# Dark Matter Production

## ...in the backdrop of unusual cosmologies...


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# Outline

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

# 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.

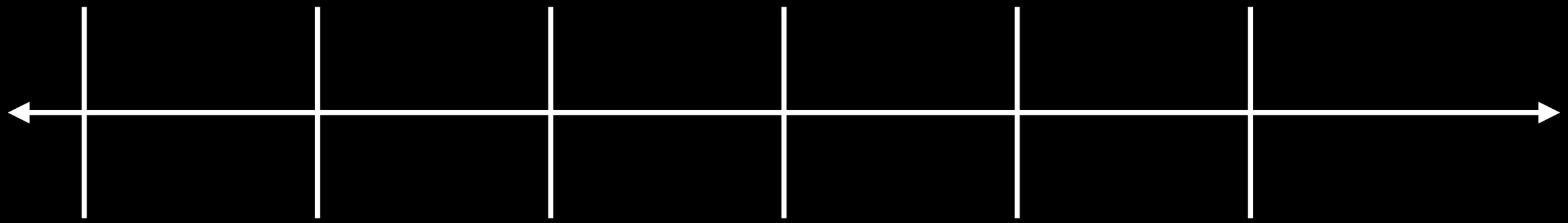
- The idea that coupling "constants" could have taken different values at different times is a familiar one. We have very good indications that at late times any such evolution must have been very slow based on a variety of measurements.

- At times before BBN, there is still some room for a theoretical physicist to play.

# Early Times are Uncertain

**EW Phase Transition?**

**QCD Confinement**



100 GeV

GeV

MeV

eV

**DM Freeze Out?**

**Today**

**Baryogenesis?**

**Big Bang Nucleosynthesis**

**CMB**

**Nuclear Physics**

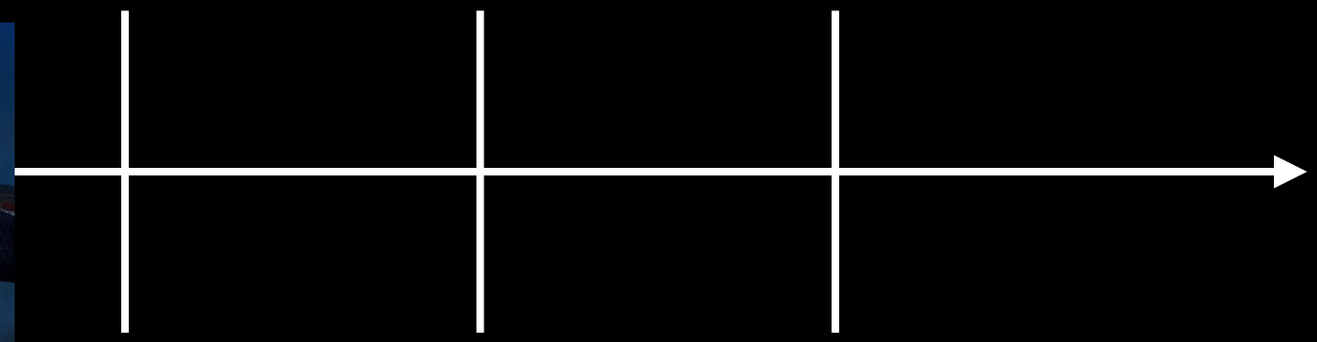
**High Energy Physics**

**Atomic Physics**

# Early Times are Uncertain

**EW Phase Transition?**

**QCD Confinement**




**Baryogenesis?**

**Big Bang Nucleosynthesis**

**CMB**

**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, and the existence of a baryon asymmetry are all indications that ingredients are missing at earlier times… the extrapolation is uncertain!**

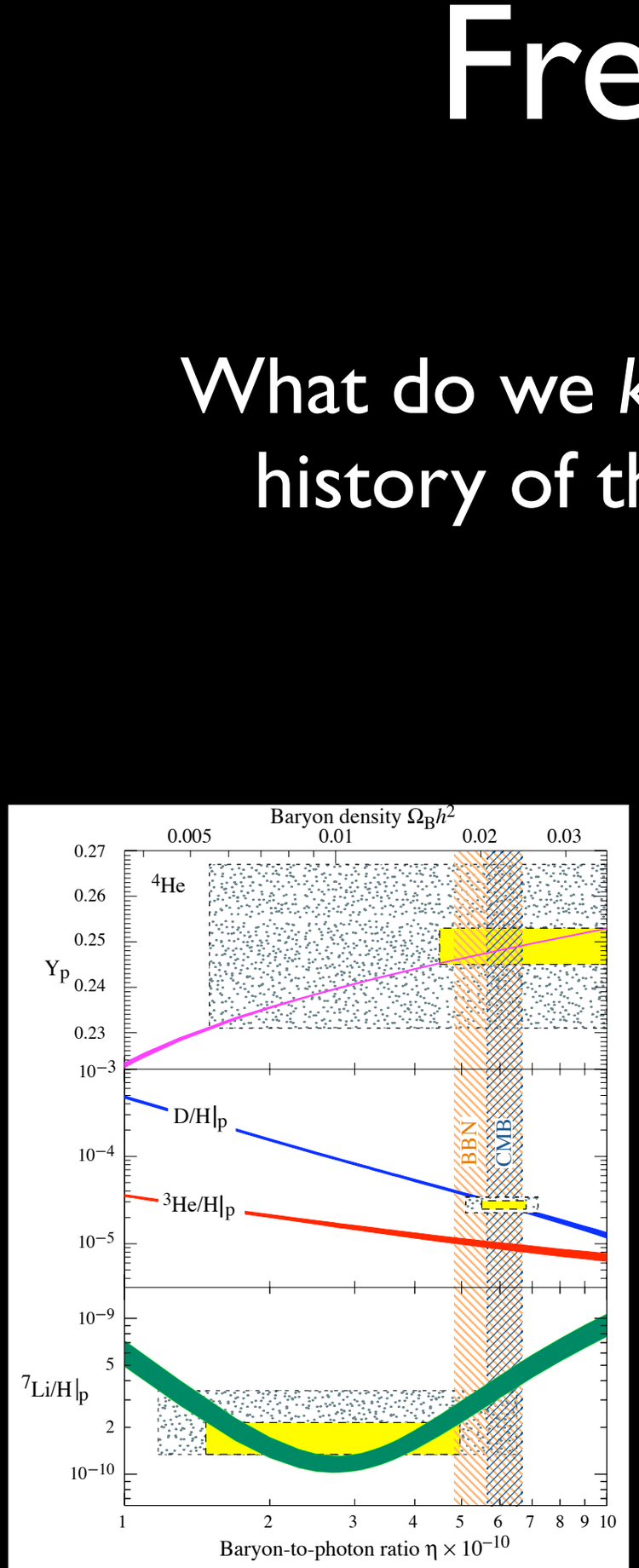
# Freeze Out Relic?

As an example to illustrate this point, let's imagine things that could go wrong with the freeze out calculation.

What do we *know* about the history of the Universe?

# Freeze Out Relic?

What do we *know* about the history of the Universe?




We understand the Universe pretty well back to the time of Nucleosynthesis, from the abundance of isotopes of H, He, and Li.

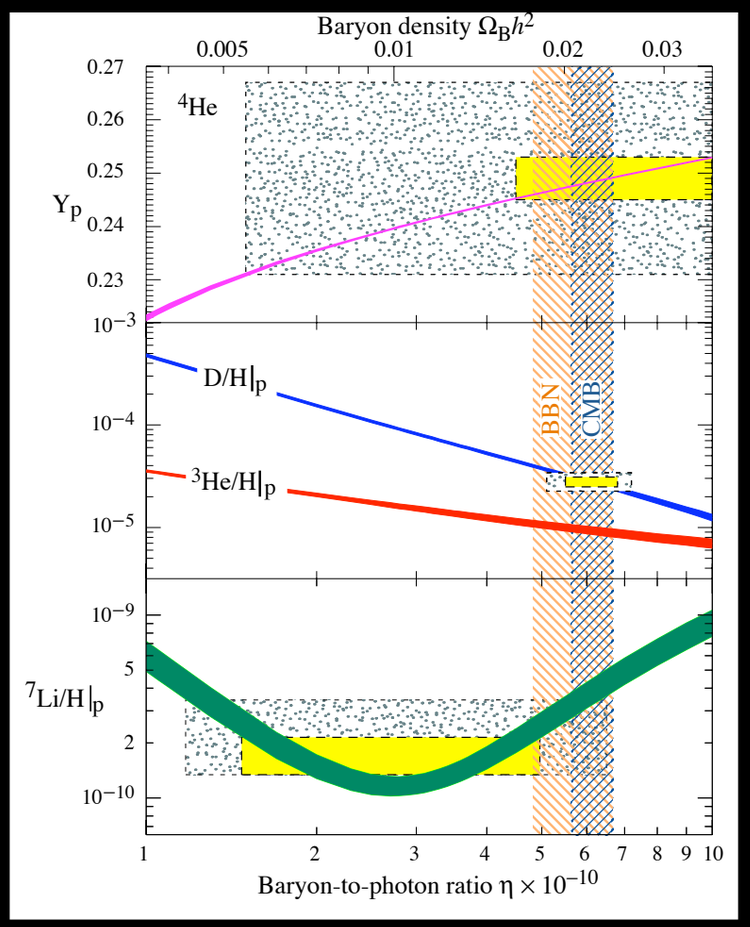
MeV

T

# Freeze Out Relic?

What does that mean for DM?

A typical WIMP had already
frozen out through annihilation

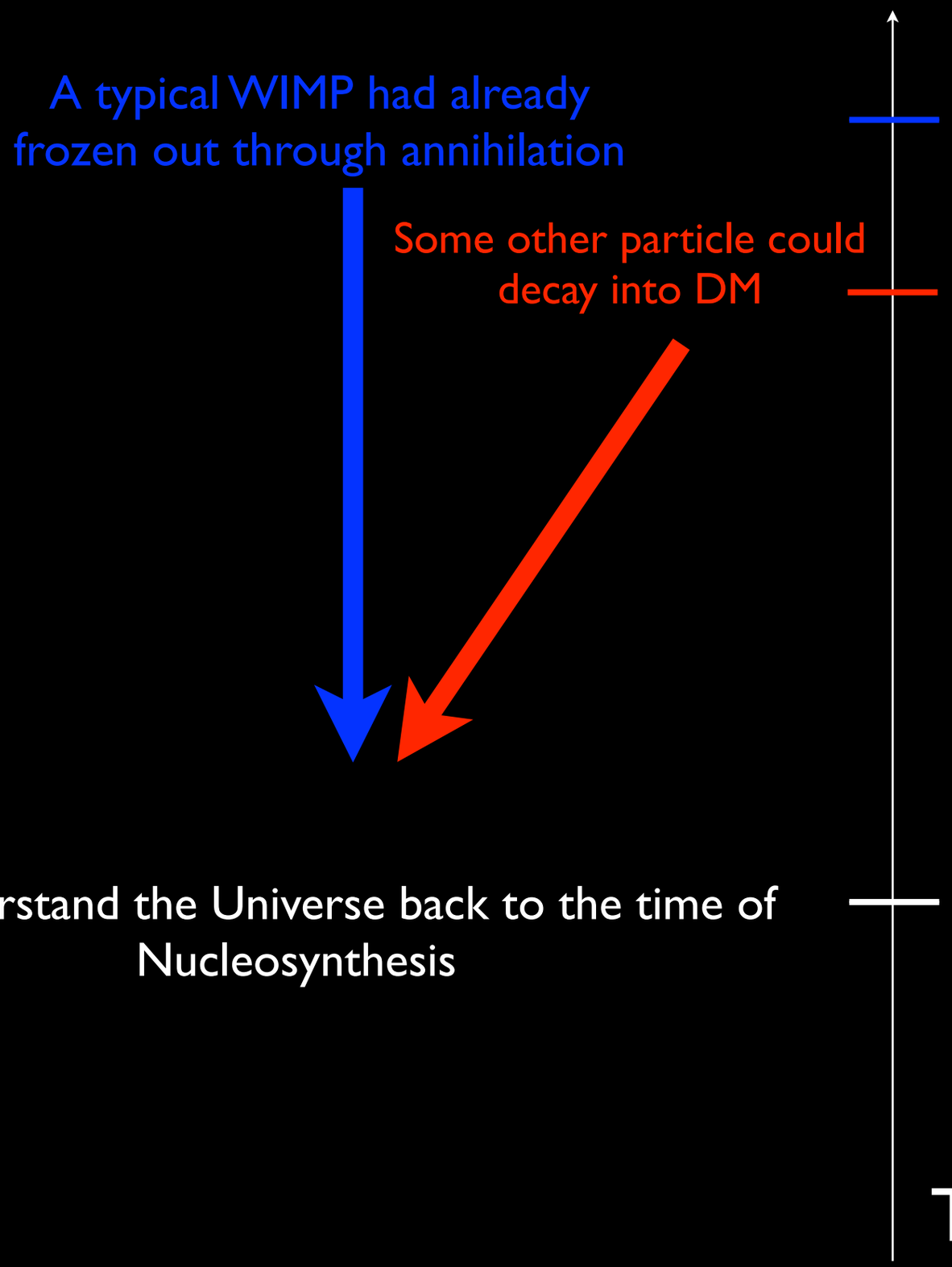



We understand the Universe back to the time of
Nucleosynthesis

MeV

T

# Lots Could Happen



# Lots Could Happen

Physics could look different from our expectations (because of a VEV, etc)

A typical WIMP had already frozen out through annihilation

Some other particle could decay into DM

We understand the Universe back to the time of Nucleosynthesis

MeV

T

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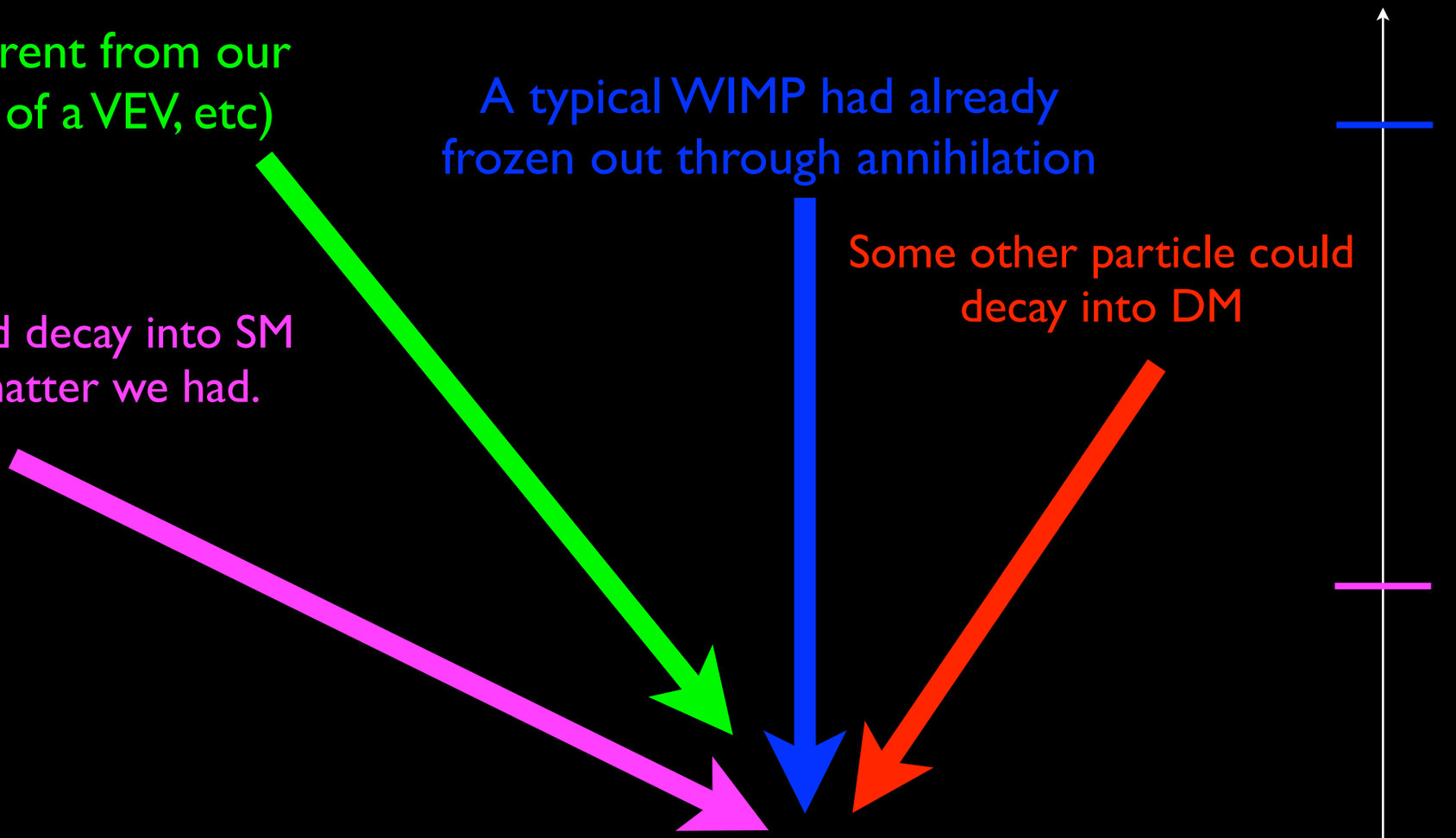
Some other particle could decay into SM stuff, diluting the dark matter we had.



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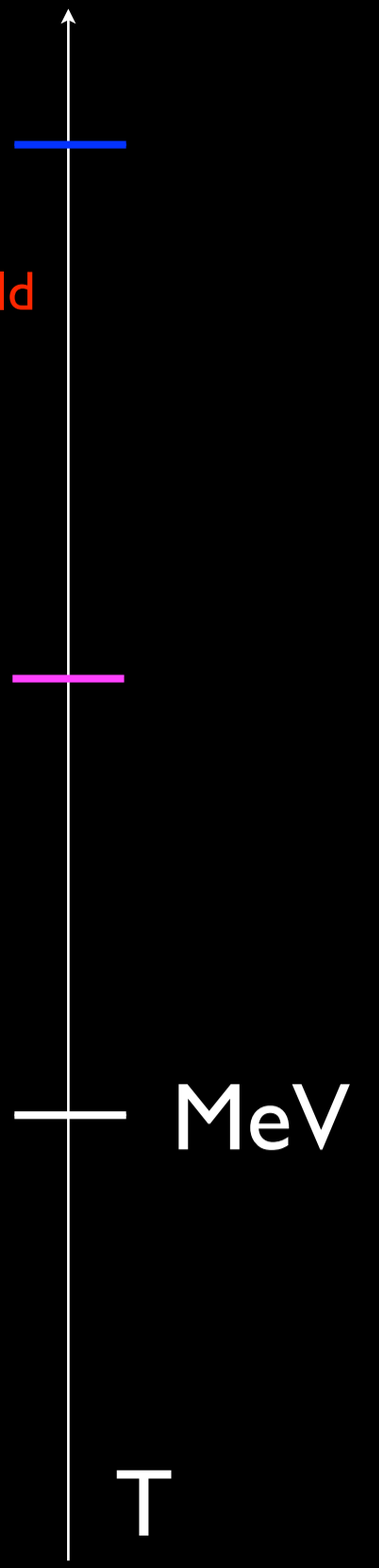

# Lots Could Happen

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There could be an unexpected early period of matter domination or inflation

We understand the Universe back to the time of Nucleosynthesis

MeV

T

# Lots Could Happen

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Some other particle could decay into SM stuff, diluting the dark matter we had.

There could be an unexpected early period of matter dominated or

This is a feature!

Understanding the annihilation cross section could verify the WIMP miracle and push back our understanding of the Universe to earlier times.

nd the Universe back to the time of Nucleosynthesis

MeV

T

# A Period of Early Confinement

# 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

DM Freeze Out: Howard, Ipek, TMPT, Turner 2112.?????

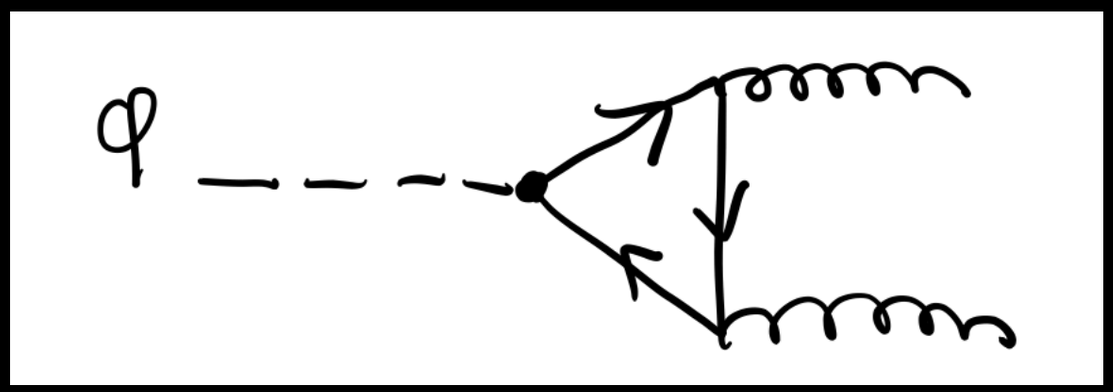
# Strong Coupling

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

1811.00559

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

- 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:

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

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

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

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

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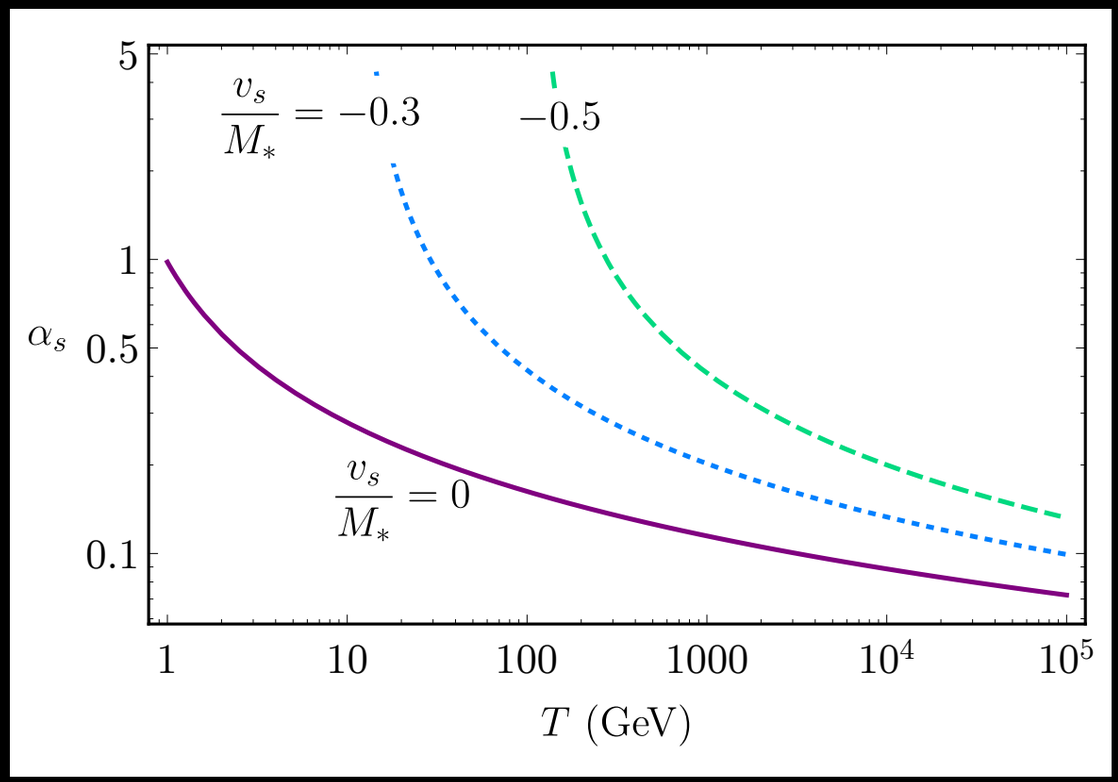
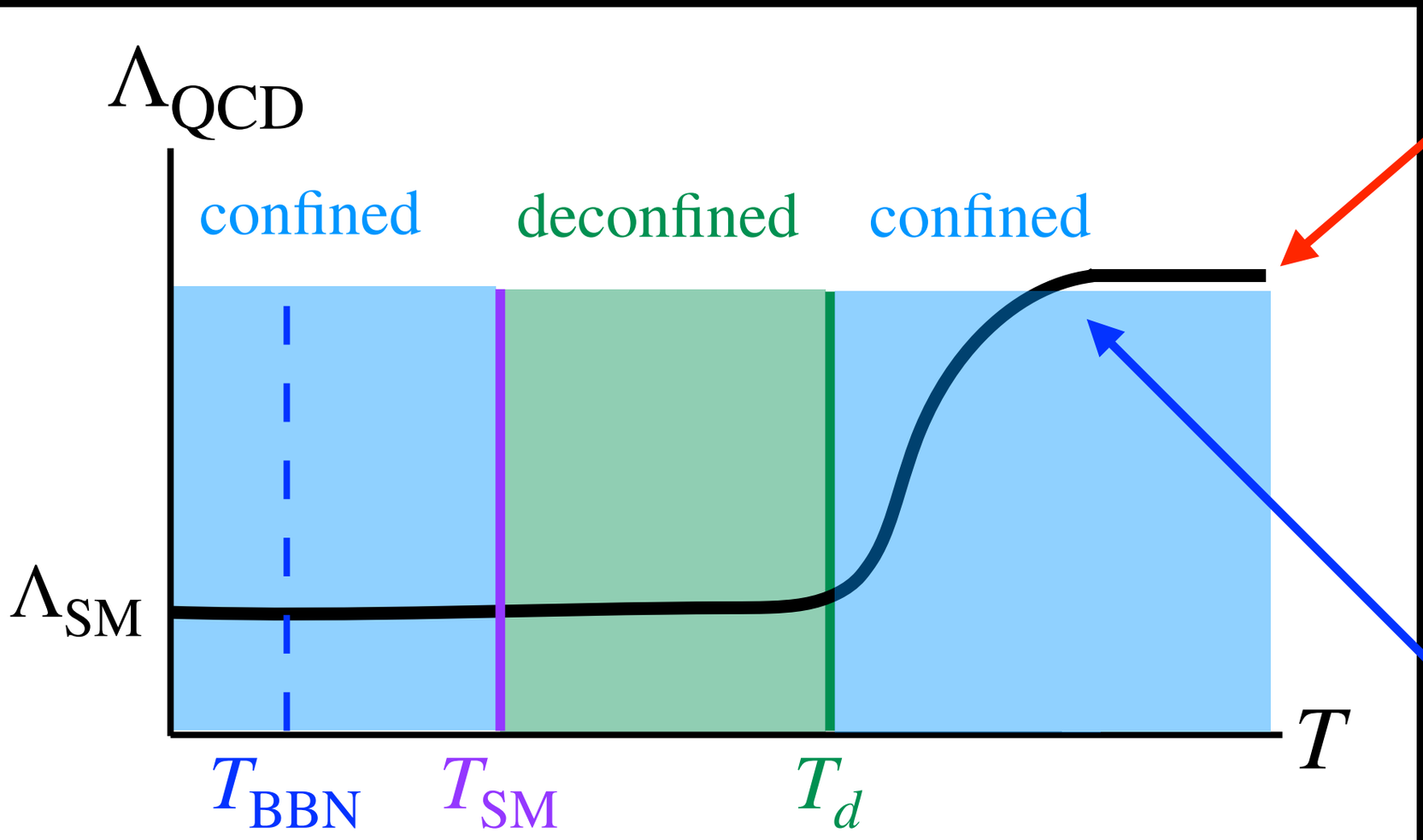


# Φ Potential

- 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

$\langle\phi\rangle = \phi_1$

$\Rightarrow \Lambda \sim$ TeV

High T

$V(\phi, T)$

Low T

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

$\Rightarrow \Lambda \sim$ GeV

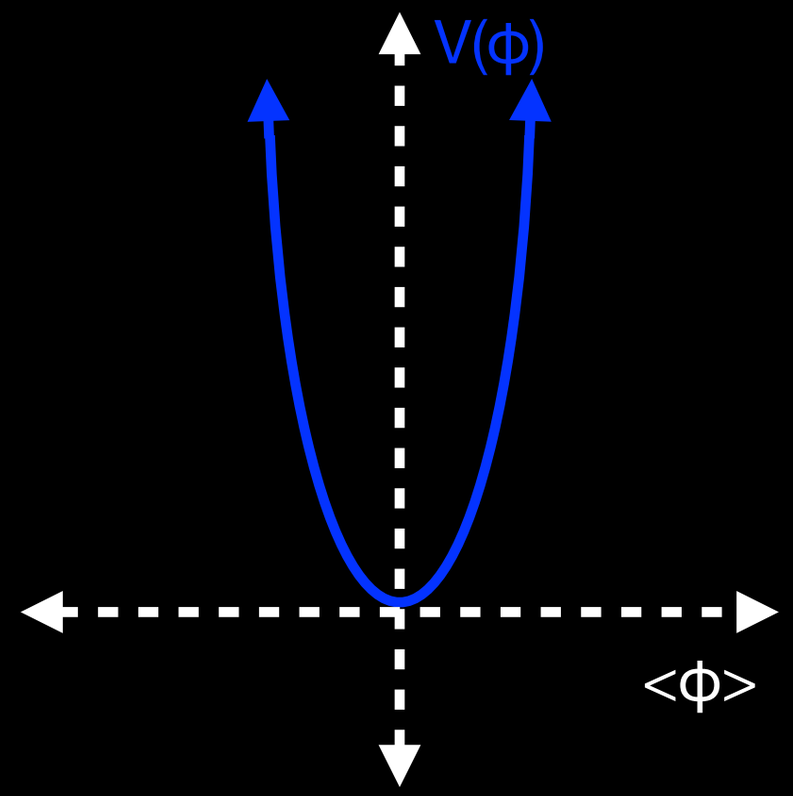
1911.01432

# 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.

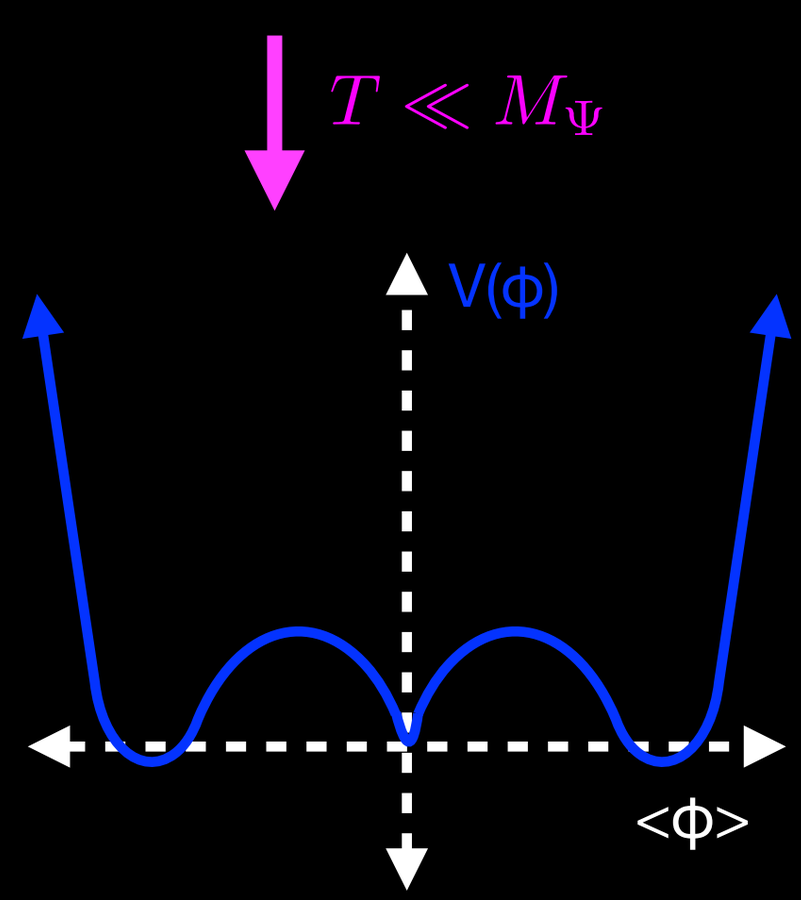
- At T~m, their corrections become exponentially suppressed.




- 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.

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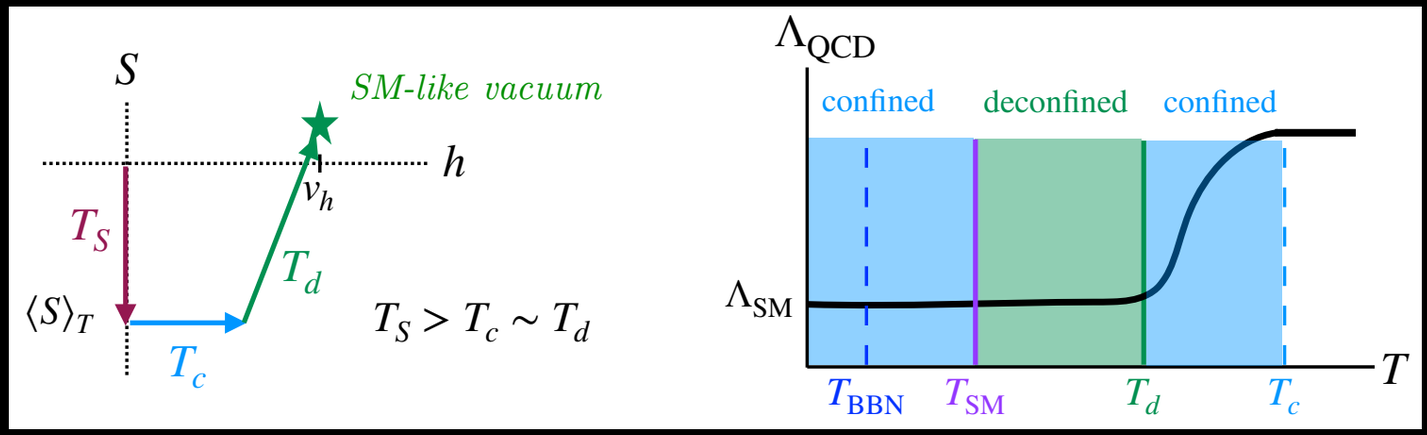
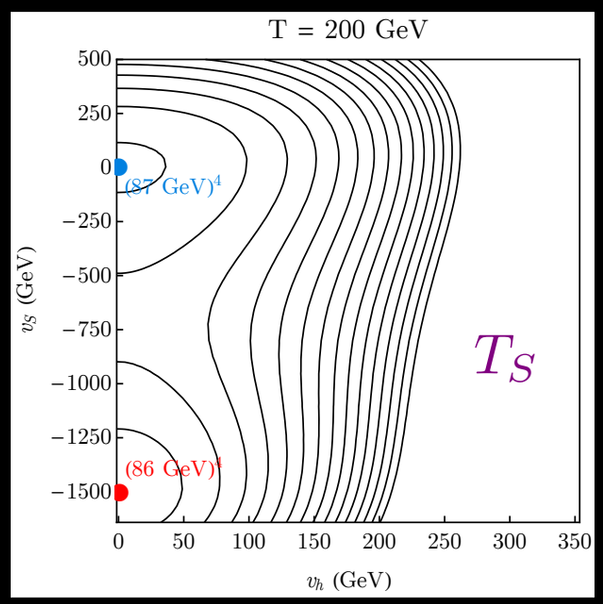
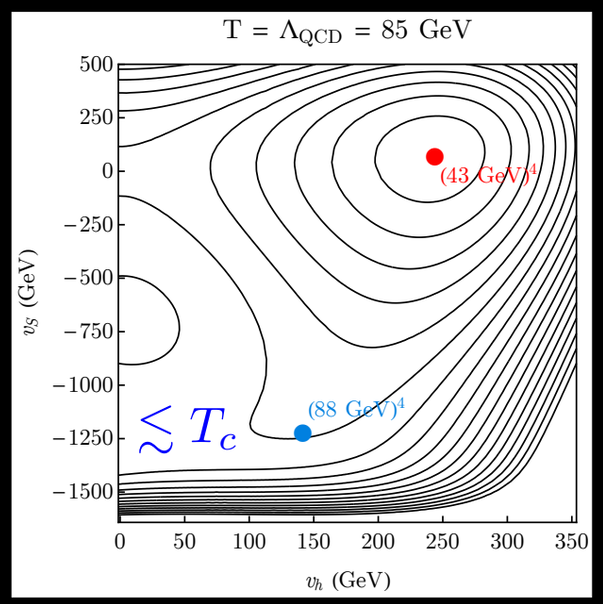
$$V(H) = -\mu^2|H|^2 + \lambda_h|H|^4 \ ,$$
$$V(S) = a_2(S-S_0)^2 + a_3(S-S_0)^3 + a_4(S-S_0)^4 \ ,$$
$$V(H,S) = -b_1 S|H|^2 + b_2 S^2|H|^2 .$$

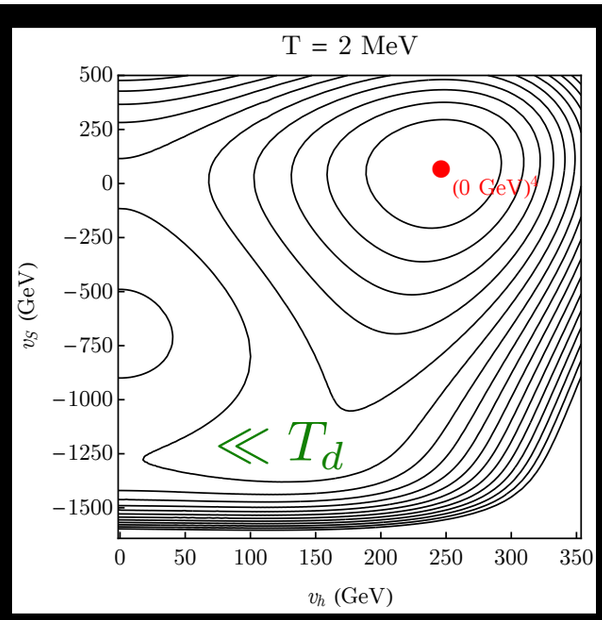
- The Higgs potential is also evolving with temperature, and its evolution could trigger a switch in the singlet potential to a new minimum.

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




- 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.

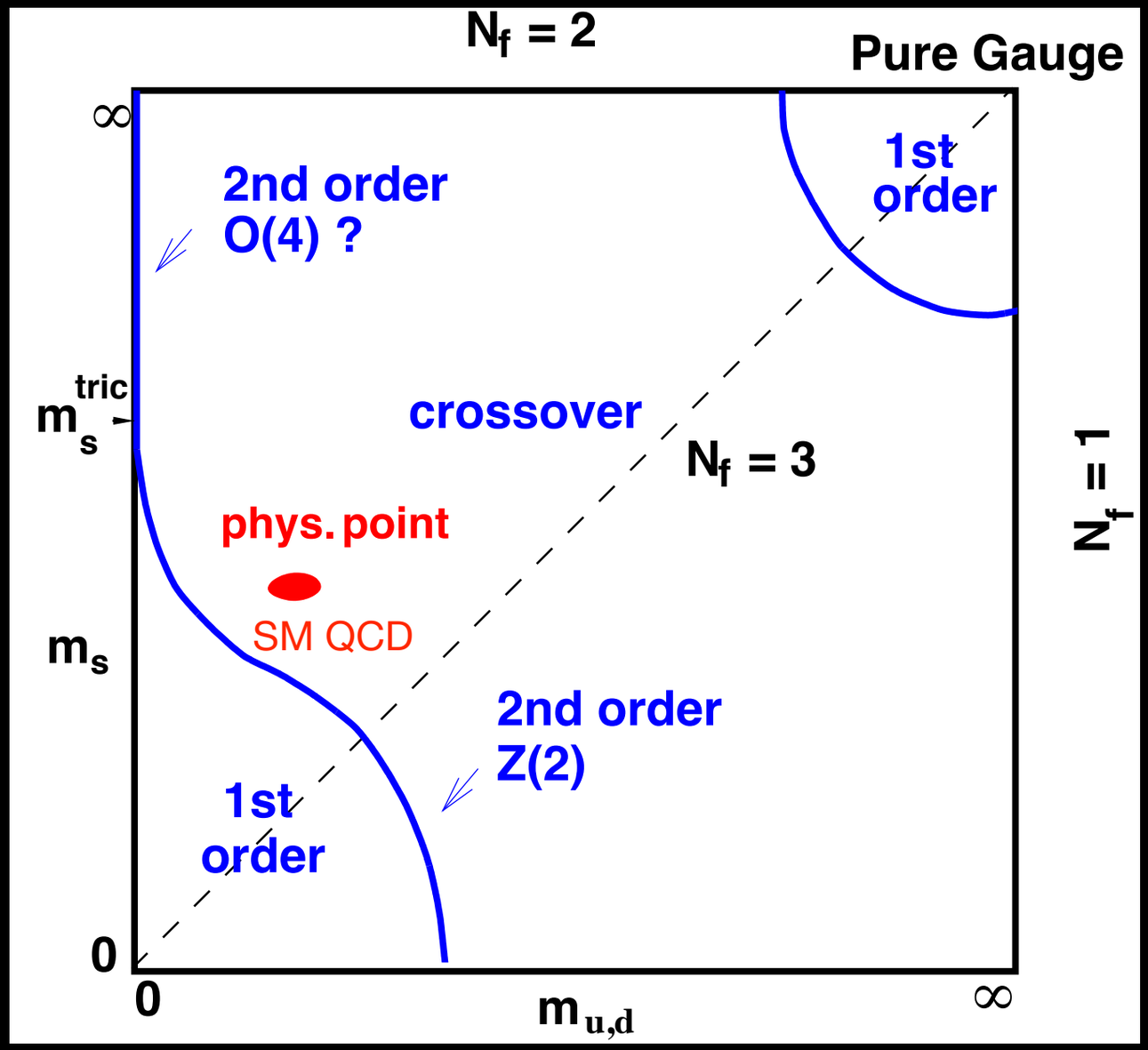
  - For $n_F = 6$ massless flavors, this is expected to be a first order transition.

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.

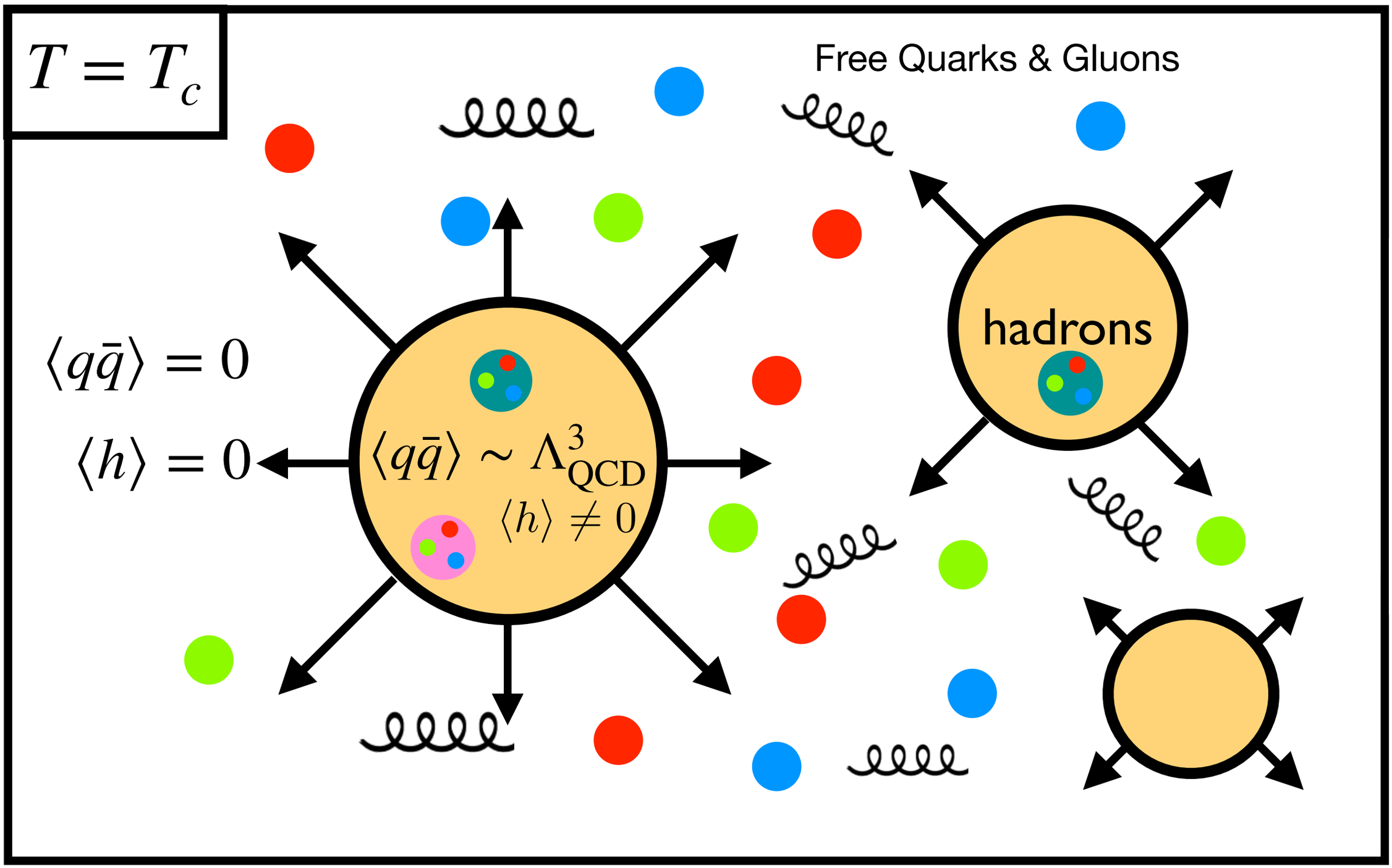
**2+1 Flavor QCD Phase Diagram**




Review by Schaefer & Wagner 0812.2855

"Old School Technicolor"

# QCD Phase Transition

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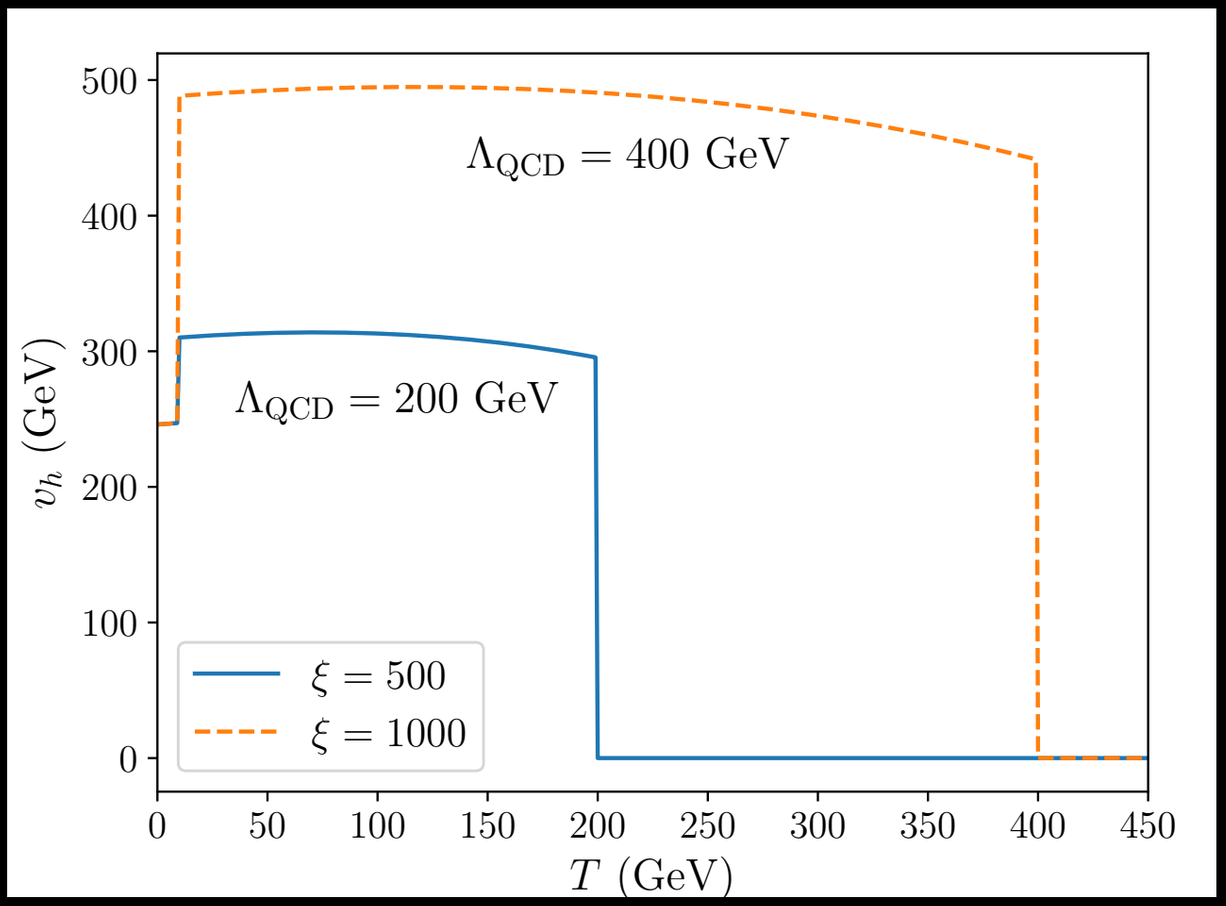
# Confined Universe

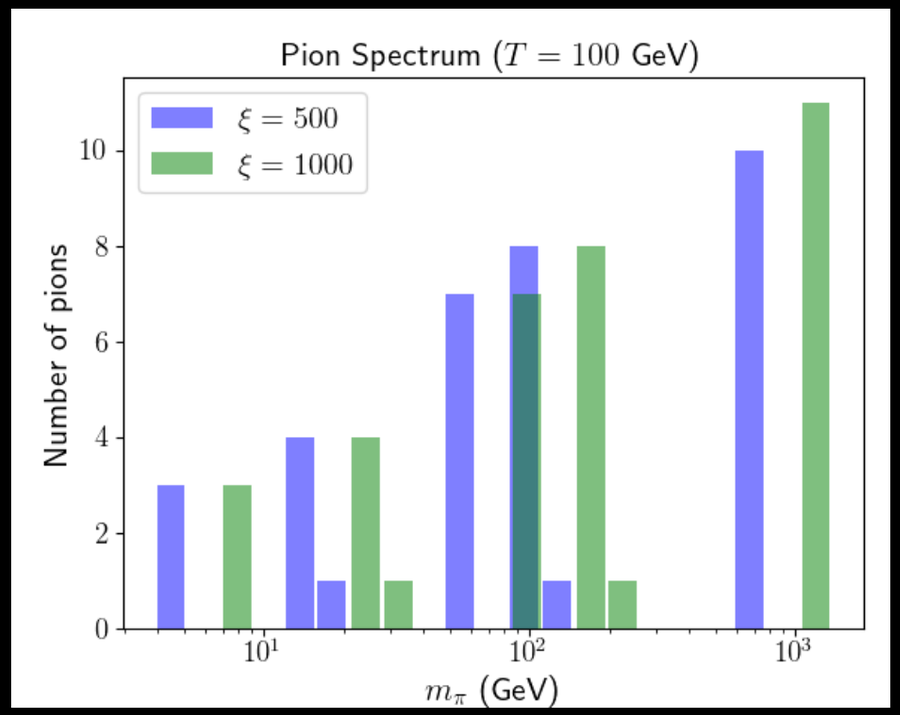
- In the confined phase, the important active degrees of freedom are the ~35 pNGB mesons.
  - Their properties are described by chiral perturbation theory, with parameters matched to low energy QCD data, and dimensionful quantities scaled up to the high scale confinement scale.

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




- The thermal corrections to the Higgs potential are dominated by the top-flavored (or bottom-flavored) mesons rather than top/bottom quarks.
- The chiral condensate acts as a tadpole for the Higgs doublet.

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

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# 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.

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

- 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.

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

- In some sense, the axion 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)

# Early Confinement

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$\Gamma_{\rm sph}$

Raise $\Lambda_{\rm QCD}$

$m_a(T)$

$\theta_{\rm eff}$

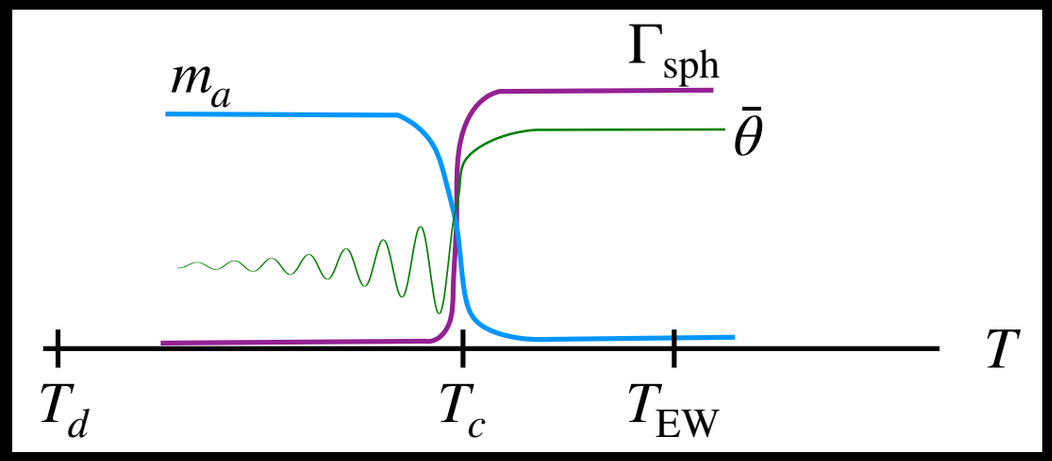
$T_{\rm QCD}$ $T_{\rm EW}$ $T_{\rm QCD}$

# Spontaneous Baryogenesis

- The non-zero $\theta_{\text{eff}}$ 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 $W\tilde{W}$:




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

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

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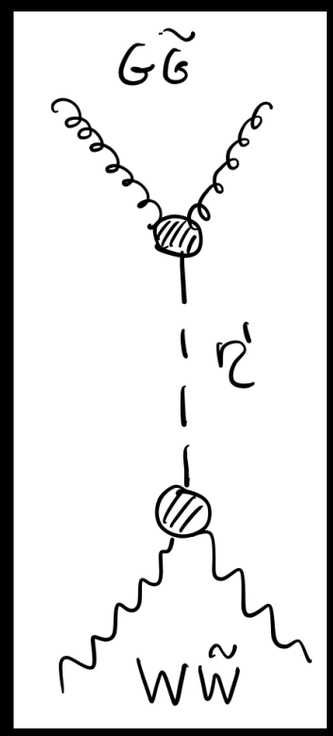

# Spontaneous Baryogenesis

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

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

- Which leads to baryon production:

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

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

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

# Baryon Asymmetry

- The resulting baryon asymmetry is:

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

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

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

- $T_{reh}$ 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 $T_{sph} \sim T_{reh}$.

- 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!

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

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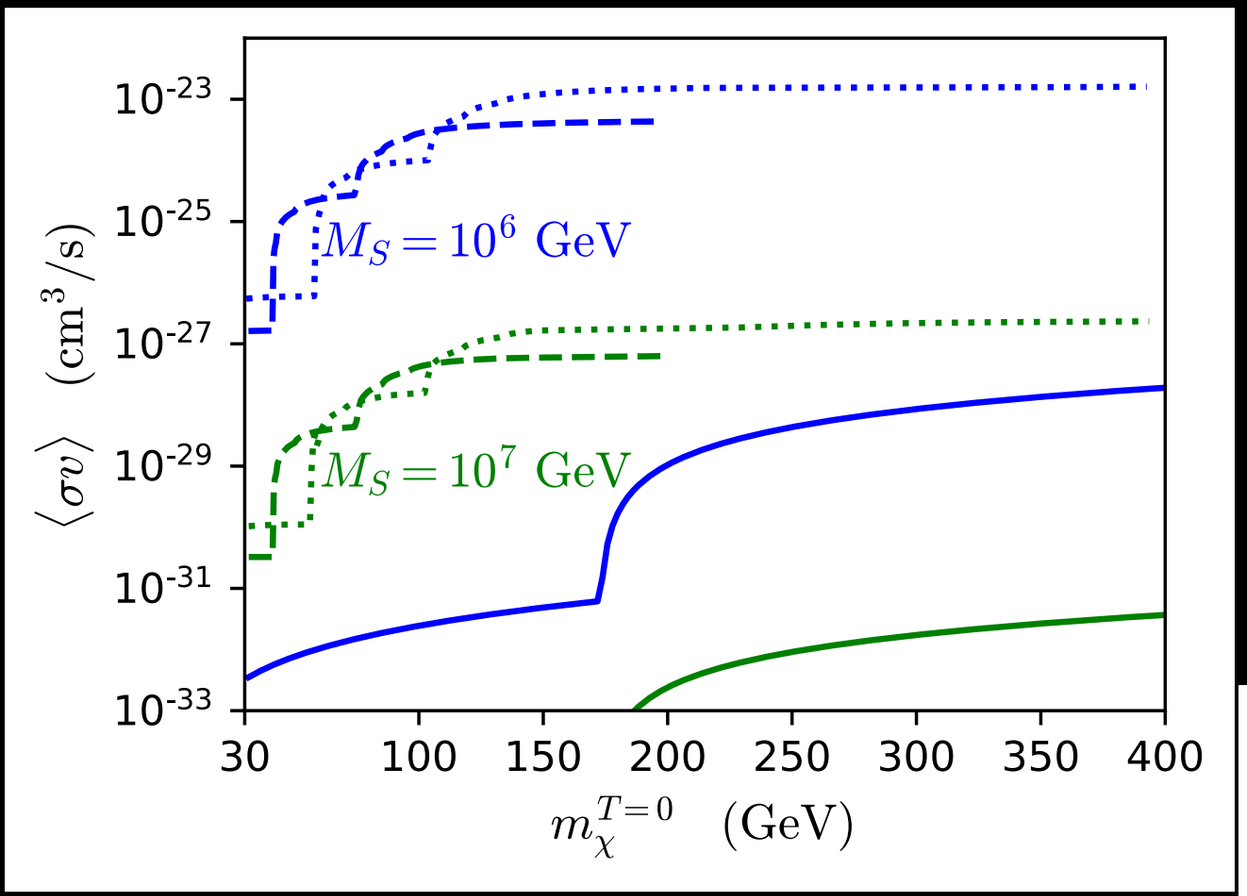
$$\beta_{ij} \equiv \pm\delta_{ij}\frac{y_i}{y_u}$$

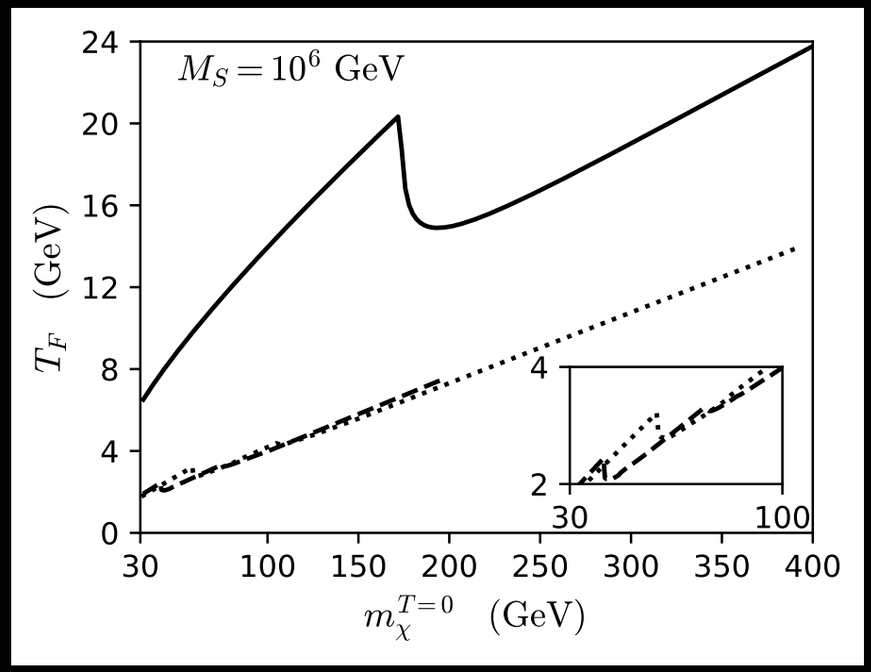
$$\frac{\kappa}{M_S^2}\ \bar{\chi}\chi\ \mathrm{tr}\left(U^\dagger\beta + U\beta^\dagger\right)$$

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

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

# Freeze Out

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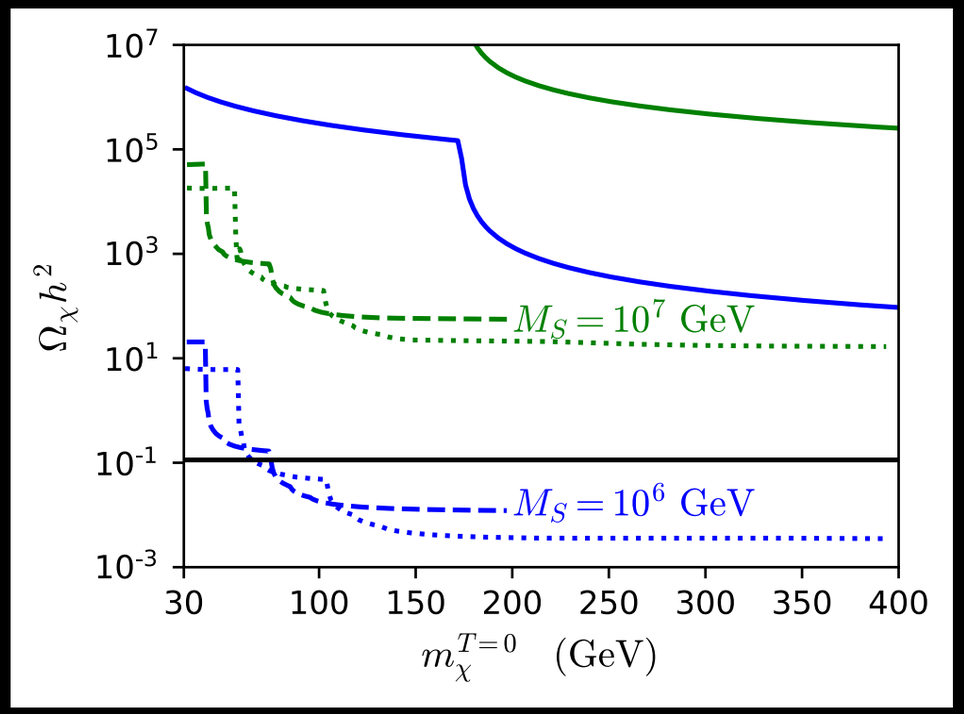


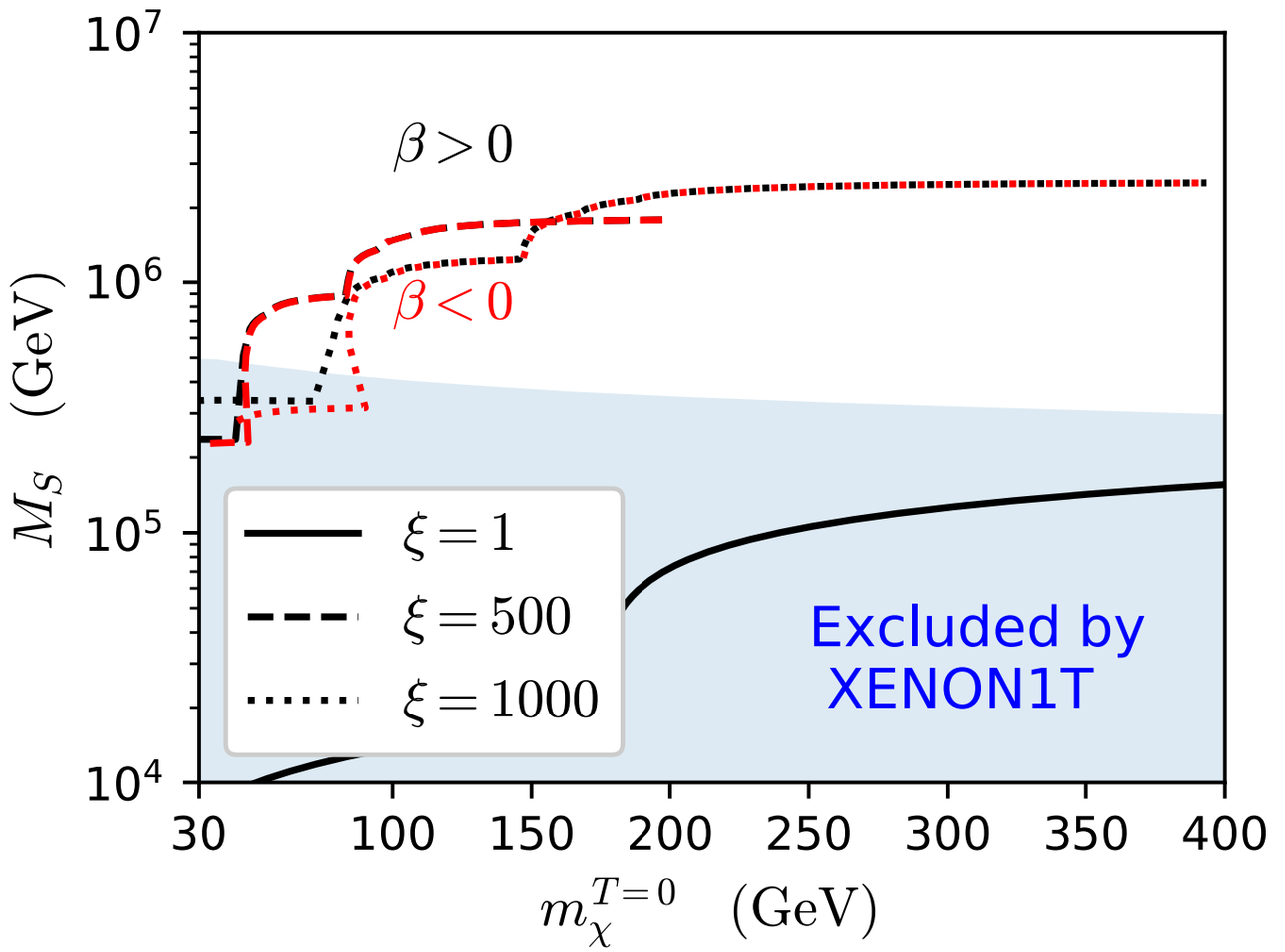

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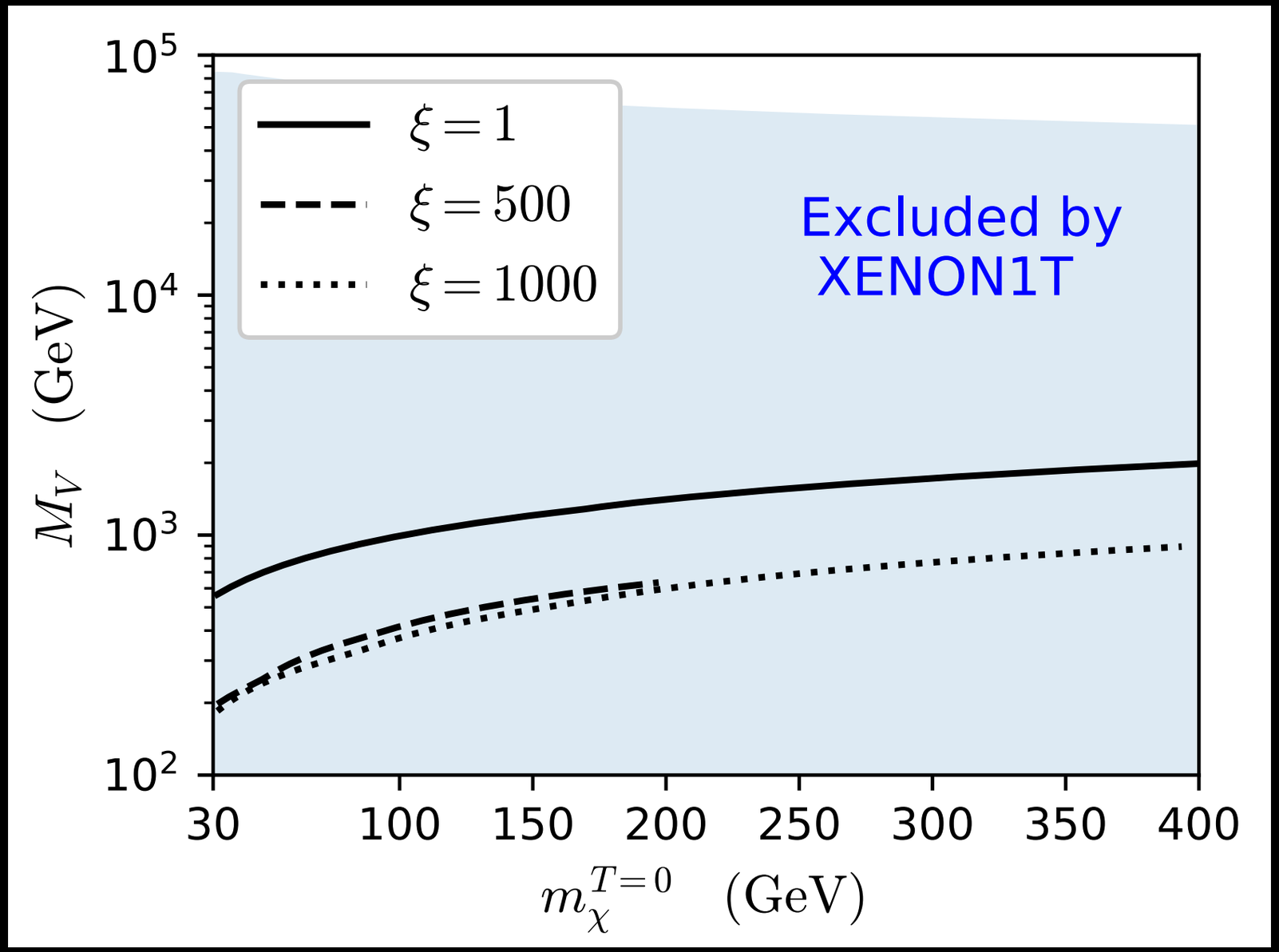



2004.06727

The situation is rather different for MFV vector interactions.

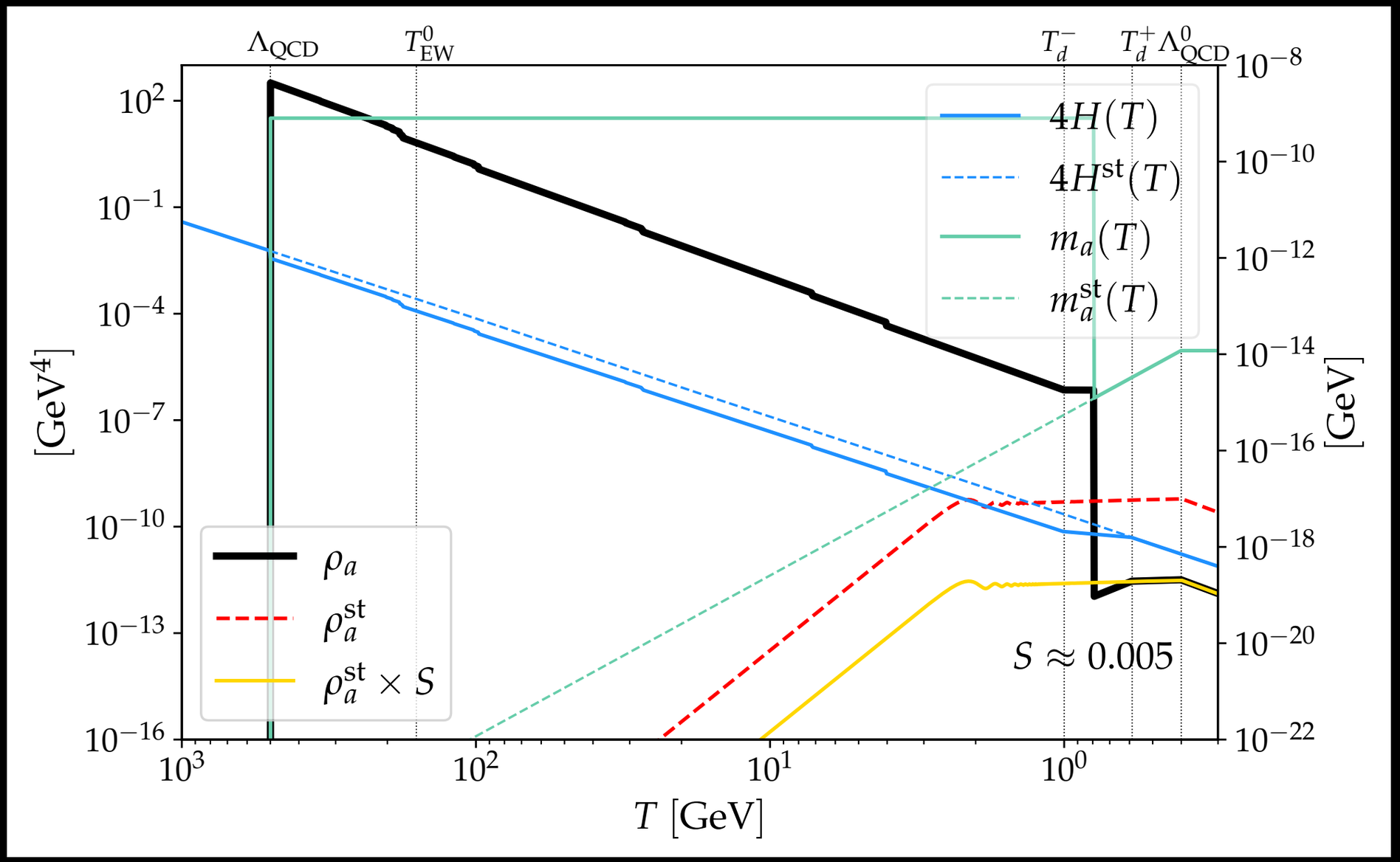
$$\frac{\lambda_{ij}}{M_V^2}\bar{\chi}\gamma^\mu\chi\ \bar{q}_i\gamma_\mu q_j$$

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

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

# Axion Production

# QCD Axion Production

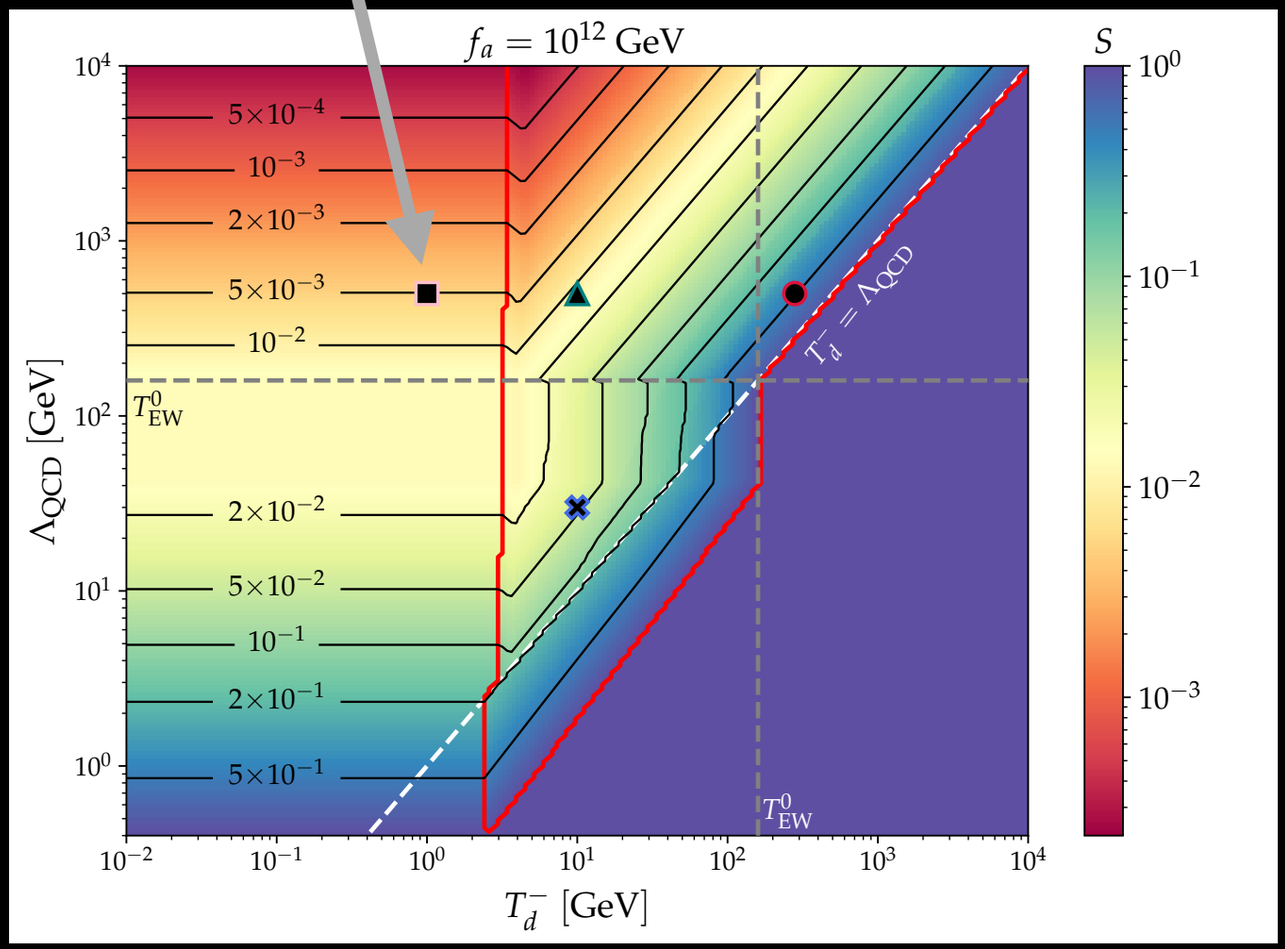


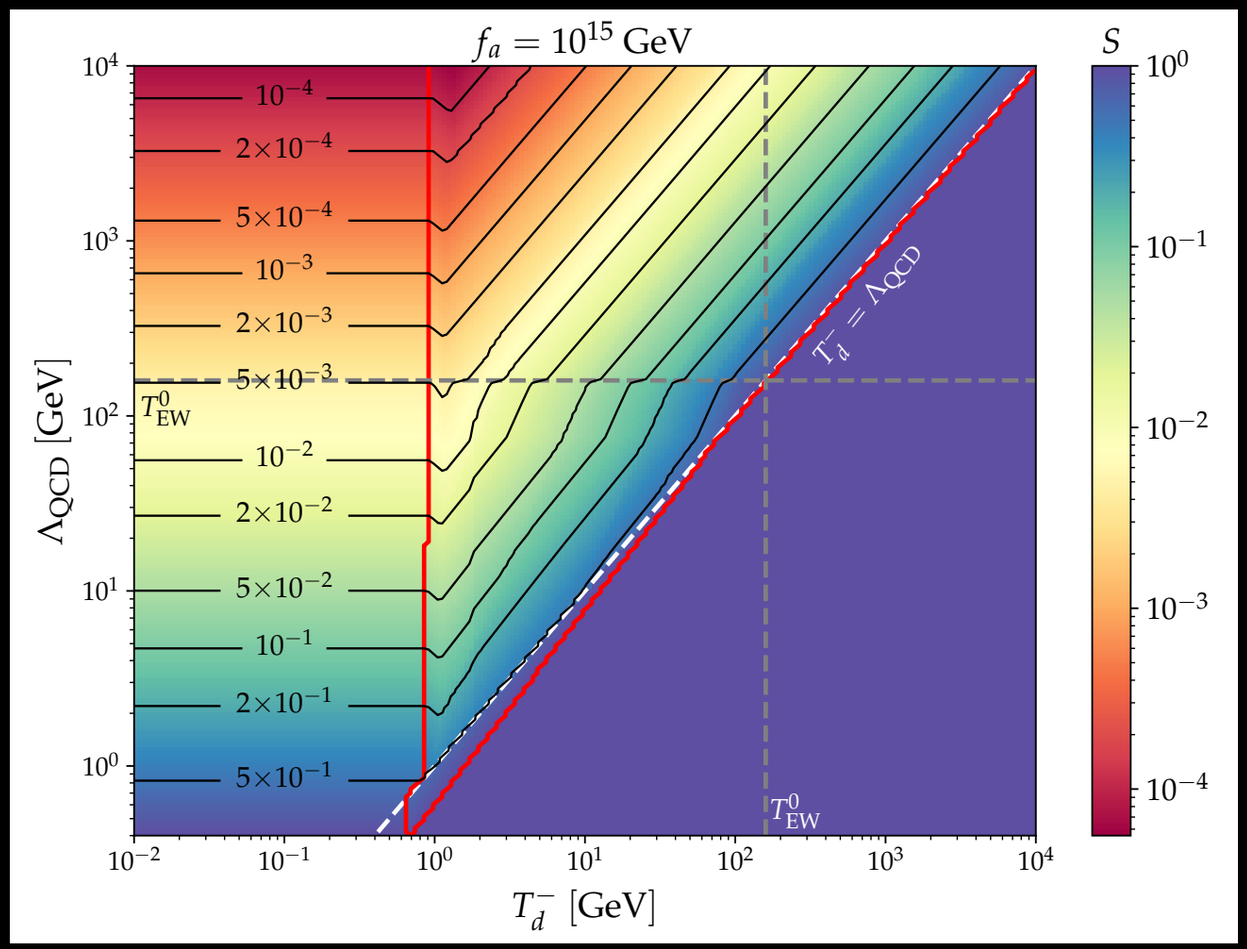

- In a theory in which the QCD axion plays the role of dark matter, a period of early QCD confinement can also make a huge difference.

Heurtier, Huang, TMPT 2104.13390

- Since the axion mass is pegged to the QCD scale, a dramatic change in Λ could cause it to start oscillating early, disrupting the usual connection between $f_a$, $\theta_0$, and the final axion density expected from misalignment production.

# Axion Production




Heurtier, Huang, TMPT 2104.13390

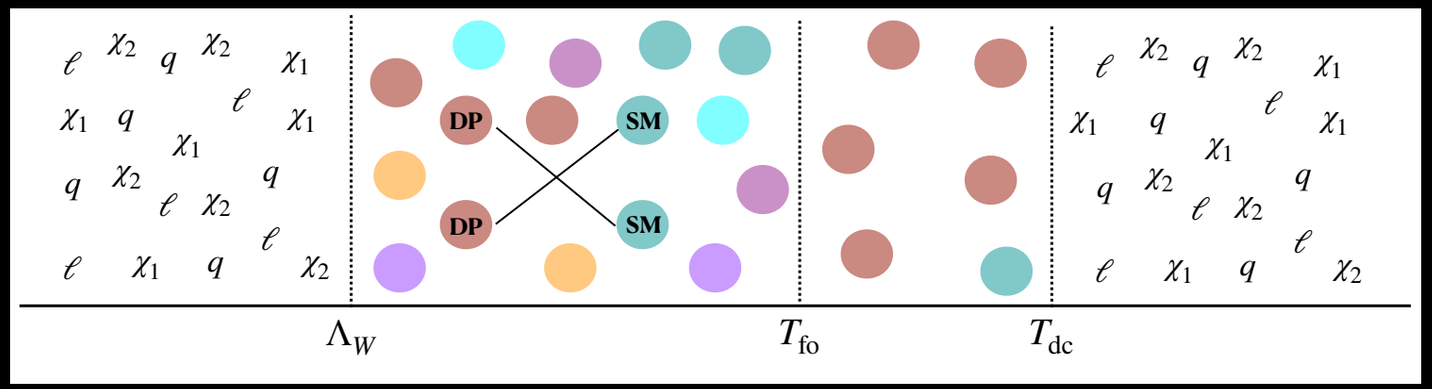
- The net result is typically a suppression of the final density of axions.

- This allows larger axion decay constants (lighter axions) to be naturally produced (from O(1) misalignment) with the correct abundance — it opens up regions of axion parameter space which would otherwise have looked very fine-tuned.

# SU(2) Confinement

- We can invoke similar constructions to modify the SU(2) coupling of the SM at early times.

- If the dark matter is a WIMP charged under the electroweak interaction, it will become bound (along with the SM doublets) into pion-like states.

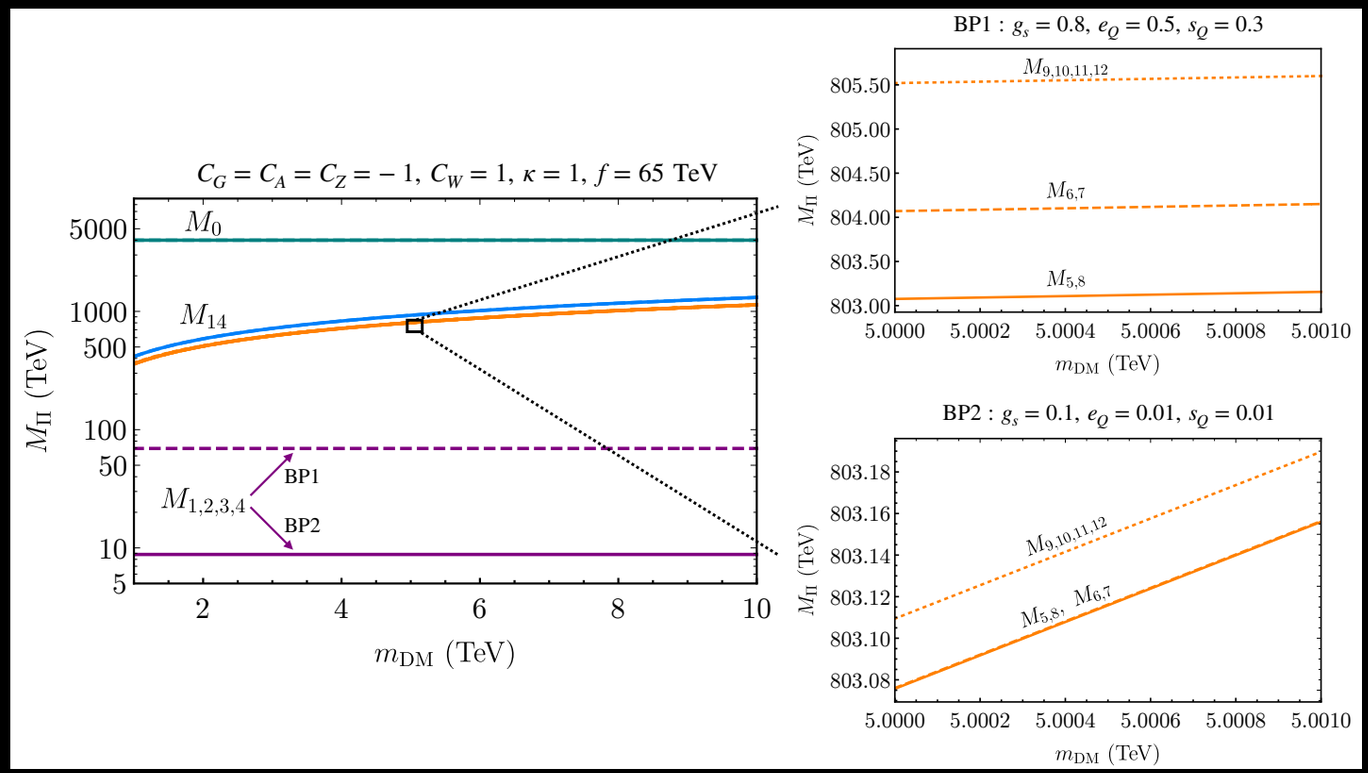



$$\mathcal{L}_\chi = i\chi_1^\dagger \bar{\sigma}^\mu D_\mu \chi 1 + i\chi_2^\dagger \bar{\sigma}^\mu D_\mu \chi 2 + m_{\rm DM}\ \chi 1 \chi 2 + \text{h.c}$$

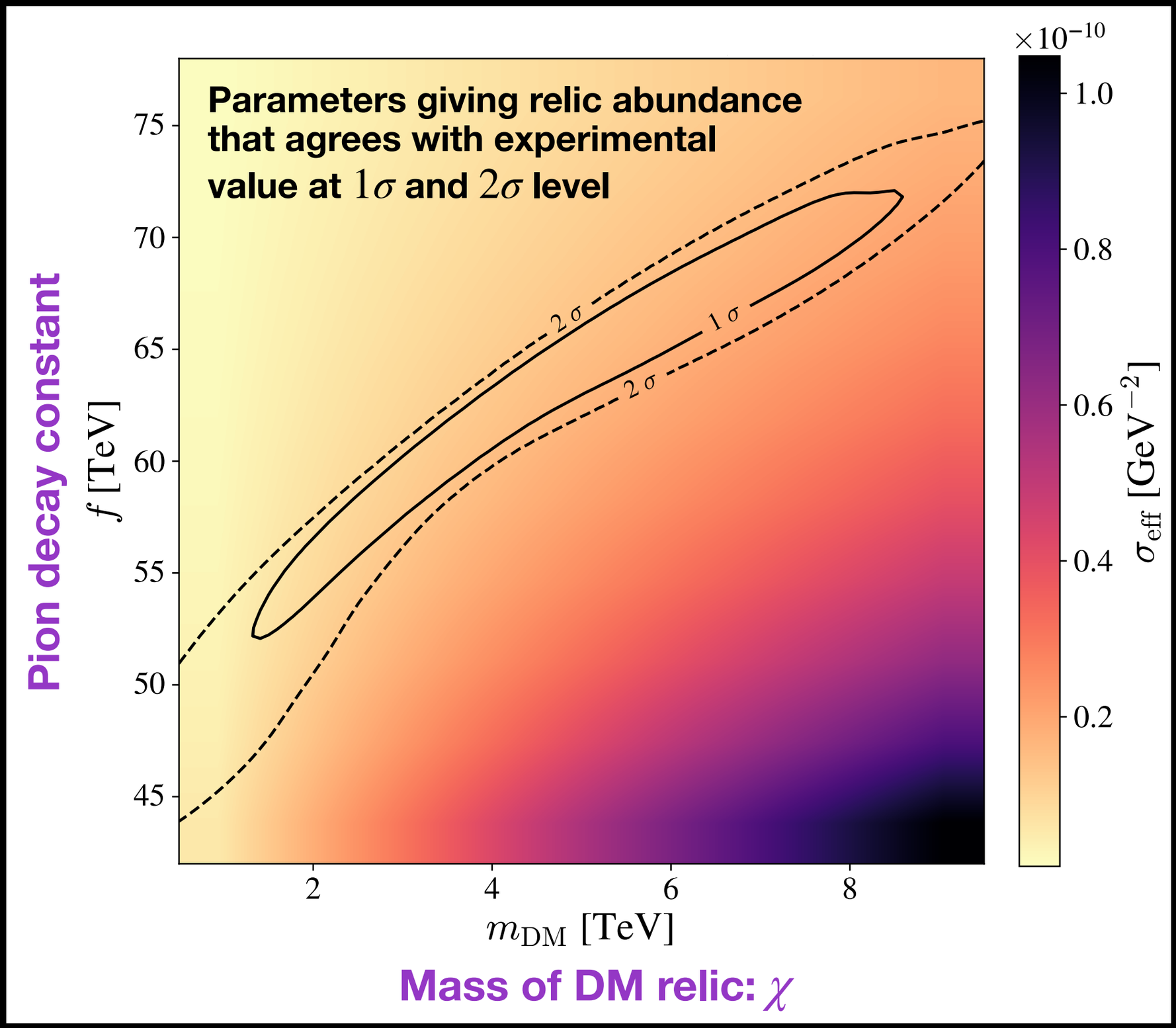
- Freeze-out could involve those dark pions, which will eventually deconfine into free WIMPs (+ SM stuff).

- We imagine that the DM lives inside a vector-like weak doublet, with a Z2 symmetry that insures its stability.

- The analogue of chiral perturbation theory determines the pion masses and interactions.



# SU(2) Confinement



# 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.

- Such unexpected epochs can dramatically change our expectations e.g. for what a fundamental theory naturally produces as a baryon asymmetry or dark matter abundance.

- I highlighted a few applications one could imagine related to realizing the baryon asymmetry, rescuing WIMP dark matter that would otherwise have been ruled out by direct searches, or an axion abundance that is natural for very light axions.

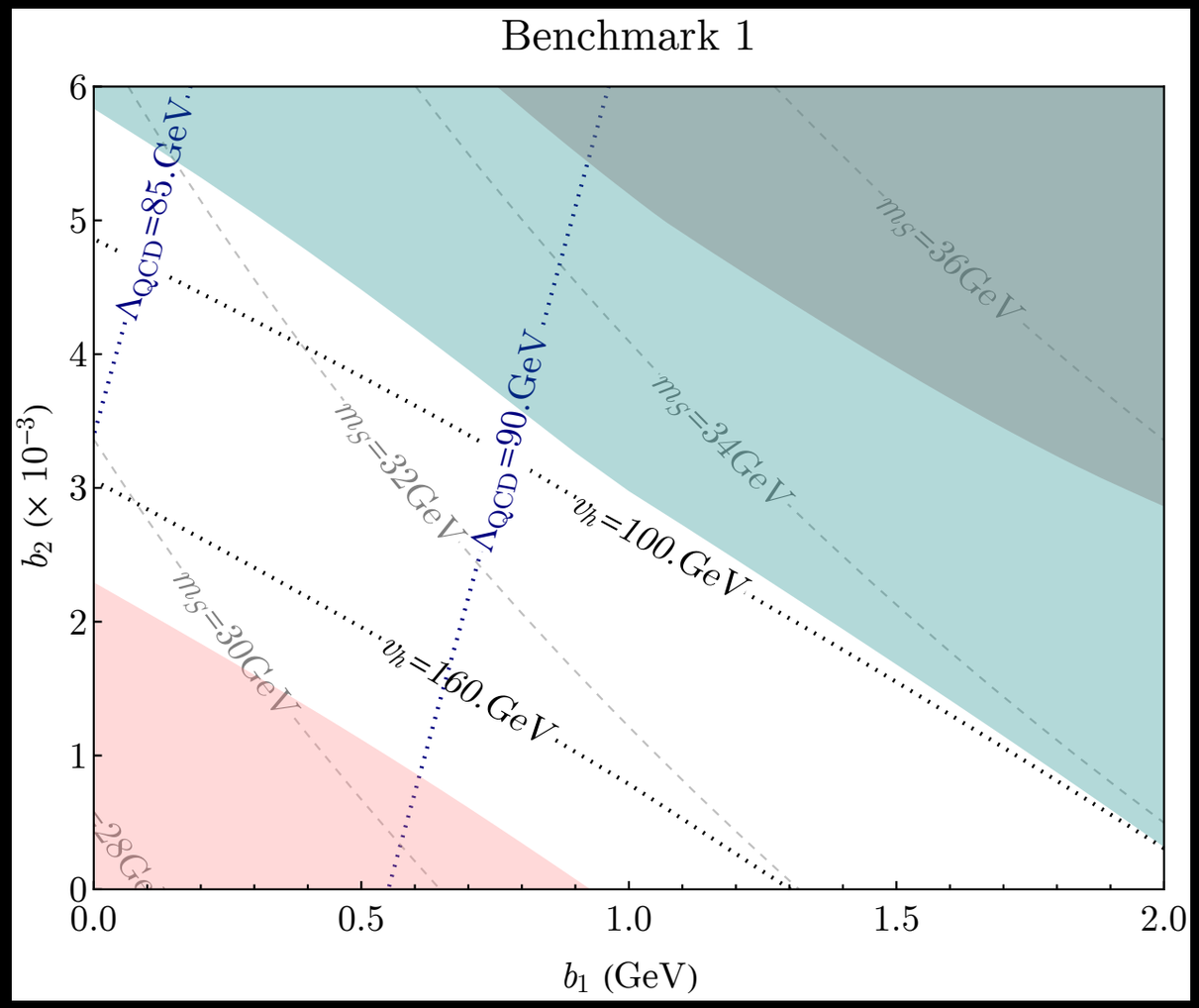
- I see this as part of a larger program in which we should strive to understand the space of what is possible in the early Universe, how to constrain the space of possibilities, and explore how they could cause us to rethink standard solutions to its mysteries.

# Thank you!

# Bonus Slides

# Singlet Phenomenology

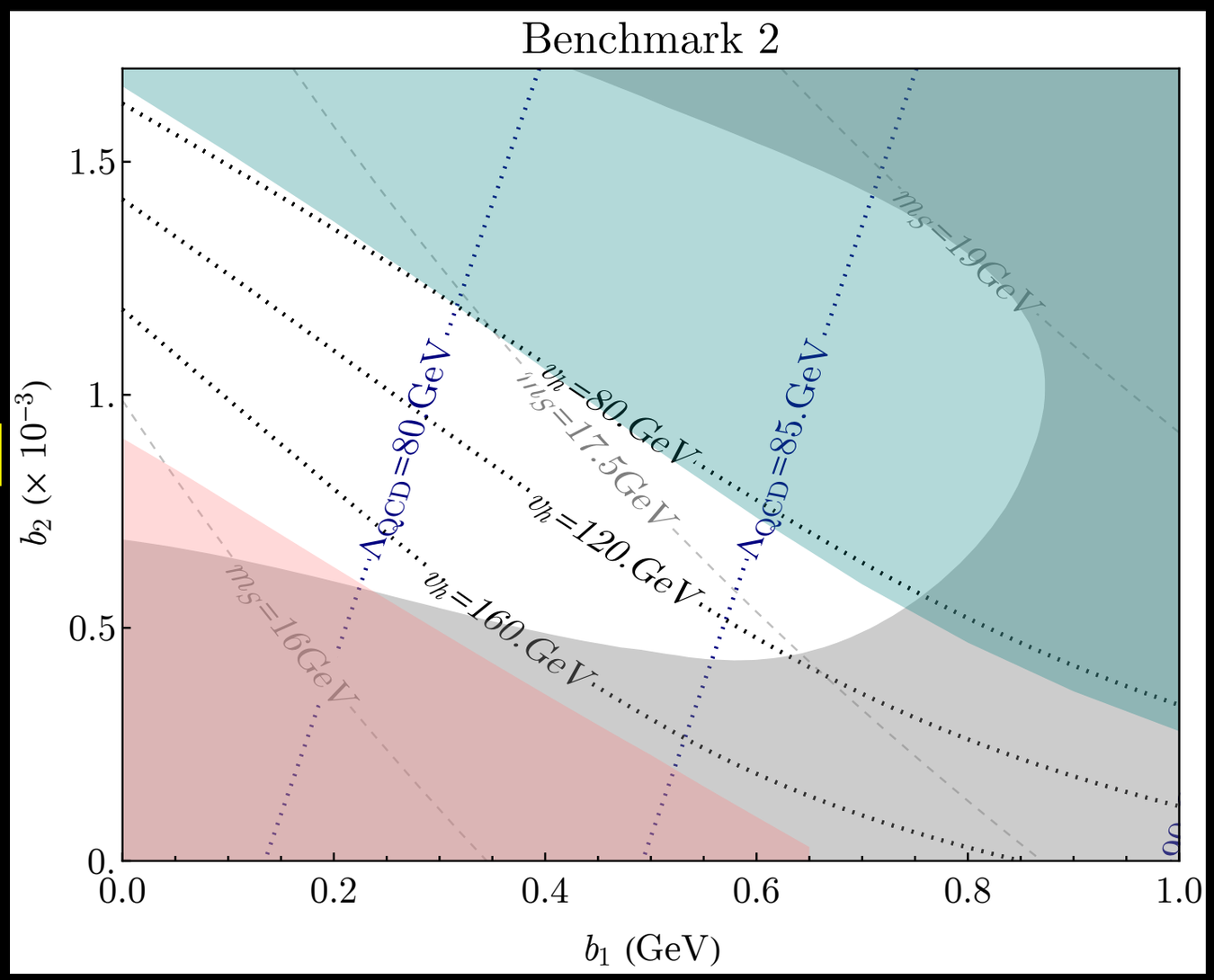
# Parameters




1911.01432

Example parameter space motivated by deconfinement triggered by the Higgs

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



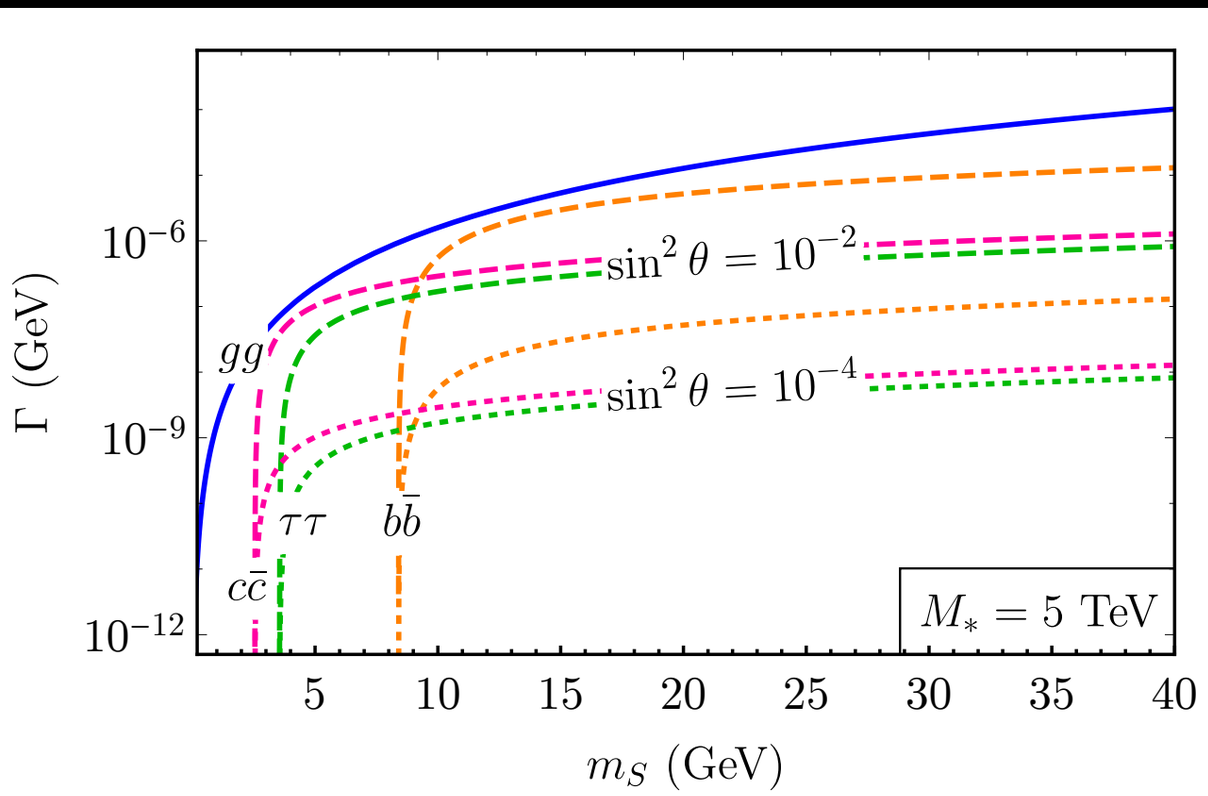

Higgs VEV switches on too slowly, allowing baryon asymmetry to be washed out by sphalerons.

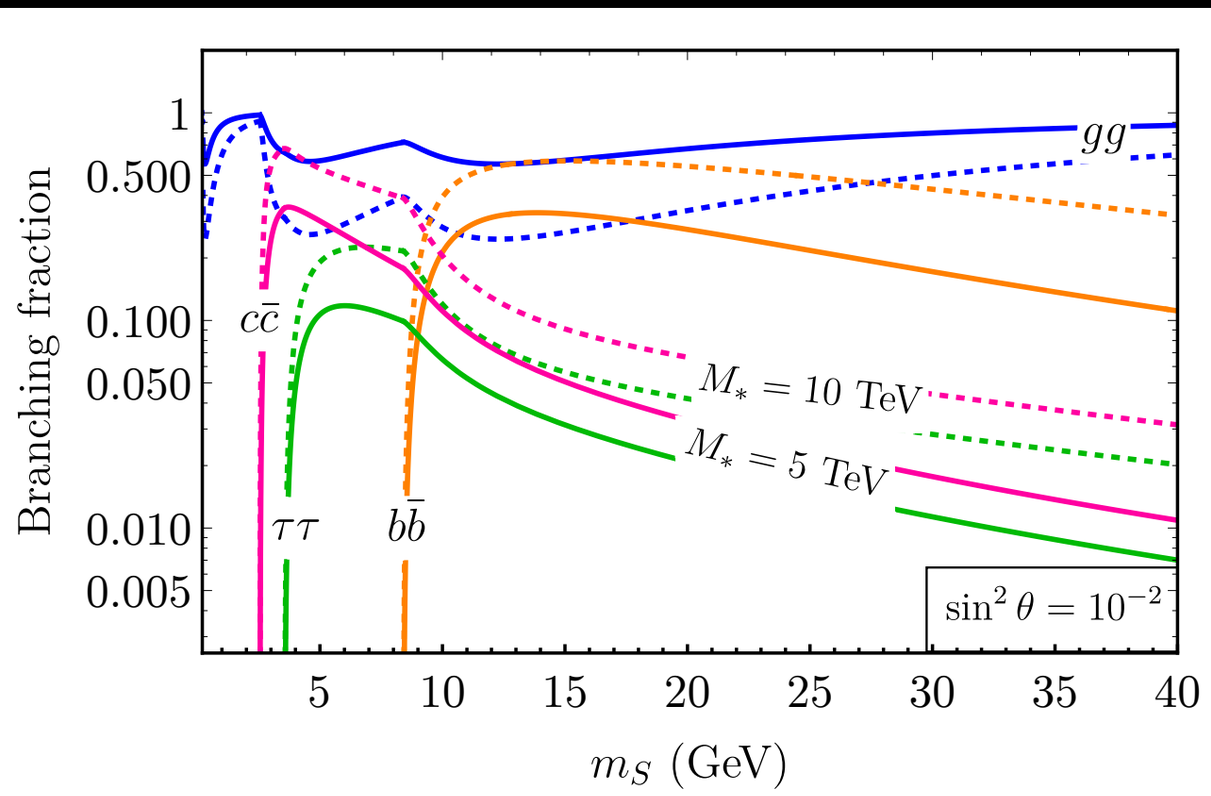
Higgs VEV switches on too fast, and sphalerons are already inactive by the time the axion starts rolling.

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

# 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 is $\theta < 10^{-3}$ 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.




1911.01432

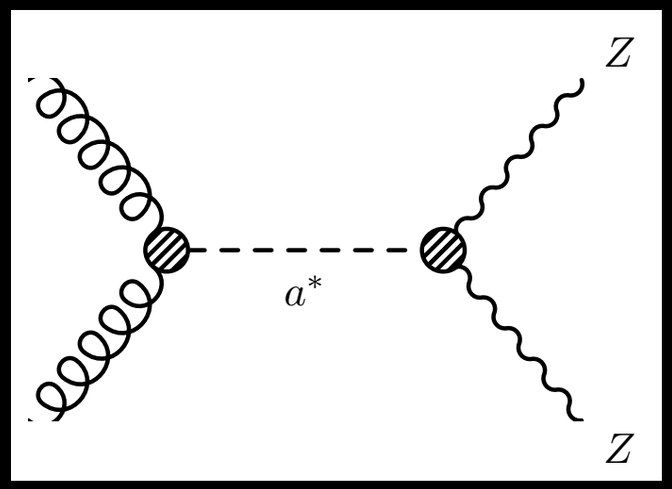
# LHC Prospects

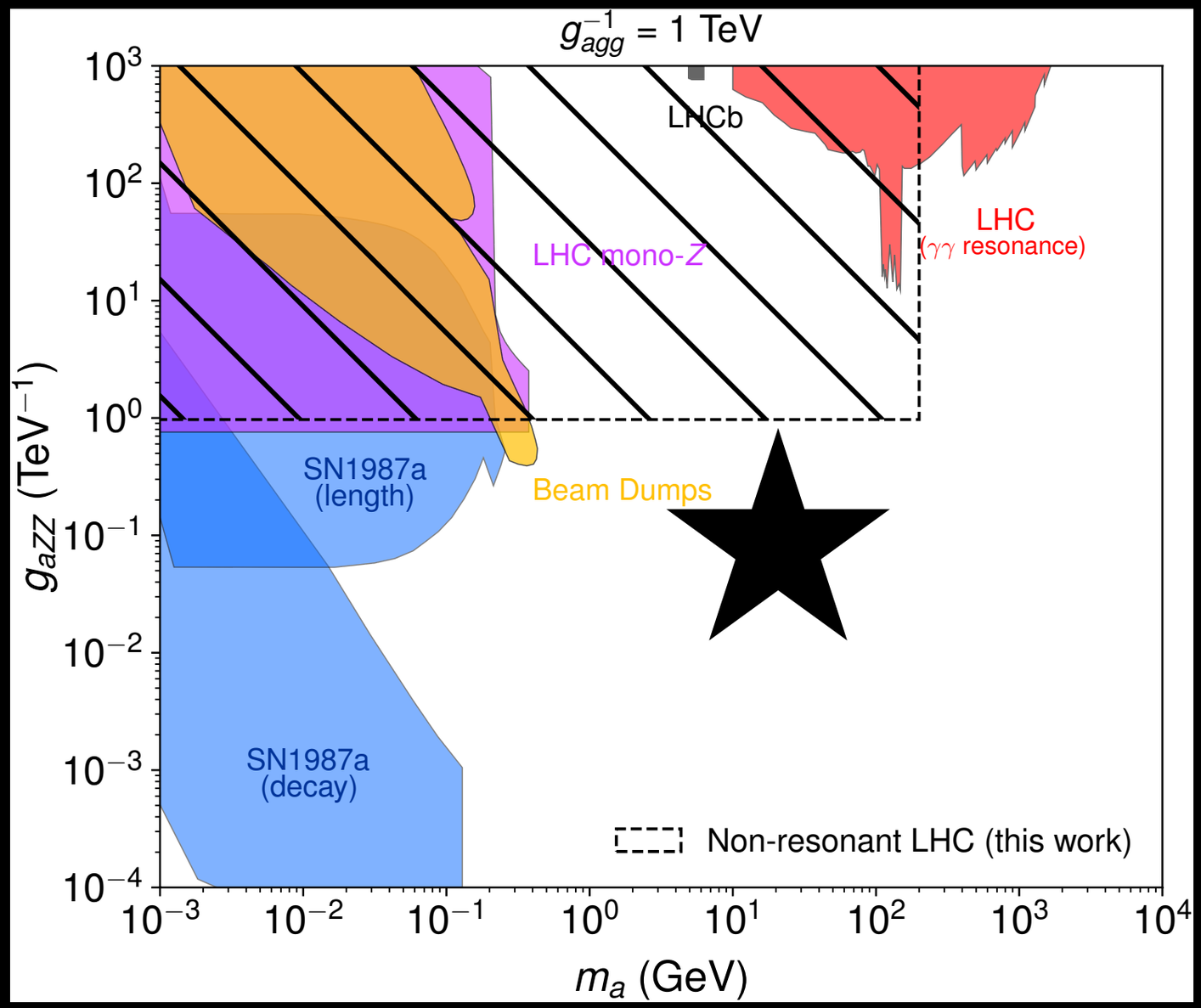
**Gavela, No, Sanz, Troconiz 1905.12953**

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

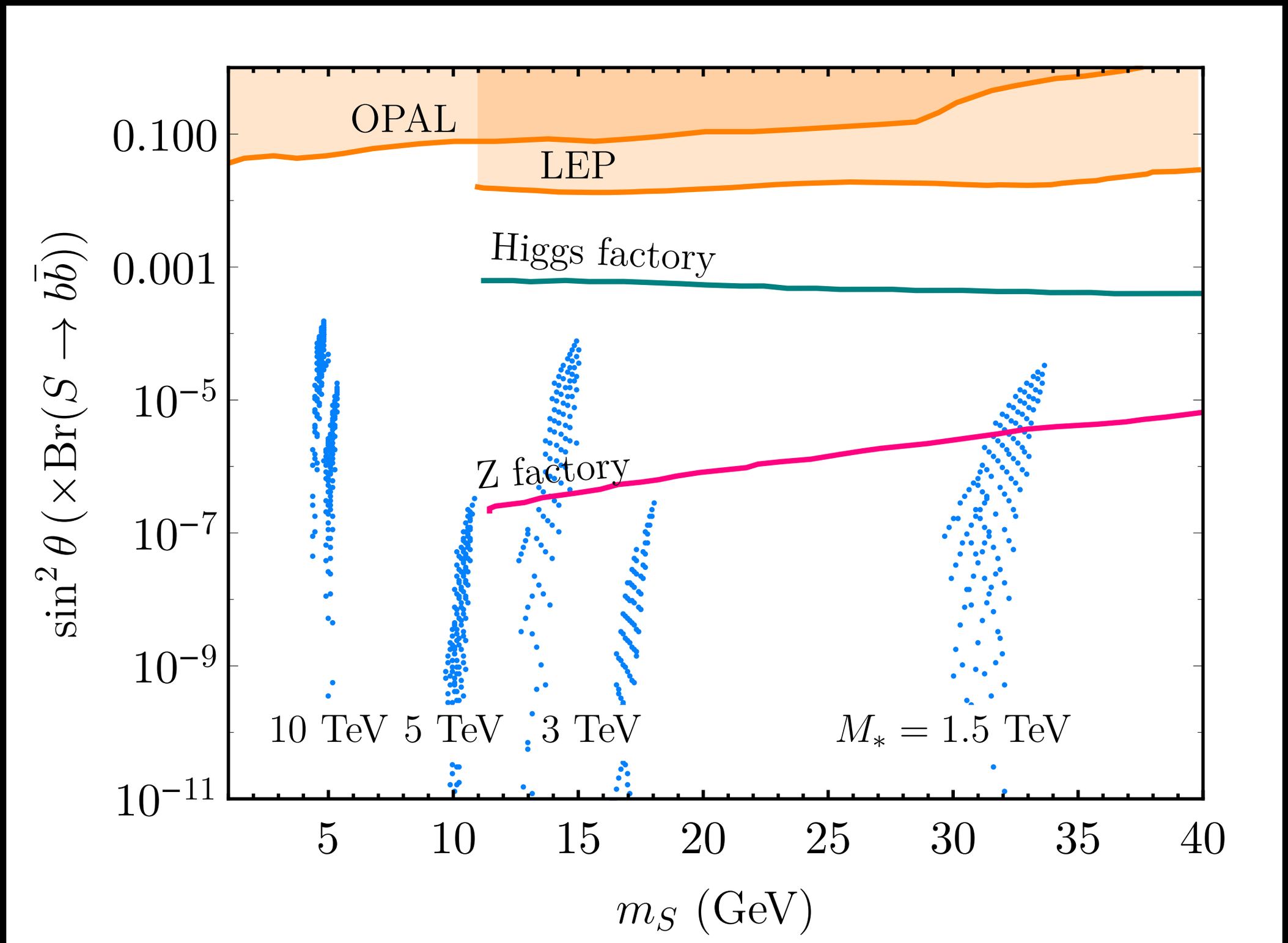
Usually it decays to dijets, which have large backgrounds.

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



# Future Colliders

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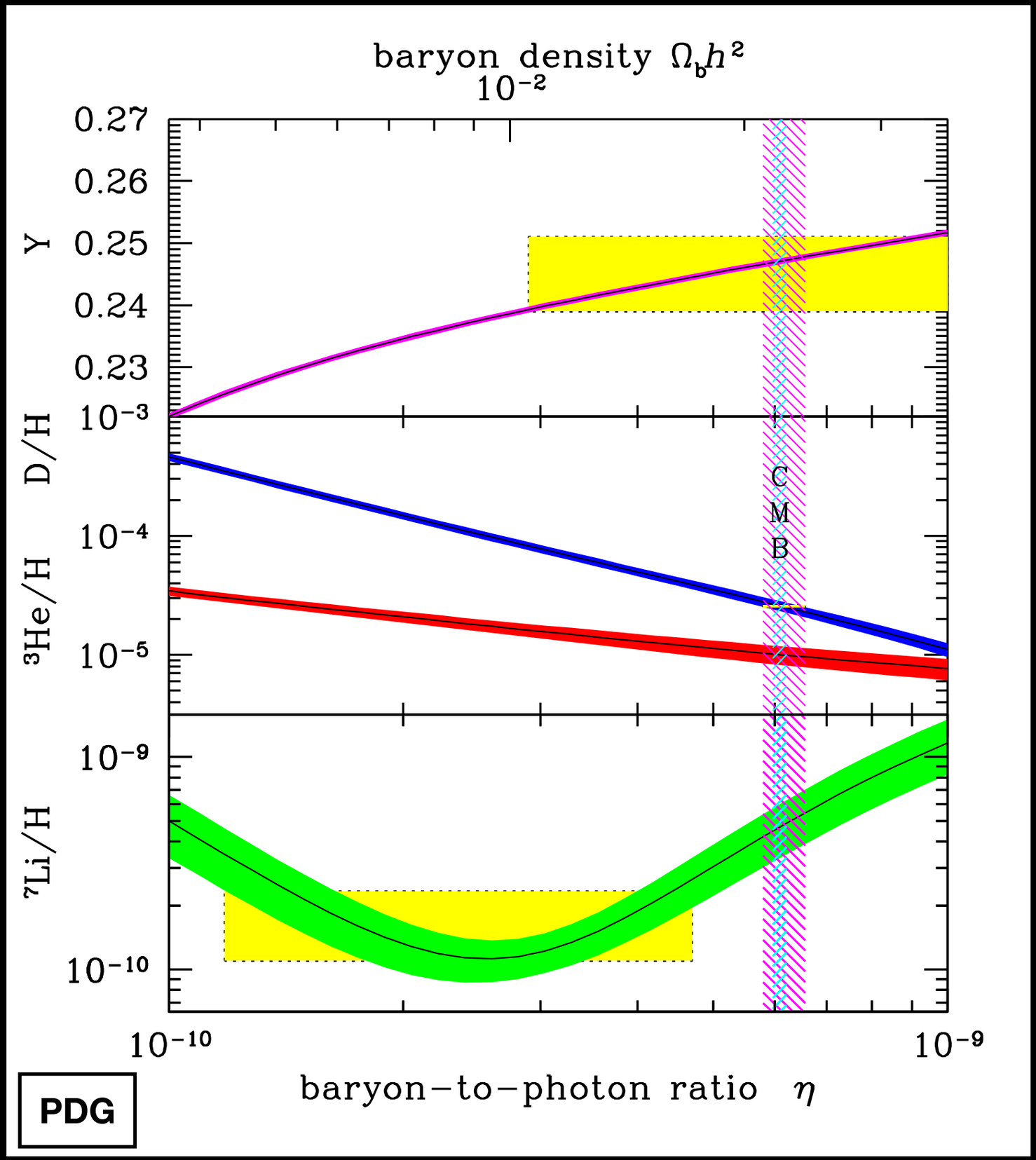
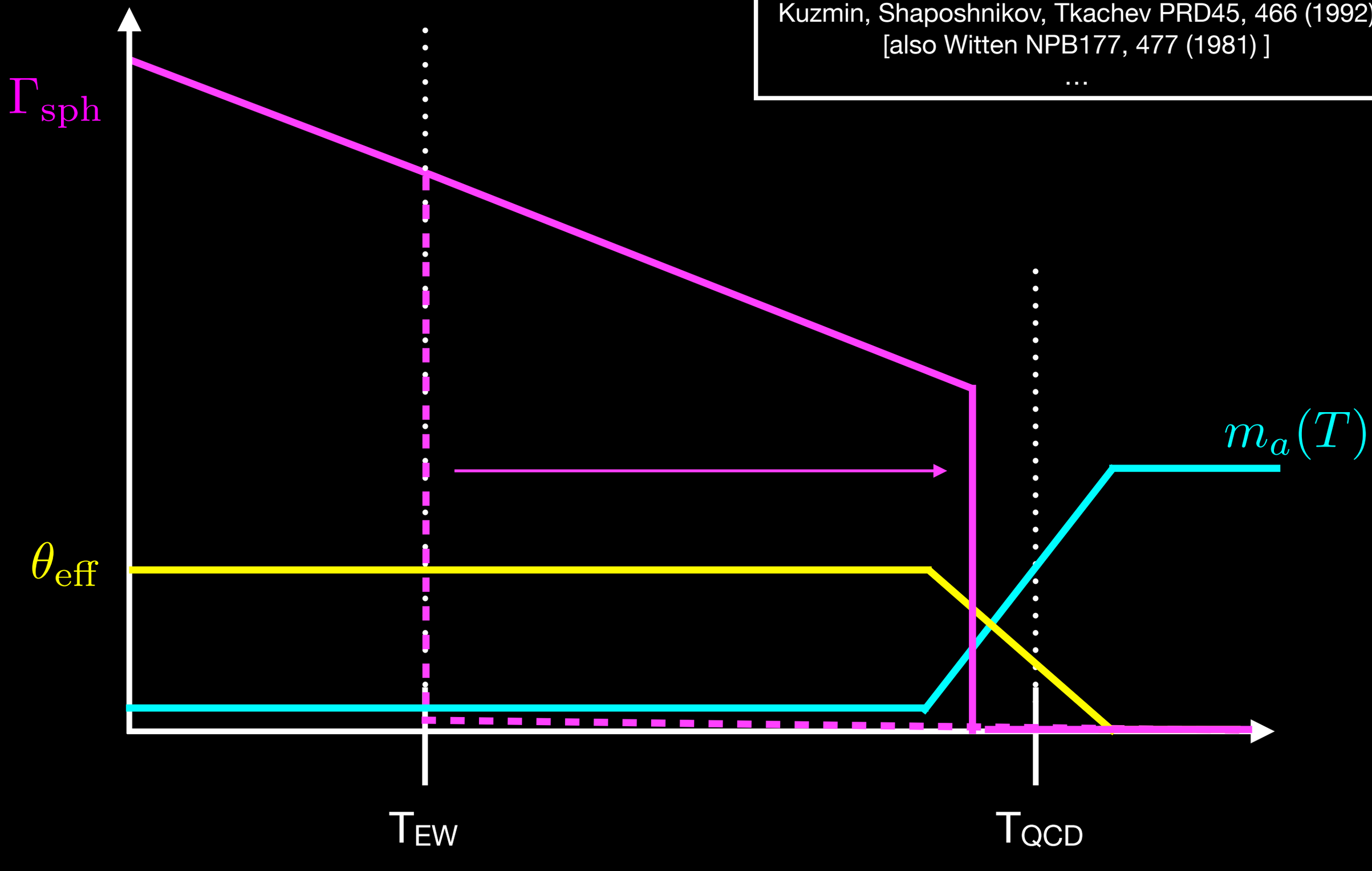
# Big Bang Nucleosynthesis

- 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

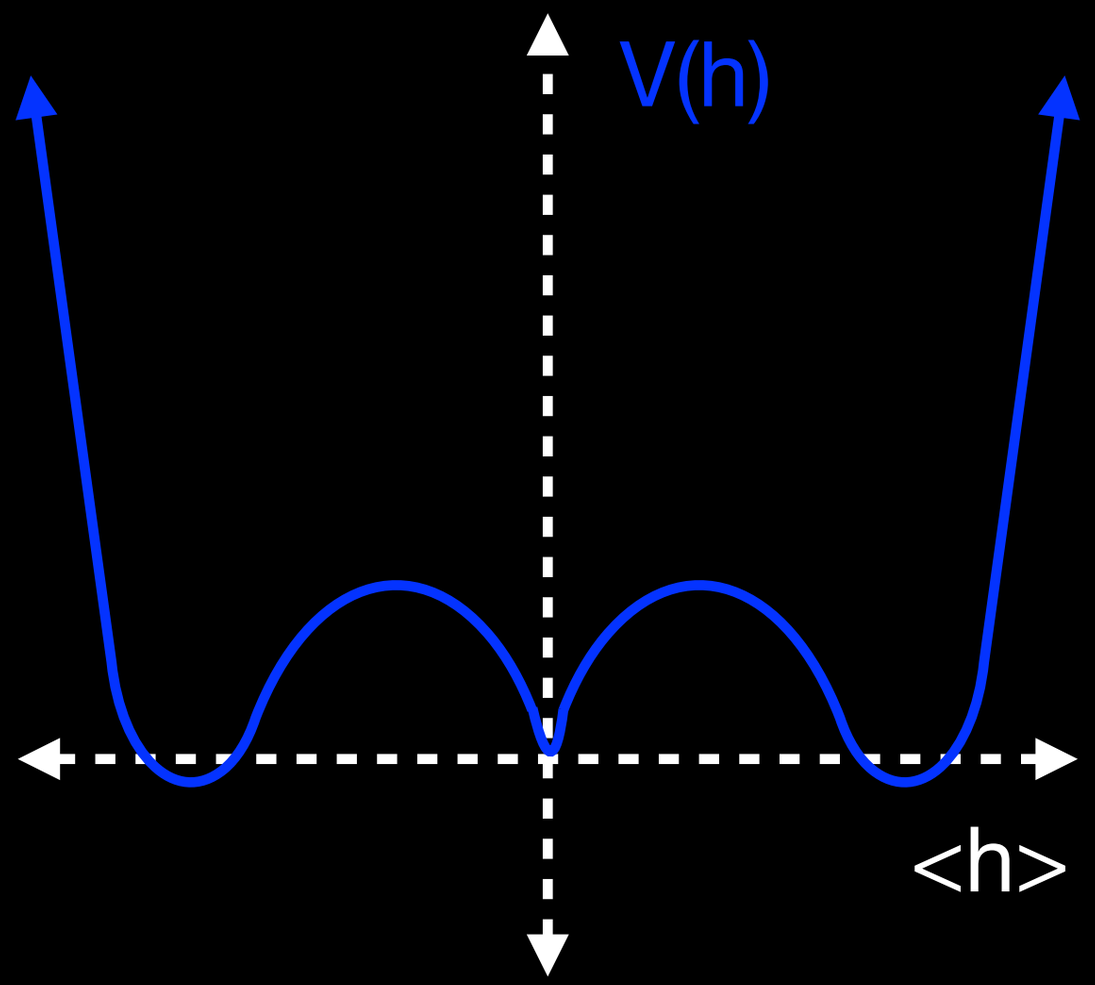
Kuzmin, Shaposhnikov, Tkachev PRD45, 466 (1992)
[also Witten NPB177, 477 (1981) ]
…



# 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:

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

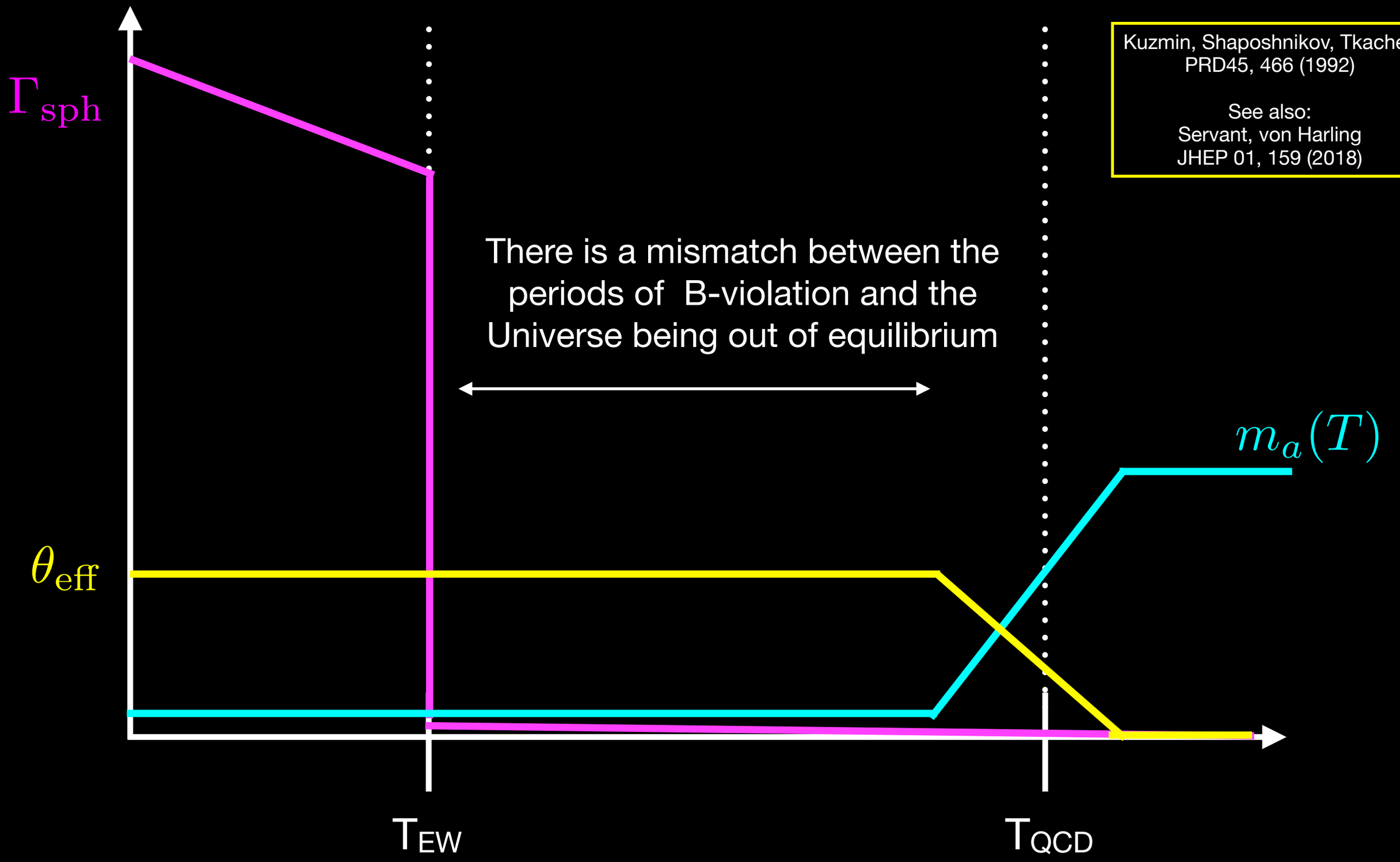
$$\simeq 5 \times 10^{-9} \left( \frac{T_{\rm QCD}}{T_{RH}} \right)^3$$

- 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 $10^{-9}$.

# The Challenge

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.)