QCD Baryogenesis

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SI, T. Tait, PRL (2019), 122, 112001, *arXiv: 1811.00559*

D. Croon, J. Howard, SI, T. Tait, *PRD* 101 (2020) 5, 055042 *arXiv:1911.01432*

S.A.R. Ellis, SI, G. White, *JHEP* 08 (2019) 002, *arXiv:1905.11994*

D. Berger, SI, T. Tait, M. Waterbury, *JHEP 07 (2020) 192*

SM QCD cannot explain the matter asymmetry

There can be large CP violation in the strong sector (axion)

BUT

NO baryon number violation!

NO 1^{st} order phase transition*

*will come back to this soon

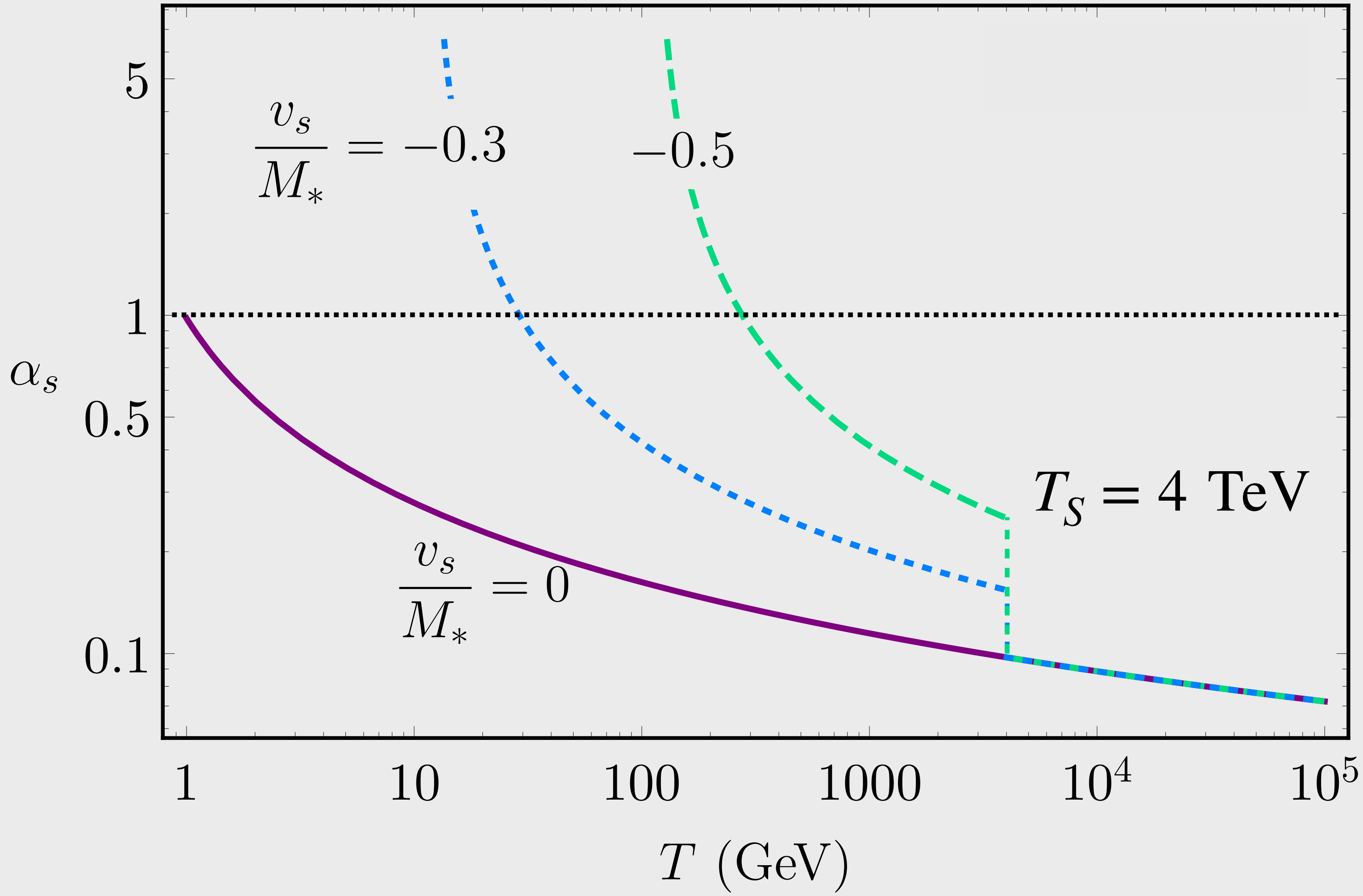
We don't know anything about what happened before Big Bang Nucleosynthesis ($T \sim \mathrm{MeV}$, $t \sim$ sec)

What if QCD was different in the early Universe?

SI, T. Tait, PRL (2019), 122, 112001, *arXiv: 1811.00559*

We can change QCD! - in the early universe

Confinement scale changes with new particles if they interact via strong interactions!



$$\mathscr{L} \supset \left(\frac{1}{g_s^2} + \frac{S}{M_*}\right) G^{\mu\nu} G_{\mu\nu}$$

$$\frac{1}{g_{\rm eff}^2} = \frac{1}{g_s^2} + \frac{v_S}{M_*}$$

$$\Lambda_{\rm QCD} \simeq \Lambda_{\rm QCD}^{\rm SM} \times \exp\left(\frac{24\pi^2}{2N_f - 33}\frac{v_S}{M_*}\right)$$

currently

$\Lambda_{QCD} \sim 400 \text{ MeV}$

billions of years ago

$\Lambda_{QCD} \sim 400 \text{ GeV}$

Things that depend on the QCD scale will be different in the early Universe

pions ~ O(100 MeV)

pions ~ O(100 GeV)

If QCD confines before EW symmetry breaking:

Above confinement: 6 massless quarks

Below confinement: quarks are no more! we have mesons

chiral symmetry breaking: $SU(6)_L \times SU(6)_R \to SU(6)_{\rm diag}$

$$\mathscr{L}_{\rm ch} \supset \frac{f_\pi^2}{4}{\rm Tr}[\partial_\mu U \partial^\mu U] + \kappa {\rm Tr}[U M]$$

the pion matrix $U(x) = e^{2iT^a\Pi^a(x)/f_\pi}$

$$\mathscr{L}_{\rm ch} \supset \sqrt{2}\kappa y_t h - \frac{\kappa}{f_\pi^2}{\rm tr}[\{T^a, T^b\}M]\pi^a\pi^b$$

$$M = \frac{h}{\sqrt{2}}{\rm diag}\left(y_u, y_d, y_s, y_c, y_b, y_t\right)$$ quark mass matrix

SM QCD

confinement ~ 400 MeV

mass of up/down quarks $< \Lambda_{\rm QCD}^{\rm SM}$

pion masses: $m_{\pi 0}^2 = \dfrac{2\kappa_0 (m_u + m_d)}{f_{\pi 0}^2}$

QCD quantities:

$$\kappa_0 \simeq (225 \text{ MeV})^3$$

$$f_{\pi 0} \simeq 94 \text{ MeV}$$

New physics QCD

confinement ~ 400 GeV

all quarks are lighter than $\Lambda_{\rm QCD}^{\rm new}$

pions are heavier:

Higgs vev

$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{v_h}{v_h^{\rm SM}} \right) \xi$$

$$\kappa \simeq \kappa_0 \, \xi^3$$

$$f_\pi \simeq f_{\pi 0} \, \xi$$

with $\xi \equiv \dfrac{\Lambda_{\rm QCD}^{\rm new}}{\Lambda_{\rm QCD}^{\rm SM}}$

T_c

$v_h = 0$

finite temperature corrections
the usual: gauge bosons, quarks,…

$T_{\rm EW}^{\rm SM}$

QCD confined

$v_h \neq 0$

no quarks,
but hadrons!

T_d

$v_h = v_h^{\rm SM}$

QCD deconfines?

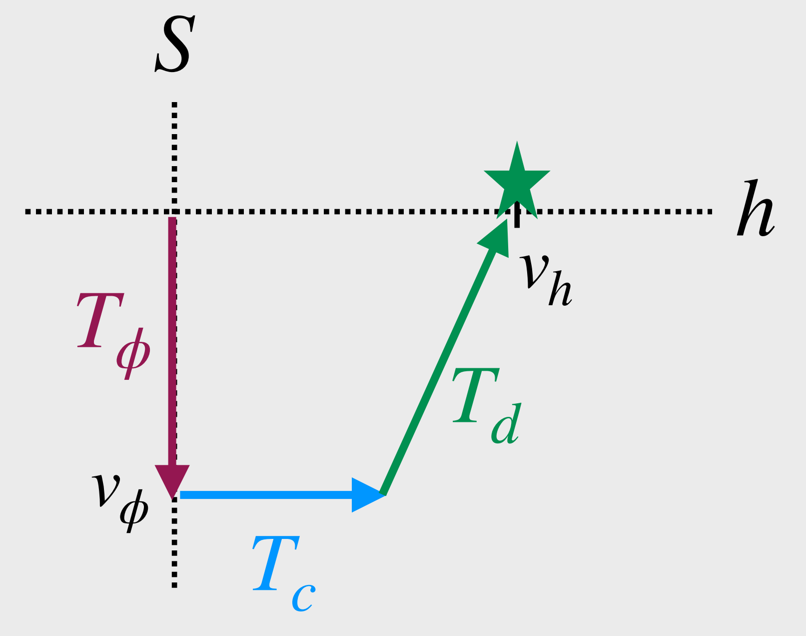
return to the SM

$\Lambda_{\rm QCD}^{\rm SM} \sim \rm GeV$

QCD confined

$T_{\rm BBN}$

Transition pattern



Thermal potential in the confined phase

- Higgs gets a tadpole term from the meson mass-term

$$V_{\rm tad}(v_h) \simeq \kappa \frac{y_t}{\sqrt{2}} v_h \simeq -0.0158\ {\rm GeV}^3 \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}} \right)^3 v_h$$

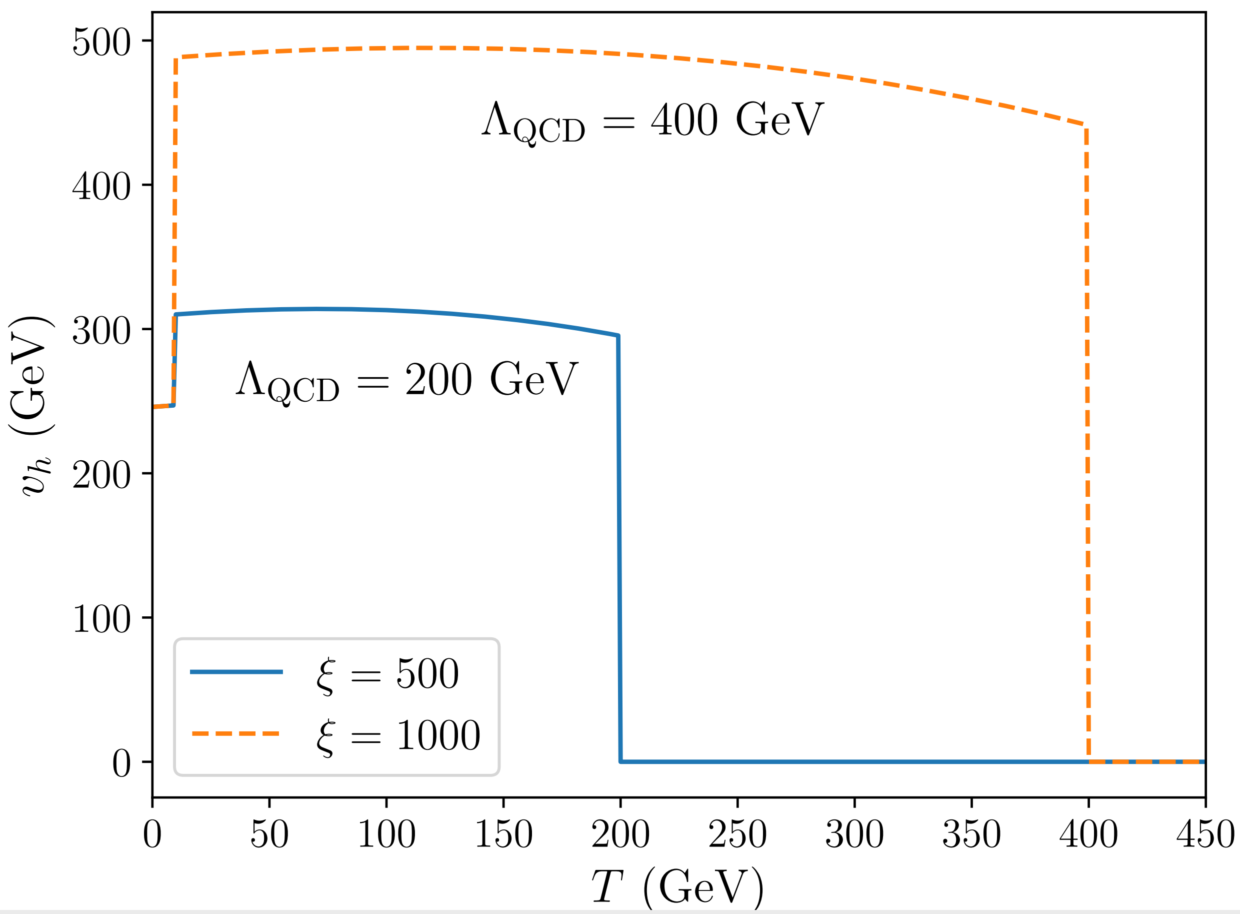
- Thermal corrections to the Higgs potential from mesons

$$V_{\rm meson}(v_h, T) = \sum_{i=1...35} \frac{T^4}{2\pi^2} J_B\left(\frac{m_i^2}{T^2} \right)$$

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

- The gluon condensate contributes to the singlet potential

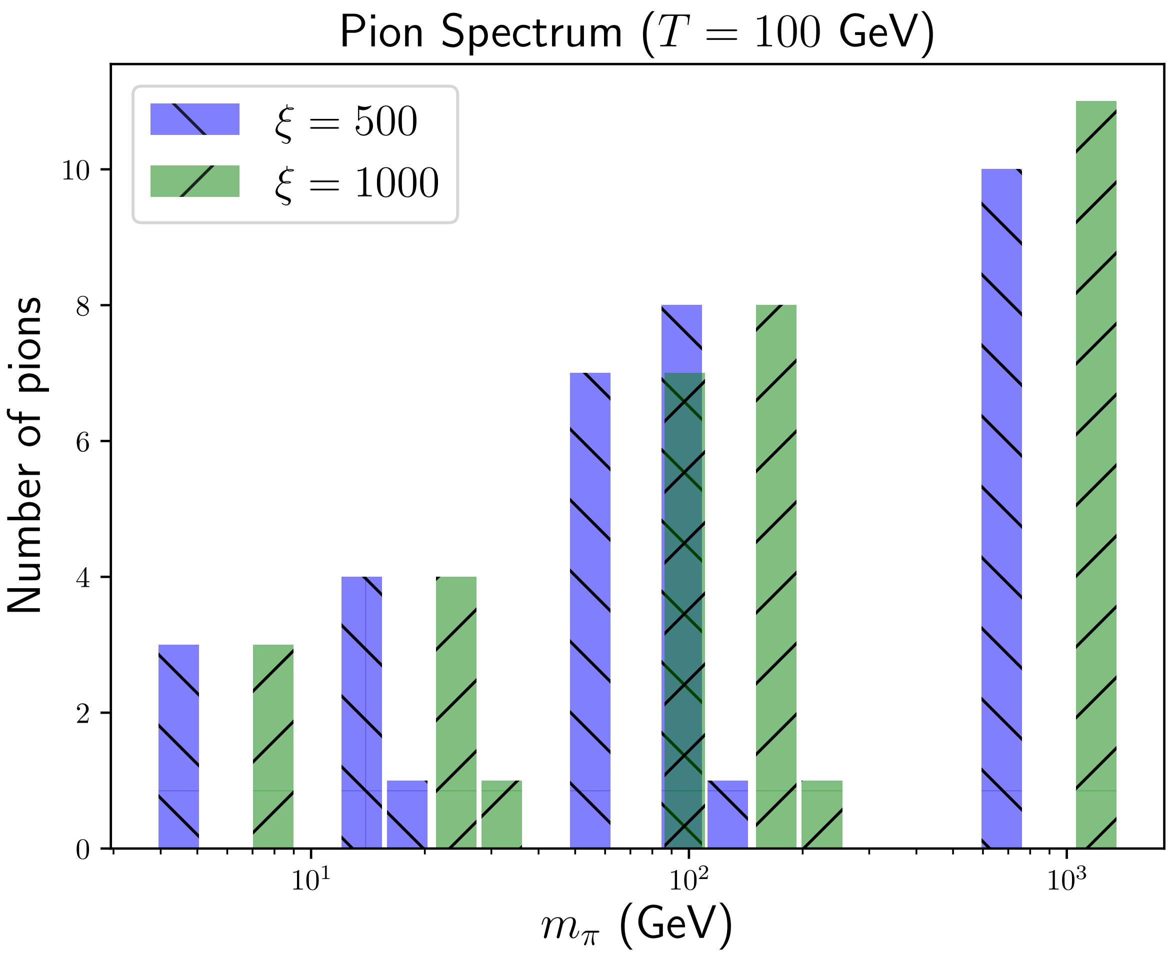
$$\frac{S}{M_*}\langle GG \rangle \longrightarrow V_{\rm GC}(v_S) \simeq \frac{v_S}{4M_*}\Lambda_{\rm QCD}^4$$



Higgs vev is larger than its SM value!

$$\xi = \frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}$$

$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}\right)\left(\frac{v_h}{v_h^{\rm SM}}\right)$$



New scalar can interact with the Higgs boson

$$V_{\text{scalar}} = -\mu^2 |H|^2 + \lambda_h |H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4 - b_1 S |H|^2 + b_2 S^2 |H|^2$$

New QCD cosmology

↓

Baryogenesis!

D. Croon, J. Howard, **SI**, T. Tait, *Phys.Rev.D* 101 (2020) 5, 055042 *arXiv:1911.01432*

$T = T_c$

QCD has CP violation!

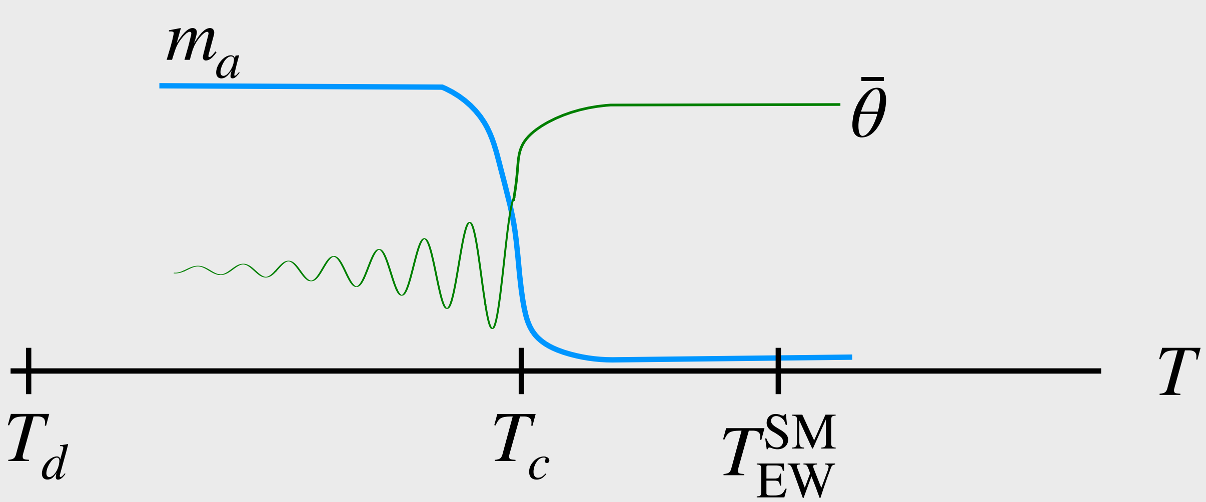
$$\mathscr{L} \supset \bar{\theta}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Axions!

$$m_a^2(T) f_a^2 \simeq \begin{cases} m_\pi^2 f_\pi^2 \zeta \left(\frac{\Lambda_{\rm QCD}}{T}\right)^n & T > T_c \\ m_\pi^2 f_\pi^2 & T < T_c \end{cases}$$

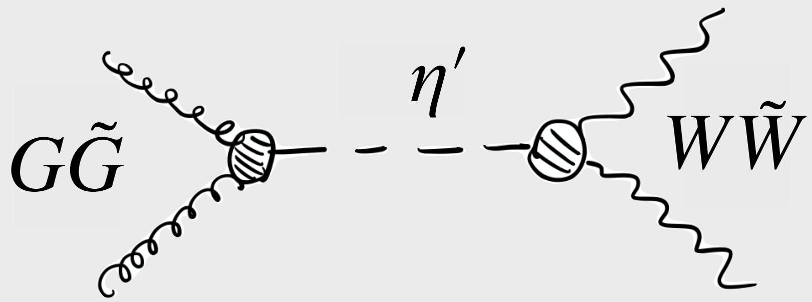
has small mass at high T

T-dependence given by number of light flavors, etc



How about B violation?

$T = T_c$



$$\partial_\mu j_B^\mu = \frac{\alpha_W}{8\pi}\mathrm{Tr}[W\tilde{W}]$$

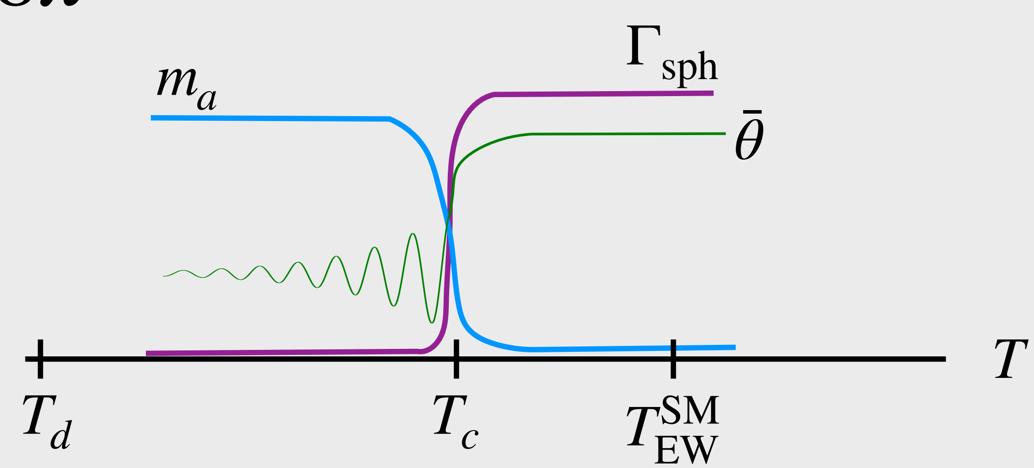
$$\Gamma_B \sim 25\alpha_W^5 T^4$$

$$\mathscr{L}_{\mathrm{eff}} = \frac{10}{f_\pi^2 m_{\eta'}^2}\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle \frac{\alpha_W}{8\pi}W\tilde{W}$$

anomalous baryon current

generates a chemical potential

$$\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle = m_a^2(T) f_a^2 \sin\bar{\theta} \quad \Rightarrow \quad \mu = \frac{10}{f_\pi^2 m_{\eta'}^2}\frac{d}{dt}\left[m_a^2(T) f_a^2 \sin\bar{\theta}(T)\right]$$



Spontaneous baryogenesis

A. Cohen, D. Kaplan, Nucl. Phys. B308 (1988) 913–928

Baryon asymmetry of the universe

Number of baryons: $n_B = \int_{t_i}^{t_f} dt \frac{\Gamma_B}{T}\mu$

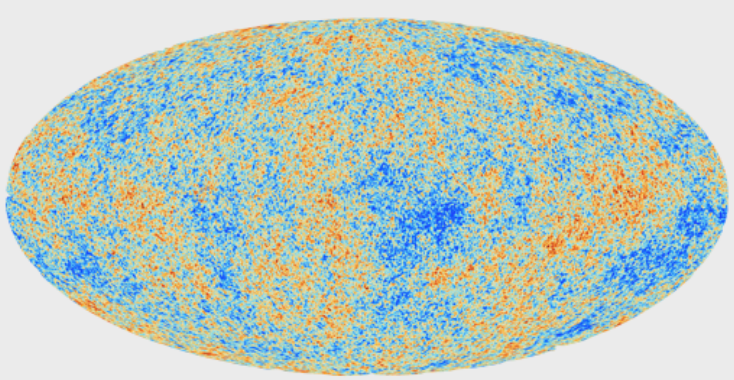
Baryon-to-entropy ratio

$$\eta = \frac{n_B}{s} \simeq \underbrace{\frac{5625}{2\pi^2 \underbrace{g_*(T_{\rm reh})}_{\sim 45}} \alpha_w^5 \sin\bar\theta \frac{\Delta\left[m_a^2(T) f_a^2\right]^{\sim m_\pi^2 f_\pi^2}}{f_\pi^2 m_{\eta'}^2}}_{} \left(\frac{T_{\rm sph}}{T_{\rm reh}}\right)^3$$

$$4.4\times 10^{-9} \sin\bar\theta \left(\frac{v_h}{v_h^0}\right)\left(\frac{\Lambda_{\rm QCD}^{\rm SM}}{\Lambda_{\rm QCD}}\right)$$

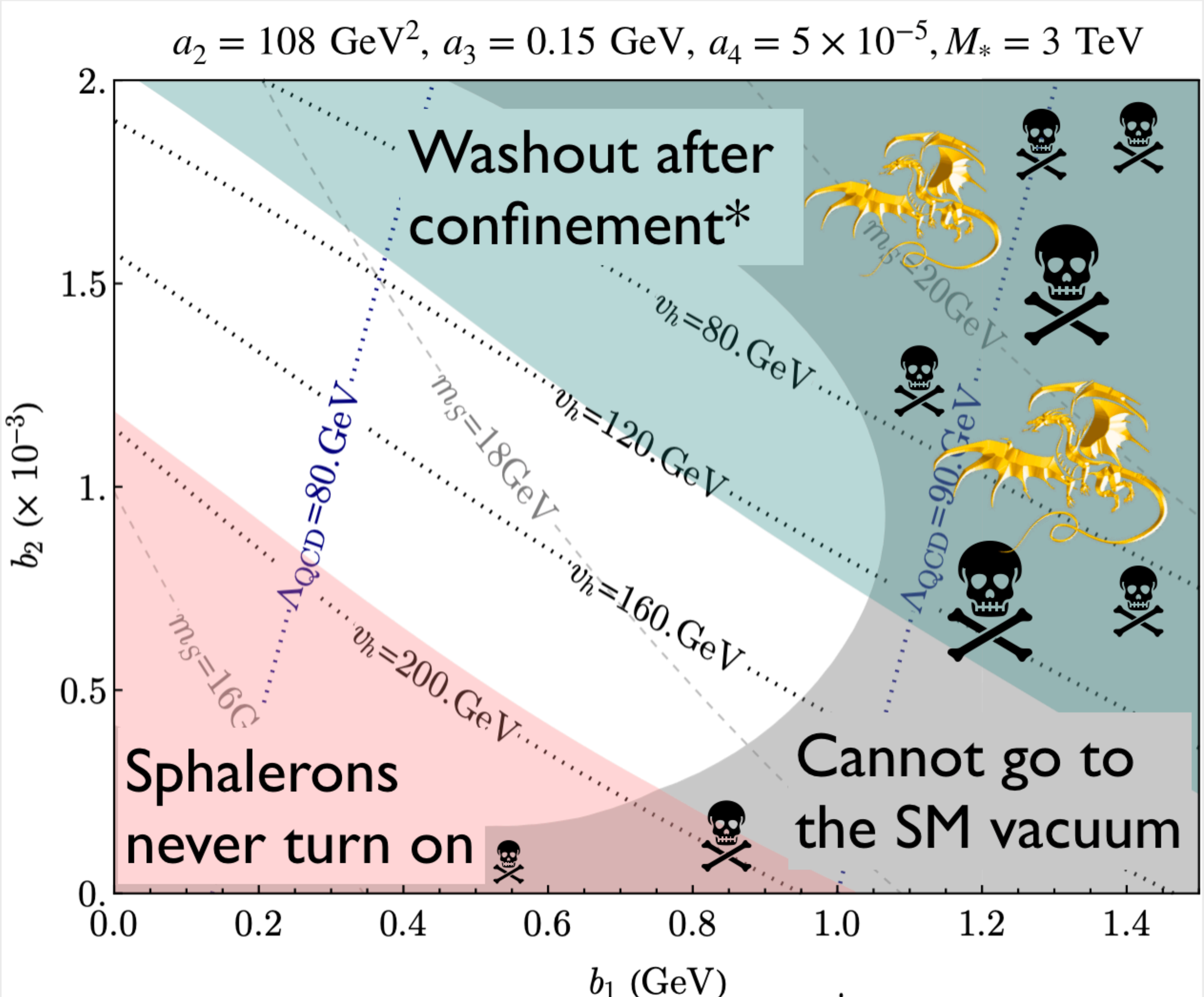
$$\eta \sim 10^{-11} \overbrace{\sin\bar\theta}^{\sim 1} \overbrace{\frac{v_h}{\Lambda_{\rm QCD}}}^{\sim 4} \left(\overbrace{\frac{T_{\rm sph}}{T_{\rm reh}}}^{>1}\right)^3$$

$$\eta_{\rm obs} \simeq 8.5\times 10^{-11}$$



fix (6 benchmark scenarios) | vary

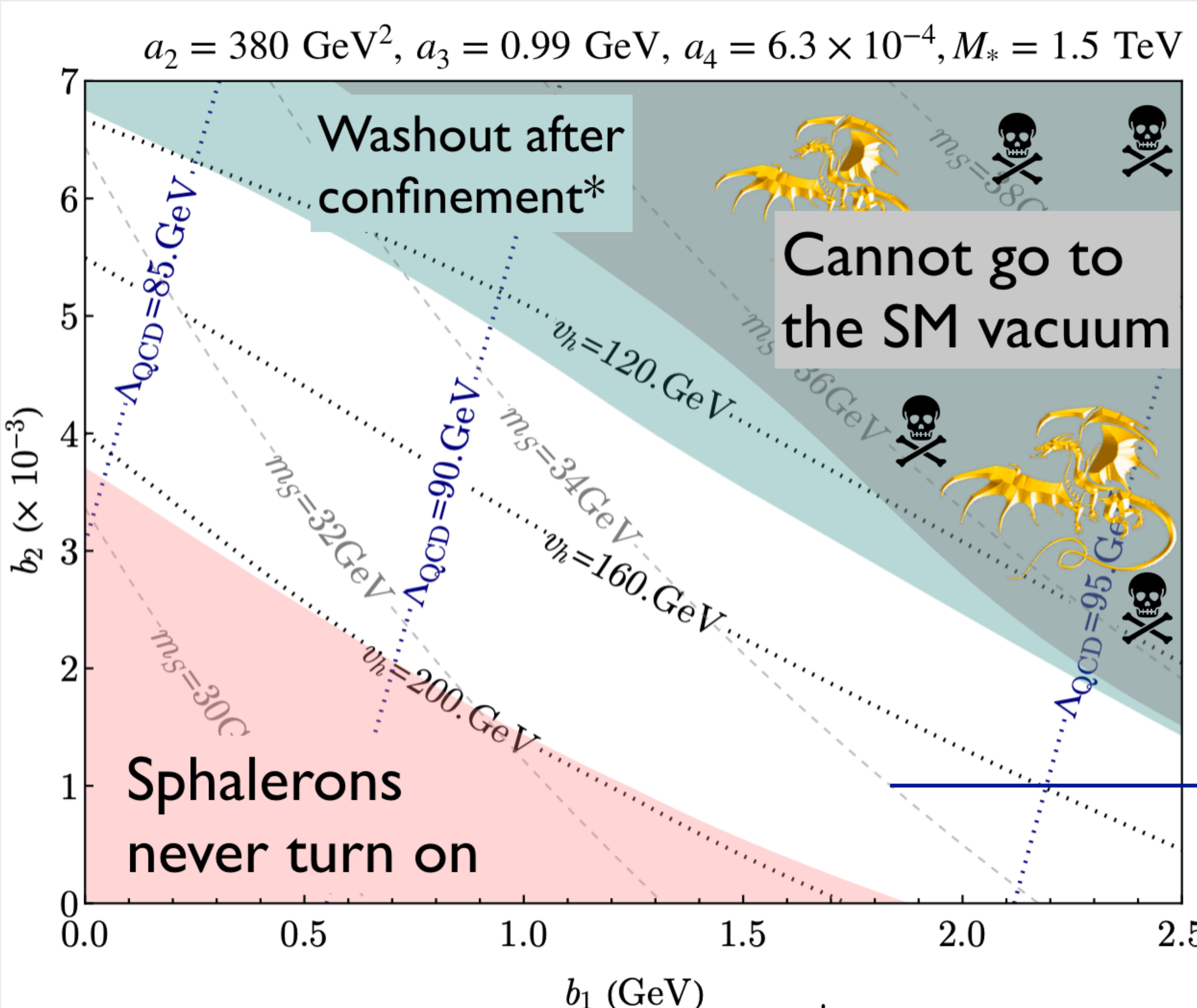
$$V_0 = -\mu^2 |H|^2 + \lambda_h |H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4 - b_1 S |H|^2 + b_2 S^2 |H|^2$$



* too conservative

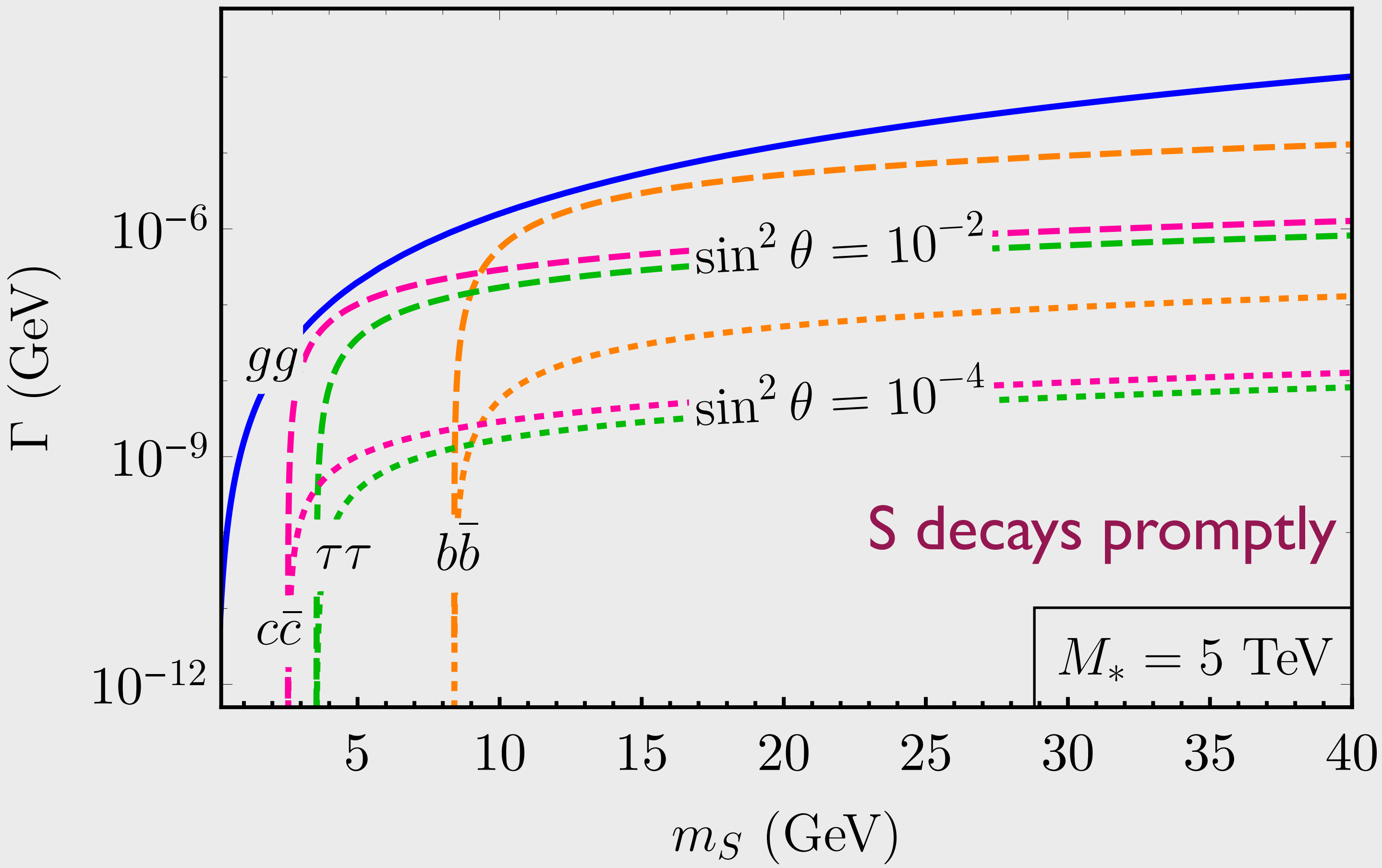
fix (6 benchmark scenarios) — vary

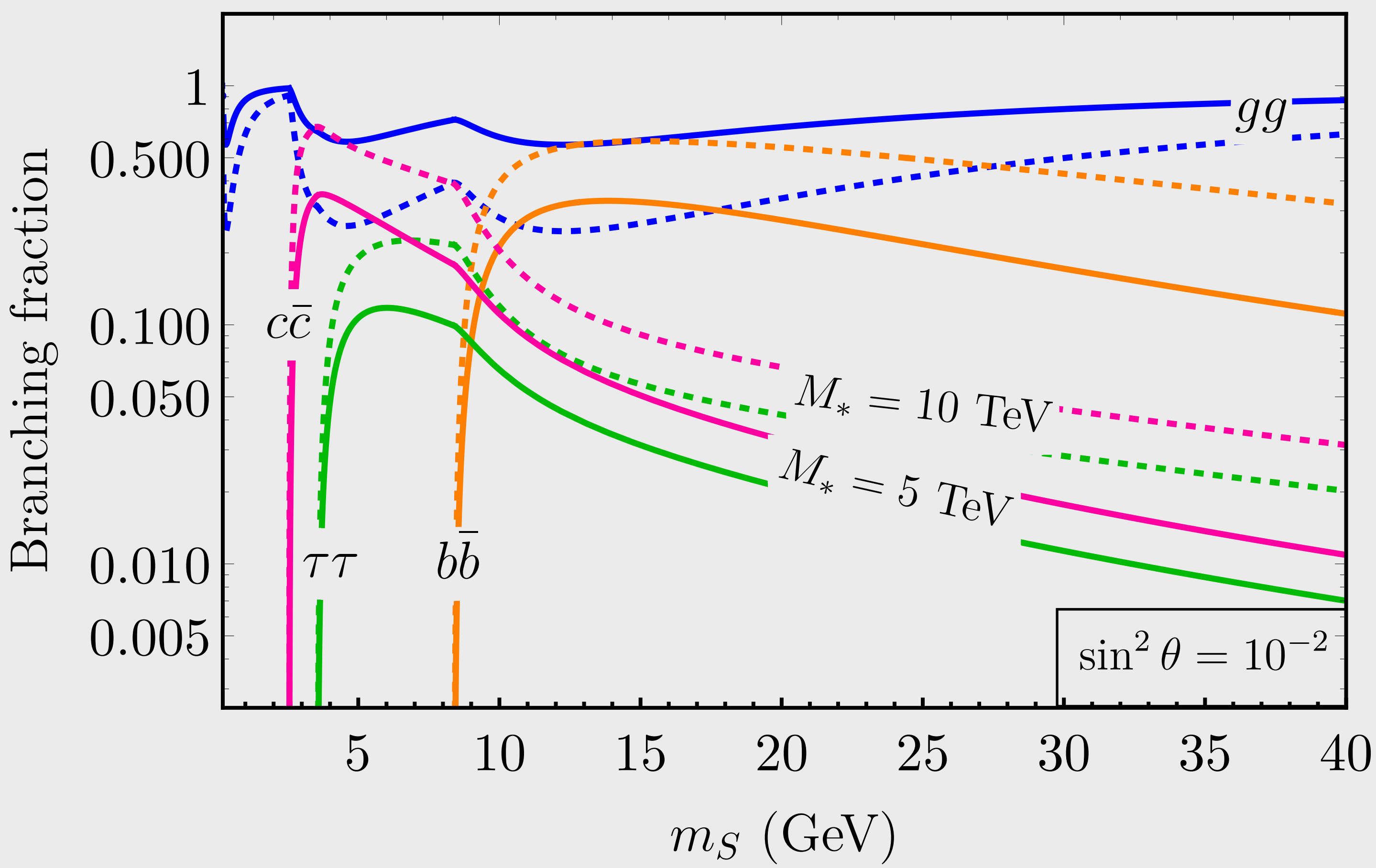
$$V_0 = -\mu^2|H|^2 + \lambda_h|H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4 - b_1 S|H|^2 + b_2 S^2|H|^2$$



light singlet!

* too conservative





Interested in $m_S \sim O(10 \text{ GeV})$

Singlet decays

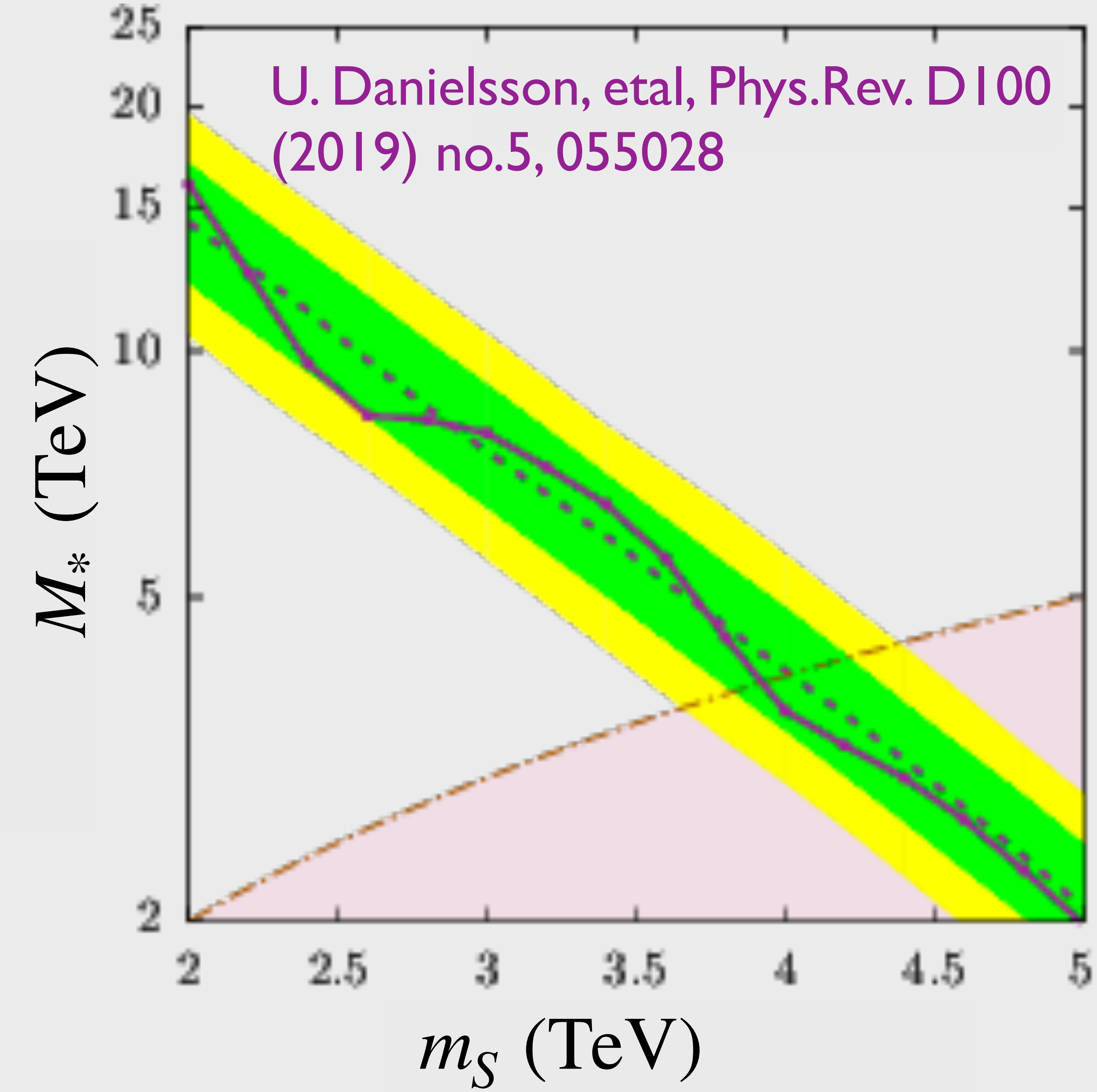
1) gluons via $(S/M_*)GG$

$$\Gamma(S \to gg) \simeq \frac{m_S^3}{8\pi M_*^2}$$

2) quarks and leptons via Higgs mixing

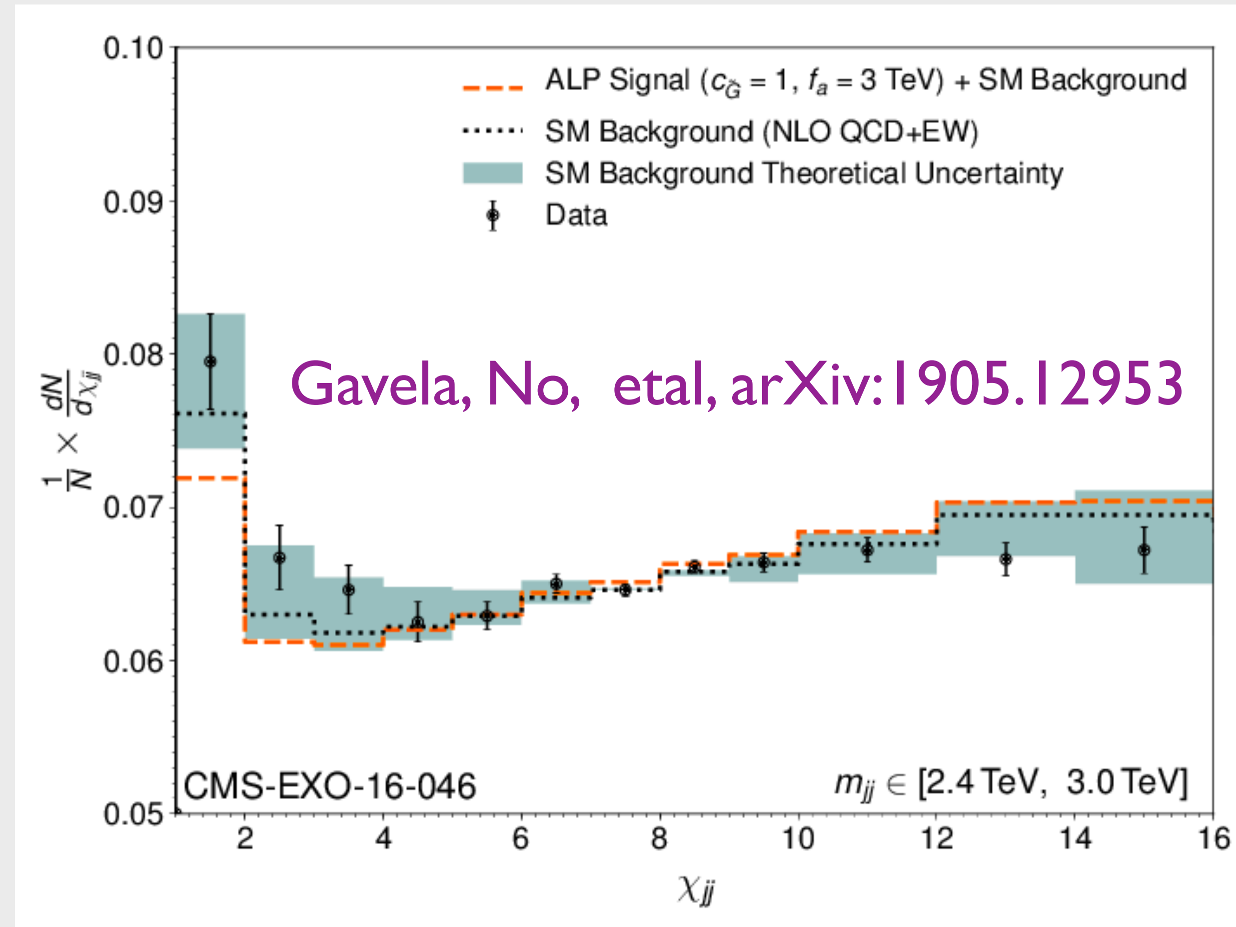
$$\Gamma(S \to f\bar{f}) \simeq \frac{N_c y_f^2 \sin^2\theta\, m_S}{8\pi}\left(1 - \frac{4m_f^2}{m_S^2}\right)^{3/2}$$

ATLAS dijet resonant searches



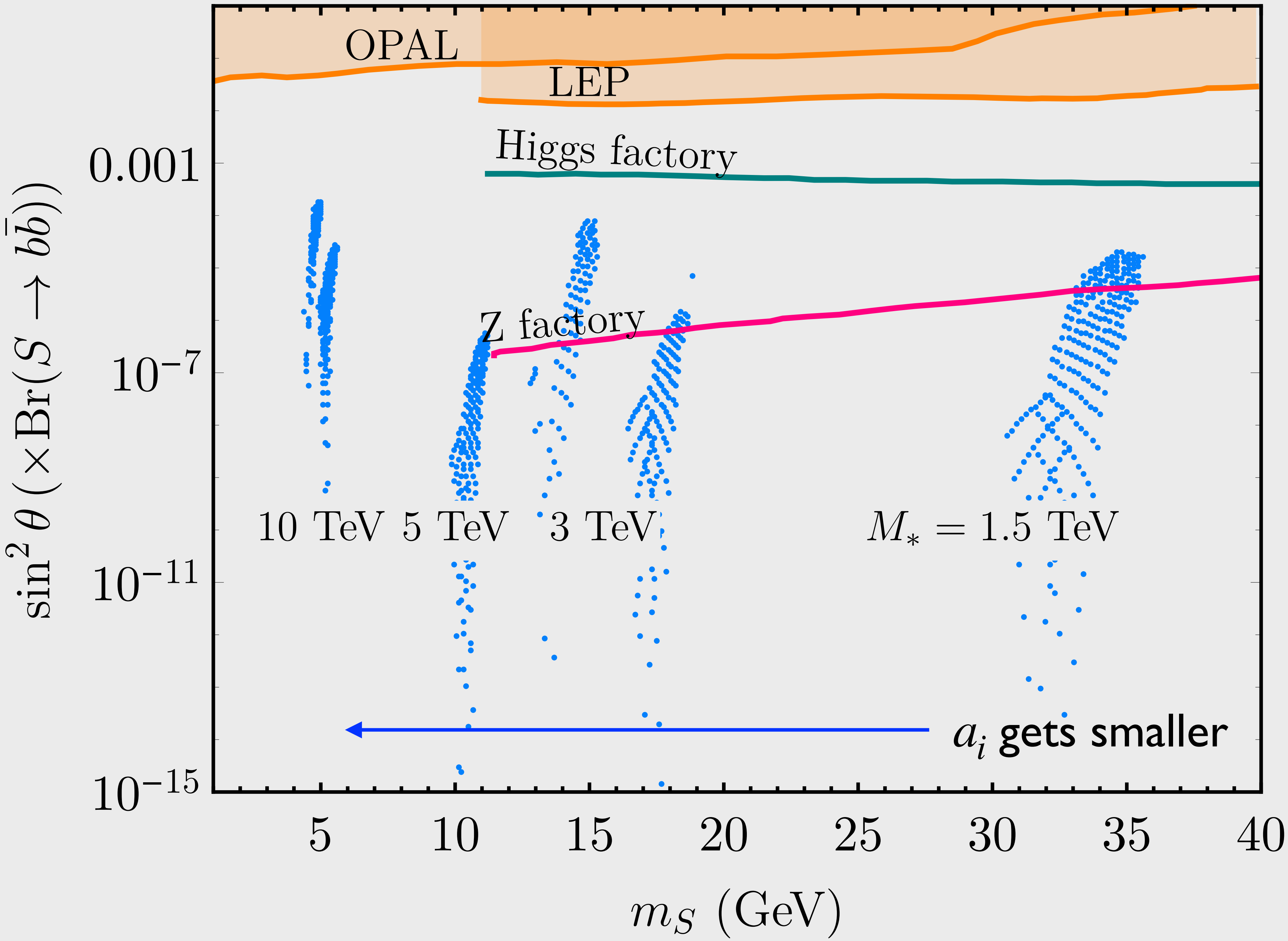
Only for very heavy S!

CMS dijet angular distribution



$M_* > 3$ TeV

This is for ALPs!
Not clear for a scalar

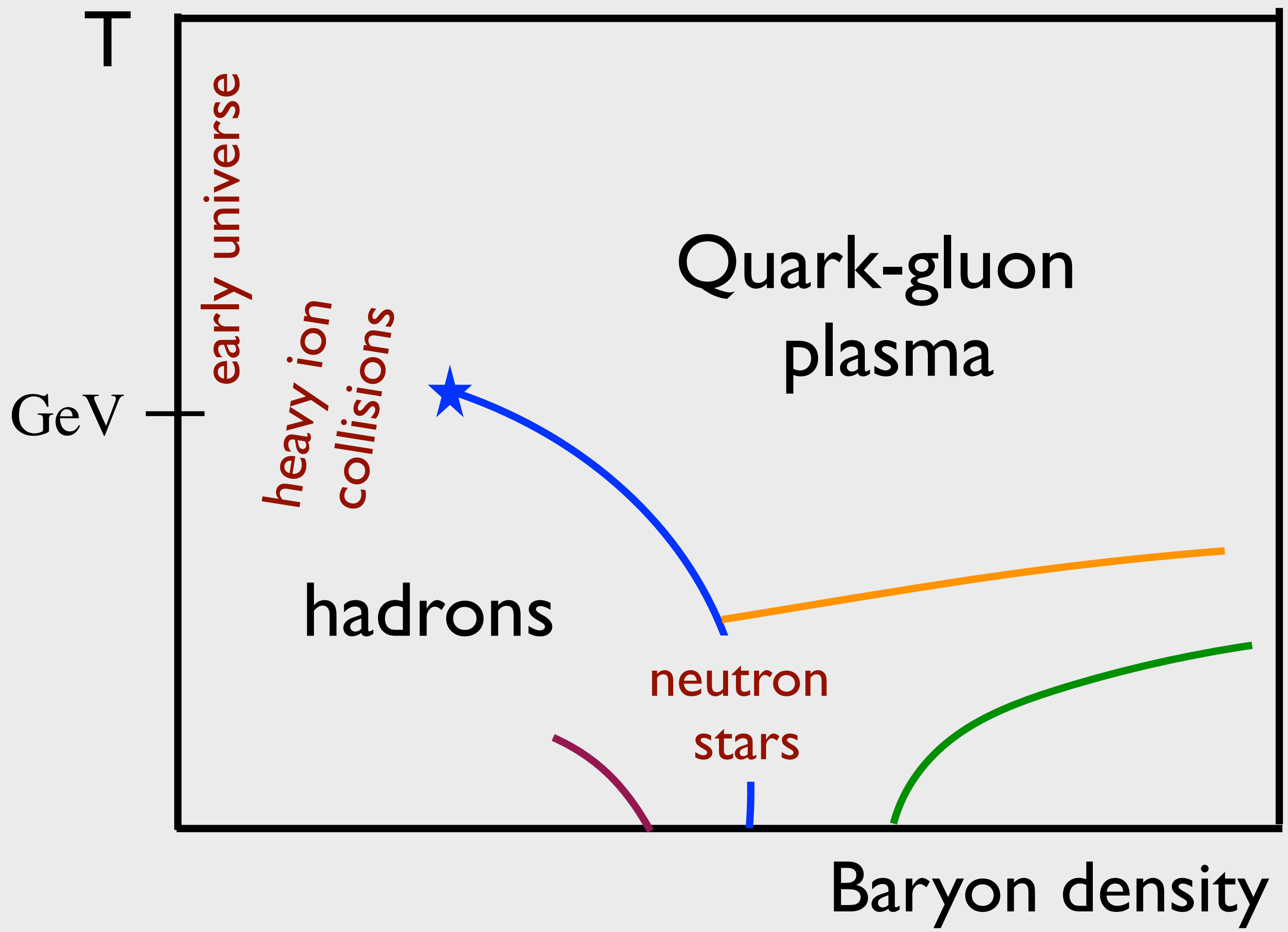


6 benchmark scenarios, there should be more!

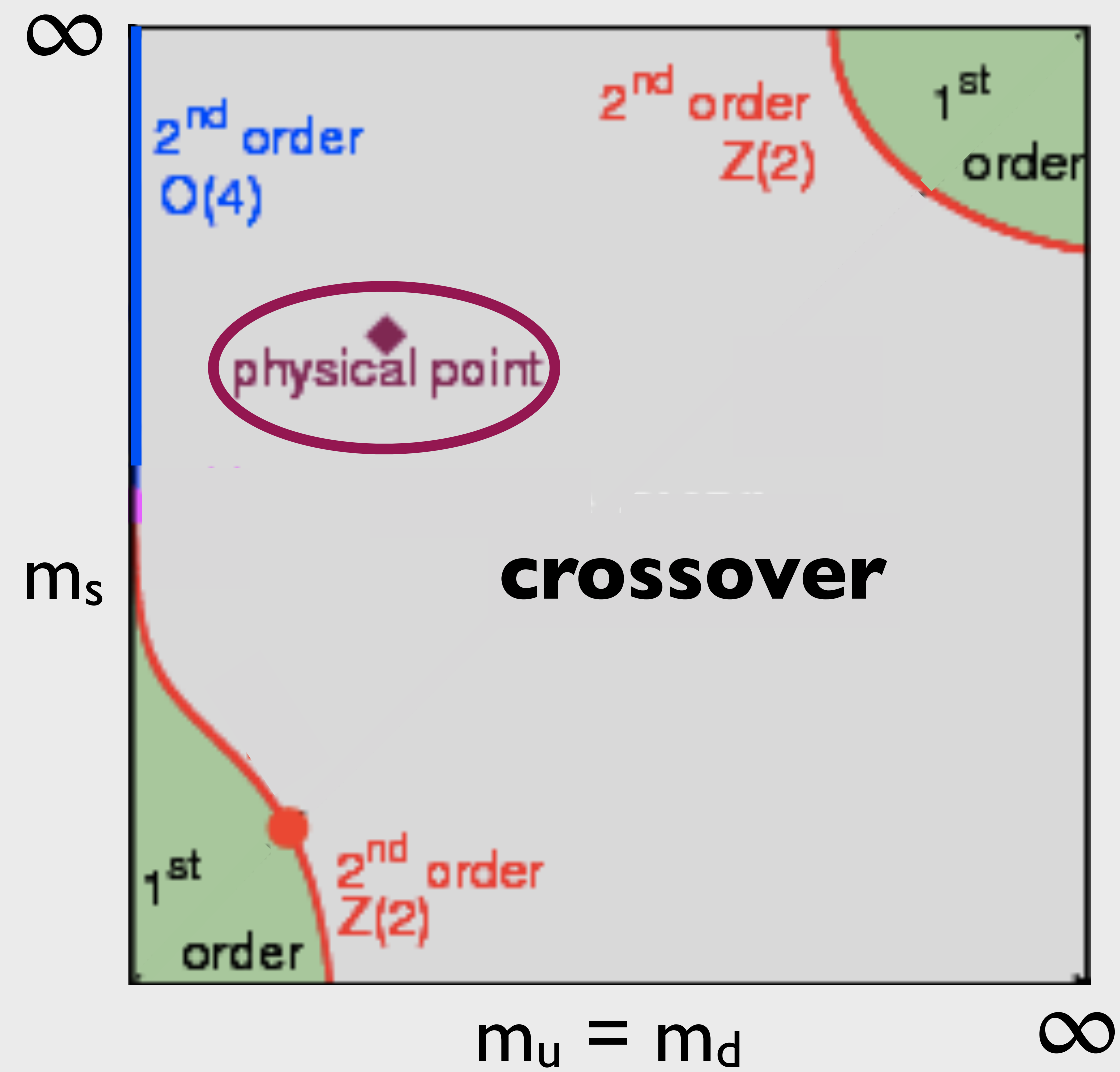
Mixing angle is too small for current searches

Singlet lighter than ~10GeV
is hard to constrain since it decays primarily to gluons

QCD Phase Diagram



J. Phys. Conf Ser. 432 012027 (2013)



If 3 or more massless quarks → First order phase transition???

R.D. Pisarski, F. Wilzcek, Phys. Rev. D29 (1984) 338–341

Maybe not :(

F. Cuteri, O. Philipsen, A. Sciarra, *arXiv: 2107.12739*
L. Dini, etal, *arXiv: 2111.12599*
J. Bernhardt, C. Fischer, *arXiv: 2309.06737*

Backup slides

High temperature

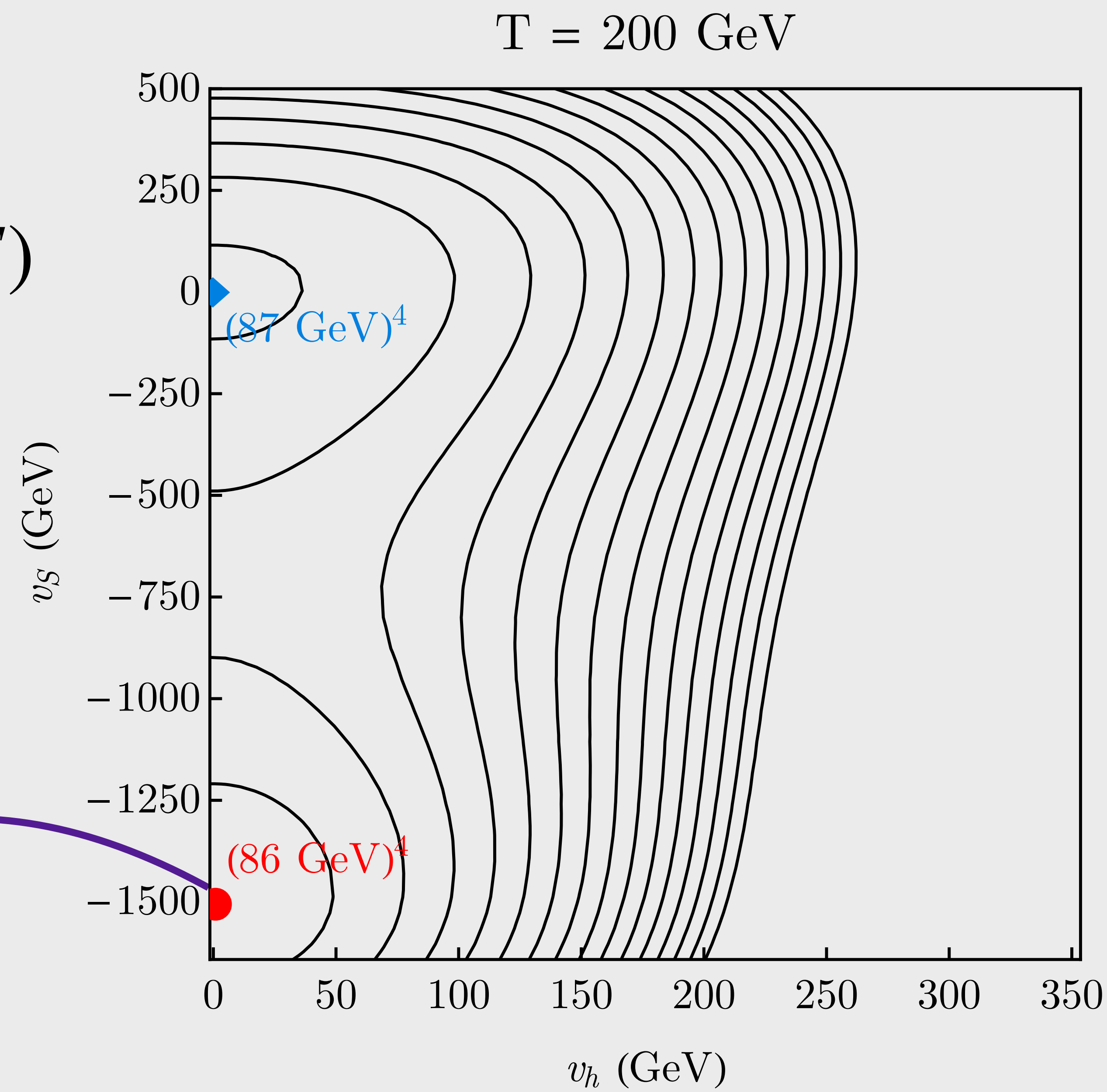
$T > T_{\text{EW}} > T_c$

Finite temperature potential:

$$V(v_h, v_s, T) = V_0(v_h, v_s) + V_{\text{gauge}}(v_h, T) + V_{\text{top}}(v_h, T)$$

$$V_0 = -\mu^2 |H|^2 + \lambda_h |H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4 - b_1 S |H|^2 + b_2 S^2 |H|^2$$

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



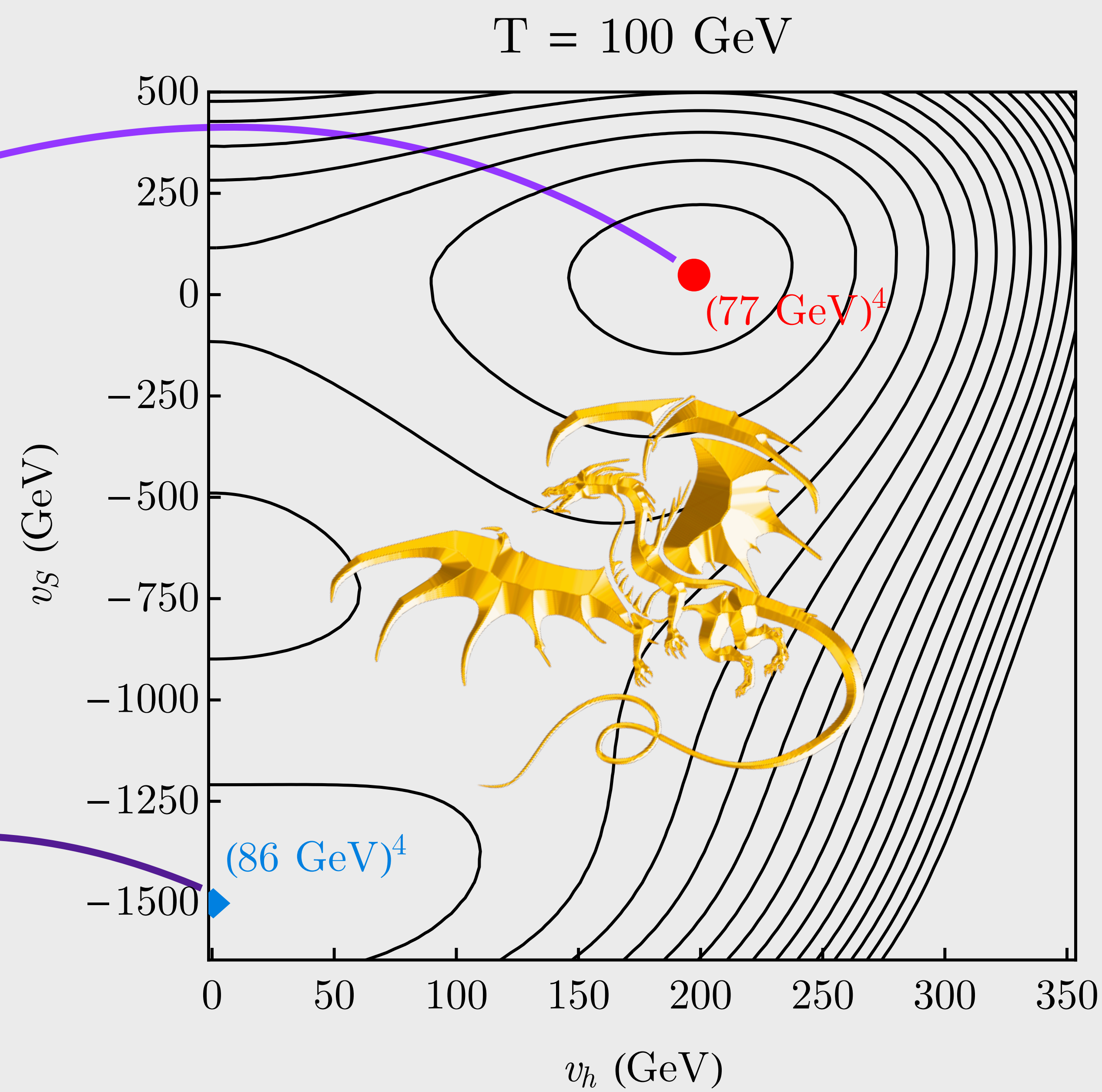
vacuum is at $v_s,\ v_h = 0$

global minimum

Below EW scale

$$T_{\rm EW} > T > T_c$$

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



Global minimum is SM-like

There is an impenetrable barrier between the two vacua!

Euclidean bounce action

$$\frac{S_E}{T} \sim \left(\frac{\Delta v_s}{\Delta V(v_s)} \right)^4 \sim 10^{-8}$$

Universe is stuck at $v_s,\ v_h = 0$

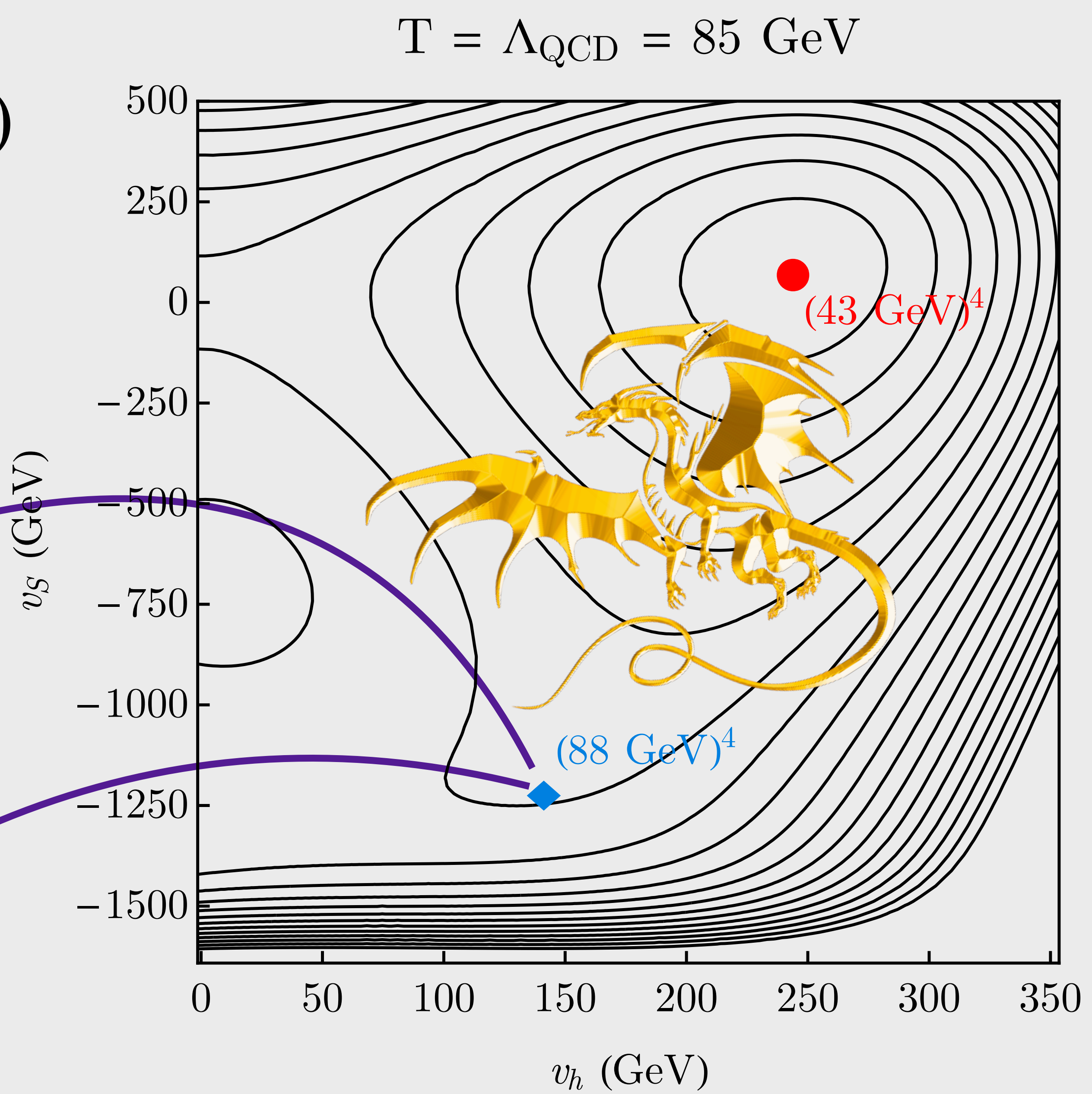
We require: $m_h = 125$ GeV
$v_h^0 = 246$ GeV

Below QCD confinement

$T_d < T \lesssim T_c$

$$V(v_h, v_s, T) = V_0(v_h, v_s) + V_{\rm gauge}(v_h, T) + V_{\rm tad}(v_h) + V_{\rm GC}(v_s) + V_{\rm meson}(v_h, T)$$

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



QCD confinement tips this vacuum towards finite v_h
(but not towards the SM value)

But there is still a barrier between the two vacua!

Universe is stuck at v_s, $v_h < v_h^{\rm SM}$

Back to the SM

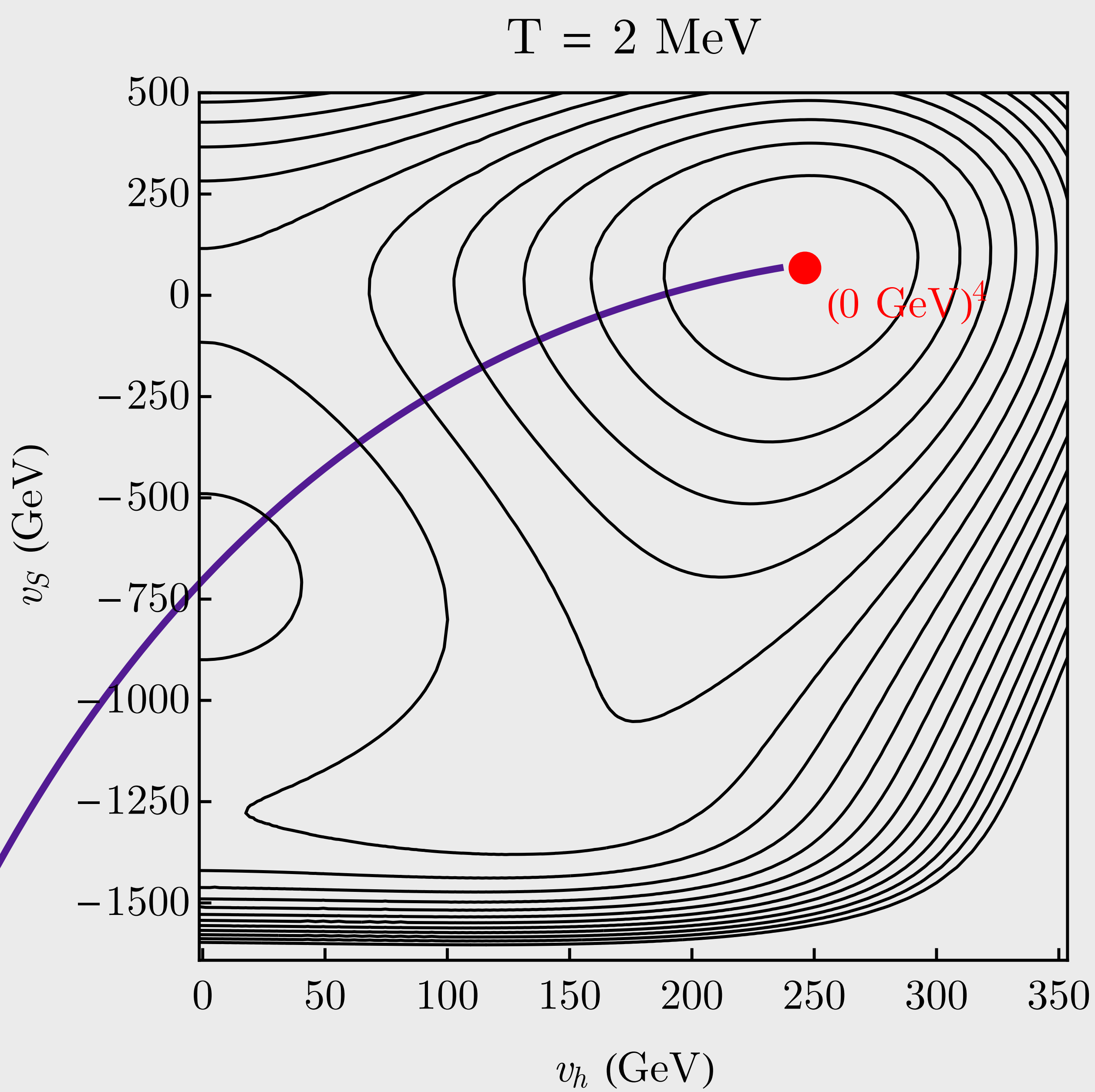
$T_c > T_d > T$

Universe has the right Higgs vev and Λ_{QCD}

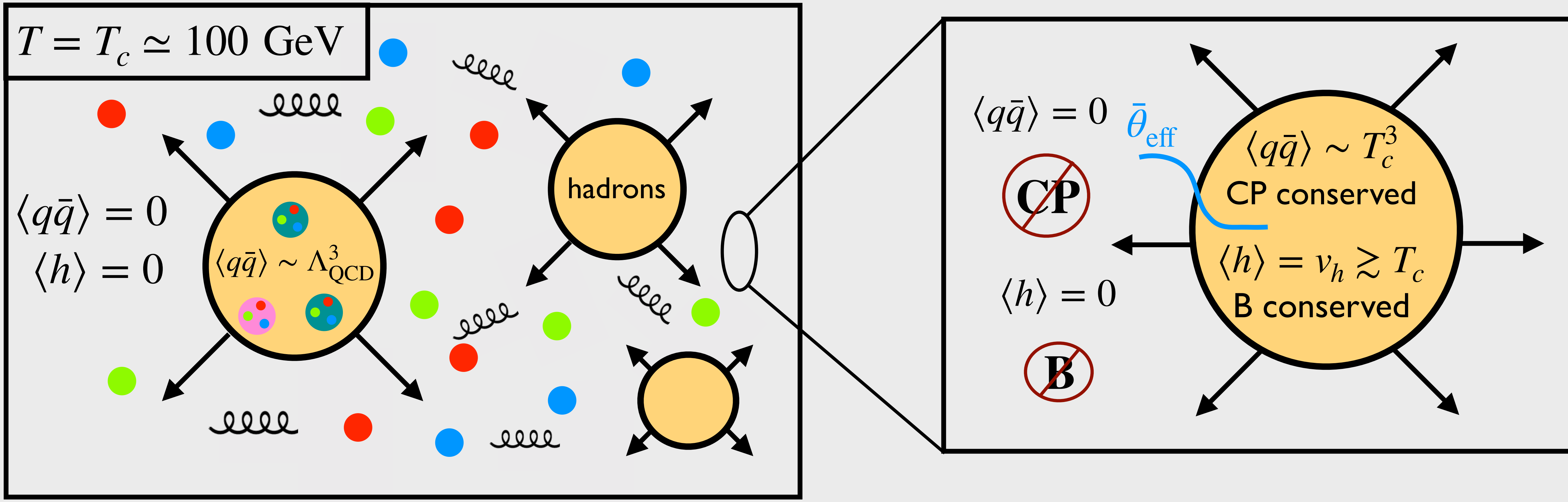
The barrier disappears

The universe can roll over instead of tunneling

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



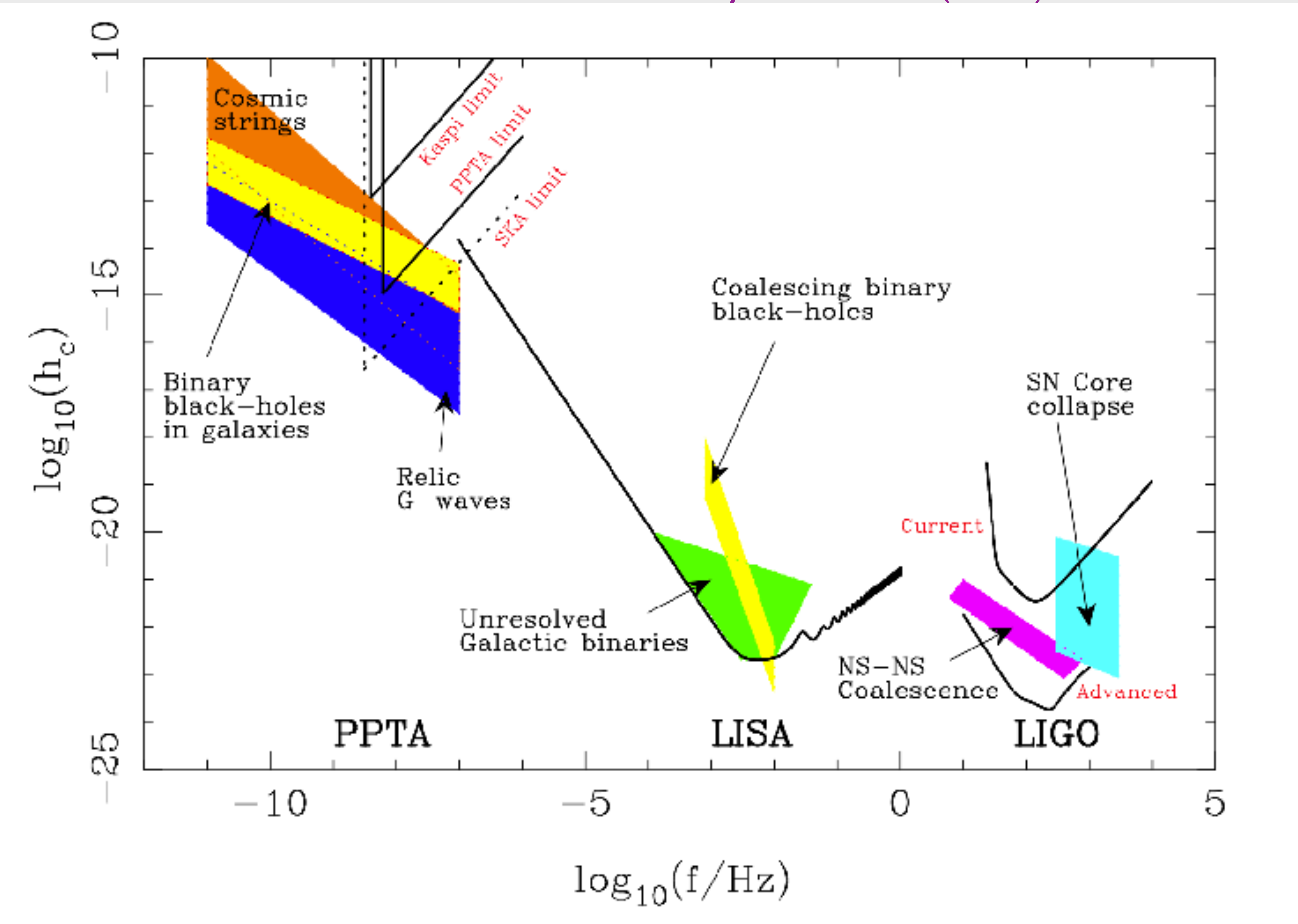
SM-like vacuum!



$$\eta \sim 10^{-11} \overbrace{\sin\bar{\theta}}^{\sim 1} \overbrace{\frac{v_h}{\Lambda_{QCD}}}^{\sim 4} \left(\overbrace{\frac{T_c}{T_{reh}}}^{> 1}\right)^3$$

$$\eta_{obs} \simeq 8.5 \times 10^{-11}$$

E. Thrane, etal, Phys.Rev. D88 (2013) no.12, 124032



Benchmark scenarios

	M_*	a_2/GeV^2	a_3/GeV	a_4
1.	1.5 TeV	380	9.9×10^{-1}	6.3×10^{-4}
2.	3 TeV	108	1.5×10^{-1}	5.1×10^{-5}
3.	3 TeV	44.2	6.14×10^{-2}	2.1×10^{-5}
4.	5 TeV	38.9	3.24×10^{-2}	6.6×10^{-6}
5.	10 TeV	9.72	4.05×10^{-3}	4.1×10^{-7}
6.	10 TeV	4.92	2.27×10^{-3}	2.6×10^{-7}

What is κ ? We can find by matching to the SM QCD!

OLD

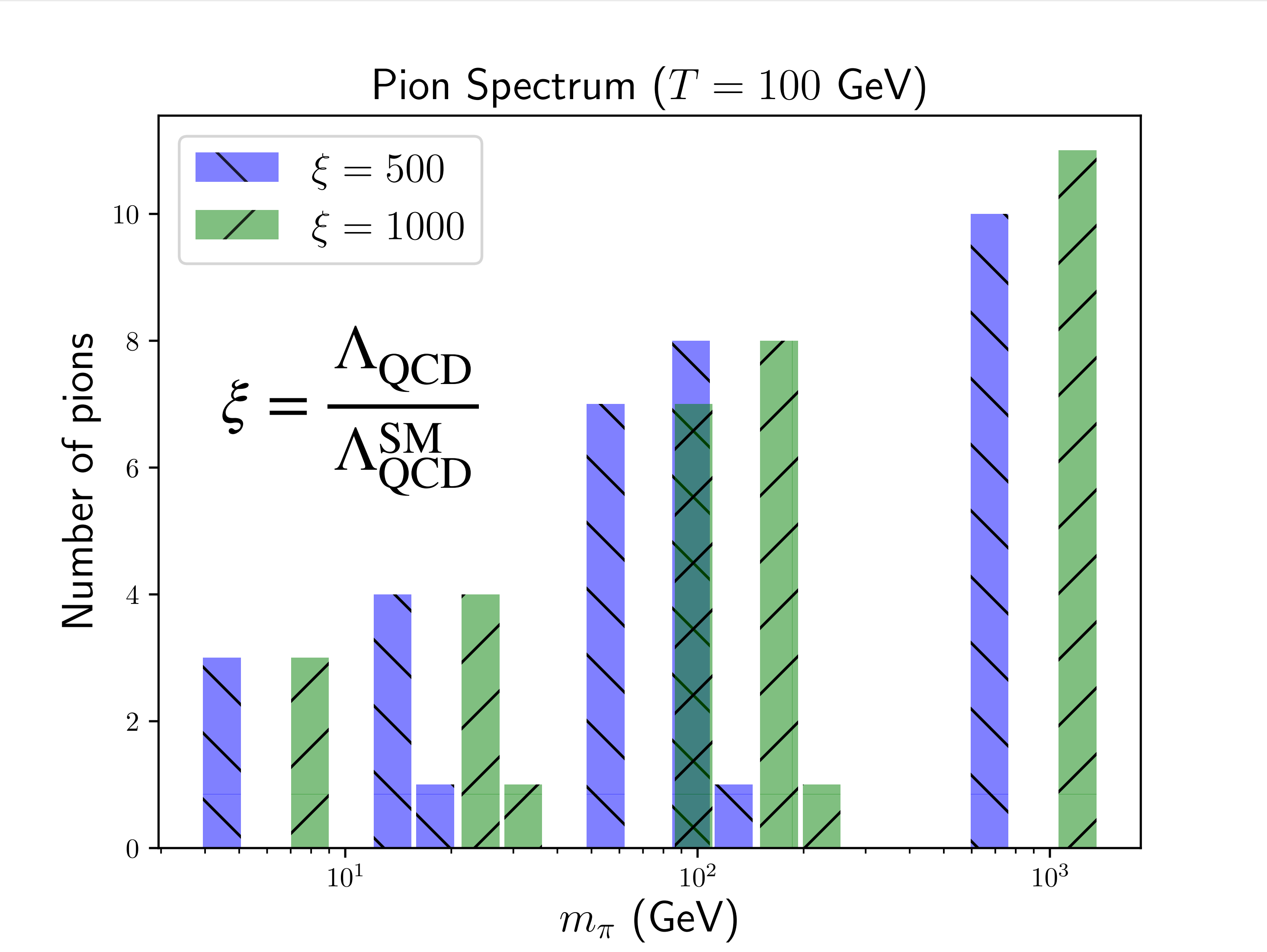
$$m_{\pi 0}^2 = \frac{2\kappa_0(m_u + m_d)}{f_{\pi 0}^2} \qquad \kappa_0 = \frac{m_{\pi 0}^2 f_{\pi 0}^2}{\sqrt{2} v_h^0 (y_u + y_d)} \simeq (224\ \text{MeV})^3$$

NEW

$$\kappa \simeq \kappa_0 \left(\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}^{\text{SM}}}\right)^3$$

$$f_\pi \simeq f_{\pi 0} \left(\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}^{\text{SM}}}\right)$$

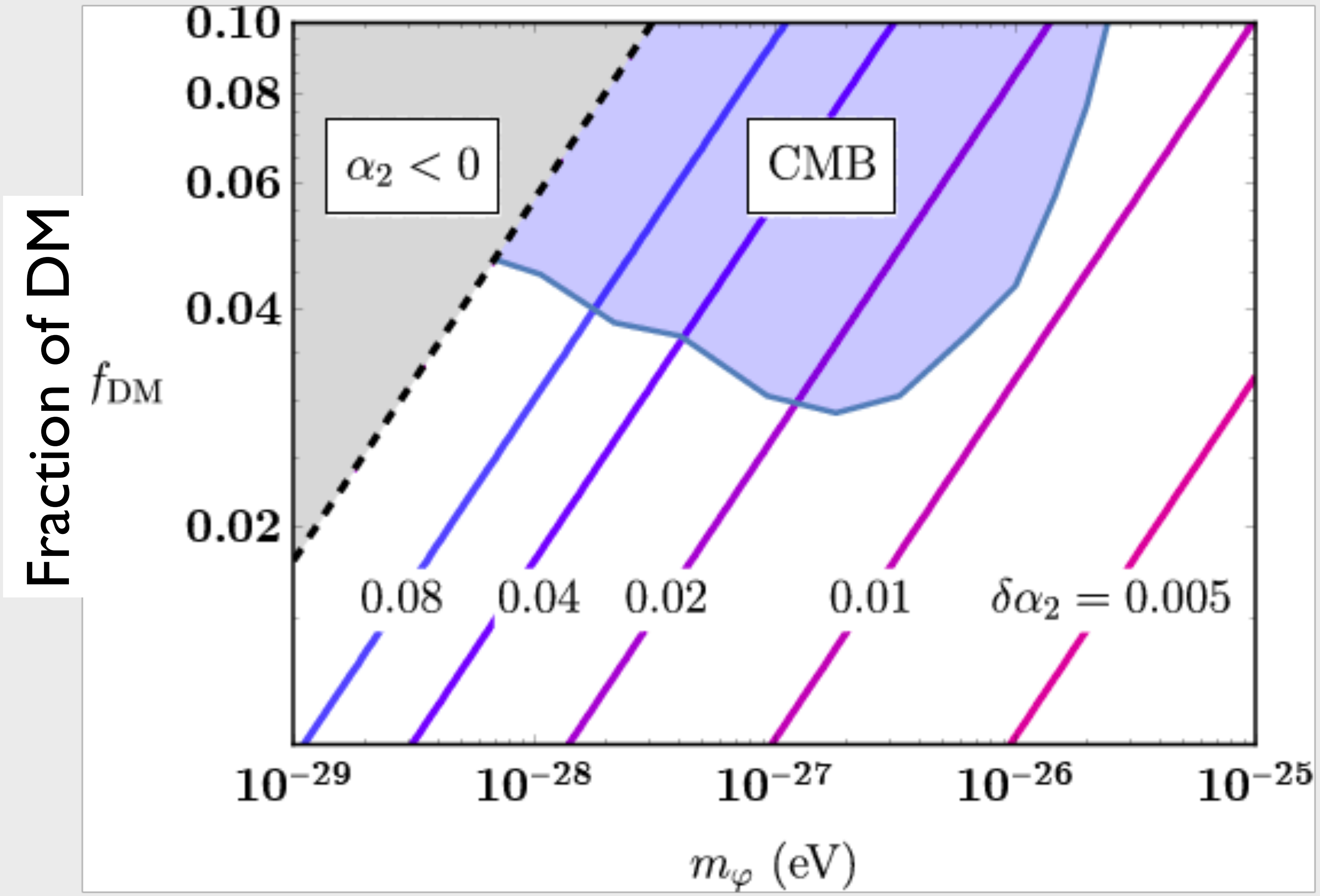
$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}^{\text{SM}}}\right)\left(\frac{v_h}{v_h^{\text{SM}}}\right)$$

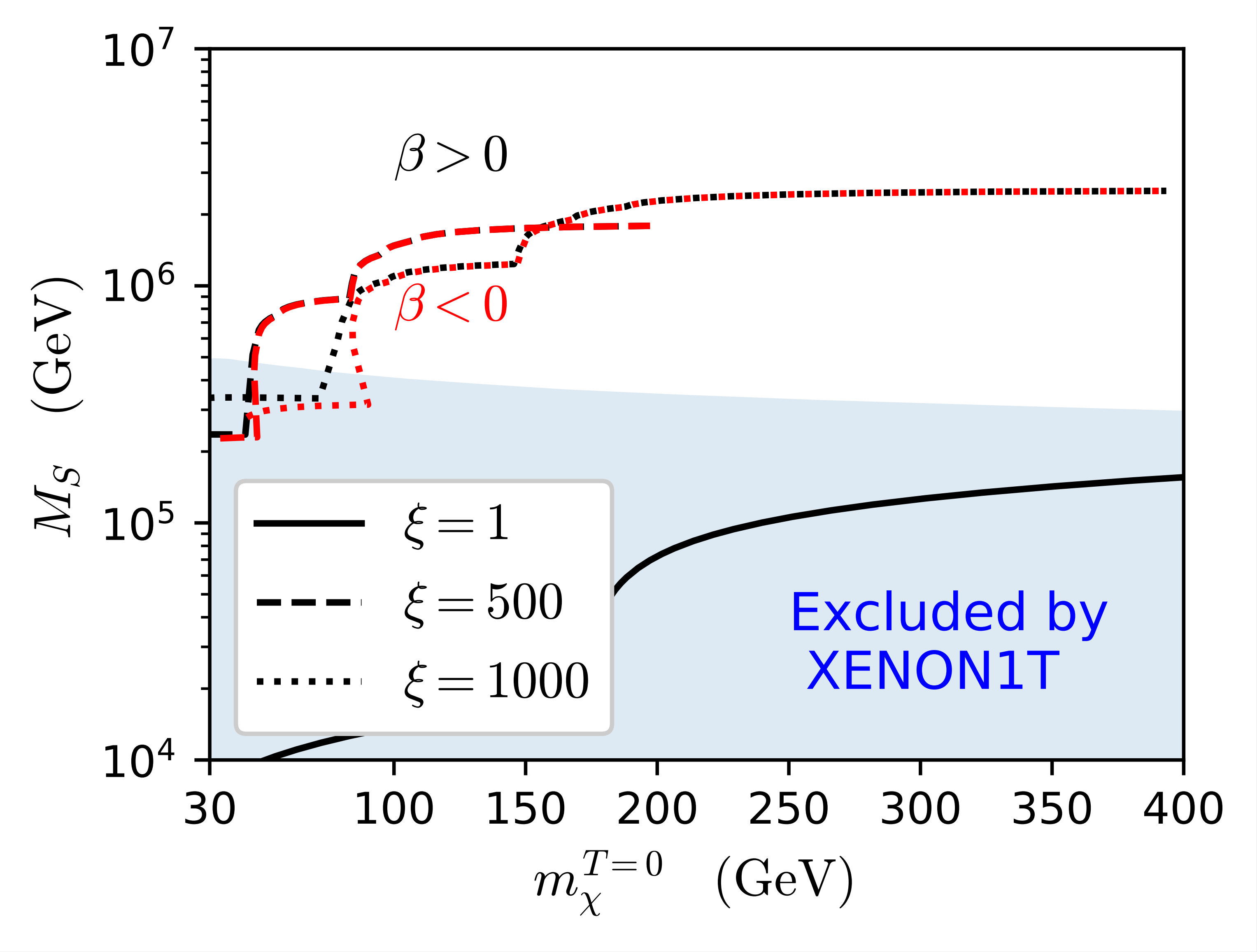


How about other gauge couplings?

S.A.R. Ellis, **SI**, G. White, *JHEP* 08 (2019) 002, *arXiv:1905.11994*

$$\mathscr{L} \supset \left(\frac{1}{g_Y^2} + \frac{\phi}{M_{\rm Pl}}\right) B^{\mu\nu} B_{\mu\nu} + \left(\frac{1}{g_2^2} + \frac{\phi}{M_{\rm Pl}}\right) W^{\mu\nu} W_{\mu\nu}$$





10^7
10^6
10^5
10^4
$\beta > 0$
$\beta < 0$
M_S (GeV)
$\xi = 1$
$\xi = 500$
$\xi = 1000$
Excluded by XENON1T
30
100
150
200
250
300
350
400
$m_\chi^{T=0}$ (GeV)