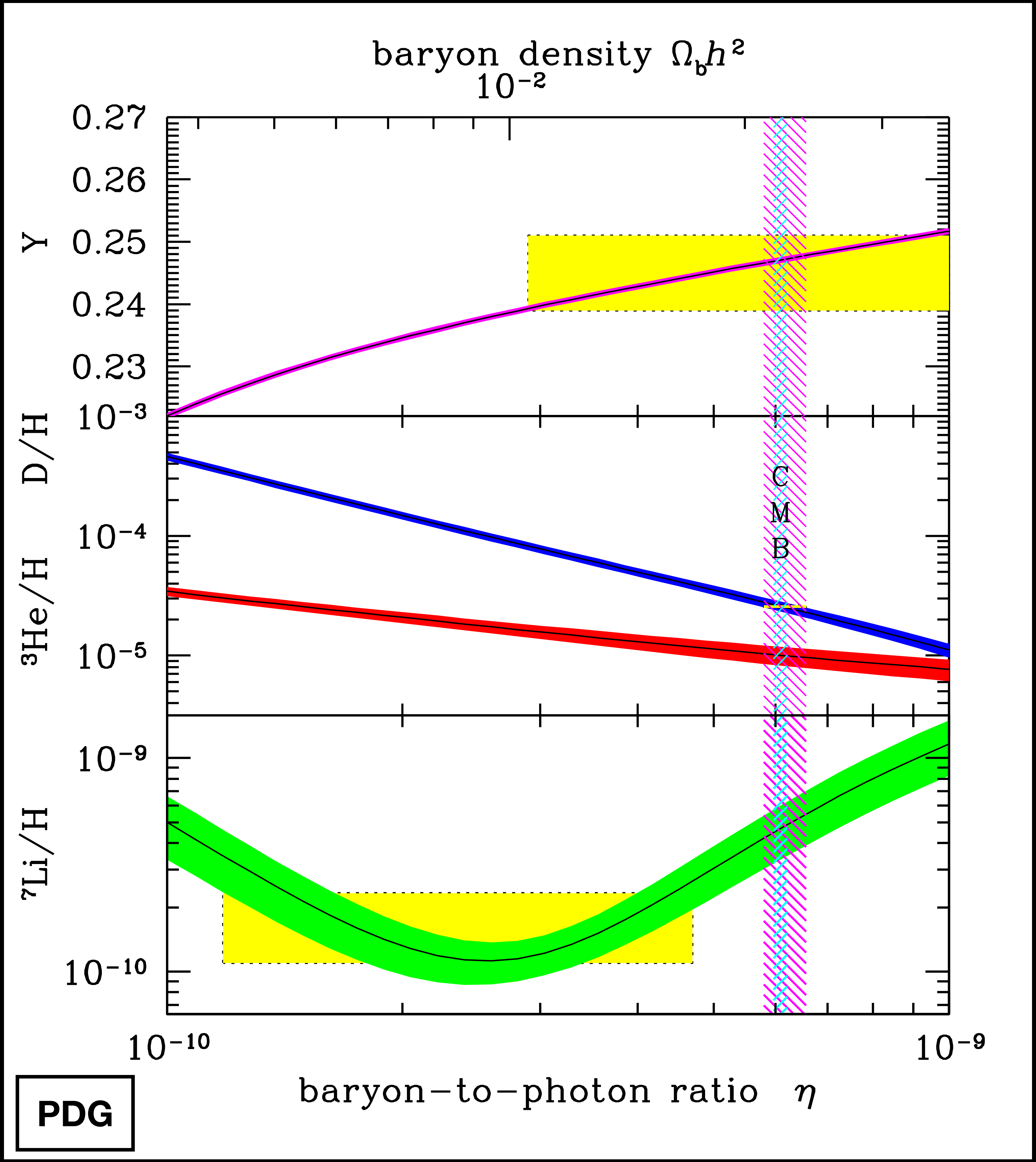
Thank you!

(Especially to Tim, David, Cora, and Mariangela for organizing!)

Bonus Slides

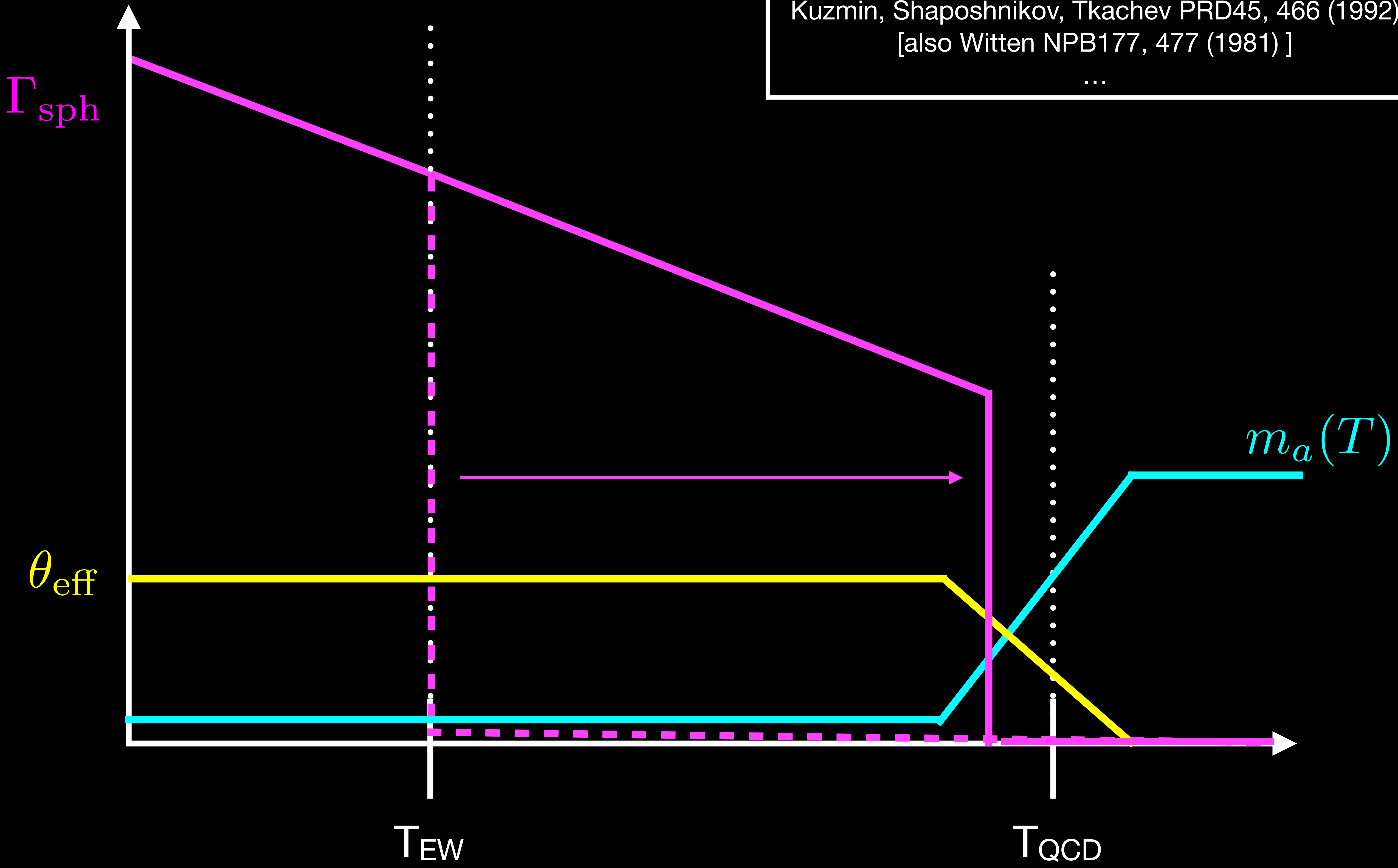
Big Bang Nucleosynthesis

- 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.



Supercooled EW Transition

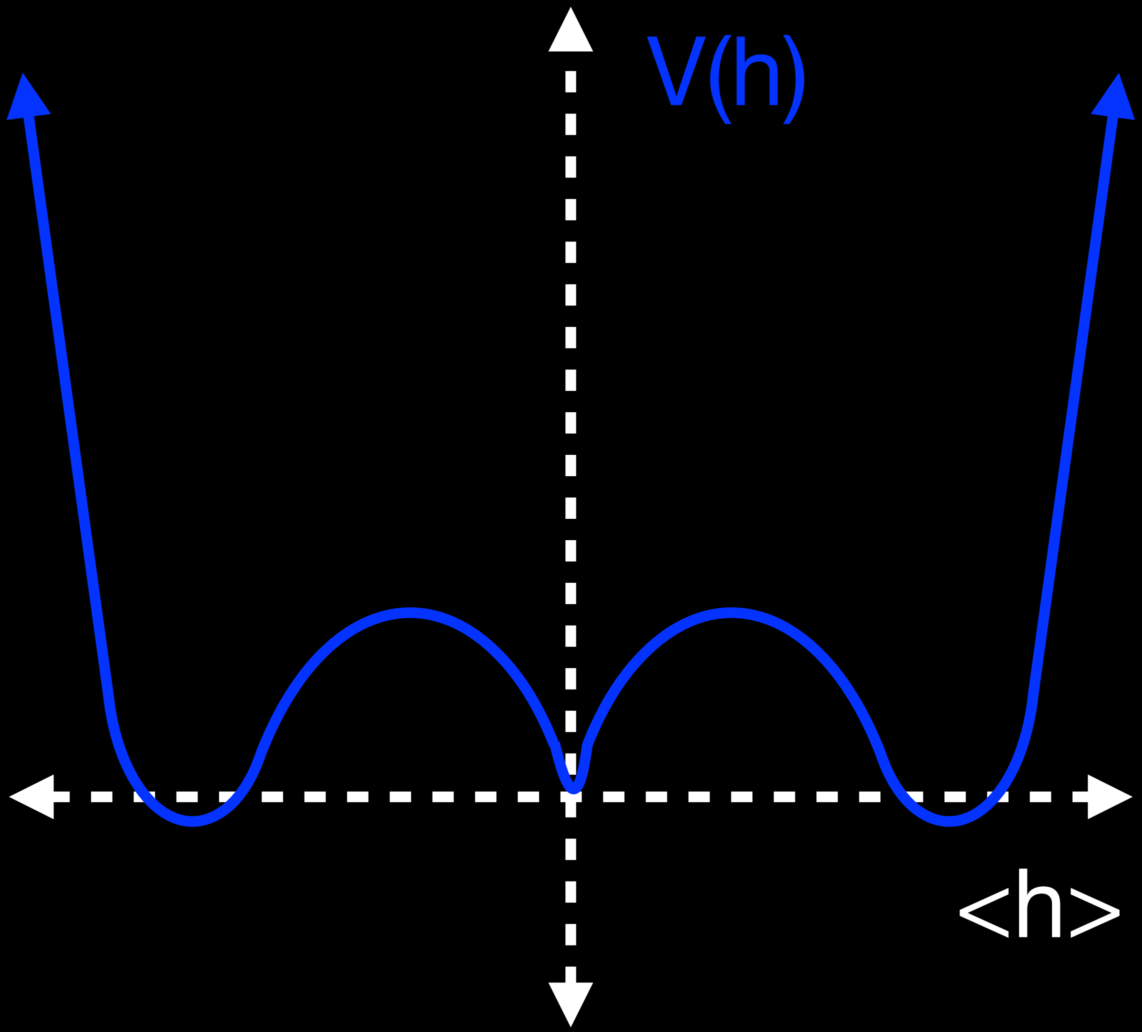
Kuzmin, Shaposhnikov, Tkachev PRD45, 466 (1992)
[also Witten NPB177, 477 (1981)]
...



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.

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}.