Dark Matter meets Quantum Gravity

Manuel Reichert

Asymptotic Safety meets Particle Physics, Dortmund, 18. December 2019

CP^3-Origins, SDU Odense, Denmark

MR, Juri Smirnov: arXiv:1911.00012

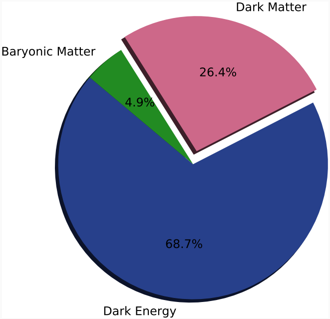
Dark Matter

Evidence from

- Rotation curves
- CMB
- Structure formation

It can be

- a particle
- modified gravity (CMB difficult)
- primordial black holes



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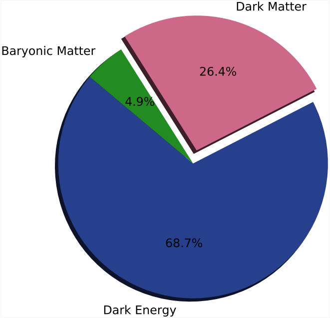
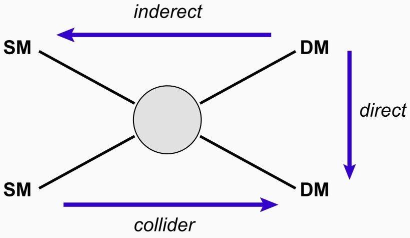


We want to use quantum gravity to constrain a given dark matter model

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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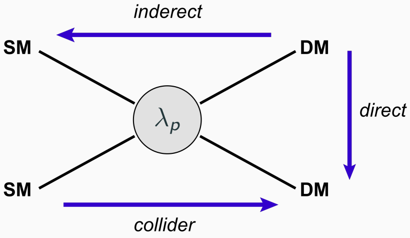

Example: Higgs portal $\lambda_p \, H^\dagger H \, S \, S^*$

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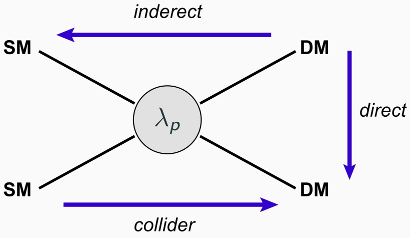

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Various production mechanisms

- Thermal production (freeze out)
- Non-thermal production

  (decay from heavier particle, during reheating)

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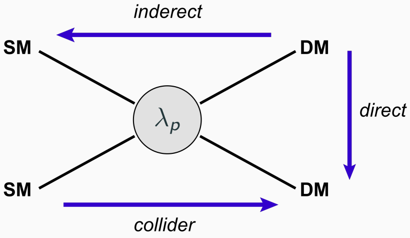

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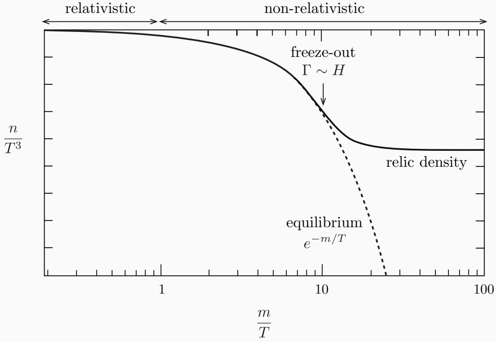
Freeze out



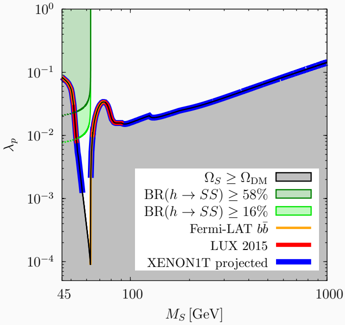
[Picture: Baumann '19]

Determines the cross section $\langle \sigma v_{\text{rel.}} \rangle$ but not the mass M_{DM}

Scalar Higgs portal

Constrain parameter space by

- Overabundance
- Experiments
- Unitarity [Smirnov, Beacom '19]
- Asymptotic Safety



[Duerr, Peréz, Smirnov '15]

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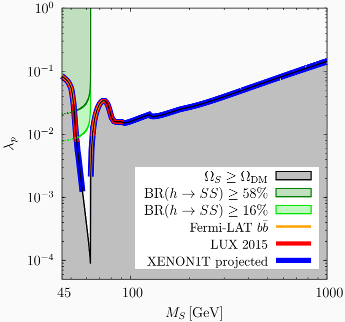

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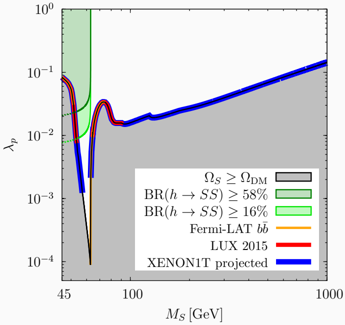
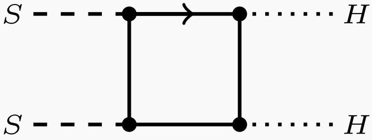


[Duerr, Peréz, Smirnov '15]

- 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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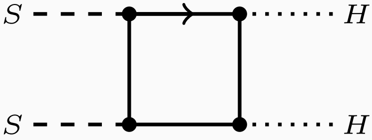
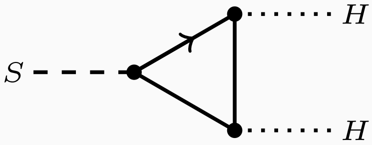


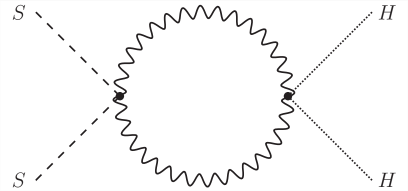
But also allows decay (breaks the stabilising Z_2 symmetry)



Decay needs to be sufficiently suppressed

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

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

Dark sector

Lagrangian of the dark sector

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

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

Our 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

Asymptotically safe quantum gravity

Weinberg's proposal '76

Non-perturbative UV fixed point of the renormalisation group flow

- Metric carries fundamental degrees of freedom
- Diffeomorphism invariance is the symmetry of the theory

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$$S_{\mathrm{EH}} = \frac{1}{16\pi G_{\mathrm{N}}} \int_x \sqrt{g}(2\Lambda - R)$$

$$k\partial_k g \equiv \beta_g \xrightarrow{k\to\infty} 0$$

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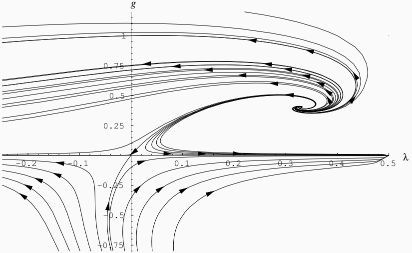

[Reuter '96; Reuter, Saueressig '01]

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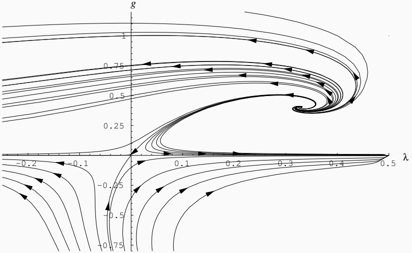
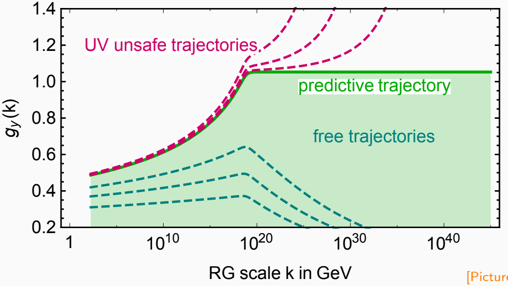


[Reuter '96; Reuter, Saueressig '01]

Use non-perturbative functional renormalisation group to compute gravity contributions to the running of the matter couplings

Boundary conditions from asymptotic safety

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



[Picture: Eichhorn, Versteegen '17]

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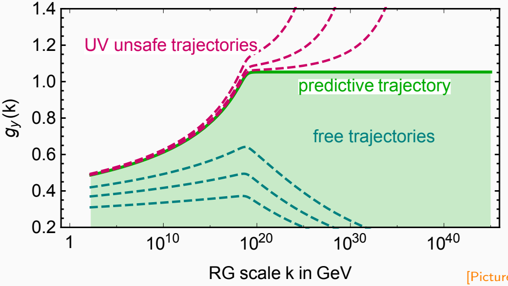

[Picture: Eichhorn, Versteegen '17]

Notice difference between

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

Quartic scalar coupling

Beta function of quartic scalar coupling

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

with UV repulsive fixed point $\lambda^* = 0$

[Percacci, Perini '03; Eichhorn, Hamada, Lumma Yamada, '17; Pawlowski, MR, Wetterich, Yamada '18]

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Boundary condition: $\lambda(M_{\mathrm{Pl}}) \approx 0$

Application to Higgs mass [Shaposhnikov, Wetterich '09]

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

$U(1)$ gauge coupling

$U(1)$ gauge beta function

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

f_g is positive

[Daum, Harst, Reuter '09; Folkerts, Litim, Pawlowski '11; Eichhorn, Versteegen '17; Christiansen, Litim, Pawlowski, MR '17]

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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 $f_g \leq 0.04$

Compatibility with SM

When is the SM compatible with Asymptotic Safety?

- For $U(1)_Y$ we need $f_g \geq 9.8 \cdot 10^{-3}$ [Eichhorn, Versteegen '17]
- For top and bottom mass we need $f_y \geq 10^{-4}$ [Eichhorn, Held '18]
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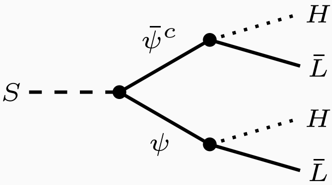
Two perspectives on the Higgs mass

- 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



S is long lived if
$M_\psi > y_D 10^{14}$ GeV

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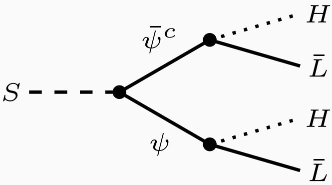

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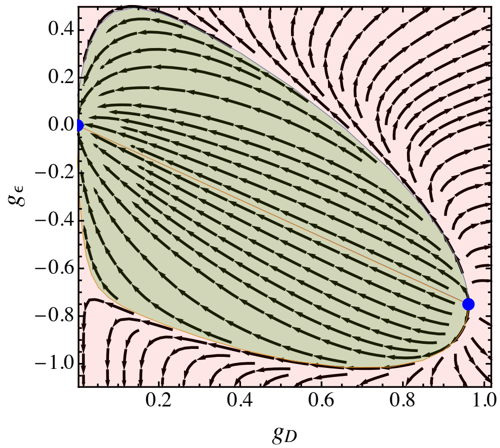
$M_\psi > y_D 10^{14}$ GeV

Predictivity from

- $\lambda_p(M_{\rm Pl}) \approx 0$
- 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_{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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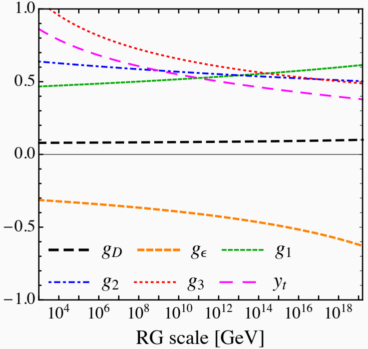
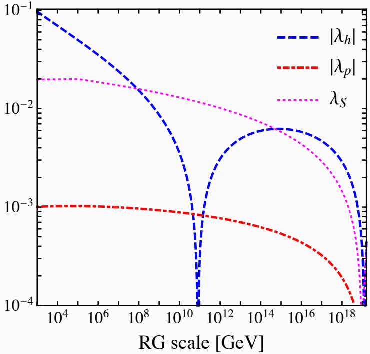




Prediction for portal coupling

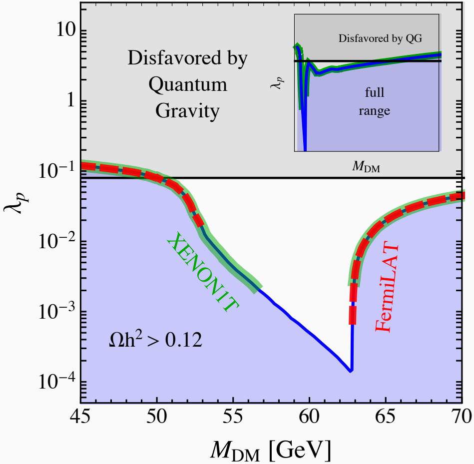
Use g_ϵ to fix Higgs mass and $f_g \leq 0.04$

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

Accepting a small difference in the Higgs mass

$$|\lambda_p(\mathrm{TeV})| \leq 0.13$$

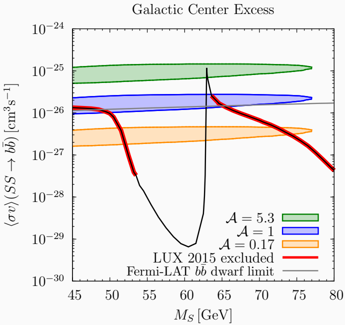
Favoured mass range scalar dark matter



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

Experimental searches

- Portal coupling can be small $\lambda_p \approx 10^{-4}$
- Above neutrino floor
- Testable with
  - Direkt detection (liquid noble gas detectors)
  - Galactic annihilation signals



Would explain galactic center excess $E_\gamma = 60\,\mathrm{GeV}$

[Duerr, Peréz, Smirnov '15]

Fermionic dark matter model

Properties

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

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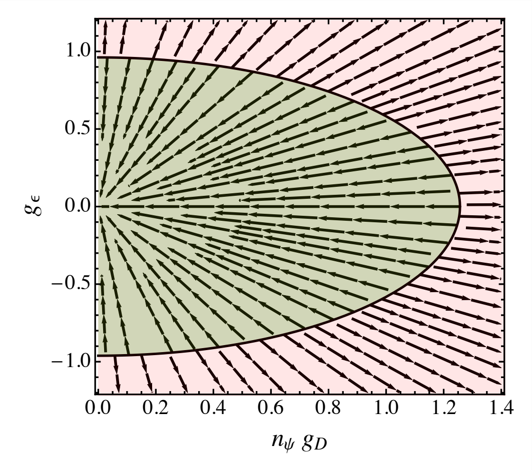
Predictivity from

- 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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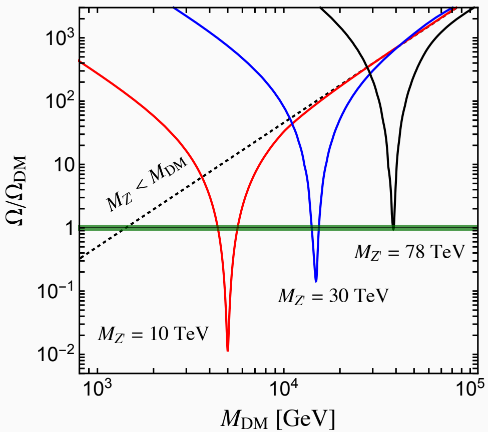
Favoured mass range fermionic dark matter



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

Experimental searches

Non-resonant

- Long life-time of mediator $\rightarrow$ annihilation signal challenging
- g_ϵ can be very small $\rightarrow$ direct detection challenging
- Measurements of total energy injections in e.g. CMB

Resonant

- Below neutrino floor above $M_{\mathrm{DM}} > 9\,\mathrm{TeV}$
- Annihilation signal search is promising
- Hidden $U(1)$ boson searches at LHC

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
- Scalar Higgs portal

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$$M_{\mathrm{DM}} < 40\,\mathrm{TeV}$$

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Thank you for your attention

Back-up

Kinetic mixing

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

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

- 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

Yukawa coupling

Yukawa beta function at one loop

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

[Zanusso, Zambelli, Vacca, Percacci '09; Oda, Yamada '15; Eichhorn, Held, Pawlowski '16; Eichhorn, Held '17]

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]