Electroweak Baryogenesis

LFC24 - Fundamental Interactions at Future Colliders

SISSA

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Based on work in progress
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Baryogenesis

Measured baryon asymmetry

CMB

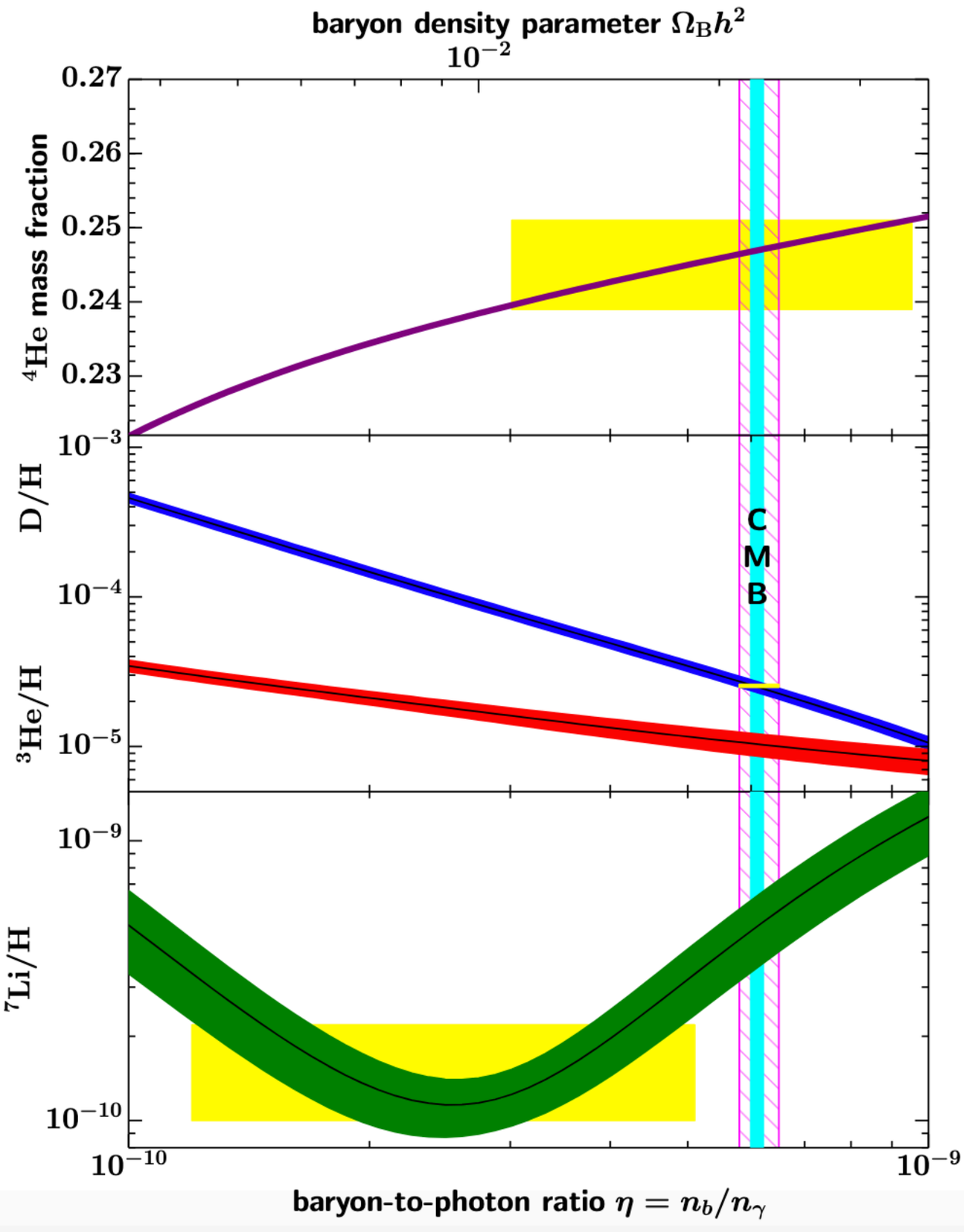
Direct measurement of $\omega_b = \Omega_B h^2 = 0.0222 \pm 0.0001$

gives

$$n_b/n_\gamma = (6.2 \pm 0.2)\, 10^{-10}$$

BBN

Abundance of light elements depend on n_b/n_γ



Baryogenesis

Sakharov conditions

Baryon number violation

Obvious

C and CP violation

Otherwise $\Gamma(X \to ... \to p) = \Gamma(\bar{X} \to ... \to \bar{p})$

Out of thermal equilibrium

Arrow of time (otherwise CPT implies no baryon number)

Baryogenesis

Sakharov conditions

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Out of thermal equilibrium

Arrow of time (otherwise CPT implies no baryon number)

SM not enough: B violation with sphalerons, **not enough CP violation** in CKM, **not enough out of thermal equilibrium**

Need BSM physics!

Interlude - Sphalerons

Baryon number (B) and **Lepton number (L)** are good symmetries of the SM classically

However B+L is anomalous!

Non-perturbative effects **violate B+L in the SM**!

At zero T tunneling effect, exponential suppression -> unobservably small!

At high T, $\Gamma \sim \exp\left[-E_{\rm sphaleron}/T\right]$

with $E_{\rm sphaleron} \sim \frac{m_W}{\alpha} f\left(\frac{m_h}{m_W}\right)$

Roughly speaking for $v/T \gtrsim 1$ **sphalerons are inactive**

Baryogenesis

Some possible scenarios:

Affleck-Dine baryogenesis

Affleck, Dine, ‘85

Scalar field with baryon number violating self-interactions

Starts out with a large vev, rolling produces baryon number

Leptogenesis

Fukugita, T. Yanagida, ‘86

Produce lepton asymmetry through decays, sphalerons reshuffle to baryon asymmetry

In its simplest version points to very high scale of new physics

Electroweak baryogenesis

Kuzmin, Rubakov, Shaposhnikov, ‘85

Baryon number violation from sphalerons

Tied to electroweak phase transition

Electroweak baryogenesis

Why **electroweak baryogenesis**?

Higgs Hierarchy Problem - New physics at the EW scale

Can give rise to necessary CP violation ✓

Can give rise to out of thermal equilibrium
1st order phase transition ✓

(B-violation is present, sphalerons) ✓

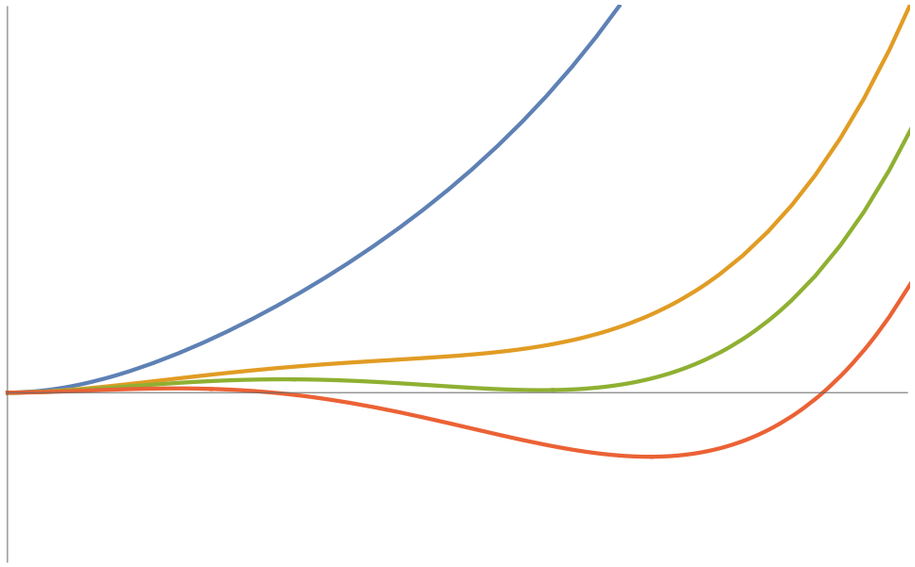
Testable

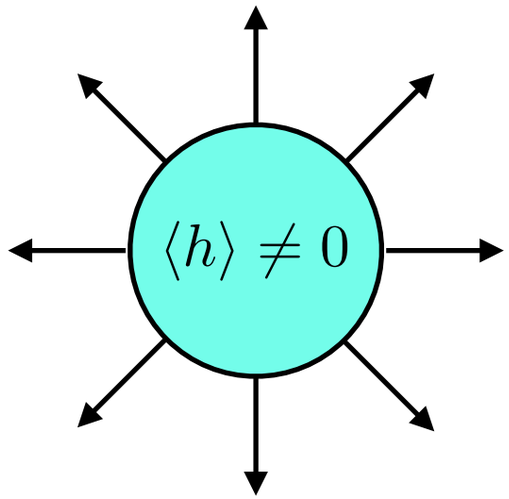
Colliders

Low energy experiments (EDMs)

Electroweak baryogenesis

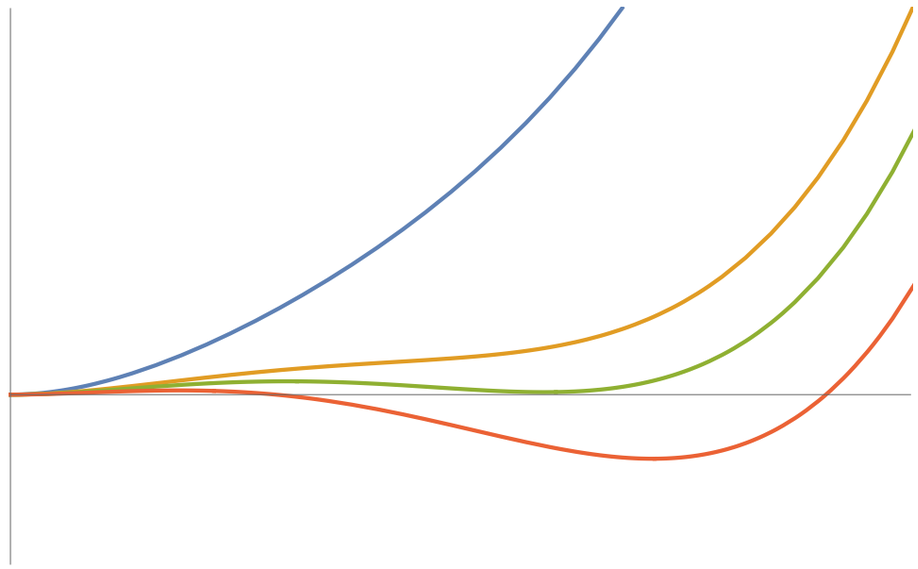
First order EW phase transition

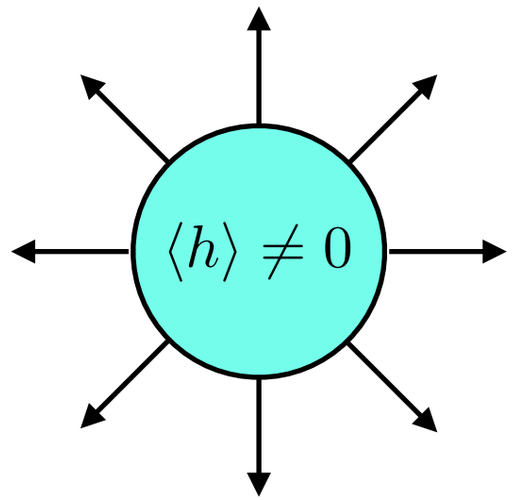




Electroweak baryogenesis

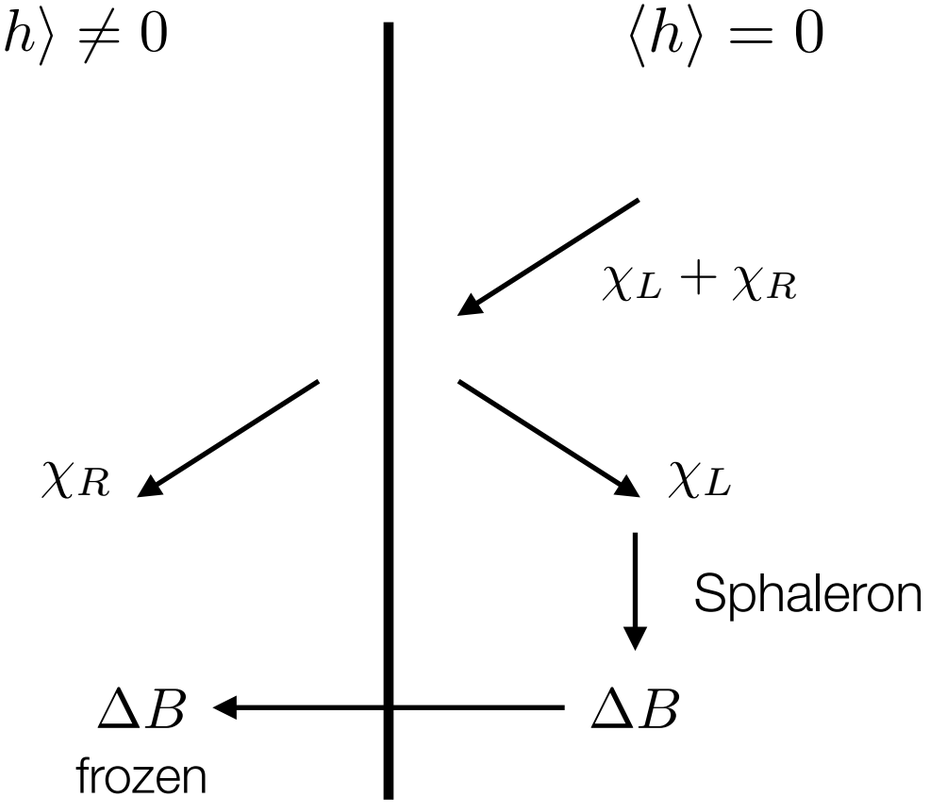
First order EW phase transition





Bubble wall

No sphaleron transitions $\langle h \rangle \neq 0$ $\langle h \rangle = 0$ Sphalerons active



Electroweak baryogenesis - electron EDM

New source of CP violation needed

generically gives rise to EDMs

Strong bounds on electron EDM

$$|d_e| < 4.1 \times 10^{-30}\, e\,\mathrm{cm}$$ Roussy, Caldwell, et al, 2022

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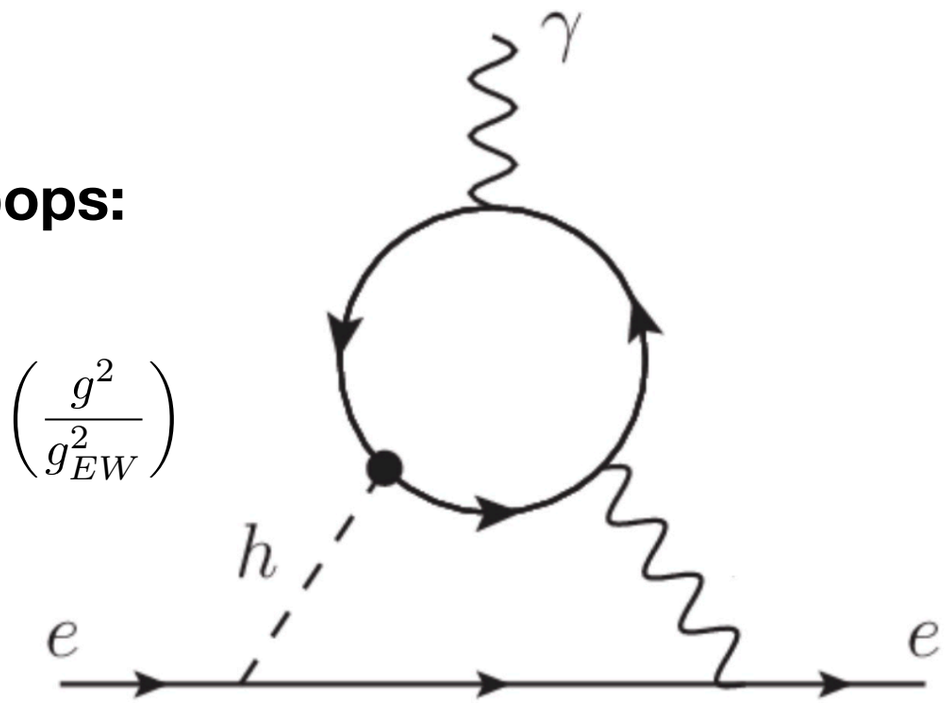
Electron EDM generically generated at two loops:

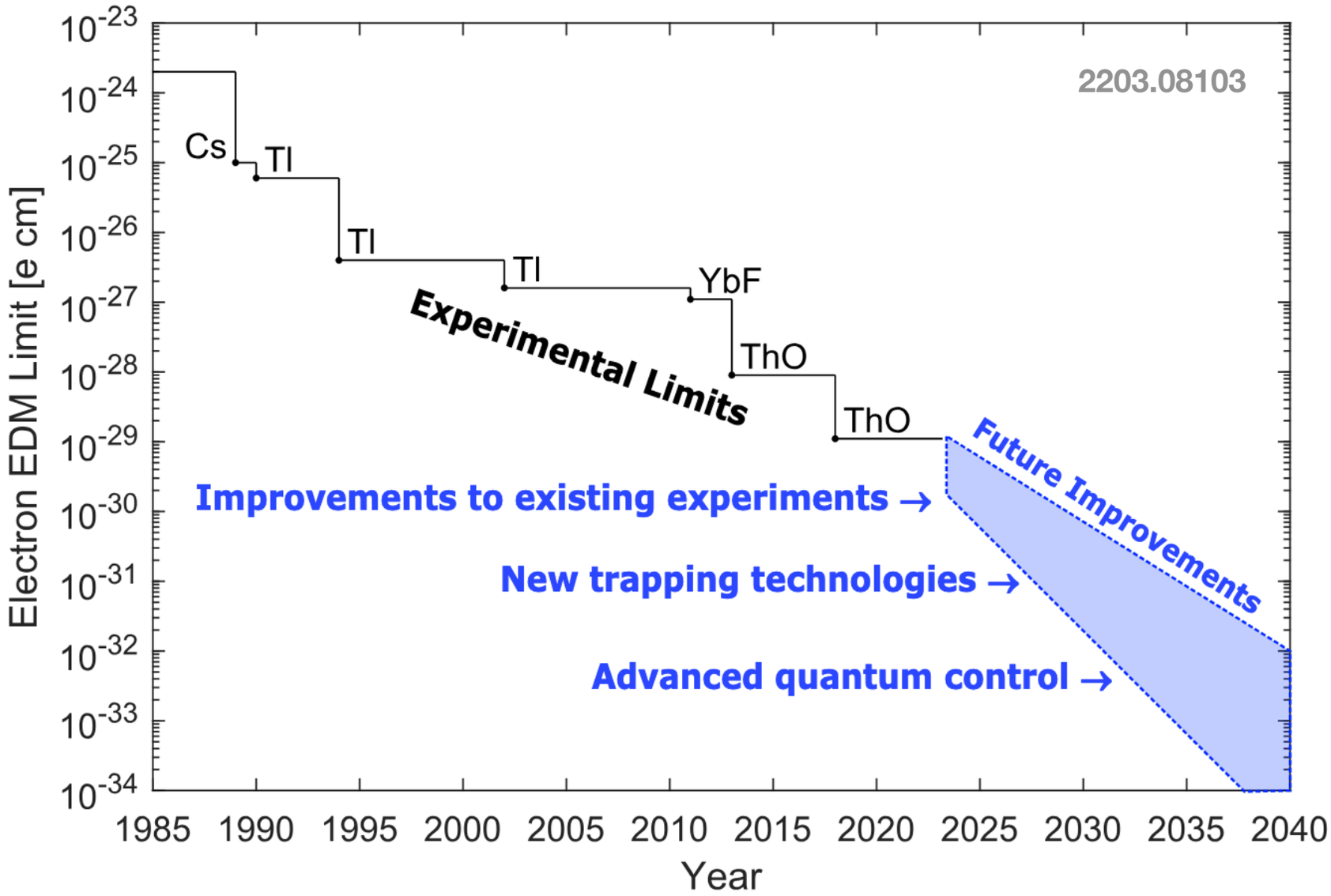
$$\frac{d_e}{e} \sim \delta_{CP} \frac{\alpha}{(4\pi)} \frac{g^2}{(16\pi^2)} \frac{m_e}{M^2} = 4 \times 10^{-30}\,\mathrm{e}\cdot\mathrm{cm} \left(\frac{\delta_{CP}}{0.1}\right) \left(\frac{1\,\mathrm{TeV}}{M}\right)^2 \left(\frac{g^2}{g_{EW}^2}\right)$$

Barr-Zee diagram



Electroweak baryogenesis - electron EDM

Significant future improvements expected



Most models of electroweak baryogenesis won't be probed at a future collider!

Electroweak baryogenesis - avoiding electron EDM

Which models survive?

Electroweak baryogenesis - avoiding electron EDM

Which models survive?

Electroweak symmetry non-restoration

Baldes, Servant 2018
Glioti, Rattazzi & Vecchi 2018
Matsedonskyi, Servant 2020
Matsedonskyi, 2020
...

Electroweak phase transition happens at higher T than expected

CP violating new physics can be heavier → Suppressed electron EDM

Electroweak baryogenesis - avoiding electron EDM

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CP violation to a dark sector

Carena, Quirós, Zhang, 2018

Need a dark sector that has nothing to do with EW hierarchy

CP violation is mediated to visible sector → Suppressed electron EDM

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Spontaneous CP violation

McDonald 1994
McDonald 1995
Comelli, Pietroni & Riotto 1993

CP was only violated in the early unverse (by some expectation value of a pseudo-scalar)

No CP violation today (apart from CKM) → No electron EDM

In Composite Higgs models:
Espinosa Gripaios Konstandin & Riva 2012
De Curtis, Delle Rose & Panico 2019

Electroweak baryogenesis - Spontaneous CP violation

New source of CP violation active during EW phase transition, not active now

Simplest toy model: SM + singlet pseudo-scalar $CP : \eta \to -\eta$

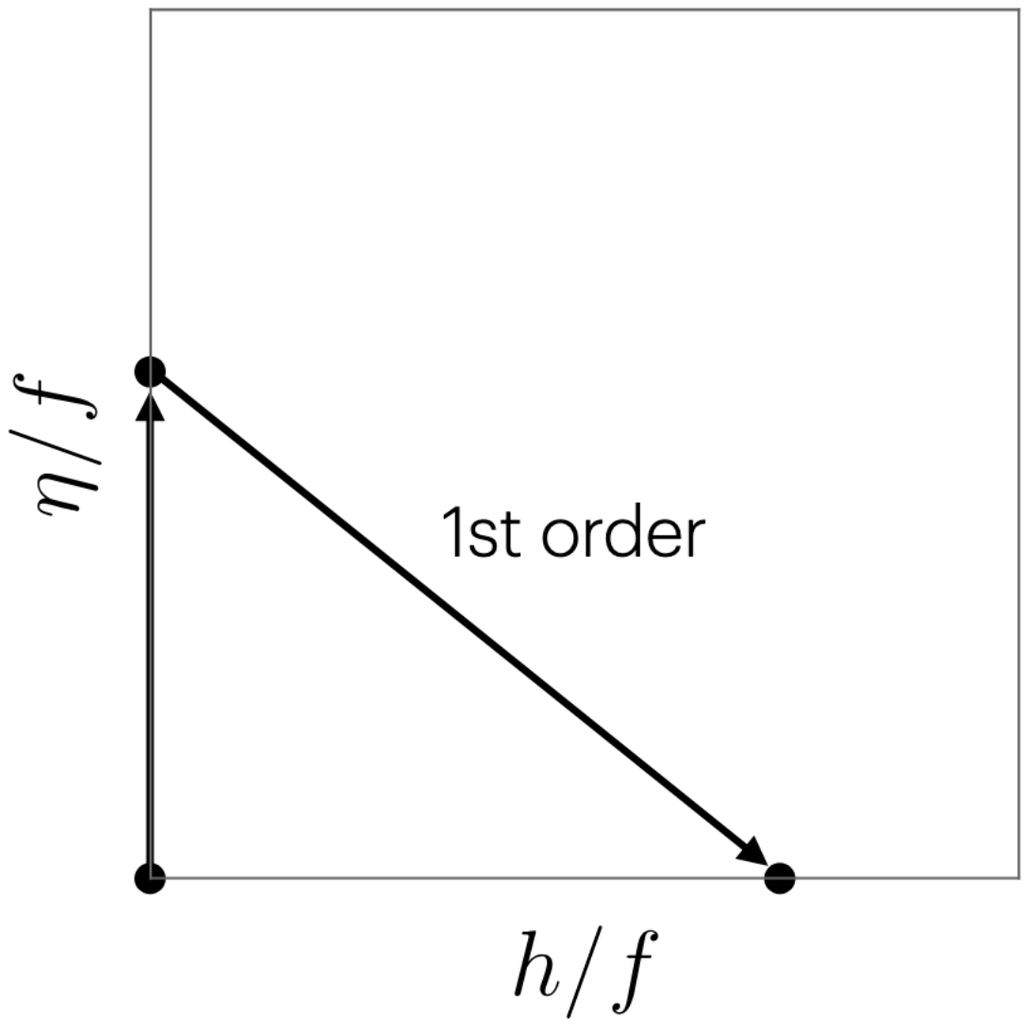
Pseudo-scalar coupling to top quarks: $ib\frac{\eta}{f}\bar{t}_L H t_R$

Singlet coupling to Higgs makes EW phase transition first order $V(\eta, h)$

EW phase transition from $\eta \neq 0, \quad h = 0$ **to** $\eta = 0, \quad h \neq 0$

Electroweak baryogenesis - Spontaneous CP violation

Two step phase transition



Baryon asymmetry generated at the second phase transition

Inside the bubbles of true vacuum sphalerons are not active, baryon number freezes out

Interlude - Composite Higgs

Minimal Composite Higgs

Agashe, Contino, Pomarol 2004

Strongly coupled sector with global SO(5) broken to SO(4)

Gives rise to 4 Goldstone bosons, the 4 components of the Higgs

Analogous to pions in QCD

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Gives rise to 4 Goldstone bosons, the 4 components of the Higgs

Analogous to pions in QCD

$$SO(4) \simeq SU(2)_L \times SU(2)_R$$

SO(5) is not exact -> potential for the Higgs

$SU(2)_L$ and $U(1)_R$ are gauged

Composite - elementary mixing does not respect SO(5)

Fermions embeddings give rise to biggest contribution to the potential

Interlude - Composite Higgs

Power counting the potential

$$V(h) = \frac{3y_t^2}{16\pi^2} g_*^2 f^4 \left(a\frac{h^2}{f^2} + \frac{b}{2}\frac{h^4}{f^4} \right)$$

g_* strong coupling

$a, b \sim O(1)$ expected

Interlude - Composite Higgs

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g_* strong coupling $\qquad$ $a, b \sim O(1)$ expected

Fine tuning from Higgs mass and coupling measurements

$$a = \frac{4\pi^2 m_h^2}{3y_t^2 g_*^2 f^2} \simeq \left(\frac{450\text{GeV}}{m_*} \right)^2 \lesssim O(0.1)$$

$$a/b \sim O(0.1) \quad \text{to have} \quad (v/f)^2 \lesssim 0.1$$

Electroweak baryogenesis - Spontaneous CP violation

Spontaneous CP violation in Composite Higgs Models

Electroweak baryogenesis - Spontaneous CP violation

Spontaneous CP violation in Composite Higgs Models

Minimal Setup:

Symmetry breaking pattern $SO(6)/SO(5)$ leads to 5 pNGBs H, η

Gripaios, Pomarol, Riva, Serra 2009

Automatically leads to coupling to top quarks: $ib\frac{\eta}{f}\bar{t}_L H t_R$

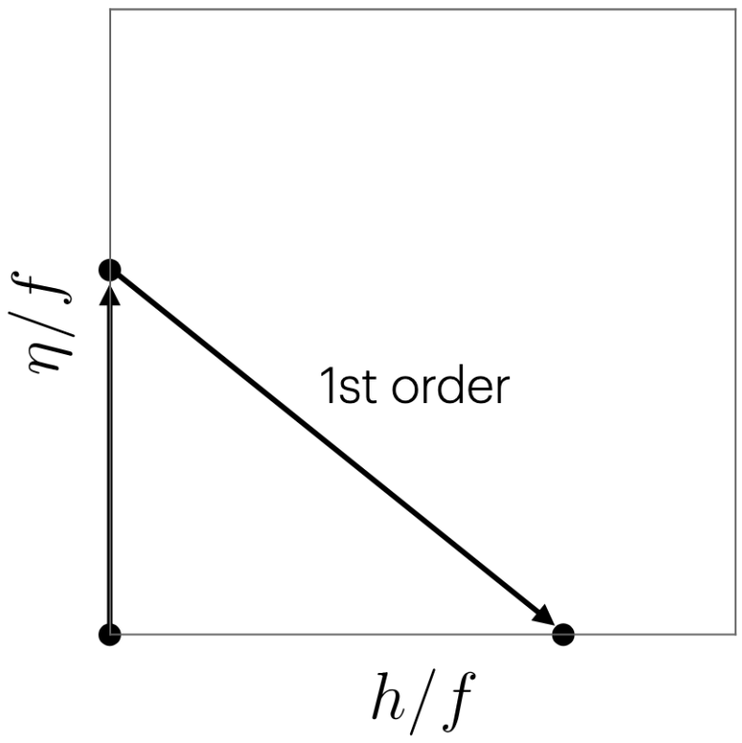
Espinosa Gripaios Konstandin & Riva 2012

Does it lead to right thermal history?

De Curtis, Delle Rose & Panico 2019

Electroweak baryogenesis - Spontaneous CP violation

Spontaneous CP violation in Composite Higgs Models



We want:

$$V(\eta, h) = \mu_\eta^2 \eta^2 + \lambda_{h\eta} \eta^2 h^2 + ...$$

$$\mu_\eta^2 < 0$$

and

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

Electroweak baryogenesis - Spontaneous CP violation

Spontaneous CP violation in Composite Higgs Models

Terms invoving only Higgs: $$V(h) = \frac{3y_t^2}{16\pi^2} g_*^2 f^4 \left(a\frac{h^2}{f^2} + \frac{b}{2}\frac{h^4}{f^4} \right)$$

Nothing changes, minimal tuning with $a \sim 0.1$

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Nothing changes, minimal tuning with $a \sim 0.1$

Terms involving η : There is a U(1) associated with η that can be preserved

Gripaios, Pomarol, Riva, Serra 2009

Potential proportional to breaking of this U(1)

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

η can be light for $\delta_\eta \ll 1$

Electroweak baryogenesis - Spontaneous CP violation

Spontaneous CP violation in Composite Higgs Models

Double tuning issue:

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

For correct thermal history

$$c_\eta \frac{v^2}{f^2} > a_\eta$$

Additional tuning of same size as Higgs tuning…

Electroweak baryogenesis - Spontaneous CP violation

Is this additional tuning necessary?

Electroweak baryogenesis - Spontaneous CP violation

A new parameter in the counting: large charge

Abelian toy model

$$g^2\left(|\phi|^2-f^2\right)^2+\epsilon\frac{g^2}{f^{n-4}}\left(\phi^n+(\phi^*)^n\right)$$

In the IR gives rise to

$$\epsilon g^2 f^4\cos\left(n\frac{\varphi}{f}\right)\sim\epsilon g^2 f^4 n^2\left(\frac{\varphi^2}{f^2}+\frac{n^2}{12}\frac{\varphi^4}{f^4}+\dots\right)$$

Large charge symmetry breaking spurion enhances the higher orders

Minimum of potential at π/n

Electroweak baryogenesis - Spontaneous CP violation

Non-abelian toy model - Gegenbauer polynomials

SO(N+1)/SO(N) breaking

$$g^2\left(|\phi|^2 - f^2\right)^2 + \epsilon\frac{g^2}{f^{n-4}}T_{i_1\ldots i_n}\left(\phi_{i_1}\ldots\phi_{i_n}\right)$$

Spurion T in symmetric-traceless n-index representation

Electroweak baryogenesis - Spontaneous CP violation

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Spurion T in symmetric-traceless n-index representation

Potential for pNGB is a Gegenbauer polynomial

Durieux, McCullough & Salvioni 2021

$$2\epsilon g^2 f^4 G_n^{\frac{N-1}{2}}\left(\cos\frac{\Pi}{f}\right)$$

Again, higher order terms are enhanced by ‘charge’ n

Electroweak baryogenesis - Spontaneous CP violation

Assume a new ‘large charge’ spurion in strong sector that breaks SO(6) explicitly to SO(5)

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

Usual top contribution

new Gegenbauer contribution

$$2\epsilon g^2 f^4 G_n^{\frac{N-1}{2}} \left(\cos\frac{\Pi}{f}\right) \quad \text{with} \quad \Pi = \sqrt{1-h^2-\eta^2}$$

Gives parametrically enhanced mixed quartic!

However need to keep all terms in expansion, cannot truncate

Electroweak baryogenesis - Spontaneous CP violation

First step - Gegenbauer dominated potential

Of course needs more tuning in the Higgs mass, but useful toy example

SO(5) breaking only from now subdominant top contribution

At high T: prefers $h = 0$

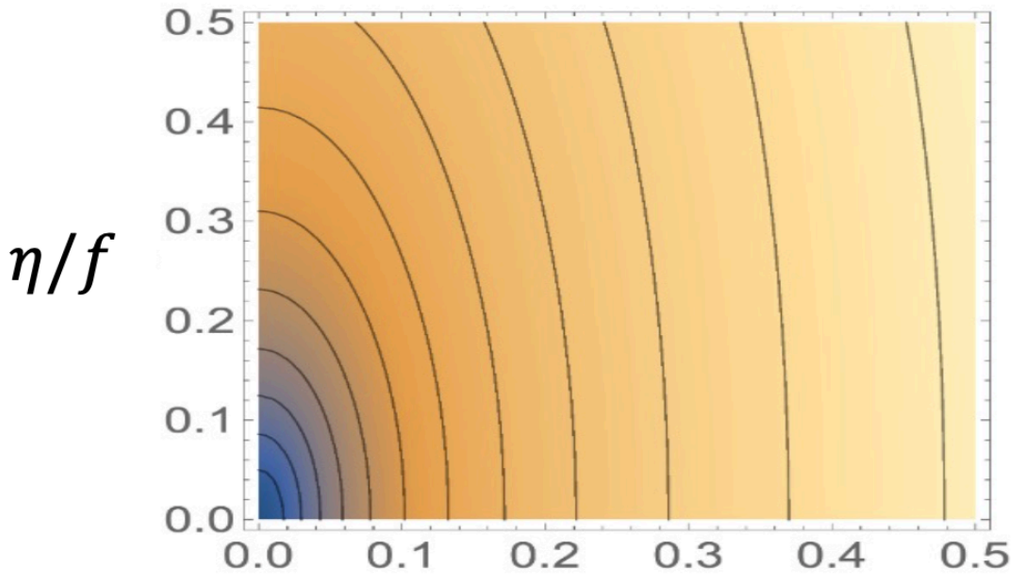
At low T: prefers $h = v$, can directly give $\eta = 0$

Only angular direction imortant for phase transition - easy analytic estimates possible

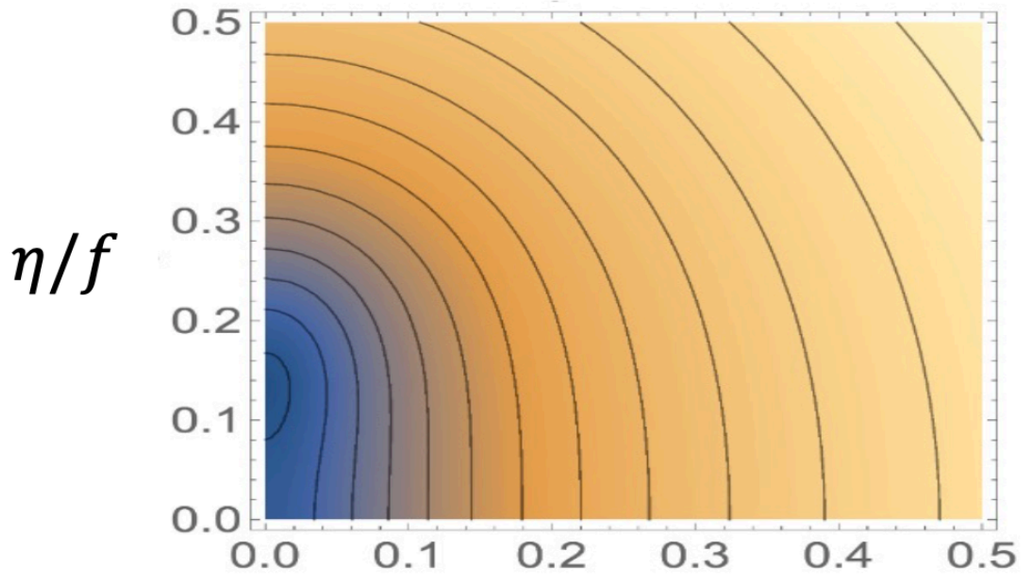
Electroweak baryogenesis - Spontaneous CP violation

Gegenbauer - Thermal history

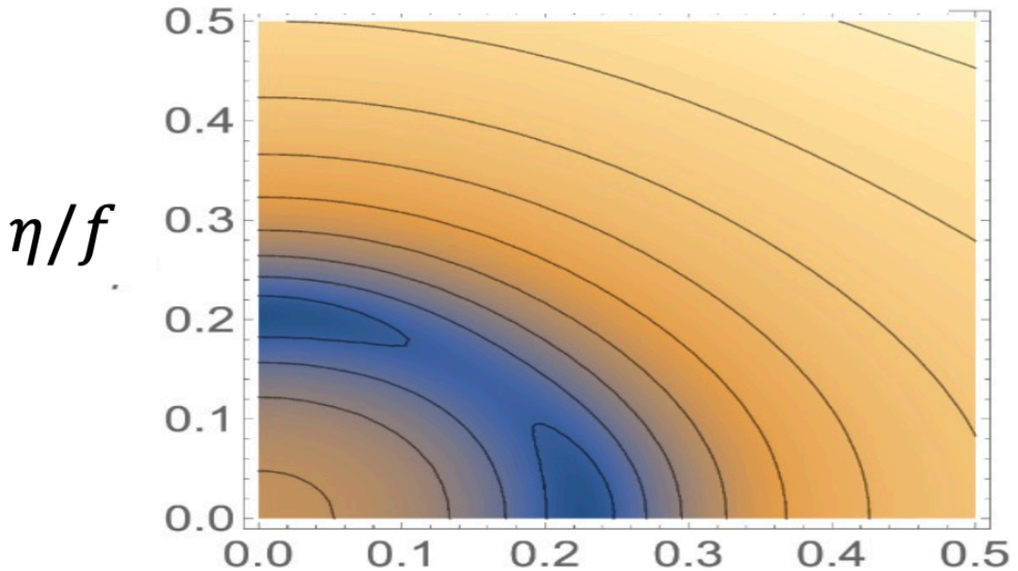
$T > T_s$



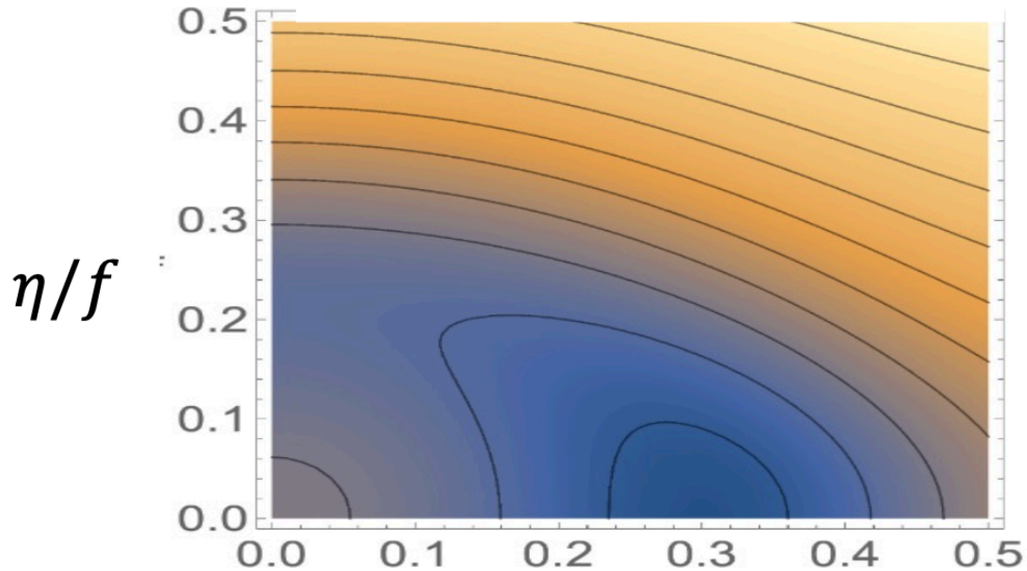
$T_c < T < T_s$



$T = T_c$



$T = 0$



Electroweak baryogenesis - Spontaneous CP violation

Model with minimal tuning - Codominance

Only possible to study numerically

Large charge needed, typically $n \approx 10$, even larger charge needed for improved Higgs coupling measurements

Large enough CP phase, will also be smaller for improved Higgs coupling measurements

Strong enough phase transitions, no washout

No additional tuning on top of 'usual' Higgs tuning $a \sim 0.1$

Electroweak baryogenesis - Spontaneous CP violation

However, large charge implies low cutoff! Hook, Rattazzi 2023

Electroweak baryogenesis - Spontaneous CP violation

However, large charge implies low cutoff!

Hook, Rattazzi 2023

$$\epsilon g^2 f^4 \cos\left(n\frac{\varphi}{f}\right) = \epsilon n^4 g^2 \hat{f}^4 \cos\left(\frac{\varphi}{\hat{f}}\right)$$

Prefactor not very small, comparable to Higgs quartic

Already 2 -> 2 scattering gives cutoff around $4\pi \hat{f} \lesssim \text{few TeV}$

Strongest unitarity bound is dominated by more quanta

Work in progress… but seems that one cannot push too far

Electroweak baryogenesis - Spontaneous CP violation

A different spurion to give a large mixed quartic

Can we write down a spurion that only gives quartics?

Electroweak baryogenesis - Spontaneous CP violation

A different spurion to give a large mixed quartic

Can we write down a spurion that only gives quartics?

Yes, use four index symmetric traceless rep. that breaks SO(5) to SO(4) $T_{i_1 i_2 i_3 i_4}$

$h^4 - 8h^2\eta^2 + 12\eta^4$ doesn't help because of signs…

Signs fixed by tracelessness condition

Electroweak baryogenesis - Spontaneous CP violation

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Signs fixed by tracelessness condition

Do we need traceless?

If not, mass terms appear $T_{i_1 i_2 i_3 i_3}\phi_{i_1}\phi_{i_2}$

Are there models in which these are small?

Electroweak baryogenesis - Spontaneous CP violation

Yes, enlarge symmetry breaking pattern: SO(7)/SO(6)

Now 6 pNGBs, H, η, ρ

Electroweak baryogenesis - Spontaneous CP violation

Yes, enlarge symmetry breaking pattern: SO(7)/SO(6)

Now 6 pNGBs, H, η, ρ

Again two different contributions to the potential

$$V(h,\eta,\rho) = V_t + V_{\rm new}$$

$$V_t(h,\eta,\rho) \supset \frac{3y_t^2}{16\pi^2} g_*^2 f^4 \left(a\frac{h^2}{f^2} + a_\rho \frac{\rho^2}{f^2} + a_\eta \delta_\eta \frac{\eta^2}{f^2} \right)$$

$$V_{\rm new} = \epsilon g_*^2 \left[(h^2+\eta^2)^2 - 14(h^2+\eta^2)\rho^2 - \frac{35}{3}\rho^4 \right]$$

Electroweak baryogenesis - Spontaneous CP violation

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$$V_{\rm new} = \epsilon g_*^2 \left[(h^2+\eta^2)^2 - 14(h^2+\eta^2)\rho^2 - \frac{35}{3}\rho^4 \right]$$

without additional tuning: $m_\rho \gg m_h$

Integrate out $\langle\rho\rangle = 0$ to find

$$V_{\rm new} = \epsilon g_*^2 (h^2+\eta^2)^2$$

However loops induce a mass term for both h & η

$$\Delta V \sim \frac{\epsilon g_*^2}{16\pi^2}(h^2+\eta^2)m_\rho^2$$ Small enough…

Electroweak baryogenesis - Spontaneous CP violation

A different spurion can give a large mixed quartic!

Needed to enlarge symmetry breaking pattern

Gives rise to a small contribution to masses of $h \,\&\, \eta$

Solves the double tuning problem, again only minimal Higgs tuning left

Predicts a new light(ish) scalar with $m_\rho \sim 800\,\mathrm{GeV}\left(\frac{m_*}{4\,\mathrm{TeV}}\right)$

Electroweak baryogenesis - Spontaneous CP violation

Collider signatures

Electroweak baryogenesis - Phenomenology of solutions to Hierarchy problem

Some specific signatures:

Light pseudoscalar: $m_\eta \sim m_h$ with significant top couplings $ib\frac{\eta}{f}\bar{t}_L H t_R$

Large charge:

Low cutoff!

Lots of new physics closeby

SO(7)/SO(6):

Another pseudoscalar, however heavier!

Conclusions

Electroweak baryogenesis is an intriguing possibility to generate baryon asymmetry

Tightly connected to the EW hierarchy problem

Current and future electron EDM measurements tightly constrain model space

Assessment of models that will survive electron EDM measurements

Realization in Composite Higgs

Simplest models have a double tuning problem

Explored different ways to solve this with new symmetry breaking spurious