Sterile neutrino dark matter

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together with A. Boyarsky, M. Shaposhnikov *et al.*

Second Galileo Xu Guan Qi meeting

*July 14, 2010*
Dark Matter in the Universe

Extensive evidence for the presence of dark, non-baryonic matter, dominating the mass balance of the Universe at scales above 100 pc.
Dark matter at cosmological scales

- $\Lambda$CDM: about 20% of total energy density is in the form of non-baryonic matter

- This dark matter is scale-free (non-interacting, “cold”, …)

- Standard Model neutrinos do not contribute significantly to the Universe mass balance at matter-dominated epoch (CMB, LSS, …)
Dark matter – a fundamental physics problem

- Is evidence for missing mass convincing? — yes
- If dark matter is made of particles – what are they?

Dark matter particles are not part of the Standard Model of particle physics
Why (and where) we expect new physics?

- **Dark matter** (not a SM particle!)
  - particles with weak cross-section will have correct abundance \( \Omega_{\text{DM}} \) ("WIMP miracle"). **New scale** \( \sim 1 \text{ TeV} \)
  - Axions. **New scale** \( 10^{10} - 10^{12} \text{ GeV} \).

- **Baryon asymmetry of the Universe**: what ensured that for each \( 10^{10} \) anti-protons there was \( 10^{10} + 1 \) proton in the early Universe?
  - **Sakharov conditions**: CP-violation; B-number violation; out-of-equilibrium particles.
  - Out-of-equilibrium decay of heavy lepton \( \chi \) at temperatures \( M_{\text{EW}} < T_{\text{decay}} < M_{\chi} \) produces correct baryon-to-entropy ratio for \( M_{\chi} > 10^{11} \text{ GeV} \) – **new energy scale**

- **Fine-tuning problems**: CP-problem, hierarchy problem, grand unification, cosmological constant problem
Hierarchy problem

Quantum corrections to the Higgs mass:

- Masses of fermions are provided by the Higgs field
- Fermion corrections to the Higgs mass are proportional to their mass $M_f^2$.
- Contributions from heavy fermions ($M_f \gg 100$ GeV) would make Higgs mass heavy $M_H \sim M_f$
- To keep Higgs boson light, one should fine-tune the parameters of the model to cancel fermions’ contribution by that of Higgs
Build a model that resolves several BSM phenomena within its framework. Worry about fine-tunings later
Experiments on neutrino oscillations determined two mass differences between neutrino mass states.

Sterile (right-handed) neutrinos provide the simplest and natural extension of the Minimal SM that describe oscillations.

Make leptonic sector of the SM symmetric.
See-saw Lagrangian

Add right-handed neutrinos $N_I$ to the Standard Model

$$\mathcal{L}_{\text{right}} = i \tilde{N}_I \phi N_I + \left( \begin{array}{c} \tilde{\nu}_e \\ \tilde{\nu}_\mu \\ \tilde{\nu}_\tau \end{array} \right) \left( \begin{array}{c} F \langle H \rangle \\ N_1 \\ N_2 \\ \ldots \end{array} \right) + \left( \begin{array}{c} N_I^c \\ N_2^c \\ \ldots \end{array} \right) \left( \begin{array}{c} M \\ \ldots \end{array} \right)$$

\[ \nu_\alpha = \tilde{H} L_\alpha, \text{ where } L_\alpha \text{ are left-handed lepton doublets} \]

- Active masses are given via usual **see-saw formula**:

  \[ (m_\nu) = -M_D \frac{1}{M_I} M_D^T \quad ; \quad M_D \ll M_I \]

- Neutrino mass matrix – **7 parameters**. Dirac+Majorana mass matrix – **11 (18) parameters** for 2 (3) sterile neutrinos. **Two** sterile neutrinos are enough to fit the neutrino oscillations data.

  **Scale of Dirac and Majorana masses is not fixed!**
Some general properties of sterile neutrino

- Sterile neutrinos are **decaying particles**

<table>
<thead>
<tr>
<th>$M_I &lt; 1$ MeV</th>
<th>$M_I &gt; 1$ MeV</th>
<th>$M_I &gt; 150$ MeV</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_I \rightarrow \nu \nu \bar{\nu}$</td>
<td>$N_I \rightarrow \nu e^+ e^-$</td>
<td>$N_I \rightarrow \pi^\pm e^\mp$</td>
<td>$N_I \rightarrow \pi^0 \nu$</td>
</tr>
</tbody>
</table>

- Short lifetime – decay in the early Universe. Can have CP-violating phases. Leptogenesis? Affects BBN?

- Lifetime $\tau \propto \theta_I^{-2} M_I^{-5}$. (Cosmologically) long lifetime – dark matter candidate?

- **Mixing angle** $\theta_I$:

$$\theta_I^2 = \sum_{\alpha=e,\mu,\tau} \frac{|F_{\alpha I}|^2 v^2}{M_I^2} \ll 1$$
The scale of right-handed masses?

“Popular” choices of see-saw parameters

- Yukawa couplings $F_{\alpha I} \sim 1$, i.e. Dirac masses $M_D \sim M_t$. Majorana masses $M_I \sim 10^{15}$ GeV.

- Attractive features:
  - Provides a mechanism of baryon asymmetry of the Universe
  - Scale of Majorana masses is possibly related to GUT scale

- This model **does not provide the dark matter particle**

- Alternative? Choose Majorana masses $M_I$ of the order of masses of other SM fermions and make Yukawa couplings small
Neutrino minimal Standard Model (νMSM)

The model solves several *beyond the Standard Model problems*

✓ ... explains neutrino oscillations

✓ ... matter-antimatter asymmetry of the Universe

✓ ... provides a viable dark matter candidate that can be cold, **warm** or **mixed** (cold+warm)
Choosing parameters of the $\nu$MSM

- If $M_{2,3} \sim 100$ MeV – 20 GeV and $\Delta M_{2,3} \ll M_{2,3}$, $\nu$MSM explains **baryon asymmetry** of the Universe.

- Neutrino experiments can be explained within the same choice of parameters.

Asaka, Shaposhnikov '05

Constraints from primordial synthes of light elements

No matter-antimatter asymmetry

No neutrino oscillations
Parameters of the third sterile neutrino?

- The third sterile neutrino can couple to the SM arbitrarily weakly. **Dark matter candidate?**

- Any DM candidate must be
  - Produced in the early Universe and have correct relic abundance
  - Be stable or cosmologically long-lived
  - Very weakly interacting with electromagnetic radiation ("dark")
  - Allow to explain the observed large scale structure
The model-independent lower limit on the mass of fermionic DM.

The smaller is the DM particle mass – the bigger is the number of particles within some region of phase-space density (defined by velocity dispersion $\sigma$ and size $R$).

For fermions Pauli principle restricts number of fermions.

Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the lower bound on the DM mass $m > 300$ eV.

New dSph’s are very dense $Q_{obs} = 10^4 - 10^5 \, M_\odot \frac{\text{kpc}^{-3} \left[ \text{km} \, \text{s}^{-1} \right]^{-3}}{}$.

Bound on any fermionic DM improved to become $M_s > 0.41 \, \text{keV}$.

Can be further improved if production model of sterile neutrinos is specified.
How sterile neutrino DM is produced?

- Phenomenologically acceptable values of $\theta_1$ are so small, that the rate of this interaction $\Gamma$ of sterile neutrino with the primeval plasma is much slower than the expansion rate ($\Gamma \ll H$)
  $\Rightarrow$ Sterile neutrino are never in thermal equilibrium

- **Simplest scenario:** sterile neutrino in the early Universe interact with the rest of the SM matter via *neutrino oscillations*:

  \[
  e^- \rightarrow e^+ \quad \text{(Neutralino)} \quad q \rightarrow q' \quad \text{(Wino)}
  \]

  \[
  \nu \rightarrow \bar{\nu} \quad N_S \quad e^\pm \rightarrow \bar{\nu} \quad N_S
  \]

- Production is sharply peaked at

  \[
  T_{\text{max}} \simeq 130 \left( \frac{M_s}{\text{keV}} \right)^{1/3} \text{ MeV}
  \]
Production through oscillations

- Sterile neutrinos have non-equilibrium spectrum of primordial velocities, roughly proportional to the spectrum of active neutrinos

\[ f_s(p) \propto \frac{\theta^2}{\exp\left(\frac{p}{T_\nu}\right) + 1} \]

- Their amount less than that of active:

\[ \Omega_s h^2 \propto \theta^2 \frac{M_s}{94 \text{ eV}} \quad \text{recall: SM neutrinos } \Omega_\nu h^2 = \sum \frac{m_\nu}{94 \text{ eV}} \]

- Average momentum \( \langle p_s \rangle \sim \langle p_\nu \rangle \gg M_s \) – sterile neutrinos are produced relativistic
The presence of lepton asymmetry makes this production much more effective – **resonant production**

To be effective this mechanism requires lepton asymmetry of the order \( \frac{n_\nu - n_\bar{\nu}}{s} \gtrsim 10^{-6} \) (compare with \( \eta_B = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10} \))

Typically, one expect the lepton asymmetry to be \( \sim \eta_B \) (sphalerons equilibrate the two)

In the \( \nu \text{MSM} \) one can generate the lepton asymmetry **below** the sphaleron scale thus making it significantly large than \( \eta_B \)

The value of lepton asymmetry can be as large as

\[
L_6 \equiv 10^6 \frac{n_{\nu e} - n_{\bar{\nu} e}}{s} \lesssim 700
\]

(present BBN bound \( L_6^{\text{BBN}} \lesssim 2500 \))
Non-resonant component

Resonant component

\[ q = \frac{p}{T_\nu} \]

Laine, Shaposhnikov'08; Boyarsky, O.R., Shaposhnikov'09
Sterile neutrinos are ultra-relativistic at production

DM particles erase primordial spectrum of density perturbations on scales up to the DM particle horizon – free-streaming length

Comoving free-streaming lengths peaks around $t_{nr}$ when $\langle p \rangle \sim m$

Free-streaming horizon determines suppression scale of power spectrum of density perturbations.

An order of magnitude estimate for the free-streaming scale?

$$\lambda_{FS}^{co} \sim 1 \text{ Mpc} \left( \frac{\text{keV}}{M_s} \right) \frac{\langle p_s \rangle}{\langle p_\nu \rangle}$$
Power spectrum of density fluctuations

Current power spectrum $P(k) \left[ (h^{-1} \text{Mpc})^3 \right]$ versus Wavenumber $k [h/\text{Mpc}]$ and Wavelength $\lambda [h^{-1} \text{Mpc}]$.

- **Cosmic Microwave Background**
- **SDSS galaxies**
- **Cluster abundance**
- **Weak lensing**
- **Lyman Alpha Forest**

Tegmark & Zaldarriaga, astro-ph/0207047 + updates

Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003
Influence of primordial velocities

$P(k) \left[ \text{(Mpc/h)}^3 \right]$ vs $k \left[ \text{h/Mpc} \right]$

CDM

WDM
M=2 keV

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STERILE NEUTRINO DM
Power spectrum for sterile neutrinos

![Graph showing the ratio of matter power spectra](image)

- **Comoving wavenumber $k$ [h/Mpc]**
- **Ratio of matter power spectra** $(P(k)/P_{\Lambda CDM}(k))^{1/2}$

- **Markers and Labels**:
  - NRP $M_1=14$ keV
  - NRP $M_1=3$ keV
  - RP $M_1=3$ keV, $L_6=16$
  - CWDM, $F_{wdm}=0.2$

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Boyarsky, Lesgourgues, O.R., Viel JCAP, PRL 2009;
Neutral hydrogen in intergalactic medium is a tracer of overall matter density. Scales $0.3h/\text{Mpc} \lesssim k \lesssim 3h/\text{Mpc}$
The Lyman-α method includes

- Astronomical data analysis of quasar spectra
- Astrophysical modeling of hydrogen clouds
- N-body+hydrodynamical simulations of DM clustering at non-linear stage
- Simultaneous fit of cosmological parameters \((\Omega_b, \Omega_M, n_s, h, \sigma_8 \ldots)\). Astrophysical parameters, describing IGM, are not known and should be fitted as well (another 20+ parameters)
- The data: Lyman-α + CMB + maybe LSS \ldots (thousands of data points, sometimes correlated)

Main challenge: reliable estimate of systematic uncertainties
Lyman-\(\alpha\) bounds on CDM+WDM mixture

\[
F_{\text{WDM}} = \frac{\Omega_{\text{WDM}}}{\Omega_{\text{WDM}} + \Omega_{\text{CDM}}}
\]

Lyman-\(\alpha\) allows to restrict the shape of primordial velocity spectrum, rather than free-streaming (for example, a fraction of warm DM \((F_{\text{WDM}})\) for given mass)
Halo substructure with sterile neutrino DM

work in progress
Halo substructure with CDM
PRELIMINARY: **Aq-A-2 halo** in CDM and CDM+WDM simulations (Gao, Theuns, Frenk, O.R., ...)

- Simulated CWDM model (right) is fully compatible with the Lyman-\(\alpha\) forest data but provides a structure of Milky way-size halo different from CDM (left)
Lifetime of sterile neutrino DM candidate

- Dominant decay channel for sterile neutrino (for $M_s < 1$ MeV) is $N \to 3\nu$.

- Life-time $\tau = 5 \times 10^{26}\text{sec} \times \left(\frac{\text{keV}}{M_s}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)^2$

- Subdominant radiative decay channel
  - Photon energy: $E_{\gamma} = \frac{M_s}{2}$
  - Radiative decay width:
    $$\Gamma_{\text{rad}} = \frac{9 \alpha_{\text{EM}} G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) M_s^5$$

- Sterile neutrino DM is not completely dark. Its decay signal can be searched for in the spectra of astrophysical objects.
A DM column density

- Flux from DM decay:

\[
F_{\text{DM}} = \Gamma_{\text{rad}} \frac{E_\gamma}{M_s} \int_{\text{fov cone}} \frac{\rho_{\text{DM}}(\vec{r})}{4\pi|\vec{D}_L + \vec{r}|^2} d^3\vec{r} \approx \frac{\Gamma_{\text{rad}} \Omega_{\text{fov}}}{8\pi} S
\]

- DM column density

\[
S = \int_{\Omega_{\text{fov}}} \rho_{\text{DM}}(r) dr
\]

– integral along the line-of-sight, averaged within the instrument’s field-of-view
Decay signal from MW-sized galaxy

Simulations: B.Moore et al. 2005
Bounds on decaying DM from various objects

- MW (HEAO-1) Boyarsky, O.R. et al. 2005
- Coma and Virgo clusters Boyarsky, O.R. et al.
- Bullet cluster Boyarsky, O.R. et al. 2006
- LMC+MW(XMM) Boyarsky, O.R. et al. 2006
- MW Riemer-Sørensen et al.; Abazajian et al.
- MW (XMM) Boyarsky, O.R. et al. 2007
- M31 Watson et al. 2006; Boyarsky et al. 2007

M31

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STERILE NEUTRINO DM
Restrictions on life-time of decaying DM

Results of almost 20 published works.
Window of parameters of sterile neutrino DM

\[ \sin^2(2\theta) \]

\[ \Omega > \Omega_{DM} \]

\[ \Omega < \Omega_{DM} \]

DM mass [keV]
Window of parameters of sterile neutrino DM

\[
\sin^2(2\theta) \quad M_{\text{DM}} [\text{keV}]
\]

\[
\begin{align*}
10^{-16} & \quad 10^{-14} & \quad 10^{-12} & \quad 10^{-10} & \quad 10^{-8} & \quad 10^{-6} \\
0.3 & \quad 1 & \quad 10 & \quad 100
\end{align*}
\]

\[\Omega > \Omega_{\text{DM}}\]

\[\Omega < \Omega_{\text{DM}}\]

Asaka, Laine, Shaposhnikov'06

Laine, Shaposhnikov'08

\[
NRP
\]

BBN limit: \[L_6^{\text{BBN}} = 2500\]

\[L_6^{\text{max}} = 700\]

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STERILE NEUTRINO DM
Window of parameters of sterile neutrino DM

\[ \sin^2(2\theta) \]

\[ M_{\text{DM}} [\text{keV}] \]

Excluded from X-rays

Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008

$\sin^2(2\theta)$

$M_{DM}$ [keV]

Excluded from X-rays

Exceeds PSD of degenerate Fermi gas

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STERILE NEUTRINO DM
Window of parameters of sterile neutrino DM

\[ \sin^2(2\theta) \]

\( M_{DM} \) [keV]

\( 10^{-16} \)
\( 10^{-14} \)
\( 10^{-12} \)
\( 10^{-10} \)
\( 10^{-8} \)
\( 10^{-6} \)

Excluded from X-rays

Excluded from PSD evolution arguments

Boyarsky, Ruchayskiy et al. 2005-2008

Boyarsky, O.R., Iakubovskyi, 2008
Sterile neutrino DM in the $\nu$MSM

Phase-space density constraints

$\Omega_{N_1} > \Omega_{DM}$

$\Omega_{N_1} < \Omega_{DM}$

$X$-ray constraints

$\sin^2(2\theta_1)$

$M_1$ [keV]

$10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$

$\Omega_{N_1} > \Omega_{DM}$

$\Omega_{N_1} < \Omega_{DM}$

$B_{\text{BBN}}$ limit: $L_6^\text{BBN} = 2500$

$L_6^\text{max} = 700$

$L_6 = 70$

$L_6 = 25$

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STERILE NEUTRINO DM

39/42
Astrophysical searches for decaying DM

- Sterile neutrino DM candidates are hard to search in labs

- The decaying dark matter is a unique all-sky signal, with variations, correlated with the distribution of galaxies/galaxy clusters

- If any candidate decay line is found, the distribution of its intensity over the sky can be predicted and checked against observations.

- This makes the search for decaying dark matter a direct detection experiment

- New instruments (EDGE/XENIA) – White paper for ESA’s call for Fundamental physics roadmap
Improved bounds on DM decay

Excluded from X-ray observations

$\Omega_s > \Omega_{DM}$

$\Omega_s < \Omega_{DM}$

Excluded from Lyman-α analysis

Probed by XENIA

$\sin^2(2\theta)$

$M_s [\text{keV}]$

$10^{-16}$ $10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$

$10^{-16}$ $10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$
Probing other sterile neutrinos

<table>
<thead>
<tr>
<th>$M_2$ [GeV]</th>
<th>$10^{-13}$</th>
<th>$10^{-12}$</th>
<th>$10^{-11}$</th>
<th>$10^{-10}$</th>
<th>$10^{-9}$</th>
<th>$10^{-8}$</th>
<th>$10^{-7}$</th>
<th>$10^{-6}$</th>
<th>$10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta^2_2$</td>
<td>0.1</td>
<td>1</td>
<td>$10^2$</td>
<td>$10^3$</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^7$</td>
<td>$10^8$</td>
</tr>
</tbody>
</table>

No matter-antimatter asymmetry

Constraints from primordial synthesis of light elements

NA62 experiment (CERN)

No neutrino oscillations

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Main conclusion: sterile neutrino is a viable dark matter candidate, satisfying all existing astrophysical and cosmological bounds.
THANK YOU FOR YOUR ATTENTION
Example: Spectral feature in Willman 1

[Loewenstein & Kusenko [0912.0552]]

68%, 90% and 99% confidence intervals

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STERILE NEUTRINO DM
Checking for DM line in dSphs

- $E_{\text{line}} = (2.51 \pm 0.07) \text{ keV}$
  - $2.44 \text{ keV} - 2.58 \text{ keV (1}\sigma\text{)}$
  - $2.30 \text{ keV} - 2.72 \text{ keV (3}\sigma\text{)}$

- Line flux $F_{\text{Wil1}} = (3.53 \pm 1.95) \times 10^{-7} \text{ photons/cm}^2/\text{sec (68}\% \text{ CL)}$

- No significant lines were found in spectra of dSphs

- We obtain the following exclusions

<table>
<thead>
<tr>
<th></th>
<th>$2.44 - 2.58 \text{ keV}$</th>
<th>$2.30 - 2.72 \text{ keV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fornax dSph:</strong></td>
<td>5.1$\sigma$</td>
<td>3.3$\sigma$</td>
</tr>
<tr>
<td><strong>Sculptor dSph:</strong></td>
<td>3.0$\sigma$</td>
<td>2.5$\sigma$</td>
</tr>
<tr>
<td><strong>Fornax + Sculptor</strong></td>
<td>5.9$\sigma$</td>
<td><strong>4.1$\sigma$</strong></td>
</tr>
</tbody>
</table>

- In case of the DM decay origin of the line we were expecting about $4\sigma$ detection from Fornax. However adding the line makes fit worse.
Checking for DM line in M31

Exclusion from Fornax + Sculptor dSph:

<table>
<thead>
<tr>
<th>2.44 – 2.58 keV</th>
<th>2.30 – 2.72 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9σ</td>
<td>4.1σ</td>
</tr>
</tbody>
</table>

Andromeda galaxy

- Diffuse spectrum above 2 keV is a featureless power law

<table>
<thead>
<tr>
<th>2.44 – 2.58 keV</th>
<th>2.30 – 2.72 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>M31, 1kpc &lt; R &lt; 3kpc: 22.7σ</td>
<td>20.1σ</td>
</tr>
<tr>
<td>M31, 5 kpc off-center: circle radius 3 kpc 10.4σ</td>
<td>10.4σ</td>
</tr>
<tr>
<td>M31, both regions 24.9σ</td>
<td>23.3σ</td>
</tr>
</tbody>
</table>

- Extremely significant exclusion from central 8 kpc of Andromeda!

- All bounds are based on the conservative DM estimate from [Widrow & Dubinski'05]!
Checking for DM line in M31

- Exclusion from Fornax and Sculptor dSphs:
  \[
  \begin{array}{c|c}
  2.44 - 2.58 \text{ keV} & 2.30 - 2.72 \text{ keV} \\
  5.9\sigma & 4.1\sigma \\
  \end{array}
  \]

- Exclusion from **central 8 kpc of Andromeda**:
  \[
  \begin{array}{c|c|c}
  2.44 - 2.58 \text{ keV} & 2.30 - 2.72 \text{ keV} & \text{DM model} \\
  24.9\sigma & 23.3\sigma & [\text{Widrow \\& Dubinski’05}] \\
  7.9\sigma & 6.9\sigma & [\text{Corbelli et al.’09}] \\
  \end{array}
  \]

1001.0644
Checking for DM line in M31

In the final version of the paper we processed observations in the region 10 – 20 kpc
**Summary of exclusions**

<table>
<thead>
<tr>
<th></th>
<th>Minimal DM amount</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Corbelli et al., Burkert profile, ( r_B = 28 ) kpc, ( M/L = 8 ))</td>
</tr>
<tr>
<td>68% CL</td>
<td>2.44 keV – 2.58 keV</td>
</tr>
<tr>
<td>99% CL</td>
<td>2.30 keV – 2.72 keV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>68% CL</th>
<th>99% CL</th>
<th>68% CL</th>
<th>99% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M31</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>within 8 central kpc</td>
<td>24.9σ</td>
<td>23.3σ</td>
<td>7.9σ</td>
<td>6.9σ</td>
</tr>
<tr>
<td><strong>M31</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–20 kpc off-center</td>
<td>12.0σ</td>
<td>10.7σ</td>
<td>11.7σ</td>
<td>10.6σ</td>
</tr>
<tr>
<td><strong>All M31 obs.</strong></td>
<td>28.2σ</td>
<td>26.2σ</td>
<td>13.6σ</td>
<td>13.2σ</td>
</tr>
<tr>
<td><strong>All M31 + Fornax</strong></td>
<td>29.0σ</td>
<td>26.7σ</td>
<td>15.2σ</td>
<td><strong>14.0σ</strong></td>
</tr>
</tbody>
</table>

- The DM origin of the spectral feature in Willman 1 at \( \sim 2.5 \) keV is excluded with **14σ** significance!
### Parameters of Aquarius simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>$m_p$</th>
<th>$\epsilon$</th>
<th>$N_{hr}$</th>
<th>$N_{lr}$</th>
<th>$N_{50}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aq-A-1</td>
<td>$1.712 \times 10^3$</td>
<td>20.5</td>
<td>4,252,607,000</td>
<td>144,979,154</td>
<td>1,473,568,512</td>
</tr>
<tr>
<td>Aq-A-2</td>
<td>$1.370 \times 10^4$</td>
<td>65.8</td>
<td>531,570,000</td>
<td>75,296,170</td>
<td>184,243,536</td>
</tr>
<tr>
<td>Aq-A-3</td>
<td>$4.911 \times 10^4$</td>
<td>120.5</td>
<td>148,285,000</td>
<td>20,035,279</td>
<td>51,391,468</td>
</tr>
</tbody>
</table>

Basic parameters of the Aquarius simulations. $m_p$ is the particle mass, $\epsilon$ is the gravitational softening length, $N_{hr}$ is the number of high resolution particles, and $N_{lr}$ the number of low resolution particles filling the rest of the volume. $M_{200} = 1.839 \times 10^{12}M_\odot$ is the virial mass of the halo, defined as the mass enclosed in a sphere with mean density 200 times the critical value. $r_{200} = 245$ kpc gives the corresponding virial radius. $M_{50} = 2.524 \times 10^{12}M_\odot$. Finally, $N_{50}$ gives the number of simulation particles within $r_{50} = 433$ kpc.

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