New Physics and the High Scale EW phase transition

Iason Baldes
In collaboration with Géraldine Servant

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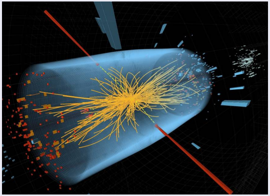
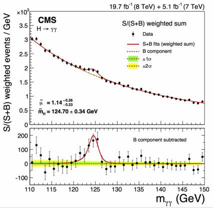
Rencontres de Blois
June 4 2019

2012. Discovery of the Brout Englert Higgs boson





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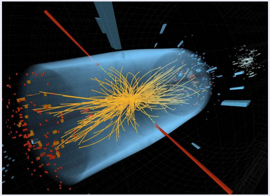

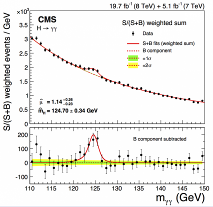

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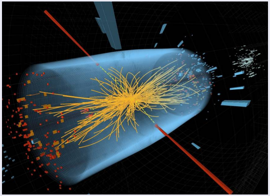

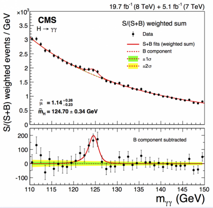

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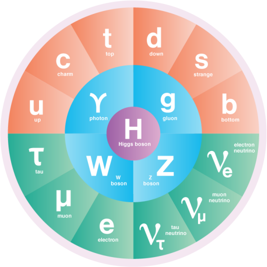

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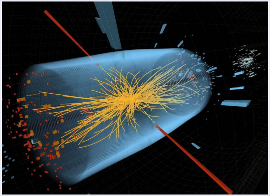

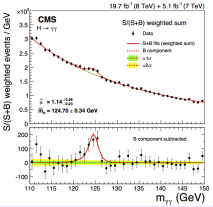

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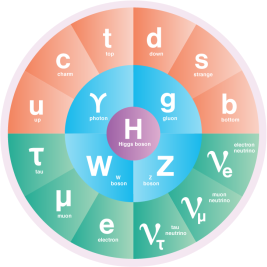
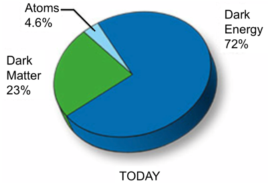
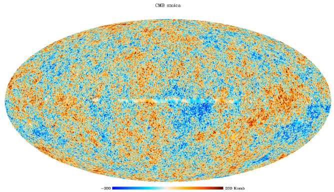




But cannot explain the observed content of the Universe

Baryogenesis Mechanisms



CMB (in agreement with BBN):

$$Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (0.86 \pm 0.02) \times 10^{-10}$$

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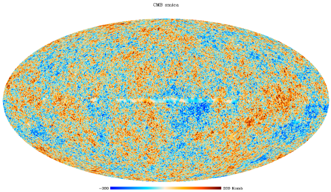

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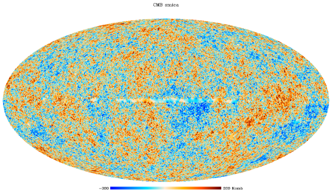

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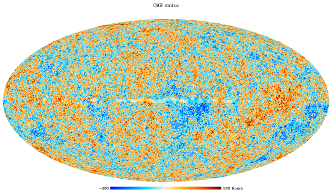

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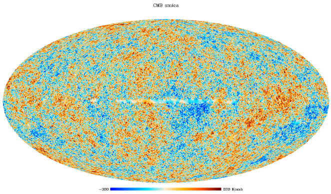

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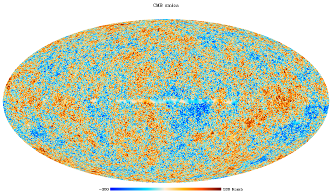

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→ Focus here is on EW baryogenesis

Electroweak baryogenesis - basic picture

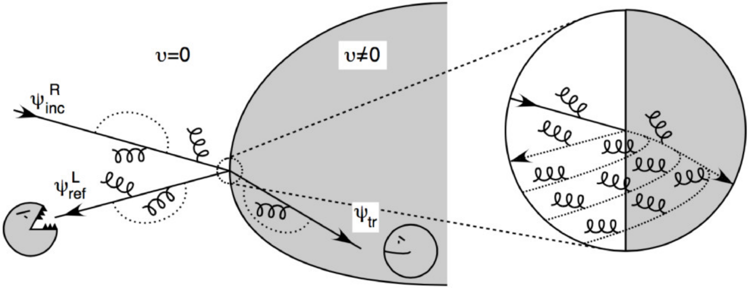
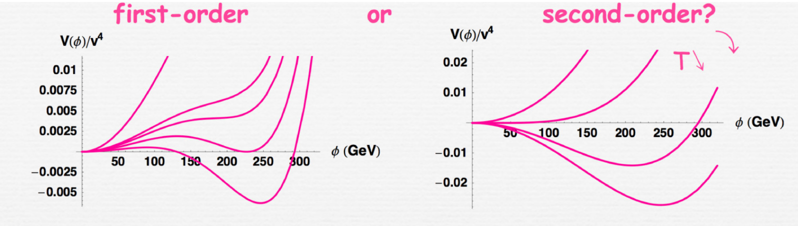


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- CP violating collisions with the bubble walls lead to a chiral asymmetry.
- Sphalerons convert this to a Baryon Asymmetry.
- This is swept into the expanding bubble where sphalerons are suppressed.

Electroweak baryogenesis - Requirements



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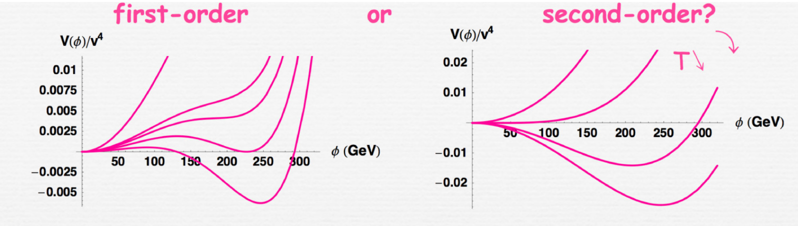

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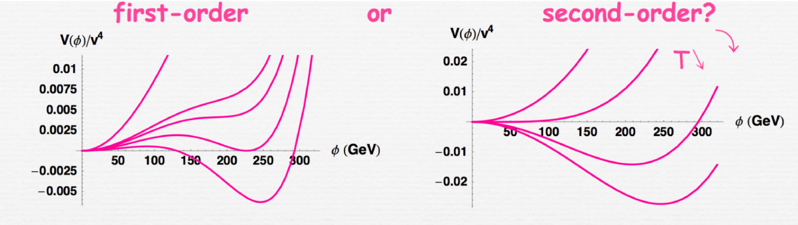

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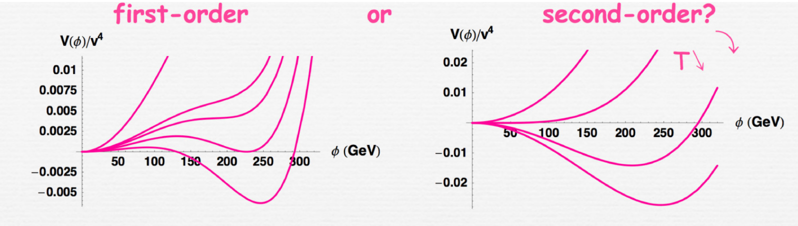

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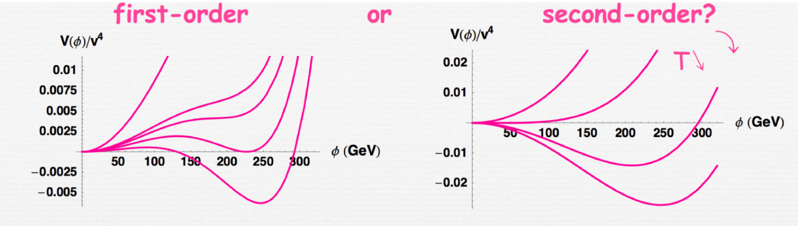

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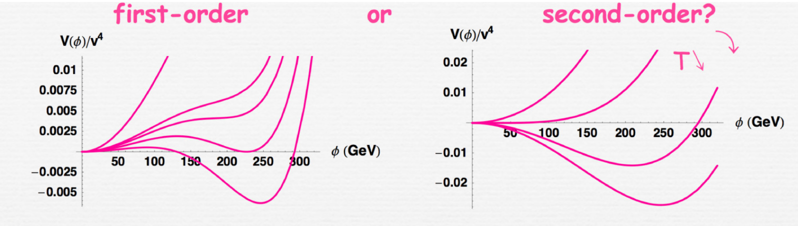

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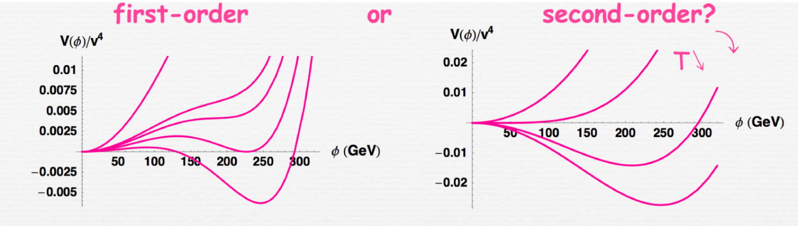

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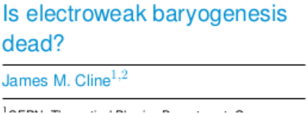
We require new EW-scale physics!

CP violation constrained by EDMs - Situation 2013-2018

ACME: $|d_e| < 8.7 \times 10^{-29}\ e\,\mathrm{cm}$ (2013) $|d_e| < 9.4 \times 10^{-29}\ e\,\mathrm{cm}$ (2017)



Is electroweak baryogenesis dead?

James M. Cline[1,2]

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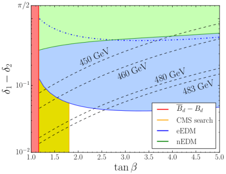

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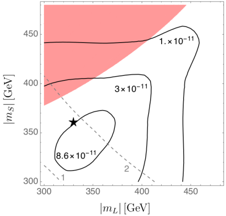

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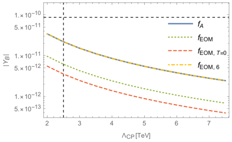

① 1611.05874 - Dorsch, Huber, Konstandin, No

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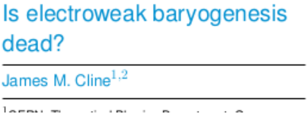

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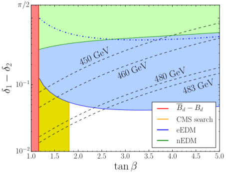

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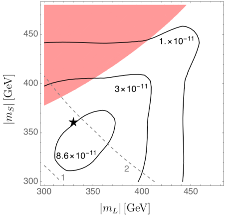

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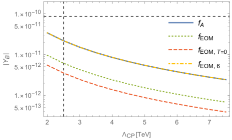

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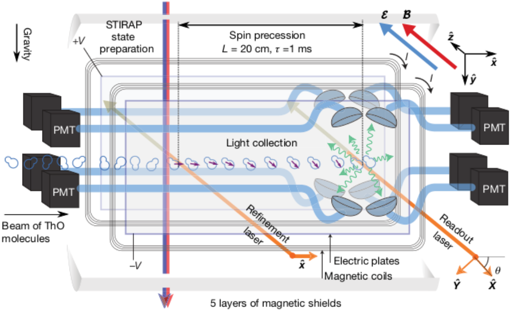
Severe constraint on EWBG!

EDMs - Situation after 18.10.2018

$$\text{ACMEII: } |d_e| < 1.1 \times 10^{-29}\ e\,\mathrm{cm}.$$



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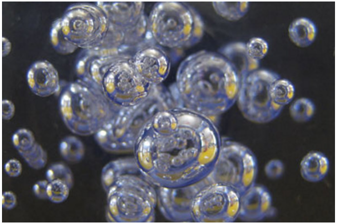
Highscale Electroweak Baryogenesis



Bold approach here:

- Lift **electroweak** baryogenesis from the **electroweak** scale.

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We will now take a novel approach and push the EWBG scale up to the flavour scale.

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Warning: large N ahead.

We will see (3) requires new (but different) physics at the EW scale.

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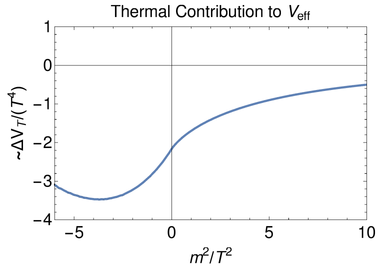


New scalar field with mass

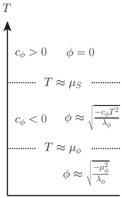
$$m_\chi^2 = \mu_\chi^2 + \frac{1}{2}\lambda_{\phi\chi}\phi^2 + 3\lambda_\chi\chi^2.$$

Take $\lambda_{\phi\chi} < 0$.

$$c_\phi T^2 \approx \left(\frac{\lambda_\phi}{2} + \frac{3g_2^2}{16} + \frac{g_Y^2}{16} + \frac{1}{4}y_t^2 + N_{\rm dof}\frac{\lambda_{\phi\chi}}{24}\right)T^2 < 0$$

$$\Longrightarrow \langle\phi\rangle = \sqrt{-\frac{c_\phi}{\lambda_\phi}}T!$$

Toy Example - Numerical analysis



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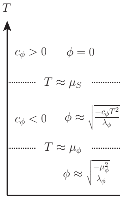

T

$c_\phi > 0 \quad \phi = 0$

$T \approx \mu_S$

$c_\phi < 0 \quad \phi \approx \sqrt{\frac{-c_\phi T^2}{\lambda_\phi}}$

$T \approx \mu_\phi$

$\phi \approx \sqrt{\frac{-\mu_\phi^2}{\lambda_\phi}}$

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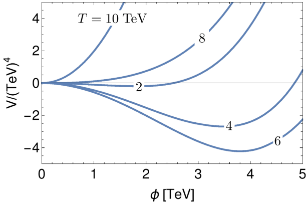
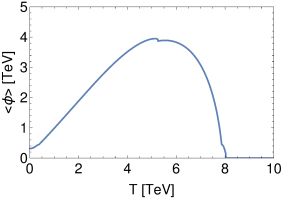
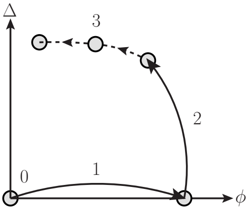




$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)$$

Complete Model



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1. flavour sector (new fermions + scalar)
2. scalar potential with higher dimensional operators
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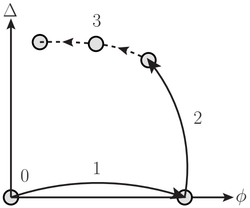

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The analysis

- Phase Transitions
- Pheno
- IR sector + Constraints

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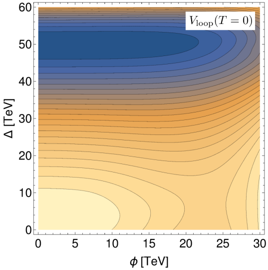
In our analysis we consider the UV flavour picture - details suppressed here.

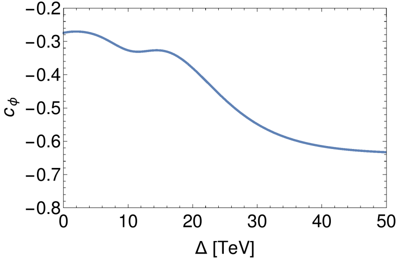
The Scalar Potential



$$V(\phi,\Delta) = \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_{\phi\Delta}}{4}\phi^2\Delta^2 + \frac{\mu_\Delta^2}{2}\Delta^2 + \frac{\lambda_\Delta}{4}\Delta^4 + \frac{1}{8\Lambda_a^2}\Delta^6 + \frac{1}{8\Lambda_b^2}\phi^2\Delta^4 + \frac{1}{8\Lambda_c^2}\phi^4\Delta^2 + \frac{1}{8\Lambda_d^2}\phi^6.$$

$$v_\Delta = 50\ \mathrm{TeV}, \qquad \lambda_{\phi\Delta} = -0.05, \qquad \lambda_\Delta = -0.23,$$
$$\Lambda_a = \Lambda_d = 100\ \mathrm{TeV}, \qquad \Lambda_b = \Lambda_c = 300\ \mathrm{TeV}.$$

Symmetry Non-restoring sector

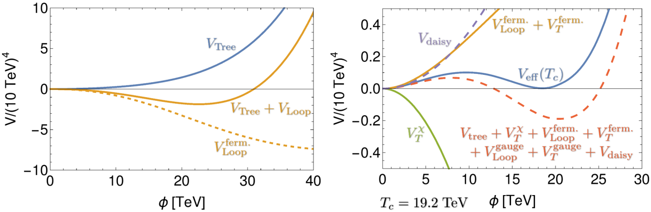


We add a few extra scalar degrees of freedom.

$$V(\phi,\chi)=\frac{\lambda_{\phi\chi}}{4}\phi^2\sum_{i=1}^{N_{\mathrm{Gen}}}\chi_i^2+\frac{\mu_\chi^2}{2}\sum_{i=1}^{N_{\mathrm{Gen}}}\chi_i^2+\frac{\lambda_\chi}{4}\sum_{i=1}^{N_{\mathrm{Gen}}}\chi_i^4$$

$$N_{\mathrm{Gen}}=2000,\qquad N_{\chi i}=1,\qquad \lambda_\chi=0.7,\qquad \lambda_{\phi\chi}=-0.012.$$

The EWPT



$$\frac{\Gamma}{V} \sim T^4 \, \mathrm{Exp}\left(-\frac{S_3}{T}\right)$$

Bubbles nucleate when

$$\frac{S_3}{T_n} \approx 4 \, \ln\left(\frac{T_n}{H}\right)$$

Thermal Evolution

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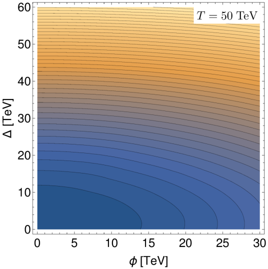

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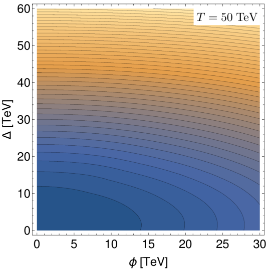

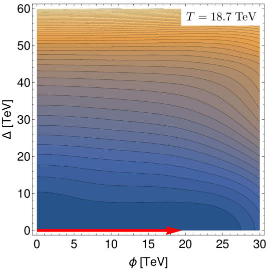

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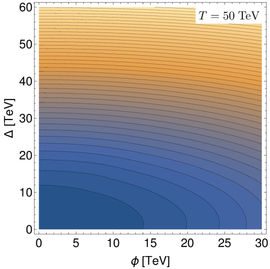

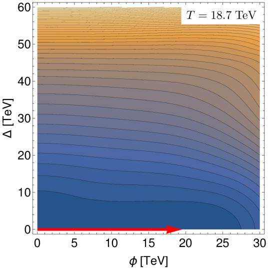

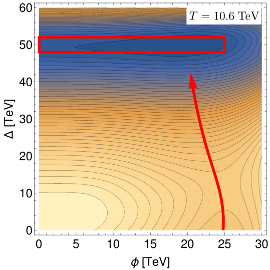

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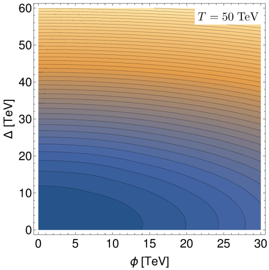
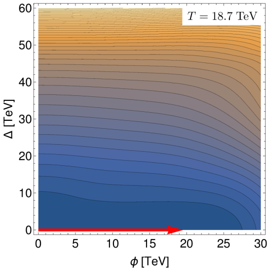
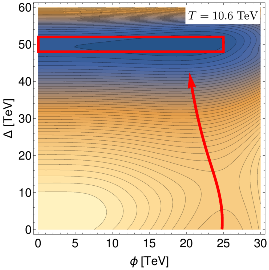
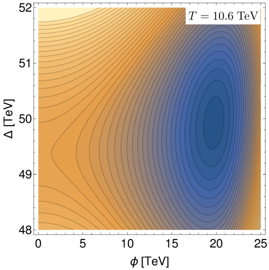
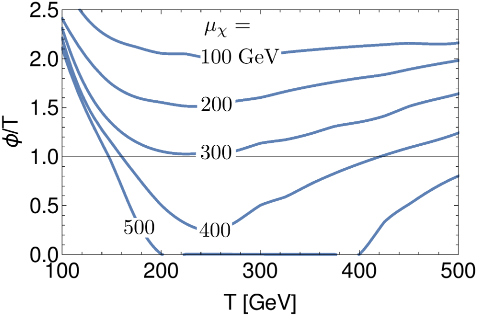








Scalar Sector in the IR



Spectrum of states with masses

$$m_{\chi_i}^2 \sim \mathcal{O}(\mu_\chi^2 + \lambda_{\phi\chi} v_\phi^2/2)$$

Constraints:

$$63\ \mathrm{GeV} \lesssim m_{\chi_i} \lesssim 300\ \mathrm{GeV}$$

Conclusions

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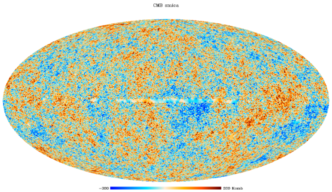
- Still somewhat at the "proof of principle" stage.
- Other options for protecting the BAU may also be possible.

Also see:

- "Unrestored EW symmetry," Meade and Ramanim, 1807.07578.
- "Electroweak Baryogenesis above the Electroweak Scale," Glioti, Rattazzi, Vecchi, 1811.11740.

The matter-antimatter asymmetry



CMB (in agreement with BBN):

$$Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (0.86 \pm 0.02) \times 10^{-10}$$

- In a symmetric universe $n_b/s = n_{\bar{b}}/s \approx 10^{-20}$
- The post-inflation causal volume is too small for baryons/antibaryons to be sufficiently separated
  ($n_b/s = n_{\bar{b}}/s \approx 10^{-10}$ would be reached at $T \approx 40$ MeV when $M_{H^{-3}} \approx 10^{-7} M_\odot$).
- Need a mechanism to generate the asymmetry

Baryogenesis

Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from thermal equilibrium (or spontaneously broken CPT)

SM + FLRW

1. (B+L) violation present in symmetric phase at $T \gtrsim 100$ GeV from non-perturbative EW sphaleron process.
2. CP violation observed in quark sector (but not strong enough).
3. Can be driven by expansion (but SM EW phase transition is a crossover).

Almost there...

Flavour sector - UV picture

In the UV completion add vector-like quarks

These transform as u_R under the SM gauge group. Superscript gives FN charge.

$$G^0_{L,R} \qquad G^1_{L,R} \qquad G^2_{L,R}$$

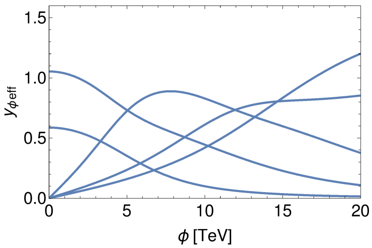
Δ is another scalar which (partially) controls the FN quark mass

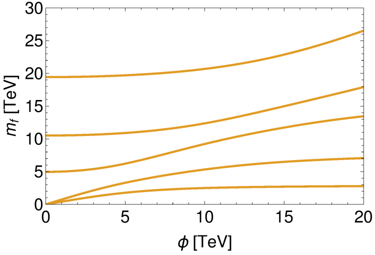
$$\mathcal{L} \supset (M+\Delta)\bar{G}^i_R G^i_L. \qquad \text{We take } M \sim a_s.$$

$$\frac{1}{\sqrt{2}}\begin{pmatrix}\bar{G}^0_R\\ \bar{G}^1_R\\ \bar{G}^2_R\\ \bar{t}_R\\ \bar{c}_R\end{pmatrix}^T \begin{pmatrix} a_s+\Delta & a_s & 0 & \phi & 0\\ a_s & a_s+\Delta & a_s & 0 & 0\\ 0 & a_s & a_s+\Delta & 0 & \phi\\ a_s+\Delta & a_s & 0 & \phi & 0\\ a_s & 0 & 0 & 0 & 0\end{pmatrix}\begin{pmatrix}G^0_L\\ G^1_L\\ G^2_L\\ t_L\\ c_L\end{pmatrix}$$

$$\epsilon \approx a_s/v_\Delta \approx 1/5$$

Effective Yukawa Couplings



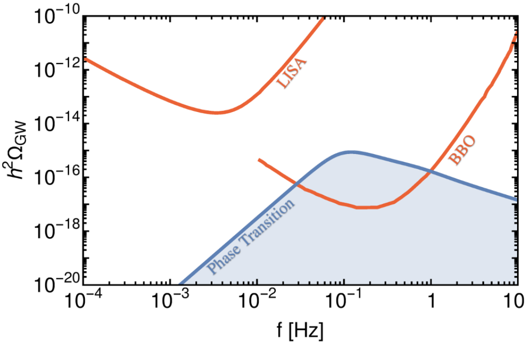


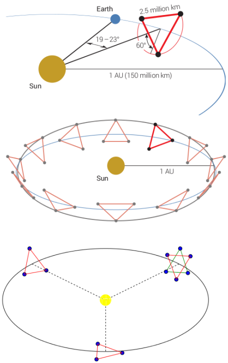
Effective Yukawa couplings

$$y^{\text{eff}}_{f\phi} = \sqrt{2}\frac{\partial m_f}{\partial \phi}, \qquad y^{\text{eff}}_{f\Delta} = \sqrt{2}\frac{\partial m_f}{\partial \Delta}.$$

For $v_\Delta \lesssim a_s$ the Yukawa couplings are large.

Gravitational wave signal





$$\frac{\beta}{H} \equiv T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)\bigg|_{T_n} \approx 180 \qquad \alpha \equiv \frac{\rho_{\text{vac}}(\text{false}) - \rho_{\text{vac}}(\text{true})}{\rho_{\text{rad}}} \approx 8 \times 10^{-3}$$

Avoiding χ_i overabundance

Options

1. The χ_i annihilate into hidden sector.
2. The χ_i decay into lighter states.

Option 2. The χ_i decay into light SM dof.

$$V \supset -\sum_i a_{\chi_i}^3 \chi_i \implies v_{\chi_i} \sim \frac{a_{\chi_i}^3}{m_{\chi_i}^2}$$

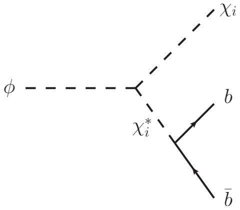
$$\text{Mixing:} \qquad \theta_i \approx \frac{\lambda_{\phi\chi} v_\phi v_{\chi_i}}{m_{\chi_i}^2 - m_\phi^2}.$$

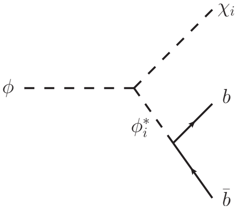
$$10^{-6} \lesssim |\theta_i| \lesssim 10^{-4} \left(\frac{2000}{N_{\mathrm{Gen}}}\right).$$

Bounded by BBN and the Higgs signal strength.

Exotic EW Higgs Decays

More decay channels open for the EW Higgs





But these are negligible

$$\sum_i \Gamma(\phi \to \chi_i^* \chi_i \to \bar{b} b \chi_i) \sim \frac{3 N_{\mathrm{Gen}} \lambda_{\phi\chi}^2 \theta_i^2 m_b^2}{128\pi^3 m_\phi} \sim 10^{-10}\ \mathrm{MeV}$$

$$\sum_i \Gamma(\phi \to \phi^* \chi_i \to \bar{b} b \chi_i) \sim \frac{3 N_{\mathrm{Gen}} \lambda_{\phi\chi}^2 v_{\chi_i}^2 m_b^2}{128\pi^3 v_\phi^2 m_\phi} \sim 10^{-7}\ \mathrm{MeV}$$