# Gravitational waves

## a window onto the Early Universe

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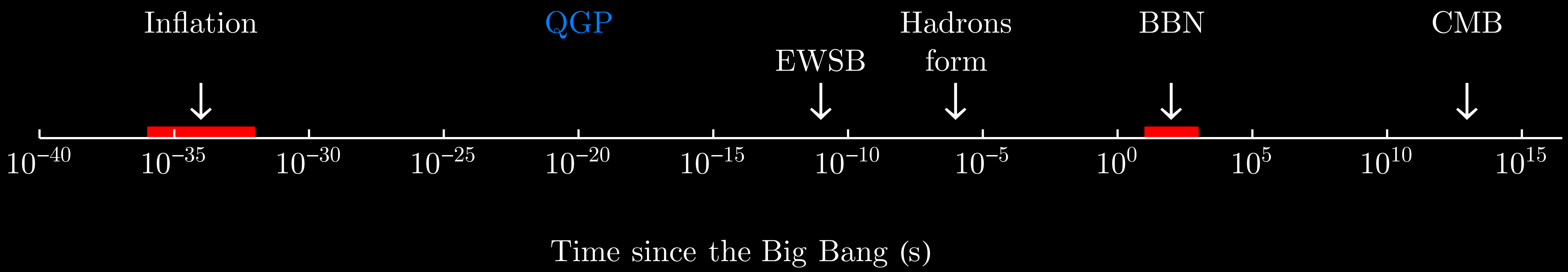
Based on

*DC, Houtz, Sanz [JHEP, arXiv:1904.10967]*

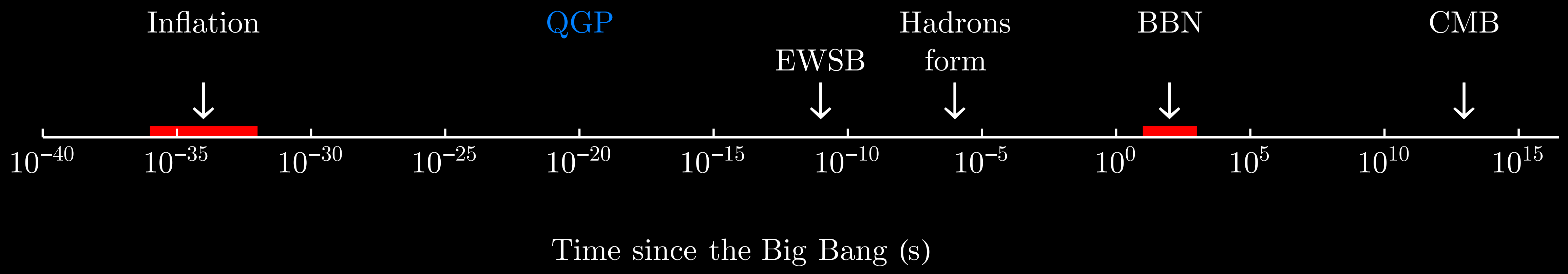
*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

# A cosmic timeline



# A cosmic timeline

Photon decoupling releases the photons of the CMB

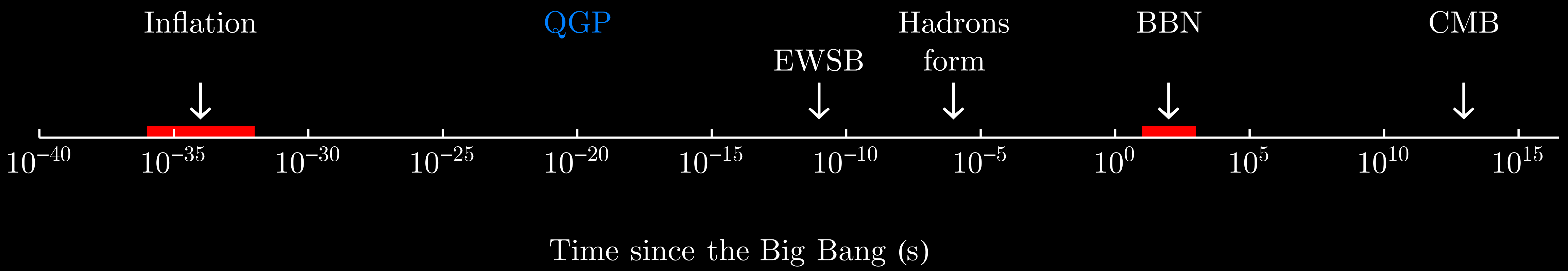



Our earliest *direct* cosmological probe (so far)

# Not (yet) on the cosmic timeline

Grand Unification of the gauge sectors of SM

Dark Matter is produced, obtains a mass and becomes non-relativistic




Through an unexplained mechanism, there is more matter than antimatter

A dynamical mechanism relaxes the strong CP angle to zero

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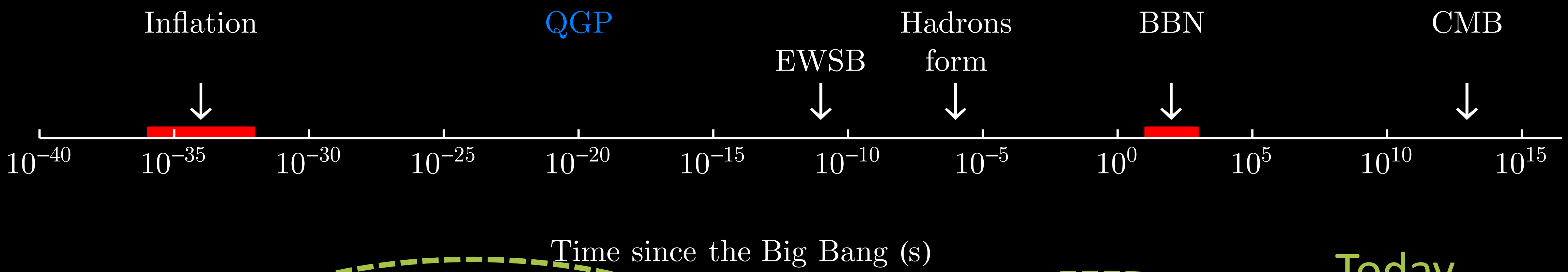



Today

Through an unexplained mechanism, there is more matter than antimatter

A dynamical mechanism relaxes the strong CP angle to zero

Gravitational waves released in the Early Universe travel unimpeded until today

# Gravitational Waves: probes of our cosmic timeline

- A memory of the past

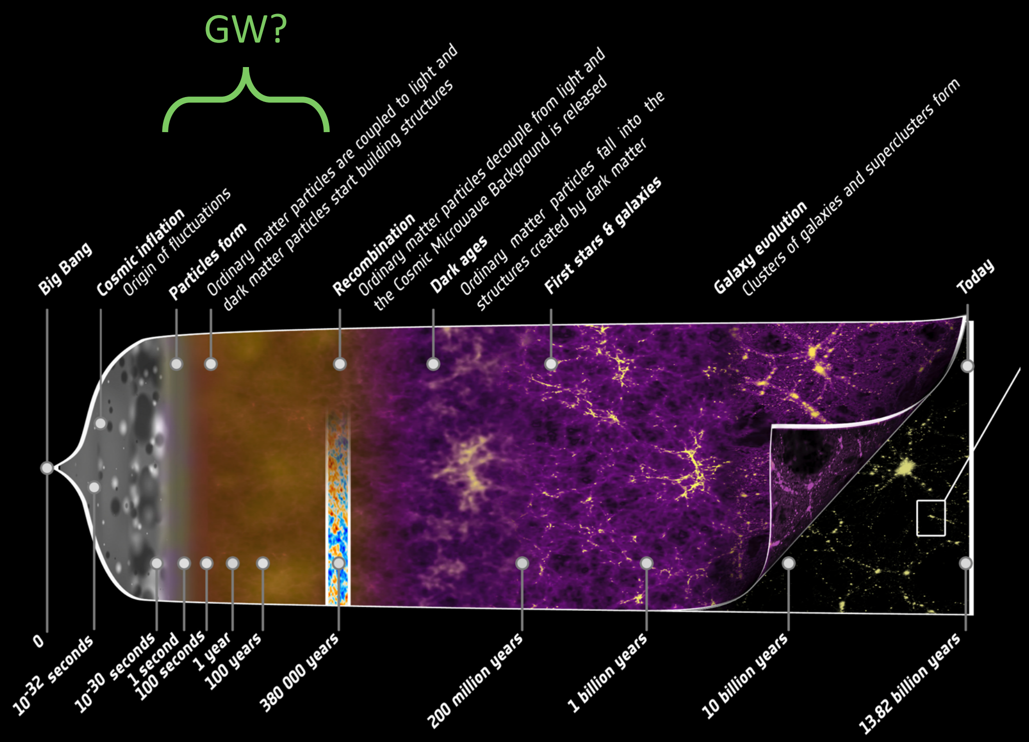
  *Information about the source is not washed out by thermal equilibration*

- A detector of the far

  *The Universe is (almost) transparent to GW*

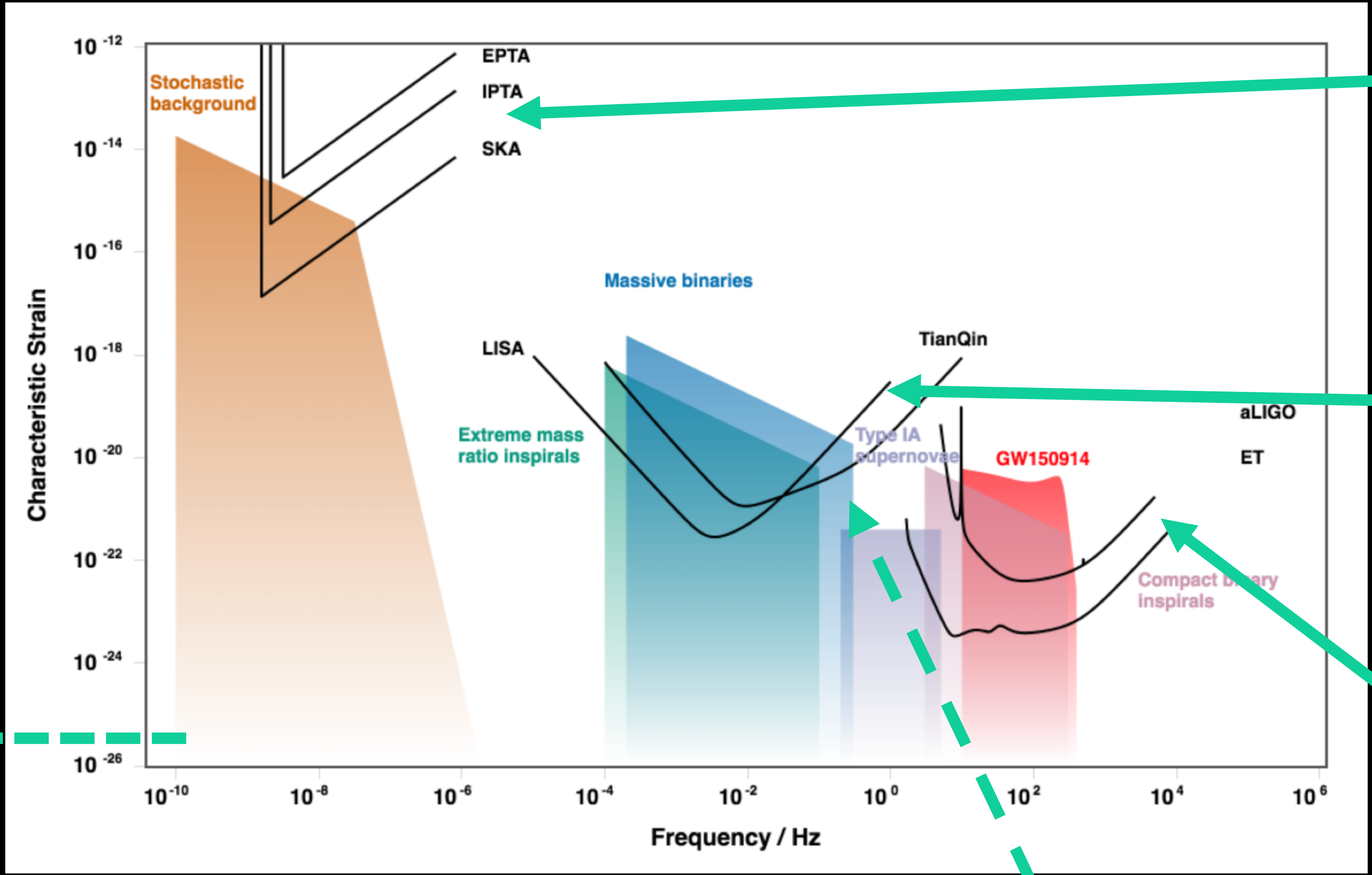
- A probe of the dark

  *Dark Matter interacts gravitationally*

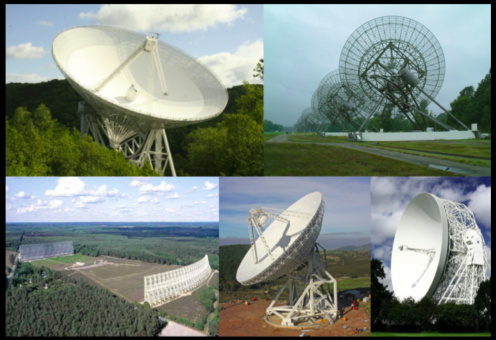


# Experimental strain-noise sensitivity bands

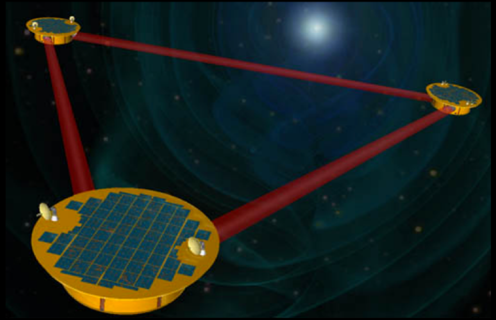
*Moore, Cole and Berry, Class.Quant.Grav. 32 (2015)*




*CMB*



*Pulsar timing arrays*



*Space-based interferometers*

*Ground-based interferometers*

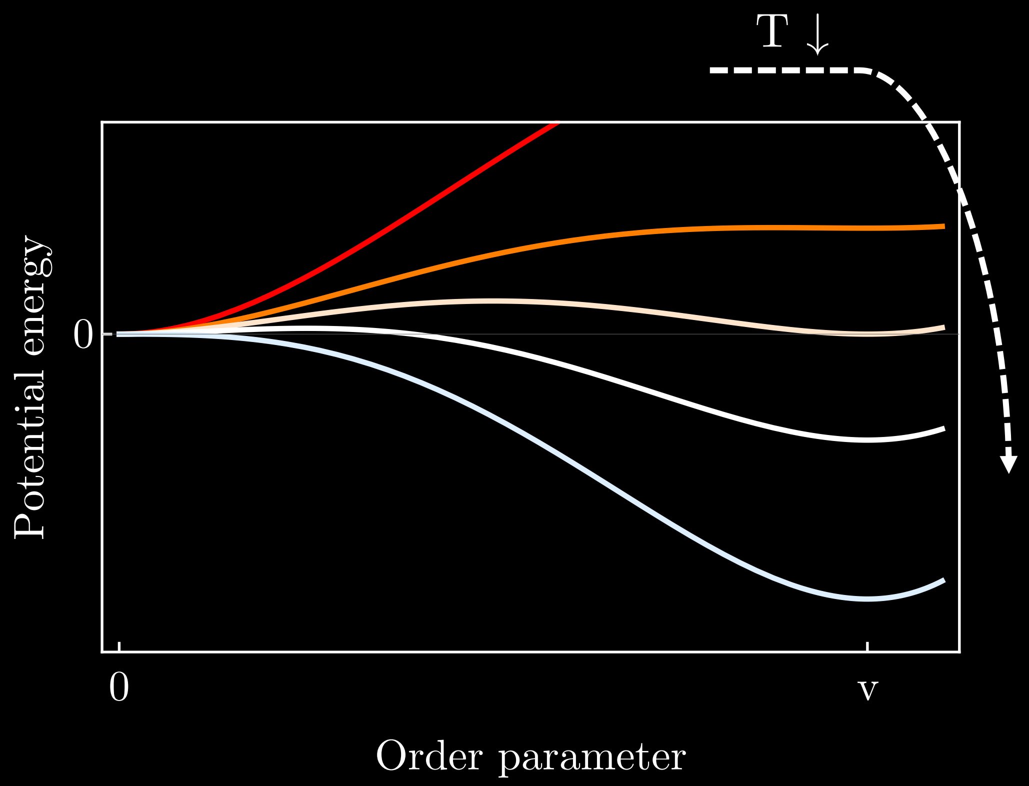
*Atom interferometers?*

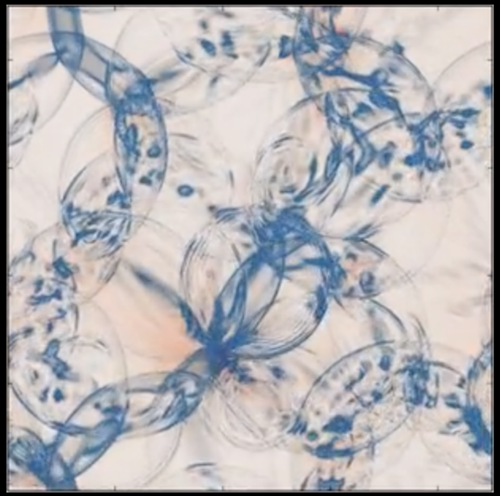
# First order phase transitions

Change in vacuum state associated with the release of latent heat

Inhomogeneous and out-of-equilibrium

Nucleation of bubbles of ”true” vacuum described by instantons



*Snapshot from simulation: Daniel Cutting, private communication*

*What happens to the energy released by the phase transition?*

It may dissipate as gravitational waves:

- Bubble collisions source GW
- Acoustic waves and turbulence in the plasma source GW

# Gravitational Wave spectra from a Cosmic PT

Three contributions: $\Omega_{\rm GW} = \Omega_{\rm col} + \Omega_{\rm sw} + \Omega_{\rm turb}$

- Collisions of the scalar bubble shells ($\sim$ the envelope approximation)
  *Dominant for runaway ($\gamma \to \infty$) bubbles*

Driven by theory + simulations

- Sound shells in the fluid kinetic energy collide
  *Dominant for non-runaway bubbles*

Driven (mostly) by simulations

- (Magnetohydrodynamic) turbulence in the fluid: Kolmogorov theory
  *Subdominant (usually*)*

Driven by theory (currently)

*See for example:*
*Weir, [1705.01783]*
*Hindmarsh, PRL, [1608.04735]*

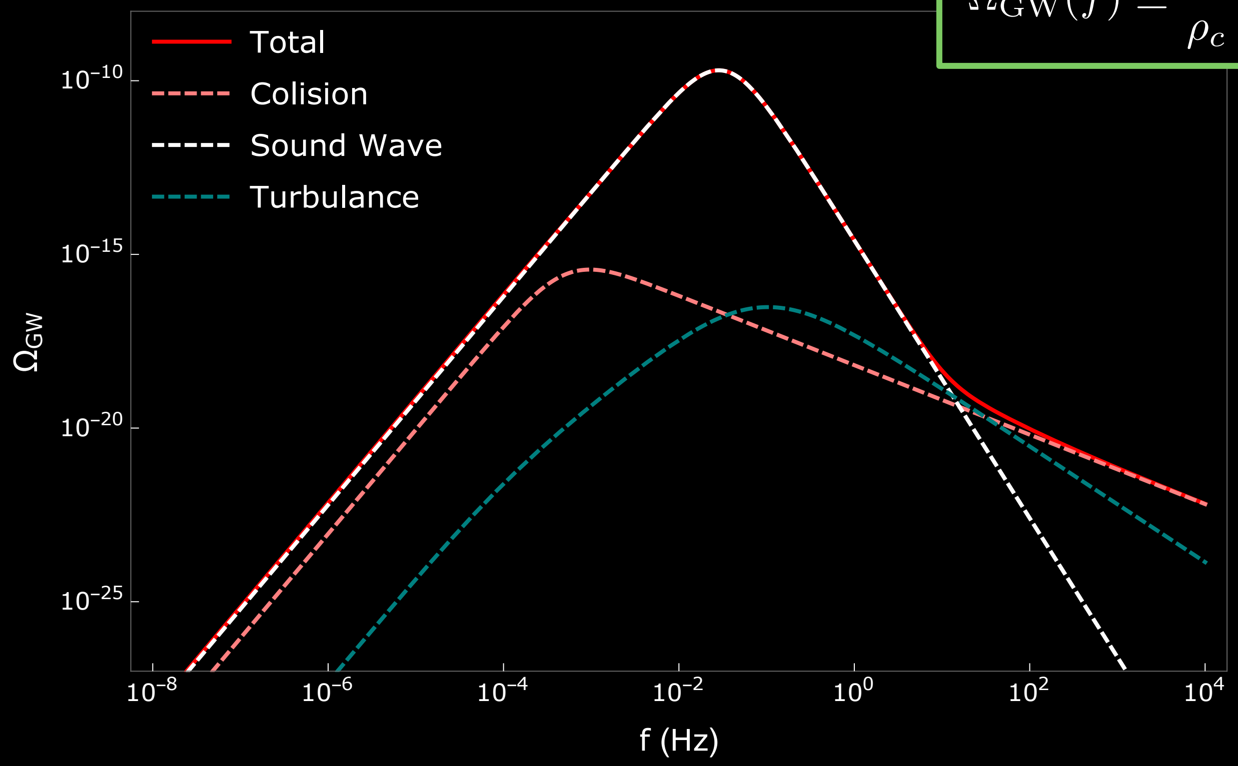
* However, see Ellis, No, Lewicki, [JCAP, arXiv:1809.08242] ENL+ Vaskonen [JCAP, arXiv:1903.09642]

# Gravitational waves from phase transitions

- The resulting GW spectrum has a broken power law form
  - $f_{peak} \sim R^{-1}$
- Power spectrum depends on thermodynamic quantities

$\alpha$ = latent heat (normalized to $\rho_{\rm rad}$)
$v_w$ = wall velocity
$\beta/H$ = transition rate parameter
$T_N$ = nucleation temperature

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$




- Spectra matched to lattice simulations

*For example: Hindmarsh, Huber, Rummukainen, Weir [PRD, 1704.05871]*

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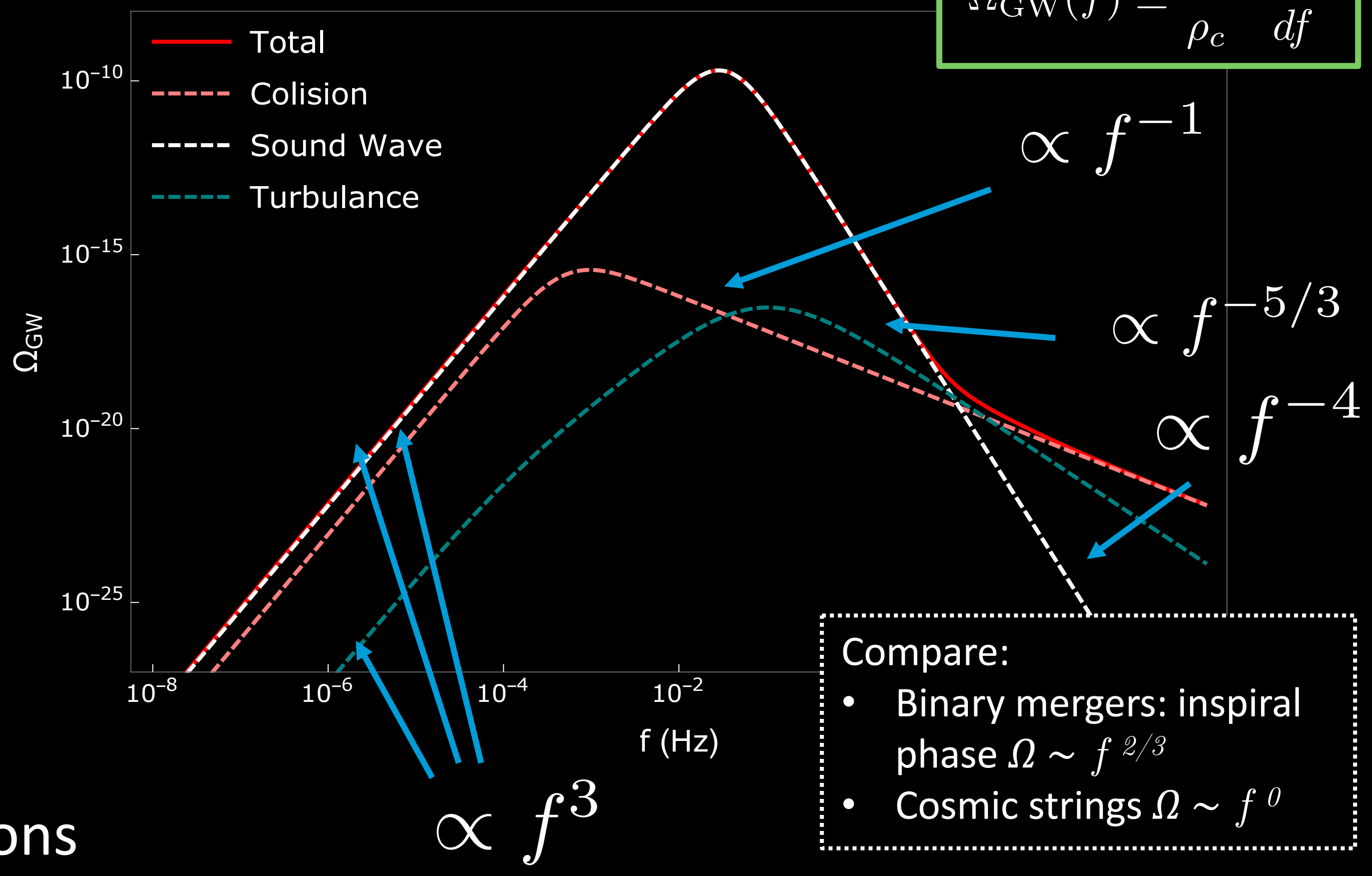
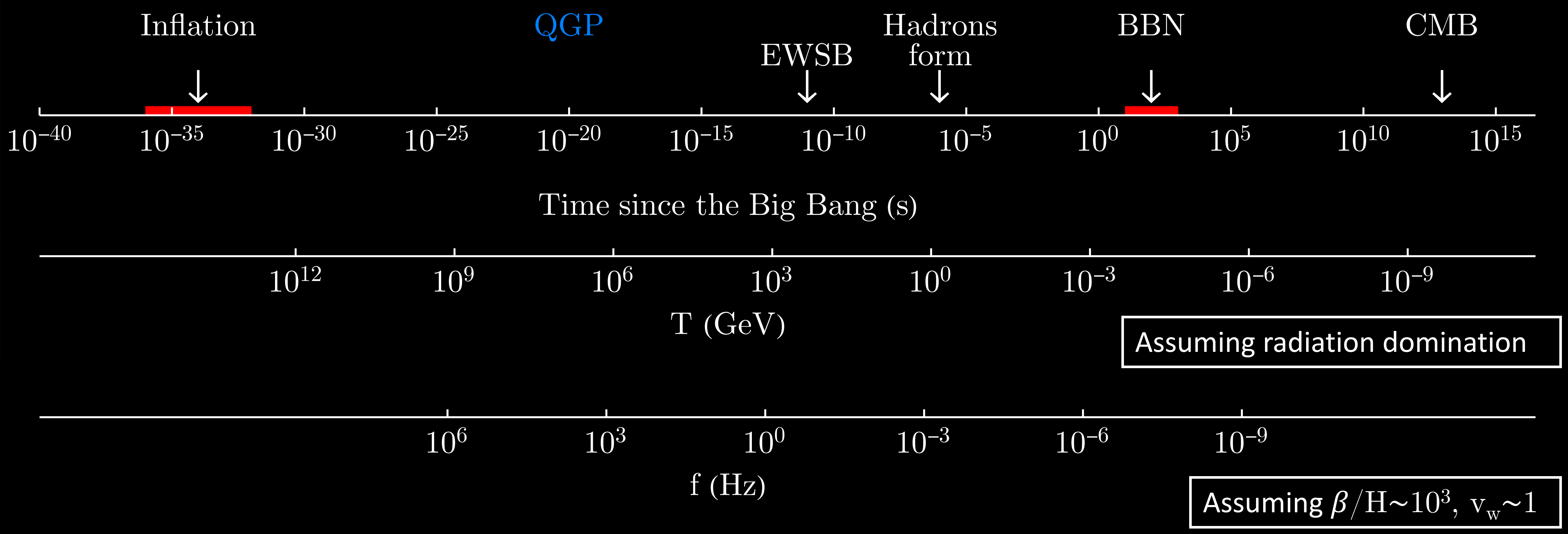



Compare:
- Binary mergers: inspiral phase $\Omega \sim f^{2/3}$
- Cosmic strings $\Omega \sim f^{0}$

# Phase transitions and the cosmic timeline



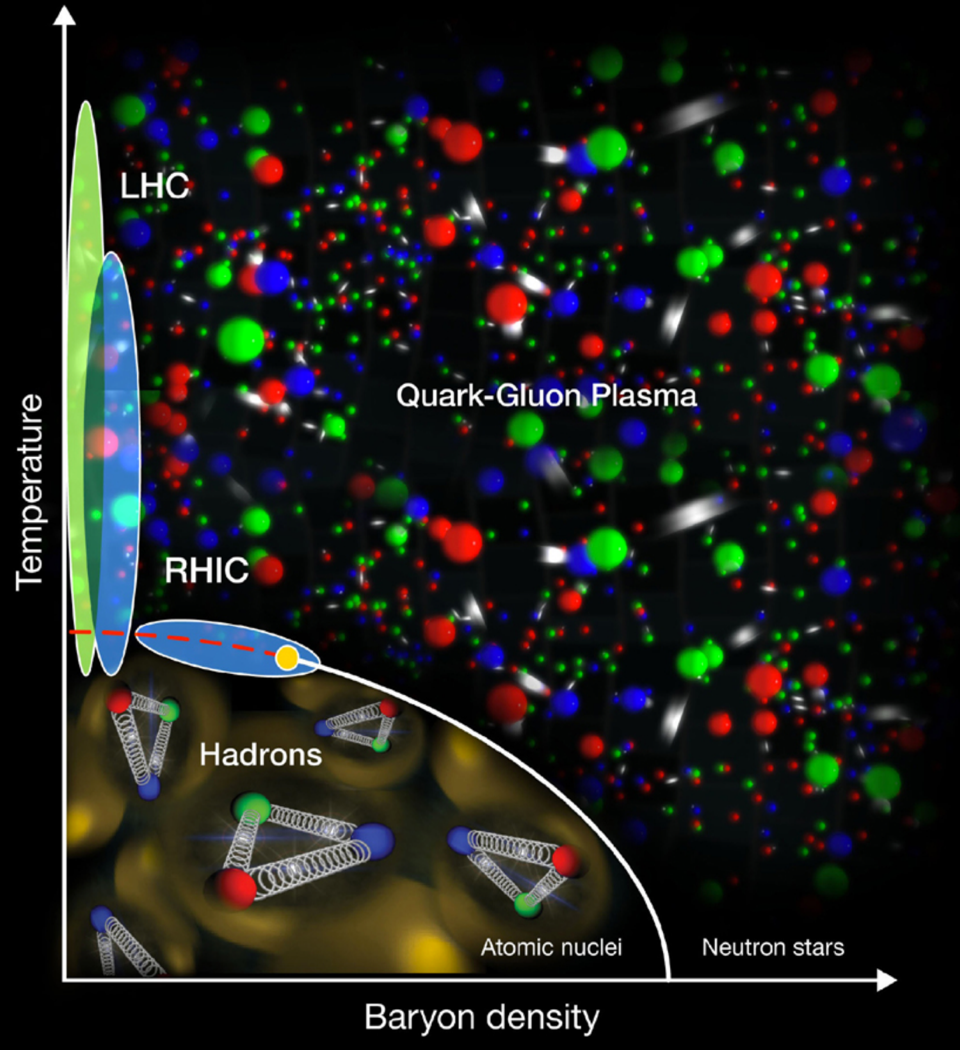

Gravitational waves released in the Early Universe travel unimpeded until today

# Confinement in the Standard Model

- QCD confines when $\alpha_s > 1$

- Confinement scale (MS-bar scheme): $\Lambda_{\text{QCD}} \sim 400\ \text{MeV}$
- At $400\ \text{MeV}$, (2+1) dynamical flavors in the SM

- Transition is crossover → no GW (or other) signature



# Motivations for QCD’ confinement

Either a *new strong sector*, or *modified QCD confinement*

- Strong CP problem (TeV axions)
  - *e.g. S. Dimopoulos, A. Hook, J. Huang, G. Marques-Tavares, [JHEP, arXiv:1606.03097]*
  - *M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez and R. Del Rey [EPJ, arXiv: 1805.06465]*
  - *P. Agrawal and K. Howe, [JHEP, arXiv:1712.05803]*
- Baryogenesis
  - *e.g. Ipek, Tait, PRL (2019)*
  - *DC, Howard, Ipek, Tait (2019)*
  - *Servant, PRL (2014)*
- Axion relic abundance
  - *e.g. Barr and Kyae, PRD (2005)*
- PBH production
  - *e.g. Jedamzik, PRD (1996)*
  - *Davoudiasl, PRL (2019)*
- Dynamical generation of scales
  - *e.g. Technicolor, Composite Higgs models*
  - *Many papers, typically ~TeV scale strong sector*
- Quark nuggets
  - *e.g. Witten, PRD (1984)*
  - *Bai, Long [JHEP, 1804.10249]*

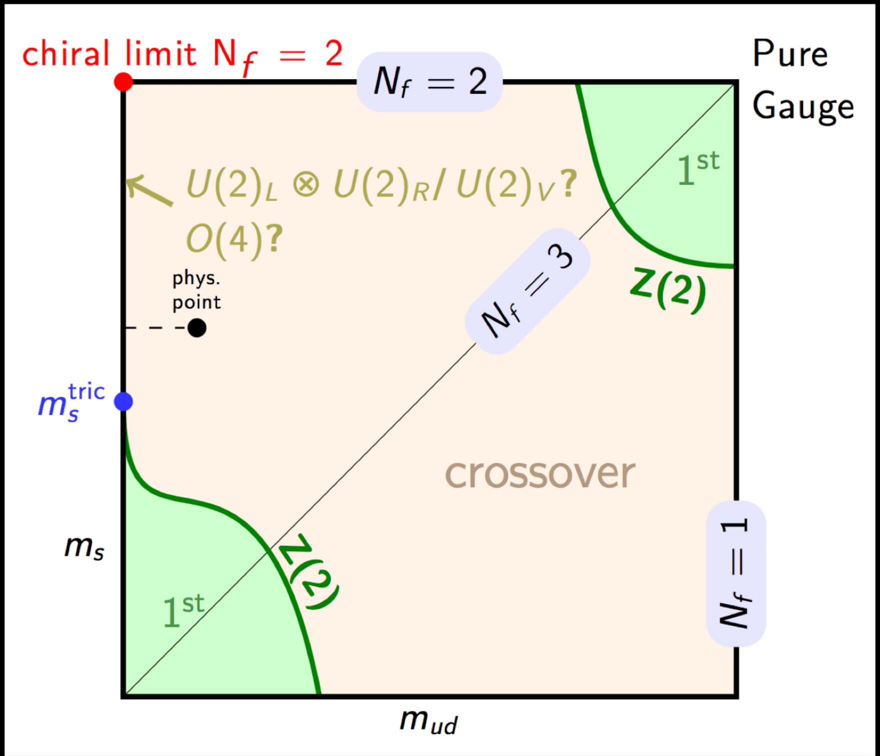
# Chiral symmetry breaking (“the $\chi$PT –PT”)

- Confinement implies chiral symmetry breaking ($N_f$ dynamical fermions):

$$SU(N_f)\times SU(N_f)\rightarrow SU(N_f)$$

- Analytic argument (based on the linear $\Sigma$-model) suggests the chiral PT is first order for
  - $N_f \geq 3$
  - $N_f = 0$ (pure gauge)

*Pisarski, Wilczek, PRD (1984)*




*“Columbia plot” in the case of $U(1)_A$ restoration [arXiv:1912.04827]*

# Studying the chiral phase transition

- Very quickly run into general issues with the calculability of a strongly coupled theory

- Proposed methods:
  - Linear Σ-model
  - Nambu-Jona-Lasinio (NJL or PNJL) models
  - Lattice simulations
  - MIT bag model

… each with strengths and weaknesses

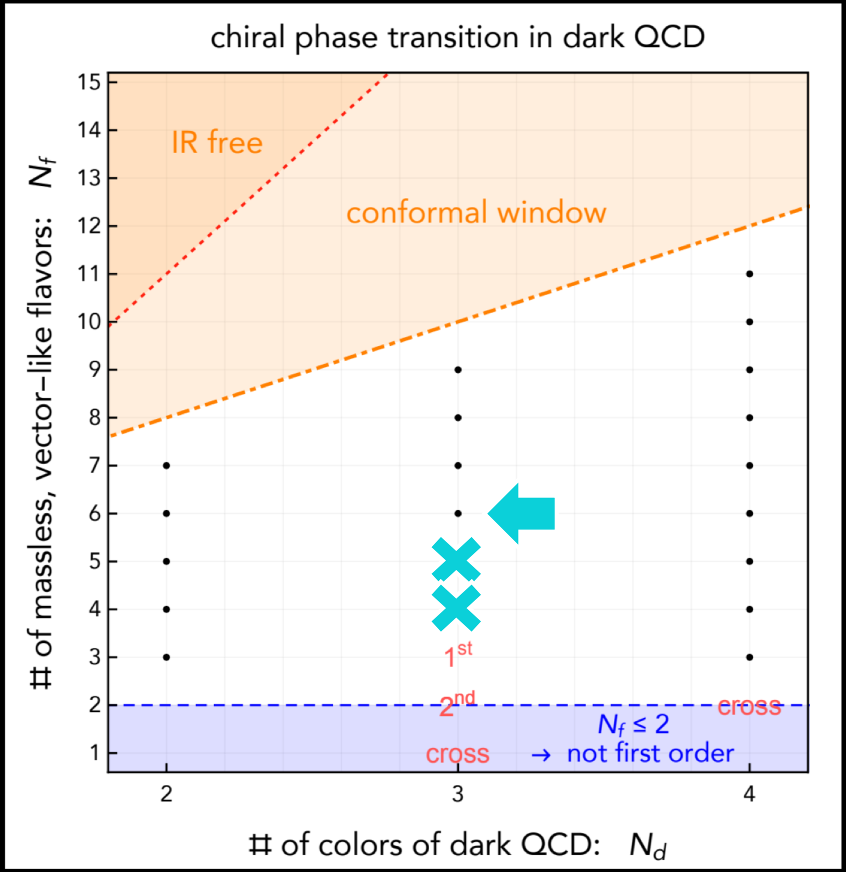
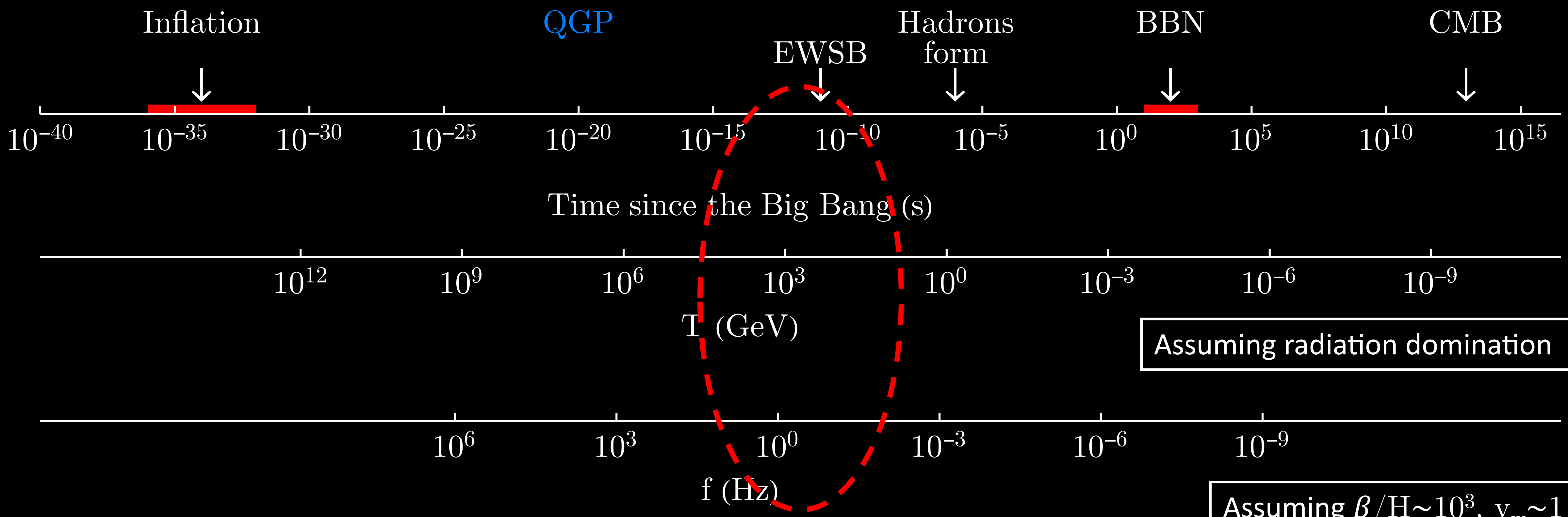



*Image: Long, Bai, Lu, arXiv:1810.04360*

# Axions on the cosmic timeline




Assuming radiation domination

Assuming $\beta/\mathrm{H}\sim10^3$, $\mathrm{v_w}\sim1$

What if? A dynamical mechanism relaxes the strong CP angle to zero.

*e.g. S. Dimopoulos, A. Hook, J. Huang, G. Marques-Tavares, [JHEP, arXiv:1606.03097]; M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez and R. Del Rey [EPJ, arXiv: 1805.06465]; P. Agrawal and K. Howe, [JHEP, arXiv:1712.05803]*

*DC, R. Houtz, and V. Sanz*
*[JHEP, arXiv:1904.10967]*

# Chiral symmetry breaking: linear $\Sigma$-model

- Low energy effective theory $(\Sigma_{ij} \sim \langle \bar{\psi}_{Rj} \psi_{Li} \rangle)$

$$V(\Sigma) = -m_\Sigma^2 \,\mathrm{Tr}\left(\Sigma\Sigma^\dagger\right) - \left(\mu_\Sigma \;\det\Sigma + h.c.\right) + \frac{\lambda}{2}\left[\,\mathrm{Tr}\left(\Sigma\Sigma^\dagger\right)\right]^2 + \frac{\kappa}{2}\,\mathrm{Tr}\left(\Sigma\Sigma^\dagger\Sigma\Sigma^\dagger\right)$$

- Note that if $\mu_\Sigma = 0$, there is an enhanced $\mathrm{SU(N_f)}\times\mathrm{SU(N_f)}\times\mathrm{U(1)_A}$ global flavor symmetry

- The $\mu_\Sigma$ terms are generated by instantons, which anomalously break the $\mathrm{U(1)_A}$ subgroup

*'t Hooft, PRD (1976)*

*DC, R. Houtz, and V. Sanz*
*[JHEP, arXiv:1904.10967]*

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- Decompose in terms of scalar mesons

$$\Sigma_{ij} = \frac{\varphi + i\eta'}{\sqrt{2N_F}}\delta_{ij} + X^a T^a_{ij} + i\pi^a T^a_{ij}$$

Order parameter

Dynamical axion

$\eta'$ is the pGB of $\mathrm{U}(1)_\mathrm{A}$
Anomalously coupled to $G\tilde{G}$
Gets a mass from the instantons of $\mathrm{SU}(\mathrm{N_C})$
(‘t Hooft 1976)

- $\eta'$ is a dynamical axion (if the $\psi$ quarks have no explicit mass terms)

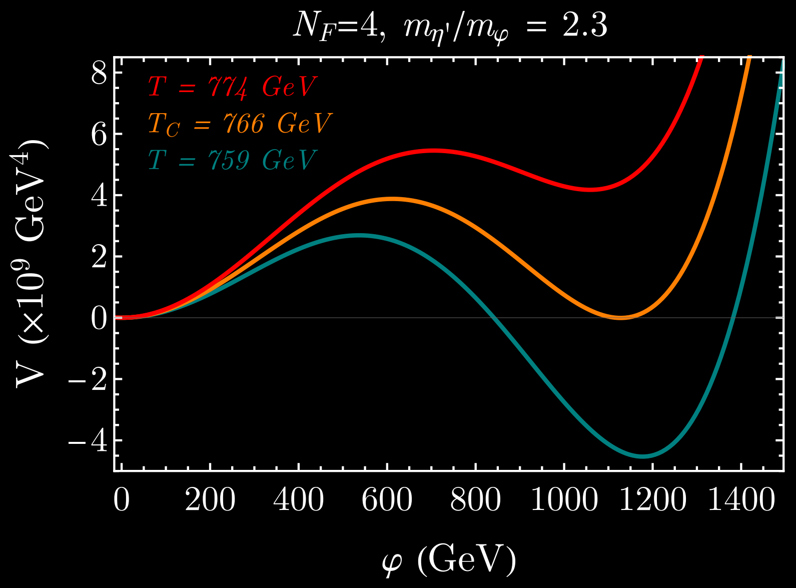
DC, R. Houtz, and V. Sanz
[JHEP, arXiv:1904.10967]
See also Long, Bai, Lu,
[arXiv:1810.04360]

# The thermal linear $\Sigma$-model

- One-loop thermal potential for the diagonal field $\varphi$ calculated in the usual way
- $m_i + \Pi_i$ runs over mesons; for example for $\mathrm{N_f} = 3$:

$$\begin{cases} V(\Sigma, T) = V(\Sigma) + V_\chi(\Sigma) + V_{T\neq 0}, \\ V_{T\neq 0} = \sum_i \frac{T^4}{2\pi^2} n_i J_B\left(\frac{m_i^2 + \Pi_i}{T^2}\right), \\ J_B(m^2) = \int_0^\infty dx\, x^2 \log\left(1 - e^{-\sqrt{x^2+m^2}}\right) \end{cases}$$

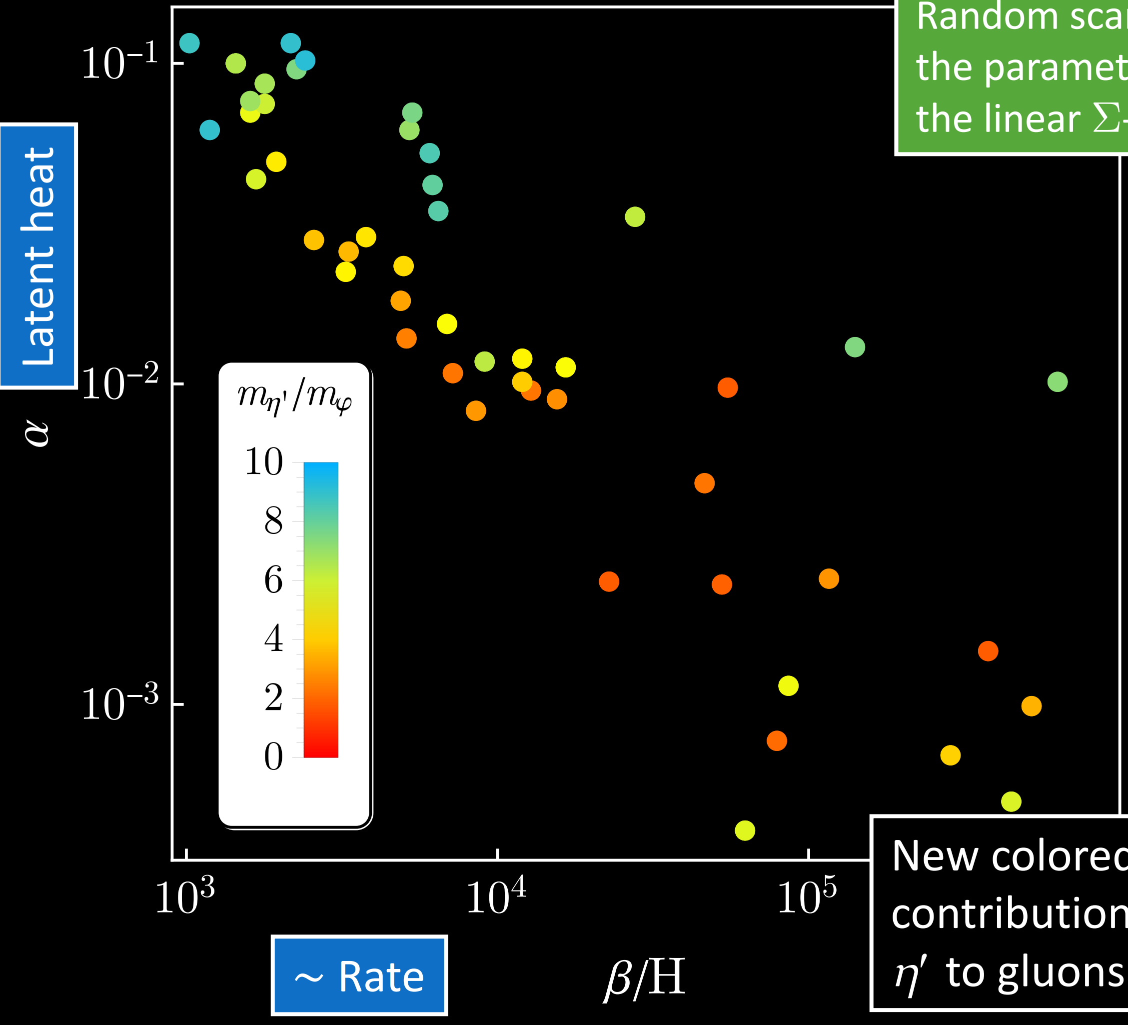
$$\begin{cases} m_\varphi^2 + \Pi_\varphi = \frac{1}{6}\left(\varphi\left(3\kappa\varphi + 9\lambda\varphi - 2\sqrt{6}\mu_\Sigma\right) - 6m_\Sigma^2 + T^2(3\kappa + 5\lambda)\right) \\ m_{\eta'}^2 + \Pi_{\eta'} = \frac{1}{6}\left(\varphi\left(\kappa\varphi + 3\lambda\varphi + 2\sqrt{6}\mu_\Sigma\right) - 6m_\Sigma^2 + T^2(3\kappa + 5\lambda)\right) \\ m_X^2 + \Pi_X = \frac{1}{6}\left(3\kappa\varphi^2 + 3\lambda\varphi^2 + \sqrt{6}\mu_\Sigma\varphi - 6m_\Sigma^2 - 18\xi + T^2(3\kappa + 5\lambda)\right) \\ m_\pi^2 + \Pi_\pi = \frac{1}{6}\left(\kappa\varphi^2 + 3\lambda\varphi^2 - \sqrt{6}\mu_\Sigma\varphi - 6m_\Sigma^2 - 18\xi + T^2(3\kappa + 5\lambda)\right) \end{cases}$$

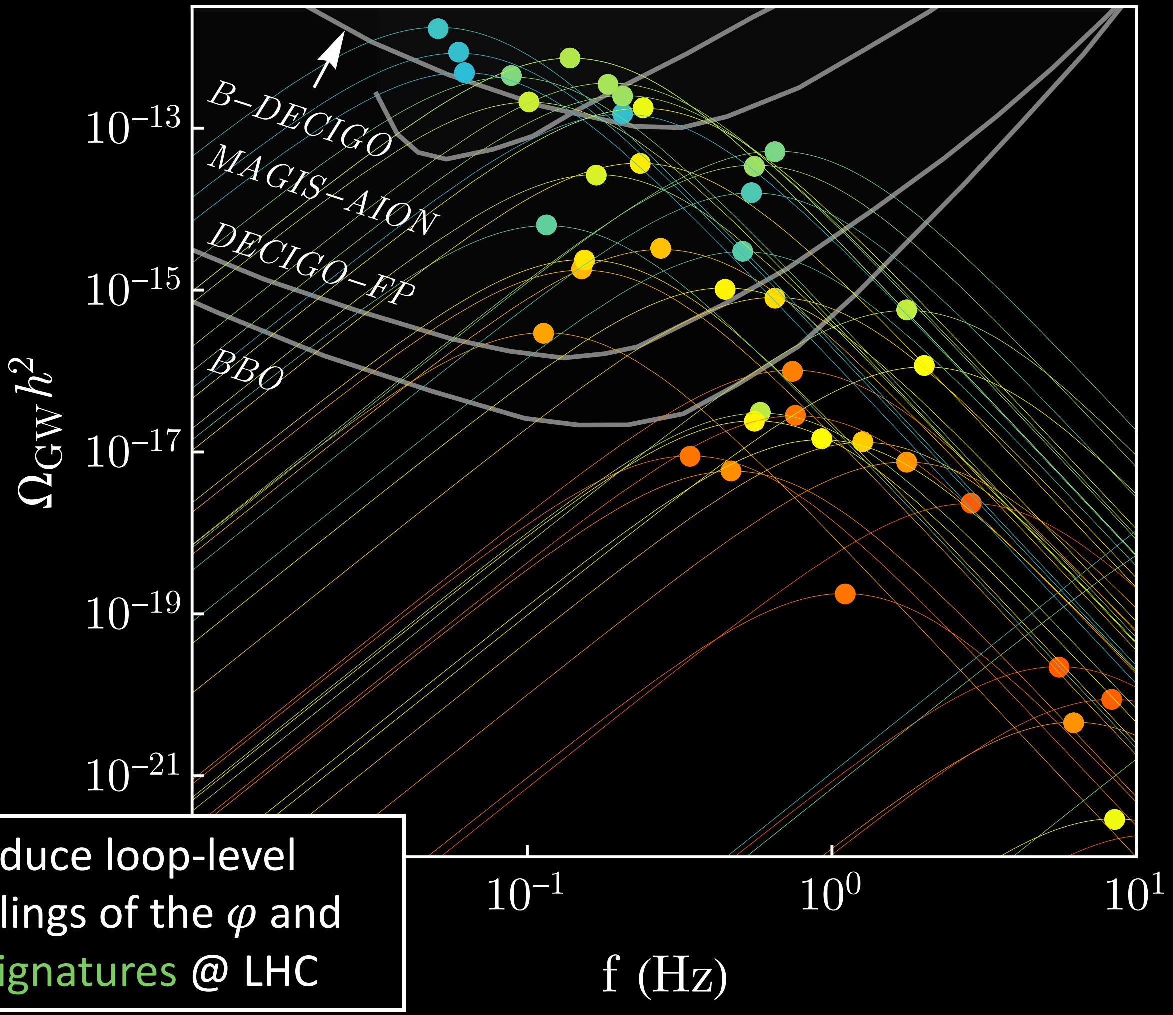


DC, R. Houtz, and V. Sanz
[JHEP, arXiv:1904.10967]

# GW in the linear Σ-model ($N_C = 3$, $N_f = 4$)

Random scan over the parameters in the linear Σ-model




New colored states induce loop-level contributions to couplings of the $\varphi$ and $\eta'$ to gluons → dijet signatures @ LHC

# Takeaways and comments

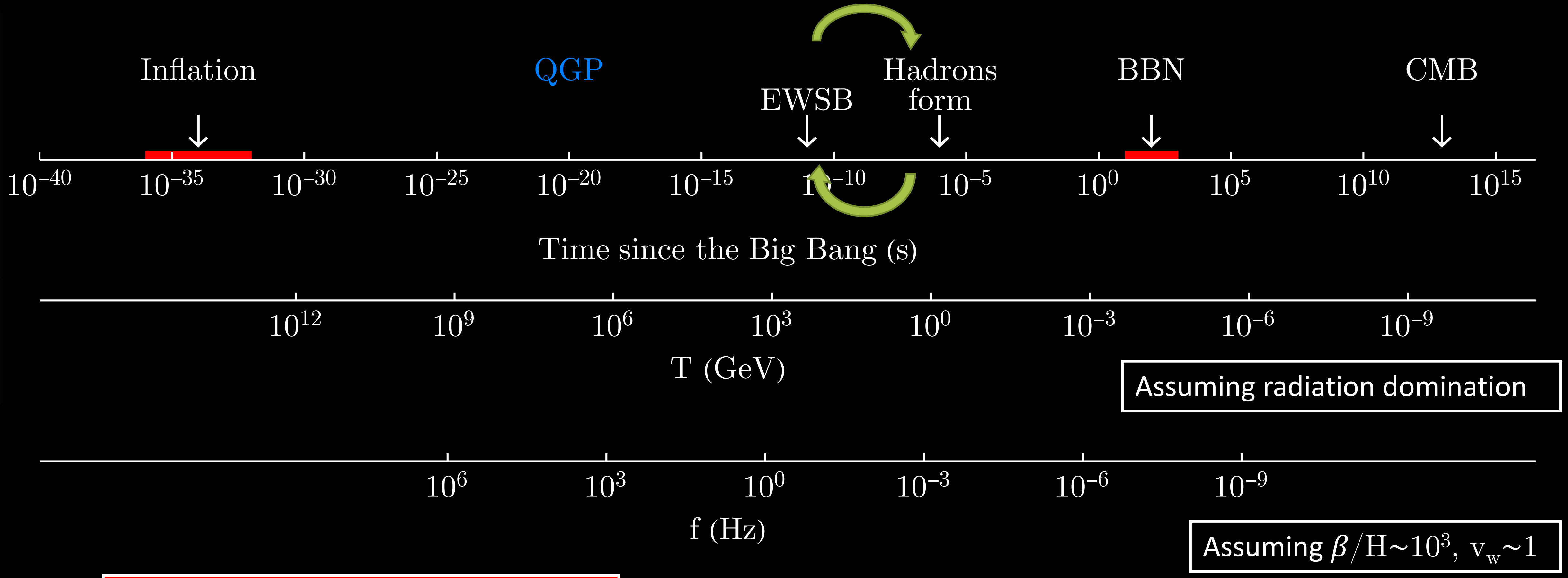
- Larger $\eta'$ axion mass $\leftrightarrow$ greater explicit symmetry breaking $\leftrightarrow$ enhanced GW amplitude
  - In some models, a large ratio $m_{\eta'} / m_{\varphi}$ is a natural prediction

*e.g. Gavela, Ibe, Quilez, Yanagida [arXiv:1812.08174]*

- New colored states induce loop-level contributions to couplings of the $\varphi$ and $\eta'$ to gluons → dijet signatures @ LHC

- GW predictions of the linear sigma model should be contrasted with other methods, such as lattice results

# An alternative cosmic timeline




Through an unexplained mechanism, there is more matter than antimatter.

*Ipek, Tait, PRL (2019)*

# Early QCD confinement

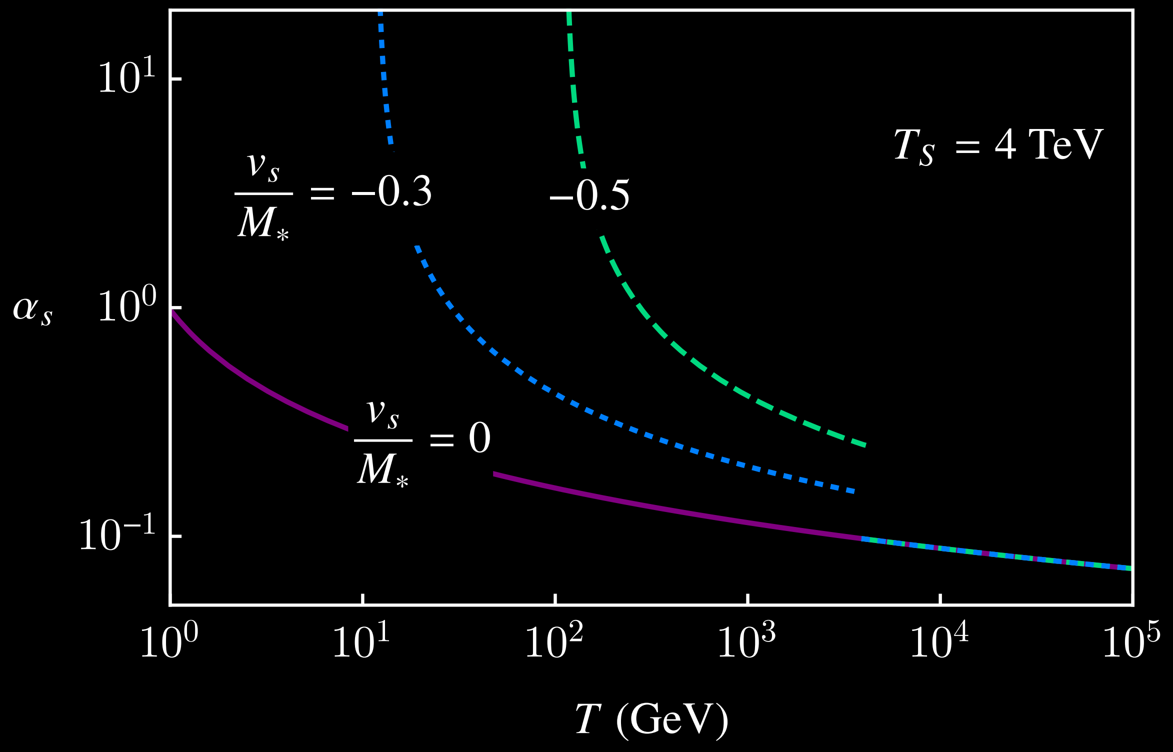
- Consider a modified gluon kinetic term,

$$-\frac{1}{4}\left(\frac{1}{g_{s0}^2}+\frac{S}{M}\right)G_{\mu\nu}G^{\mu\nu}$$

- The QCD confinement scale then depends on S,

$$\Lambda_{\rm QCD}(S)=\Lambda_0\, e^{\frac{24\pi^2}{2N_f-33}\frac{S}{M}}$$

(1-loop MS-bar)



*Ipek, Tait, PRL (2019)*

# Early QCD confinement

- Consider a modified gluon kinetic term,

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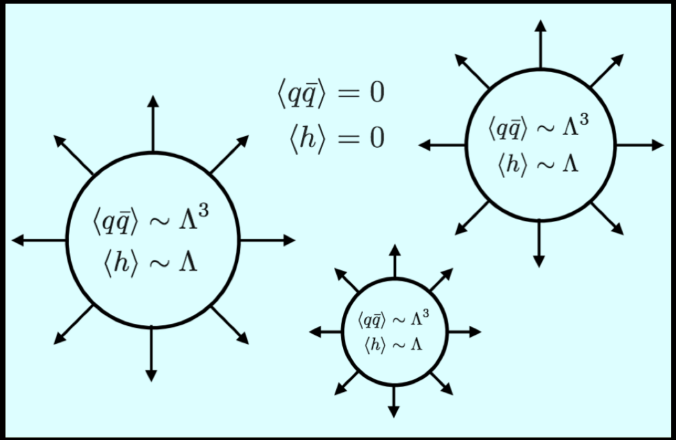
- Suppose confinement precedes EWSB

- Then confinement triggers EWSB, as the meson condensate leads to a tadpole term for the Higgs:

$$V(h) \ni -y_t h\langle \bar{q}q\rangle \sim -y_t \frac{\Lambda^2}{4\pi} h\langle\Sigma\rangle$$



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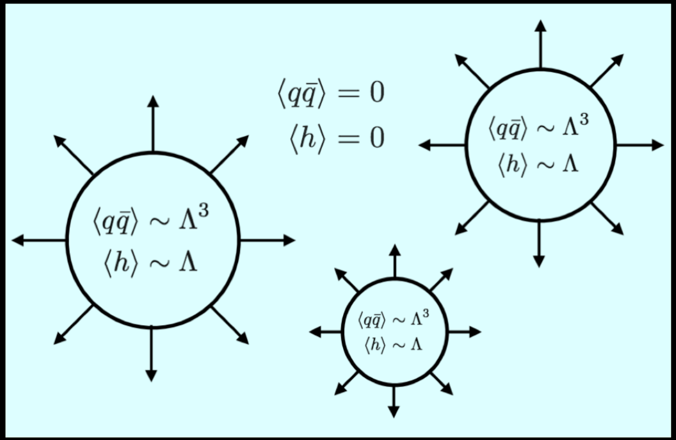
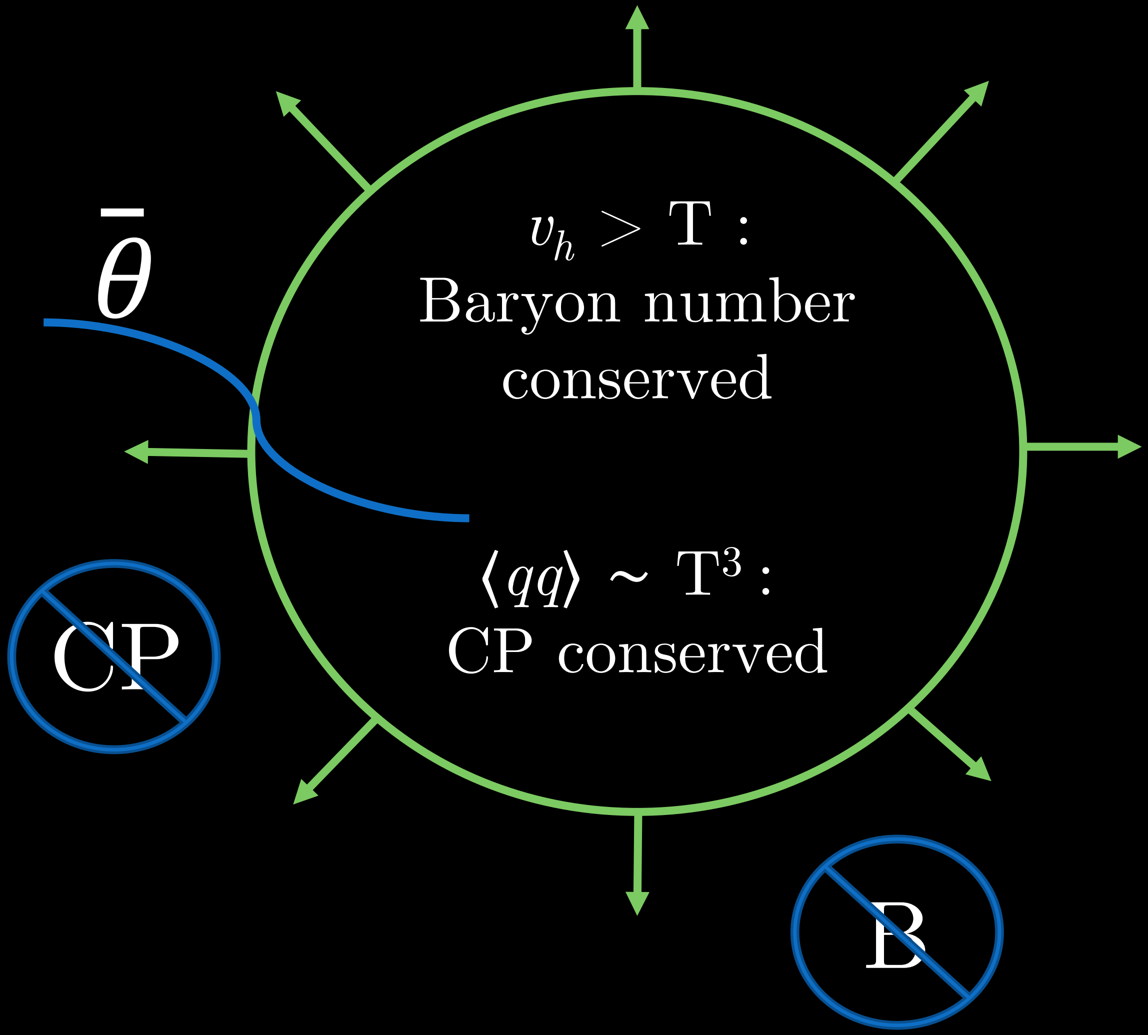



+ imagine also that the strong CP problem is addressed by an axion

# Confinement + EWSB via bubble nucleation




$$\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle = m_a^2(T) f_a^2 \sin\bar{\theta}(T)$$

$$\mathcal{L}_{\text{eff}} \ni \frac{10}{f_\pi^2 m_{\eta'}^2}\frac{\alpha_s}{8\pi}G\tilde{G}\frac{\alpha_w}{8\pi}W\tilde{W}$$

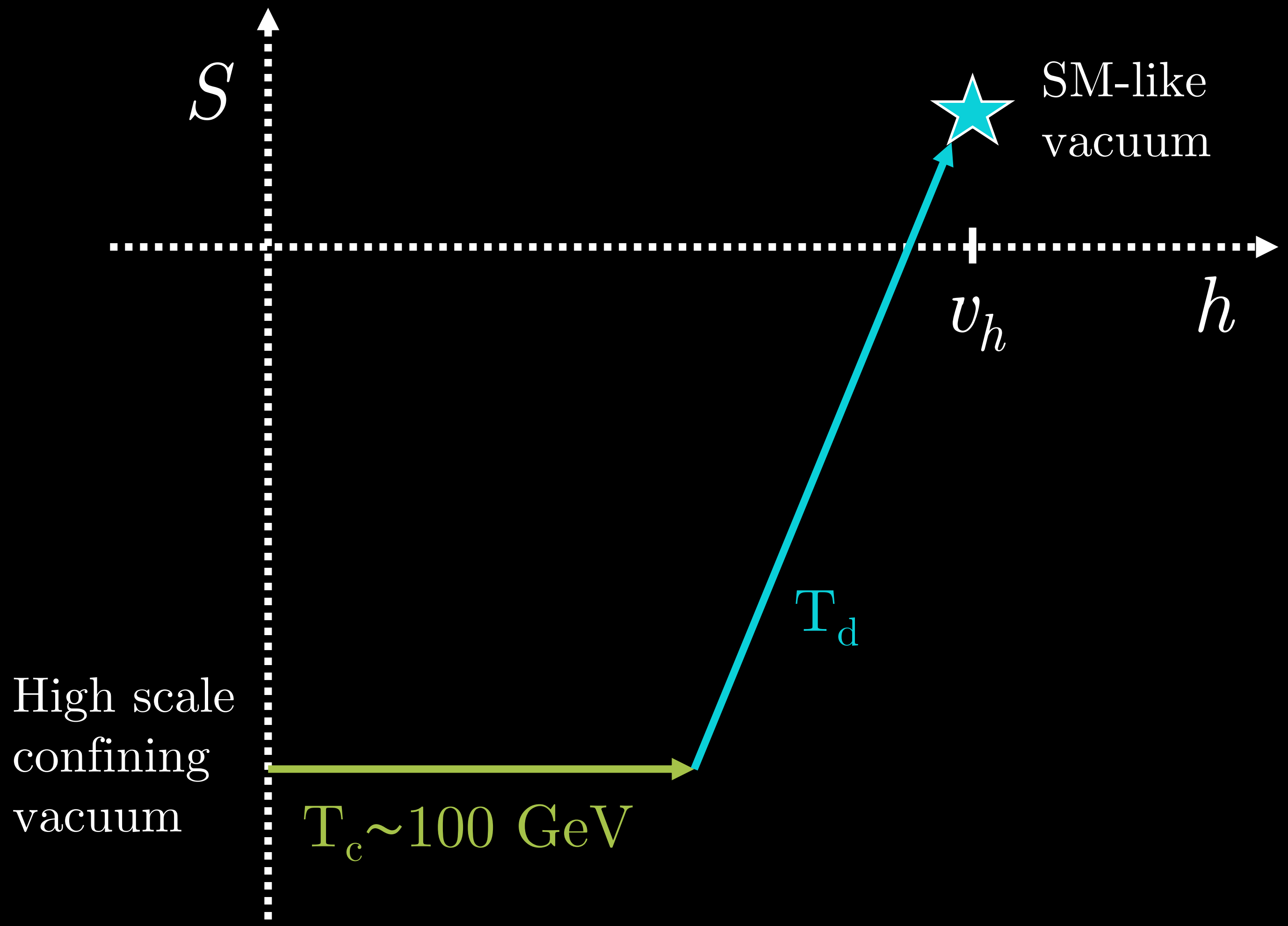
*Servant, PRL (2014) , see also Kuzmin, Shaposhnikov, Tkatchev, PRD (1992)*

$$\mu_B = \frac{d}{dt}\left[\frac{10}{f_\pi^2 m_{\eta'}^2} m_a^2(T) f_a^2 \sin\bar{\theta}(T)\right]$$

From the the chiral anomaly $\partial_\mu j_B^\mu = (\alpha_W/8\pi)\mathrm{Tr}[W\widetilde{W}]$

$$n_B = \int_{t_i}^{t_f} dt\, \frac{\Gamma_{\text{sph}}(T)}{T}\mu_B$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\left(\frac{1}{g_{s0}^2} + \frac{S}{M}\right) G_{\mu\nu}G^{\mu\nu} - V(S) - V(H) + b_1 S|H|^2 - b_2 S^2 |H|^2$$




- How can we study the physics in the confined phase?
- What regions of parameter space realize baryogenesis?
- What are the observational signatures of early (de-)confinement?

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

# In the confined phase, quarks → mesons

- In terms of $U = e^{2i\, T^a \Pi^a / f_\pi}$ ( $T^a$ are the generators of $\mathrm{SU}(6)_\mathrm{V}$)

$$\mathcal{L}_{\chi PT} = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu U \partial^\mu U\right] + \alpha\, \mathrm{Tr}\left[U M\right] + \text{ H.c.}$$

- $M$ includes the Yukawa couplings, approximately,

$$M = \mathrm{diag}\left(0, 0, 0, 0, 0, \frac{y_t h}{\sqrt{2}}\right)$$

→ This gives the tadpole term in the Higgs potential!

- $\mathrm{SU}(6)/\mathrm{SU}(5)$ gives 11 *top-flavored* pions ↔ 10 SU(6) generators have nonzero entries for $T^{i6}$ or $T^{6i}$, 1 with $T^{66}$

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

# The Higgs potential in the confined phase

- Can calculate + relate the Higgs tadpole term to SM quantities,

$$\alpha\,\mathrm{Tr}\,[UM] + \text{ H.c.} = \frac{y_t}{y_u + y_d}\frac{m_0^2 f_0^2}{v_h}\, h \left(\frac{\Lambda}{\Lambda_{\rm SM}}\right)^3$$

- And the thermal potential, $V(h,T) \ni \sum_{i\in\text{mesons}} \frac{T^4}{2\pi^2} n_i J_B\left(\frac{m_i^2 + \Pi_i}{T^2}\right),$

Pion mass in SM QCD

$$m_{35}^2 = \frac{m_0^2}{1+5\sqrt{15}}\frac{y_t h}{(y_u+y_d)v_h}\left(\frac{\Lambda}{\Lambda_{\rm SM}}\right)$$

$$m_{25,\ldots,34}^2 = \frac{3m_0^2}{1+5\sqrt{15}}\frac{y_t h}{(y_u+y_d)v_h}\left(\frac{\Lambda}{\Lambda_{\rm SM}}\right)$$

Top-flavored pions

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

# Towards a minimal realistic model

- The scalar sector is given by,

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\left(\frac{1}{g_{s0}^2} + \frac{S}{M}\right) G_{\mu\nu}G^{\mu\nu} - V(S) - V(H) + b_1 S|H|^2 - b_2 S^2|H|^2$$

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

+ an axion

- The potential depends on 10 parameters,

$$\mu,\ \lambda,\ a_2,\ a_3,\ a_4,\ S_0,\ b_1,\ b_2,\ \Lambda_0,\ M_*$$

$V(H)$: $\mu, \lambda$

$V(S)$: $a_2, a_3, a_4, S_0$

Portal couplings: $b_1, b_2$

Confinement scale at $S=0$: $\Lambda_0$

Wilson coefficient gluon coupling: $M_*$

# Towards a minimal realistic model

- The scalar sector has 10 parameters,

$$\underbrace{\mu,\ \lambda}_{V(H)},\ \underbrace{a_2,\ a_3,\ a_4,\ S_0}_{V(S)},\ \underbrace{b_1,\ b_2}_{\text{Portal couplings}},\ \underbrace{\Lambda_0}_{\text{Confinement scale at } S=0},\ \underbrace{M_*}_{\text{Wilson coefficient gluon coupling}}$$

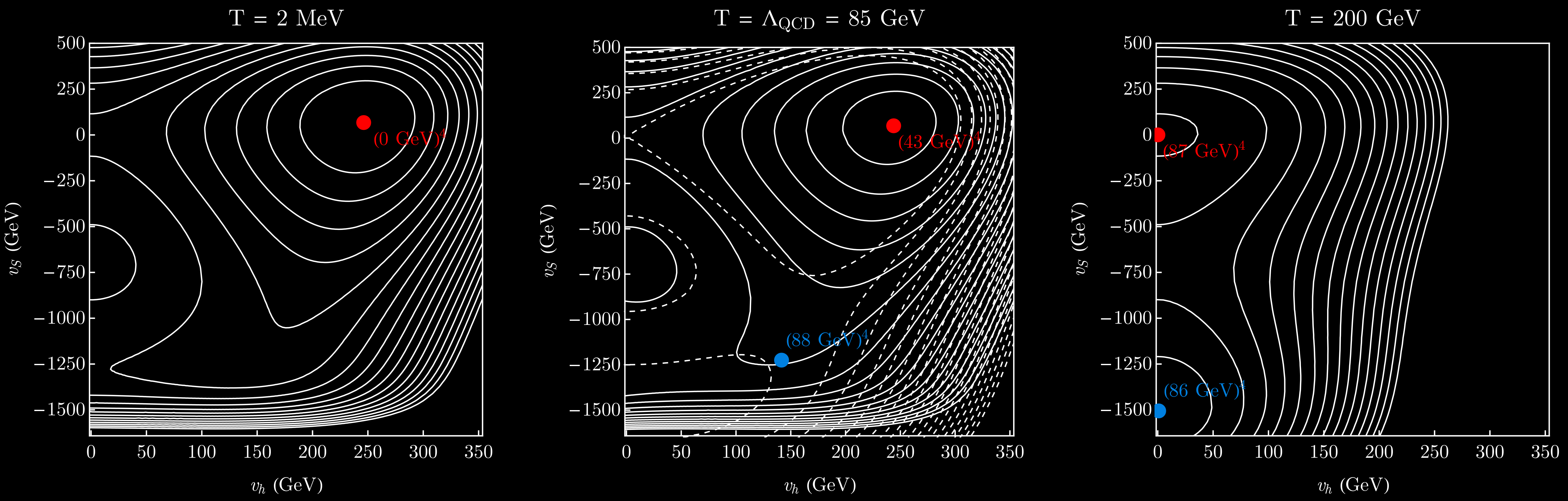
- But they are not all free,
  - Fix $\mu$ and $\lambda$ using the Higgs (mass eigenstate and VEV) in the SM-like vacuum
  - Fix $S_0$ as a function of other parameters by setting the SM-like QCD scale
  - Example benchmark point:

| $\Lambda_0$ | $M_*$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|
| 500 MeV | 3 TeV | 108 $\mathrm{GeV}^2$ | 0.15 GeV | $5.1 \times 10^{-5}$ |

We look for the couplings that realize the following,

Time ←

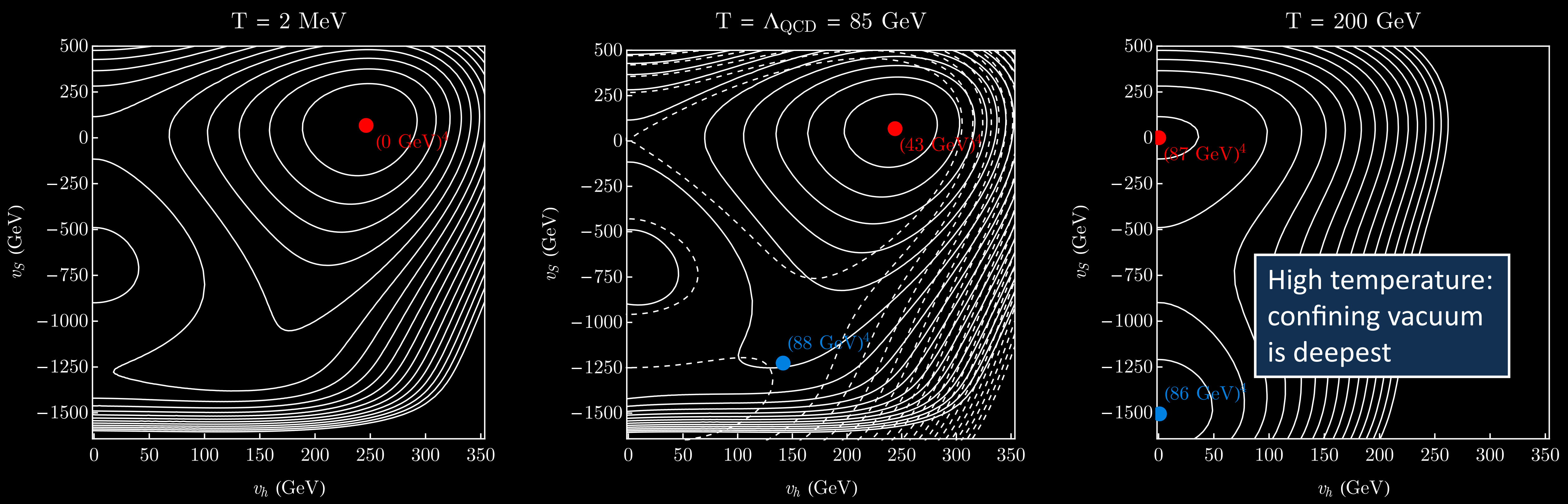
Temperature →




*Dashed (solid) lines: potential in the unconfined (confined) phase*

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

We look for the couplings that realize the following,

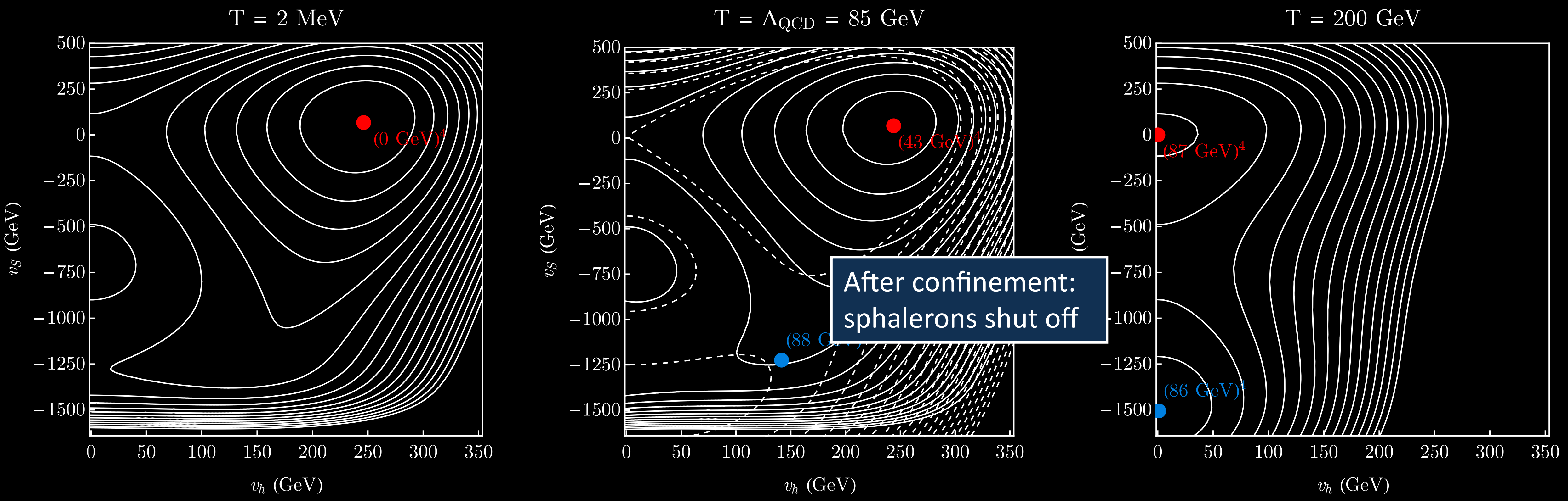



*Dashed (solid) lines: potential in the unconfined (confined) phase*

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

We look for the couplings that realize the following,

Before confinement: SM-like vacuum is deeper, but tunneling is suppressed

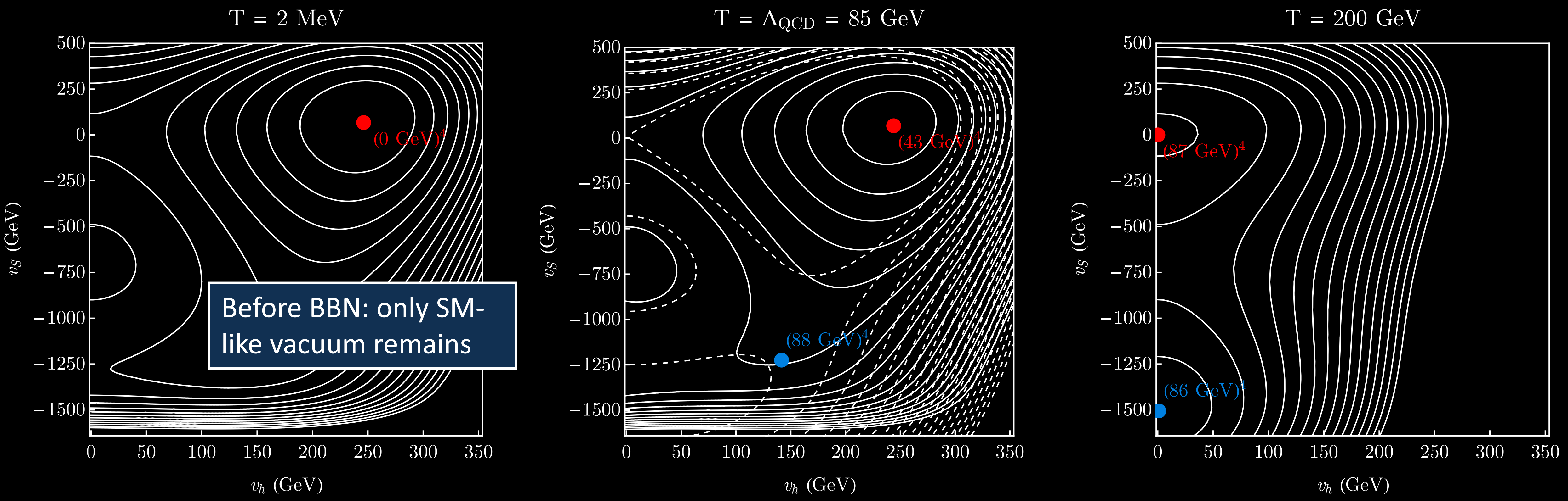



After confinement: sphalerons shut off

*Dashed (solid) lines: potential in the unconfined (confined) phase*

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

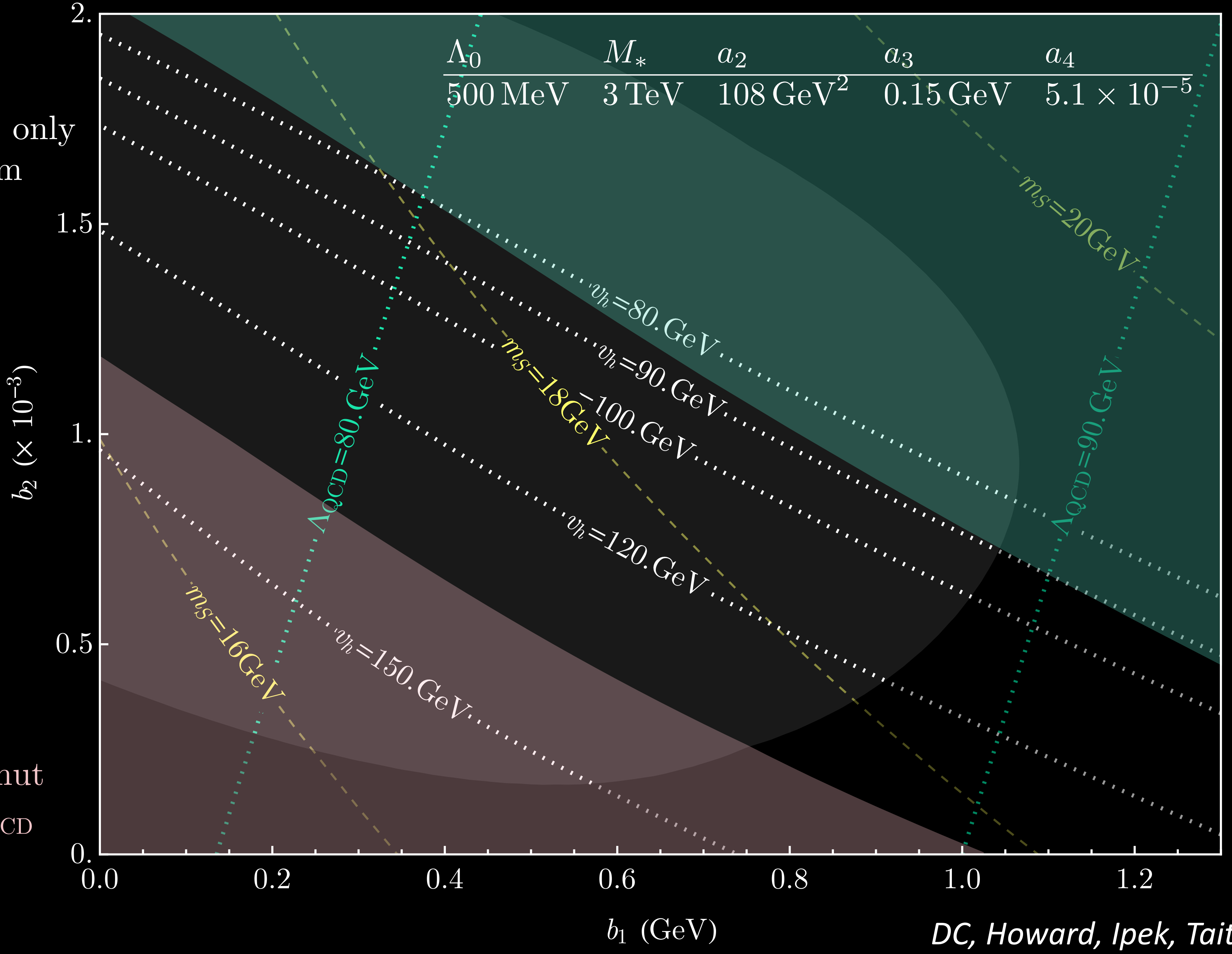
We look for the couplings that realize the following,




*Dashed (solid) lines: potential in the unconfined (confined) phase*

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

Lighter region: only SM-like vacuum remains ✓

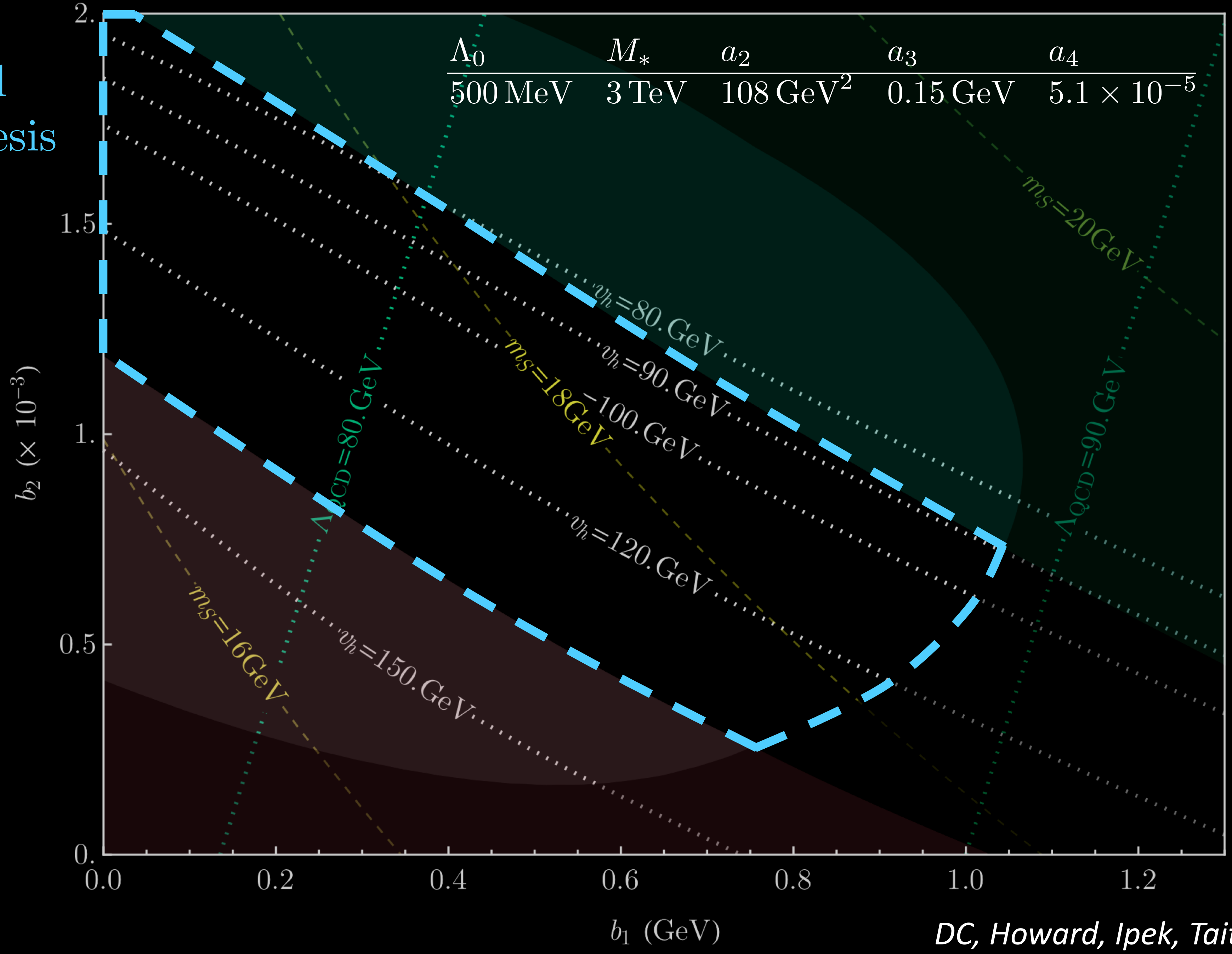



Sphalerons do not shut off at $\Lambda_{QCD}$

Sphalerons shut off before $\Lambda_{QCD}$

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

Successful baryogenesis




DC, Howard, Ipek, Tait, [arXiv:1911.01432]

# Collider constraints (gluon coupling)

- Singlet typically has mass $m_s^2 \sim b_2\, v_h^2 = \mathrm{O}(10\ \mathrm{GeV})^2$
- Dominantly produced by gluon fusion
- Dominantly decays back to gluons with $c\tau \lesssim 10^{-7}\ \mathrm{cm}$

- $\mathrm{M} \gtrsim 3\ \mathrm{TeV}$ by (non-resonant) dijet constraints @ LHC (for pseudoscalar equivalent) *Gavela, No, Sanz, de Troconiz [arXiv:1905.12953]*

- In particular models (for example VLQ) constraints from top-partner searches apply

*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

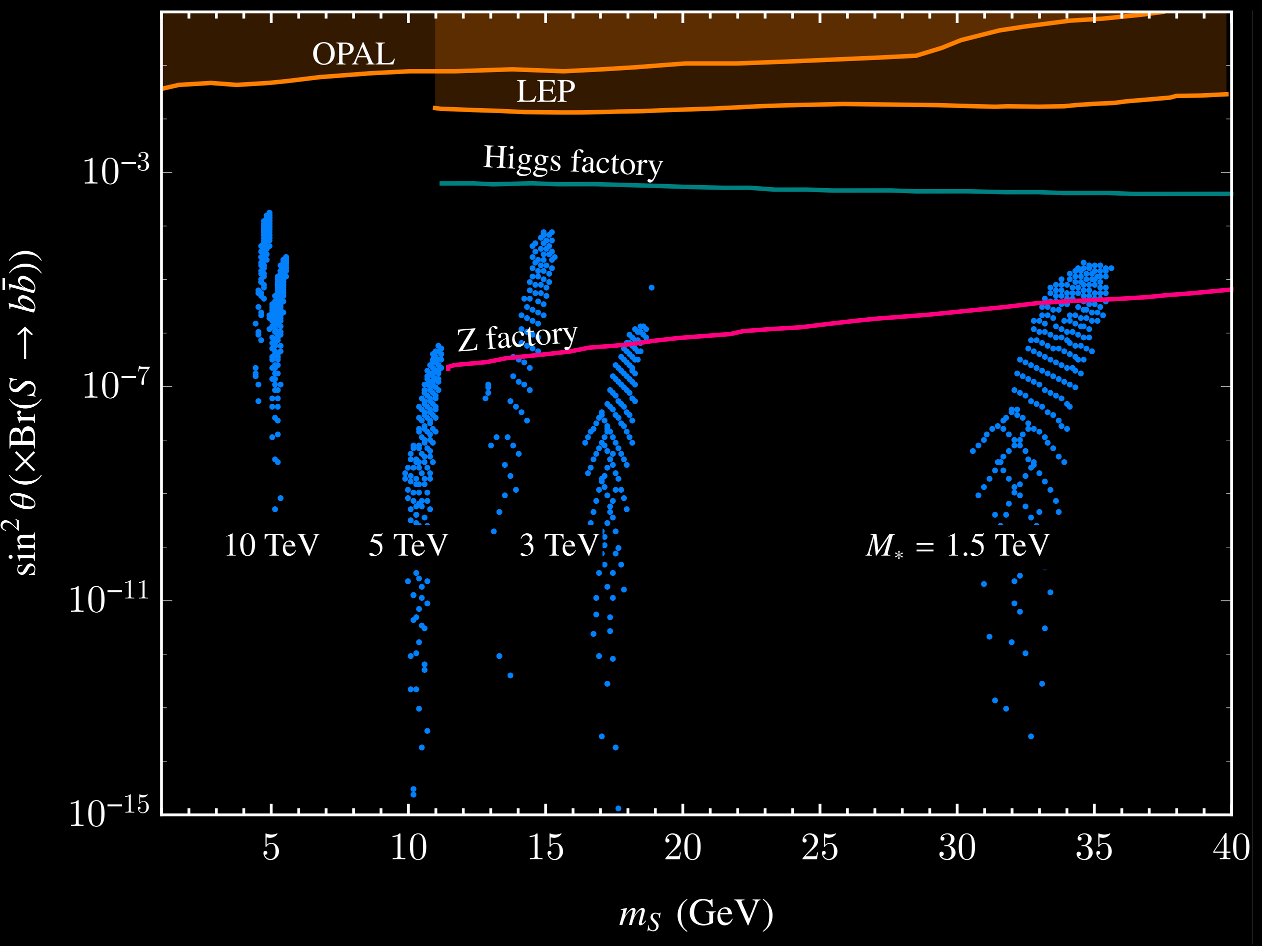
# Collider constraints (scalar mixing)

Potentially probed by future Z-factories?

- Singlet typically has mass $m_s^{\,2} = \mathrm{O}(10\ \mathrm{GeV})^2$
- Mixing angle with the Higgs is typically very small

$$\Gamma(s \to f\bar{f}) \simeq \frac{N_c\, y_f^2 \sin^2\theta\, m_S}{8\pi}\left(1 - \frac{4m_f^2}{m_S^2}\right)^{3/2}$$

- Subdominant $b$-quark decay mode evades current constraints




*DC, Howard, Ipek, Tait, [arXiv:1911.01432]*

# Gravitational waves

- High scale QCD confinement ($\Lambda_{QCD} \sim O(10\text{-}100\ \mathrm{GeV})$) occurs for $N_f = 6$ (as the EW symmetry is unbroken) and is therefore first order

- Deconfinement likely also occurs while $N_f > 3$

→ Potential double peaked GW signal in the LISA frequency band

- Since the same DOF participate in both transitions, the resulting plasma dynamics would have to be simulated

# Final takeaways

- New confining phase transitions may occur in QCD’ models
  - Solutions to the strong CP problem
  - Models with new strongly interacting sectors
- QCD confinement itself may be modified
  - Effective coupling strength changed by a scalar
  - Late origin of quark masses
- Studying the (GW) phenomenology of such models is an interesting (and difficult) challenge