The Nature of Dark matter

Oleg Ruchayskiy
on behalf of participants
of the proposal 76480 (AO-14)
PI: A. Boyarsky

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Dark matter in astrophysics and cosmology

One of the most firmly established evidence for new physics

Dark matter in astrophysics

- Dynamics of stars in galaxies and gas in galaxies . . .
- Dynamics of galaxies in galaxy clusters . . .
- Hot X-ray emitting gas in galaxy clusters . . .
- Gravitational lensing . . .
Dark matter in cosmology

- The Universe is full of structures today
- ... but was very homogeneous in the past

At recombination baryon density contrast \( \delta_{\text{baryon}} \sim 10^{-5} \)
- Small overdensities grow linear with redshift
- Without dark matter today \( \delta_{\text{baryon}} \sim (1 + z)10^{-5} \sim 10^{-2} \)

Dark matter is the substance that was not coupled to photons and drove the formation of structures in the Universe
Neutrino dark matter

Cosmic neutrinos
- Neutrino seems to be a perfect dark matter candidate: neutral, stable, massive, abundantly produced in the early Universe
- We know how neutrinos interact and we can compute their primordial number density \( n_\nu = 3 \times 112 \text{ cm}^{-3} \)
- 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 \( \sim 300 \text{ – } 400 \text{ eV} \)
- If particles with such mass were weakly interacting (like neutrino) – they would overclose the Universe \( (\Omega \sim 3!) \)
Beyond neutrino DM: weakly interacting particles

Dark matter cannot be both light and weakly interacting

Possible way out?

- Make dark matter particles heavy but keep interaction strength $\sim G_F$
- Number of such particles is Boltzmann-suppressed $n_{DM} \ll n_{\nu}$
- Particles should be stable – a symmetry should protect it from decay
- This class of dark matter candidates is known as Weakly Interacting Massive Particles (or WIMP$\$s)

- A typical WIMP-predicting particle physics model:
- LHC is searching for these particles, but nothing has been found so far
No new physics at electroweak scale. Alternatives?
Beyond neutrino DM: **super**-weakly interacting particles

No traces of new weakly coupled particles – what are the alternatives?

- Keep dark matter **light** but **reduce** its interaction strength $\ll G_F$
- Number of such particles is low, $n_{DM} \ll n_{\nu}$, because they were never produced in the early Universe in large amounts
- The particles can be light (all the way down to Tremaine-Gunn bound)
- No need to stabilize them – low mass and feeble interaction cross-section can make them **cosmologically long-lived**
- Such particles **appear in many particle physics models** (sterile neutrino, gravitino, axino, . . .)
Light decaying dark matter

- Two-body decay into two massless particles ($\text{DM} \rightarrow \gamma + \gamma$ or $\text{DM} \rightarrow \gamma + \nu$)
- Monochromatic decay line $E_\gamma = \frac{1}{2}m_{\text{DM}}c^2$
- The width of the decay line is determined by Doppler broadening:
  \[
  \frac{\Delta E}{E_\gamma} \sim \frac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-2}
  \]

Decay signal $\propto \int \rho_{\text{DM}}$

Annihilation signal $\propto \int \rho_{\text{DM}}^2$
Searches for radiatively decaying dark matter

Life-time $\tau$ [sec]

$M_{DM}$ [keV]

$10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$

XMM, HEAO-1
HEAO-1
PSD exceeds degenerate Fermi gas
$\tau = $ Universe life-time $\times 10^8$

Life-time $\tau$ [sec]

$m_\phi$ [MeV]

$0.01$ $0.1$ $1$ $10$ $10^2$ $10^3$ $10^4$

HEAO-1
INTEGRAL
COMPTEL
EGRET
FERMI

“Next decade of sterile neutrino studies”

[1306.4954]

Essig et al.’13
Two groups reported a line-like feature in X-ray spectra of dark matter-dominated objects

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{1}, Randall K. Smith\textsuperscript{1} Michael Loewenstein\textsuperscript{2}, and Scott W. Randall\textsuperscript{1}

\textsuperscript{1} Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
\textsuperscript{2} NASA Goddard Space Flight Center, Greenbelt, MD, USA.


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

A. Boyarsky\textsuperscript{1}, O. Ruchayskiy\textsuperscript{2}, D. Iakubovskyi\textsuperscript{3,4} and J. Franse\textsuperscript{1,5}

\textsuperscript{1}Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
\textsuperscript{2}Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

PRL (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 – 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor $\sim 0.3$ dex)
## Datasets

**Boyarsky, O.R. et al. PRL (2014) [1402.4119]**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Time (Msec)</th>
<th>$\Delta \chi^2$</th>
<th>Significance for 2 d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M31 galaxy</td>
<td>0.98</td>
<td>13.0</td>
<td>3.2σ</td>
</tr>
<tr>
<td>Perseus off-cluster (MOS)</td>
<td>0.63</td>
<td>9.1</td>
<td>2.5σ</td>
</tr>
<tr>
<td>Perseus off-cluster (PN)</td>
<td>0.22</td>
<td>8.0</td>
<td>2.4σ</td>
</tr>
<tr>
<td>Blank sky</td>
<td>15.7</td>
<td>No detection</td>
<td></td>
</tr>
<tr>
<td>M31 + Perseus (MOS)</td>
<td></td>
<td>25.9</td>
<td>4.4σ</td>
</tr>
</tbody>
</table>

Global significance of detecting the same signal in 3 datasets: **4.8σ**


<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>73 clusters (XMM, MOS)</td>
<td>6.78</td>
<td>22.8</td>
<td>4.3σ</td>
</tr>
<tr>
<td>73 clusters (XMM, PN)</td>
<td>2.06</td>
<td>13.9</td>
<td>3.3σ</td>
</tr>
<tr>
<td>69 distant clusters (XMM, MOS)</td>
<td>4.9</td>
<td>16.5</td>
<td>3.7σ</td>
</tr>
<tr>
<td>69 distant clusters (XMM, PN)</td>
<td>4.9</td>
<td>16.5</td>
<td>3.7σ</td>
</tr>
<tr>
<td>Perseus center (XMM, MOS)</td>
<td>0.32</td>
<td>12.8</td>
<td>3.1σ</td>
</tr>
<tr>
<td>Perseus center (Chandra, ACIS-S)</td>
<td></td>
<td>11.8</td>
<td>3.0σ</td>
</tr>
</tbody>
</table>
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
- challenged it existence in other objects
  Malyshev et al.; Anderson et al.; Tamura et al.; Sekiya et al.
- argued astrophysical origin of the line
  Gu et al.; Carlson et al.; Jeltema & Profumo; Riemer-Sørensen; Phillips et al.

A common explanation for every detection and non-detection?

- When comparing bounds from different objects one should be careful – uncertainty in the dark matter content in each of them results in large
Dark matter is universal

Dark matter is a universal substance, present in every galaxy (spiral, elliptical, dwarf spheroidal) and every galaxy cluster.

From the point of view of astrophysical processes these objects are very distinct!
Galactic center
Boyarsky, O.R. et al. PRL 115, 161301

- MOS camera
- 1.82 Msec
- \(4\sigma+\) statistical significance
- Also detected in S. Riemer-Sorensen [1405.7943]; T. Jeltema & S. Profumo [1408.1699]
Non-trivial consistency check
Boyarsky, O.R. et al. PRL 115, 161301
Dwarf spheroidal galaxies – smallest DM-dominated objects known

- Dwarf spheroidals are “galaxies inside our Galaxy”
- These are ancient galaxies “swallowed” by the Milky Way
- Perfect observational targets:
  - They are “dense”
  - They are “dark” ($M/L \sim 10^2 - 10^3$)
  - They are compact (typical sizes $5' - 30'$)
  - They are nearby (distances $30 - 100$ kpc)
- Dwarf spheroidal galaxies are too light and compact to confine X-ray emitting gas ($k_B T \sim G_N \frac{M_{\text{Mass}}}{\text{Size}}$)

- The best target for XMM – dwarf galaxy in the constellation of Draco – Draco dSph galaxy
- XMM-Newton’s time allocation committee granted us 1.4 Mega-seconds in AO-14

PI: A. Boyarsky
Choice of the target

Preferred target

Geringer-Sameth et al. (2014)
Why XMM?

- Signal-to-noise ratio improves as
  \[
  \frac{S}{N} = \int \rho_{DM} \sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E}
  \]

- XMM is the best among today’s missions, mainly due to its **Grasp**

Adopted from
- Boyarsky, den Herder et al.’2006;
- Neronov, O.R. et al.’2014
The line is detected in the spectrum of Draco dSph with low significance ($\Delta \chi^2 = 5.3$)

Line flux/position are consistent with previous observations:

$E = 3.54 \pm 0.06$ keV,

$F = (1.65 \pm 0.7) \times 10^{-6}$ cts/sec/cm$^2$

There is a shift in position ($\sim 1\sigma$) between MOS and PN

The data is consistent with DM interpretation for lifetime

$\tau_{DM} > (7-9) \times 10^{27}$ sec
The nature of dark matter is one of the main puzzles of modern physics. We have no idea what is dark matter mass or what type of interactions it has. A 3.5 keV spectral feature is consistent with a signal originating from dark matter decays. Systematics? – Unlikely:
- Correctly scales with redshift
- Signal not detected in some long-exposure datasets

Astrophysics (e.g. K \text{ xviii} or S \text{ xvi} charge exchange)? – Possible, but does not fit all observations!

XMM observation of Draco Dwarf Spheroidal Galaxy is a critical test!
The results from very large AO-14 observational programme support dark matter hypothesis.
Detecting a line from a dwarf galaxy at $\sim 3\sigma$ level would be crucial.
Requires another observation like this.
The line in the center of the Perseus cluster has flux $2.1^{+1.1}_{-1.0} \times 10^{-5}$ cts/sec/cm$^2$ (XMM, excluding central 1’ circle) 

The presence of the line is confirmed by Suzaku studies 

Existing 200 ksec of Hitomi spectrum of Perseus galaxy cluster should see this line even with reduce sensitivity!

Information about the line in the Perseus center (its position, intensity, width) will be crucial in deciding on further strategy of searching for 3.5 keV line with XMM and other instruments.
Outlook

If this is the dark matte signal...

A lot of exciting science

• Dark matter tomography becomes possible!
• We will be able to see 3D structures in the Universe —
  • visualized cosmic web
  • histories of major mergers
  • tidal streams
  • 3D structures of galaxy clusters
  • ...
• X-ray astronomy becomes major cosmological tool of next decades

And a major challenge for particle physics

...to detect a particle that is 73 times lighter than electron and interacts 10 orders of magnitude weaker than neutrino!
XMM-Newton is (and will remain for a long time) the best instrument to discover light decaying dark matter.
**XMM-Newton** is (and will remain for a long time) the best instrument to discover light decaying dark matter

Thank you for your attention!
Backup slides
Perseus cluster with Suzaku [1604.01759]
Jeroen Franse et al. “Radial Profile of the 3.55 keV line out to R200 in the Perseus Cluster”

- 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.)
- Not sensitive enough to probe off-center surface brightness profile
- Upper bound consistent with XMM results of (Boyarsky et al.’14)
Stacked galaxy clusters with Suzaku
Bulbul et al. [1605.02034]
Draco dSph 2015 observations

Oleg Ruchayskiy (NBI)

The nature of dark matter
Draco dSph in 2009 vs. 2015

Draco MOS spectra binned by 65 eV, 2009 year (black), 2015 year (red)

Draco PN spectra binned by 65 eV, 2009 year (black), 2015 year (red)
Independent analysis of the 2009+2015 Draco observations was done in [1512.01239]

No line detected even in PN camera

Much stronger upper limits on flux

Black cross: detection of Ruchayskiy et al. [1512.07217]

Black down arrow: 2\(\sigma\) upper limit from Ruchayskiy et al. [1512.07217]
JP15 [1512.07217] is a very succinct paper. No details of data analysis. Trying to reproduce the results we made a number of modifications of our procedure.

<table>
<thead>
<tr>
<th>PN dataset/data processing</th>
<th>Flux, $10^{-6}$ ph/cm$^2$/s</th>
<th>$\Delta \chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2015 year dataset (26 obs.) used in R15</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65 eV bin, 2.3-11 keV, NXB+CXB</td>
<td>$1.65^{+0.67}_{-0.70}$</td>
<td>5.3</td>
</tr>
<tr>
<td>65 eV bin, 2.3-11 keV, NXB+CXB no OOT corr.</td>
<td>$1.57^{+0.74}_{-0.74}$</td>
<td>4.3</td>
</tr>
<tr>
<td>5 eV bin, 2.3-11 keV, NXB+CXB</td>
<td>$1.50^{+0.67}_{-0.71}$</td>
<td>4.4</td>
</tr>
<tr>
<td>5 eV bin, 2.5-5 keV, NXB+CXB</td>
<td>$1.56^{+0.71}_{-0.76}$</td>
<td>3.9</td>
</tr>
<tr>
<td>5 eV bin, 2.5-5 keV, NXB</td>
<td>$1.18^{+0.71}_{-0.70}$</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>2009+2015 years dataset (31 obs.) used in JP15</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65 eV bin, 2.3-11 keV, NXB+CXB</td>
<td>$1.47^{+0.72}_{-0.74}$</td>
<td>4.2</td>
</tr>
<tr>
<td>5 eV bin, 2.5-5 keV, NXB</td>
<td>$1.04^{+0.66}_{-0.70}$</td>
<td>2.2</td>
</tr>
</tbody>
</table>