CONFORMAL HIGGS PORTAL MODELS

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T. Prokopec, Leonardo da Rocha, Michael Schmidt, Bogumila Swiezewska, 1801.05258 [hep-ph], arXiv:1805.09292 [hep-ph]

Stefano Lucat and T. Prokopec and , Bogumila Swiezewska: arXiv:1804.00926 [gr-qc]

Stefano Lucat and T. Prokopec, arXiv:1705.00889 [gr-qc]; 1709.00330 [gr-qc];1606.02677 [hep-th]

Valday, QUARKS-2018, 30-05-2018

CONTENTS

MOTIVATION

►PRINCIPAL QUESTIONS:

- CAN WEYL SYMMETRY BE ENCORPORATED IN PARTICLE PHYSICS AND GRAVITY (AT HIGH ENERGIES)?
- WHAT IS ITS SIMPLEST AND MOST NATURAL IMPLEMENTATION?
- HOW TO TEST IT?

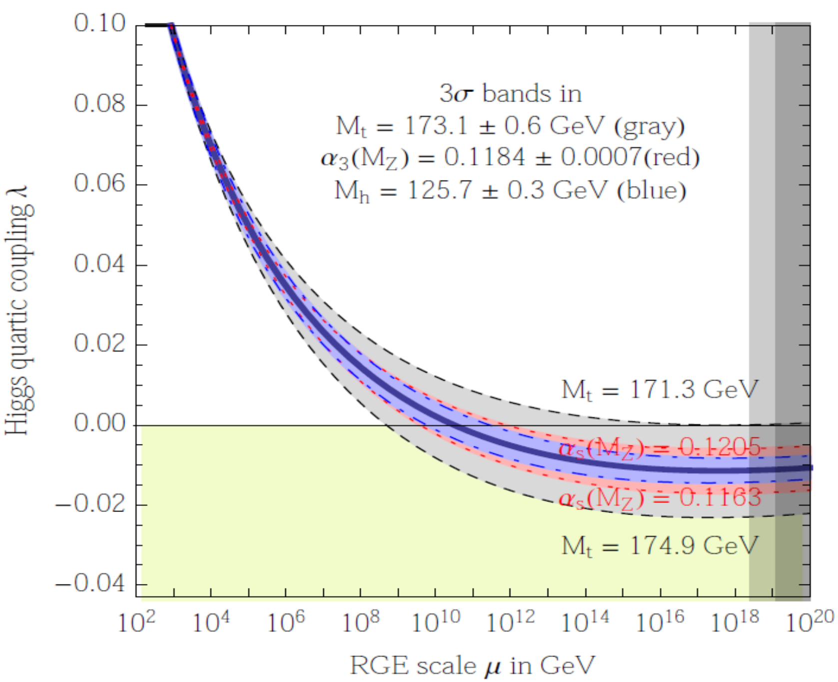
►ANSWERS:

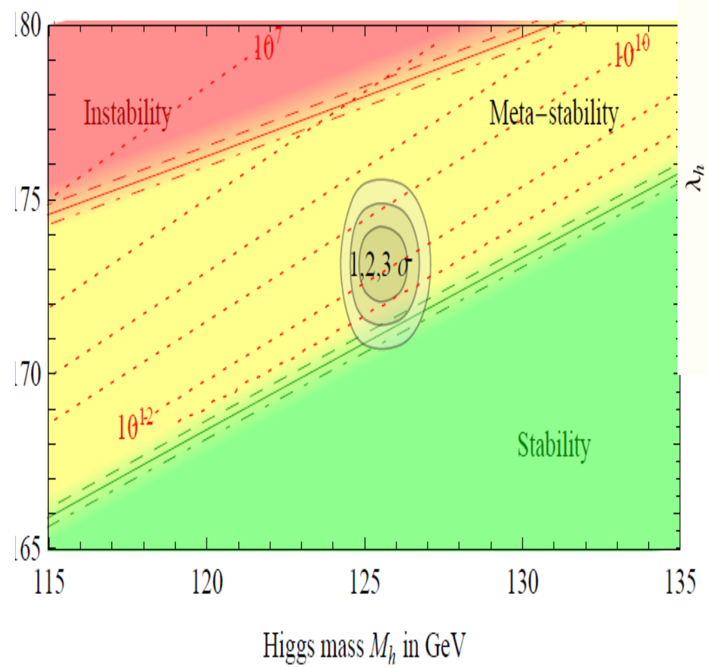
- YES
- TORSION TENSOR, BECAUSE IT MAKES (PURE) GRAVITY CONFORMAL
- TESTS: - simple conformal extension of SM (Higgs close to conformal point)
  - observing torsion waves in gravitational observatories
  - gravitational wave and baryon production at the strong EWPT
  - inflationary observables in conformal inflationary models are constrained
  - surprises from the Planck scale physics (?)

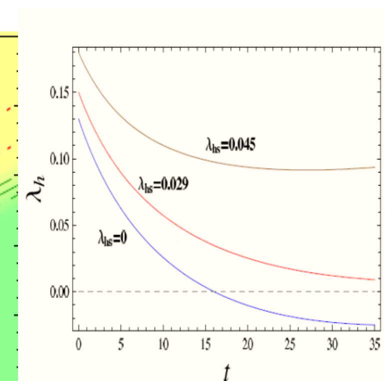
PHYSICAL MOTIVATION

- AT LARGE ENERGIES THE STANDARD MODEL IS <u>ALMOST</u> CONFORMALLY INVARIANT.
- HIGGS MASS AND KINETIC TERMS BREAK THE SYMMETRY
- OBSERVED HIGGS MASS: $m_H = 125.3\text{GeV}$ is close to the stability bound
- STABILITY BOUND: $m_H \approx 129\text{GeV}$: CAN BE ATTAINED BY ADDING SCALAR

Oleg Lebedev, e-Print: arXiv:1203.0156 [hep-ph]







Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, 1205.6497 [hep-ph]

THEORETICAL MOTIVATION

THEORETICAL MOTIVATION

- HIGGS MASS TERM RESPONSIBLE FOR GAUGE HIERARCHY PROBLEM

- IF WE COULD FORBID IT BY SYMMETRY, THE GHP WOULD BE SOLVED

- THIS SYMMETRY COULD BE WEYL SYMMETRY IMPOSED CLASSICALLY

- HIGGS MASS, NEWTON & COSMOLOGICAL CONSTANT GENERATED DYNAMICALLY BY THE COLEMAN-WEINBERG (CW) MECHANISM

- ONCE FINE TUNED TO THE OBSERVED VALUE, CC IS STABLE UNDER A CHANGE OF THE RENORMALIZATION SCALE.

Stefano Lucat and T. Prokopec and , Bogumila Swiezewska: arXiv:1804.00926 [gr-qc]

- IF GRAVITY IS CONFORMAL IN UV, IT MAY BE FREE OF SINGULARITIES (BOTH COSMOLOGICAL AND BLACK HOLE).

WEYL SYMMETRY IN CLASSICAL GRAVITY

CLASSICAL WEYL SYMMETRY

- WEYL TRANSFORMATION ON THE METRIC TENSOR

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = e^{2\theta(x)} g_{\mu\nu} \qquad \mathrm{d}\tau \to \mathrm{d}\tilde{\tau} = e^{\,\theta(x)}\mathrm{d}\tau$$

- GENERAL CONNECTION Γ, TORSION TENSOR T, CHRISTOFFEL CON $\overset{\circ}{\Gamma}$

$$\Gamma^{\lambda}{}_{\mu\nu} = T^{\lambda}{}_{\mu\nu} + T_{\mu\nu}{}^{\lambda} + T_{\nu\mu}{}^{\lambda} + \overset{\circ}{\Gamma}{}^{\lambda}{}_{\mu\nu}$$

$$\delta \overset{\circ}{\Gamma}{}^{\mu}{}_{\alpha\beta} = \delta^{\mu}{}_{(\alpha}\partial_{\beta)}\theta \quad \overset{\text{POSTULATE}}{\Rightarrow\Rightarrow} \quad \delta\Gamma^{\mu}{}_{\alpha\beta} = \delta^{\mu}{}_{\alpha}\partial_{\beta}\theta \;\Rightarrow\; \boxed{\delta T^{\mu}{}_{\alpha\beta} = \delta^{\mu}{}_{[\alpha}\partial_{\beta]}\theta}$$

- RIEMANN TENSOR IS INVARIANT: $\delta R^{\alpha}{}_{\beta\gamma\delta} = 0$

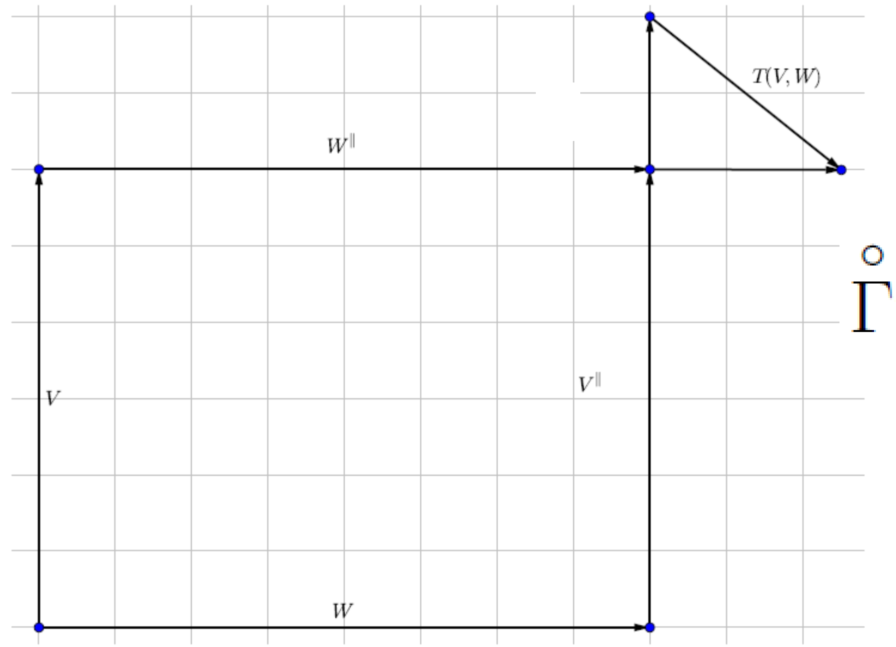
- THIS IMPLIES THAT THE VACUUM EINSTEIN EQUATION IS WEYL INV:

$$\boxed{G_{\mu\nu} = 0, \qquad \delta G_{\mu\nu} = 0}$$

GEOMETRIC VIEW OF TORSION

- (VECTORIAL) TORSION TRACE 1-FORM:

$$\mathcal{T} \equiv \mathcal{T}_\mu \mathrm{d}x^\mu = \frac{2}{D-1} T^\lambda{}_{\lambda\mu} \mathrm{d}x^\mu$$



- TRANSFORMS AS A VECTOR FIELD:

$$\mathcal{T} \to \mathcal{T} + \mathrm{d}\theta$$

- WHEN A VECTOR IS PARALLEL-TRANSPORTED, TORSION TRACE INDUCES A LENGTH CHANGE: CRUCIAL IN WHAT FOLLOWS

PARALLEL TRANSPORT AND JACOBI EQUATION

- GEODESIC EQUATION:

$$\nabla_{\dot\gamma}\frac{dx^\mu}{d\tau} \equiv \frac{dx^\lambda}{d\tau}\nabla_\lambda\frac{dx^\mu}{d\tau} = 0$$

$$\Gamma^\lambda{}_{\mu\nu} = T^\lambda{}_{\mu\nu} + T_{\mu\nu}{}^\lambda + T_{\nu\mu}{}^\lambda + \mathring{\Gamma}^\lambda{}_{\mu\nu}$$

$\mathring{\Gamma}$ = LEVI-CIVITA

$$T[X,Y] = -\frac{1}{2}(\nabla_X Y - \nabla_Y X - [X,Y])$$

$$T^\lambda{}_{\mu\nu} = \Gamma^\lambda{}_{[\mu\nu]} = \frac{1}{2}\left(\Gamma^\lambda{}_{\mu\nu} - \Gamma^\lambda{}_{\nu\mu}\right)$$

→ TRANSFORMS MULTIPLICATIVELY (as $1/d\tau^2$)

$$\nabla_{\dot\gamma}\frac{dx^\mu}{d\tau} = 0 \Rightarrow e^{-2\theta(x)}\nabla_{\dot\gamma}\frac{dx^\mu}{d\tau} = 0$$

NB: TRANSFORMATION OF $d\tau$ COMPENSATED BY TRANSFORMATION OF Γ !

- JACOBI EQUATION (JACOBI FIELDS J ⊥ $\dot\gamma$) AND RAYCHAUDHURI EQ:

$$\nabla_{\dot\gamma}\nabla_{\dot\gamma}J + 2\nabla_{\dot\gamma}T[\dot\gamma, J] = R[\dot\gamma, J]\dot\gamma$$

→ ALSO TRANSFORMS MULTIPLICATIVELY (as $1/d\tau^2$) UNDER WEYL TRANS

- SUGGESTS TO DEFINE A GAUGE INVARIANT PROPER TIME:

$$(d\tau)_{g.i.} = \exp\left(-\int_{x_0}^{x} T_\mu dx^\mu\right) d\tau :=$$ PHYSICAL TIME OF COMOVING OBSERVERS!

T. Prokopec, het Lam, e-Print: arXiv:1606.01147

WEYL SYMMETRY IN MATTER SECTOR

SCALAR MATTER

- CONFORMAL WEIGHT w_ϕ OF A CANONICAL SCALAR:

$$\phi \to e^{-\frac{D-2}{2}\theta}\phi \quad \Rightarrow w_\phi = -\frac{D-2}{2}$$

- CONFORMAL (WEYL) COVARIANT DERIVATIVE:

$$\nabla_\mu \phi = \partial_\mu \phi + \frac{D-2}{2} T_\mu \phi$$

TORSION TRACE: $\mathcal{T} \equiv \mathcal{T}_\mu \mathrm{d}x^\mu = \frac{2}{D-1} T^\lambda{}_{\lambda\mu} \mathrm{d}x^\mu$

ACTS AS A GAUGE CONNECTION!

(no i - the group is non-compact)

- CONFORMALLY INVARIANT SCALAR ACTION:

KINETIC/GRADIENT TERMS; SELF-COUPLING & COUPLING TO GRAVITY

$$\int dx^D \sqrt{-g}\,\left(-\frac{1}{2} \nabla_\mu \phi \, \nabla_\nu \phi g^{\mu\nu}\right)$$

$$\int d^D x \sqrt{-g} \left\{ -\frac{\xi}{2} \phi^2 R - \frac{\lambda}{4!} \phi^4 \right\}$$

VECTOR & FERMIONIC MATTER

- CONFORMAL WEIGHTS OF CANONICAL FERMIONS AND VECTORS:

$$\psi \to e^{-\frac{D-1}{2}\theta}\psi$$

$$A_\mu \to e^{-\frac{D-4}{2}\theta}A_\mu$$

$$\Rightarrow w_\psi = -\frac{D-1}{2}, \quad w_A = -\frac{D-4}{2}$$

<u>NB:</u> FERMIONS ARE CONFORMAL IN D DIMENSIONS, VECTORS IN D=4:

$$\nabla_\mu \psi \to e^{-\frac{D-1}{2}\theta(x)}\,\nabla_\mu \psi \qquad \nabla_\mu A_\nu \to \nabla_\mu A_\nu$$

- INVARIANT ACTIONS:

FERMIONS: $$\int \mathrm{d}^4x\sqrt{-g}\left[\frac{i}{2}\left(\bar\psi\gamma^\mu(\nabla_\mu + eA_\mu)\psi - (\nabla_\mu - eA_\mu)\bar\psi\gamma^\mu\psi\right) - g_y\phi\bar\psi\psi\right]$$

VECTORS: $$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}\,\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) \qquad \int d^Dx\, f\,\mathrm{Tr}\left[F_{\mu\nu}\tilde F^{\mu\nu}\right]$$

NB1: IN D≠4, TORSION BREAKS GAUGE SYMMETRY!
NB2: TORSION TRACE ACTS AS A GAUGE CONNECTION (no i)!

CLASSICALLY CONFORMAL STANDARD MODEL & GRAVITY

- HIGGS SECTOR $$\int \mathrm{d}^D x\sqrt{-g}\left[-\frac{1}{2}(D_\mu H)^\dagger D^\mu H - \lambda_H (H^\dagger H)^2 + g_{H\Phi} H^\dagger H \Phi^2 - \lambda_\Phi \Phi^4\right]$$

COVARIANT DERIVATIVE: $$D_\mu H = \partial_\mu H + \frac{D-2}{2}\mathcal{T}_\mu H - ig\sum_a W_\mu^a \sigma^a \cdot H - ig' Y B_\mu H$$

$\Rightarrow$ CAN EXHIBIT DYNAMICAL SYMMETRY BREAKING VIA THE CW MECHANISM

- DILATON ACTION:

$$S[\phi, g_{\mu\nu}] = \int dx^D \sqrt{-g}\,[-\frac{\xi}{2}\,\phi^2 R - \frac{1}{2}\nabla_\mu\phi\,\nabla_\mu\phi g^{\mu\nu} - \frac{\lambda_\phi}{4}\phi^4]$$

- ACTION FOR FERMIONS:

$$\int \mathrm{d}^4 x\sqrt{-g}\left[\frac{i}{2}\left(\bar\psi\gamma^\mu(\nabla_\mu + eA_\mu)\psi - (\nabla_\mu - eA_\mu)\bar\psi\gamma^\mu\psi\right) - g_y\phi\bar\psi\psi\right]$$

- GRAVITATIONAL ACTION (LAST TERM IS BOUNDARY [GB] TERM IN D=4):

$$\int \mathrm{d}^D x\sqrt{-g}\left(\xi_1 R^2 + \xi_2 R_{\mu\nu}R^{\mu\nu} + \xi_3 R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}\right)$$

<u>NB</u>: SM+GRAVITY CAN BE MADE WEYL INVARIANT ONLY IN D=4.

DETECTING TORSION WAVES

GRAVITATIONAL WAVES

- GRAVITATIONAL WAVES

$$\frac{d^2 J^i}{dt^2} = \frac{1}{2}\ddot{h}_{ij}(t,\vec{x})J^j$$

Plus polarization: $h_{xx} = -h_{yy} = h_+ \cos(\omega t - kz)$

$$J^x(t,z) = J^x_{(0)}\left[1 + (h_+/2)\cos(\omega t - kz)\right]$$

Cross polarization: $h_{xy} = h_{yx} = h_\times \cos(\omega t - kz)$

$$J^x(t,z) = J^x_{(0)} + (h_\times/2)J^y_{(0)}\cos(\omega t - kz)]$$

DETECTORS FOR TORSION WAVES

► GW INTEFEROMETERS such as aLIGO/VIRGO

- TORSION TRACE

$$\ddot{J}^i = J^0 \dot{\mathcal{T}}^i + J^j \partial_j \mathcal{T}^i \qquad \mathcal{T}^i = \mathcal{T}^i_{(0)} \cos(\omega t - kz)$$

► LONGITUDINAL $\mathcal{T}^i_{(0),L} = \delta^i_z \frac{\omega}{m}\,,\ \mathcal{T}^0_{(0),L} = -\frac{\|\vec{k}\|}{m}$

○ DETECTOR RESPONSE

$$\Delta J^z_{(0)} = -\frac{c^2 k}{\omega^2} \mathcal{T}^z_{(0),L} J^z_{(0)} \approx -\frac{c}{\omega} \mathcal{T}^z_{(0),L} J^z_{(0)}\,, \qquad \Delta J^{x,y}_{(0)} = 0\,.$$

► TRANSVERSE $\mathcal{T}^i_{(0),T} = \frac{1}{\sqrt{2}} \left(\delta^i_x \pm \delta^i_y\right)\,,\ \mathcal{T}^0_{(0),T} = 0$

○ DETECTOR RESPONSE

$$\Delta J^z_{(0)} = 0\,, \qquad \Delta J^{x,y}_{(0)} = -\frac{c^2 k}{\omega^2} \mathcal{T}^{x,y}_{(0),T} J^z_{(0)} \approx -\frac{c}{m} \mathcal{T}^{x,y}_{(0),T} J^z_{(0)}$$

- GRAVITATIONAL WAVES vs TORSION WAVES: a comparsion

► PHASE SHIFT ¼ PERIOD
► FREQUENCY DEPENDENCE
► TORSION TRACE (L) COUPLES TO TRACE OF STRESS-ENERGY TENSOR

TORSION SOURCES

- E.G.: TORSION TRACE: LONGITUDINAL MODE $\mathcal{T}_\mu = \partial_\mu \theta$
  - ► ITS MASS IS PROTECTED BY THE CONFORMAL WARD-TAKAHASHI,

$$\Box\theta = \frac{8\pi G_N}{c^4}\frac{T^\mu_\mu}{6} \, , \, \Box h_{ij} = \frac{8\pi G_N}{c^4} T_{ij}$$

  - ► THIS IMPLIES ABOUT 1 order of magnitude suppression when compared with the amplitude of gravitational waves, i.e.

$$\frac{\theta}{h_{ij}} \sim \frac{e^2}{2}$$

    - ○ e=sources excentricity (can be as large as ~0.5)
  - ► DETECTABLE BY THE NEXT GENERATION OF OBSERVATORIES such as EINSTEIN TELESCOPE.

CONFORMAL EXTENSIONS OF SM:

CONFORMAL HIGGS PORTAL MODELS: SU(2)cSM

SU(2)cSM

○ NO HIGGS MASS TERM, BUT

○ ADITIONAL TERMS IN THE PORTAL LAGRANGIAN:

$$\delta L = -\lambda_{H\Phi}|\Phi|^2|H|^2 - \lambda_{\Phi}|\Phi|^4 - \left(D_\mu\Phi\right)^{+} D_\nu\Phi - \frac{1}{4}Tr\left[X_{\mu\nu}X^{\mu\nu}\right]$$

○ Φ & X_μ IN FUNDAMENTAL AND ADJOINT REPRESENTATION OF $SU(2)_X$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu\,, \qquad D_\mu\Phi = \partial_\mu\Phi + \frac{D-2}{2}T_\mu\Phi + ig_X X_\mu$$

○ SIMPLEST MODEL: <u>PERT</u> AT PLANCK SCALE AND EXHIBITS <u>CW</u> MECH

○ MANY OTHER VARIANTS POSSIBLE: $SU(N)_X$ + HIDDEN FERMIONS

PROBLEMS WITH PERTURBATIVITY

- PERTURBATION THEORY IN MULTISCALE THEORIES: A DOUBLE SUM:

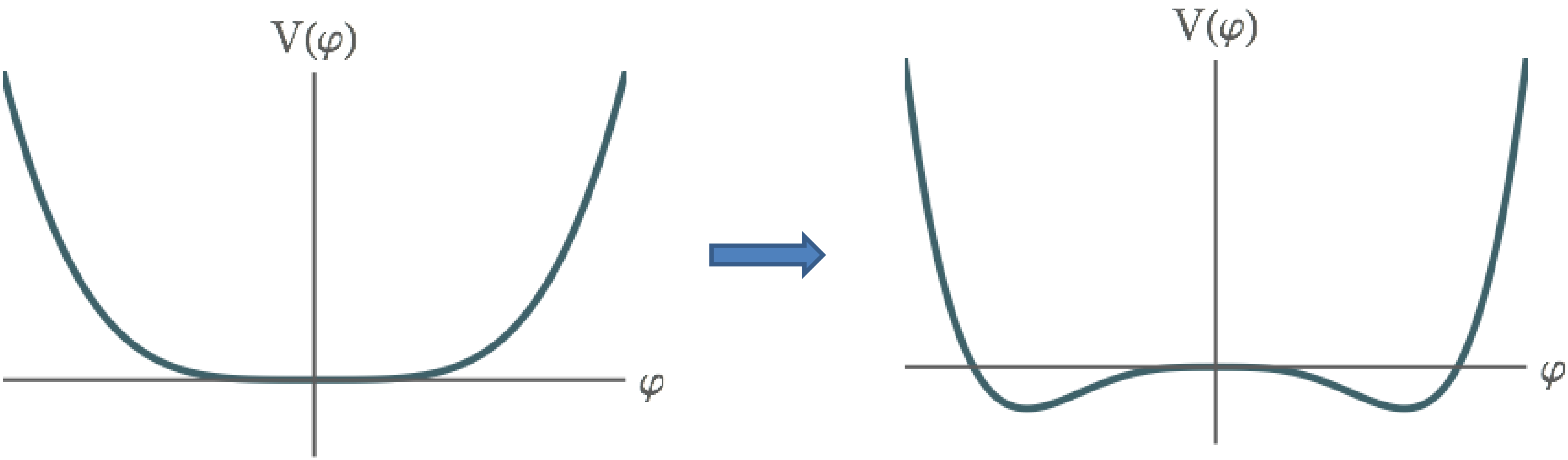
$$V_{\rm eff} \supset \sum_{m,n} \sum_{i,j=0,i+j\geq 2}^{\infty} \lambda_m{}^i \, L_n{}^j \phi_n{}^{2l} \phi_m{}^{4-2l}, \qquad L_n \equiv \log\left[\frac{\phi_n}{\mu}\right], \quad l=0,1$$

- WHEN SOME OF L_n ARE LARGE, THAT CAN DESTROY PERTURBATIVITY OF THE THEORY
- PERTURBATIVITY CAN BE RESTORED BY RG IMPROVING $V_{\rm eff}$
- MULTISCALE METHOD – $\frac{\phi_n}{\mu} \to \frac{\phi_n}{\mu_n}$ – IS EXACT, BUT COMPLICATED
- WE HAVE DEVELOPED A SIMPLE, SINGLE SCALE METHOD THAT WORKS WELL

T. Prokopec, Leonardo da Rocha, Michael Schmidt, Bogumila Swiezewska, 1801.05258 [hep-ph], 1805.09292 [hep-ph]

WHY RG IMPROVED EFFECTIVE POTENTIAL?

○ TREE POTENTIAL EFFECTIVE POTENTIAL



○ QUANTUM LOOPS MAY INDUCE SPONTANEOUS CONDENSATION OF SCALARS.

○ NAIVE PERTURBATIVE POTENTIAL CANNOT BE TRUSTED.

S. Coleman and E. Weinberg, Phys. Rev. D7 (1973) 1888

A SINGLE SCALE METHOD

T. Prokopec, Leonardo da Rocha, Michael Schmidt, Bogumila Swiezewska,
1801.05258 [hep-ph], arXiv:1805.09292 [hep-ph]

RENORMALIZATION GROUP EQUATION

- CALLAN-SYMANZIK EQUATION
  - $\mu \frac{d}{d\mu} \Gamma_{\text{eff}} = 0$ IS EXACT, BUT COMPLICATED TO SOLVE

- IR LIMIT - FOR EFFECTIVE POTENTIAL

$$\mu \frac{\mathrm{d}V}{\mathrm{d}\mu}(\mu;\lambda,\phi) = \left(\mu \frac{\partial}{\partial\mu} + \sum_{i=1}^{N_\lambda} \beta_i \frac{\partial}{\partial\lambda_i} - \frac{1}{2}\sum_{a=1}^{N_\phi} \gamma_a \phi_a \frac{\partial}{\partial\phi_a}\right) V(\mu;\lambda,\phi) = 0$$

MULTI FIELD METHOD

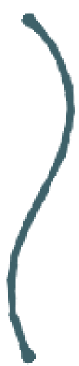
- COLEMAN WEINBER 1 LOOP POTENTIAL

$$V^{(1)}(\mu, \lambda, \phi) = \frac{1}{64\pi^2} \sum_a n_a m_a^4(\lambda, \phi) \left[\log \frac{m_a^2(\lambda, \phi)}{\mu^2} - \chi_a \right]$$

- BY USING METHOD OF CHARACTERISTIC, RG FLOW PERTURBATIVE POTENTIAL TO THE TREE LEVEL SURFACE WHERE $V^{(1)}(\mu, \lambda, \phi)$ VANISHES!

To compute $V(\mu, \lambda, \phi)$

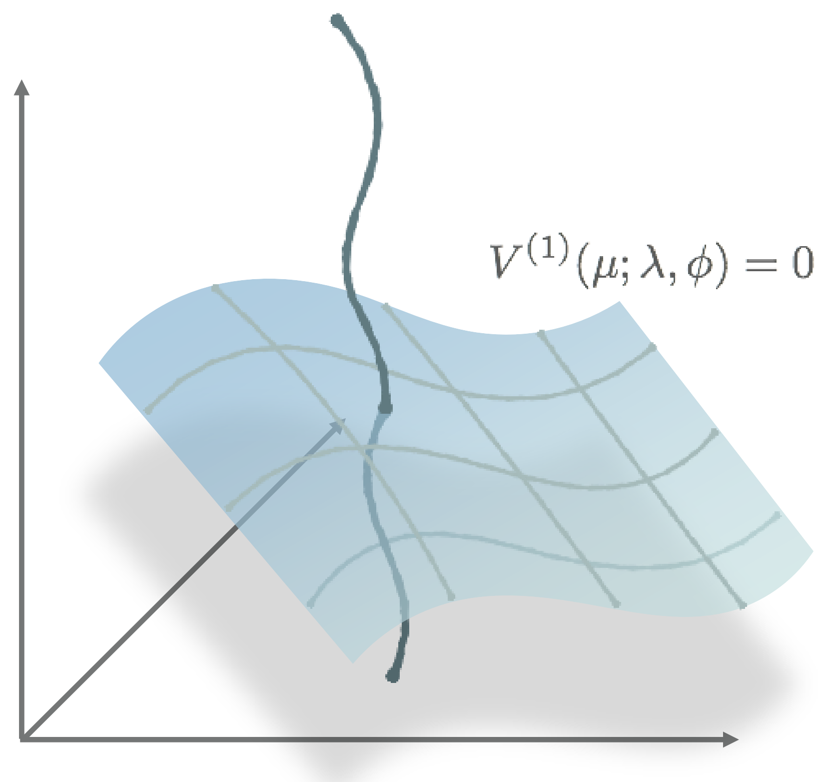
t_*



Run to the tree-level surface

Evaluate

$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$



MULTI FIELD METHOD

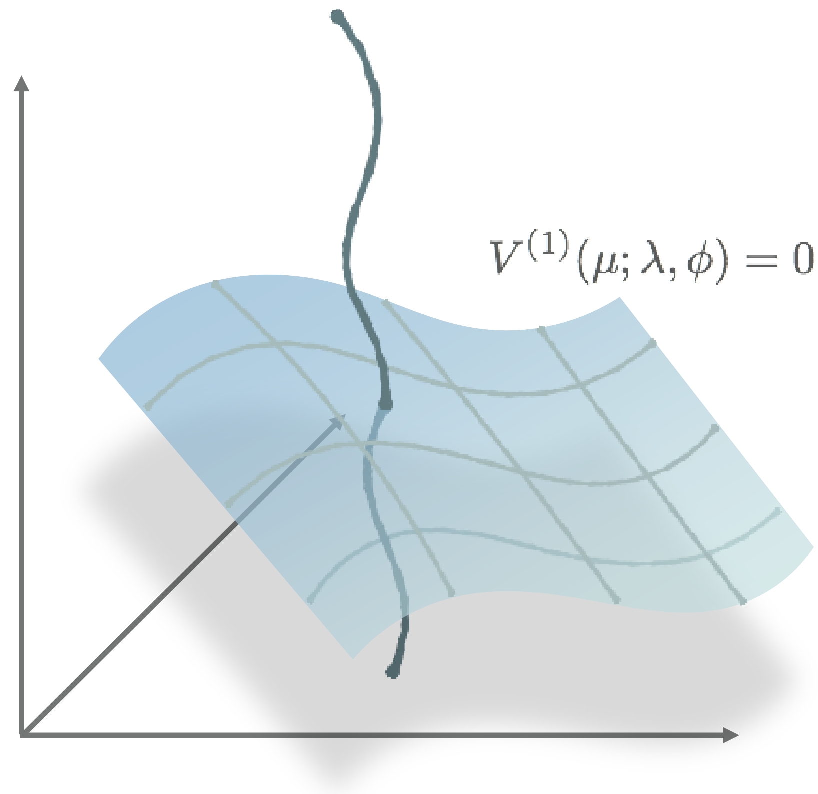
$$V(\mu,\lambda,\phi) = V^{(0)}(\bar{\lambda}(t_*),\bar{\phi}(t_*))$$

What is t_*

$$V^{(1)}(\bar{\mu}(t_*);\bar{\lambda}(t_*),\bar{\phi}(t_*)) = 0$$

To leading order in $\hbar$

$$t_*^{(0)} = \frac{V^{(1)}(\mu,\lambda,\phi)}{2\mathbb{B}(\lambda,\phi)}$$



VACUUM STABILITY

$$\boxed{\lim_{\phi\to\infty} V(\phi) = ?}$$

ONE LOOP POTENTIAL NOT SUITABLE FOR THIS QUESTION $\Rightarrow$ NEED OF RG IMPROVEMENT

$$\boxed{V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))}$$

ENOUGH TO CONSIDER TREE LEVEL CONDITION EVALUATED AT LARGE SCALE $\sim M_{\mathrm{P}}$.

INTERLUDE

- RG improved effective potential needed in multi-field models
- RG improvement by running to the hypersurface where (one-)loop corrections vanish
- The RG scale given implicitly (can be computed numerically) or approximately
- Applicable to study vacuum stability

APPLICATION: SU(2)cSM

T. Prokopec, Leonardo da Rocha, Michael Schmidt, Bogumila Swiezewska, arXiv:1805.09292 [hep-ph]

SU(2)CSM

cSM:

$SU(2)_L \times U(1)_Y$

Φ

Hidden sector:

$SU(2)_X$

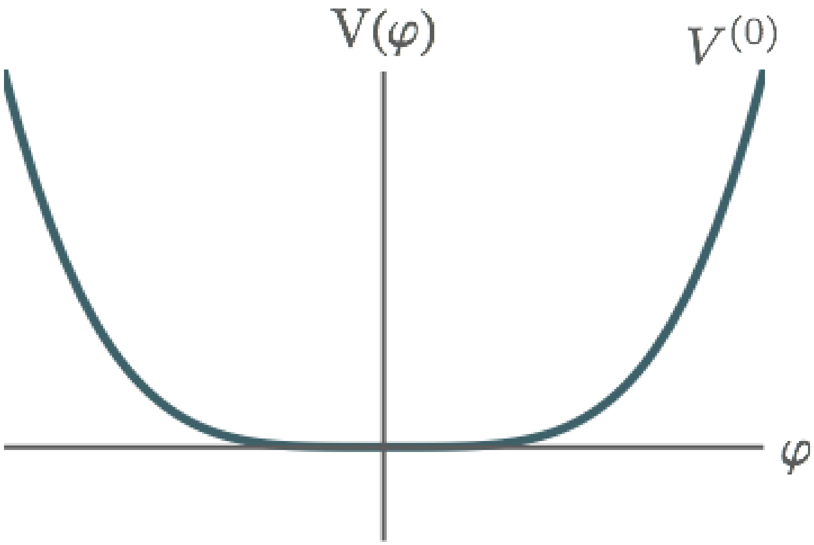
Ψ

$$V^{(0)}(\Phi,\Psi) = \lambda_1 \left(\Phi^\dagger\Phi\right)^2 + \lambda_2 \left(\Phi^\dagger\Phi\right)\left(\Psi^\dagger\Psi\right) + \lambda_3 \left(\Psi^\dagger\Psi\right)^2 ,$$

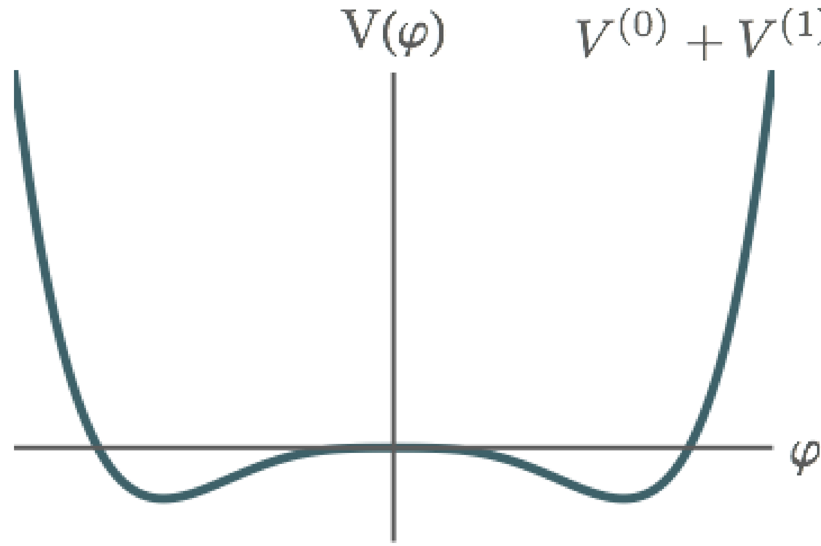
See also: T. Hambye, A.Strumia, PRD88 (2013) 055022, C.D.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026

RADIATIVE SYMMETRY BREAKING IN SU(2)cSM

- TREE POTENTIAL



EFFECTIVE POTENTIAL



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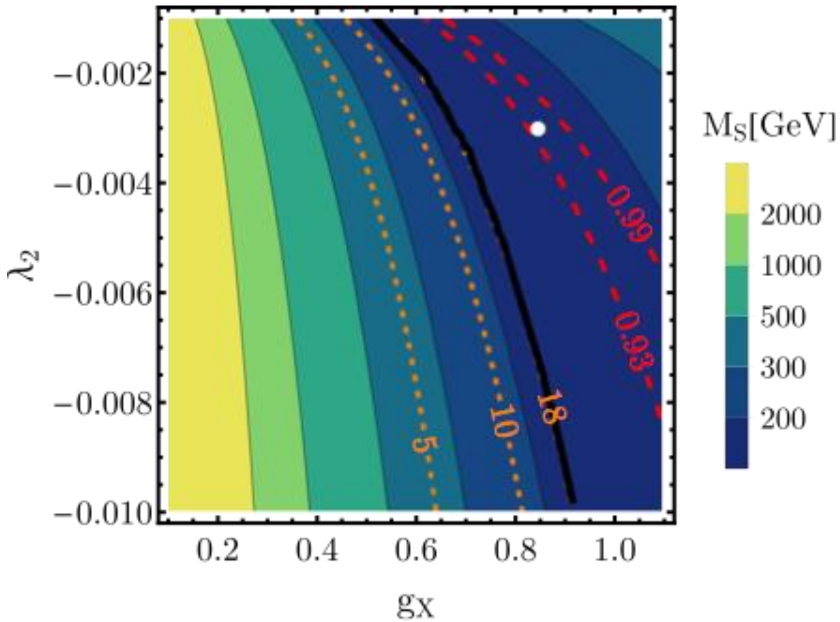
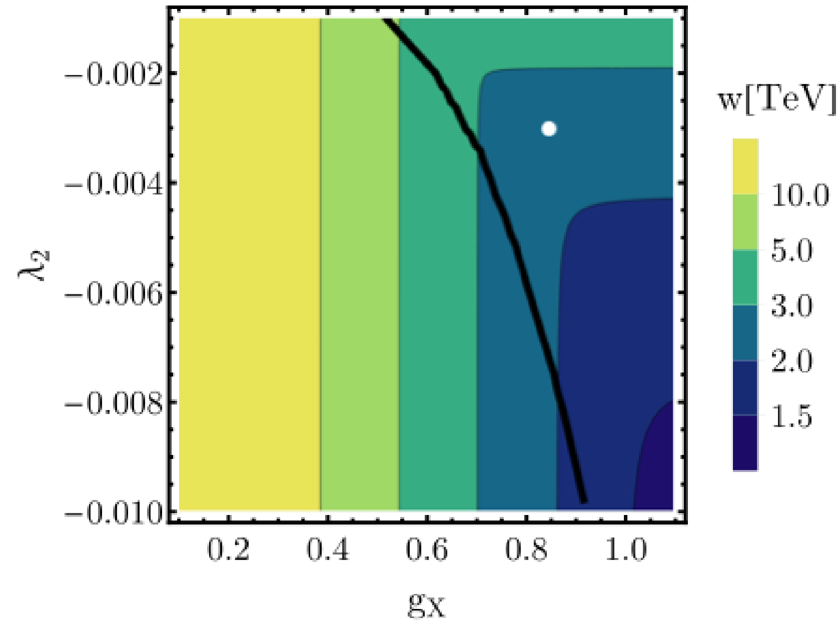
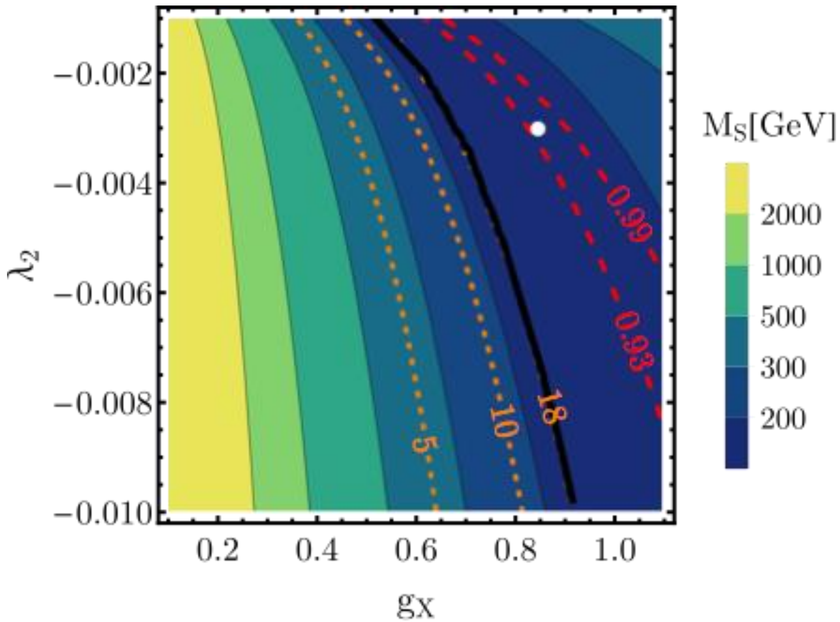
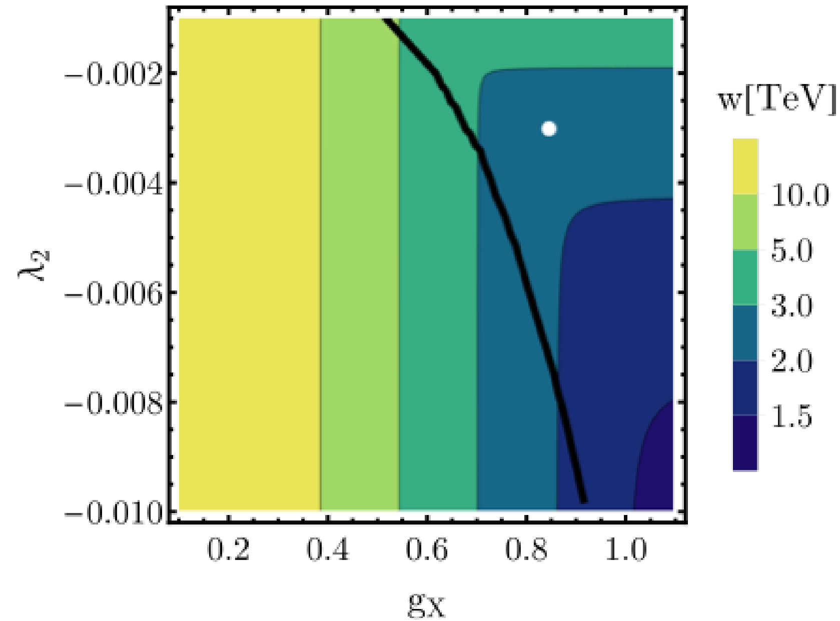




	μ [GeV]	λ_1	λ_2	λ_3	g_X	w [GeV]	$V_{\text{SM}}^{(1)}$[GeV^4]	$V_{\text{X}}^{(1)}$[GeV^4]	$V^{(1)}/V^{(0)}$
CW	246	0.1236	-0.0030	-0.0047	0.8500	2411	$2.38 \cdot 10^7$	$3.18 \cdot 10^{10}$	0.802
GW	940	0.1055	-0.0030	$2 \cdot 10^{-5}$	0.8141	2722	$6.28 \cdot 10^7$	$-1.08 \cdot 10^{10}$	551
RG	738	0.1085	-0.0030	-0.0007	0.8202	2698	$5.75 \cdot 10^7$	$-4.27 \cdot 10^7$	0.002

RADIATIVE SYMMETRY BREAKING IN SU(2)cSM





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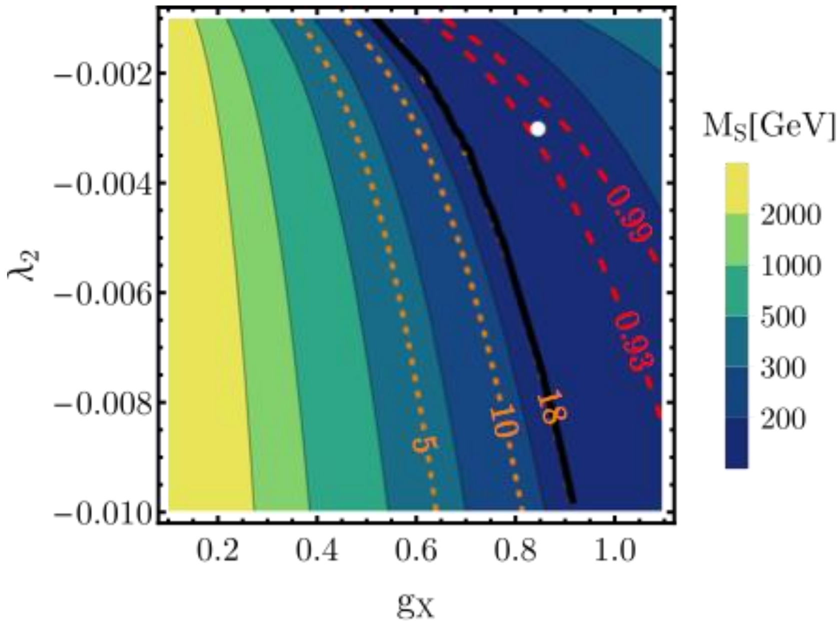
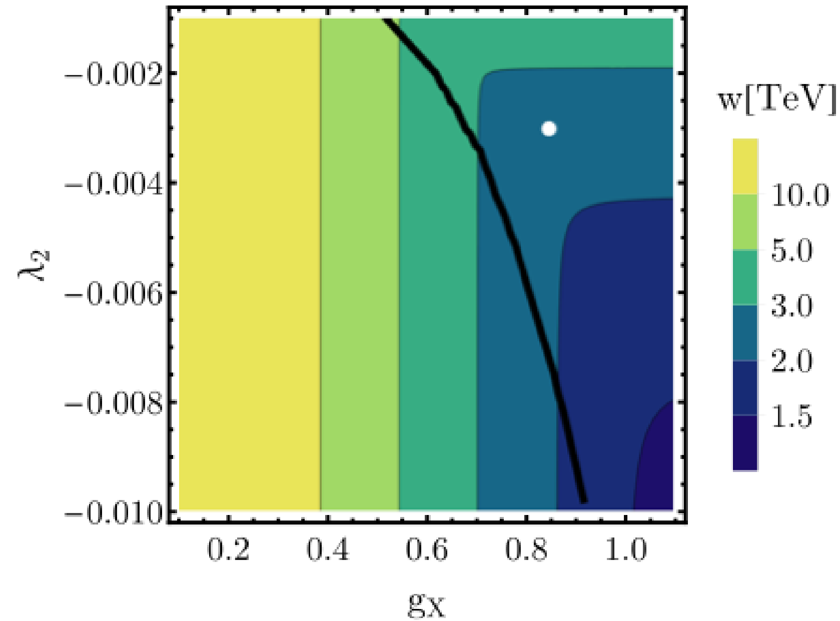
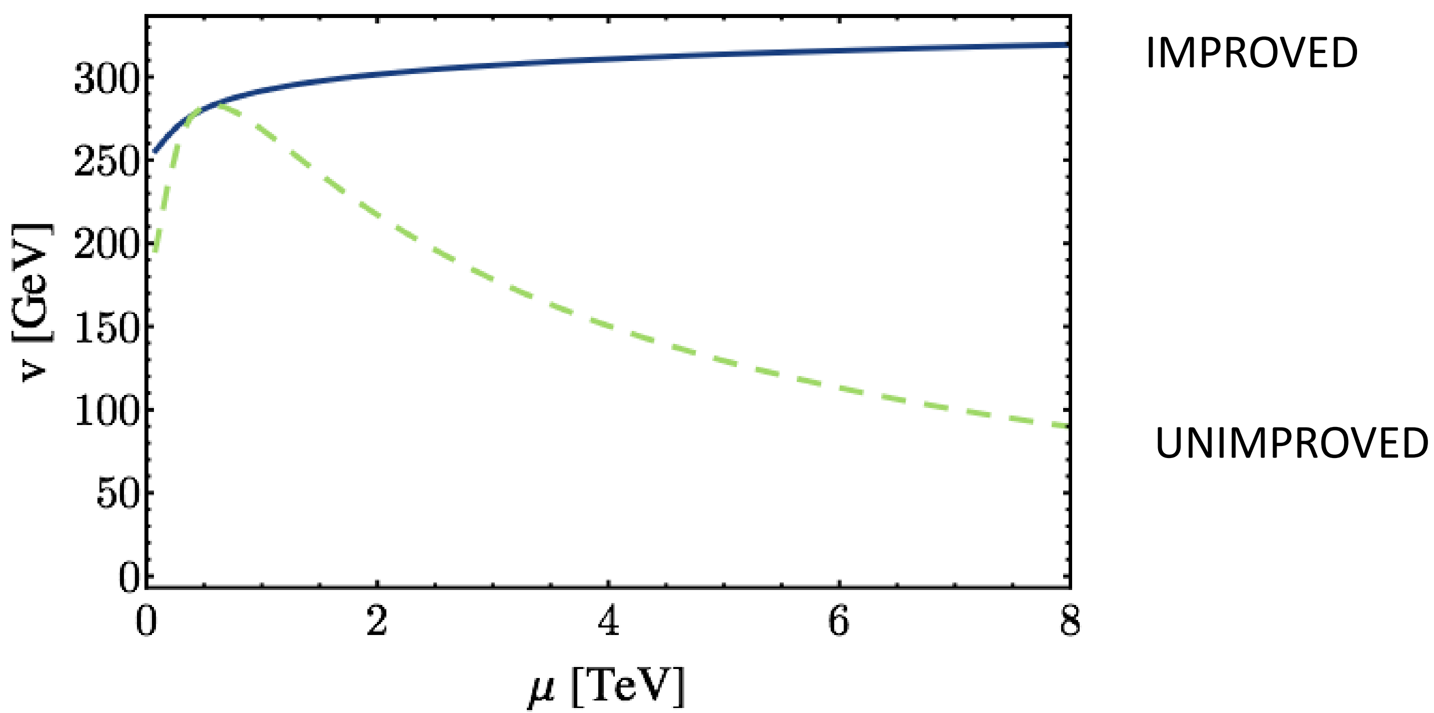


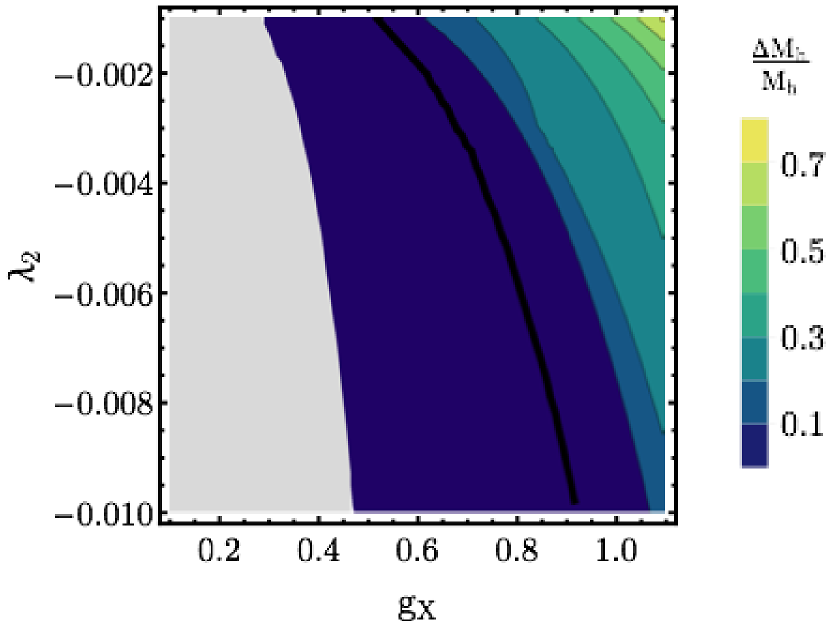


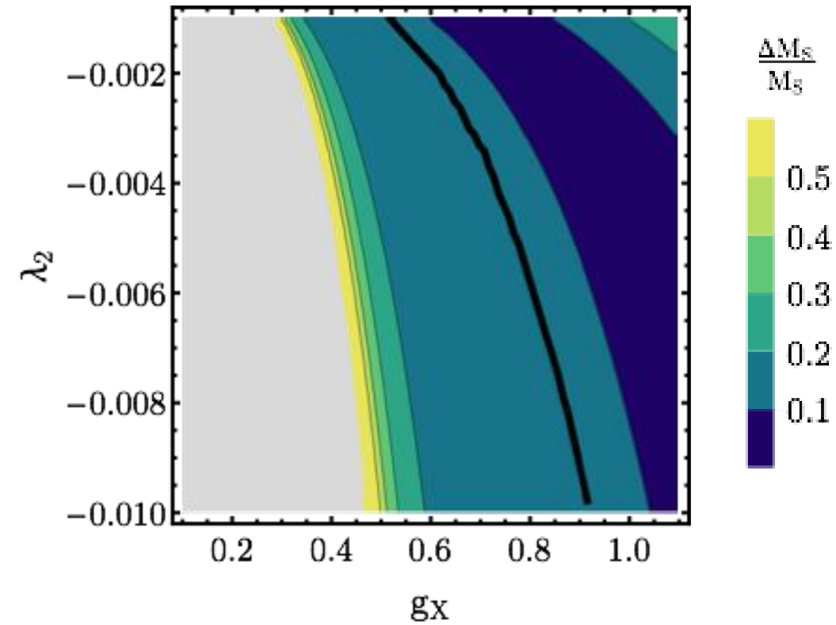
	μ [GeV]	λ_1	λ_2	λ_3	g_X	w [GeV]	$V_{\rm SM}^{(1)}$[GeV^4]	$V_{\rm X}^{(1)}$[GeV^4]	$V^{(1)}/V^{(0)}$
CW	246	0.1236	-0.0030	-0.0047	0.8500	2411	$2.38 \cdot 10^7$	$3.18 \cdot 10^{10}$	0.802
GW	940	0.1055	-0.0030	$2 \cdot 10^{-5}$	0.8141	2722	$6.28 \cdot 10^7$	$-1.08 \cdot 10^{10}$	551
RG	738	0.1085	-0.0030	-0.0007	0.8202	2698	$5.75 \cdot 10^7$	$-4.27 \cdot 10^7$	0.002

RUNNING VEVs



RUNNING MASSES

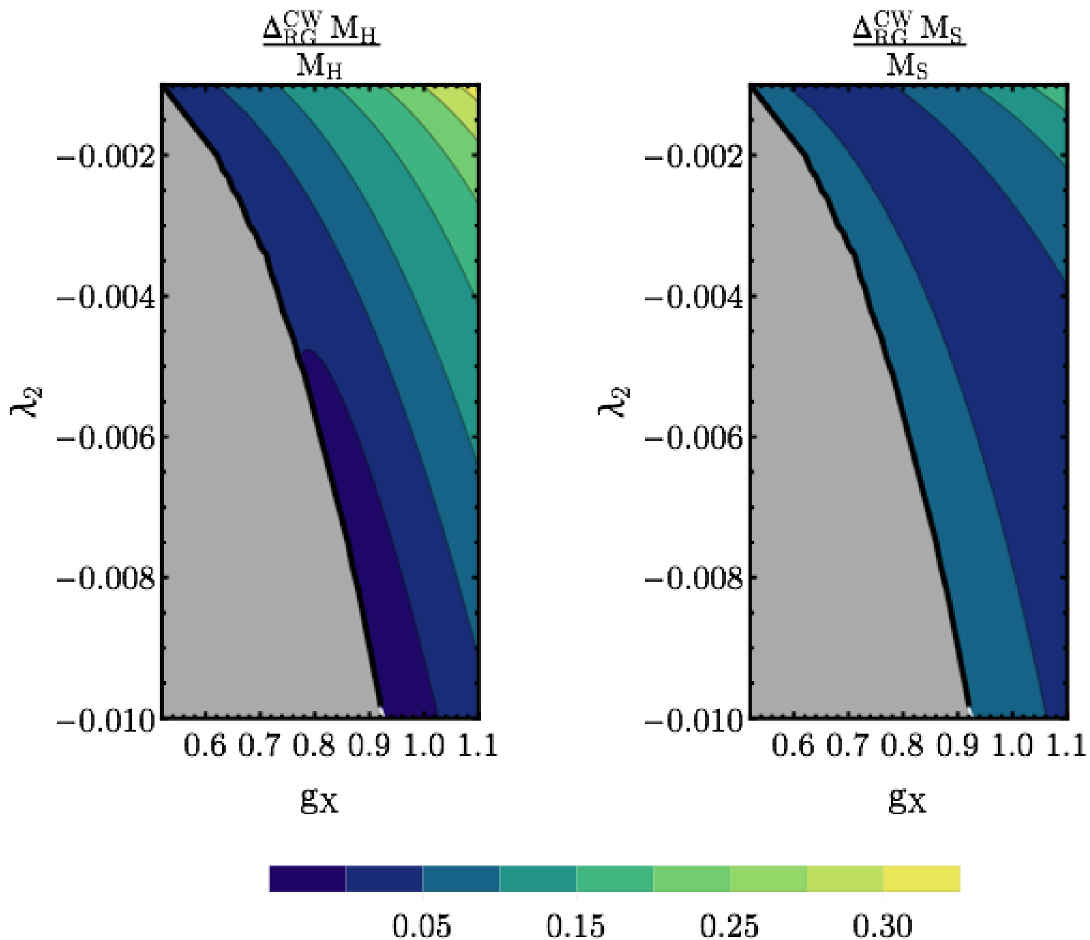




Change induced (mainly) by

$$\mu = 246\,\mathrm{GeV} \to \mu = 940\,\mathrm{GeV}$$

RUNNING MASSES



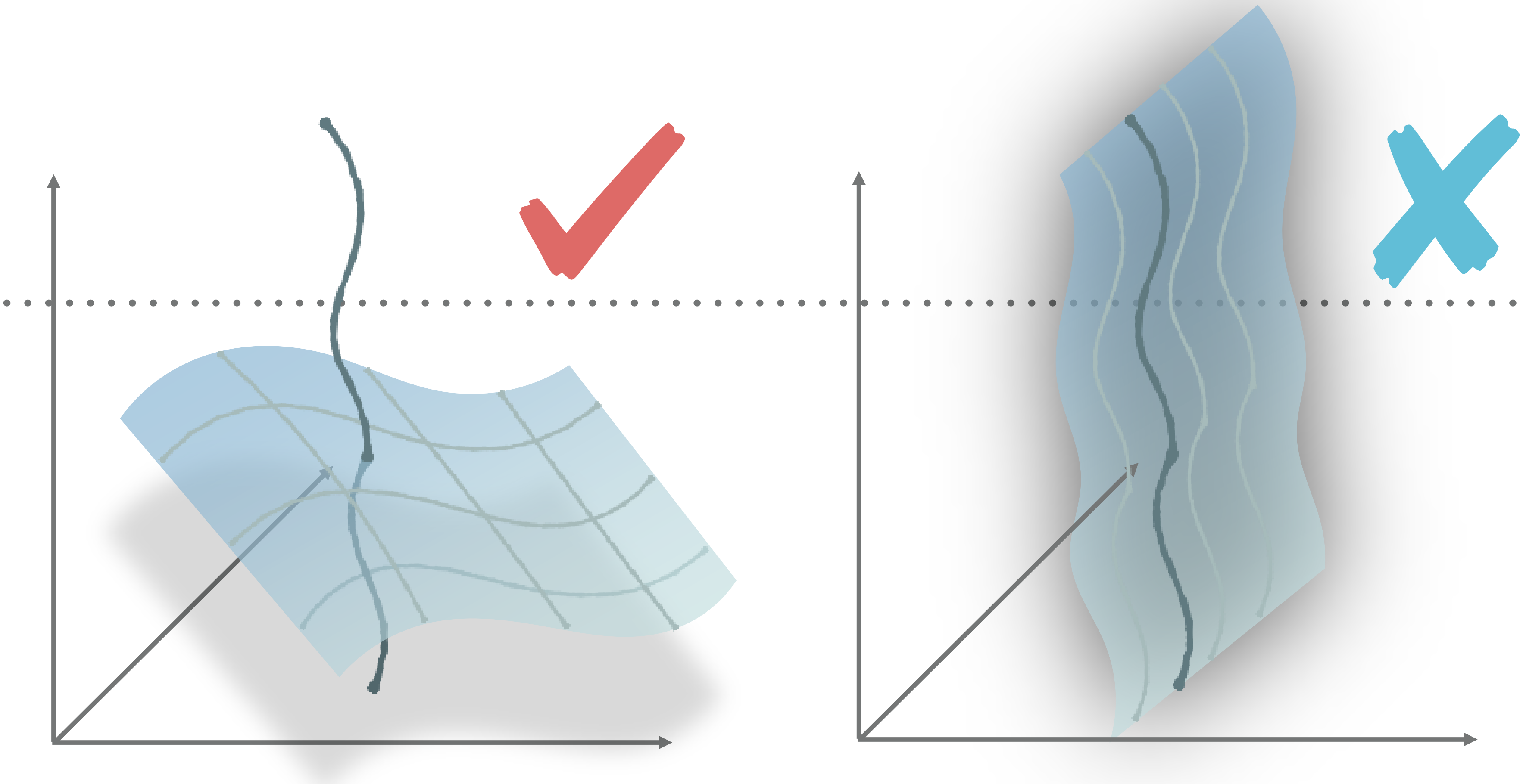
INTERLUDE 2

- RG improved effective potential gives VEVs that are less scale dependent
- RG improves perturbative behaviour of the expansion
- Less scale dependent effective potential gives less scale dependent masses

TECHNICAL REMARK

VALIDITY OF THE METHOD

BOUNDARY SURFACE OF TREE POTENTIAL MUST BE NONCHARACTERISTIC



CONFORMAL SYMMETRY AND COSMOLOGICAL CONSTANT

CONFORMAL MODEL

Stefano Lucat and T. Prokopec and , Bogumila Swiezewska: arXiv:1804.00926 [gr-qc]

○ ACTION, CLASSICALLY CONFORMAL

$$S[\phi, g_{\mu\nu}, T, \psi_i] = \int d^4x \sqrt{-g} \left\{ \alpha\, \phi^2 R + \beta R^2 - \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi - \frac{\lambda}{4} \phi^4 \right\} + S_m[\psi i, g_{\mu\nu},, T]$$

○ ON SHELL EQUIVALENT ACTION

$$S[\phi, g_{\mu\nu}, T, \psi_i] = \int d^4x \sqrt{-g} \left\{ \frac{1}{2} \omega^2 R - \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi - \frac{1}{8\beta} (\alpha\phi^2 - \omega^2)^2 - \frac{\lambda}{4} \phi^4 \right\} + S_m[\psi i, g_{\mu\nu},, T]$$

○ <u>FIELDS</u>: GRAVITON g, TORSION T, DILATON ω, SCALARON ϕ, MATTER FIELDS ψ

○ DILATON & SCALAR CONDENSE BY THE COLEMAN WEINBERG MECHANISM

○ GRAVITATIONAL (MATTER) CONTRIBUTIONS TO CC ARE POSITIVE (NEGATIVE)

○ ONE CAN FINE TUNE THEM ONCE TO THE OBSERVED VALUE (~62 digits)

○ ONCE TUNED, THE VALUE OF CC IS STABLE UNDER A CHANGE OF RG SCALE

CONCLUSIONS AND OUTLOOK

CONCLUSIONS AND OUTLOOK

● CHALLENGE: USE FRG METHODS TO STUDY HOW THIS THEORY DIFFERS FROM THE USUAL GRAVITY
[experimental tests: earthly, SOLAR, cosmo, etc]

● CHALLENGE 2: IS ANYTHING DIFFERENT WRT UNITARITY.
NOTE THAT DUE TO ABSENCE OF THE PLANCK SCALE,
THE GHOST PROPAGATOR SHOULD BE MASSLESS (WORSE?)

● CHALLENGE 3: CONFRONT THIS NOVEL THEORY AS MUCH AS POSSIBLE WITH OBSERVATIONS

● CHALLENGE 4: CAN WE GET RID OF (COSMOLOGICAL AND BLACK HOLE) SINGULARITIES?

$$(d\tau)_{g.i.} = \exp\left(-\int_{x_0}^{x} T_\mu dx^\mu\right) d\tau :=$$ PHYSICAL TIME OF COMOVING OBSERVERS