Curing Sterile Neutrino Dark Matter with a Dark Force

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Based on
Torsten Bringmann, Paul Frederik Depta, Marco Hufnagel, JK, Joshua T. Ruderman, Kai Schmidt-Hoberg, arXiv:2206.10630

Introduction

- WIMP Dark Matter theoretically appealing but not observed
- Alternative: sterile neutrino ν_s with mass $m_s \sim$ keV
- Mixing angle θ with Standard Model neutrino ν_a
- Dodelson-Widrow production by oscillations in early Universe

  Dodelson & Widrow, PRL **72** (1994)

$$\Omega_s h^2 \simeq 0.1 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{1\,\text{keV}}\right)^2$$

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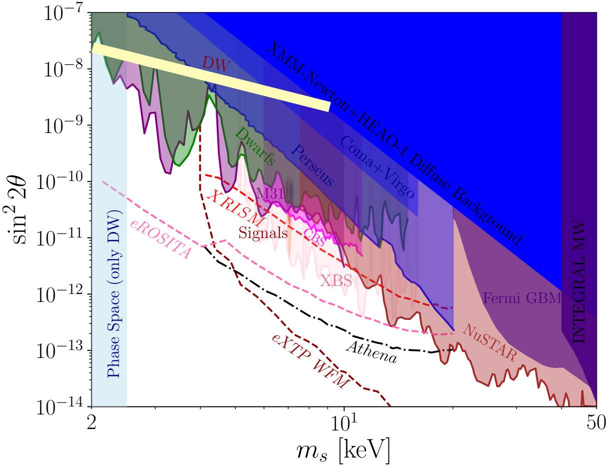
- Decay $\nu_s \to \nu_a \gamma$ at 1-loop level

$$\Gamma \propto \sin^2 2\theta \, {m_s}^5$$

$\rightsquigarrow$ Bounds from searches for X-ray line

Abazajian, Fuller, Tucker, APJ **562** (2001)

Dodelson-Widrow Mechanism Cannot Produce All DM



Abazajian et al., arXiv:2203.07377

Alternative Production Mechanisms

- Resonant production in presence of lepton asymmetry
  Shi & Fuller, PRL **82** (1999)
- Scalar decay
  Shaposhnikov & Tkachev, PLB **639** (2006)
  Kusenko, PRL **97** (2006); Petraki & Kusenko, PRD **77** (2008)
  Roland, Shakya, Wells, PRD **92** (2015)
  Merle & Totzauer, JCAP **06** (2015); König, Merle, Totzauer, JCAP **11** (2016)
- New interactions of Standard Model neutrinos
  De Gouvêa, Sen, Tangarife, Zhang, PRL **124** (2020)
  Kelly, Sen, Tangarife, Zhang, PRD **101** (2020)
  Chichiri, Gelmini, Lu, Takhistov, `arXiv:2111.04087`
  Benso, Rodejohann, Sen, Ramachandran, PRD **105** (2022)
- Extended gauge sector
  Bezrukov, Hettmansperger, Lindner, PRD **81** (2010)
  Kusenko, Takahashi, Yanagida, PLB **693** (2010)
  Dror, Dunsky, Hall, Harigaya, JHEP **07** (2020)
- ⟨`Insert your favorite model here`⟩
- New interactions of sterile neutrinos
  Hansen & Vogl, PRL **119** (2017)
  Johns & Fuller, PRD **100** (2019)
  Bringmann, Depta, Hufnagel, JK, Ruderman, Schmidt-Hoberg, `arXiv:2206.10630`

Model Setup

- Standard Model neutrino ν_a
- Sterile neutrino ν_s, mass $m_s \sim$ keV, right-handed spinor
- Scalar singlet ϕ, mass $m_\phi \gtrsim 2\, m_s$
- Yukawa coupling y between scalar and gauge eigenstate ν_s'

$$\mathcal{L}_\phi^{\text{int}} = \frac{y}{2} \overline{\nu_s'^c}\, \phi\, \nu_s' + \text{h.c.}$$

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- Rotation to mass eigenstate basis by mixing angle θ
  $\rightsquigarrow$ Neutrino-scalar interactions

$$\mathcal{L}_\phi^{\text{int}} = \frac{y}{2} \phi \left(\cos^2\theta\, \overline{\nu_s^c} \nu_s - \sin 2\theta\, \overline{\nu_a} \nu_s + \sin^2\theta\, \overline{\nu_a} \nu_a^c \right) + \text{h.c.}$$

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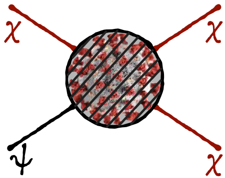
- Assume scalar self-interactions and Higgs portal to be irrelevant

One Model, Three Conclusions

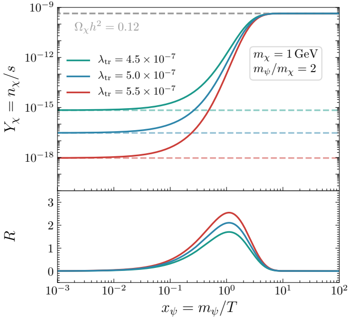
- Hansen & Vogl, PRL **119** (2017)
  - $m_\phi \sim 10^2$ keV
  - Number-changing interactions (e.g., in scalar potential)
  - Viable ν_s Dark Matter for $m_s \simeq 4$ keV or lepton asymmetry
- Johns & Fuller, PRD **100** (2019)
  - $m_\phi > 1$ GeV
  - Interactions affect in-medium neutrino potential
  - Either no impact or runaway production for $T \sim 10^2$ MeV
- Bringmann, Depta, Hufnagel, JK, Ruderman, Schmidt-Hoberg
  - $m_\phi \gtrsim 2\, m_s$
  - Viable ν_s Dark Matter due to exponential growth of abundance

Dark Matter Pandemic

Conversion of heat bath particles ψ to DM particles χ
$\rightsquigarrow$ phase of exponential growth



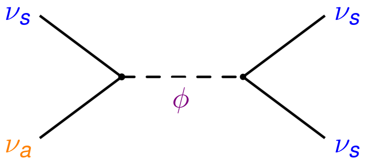
$\rightsquigarrow$



Bringmann, Depta, Hufnagel, Ruderman, Schmidt-Hoberg, PRL **127** (2021)

Exponentially Growing Sterile Neutrinos

- Heat bath particle: $\psi = \nu_a$
- Dark Matter particle: $\chi = \nu_s$
- Conversion via scalar ϕ (almost on-shell $\rightsquigarrow$ s-channel dominates)



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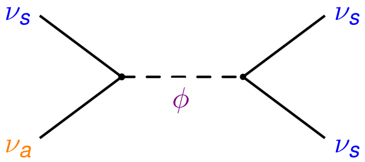
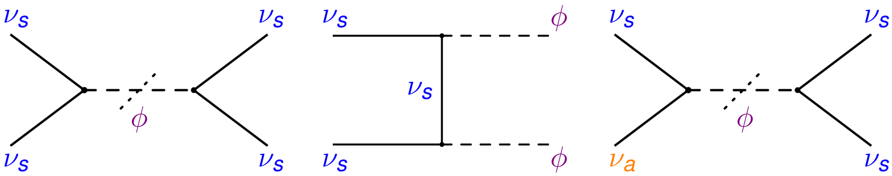


- Small initial ν_s abundance produced by Dodelson-Widrow
- Freeze-in production $\nu_a \nu_a \to \nu_s \nu_s$ negligible due to tiny mixing

Calculation of Dark Sector Densities

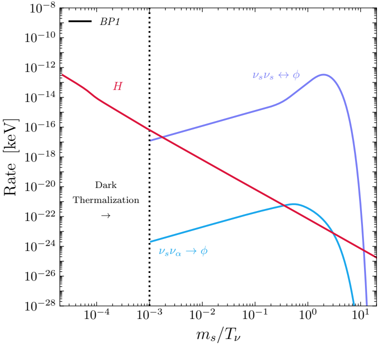
- Initial condition: ν_s abundance from Dodelson-Widrow mechanism
  Asaka, Laine, Shaposhnikov, JHEP **01** (2007)
- $\nu_s \nu_s \leftrightarrow \phi \rightsquigarrow$ dark sector thermalizes
- Boltzmann equations for number and energy densities

$$\dot{n}_s + 3Hn_s = C_{n_s}$$
$$\dot{n}_\phi + 3Hn_\phi = C_{n_\phi}$$
$$\dot{\rho} + 3H(\rho + P) = C_\rho$$



Results I

$m_s = 12\,\text{keV}$, $m_\phi = 36\,\text{keV}$, $\sin^2 2\theta = 2.5 \cdot 10^{-13}$, $y = 1.905 \cdot 10^{-4}$



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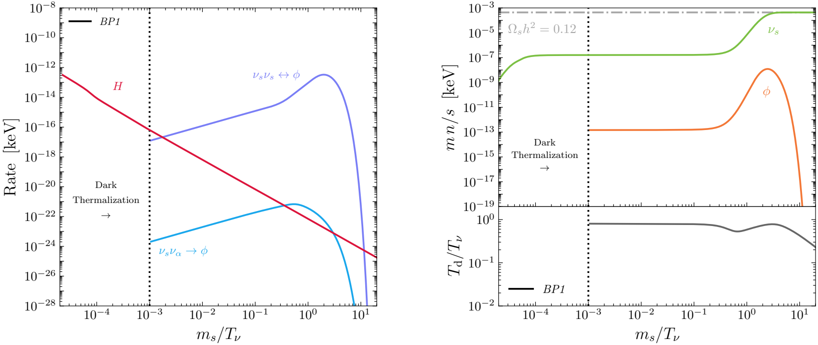
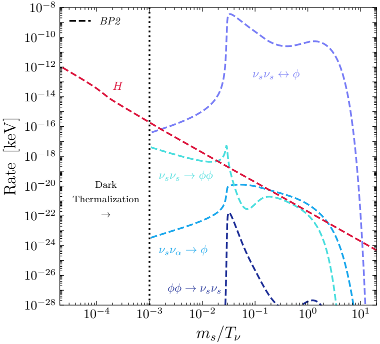


$T_\nu \ll m_\phi \rightsquigarrow$ transmission inefficient $\rightsquigarrow$ exponential growth ends

Results II

$m_s = 20\,\text{keV}$, $m_\phi = 60\,\text{keV}$, $\sin^2 2\theta = 3.0 \cdot 10^{-15}$, $y = 1.602 \cdot 10^{-3}$



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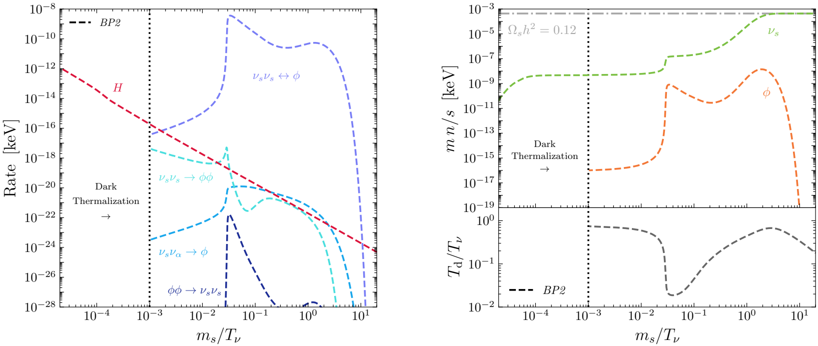
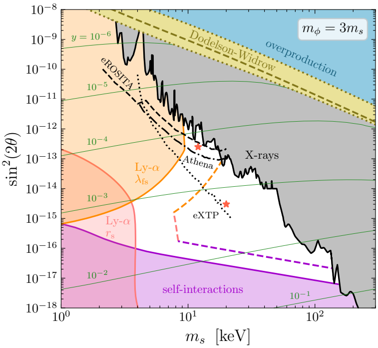


$\theta \downarrow \rightsquigarrow y \uparrow \rightsquigarrow \nu_s\nu_s \to \phi\phi$ ($\to 4\nu_s$) becomes relevant

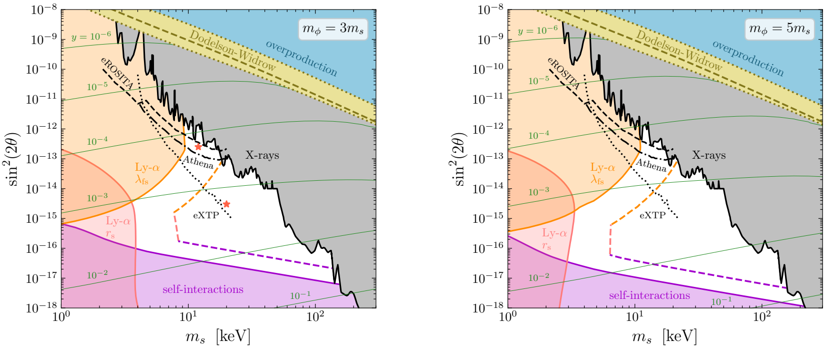
Constraints

- X-ray searches $\rightsquigarrow$ upper limit on θ as function of m_s
- Lyman-α forest $\rightsquigarrow$ lower limit on m_s as function of θ
  - ν_s–ν_s scatterings before kinetic decoupling
  - ν_s free-streaming after kinetic decoupling
- DM self-interactions $\rightsquigarrow$ upper limit on y $\rightsquigarrow$ lower limit on θ

Viable Parameter Space



Yukawa coupling y chosen to yield observed Dark Matter density



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Conclusions

- Sterile neutrinos: well-motivated, straightforward extension of SM
- Mass $\sim$ keV $\rightsquigarrow$ excellent Dark Matter candidate
- Automatically produced in early Universe
- Testable by X-ray searches $\rightsquigarrow$ simplest scenario ruled out
- Minimal extension: addition of scalar singlet
  $\rightsquigarrow$ viable model with qualitatively new production mechanism

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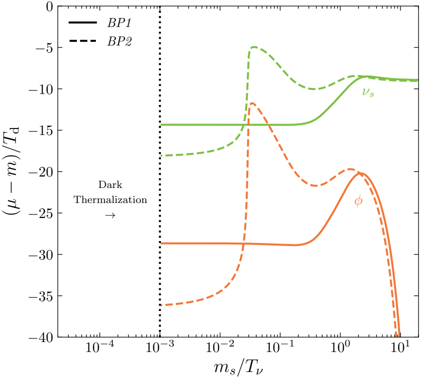
- Minimal extension: addition of scalar singlet
  $\rightsquigarrow$ viable model with qualitatively new production mechanism
- Future tests
  - More sensitive X-ray searches
  - Better understanding of Ly-α forest
  - Stronger lower limit on m_s from 21 cm observations
  - Stronger constraints on Dark Matter self-interactions
  - Suppression of astrophysical neutrino flux via $\nu_a \nu_s \to \phi$
  - Impact on supernovae? Johns & Fuller, PRD **100** (2019)

Chemical Potentials

DW production $\rightsquigarrow$ $p_s \sim p_a$ but $n_s \ll n_a$

$\rightsquigarrow$ negative chemical potential $\mu_s \ll -T_d$



BP2: $\nu_s\nu_s \to \phi\phi \to 4\nu_s \rightsquigarrow n_s \uparrow,\ T_d \downarrow \rightsquigarrow \mu_s \uparrow$