Constraints on decaying Dark Matter from XMM-Newton observations of M31

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Dark Matter problem

Evidences include:
- velocity curves in clusters and galaxies
- observations of galaxy clusters in Xrays
- the gravitational lensing data (excluded *MACHOs*)
- cosmic microwave background anisotropies (WMAP)

DM - ~22% of the total energy density - *largely unknown*

DM affects structure formation

Hot DM	**Warm DM**	**Cold DM**
significant velocity dispersion		*negligible velocity dispersion*

WDM particle candidates

No candidates in Standard Model!

- gravitinos and axinos in supersymmetric models
- sterile neutrino with the mass in the keV range. *νMSM:*

(Asaka & Shaposhnikov 2005; Asaka et al. 2005)

$$\delta\mathcal{L} = \overline{N}_I i\partial_\mu\gamma^\mu N_I - f^\nu_{I\alpha}\Phi\overline{N}_I L_\alpha - \frac{M_I}{2}\overline{N^c_I}N_I + h.c.$$

under the minimal number of assumptions
explains several *observed* phenomena beyond the MSM*:*

neutrino oscillations, baryon asymmetry, pulsar kicks (?),..

Decaying Dark Matter

there is radiative decay channel into an active neutrino and a photon, emitting monoenergetic photon with energy **E = m$_s$ /2**

The flux of the DM decay from a given direction

$$F_{DM} = \frac{\Gamma E_\gamma}{m_s}\int_{fov\ cone}\frac{\rho_{DM}(\mathbf{r})}{4\pi|\mathbf{D}_L+\mathbf{r}|^2}\mathbf{dr}.$$

Decay rate:

$$\Gamma = \frac{9\alpha G_F^2}{1024\pi^4}\sin^2(2\theta)m_s^5 \approx 1.38\cdot 10^{-30}s^{-1}\left[\frac{\sin^2(2\theta)}{10^{-8}}\right]\left[\frac{m_s}{1\ \mathrm{keV}}\right]^5$$

(Pal & Wolfenstein 1982; Barger et al. 1995)

For distant objects:

$$F_{DM} = \frac{M^{fov}_{DM}\Gamma}{4\pi D_L^2}\frac{E_\gamma}{m_s}$$

For small FOV:

$$F_{DM} = \frac{\Gamma S_{DM}\Omega E_\gamma}{4\pi m_s}$$

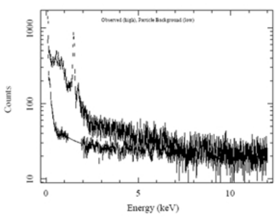
$$S_{DM} = \int_{l.o.s.}\rho_{DM}(r)dr$$

Data reduction and background substraction

Obs. ID	Starting time, UTC	Filter	Cleaned MOS1/MOS2/PN exposure, ks
0112570401	2000-06-25 08:12:41	Medium	30.8/31.0/27.6
0109270101	2001-06-29 06:15:17	Medium	40.1/41.9/47.4
0112570101	2002-01-06 18:00:56	Thin	63.0/63.0/55.3

Extended Sources Analysis Software (ESAS)

This method, recently developed by ESAC/GSFC team, allows to subtract instrumental and cosmic backgrounds separately

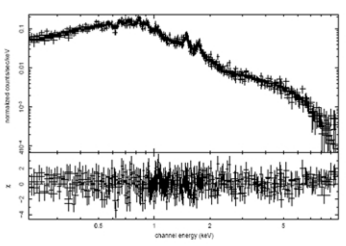


Observed spectrum (top) and modeled instrumental background (bottom) MOS1 from ObsID 0112570101, region ring5-13. It can be seen that the spectrum and modeled background almost coincide for E > 7 keV.

Blank-sky background subtraction (SBS)

We processed the same M31 observations, using both MOS and PN data. Scripts written by the XMM-Newton group in Birmingham were used.

Fitting the spectra in XSPEC



Folded spectra and best-fit model from circle5 region, with excluded point sources

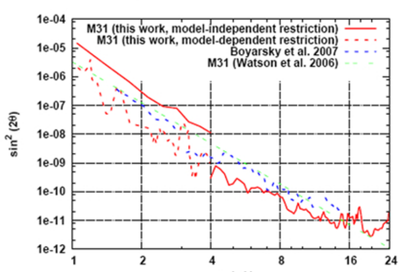
Region	Reduced χ^2	Number d.o.f.
ESAS, circle5	1.071	399
SBS MOS, circle5	1.102	371
ESAS, ring5-13	1.109	1608
SBS MOS, ring5-13	0.994	1735
SBS PN, ring5-13	1.007	2754
SBS PN-OOT, ring5-13	0.995	2715
SBS MOSPN-OOT, ring5-13	1.009	4082

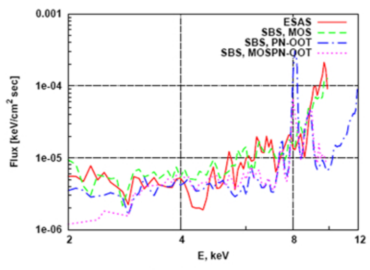
We use combination of the following models:

*apec+(apec+pow)*wabs* - cosmic background
bknpow/b - soft proton contamination
diskbb+bbody - not excluded point sources
3 vmekal - diffuse M31 component (abundances fixed from optical observations)

Producing restrictions on sterile neutrino parameters

We use *model-dependend* "statistical method" (e.g. Boyarsky et al. (2006d)) below 2 keV and *model-independent* "full flux" above.





Our final restrictions

Andromeda Galaxy(M31)

Calculation of DM mass

we use two spatial regions: **circle5** and **ring5-13**, with and without **resolved point sources**.
To estimate the systematic uncertainties and to find the most conservative estimate, **we analyze various DM profiles**

- **(K1)** *Before* adiabatic contraction stage, Klypin et al. (2002) assume that DM distribution is purely Navarro-Frenk-White (NFW) (Navarro et al. 1997):
- **(K2)** This non-analytical model is the result of adiabatic contraction of **K1** profile
- **(KING)** Modified isothermal profile (King 1962; Einasto et al. 1974):

$$\rho_{ISO}(r) = \begin{cases}\rho_0\left(\left[1+\frac{r^2}{r_c^2}\right]^{-1} - \left[1+\frac{r_0^2}{r_c^2}\right]^{-1}\right) & r\leqslant r_0,\\ 0 & r>r_0.\end{cases}$$

where $\rho_0 = 0.413 M_\odot\ \mathrm{pc}^{-3}$, $r_c = 1.47$ kpc, $r_0 = 117$ kpc.

- **(N04)** Density distribution of Navarro et al. (2004):

$$\rho_{N04}(r) = \rho_c\exp\left[-\frac{2}{\alpha}\left(\frac{r^\alpha}{r_c^\alpha}-1\right)\right],$$

α, according to simulations, equals to 0.172 (Navarro et al. 2004)

- **(GFBG)** Preferred Navarro-Frenk-White distribution from Geehan et al. (2006): $M_{vir} = 6.80\times 10^{11}\ M_\odot$; $r_s = 8.18$ kpc; $C = 22$.
- **(EW)** Preferred DM distribution of Evans & Wilkinson (2000):

$$\rho_{DM}(r) = \frac{M}{4\pi}\frac{a^2}{r^2(a^2+r^2)^{3/2}},$$

where $M = 12.3\times 10^{11}\ M_\odot$, $a = 95$ kpc.

- **(MOORE)** Moore profile (Moore et al. 1999):

$$\rho_{MOORE}(r) = \frac{\rho_c}{\left(\frac{r}{r_c}\right)^{1.5}\left[1+\left(\frac{r}{r_c}\right)^{1.5}\right]},$$

where $\rho_c = 4.43\cdot 10^{-3} M_\odot\ \mathrm{pc}^{-3}$, $r_c = 17.9$ kpc.

- **(NFW)** Navarro-Frenk-White profile:

$$\rho_{NFW}(r) = \frac{\rho_c}{\frac{r}{r_c}\left[1+\left(\frac{r}{r_c}\right)^2\right]},$$

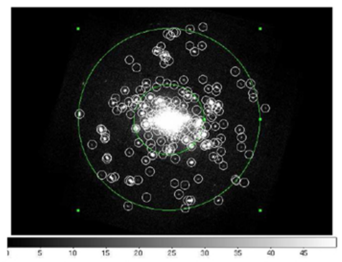
$\rho_c = 5.20\cdot 10^{-2} M_\odot\ \mathrm{pc}^{-3}$, $r_c = 8.31$ kpc.

- **(BURK)** Burkert profile (Burkert 1995):

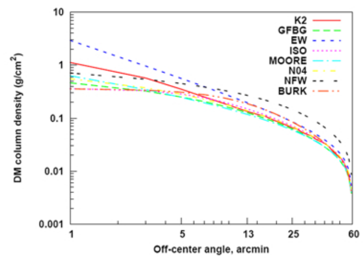
$$\rho_{BURK}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_c}\right)\left(1+\frac{r^2}{r_c^2}\right)},$$

where $\rho_0 = 0.335 M_\odot\ \mathrm{pc}^{-3}$, $r_c = 3.43$ kpc.

Selected regions in the central part ofM31 (shown in linear scale). Small circles correspond to excluded point source regions, large circles have radius of 5 and 13 arcmin



M31 DM column density versus off-center angle as result of our Monte Carlo integration, based on DM profiles of Sec. 3.1. (Point sources are not excluded):.

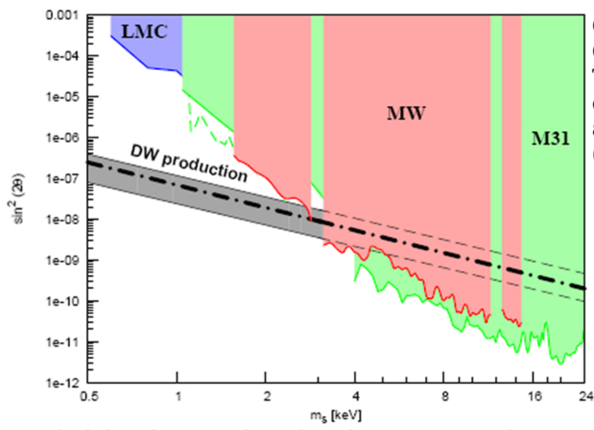


Model	circle5	Removed from circle5, %	ring5-13	Removed from ring5-13, %
K1, without sources	0.768 ± 0.013	76.6	9.86 ± 0.14	21.5
K2, without sources	2.34 ± 0.13	80.4	18.20 ± 0.43	22.8
GFBG, without sources	1.46 ± 0.04	77.8	15.82 ± 0.38	22.8
EW, without sources	3.86 ± 0.28	83.9	28.41 ± 0.64	33.2
ISO, without sources	1.632 ± 0.002	75.5	18.88 ± 0.02	22.9
MOORE, without sources	1.52 ± 0.01	79.3	14.81 ± 0.03	23.7
N04, without sources	1.708 ± 0.004	77.5	18.19 ± 0.03	23.0
NFW, without sources	1.71 ± 0.01	77.5	18.19 ± 0.04	23.0
BURK, without sources	1.666 ± 0.002	75.1	21.65 ± 0.04	22.5

DM mass (in 10^9 M$_\odot$) without point sources: results of our Monte Carlo integration. The fraction of DM, removed together with the point sources,

Results and conclusions

Using XMM-Newton data on the central region of Andromeda galaxy (M31), we obtained new restrictions on sterile neutrino Dark Matter parameters. We analyzed various DM distributions of the central part of M31, and obtained the most conservative estimate of the DM mass using the model of Geehan et al. (2006).



Current X-ray constraints, Colored regions are excluded. The grey region shows the range of parameters which give correct abundance in the DW model (Asaka et al.2007).

We find that the upper bound on the DM mass in the DW ("Dodelson-Widrow" - production through (non-resonant) oscillations with active neutrino) scenario is reliably below 4 keV

If we combine our result with the Lyman-aplha recent analysis restriction m>5.6 keV, **model in which all 100% of the DM is produces through the DW scenario is ruled out**

The comparison of our upper limit with the lower bound on sterile neutrino pulsar kick mechanism (Fuller et al. 2003) improves the previous bounds and can exclude part of the parameter region (for 4 keV< ms < 20 keV)

The results of this work are equally applicable to any decaying DM candidate (e.g. gravitino).