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

WIN 2017

based on work with many collaborators:
(1704.07838, ApJ 836 (2017)61, JCAP 1611(038), JCAP 1604(003), JCAP 1506(011))

Maximilian Totzauer

June 20, 2017

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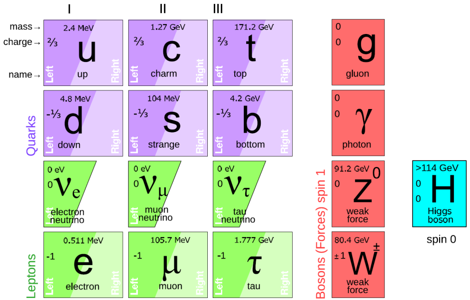
7. Conclusion and Outlook

Brief introduction into Sterile Neutrinos

What is a sterile neutrino?



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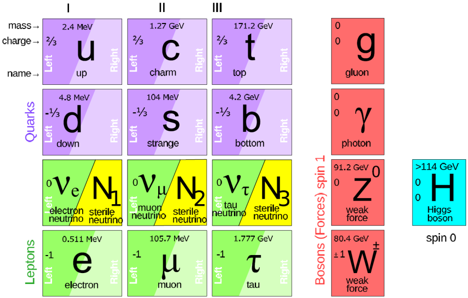

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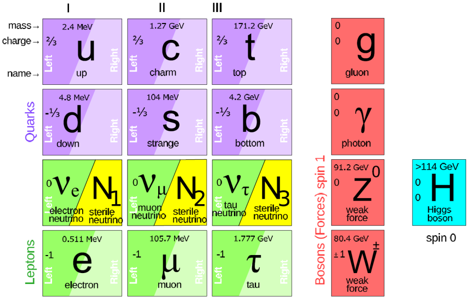

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- Potential right-handed partners would carry no charge under $SU(3)_c \times SU(2)_L \times U(1)_Y \Rightarrow$ dubbed sterile neutrinos (usually denoted N or $N_{R,i}$).
- Number of right-handed states a priori arbitrary.

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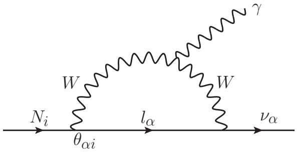
- Could explain high pulsar velocities.
- Can be (a part of) the cosmic DM.
- If so: would have a rather clear signal for $\sin^2(2\theta) \neq 0$:



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.

Production Templates for Dark Matter

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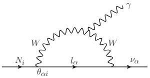
  $\Omega_{\mathrm{DM}} \sim \sigma^{+1}$.
- Decay of parent particles: Highly non-thermal process, parent P itself can freeze in or out or be a decay product itself.
  $\Omega_{\mathrm{DM}} = \Omega_{\mathrm{DM}} \left(\sigma_{\mathrm{P} \leftrightarrow \mathrm{SM}}, \Gamma_P \right)$

Production Mechanisms for Sterile Neutrino Dark Matter

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), $\Omega_{\mathrm{DM}} \propto \sin^2(2\theta)$



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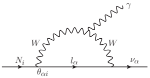

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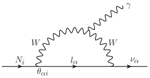

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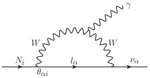

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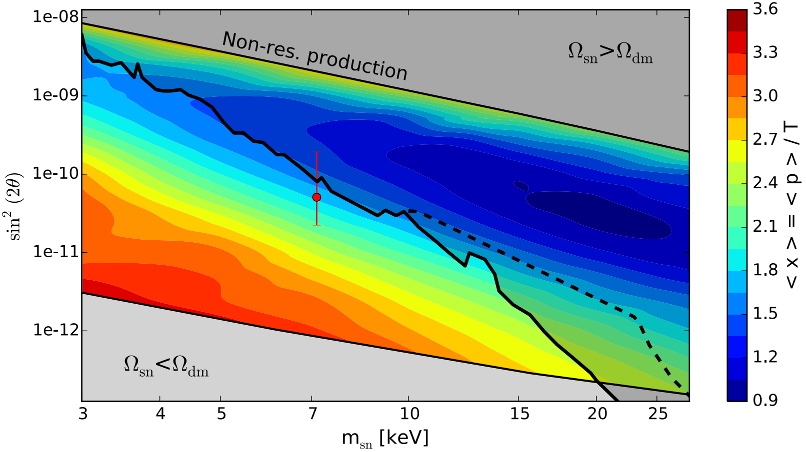
DW / SF and structure formation

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



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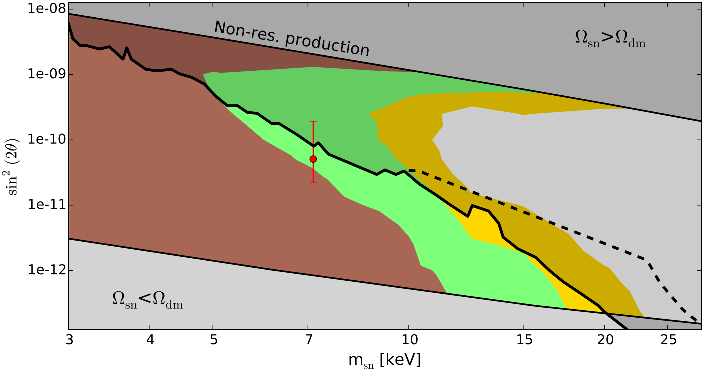

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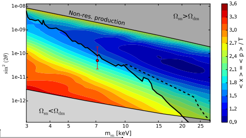

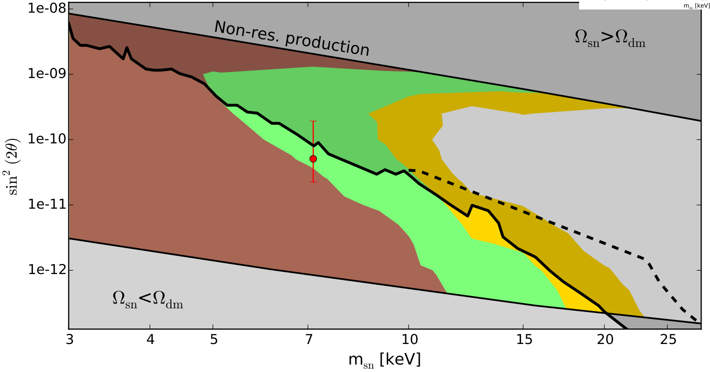

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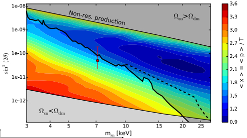

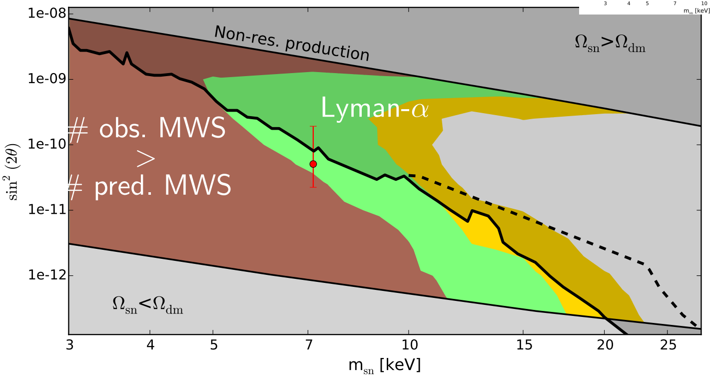

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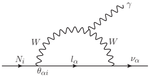

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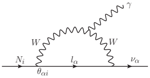

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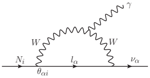

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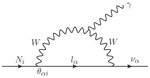

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- DW/SF + late thermalisation in dark sector → Talk by R. S. L. Hansen.
- Decay production via some parent particle, e.g. real scalar singlet S coupled to Higgs sector.

The Scalar Decay Model for keV Steriles

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  $S \to NN$.
- 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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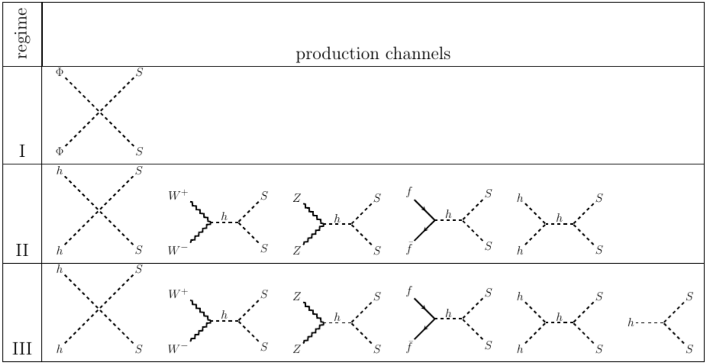
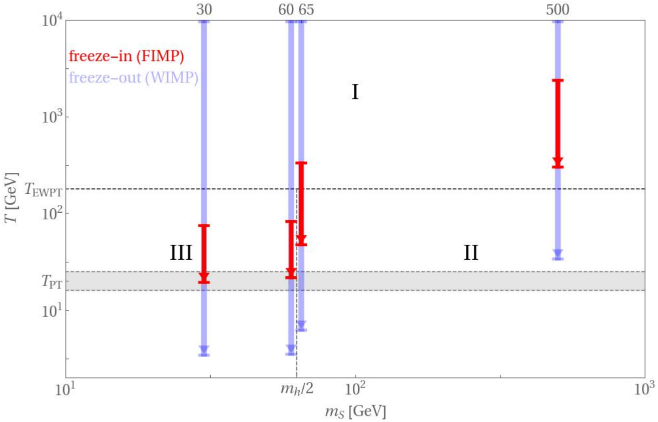


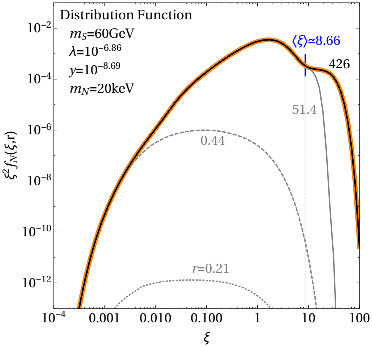
A simple model for scalar decay – different m_S

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



A simple model for scalar decay – non-thermal spectra

The interplay between decay of S in-eq. and out-of-eq. can yield highly non-thermal spectra:



A Primer in Cosmic Structure Formation.

The Cosmic Web: Far from homogeneous on small scales

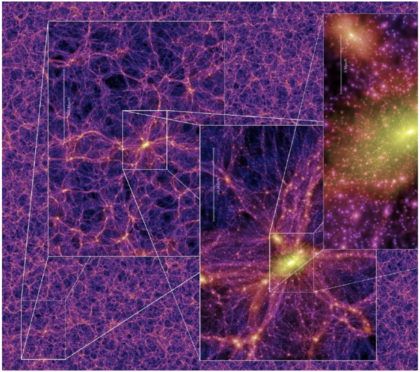


Figure: credit: MilleniumSimulation, Cold Dark Matter Simulation

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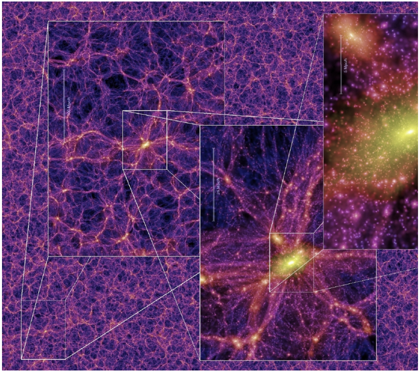

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Simulation matches observations very well, except for smallest scales (Missing Satellites, Too-Big-Too-Fail, Cusp-Core-Problem).

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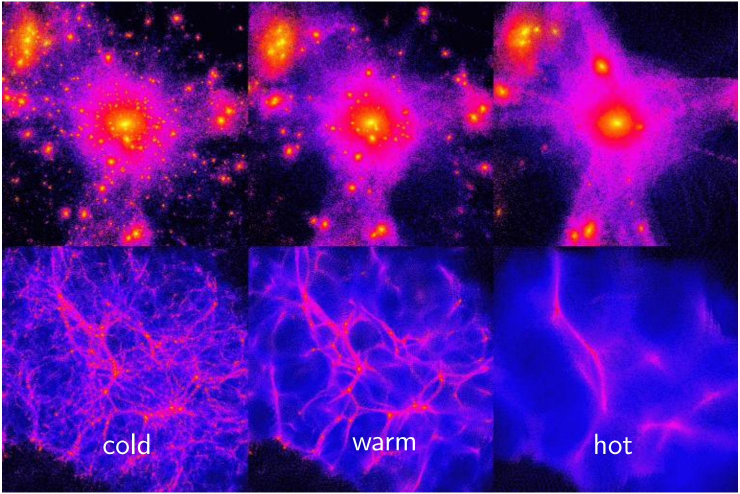
- First, perturbations grow linearly (solve equations semi-analytically), then non-linearly (need for N-body simulations).

Simulating the Cosmic Web



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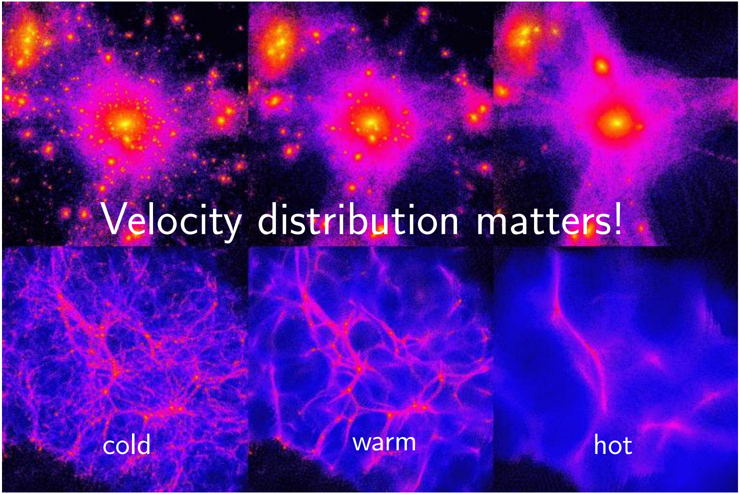

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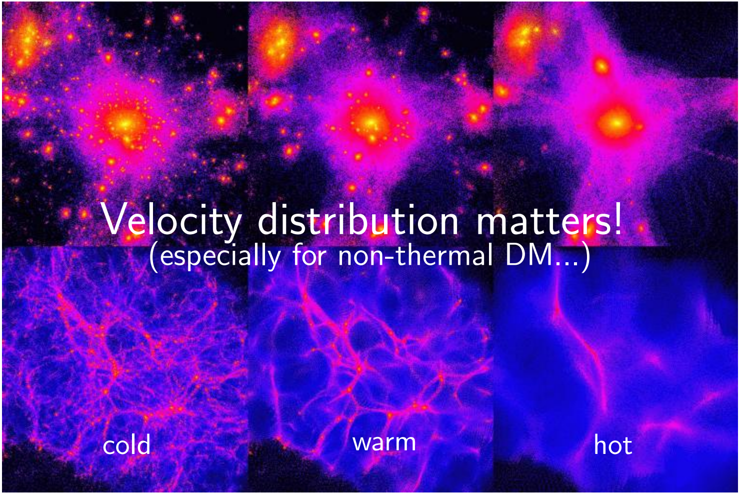

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Measuring the cosmic web: DM power spectrum $P(k)$

Different scales $\rightarrow$ different techniques:

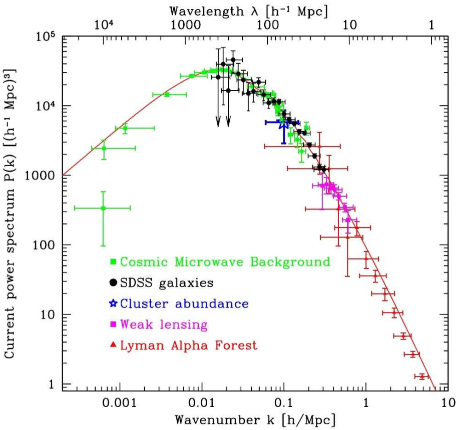

Figure: Small scales probed by Lyman-α forest. (taken from 1005.1100)

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

The particle physicist's comfort zone: λ_{fs}

Simplest back-of-the-envelope-approach:

$$\lambda_{\text{fs}} = \int_{t_{\text{prod}}}^{t_0} \mathrm{d}t \frac{\langle v(t) \rangle}{a(t)}$$

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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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- Problem: Most bounds obtained for thermal dark matter. Complete simulation of small-scale structure and statistical analysis non-trivial.

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Next step:

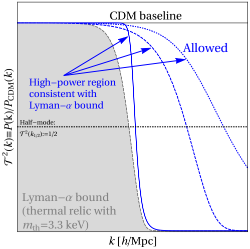
- Compute power spectrum $P(k)$ and compare to observations.
- Convetional: normalise to CDM benchmark:

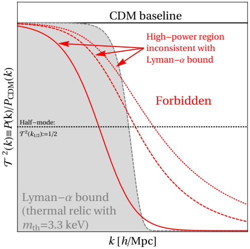
$$\mathcal{T}^2(k) \equiv \frac{P(k)}{P_{\mathrm{CDM}}(k)}$$

- Compare to observables like the Lyman-α forest.
- Problem: Most bounds obtained for thermal dark matter. Complete simulation of small-scale structure and statistical analysis non-trivial.
- Advantage: Thermal benchmark has only one parameter, $\mathcal{T}^2_{\mathrm{therm}}(k) = \mathcal{T}^2(k, m_{\mathrm{therm}})$.

Comparing a DM model to observations

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





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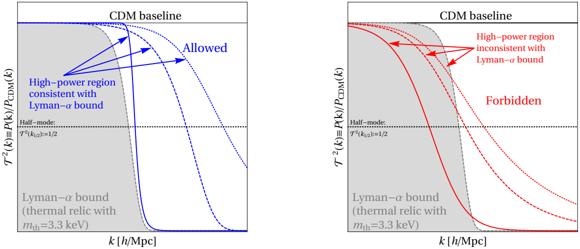

- If region of high power (i.e. at $\mathcal{T}^2 \geq 1/2$) agrees with observation (i.e. $\mathcal{T}^2 > \mathcal{T}^2_{\rm ref,therm}$), model is considered allowed.

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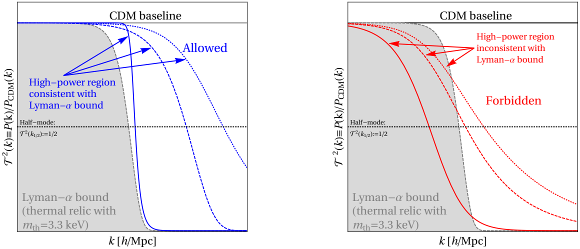

- If region of high power (i.e. at $\mathcal{T}^2 \geq 1/2$) agrees with observation (i.e. $\mathcal{T}^2 > \mathcal{T}^2_{\mathrm{ref,therm}}$), model is considered allowed.
- Only approximate, as we want to test non-thermal dark matter.

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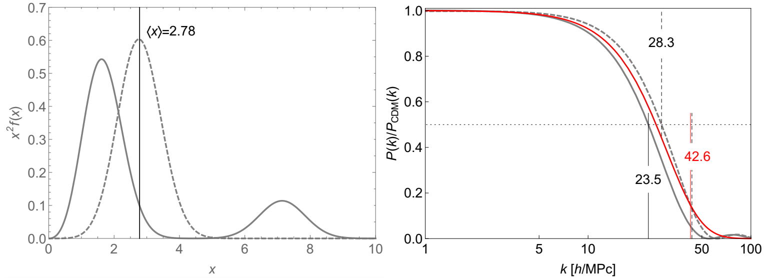

Figure: Mock spectra with identical $\langle x \rangle$ (by construction) but different squared transfer function $\mathcal{T}^2$.

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!

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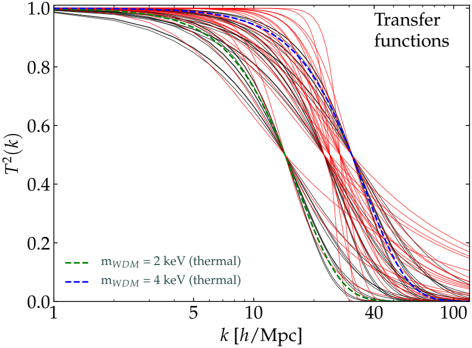
- Or: compute δA and $N_{\rm sat}$ analytically in linear theory (well backed by N-body simulations).

A model independent approach (1704.07838)

The grid of reference power spectra:



Estimators δA and $N_{\rm sat}$ derived and compared to benchmark in 1704.07838.

A synopsis of methods: the SD model revisited

Structure formation of the SD model

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Structure formation of the SD model
Constraining the parameter space of the scalar decay model (λ, y, m_S, m_N).

SD model and the half-mode analysis

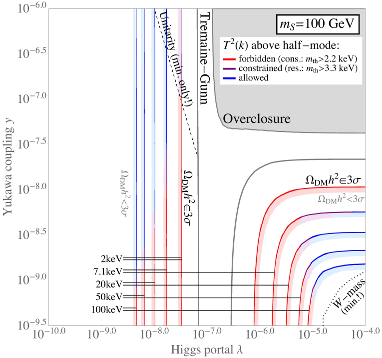

Figure: Constraints from structure formation in the plane λ-vs.-y for $m_S = 100 GeV$. Taken from JCAP 1611(038) (König, Merle, MT).

SD model and the half-mode analysis

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

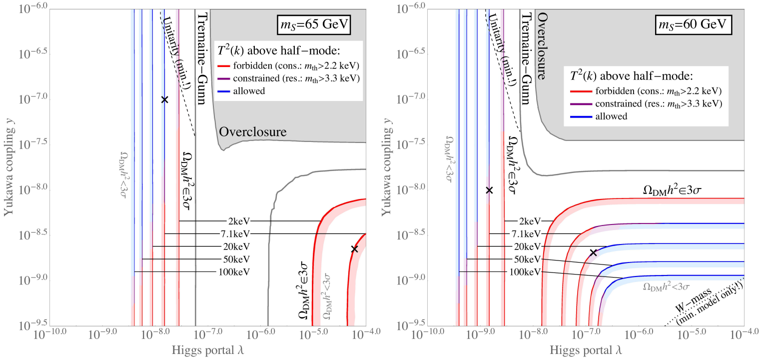

Figure: For $m_S = 65\,\mathrm{GeV}$, the 'freeze-out region' is completely forbidden!

Half-mode analysis vs. free-streaming

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

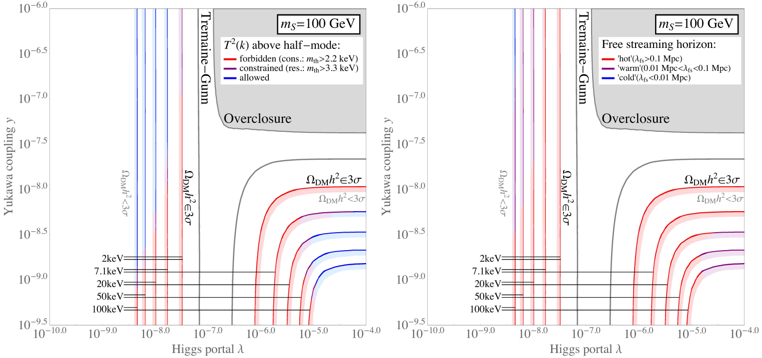

Figure: The free-stremaing approach (with the standard boundaries) is much more restrictive!

Half-mode analysis vs. high-z galaxy count

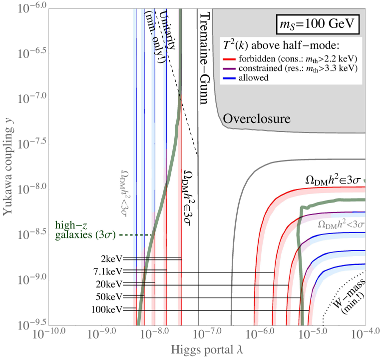

Figure: Regions in accordance with the count of high-z galaxies. Adapted from ApJ 836(61) (Menci, Merle, MT et al.).

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

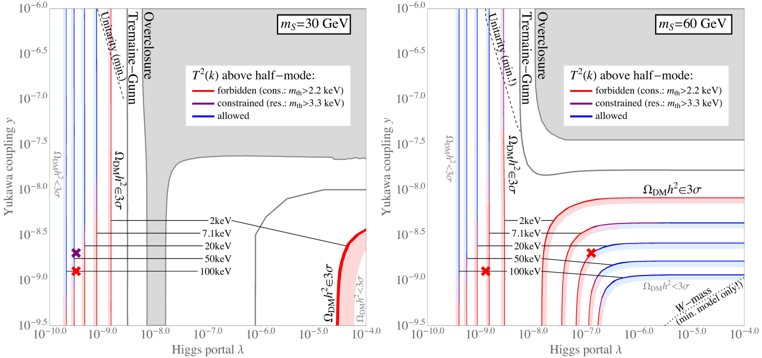

Figure: Judgement from MW satellites and refined Ly-α. Note the slight offset of the crosses from the iso-mass-lines. Adapted 1704.07838 (Murgia, Viel, Merle, Schneider, MT).

Conclusion

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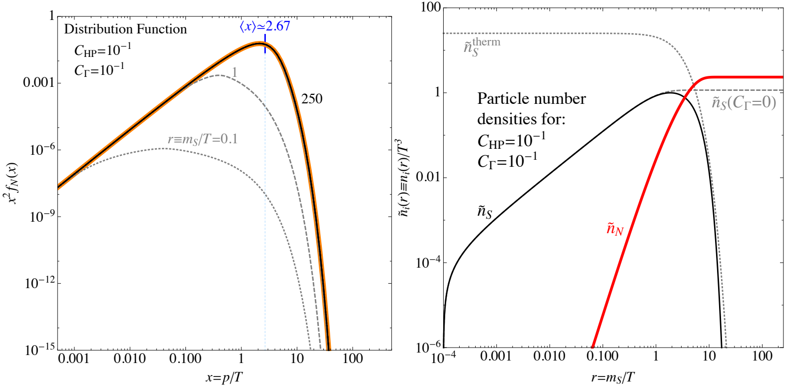
- New methods for non-thermal DM (half-mode, high-z counts, MW satellite counts, refined Ly-α) can capture spectral analysis and agree well amon each other.
- Free-streaming *not* very reliable for non-thermal spectra.
- Future experiments like KATRIN–TRISTAN, ECHo, DyNO will probe the parameter space 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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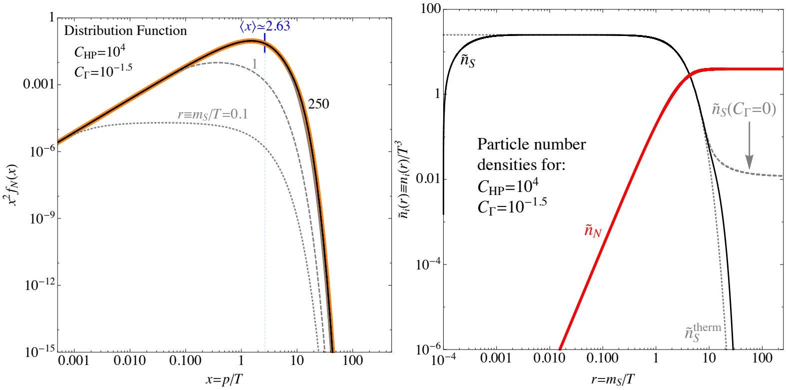

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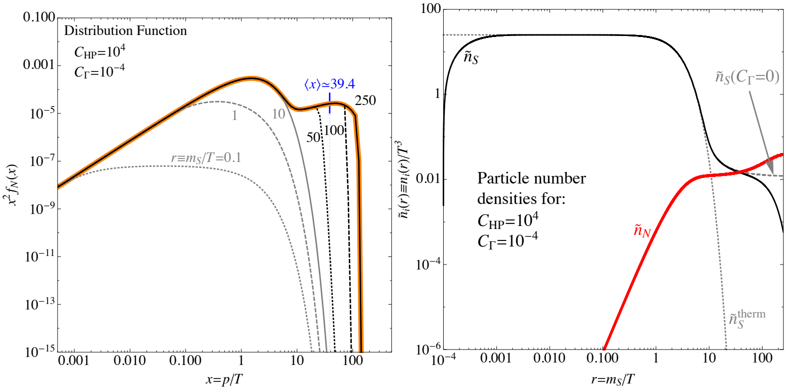

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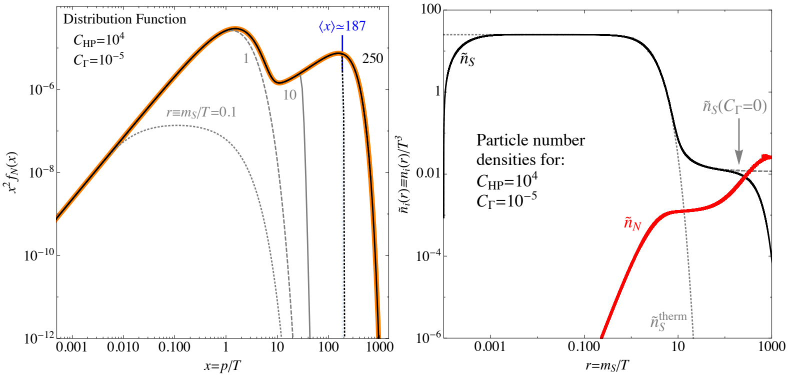
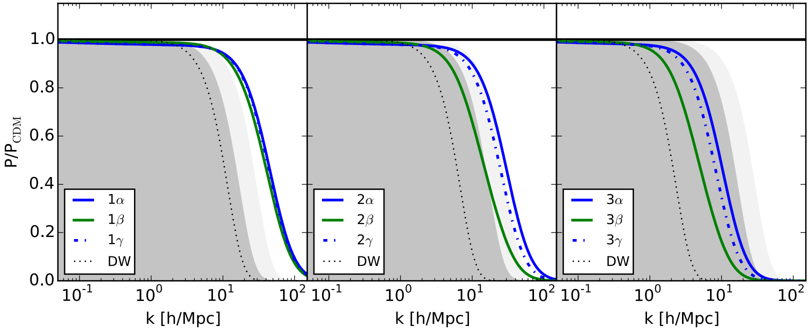


Backup II – Effect of DW on scalar decay



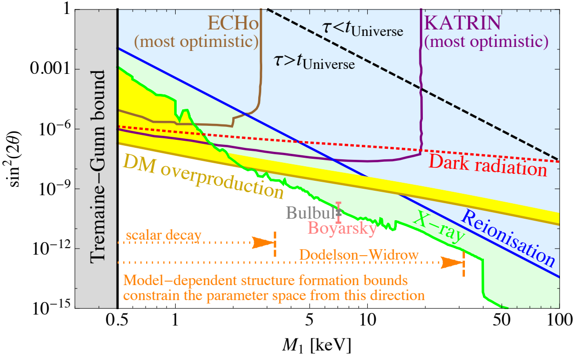
α : SD($\mathcal{C}_{\rm HP}, \mathcal{C}_\Gamma$) β : SD($\mathcal{C}_{\rm HP}, \mathcal{C}_\Gamma$) + max DW γ : SD($\mathcal{C}_{\rm HP}, \mathcal{C}_\Gamma, m_N \stackrel{!}{=} m_N(\beta)$)

Backup III – The estimators for Ly-α and MW satellites

- The estimator δA is dervied from the power spectrum as follows:
  1. $P_{1D}(k) \equiv 1/(2\pi) \int_k^\infty \mathrm{d}k' k' P(k')$.
  2. $r(k) \equiv P_{1D}(k) / P_{1D}^{\Lambda\mathrm{CDM}}(k)$.
  3. $A = \int_{k_{\mathrm{min}}} k_{\mathrm{max}} \mathrm{d}k r(k)$.
  4. $\delta A = (A_{\Lambda\mathrm{CDM}} - A) / A_{\Lambda\mathrm{CDM}}$.
- The estimator N_{sat} can be computed as
  1. Start with differential halo mass function $\mathrm{d}N/\mathrm{d}M_{\mathrm{sub}}$ (also computable in linear theory with Press&Schechter approach).
  2. Integrate from $M_{\mathrm{sub}} = 10^8 M_\odot/h$ (for $M_{\mathrm{MW}} = 1.7 \times 10^12 M_\odot/h$).

Backup IV – Bounds including lab experiments

Synopsis of bounds onto the plane of m_N vs. $\sin^2(2\theta)$:



Courtesy of A. Merle