Production mechanisms for keV sterile neutrino dark matter in the Early Universe

based on JCAP06 (2015) 011, JCAP04 (2016) 003 & 1509.01289
in collaboration with J. König, A. Merle and A. Schneider

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LMU

Introduction to sterile ν Dark Matter

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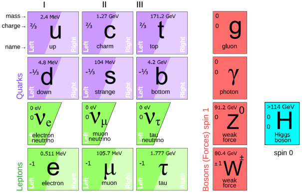

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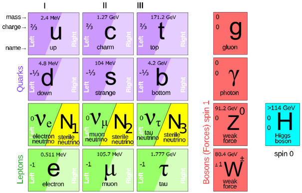

(#(ν_S) unrestricted,#(ν_S)$\geq$ 2 to generate $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$ via seesaw)

How to look for sterile ν Dark Matter?

The fingerprint of sterile neutrino DM

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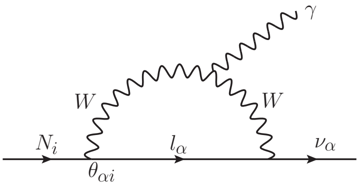

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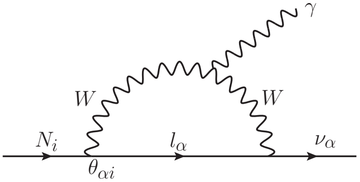

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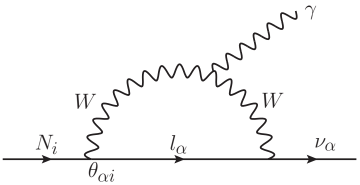

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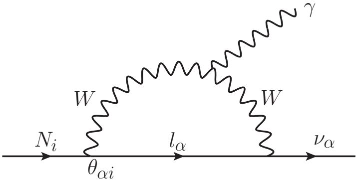

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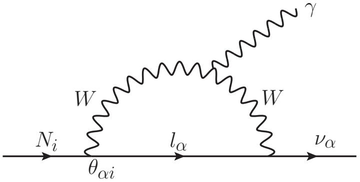

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$\Rightarrow$ Non-observation gives bounds in the plane m_N vs. $\sin^2(\theta_{\alpha i})$

What models are on the market?
A short overview

What *types* of DM production are there?

Brief review on freeze-in and freeze-out

- In freeze-out, particles drop out of thermal equilibrium when $H \geq \Gamma_{\rm int}$.
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- In freeze-in, particle never enters thermal equilibrium due to very feeble interactions.
  Intrinsically non-thermal spectrum of the particle $\Rightarrow$ should work on the level of *momentum distributions*, *not only* particle densities!
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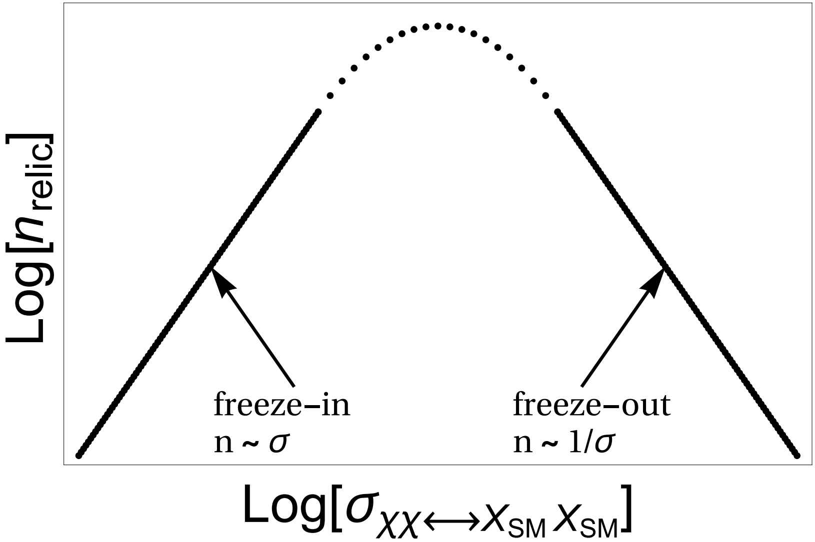

Boltzmann equations – rates vs. spectra

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- Boltzmann equation on distribution level $f(t, p)$

$$\frac{\partial f}{\partial t} - H(t)\, p \frac{\partial f}{\partial p} = \mathcal{C}[f] \tag{1}$$

where $\mathcal{C}[f]$ is a functional of f.

What production mechanisms are there for sterile neutrinos?

Dodelson-Widrow production (DW)

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- However, active-sterile conversion affects other production mechanisms and can cause corrections of a few percent (JCAP1604 (2016) 003).
- Freeze-in type mechanism $\Rightarrow$ non thermal spectrum of DM.

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- New analyses concerning cosmic structure formation put some tension on SF production (we'll get there).

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- Additional entropy release hard to reconcile with BBN.

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- Wide range of possibilities for parent particle X:
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  - scalar singlet BSM (e.g. JCAP1506(011))
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- spectral features of ν_S dependent on whether
  a) X freezes-in
  b) X decays in-equilibrium before freeze-out
  c) X freezes-out and decays out-of-equilibrium
  d) combination of b) & c) $\Rightarrow$ non-trivial spectra with more than one scale possible.

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$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left[i\overline{N}\partial\!\!\!/ N + \frac{1}{2}\left(\partial_\mu S\right)\left(\partial^\mu S\right) - \frac{y}{2} S \overline{N^c} N + \text{h.c.} \right] - V_{\rm scalar}$$

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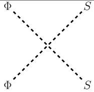
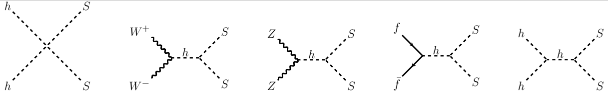
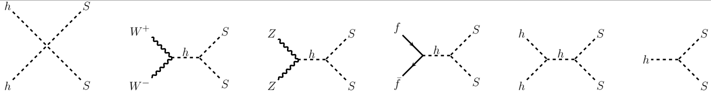
- Mixing θ_α switched off in this model (cf. JCAP1604 (2016) 003).

A simple model for scalar decay – parameters

The relevant parameters of the setup:

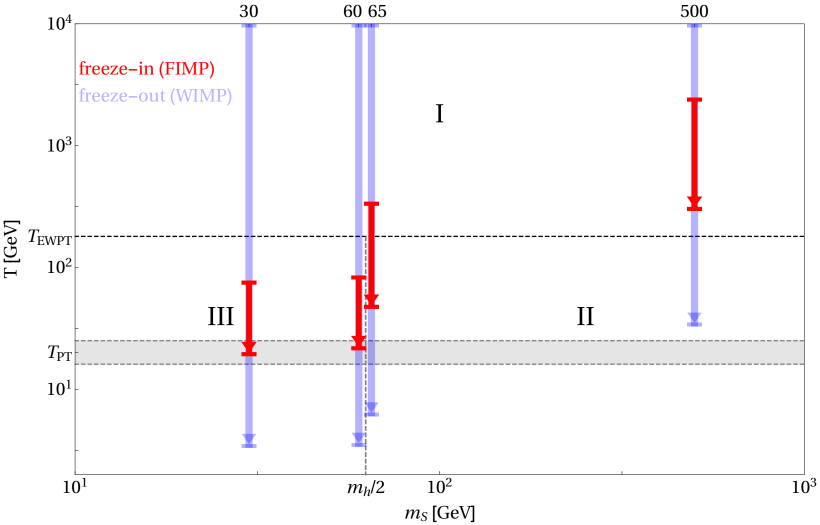
- Yukawa coupling y $\left(-\mathcal{L} \supset \frac{y}{2} S \overline{N^c} N\right)$.
- Higgs portal λ $\left(-\mathcal{L} \supset 2\lambda \left(\Phi^\dagger \Phi\right) S^2\right) \Rightarrow$ different production channels before and after EWPT.
- scalar mass m_S.
- mass of sterile neutrino m_N.

Different regimes for the production of the scalar S

regime	production channels
I	
II	
III	

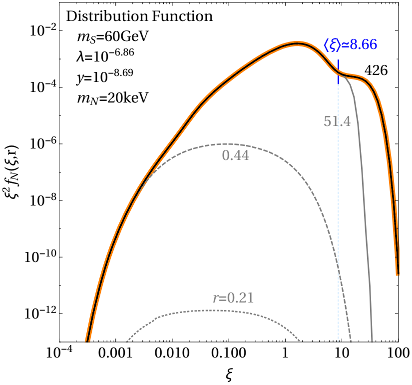
regime I: before EWPT
regime II: after EWPT, $m_S > m_h/2$
regime III: after EWPT, $m_S \leq m_h/2$

The interplay of the different regimes



Exampe spectrum of sterile neutrinos in scalar decay

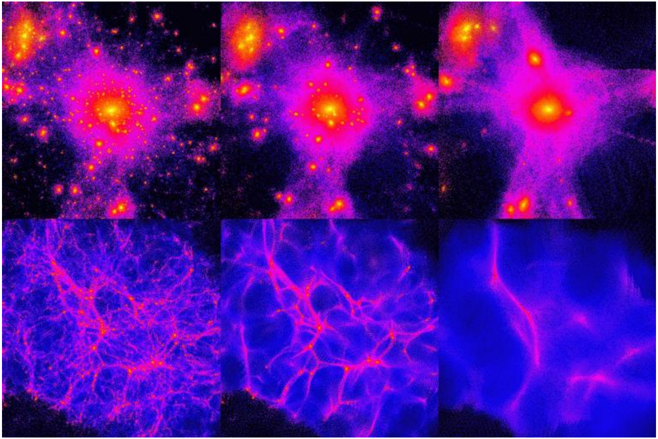
A (not really contrived) example distribution f of sterile neutrinos from scalar decay



Constraints from structure formation

How to assess structure formation

Hot, warm or cold Dark Matter? – Structure formation



Matter distribution on small scales (top) and large scales (bottom) for cold (left), warm (centre) and hot (right) thermal Dark Matter

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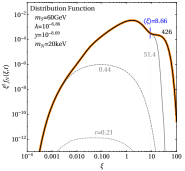

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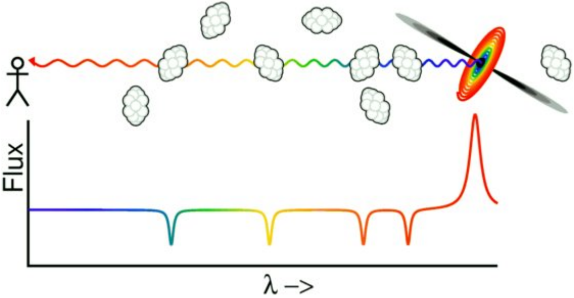
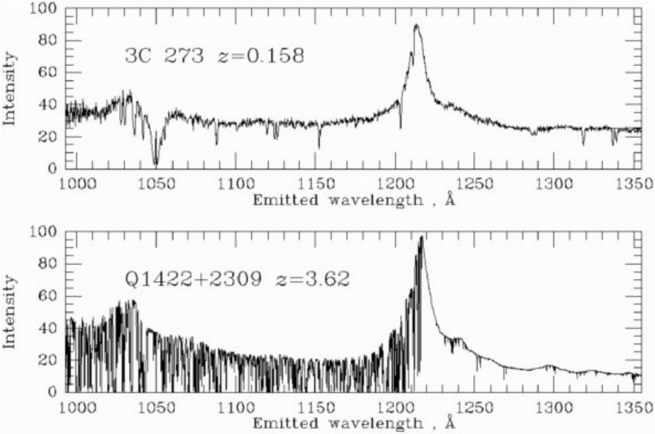


Structure formation – Leaving the comfort zone

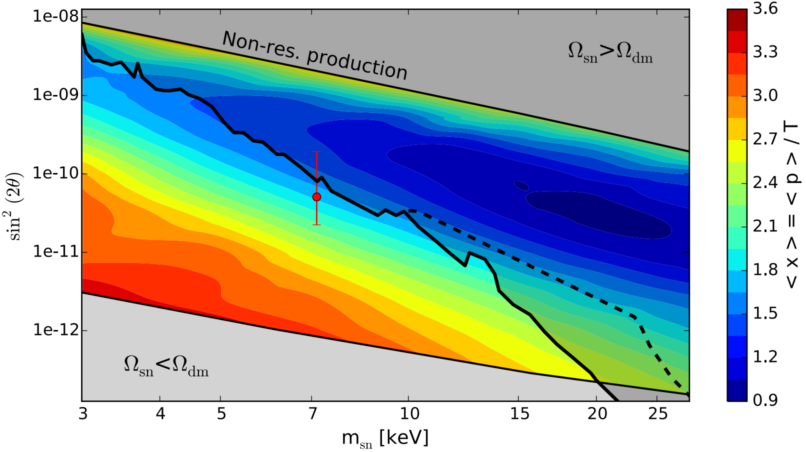
Lyman-α spectra from close (top) and far (bottom) QUASARS:



Constraints on the models for sterile neutrino dark matter

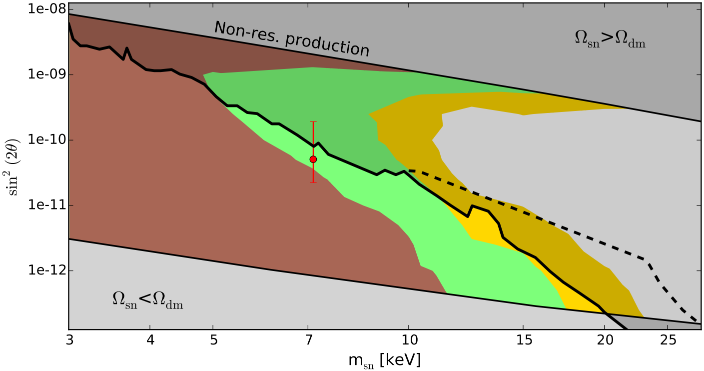
Shi-Fuller-mechanism and structure formation

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



Shi-Fuller-mechanism and structure formation II

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



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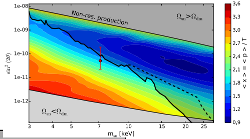

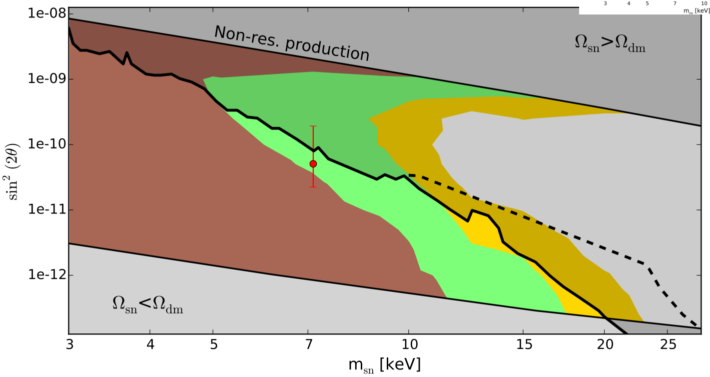

Shi-Fuller-mechanism and structure formation II

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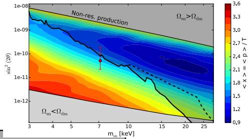
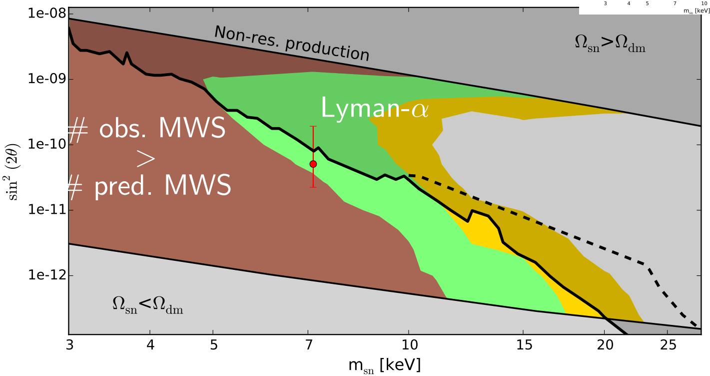
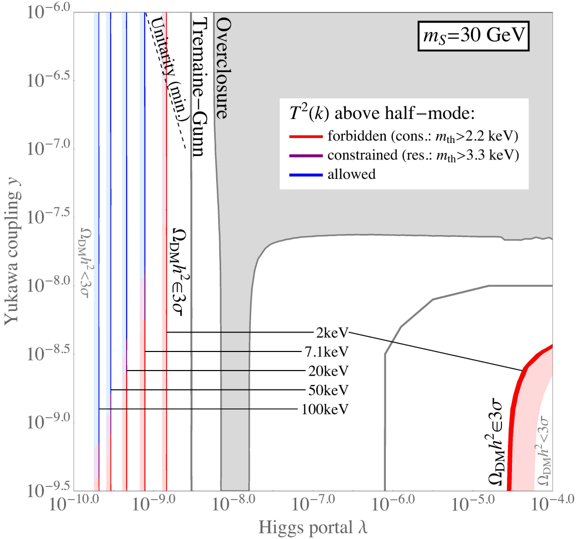
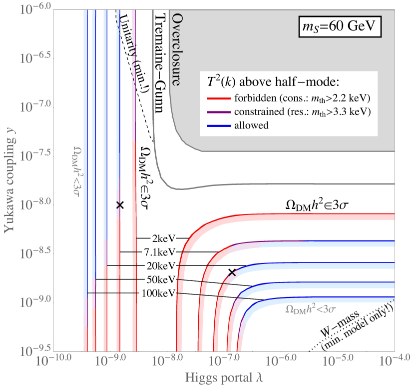


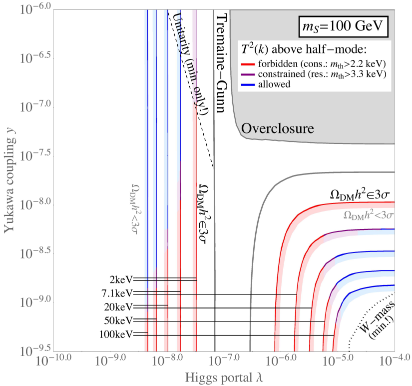


Scalar Decay and structure formation



Scalar Decay and structure formation II





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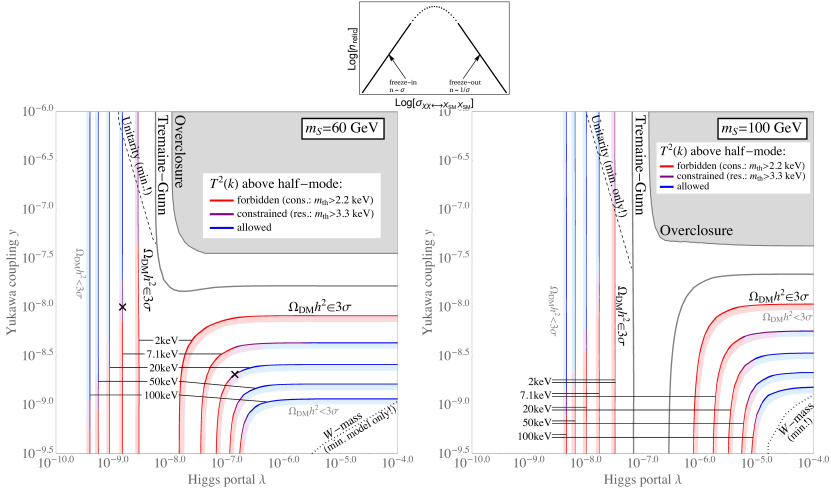
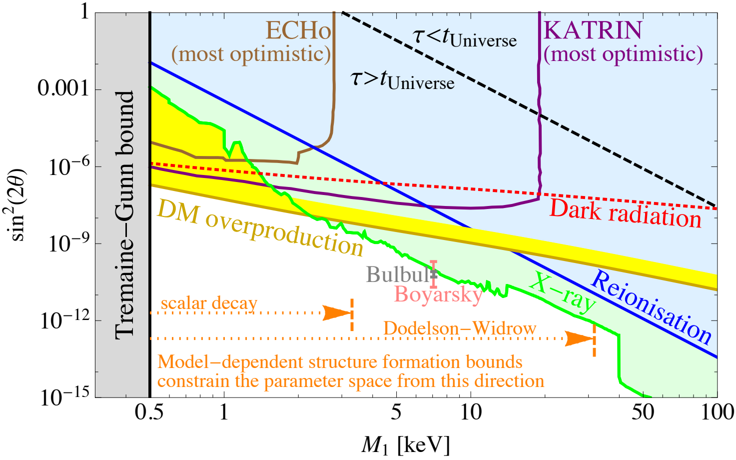


Conclusion and Outlook

Synopsis of current and future bounds



courtesy of A. Merle

Conclusion & Outlook

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- Complementary input from lab experiments such as KATRIN, ECHo or Project8 might provide orthogonal insights on keV steriles.

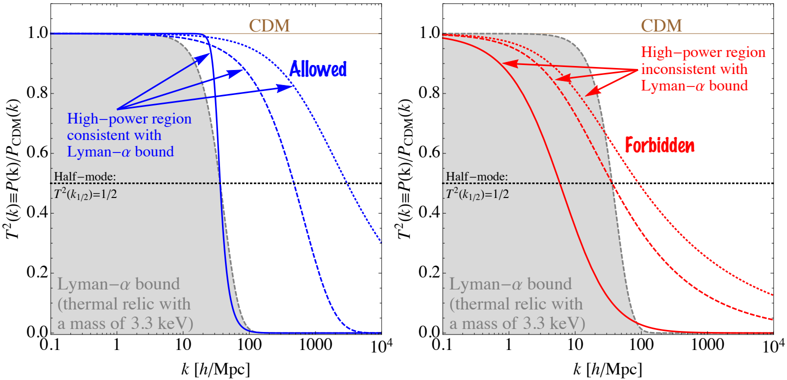
Some shameless advertising at the end

- König, Merle & MT, arXiv:1609.01289
  $\rightarrow$ Fully numerical analysis of scalar decay in the whole relevant mass range.
- Drewes et al., arXiv:1602.04816,
  A White Paper on keV Sterile Neutrino Dark Matter
  $\rightarrow$ Whitepaper on the field released in 02/16 with contributions from $\mathcal{O}(100)$ authors.

Thank you for your attention!

Backup

Halfmode-Analysis



Benchmark cases for $m_S = 60\,\mathrm{GeV}$, FIMP & WIMP