Summary of 3.5 keV line searches and the influence of the corresponding sterile neutrino dark matter on the process of reionization

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Two basic questions about dark matter (DM):

- **Is the evidence for DM convincing?**

  Yes.

  There are still other options nevertheless.

- **Is DM made up of particles?**

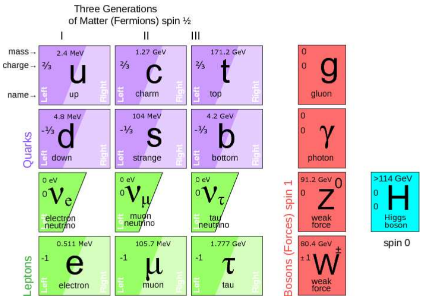
  Plausible assumption.

  But no **hard** evidence. More exotic possibilities such as primordial black holes or MACHOs are not completely ruled out.

- In this talk, I will assume the existence of **dark matter particle**.

Can DM be made out of elementary particles?

- We need a **massive**, **long-lived**, **neutral** particle.
- The only **known** DM candidate particle are **neutrinos**.
- There should be **relic** neutrinos, similar to CMB photons.
- Particle physics experiments show that at least two neutrinos have **non-zero mass** $0.01 \lesssim m_\nu \lesssim 2.5$ eV.



- **neutrinos** violate **phase-space density bound** and spoil **structure formation**.

Free streaming of neutrino dark matter

- Free relativistic particles do not cluster;
- DM particles smooth spectrum of initial density perturbation at scales below **free streaming length**

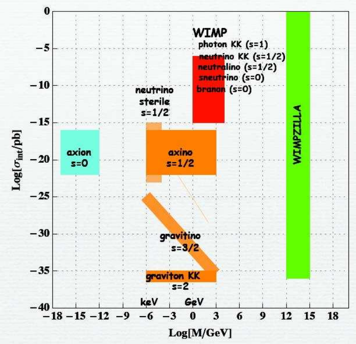
$$\lambda_{FS}^{\text{co}} = \int_0^t \frac{v(t')dt'}{a(t')}$$

  - Free streaming length is approximately equal to scale, travelled by DM particles before **transition to non-relativistic velocities t_{nr}** (for$\langle p \rangle \sim m$).
  - Neutrino DM would **smooth out** fluctuations at scales smaller than $\lambda_{FS}^{\text{co}} > 1$ Gpc - **contrary** to LSS and CMB observations.

Neutrinos appear to be **too "hot"** for DM – need to look **outside** the Standard Model.

(An imcomplete) list of DM candidates

- A lot of DM candidates motivated by attempts to solve different problems in fundamental physics.
- **Huge** spread between their masses and interaction strengths.
- Theoretical bias aside, we look on allowed parameter space.



Decaying dark matter

- **Whatever can happen will happen** (Murphy's law) may be transformed to
- **Whatever can decay will decay**
- if no **special symmetry** is imposed.
- E.g. conservation of baryon number $\Rightarrow p \nrightarrow e^+\pi^0$.
- Conservation of electric charge $\Rightarrow e \nrightarrow \gamma\nu_e$.
- Can DM be decaying? Yes, we have physically motivated candidates able to produce the bulk of DM with observed properties, e.g. light super-weakly coupled **sterile** (right-handed) **neutrinos**.

Can dark matter be decaying?

Observations: DM is stable for at least **billions of years**.

Assume that DM decays through **super-weak** interaction due to Fermi-like coupling constant θG_F, $\theta \ll 1$.

From dimensional grounds, one could estimate the lifetime of DM decay to much lighter particles

$$\tau_{\text{DM}} \sim \left(\theta^2 G_F^5 m_{\text{DM}}^5\right)^{-1}, \quad \hbar = c = 1$$

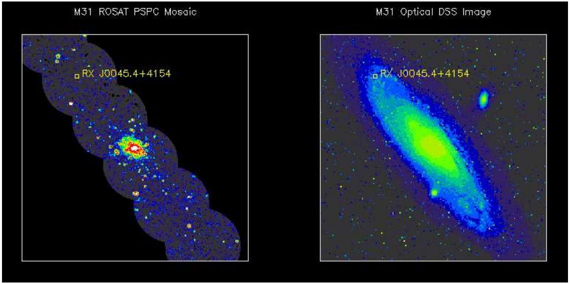
$$m_{\text{DM}} \sim \left(\theta^2 \tau_{\text{DM}} G_F^2\right)^{-1/5} \simeq 7 \text{ keV} \left(\frac{\theta^2}{10^{-6}}\right)^{-1/5} \left(\frac{\tau_{\text{DM}}}{\tau_{\text{Univ}}}\right)^{-1/5}$$

Decaying DM detection

- Cosmologically large lifetime ⇒ "much weaker than electro-weak" interaction strength with other particles.
- Laboratory detection becomes **challenging**.
- Are there any **alternatives**?

Decaying DM detection

- DM may be decaying with a cosmologically long life-time (age of the Universe or even longer). Can we **detect** such decay?
- For Andromeda galaxy, one could have 10^{74} DM particles with 7 keV mass.
- With lifetime $\sim$ age of the Universe, it would produce 10^{56} decays/s releasing 10^{45} erg/s, or **6 orders of magnitude larger** the total X-ray luminosity of M31.



DM decay line

- Signature of 2-body radiative decay (e.g. DM$\to \gamma + \gamma$, DM$\to \gamma + \nu$): **monochromatic line** from **all** DM overdensities.
- Due to small ($v \sim 10^{-4} - 10^{-2}$) Doppler broadening the line is **narrow**.
- Line position **evolves** with redshift.
- Line energy $E_\gamma = \frac{1}{2} m_{\mathrm{DM}} c^2$ (e.g. 3.5 keV for 7 keV mass DM)
- Flux from DM decay:

$$F_{\mathrm{DM}} = \frac{E_\gamma}{m_{\mathrm{DM}} \tau_{\mathrm{DM}}} \int\limits_{\text{fov cone}} \frac{\rho_{\mathrm{DM}}(\vec{r})}{4\pi |\vec{D}_L + \vec{r}|^2} d^3\vec{r} \approx \frac{\Omega_{\mathrm{fov}}}{8\pi m_{\mathrm{DM}} \tau_{\mathrm{DM}}} \mathcal{S}$$

- **DM column density**

$$\mathcal{S} = \int\limits_{\Omega_{\mathrm{fov}}} \rho_{\mathrm{DM}}(r) dr$$

– integral along the line-of-sight, averaged within the instrument's field-of-view – **slowly** grows with halo mass ($\sim M^{0.2}$) – 0911.1774.

X-ray instruments

Atmosphere below ~ 100 km is **opaque** to keV photons.

Launch detectors to outer space with satellites (lifetime – **years**) or sounding rockets (lifetime – **minutes**).

Satellite-based detectors – XMM-Newton (1999-), Chandra (1999-), Suzaku (2005-2015) – CCD imagers with **moderate** energy resolution (50-100 eV), small FoV (a fraction of 1°) and large effective area (a fraction of m^2) due to focusing optics.

XMM-Newton and Chandra also carry **grazing spectometers** – excellent energy resolution (~ 1 eV) but only for **point sources** (no DM).

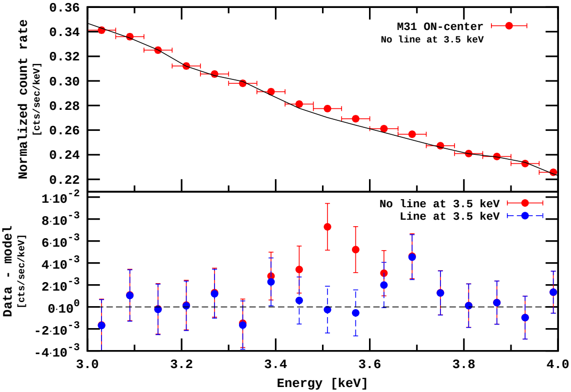
Rocket-based detectors – **microcalorimeters** with good energy resolution (5-10 eV), small effective area ($1cm^2$) with no focusing optics, large FoV ($\sim$1 sr).

Satellite-based microcalorimeters – 2 attempts so far, **both unlucky** – Suzaku (2005) and Hitomi (2016).

Direct astrophysical detection of decaying DM

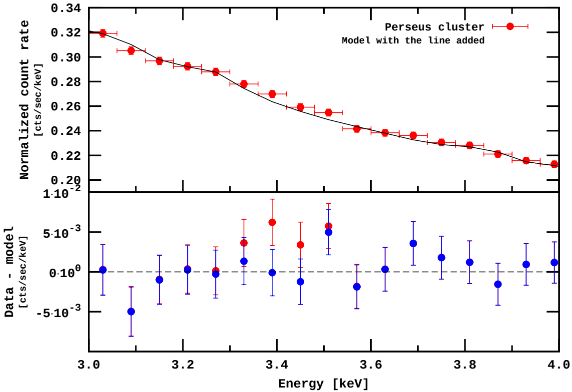
- Many DM-dominated objects would provide comparable decay signal. Freedom in choosing observation targets that optimize the signal-to-noise ratio (with well-controlled astrophysical backgrounds).
- Candidate line can be **distinguished** from astrophysical backgrounds by studying its **surface density** and **sky distribution**
- Astrophysical detection of decaying DM becomes **direct**!

An example – M31 centre/XMM-Newton



Line at 3.53 ± 0.03 keV, 3.2σ local (A. Boyarsky, **D.I.** et al, 1402.4119).

The same line in Perseus outskirts/XMM-Newton

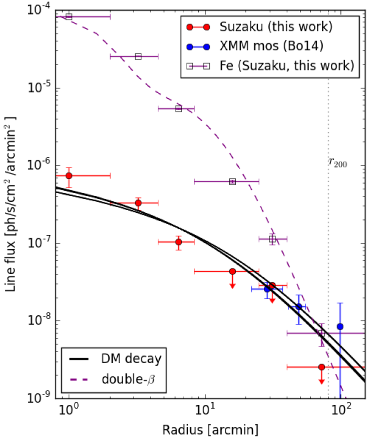


Combined M31+Perseus fit gives 3.52 ± 0.02 keV, 4.4σ local.

Perseus on-centre detections:

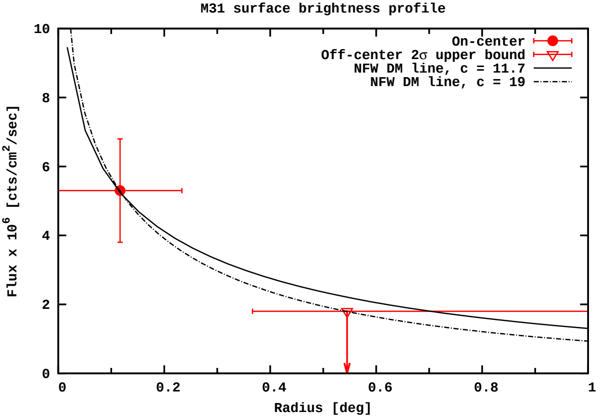
- E. Bulbul et al., 1402.2301 – detects a line at 3.57 keV (XMM-Newton and Chandra).
- **D.I.**, E. Bulbul et al. 1508.05186, – confirms this detection (XMM-Newton).
- O. Urban et al., 1411.0050 – detects a line (Suzaku).
- T. Tamura et al., 1412.1869 – does not detect a line (Suzaku).
- J. Franse et al., 1604.01759 – detects the line at 7.6σ and builds its radial profile (Suzaku).

3.5 keV line profile in Perseus – 1604.01759:



Distributed according to decaying DM line from NFW profile (but see 1411.1758 with completely different method for Perseus and GC).

3.5 keV line profile in M31:



Distributed according to decaying DM line from NFW (or even cuspier!) profile.

Galactic Centre:

- S. Riemer-Sørensen, 1405.7943 – detects a line at 3.51 keV (no significance shown); fit with arbitrary 3.51 keV line normalization prefers zero extra lines;
- T. Jeltema and S. Profumo, 1408.1699 – detects extra line at $\sim$3.51 keV.
- A. Boyarsky, J. Franse, **D.I.**, O. Ruchayskiy, 1408.2503 – detects extra line at 3.539 ± 0.011 keV.
- The line is not seen in a **prolonged blank-sky dataset** – strongly prefers **cuspy profiles** (assuming decaying DM origin).

Other galaxy clusters:

- E. Bulbul et al., 1402.2301 – detection in combination of Coma, Centaurus and Ophiuchus (XMM-Newton).
- O. Urban et al., 1411.0050 – detection in Coma and Ophiuchus (Suzaku).
- **D.I.**, E. Bulbul et al. 1508.05186, – detection in Perseus, Coma, A85, A2199, A496, A2319, A3266, AS805 at $\gtrsim 2\sigma$ level (XMM-Newton).

Summary of detections:

The line is detected at $\gtrsim 2\sigma$ level in

- central parts of 9 **individual** galaxy clusters + different **stacks** of galaxy clusters (XMM-Newton: 1402.2301, Chandra: 1605.02034) + Perseus cluster outskirts;
- M31 central part;
- Galactic Centre;
- Draco dwarf spheroidal (XMM-Newton, PN CCD camera) – O. Ruchayskiy, **D.I.** et al. 1512.07217

Summary of non-detections:

The new line is **not** detected at $\gtrsim 2\sigma$ level in

- central part of Virgo cluster – 1402.2301, 1508.05186.
- blank-sky spectrum and M31 periphery – 1402.4119.
- stack of dwarf spheroidals – D. Malyshev et al. 1408.3531;
- stack of galaxy peripheries – M. Anderson et al. 1408.4115;
- blank-sky spectrum – N. Sekiya et al. 1504.02826;
- Draco dwarf spheroidal – T. Jeltema and S. Profumo 1512.01239;
- stacked clusters observed by Chandra – F. Hofmann et al. 1606.04091.

Detections vs non-detections

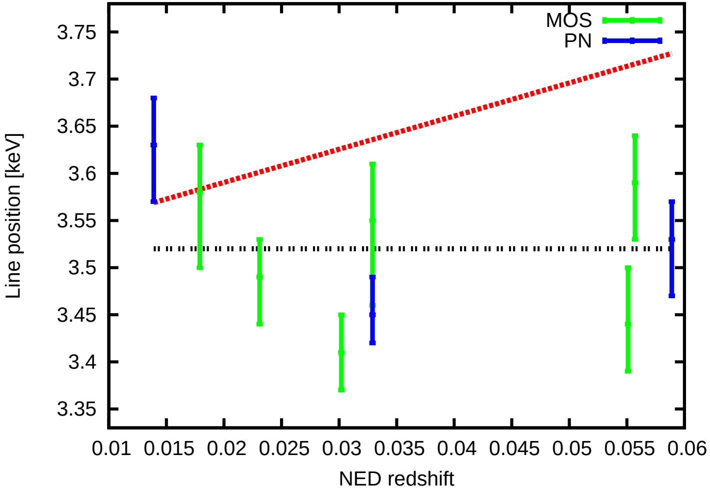
Status of detections in Draco (XMM-Newton) and Perseus (Suzaku) **is still uncertain**:

- In Draco/PN – 1512.07217 **does see** an excess at $\Delta\chi^2 = 5.3$ while 1512.01239 **does not**;
- In Draco/MOS – 1512.07217 obtain **much weaker** bounds than 1512.01239;
- Similar situation **happened** with M31 (1402.4119 saw a line at 3.2σ while 1408.1699 did not) but was resolved by applying **physically motivated continuum model** in **wide energy range**, see 1408.4388 and 1411.1759;
- The corresponding work on Draco is **in progress**;
- It is **still unclear** why 1412.1869 does not see the line in Perseus/Suzaku while 1411.0050 and 1604.01759 do.

Line origin: systematics?

- **Three telescopes**: XMM-Newton, Chandra, Suzaku
- **Five detectors**: EPIC MOS, EPIC PN, ACIS-S, ACIS-I, XIS
- Nearby and combined clusters, M31 and GC
- Correct dependence from **redshift**: combined spectrum (Bulbul et al.), Perseus vs. M31 (Boyarsky et al.)
- Unknown effect due to brighness – No! We checked bright objects without DM and **did not see** the signal

Correct dependence from redshift – 1508.05186

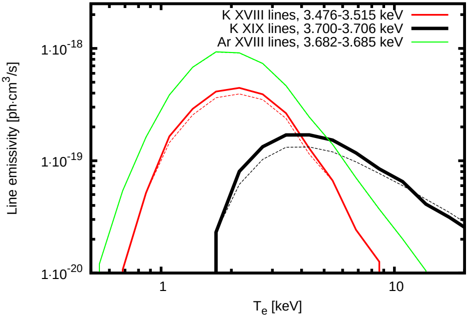


Line origin: atomic emission?

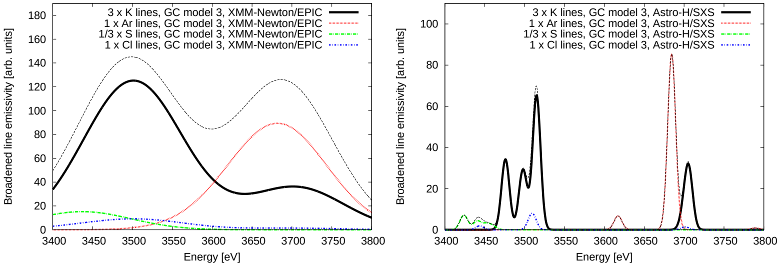
- Close complex line of K XVIII at 3.47-3.515 keV;
- Natural for clusters and GC but is **not** expected for M31 (no brighter lines from other elements);
- Uncertainties for K adundance **up to** an order of magnitude – e.g. D. Romano et al. 1006.5863, K. Phillips et al. 1507.04619;
- If the line is due to K XVIII – should see enhanced K XIX lines at 3.7 keV;
- S XVI charge exchange lines at 3.45-3.47 keV – Gu et al. 1511.06557.

Potassium lines at X-rays – 1507.02857:

- No strong counterparts to K XVIII line complex at 3.47-3.515 keV;
- The strongest is the K XIX line complex at 3.700-3.706 keV;
- Affected by **nearby** Ar lines – need for a **microcalorimeter**!

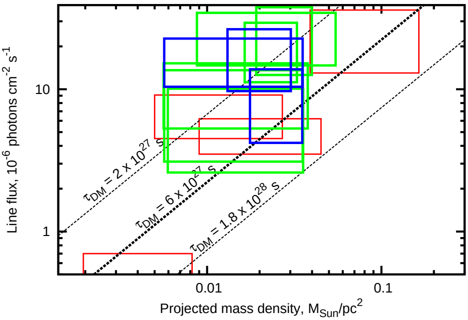


Need for a microcalorimeter – 1507.02857:



Radiatively decaying DM lifetime:

- **Observations** point to $\tau_{\rm DM} = (3.5 - 8) \times 10^{27}$ s – 1408.2503, 1508.05186;
- Apparent 2σ tension with some **non-observations** (but see the role of continuum-induced systematics).



An incomplete list of particle candidates

The 3.5 keV X-ray line from decaying **gravitino** dark matter. **Axino** dark matter in light of an anomalous X-ray line. The Quest for an Intermediate-Scale Accidental **Axion** and Further **ALPs**. keV Photon Emission from Light **Nonthermal Dark Matter**. X-ray lines from R-parity violating decays of keV **sparticles**. Neutrino masses, leptogenesis, and **sterile neutrino** dark matter. A Dark Matter Progenitor: **Light Vector Boson Decay** into (Sterile) Neutrinos. A 3.55 keV Photon Line and its Morphology from a 3.55 keV ALP Line. 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model. X-ray line signal from decaying **axino** warm dark matter. The 3.5 keV X-ray line signal from **decaying moduli** with low cutoff scale. X-ray line signal from 7 keV **axino** dark matter decay. Can a **millicharged dark matter** particle emit an observable gamma-ray line? Effective field theory and keV lines from dark matter. Resonantly-Produced 7 keV **Sterile Neutrino Dark Matter** Models and the Properties of Milky Way Satellites. Cluster X-ray line at $3.5\,\mathrm{keV}$ from axion-like dark matter. Axion Hilltop Inflation in Supergravity. A 3.55 keV hint for decaying axion-like particle dark matter. The 7 keV axion dark matter and the X-ray line signal. An X-Ray Line from **eXciting Dark Matter**. 7 keV sterile neutrino dark matter from split flavor mechanism.

Alternatives to radiatively decaying dark matter?

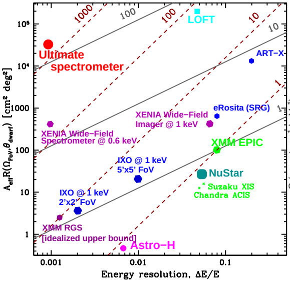
- decay of excited dark matter states – 1402.6671, 1404.3729, 1404.4795, 1408.0233, 1408.6532, 1409.2867, 1410.7766, 1501.03496;
- annihilating dark matter – 1404.1927, 1403.1570, 1405.3730, 1506.02032;
- dark matter decaying into ALPs with further conversion to photons in magnetic field – 1403.2370, 1404.7741, 1406.5518, 1410.1867.

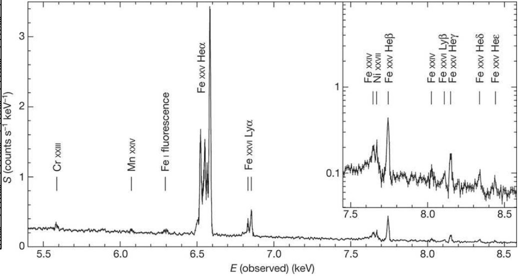
Predict **cuspier** distribution.

See e.g. review of **D.I.**, 1510.00358 for more details.

New missions:

- We need **both** high throughput and high energy resolution.
- Hitomi (2016), Micro-X (1506.05519, 2017+), eROSITA (1505.07829, 2017+), LOFT (1312.5178, 2024+) and Athena (1509.02758, 2028+) would probe the parameter space.
- Hitomi **has been crashed** just after its first observation of Perseus core as a part of calibration program (see 1607.04487).





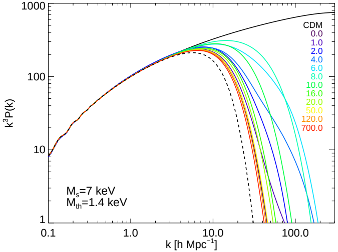
New objects:

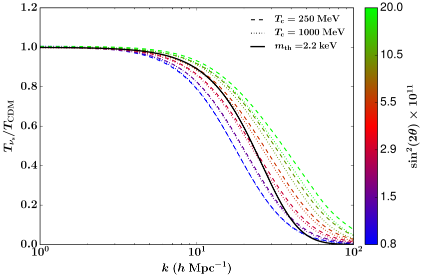
- Thousands of X-ray observations are publicly available;
- Lots of modeling – needs a **pre-detection step**;
- **Easy** doable with wavelet methods – can detect a 3σ narrow line at 1.8σ level;
- 235 potential targets from XMM/MOS only – lots of work to be done.

See D. Savchenko and **D. I.**, 1511.02698 for details.

keV mass DM and structure formation:

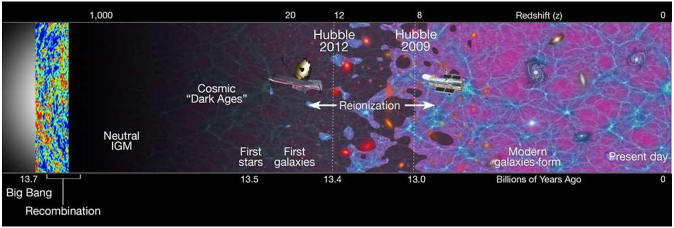
Non-zero initial velocities of DM particle modify structure formation. The simplest measure – difference of DM power spectrum from CDM scenario.





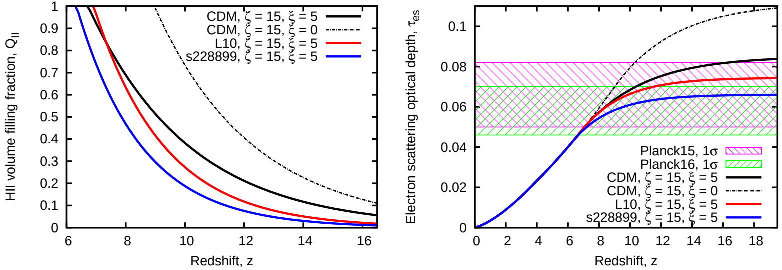
keV mass DM and reionization:

An example of such influence – the process of **reionization**.
It is usually modeled with 'pure astrophysics', but recent works – Dayal et al. 1501.02823, Rudakovskyi and **D.I.** 1604.013441, Bose et al. 1605.03179 – show the influence of keV mass DM can be **of the same order** that 'conventional' astrophysics (e.g. QSO/Pop III stars, H I clumping etc.).



keV mass DM and reionization: 1604.01341

7 keV sterile neutrino potentially responsible for 3.5 keV line can reproduce reionization with **smaller** electron scattering depth τ_{es}, **similar** redshift of reionization and **sharper** reionization (e.g. smaller kSZ effect) compared to CDM.



Conclusions

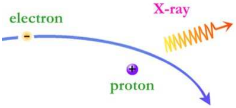
- There is a line at ~ 3.55 keV with **cosmic** origin;
- Its astrophysical explanation is **testable** with future X-ray instruments;
- Its DM decay (e.g. sterile neutrino) explanation is **possible**;
- In our reference model (νMSM), it also affects **structure formation** e.g. producing **fewer** substructures and **sharpening** reionization.

Thank you for your attention!

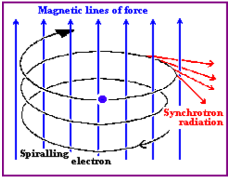
Backup slides:

X-ray emission from space

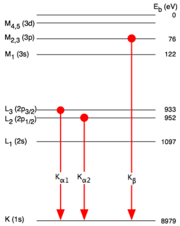
thermal



non-thermal



emission lines



The data

Our data (1402.4119)

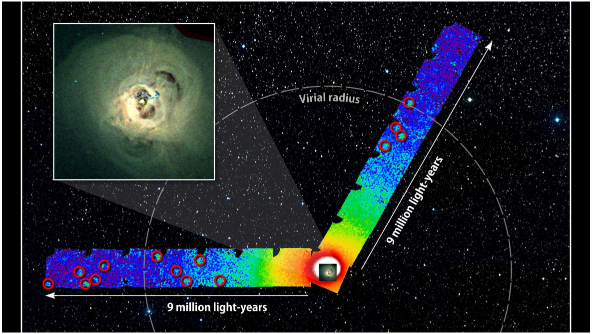
Andromeda galaxy (M31)	XMM-Newton, center & outskirts
Perseus galaxy cluster	XMM-Newton, outskirts only
Blank-sky background	XMM-Newton

Bulbul et al. 2014 (1402.2301)

73 galaxy clusters $z < 0.35$, including Coma, Perseus	XMM-Newton, centers only.
Perseus cluster	Chandra, center
Virgo cluster	Chandra, center

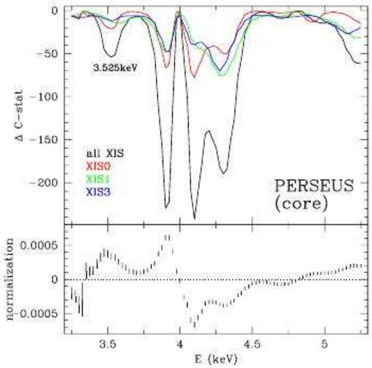
Position: ~3.53-3.57 keV. Statistical error of line position ~ 30 eV. Systematics (~ 50 eV – between different cameras, detection of known instrumental lines)

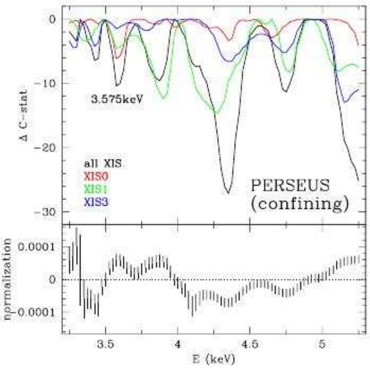
Perseus cluster



- Bulbul et al. took only 2 central XMM observations – $14'$ around the central part.
- We took 16 observations **excluding** 2 central XMM observations to avoid complex modeling of central emission.

Perseus observed by Suzaku/XIS – 1411.0015





Other clusters observed by Suzaku/XIS

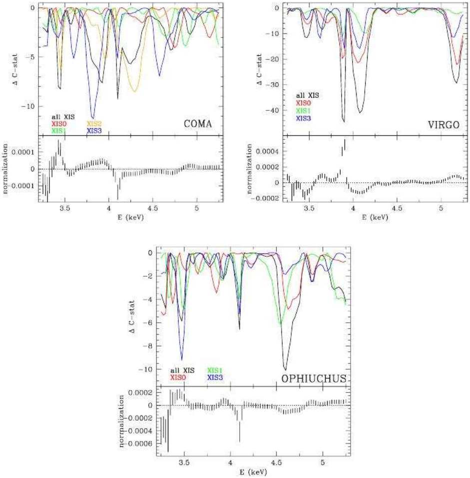
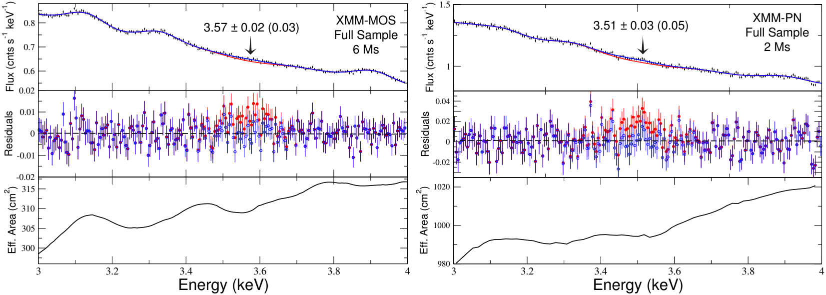


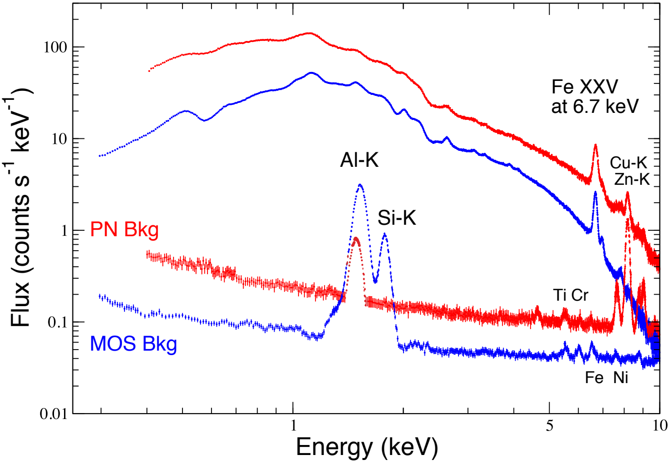
Figure 3. As Fig. 2 for the Coma, Virgo and Ophiuchus Clusters.

Combined spectrum from Bulbul et al.



- All spectra are counted in **emitters** frame;
- Intrumental background is **subtracted**.

Perseus galaxy cluster



Local statistical significance

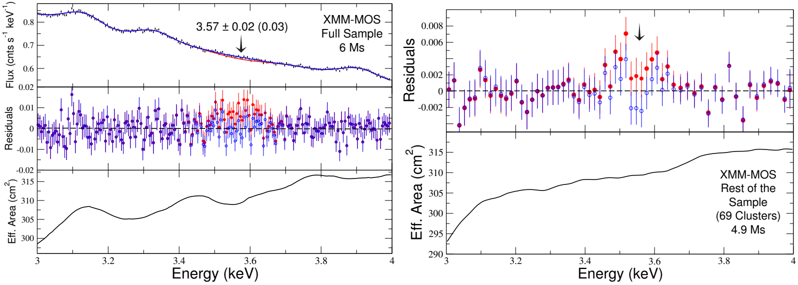
Our data

Andromeda galaxy	$\Delta\chi^2 = 13.0$	3.2σ for 2 d.o.f.
Perseus cluster (MOS)	$\Delta\chi^2 = 9.1$	2.5σ for 2 d.o.f.
Perseus cluster (PN)	$\Delta\chi^2 = 8.0$	2.4σ for 2 d.o.f.
Blank-sky	—	
M31 + Perseus (MOS)	$\Delta\chi^2 = 25.9$	4.4σ for 3 d.o.f.

Bulbul et al. 2014

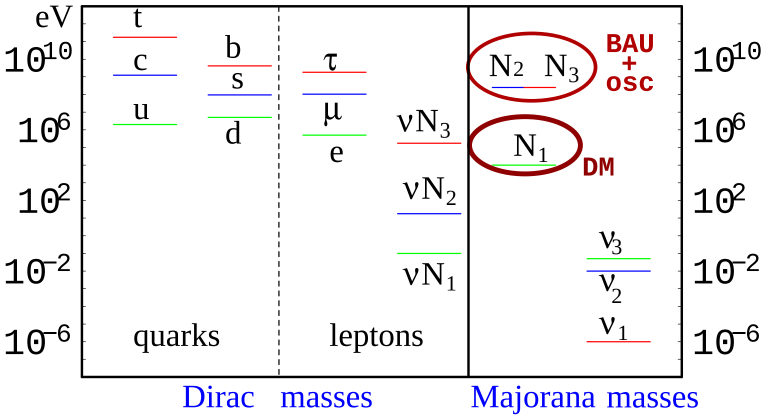
73 clusters (XMM, MOS)	$\Delta\chi^2 = 22.8$	4.3σ for 2 d.o.f.
73 clusters (XMM, PN)	$\Delta\chi^2 = 13.9$	3.3σ for 2 d.o.f.
Perseus core (XMM, MOS)	$\Delta\chi^2 = 12.8$	3.1σ for 2 d.o.f.
Perseus core (XMM, PN)	—	
Perseus core (Chandra, ACIS-S)	$\Delta\chi^2 = 11.8$	3.0σ for 2 d.o.f.
Perseus core (Chandra, ACIS-I)	$\Delta\chi^2 = 6.2$	2.5σ for 1 d.o.f.
Virgo cluster (Chandra, ACIS-I)	—	

A dip in the effective area?



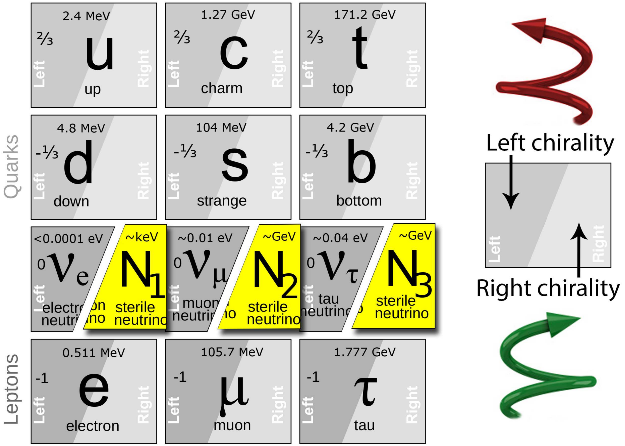
- **The simplest method to find a weak line:** divide **powerlaw** spectrum on the effective area with the **dip** at ~ 3.5 keV
- The dip **is absent** in combined spectrum of galaxy clusters, in contrast to signal (Bulbul et al.)
- The dip should be seen in the **blank-sky spectrum** (Boyarsky et al.)

νMSM model



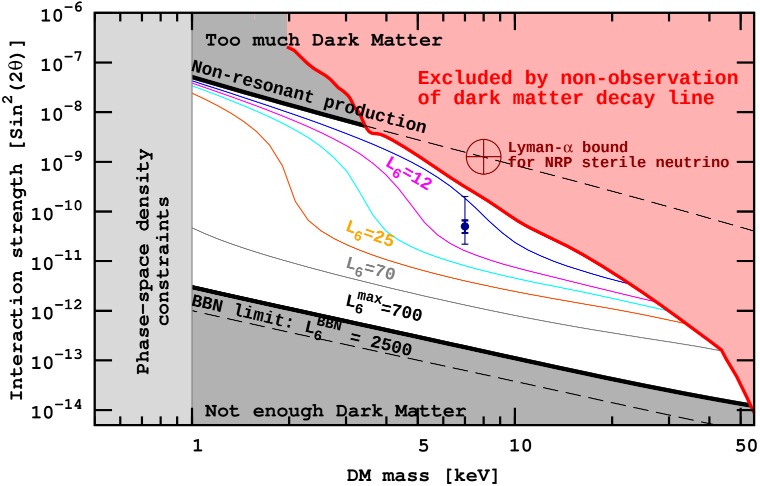
See review of Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

Sterile neutrino: νMSM model

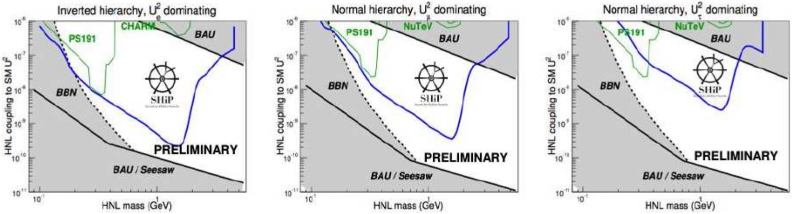


Standard Model + right-handed neutrinos

νMSM and new line

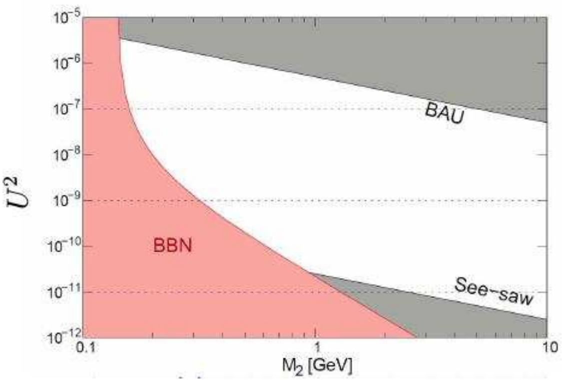


Search for Hidden Particles (SHiP) sensitivity for heavy sterile neutrinos:

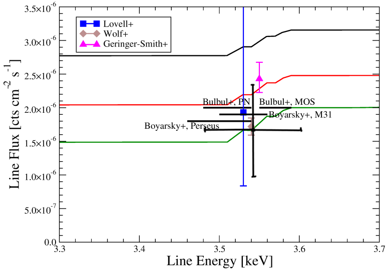


Heavier signs of νMSM

Constrained by neutrino masses (see-saw), Big Bang Nucleosynthesis and production of significant baryon asymmetry.
Can be searched on **dedicated accelerator experiments**.



Draco PN results: R15 vs JP15

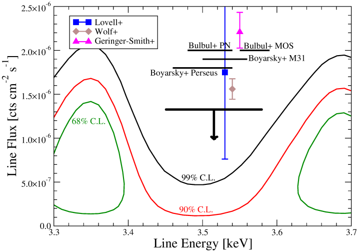


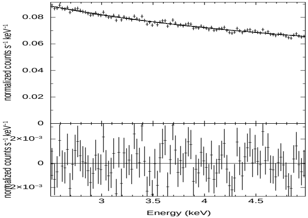
- R15 detection in PN – position 3.54±0.06 keV, flux $1.65^{+0.67}_{-0.70} \times 10^{-6}$ ph/cm^2/s, $\Delta\chi^2 = 5.3$ – is overplotted to JP15 contours;
- Possible reasons for R15 difference with JP15 – correction of out-of-time events (unclear whether JP15 did it), more reliable binning (closer to FWHM), wider energy range, more realistic model (CXB+NXB).

Table for Draco/PN new line detections

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

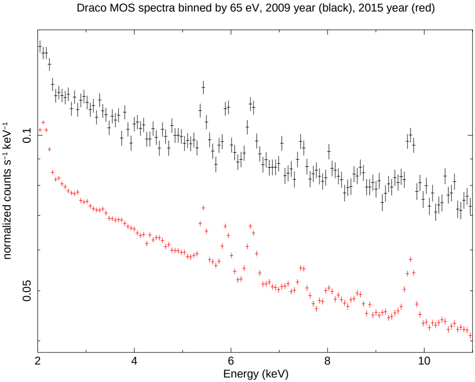
MOS+PN bounds from R15 vs MOS bounds from JP15





- 2σ upper bound from MOS+PN of R15 is 1.3×10^{-6} ph/cm^2/s, **much** weaker than MOS bounds inferred by JP15;
- Probable reason – failure of the unphysical JP15 model (effective NXB at 2.5-5.0 keV) to describe their MOS data near 3.5 keV – apparent **dip** with $\Delta\chi^2 \sim 10$.

Instrumental background (MOS)



Instrumental background (PN)