keV Sterile Neutrino Dark Matter from Singlet Scalar Decays

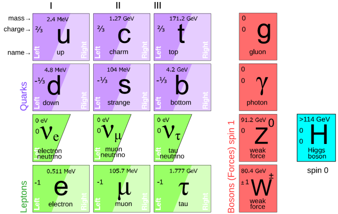
IMPRS-EPP student seminar

based on 1502.01011 in collaboration with Alexander Merle

Maximilian Totzauer

April 17, 2015

What is a sterile neutrino in the first place?



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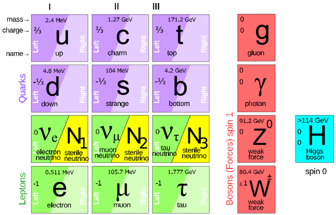

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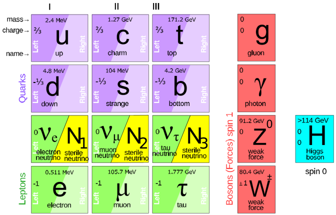

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- Mixing of heavy mass eigenstates into the eigenstates of the weak interaction (mixing angles, usually denoted θ).

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- Neutrinos in the SM are massless, but neutrino oscillations suggest something different! $\Rightarrow$ (Heavy) sterile neutrinos naturally allow for small masses of the active neutrinos (seesaw mechanism).

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- A massive, electrically neutral particle is a natural candidate for Dark Matter.
- Recent excitement about tentative signal ($N \to \nu\gamma$) at $E_\gamma = 3.55\,\mathrm{keV} \Rightarrow M_R = 7.1\,\mathrm{keV}$?

Which experimental insights constrain DM models?

- Relic abundance constraint: ($\Omega_{\mathrm{DM}} h^2 = 0.1188$).
  Multi-component DM models of course feasible,
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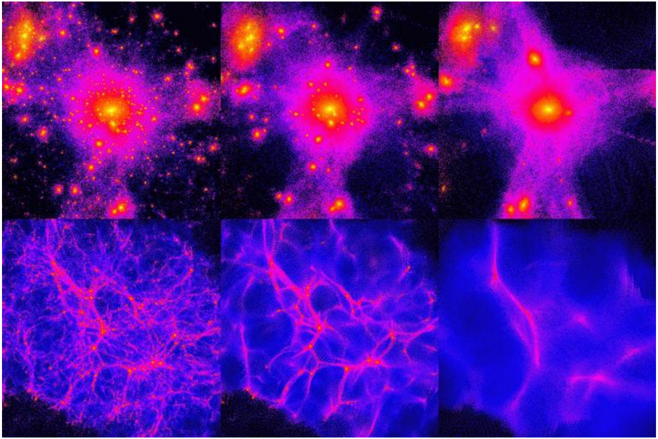
- Constraints on N_{eff}: Additional degrees of freedom in radiation heavily constrained by the CMB and BBN.
- Structure formation: Cold Dark Matter fits the observed large-scale structure almost perfectly (e.g. missing satellite problem). If Dark Matter was too light (and thereby most likely too fast), there would be less structure today!

Hot, warm or cold Dark Matter? – Structure formation



Cold (left), warm (centre) and hot (right) Dark Matter

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Alternative: freeze-in: Interaction (e.g. $\chi\chi \leftrightarrow X_{\mathrm{SM}}X_{\mathrm{SM}}$) too feeble to obtain equilibrium. Occasional production of DM from plasma until $T \leq m_{\mathrm{DM}}$.

- Relic abundance $\propto \sigma_{\mathrm{ann}}$
- Non-thermal spectrum

Possible production mechanisms for keV steriles as Dark Matter

- Dodelson-Widrow-mechanism (hep-ph/9303287) Production from the plasma via active-sterile-mixing; equilibrium never achieved; (freeze-in type)
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$\Rightarrow$ numerical treatment on the level of distribution functions!

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where

$$V_{\rm scalar} = -\mu_H^2 H^\dagger H - \frac{1}{2}\mu_S^2 S^2 + \lambda_H \left(H^\dagger H\right)^2 + \frac{\lambda_S}{4} S^4 + 2\lambda \left(H^\dagger H\right) S^2$$

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  $S \rightarrow NN$
- Mixing θ switched off in this model.

Sterile neutrinos from scalar decays – particle physics

The relevant parameters of the setup:

- Yukawa coupling y ($-\mathcal{L} \supset \frac{y}{2} S \overline{N^c} N$).
- Higgs portal λ ($-\mathcal{L} \supset 2\lambda \left(H^\dagger H\right) S^2$)
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Convenient parametrisation for our analysis:

- $\mathcal{C}_\Gamma \equiv \frac{M_0}{m_S} \frac{y^2}{16\pi} = \frac{M_0}{m_S} \frac{\Gamma}{m_S}$ (effective decay width)
- $\mathcal{C}_{\mathrm{HP}} \equiv \frac{M_0}{m_S} \frac{\lambda^2}{16\pi^3}$ (effective Higgs portal)
- with $M_0 \equiv \left(\frac{45 M_{\mathrm{Pl}}^2}{4\pi^3 g_*}\right)^{1/2} = 7.35 g_*^{-1/2} \times 10^{18}\,\mathrm{GeV}$

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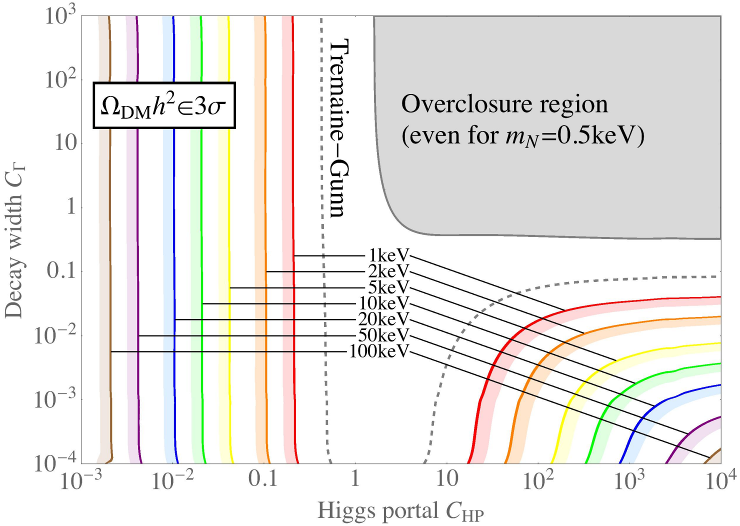
$\Rightarrow$ Numerically difficult partial integro-differential equations.

Confronting the model with reality – relic abundance



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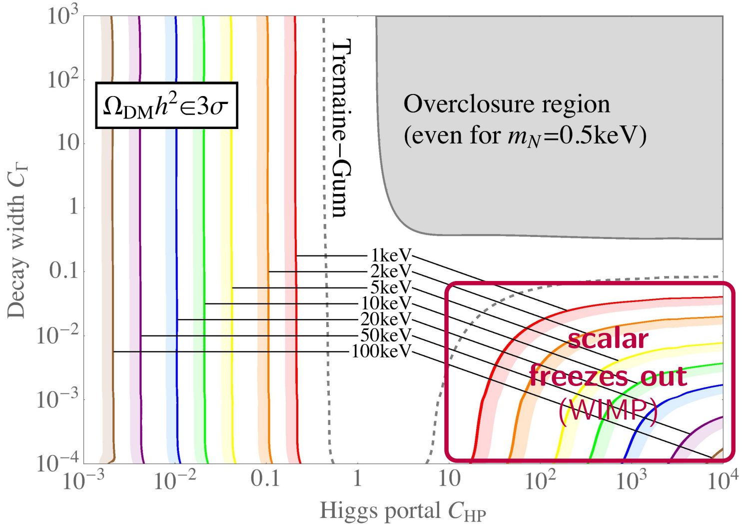

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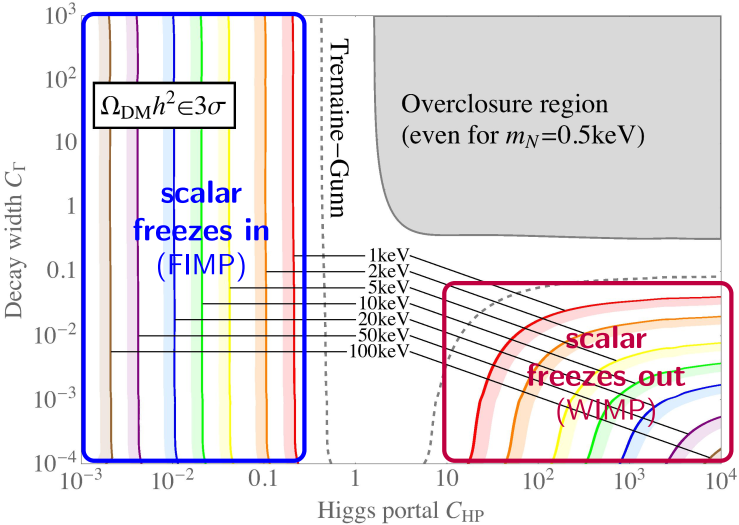

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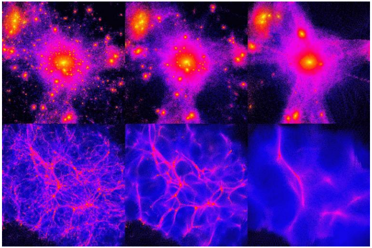

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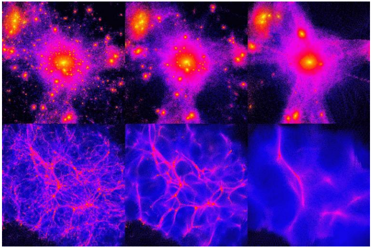

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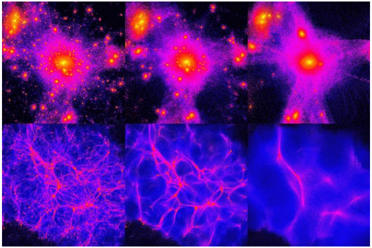

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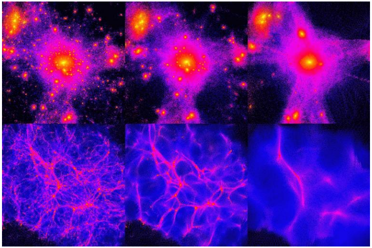

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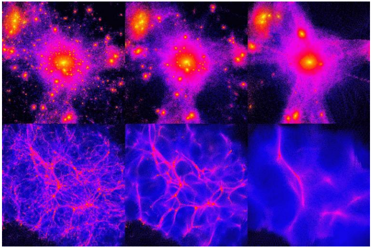

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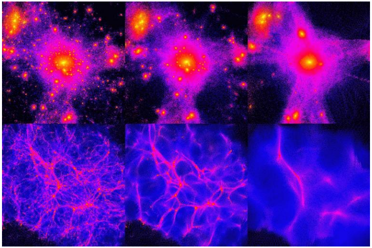

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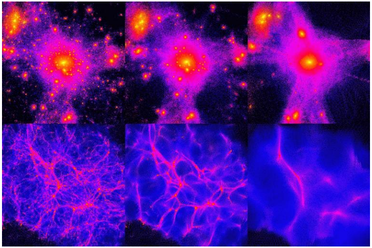

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- But: Full large-scale simulations expensive and usually based on thermal spectra
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$\Rightarrow$ Use $\lambda_{\rm FS}$ for the time being, more detailed analyses ongoing.

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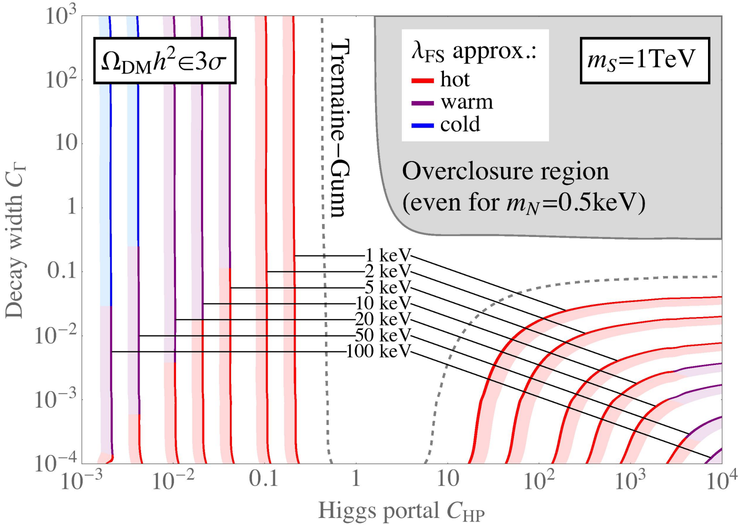
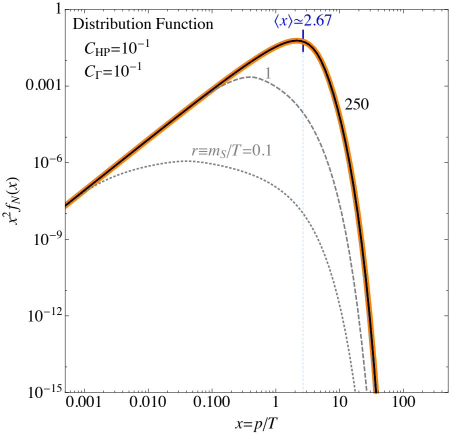


Why might λ_{FS} be particularly bad in our model?

FIMP case: SN spectrum cooler than thermal one ($\langle x \rangle_{\mathrm{th}} = 3.15$)



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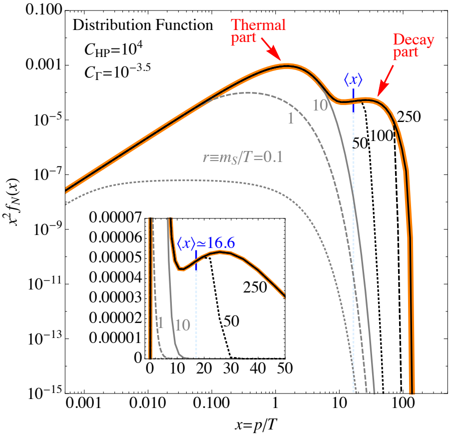
WIMP case: SN from scalars in equilibrium and frozen-out scalars!



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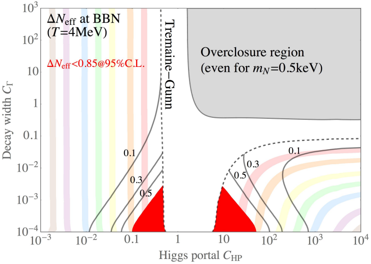
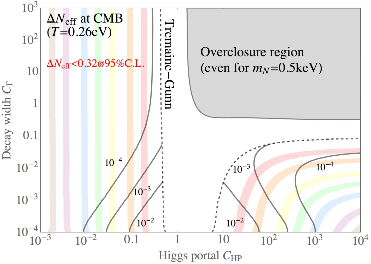
Confronting the model with reality – CMB and BBN

Extra radiation and the time of CMB decoupling / BBN would leave imprints in power spectrum / primordial He-abundance:



(a) Constraints from Big Bang Nucleosynthesis (BBN) (red patches excluded)



(b) Constraints from the Cosmic Microwave Background (CMB) (nothing excluded)

Conclusion

- Decay of scalar particles as relatively unconstrained production mechanism for keV sterile neutrinos as DM.

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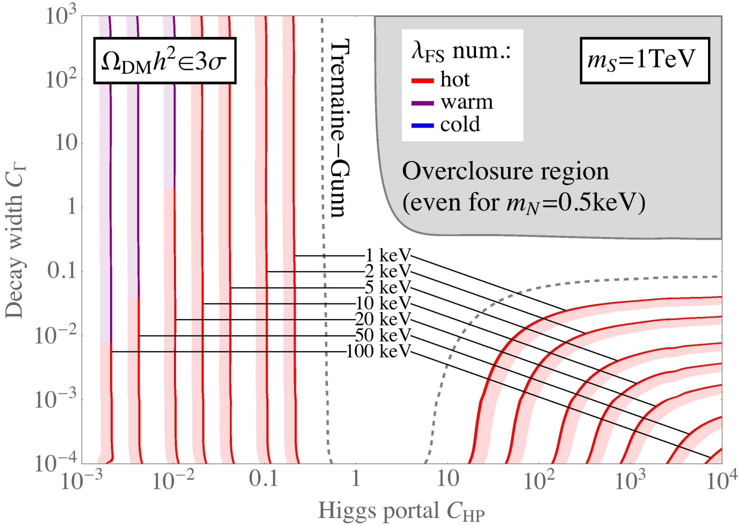
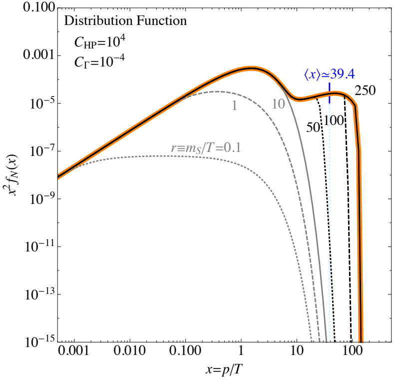
- Include DW contribution (non-zero mixing θ, work in progress).

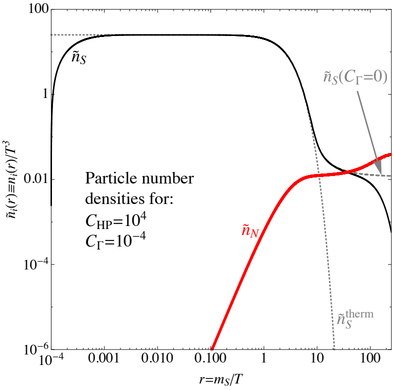
Thank you for your attention!

Backup I – Numerical free-streaming horizon



Backup II – Evolution of abundances vs. evolution of distribution function





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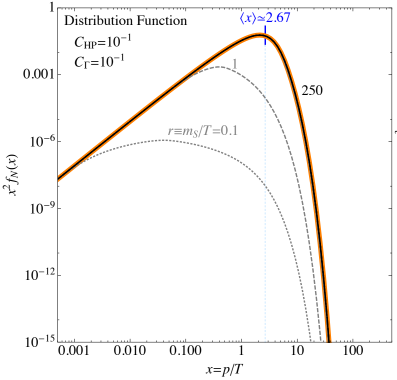

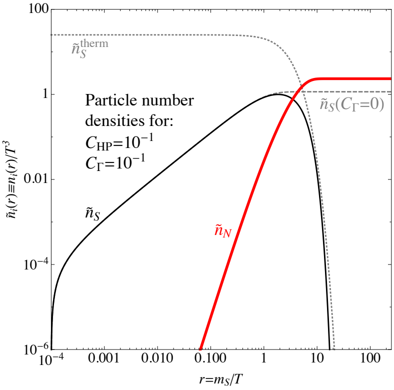

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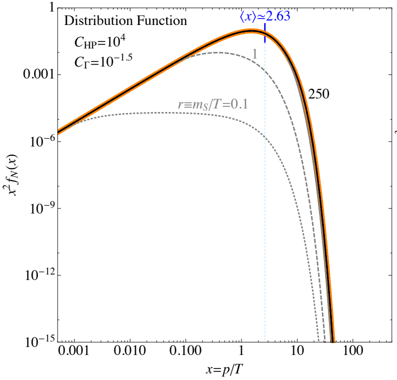

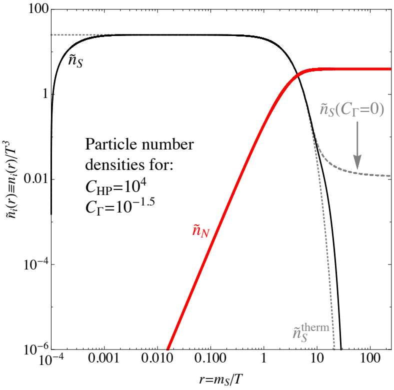

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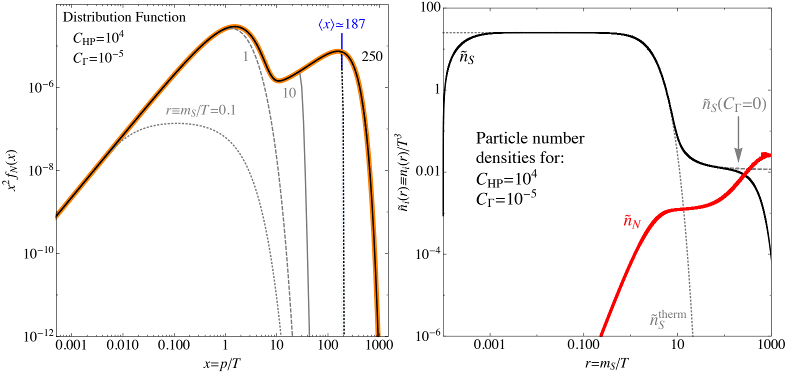

Backup III – Assessing the approximation of $g_* = \text{const.}$