Electroweak phase transitions and other connections to cosmology

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- Outline

- Electroweak phase transition
  - Higgs potential at finite temperature
  - Cosmological ewsb in the standard model
  - How to make the phase transition strongly first order
  - Electroweak phase transition at future colliders
  - Complimentarity with GW and other searches
- Extra scalars and dark sectors
  - Higgs portal wimp
  - Long lived scalar particles
- Flavons in the early Universe

Higgs potential at finite temperature

$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

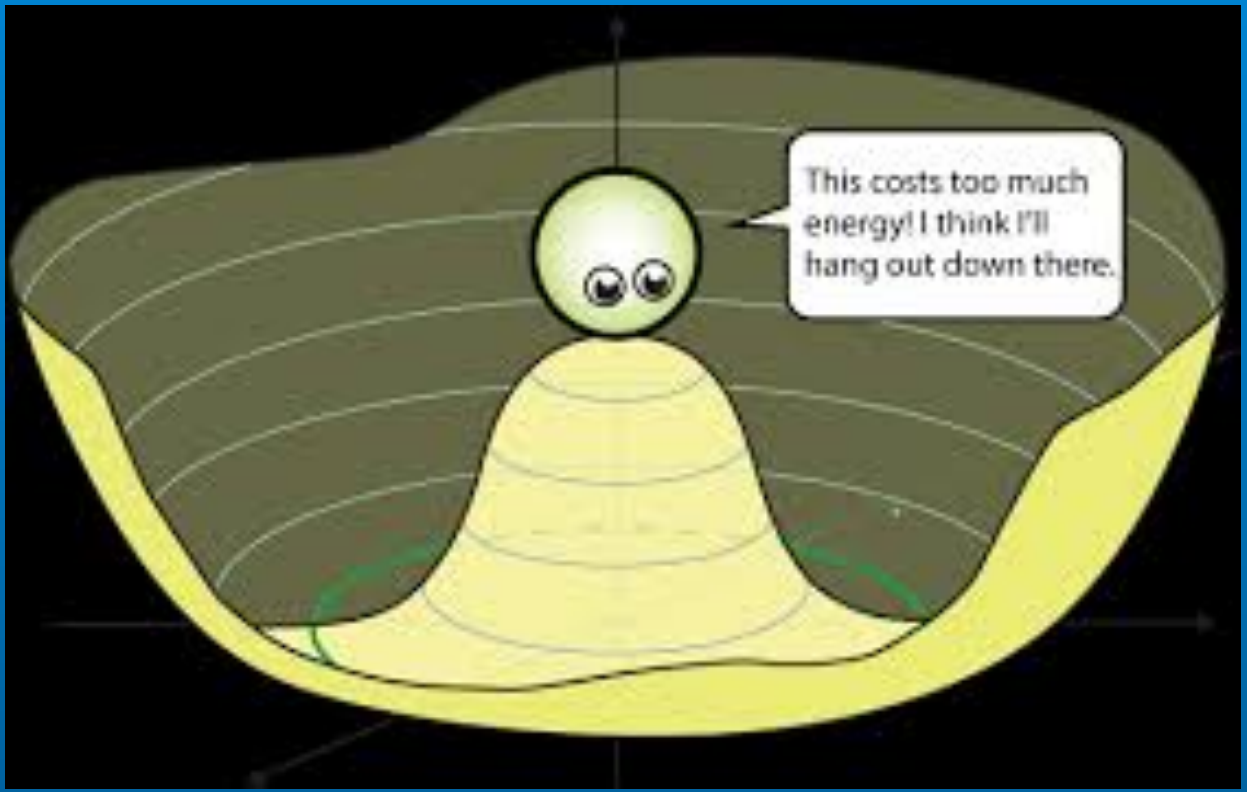


Image credit: Quantum Diaries

Higgs potential at finite temperature

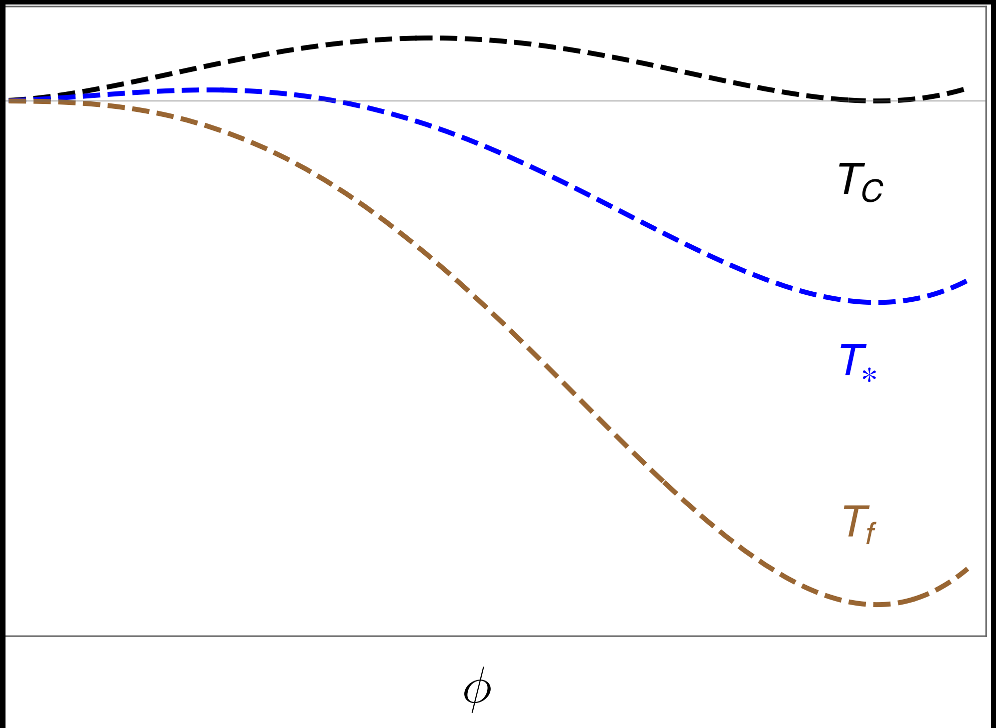
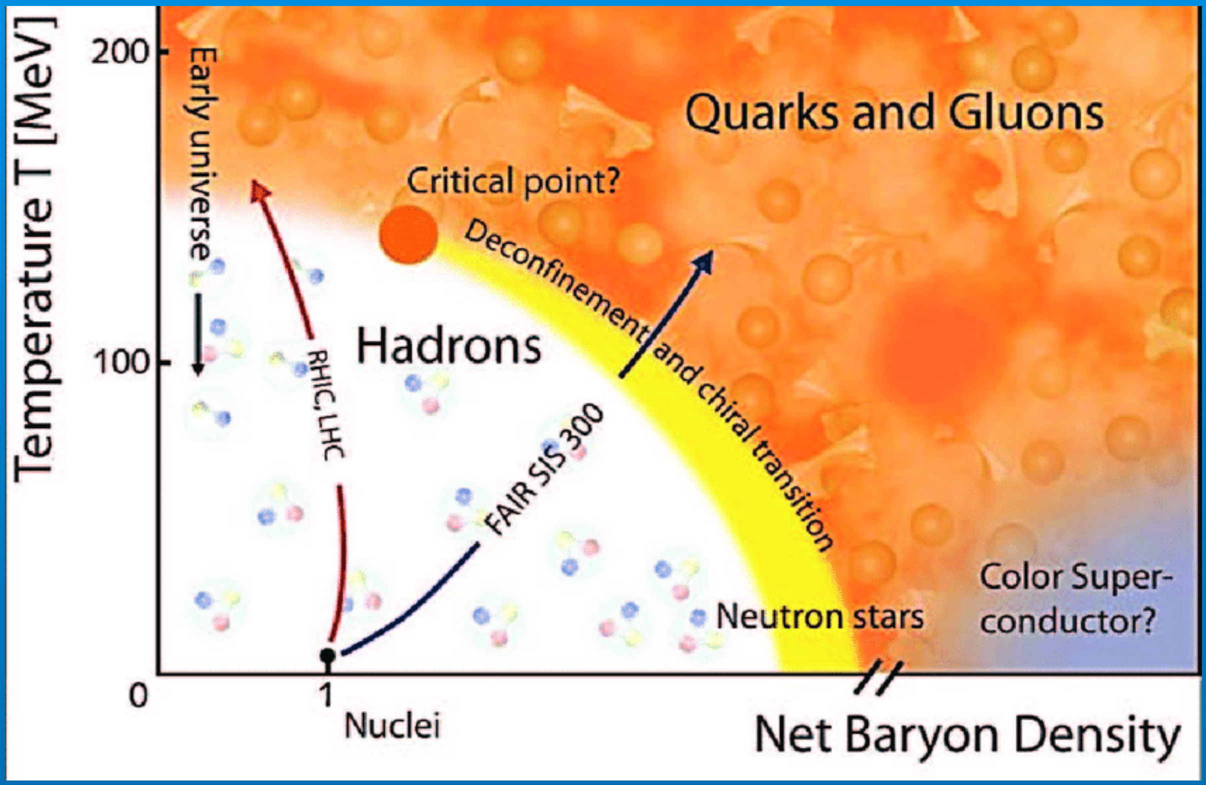
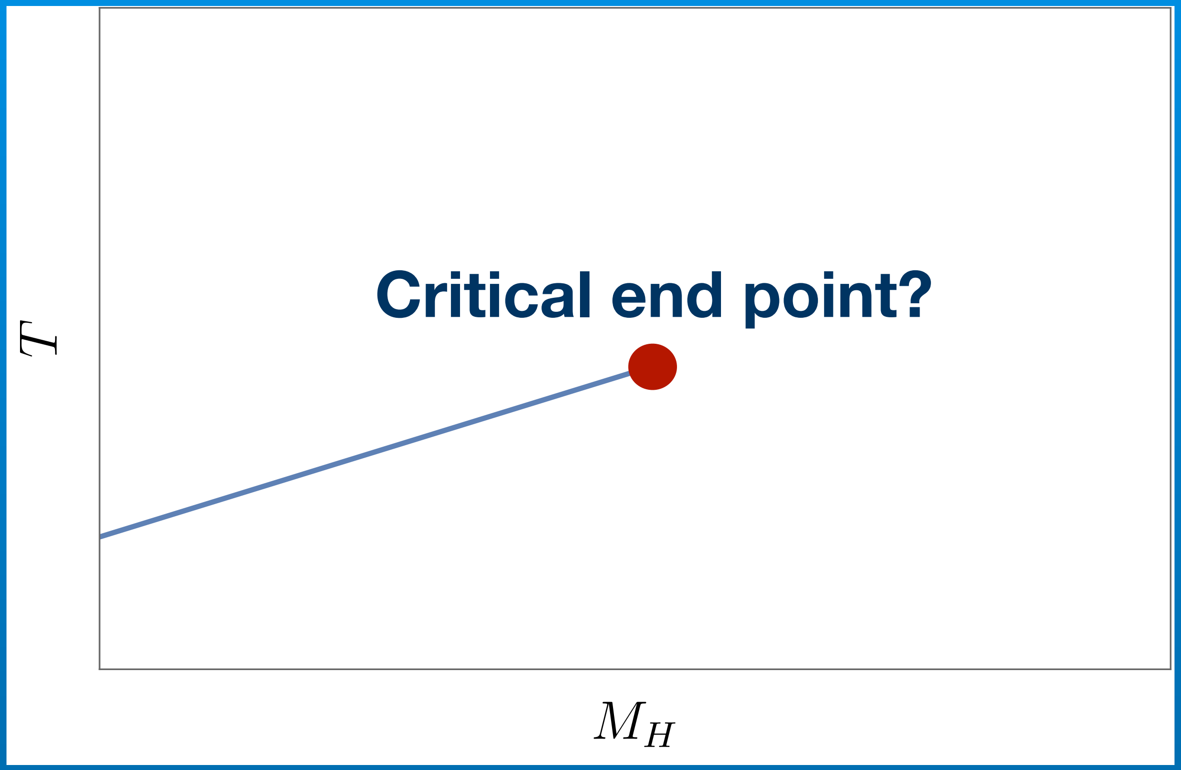


Image credit: Tim Dean

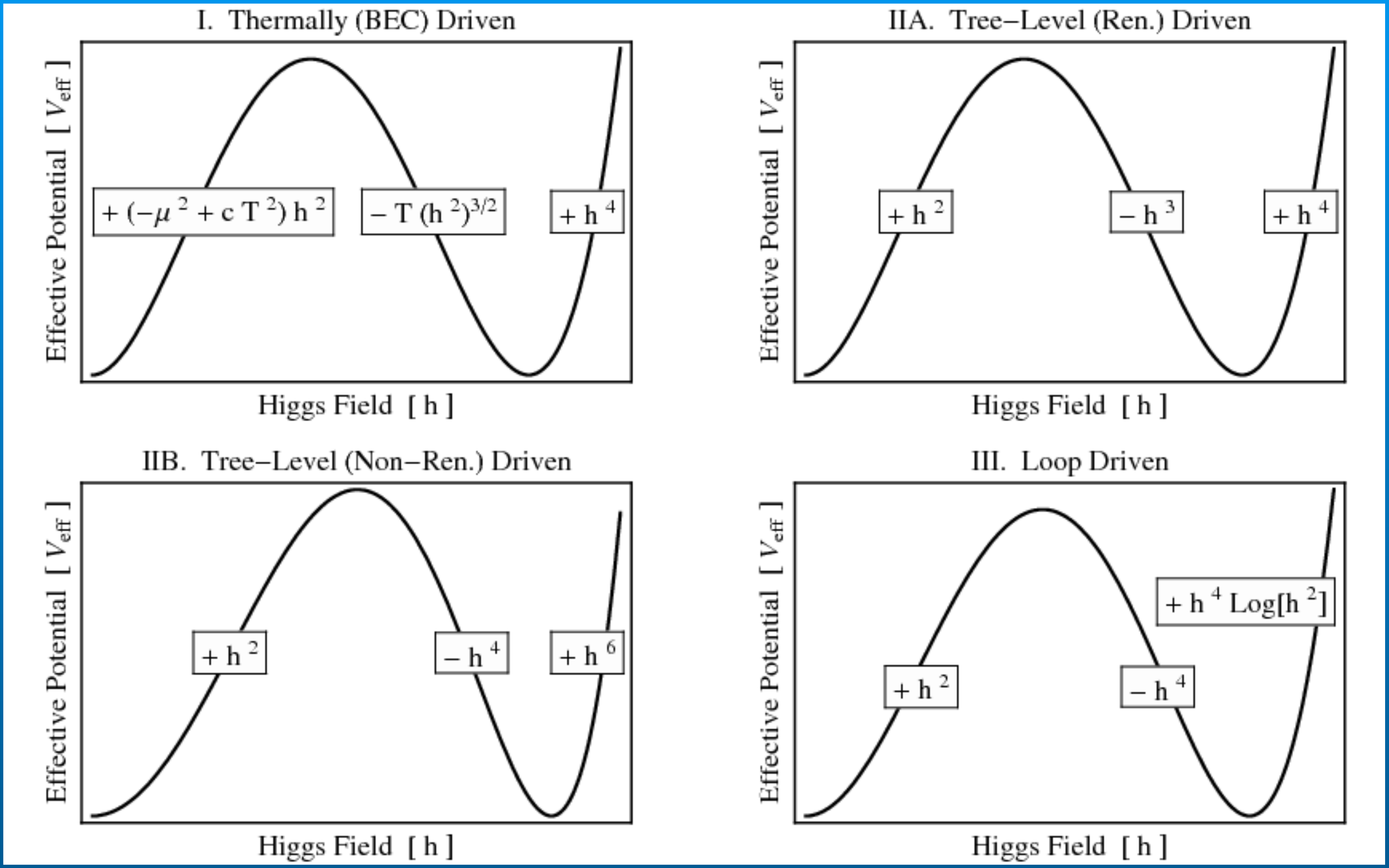
Cosmological electroweak symmetry breaking in the Standard Model





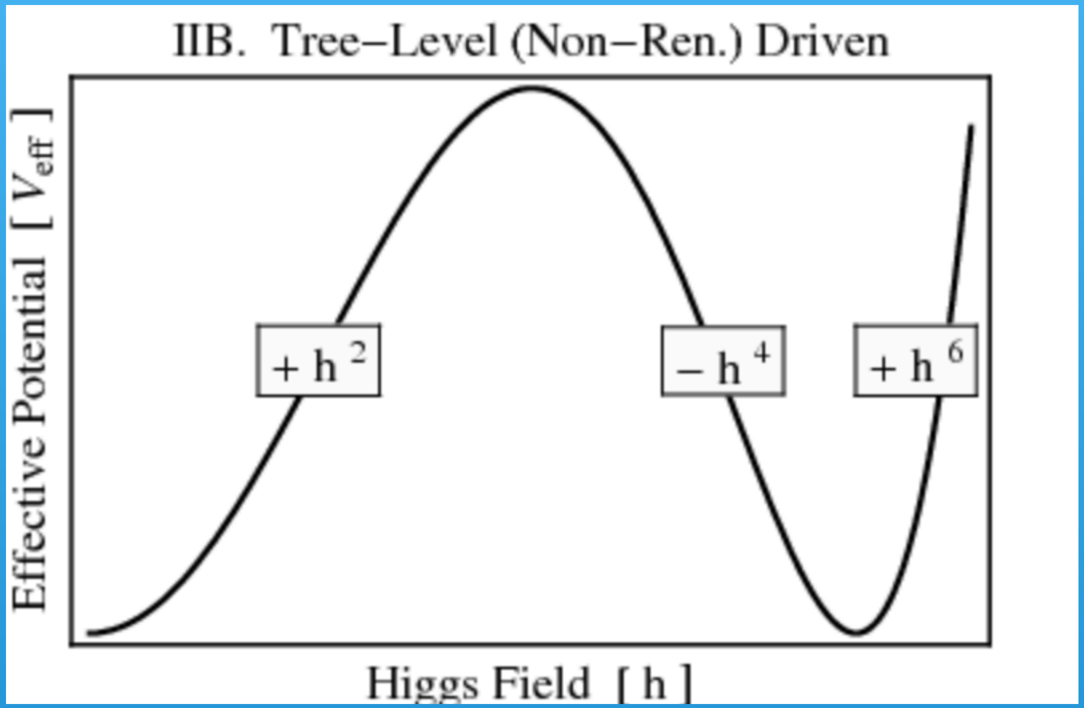
P. Bicudo, M. Cardoso, N. Cardoso 1102.5531

How to make the ewpt strongly first order



Daniel J. H. Chung, Andrew J. Long, Lian-Tao Wang 1209.1819

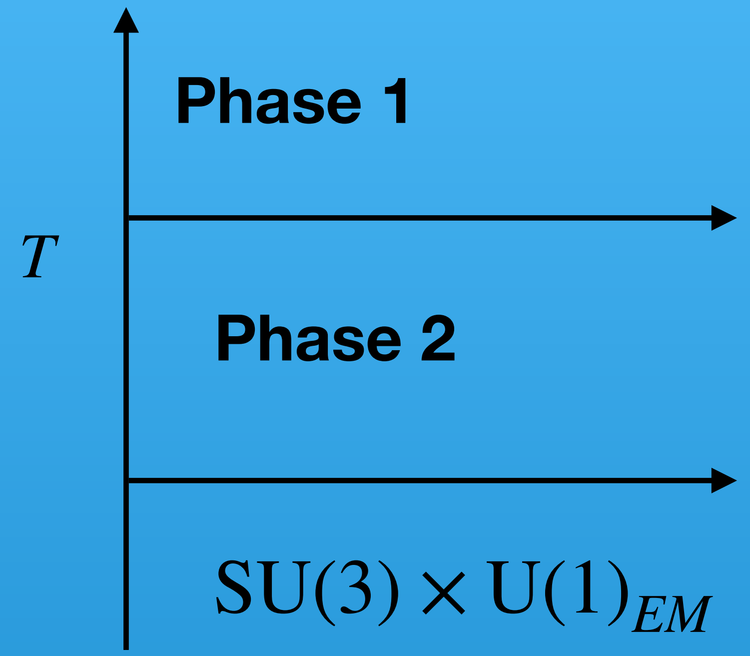
A caveat



Since the SM EWPT is a long way away (in parameter space) from a first order transition, SMEFT for the most part fails to accurately reproduce the result of a UV theory (see 2012.03953)

Another caveat

1) Phase transition can be multistep (1212.5652)



2) Can avoid electroweak symmetry ever being restored! (1807.07578)

Both options also require new particles (usually scalars) below ~1 TeV

Electroweak phase transition as a collider target

Big question: Can a future collider give a yes no answer on “was cosmological EWSB achieved through a first order phase transition?”

Electroweak phase transition as a collider target

Big question: Can a future collider give a yes no answer on "was cosmological EWSB achieved through a first order phase transition?"

Step 1 → Choose a scenario so hard to detect that if a collider can rule in/out a first order EWPT you can claim a detector can give a definitive answer on the nature of EWSB

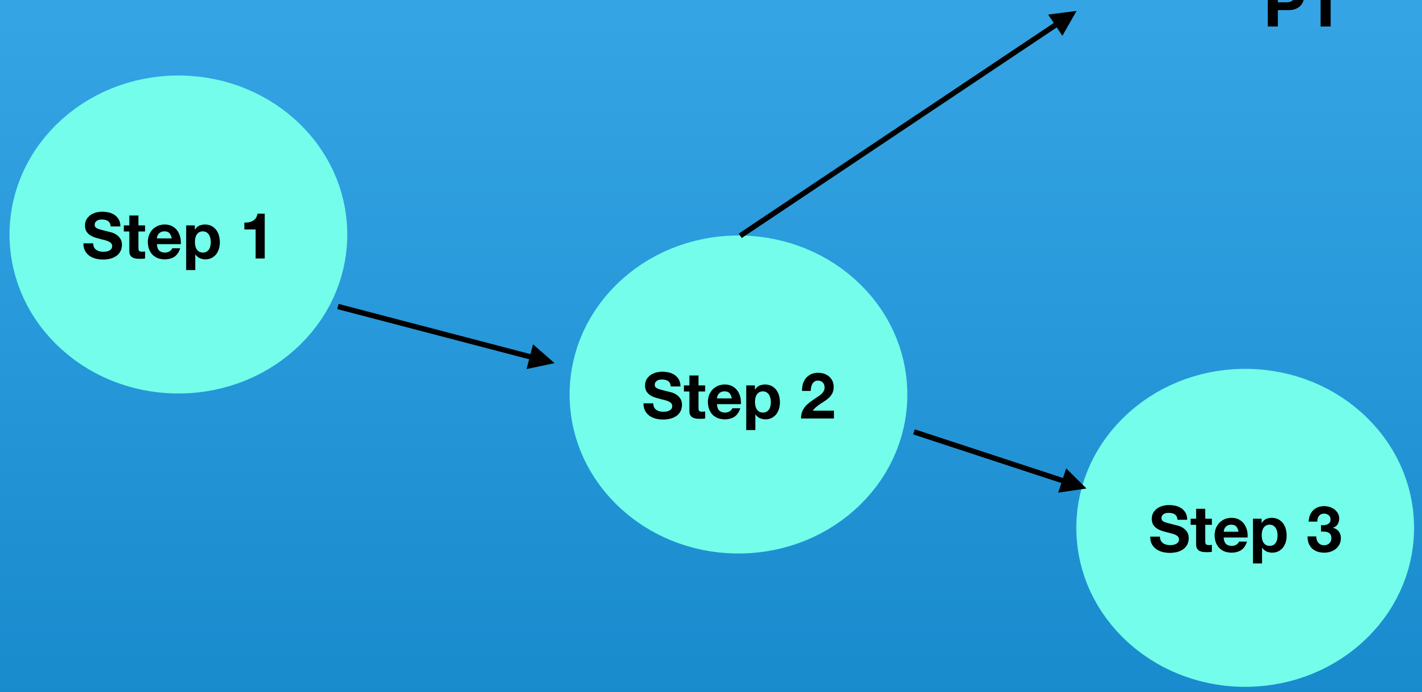
Step 1 → **Step 2** → **Step 3**

Nice review: 1912.07189

Electroweak phase transition as a collider target

Big question: Can a future collider give a yes no answer on "was cosmological EWSB achieved through a first order phase transition?"

Find all parameter points in the scenario that give a strong first order PT

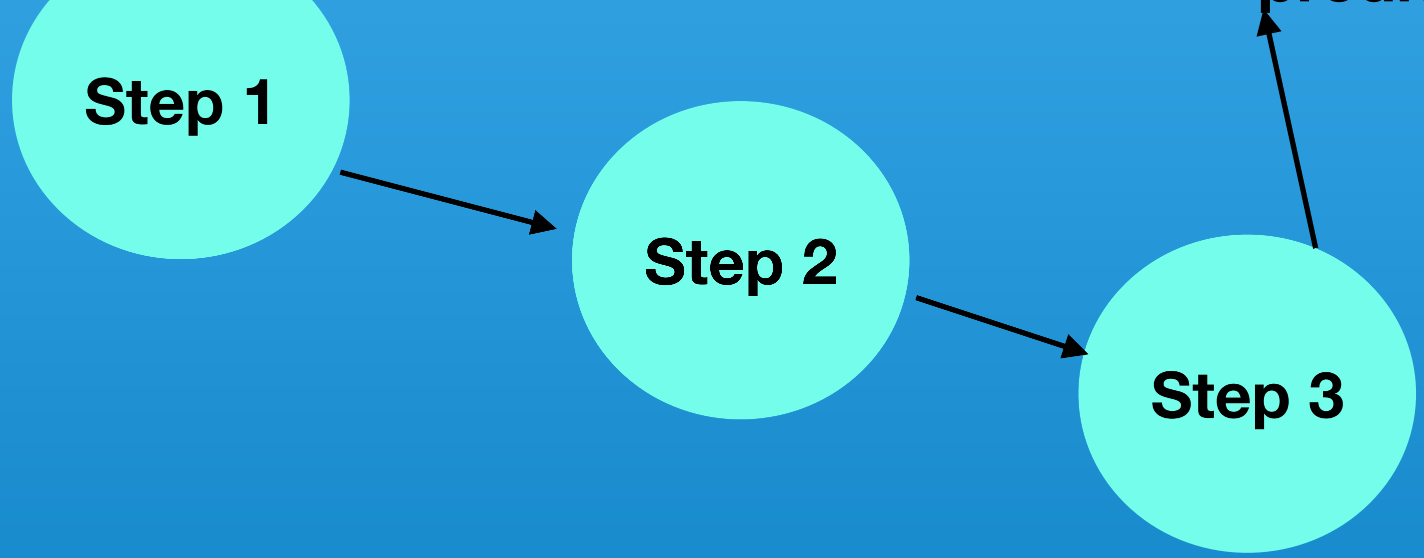


Nice review: 1912.07189

Electroweak phase transition as a collider target

Big question: Can a future collider give a yes no answer on “was cosmological EWSB achieved through a first order phase transition?”

Find what specifications a collider so that all parameter space that gives a strong first order phase transition results in a 5 sigma departure from SM predictions



Nice review: 1912.07189

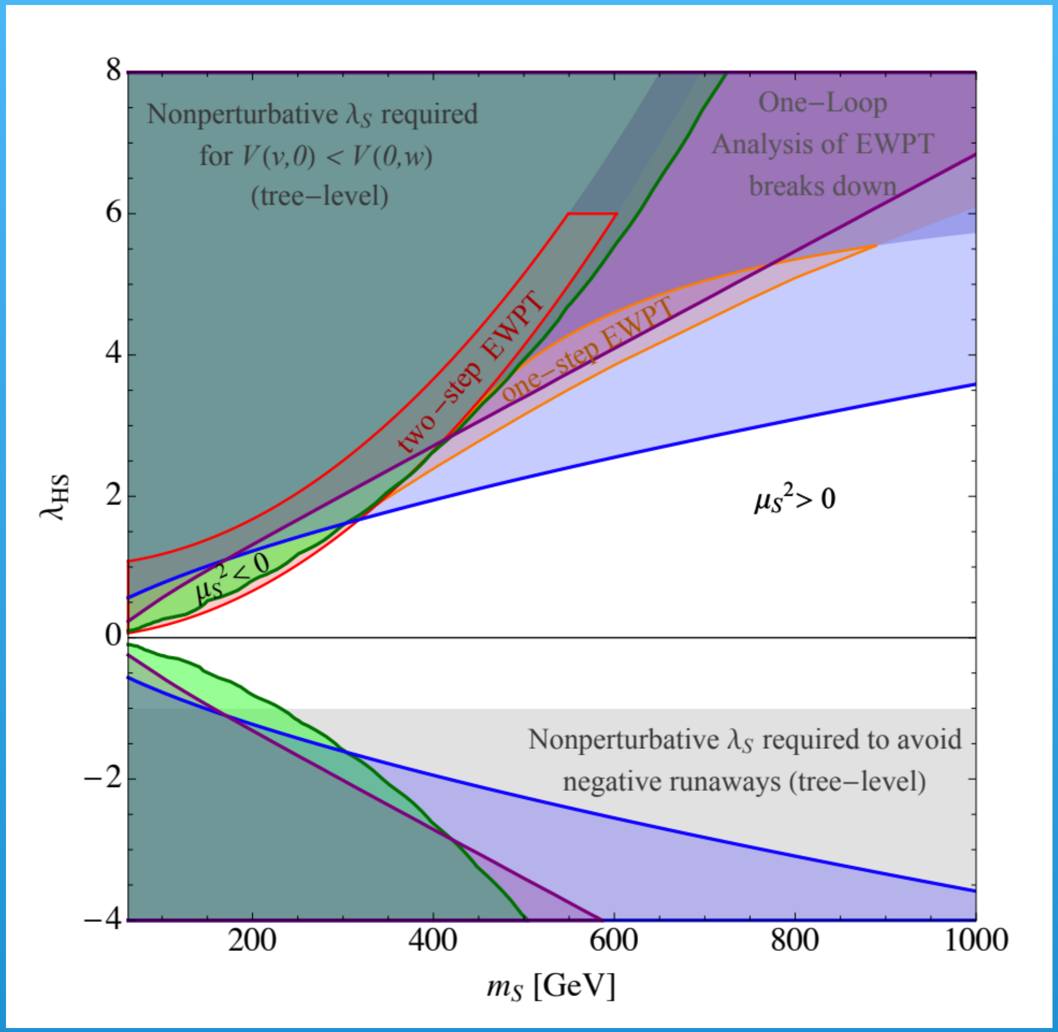
Choose your nightmare

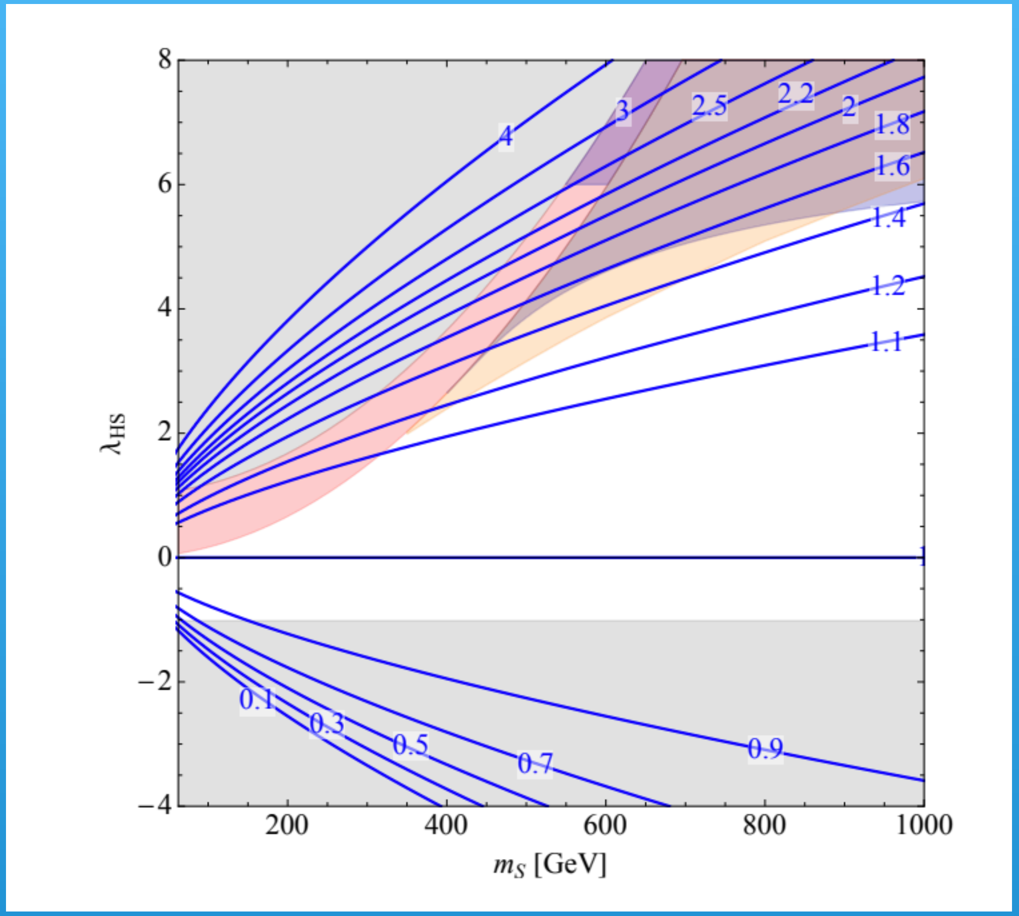
Step 1 → **Step 2** → **Step 3**

Nightmare 1 (1409.0005)

$$V_0 = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{4}\lambda_S S^4.$$

With $m_S > m_H/2$





$$\lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{hs}^3 v^3}{24\pi^2 m_s^2} \gtrsim 1.2$$

Requires 100 TeV collider at $3\mathrm{ab}^{-1}$ or a 1 TeV ILC with $1\mathrm{ab}^{-1}$

Choose your nightmare

Step 1

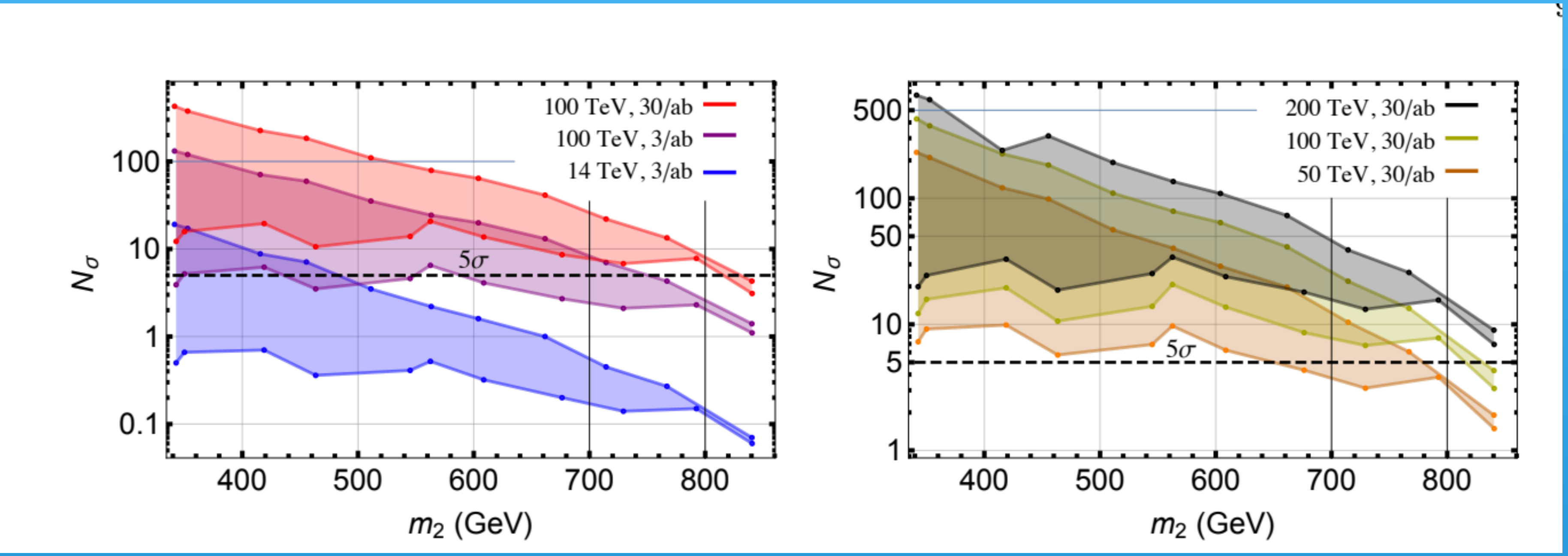
Step 2

Step 3

Nightmare 2 (1605.06123)

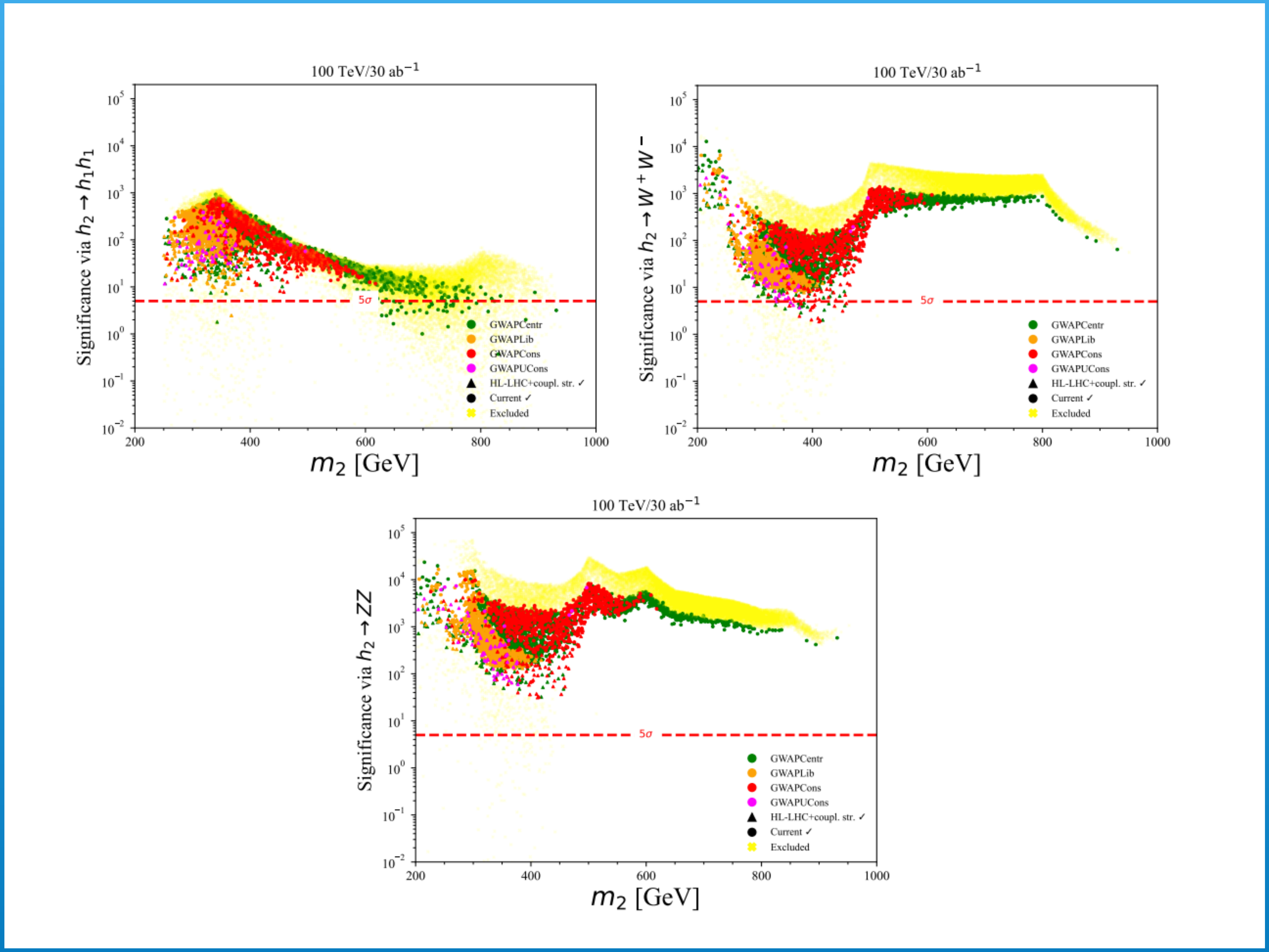
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4. \quad (2)$$

Dihiggs production



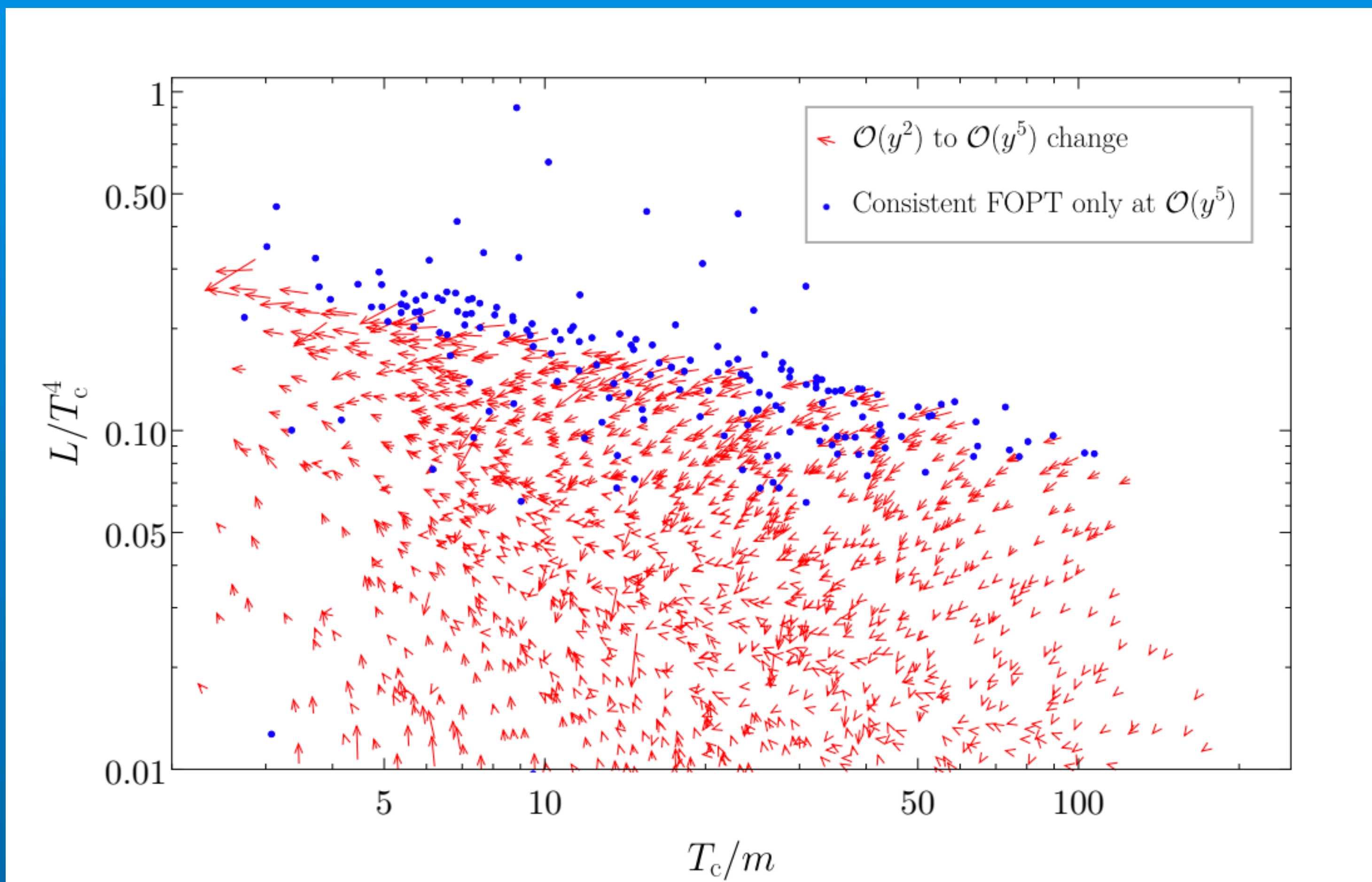
Some caveats

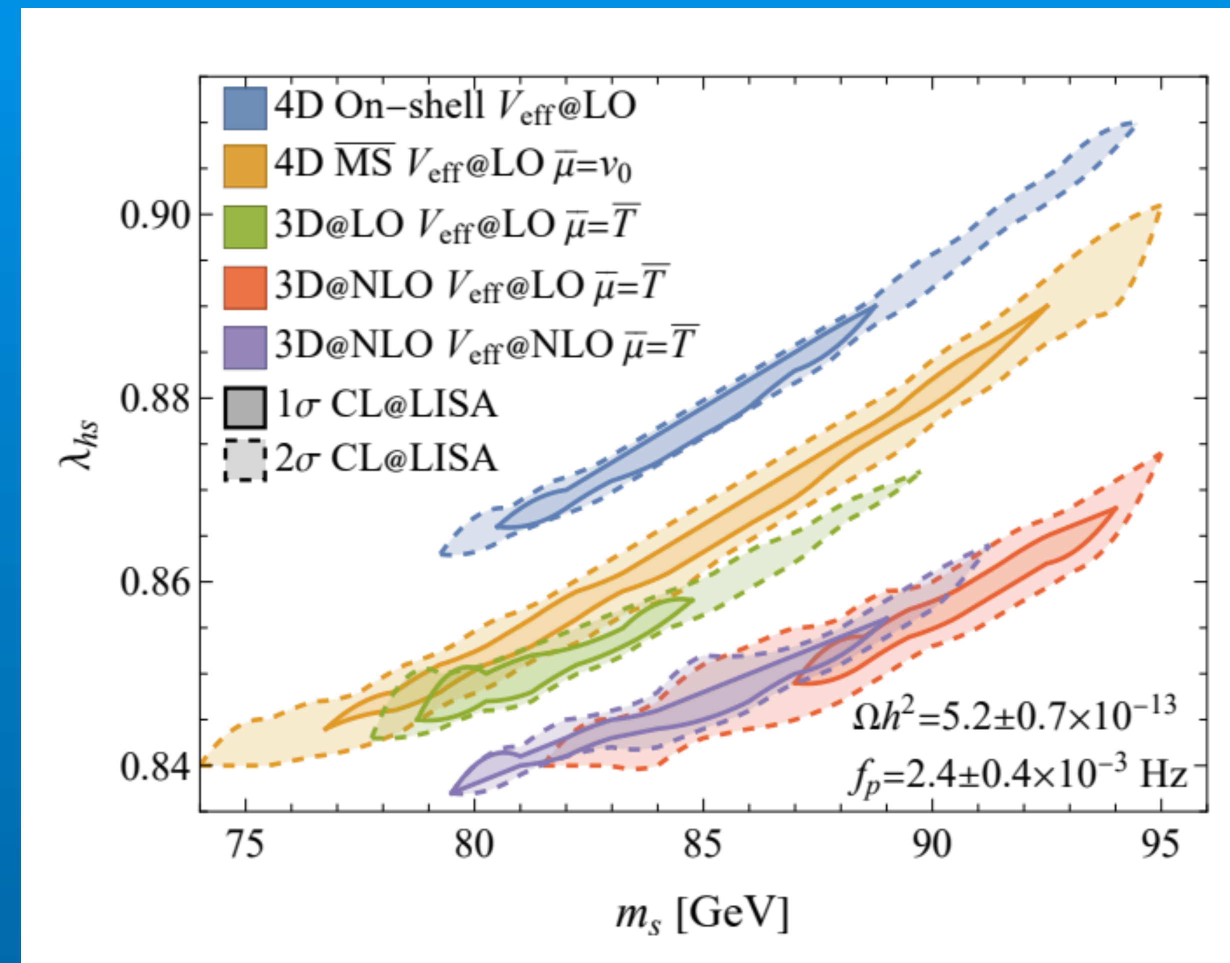
1) Theoretical uncertainties are huge
2) Other channels can dominate



2010.00597

Does the blob move?

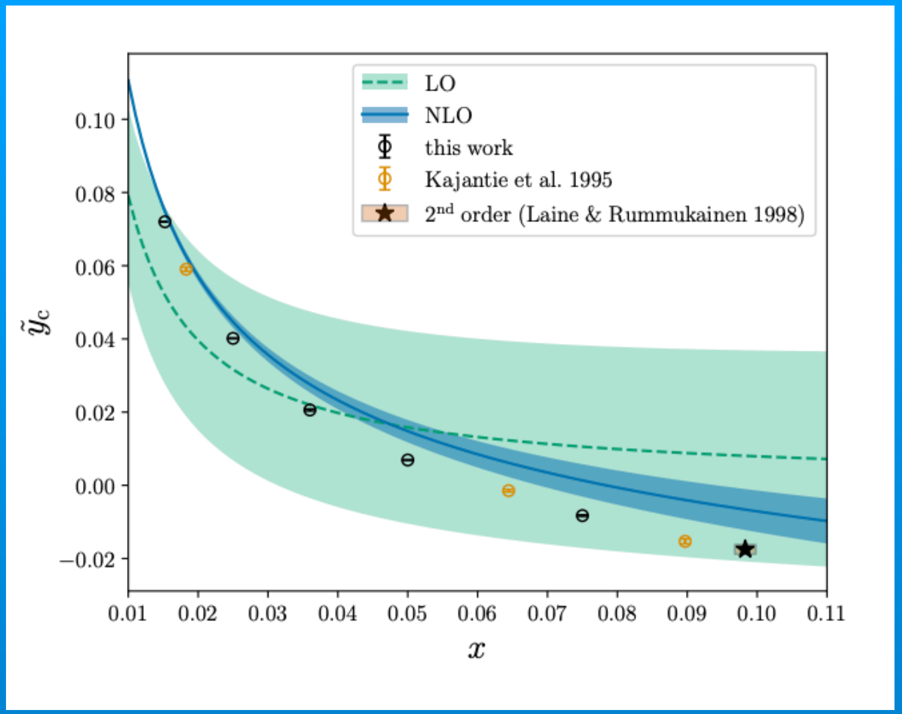


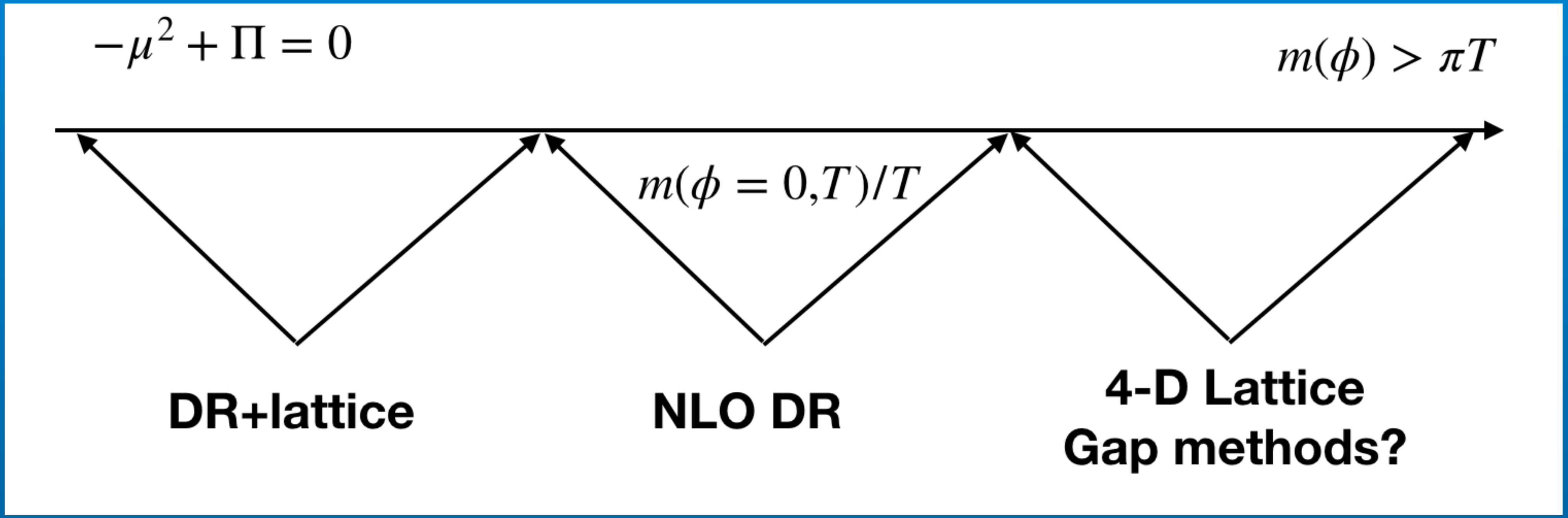


Gould Xie 2310.02308

Lewicki, Merchand, Sagunski, Schicho and Schmitt 2403.03769

Theoretical uncertainties are hard to deal with





Gould, Guyer, Rummukainen: 2205.07238

Sadly can’t just plug and chug

But DRALGO will let you handle the chunk of parameter space where the HT expansion is valid and PTs aren’t too weak

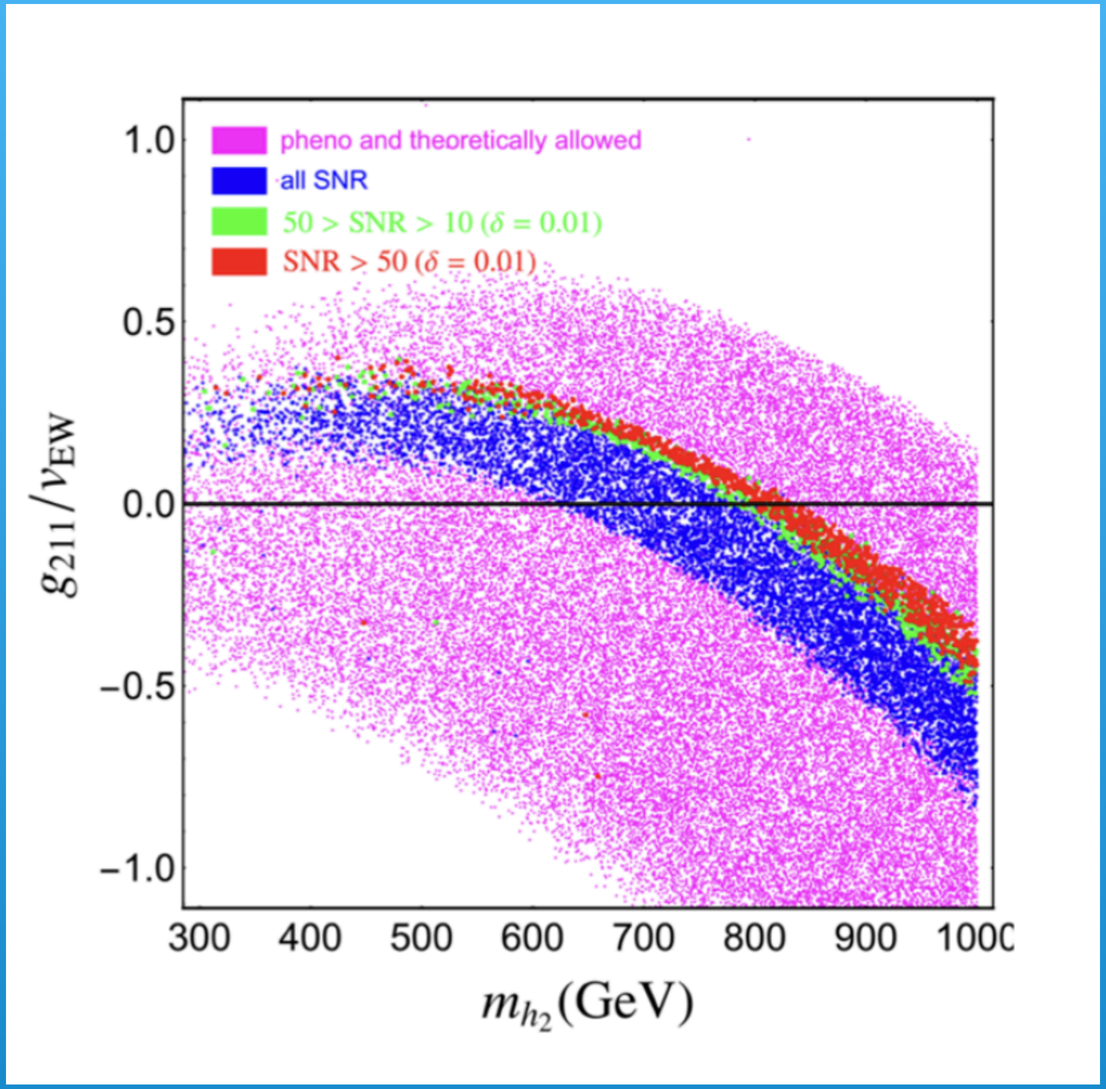
$$m_H(T_C, v = 0)/T_C > \epsilon, m_G(T_C, v = 0)/T_C > \epsilon$$

Some work to do:

1) Can you fake a signal of a SFOEWPT with a random scalar?
2) Can we beat down theoretical uncertainties?
3) Are we sure these two models are the worst case scenarios? How do we know 2 singlet scalars have harder to reach parts of the parameter space
4) What is the complimentarity with other experiments (e.g. gravitational waves, W-mass?)

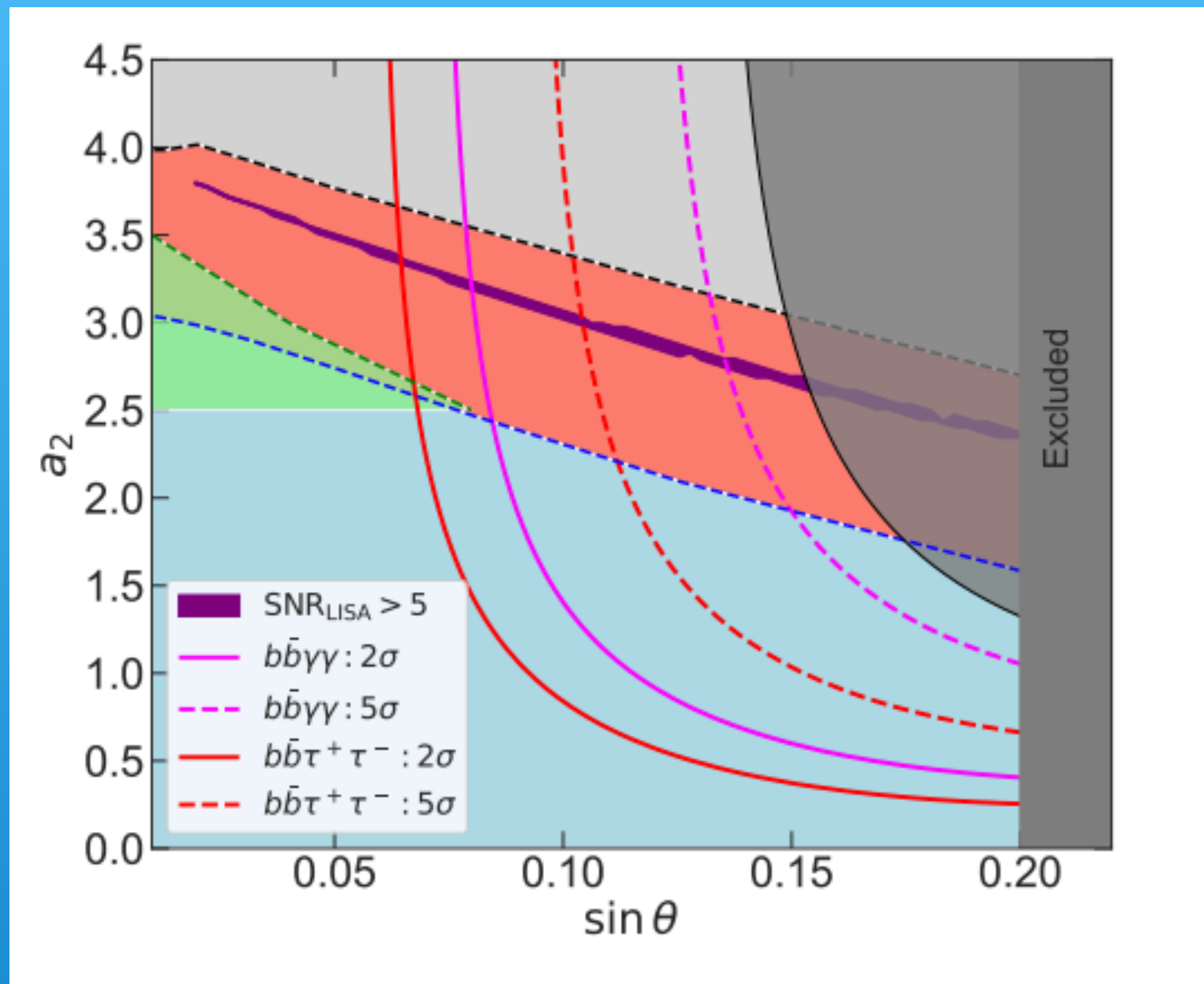
Complimentarity 1 - Gravitational waves

Colliders can find it hard to see when $g_{211} \to 0$ (h2,h1,h1 effective coupling)



2007.15654

Complimentarity 1 - Gravitational waves

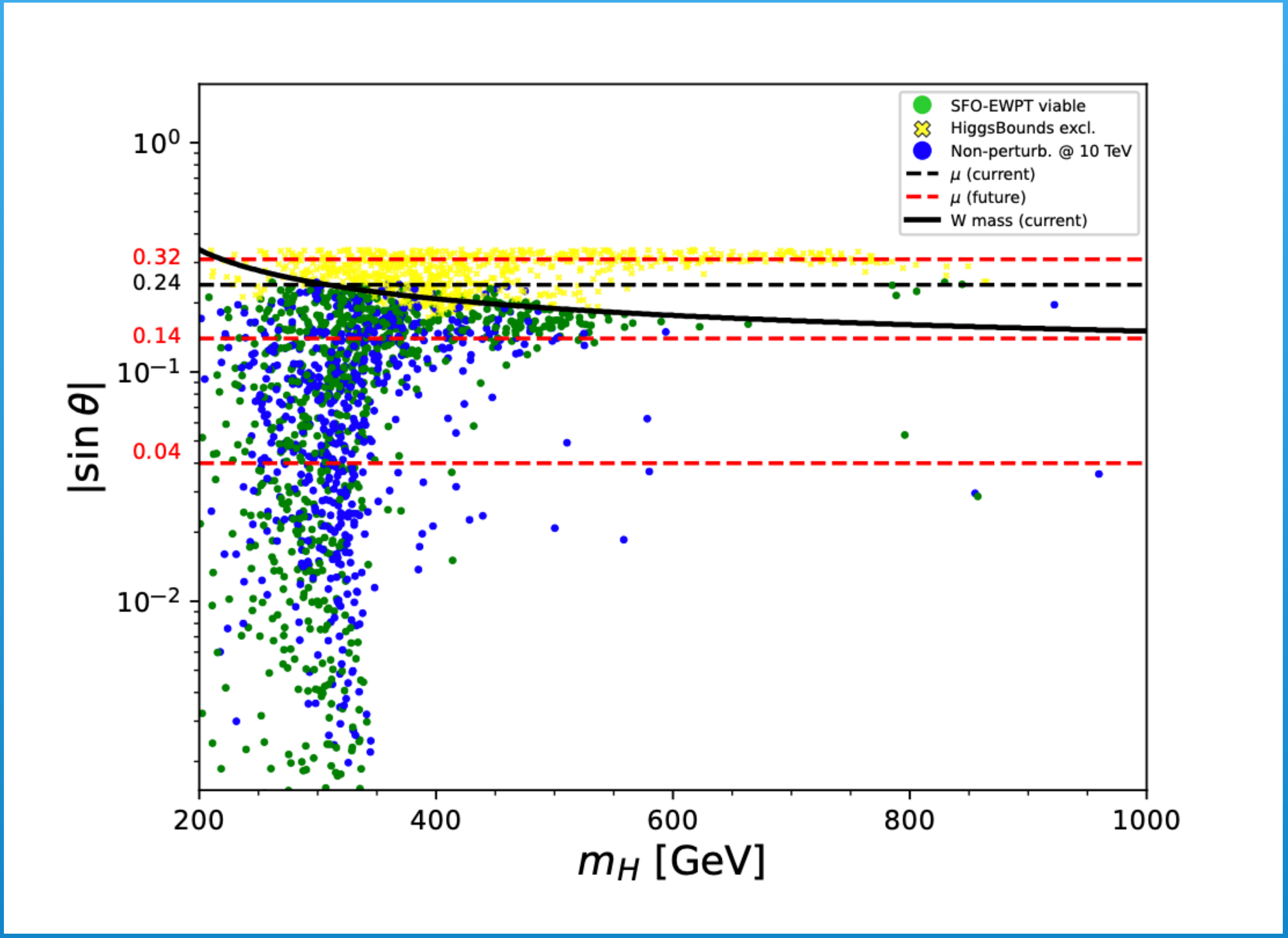


HL-LHC

$$V_0 = \frac{1}{2}\bar{\mu}_3^2\bar{v}^2 + \frac{1}{4}\bar{\lambda}_3\bar{v}^4 + \frac{1}{4}\bar{a}_{1,3}\bar{v}^2\bar{s} + \frac{1}{4}\bar{a}_{2,3}\bar{v}^2\bar{s}^2 + \bar{b}_{1,3}\bar{s} + \frac{1}{2}\bar{b}_{2,3}\bar{s}^2 + \frac{1}{3}\bar{b}_{3,3}\bar{s}^3 + \frac{1}{4}\bar{b}_{4,3}\bar{s}^4$$

2409.17554

Complimentarity 2: W mass and electroweak precision



2205.14379

Summary part 1:

- New scalars can change the nature of cosmological electroweak symmetry breaking
- These scalars tend to need to be sub TeV
- This makes the nature of electroweak symmetry breaking a great collider target
- Surveying “nightmare scenarios” suggests that an first order EWPT can at least be falsified at next generation colliders
- There is still a lot of work to be done to see if next generation colliders can give a definitive answer on the nature of cosmological EWSB
- There is plenty of complimentarity between searches for final states at colliders and other means of detection (W mass, gravitational waves etc)

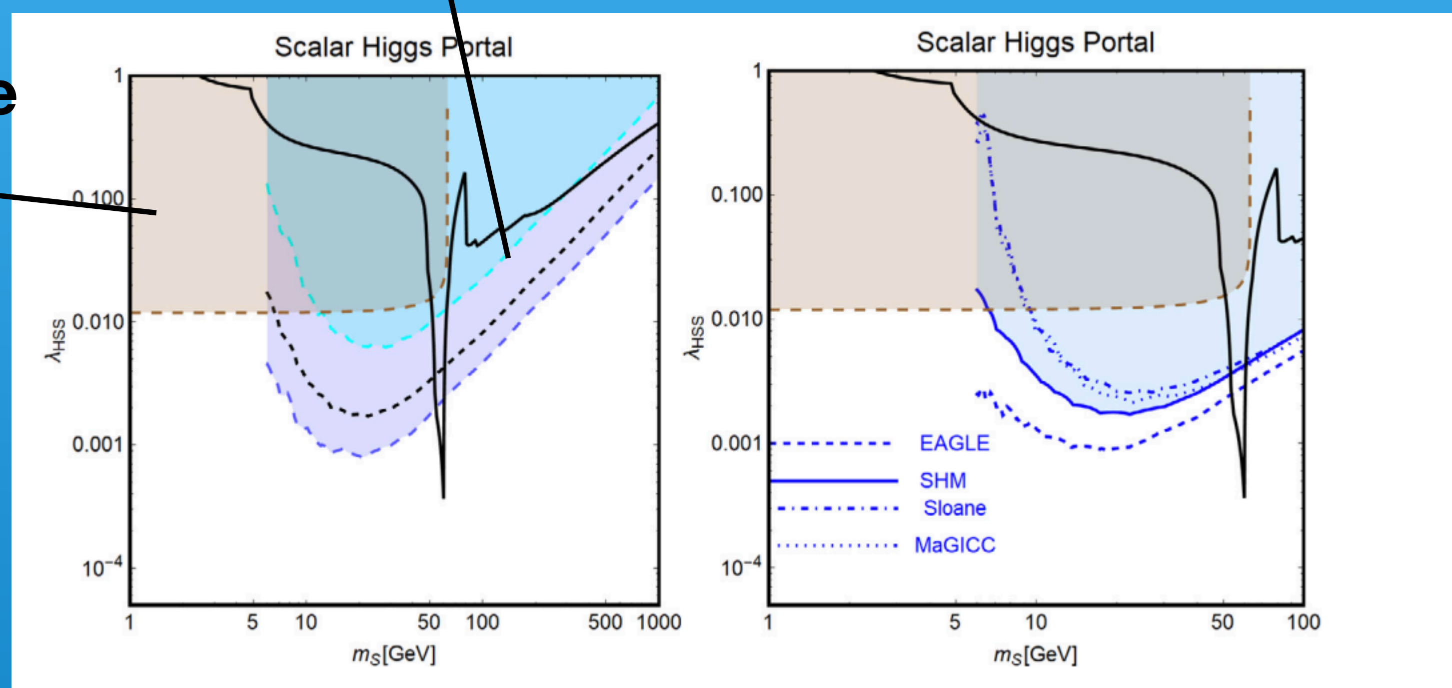
Part 2 scalars and hidden sectors

Higgs portal Dark matter

Current Xenon 1T bounds

$$\lambda_{HSS} H^2 S^2$$

Higgs->invisible

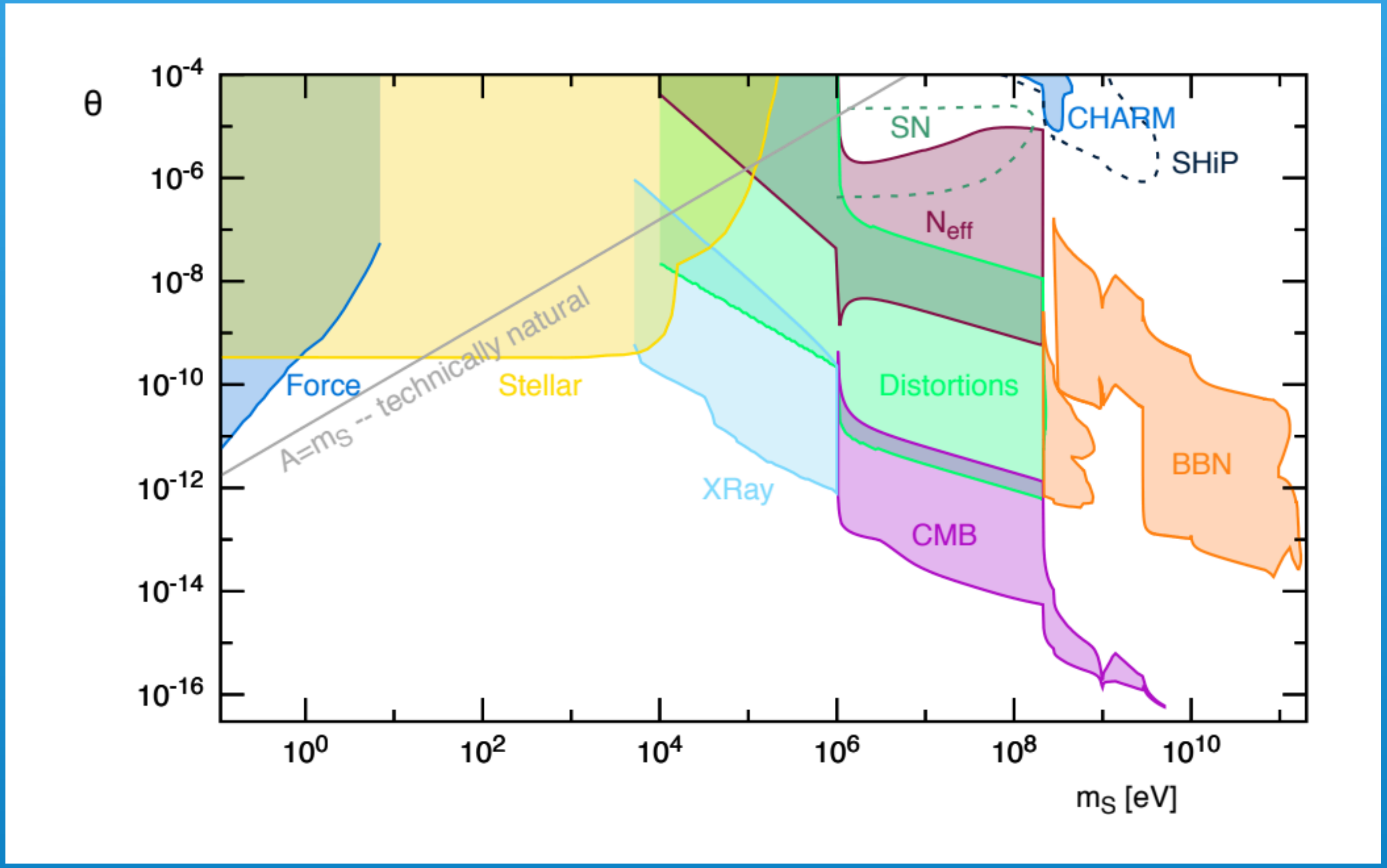


1903.03616

Cosmological consequences of long lived scalar particles

If a scalar field mixes with the Higgs, it can release EM radiation which can mess up BBN or reionize the Universe and mess up the CMB

$$\mathcal{L}_{H/S} \supset \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - \frac{1}{2} m_S^2 S^2 - A S H^\dagger H.$$



1812.07585

Part 3: cosmological evolution of SM parameters

Basic idea with wide application, modify y where y is some SM coupling, by making it field dependent

$$y \to y_0 + \frac{\phi(t)}{\Lambda}$$

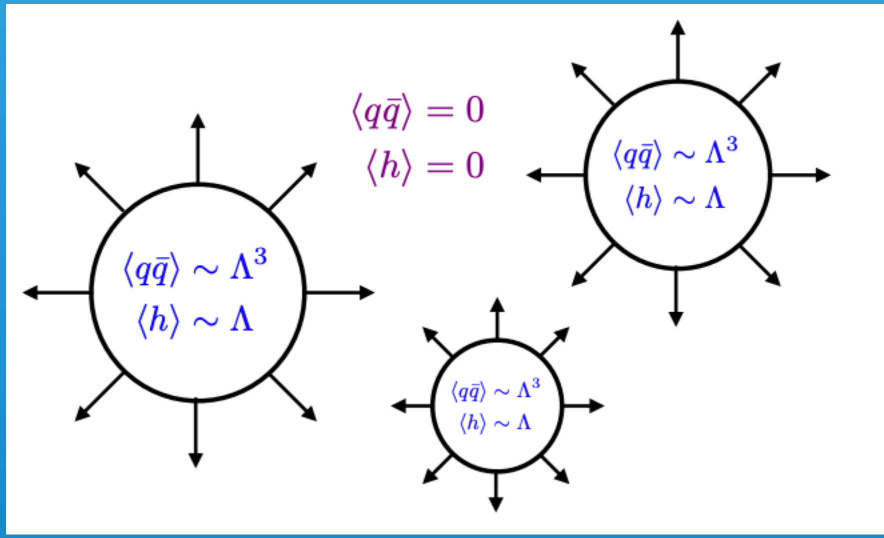
Will focus on the cosmology not the pheno

A prominent recent idea was to modify the strong coupling

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{1}{g_{s0}^2} + \frac{\phi}{M_*}\right) G_{\mu\nu}G^{\mu\nu},$$

1811.00559

One can then have the QCD transition occur above the scale of EWSB, which means the transition will be first order



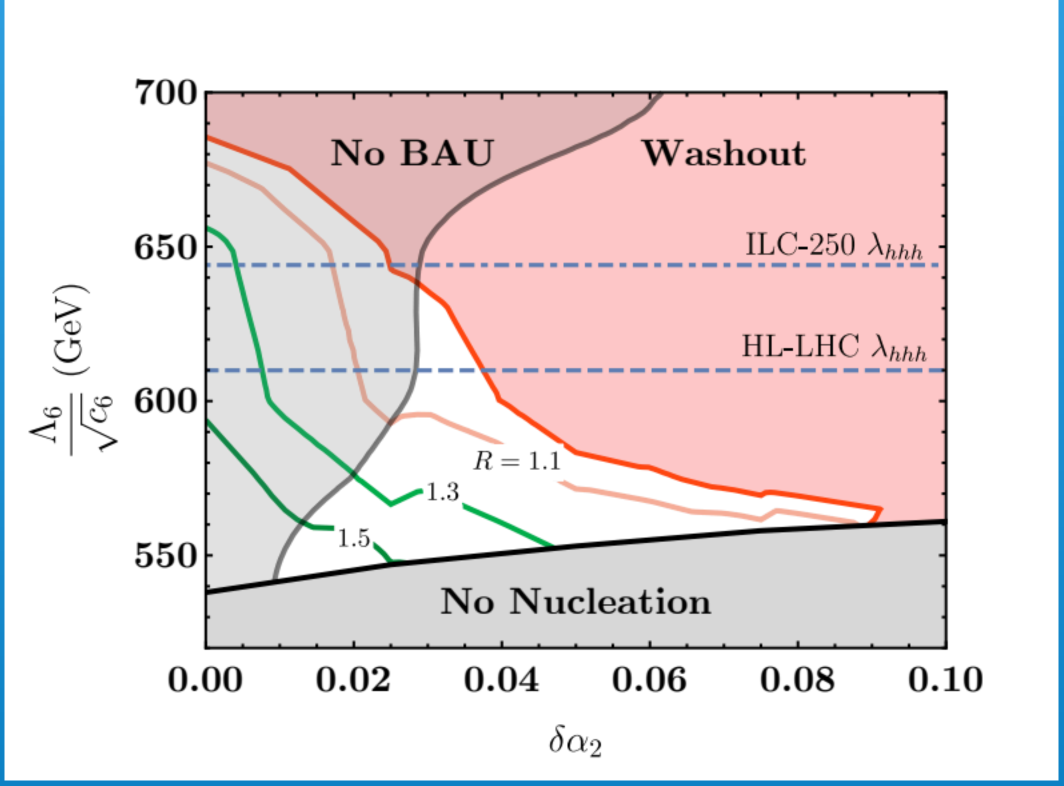
Another possibility is to do electroweak baryogenesis with modified sphaleron rates

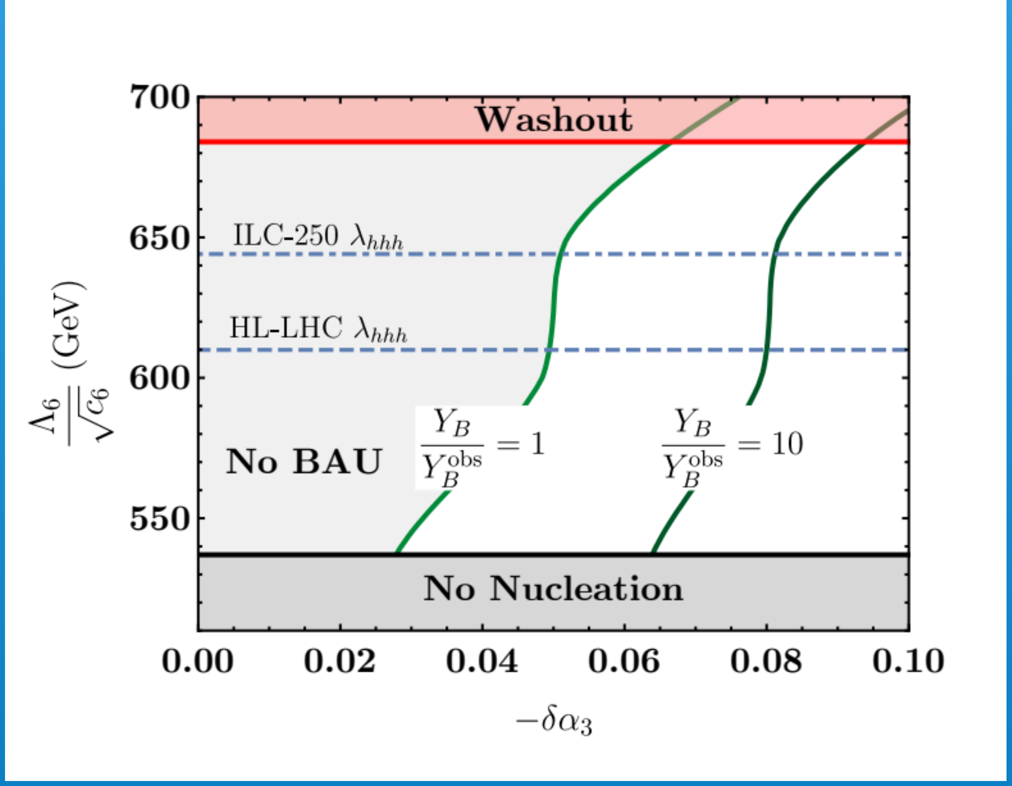
$$\mathcal{L} \supset -\frac{1}{4g_Y^2}\left(1-\frac{c_{g_Y}\varphi_Y}{\Lambda_Y}\right)B^{\mu\nu}B_{\mu\nu} - \frac{1}{4g_2^2}\left(1-\frac{c_{g_2}\varphi_2}{\Lambda_2}\right)W^{\mu\nu,a}W^a_{\mu\nu}$$
$$-\frac{1}{4g_3^2}\left(1-\frac{c_{g_3}\varphi_3}{\Lambda_3}\right)G^{\mu\nu,A}G^A_{\mu\nu} - V_{SM}(H) - \frac{c_6}{\Lambda_6^2}|H|^6 + \frac{\delta_{CPV}}{\Lambda_{\rm CPV}^2}\bar{Q}_L\tilde{H}t_R|H|^2, \qquad (2.1)$$

$$\Gamma_{\rm WS} \simeq 120\,\alpha_2^5\,T \quad \text{and} \quad \Gamma_{\rm SS} \simeq 132\,\alpha_3^5\,T\ .$$

$$\frac{1}{g_{i,\rm eff}^2} \equiv \frac{1}{g_i^2}\left(1-\frac{c_{g_i}\varphi_i}{\Lambda_i}\right).$$

$$\delta\alpha_i = (\alpha_{i,\rm eff} - \alpha_{i,\rm SM})|_{T=T_{\rm EW}}\ .$$



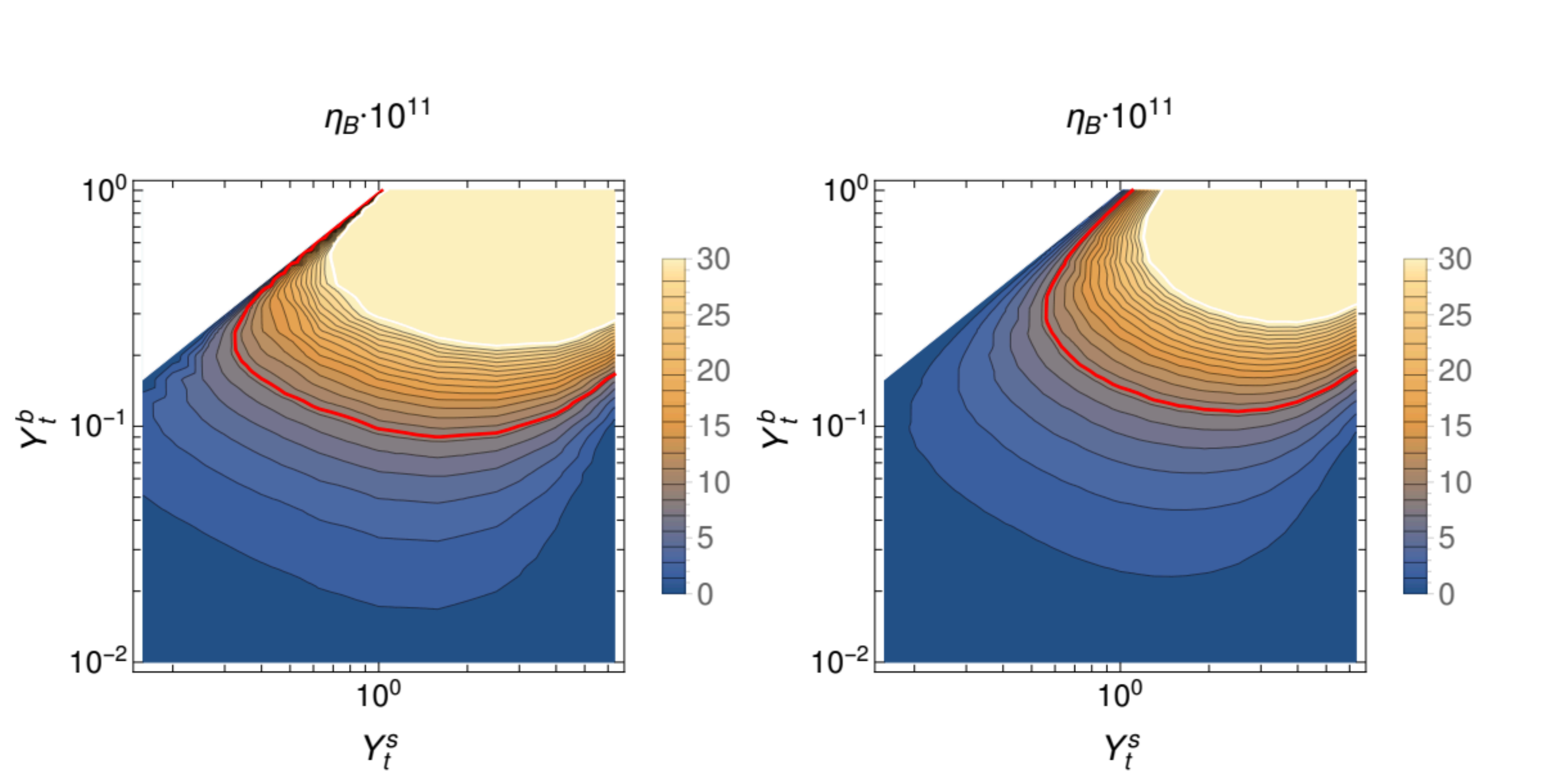


1905.11994

Electroweak baryogenesis with a varying top Yukawa

$$Y_t(z) = Y_c + Y_v(z)e^{i\theta} \quad \text{where} \quad Y_v(z) = Y_v^b + (Y_v^s - Y_v^b)\left[1 - \frac{\phi(z)}{v}\right]$$

Varying just the top Yukawa:



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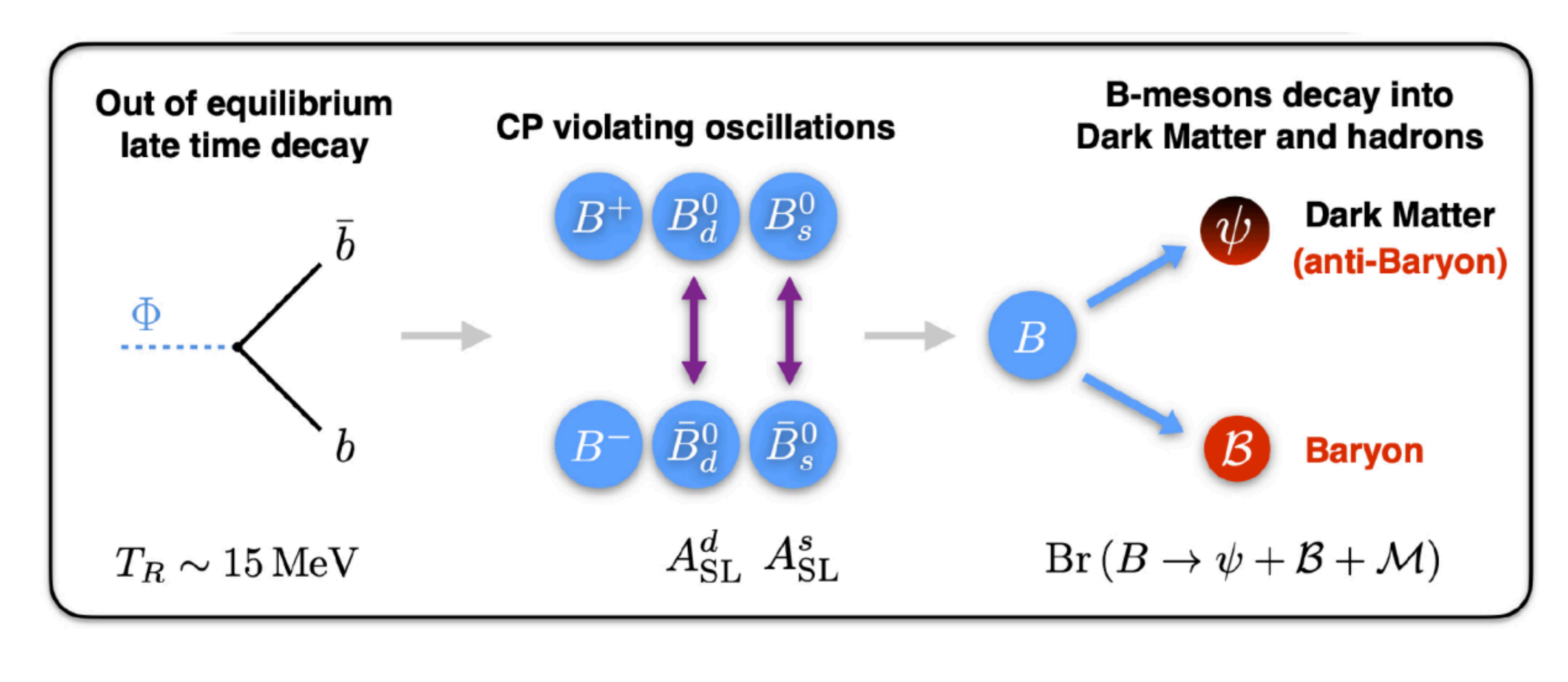
Can do mesogenesis with SM quark masses



2101.02706,1810.00880

Can do mesogenesis with SM quark masses

Can be achieved by a triplet scalar field

$$\mathcal{L}_{\mathcal{Y}} = -\sum_{i,j} y_{u_i d_j} \mathcal{Y}^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} \bar{\psi}_{\mathcal{B}} \mathcal{Y} d^c_{kR} + \text{h.c.} \quad (2)$$

Mesogenesis predicts a baryon asymmetry of the size

$$Y_{\mathcal{B}} \simeq 5 \times 10^{-5} \sum_{i=d,s} \left[\text{Br}\left(B_i^0 \to \bar{\psi}_{\mathcal{B}}\, \mathcal{B}_{\text{SM}}\right) A^i_{sl}\right] \alpha_i(T_d)\,,$$

Which is too small with SM parameters

$$A^d_{sl}|_{\text{SM}} = (-4.7 \pm 0.4) \times 10^{-4}\,,$$
$$A^s_{sl}|_{\text{SM}} = (2.1 \pm 0.2) \times 10^{-5}\,.$$

$$\text{Br}(B_i^0 \to \bar{\psi}_B B_{\text{SM}}) \lesssim 3 \times 10^{-5}$$

The branching ratio is sensitive to the mass of $\mathscr{Y}$, so if it was different in the early Universe, the branching ratio can be enhanced by a factor of $\left(\frac{m_{\mathscr{Y}_f}}{m_{\mathscr{Y}_i}}\right)^4$

Meaning that one can generate the baryon asymmetry of the Universe with SM CP violation

2408.12647

Conclusion

Plenty of applications for extended scalar sectors.
Focusing on theories with low energy consequences I have talked about the three main consequences of extended scalars

1) **modifying the nature of cosmological electroweak symmetry**
2) **a candidate in a hidden sector**
3) **Modifying the cosmic history of SM coupling constants and masses**

Much of the work to be done is on understanding the consequences of future experiments on cosmologically interesting new scalar fields