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]

Probing the first second of our Universe

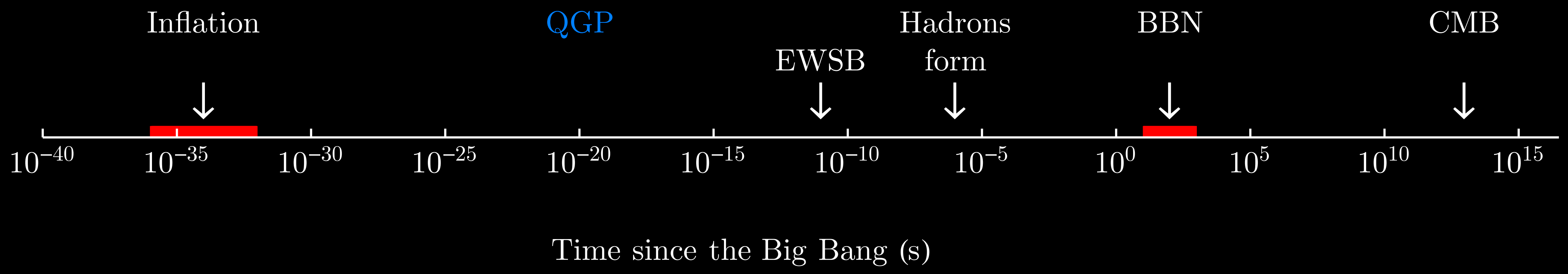
The answers to many fundamental physics questions lie in the first second of our Universe

Grand Unification of gauge forces?

Dark Matter production, mass mechanism, and abundance?

Solution to the strong-CP problem?

Explanation of the matter-antimatter asymmetry?



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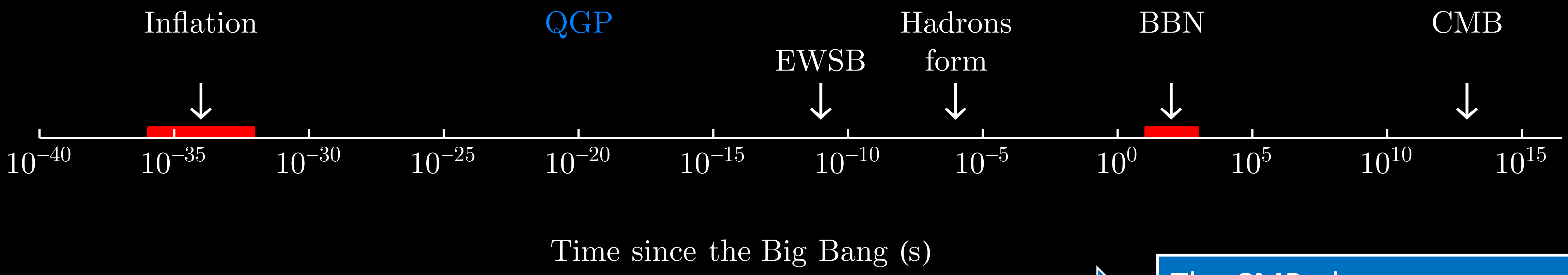


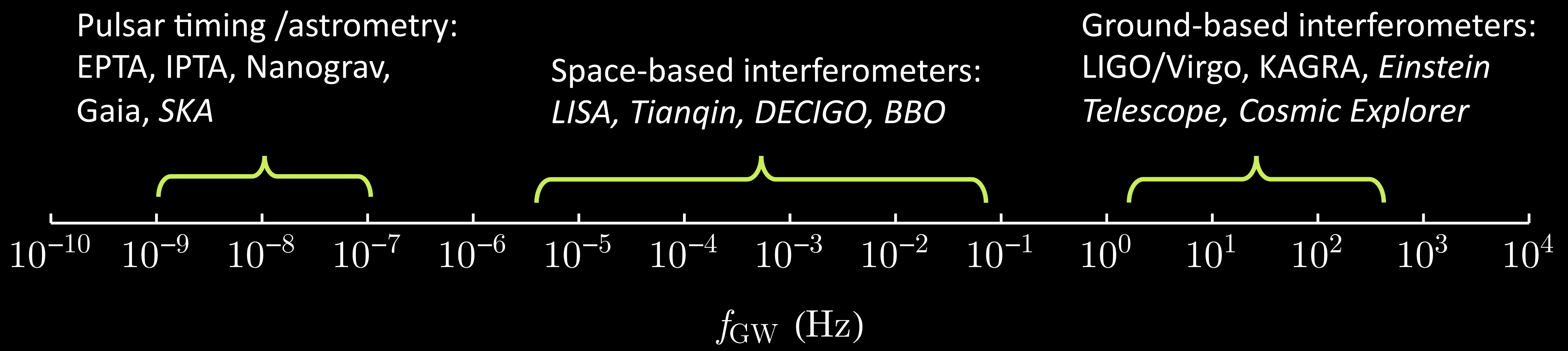
During this second, the Universe was opaque to photons

The CMB photons constitute our earliest *direct* cosmological probe

Gravitational waves released in the Early Universe travel unimpeded until today

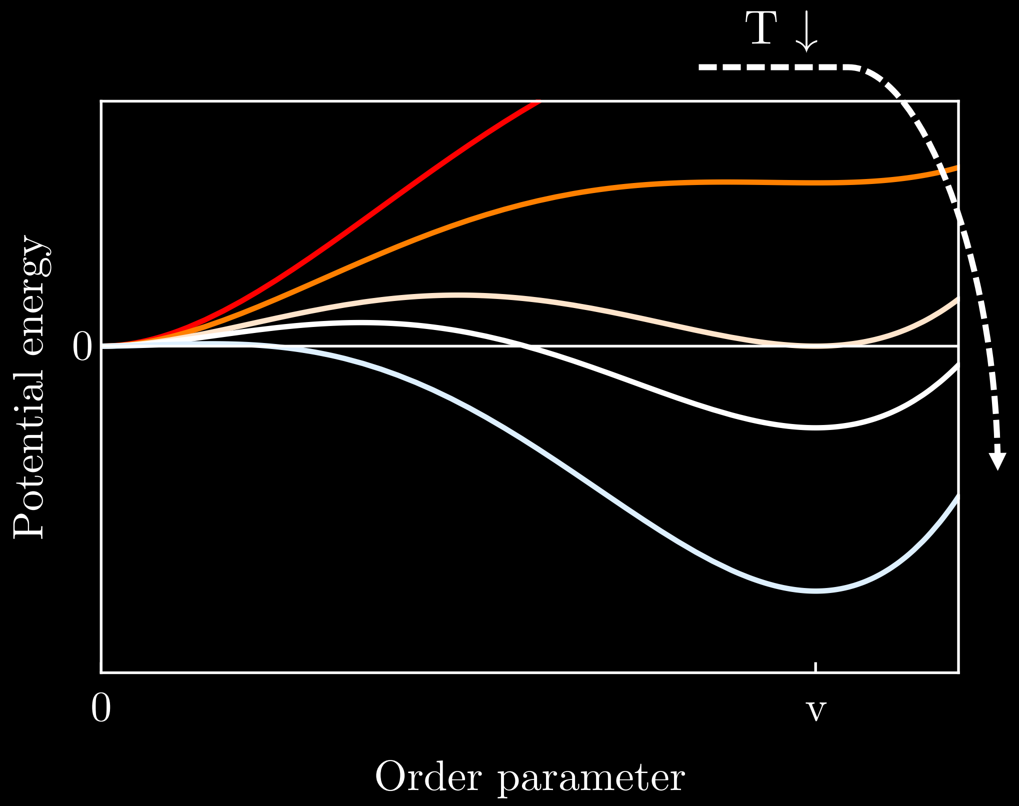
Gravitational waves

- First (direct) observation in 2015, many detections since!
- Planned/proposed experiments across many decades in frequency:



- *Huge opportunity for particle astrophysics and cosmology!*

First order phase transitions

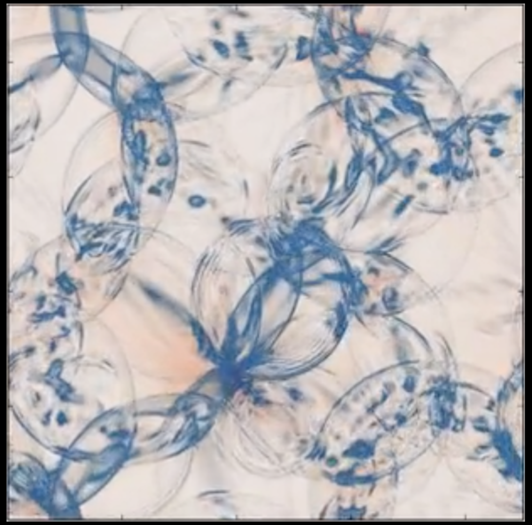


Out of equilibrium change in vacuum state

- Nucleation of bubbles of ”true” vacuum
- Once nucleated, bubbles grow
- Release of latent heat

The released energy may dissipate as gravitational waves:

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



Snapshot from simulation: Daniel Cutting, private communication

Gravitational waves from phase transitions

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

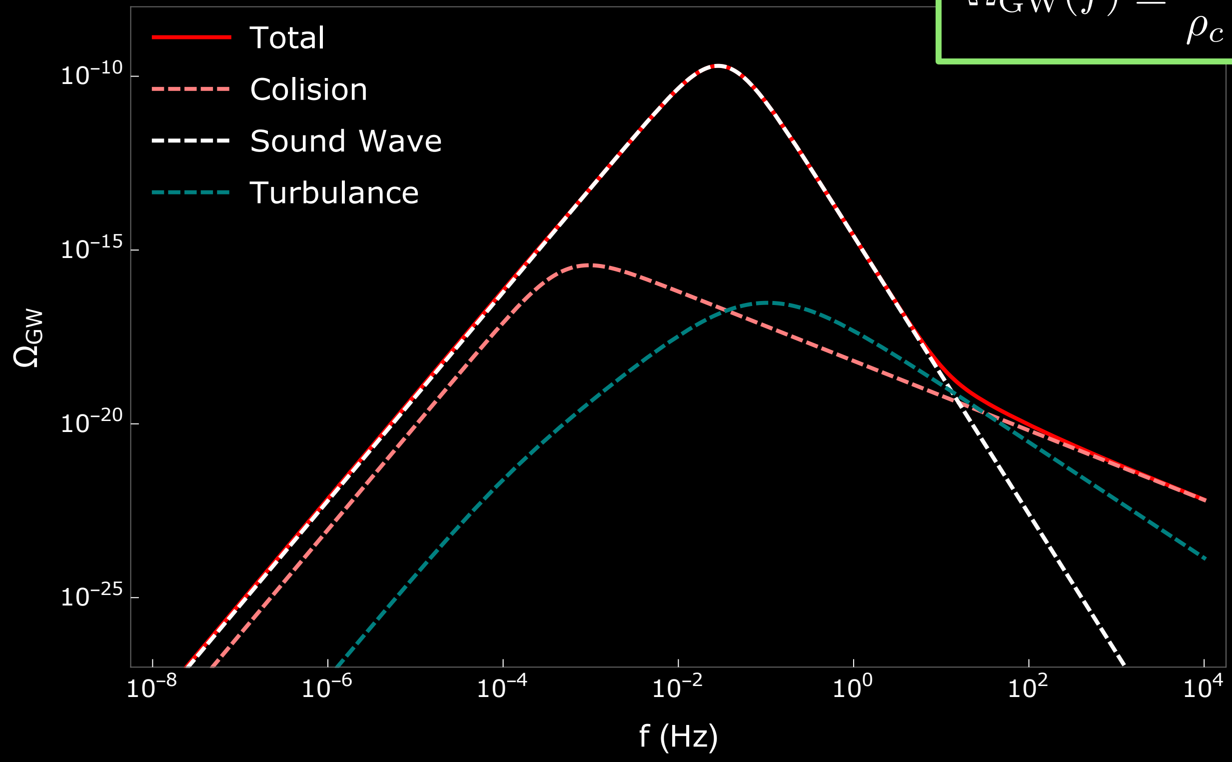
- Broken power law GW spectrum
  - $f_{peak} \sim R^{-1}$
- Power spectrum depends on thermodynamic quantities

α = latent heat (normalized to ρ_{rad})
v_w = wall velocity
β/H = transition rate parameter
T_N = nucleation temperature

- Spectra matched to lattice simulations

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

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



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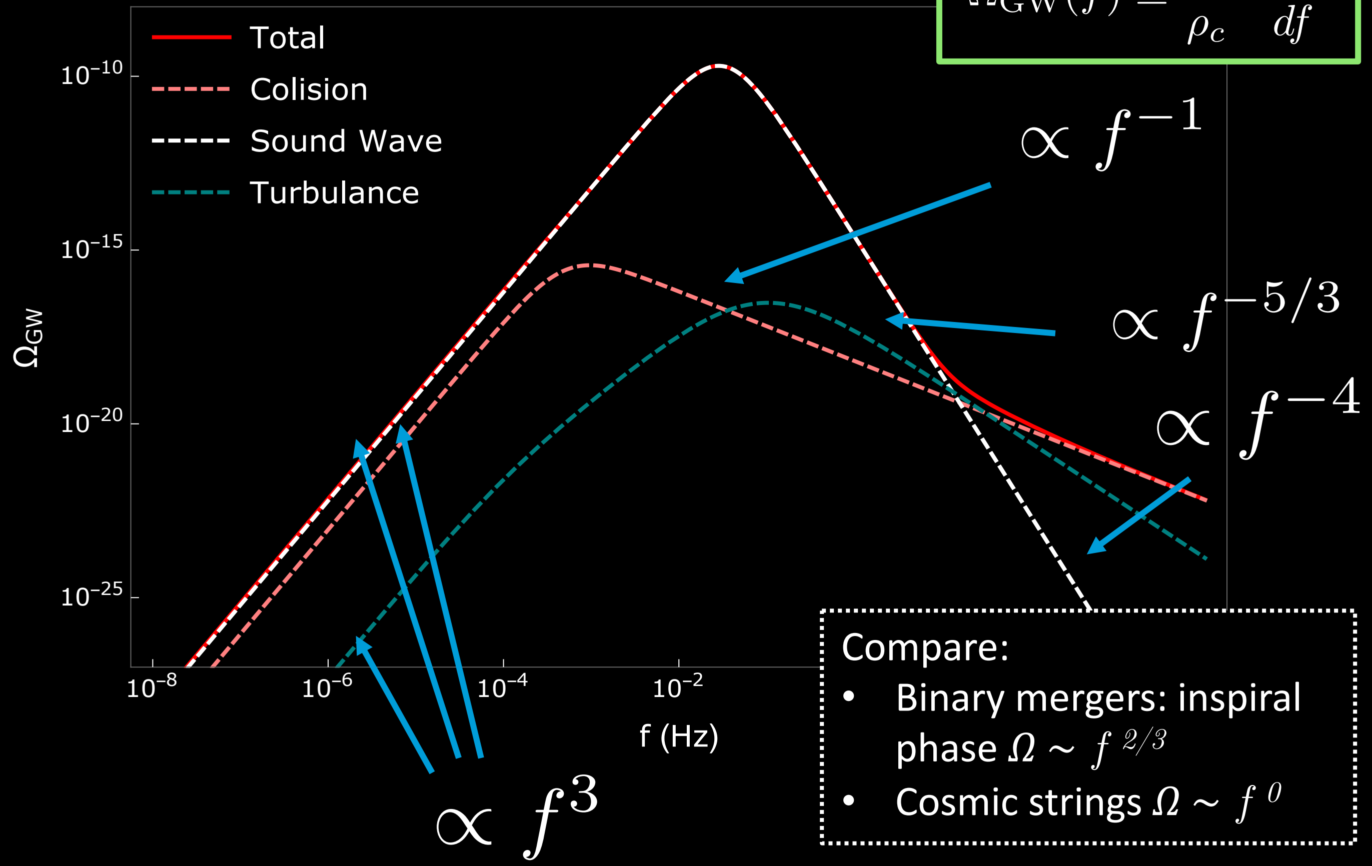
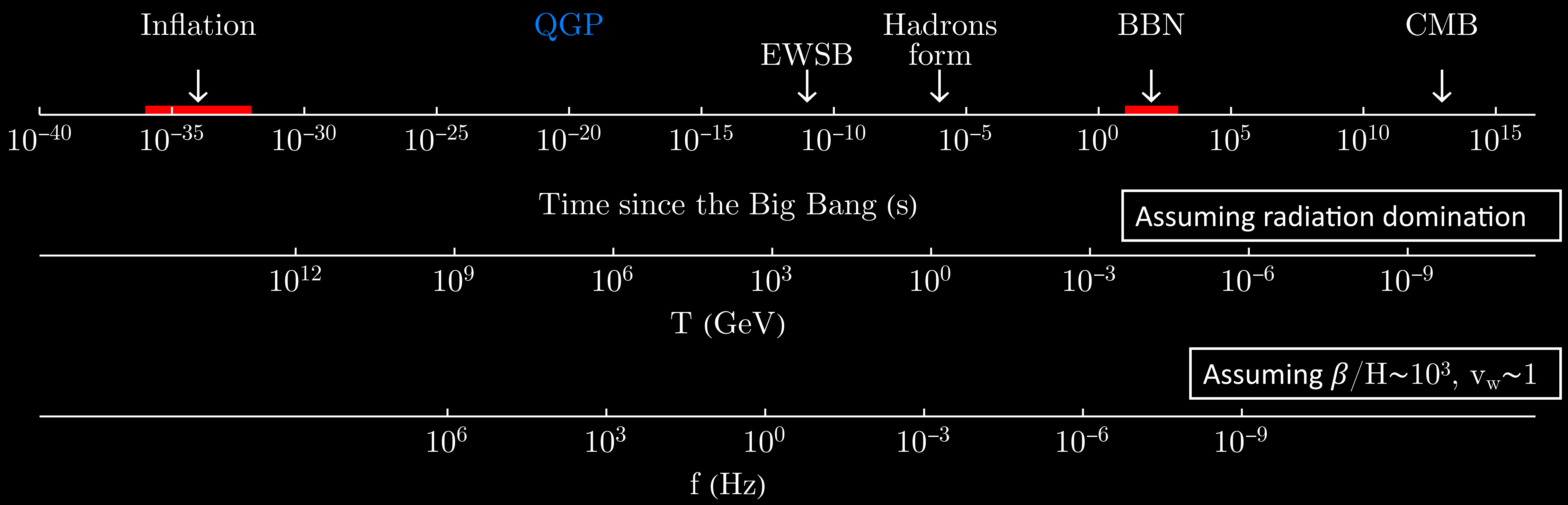


Compare:
- Binary mergers: inspiral phase $\Omega \sim f^{2/3}$
- Cosmic strings $\Omega \sim f^{0}$

Phase transitions and the cosmic timeline



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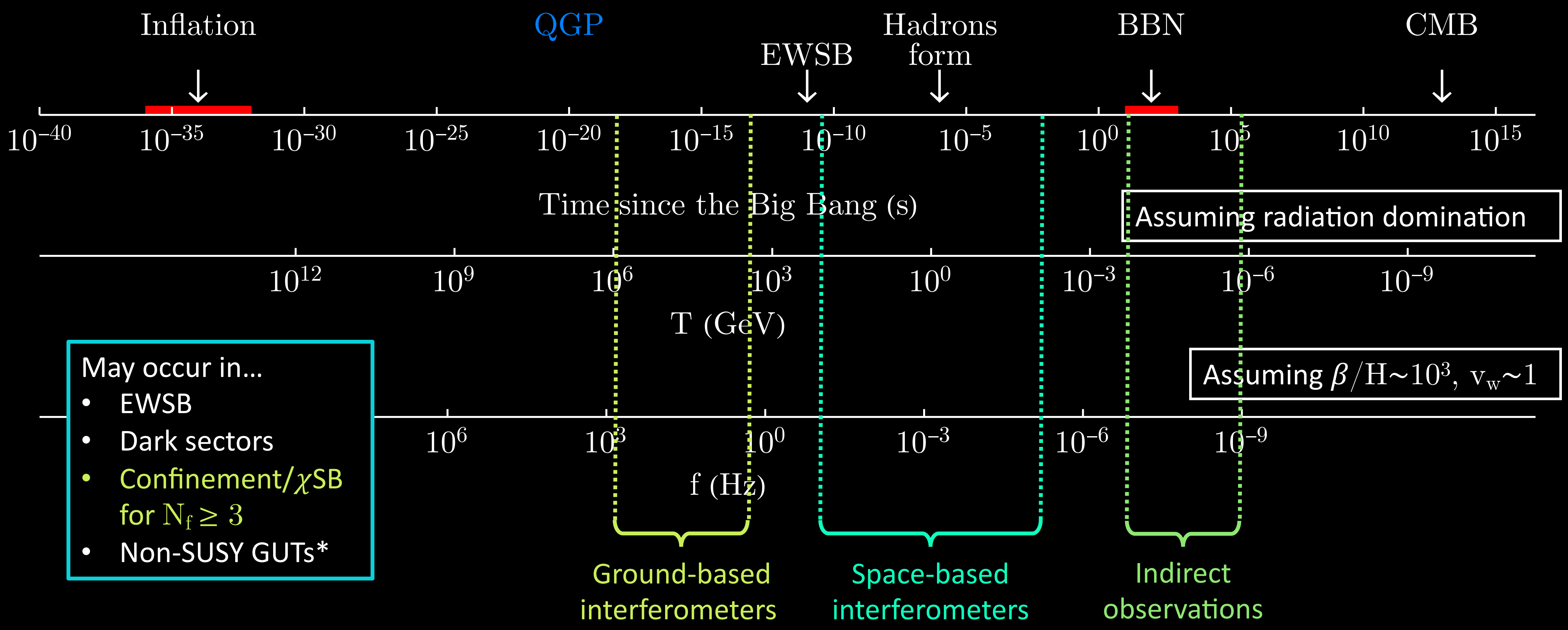
Phase transitions and the cosmic timeline

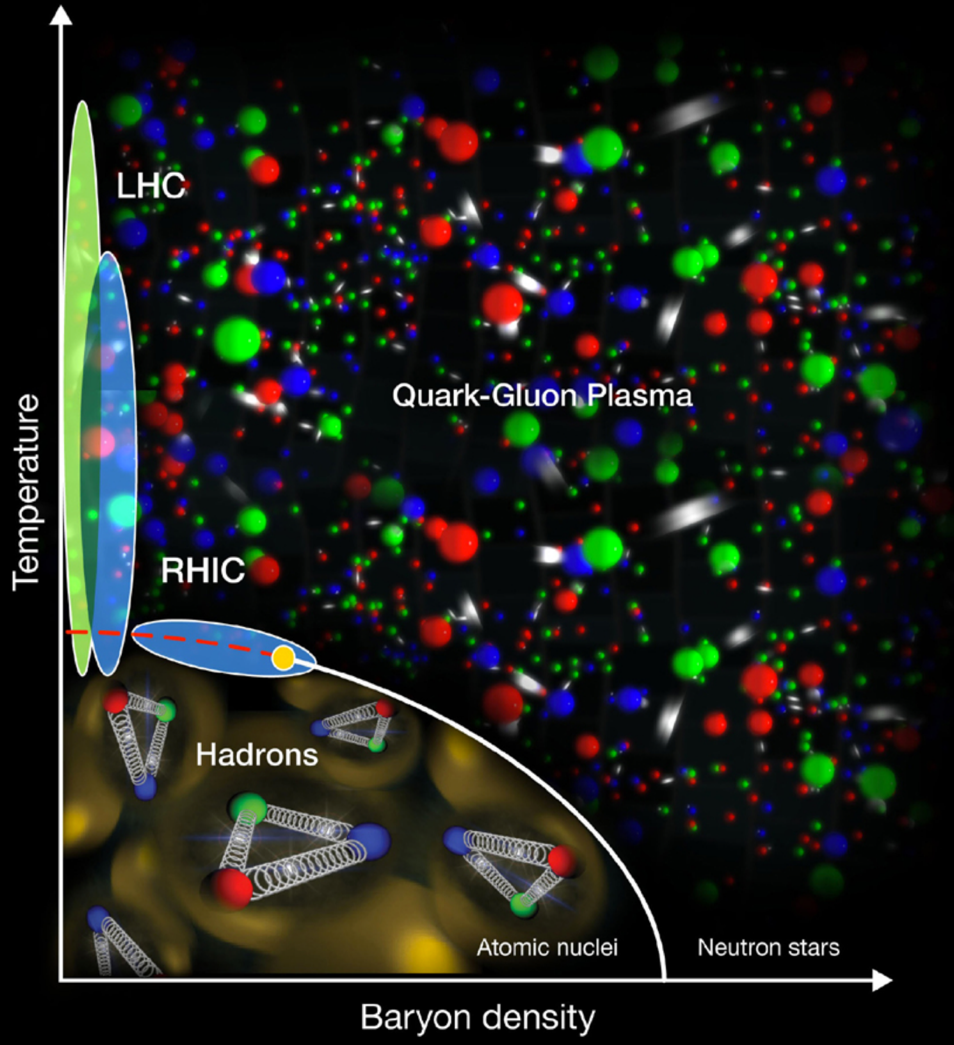


May occur in…

- EWSB
- Dark sectors
- Confinement/χSB for $N_f \geq 3$
- Non-SUSY GUTs*

Confinement in the Standard Model

- QCD confines when $\alpha_s > 1$
- Confinement scale (MS-bar scheme): $\Lambda_{\rm QCD} \sim 400~\rm MeV$
- At $400~\rm MeV$, (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*

- Baryogenesis
  - *e.g. Ipek, Tait, PRL (2019)*
  - *DC, Howard, Ipek, Tait (2019)*
  - *Servant, PRL (2014)*
- 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]*
- 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]*

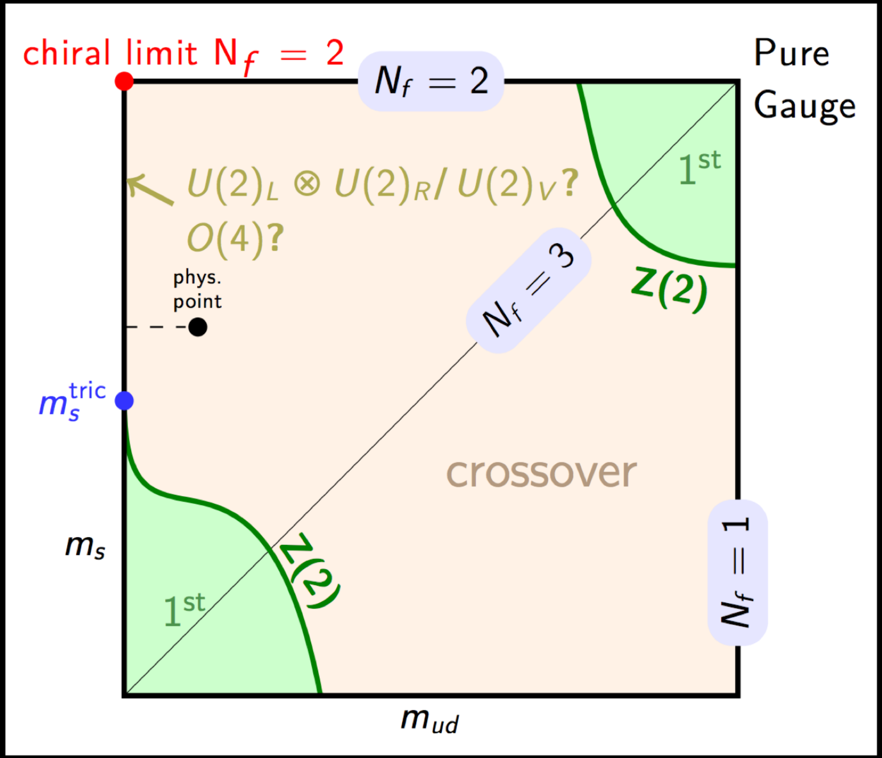
Chiral symmetry breaking ("the χPT –PT")

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

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

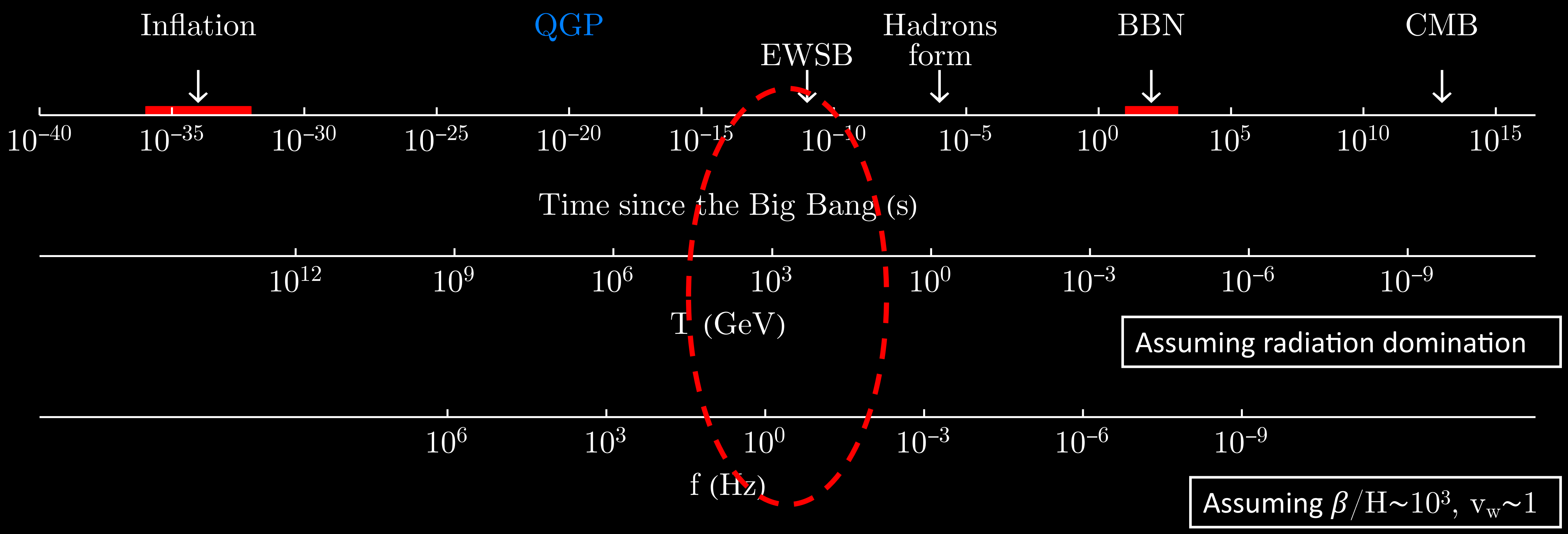
- Analytic argument (based on the linear Σ-model) suggests the chiral PT is first order if
  - $N_f \geq 3$
  - $N_f = 0$ (pure gauge)

  Pisarski, Wilczek, PRD (1984)
- Largely confirmed with other methods



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

Axions on the cosmic timeline



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]

Chiral symmetry breaking: linear Σ-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 $\mathrm{SU(N_f)\times SU(N_f)\times U(1)_A}$ global flavor symmetry

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

't Hooft, PRD (1976)

Chiral symmetry breaking: linear Σ-model

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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

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

- η' is a dynamical axion (if the ψ quarks have no explicit mass terms)

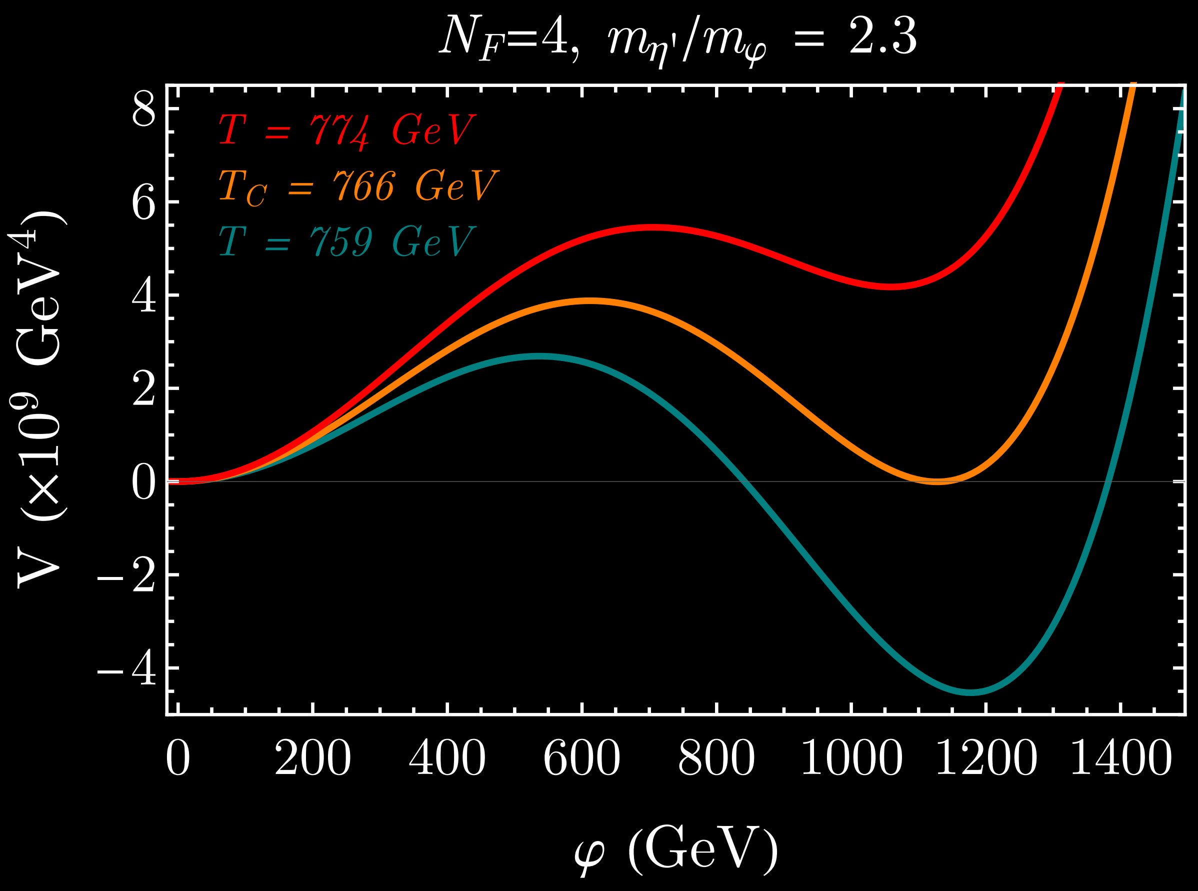
The thermal linear Σ-model

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

- One-loop thermal potential for the diagonal field φ

$$V_{T\neq 0}(\varphi, T) = \sum_{i \ni \text{mesons}} \frac{T^4}{2\pi^2} n_i J_B\left(\frac{m_i^2 + \Pi_i}{T^2}\right),$$

$$J_B(m^2) = \int_0^\infty dx\, x^2 \log\left(1 - e^{-\sqrt{x^2+m^2}}\right)$$

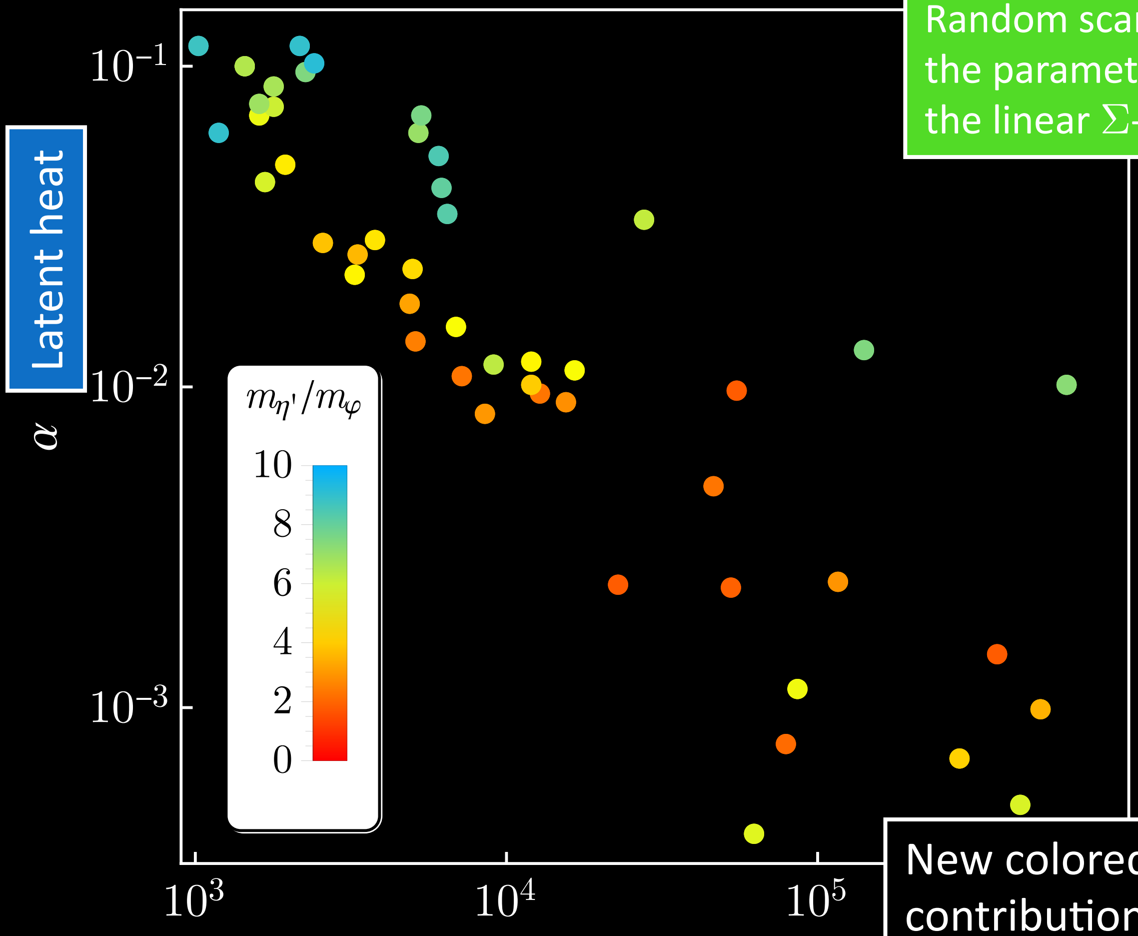


- $m_i + \Pi_i$ runs over meson loops

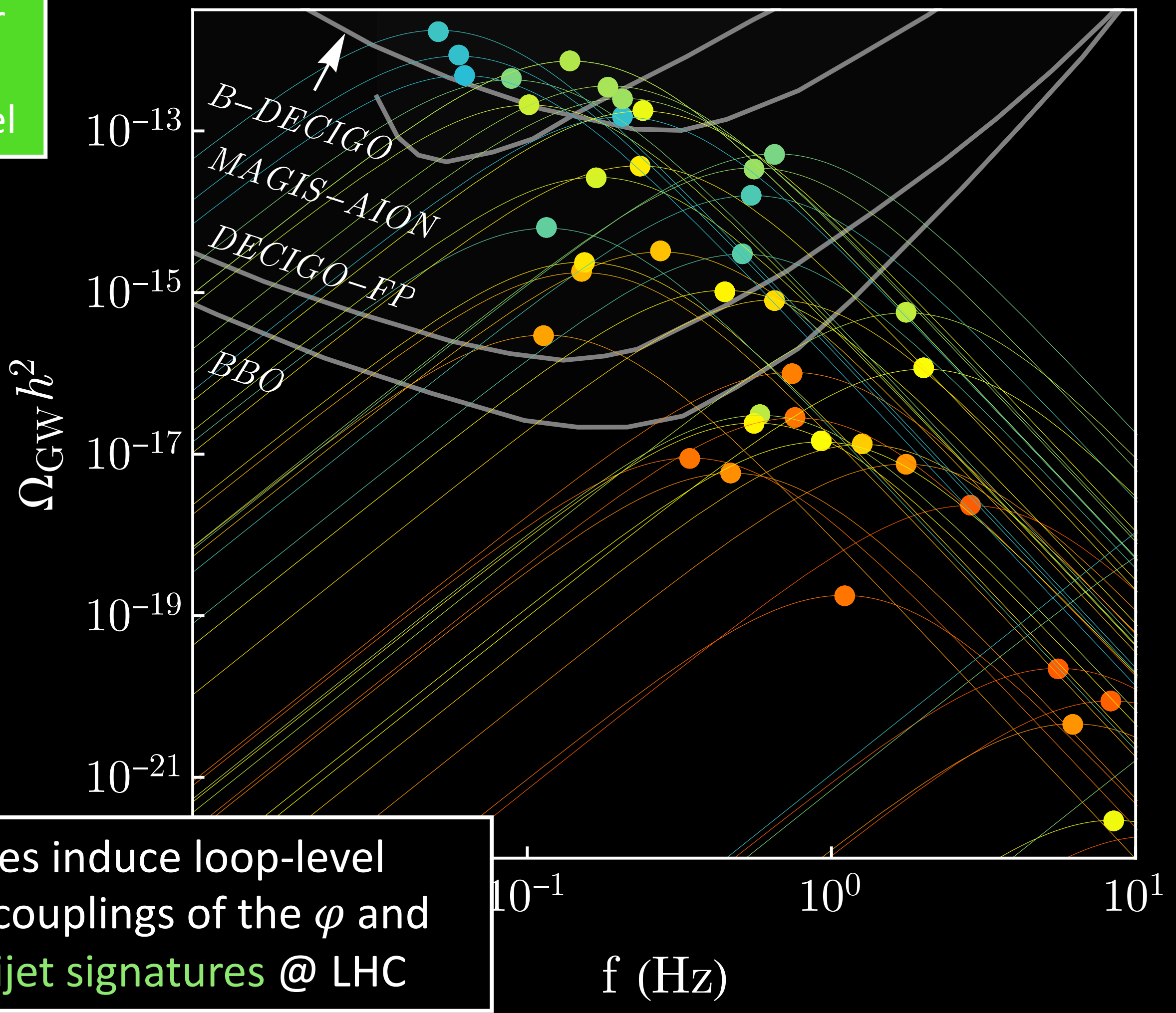
- Chiral symmetry restoration
  - High temperatures: $\varphi = 0$
  - Low temperatures: $\varphi \neq 0$

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

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



Random scan over the parameters in the linear Σ-model



New colored states induce loop-level contributions to couplings of the φ and η' to gluons → dijet signatures @ LHC

Take away and comments

- Larger η' axion mass $\leftrightarrow$ greater explicit $\mathrm{U}(1)_{\mathrm{A}}$ symmetry breaking $\leftrightarrow$ enhanced GW amplitude
  - Large ratios $m_{\eta'}/m_{\varphi}$ is a natural prediction in some models
  - Intimately related to $\mathrm{U}(1)_{\mathrm{A}}$ restoration

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

Pisarski, Wilczek, PRD (1984)

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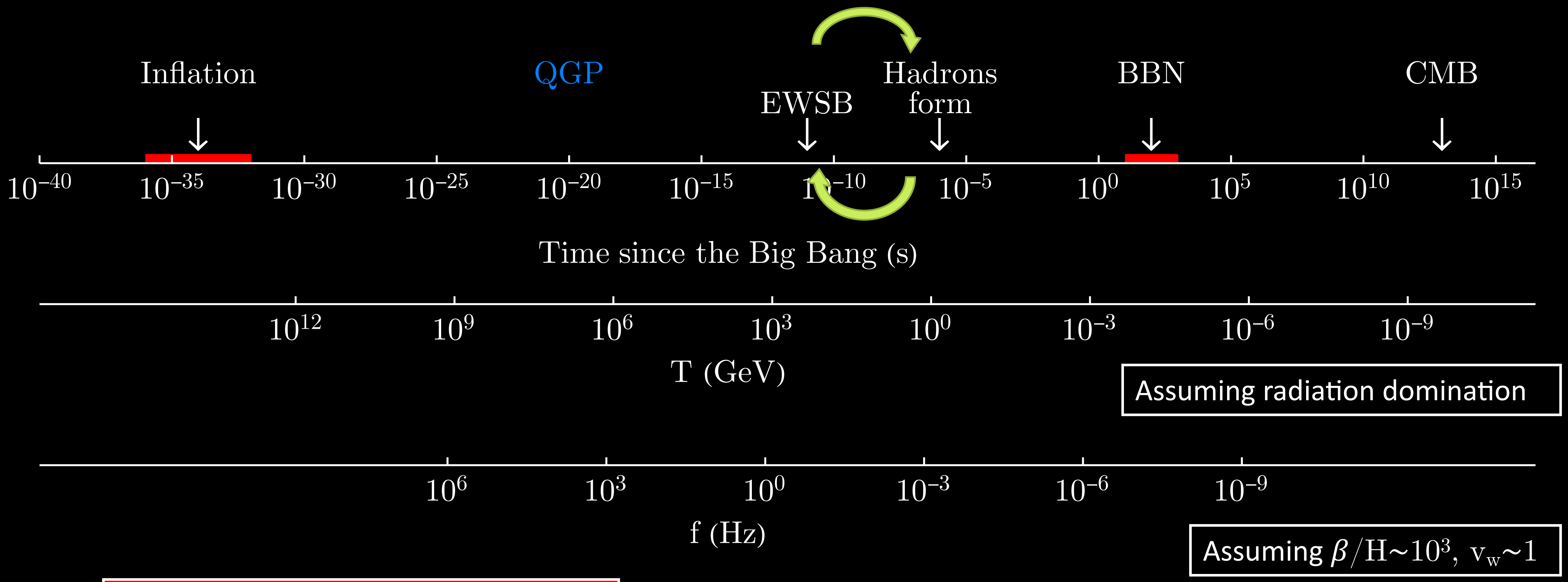
- GW predictions of the linear sigma model should be contrasted with other methods, such as lattice QCD → future work

An alternative cosmic timeline



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

Early QCD confinement

Ipek, Tait, PRL (2019)

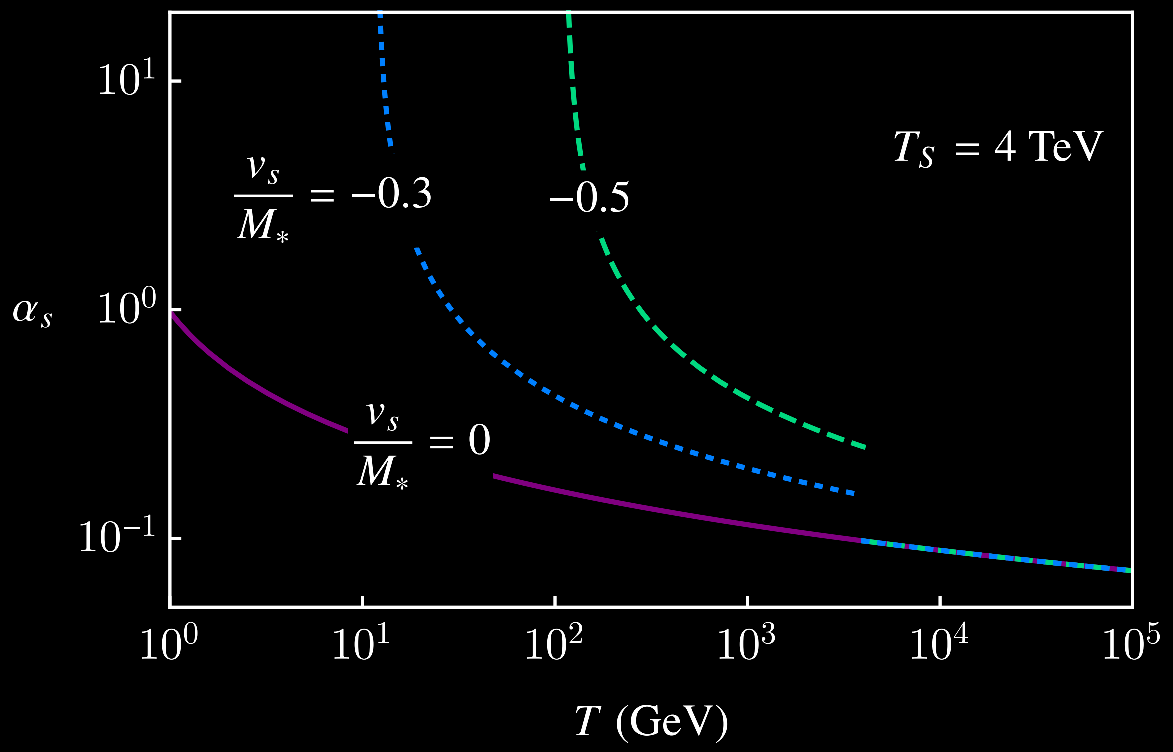
- Consider a modified gluon kinetic term,

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

- 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)



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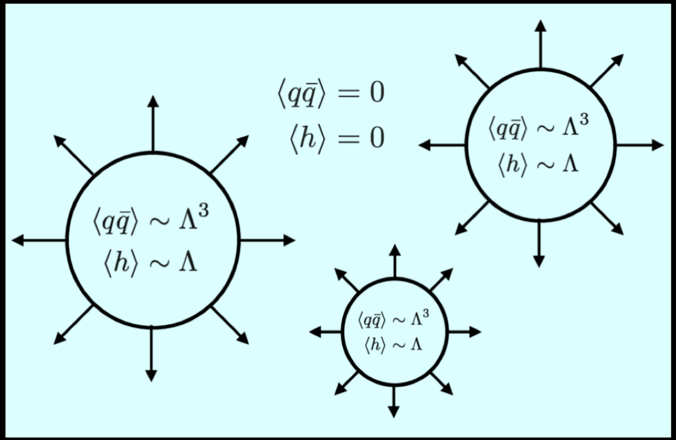
- Suppose confinement precedes EWSB

- 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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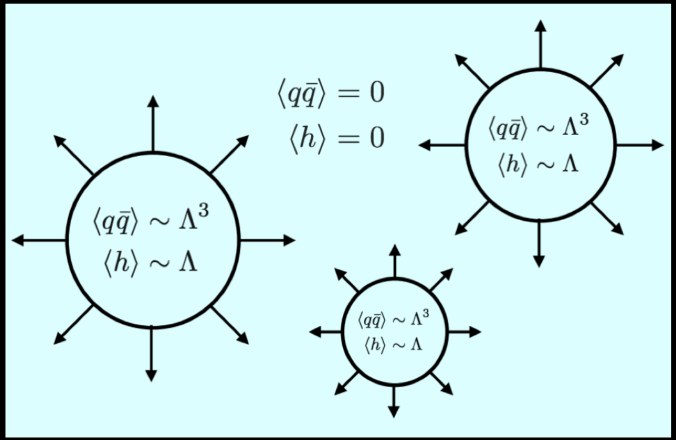
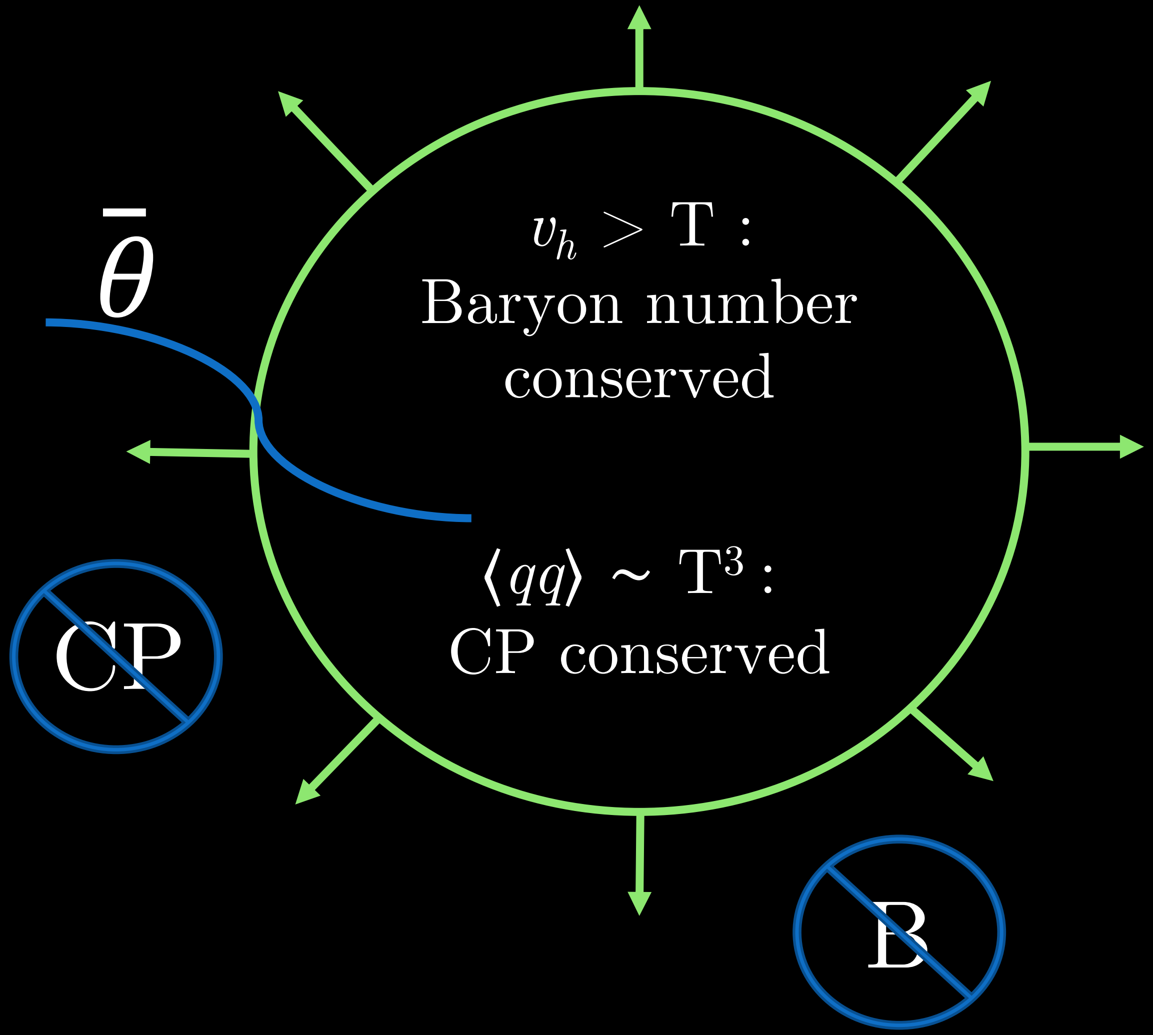


$$V(h) \ni -y_t h\langle\bar{q}q\rangle \sim -y_t\frac{\Lambda^2}{4\pi}h\langle\Sigma\rangle$$

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

Confinement + EWSB via bubble nucleation



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

→ Leads to $\langle W\tilde{W}\rangle$ through the η'

From the the chiral anomaly

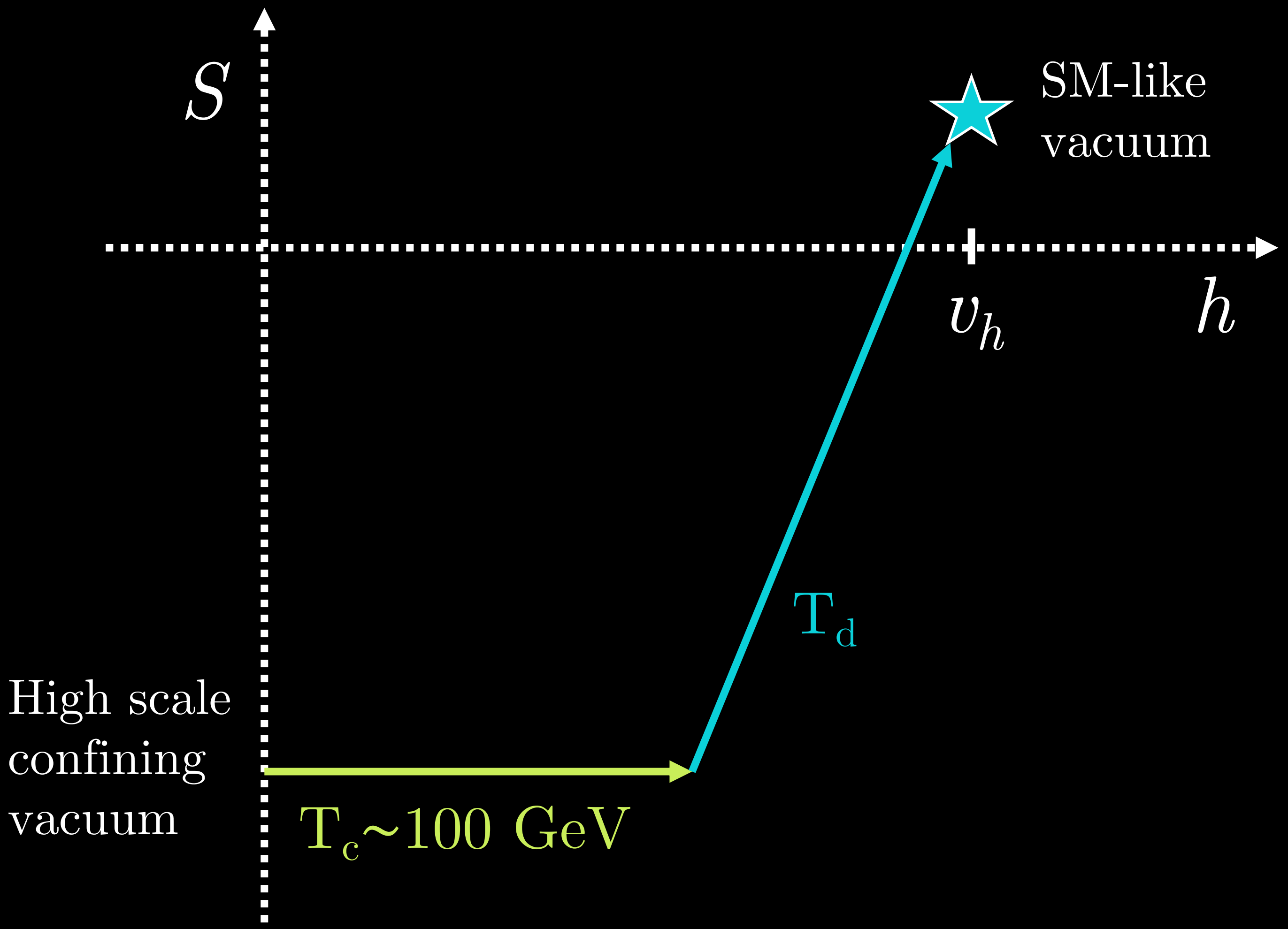
$\partial_\mu j^\mu_B = (\alpha_W/8\pi)\mathrm{Tr}[W\widetilde{W}]$

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

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

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

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



- 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 $\mathrm{SU}(6)_\mathrm{V}$)

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

- 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,

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

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

Pion mass in SM QCD

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

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

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,

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

$V(H)$: μ, λ

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

Portal couplings: b_1, b_2

Confinement scale at $S=0$: Λ_0

Wilson coefficient gluon coupling: M_*

Towards a minimal realistic model

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Portal couplings: b_1, b_2

Confinement scale at $S=0$: Λ_0

Wilson coefficient gluon coupling: M_*

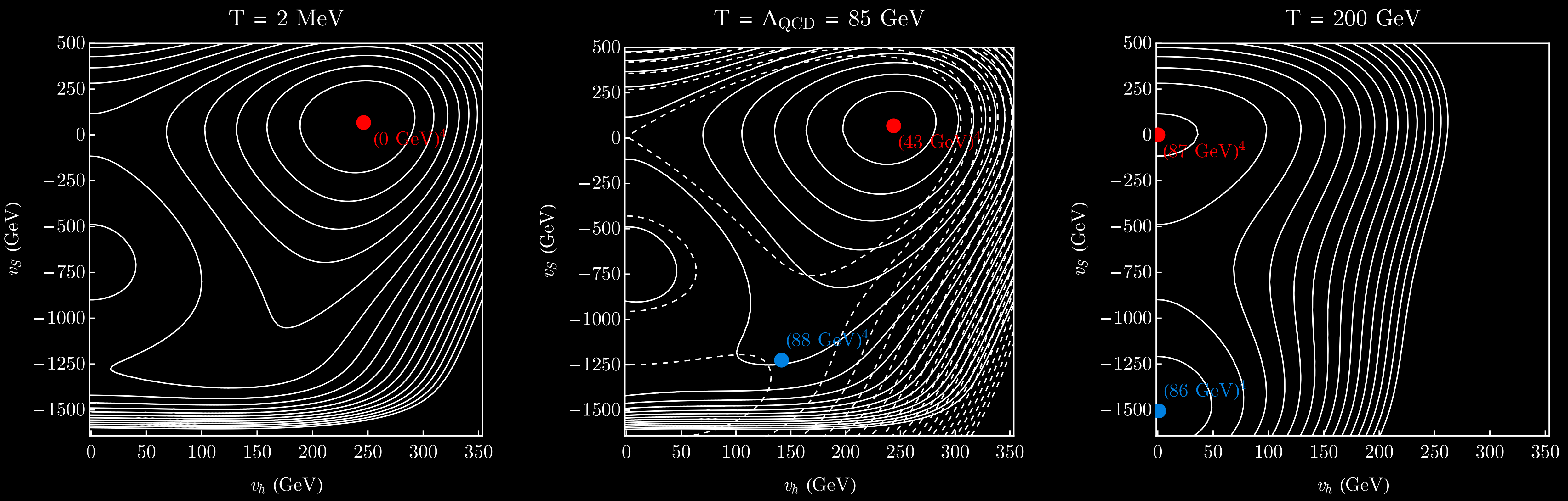
- But they are not all free,
    - Fix μ and λ using the Higgs (mass eigenstate and VEV) in the SM-like vacuum
    - Fix S_0 as a function of other parameters by setting the SM-like QCD scale
    - Example benchmark point:

Λ_0	M_*	a_2	a_3	a_4
$500\,\mathrm{MeV}$	$3\,\mathrm{TeV}$	$108\,\mathrm{GeV}^2$	$0.15\,\mathrm{GeV}$	5.1×10^{-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]

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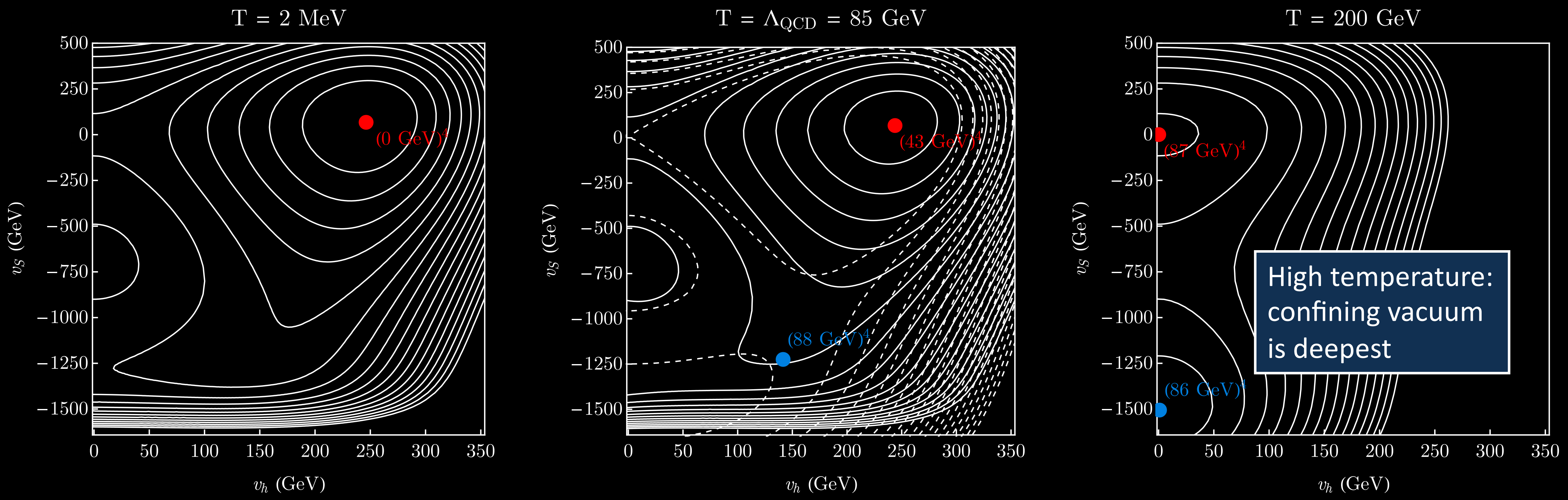
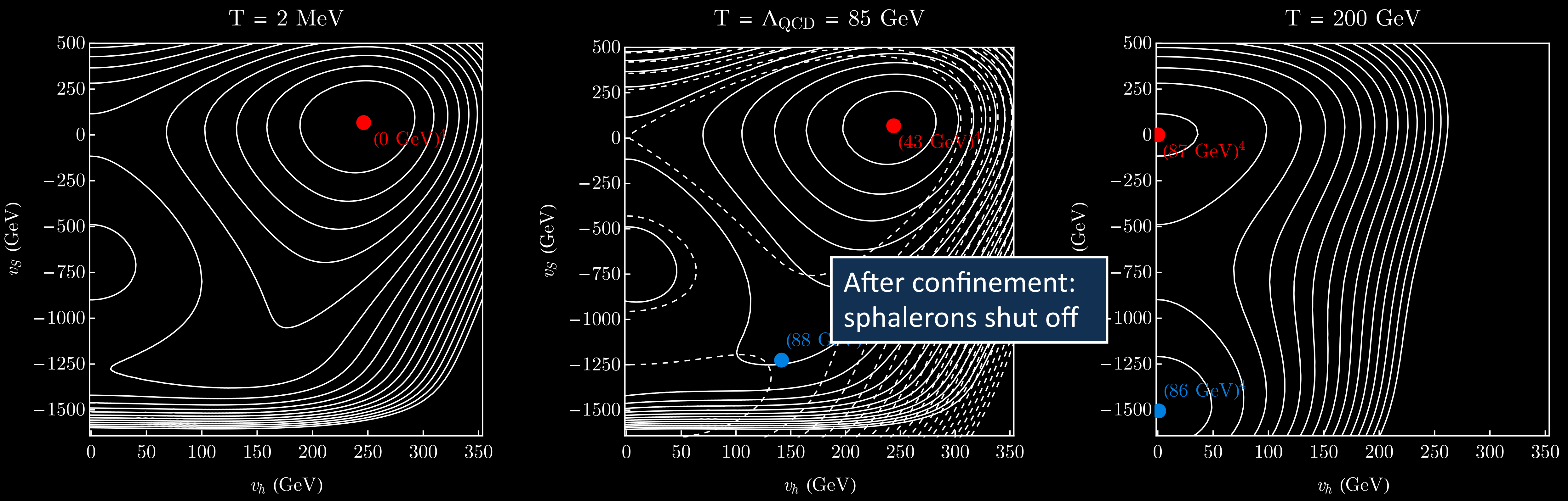


Dashed (solid) lines: potential in the unconfined (confined) phase

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

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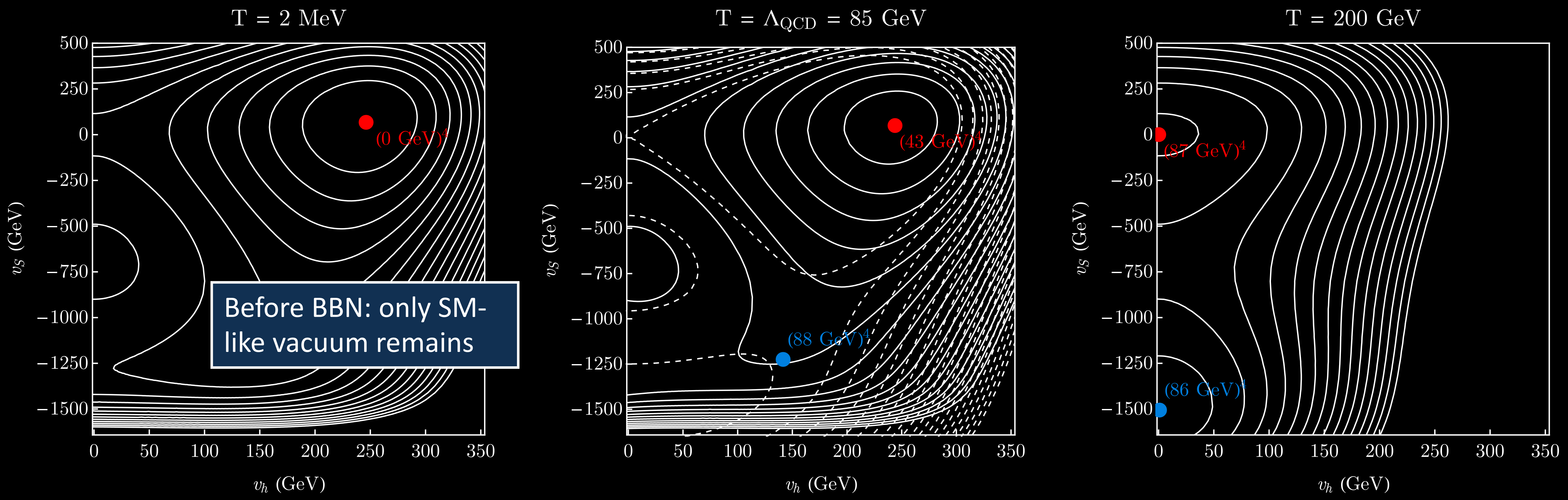

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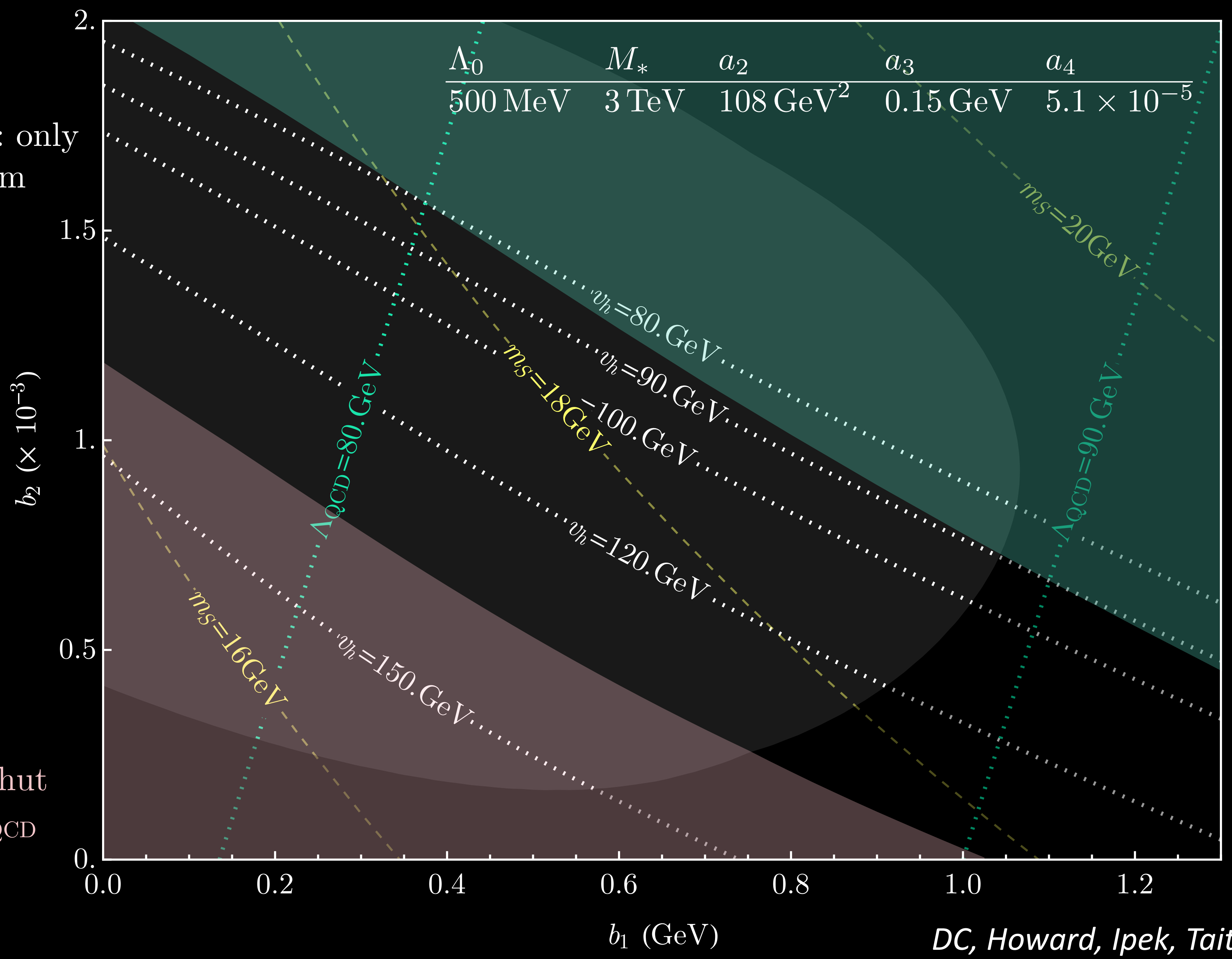
DC, Howard, Ipek, Tait, [arXiv:1911.01432]

Lighter region: only SM-like vacuum remains ✓

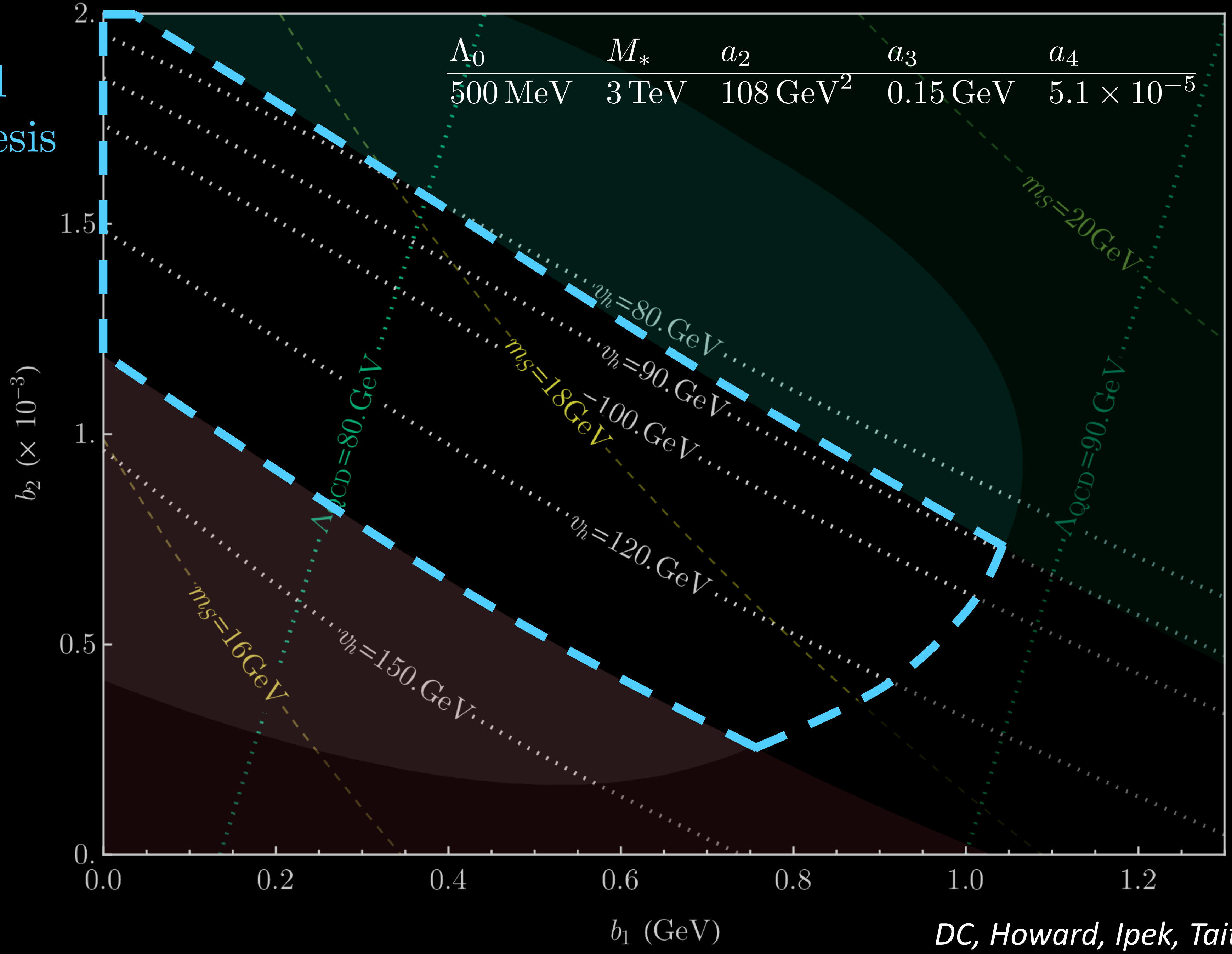


Sphalerons do not shut off at Λ_{QCD}

Sphalerons shut off before Λ_{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 pseudo-scalar 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)

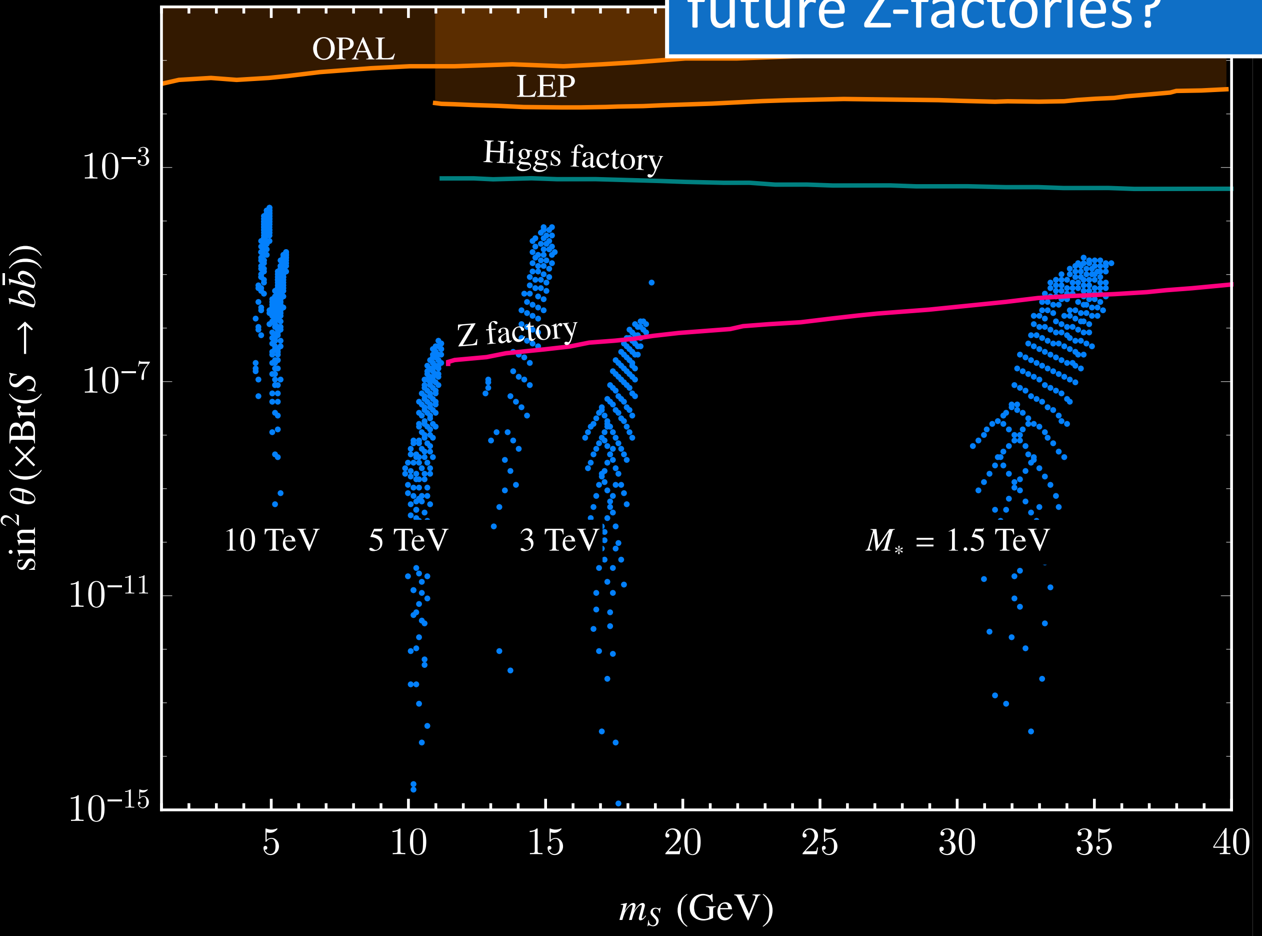
- Singlet typically has mass
  $m_s{}^2 = \mathrm{O}(10\ \mathrm{GeV})^2$

- 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

Potentially probed by future Z-factories?



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

Gravitational waves

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

- Deconfinement likely also occurs while $\mathrm{N_f}>3$

→ Potential double peaked GW signal in the LISA frequency band

- Since the same DOF participate in both transitions, the resulting plasma dynamics is non-trivial → discussions in progress

Final takeaways

- *Gravitational waves offer a window onto the early Universe, potentially allowing us to probe quark confinement*

- 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 largely still open) challenge

Thank you!

Questions?