Diluted Equilibrium Sterile Neutrino Dark Matter

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References I

Amol V. Patwardhan, George M. Fuller, Chad T. Kishimoto, and Alexander Kusenko
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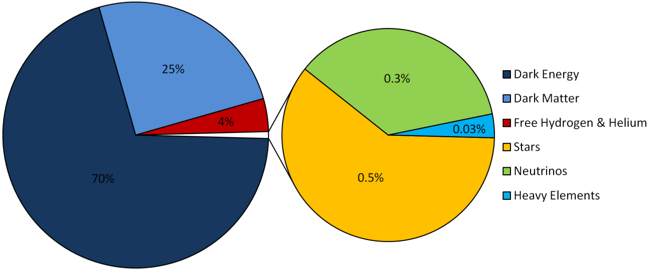
arXiv:1507.01977

Outline

The mandatory pie chart



Dark matter: evidence and various candidates

- Gravitational effects
  - Galactic rotation curves and velocity dispersion
  - Lensing
  - Cosmic microwave background
  - Baryon acoustic oscillations

- Hot, cold or warm dark matter (collisionless damping scale)
  - Baryonic DM
  - Neutrinos
  - Primordial black holes
  - Weakly interacting massive particles (WIMPs)
  - Asymmetric dark matter
  - Axions
  - Sterile neutrinos
  - ... and more

Sterile neutrinos

- Neutrinos have non-zero rest masses
- Suggests possible "sterile" (right-handed) neutrino states
- Steriles may mix with actives (i.e., not really sterile!)

$$|\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

- Sub-weak interaction cross section $\sigma \sim G_F^2\, E_\nu^2\, \sin^2 2\theta$
- $m_s \sim \mathcal{O}(\text{eV})$ – GUT scale

Sterile neutrino dark matter: various models

- Neutrino-neutrino scattering induced decoherence
  - Dodelson and Widrow, Phys. Rev. Lett. 72, 17 (1994)
- Resonant production (lepton-number enhanced decoherence)
  - Shi and Fuller, Phys. Rev. Lett. 83, 3120 (1999)
  - Abazajian, Fuller and Patel, Phys. Rev. D 64, 023501 (2001)
  - Kishimoto and Fuller, Phys. Rev. D 78, 023524 (2008)
  - Abazajian, Phys. Rev. Lett. 112, 161303 (2014)
- νMSM: minimal standard model with right-handed neutrinos
  - Asaka and Shaposhnikov, Physics Letters B 620 (2005) 17–26
  - Asaka *et. al.*, Physics Letters B 631 (2005) 151–156
  - Canetti *et. al.*, Phys. Rev. D 87, 093006 (2013)
- Scalar decay
  - Kusenko, Phys. Rev. Lett. 97, 241301 (2006)
  - Petraki and Kusenko, Phys. Rev. D 77, 065014 (2008)
- Additional gauge symnmetry
  - Tsuyuki, Phys. Rev. D 90, 013007 (2014)

Sterile neutrino dark matter: various models

Production mechanism	Dodelson Widrow	Resonant (medium enhanced)	MSM (involves resonant porduction)	Dilution	Gauge symmetry breaking (involves dilution)	Scalar decay
DM character	Warm	Cool	Cool	Cold	Cold	Cold
Tooth fairies	None	Lepton number	Heavy steriles N_2, N_3, nearly degenerate	Additional sterile (diluton)	Heavy steriles N_2, N_3, additional gauge symmetry	SU(2) scalar
Warts	Cannot constitute all of DM	Large early Lepton # affecting baryogenesis?	Collider considerations?	1. Requires thermalization, 2. Issues with bayrogenesis	What happens to N_3?	Collider considerations?
Predictions/ handles	Constrained by X-ray + Ly-α data	Lepton # constraints from BBN, CMB	1. N_2, N_3 detection, 2. Lepton# constraints from BBN, CMB	???	???	SU(2) scalar detection

Table 1: Different models for sterile neutrino DM production in the early universe

Sterile neutrino dark matter: constraints

- Constraints on sterile neutrino mass-mixing parameter space
- X-ray/γ-ray observations, small- and large-scale structure, phase space considerations

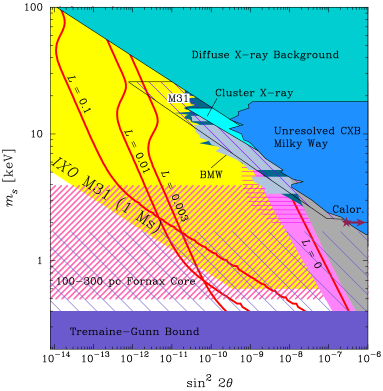


Figure: K. Abajazian (2009)

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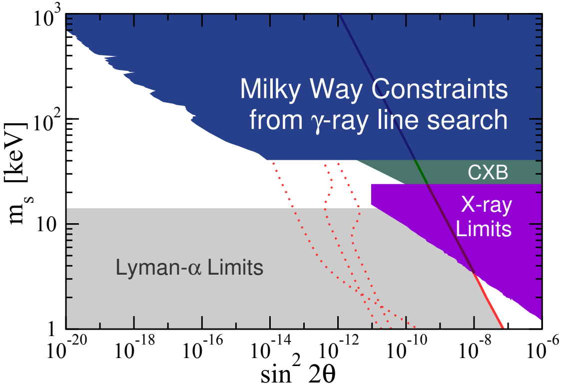

Figure: Yüksel, Beacom and Watson (2008)

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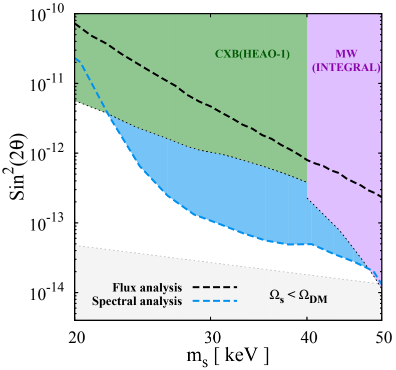

Figure: Ng et. al. (2015)

Sterile neutrino dark matter: constraints

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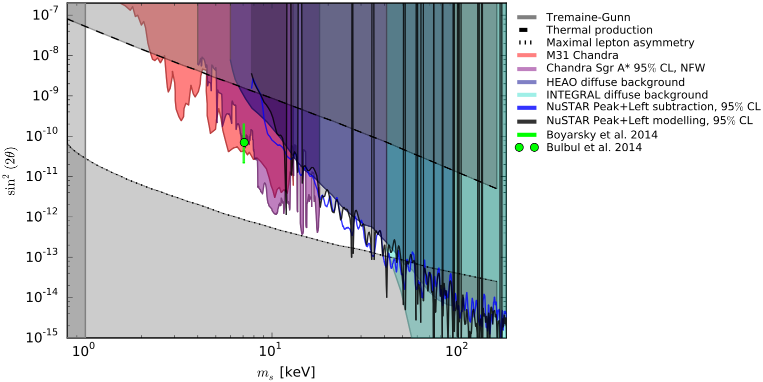


Figure: Riemer-Sørensen et. al. (2015)

Outline

1. Introduction: sterile neutrino dark matter
2. Diluted equilibrium sterile neutrino dark matter (DESNDM)
3. DESNDM: consequences and handles
4. Conclusions

"Diluted equilibrium" sterile neutrino dark matter

- Dark matter candidate sterile neutrino has an initial equilibrium distribution
  - Problem: overclosure for $m_s \gtrsim 100$ eV
- Relic density subsequently lowered by an epoch of entropy generation ("dilution")

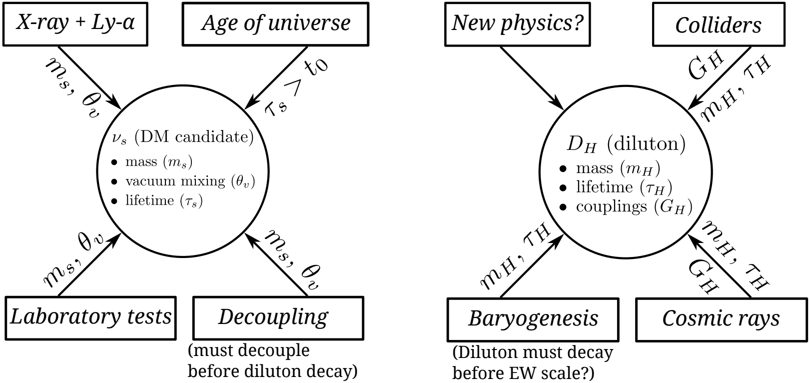
DESNDM: ingredients

- Sterile neutrino ($m_s \sim$ keV–MeV) in thermal/chemical equilibrium in the very early universe
  - Requires additional interactions
- Entropy generation from out-of-equilibrium particle decay
  - Dilution generator, i.e., "diluton" with $m_H \sim$ TeV–EeV, also in equilibrium initially
  - Examples: heavier sterile neutrino, LSP with broken R-parity

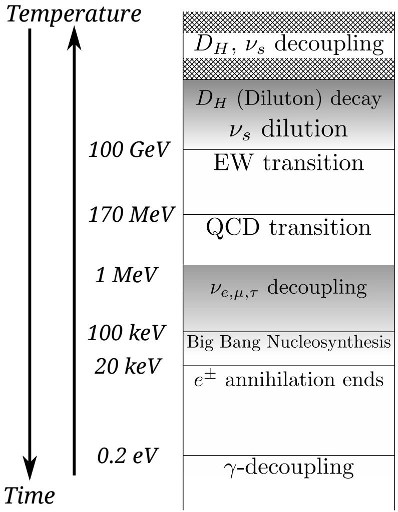
DESNDM model: mechanism

- Both particles decouple at $T > T_{\text{electroweak}} \sim 100$ GeV
- Diluton decays prior to weak decoupling (preferably prior to EW transition), injecting entropy into the plasma
- Diluton mass and lifetime can be chosen to give the appropriate amount of dilution
- Can dilute the sterile neutrino to the right relic density to constitute dark matter

Ingredients/handles



Timeline



- Diluton should decay prior to weak decoupling to preserve BBN/$N_{\rm eff}$
- Diluton decay prior to electroweak scale more baryogenesis-friendly

Sterile neutrino cooling

- Co-moving entropy $S \propto g_s\, a^3\, T^3$
- $\Delta_{\rm x} S = 0$ by symmetry
  - But $\Delta_{\rm t} S \neq 0$, e.g., if particles decaying out-of-equilibrium!
- $g_s\, a^3\, T^3 = g_{s,i}\, a_i^3\, T_i^3\, F$, where $F =$ "diution factor"
- For sterile neutrinos (decoupled), $a\, T_{\nu_s} = a_i\, T_{\nu_s,i}$
- Ratio of sterile neutrino to photon temperature at late times given by

$$\frac{T_{\nu_s}}{T_\gamma} = \left[\frac{4}{11} \cdot \frac{g_{s,\text{wd}}}{g_{s,i}} \cdot \frac{1}{F}\right]^{1/3}$$

Dark matter mass and relic density

- For relativistic F-D spectral shape w/ temp parameter T_{ν_s},

$$\rho_{\nu_s} = \left[(3\,\zeta(3)\,T_{\nu_s}^3)/(2\pi^2)\right] \cdot m_s$$

- Sterile neutrino rest-mass for closure parameter $\Omega_s\,h^2$ is

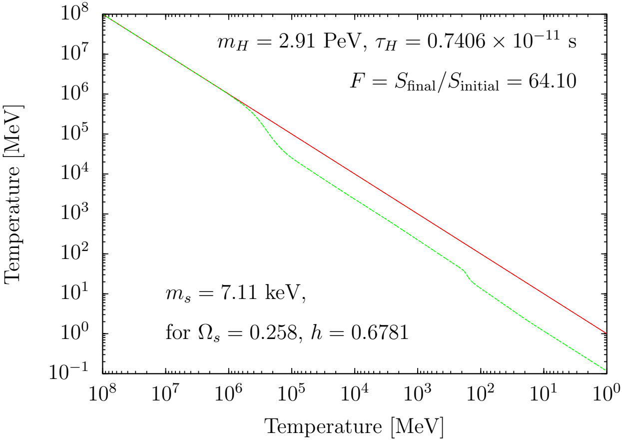
$$m_s \approx 2.24\,\mathrm{keV} \left(\frac{g_{s,i}/g_{s,\mathrm{wd}}}{10}\right) \left(\frac{F}{20}\right) \left(\frac{\Omega_s\,h^2}{0.12}\right)$$

- Relic density set by entropy injection from out-of-equilibrium decay of a different particle (the diluton)

- Key feature: relic density not a function of active-sterile mixing angle!

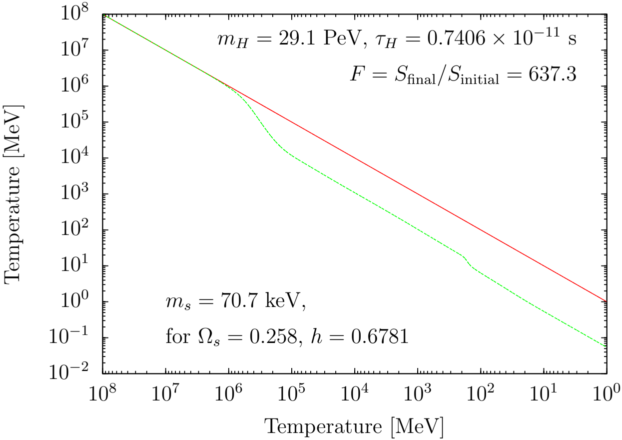
Dilution: cooling curves

Dilution event "cools" the energy spectrum of the lighter sterile neutrino, making it a lot colder than its rest mass would suggest!



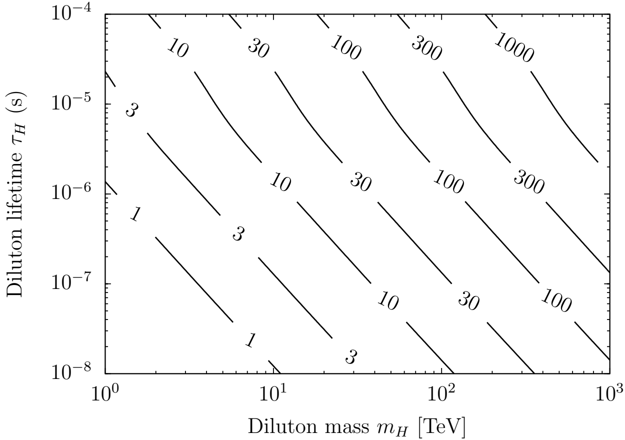
Dilution: cooling curves

Dilution event "cools" the energy spectrum of the lighter sterile neutrino, making it a lot colder than its rest mass would suggest!



DESNDM: Parametric plots

Contours of sterile neutrino rest-mass in keV that gives the appropriate relic density $\Omega_s = 0.26$, plotted across a parameter space of diluton rest-mass and decay lifetime



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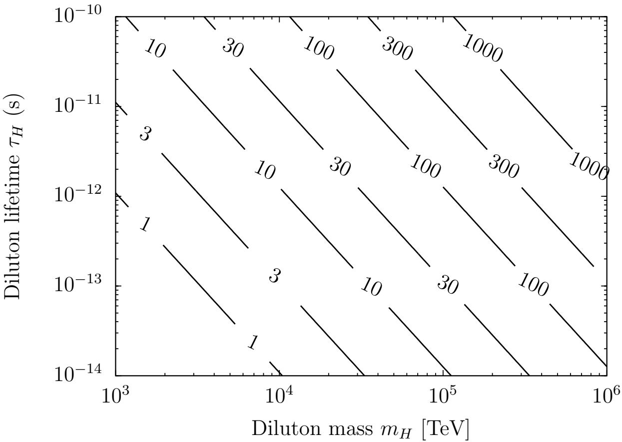


Outline

Dark matter collisionless damping

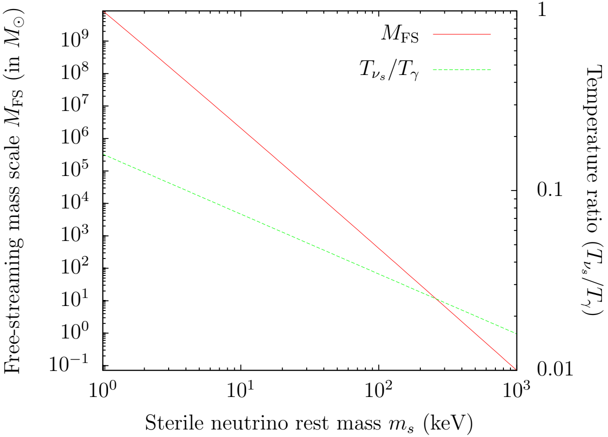
- Fluctuations damped by dark-matter particle free-streaming
- Collisionless damping scale estimated as

$$M_{\mathsf{FS}} \approx 3.7 \times 10^5 \, M_\odot \left(\frac{2\,\mathsf{keV}}{m_s}\right)^3 \left(\frac{T_{\nu_s}/T_\gamma}{0.1}\right)^3 \left(\frac{\Omega_m \, h^2}{0.14}\right)$$
$$\times \left[5.1 + \ln\left(\frac{m_s}{\mathsf{keV}} \cdot \frac{T_\gamma}{T_{\nu_s}} \cdot \frac{1}{\Omega_m h^2}\right)\right]^3 ,$$

- Smaller $M_{\mathsf{FS}} \Rightarrow$ "colder" dark matter

Collisionless damping scale

Dark matter collisionless damping scale in our model, as a function of sterile neutrino rest-mass. Can be probed down to 10^9–$10^{10}\, M_\odot$ with Ly-α forest observations, possibly lower ($10^6\, M_\odot$?) with future 21-cm observations. $M_{\mathsf{FS}} \sim 10^7$–$10^8\, M_\odot$ could influence small-scale structure (ref. Kenny's talk).



X-ray/γ-ray emission

- $\nu_s \to \nu + \gamma$ decay through effective electromagnetic vertex

$$\Gamma_{\nu_s \to \nu\gamma} \approx 6.8 \times 10^{-33}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta_v}{10^{-10}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

- Monochromatic photon emission at $E_\gamma = m_s/2$
- Constraints on mass-mixing parameter space using X-ray/γ-ray telescopes, e.g., HEAO, Chandra, XMM, Suzaku, NuSTAR, Fermi-GBM, INTEGRAL
- Future experiments: Astro-H, ATHENA, X-ray microcalorimeter sounding rockets

Recent hints?

- Unidentified X-ray line found at 3.55 keV in Chandra and XMM-Newton data, from various sources
  - Various galaxy clusters, M31 (Andromeda), Milky way GC
- Initial detection and analysis by two independent groups (Bulbul *et. al.* 1402.2301, Boyarsky *et. al.* 1401.4119, 1408.2503)
- Possible interpretation as byproduct of sterile neutrino decay
  - $m_s \approx 7.1$ keV, $\sin^2 2\theta_v \sim 10^{-10}$

The X-ray line saga

- Refutation (Jeltema and Profumo 1408.1699)
- Non-detection in stacked galaxy spectra (Anderson *et. al.* 1408.4115)
- Rebuttals from original authors (1408.4388, 1409.4143)
- Morphological analysis of 3.5 keV emission from GC and Perseus (Carlson *et. al.* 1411.1758)
- Reply to the rebuttals (Jeltema and Profumo 1411.1759)
- Riemer-Sorensen 1405.7943, Malyshev *et. al.* 1408.3531, Iakubovsky *et. al.* 1410.2852, Urban *et. al.* 1411.0050, Lovell *et. al.* 1411.0311, Tamura *et. al.* 1412.1869

Scattering-induced decoherence

- Sterile neutrinos with non-zero mixing produced in the early universe by scattering-induced decoherence (Dodelson-Widrow, 1994)

$$\Omega_{\mathsf{DW}} \sim 0.2 \left(\frac{\sin^2 \theta_v}{3 \times 10^{-9}} \right) \left(\frac{m_s}{3 \text{ keV}} \right)^{1.8}$$

- Unavoidable, as long as steriles exist with $\theta_v > 0$
- Additional contribution to the number density: $\sim 2\%$ of total DM for $m_s = 7.1$ keV, $\sin^2 2\theta_v = 7 \times 10^{-11}$
- “Warm dark matter” component. Constrainable?

Other constraints

- Dominant decay channel for keV–MeV rest-mass is $\nu_s \to 3\nu$

$$\Gamma_{\nu_s \to 3\nu} = \frac{G_F^2}{192\pi^3}\, m_s^5\, \sin^2\theta_v$$

- Require that $\tau_s \approx 1/\Gamma_{\nu_s \to 3\nu} \gtrsim 10^{18}$ s,

$$\Rightarrow \left(\frac{m_s}{10\,\text{keV}}\right)^5 \left(\frac{\sin^2\theta_v}{10^{-10}}\right) \lesssim 3 \times 10^6$$

- Compact object constraints: can be evaded if mixing angles small enough, and if rest-masses heavy enough to avoid resonances in cores

- Laboratory constraints: KATRIN and other beta-decay endpoint experiments can constrain $|m_{ee}|$, and therefore the contribution of the sterile state

Handles on the diluton

- Current and future colliders could probe diluton rest-masses $m_H \sim$ TeV, through observing decays or constraining lifetime
- Dilutons that are heavy sterile neutrinos could influence electroweak precision variables, e.g., W-boson mass, invisible Z-decay width, CC-to-NC ratio for neutrino scattering. Likely influence on $0\nu\beta\beta$ in certain parameter regimes (ref. Emiliano's talk)
- Higher-mass dilutons produced in cosmic rays?

Outline

Summary

- Sterile neutrinos are a viable dark matter candidate
- Recent results reporting an unidentified X-ray line have sparked interest in this field
- A number of sterile neutrino dark-matter production mechanisms have been proposed (and are being proposed)
- The Diluted equilibrium sterile neutrino dark matter model can evade all of the current bounds from X-ray observations and from structure
- More stringent future bounds could constrain parameter space

Bonus: early matter-dominated epochs

- Epoch of early matter domination prior to diluton decay
  - Jeans mass drops below horizon mass
  - Sub-horizon fluctuations (10^{-7}–$10^{-5} M_\odot$) can begin to grow
  - Damped by radiative diffusion, scales too small in any case

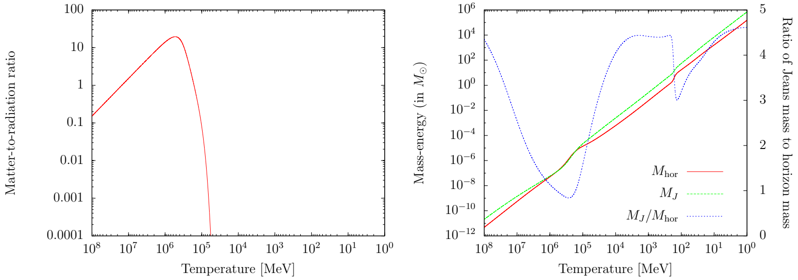


Figure: (left) Matter-to-radiation ratio; (right) Jeans and horizon mass