Quantum gravity fluctuations flatten the Planck-scale Higgs-potential

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based on work with Astrid Eichhorn, Yuta Hamada and Masatoshi Yamada

arxiv:1712.00319, accepted in PRD

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March 26, 2018

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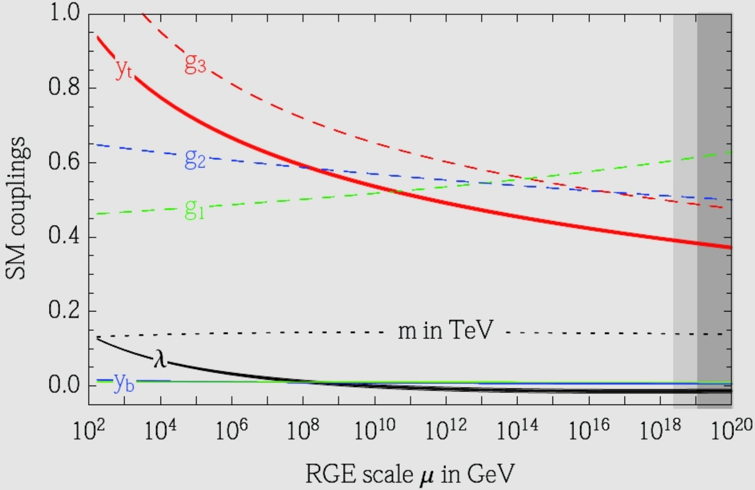
Outline

- General basics of Dark Matter
- Higgs Portal to the Dark sector
- Compatibility with Asymptotic Safety

No Landau pole up to Planck scale



Buttazzo et al. (2014), arxiv: 1307.3536

Standard Model possibly valid up to the Planck scale

But

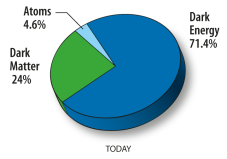
What about Beyond Standard Model (BSM) phenomena?

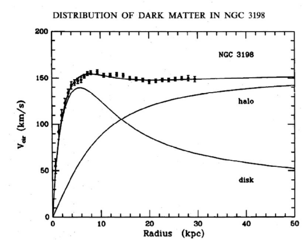
(Neutrino masses & oscillations, **Dark Matter**, baryon asymmetry...)

Aim: Study gravational effects on SM-DM model

Dark Matter basics

- Baryonic Matter **only makes up 5%** of the energy density of the universe
- Particle? primordial Black Holes? MOND?
- **BUT** we know there is something
  - Galaxy rotation curves
  - Gravitational Lensing
  - Hot Gas
  - Bullet Cluster





More On Dark Matter

Cold DM relic density $\Omega_{\mathrm{CDM}} h^2 = 0.1198 \pm 0.0026$

reduced Hubble constant $h = H_0/(100 \mathrm{km\,s^{-1} Mpc^{-1}})$

Cold Dark Matter: $\omega = \frac{p}{\rho} = 0$

$\rightarrow$ eq. of state of non-relativistic gas

p: pressure

ρ: energy density

Connections to the Standard Model

Fermion(s), scalar(s), vector boson(s) $\left(\frac{E}{M}\right)^{\Delta}$

fermions ψ	$[3/2]$
scalars ϕ	$[1]$
vectors A_μ	$[1]$

We must include all operators allowed by symmetries!

renormalizable operators are relevant in an EFT framework

Higgs Portal to the Dark Sector

Silvera & Zee 1985, McDonald 1994, Burgess 2001

QFT tells us that we must include all operators allowed by symmetries

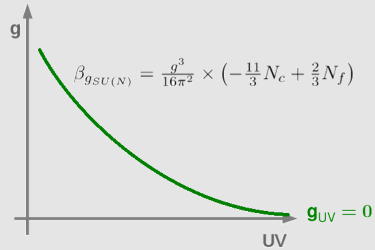
$\Rightarrow$ Higgs Portal coupling: $\lambda_{H\chi} \mathcal{O}_{DM} H^\dagger H$

If $\mathcal{O}_{DM} = \phi^2$, $[\lambda_{H\chi}] = 0$

$\rightarrow$ Might be relevant in the IR

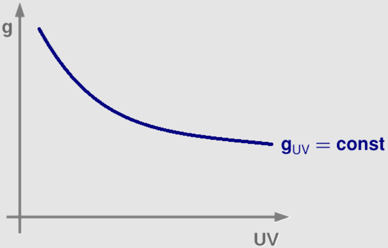
Asymptotic Freedom

Scale invariance at a **Gaussian** fixed point ensures a **free** (perturbatively renormalizable) UV theory



Asymptotic Safety

Scale invariance at a **non-Gaussian** fixed point ensures a **safe** (non-perturbatively renormalizable) UV theory



Asymptotic Safety conjecture

- Fact: Einstein-Hilbert action is perturbatively non-renormalizable in d=4

't Hooft & Veltman 1974, Goroff & Sagnotti 1985

$$S_{\mathrm{EH}} = \frac{1}{16\pi G}\int \mathrm{d}^d x \sqrt{g}[-R + 2\Lambda] \tag{1}$$

$$[G] = [M]^{2-d}$$

- Non-perturbatively renormalizable? $\rightarrow$ Asymptotic Safety scenario

Weinberg 1976

Critical Exponents

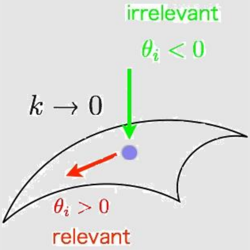
Classification of flow around fixed point g^*

$$\partial_t g_i = \underbrace{\beta_i(g_*)}_{=0} + \sum_j \frac{\partial \beta_i}{\partial g_j}\Big|_{g_n = g_*} (g_j - g_{*j}) + \cdots \approx \sum_j M_{ij}\, \delta g_j$$

eigenvalue

Solution of RG eq.

$$g_i(k) = g_i^* + \sum_I C_I\, V_i^I \left(\frac{k}{\Lambda}\right)^{-\theta_I}$$



A Higgs Portal in Asymptotic Safety

Higgs Portal coupling: $\lambda_{\mathrm{H}\chi}\mathcal{O}_{\mathrm{DM}}\, H^\dagger H$

singlet scalar field χ singlet scalar field ϕ

Consider also $\lambda_\phi \phi^4$ and $\lambda_\chi \chi^4$ $\Rightarrow$ $[\lambda_\phi] = [\lambda_\chi] = 0$

(Marginal Couplings)

Effective Action

$$\Gamma_k = \Gamma_k^{\mathrm{EH}} + \Gamma_k^{\mathrm{matter}}$$

$$\Gamma_k^{\mathrm{EH}}[g] = \frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{g}[-R+2\Lambda] + \mathrm{S_{gf}} + \mathrm{S_{gh}}$$

$$\Gamma_k^{\mathrm{matter}}[\phi,\chi] = \int \mathrm{d}^4x\sqrt{g}\left[V(\phi,\chi) + \frac{Z_{k,\phi}}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{Z_{k,\chi}}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi\right]$$

with

$$V(\phi,\chi) = \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{8}\phi^4 + \frac{\lambda_{\phi\chi}}{8}\chi^2\phi^2 + \frac{m_\chi^2}{2}\chi^2 + \frac{\lambda_\chi}{8}\chi^4$$

Fixed points

All beta functions vanish: $\boxed{\beta_i(\tilde{g}^*) = 0}$

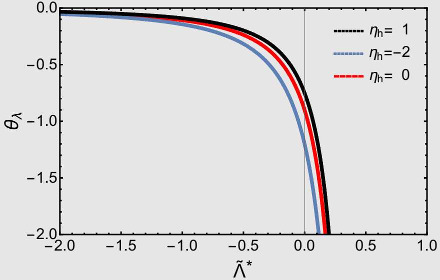
Fixed point indicates scale-invariant regime

This work: Gaussian matter-fixed point, i.e.
$m^2_{\phi *} = m^2_{\chi *} = \lambda_{\phi *} = \lambda_{\chi *} = \lambda_{\phi\chi *} = 0$
$\Rightarrow$ Expected by shift symmetry

$\Rightarrow$ Flat potential at Planck scale

Gravitational Parameter Space of our truncation

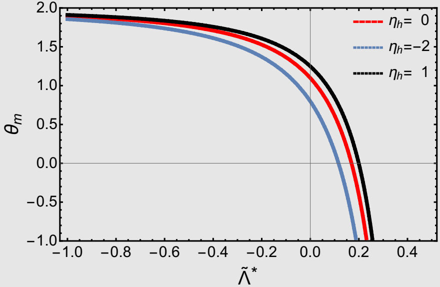
$$\alpha = 0,\ \beta = 1 \text{ and } G^* = 1$$



$\theta_\lambda \leq 0$

$\theta_\lambda = 0$ for $\tilde{\Lambda}^* \to -\infty$

Note: $\lambda = (\lambda_\phi, \lambda_\chi, \lambda_{\phi\chi})$



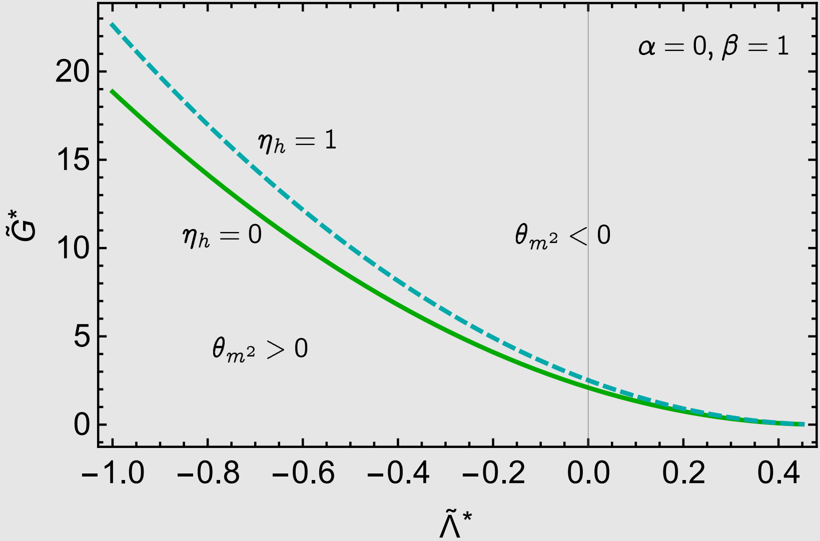
Two regimes

$\theta_{m^2} > 0$ for $\tilde{\Lambda}^* < \tilde{\Lambda}^*_{\text{crit}}$

$\theta_{m^2} < 0$ for $\tilde{\Lambda}^* > \tilde{\Lambda}^*_{\text{crit}}$

$\theta_{m^2} = 0$

sign of θ_m^2 depends on G^* and Λ^*



Potential phenomenological implications

- Portal coupling irrelevant in the entire gravitational parameter space

  ⇒ No connection to Standard Model

  ⇒ Non-thermal productions mechanisms
- Gravitational Dark Matter
- Misalignment Mechanism

$\theta_\lambda < 0$

Decoupled dark sector

$\theta_{m^2} > 0$

- Gravitational Dark Matter
- Misalignment Mechanism

$\theta_{m^2} < 0$

- Gravitational Dark Matter
- Misalignment Mechanism

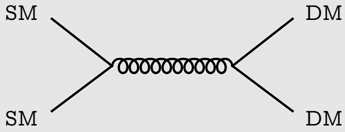
+

Resurgence mechanism

Thermal Gravitational Dark Matter?

- Cross-section: $\langle \sigma v \rangle \sim (\hbar G k_B T)^2 \sim (k_B T)^2 / M_{\mathrm{P}}^4$
  $\Rightarrow$ Cross-section supressed for $k_B T < M_P$
- Interaction rate Γ vs. Expansion of the universe $H = \dot{a}/a$

  a(t): scale factor of a spatially homogeneous and isotropic universe
- $\Rightarrow \frac{\Gamma_\phi}{H} \approx G^2 M_{\mathrm{P}} (k_B T)^3 \approx \left(\frac{T}{10^{32}\mathrm{K}} \right)^3$
- $T_{max,universe} = \mathcal{O}(10^{29}\mathrm{K}) \Rightarrow$ NO thermal grav. DM



Misalignment Mechanism

- Spatially homogeneous, but time-dependent initial field value $\chi_1(t) \gg 0$

$$\ddot{\chi} + 3H\dot{\chi} + m_\chi^2 \chi = 0 \quad (2)$$

Note: $m_\chi \neq m_\chi(T)$

Early universe $(H \gg m_\chi)$

Not so early universe $(H \ll m_\chi)$

Cross-over

$$3H(T_\chi) = m_\chi$$

$$\to T_\chi = T_\chi(m_\chi)$$

Misalignment Mechanism

- Spatially homogeneous, but time-dependent initial field value $\chi_1(t) \gg 0$

$$\ddot{\chi} + 3H\dot{\chi} + m_\chi^2 \chi = 0 \qquad (3)$$

Note: $m_\chi \neq m_\chi(T)$

Aim: Determine the dark matter mass m_χ

How to: Use fact that $\dfrac{\rho(T)a^3(T)}{s(T)a^3(T)}$ is a conserved quantity

$\rho(T)a^3(T)$ is the energy density in a co-moving volume

$s(T)a^3(T)$ is the entropy in a co-moving volume

A recipe to compute the DM mass

Misalignment Mechanism

- Spatially homogeneous, but time-dependent initial field value $\chi_1(t) \gg 0$

$$\ddot{\chi} + 3H\dot{\chi} + m_\chi^2 \chi = 0 \quad (2)$$

Note: $m_\chi \neq m_\chi(T)$

Early universe ($H \gg m_\chi$)

Not so early universe ($H \ll m_\chi$)

Cross-over

$3H(T_\chi) = m_\chi$

$\rightarrow T_\chi = T_\chi(m_\chi)$

(1) $\dfrac{\rho(T)a^3(T)}{s(T)a^3(T)}$ is conserved

$$\rho_\chi(T_\chi) \sim \frac{1}{2} m_\chi^2 \chi_1^2$$

(2) Consider $\dfrac{\rho_\chi(T_\chi)}{s(T_\chi)} = \dfrac{\rho_\chi(T_0)}{s(T_0)}$

Measured by Planck Collaboration

$$s(T_\chi) \sim T_\chi^3$$

(3) $3H_{\text{rad}}(T_\chi) = m_\chi \qquad \rightarrow T_\chi = T_\chi(m_\chi)$

Misalignment Mechanism

$$\Rightarrow m_\chi \sim 10^{-20}\,\text{eV}\left(\frac{10^{17}\,\text{GeV}}{\chi_1}\right)^4$$

Remember: $\chi_1 >> 0$

How to choose χ_1?

$\theta_\lambda < 0$

Decoupled dark sector

$\theta_{m^2} > 0$

-Gravitational Dark Matter
-Misalignment Mechanism

$\theta_{m^2} < 0$

$\tilde{m}^2 = \tilde{m}_0^2 \left(\frac{k}{\Lambda}\right)^{-\theta}$

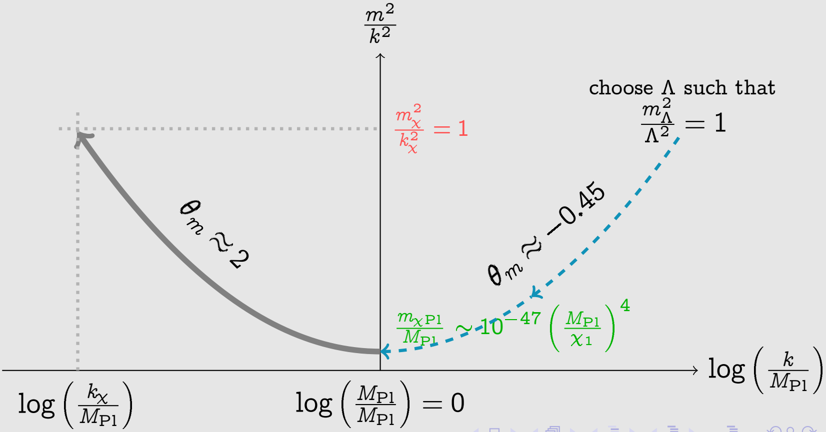
need cut-off Λ

-Gravitational Dark Matter
-Misalignment Mechanism
+
Resurgence mechanism

Resurgence Mechanism

Masatoshi Yamada & Christof Wetterich 2017

- $\theta_{m^2} < 0 \rightarrow$ need cut-off
- Link physical mass m_χ to "natural" UV-cutoff Λ
- How to choose a clever initial field value χ_1?



Resurgence Mechanism

and how to choose a clever initial field value χ_1

Mass at cut-off Λ

$$\tilde{m}_\chi^2(\Lambda) = \tilde{m}_\chi^2(k_\chi)\left(\frac{k_\chi}{M_{\mathrm{P}\ell}}\right)^2\left(\frac{M_{\mathrm{P}\ell}}{\Lambda}\right)^{-0.45} \quad (4)$$

Note: $\tilde{m}_\chi^2(\Lambda) = \frac{m_\chi^2(\Lambda)}{\Lambda^2}$ and $\tilde{m}_\chi^2(k_\chi) = \frac{m_\chi^2(k_\chi)}{k_\chi^2}$

Naturalness condition: $\tilde{m}_\chi^2(k_\chi) = \tilde{m}_\chi^2(\Lambda) = 1$

$\Rightarrow \Lambda \sim \left(\frac{M_{\mathrm{P}\ell}}{m_\chi}\right)^{40/9} M_{\mathrm{P}\ell}$ where $m_\chi \sim 10^{-20}\,\mathrm{eV}\left(\frac{10^{17}\,\mathrm{GeV}}{\chi_1}\right)^4$

$\Rightarrow \Lambda \sim 10^{249}\left(\frac{\chi_1}{M_{\mathrm{P}\ell}}\right)^{160/9} M_{\mathrm{P}\ell}$

Natural cut-off of Higgs ($\theta = -0.45$): $\Lambda_{\mathrm{nat}} = 10^{94}\mathrm{GeV} \longrightarrow$

$$\chi_1 \approx 10^{-10} M_{\mathrm{P}\ell} \Rightarrow \quad m_\chi(k_\chi) = 10^{-68}\mathrm{eV}$$

$\theta_\lambda < 0$

Decoupled dark sector

$\theta_{m^2} > 0$

$\tilde{m}^2 = \tilde{m}_0^2 \left(\frac{k}{\Lambda}\right)^{-\theta}$

fundamental asymptotic safety

-Gravitational Dark Matter
-Misalignment Mechanism

$\theta_{m^2} < 0$

-Gravitational Dark Matter
-Misalignment Mechanism
+
Resurgence mechanism

Conclusions

- Dark sector decoupled from Standard Model
- Non-thermal dark matter production mechanisms needed (e.g. Misalignment mechanism)
- Two regimes ($\theta_m^2 > 0, \theta_m^2 < 0$)