X-Ray Constraints on Sterile Neutrino Dark Matter

Dominic Sicilian

Collaborators: E. Bulbul, F. Civano, N. Cappelluti, C.S. Reynolds, M. Moscetti
A Strange Feature in the X-Rays...

- **3.5 keV**: Unidentified emission line
  - Dark matter dominated objects
  - 9 works, 4 telescopes

- Thought to be evidence of **Sterile Neutrino dark matter**
Probing The Milky Way’s Dark Matter Halo for the 3.5 keV Line

• **The Astrophysical Journal** (December 2020)

• ~51 Ms of archival *Chandra* data
  • Peering through the Milky Way’s Dark Matter Halo

• Objectives:
  • Investigate the 3.5 keV line and the sterile neutrino dark matter hypothesis
  • Constrain the parameter space
Sterile Neutrino Dark Matter
Standard Model (and beyond)

• No particle meets dark matter criteria
  • New particle must be added

• Fermions: right- and left-handed chirality
  • Exception: Neutrinos

• Right-handed neutrinos—logical addition to Standard Model

• Could help solve several mysteries
  • Neutrino mass
  • Matter-antimatter asymmetry
  • Dark Matter
Right-Handed Neutrinos

- Do **not** couple to weak interaction
  - Dubbed “**Sterile**” Neutrinos
  - **Left**-handed: “**active**” neutrinos

- Neutrino flavor “mixing”
  - Probability: depends on **Mixing Angle** $\theta$

- $\theta \sim 0.5$ for Standard Model mixing
  - Common between active flavors

- $\theta \sim 10^{-6}$ for sterile dark matter flavor
  - Little to no mixing with active neutrinos

Sterile dark matter flavor

The 3 active neutrino “flavors”

Drewes 2019

Dominic Sicilian
Sterile Neutrino Decay ("\(\theta\)-suppressed")

- Sterile neutrino decay rate:

\[
\Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29} \text{s}^{-1} \left( \frac{\sin^2(2\theta)}{10^{-7}} \right) \left( \frac{m_s}{1\text{keV}} \right)^5
\]

- Products: active neutrino and photon
  - Each has half the total sterile neutrino mass-energy
  - \(m_s \sim 10\text{ keV}\) gives photon \(E \sim 5\text{ keV}\)

- Decay should be detectable by X-ray observatories

Dominic Sicilian
The 3.5 keV Line
3.5 keV line detections

**XMM-Newton:**
- **73 galaxy clusters**, ~4.5σ (Bulbul+2014)
- **Andromeda** (M31), 3σ (Boyarsky+2014)
- **Galactic Center** of Milky Way, 5.7σ (Boyarsky+2015)

**Chandra:**
- **Perseus cluster**, ~4.5σ (Bulbul+2014)
- **Dark Matter Halo** of Milky Way, ~3σ (Cappelluti+2018)
- **Galactic Bulge** of Milky Way, >3σ (Hofmann+2019)

**Suzaku:**
- **Perseus cluster**, ~5σ (Urban+2015; Franse+2016)
- **Galactic Bulge** of Milky Way, >3σ (Hofmann+2019)

**NuSTAR:**
- **Bullet cluster**, >3σ (Wik+2014; Franse+2016)
- **Dark Matter Halo** of Milky Way, 11σ (Neronov+2019)
- **Earth’s Dark Side**, >3σ (Perez+2017)

*Suggests NuSTAR detections are instrumental features*
Prior constraints (2014-2020)

**3.5 keV Non-Detections:**

- **Galaxy clusters**, *Suzaku* (Bulbul+2016)
- **Draco dwarf galaxy**, *XMM-Newton* (Ruchayskiy+2016)
- **Perseus cluster**, *Hitomi* (Hitomi+2017)
- **Galaxy clusters**, *XMM-Newton* (Bhargava+2020)
- **Dark Matter Halo** of Milky Way, *XMM-Newton* (Dessert+2020)

*All show at least marginal consistency with detections*

- **Science goal #1**: Investigate possible $m_s \sim 7$ keV sterile neutrino dark matter particle
Prior constraints (2014-2020)

- **Science goal #2:** Constrain **Mass** vs **Mixing Angle** parameter space

- Use non-detections of new lines across spectrum
  - **Mass:** twice the line Energy

- Mixing Angle term: Compute from decay rate using
  - Line Flux
  - Total dark matter in field of view
Looking for the 3.5 keV Line in archival *Chandra* data
The Ultimate 3.5 keV Line Search

- Isolate possible dark matter signal
  - Eliminate all baryonic X-ray sources

51 Ms of archival *Chandra* Source Catalog data; ~1900 observations from 2000-2014

Dominic Sicilian
Wide spatial distribution

- Compare line flux/upper-limits with Navarro-Frenk-White (NFW) distribution of dark matter
Results
Modeling 51 Ms of *Chandra* Data

- **CXB**: absorbed powerlaw
- **Particle background**: powerlaw plus emission features
- All fitting: Markov Chain Monte Carlo (MCMC)

Model of total data set:
Models of the 4 bins

Bin 1

Bin 2

Bin 3

Bin 4

Dominic Sicilian
3.5 keV Line Upper Limits

- Added a ~3.5 keV emission component on top of model
- Tested significance with two methods
  - \( \chi^2 \)
  - Bayesian Information Criterion (BIC)
- Both confirm non-detection

<table>
<thead>
<tr>
<th>Bin</th>
<th>( I_{3.51} ) Upper-Limit [10^{-7} ph cm^{-2} s^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.45</td>
</tr>
<tr>
<td>2</td>
<td>4.67</td>
</tr>
<tr>
<td>3</td>
<td>4.54</td>
</tr>
<tr>
<td>4</td>
<td>3.42</td>
</tr>
<tr>
<td>ALL</td>
<td>2.34</td>
</tr>
</tbody>
</table>
Data without Source Removal

- Point-source removal process reduces statistics

<table>
<thead>
<tr>
<th>Data</th>
<th>Total Counts</th>
<th>Particle Background Counts</th>
<th>Signal-to-Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full fields</td>
<td>151177565</td>
<td>139226685</td>
<td>971.98</td>
</tr>
<tr>
<td>Source-removed</td>
<td>126560247</td>
<td>118028924</td>
<td>758.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bin</th>
<th>$\theta_{GC}$ [deg]</th>
<th>$t_{exp}$ [Ms]</th>
<th>ObsIDs</th>
<th>Counts (w/sources)</th>
<th>Counts (w/out)</th>
<th>$A_i$ [deg$^2$]</th>
<th>$A_f$ [deg$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10–74</td>
<td>8.00</td>
<td>306</td>
<td>1569344</td>
<td>1224559</td>
<td>19.18</td>
<td>13.44</td>
</tr>
<tr>
<td>2</td>
<td>74–114</td>
<td>14.07</td>
<td>715</td>
<td>3540528</td>
<td>2666281</td>
<td>57.96</td>
<td>43.98</td>
</tr>
<tr>
<td>3</td>
<td>114–147</td>
<td>17.58</td>
<td>473</td>
<td>4374038</td>
<td>2785435</td>
<td>36.24</td>
<td>19.57</td>
</tr>
<tr>
<td>4</td>
<td>$&gt;147$</td>
<td>11.00</td>
<td>413</td>
<td>2466970</td>
<td>1855048</td>
<td>27.63</td>
<td>19.05</td>
</tr>
<tr>
<td>TOTAL</td>
<td>50.65</td>
<td>1907</td>
<td></td>
<td>11950880</td>
<td>8531323</td>
<td>141.01</td>
<td>96.04</td>
</tr>
</tbody>
</table>
Source-intact models

- Same methodology as main data set
- Contains more dark matter \textbf{and} more baryons
- Yields stronger non-detection than main data set
3.5 keV Line Profile

- Shown: Upper-limits compared to two NFW profiles

- Exact match with XMM Halo constraints

- NuSTAR detections excluded

- Correspondence to NFW profile **not** fully excluded

Dominic Sicilian
Background-subtracted spectrum

Particle background spectrum
Parameter space

• **Blue:** $\sim 7$ keV sterile neutrino constraint

• **Red:** New continuum constraints

• Systematic uncertainty reflects two extreme NFW profiles
Recent Works

• New constraints: Foster+2021
  • 547 Ms (!!!) of XMM-Newton data
  • See Abazajian 2021

• Dekker+2021 eROSITA simulations on MW satellites can constrain $m_s < 20$ keV
  • Only 2.5 ks exposure
Conclusions

• 3.5 keV line’s decaying dark matter interpretation has been heavily constrained; not wholly ruled out

• Sterile neutrino dark matter parameter space has been strongly constrained

• Other insights from current/future missions
  • XRISM’s spectral resolution will allow us to resolve & disentangle 3.5 keV emission from nearby features
  • eROSITA’s all-sky coverage will improve understanding of 3.5 keV line’s radial profile
  • eROSITA may also rule out the rest of the $m_s < 20$ parameter space

Dominic Sicilian
Thank you!

Dominic Sicilian
References