Sterile neutrino dark matter

Dodelson-Widrow and beyond

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N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

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Outline

What we know (and don't know) about dark matter

- $\Omega_{\rm DM}h^2 \simeq 0.12$ at $z = 0 \rightarrow$ Evidence purely gravitational
    - Cosmic microwave background
    - Baryon acoustic oscillations
    - Galactic rotation curves and velocity dispersion
    - Gravitational lensing
- Stable over cosmological timescales
- No strong or electromagnetic interactions with visible matter
- Non-relativistic kinematics at $z = 0$, probably also at $z = 3000$ (matter-radiation equality) — DM not "hot"
- What we don't know: identity and interactions of DM

Dark matter candidates

- Often a byproduct of beyond-standard-model theories that also solve another problem (e.g., hierarchy problem, strong CP, neutrino mass, etc.)

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

- DM $\in$ Dark sector

What we know (and don't know) about neutrinos

What we know:

- Electrically neutral
- Interact with W and Z bosons (3 flavors)
- Exhibit flavor oscillations $\implies$ propagating neutrinos have mass differences and are not weak interaction eigenstates
- *Nearly* massless (at least 2 states with $0 < m_\nu \lesssim \mathrm{eV}$)

What we do not know:

- Absolute neutrino masses and their hierarchy (sign of Δm^2_{32})
- Origin of neutrino mass and mixing
- Dirac or Majorana nature
- Electromagnetic properties, non-standard interactions, etc.

Sterile neutrinos

- Neutrino oscillations ⇒ non-zero rest masses
- Suggests possible right-handed, or "sterile", neutrino states, with no interactions with SM gauge bosons
- For example, neutrino masses can be generated via the (Seesaw) Lagrangian

$$\mathcal{L} \supset -\lambda_{\alpha i} L^\alpha H N^i - \sum_{i,j}^{3} \frac{M_{ij}}{2} N_i N_j,$$

where $N_i = 1, \ldots, n$ are new fermions with no SM gauge interactions

Mass and mixing angle generation

- After electroweak symmetry breaking, the above Lagrangian diagonalizes into $n+3$ mass eigenstates, ν_i. If $M \gg \lambda \langle H \rangle$:
  - $m_i \sim \lambda^2 \langle H \rangle^2 / M$, for $i = 1, \ldots, 3$
  - $m_i \sim M$ for $i = 4, \ldots, n$
- Two of the masses M_i required to be $\gtrsim 100$ GeV to account for solar and atmospheric Δm^2. Rest of the M_i unconstrained — anywhere from $\mathcal{O}$(eV) – GUT scale
- Mixing angles: $\theta^2_{\alpha i} \sim \lambda^2_{\alpha i} \langle H \rangle^2 / M^2$

Sterile neutrinos

- Caveat: Seesaw Lagrangian can also give rise to sterile ν mixing with active ν

$$|\nu_\alpha\rangle = \cos\theta_{14}\,|\nu_1\rangle + \sin\theta_{14}\,|\nu_4\rangle$$
$$|\nu_s\rangle = -\sin\theta_{14}\,|\nu_1\rangle + \cos\theta_{14}\,|\nu_4\rangle$$

- Sterile neutrino can oscillate into an active neutrino as it propagates, giving it an effective sub-weak interaction $\sigma \sim G_F^2\,E_\nu^2\,\sin^2 2\theta$

- In the simplest scenario, the active-sterile mixing angle θ is responsible for production in the early universe, as well as decay in the late universe

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Sterile neutrino dark matter: various models

- Neutrino-neutrino scattering induced decoherence
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- 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)

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  - 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)
  - Drewes and Kang, J. High Energ. Phys. 2016, 51 (2016)
  - König *et al.*, JCAP11(2016)038
  - Abazajian and Kusenko, Phys. Rev. D 100, 103513 (2019)

… and some more!

- Additional gauge symmetry
  - Tsuyuki, Phys. Rev. D 90, 013007 (2014)
  - Dror *et al.*, J. High Energ. Phys. 2020, 168 (2020)
- Dodelson-Widrow with nonstandard ν-ν interactions
  - De Gouvêa *et al.*, Phys. Rev. Lett. 124, 081802 (2020)
  - Johns and Fuller, Phys. Rev. D 100, 023533 (2019)
  - Kelly *et al.*, Phys. Rev. D 101, 115031 (2020)
  - Kelly *et al.*, Phys. Rev. Lett. 127, 041101 (2021)
  - Benso *et al.*, Phys. Rev. D 105, 055016 (2022)
- νMSM + light scalar
  - Bezrukov *et al.*, Phys. Rev. D 99, 083507 (2019)

Dodelson-Widrow: scattering-induced decoherence

- Proposed as mechanism for producing sterile neutrino DM with $m_s \sim$ keV in the early universe
- In the *very* early universe, sterile-ν production blocked by quantum Zeno effect, and in-medium suppression of active-sterile mixing. Therefore, zero initial abundance (if mixing angle small enough)
- As temperature drops to $\mathcal{O}(100\text{–}1000)$ MeV, production can begin through scattering-induced decoherence
- Active neutrinos ν_α in thermal and chemical equilibrium. ν_α partly oscillates into ν_s in-between scattering events. Small chance to collapse into ν_s at each event

Dodelson-Widrow: scattering-induced decoherence

- Boltzmann equation:

$$T\frac{df_{\nu_s}}{dT} = \frac{\Gamma_\alpha}{2H}\langle P_{\alpha s}\rangle f_{\nu_\alpha},$$

where

$$\langle P_{\alpha s}\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Delta\cos 2\theta - V)^2 + (\Gamma_\alpha/2)^2}$$

- $V = V_T(T) + V_L(T, L_{\nu_\alpha})$. In the early universe, $V_T < 0$, and $V_L \propto L_{\nu_\alpha}$

- Dodelson-Widrow assumed no lepton asymmetry ($V_L = 0$)

Sterile neutrino dark matter: constraints

Main constraints come from electromagnetic decay (X-ray/γ-ray observations), small-scale structure, phase space considerations

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

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

- 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

- Improved bounds likely from current and future experiments: eROSITA, XRISM, eXTP, ATHENA, etc.

Sterile neutrino dark matter: constraints

- Sterile neutrinos 'warmer' than WIMPs $\Longrightarrow$ damping of structure at scales smaller than their free-streaming scale
- Free-streaming scale and m_s related by production mechanism, therefore careful interpretation of constraints is needed
- Analysis of DM phase space distribution in dwarf spheroidal galaxies rules out $m_s \lesssim 1$–$2\,\mathrm{keV}$ [Tremaine and Gunn (1979), Boyarsky et al. (2008)]
- Other bounds from Lyman-α forest, Milky-way satellites, lensing substructure, impose lower limits of $m_s \sim 5$–20 keV for various viable models of interest [see Zelko et al., arXiv:2205.09777]

Sterile neutrino dark matter: constraints

- Constraints on parameter space of sterile neutrino mass m_s vs mixing $\sin^2 2\theta$

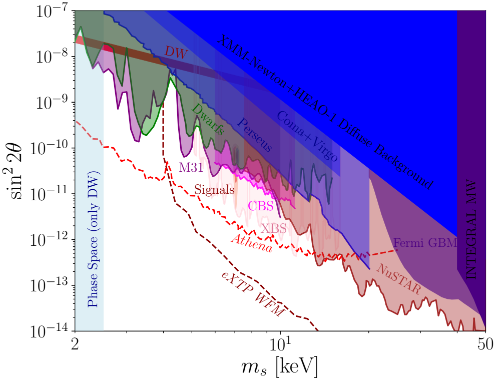


Figure: K. Abazajian, arxiv:2102.01083. Does not include the latest bounds from arXiv:2205.09777 using Lensing + Ly-α + MW satellites.

Beyond Dodelson-Widrow

- Dodelson-Widrow mechanism ruled out by a combination of X-ray and structure/phase-space constraints
- If production can be enhanced in the early-universe, then one can make same amount of DM with smaller value of θ_s
- Some mechanisms enhance the scattering-induced decoherence rate (e.g., resonant production, nonstandard neutrino self-interactions), whereas other mechanisms provide an alternate pathway for production (e.g., scalar decay, additional gauge symmetry)
- The idea is to alter the relationship between how the mixing angle governs early universe production and how it causes electromagnetic decay in the late universe. In some cases, the relationship is severed entirely.

Resonant production

- A nontrivial cosmological lepton number in the neutrino sector can lead to a Mikheyev-Smirnov-Wolfenstein (MSW) resonant enhancement of sterile-ν production at a certain temperature

$$\langle P_{\alpha s}\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Delta \cos 2\theta - V)^2 + (\Gamma_\alpha/2)^2},$$

  where $V = V_T(T) + V_L(T, L_{\nu_\alpha})$, and V_L can be > 0. Then, resonant enhancement happens when $\Delta \cos 2\theta - V = 0$.

- Resonantly produced ν_s tend to have a "colder" distribution

- The cosmological lepton number is constrained through observations of primordial light element abundances (^{2}D and ^{4}He). A large lepton number ($L_\nu \sim 10^{-2}$–10^{-1}) can affect the outcome of big-bang nucleosynthesis

Resonant production: constraints

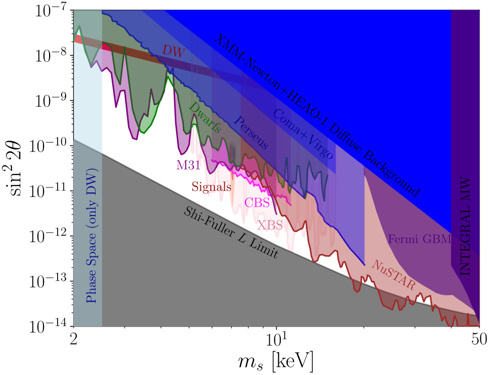


Figure: Adopted from slides by K. Abazajian. Latest constraints from arXiv:2205.09777 appear likely to rule out entire parameter space for resonant production of sterile neutrino DM.

Enhanced neutrino self-interactions

- Non-standard self-interactions (e.g., $\mathcal{L} \supset \lambda_\phi \nu_\alpha \nu_\alpha \phi$) among neutrinos that are must stronger than the weak interaction can enhance the ν_s production rate relative to Dodelson-Widrow, allowing for smaller θ_s values to produce the correct DM density, and therefore evading the X-ray bounds.

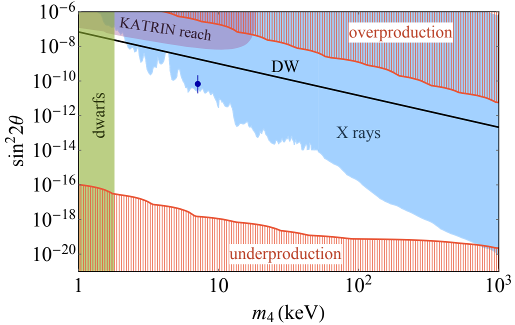


Figure: A. de Gouvêa et al. (2020)

Outline

"Diluted equilibrium" sterile neutrino dark matter

- Dark matter candidate sterile neutrino freezes out from an initial equilibrium distribution
  - Problem: overclosure for $m_s \gtrsim 100$ eV. Unless . . .

- Relic density subsequently lowered by an epoch of entropy generation ("dilution")

- Entropy dilution from out-of-equilibrium decay of a heavier particle is a component of several sterile neutrino models (e.g., νMSM, or models with additional gauge symmetry). Although in some of these models (e.g., νMSM), the ν_s does not start from an equilibrium abundance

DESNDM: ingredients

- Patwardhan, Fuller, Kishimoto, Kusenko, Phys. Rev. D 92, 103509 (2015)

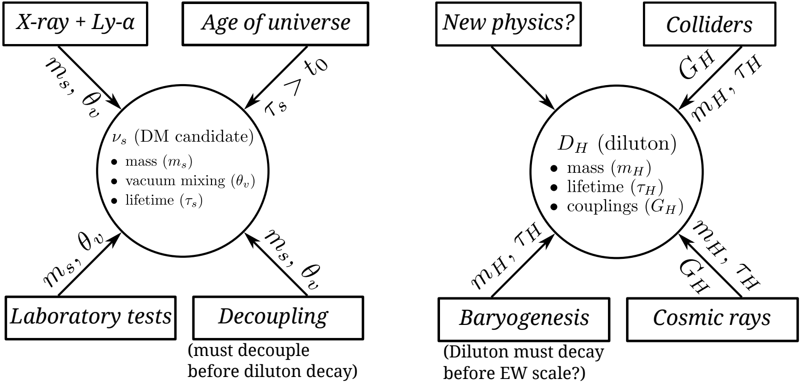
- Sterile neutrino ($m_s \sim$ keV–MeV) in thermal/chemical equilibrium in the very early universe
  - Requires additional interactions (e.g., left-right symmetry)

- 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

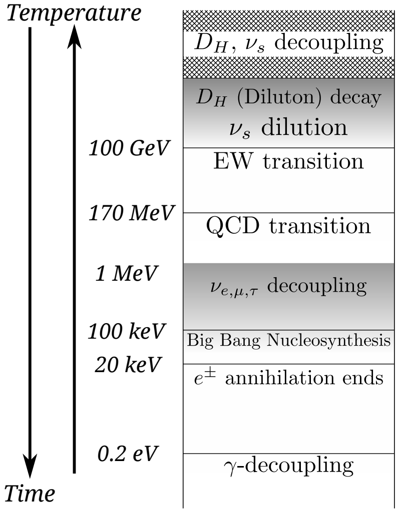
DESNDM model: mechanism

- 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 $S \propto g_s\, a^3\, T^3$
- $\Delta_{\mathrm{x}} S = 0$ by symmetry
    - But $\Delta_{\mathrm{t}} S \neq 0$, 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

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

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

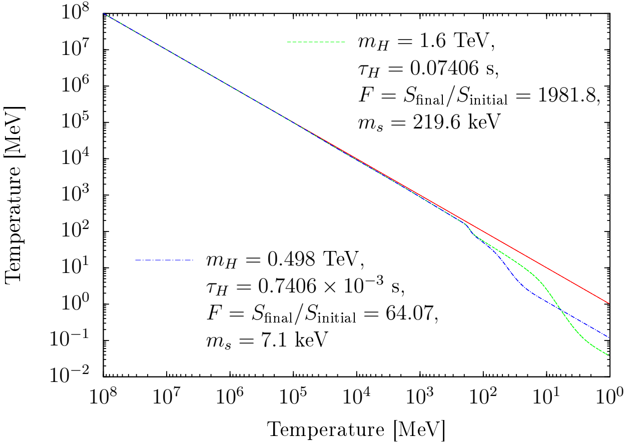
$$m_s \approx 2.26\,\mathrm{keV} \left(\frac{g_{s,i}/g_{s,\mathrm{wd}}}{10}\right) \left(\frac{F}{20}\right) \left(\frac{\Omega_s\, h^2}{0.12}\right)$$

- 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!



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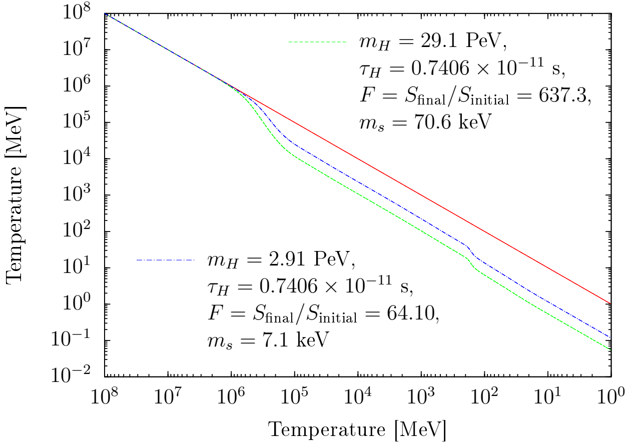
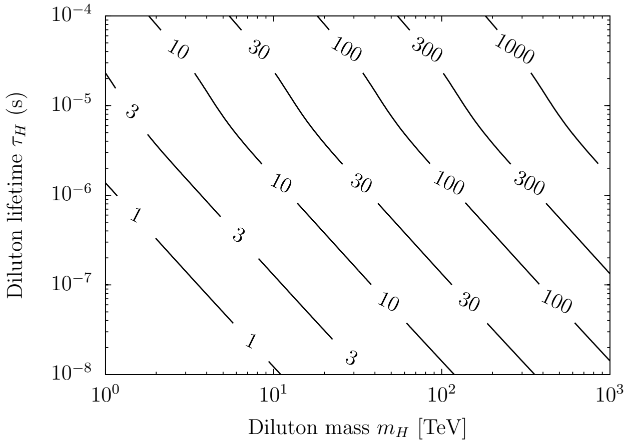


DESNDM: Parametric plots

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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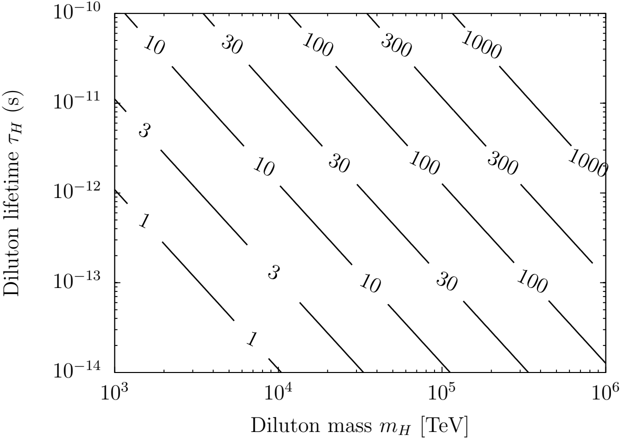


Dark matter collisionless damping

- Fluctuations damped by dark-matter particle free-streaming

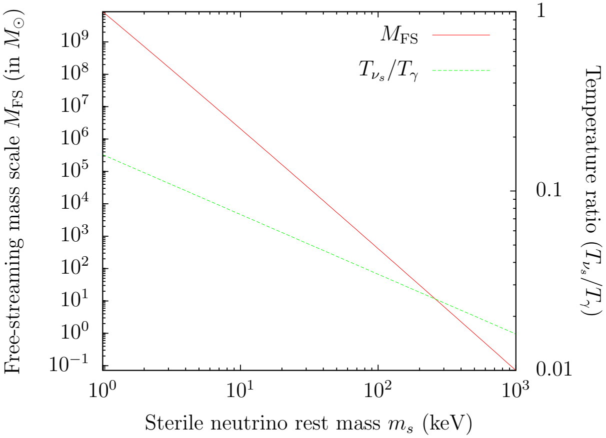
- Collisionless damping scale estimated as

$$M_{\mathrm{FS}} \approx 4 \times 10^5 \, M_\odot \left(\frac{2\,\mathrm{keV}}{m_s}\right)^3 \left(\frac{T_{\nu_s}/T_\gamma}{0.1}\right)^3 \left(\frac{\Omega_m\, h^2}{0.14}\right)$$
$$\times \left[10 + \ln\left(\frac{m_s}{2\,\mathrm{keV}} \cdot \frac{0.1}{T_{\nu_s}/T_\gamma} \cdot \frac{0.14}{\Omega_m\, h^2}\right)\right]^3 ,$$

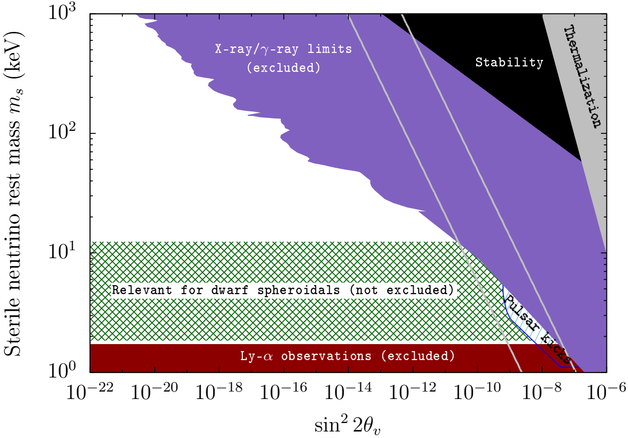
- Smaller M_{FS} $\Rightarrow$ "colder" dark matter

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. $M_{\mathsf{FS}} \sim 10^6$–$10^9\,M_\odot$ could influence small-scale structure.

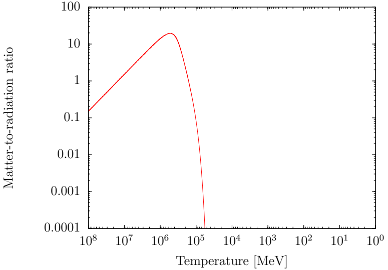


DESNDM: constraints



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



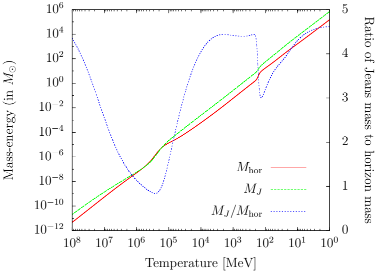


Figure: (left) Matter-to-radiation ratio; (right) Jeans and horizon mass

Other constraints

- Core-collapse supernova cooling bound: can be evaded if θ_s small enough, or if m_s heavy enough to avoid MSW resonance
  - Feedback from changing matter potential as a result of $\nu_\alpha \to \nu_s$ conversion inhibits further production of ν_s. This weakens existing constraints on the DM parameter space from CCSN [Suliga et al., JCAP 08 (2020) 018].
- Laboratory constraints: beta-decay (or electron capture) endpoint experiments can constrain $|m_{\nu_e}|$, and therefore the contribution of the sterile state
  - KATRIN, TRISTAN: Tritium beta decay - $m_s < 17.5\,\mathrm{keV}$
  - ECHo, HOLMES: ^{163}Ho electron capture - $m_s < 2.5\,\mathrm{keV}$
  - HUNTER: ^{131}Cs electron capture - $m_s < 350\,\mathrm{keV}$
  - BeEST: ^{7}Be electron capture - $m_s < 860\,\mathrm{keV}$

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
- Higher-mass dilutons produced in cosmic rays?

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). Several follow-up observations since then.
- Possible interpretation as byproduct of sterile neutrino decay
  - $m_s \approx 7.1$ keV, $\sin^2 2\theta_v \sim 10^{-10}$
- But could also be atomic physics

Outline

Summary

- Sterile neutrinos are a naturally well-motivated and viable dark matter candidate, although the parameter space for producing the correct DM relic density continues to become increasingly endangered in the face of improving observational data
- Some of the production mechanisms directly depend on the active-sterile mixing angle, but others do not — these are much harder to get a handle on, although not impossible
- Recent results reporting an unidentified X-ray line have sparked some additional interest in this DM candidate over the last several years

Bonus slides