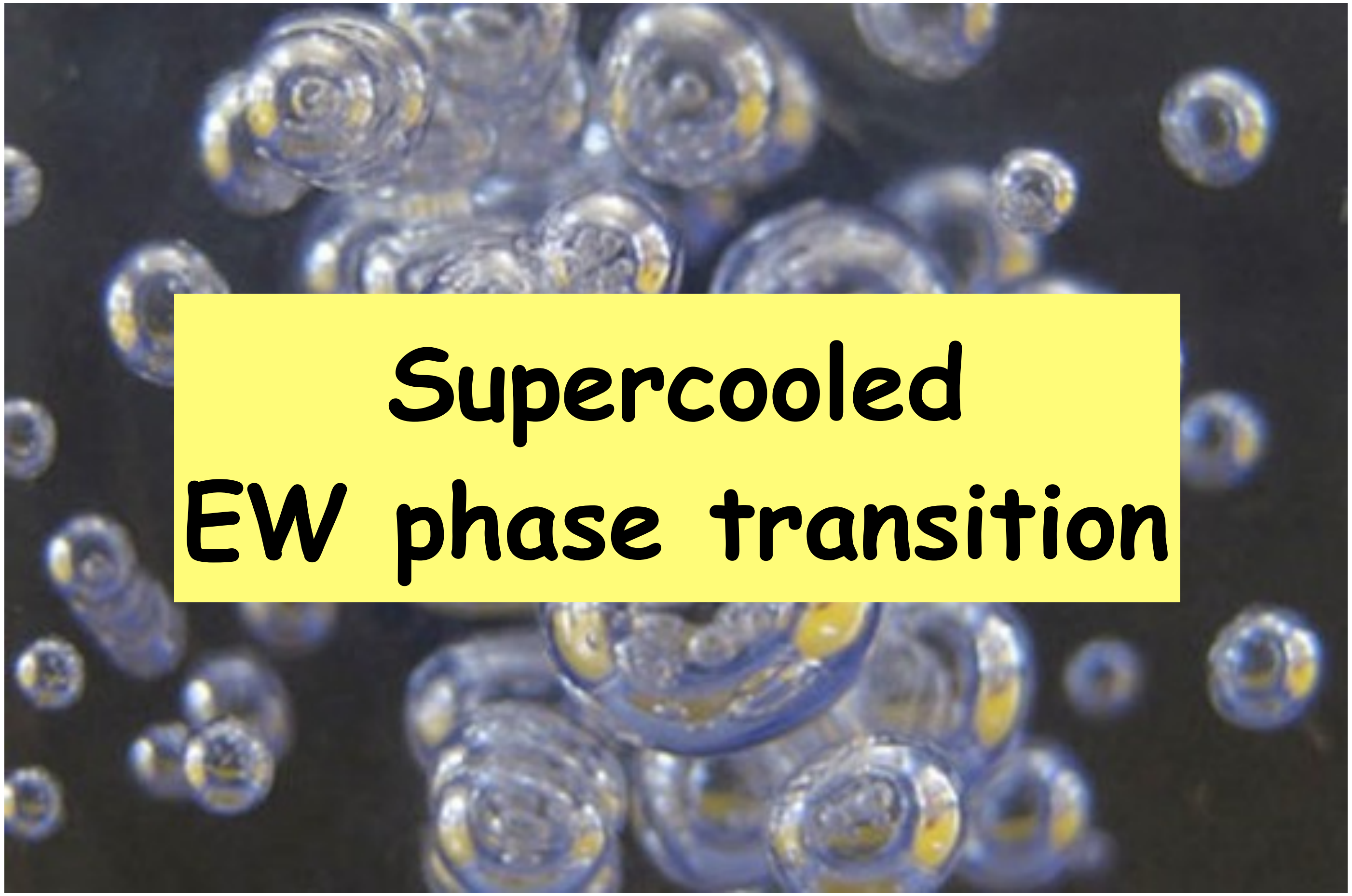


Supercooled EW phase transition

Géraldine SERVANT

DESY/U.Hamburg

Cosmograv workshop, UPMC Paris, June 15 2018

HELMHOLTZ | GEMEINSCHAFT

DESY

Universität Hamburg

(

3-minute mini-talk on Higgs relaxation after inflation

arXiv:1805.04543

Nayara Fonseca's slide

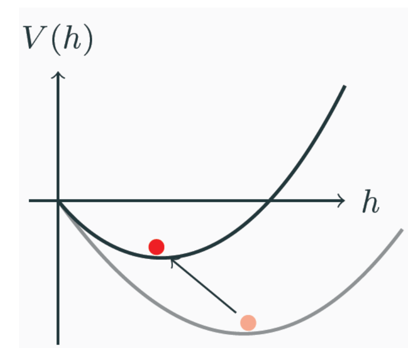
Dissipation from particle production friction (SM vectors)

Hook, Marques-Tavares '16

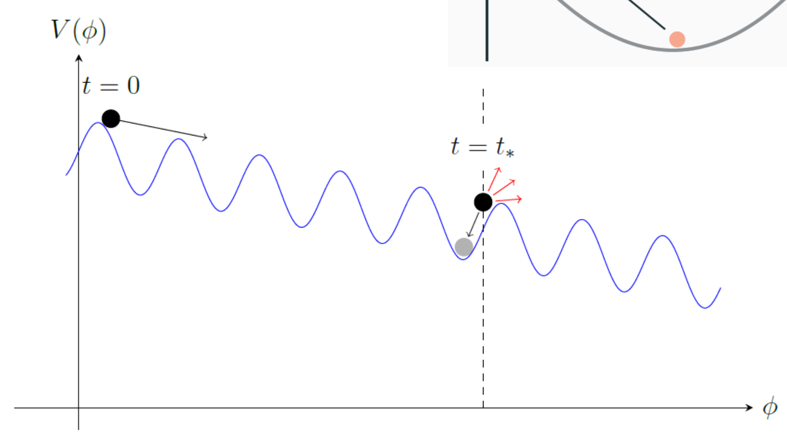
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\phi}{4f}V_{\mu\nu}\widetilde{V}^{\mu\nu} + \frac{g_V^2}{2}V_\mu V^\mu h^2 - \mathcal{V}(\phi,h)$$

$$\mathcal{V} \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4\cos\left(\frac{\phi}{f'}\right)$$

$m_h^2 < 0$



- the evolution starts in the broken phase, i.e. the vev is large: $\Phi_{ini} < \Lambda/g$.
- the relaxion is coupled to a massive SM vector field;
- constant barriers, ϕ has enough $\dot{\phi}^2$ to jump Λ_b^4
- $-g\Lambda^3\Phi$ makes the relaxion roll to larger values, decreasing the Higgs vev



➢ Higgs vev is sufficiently small ↔ V_μ experiences a tachyonic instability

$(\omega_k)^2 < 0$

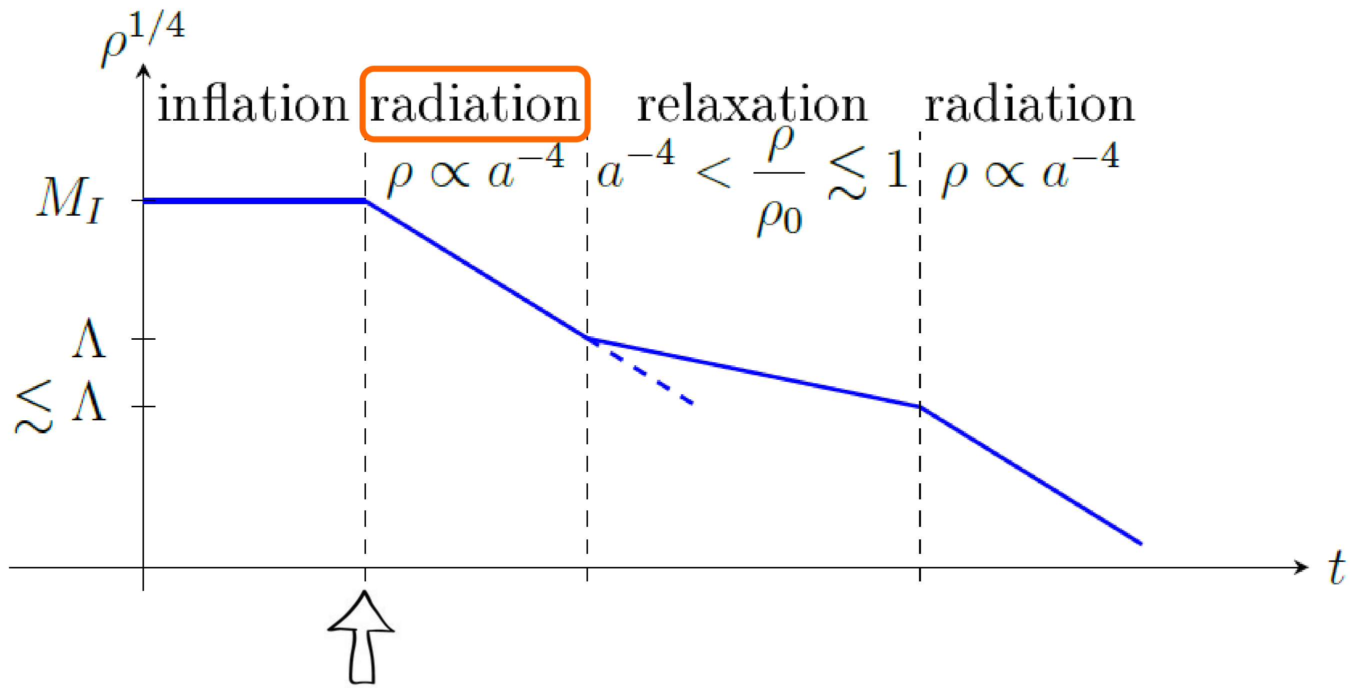
$$\ddot{V}_\pm + \left(k^2 + m_V^2 \mp k\frac{\dot{\phi}}{f}\right)V_\pm = 0 \qquad m_V^2 = g_V^2 h^2$$

➢ When V_+ grows exponentially, the $V\widetilde{V}$ term slows down the field ϕ

Higgs Relaxation without inflation

NF, E. Morgante, G. Servant '18

I. Relaxion-Higgs Cosmological Evolution after inflation



- End of inflation: energy stored in the inflation is transferred to light particles
- Radiation era starts

Higgs Relaxation without inflation

NF, E. Morgante, G. Servant '18

III. Parameter space

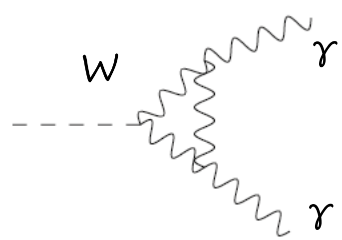
- **Photon coupling $\phi\tilde{\gamma}\gamma$ should be suppressed**

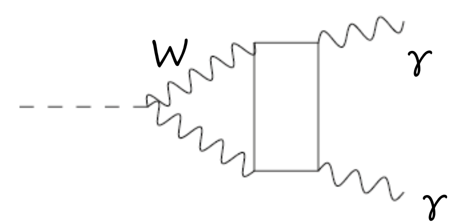
$$\Delta t_\gamma > H^{-1}$$

Sources:

- **Higgs mixing:** $\propto g'\phi\, h^2$ (trivial)
- *Other relevant contributions* (Craig-Hook-Kasko [1805.06538]):
  - Low energies (1-loop RG evolution): $1/f_{fermion} \neq 0$
  - $m\phi \neq 0$ (axion shift symmetry broken): $1/f_\gamma \neq 0$

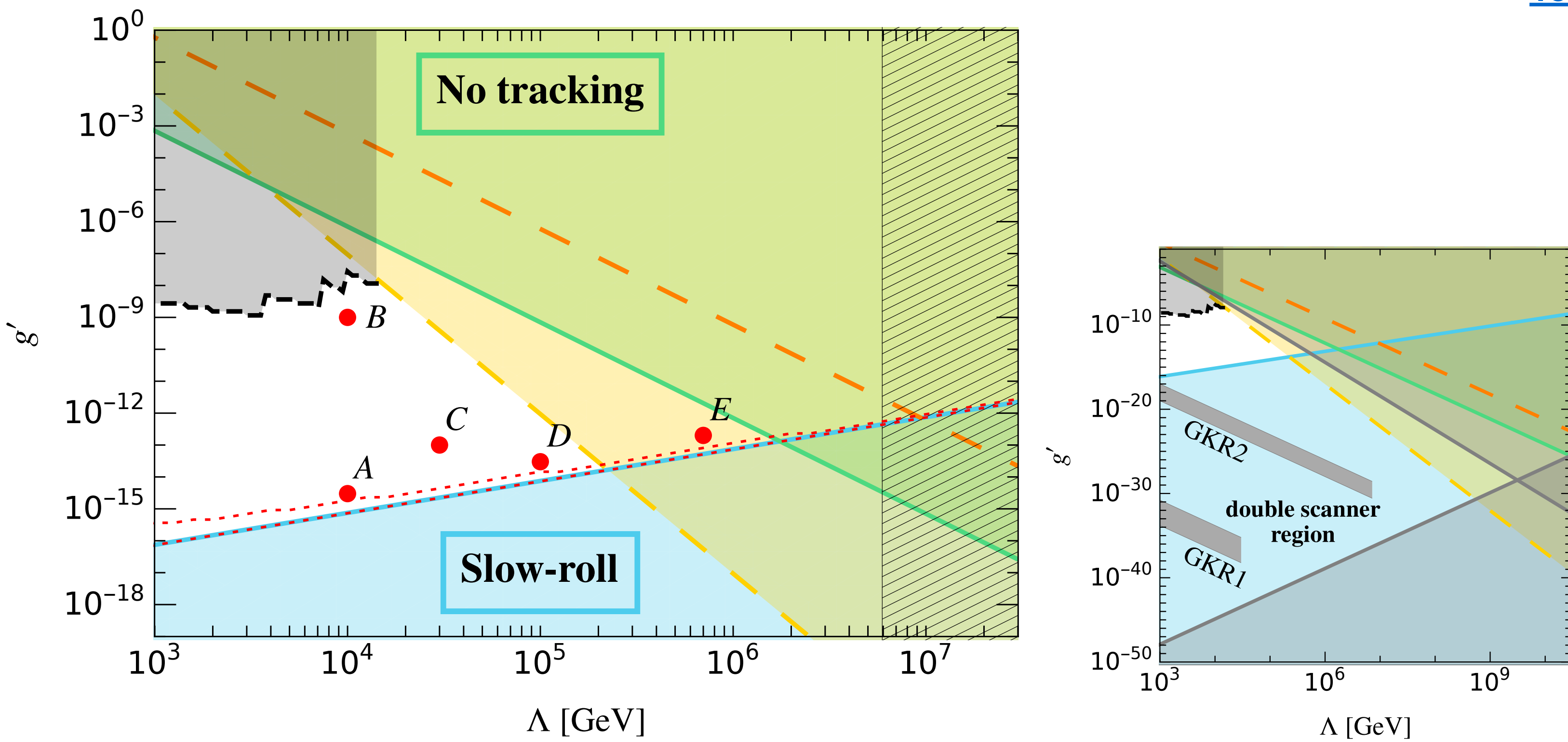
like:





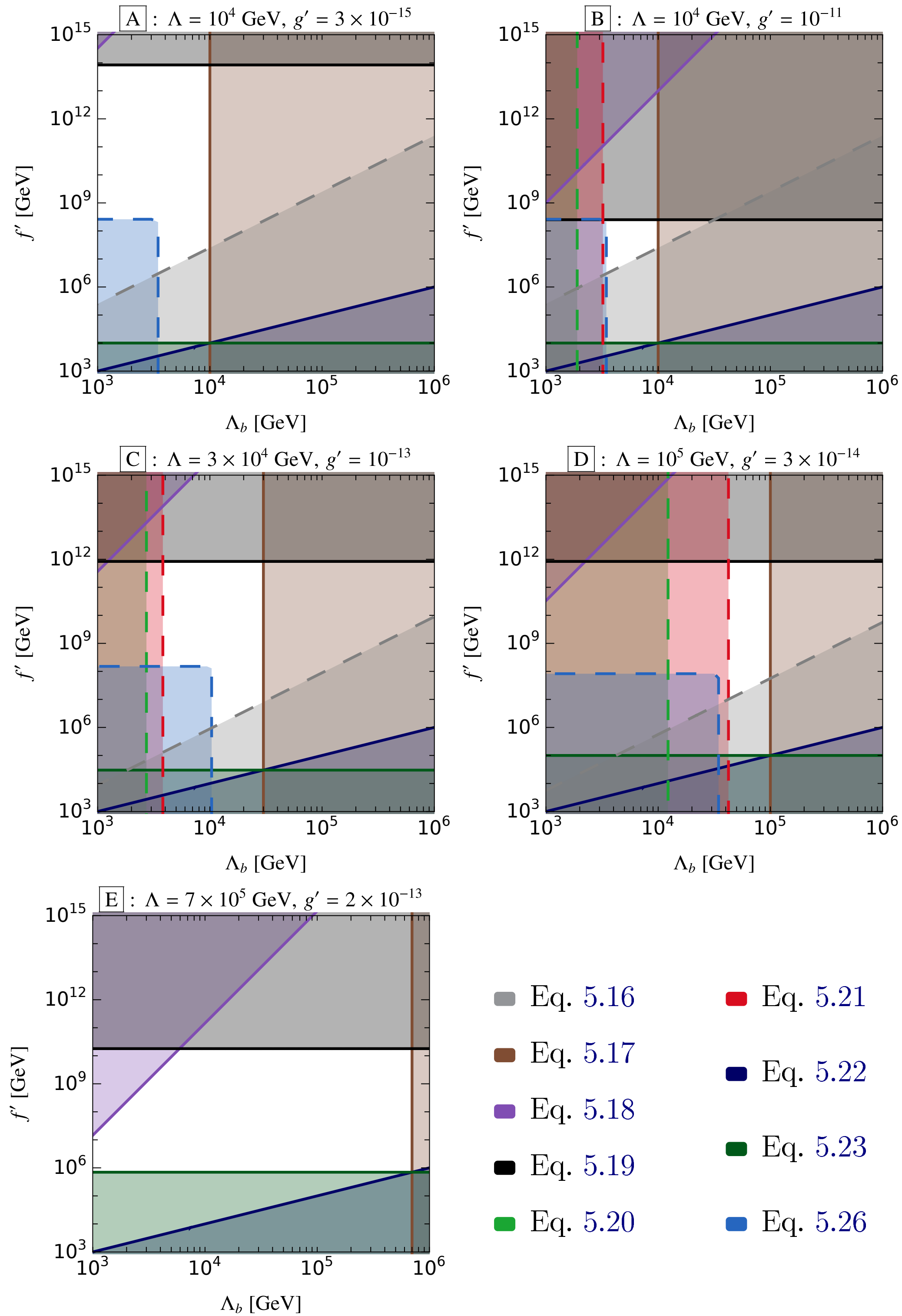
$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f'}\right)$$

1805.04543v2

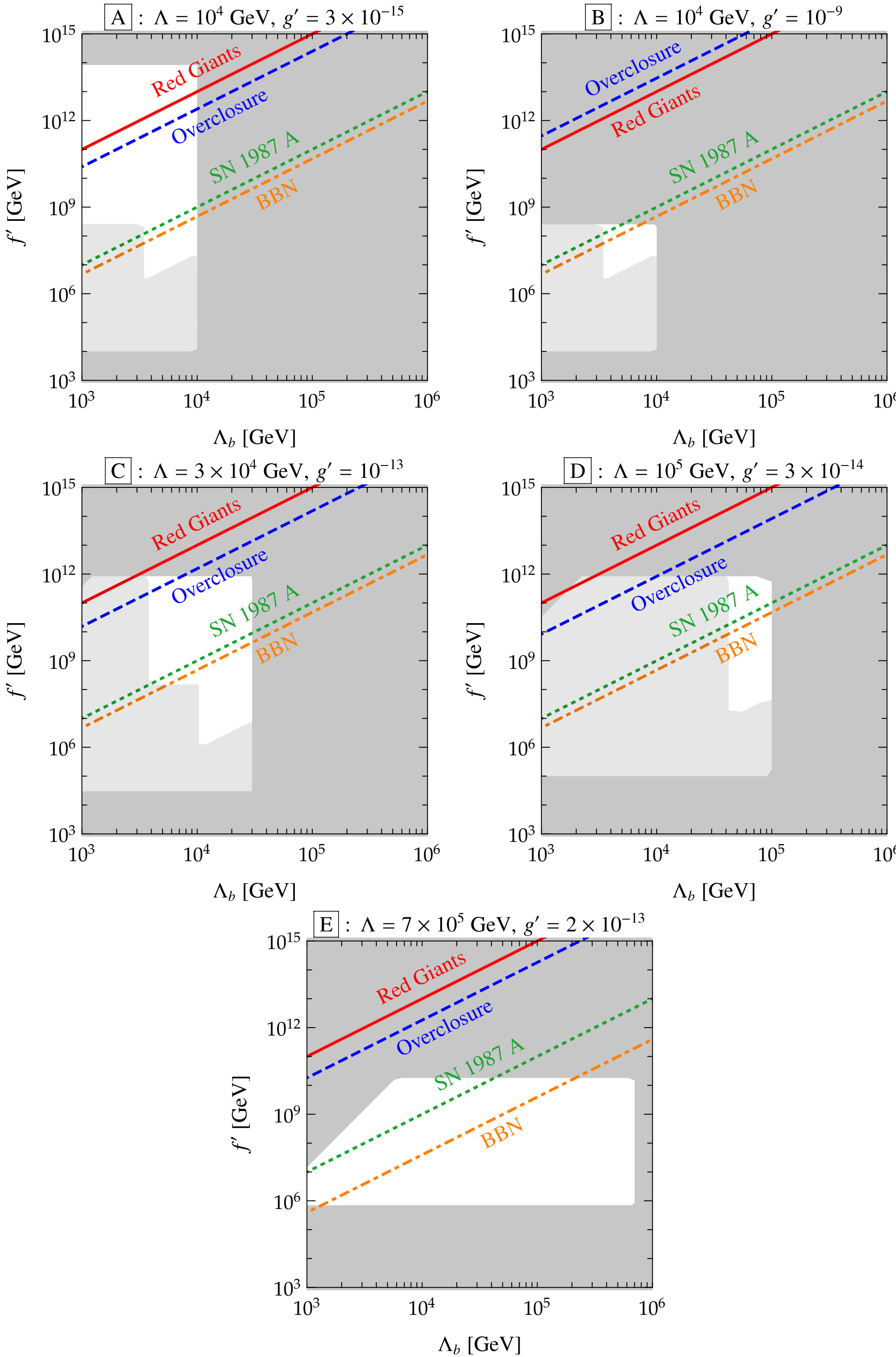


- Slow-roll (Eq. 5.14)
- Untracked minimum (Eq. 5.15)
- Induced $\phi\tilde{\gamma}\gamma$ coupling not suppressed (Eq. 5.16)
- Small barriers + efficient dissipation (Eq. 5.24)
- Small barriers + small Higgs mass variation (Eq. 5.25)

[1805.04543v2](1805.04543v2)



[1805.04543v2](https://arxiv.org/abs/1805.04543v2)



scenario A: $m_\phi \in [2m_\mu,\ 4\,\text{GeV}]$

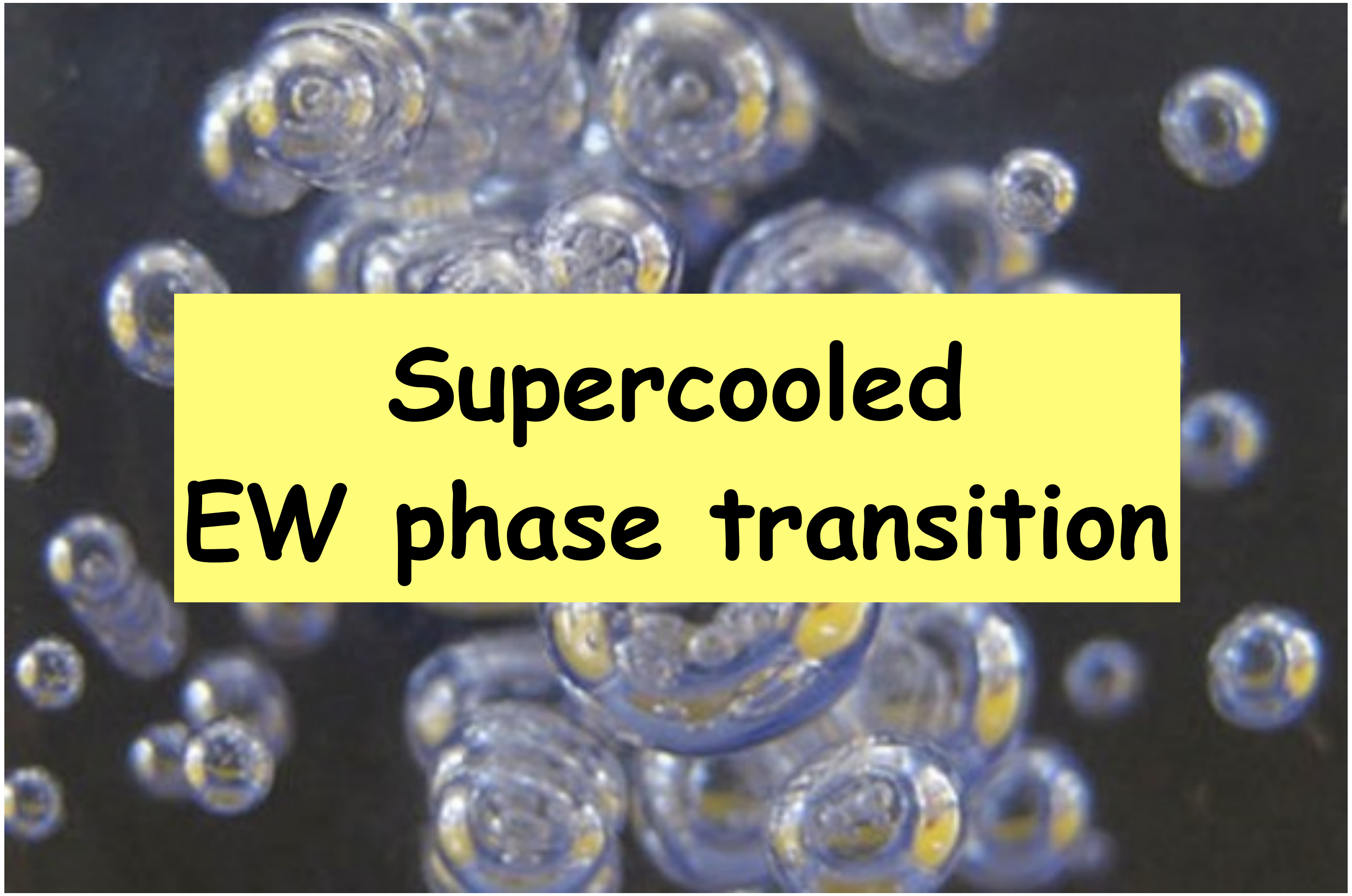
scenario B: $m_\phi \in [2m_\mu,\ 4\,\text{GeV}]$

scenario C: $m_\phi \in [2m_\mu,\ 112\,\text{GeV}]$

scenario D: $m_\phi \in [2m_\mu,\ 178\,\text{GeV}]$

scenario E: $m_\phi \in [2m_c,\ 700\,\text{TeV}]$,

)



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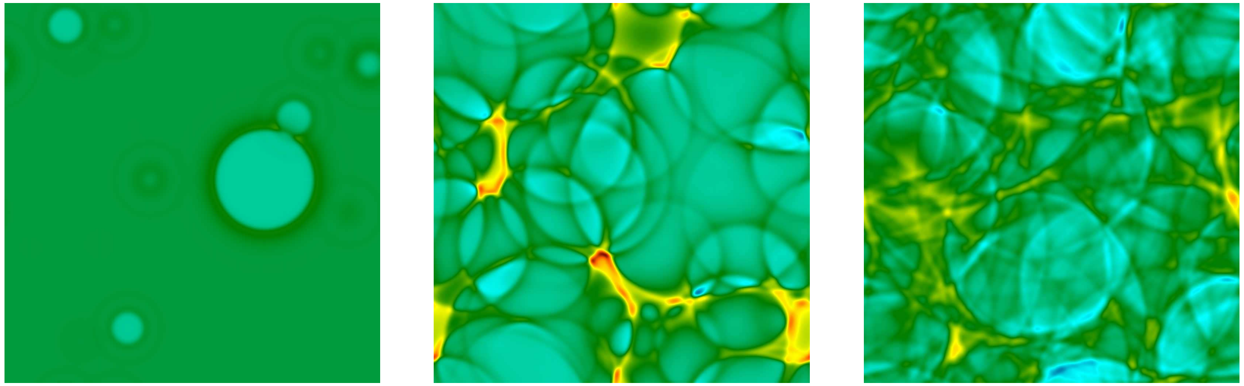
Matter Anti-matter asymmetry of the universe

$$\boxed{\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}}$$

$$5.7 \leq \eta_{10} \leq 6.7 \ (95\%\mathrm{CL})$$

Baryogenesis
at a first-order
EW phase transition



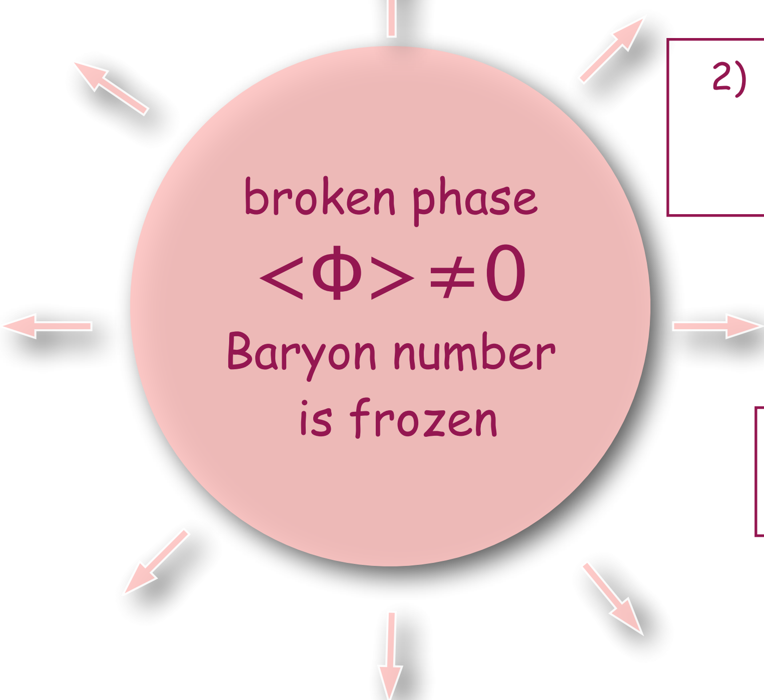
[image credit:1304.2433]

Baryon asymmetry and the EW scale

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91

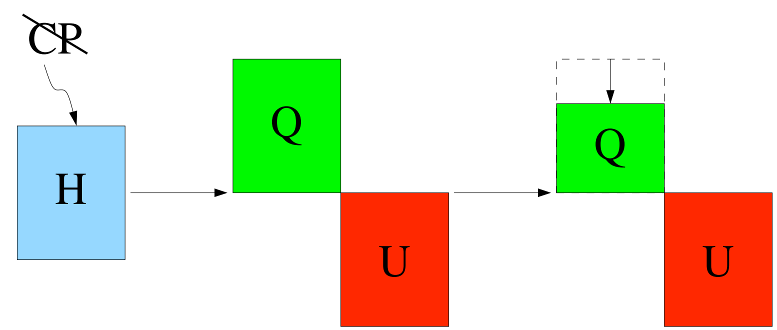
1) nucleation and expansion of bubbles of broken phase



2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux
in front of the wall

3) In symmetric phase, <Φ>=0, very active sphalerons convert chiral asymmetry into baryon asymmetry

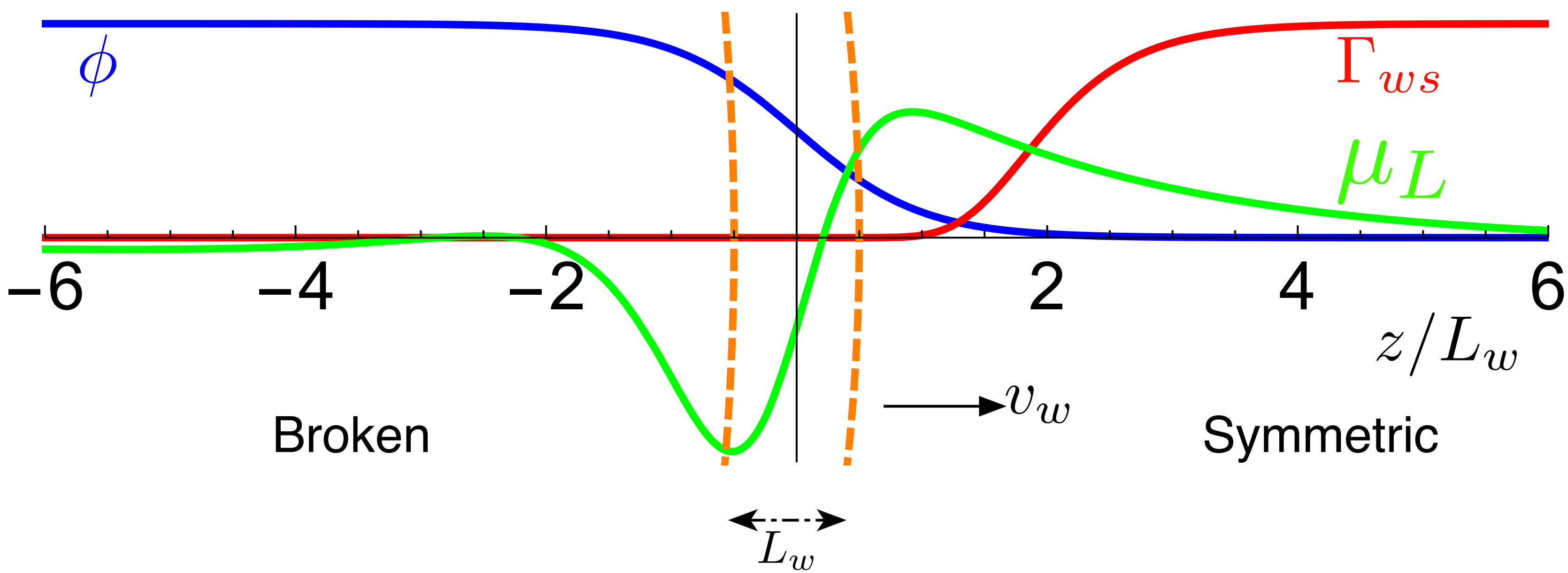


Electroweak baryogenesis mechanism relies on a first-order phase transition satisfying $\dfrac{\langle\Phi(T_n)\rangle}{T_n} \gtrsim 1$

The Electroweak Baryogenesis Miracle:

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} \mathrm{d}z\ \Gamma_{ws}\ \mu_L\ \mathrm{Exp}\left[-\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} \mathrm{d}z_0 \Gamma_{ws}\right]$$

$$\Gamma_{ws} = 10^{-6}\ T\ e^{-\frac{E_{sph}}{T}\frac{\phi(T)}{v}}$$



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$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} \mathrm{d}z\ \Gamma_{ws}\ \mu_L\ \mathrm{Exp}\left[-\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} \mathrm{d}z_0 \Gamma_{ws}\right]$$

$$\Gamma_{ws} = 10^{-6}\ T\ e^{-\frac{E_{sph}}{T}\frac{\phi(T)}{v}}$$

$$\eta_B \sim \frac{\Gamma_{ws}\ \mu_L\ L_w}{g_*\ T}$$

$$\mu_L \sim M'' M \sim \frac{\delta_{CP}}{L_w^2\ T} \qquad\qquad L_w \sim \frac{1}{T}$$

$$\eta_B \sim \frac{\Gamma_{ws}\ \delta_{CP}}{g_*\ L_w\ T^2} \sim \frac{10^{-6}\ \delta_{CP}}{g_*} \sim 10^{-8} \delta_{CP}$$

All parameters fixed by electroweak physics. If new CP violating source of order 1 then we get just the right baryon asymmetry.

Objective # I

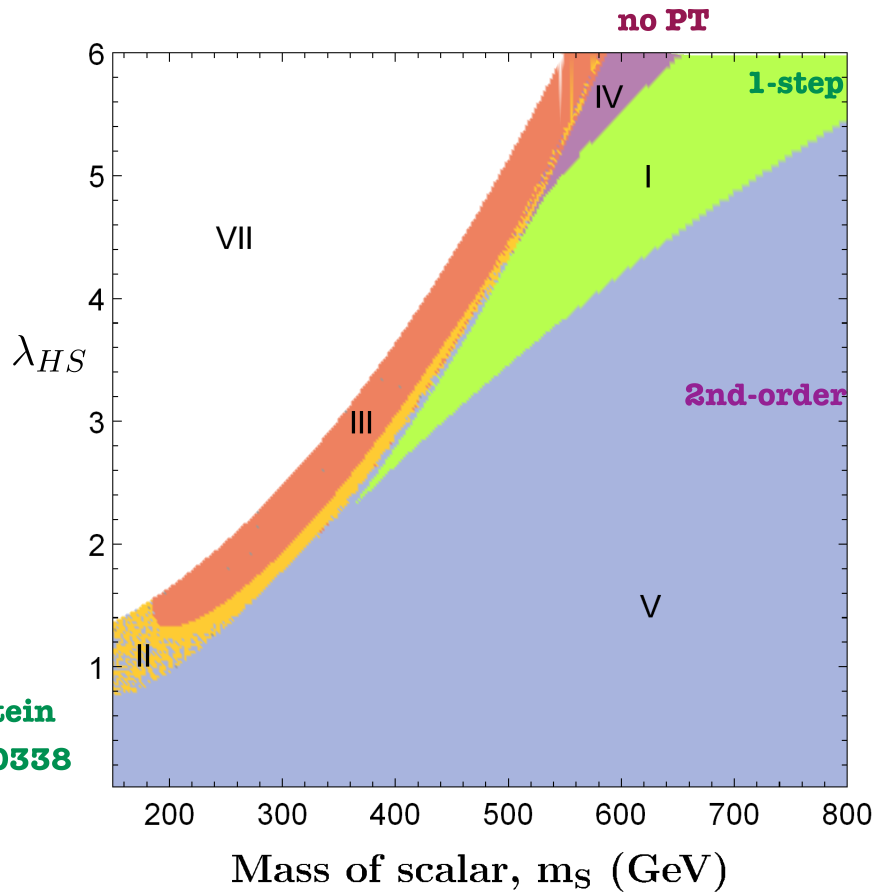
Strong 1st-order EW phase transition

An easy way: the SM+ a real scalar singlet

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

Poorly constrained as S has no VEV today:

no Higgs-S mixing-> no EW precision tests , tiny modifications of higgs couplings at colliders



Kurup-Perelstein [1704.0338

A natural way: dilaton-like potential

naturally leads to supercooling

not a polynomial

$$V = V(\sigma) + \frac{\lambda}{4}(\phi^2 - c\sigma^2)^2$$

$$c = \frac{v^2}{\langle\sigma\rangle^2}$$

Higgs vev controlled by dilaton vev (e.g. Randall-Sundrum scenario)

$$\boxed{V(\sigma) = \sigma^4 \times f(\sigma^\epsilon)}$$

|ε|<<1

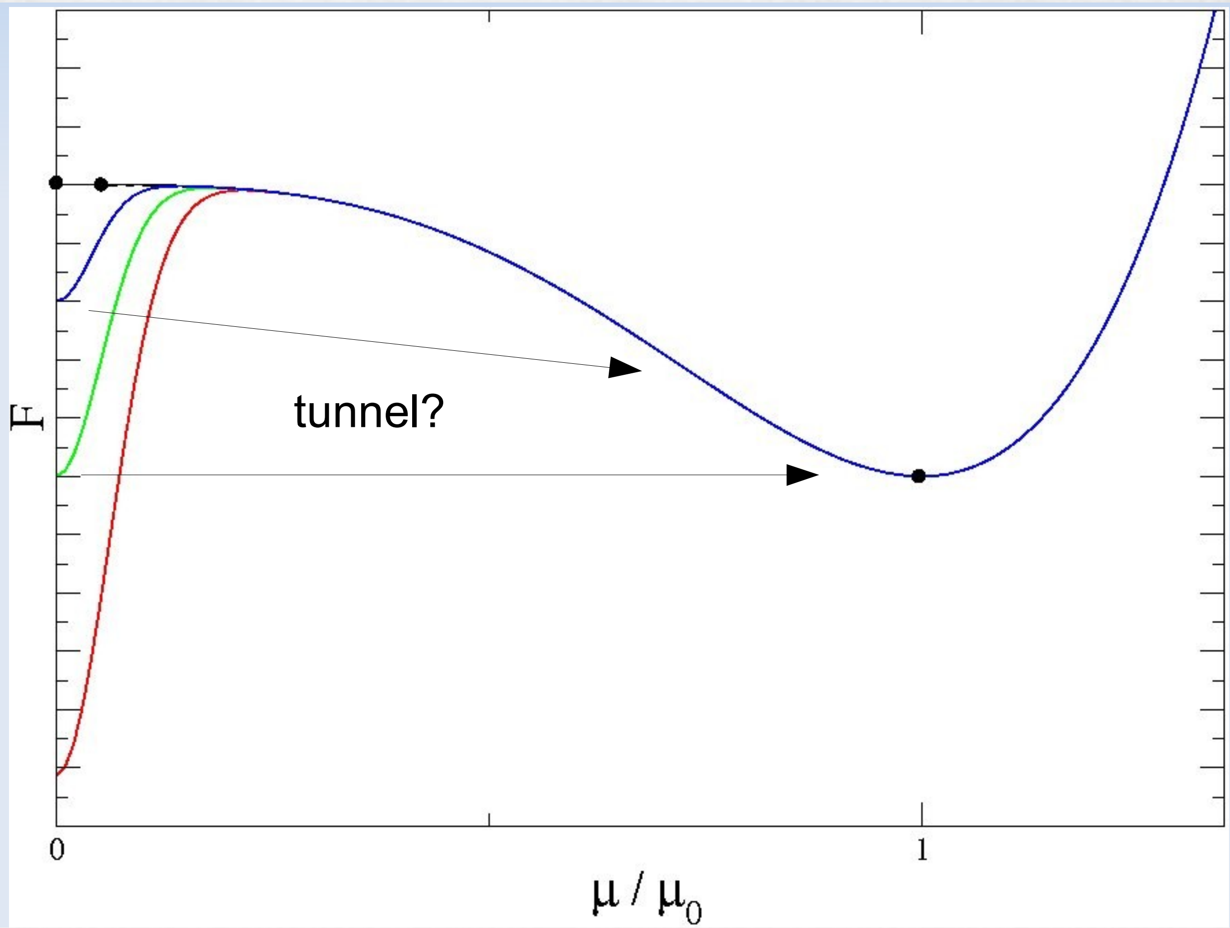
similar to Coleman-Weinberg mechanism where a slow Renormalization Group evolution of potential parameters can generate widely separated scales

Nucleation temperature can be parametrically much smaller than the weak scale

Deconfining phase transition

Quarks/gluons that are confined in the broken phase induce a difference in free energy between the two phases

$$\Delta F = \frac{\pi^2}{90}\,\Delta g\, T^4$$



Creminelli, Nicolis, Rattazzi'01

Randall, Servant'06

Hassanain, March-Russell, Schwellinger'07

Nardini,Quiros,Wulzer'07

Konstandin,Servant'1

Konstandin,Nardini,Quiros'10

Bunk, Hubisz, Jain'1

Dillon, El-Menoufi,Huber,Manuel'1

VonHarling,Servant'1

QCD-induced Electroweak Phase Transition

[Von Harling, Servant'17]

EW symmetry breaking may be induced by QCD in models where the scalar potential is nearly conformal and leads to large supercooling

-> Randall-Sundrum phase transition

QCD-induced Electroweak Phase Transition

[Von Harling, Servant'17]

Dilaton potential receive effects from the QCD condensate!

This effect had been ignored so far.

Contributes to remove the barrier in the potential at the QCD scale so that the dilaton can roll and trigger electroweak symmetry breaking.

Region of parameter space where the electroweak phase transition proceeds is substantially increased.

Such class of models therefore naturally leads to an electroweak phase transition taking place at QCD temperatures, with interesting cosmological implications and signatures.

QCD Condensate

Effect on dilaton potential had been ignored so far

$$\langle G^{(0)}_{\mu\nu}\, G^{(0)\,\mu\nu} \rangle \;=\; 4\pi \;\cdot\; (7 \pm 1) \cdot 10^{-2}\ \mathrm{GeV}^4\,,$$

$$\langle\, \overline{\psi}^{(0)}_{u,d}\, \psi^{(0)}_{u,d}\,\rangle \;=\; -(1.65 \pm 0.15) \cdot 10^{-2}\ \mathrm{GeV}^3\,.$$

$$T^\rho_\rho \supset -\frac{b_{\mathrm{QCD}}}{32\pi^2}\, G^{(0)}_{\mu\nu}\, G^{(0)\,\mu\nu} \;+\; \sum_{\mathrm{quarks}} m_q\, \overline{\psi}^{(0)}_i \psi^{(0)}_i$$

$$V \;=\; \frac{1}{4}\,\langle\, T^\rho_\rho\,\rangle$$

Depends on μ VEV!

$$\langle G^{(0)}_{\mu\nu}\, G^{(0)\,\mu\nu} \rangle \;\sim\; (\Lambda_{\mathrm{QCD}}(\mu))^4\,,$$

$$\langle\, \overline{\psi}^{(0)}_{u,d}\, \psi^{(0)}_{u,d}\,\rangle \;\sim\; (\Lambda_{\mathrm{QCD}}(\mu))^3\,.$$

Dilaton potential receive effects from the QCD condensate!

$$S \supset \int d^5x \sqrt{g} \left(-\frac{1}{4g_5^2} G_{MN} G^{MN} - \delta(y - y_{\rm UV}) \frac{\tau_{\rm UV}}{4} G_{\mu\nu} G^{\mu\nu} - \delta(y - y_{\rm IR}) \frac{\tau_{\rm IR}}{4} G_{\mu\nu} G^{\mu\nu} \right)$$

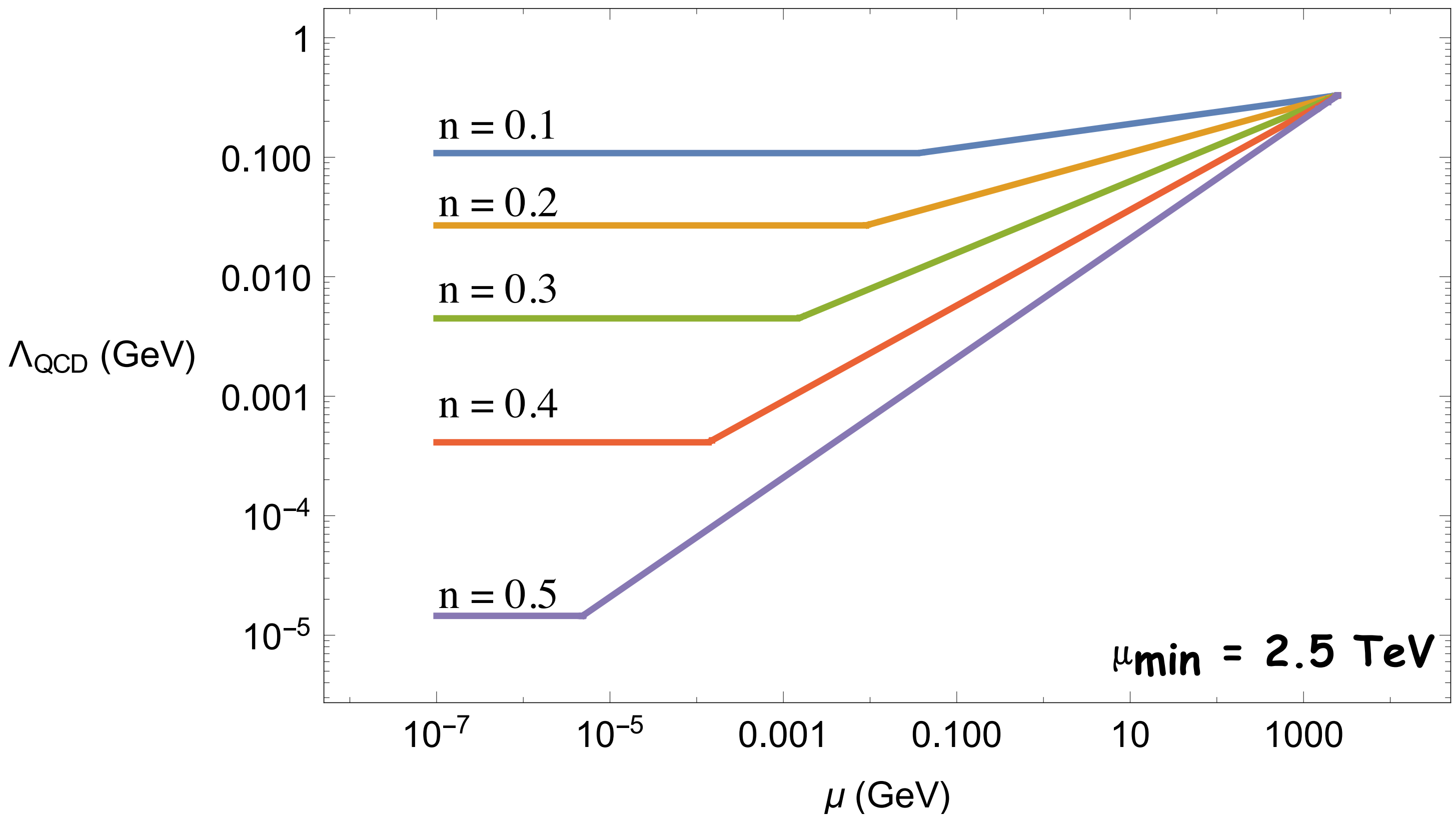
$$S \supset \int d^4x \, \frac{-1}{4\, g^2} \, G^{(0)}_{\mu\nu} \, G^{(0)\,\mu\nu}$$

$$\frac{1}{g^2} = \frac{\log \frac{k}{\mu}}{k g_5^2} + \tau_{\rm UV} + \tau_{\rm IR}$$

$$\frac{1}{g(Q)^2} = \frac{\log \frac{k}{\mu}}{k g_5^2} - \frac{b_{\rm UV}}{8\pi^2} \log \frac{\rm k}{\rm Q} - \frac{b_{\rm IR}}{8\pi^2} \log \frac{\mu}{\rm Q} + \tau_{\rm UV} + \tau_{\rm IR} \quad (\text{for } Q < \mu)$$

Depends on μ VEV!

The QCD confinement scale as a function of the IR scale μ

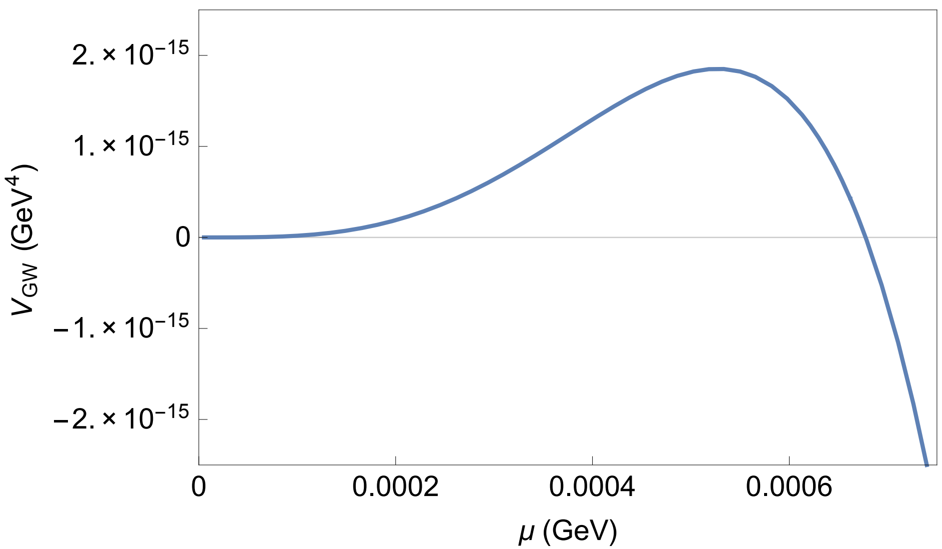


$$n \equiv \frac{b_{\rm IR} - b_{\rm CFT}}{b_{\rm UV} + b_{\rm IR}}$$

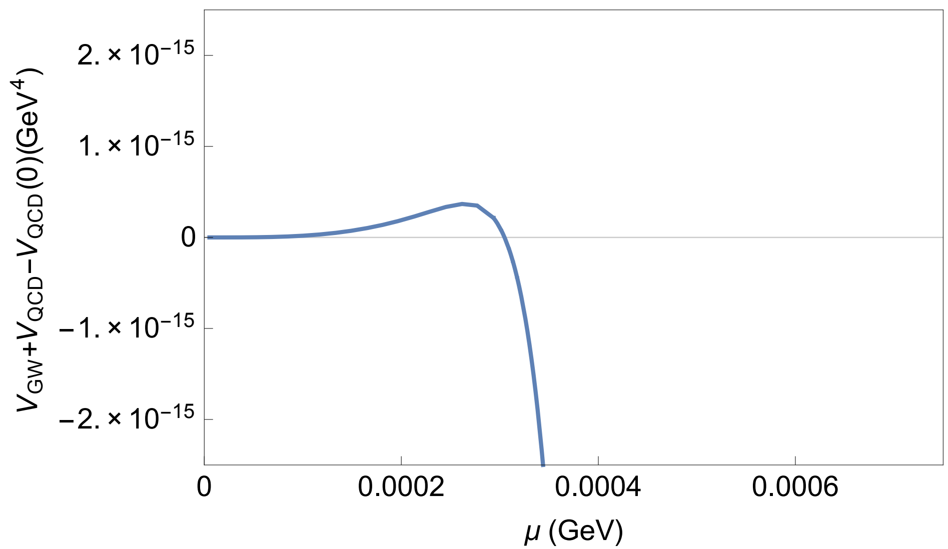
Goldberger-Wise potential around its barrier without and with the contribution from the gluon condensate

$n = 0.15,\ \mu_{min} = 2.5$ TeV $\varepsilon = 1/20$

without



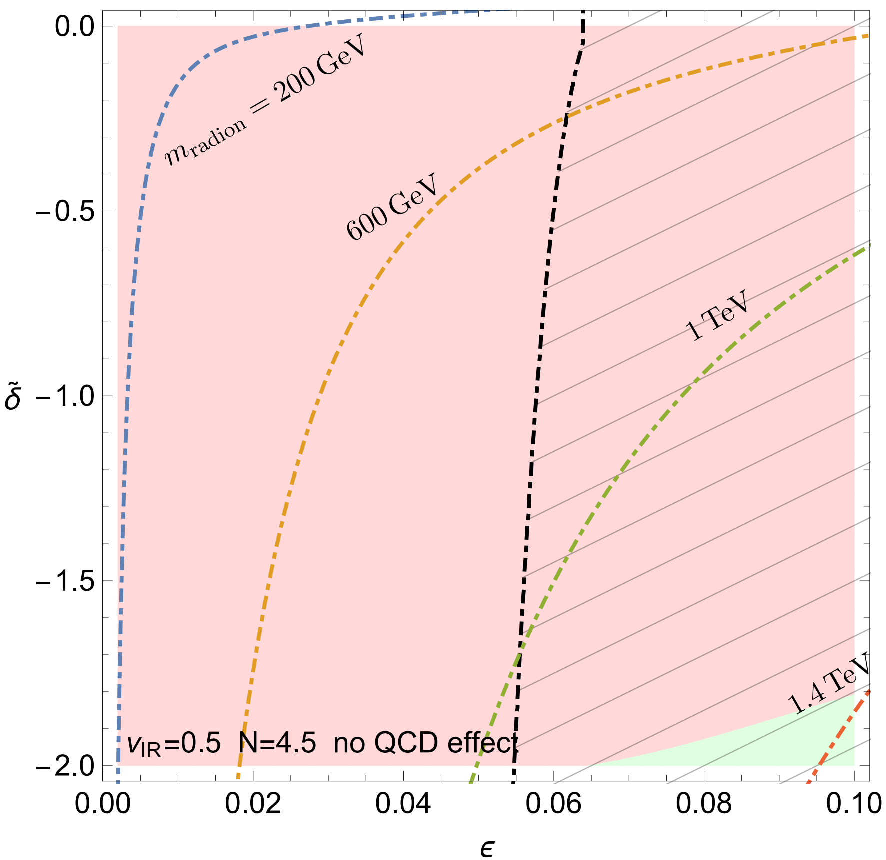
with



$$V_{\rm QCD}(\mu, \langle H \rangle = 0) \approx -\frac{b_{\rm QCD}}{17} \left(\Lambda_{\rm QCD}(\mu)\right)^4$$

Open parameter space without and with the QCD effect

without



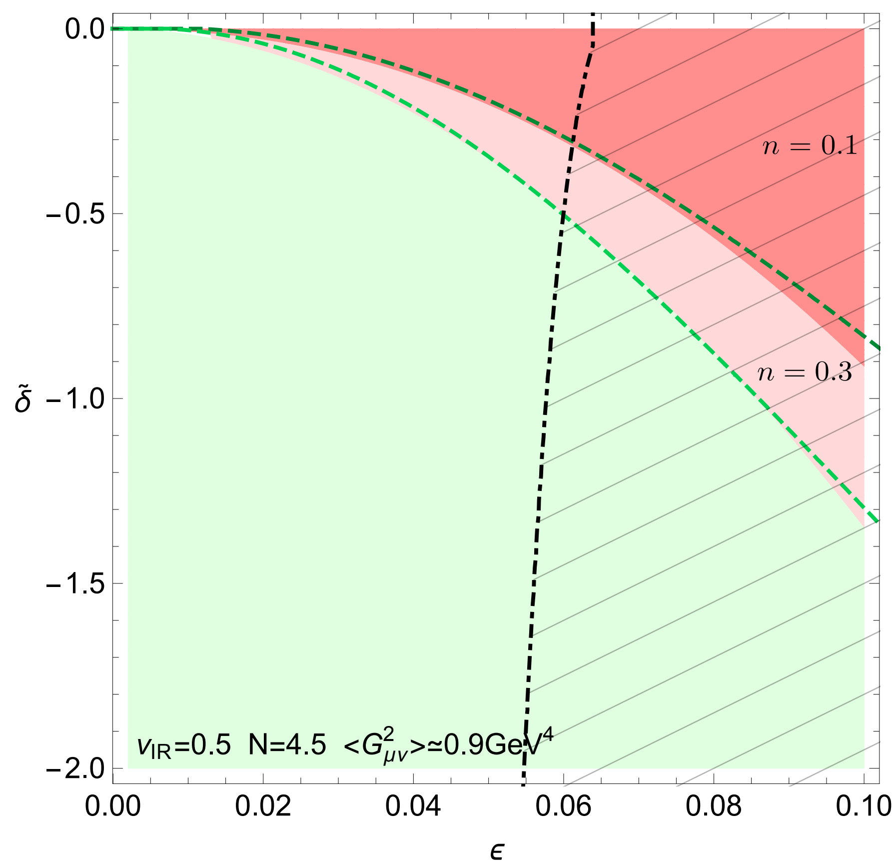
$v_{\rm IR} = 0.5.$

red: no tunnelling

green: tunnelling

$\mu_{\rm min} = 2.5\,\mathrm{TeV}$

with



red: no tunnelling

green: tunnelling

$\mu_{\rm min} = 2.5\,\mathrm{TeV}$

Conclusion:

In large region of parameter space,
EW phase transition induced by QCD.

Application:

Baryogenesis from strong CP violation and the QCD axion

Servant, 1407.0030

A coupling of the type ~ $\frac{a(t)}{f_a} F\tilde{F}$ ← EW field strength

will induce from the motion of the axion field a chemical potential for baryon number given by

$$\frac{\partial_t a(t)}{f_a}$$

This is non-zero only once the axion starts to oscillate after it gets a potential around the QCD phase transition.

Time variation of axion field can be CP violating source for baryogenesis if EW phase transition is supercooled

$\longrightarrow$ **Cold Baryogenesis**

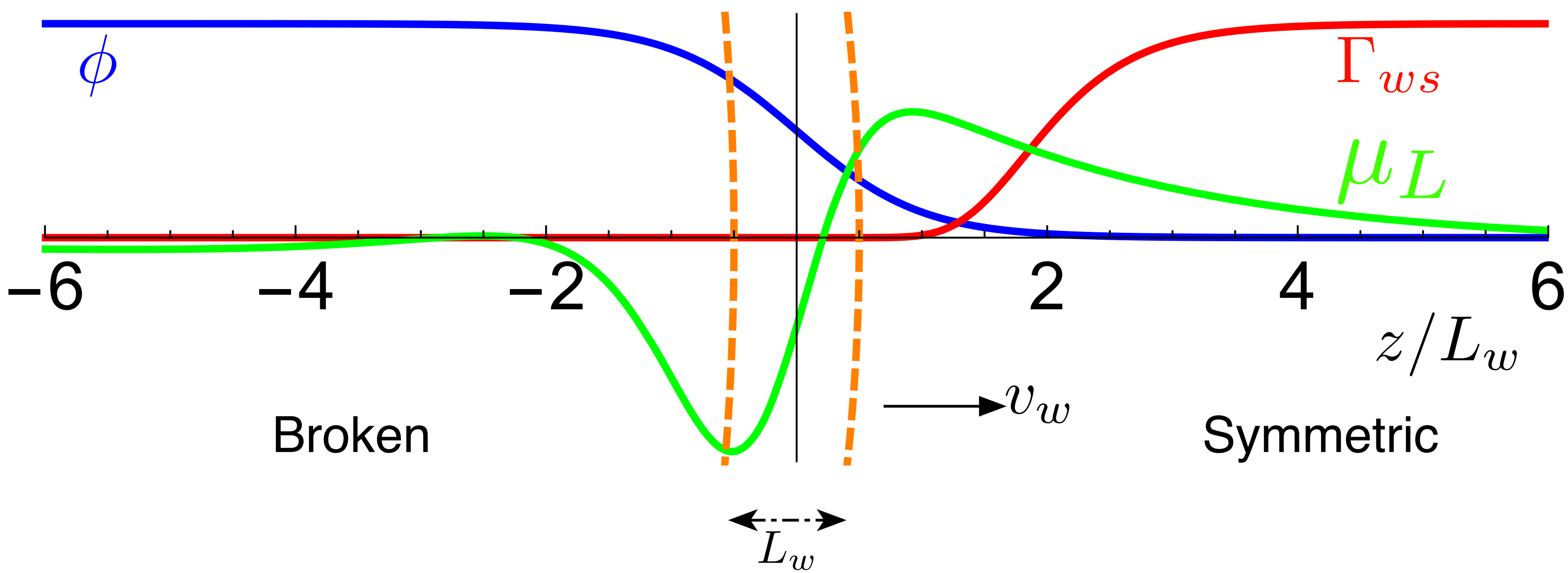
requires a coupling between the Higgs and an additional light scalar: testable @ LHC & compatible with usual QCD axion Dark matter predictions

Objective # II

New large sources of CP violation

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} \mathrm{d}z\ \Gamma_{ws}\ \mu_L\ \mathrm{Exp}\left[-\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} \mathrm{d}z_0 \Gamma_{ws}\right]$$

$$\Gamma_{ws} = 10^{-6}\ T\ e^{-\frac{E_{sph}}{T}\frac{\phi(T)}{v}}$$



Cline, Joyce, Kainulainen '00
Konstandin, Prokopec, Schmidt '04
Huber Fromme '06
Bruggisser, Konstandin, Servant '17

Kinetic equations

$$\left(k_z \partial_z - \frac{1}{2}\left(\left[V^\dagger \left(m^\dagger m\right)' V\right]\right)_{ii} \partial_{k_z}\right) f_{L,i} \approx \mathbf{C} + \mathcal{S}$$

$$\left(k_z \partial_z - \frac{1}{2}\left(\left[V^\dagger \left(m^\dagger m\right)' V\right]\right)_{ii} \partial_{k_z}\right) f_{R,i} \approx \mathbf{C} - \mathcal{S}$$

collisions **source**

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}y \; K_i(y) \; \bar{\mathcal{S}}_i(y)$$

diffusion effects & sphalerons

CP-violating source

Usual CP-violating sources in EW baryogenesis:

-Charginos/neutralinos/sfermions (MSSM) **Cline et al, Carena et al...**

-Varying phase in effective Top quark Yukawa

SM+singlet, **Fromme-Huber**

Composite Higgs, **Espinosa, Gripaios, Konstandin, Riva, '11**

2-Higgs doublet model **Konstandin et al, Cline et al**

- two recent alternatives: strong CP QCD axion (**Servant '14**)

and CP in DM sector (**e.g. Cline'17**)

the CKM matrix as the CP-violating source

In the SM: $\eta_B \lesssim 10^{-2}\Delta_{CP}$ Farrar, Shaposhnikov '93

$$\Delta_{CP} \sim \left(M_W^6 T_c^6\right)^{-1} \prod_{\substack{i>j \\ u,c,t}} \left(m_i^2 - m_j^2\right) \prod_{\substack{i>j \\ d,s,b}} \left(m_i^2 - m_j^2\right) J_{CP}$$

Gavela, *et al.* '93
Huet, Sather '94

Jarlskog constant

$$J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin(\delta) = (3.0 \pm 0.3) \times 10^{-5},$$

Based solely on reflection coefficients

If large masses during EW phase transition
->no longer suppression of CKM CP violation

Berkooz, Nir, Volansky '04

New idea: Varying SM Yukawas as CP violating source

Bruggisser, Konstandin, Servant ‘17

$$S \sim \ \mathrm{Im}\left[V^\dagger m^{\dagger\prime\prime} m V\right]$$

V: transformation matrix for mass diagonalization

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

For constant y:

$$S \sim \underbrace{\ \mathrm{Im}\left[V^\dagger Y^\dagger Y V\right]\ }_{=0} \phi'' \phi$$

1-Flavour case

$$m = |m|e^{i\theta}$$

$$S \propto \mathrm{Im}\left[V^{\dagger} m^{\dagger\,\prime\prime} m V\right] = \left(|m|^2\theta'\right)'$$

requires variation of phase

More than 1 flavour: no need for variation of phase

Bruggisser et al '17

Flavour-EW symmetry breaking cosmological interplay

- Effect of varying Yukawas on EW phase transition

  Baldes, Konstandin, Servant, 1604.04526

- Implementation in Froggatt-Nielsen

  Baldes, Konstandin, Servant, 1608.03254

- Natural realisation of Yukawa variation in Randall-Sundrum

  Von Harling, Servant, 1612.02447

- Calculation of baryon asymmetry in models of variable Yukawas

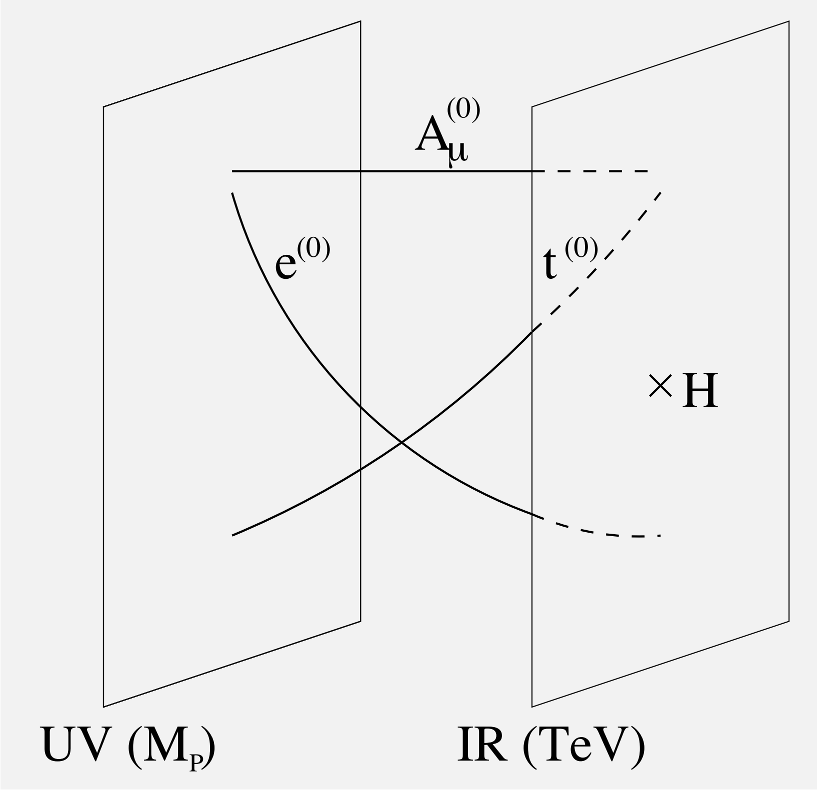
  Bruggisser, Konstandin, Servant, 1706.08534

- Outcome in composite Higgs models

  Bruggisser, VonHarling, Matsedonskyi, Servant, 1803.08546 & 1804.07314

Naturally varying Yukawas: The Randall-Sundrum case

Von Harling, Servant '16



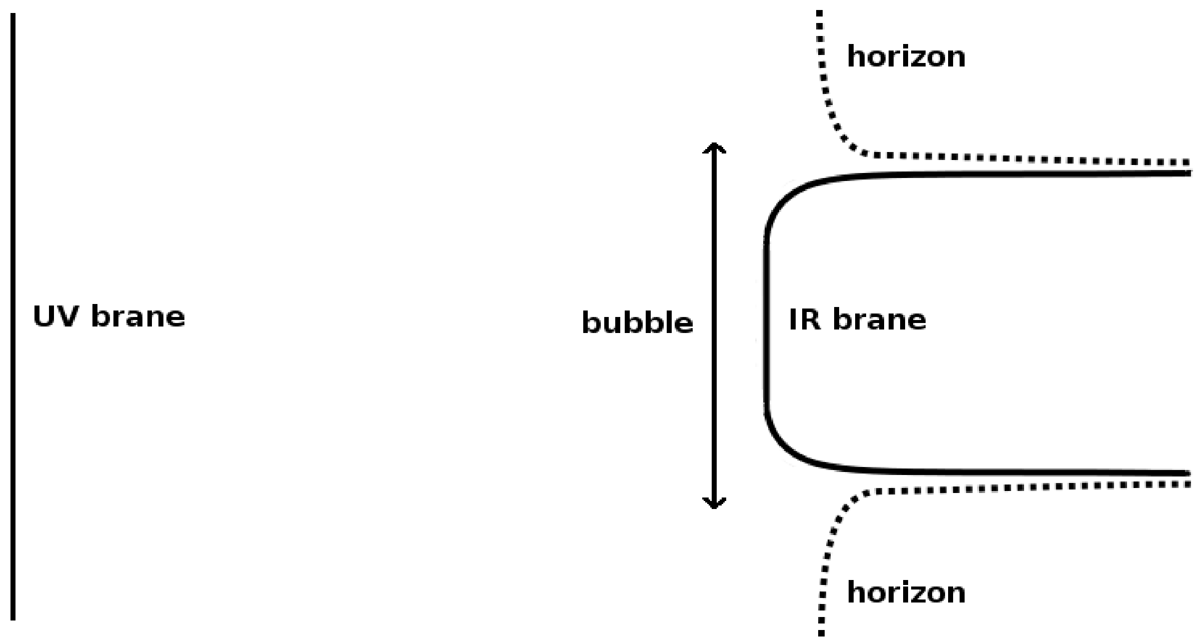
AdS_5 metric

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

$$S \supset \int d^4x \left(\eta^{\mu\nu}\partial_\mu H^\dagger \partial_\nu H - e^{-2ky_{\rm IR}} M_P^2 |H|^2 + \lambda |H|^4\right)$$

radion $\sigma \equiv e^{-ky_{\rm IR}}$

EW phase transition in Randall-Sundrum



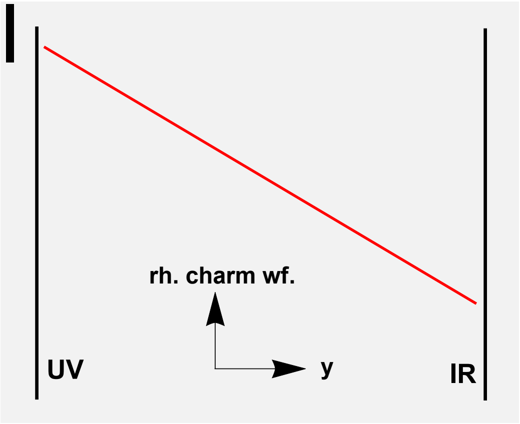
In minimal Randall-Sundrum models, Yukawas decrease across the bubble wall

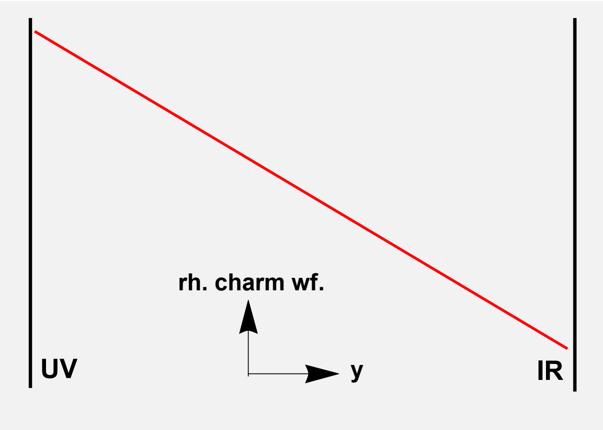
CONSTANT bulk fermion mass term:

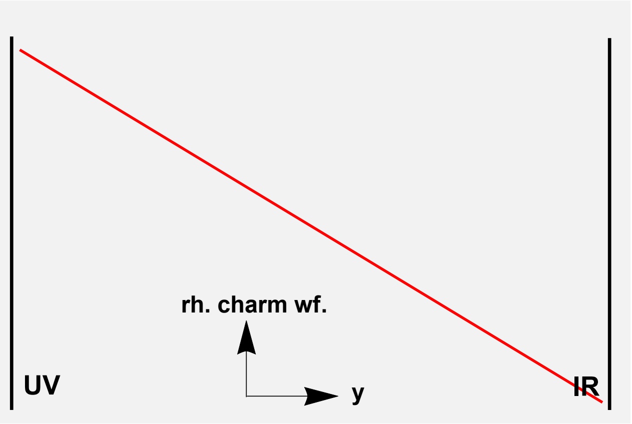
$$S \supset -\int d^5x \sqrt{g}\, c\, k\, \overline{\psi}\psi$$

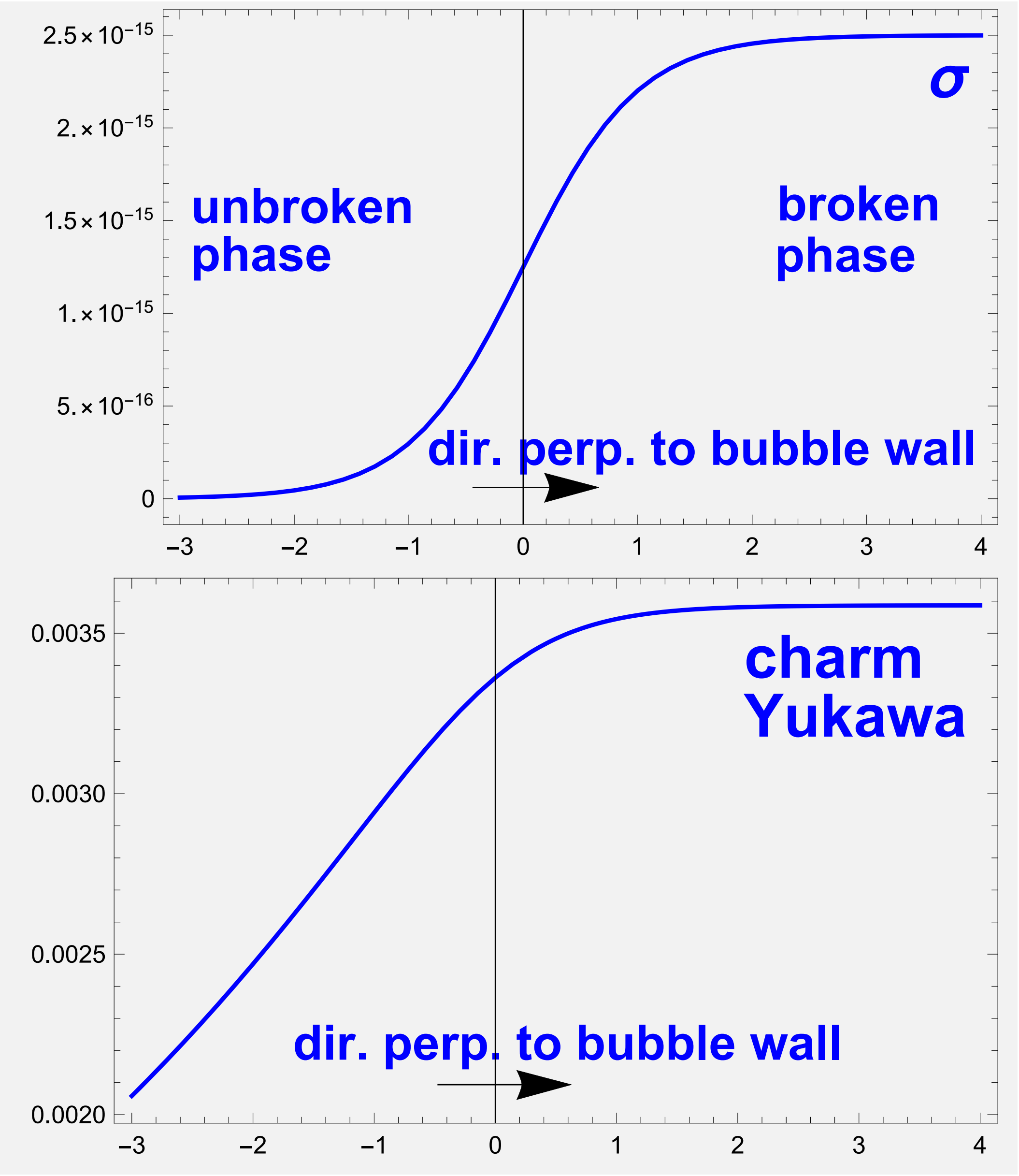
resulting 4D effective Yukawas:

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









$\Rightarrow$ Yukawas decrease along bubble wall

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

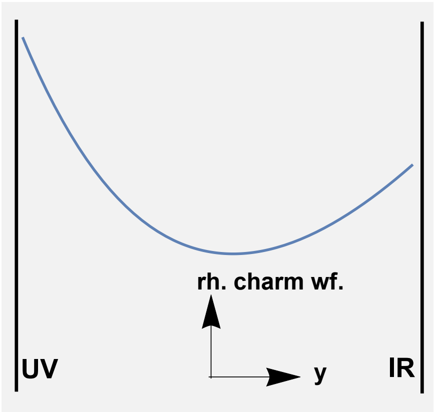
Now, assume following natural possibility:
bulk fermion mass term comes from Yukawa coupling with Goldberger-Wise scalar:

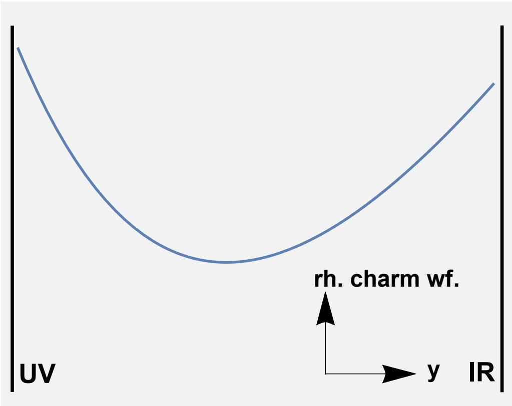
$$S \supset -\int d^5x \sqrt{g}\, \rho\langle\phi\rangle\, \overline{\psi}\psi$$

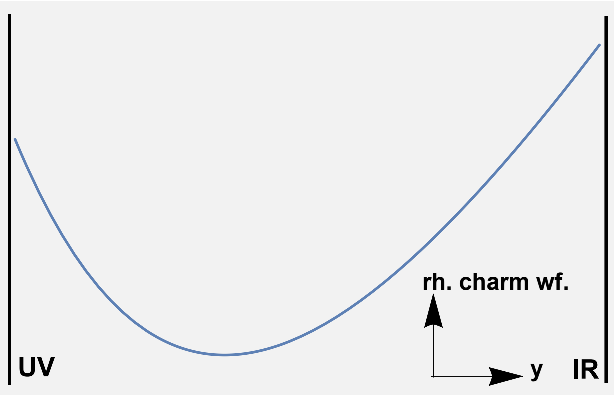
$\Rightarrow$ Position-dependent mass term!

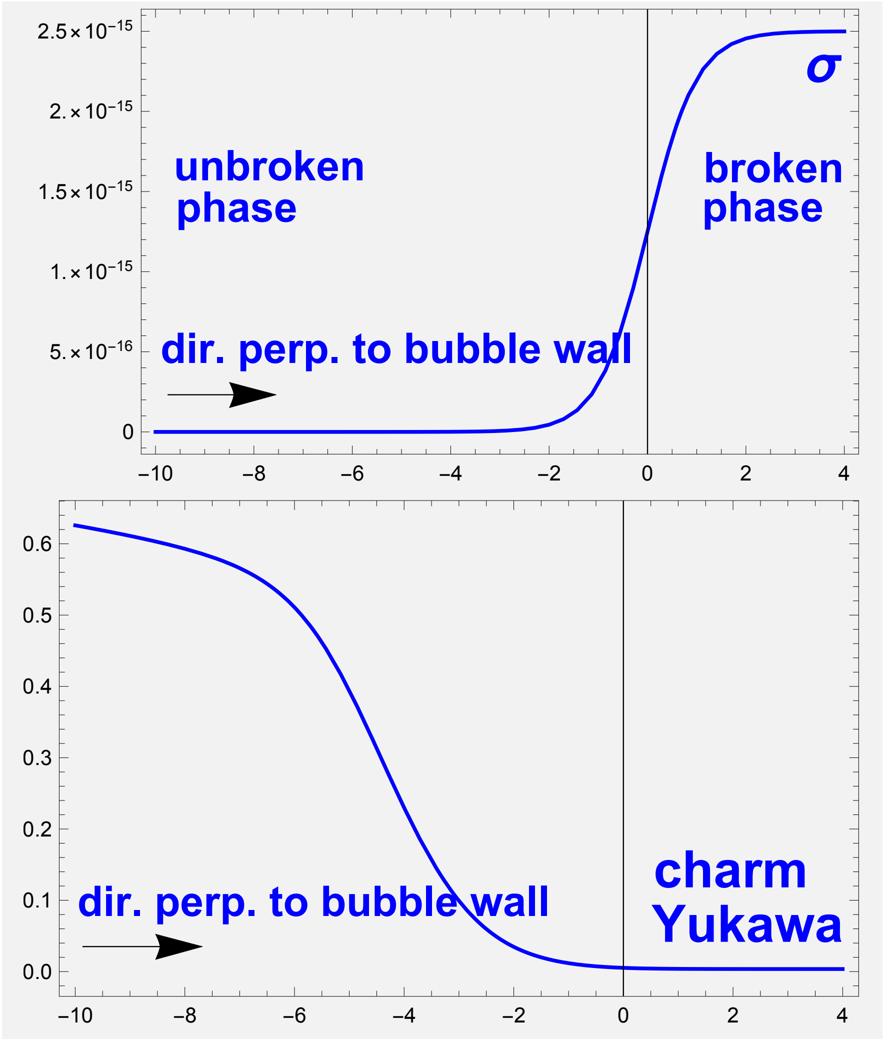
resulting 4D effective Yukawas:

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





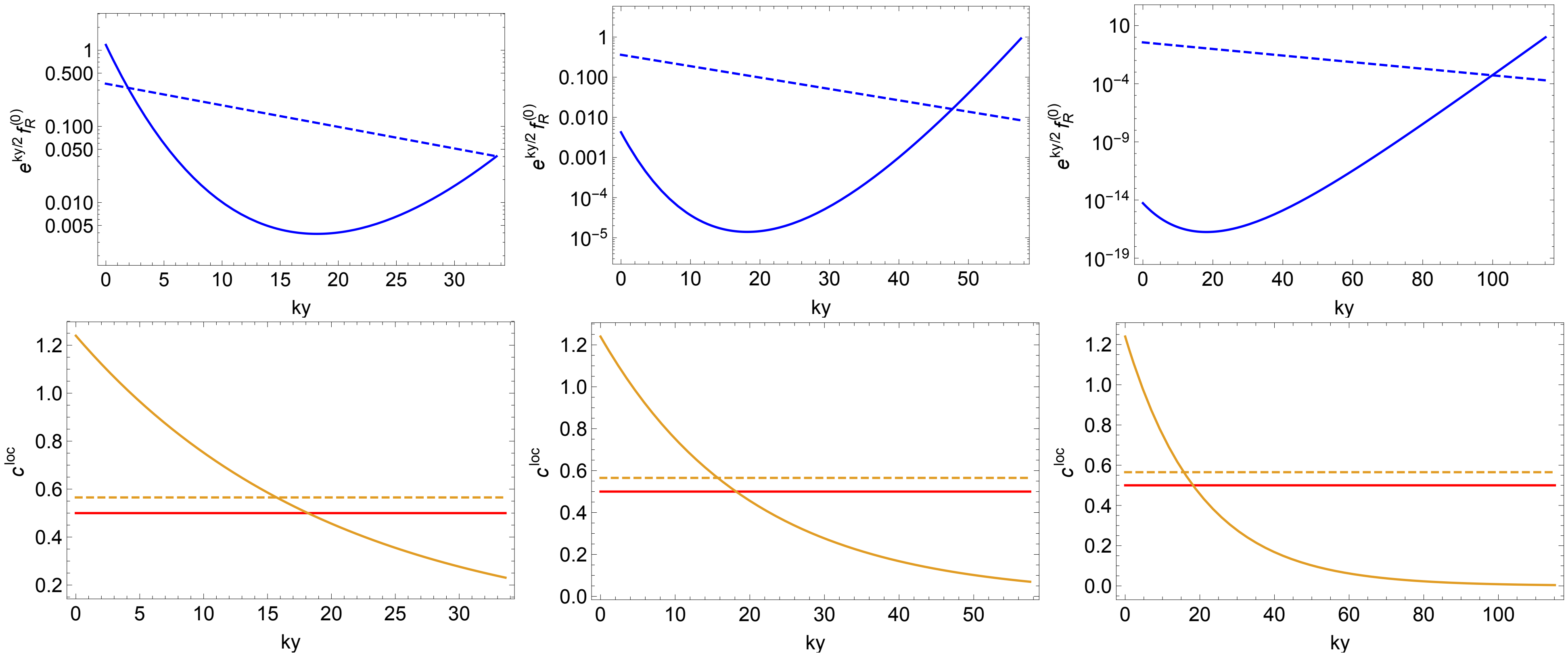




$\Rightarrow$ Yukawas increase along bubble wall

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

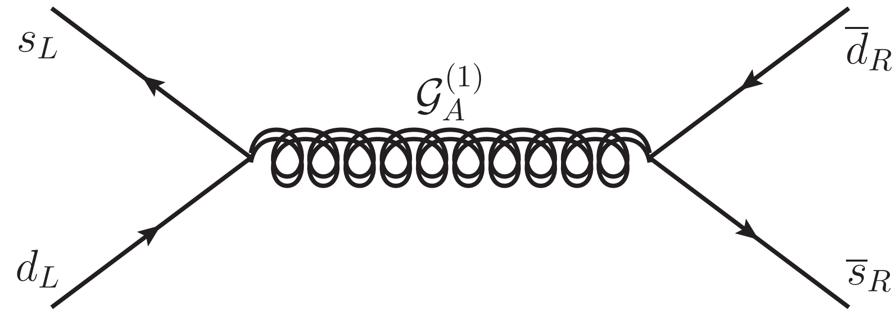
Wave function when going back in time



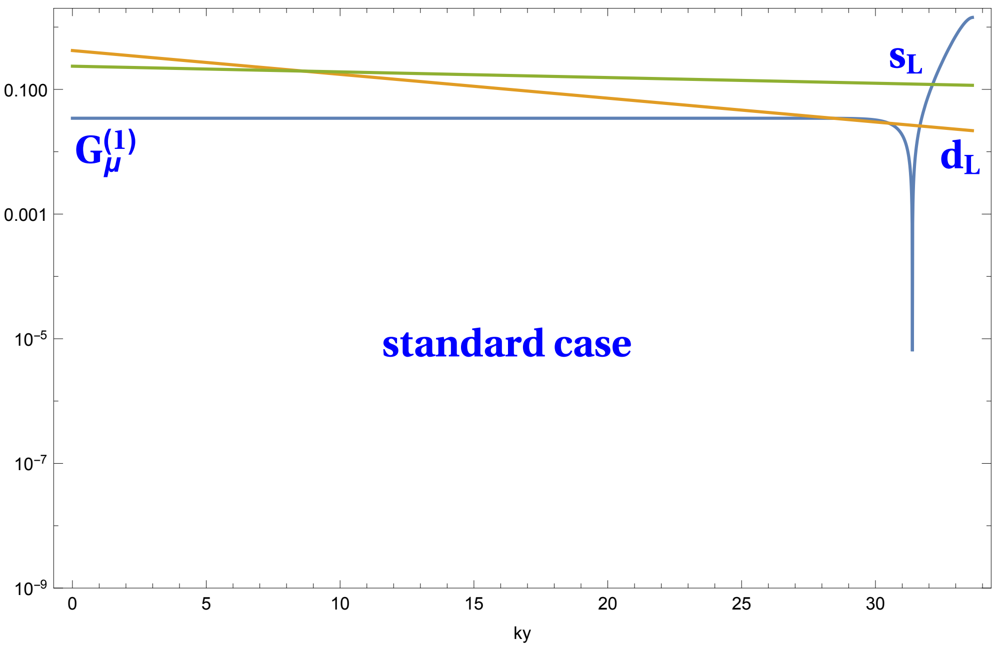
Bonus:

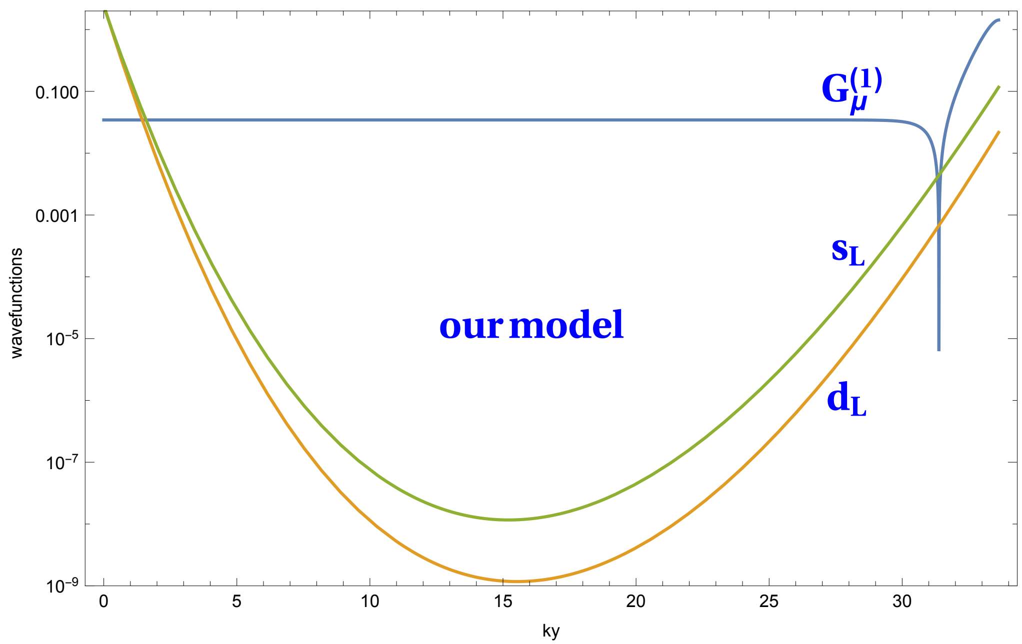
Modified wave functions give suppression of CP-violating processes which are very constraining in the standard case

CP violation in K-Kbar mixing



Suppression of overlap integral





Constraint for standard case of constant bulk mass terms:

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

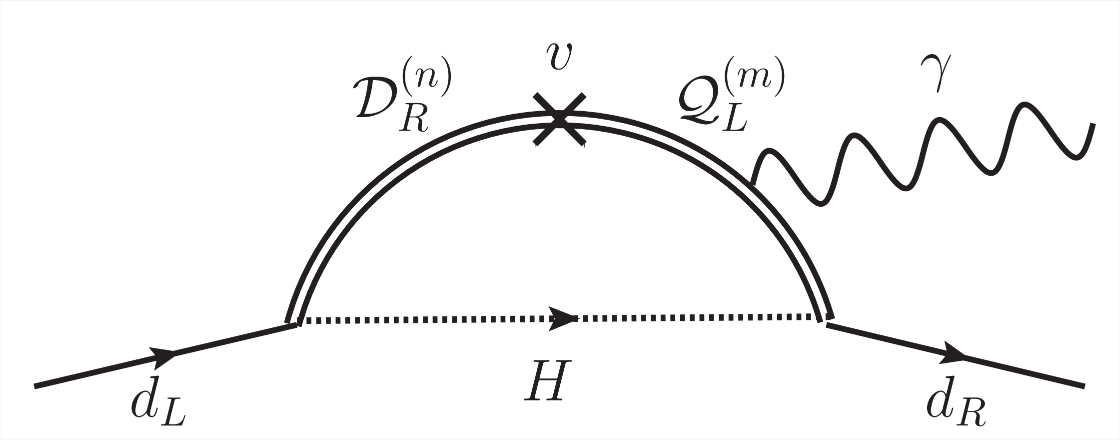
- In our scenario instead:

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

$\Rightarrow$ Significant improvement!

Neutron EDM

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



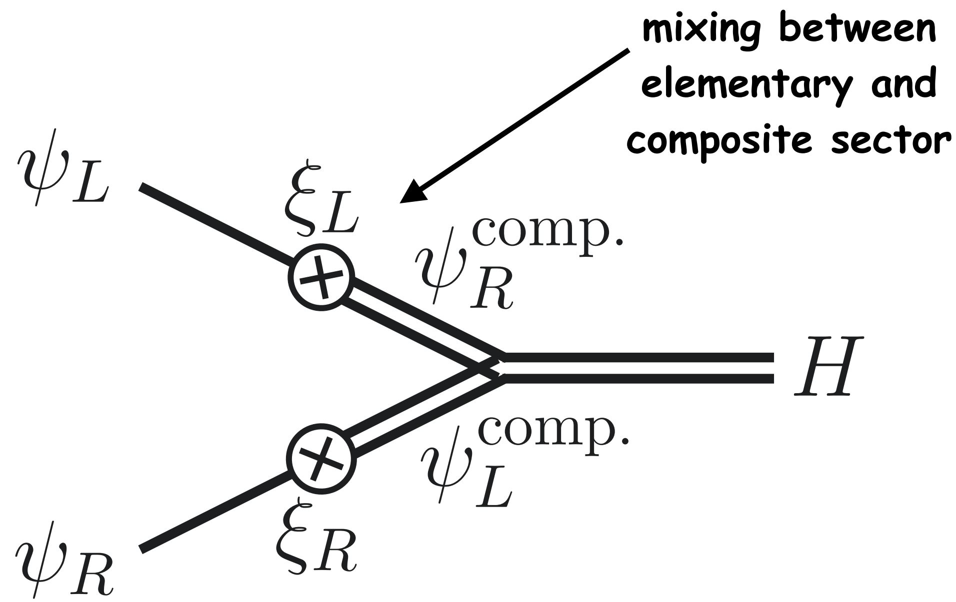
- Constraint for standard case of constant bulk mass terms:

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

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

CFT Interpretation

$$\mathcal{L} \supset \mathcal{L}_{\rm CFT} + i\,\mathcal{Z}\,\bar{\psi}_L \gamma^\mu \partial_\mu \psi_L + \frac{\omega}{\Lambda_{\rm UV}^{\Delta-5/2}} (\bar{\psi}_L \mathcal{O}_R + {\rm h.c.})\,,$$



Effective Yukawa coupling

$$y(\Lambda_{\rm IR}) \propto \xi_L(\Lambda_{\rm IR}) \times \xi_R(\Lambda_{\rm IR})$$

mu: scale of spontaneous breaking of conformal invariance in the IR

$$\xi(\mu) \equiv \frac{\omega(\mu)}{\sqrt{\mathcal{Z}(\mu)}} \left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\Delta(\mu)-5/2}$$

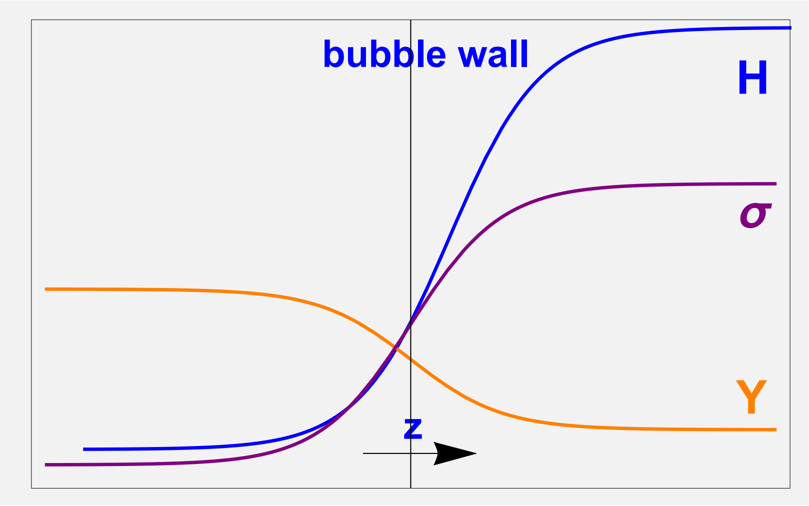
$$\Delta(\mu) = 2 + \tilde{c} \left(\frac{\mu}{\Lambda_{\rm UV}}\right)^{\epsilon}$$

Summary

Minimal modification of RS: Yukawa coupling between Goldberger-Wise scalar and bulk fermions

naturally large yukawas and enhanced CP violation in bubble walls during EW phase transition

eases constraints from CP violation in K Kbar mixing



EW phase transition
in Composite Higgs models

Bruggisser, Von Harling, Matsedonskyi, Servant, '18

Higgs : PNGB with decay constant f

Higgs potential: trigonometric function of h/f, arises due to Goldstone symmetry breaking sources responsible for the fermion mass generation

$$V_h^{\mathrm{NDA}}[y,\chi] = \alpha^{\mathrm{NDA}}[y,\chi]\sin^2[h/\chi] + \beta^{\mathrm{NDA}}[y,\chi]\sin^4[h/\chi]$$

mixing between elementary
& composite sectors

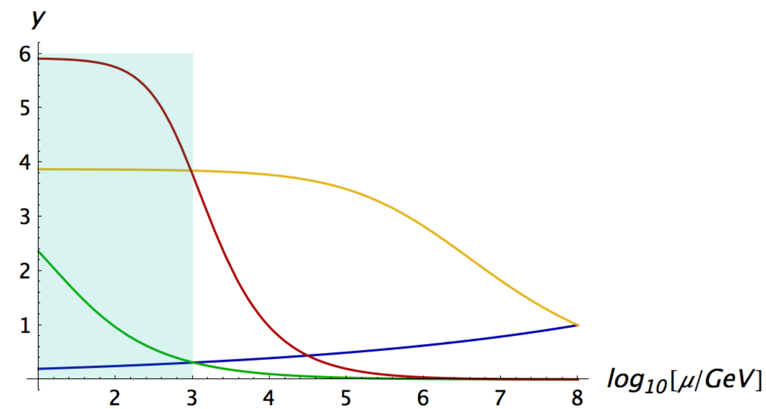
dilaton VEV, $\langle\chi\rangle \sim f$

Partial fermion compositeness

E

Λ_{UV} $\qquad$ $\mathcal{L} \supset y_i \bar{q}_i \mathcal{O}_i$

$$\frac{\partial y_i}{\partial \log \mu} = \gamma_i y_i + c_i \frac{y_i^3}{g_\star^2} + \ldots$$



$g_\star f$ $\qquad$ $\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$

Goldstone matrix containing the Higgs

$U \sim \exp[ih/f]$

Integrating out ψ_i with $m_\psi \sim g_\star f$

SM Yukawas determined by the mixings at the confinement scale

$$\lambda_q \sim \frac{y_L y_R}{g_\star}$$

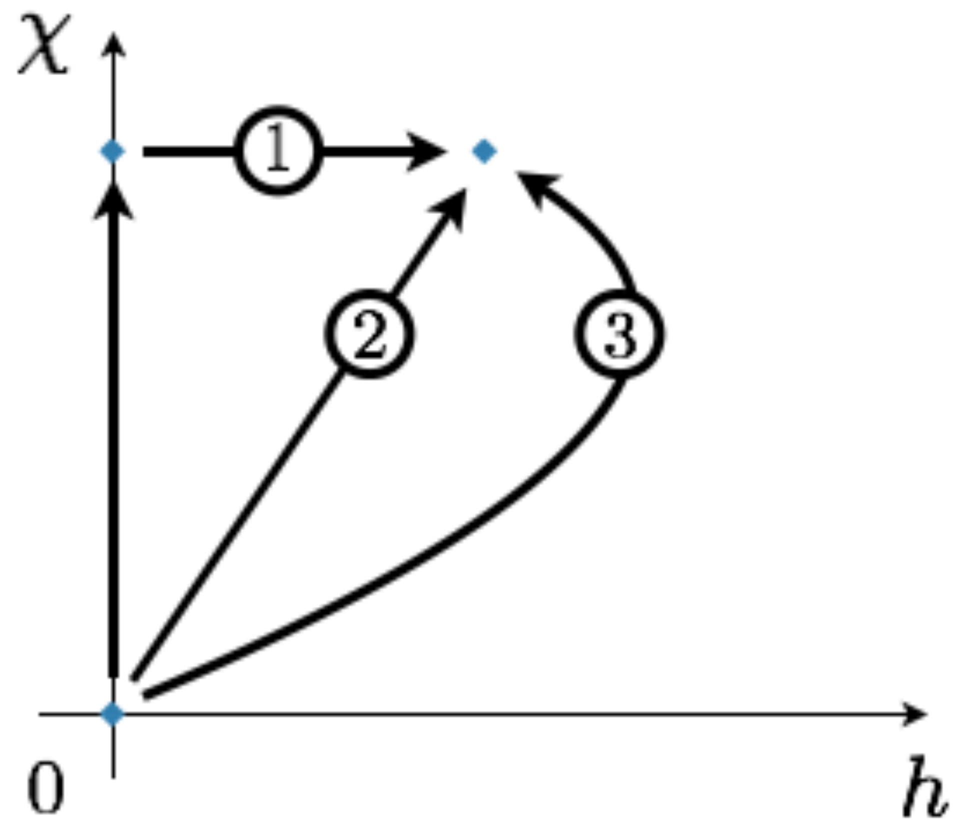
Mass hierarchy generated by order one differences in the scaling dimensions of $\mathcal{O}_i$

EW phase transition in Composite Higgs models

$$V_h^{\rm NDA}[y,\chi] = \alpha^{\rm NDA}[y,\chi]\sin^2[h/\chi] + \beta^{\rm NDA}[y,\chi]\sin^4[h/\chi]$$

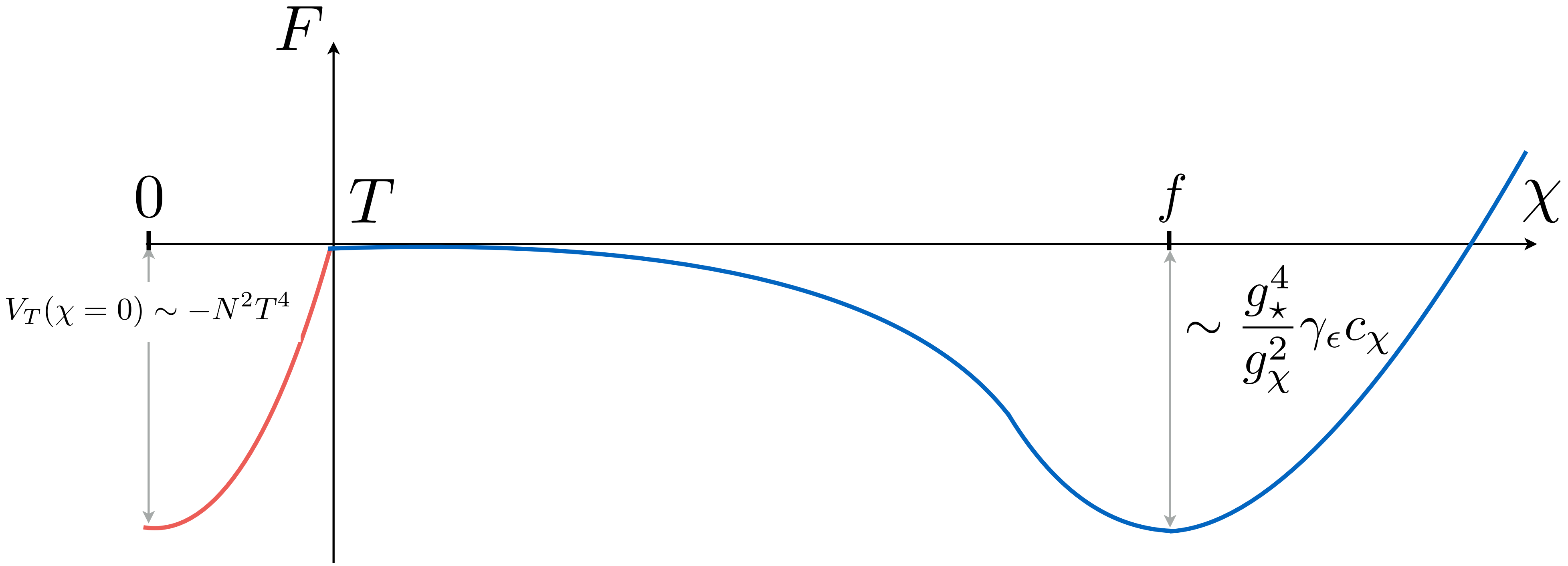
with $\alpha^{\rm NDA}[y,\chi] = \pm\frac{N_c y^2}{(4\pi)^2} g_\star^2 \chi^4$ and $\beta^{\rm NDA}[y,\chi] = \pm\frac{N_c y^2}{(4\pi)^2} g_\star^2 \chi^4 \left(\frac{y}{g_\star}\right)^{p_\beta}$

Novelty: we take the y's (and f) to be dynamical: **y=** $y(\chi)$

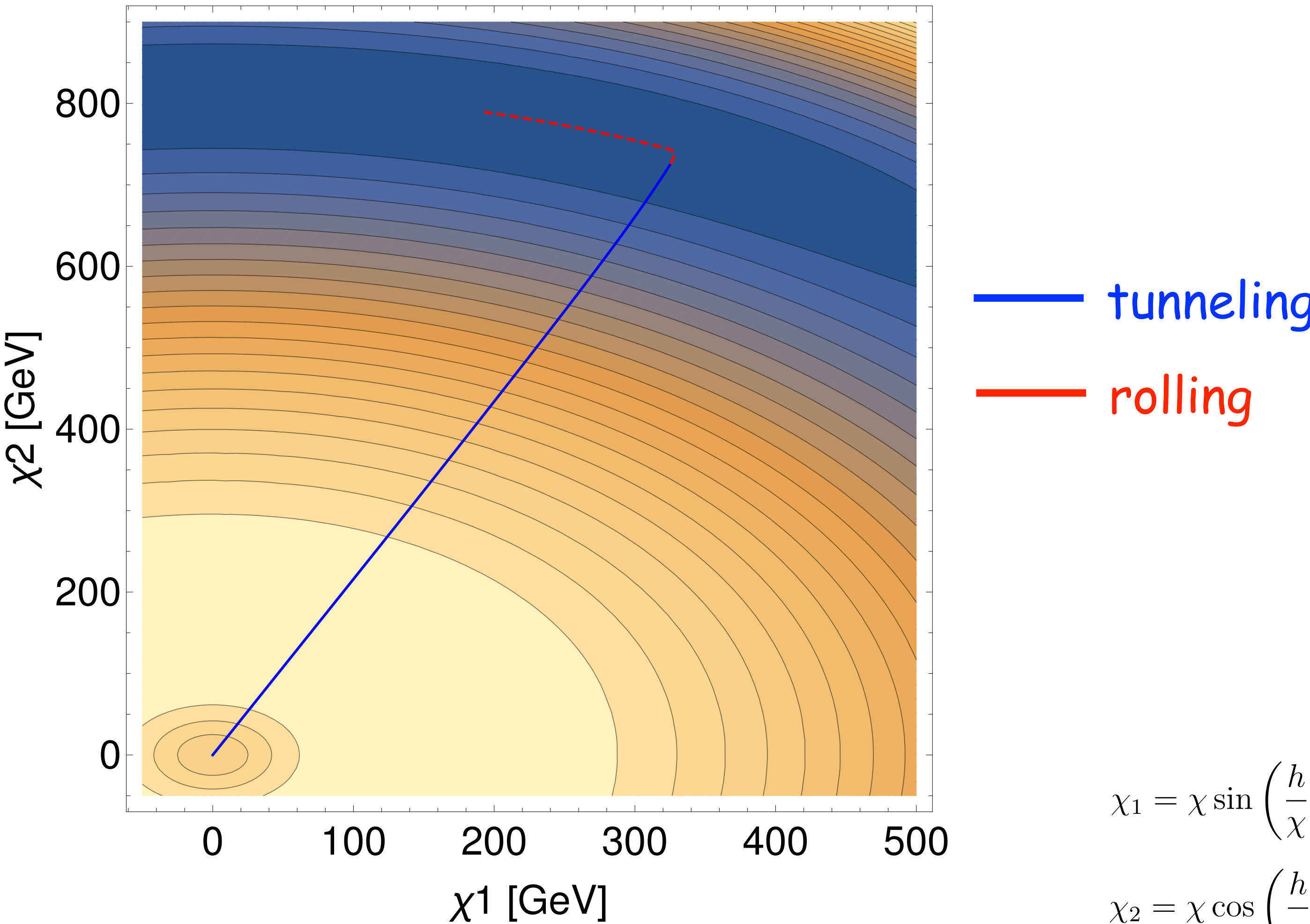


χ
1
2
3
0
h

Dilaton potential



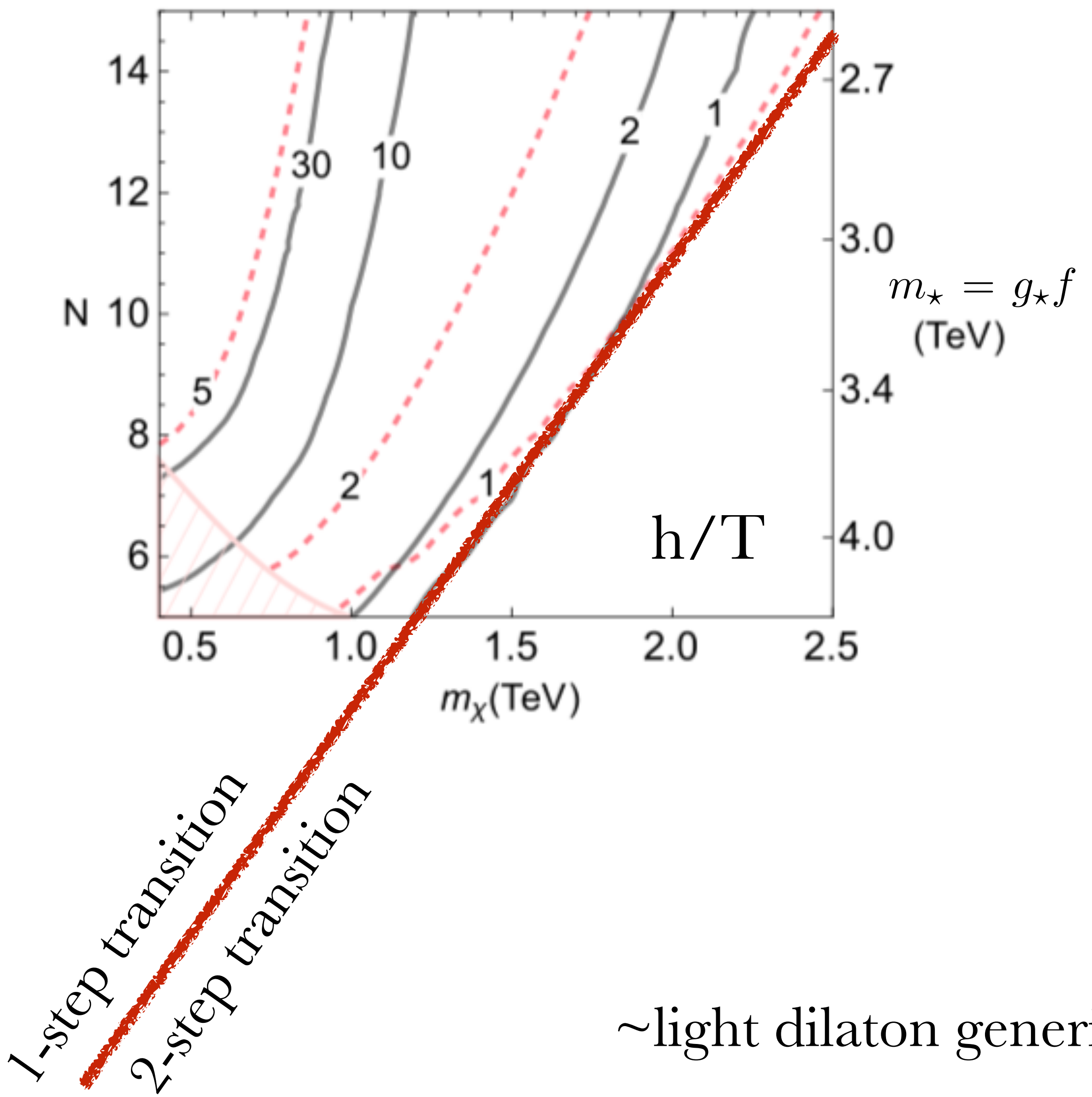
Tunneling trajectory



$$\chi_1 = \chi \sin\left(\frac{h}{\chi}\right)$$

$$\chi_2 = \chi \cos\left(\frac{h}{\chi}\right)$$

Strength of EW phase transition



glueball

meson

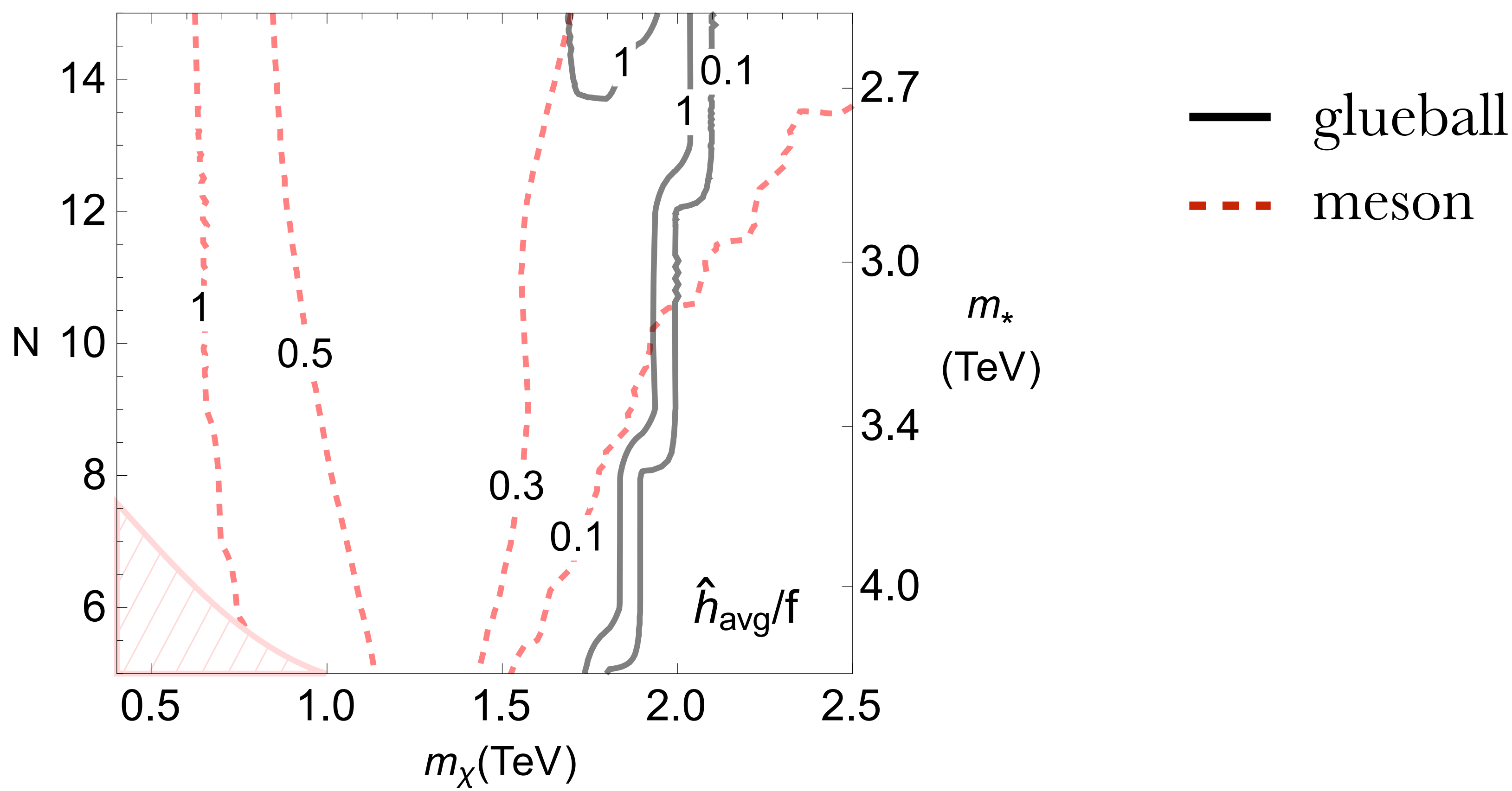
$g_\star = 4\pi/\sqrt{N}$

large range of N with h/T~1

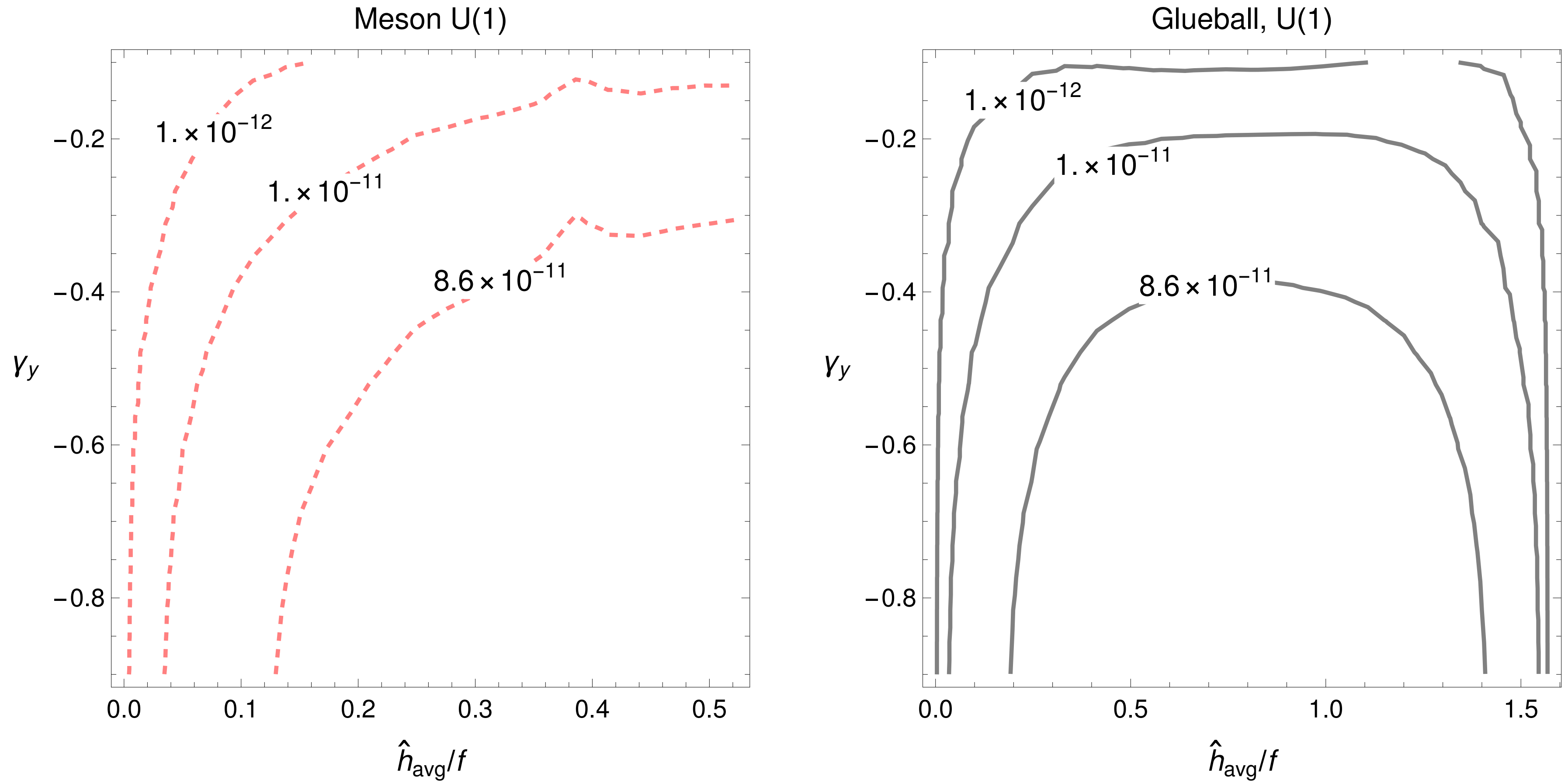
~light dilaton generically needed

$\rightarrow$ direct searches+Higgs physics

Average tunnelling direction



Baryon asymmetry



Observables

— Dilaton production

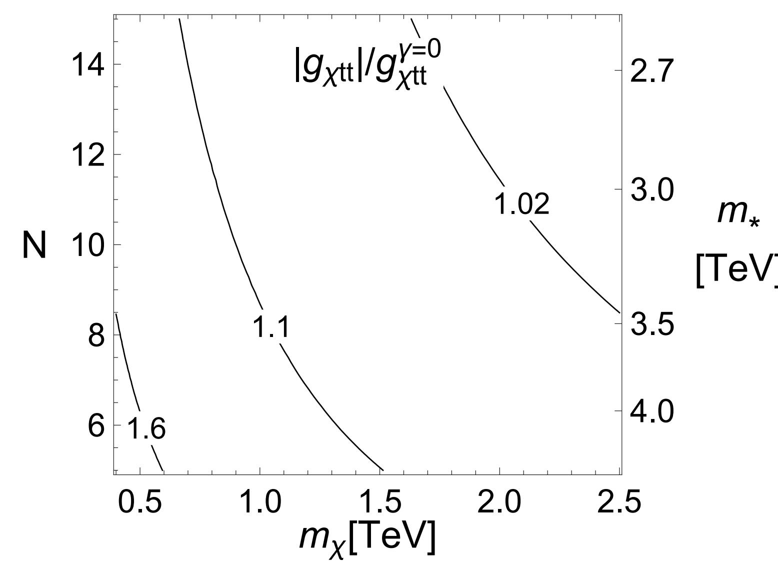
—Sizeable energy dependence of the elementary-composite fermion mixings ->

modified couplings of the dilaton to the massive SM states

top mass: $$\lambda_t[\chi]\,\chi\,\sin\frac{h}{f}\,\bar{t}_L t_R \supset \bar{t}_L t_R\, h\left(\lambda_t^0\frac{\chi}{f} + \beta_{\lambda_t}\frac{\chi - f}{f}\right)$$

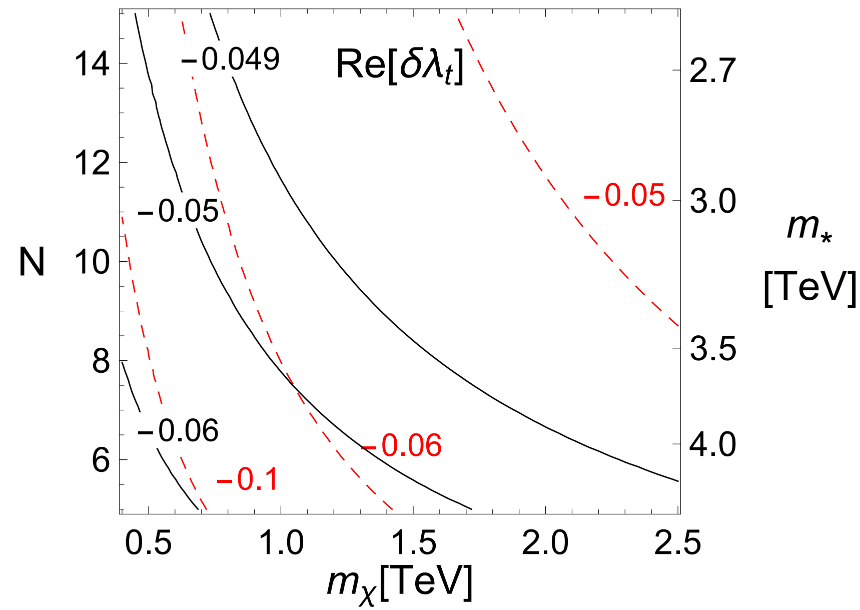
contribution from varying mixing

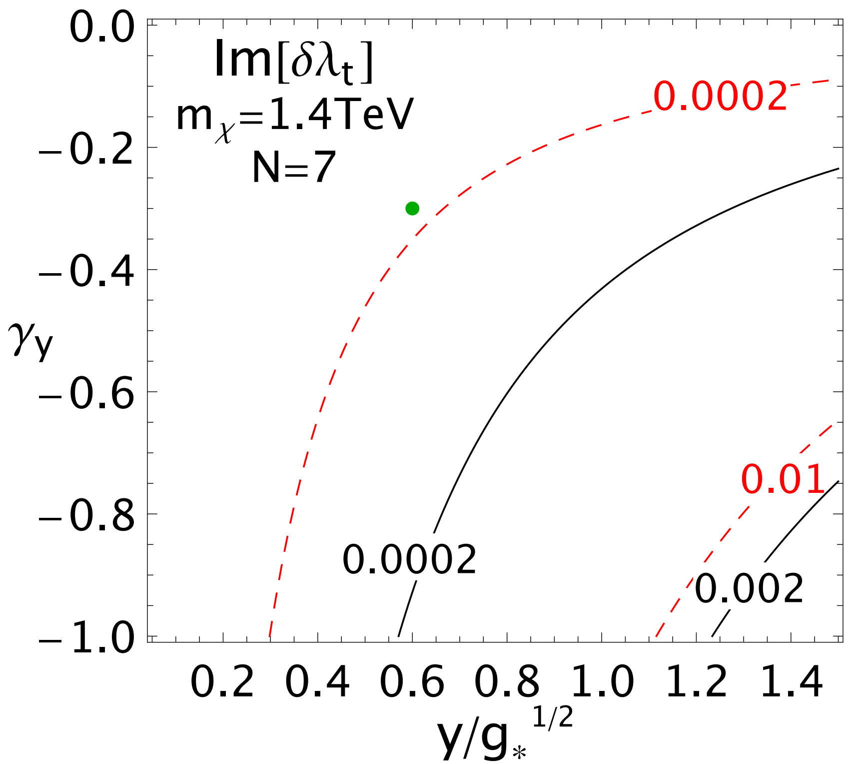
Notable effect for dilaton-top coupling which provides information on tunnelling direction



Observables

—CP-violating top-Higgs
and top-dilaton couplings

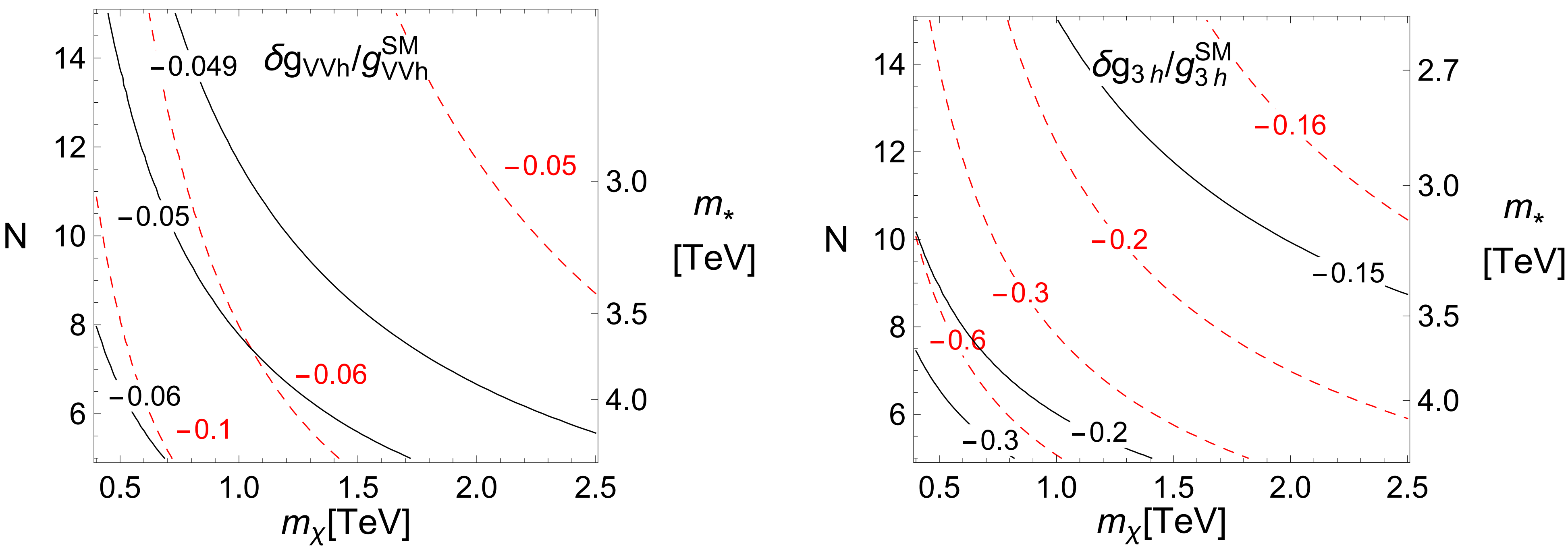




current sensitivity: ~ 2 . 10^-2
future sensitivity: ~ 2 . 10^-4

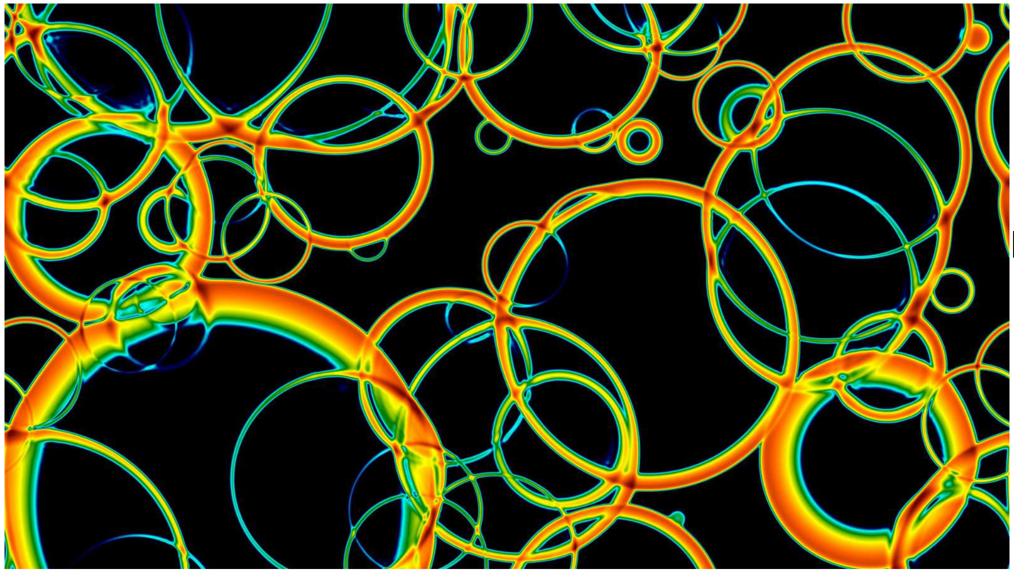
Observables

—Higgs coupling to EW gauge bosons and Higgs self-coupling



Gravity wave signals from 1st order cosmological phase transitions

[LISA Cosmology Working group, 1512.06239]



[Credit:David Weir]

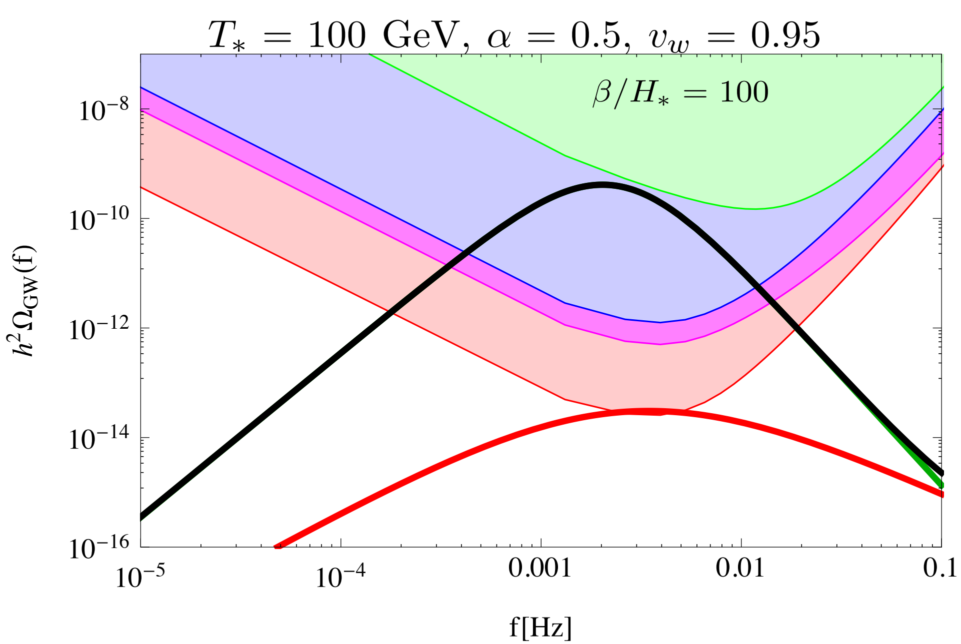
Fluid flows

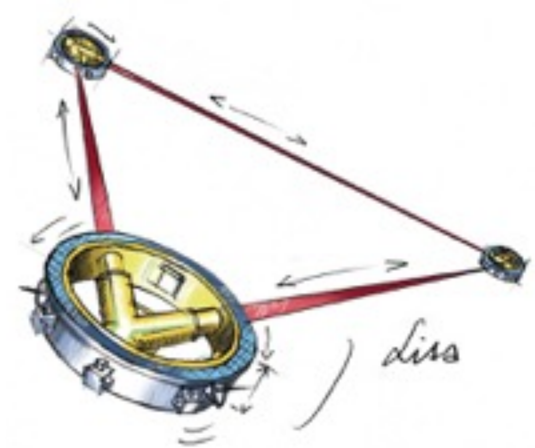
turbulence

Magnetic fields

Stochastic background of gravitational radiation

EW phase transition -> mHz -> LISA!





key quantities controlling the GW spectrum

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 8\pi G a^2 T_{ij}^{(TT)}(k,t)$$

$$T_{ab}(\mathbf{x}) = (\rho + p)\frac{v_a(\mathbf{x})v_b(\mathbf{x})}{1 - v^2(\mathbf{x})}$$

Source of GW: anisotropic stress

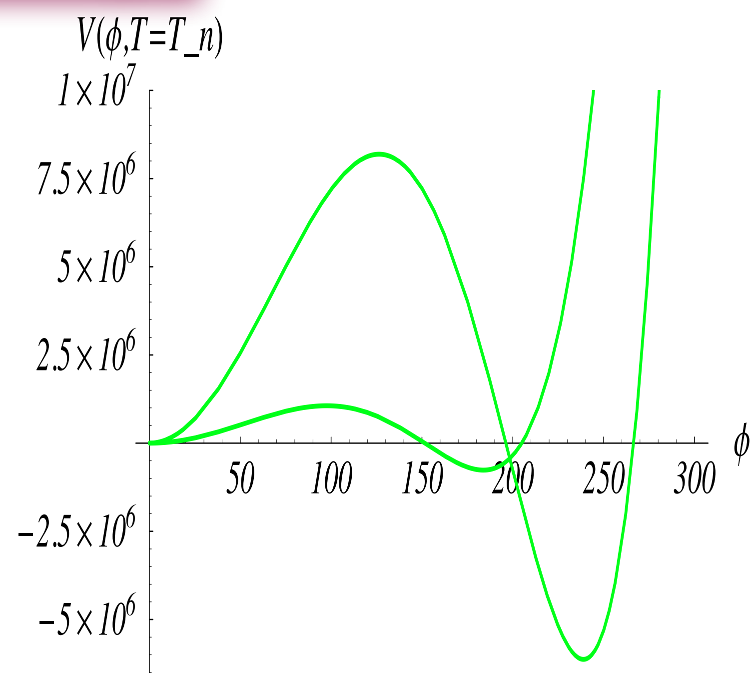
β : (duration of the phase transition)$^{-1}$

set by the tunneling probability $P \propto e^{\beta t} \propto \frac{T^4}{H^4} e^{-S_3/T} \sim 1$ ➜ $\frac{S_3}{T} \sim 140$

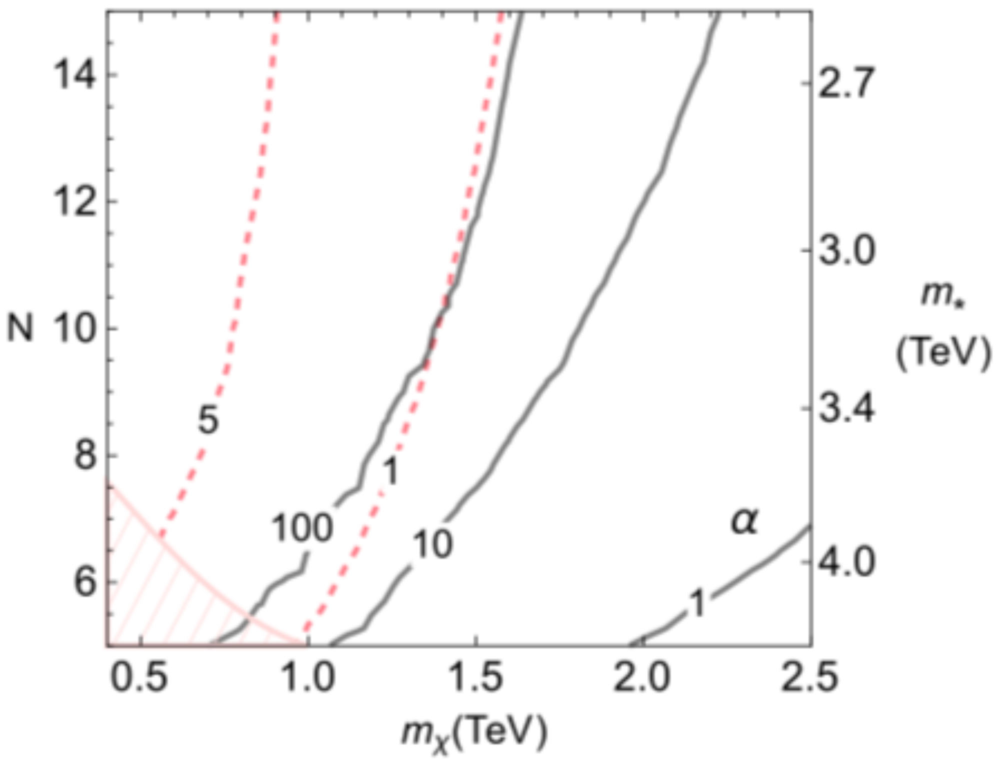
and typically $\frac{\beta}{H} \sim \mathcal{O}(10^2 - 10^3)$

α : vacuum energy density/radiation energy density

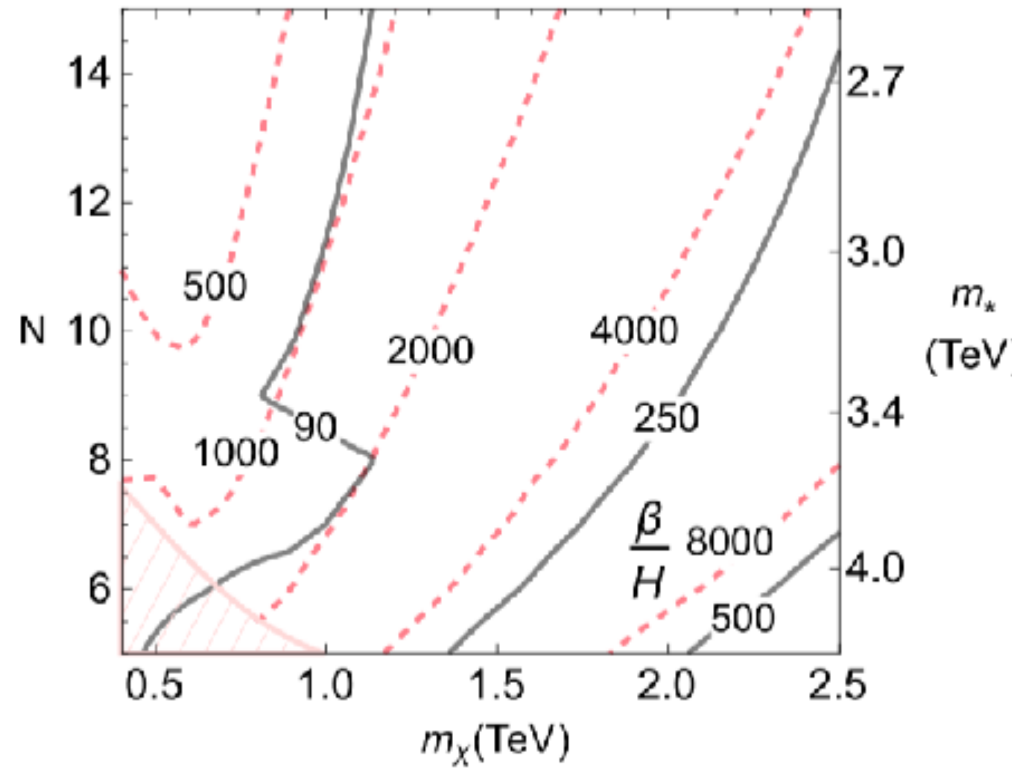
α and β : entirely determined by the effective scalar potential at high temperature



$\alpha \sim$ latent heat



$\beta \sim$ transition rate



LISA sensitivity

$\alpha \gtrsim 0.1$

$1 \lesssim \beta/H \lesssim 10^4$

Conclusion

- Non-trivial coupled Higgs-dilaton evolution

-> EW phase transition generically strong

-> Built-in way to introduce large CP violation during EW phase transition

-> EW Baryogenesis is a natural output in Composite Higgs models