Sterile Neutrino Candidates for the 3.5 keV Line

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Sterile Neutrinos as Dark Matter: History

- “Super-weak” neutrinos ($G < G_F$) [Olive & Turner, 1982]: Earlier Decoupling, abundance set by standard dark matter production mechanism of decoupling temperature and degrees of freedom disappearance.

- “Sterile” neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization. WDM.

- “Resonant” sterile neutrinos [Shi & Fuller, 1999]: Finite temperature production with non-zero lepton number resonant enhanced production. WDM to CDM. “Cool” Dark Matter.

- “Precision” Sterile Neutrino Dark Matter & Proposal for X-ray Detection [Abazajian, Fuller & Patel 2001; KA 2005]: Full momentum-space production description with QCD transition corrections, resonant to non-resonant solutions as a continuum in lepton number.
Sterile $\nu$ WDM Radiative Decay in the X-ray

Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

$\nu_s \rightarrow \nu_\alpha + \gamma$

$E_\gamma = \frac{m_s}{2} \sim 1$ keV

$\Gamma_\gamma = 1.62 \times 10^{-28}$ s$^{-1}$ \(\left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right) \left(\frac{m_s}{7 \text{ keV}}\right)^5\)

Virgo Cluster: $10^{78}$ DM particles
Upper Mass Limit on $\nu_s$ DM: X-ray observations of Virgo

Abazajian, Fuller & Tucker 2001

$m_s = 4$ keV

$m_s = 5$ keV
Sterile Neutrino Dark Matter: Parameter Space Summary

\[ \sin^2 2\theta \]

\[ m_s \text{ [keV]} \]

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In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ∼10 times greater than Chandra and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably could be achieved through several long observations over a few years. An exposure equivalent to this could be obtained by a stacking analysis of the spectra of a number of similar clusters (see, e.g., Brandt et al. 2001; Tozzi et al. 2001). Constellation X, with very long integration times, holds out the prospect of covering nearly the entire WDM parameter space of interest for
The Detection of an Unidentified Line

4 to 5σ

73 clusters

3.57 ± 0.02 (0.03)

XMM - MOS

Full Sample
6 Ms

Sterile Neutrino Dark Matter: Parameter Space Summary

\(\sin^2 2\theta\) vs. \(m_s [\text{keV}]\)

- **DW**
- **XMM-Newton+HEAO-1 Diffuse Background**
- **Coma+Virgo**
- **M31**
- **Perseus**
- **Signals**
- **Fermi GBM**
- **INTEGRAL MW**

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The Detection of an Unidentified Line II

Boyarsky et al. PRL arXiv:1402.4119

73 clusters

-4 \cdot 10^{-3} -2 \cdot 10^{-3} 0 \cdot 10^{-3} 2 \cdot 10^{-3} 4 \cdot 10^{-3} 6 \cdot 10^{-3} 8 \cdot 10^{-3} 1 \cdot 10^{-2} 3.0 3.2 3.4 3.6 3.8 4.0

Data - model [cts/sec/keV]

No line at 3.5 keV
Line at 3.5 keV

Andromeda (M31)

1 galaxy

3σ
JP claimed that the Galactic Center excludes a dark matter interpretation

» JP makes the assumption of all of the 3.5 keV flux comes from K XVIII, subtracting that fit from the data & then placing constraints on dark matter decay from the Galactic Center with the modified data.

» Logical equivalent of adding K XVIII line to data, then using modified data to claim detection of a dark matter line.

» The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv: 1408.2503].

» JP methodology in this GC analysis is representative of the problematic nature of their analyses on this subject.
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by $11.8\sigma$

**Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$**

Despite overwhelming systematic uncertainties that are of order the signal, the authors quote statistical errors only.

Proper methodology would find a more robust, less systematics dominated method & not quote irrelevant statistical evidence which reach an invalid conclusion.
8 New Cluster Detections at >2σ Reported in August Consistent with DM in FOV, with proper redshifting of line
7 keV Resonant Production: very different from thermal WDM

Initial 7 keV calculation:
Abazajian PRL
arXiv:1403.0954

Detailed production:
Venumadhav,
Cyr-Racine,
Abazajian & Hirata
arXiv:1507.06655

Matter (thermal) mixing angle:

\[
\sin^2 2\theta_m = \frac{\Delta^2(p) \sin^2 2\theta}{\Delta^2(p) \sin^2 2\theta + [\Delta(p) \cos 2\theta - V^D - V^T(p)]^2}
\]

⇒ \( \epsilon_{\text{res}} \approx \frac{\delta m^2}{(8\sqrt{2}\zeta(3)/\pi^2) G_F T^4 L} \)

\approx 3.65 \left( \frac{\delta m^2}{(7 \text{ keV})^2} \right) \left( \frac{10^{-3}}{L} \right) \left( \frac{170 \text{ MeV}}{T} \right)^4
WDM Solution to All Local Group Galaxy Properties? [c.f. James Bullock’s talk]

“It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations” of the Milky Way Satellites: “the total satellite abundance, their radial distribution and their mass profile” (or TBTF)

Anderhalden et al. arXiv:1212.2967

CDM vs. WDM 2keV
7 keV Transfer function brackets
thermal WDM 2 keV "sweet spot"

Venumadhav+
arXiv:1507.06655
7 keV Alleviation of Too Big To Fail…

Confirmation: Hitomi (Astro-H) X-ray Telescope

Successful launch *yesterday*

Confirmation Wish List: #2 Sounding Rocket X-ray Observations: Micro-X & XQC

Figueroa-Feliciano+ 1506.05519
Confirmation Wish List #3: kink searches in nuclear $\beta$-decay

Mertens+ 2014
Summary

- An unidentified line has been detected at $4\sigma$ to $5\sigma$ in two independent samples of stacked X-ray clusters with XMM-Newton, with several subsamples showing the line. It is independently seen by the same group in the Perseus Cluster with Chandra data. (Bulbul et al. ApJ 2014)

- Within a week, an independent group found a line at the same energy toward Andromeda (M31) and Perseus with *XMM-Newton*, with combined statistical evidence of $4.4\sigma$. (Boyarsky et al. PRL 2014).

- Seen in 8 more clusters at lower significance. No consistent astrophysical interpretation exists.

- Many follow up observations planned: Hitomi (ASTRO-H) launched, Micro-X & XQC in Southern Hemisphere

- A simple model for the signal is resonant sterile neutrino production at with a cosmological $L$. The signal crosses a transition region from “cold” dark matter to “warm” dark matter, particularly at a small-scale structure cutoff scale of great interest in galaxy formation of the local group of galaxies, ~2 keV thermal WDM.
Note:

\[ m \sim \text{keV} \neq \text{eV} \neq 0 \]

\[ N_{\text{eff}} = 3.15 \pm 0.23 \text{ (Planck Collab. 2015)} \]

\[ \Rightarrow \text{constrains } \textit{dark radiation, not dark matter} \]
8 New Cluster Detections at $>2\sigma$ Reported in August

![Graph showing line positions in keV against NED redshift for various clusters including Abell S805, Abell 2199, Coma, Abell 496, Perseus, Abell 2319, Abell 3266, and Abell 85.](image_url)
Sterile Neutrinos
Beyond the Standard Model of Particle Physics

- Phenomenological Insertion of Majorana & Dirac Mass Terms of Comparable Magnitude (atmos. & solar) (e.g. $\nu_{\text{MSM}}$ Asaka et al 2006)

- Left-Right Symmetric Models (Pati & Salam 1974; Mohapatra & Pati 1975)

- Higher Dimensional Operators in String-Inspired models (Langacker 1998)

- Bulk Fermions in Large Extra Dimensions (ADD; Dvali & Smirnov 2000)

- Axino in R-parity Violating Minimal Supersymmetric Models (Chun & Kim 1999)