EPFL

Electroweak Baryogenesis without Electric Dipole Moments

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Based on the work with:

Irwan Le Dorze, Riccardo Rattazzi & Stefan Stelzl

Baryon Asymmetry of Universe

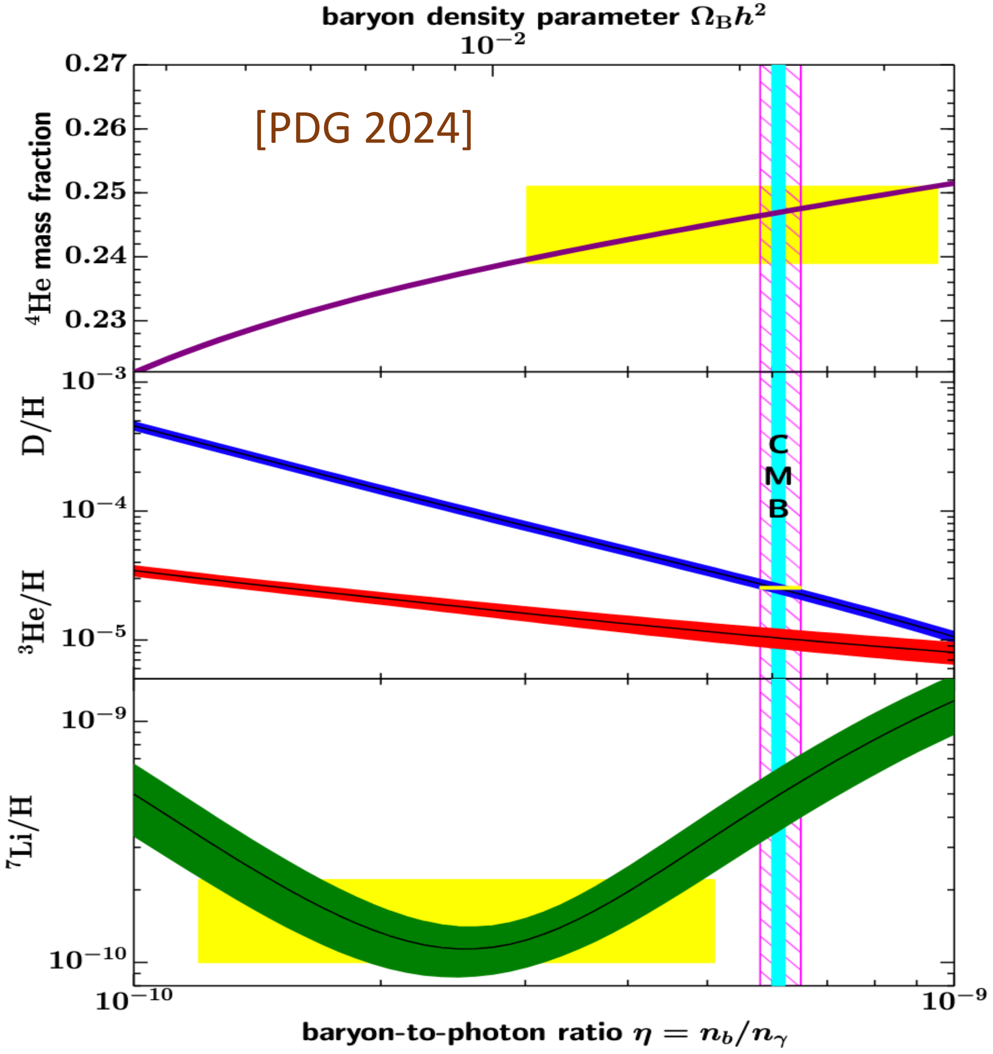
- From CMB:

$$\Omega_B h^2 = 0.02237 \pm 0.00015$$

- From BBN: Abundance of light elements depends on $\frac{n_B}{n_\gamma}$

$$\frac{n_B}{n_\gamma} \approx (6.04 \pm 0.2)\times 10^{-10}$$

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} \approx 8\times 10^{-11}$$



Electroweak baryogenesis

Dimopoulos & Susskind 1978
Kuzmin, Rubakov & Shaposhnikov 1985
Cohen, Kaplan & Nelson 1990

- The observed baryon asymmetry not explained within the SM

EW baryogenesis provides a mechanism

✓Closely tied to the physics at the EW scale

✓Testable at colliders and low-energy experiments

Three Sakharov conditions for generating baryon asymmetry:

- Baryon number violation: electroweak sphalerons
- Out of equilibrium dynamics: a first order electroweak phase transition (with a modified dynamics compared to the SM)
- C and CP violation: new source of CP violation

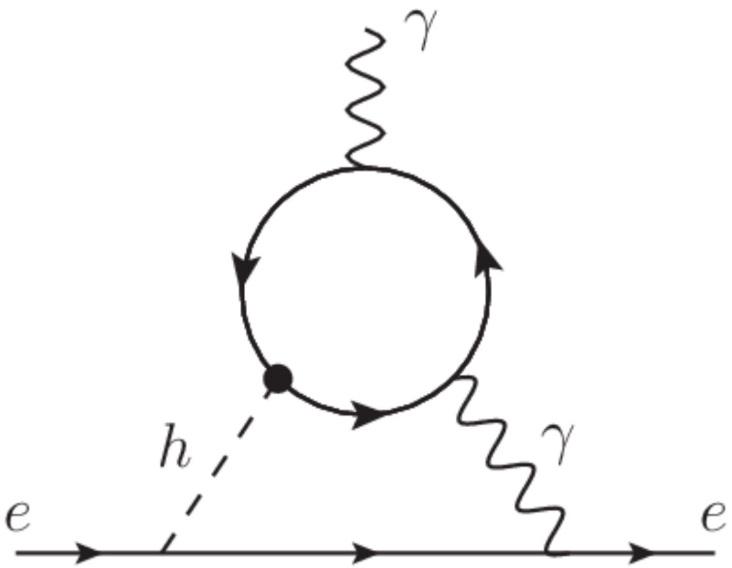
Electric dipole moment constraints

- The CP violation introduced for EWBG generically feeds into electron EDM at two loops
- Current bound on electron EDM:

$$d_e < 4 \times 10^{-30} \text{ e cm}$$

Roussy, Caldwell et al, 2022

$$\frac{d_e}{e} \sim \delta_{\rm CP} \frac{g^2 \alpha}{(4\pi)^3} \frac{m_e}{M^2} \sim \frac{\delta_{\rm CP}}{10^{-2}} g^2 \left(\frac{300 \text{ GeV}}{M}\right)^2 4\times 10^{-30} \text{ cm}$$



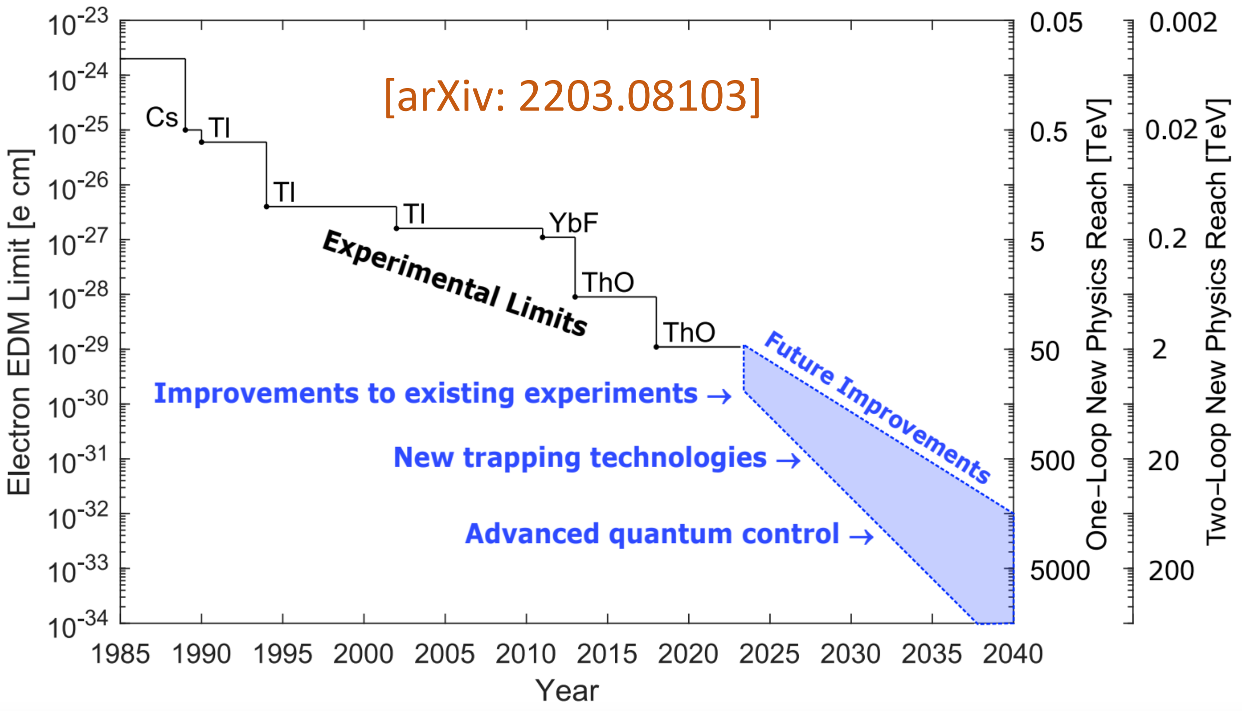
Electric dipole moment constraints

- Current bound on electron EDM:

$$d_e < 4 \times 10^{-30} \text{ e cm}$$

[Roussy, Caldwell et al, 2022]

- Significant further improvement expected



- What are the scenarios of EWBG that can avoid EDM bounds?

Avoiding EDM bounds

- Electroweak symmetry non-restoration
  - Introduce new degrees of freedom interacting with Higgs such that EW symmetry is not restored until $T \gg m_w$
  - States of $M \gg m_w$ with CPV interactions can be active during the EWPT
- Sequestering: CP violation in a dark sector
  - CP asymmetry produced in a dark sector and transferred to the visible sector
  - Contribution to EDM suppressed
- Spontaneous CP violation

Weinberg 1974
Meade & Ramani 2018
Baldes & Servant 2018
Glioti, Rattazzi & Vecchi 2018

e.g. Carena, Quiros, Zhang 2018

EW baryogenesis with spontaneous CP violation

- New source of CP violation active at the EWPT but relaxed to zero at $T = 0$

  ✓ CP violation responsible for EWBG does not contribute to EDMs

McDonald 1994
McDonald 1995
Comelli, Pietroni & Riotto 1993

In Composite Higgs models:
Espinosa Gripaios Konstandin & Riva 2012

EWBG with spontaneous CP violation

- New source of CP violation active at the EWPT but relaxed to zero at $T = 0$
  - ✓ CP violation responsible for EWBG does not contribute to EDMs
- Simplest example: SM+ a singlet (CP-odd) scalar
- New scalar provides also the possibility of a first order PT

$$\mathcal{L} \supset -V(h,\eta) + i y_t \, b \frac{\eta}{f} \, \bar{t}_L H \, t_R$$

$$\delta_{\text{CP}} \sim b \frac{\Delta\eta}{f}$$

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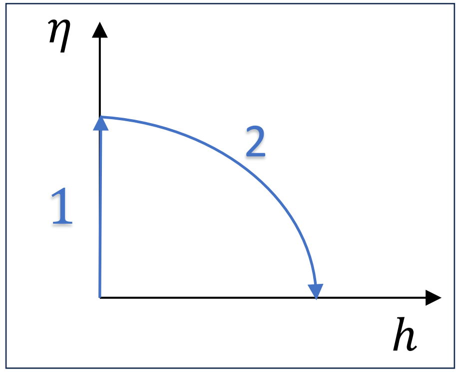
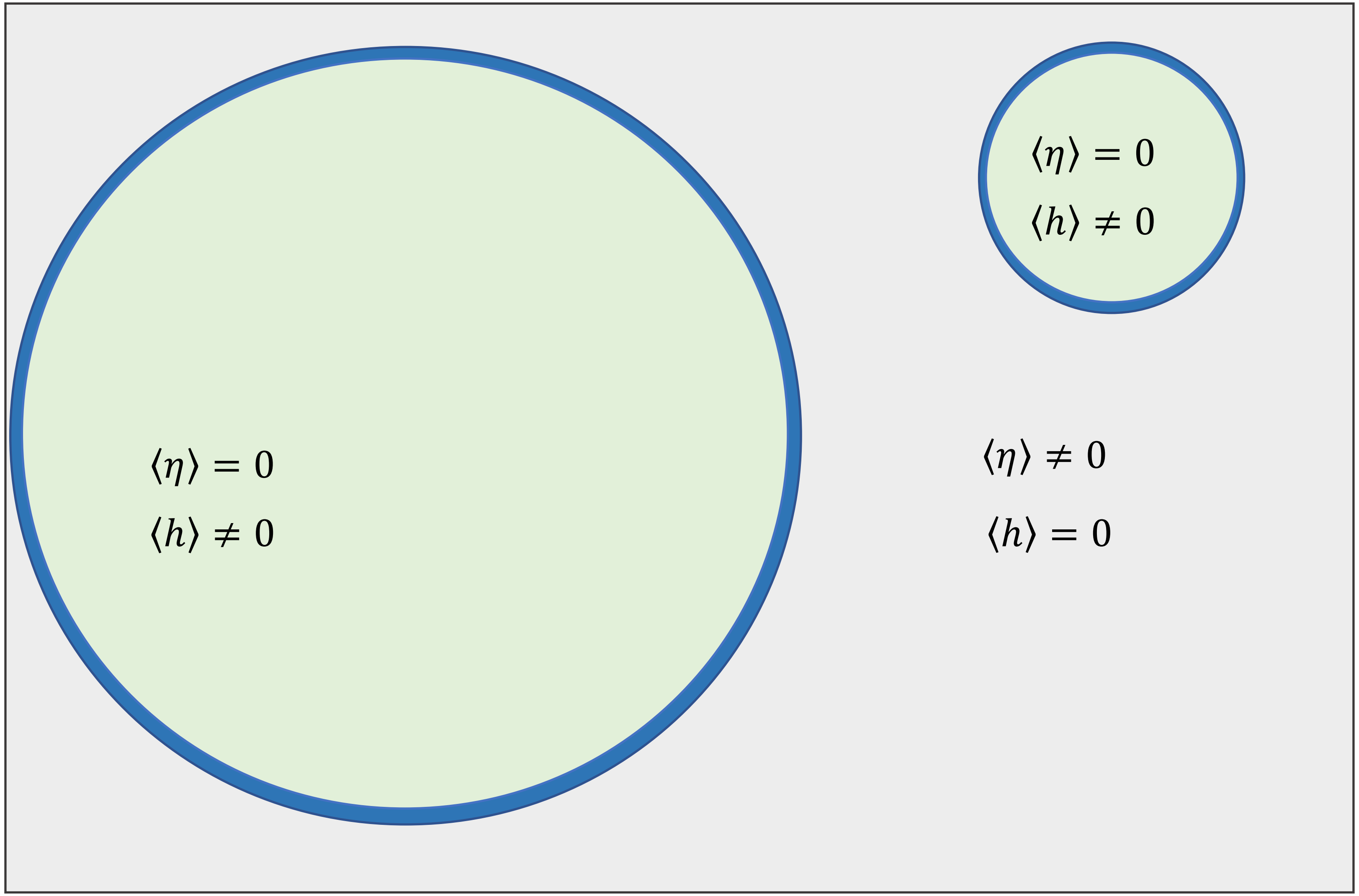
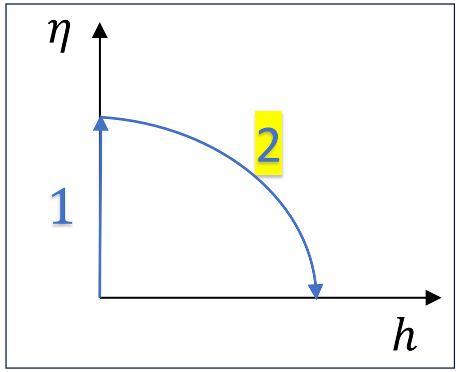
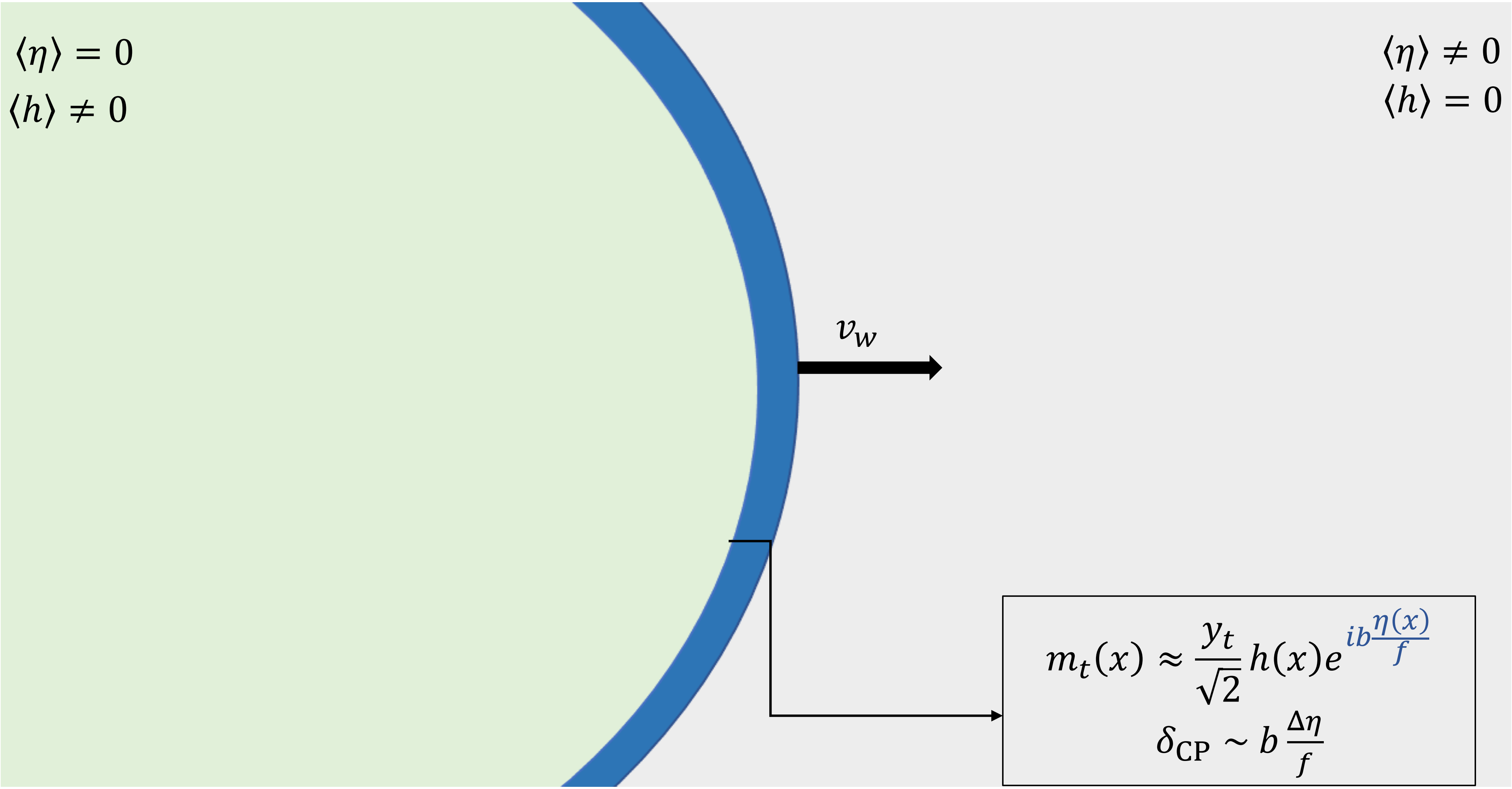


EW phase transition and EW baryogenesis





EW baryogenesis



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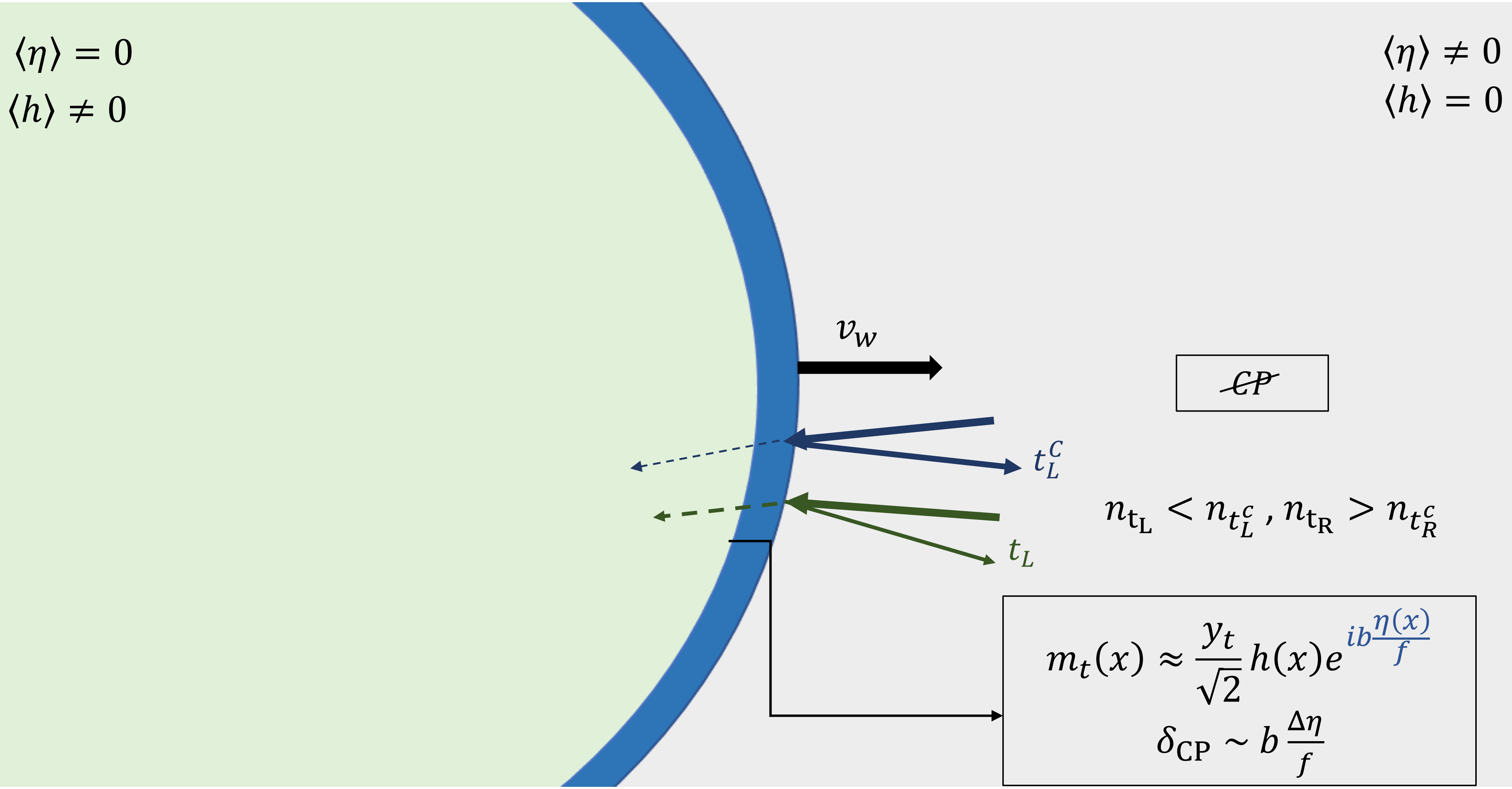

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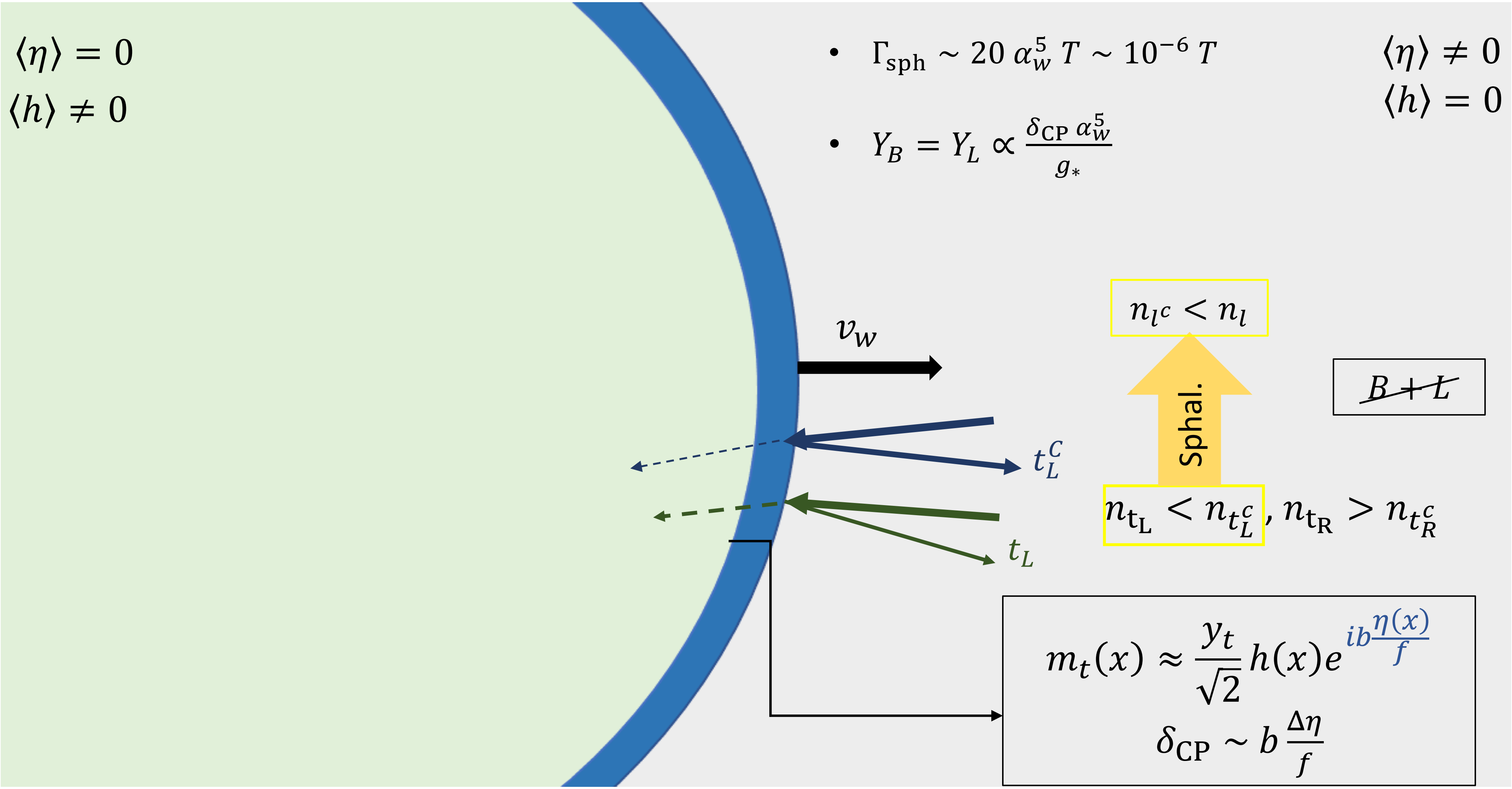


EW baryogenesis

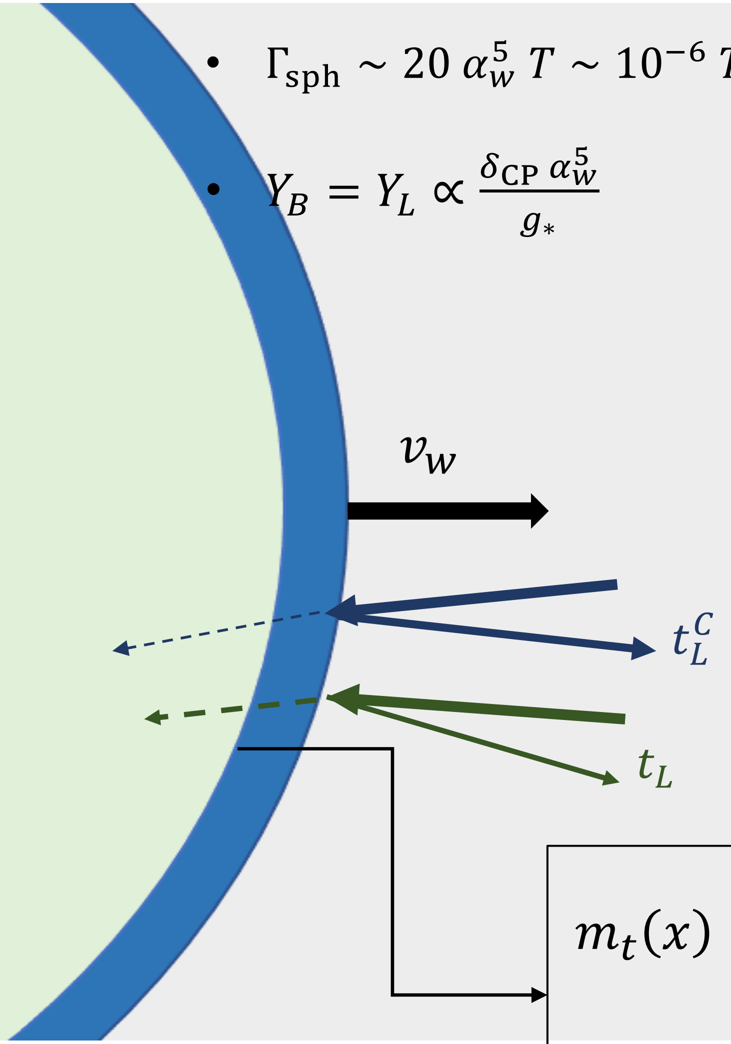
$\langle \eta \rangle = 0$

$\langle h \rangle \neq 0$

- $\Gamma_{\text{sph}} \sim 20\, \alpha_w^5\, T \sim 10^{-6}\, T$
- $Y_B = Y_L \propto \frac{\delta_{\text{CP}}\, \alpha_w^5}{g_*}$

$\langle \eta \rangle \neq 0$

$\langle h \rangle = 0$



- $\Gamma_{\text{sph}} \propto e^{-\frac{E_{sph}}{T}}, E_{\text{sph}} \sim \frac{2g\langle h \rangle}{\alpha_w}$
- $\Gamma_{\text{sph}} \lesssim H$
- $\frac{g\,\langle h \rangle}{T} \gtrsim \frac{\alpha_w}{2} \ln \frac{M_{Pl}}{T} \sim 0.6$
- $\langle h \rangle / T \gtrsim 1$, to avoid washout

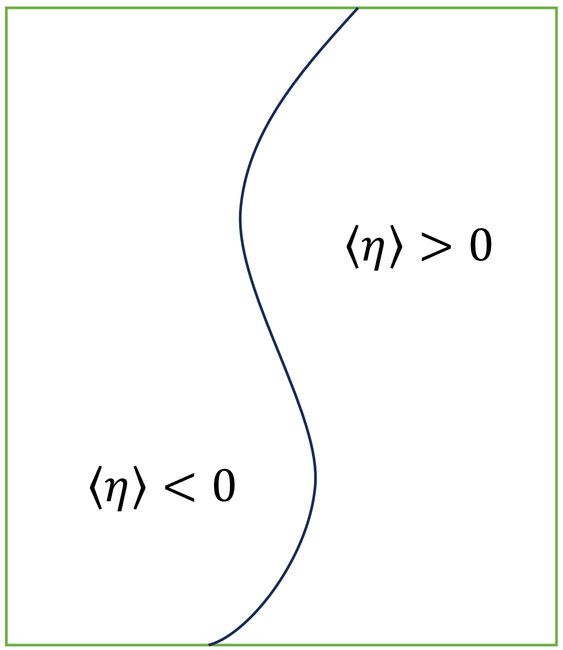
$$m_t(x) \approx \frac{y_t}{\sqrt{2}} h(x) e^{ib\frac{\eta(x)}{f}}$$

$$\delta_{\text{CP}} \sim b\, \frac{\Delta \eta}{f}$$

EWBG with spontaneous CPV: need for *explicit* CPV

McDonald 1995
Espinosa Gripaios Konstandin & Riva 2012

- Only spontaneous CPV not enough
- Different domains with opposite asymmetry formed
- Final asymmetry averages to zero
- A small explicit breaking biases domains with a particular sign
- A tiny explicit breaking is enough for the domains with the wrong sign to vanish before the EWPT $\frac{\Delta V}{T^4} \gg \frac{H}{T} \sim \frac{T}{M_{\rm Pl}} \sim 10^{-16}$
- Negligible contribution to EDMs



Outline

- Introduction: Electroweak baryogenesis and EDMs
- Electroweak baryogenesis with spontaneous CP violation
- Realization in Composite Higgs: A problem of double tuning

Solutions

- Quartic couplings without mass terms
- Symmetry breaking with higher representations: a new parameter in power counting

Composite Higgs

Composite Higgs models:

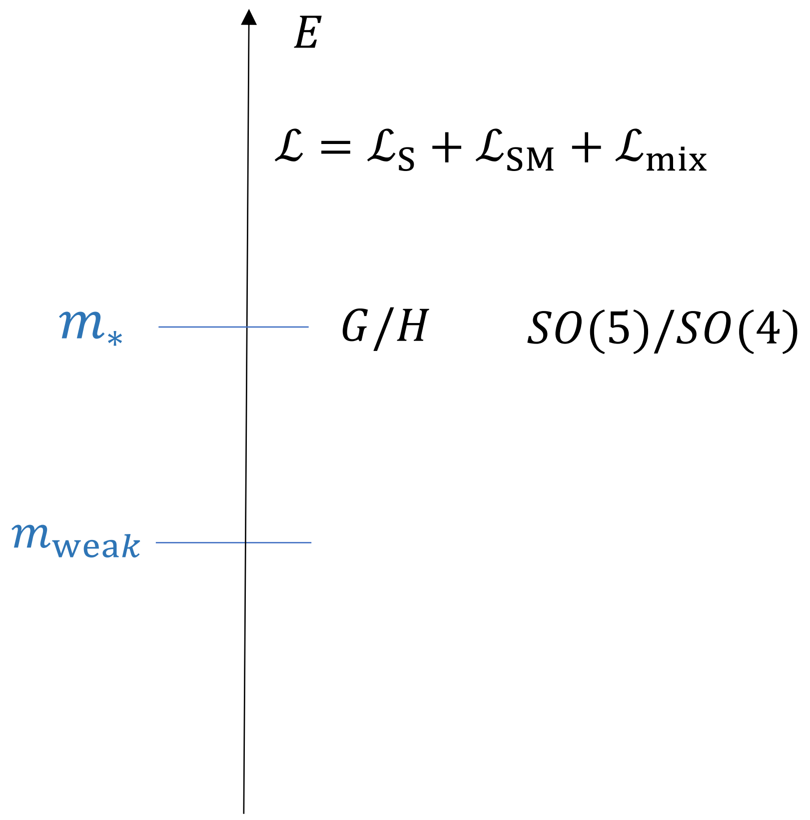
- Highly motivated as they address the large hierarchies
- Higgs a confined composite state of strong dynamics around the TeV scale
- Can both the Higgs and the new singlet scalar be composite PNGBs of the strong dynamics?

Minimal Composite Higgs model

Agashe Contino Pomarol 2004
review: Panico & Wulzer 2015

- A strongly coupled sector with a SO(5) global symmetry broken spontaneously to SO(4)
- 4 Goldstones : the 4 (real) fields form the Higgs doublet
- $SO(4) \simeq SU(2)_L \times SU(2)_R$
- $SU(2)_L$ and $T_R^3 + X$ gauged
- Explicit breaking of symmetry by composite-elementary mixing and gauge interactions $\longrightarrow$ generate a potential for the Higgs

$$\mathcal{L}_{\text{mix}} = g A_\mu J^\mu + \lambda_i \psi_i O_i$$



Estimating the parameters of the potential

$$V = \frac{3y_t^2}{16\pi^2} g_*^2 f^4 \left(a_h \left(\frac{h}{f}\right)^2 + \frac{b_h}{2}\left(\frac{h}{f}\right)^4 \right), \qquad a_h, b_h = \mathcal{O}(1) \quad \text{expected}$$

Current data can be accommodated by $g_* \sim 2,\ b_h \sim 1,\ a_h \lesssim 0.1$

- Higgs quartic obtained for $g_* \sim 2,\ b_h \sim 1$

- $a_h = \frac{m_h^2}{m_*^2}\frac{4\pi^2}{3y_t^2} \approx \left(\frac{450\text{ GeV}}{m_*}\right)^2 \lesssim \mathcal{O}(0.1)$

  Bound from direct searches for top partners: $m_* \gtrsim 1.5$ TeV

  Matsedonskyi Panico & Wulzer 2015
  CMS 229.07327, ATLAS 2210.15413

  Need $a_h \lesssim 0.1$ to accommodate the observed m_h

  Although bound on vector resonances $m_\rho \gtrsim 4.5$ TeV suggests $a_h \lesssim \mathcal{O}(0.01)$, unless top partners lighter

- Higgs precision measurements, requires $\left(\frac{v}{f}\right)^2 \lesssim 0.1$

  Need $a_h/b_h \lesssim \mathcal{O}(0.1)$ to accommodate the current precision, no more tuning needed

Realization of EWBG with spontaneous CPV in Composite Higgs

- A strongly coupled sector with $SO(6)$ symmetry broken spontaneously to $SO(5)$
- 5 Goldstones : H and η
- Possible two-step PT
- CPV phase by the coupling to top

$$i\, b\, y_t \frac{\eta}{f}\, \bar{t}_L H\, t_R$$

$$\delta_{\mathrm{CP}} \sim b \frac{\Delta\eta}{f}$$

Gripaios Pomarol Riva & Serra 2009

Espinosa Gripaios Konstandin & Riva 2012

De Curtis, Delle Rose & Panico 2019

Estimating the parameters of the potential

- Terms involving h only:

$$\frac{3y_t^2}{16\pi^2} g_*^2 f^4 \left(a_h \left(\frac{h}{f}\right)^2 + \frac{b_h}{2}\left(\frac{h}{f}\right)^4 \right), \qquad a_h, b_h = \mathcal{O}(1)$$

- The little hierarchy:
  - ➢Need $a_h \lesssim \mathcal{O}(0.1)$ to accommodate m_h
  - ➢Need $a_h/b_h \lesssim \mathcal{O}(0.1)$ to accommodate Higgs precision measurements, requiring $\left(\frac{v}{f}\right)^2 \lesssim 0.1$

Estimating the parameters of the potential

Terms involving η

- $SO(6) \supset SO(4) \times SO(2)_\eta$

$$\begin{pmatrix} SO(4) & \\ & SO(2)_\eta \end{pmatrix}$$

- η shifts under $SO(2)_\eta$
- Mixing of the elementary fermions can be chosen to respect $SO(2)_\eta$

  or break it by an arbitrarily small amount ($\delta_\eta \ll 1$)

Gripaios Pomarol Riva & Serra 2009

- Parameterize the suppression of $U(1)_\eta$ symmetry breaking by $\delta_\eta < 1$:

$$\frac{3y_t^2}{16\pi^2} g_*^2 f^2 \, \delta_\eta \left(a_\eta \left(\frac{\eta}{f}\right)^2 + \frac{b_\eta}{2} \left(\frac{\eta}{f}\right)^4 + b_{h\eta} \left(\frac{h}{f}\right)^2 \left(\frac{\eta}{f}\right)^2 \right), \qquad a_\eta, b_\eta, b_{h\eta} = \mathcal{O}(1)$$

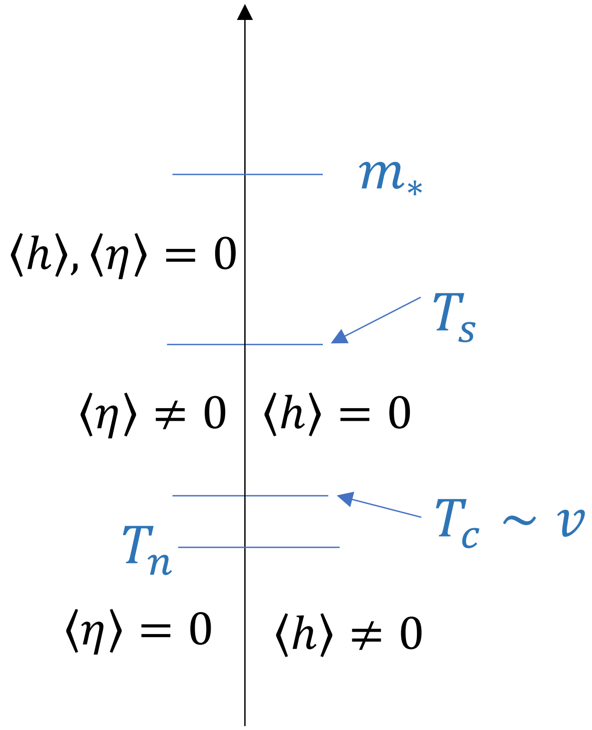
- η can be naturally as light or lighter than the Higgs for $\delta_\eta \ll 1$

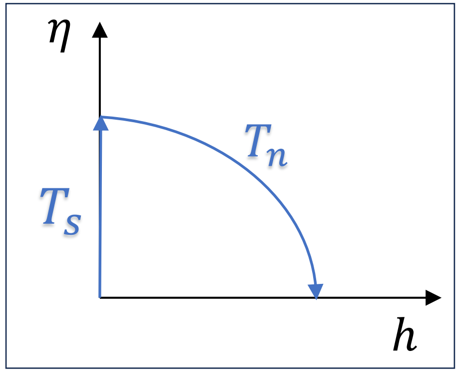
Thermal history: big picture

- The strongly coupled sector confines/ develops a mass gap at $T \sim m_*$
- Below m_* the PNGBs and the SM particles dominate the dynamics
- At some T_s, η gets a VEV
- At T_c, EWSB vacuum becomes preferable and the EWPT begins
- EWPT completes at T_n by nucleation of the bubbles

  Baryon asymmetry generated at the bubble walls

- Rate of sphalerons suppressed inside the bubbles, baryon number freezes out





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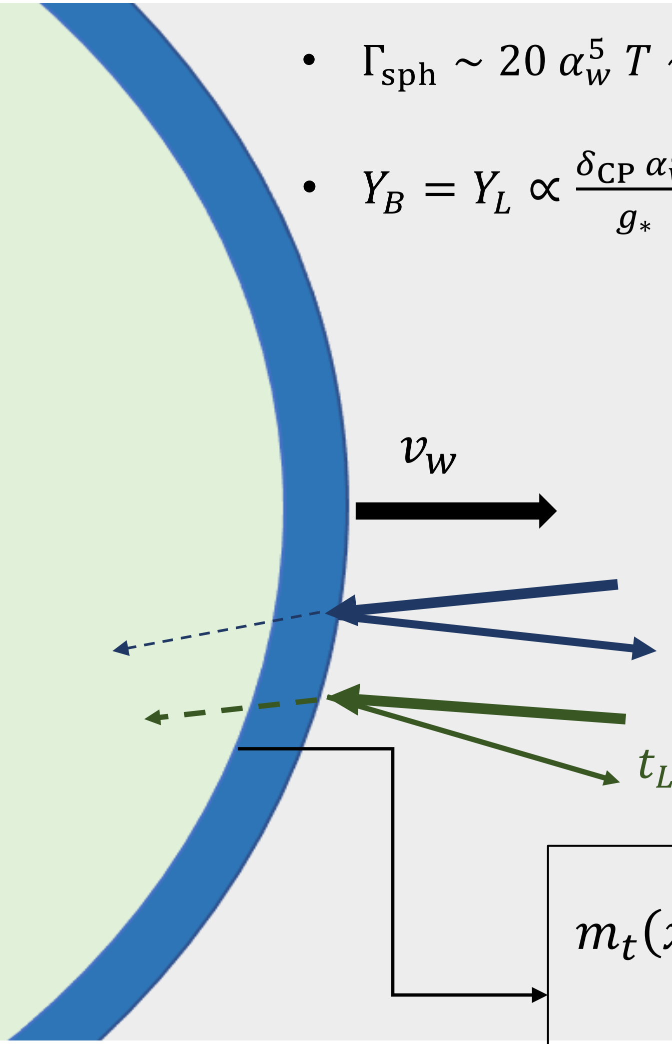

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$$m_t(x) \approx \frac{y_t}{\sqrt{2}} h(x) e^{ib\frac{\eta(x)}{f}}$$

$$\delta_{\rm CP} \sim b\,\frac{\Delta\eta}{f}$$

Problem of double-tuning

- Necessary condition to achieve a two-step PT:

$$c_\eta > 0 \quad \rightarrow \quad \mu_\eta^2 < 0$$

$$V(h,\eta) = \frac{1}{2}\mu_h^2 h^2 + \frac{1}{2}\mu_\eta^2\eta^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_\eta \eta^4 + \frac{1}{2}\lambda_{h\eta} h^2\eta^2$$

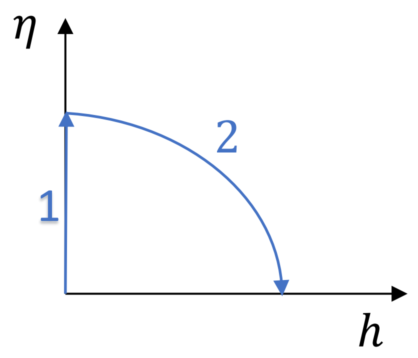
$$+\frac{1}{2}\mathrm{c_h T^2\, h^2} + \frac{1}{2}\mathrm{c}_\eta \mathrm{T}^2\eta^2$$

- Stability of EWSB vacuum at T=0:

$$m_\eta^2 = \mu_\eta^2 + \lambda_{h\eta} v^2 > 0$$

- Need $\lambda_{h\eta}$ big enough $\quad |b_{h\eta}|\left(\frac{v}{f}\right)^2 \gtrsim |a_\eta|$

$$|a_\eta / b_{h\eta}| \lesssim \left(\frac{v}{f}\right)^2 \lesssim \mathcal{O}(0.1)$$



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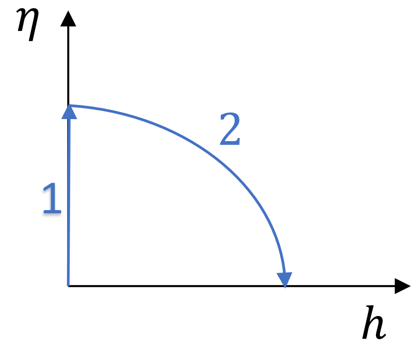


- Need $\lambda_{h\eta}$ big enough $\quad |b_{h\eta}|\left(\frac{v}{f}\right)^2 \gtrsim |a_\eta|$

$$|a_\eta/b_{h\eta}| \lesssim \left(\frac{v}{f}\right)^2 \lesssim \mathcal{O}(0.1)$$

A second tuning in the realizations so far in the literature

➢ Is there a more natural realization?

✓ Can be solved if there a natural way to generate quartic couplings, but with suppressed mass terms

Quartic couplings without (with suppressed)mass terms?

Two solutions:

(1) There are spurions that (at leading order) give rise to quartic couplings only

Mass terms arise at higher orders in the spurion(s)

(2) A new parameter: large charge (or large representations)

Explicit symmetry breaking by a large charge spurion enhances the higher order terms

Quartic couplings without mass terms

- Is there a spurion that gives rise to only quartic couplings and vanishing mass terms?
- Yes, there is a unique totally symmetric traceless rank 4- tensor breaking SO(5) to SO(4):

$$T_{IJKL} = \left(\delta^{(4)}_{IJ}\delta^{(4)}_{KL} + \text{perms.}\right) - 6\left(\delta^{(4)}_{IJ}\delta_{K5}\delta_{L5} + \text{perms.}\right) + 8\,\delta_{I5}\delta_{J5}\delta_{K5}\delta_{L5}$$

- Gives *opposite sign* contributions for λ_η and $\lambda_{h\eta}$:

$$\Delta V \propto T_{IJKL}\,\Sigma_I\Sigma_J\Sigma_K\Sigma_L.$$

$$\Delta V \propto (h^4 - 8\,h^2\eta^2 + 12\eta^4)$$

$$\Sigma \equiv U[\pi]\langle\Phi\rangle = \left(h_1, h_2, h_3, h_4, \eta, \sqrt{f^2 - \sum_i h_i^2 - \eta^2}\right)^T$$

- Relative sign dictated by traceless condition

A larger coset: SO(7)/SO(6)

- Another extra singlet PNGB (ρ), which can be naturally heavier and decoupled from EWPT

- Similar spurion can give positive $\lambda_\eta, \lambda_{h\eta}$ and λ_h, negative sign appearing only in couplings of ρ

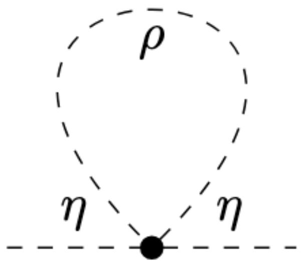
$$\Delta V = \frac{\kappa}{4}\left((h^2+\eta^2)^2 - 14(h^2+\eta^2)\rho^2 + \frac{35}{3}\rho^4\right)$$

- Large ρ mass from the top coupling contributions can lead to $\langle\rho\rangle = 0$

Contribution to the mass term

- Considering only κ, no mass terms generated
- As a consequences of symmetry, the quadratically divergent contributions cancel
- A finite IR contribution, as m_ρ gets its mass from other spurions (top contribution)

$$\Delta\mu_\eta^2 \sim \frac{14\kappa}{16\pi^2} m_\rho^2 \ln\frac{m_*}{m_\rho}$$



- Enough suppression to be smaller than the contribution from top

The potential

- Top embeddings: t_R in the 7 and Q_L in the 27 (two-index symmetric traceless irrep)
- Q_L embedding breaks η shift symmetry by a small amount (δ_η)

$$V_t = c\frac{3y_t^2}{16\pi^2}g_*^2\left(\epsilon f^2h^2 + h^4 + f^2\rho^2 + 2\delta_\eta f^2\eta^2 + 2\delta_\eta\eta^2h^2 + \rho^2h^2\right)$$

- t_R embedding such that it only breaks the shift symmetry associated with ρ (no contribution to H and η potentials)

$$\Delta V_t = \tilde{c}\frac{3g_*^2}{16\pi^2}m_*^2\rho^2$$

- Additional contribution by the new spurion:

$$\Delta V = \frac{\kappa}{4}\left((h^2+\eta^2)^2 - 14(h^2+\eta^2)\rho^2 + \frac{35}{3}\rho^4\right)$$

The potential

- Top induced potential:

From Q_L mixing:

$$V_t = c\frac{3y_t^2}{16\pi^2}g_*^2\left(\epsilon f^2h^2 + h^4 + f^2\rho^2 + 2\delta_\eta f^2\eta^2 + 2\delta_\eta\eta^2h^2 + \rho^2h^2\right)$$

- Contribution by the new spurion:

$$\Delta V = \frac{\kappa}{4}\left((h^2+\eta^2)^2 - 14(h^2+\eta^2)\rho^2 + \frac{35}{3}\rho^4\right)$$

- The leading thermal correction is captured by a thermal masses:

$$\Delta V_t(h,\eta) = \frac{1}{2}\mathrm{c_h}\mathrm{T}^2\,\mathrm{h}^2 + \frac{1}{2}\mathrm{c}_\eta\mathrm{T}^2\eta^2$$

$$c_h = \frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}\right)$$

$$c_\eta = \frac{1}{12}\left(4\lambda_{h\eta} + \lambda_\eta\right)$$

Parameter space

- Potential terms involving h and η contain

  5 parameters

- fixing observed m_h and , v and setting

  $\left(\frac{v}{f}\right)^2 = 0.1$, leaves only 2 parameters

$$V_t = c\frac{3y_t^2}{16\pi^2}g_*^2\left(\epsilon f^2h^2 + h^4 + f^2\rho^2 + 2\delta_\eta f^2\eta^2 + 2\delta_\eta\eta^2h^2 + \rho^2h^2\right)$$

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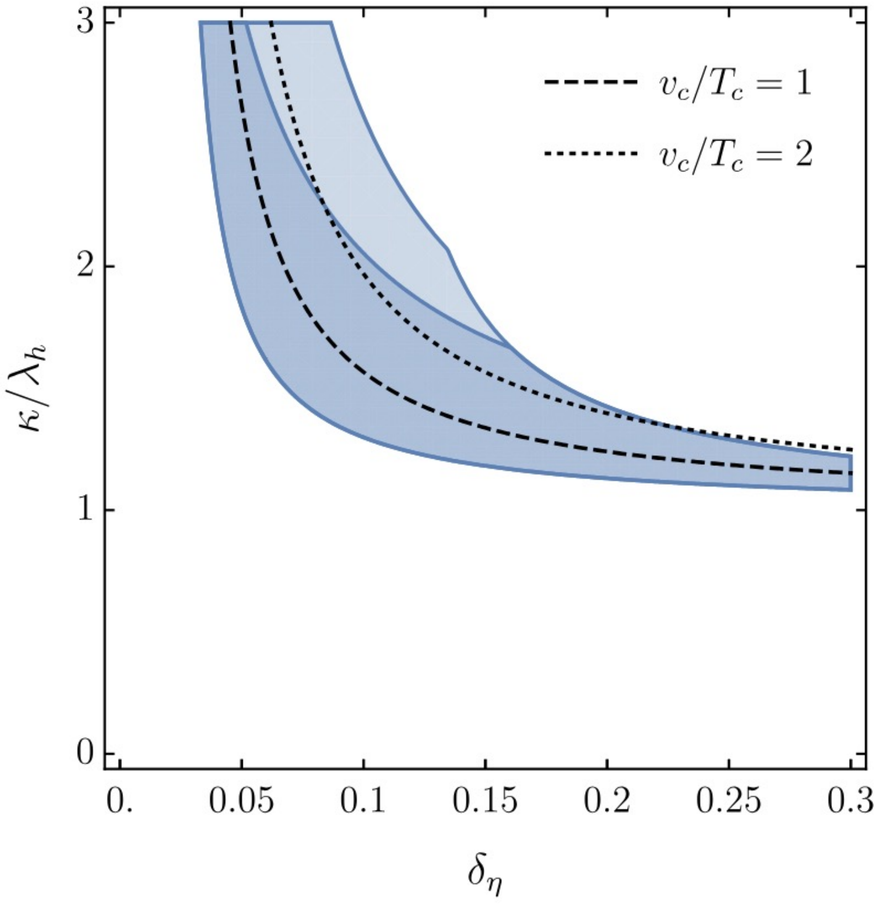


Parameter space

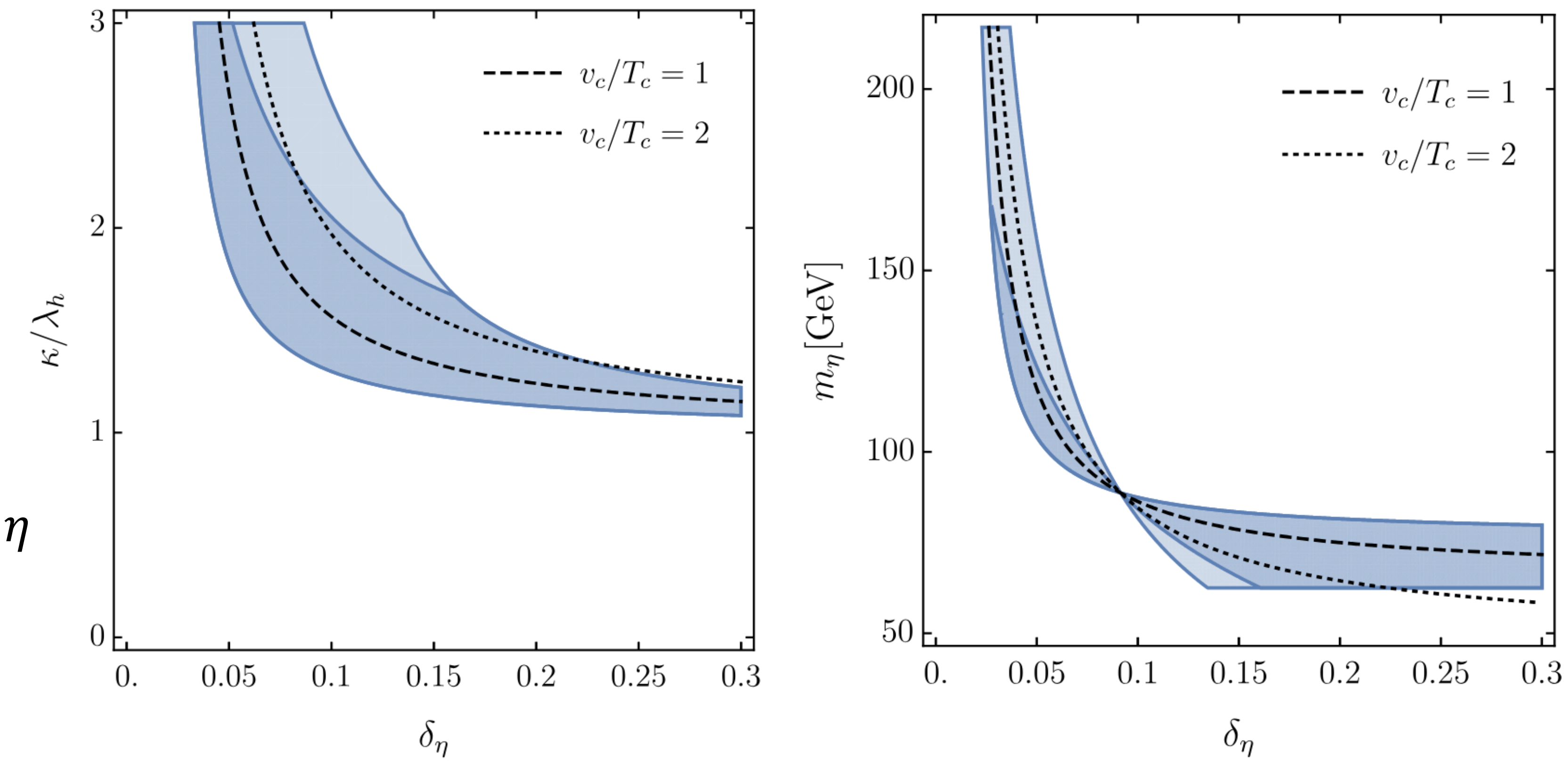
Constraints:

- Thermal history:

A first order phase transition from $\langle \eta \rangle \neq 0$ to $\langle h \rangle \neq 0$
The transition completes via bubble nucleation

- $m_\eta > m_h/2$ to avoid $h \to \eta\, \eta$ decay

- $v/T \gtrsim 1$, large enough to avoid washout of the baryon asymmetry



Quartic couplings without mass terms?

Two solutions:

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Mass terms arise at higher orders in the spurion(s)

(2) A new parameter: large charge (or large representations)

Explicit symmetry breaking by a large charge spurion enhances the higher order terms

A new parameter in power counting: a toy model

$$V(\Phi) = g^2(|\Phi|^2 - f^2)^2 + \epsilon \frac{g^2}{f^{N-4}} (\Phi^{n} + \Phi^{*n}) \qquad (\epsilon \ll 1)$$

- Potential for the PNGB:

$$V(\pi) = 2\,\epsilon g^2 f^2 \cos\left(n \frac{\pi}{f}\right)$$
$$= V(0) + \epsilon\, n^2 g^2 f^2 \left(-\pi^2 + \frac{n^2}{12\, f^2}\, \pi^4 + \cdots\right)$$

- Explicitly symmetry breaking by a large charge spurion enhances the higher order terms

The non-abelian version: Gegenbauer polynomials

$$\Phi = (\Phi_1, \Phi_2, \dots, \Phi_N)^T$$

$$V(\Phi) = g^2\left((\Phi.\Phi)^2 - f^2\right)^2 + \epsilon\ T_{i_1 i_2 \dots i_n} \frac{g^2}{f^{N-4}} \Phi_{i_1}\Phi_{i_2} \dots \Phi_{i_n} \qquad (\epsilon \ll 1)$$

- SO(N) broken spontaneously to SO(N-1)
- Small explicit breaking to SO(N-1) by an operator in the n-index symmetric traceless irrep
- T totally symmetric and traceless

The non-abelian version: Gegenbauer polynomials

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- SO(N) broken spontaneously to SO(N-1)
- Small explicit breaking to SO(N-1) by an operator in the n-index symmetric traceless irrep
- T totally symmetric and traceless
- Potential for the PNGB:

$$V(\pi) = a\,\epsilon g^2 f^2 G_n^{\frac{N}{2}-1}\left(\cos\frac{\Pi}{f}\right)$$

$$= const + a'\epsilon\, n^2 g^2 f^4 \left(-\sin^2\frac{\Pi}{f} + \frac{(n+6)(n-2)}{28\, f^2}\sin^4\frac{\Pi}{\mathrm{f}} + \cdots\right)$$

Durieux, McCullough & Salvioni 2021

A more natural EWBG- Gegenbauer contribution

- Assume new source of explicit breaking with a spurion transforming in a higher representation of SO(6)

$$V(h,\eta) = V_t(h,\eta) + \mathrm{V_G}(\mathrm{h},\eta)$$

$$\mathrm{V_G}(\mathrm{h},\eta) = \epsilon_G\, g_*^2\, f^2 G_n^2 \left(\sqrt{1-(h/f)^2-(\eta/f)^2}\right)$$

$$V_t(h,\eta) = \frac{1}{2}\mu_{h,t}^2 h^2 + \frac{1}{2}\mu_{\eta,t}^2 \eta^2 + \frac{1}{4}\lambda_{h,t} h^4 + \frac{1}{4}\lambda_{\eta,t}\eta^4 + \frac{1}{2}\lambda_{h\eta,t} h^2\eta^2$$

A more natural EWBG- Gegenbauer contribution

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- $\mathrm{V_G}$ gives parametrically enhanced $\lambda_{h\eta}$: $\frac{\lambda_{h\eta}}{\mu_\eta^2} \propto n^2/f^2$

Finite temperature corrections

- The corrections controlled by ϵ_G are restricted to have the same form by symmetry

Koutroulis, McCullough, Merchand
Pokorskia & Sakurai 2023

$$\mathrm{V_G}(\mathrm{h},\eta,T) = \left(1-\left(\frac{\mathrm{T}}{T_{\mathrm{F}}}\right)^2\right)\epsilon_G\, g_*^2\, f^2 G_n^2\left(\sqrt{1-(h/f)^2-(\eta/f)^2}\right)$$

$$T \ll T_{\mathrm{F}}$$
$$T_{\mathrm{F}} \sim 5f/n$$

- The leading effect of other couplings is to provide a thermal mass

$$\Delta V_t(h,\eta) = \frac{1}{2}\mathrm{c_h}\mathrm{T}^2\,\mathrm{h}^2 + \frac{1}{2}\mathrm{c}_\eta\mathrm{T}^2\eta^2$$

$$\mathrm{c_h} > \mathrm{c}_\eta$$

The more natural regime: Gegenbauer co-dominance

- Top induced potential:

Top embeddings: t_R mixing with the singlet and Q_L with the 14 (two-index symmetric traceless irrep)

From Q_L mixing:

$$V_t(h,\eta) = c\,\frac{3y_t^2}{16\,\pi^2} g_*^2(\epsilon\, f^2 h^2 + h^4 + 2\delta_\eta f^2\eta^2 + 2\delta_\eta h^2\eta^2)$$

- Contribution of the new spurion:

$$\mathrm{V_G}(\mathrm{h},\eta) = \epsilon_G\, g_*^2\, f^2 G_n^2\left(\sqrt{1-(h/f)^2-(\eta/f)^2}\right)$$

  - Fixing observed m_h and , v and setting $\left(\frac{v}{f}\right)^2 = 0.1$, and choosing n leaves only 2 more parameters

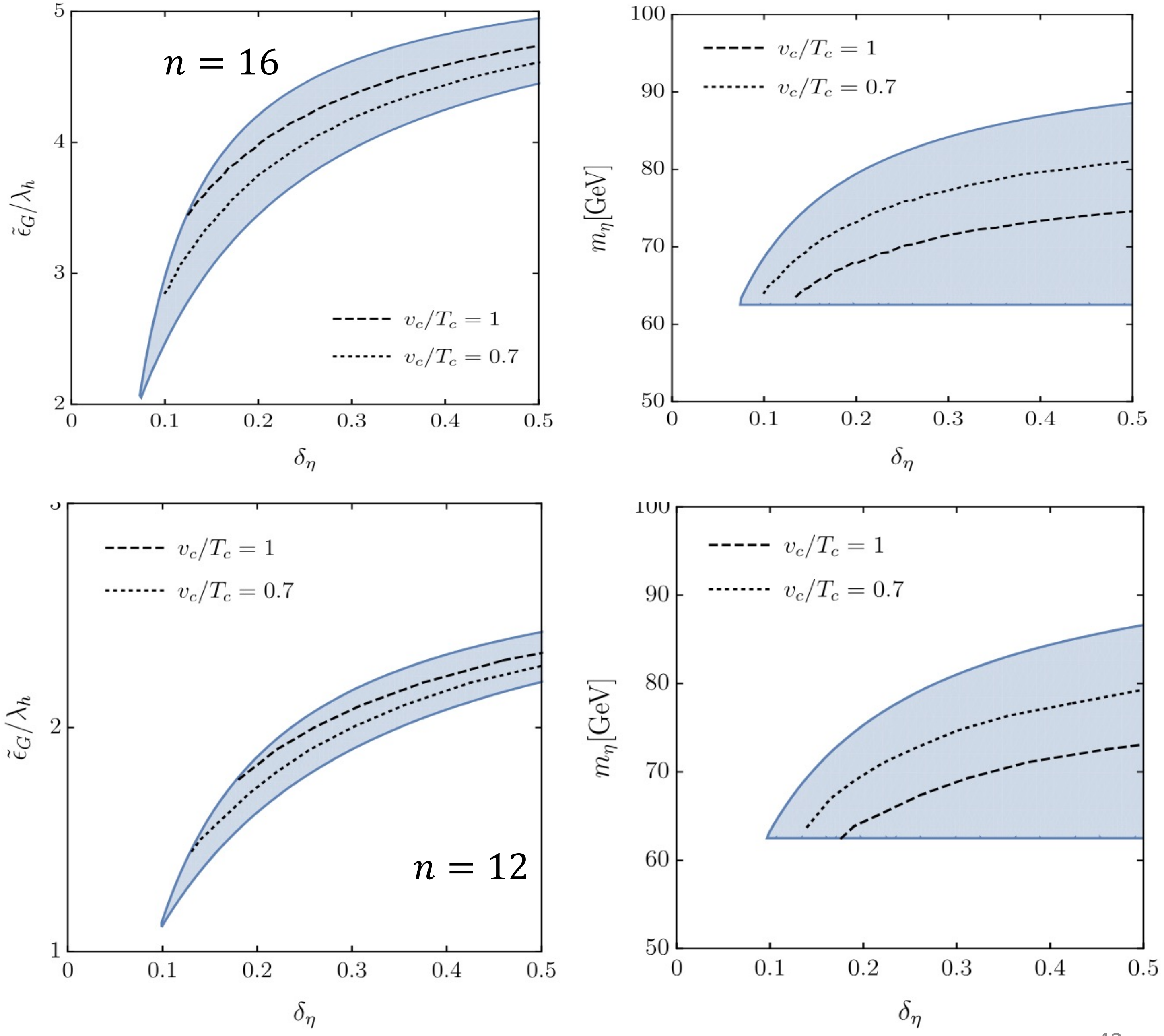
Parameter space

- Only the usual tuning needed for the Higgs mass
- Thermal history:

A first order phase transition from $\langle \eta \rangle \neq 0$ to $\langle h \rangle \neq 0$

The transition completes via bubble nucleation

- $m_\eta > m_h/2$ to avoid $h \to \eta\,\eta$ decay
- $v/T \gtrsim 1$, to avoid washout of the baryon asymmetry



Large charge, low cutoff

Change & Luty 2019
Falkowski & Rattazzi 2019
Craig, Garcia Garcia & Kribs 2019
ME, Hook, Kumar, Tsai 2021

- Perturbative unitarity constraints for processes involving large number of particle require lower cutoff of the EFT as n increases
- For a toy model $$V(\varphi) = -\lambda \frac{f^4}{n^4} \cos\left(\frac{n\varphi}{f}\right)$$
  - Bound on the CM energy within the EFT: $$E \leq \frac{4\pi f}{\sqrt{27n}} \log^{3/2}\left[\frac{8\pi}{\lambda}\left(\frac{2}{3}\log(8\pi/\lambda)\right)^3\right]$$
  - For $k_* \rightarrow k_*$ scattering with $$k_* \simeq \frac{1}{2}\log\left[\frac{8\pi}{\lambda}\left(\frac{2}{3}\log(8\pi/\lambda)\right)^3\right]$$
- UV physics should modify the amplitude before reaching such CM energy
- While not obvious how precisely this translates to a bound on the cutoff applying to general UV completions, the bound should lie between $(E/k)_{\max} \lesssim \Lambda_{\max} \lesssim E_{\max}$

Large charge, low cutoff

- Perturbative unitarity constraints for processes involving large number of particle require lower cutoff of the EFT as n increases

- UV physics should modify the amplitude before reaching such CM energy

- Bound on the cutoff considering general UV completions bound should lie between

$$\frac{E_{\max}}{k_*} \lesssim \Lambda_{\max} \lesssim E_{\max}$$

- For the complete model:

(for $\frac{\tilde{\epsilon}}{\lambda_h^{SM}} = 2$)

n	$\Lambda_{\max} \sim E_{\max}$	$\Lambda_{\max} \sim (E/k)_{\max}$
8	$\Lambda \lesssim 19$ f	$\Lambda \lesssim 5$ f
12	$\Lambda \lesssim 11$ f	$\Lambda \lesssim 2.2$ f
16	$\Lambda \lesssim 8$ f	$\Lambda \lesssim 1.5$ f

Summary and conclusions

- Electroweak baryogenesis an intriguing possibility for explaining the baryon asymmetry, potentially testable
- EDM measurements already strongly constrain the models; significant further improvements are expected
- Spontaneous CP violation at the EW PT provides a scenario to hide EWBG from EDMs
- Realization in Composite Higgs: SO(6)/SO(5) symmetry gives rise to H and a new SM singlet pseudoscalar
- First/simplest models realizing a 2-step PT have a double-tuning problem
- Two solutions for the new tuning problem:
    - A new 4-index symmetric traceless spurion, giving rise to quartic couplings only, realization in SO(7)/SO(6)
    - explicit symmetry breaking involves operators of higher representations/ large charge

Thank you!

Extra Slides

Analytic study: Gegenbauer dominance

- A simplifying regime: the SO(5)-symmetric part of the potential dominates
- Goldstones $\vec{\Pi} = (h1, h2, h3, h4, \eta)$ transform as 5 of SO(5)
- A VEV for $\vec{\Pi}$ breaks SO(5) spontaneously to SO(4)
- 4 Goldstones: at a generic VEV, EW symmetry broken, 3 eaten by the EW gauge bosons, one remains (θ)
- Dynamics of the PT more simply analyzed in terms of θ

Analytic study: Gegenbauer dominance

- The SO(5)-breaking part of the potential:

$$\Delta V = \frac{1}{4}\lambda_{h,t}h^4 + \frac{1}{4}\left(\mu_{h,t}^2 - \mu_{\eta,t}^2 + \left(c_h - c_\eta\right)T^2\right)(h^2 - \eta^2)$$

- Parametrizing $h = v_c \cos\theta, \eta = v_c \sin\theta$:

$$\Delta V(\theta, T) = -\frac{\lambda_{h,t}}{8} v_c^4 \left[\cos(4\theta) + 4\,\alpha(T)\cos(2\theta)\right]$$

Prefers one phase over the other

Provides a barrier between two phases

$$\alpha(T) = \frac{\mu_{h,t}^2 - \mu_{\eta,t}^2 + \left(c_h - c_\eta\right)T^2 + 2\lambda_{h,t}\, v_c^2}{-2\,\lambda_{h,t} v_c^2}$$

- At T_c: $\alpha(T_c) = 0$,

➢ Need $\lambda_{h,t}$<0

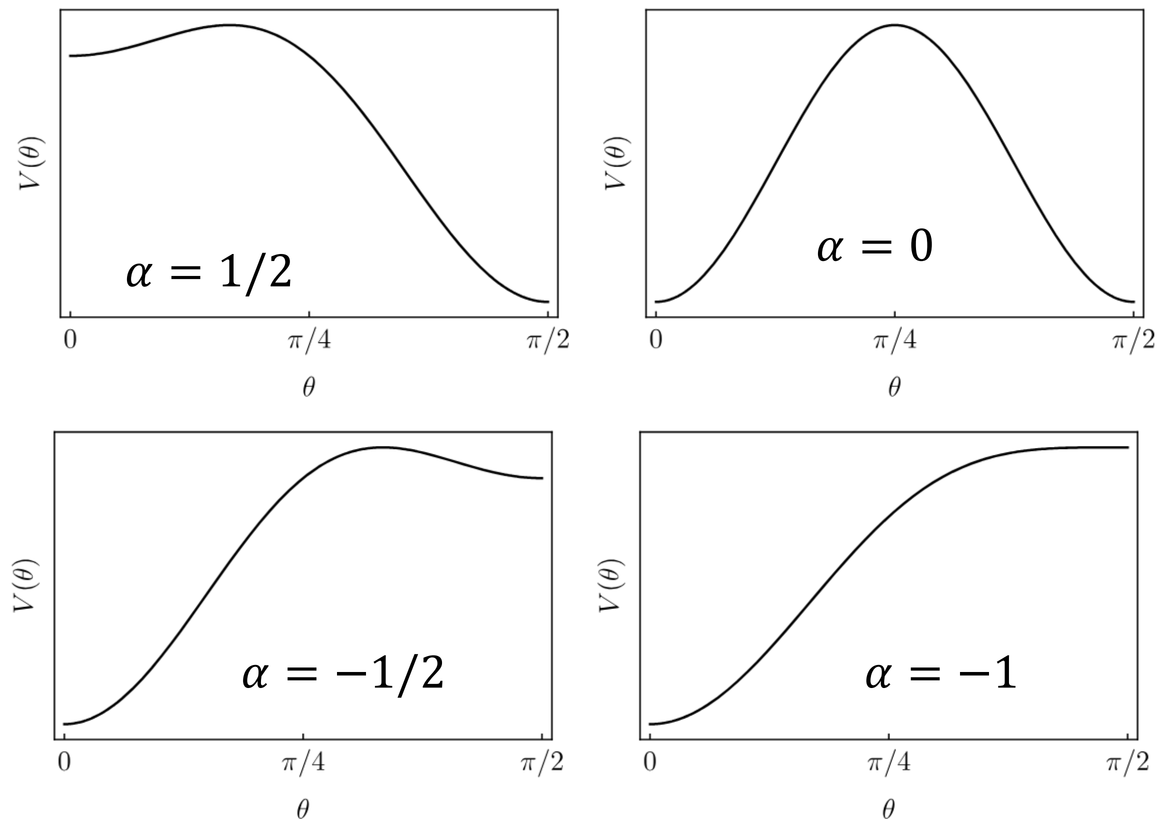
Analytic study: Gegenbauer dominance

$$\Delta V(\theta, T) = -\frac{\lambda_{h,t}}{8} v_c^4 \left[\cos(4\theta) + 4\,\alpha(T)\cos(2\theta)\right]$$

- Need $\lambda_{h,t}$<0

- Thermal history determined by $\alpha(T)$

$$\alpha(T) = \frac{\mu_{h,t}^2 - \mu_{\eta,t}^2 + (c_h - c_\eta)T^2 + 2\lambda_{h,t}\, v_c^2}{-2\,\lambda_{h,t} v_c^2}$$



Gegenbauer dominance- bubble nucleation

$$\Delta V(\theta, T) = -\frac{\lambda_{h,t}}{8} v_c^4 \left[\cos(4\theta) + 4\,\alpha(T)\cos(2\theta)\right]$$

- Bubble nucleation rate: $$\Gamma \sim T^4 \exp\left(-\frac{S_3}{T}\right)$$
- PT completes when $$\Gamma \gtrsim H^4 \;\rightarrow\; \frac{S_3}{T} \approx 4\ln\left(\frac{M_{\rm Pl}}{T_C}\right) \approx 140$$
- Or by "zero-T (quantum)" bubbles when $$S_4 \approx 4\ln\left(\frac{M_{\rm Pl}}{T_C}\right) \approx 140$$
- Near T_c, thin wall bubbles $$S_3^{\rm thinwall} = \frac{2\pi\varphi}{3|\lambda_{4\theta}|^{1/2}\alpha^2}$$
- Outside this regime: $$S_3 = \frac{4\pi\varphi}{|\lambda_{4\theta}|^{1/2}}\left[\frac{(1-\alpha^2)^{5/2}(1+1.87\alpha^2)}{6\alpha^2} + 0.19(1+\alpha)^{1/2}\right]$$

Coleman 1977
Linde 1981

Gegenbauer dominance- bubble nucleation

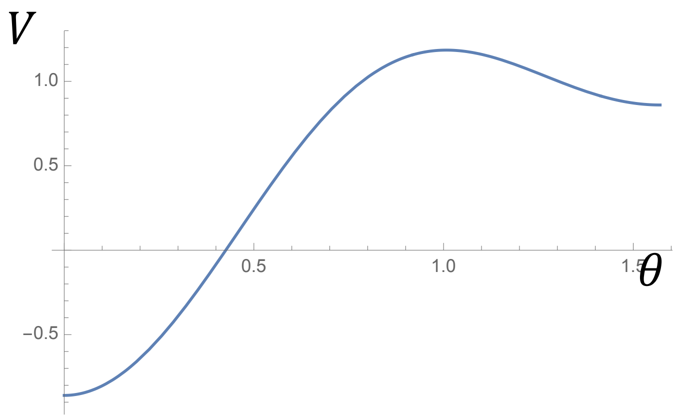
- Depending on the parameters two cases possible

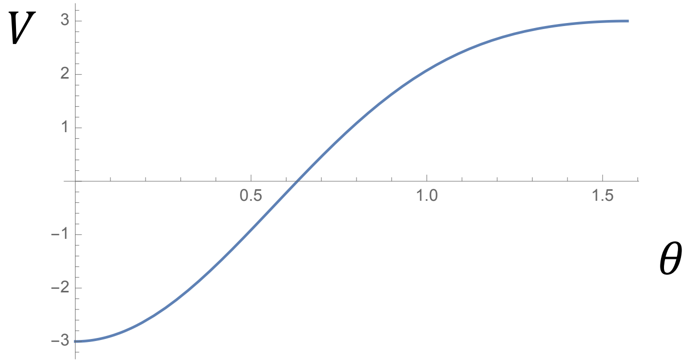
  i. The barrier persists until $T = 0$

  ➢ S_3/T reaches a minimum at a finite T, possible that PT does not complete

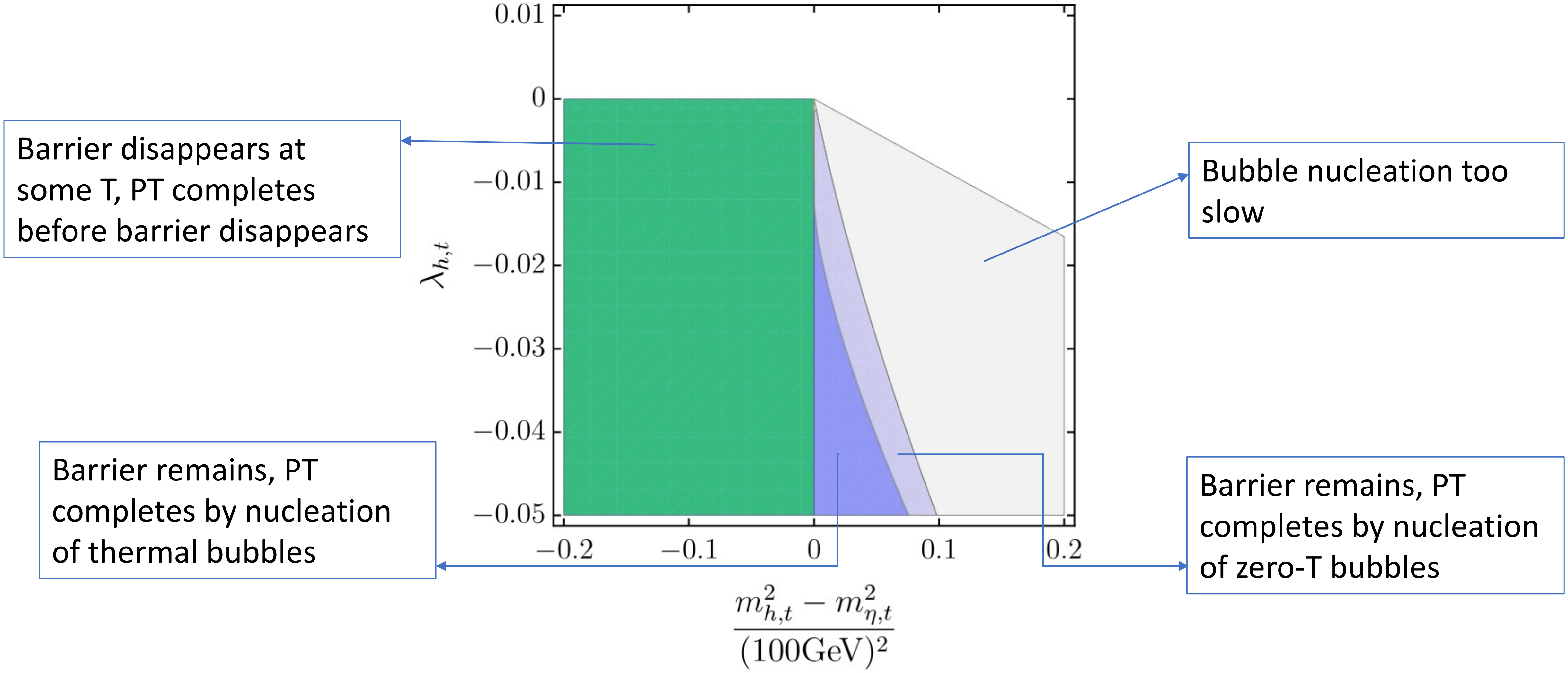
  ii. The barrier disappears before $T = 0$

  ➢ S_3/T approaches zero as barrier shrinks, PT always completes while the barrier is present





Parameter space: Gegenbauer-dominance



Partial compositeness

- Elementary quark fields mixing with operators of the strongly coupled sector:

$$\lambda_{q_i}\, \bar{q}_i O_q^i + \lambda_{d_i}\, \bar{d}_i O_d^i + \lambda_{u_i}\, \bar{u}_i O_u^i$$

- Yukawa couplings: $y_u^i \sim \frac{\lambda_{q_i}\lambda_{u_i}}{g_*}$ $\quad y_d^i \sim \frac{\lambda_{q_i}\lambda_{d_i}}{g_*}$

  ➢ Small difference between operator dimensions generates large flavor hierarchies

- Composite operators O fall in representation of the symmetry group of the strong sector, (e.g of SO(5) in the minimal model)
- Embedding of the elementary quarks in these representation dictates the form of their coupling structure as well as their contribution to the Higgs potential/interactions

EW Precision and Flavor constraints

- Flavor constraint on generic CH with partial compositeness, very strong
- However imposing flavor (and CP) symmetries they can be relaxed: with $g_* \sim 3$, $f \sim 1.5\ \mathrm{TeV}$ could be compatible with bounds

Glioti, Rattazzi, Ricci, Vecchi 2024

- EW precision: $\hat{S} \sim \frac{m_W^2}{m_*^2} \sim 10^{-3}\left(\frac{2.5\ \mathrm{TeV}}{m_*}\right)^2$

Giudice, Grojean, Pomarol, Rattazzi 2008

- With custodial symmetry, $m_* \sim 2-3\ \mathrm{TeV}$ compatible with current bounds

Phenomenology of η

- Coupling to top: $i\, b\, y_t \frac{\eta}{f}\, \bar{t}_L H\, t_R$
- Cross section for production: $\sim \left(\frac{v}{f}\right)^2 \times \sigma_H$ with similar mass SM H
- Branching ratios depend on embeddings, in particular of b (if decay to $t\bar{t}$ not allowed)
- Current bound from $H \to \gamma\gamma$, at $\sim 1/4$-$1/3$ of a SM-like Higgs with similar branching ratios