Quantum Gravity meets Dark Matter

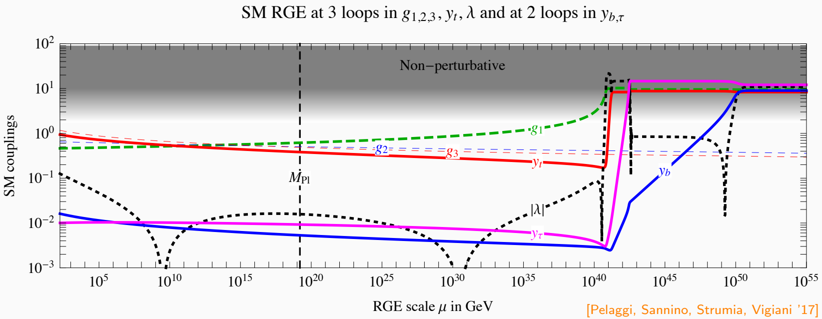
Manuel Reichert

Cold Quantum Coffee, Heidelberg University, 23. October 2019

CP^3-Origins, SDU Odense, Denmark

MR, Juri Smirnov: arXiv:1910.xxxxx

Couplings of the Standard Model



[Pelaggi, Sannino, Strumia, Vigiani '17]

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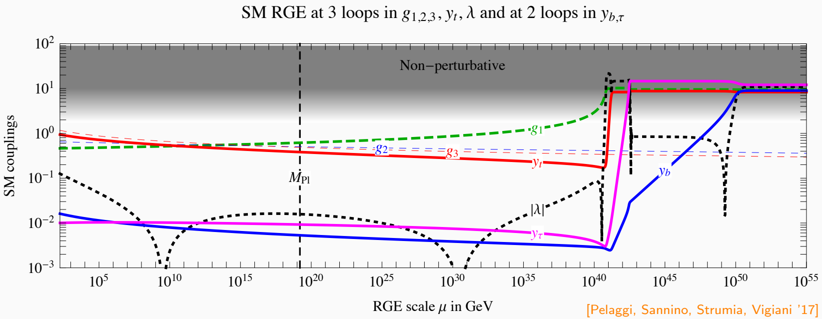

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Potentially UV complete theories

- Asymptotically safe QG
- Large N gauge theories
- ...

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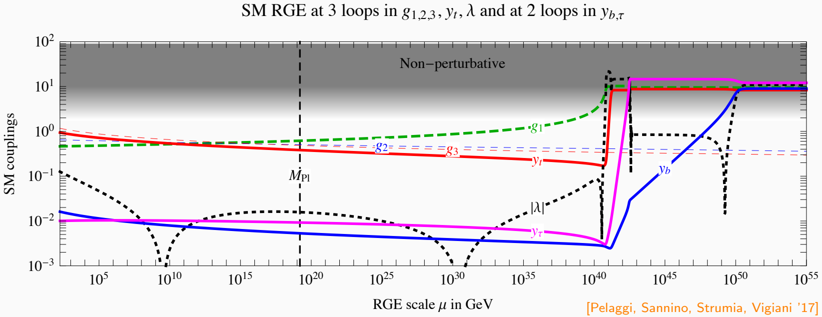

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Phenomenology

- Baryogenesis
- Dark matter
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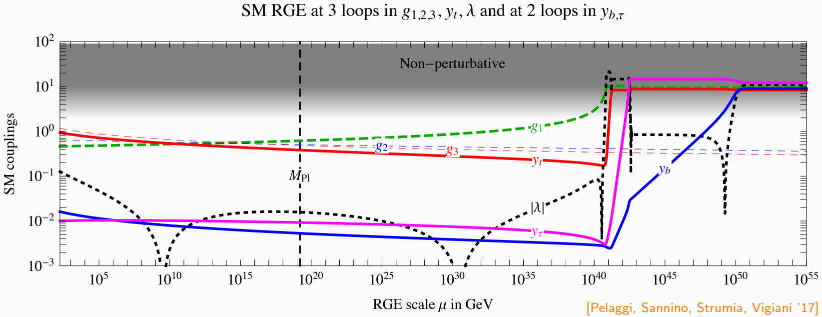

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Asymptotically Safe Quantum Gravity

Quantum gravity in perturbation theory

Einstein-Hilbert action with $g_{\mu\nu} = \eta_{\mu\nu} + \sqrt{G_\mathrm{N}}\, h_{\mu\nu}$

$$S_\mathrm{EH} = \frac{1}{16\pi G_\mathrm{N}} \int_x \sqrt{\det\, g_{\mu\nu}}\,(2\Lambda - R(g_{\mu\nu}))$$

Perturbatively non-renormalisable

$$[G_\mathrm{N}] = -2$$

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Actual evidence by two-loop Goroff-Sagnotti counter term

$$S_\mathrm{GS} \sim \int_x \sqrt{\det g_{\mu\nu}} C_{\mu\nu}{}^{\kappa\lambda} C_{\kappa\lambda}{}^{\rho\sigma} C_{\rho\sigma}{}^{\mu\nu}$$

['t Hooft, Veltmann '74; Goroff, Sagnotti '85]

Start of an infinite series of counter terms: No predictivity

Quantum gravity in perturbation theory

Higher-derivative gravity

$$S_{\text{HD}} = \int_x \sqrt{\det\, g_{\mu\nu}} \left(\frac{1}{2\lambda}\, C^2 - \frac{w}{3\lambda}\, R^2 \right) + S_{\text{EH}}$$

Perturbatively renormalisable

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But perturbatively non-unitary

$$G_{\mathrm{graviton}} \sim \frac{1}{p^2 + p^4/M_{\mathrm{Pl}}^2} = \frac{1}{p^2} - \frac{1}{M_{\mathrm{Pl}}^2 + p^2}$$

[Stelle '74]

Asymptotically safe quantum gravity

Weinberg's proposal '76

Non-perturbative UV fixed point of the renormalisation group flow

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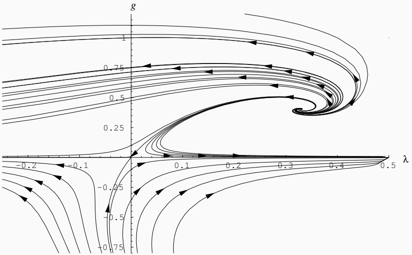

[Reuter '96; Reuter, Saueressig '01]

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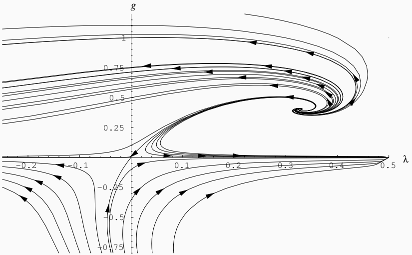

[Reuter '96; Reuter, Saueressig '01]

Predictivity ⇔ UV critical hypersurface is finite dimensional

Unitarity ⇔ Properties of the spectral function

Expansion in curvature invariants

- $\mathcal{O}(R^0)$: Λ
- $\mathcal{O}(R^1)$: R
- $\mathcal{O}(R^2)$: R^2, $R_{\mu\nu}R^{\mu\nu}$, $C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}$
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- $\mathcal{O}(R^4)$: ...

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Aims at apparent convergence

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Let's zoom into EH truncation!

Aims at apparent convergence

Challenge: keeping track of diffeomorphism invariance

Metric split

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \sqrt{Z_h G_N} h_{\mu\nu}$$

Gauge-fixed Einstein-Hilbert action with regulator

$$S = S_{\text{EH}}[g = \bar{g} + h] + S_{\text{gf}}[\bar{g}, h] + S_{\text{gh}}[\bar{g}, h, c, \bar{c}] + S_{\text{reg}}[\bar{g}, h]$$

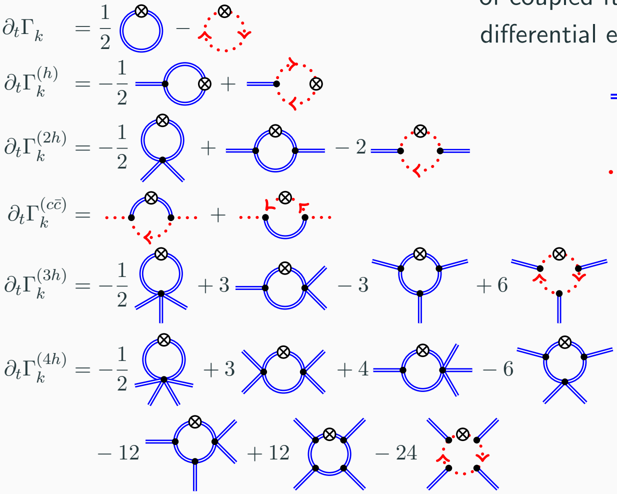
Effective action depends separately on $\bar{g}_{\mu\nu}$ and $h_{\mu\nu}$

$$\Gamma_k \equiv \Gamma_k[\bar{g}, h]$$

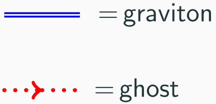
The dynamics are carried by the correlators of $h_{\mu\nu}$

$$\frac{\delta^n \Gamma_k}{\delta h^n} \equiv \Gamma_k^{(nh)} \equiv \langle h_1 \dots h_n \rangle$$

Vertex expansion of the effective action

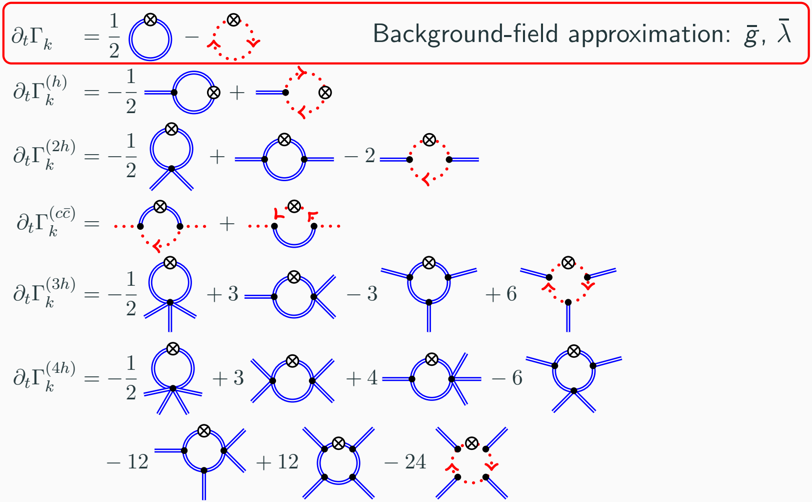


Infinite tower
of coupled functional
differential equations



$\partial_t \Gamma_k^{(n)}$ depends on
$\Gamma_k^{(2)}, \ldots, \Gamma_k^{(n+2)}$

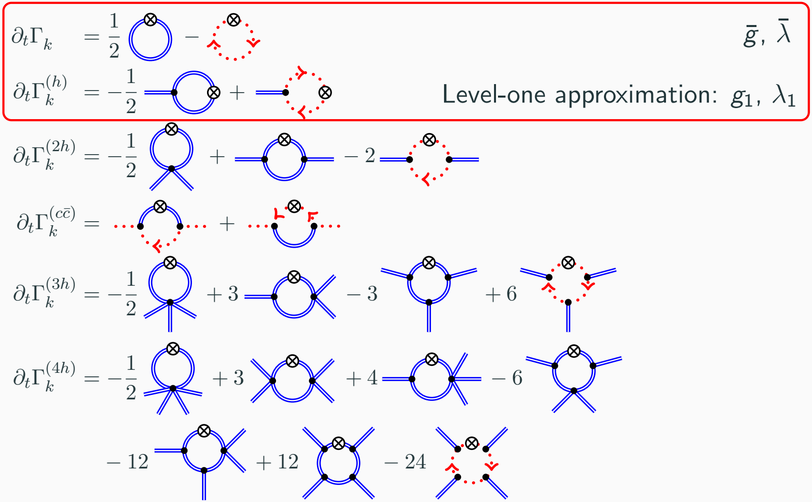
[Reuter '96; ...]



$\partial_t \Gamma_k = \frac{1}{2}$ − Background-field approximation: $\bar{g}$, $\bar{\lambda}$
$\partial_t \Gamma_k^{(h)} = -\frac{1}{2}$ +
$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2}$ + − 2
$\partial_t \Gamma_k^{(c\bar{c})} =$ +
$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2}$ + 3 − 3 + 6
$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2}$ + 3 + 4 − 6
− 12 + 12 − 24

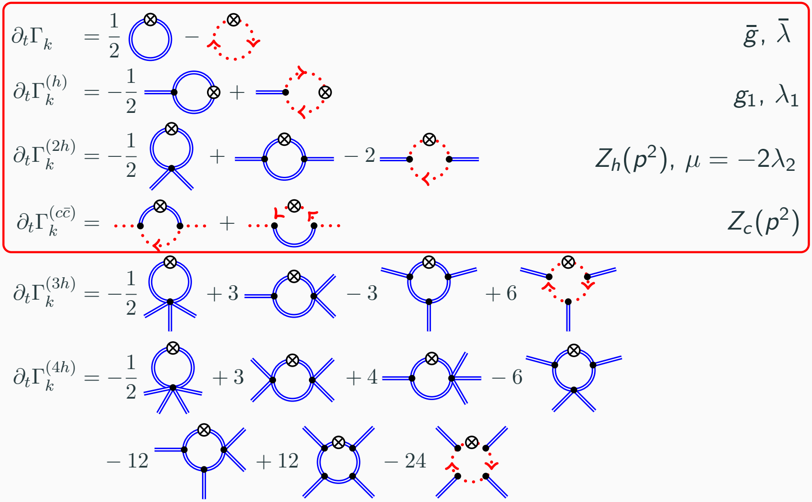
Vertex expansion of the effective action

[Manrique, Reuter, Saueressig '11; ...]



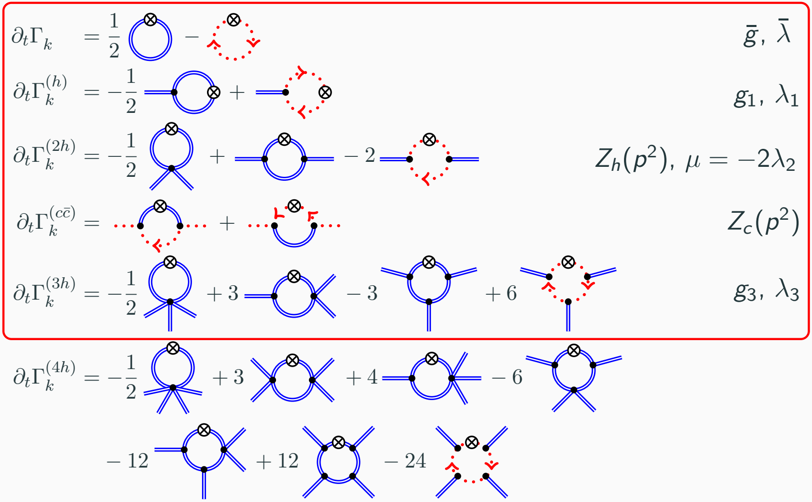
Vertex expansion of the effective action

[Christiansen, Litim, Pawlowski, Rodigast '14; . . .]



Vertex expansion of the effective action

[Christiansen, Knorr, Meibohm, Pawlowski, MR '15; . . .]



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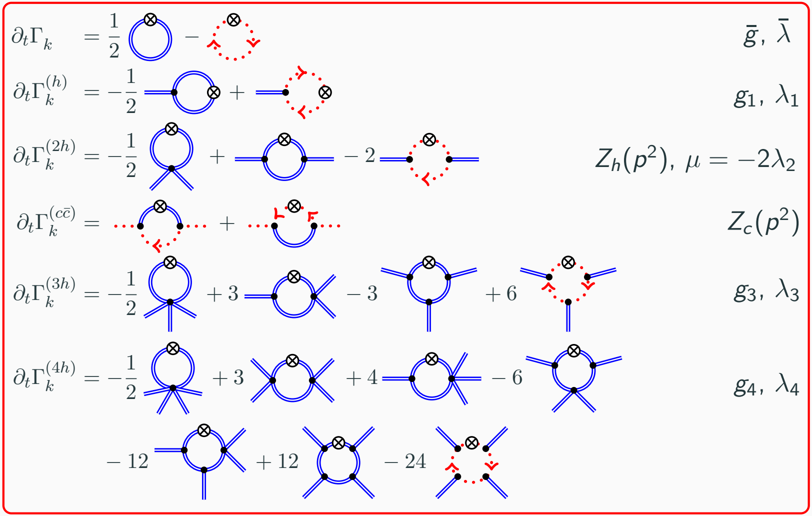

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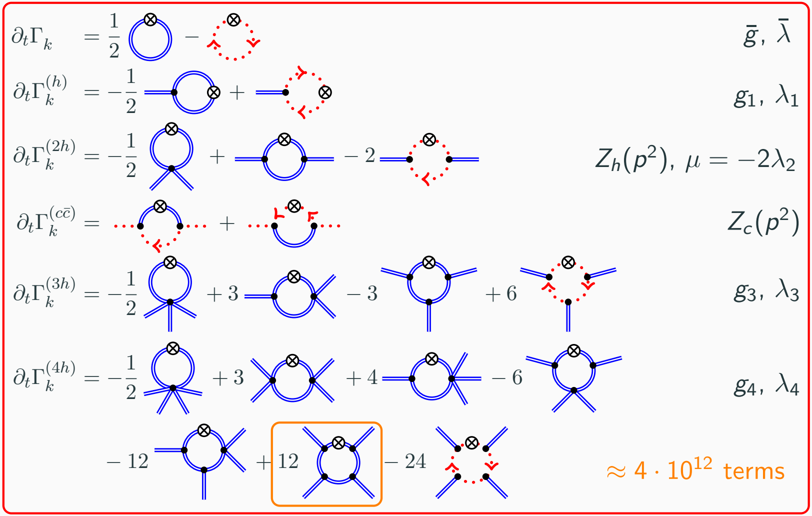
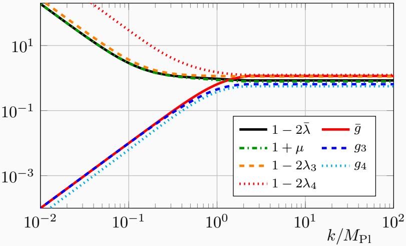


UV fixed point

IR behaviour

General relativity



UV fixed point

Asymptotic safety

$$(\mu^*,\, \lambda_3^*,\, \lambda_4^*,\, g_3^*,\, g_4^*) = (-0.45,\, 0.12,\, 0.028,\, 0.83,\, 0.57)$$

$$\theta_i = (4.7,\, 2.0 \pm 3.1\,\mathrm{i},\, -2.9,\, -8.0)$$

Three relevant directions: Λ, R and R^2

[Denz, Pawlowski, MR '16]

Towards a Standard-Model–gravity system

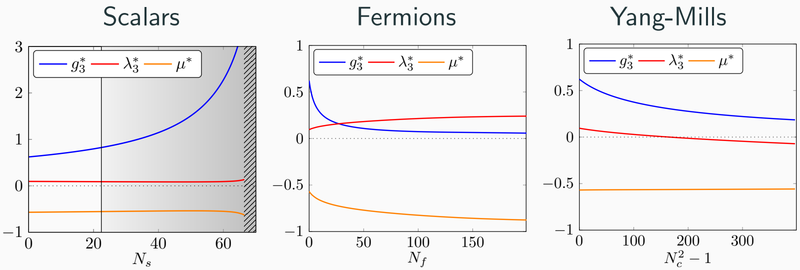
$$S = \frac{1}{16\pi G_N} \int \mathrm{d}^4x \sqrt{g}\,(2\Lambda - R) \qquad \text{Gravity}$$

$$+ \frac{1}{2} \sum_{i=1}^{N_s} \int \mathrm{d}^4x \sqrt{g} g^{\mu\nu} \partial_\mu \varphi^i \partial_\nu \varphi^i \qquad \text{Scalars}$$

$$+ \sum_{j=1}^{N_f} \int \mathrm{d}^4x \sqrt{g} \bar{\psi}_j \not{\nabla} \psi_j \qquad \text{Fermions}$$

$$+ \frac{1}{2} \int \mathrm{d}^4x \sqrt{g}\, g^{\mu\nu} g^{\rho\sigma}\, \mathrm{tr}\, F_{\mu\rho} F_{\nu\sigma} \qquad \text{Yang-Mills}$$

UV fixed point with matter



[Meibohm, Pawlowski, MR '16]

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Gravity dominates the UV behaviour: $G_{\text{eff}} \sim \frac{g_3}{1+\mu}$

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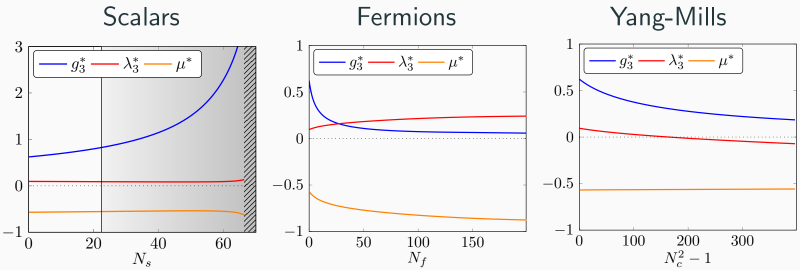

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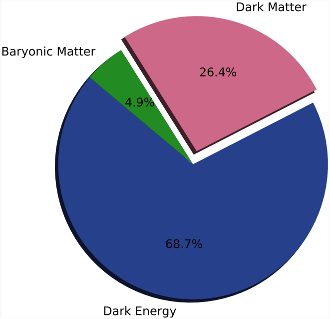
One force to rule them all

Dark Matter

Dark Matter

Dark Matter evidence from

- Rotation curves
- CMB
- Structure formation
- ...



Dark Matter

Dark Matter can be

- a particle
- a modified gravitational interaction
- primordial black holes
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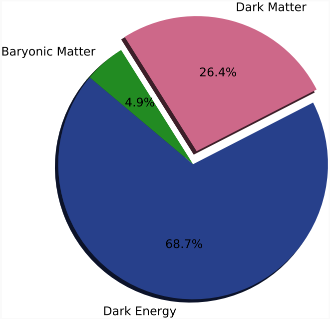

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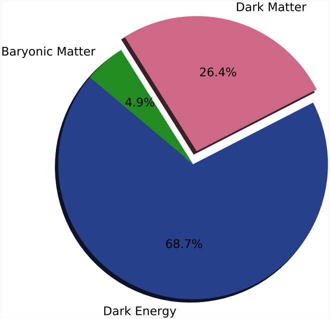
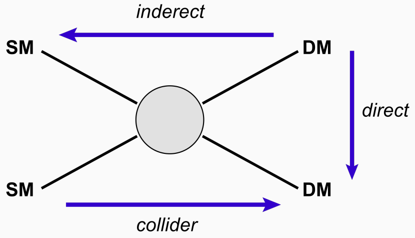


We want to use quantum gravity to constrain a given dark matter model

Dark Matter

A dark matter candidate

- is stable or long-lived on cosmic time scales
- has a portal interaction with the SM fields



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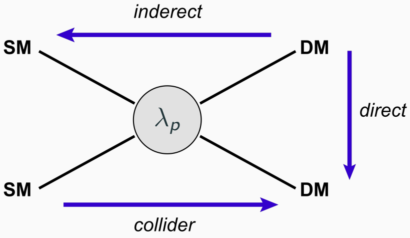

Example: Higgs portal $\lambda_p\, H^\dagger H\, S\, S^*$

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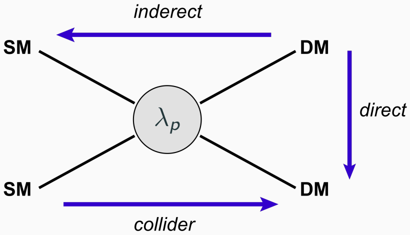

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Various production mechanisms

- Thermal production (freeze out)
- Non-thermal production
  (decay from heavier particle, during reheating)

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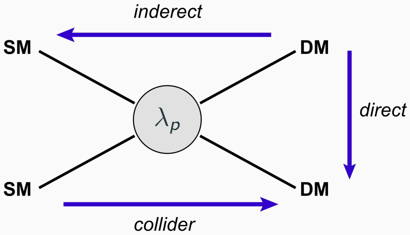

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Number density of DM candidate is described by the Bolzmann equation

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3H\, n_\chi = -\langle\sigma(\chi\chi \to \mathrm{SM}) v_{\mathrm{rel.}}\rangle (n_\chi^2 - n_{\chi,\mathrm{eq}}^2)$$

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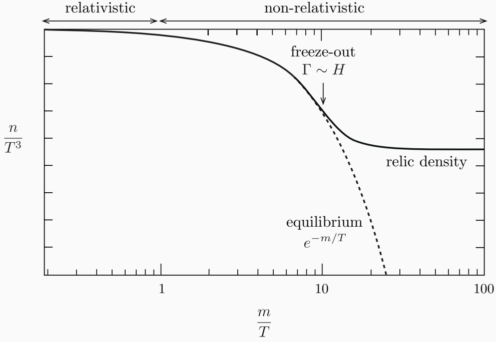

[Picture: Baumann '19]

Freeze out

Number density of DM candidate is described by the Bolzmann equation

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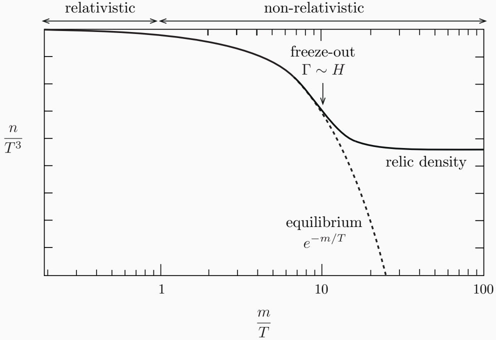
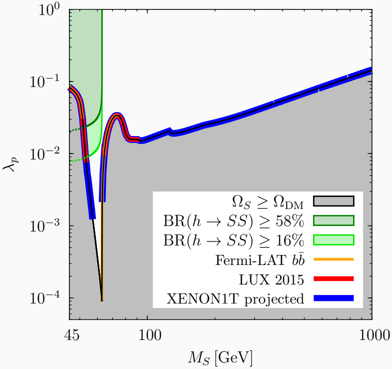


[Picture: Baumann '19]

Smaller portal coupling $\longrightarrow$ earlier decoupling $\longrightarrow$ larger relic density

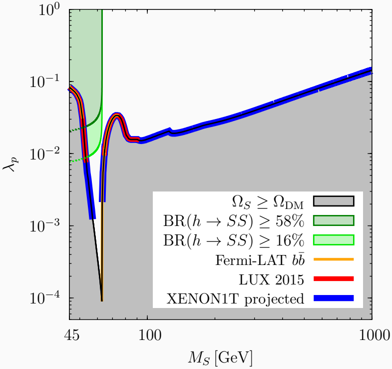
Scalar Higgs portal



[Duerr, Perez, Smirnov '15]

- Higgs resonance at $m_S \approx m_h/2$ allows for smaller coupling values

Scalar Higgs portal

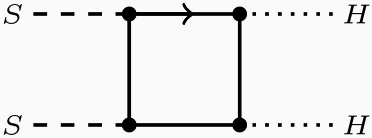


[Duerr, Perez, Smirnov '15]

- Higgs resonance at $m_S \approx m_h/2$ allows for smaller coupling values
- Quantum gravity prediction $\lambda_p(M_{\rm Pl}) = 0$
- Portal coupling remains zero also below $M_{\rm Pl}$ [Eichhorn, Hamada, Lumma, Yamada '18]

How can we generate the portal coupling?

Yukawa interaction can generate λ_p



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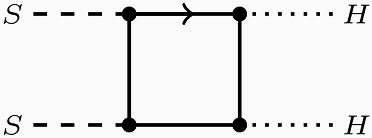
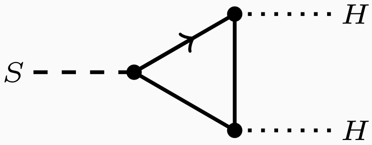


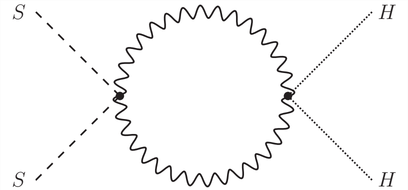
But also allows decay (breaks the stabilising Z_2 symmetry)



Yukawa interaction is fine as long as ψ cannot decay into light particles

How can we generate the portal coupling?

Gauge interaction $U(1)_X$



- Stability: interaction preserves Z_2 symmetry
- Kinetic mixing: no charge of Higgs boson under $U(1)_X$ needed

Kinetic mixing

Lagrangian of $U(1)_X$ and $U(1)_Y$

$$\mathcal{L} \sim \frac{1}{4} F^X_{\mu\nu} F^{\mu\nu}_X + \frac{1}{4} F^Y_{\mu\nu} F^{\mu\nu}_Y + \frac{\epsilon}{2} F^X_{\mu\nu} F^{\mu\nu}_Y$$

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- Eliminate $F^X_{\mu\nu} F^{\mu\nu}_Y$ by rotations and rescalings of the gauge fields
- Price to pay: non-diagonal covariant derivative

$$\mathcal{D}_\mu = \partial_\mu + i\,(g_Y n_Y)\, B_\mu + i\,(g_D n_X + g_\epsilon n_Y)\, Z'_\mu$$

- New gauge couplings g_D and g_ϵ

Dark sector

Lagrangian of the dark sector

$$
\begin{aligned}
\mathcal{L}_D &\sim \mathcal{L}_{\mathrm{scalar}} + \mathcal{L}_{\mathrm{fermion}} + \mathcal{L}_{\mathrm{gauge}} \\
&\sim \frac{1}{2} D_\mu S D^\mu S^* + \lambda_p H^\dagger H S S^* + \lambda_S (S S^*)^2 + \frac{m_S^2}{2} S S^* \\
&\quad + i\bar{\psi}\not{D}\psi + M_\psi \bar{\psi}\psi + y_\psi\, S\bar{\psi}\psi^c \\
&\quad + \frac{1}{4} F^X_{\mu\nu} F_X^{\mu\nu} + \frac{\epsilon}{2} F^Y_{\mu\nu} F_X^{\mu\nu} + \frac{M_{Z'}^2}{2} \left(Z'_\mu - \partial_\mu \zeta \right)^2
\end{aligned}
$$

- Stueckelberg mechanism to give mass to Z'
- Vector-like fermion ψ for vacuum stability of S
- S or ψ is dark matter candidate depending on mass hierarchy

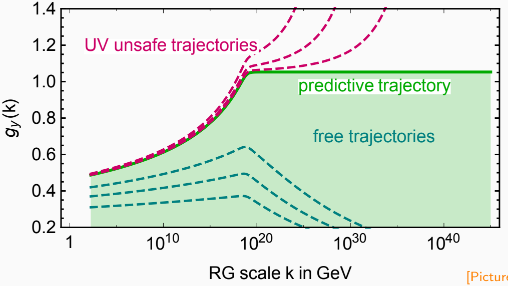
Dark Matter meets Quantum Gravity

Philosophy

- Standard Model extension that allows for a Dark Matter candidate
- Simple dark matter models preferred
- Demand that the model is UV complete with quantum gravity
- Assume no further particle content

Boundary conditions from asymptotically safety

If matter couplings become too large, they run into a Landau pole



[Picture: Eichhorn, Versteegen '17]

Boundary conditions from asymptotically safety

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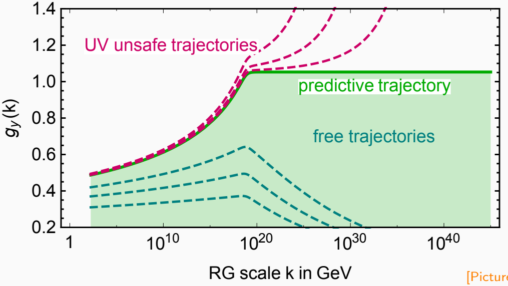

[Picture: Eichhorn, Versteegen '17]

Notice difference between

- UV attractive (relevant) direction
- UV repulsive (irrelevant) direction

Quartic scalar coupling

Beta function of quartic scalar coupling

$$\beta_\lambda = \beta_{\lambda,\mathrm{matter}} + f_\lambda$$

with *UV repulsive* fixed point $\lambda^* = 0$ [Pawlowski, MR, Wetterich, Yamada '18]

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Application to Higgs mass [Shaposhnikov, Wetterich '09]

$$m_h = 126 - 136\,\mathrm{GeV}$$

$U(1)$ gauge coupling

$U(1)$ gauge beta function

$$\beta_g = \beta_{g,\text{matter}} - f_g g$$

$U(1)$ gauge coupling

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f_g is positive

[Christiansen, Litim, Pawlowski, MR '17]

$$f_g = \frac{\tilde{G}}{16\pi}\left(\frac{8}{1-2\tilde{\Lambda}} - \frac{4}{(1-2\tilde{\Lambda})^2}\right)$$

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$$f_g = \frac{\tilde{G}}{16\pi}\left(\frac{8}{1-2\tilde{\Lambda}} - \frac{4}{(1-2\tilde{\Lambda})^2}\right)$$

Boundary condition at one loop ($\beta_{g,\text{matter}} = \beta_{g,\text{1-loop}} g^3$)

$$g(M_{\text{Pl}}) \leq \sqrt{\frac{f_g}{\beta_{g,\text{1-loop}}}}$$

We use $f_g \leq 0.04$

Yukawa coupling

Yukawa beta function at one loop

$$\beta_y = \beta_{y,\text{1-loop-yukawa}}\, y^3 - \beta_{y,\text{1-loop-gauge}}\, y - f_y\, y$$

Boundary condition

$$y(M_{\text{Pl}}) \leq \sqrt{\frac{f_y + \beta_{y,\text{1-loop-gauge}}}{\beta_{y,\text{1-loop-yukawa}}}}$$

Application: top mass and difference between top & bottom mass

[Eichhorn, Held '17; '18]

Compatibility with SM

When is the SM compatible with Asymptotic Safety?

- For $U(1)_Y$ we need $f_g \geq 9.8 \cdot 10^{-3}$
- For top and bottom mass we need $f_y \geq 10^{-4}$ [Eichhorn, Held '18]
- The Higgs mass is slightly wrong $m_h \approx 130\,\text{GeV}$ [Shaposhnikov, Wetterich '09]

Two perspectives on the Higgs mass

- Accept small difference
- Use freedom of SM extension to adjust Higgs mass

Scalar dark matter model

Properties

- $U(1)_X$ is identified with $U(1)_{B\text{-}L}$
- Right-handed neutrinos to make B-L anomaly free
- Dark fermions for vacuum stability; decay via neutrino channel

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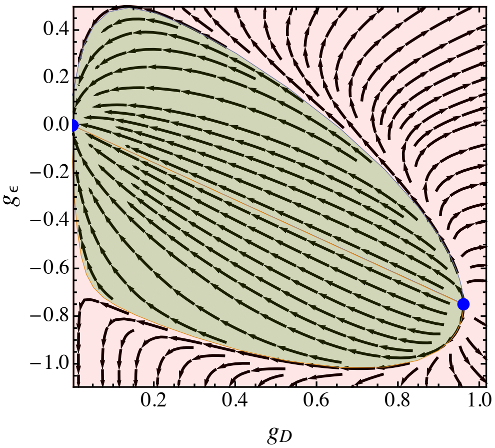
Predictivity from

- $\lambda_p(M_{\text{Pl}}) \approx 0$
- λ_p induced by g_D and g_ϵ, which are bounded as well
- Vacuum stability of S is crucial

Allowed range for g_D and g_ϵ



Asymptotically free couplings, if their values are in the green area at $M_{\rm Pl}$

Example running

- Choose $g_D(M_{\mathrm{Pl}})$
- Adjust $g_\epsilon(M_{\mathrm{Pl}})$ to match Higgs mass
- Add fermions for vacuum stability

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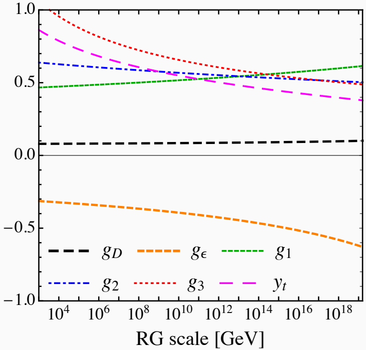

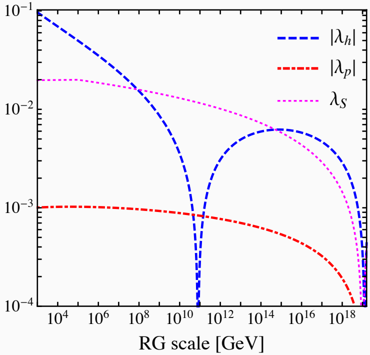

Prediction for portal coupling

Use g_ϵ to fix Higgs mass and $f_g \leq 0.04$

$$|\lambda_p(\text{TeV})| \leq 0.08$$

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Use g_ϵ to fix Higgs mass and $f_g \leq 0.04$

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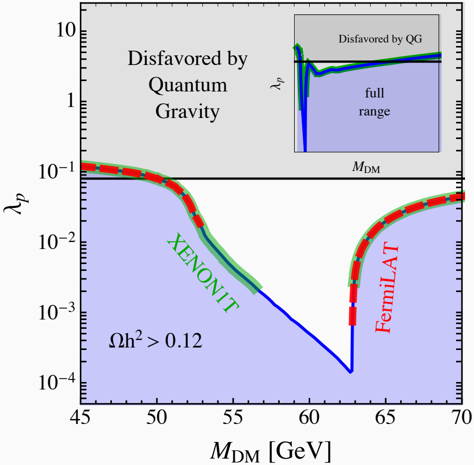
Accepting a small difference in the Higgs mass

$$|\lambda_p(\text{TeV})| \lesssim 1.1\, f_g + 54\, f_g^2$$

$$m_{h,\text{min}} \approx (136 - 382\, f_g)\,\text{GeV}$$

For $f_g = 0.04$ we find $|\lambda_p| \leq 0.13$

Favoured mass range scalar dark matter



$$56\,\text{GeV} < M_{\rm DM} < 63\,\text{GeV}$$

Fermionic dark matter model

Properties

- $U(1)_X$ with free quantum number n_ψ for fermion
- Scalar Higgs portal optional

Fermionic dark matter model

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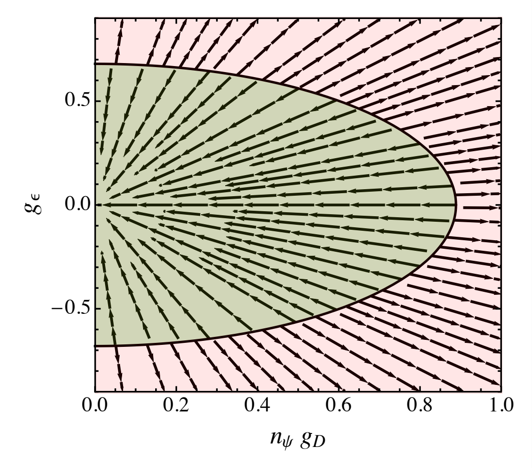
Predictivity from

- Upper bound on $n_\psi g_D$
- Annihilation cross section $\sim n_\psi g_D$
- n_ψ drops out

Allowed range for g_D and g_ϵ



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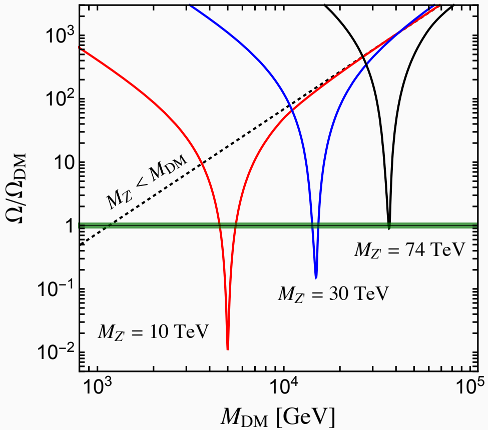
Favoured mass range fermionic dark matter



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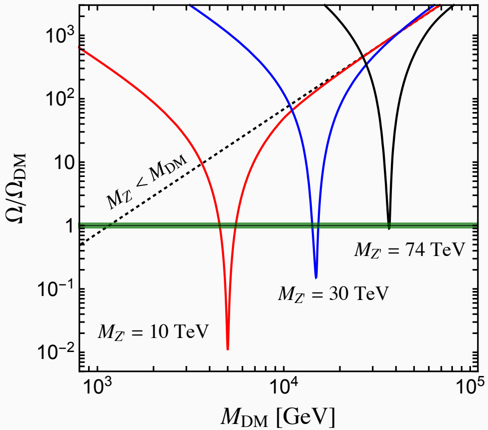

- non-resonant $M_{Z'} < M_{\rm DM}$: $M_{\rm DM} < 2\,\text{TeV}$
- resonant $M_{Z'} > M_{\rm DM}$: $M_{\rm DM} < 40\,\text{TeV}$

Summary

- Dark matter models guided by simplicity
- Demand asymptotic safety or freedom of all couplings
- Boundary conditions at M_{Pl} leads to constraints on the mass
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Thank you for your attention