keV sterile neutrinos and new tests for non-thermal DM candidates

IMPRS EPP — Young Scientists' Workshop

based on work with many collaborators:
(1704.07838, ApJ 836(61), JCAP 1611(038), JCAP 1604(003), JCAP 1506(011))

Maximilian Totzauer

July 18, 2017

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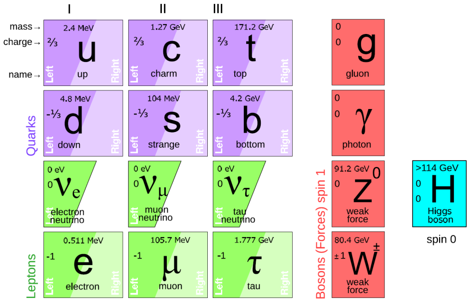
What to expect

What is a sterile neutrino?



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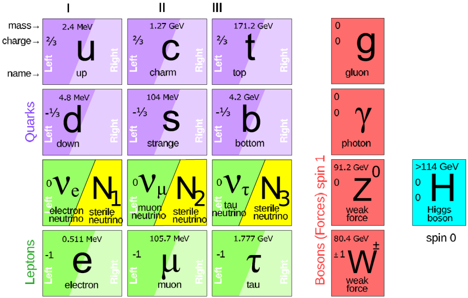

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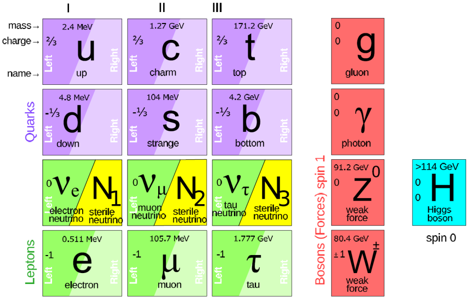

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- Number of right-handed states a priori arbitrary.

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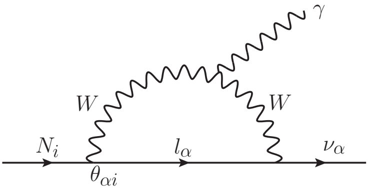
- Can be (a part of) the cosmic DM
- If so: would have a rather clear signal for $\sin^2(2\theta) \neq 0$:



Decay $N \to \nu\gamma$ gives photons with $E_\gamma = m_N/2$.

Claim for a signal @ $E_\gamma = 3.55\,\mathrm{keV}$ in 2014, highly disputed & still unresolved issue

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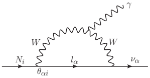
- Decay of parent particles: Highly non-thermal process, parent P itself can freeze in or out or be a decay product itself.
  $\Omega_{\mathrm{DM}} = \Omega_{\mathrm{DM}} \left(\sigma_{\mathrm{P} \leftrightarrow \mathrm{SM}}, \Gamma_P \right)$

How to fill the templates with physical models for SN?

The popular production mechanisms are:

- Dodelson-Widrow production (DW), aka non-resonant active-sterile conversion (freeze-in), $\Omega_{\rm DM} \propto \sin^2(2\theta)$



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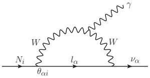

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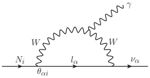

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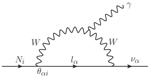

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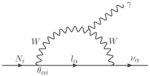

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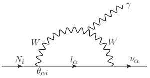

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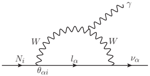

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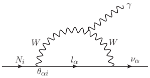

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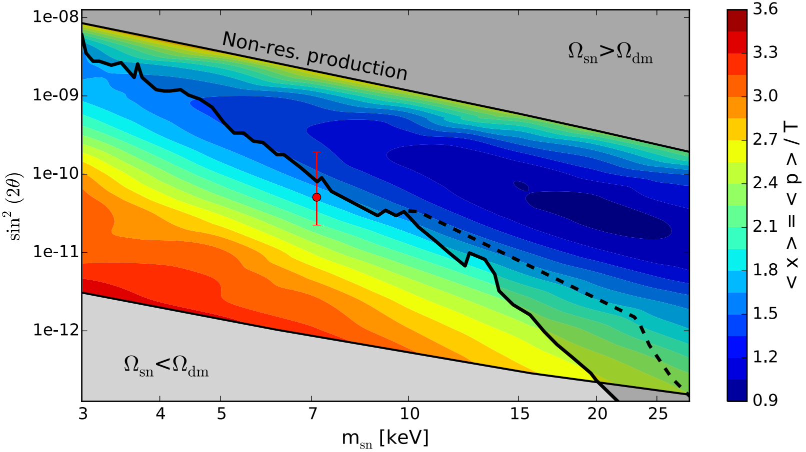
- DW/SF + late thermalisation in dark sector.
- Decay production via some parent particle, e.g. real scalar singlet S coupled to Higgs sector.

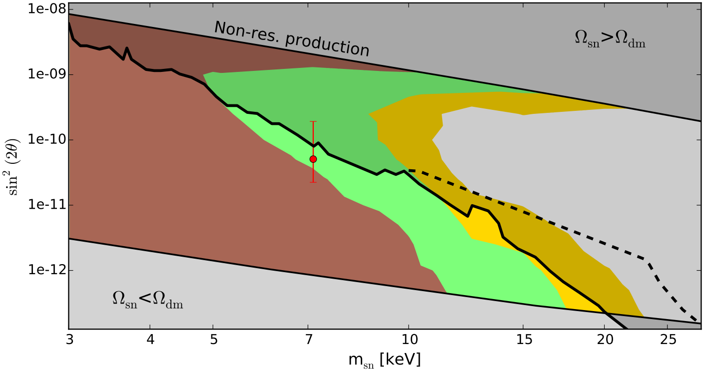
DW / SF and structure formation

"Temperature map" of SF (taken from 1601.07553 by A. Schneider)



DW / SF and structure formation II

Constraints from # of MW satellites and Lyman-α-forest (1601.07553).



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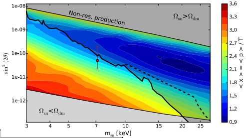

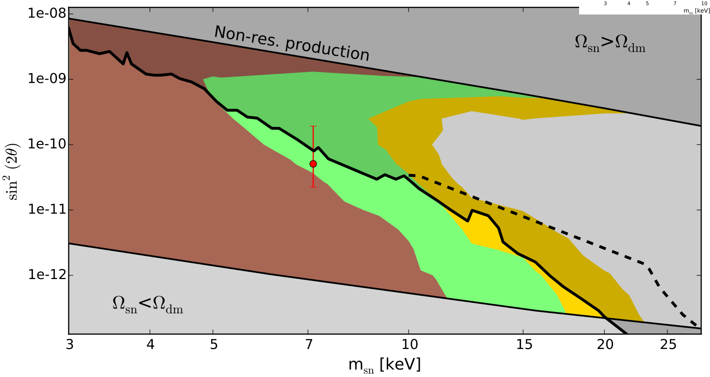

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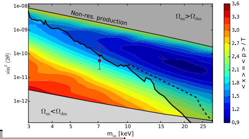

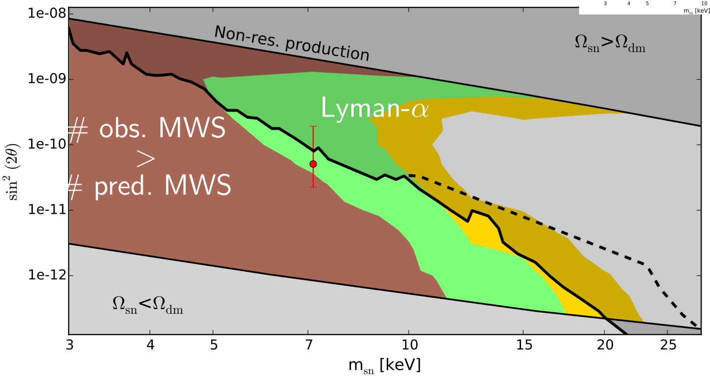

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- Mixing $\sin^2\theta$ switched off in this model (good approx., cf. 1512.05369 (Merle, Schneider, MT)) $\Rightarrow$ Can however be arbitrarily small, not needed to produce ν_S

A simple model for scalar decay – production channels

Production of scalar S from SM d.o.f. depending on whether
$T > T_{\rm EW}$ (I) // $T < T_{\rm EW}$ & $m_S > m_h/2$ (II) // $T < T_{\rm EW}$ & $m_S < m_h/2$ (III).

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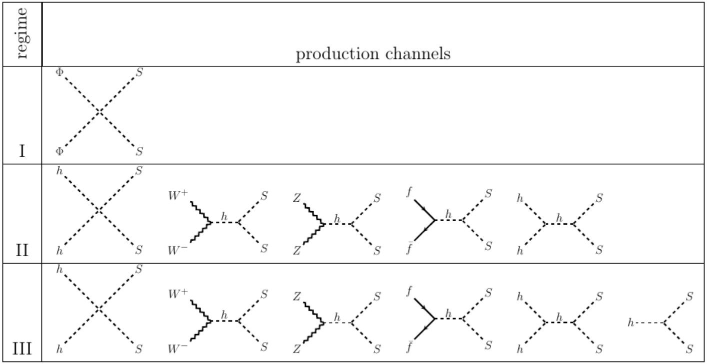
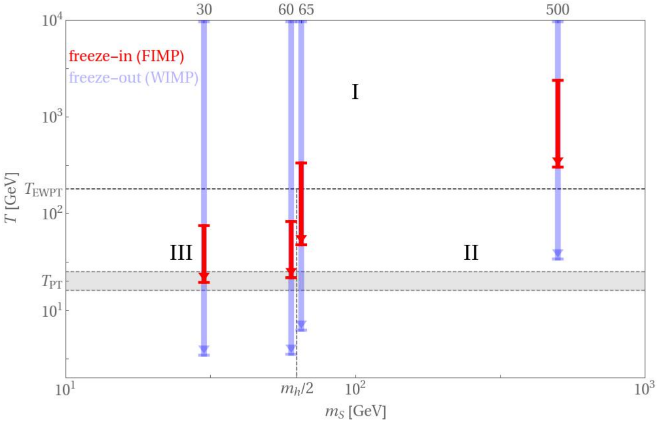


A simple model for scalar decay – different m_S

Depending on λ and m_S, different production regimes are relevant:



The Cosmic Web: Far from homogeneous on small scales

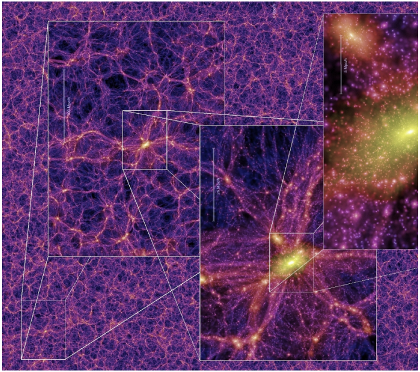


Figure: credit: MilleniumSimulation, Cold Dark Matter Simulation

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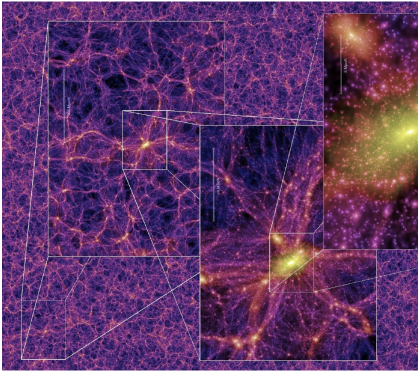

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This simulation matches observations very well, except for smallest scales (Missing Satellites, Too-Big-Too-Fail, Cusp-Core-Problem)

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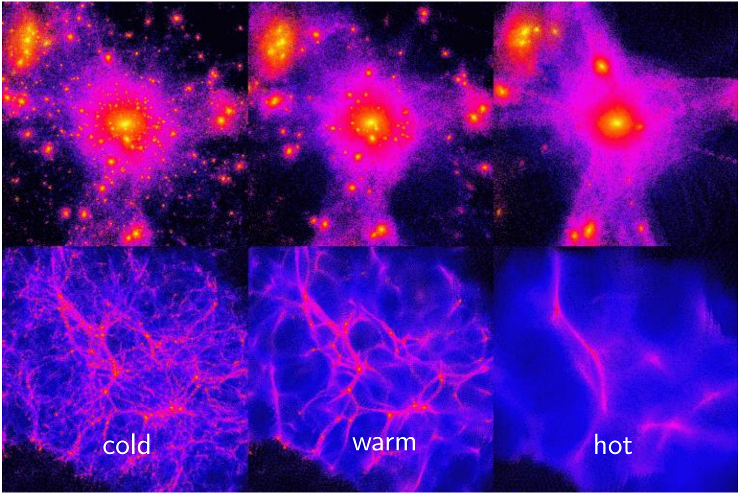
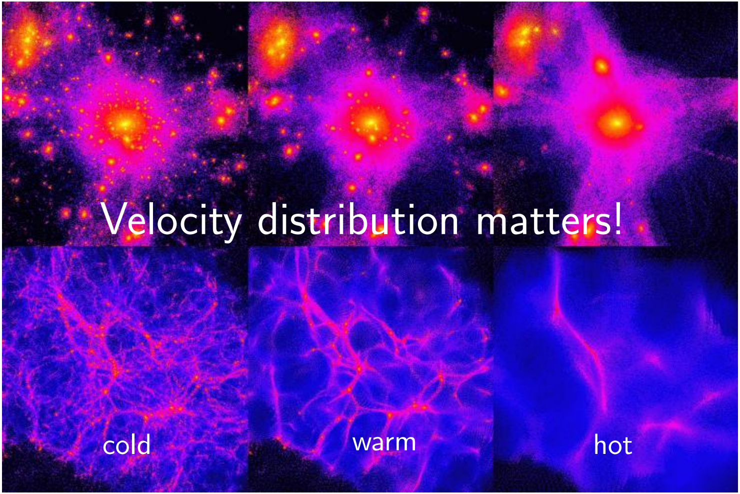
- First, perturbations grow linearly (solve equations semi-analytically), then non-linearly (need for N-body simulations).

Simulating the Cosmic Web



credit: ITC @ University of Zurich

Simulating the Cosmic Web



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Measuring the cosmic web

Different scales → different techniques:

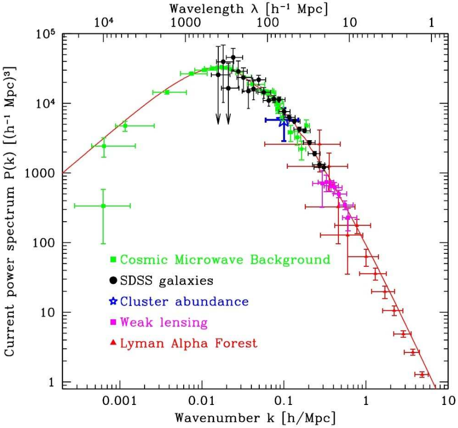

Figure: Small scales probed by Lyman-α forest. (see 1005.1100)

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- $\Rightarrow$ many line-of-sight profiles allow for a 3D reconstruction of densitites.

The particle physicist's comfort zone: $\lambda_{\rm fs}$

Simplest back-of-the-envelope-approach:

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Problem: Average might not be a good description, especially for non-thermal dark matter (more to come...)

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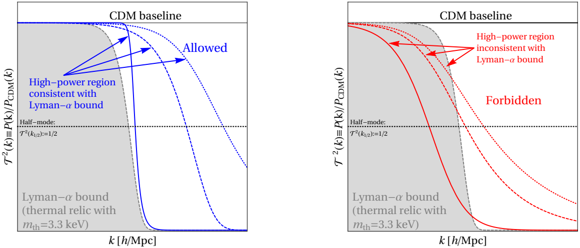
- Compare to observables like the Lyman-α forest.

Comparing a DM model to observations

A simple but reliable method: the half-mode analysis (JCAP 1611(038))



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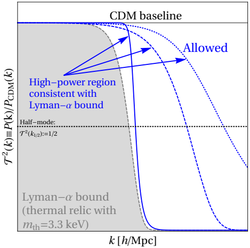

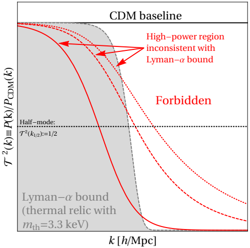

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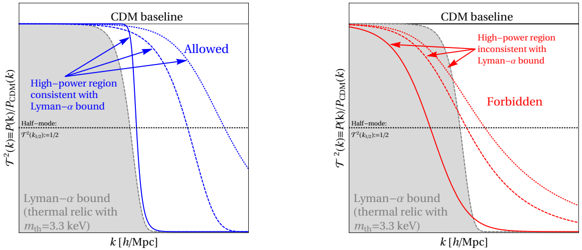

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Is the whole song and dance necessary?

Can we retune the boundaries of $\lambda_{\rm fs}$? No, we can't as the average is not a good estimator!

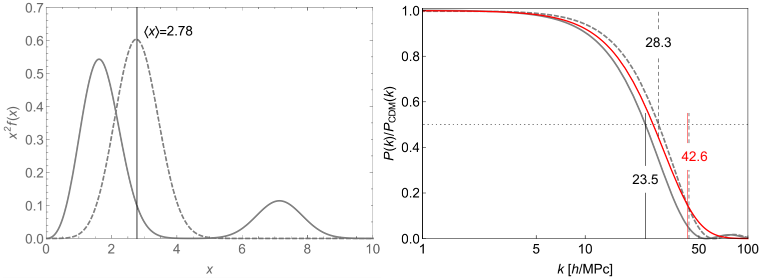

Figure: Mock spectra with identical $\langle x \rangle$ (by construction) but different squared transfer function $\mathcal{T}^2$.

More advanced methods

The simple half-mode analysis has been tested in 1704.07838 and in ApJ 836(61) using

- integrated deviation of linear power spectrum from benchmark derived from Lyman-α data,
- the number of MW subhaloes in comparison to the number of observed satellites,
- the count of ultra-faint galaxies at redshift $z = 6$.

$\Rightarrow$ Very close agreement to half-mode analysis found!

SD model and the half-mode analysis

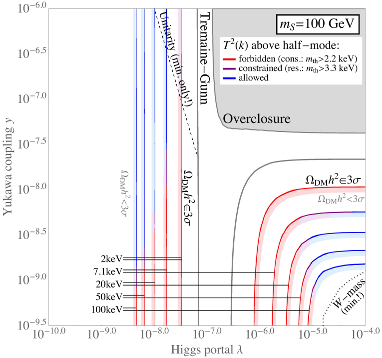

Figure: Constraints from structure formation in the plane λ-vs.-y for $m_S = 100 GeV$. Taken from JCAP 1611(038) (König, Merle, MT).

SD model and the half-mode analysis

For other masses m_S, the picture looks similar but not identical:

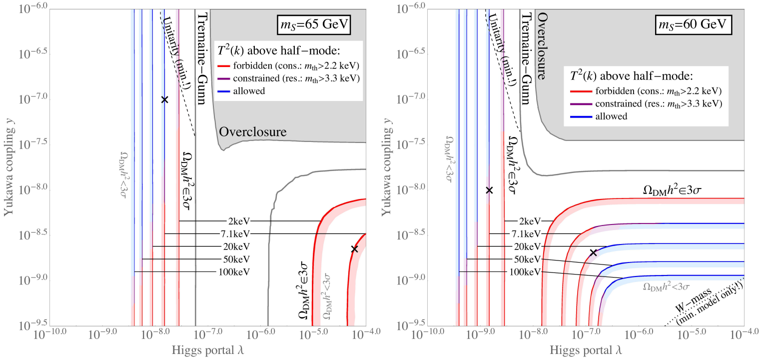

Figure: For $m_S = 65\,\mathrm{GeV}$, the 'freeze-out region' is completely forbidden!

Half-mode analysis vs. free-streaming

Comparison of the free-streaming approach and the half-mode analysis:

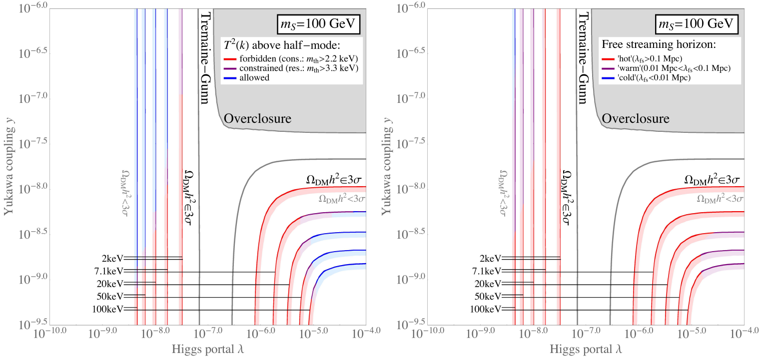

Figure: The free-stremaing approach (with the standard boundaries) is much more restrictive!

Half-mode analysis vs. high-z galaxy count

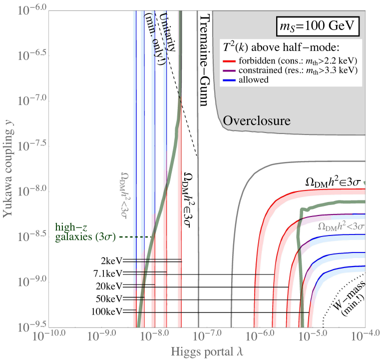

Figure: Regions in accordance with the count of high-z galaxies. Adapted from ApJ 836(61) (Menci, Merle, MT et al.).

Half-mode analysis vs. refined Ly-α and MW satellite counts

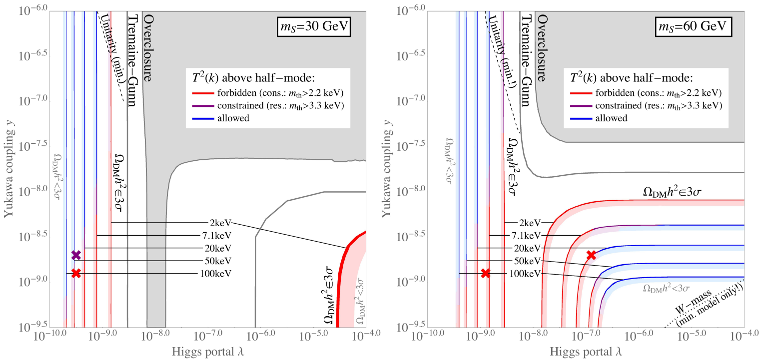

Figure: Judgement from MW satellites and refined Ly-α. Note the slight offset of the crosses from the iso-mass-lines. Adapted 1704.07838 (Murgia, Viel, Merle, Schneider, MT).

Conclusion

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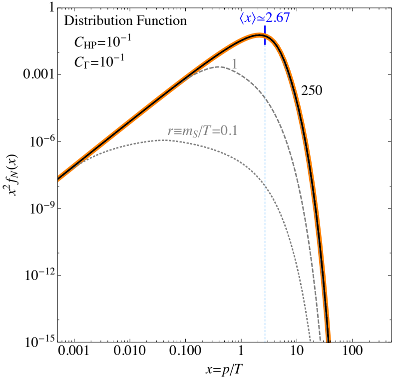
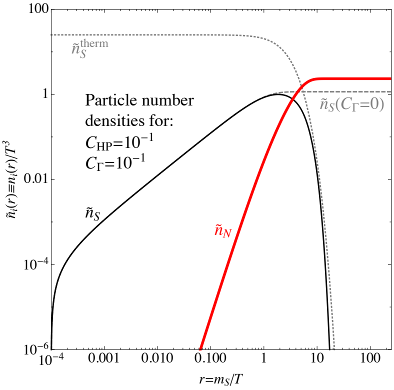
- Cosmic Web is a powerful observable to constrain DM models
- keV sterile neutrinos are theoretically well motivated candidates for DM. A production process in accordance with all bounds cannot be trivial.
- Scalar singlet decay is among the most favourable production mechanisms for sterile neutrino DM.
- New methods for non-thermal DM (half-mode, high-z counts, MW satellite counts, refined Ly-α) can capture spectral analysis and agree quite well. Free-streaming *not* very reliable for non-thermal spectra.
- Future experiments like KATRIN–TRISTAN, ECHo, DyNO will probe the parameter space m_N-$\sin(2\theta)$ in clean lab environments. They will either find nothing (sensitivity) or put Standard Cosmology into a lot of trouble.

Thank you for your attention!

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





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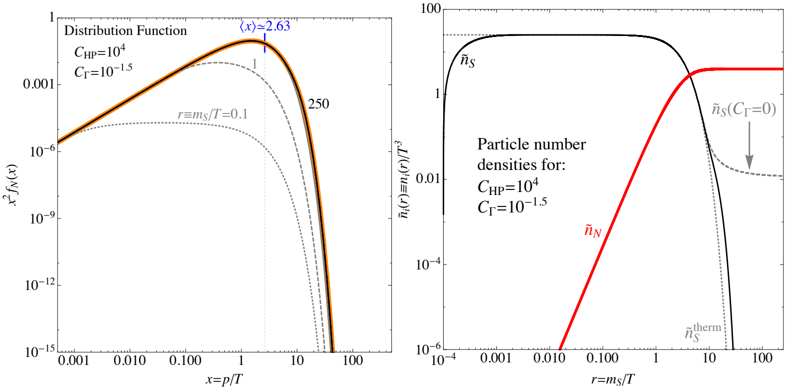

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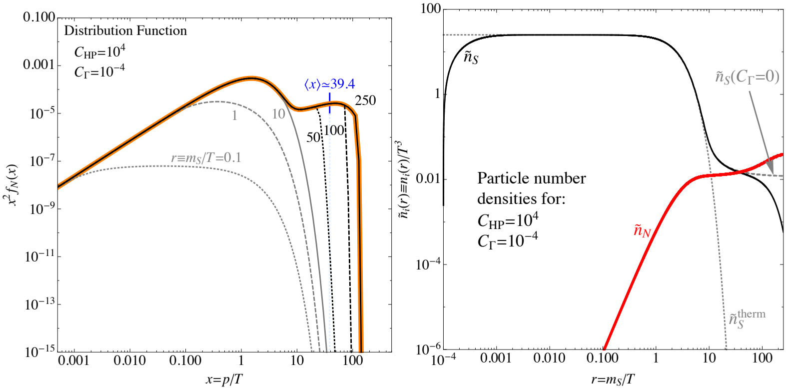

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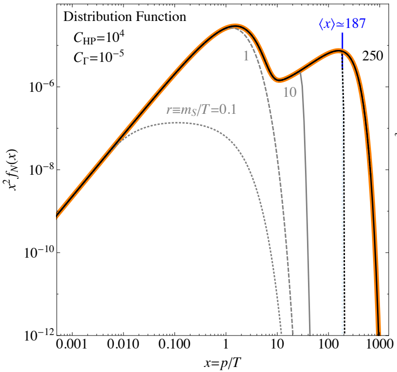
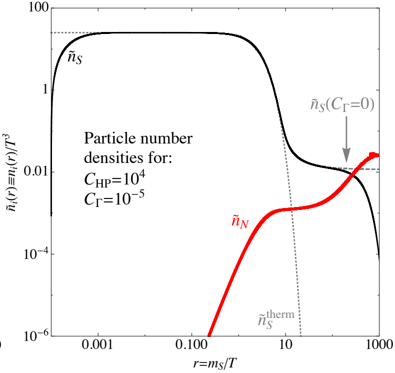
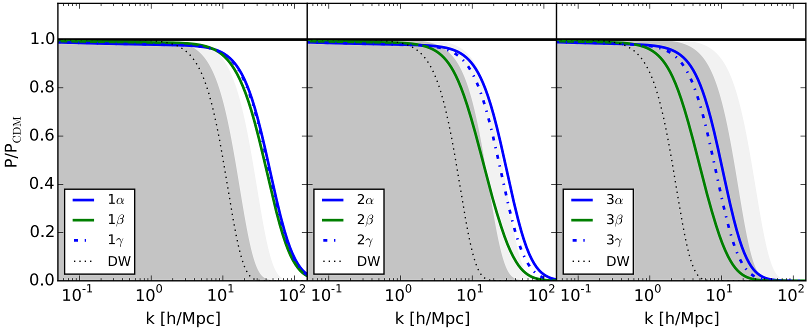




Backup II – Effect of DW on scalar decay



α : SD($\mathcal{C}_{\mathrm{HP}}, \mathcal{C}_{\Gamma}$) β : SD($\mathcal{C}_{\mathrm{HP}}, \mathcal{C}_{\Gamma}$) + max DW γ : SD($\mathcal{C}_{\mathrm{HP}}, \mathcal{C}_{\Gamma}, m_N \stackrel{!}{=} m_N(\beta)$)