Sterile neutrinos as dark matter

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Neutrino dark matter

Neutrino seems to be a perfect dark matter candidate: neutral, long-lived, massive, abundantly produced in the early Universe

**Cosmic neutrinos**

- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 112 \text{ cm}^{-3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11 \text{ eV}$

**Tremaine-Gunn bound (1979)**

- Such light neutrinos cannot form small galaxies – one would have to put too many of them and violated Pauli exclusion principle
- Minimal mass for fermion dark matter $\sim 300 - 400 \text{ eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would **overclose the Universe**
The final blow to neutrino as dark matter came in mid-80s when M. Davis, G. Efstathiou, C. Frenk, S. White, et al. “Clustering in a neutrino-dominated universe”

They argued that structure formation in the neutrino dominated Universe (with masses around 100 eV would be incompatible with the observations)


Abstract

The nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution has been simulated The conventional neutrino-dominated picture appears to be ruled out.
Two generalizations of neutrino DM

- Dark matter cannot be both light and weakly interacting at the same time.
- To satisfy Tremaine-Gunn bound the number density of any dark matter made of fermions should be less than that of neutrinos.
- Neutrinos are light, therefore they decouple relativistic and their equilibrium number density is $\propto T^3$ at freeze-out.

First alternative: WIMP

One can make dark matter heavy and therefore their number density is Boltzmann-suppressed ($n \propto e^{-m/T}$) at freeze-out.

Second alternative: super-WIMP

One can make dark matter interacting super-weakly so that their number density never reaches equilibrium value.
Need a particle “like neutrino” but with larger mass and weaker interaction strength

Sterile neutrino $N$: admixture of a new, heavier, state to the neutrino

“Inherits” interaction from neutrino

\[
\mathcal{L}_{int} = \frac{g}{\sqrt{2}} W^+_\mu N^c U^* \gamma^\mu (1 - \gamma_5) \ell^- + \frac{g}{2 \cos \theta_W} Z_{\mu N^c} U^* \gamma^\mu (1 - \gamma_5) \nu + \ldots
\]
Sterile neutrino + Okkam razor

Sterile neutrinos can explain...

- Neutrino masses: Bilenky & Pontecorvo’76; Minkowski’77; Yanagida’79; Gell-Mann et al.’79; Mohapatra & Senjanovic’80; Schechter & Valle’80
- Baryon asymmetry: Fukugita & Yanagida’86; Akhmedov, Smirnov & Rubakov’98; Pilaftsis & Underwood’04-05;
- Dark matter: Dodelson & Widrow’93; Shi & Fuller’99; Dolgov & Hansen’00

A minimal model of particle physics and cosmology: \( \nuMSM \)

Sharing success of the Standard Model at accelerators and resolving major BSM observational problems

Asaka & Shaposhnikov’05; Review: Boyarsky+’09
Properties of sterile neutrino dark matter

- Can be **light** (down to Tremaine-Gunn bound)
- Can be **decaying** (via small mixing with an active neutrino state)

\[ \int \rho_{\text{DM}}(r) \]

- Can be **warm** (born relativistic and cool down later)

The decay signal is proportional to \( \int \rho_{\text{DM}}(r) \)
Signal from different DM-dominated objects


\[ S = \int \rho_{dm}(r) dr \]

(Column density)
Search for Dark Matter decays in X-rays

See “Next decade in sterile neutrino studies” by Boyarsky et al. [Physics of the Dark Universe, 1 (2013)]

Available X-ray satellites:
Suzaku, XMM-Newton,
Chandra, INTEGRAL, NuStar

Signal-to-noise \( \propto \frac{S_{DM} \sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E}}{\text{signal-over-background}} \)

All types of individual objects/observations have been tried: galaxies (LMC, Ursa Minor, Draco, Milky Way, M31, M33, ...); galaxy clusters (Bullet cluster, Coma, Virgo, ...) with all the X-ray instruments.
Detection of An Unidentified Emission Line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul\textsuperscript{1,2}, Maxim Markevitch\textsuperscript{2}, Adam Foster\textsuperscript{3}, Randall K. Smith\textsuperscript{1} Michael Loewenstein\textsuperscript{2}, and Scott W. Randall\textsuperscript{1}

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An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{27} - 10^{28}$ sec (uncertainty: factor $\sim 3 - 5$)

Decaying dark matter?
Interpretations

There are 4 classes of interpretations

- Statistical fluctuation (there is nothing there at all!)
- Unknown astrophysical emission line (emission line of some chemical element)
- Instrumental feature (systematics) (We do not know our telescopes well enough)
- Dark matter decay line
Significance of the original signal

**M31 galaxy**  $\Delta \chi^2 = 13.0$  3.2$\sigma$ for 2 d.o.f.
**Perseus cluster (MOS)**  $\Delta \chi^2 = 9.1$  2.5$\sigma$ for 2 d.o.f.
**Perseus cluster (PN)**  $\Delta \chi^2 = 8.0$  2.4$\sigma$ for 2 d.o.f.
**M31 + Perseus (MOS)**  $\Delta \chi^2 = 25.9$  4.4$\sigma$ for 3 d.o.f.

**Global** significance of detecting the same signal in 3 datasets: 4.8$\sigma$

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**73 clusters (XMM, MOS)**  $\Delta \chi^2 = 22.8$  4.3$\sigma$ for 2 d.o.f.
**73 clusters (XMM, PN)**  $\Delta \chi^2 = 13.9$  3.3$\sigma$ for 2 d.o.f.

**Perseus center (XMM, MOS)**  $\Delta \chi^2 = 12.8$  3.1$\sigma$ for 2 d.o.f.
**Perseus center (Chandra, ACIS-S)**  $\Delta \chi^2 = 11.8$  3.0$\sigma$ for 2 d.o.f.
**Perseus center (Chandra, ACIS-I)**  $\Delta \chi^2 = 6.2$  2.5$\sigma$ for 1 d.o.f.

More detections followed!
We are surrounded by the Milky Way halo on all sides.

Expect signal from any direction. Intensity drops with off-center angle.

Surface brightness profile of the Milky Way would be a “smoking gun”.

We are here

Dark matter is everywhere
No line is seen in 16 Msec observations of off-center Milky Way

Confirmed by

- [(Sekiya et al. [1504.02826]) with Suzaku]
- [(Figueroa-Feliciano et al. [1506.05519]) with XQC]

Is this the end of the story?
Gaalactic center – a non-trivial consistency check

- 4σ+ statistical significance
- Also in S. Riemer-Sorensen’14; Jeltema & Profumo’14

The observed signal fits into the predicted range
Another X-ray satellite: NuStar

- Has small field of view, would not be competitive with XMM, Chandra or Suzaku
- **But!** NuStar has a special 0-bounce photons mode where FoV is 30 deg$^2$
The 3.5 keV is present in the 0-bounce spectrum of the Cosmos field and CDFS (total cleaned exposure 7.5 Msec)

Combined detection has 11σ significance

The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band

The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure

However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux
Line in Chandra from the same region of the sky
Cappelluti+’17 [1701.07932]

- Combined 10 Msec of Chandra observation of COSMOS and CDFS fields (same as NuStar)
- $3\sigma$ detection of a line at $\sim 3.5$ keV
- Flux is compatible with NuStar
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115^\circ$ off center)
Not systematics!

By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely.

- Line is changing with redshift
- ACIS-I is a silicon CCD while the imagers of NuSTAR are two Cadmium-Zinc-Telluride detectors
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely
- Different orbits of satellites – cosmic ray origin is unlikely
- Datasets accumulated over different periods (15yrs for Chandra vs. 3yrs for Nustar) – not related to, e.g. solar activity

Is this a line from atomic transition(s)?

As argued by [Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+]
Next step for 3.5 keV line: resolve the line

- A new microcalorimeter with a superb spectral resolution – Hitomi (Astro-H) was launched February 17, 2016

- During the first month of observations (calibration phase) it observed the central part of the Perseus galaxy cluster where strong line was detected by XMM & Suzaku

- Spectrometer of Hitomi is able to resolve atomic lines, measure their positions and widths (due to Doppler broadening)

Unfortunately, the satellite was lost few weeks after the launch
What did we learn with existing Hitomi data?

- Even the short observation of Hitomi showed no nearby astrophysical lines in Perseus cluster $\rightarrow$ 3.5 keV line is not astrophysical [Hitomi collaboration, 1607.04487]

- Astrophysical lines in the center are Doppler broadened with velocity $v_{th} \sim 10^2$ km/sec (as measured by Hitomi collaboration)

- Decaying dark matter line broadening is determined by the virial velocity of the Perseus galaxy cluster, $v_{vir} \sim 10^3$ km/sec

- For XMM/Chandra/Suzaku/Nustar there was no difference – they resolution did not allow to distinguish broad from narrow lines

- Hitomi sensitivity to broad line is much weaker

[1705.01837]
Surface brightness profile of the 3.5 keV line in the Milky Way. PRELIMINARY

All detection in the Milky Way follow the same trend
Future of decaying dark matter searches in X-rays

**Another Hitomi (around 2020)**

It is planned to send a replacement of the Hitomi satellite

**Microcalorimeter on sounding rocket (2019)**

- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line’s position and width

**Athena+ (around 2028)**

- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10 \times$ that of XMM)
- Super spectral resolution

“Dark matter astronomy era” begins?
Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$

(Absorption $1s \rightarrow 2p$)

Absorption occurs at $\lambda = 1215.67\text{Å}$ in the local reference frame of hydrogen cloud.

Observer sees the forest: $\lambda = (1 + z)1215.67\text{Å}$
Suppression in the flux power spectrum (SDSS)

What we want to detect

- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the $\Lambda$CDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

- We observe flux power spectrum – projected along the line-of-sight power spectrum of neutral hydrogen absorption lines

3D linear matter power spectra

BOSS (SDSS-III) Ly-$\alpha$ [1512.01981]
High-resolution Ly-α forest

Warm dark matter predicts suppression (cut-off) in the flux power spectrum derived from the Lyman-α forest data.

Lyman-α from HIRES data [1306.2314]

- HIRES flux power spectrum exhibits suppression at small scales
- Is this warm dark matter?
But we measure neutral hydrogen!

Lyman-$\alpha$ forest method is based on the underlying assumption

The distribution of neutral hydrogen follows the DM distribution

Baryonic effects

- Temperature at redshift $z$ (Doppler broadening) – increases hydrogen absorption line width
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)
Baryonic effects: Doppler broadening

- The gas is following Maxwell distribution (in the direction along the l.o.s.):

\[ f(v_z) = \frac{1}{\sqrt{\pi b_T}} e^{-\frac{v_z^2}{b_T^2}} \]  

- \( b_T = \sqrt{\frac{2kT}{m}} \) being the thermal dispersion.

Effect of Doppler broadening for CDM flux power spectra

CDM + Doppler broadening

- CDM with the IGM temperature $\sim 10^4$ K is able to explain the MIKE/HIRES flux power spectrum.
- Different temperature mean different neutral hydrogen fraction $\Rightarrow$ form of the spectrum changes.
- For the range of temperatures the optical depth is within observational limits ($\tau_{\text{EFF}}(z = 5) = 1.8 \pm 0.1$).
What is known about the IGM thermal history?

Current measurements of IGM temperature

- There are many measurements at $z < 5$
- There is a single measurement above $z = 6$
- History of reionization at higher redshifts is poorly constrained
Can we explain shape of the flux power spectrum by the free-streaming of DM particles?

[Garzilli, Boyarsky, Ruchayskiy (2015)]

Yes! We can

- The shape of the flux power spectrum can be explained by various DM models with non-zero free streaming
- Can be explained by:
  - thermal relics with $M \sim 2.7$ keV
  - resonantly produced sterile neutrinos with $M = 7$ keV and $L_6 \sim 8 - 12$
- WDM evolution can fit the shape $P(k)$ at different redshifts

If the shape of the HIRES flux power spectrum is explained by the DM free-streaming, one predicts IGM medium with $T \sim 2000 - 5000$ K at $z \sim 5$
Current sterile neutrino DM parameter space

By accident (or maybe not) the sterile neutrino dark matter interpretation of 3.5 keV line predicts exactly the amount of suppression of power spectrum observed in HIRES/MIKE (and fully consistent with all other structure formation bounds)
What fits the data better?

[Garzilli, Boyarsky, Ruchayskiy (2015)]

Data has slight preference towards WDM with cold IGM temperature
The latest results from Ly-\(\alpha\) forest [1706.03118]

- Data from SDSS-III (BOSS) + X-Shooter + HIRES
- Limited set of thermal histories
Conclusions

Thank you for your attention!
Conclusions

- The 3.5 keV line has been observed by 4 X-ray satellites
- The line passes a number of “sanity checks” for a decaying dark matter candidate
- By accident (or maybe not) sterile neutrino dark matter interpretation of 3.5 keV line predicts exactly the amount of suppression of power spectrum observed in HIRES/MIKE (and fully consistent with all other structure formation bounds)
- High-resolution X-ray satellite will eventually tell us the origin of the line
Backup slides
Why clusters do not obviously win?

- Virial theorem relates size of the object and temperature of the gas

\[ k_B T \sim G_N \frac{\text{Mass}}{\text{Size}} \]

- in terms of numbers

\[ T \sim 10 \text{ keV} \left( \frac{\text{Overdensity}}{10^3} \right) \left( \frac{\text{Size}}{\text{Mpc}} \right) \]

\[ \text{Counts/s/keV} \]

\[ \text{Energy (keV)} \]

\[ \text{Observed – Model} / \text{Model} \]

[Werner et al.’2006]
Challenges: X-ray sky is never “empty”

- ... non-cosmic background is due primarily to energetic particles interacting directly with the detector, or interacting with material around the detector and producing fluorescent X-rays that then strike the detector.
- This ”particle-induced background” has multiple components and each component is temporally variable, although on different scales.

[(Lumb et al. (2005); Kuntz & Snowden 2008)]
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Decaying dark matter?
Perseus galaxy cluster (0.5/0.2 Msec)

Bulbul et al. took only 2 central XMM observation – 14′ around the cluster’s center. Also Carlson et al.; Urban et al.

We took 16 observations excluding 2 central XMM observations to avoid modeling complicated central emission.
Andromeda galaxy
Andromeda galaxy (1 Msec)

Zoom at 3-4 keV range

Interpretations I

There are 4 classes of interpretations

- Statistical fluctuation (there is nothing there at all!)
- Unknown astrophysical emission line (emission line of some chemical element)
- Instrumental feature (systematics) (We do not know our telescopes well enough)
- Dark matter decay line
One can check that the signal

- Appears in various datasets. Becomes more significant with increased statistics ⇒ rules out *Statistical fluctuation*
- Detected with different instruments ⇒ rules out *Systematics*
- Correctly scales with redshift? ⇒ rules out *Systematics*
- Intensity of the line correctly changes within the object ⇒ rules out *Systematics* and *Astrophysical explanation*
- Correlates with (expected!) dark matter density in different objects ⇒ Confirms *dark matter origin*
Perseus surface brightness profile (2014)
Perseus cluster with XMM + Suzaku (2016)
J. Franse et al. “Radial Profile of the 3.55 keV line out to R200 in the Perseus Cluster”
[[1604.01759]]

- Confirms the line’s presence in the Perseus cluster’s core (c.f. Bulbul et al.; Urban et al.; in contrast with Tamura et al.)
- Off-center consistent with XMM results of (Boyarsky et al.’14)
- Surface brightness profile different from that of astrophysical lines and consistent with Dark Matter interpretation
Redshift scaling

Full sample of [Bulbul et al.] included both nearby and distant clusters

All spectra blue-shifted in the reference frame of clusters

- Perseus redshift means energy shift by $\sim 60\text{ eV}$ ($z \approx 0.018$)
- We detect it with $\sim 2\sigma$ (position of the line has about 30 eV uncertainty)
Stacked galaxy clusters with XMM + Suzaku


Distant clusters dataset with Suzaku satellite – consistent with XMM [(Bulbul et al. [1605.02034])]

The signal scales with redshift – unlike detector lines it gets stronger when one co-adds blueshifted spectra
Subsequent works

For overview see e.g. [1602.04816] “A White Paper on keV Sterile Neutrino Dark Matter”

- Subsequent works confirmed the presence of the 3.5 keV line in some of the objects
  Boyarsky O.R., Iakubovskyi; Franse;
  Bulbul; Urban; Cappelluti+
- challenged it existence in other objects
  Malyshev; Anderson; Tamura; Sekiya+
- argued astrophysical origin of the line
  Gu; Carlson; Jeltema & Profumo;
  Riemer-Sørensen; Phillips+

No common explanation for every detection and non-detection

... apart from decaying dark matter signal

... given uncertainties of our knowledge of the Dark Matter content in individual objects
Dwarf spheroidal satellites of the Milky Way

- Small galaxies inside the Milky Way
- About 30 are observed
- Too small to confine X-ray emitting gas – really dark
- Best observational targets: nearby, dark, dark matter content known fairly well

Dwarf spheroidal satellites of the Milky Way

[Based on [1408.0002]]
Dwarf spheroidal satellites of the Milky Way

[Based on [1408.0002]]
Dedicated observation of Draco dwarf

- XMM-Newton’s time allocation committee has just granted us 1.4 Mega-seconds (PI: A. Boyarsky)
- This is 10% of the XMM’s annual observational budget!

...the panel recognised that a detection of the 3.5 keV line in Draco would be a spectacular discovery. Even the non-detection represents an important result since it will rule out the dark matter origin of the 3.5 keV line detected by several teams earlier this year. Overall, the panel felt that this observation can and will trigger a lot of discussion on this topic...
Draco observations

Ruchayskiy, Boyarsky et al. “Searching for decaying dark matter in deep XMM-Newton observation of the Draco dwarf spheroidal” [[1512.07217]]

- Positive result from an X-ray quiet object would be conclusive
- Exposure time was chosen to have $2\sigma$ signals in both camera leading to a $3\sigma+$ combined detection detection from Draco dSph
- MOS camera had a downward fluctuation (or there is some unknown systematics)
- Unfortunately, this neither confirm nor rule out anything
What if this signal is real?

The signal can be interpreted in terms of 7 keV sterile neutrino with the mixing angle $\sin^2 \theta \sim 10^{-11}$. Lepton asymmetry $L_6 \sim 10$ in the $\nu$MSM [Boyarsky+ 2014]
What if this signal is real?

The sterile neutrino with such mass/mixing angle fits the high-resolution Lyman-α data (in $k$- and redshift space) [Garzilli+ 2015; 2017]
What if this signal is real?

The model reproduces observational properties of Milky Way and Local Group [Lovell+ [1611.00010]]
From 3D to 1D matter power spectrum

- Dimensionless linear matter power spectrum of CDM:
  \[ \Delta^2(k) \equiv \frac{k^3 P(k)}{2\pi^2} \]  
  (2)

- Projection along the line-of-sight:
  \[ P_{1d}(k) = \frac{1}{2\pi} \int_k^\infty P(k') k' dk' \propto \log k \]  
  (3)

  and correspondingly

  \[ \Delta^2_{1d}(k) = k P_{1d}(k) \propto \log k, \quad \text{large } k \]  
  (4)

- CDM 1D matter power spectrum grows at small scales!

- Lyman-\(\alpha\) forest does not measure 1D power-spectrum in real space

- It measures absorption features – power spectrum in redshift space
Redshift-space distortion

\[ z_{\text{obs}} = z_{\text{true}} + \frac{v_{\text{pec}}}{c} \]
Redshift distortion space effect? I

- Even for $\Lambda$CDM the non-linear power spectrum (measured from the redshifts of lines as in Lyman-$\alpha$) will exhibit the suppression at small scales (matter falls towards overdensities)

[Desjacques & Nusser’04]
In the HIRES spectra the suppression happens at scales

\[ k_v \sim 0.02 \text{ sec/km} \]

This corresponds to the following comoving scale (at \( z = 5 \)):

\[ k_r \sim 8 \text{ h/Mpc} \]

Naively, this is what Desjacques & Nusser predicted?

[Desjacques & Nusser’04]
Redshift distortion effect. Resolution studies


- The work [Desjacques & Nusser’04] was based on simulations with too low resolution: $N = 256^3$, $L_{\text{box}} = 100 \, \text{Mpc}/h$. As a result, one cannot make predictions for

$$k \gtrsim \frac{N}{L_{\text{box}}} \approx 2.5 \, h/\text{Mpc}$$

- Making a better resolution simulation shows that the effect happens at too small scales to affect HIRES spectra

Flux power spectrum without baryonic effects (i.e. neutral hydrogen follows DM distribution)
Subsequent works

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- No common explanation for every detection and non-detection
- ... apart from decaying dark matter signal
  ... given uncertainties of our knowledge of the Dark Matter content in individual objects
Baryonic effects: Pressure support

- Reionization heats the gas
  - $\Rightarrow$ Gas pressure increases
- Pressure opposes collapse of structures below the Jeans scale
  
  \[
  \ell_J(t) = \frac{c_s(t)}{a(t) \sqrt{4 \pi G N \bar{\rho}(t)}}
  \]  

- As a result at small scales baryonic perturbations lag behind the DM ones:
  
  \[
  \delta_b(k) = \delta_{\text{DM}}(k) e^{-k^2 \ell_F^2(t)}
  \]  

  — suppression of the flux power spectrum as compared to the matter power spectrum \[\text{[Gnedin & Hui'98]}\]
- The filtering scale $\ell_F$ at redshift $z$ is related to the Jeans length in the past \[\text{[Gnedin & Hui'98]}\]
  
  \[
  \ell_F^2(t) = \frac{1}{D_+(t)} \int_0^t dt' a^2(t') \left[ \ddot{D}_+(t') + 2H(t') \dot{D}_+(t') \right] \ell_J^2(t') \int_t^{t''} \frac{dt''}{a^2(t'')}
  \]
Baryonic effects: Pressure support II

- Filtering scale depends on the temperature history of IGM
- If in the past the Universe was hot, large Jeans length erased perturbations up to some large scale $\ell_{J}^{past}$
- Filtering scale today will be (roughly) the maximal Jeans scale over the period of reionization
- If the gas has since cooled (for example, because the sources of ionization had turned off) – it takes time for gas to relax