Searching for Dark Matter with X-ray lines

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Perseus Cluster (Chandra)
Dark Matter problem

- BBN/ CMB
- Clusters
- Galaxies/Local
Dark Matter Detection

• Direct Detection

• Collider Search

• Indirect Detection
Dark Matter Indirect Detection

DM → γ, ν, q… → Physics → γ, ν, q… → DM

Particle Physics

 Astrophysics/detector

\[
\frac{dF}{dE} = \frac{1}{4\pi m_\chi} \frac{\Gamma}{dE} \int d\Omega \int d\ell \rho_\chi[r(\ell)]
\]
X-ray Searches of Dark Matter

• Sensitive instruments

• Well Motivated Candidates
  – Sterile Neutrino (keV)
  – Axion-like Dark Matter
  – Gravitino
  – Exciting Dark Matter
  – +++++++
Sterile Neutrino Dark Matter Production

- Non-resonant production
  - Dodelson Widrow 1994
  - Warm DM

- Resonant production
  - Shi Fuller 1999
  - Modified by primordial lepton asymmetry
  - Cool DM

- Decay of heavy particles
  - E.g., Petraki Kusenko 2008
  - Collider signatures
Phase space constraint

Model Dependent (nuMSM)

Not applicable in, e.g.
0711.4646
Petraki, Kusenko,
1507.01977
Patwardhan et al
Etc etc

\[ \Omega_{\chi}^{\nu_s} > \Omega_{\chi}^{\text{obs}} \]

\[ \Omega_{\chi}^{\nu_s} < \Omega_{\chi}^{\text{obs}} \]
3.5 keV line excess!

- Bulbul et al (2014)

Stacked 73 clusters XMM-MOS (4-5σ)

Also
Chandra Perseus 2.5σ and 3.4σ
3.5 keV line excess!

- Boyarsky et al (2014)

\[ \sin^2(2 \theta) \sim 2 \text{-} 20 \times 10^{-11} \]
Follow-up Observations (2014)

1. Rimer-Sorensen [1405.7943] Chandra GC
4. Malyshev + [1408.3531] XMM dwarfs
5. Anderson + [1408.4115] Chandra+XMM Galaxies
6. Urban + [1411.0050] Suzaku Clusters
Follow-up Observations (15-17)

1. Sekiya+ [1504.02826] Suzaku Diffuse Background
2. Figueroa-Feliciano+ [1506.05519] XQC MW
3. Riemer-Sorensen+ [1507.01378] NuSTAR Bullet Clusters
4. Iakubovskyi+ [1508.05186] XMM Individual Clusters
5. Jeltema Profumo [1512.01239] XMM Draco
6. Ruchayskyiy+ [1512.07217] XMM Draco
7. Franse+ [1604.01759] Suzaku Perseus
8. Bulbul+ [1605.02034] Suzaku Stacked Clusters
9. Hofmann+ [1606.04091] Chandra Stacked Clusters

10. Neronov+ [1607.07328] NuSTAR MW
12. Perez+ [1609.00667] NuSTAR GC
13. Cappelluti [1701.07932] Chandra Deep field 10 Ms (3 sigma)

And some that I may have missed......
Everything
What is the 3.5 keV line?

• New astrophysical lines
  – Sulphur charge exchange line?
    Gu + 2015, Shah+ 2016

• Atomic abundance/ emissivity
  – Systematics? Urban + 2015 ......

• Particle Physics Models
  – ALP magnetic conversion [B-field]?
    Cicoli+ 2014........
  – Exciting Dark Matter [Velocity]?
    Finkbeiner & Weiner 2014
  – ++++++
What to do next?

- New Instruments?
  - Astro-H (Hitomi)
  - Sounding Rockets
  - NuSTAR
  - Insight/HXMT ??

- New Techniques?
  - Velocity Spectroscopy

other detections (Bu14a, Franse et al. 2016). Studying the origin of the 3.5 keV line with CCD resolution observations of galaxy clusters and other astronomical objects appears to have reached its limit; the problem requires higher-resolution spectroscopy such as that expected from *Hitomi* (Astro-H).

Bulbul+ 2016
Astro-H (Hitomi)

- Launched in Feb 17, 2016
- $10^{-3}$ energy resolution

Figure 48: Simulated spectra of the Perseus core at $z = 0.0178$ with (black) and without (red) a dark matter line at 3.55 keV after an exposure of 1 Msec by SXS. For the dark matter line, we adopt the flux $3 \times 10^5$ ph s$^{-1}$ cm$^{-2}$ within the field-of-view of SXS from Table 5 of Bulbul et al. (2014) and $W_{dm} = 35$ eV corresponding to the velocity dispersion $v_{dm} = 1300$ km s$^{-1}$. For the ICM thermal emission, we assume $kT = 4$ keV and $Z = 0.7$ solar with no turbulent broadening.

Mainly due to the Galactic line emission. A major improvement in the sensitivity is expected in the hard band for the flux within the field-of-view of SXS, whereas the sensitivity is largely limited by the small grasp of SXS for the flux from the larger sky area. We stress that a highly improved spectral resolution will still be indispensable for identifying or rejecting any candidate lines once they are suggested.

Acknowledgments
We thank Louis Strigari, Ayuki Kamada, and Naoki Yoshida for many useful discussions on the dark matter search and their considerable input to Section 9.

Appendix
A Systematic Errors in Gas Velocities
For bright X-ray sources such as cores of nearby galaxy clusters, the accuracy of gas velocity measurements by ASTRO-H SXS can be limited by systematic errors rather than statistical errors. This section summarizes potential sources of the systematic errors and how they affect the measurements of bulk and turbulent velocities.

A.1 Bulk Velocity
Calibration errors in the energy gain $E_{\text{gain}}$ directly lead to the uncertainty in the line-of-sight bulk velocity measured by a line shift as

$$v_{\text{bulk}} = \frac{c}{E_{\text{gain}} E_{\text{obs}}} \times 45 \text{ km/s}.$$

Simulation

Kitayama+
1412.1176
Astro-H (Hitomi)

- Launched in Feb 17, 2016
- $10^{-3}$ energy resolution

**May not 100% answer the dark matter question**
Dark Matter Velocity Spectroscopy

Speckhard, KCYN, Beacom, Laha
Phys. Rev. Lett. 116, 031301

Milky Way illustration by Nick Risinger (CC:BY); additional graphics by APS/Alan Stonebraker
Milky Way Gas (Background)

- Gas and the Sun co-rotate in a disk
  - \( V^2 \sim GM/r \)

- Astro-physical line
  - Red shifted in + longitude!

\[
\nu_{\text{LOS}} = (\vec{v}_{\text{gas}} - \vec{v}_\odot) \cdot \hat{r}_{\text{LOS}} > 0
\]
Dark Matter

• Velocity of the Sun
  – (+)220 km/s, +longitude

• Mean dark matter velocity
  ~ 0

• DM line
  – Blue shifted for +longitude

\[ \nu_{\text{LOS}} = (\vec{v}_\chi - \vec{v}_\odot) \cdot \hat{r}_{\text{LOS}} < 0 \]
Dark Matter Velocity Spectroscopy

- Need to model both line shifts and line widths

\[
\frac{dF}{dE} = \frac{1}{4\pi} \frac{\Gamma}{m_\chi} \frac{dN}{dE} \int d\Omega \int d\ell \rho_\chi[r(\ell)]
\]

Line dispersion
- MW Gravitational potential

Atomic tomography

\[
\frac{1}{R_\odot \rho_\odot} \int ds \rho_\chi(r[s, \psi]) \frac{d\tilde{N}(E - \delta E_{\text{MW}}, r[s, \psi])}{dE}
\]
DM – Astro Separation (MW)

- Clean separation
  - DM
  - Astro
  - Detector effect

- Two obs. -> 3.6σ

- Minimal theoretical uncertainty
Spectrum

- 2Ms Astro-H observation
  \[ \rightarrow > 5 \text{ sigma detection} \]
- Taken into account both intrinsic and detector line dispersion.
DM Velocity Spectroscopy

- Extra handle for testing line-like signal
  - The “smoking gun” sometimes is not enough

- If DM decay/annihilation produces a line.
  - HERD (GeV-TeV)
    - Photons and electrons
    - 2020?

- Dark astronomy/cosmology
A Series of Unfortunate Events......

Software error doomed Japanese Hitomi spacecraft

Space agency declares the astronomy satellite a loss.
A new Mission!

- Two detectors
- 2020-2021?

The XRISM project initiated by JAXA

JAXA has established the project team for X-Ray Imaging and Spectroscopy Mission (XRISM, previously ASTRO-H) which had been in preparation under the name X-ray Astro-H. Held in June, JAXA confirmed that all aspects of project implementation, including the management system, are all satisfactory, and that the necessary countermeasures for the ASTRO-H project team dated 2018 July 1.

XRISM is scheduled for launch during the Japanese Fiscal Year 2020 (April 2020-March 2021).
Sounding rocket (XQC, Micro-X)

http://space.mit.edu/micro-x/open-house/files/Micro-X-Pup-A-2.png
Sounding Rockets

• XQC (2011, 106s)
• Micro-X
  – Will likely detect the line!

Figueroa-Feliciano+ [1506.05519]
Velocity Spectroscopy with Micro-X?

• Wide FOV

• Tested with Nbody simulation
  – Micro-X
  – 6 obs, >3σ

• Looks promising!

1611.02714
Powell, Laha, KCYN, Abel
Sterile Neutrino Dark Matter

Model Dependent (nuMSM)

Not applicable in, e.g. 0711.4646, Petraki, Kusenko, 1507.01977, Patwardhan et al, Etc etc

$\Omega_\chi^{\nu_s} > \Omega_\chi^{obs}$

$\Omega_\chi^{\nu_s} < \Omega_\chi^{obs}$

$\sin^2 2\theta$

$m_\chi$ [ keV ]

MW satellite counts and phase space constraints

Previous X-ray constraints

$\nu$MSM

Model Independent
NuSTAR

• Nuclear Spectroscopic Telescope Array

• Neronov, Malyshev, Eckert [1607.07328]
  – Diffuse sky, MW halo

• Perez, KCYN, Beacom, Hersh, Horiuchi, Krivonos [1609.00667]
  – Galactic Center
NuSTAR

- Focusing observations
Zero Bounce Photons

- 1000cm$^2$ -> 10cm$^2$
- 0.1deg -> 2deg
- Diffuse Dark Matter ✔

11/21/18
Kenny C.Y. NG, IPMU 2018
NuSTAR MW GC Observation

Perez, KCYN, Beacom, Hersh, Horiuchi, Krivonos 2016 (1609.00667)

- 6 observations ~ 0.5Ms combining two detectors
Spectra

- A + B detector

Perez+ 2016
NuSTAR Background Model?

- Default background model from Wik et al 2014
- Phenomenological model

Neronov+ 2016
Checking 3.5 keV in more detail

• Occulted data in GC obs (Earth blocked)

• Not as significant (less statistic)

• Flux consistent

Preliminary

Line norm (90% C.L.) [ph cm$^{-2}$ deg$^{-2}$ s$^{-1}$ integrated over line] =
Mod A: 0 - 2e-4
Mod B: 2e-5 - 2e-4

Line norm (90% C.L.) [ph cm$^{-2}$ deg$^{-2}$ s$^{-1}$ integrated over line] =
Mod A: 0 - 1e-4
Mod B: 1e-5 - 1e-4
3.5 keV in NuSTAR

• Work in progress

• But this suggest:
  – Detector artifact
  – Detector emission
  – Maybe Solar

• Not sure about the other instruments
  – Very different detector design!

Preliminary
FIG. 5. Data and folded model spectra from FPMA (left) and FPMB (right) in 3–110 keV. Model components include the GXRE (line and continuum), the CXB (continuum), and detector backgrounds (line and continuum). The astrophysical components come from regions indicated in Fig. 4. The bottom panel shows the data relative to the best-fit model. All errors shown are statistical errors. We include an additional 5% uncorrelated systematic error (not shown) during spectral fitting and line analysis.

Our spectral model consists of four components, two from astrophysical sources and two internal to the detector. The GRXE, believed to be largely due to unresolved magnetic cataclysmic variables [25–27], is modeled as a one-temperature thermal plasma with collisionally-ionized elemental line emission [29], which describes the X-ray emitting accretion stream onto these objects, plus a 6.4 keV neutral Fe line, with the normalization of the Gaussian line and the normalization, temperature, and abundance of the plasma left as free parameters. Using the NuSTAR GC source catalog [18], the total 10–40 keV flux of resolved 2-bounce sources in our FOV is \( \sim 10^{6.6} \) ph s\(^{-1}\) cm\(^{-2}\). This negligibly small contribution of flux is absorbed into our GRXE model. The temperature of the GRXE in this one-temperature model varies by up to 20% between the six observations, motivating the uncorrelated systematic error that is included in our fit of the combined spectrum. The cosmic X-ray background (CXB), due to extragalactic emission, is modeled as a cut-off power-law, with parameters fixed to those measured by INTEGRAL [30]. These spectra are attenuated to account for absorption by the interstellar medium, with interstellar abundances as defined in [31] and photoionization cross-sections as defined in [32, 33].

The effective area for these two model components, which describe photons arriving from astrophysical sources, is multiplied by the energy-dependent efficiency for photons to pass through the detector beryllium shield. All model components include an absorption term that accounts for detector focal-plane material.

The internal detector background consists of a continuum component, modeled as a broken power-law with a break at 124 keV, and both activation and fluorescent line complexes, modeled as 29 Lorentzian lines [16]. The continuum photon indices and line energies are fixed, but normalizations for each component are fit separately for FPMA and FPMB. Since these components describe backgrounds that are internal to the detectors, they are not corrected for the efficiency of the beryllium shield. The solar background, modeled as a \( \sim 1 \) keV thermal plasma as derived in [16], is also included in this component.

In Fig. 5 we show the 3–110 keV data and folded best-fit spectral model for FPMA and FPMB, respectively. This model contains 69 free parameters and 45 frozen parameters, with the fit performed over 312 \( \times \) 2 (FPMA and FPMB) total bins. We emphasize that these two data sets are independent of each other; our results are obtained by statistically combining them. Spectral fitting and flux derivations were performed in XSPEC version 12.9.0 [34]. The combined fit yields a \( \chi^2 = 540.02 \) for 554 degrees of freedom, or \( \chi^2/\text{n.d.o.f.} = 0.97 \) (both statistical and 5% systematic errors included). The physical interpretation of the best-fit GRXE spectrum will be the subject of a future paper, and is not important for this.
Dark Matter Limit

Resonantly produced Sterile Neutrino Dark Matter in nuMSM

Strong limits above \~10\,keV

Perez+ 2016
NuSTAR Andromeda

- 8 observations
- 1.2 Ms (A + B module)

KCYN, Roach, Perez, Beacom, Horiuchi, Krivonos, Wik
181X.XXXXX

Preliminary

11/21/18
Kenny C.Y. NG, IPMU 2018
NuSTAR M31 Spectrum

- **0-bounce + 2 bounce!**
  - 1.5x (decay) – 2.5x (ann.) signal boost
- **> 5keV**
  - Understanding the low energy background (in prep.)
- Lower astrophysical background
- Statistically combined (not stacked)
NuSTAR M31 Constraints

• Closing in the nuMSM window
  – New production method for SnuDM

• Updated production computation
Conclusion

- Jury is still out for the 3.5 keV line.
- New Hitomi (maybe 2021)  
  - Apply Velocity Spectroscopy
- Micro-X (1 flight launched Jul 2018)
- NuSTAR may be surprisingly powerful at 3.5keV  
  - Or maybe not
- NuMSM under siege
- Athena (~ 2029) ......

Thanks you!
Correction factor

![Graph showing correction factors for decay and annihilation as a function of energy. The graph has a logarithmic x-axis labeled 'Energy [keV]' ranging from $10^1$ to $10^2$, and a linear y-axis ranging from 0.0 to 3.0. Two lines are plotted: one blue labeled '2b correction factor [decay]' and one orange labeled '2b correction factor [annihilation].']
NuSTAR

- Focusing observations

### Table 2: Key Observatory Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>3 – 78.4 keV</td>
</tr>
<tr>
<td>Angular resolution (HPD)</td>
<td>$58''$</td>
</tr>
<tr>
<td>Angular resolution (FWHM)</td>
<td>$18''$</td>
</tr>
<tr>
<td>FoV (50% resp.) at 10 keV</td>
<td>$10''$</td>
</tr>
<tr>
<td>FoV (50% resp.) at 68 keV</td>
<td>$6''$</td>
</tr>
<tr>
<td>Sensitivity (6 – 10 keV) [10$^6$ s, 3σ, ΔE/E = 0.5]</td>
<td>$2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Sensitivity (10 – 30 keV) [10$^6$ s, 3σ, ΔE/E = 0.5]</td>
<td>$1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Background in HPD (10 – 30 keV)</td>
<td>$1.1 \times 10^{-3}$ cts s$^{-1}$</td>
</tr>
<tr>
<td>Background in HPD (30 – 60 keV)</td>
<td>$8.4 \times 10^{-4}$ cts s$^{-1}$</td>
</tr>
<tr>
<td>Spectral resolution (FWHM)</td>
<td>400 eV at 10 keV, 900 eV at 68 keV</td>
</tr>
<tr>
<td>Strong source (&gt; 10σ) positioning</td>
<td>$1.5''$ (1σ)</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>2 μs</td>
</tr>
<tr>
<td>Target of opportunity response</td>
<td>&lt; 24 hr</td>
</tr>
<tr>
<td>Slew rate</td>
<td>0.06° s$^{-1}$</td>
</tr>
<tr>
<td>Settling time</td>
<td>200 s (typ)</td>
</tr>
</tbody>
</table>
Zero Bounce Photons

FIG. 2: The ratio of the aperture and the focused parts of the dark matter signal as a function of energy.

Neronov+ 2016
NuSTAR diffuse MW

Neronov+ 2016
[Latest] Chandra Deep Sky 1701.07932

- ~3 sigma detection
Velocity Spectroscopy

- $10^{-3}$ E resolution $\leftrightarrow$ Typical MW velocity ($\sim 100$ km/s)
  - Velocity effects become important!

- CO, AL26
[Latest] Chandra Deep Sky 1701.07932

• Morphology consistent with NFW

• Consistent rates