Cosmological evolution of Yukawa couplings: the 5D perspective

Benedict von Harling

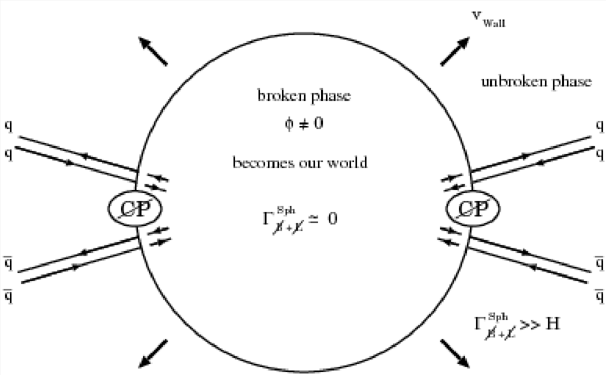
DESY

in collaboration with Géraldine Servant

1612.02447

Motivation: Electroweak baryogenesis

figure from hep-ph/0205279



- Appealing scenario to generate baryon asymmetry of the universe
- *CP*-violating effects in bubble wall create *CP*-asymmetry
- Then turned into baryon asymmetry by sphalerons in front of wall
- Then swept inside bubble where sphalerons are inactive

Electroweak baryogenesis in Randall-Sundrum models

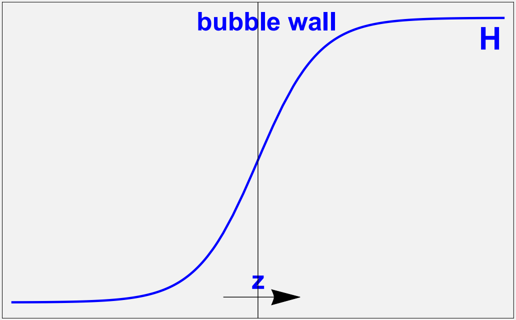
- But electroweak baryogenesis does not work in SM because
  - a) EW phase transition not first-order
  - b) *CP*-violation from CKM too small
- Here consider SM embedded into 5-dimensional warped space, the so-called Randall-Sundrum model
  - EW phase transition typically strongly first-order in RS
    $\Rightarrow$ solves problem a)
    (see also talk by Jay Hubisz)
  - This talk: Solution to problem b) in RS
    (see also talks by Sebastian Bruggisser and Géraldine Servant)
- Minimal extension: Only requires Yukawa coupling between fields already present in RS (Goldberger-Wise scalar and bulk fermions)
- Bonus: Alleviates flavour constraints on RS models

CP-violation from varying Yukawas

New source of CP-violation in transport equation:

$$S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger M^{\dagger''} M\, V\right]$$

[S. Bruggisser, T. Konstandin, G. Servant, to appear]



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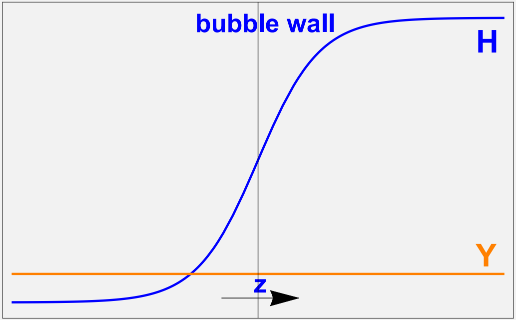

- $M = {\color{red}Y}\, H(z) \quad \Rightarrow \quad S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger Y^\dagger Y\, V\right] = 0$

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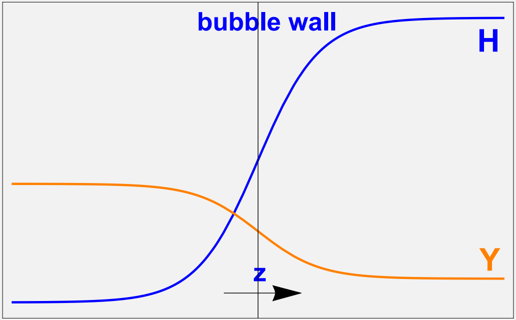

- $M = Y\, H(z) \quad \Rightarrow \quad S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger Y^\dagger Y\, V\right] = 0$
- $M = Y(z)\, H(z) \quad \Rightarrow \quad S_{\not{C}\not{P}} \neq 0$

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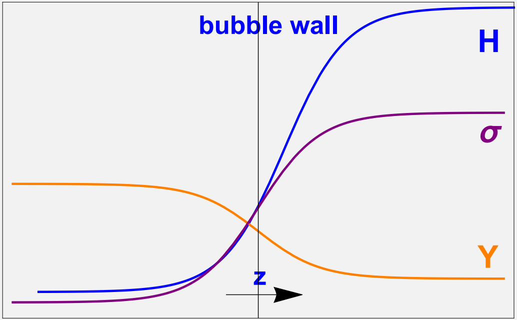
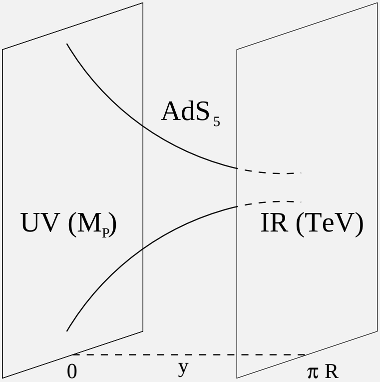


- $M = Y\, H(z) \quad \Rightarrow \quad S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger Y^\dagger Y\, V\right] = 0$
- $M = Y(z)\, H(z) \quad \Rightarrow \quad S_{\not{C}\not{P}} \neq 0$
- Here: $Y = Y(\sigma(z)) \neq$ const. , where σ is the radion

Recap of the Randall-Sundrum model

figure from arXiv:1008.2570



- Metric given by (AdS_5):

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

- 5th dimension bounded by 2 branes at $y = 0$ and $y = y_{\rm IR}$

Recap of the Randall-Sundrum model

- To stabilize extra dimension, introduce scalar field with slowly varying VEV (Goldberger-Wise mechanism):

$$\langle \phi \rangle \simeq v_{\mathrm{UV}} e^{-\epsilon k y}$$

$\Rightarrow$ Potential for radion $\sigma = e^{-k y_{\mathrm{IR}}}$ (RHS in potential below, $\mu \leftrightarrow \sigma$)

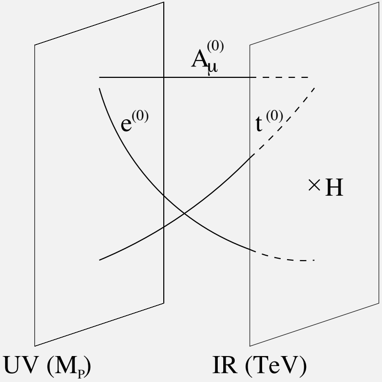
- Temperatures $T \gg e^{-k y_{\mathrm{IR}}} M_P \sim$ TeV $\Rightarrow$ geometry deformed to AdS -Schwarzschild (LHS in potential below, T_h horizon temperature)
- When universe cools to $T \sim$ TeV $\Rightarrow$ phase transition from AdS-Schwarzschild to AdS_5 with IR brane

figure from hep-th/0107141

Recap of the Randall-Sundrum model

- Higgs localized on IR brane $\Rightarrow$ solves (most of) hierarchy problem
- Fermions and gauge bosons live in bulk
- Different localization of fermions generates hierarchy in Yukawas, small if near UV brane (e.g. electron) and large if near IR brane (e.g. top)

figure from 1008.2570



Generation of the fermion mass hierarchy

- Mass term of bulk fermions:

$$S \supset -\int d^5x\sqrt{g}\, c\, k\, \overline{\psi}\psi$$

- Wavefunction of massless fermion KK:

$$f^{(0)}(y) = \mathcal{N}_c^{(0)}\, e^{(2-c)\, ky}$$

$\Rightarrow$ Overlap with IR brane depends exponentially on c!

- 5D Yukawa couplings on IR brane:

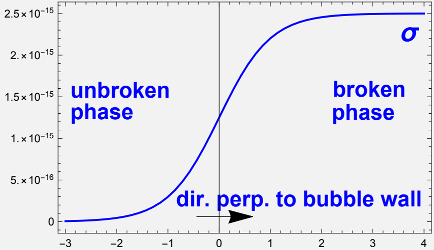
$$S \supset \int d^5x\, \sqrt{g}\, \delta(y - y_{\mathrm{IR}})\lambda\, \tilde{H}\bar{\psi}_L\psi_R$$

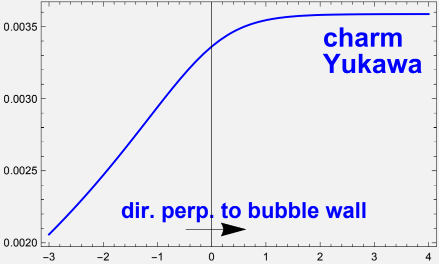
$\Rightarrow$ 4D Yukawa couplings given by (depends on radion $\sigma \equiv e^{-ky_{\mathrm{IR}}}$!):

$$y(\sigma) = \lambda\sqrt{\frac{1-2c_L}{1-\sigma^{1-2c_L}}}\sqrt{\frac{1-2c_R}{1-\sigma^{1-2c_R}}}$$

- Fermions localized near UV (IR) brane for $c > 1/2$ ($c < 1/2$)

Variation of Yukawas across the bubble wall

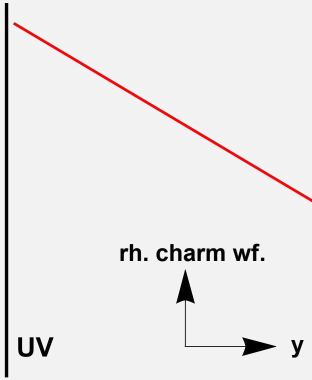




$\Rightarrow$ Yukawas decrease along bubble wall

$\Rightarrow$ not enough CP-violation from $S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger M^{\dagger''} M\, V\right]$

Why do Yukawas decrease across the bubble wall?



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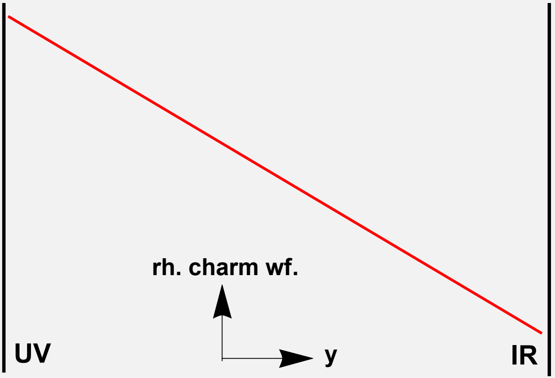

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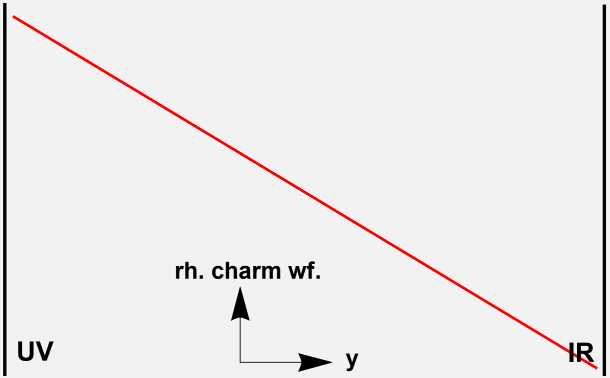
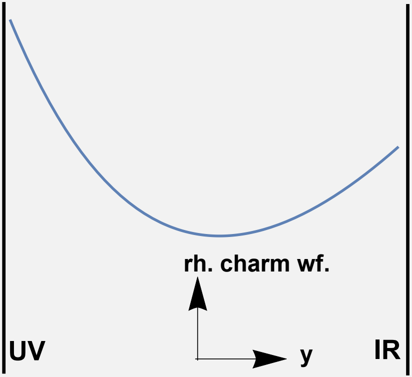


A wavefunction like this would be much better:



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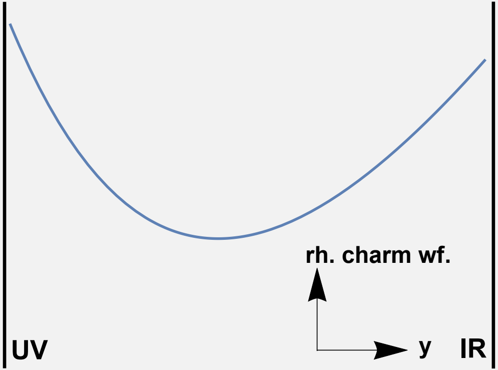

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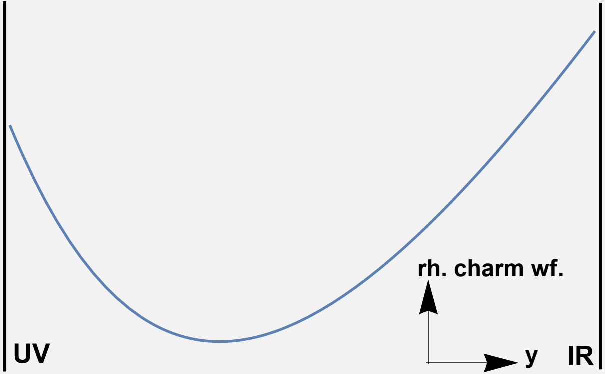


Modified fermion profiles from Goldberger-Wise

- Use Goldberger-Wise VEV to generate bulk fermion mass:

$$S \supset -\int d^5x\sqrt{g}\,\rho\phi\,\overline{\psi}\psi$$

- Approximate $\langle\phi\rangle \simeq v_{\mathrm{UV}}\, e^{-\epsilon k y}$ and define $\tilde{c} \equiv \rho v_{\mathrm{UV}}/k\,,\; c^{\mathrm{loc}}(y) \equiv \tilde{c}\, e^{-\epsilon k y}$:

$$S \supset -\int d^5x\sqrt{g}\; c^{\mathrm{loc}}(y)\, k\, \overline{\psi}\psi$$

$\Rightarrow$ Position-dependent mass term!

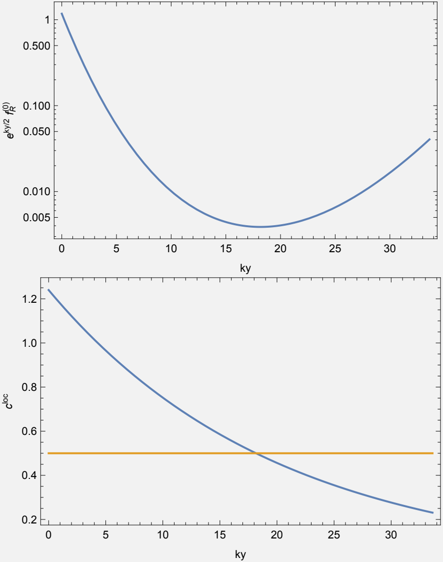
- Wavefunction of massless fermion KK now:

$$f^{(0)}(y) = \mathcal{N}^{(0)}_{\tilde{c}}\; e^{2ky+\frac{\tilde{c}}{\epsilon}e^{-\epsilon k y}}$$

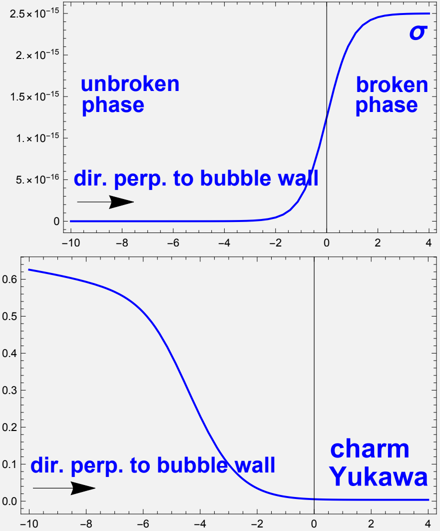
- Resulting 4D Yukawa coupling:

$$y(\sigma) = \lambda k\, \mathcal{N}^{(0)}_{\tilde{c}_L}\mathcal{N}^{(0)}_{\tilde{c}_R}\,\sigma^{-1}\, e^{\frac{(\tilde{c}_L+\tilde{c}_R)\,\sigma^{\epsilon}}{\epsilon}}$$

Wavefunction and c^{loc} of right-handed charm



Variation of Yukawas across the bubble wall



$\Rightarrow$ Yukawas increase along bubble wall

$\Rightarrow$ more CP-violation from $S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger M^{\dagger\prime\prime} M\, V\right]$

Electroweak baryogenesis with varying Yukawas

- For 1 flavour with $m(z) = |m(z)| e^{-i\theta(z)}$:

$$\Rightarrow \; S_{\not{C}\not{P}} \propto \mathrm{Im}\left[V^\dagger M^{\dagger''} M\, V\right] = [|m(z)|^2 \theta']'$$

In our model, $\theta = \text{const.} \;\Rightarrow$ Need at least 2 flavours!

- [S. Bruggisser, T. Konstandin, G. Servant, to appear] study benchmark point for top-charm
- Assume $\sigma(z) = \sigma_{\text{today}}\,(1 + \tanh(z/L_w))\,/2$ and parameters $L_w = 6.5\,T_c$, $v_w = 0.1$ and $\langle H \rangle (T_c)/T_c = 2.5$

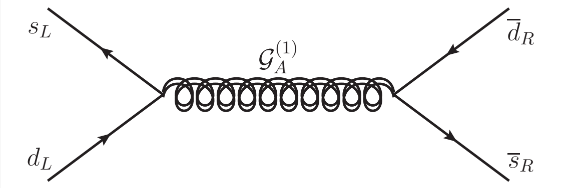
$$\Rightarrow \; \eta \approx 9.8 \cdot 10^{-11} \quad \Rightarrow \quad \text{Right baryon asymmetry!}$$

Flavour- and *CP*-violation today

- New *CP*-violating sources for electroweak baryogenesis typically strongly constrained
- Our source only active during phase transition, Yukawa matrices today not changed $\Rightarrow$ No new constraints from this new source!
- Goldberger-Wise scalar mediates new flavour- and *CP*-violating processes but can be made sufficiently small
- Even better: Modified wavefunctions give suppression of *CP*-violating processes which are very constraining in standard case!

CP-violation in $K - \overline{K}$-mixing

- Dominant constraint on IR scale $e^{-ky_{\rm IR}} M_P$ from CP-violation in $K - \overline{K}$-mixing (ϵ_K) $\Rightarrow$ Limits naturalness!
- Dominant contribution mediated by first gluon KK $\mathcal{G}_\mu^{(1)}$:



- Relevant coupling of quarks to gluon:

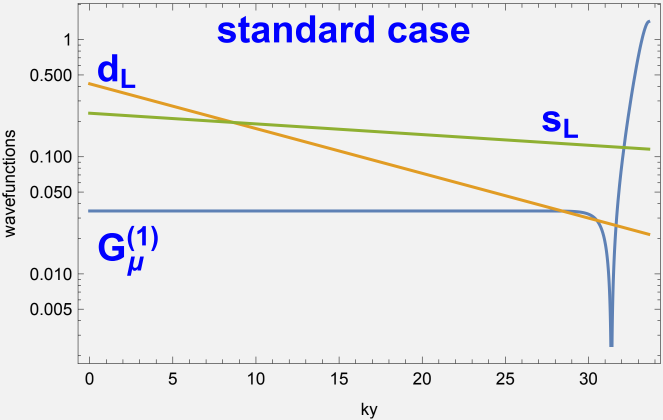
$$S \supset \int d^5x \sqrt{g}\, g_5\, \mathcal{G}_A\, E_a^A\, \overline{\psi}\gamma^a\psi$$

- $\Rightarrow$ Vertices determined by overlap integral

$$\tilde{g}_4^{L,R} = g_5 k^{1/2} \int_0^{y_{\rm IR}} dy\, e^{-3ky}\, f_{\mathcal{G}}^{(1)}\, f_{\psi_{L,R}}^{(0)} f_{\psi_{L,R}}^{(0)}\,,$$

where $\tilde{g}_4^{L,R}$ are matrices in flavour-space

Suppression of overlap integral



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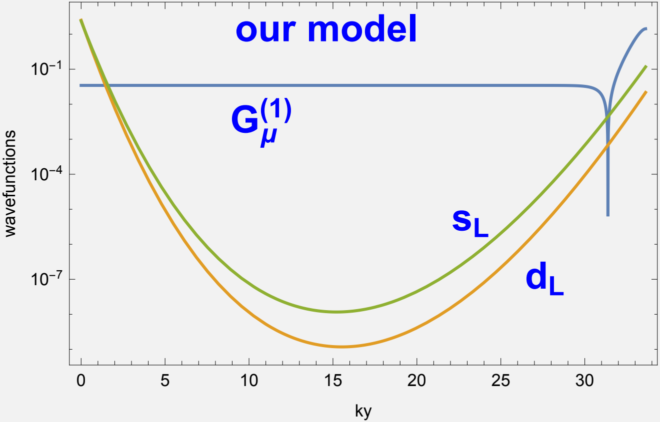


Easing of limits from CP-violation in $K - \overline{K}$-mixing

- Saw that $f_{\mathcal{G}}^{(1)}(y) = \text{const.} + \tilde{f}_{\mathcal{G}}^{(1)}(y)$. $\Rightarrow$ Overlap integral becomes

$$\tilde{g}_4^{L,R} = g_5 k^{1/2} \int_0^{y_{\rm IR}} dy\, e^{-3ky} \left(\text{const.} + \tilde{f}_{\mathcal{G}}^{(1)}(y)\right) f_{\psi_{L,R}}^{(0)} f_{\psi_{L,R}}^{(0)}$$

- Need to rotate $U_{L,R}^{\dagger} \tilde{g}_4^{L,R} U_{L,R}$ to obtain coupling to mass eigenstates $\Rightarrow$ Constant piece gives flavour-diagonal contribution, remaining piece $\tilde{f}_{\mathcal{G}}^{(1)}(y)$ leads to suppressed overlap integrals for new wavefunctions
- Constraint for standard case of constant bulk mass terms:

$$m_{\mathcal{G}}^{(1)} \gtrsim \frac{3}{\lambda_*}(22 \pm 6)\,\text{TeV} \quad \Rightarrow \quad e^{-k y_{\rm IR}} k \gtrsim \frac{3}{\lambda_*}(9 \pm 3)\,\text{TeV}$$

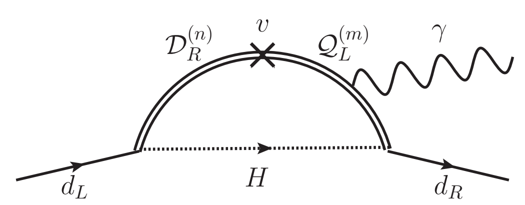
- In our scenario instead:

$$m_{\mathcal{G}}^{(1)} \gtrsim \frac{3}{\lambda_*}(7 \pm 2)\,\text{TeV} \quad \Rightarrow \quad e^{-k y_{\rm IR}} k \gtrsim \frac{3}{\lambda_*}(3 \pm 1)\,\text{TeV}$$

$\Rightarrow$ Significant improvement!

Neutron EDM

- Important constraint on IR scale $e^{-ky_{\rm IR}} M_P$ also from neutron EDM. Dominant contribution:



- Constraint for standard case of constant bulk mass terms:

$$m_\psi^{(1)} \gtrsim \frac{\lambda_*}{3}\, 26\,\text{TeV} \quad \Rightarrow \quad e^{-ky_{\rm IR}} k \gtrsim \frac{\lambda_*}{3}\, 11\,\text{TeV}$$

- Again expect that constraints eased in our scenario since first fermionic KKs are heavier than for constant bulk mass terms

Conclusions

- Considered minimal modification of RS: Yukawa coupling between Goldberger-Wise scalar and bulk fermions
- Can naturally lead to large Yukawa couplings and enhanced CP-violation in bubble walls during eletroweak phase transition
- First take home message: This minimal modification makes electroweak baryogenesis viable in RS
- Not covered here: 1) Derivative coupling of Goldberger-Wise scalar to Yukawa operator on IR brane allows for enhanced CP-violation from just 1 flavour; 2) CFT interpretation
- Second take home message: Our scenario eases constraints from CP-violation in $K - \overline{K}$-mixing (and perhaps neutron EDM)
- Interesting case of 'flavour cosmology', not much studied before (see also [I. Baldes,T. Konstandin, G. Servant, 1604.04526 & 1608.03254] in context of Froggatt-Nielsen mechanism)

Backup: The phase transition