Sterile neutrinos as dark matter

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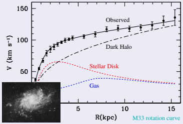
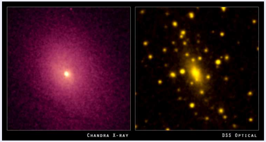
NuFact 2017

Dark Matter in the Universe

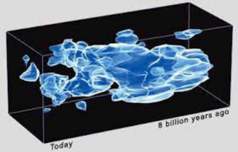
Astrophysical evidence:



Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx$ const

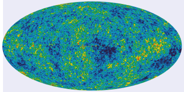


Expected: $\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{gals}}$
Observed: 10^2 times more mass confining ionized gas

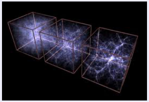


Lensing signal (direct mass measurement) **confirms** other observations

Cosmological evidence:



Jeans instability turned tiny density fluctuations into visible structures



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 $n_\nu = 112\,\mathrm{cm}^{-3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$

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 $\sim 300 - 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would **overclose the Universe**

"Between friends"

- 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)

http://www.adsabs.harvard.edu/abs/1983ApJ...274L...1W

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

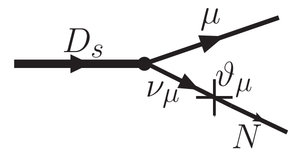
One can make dark matter **heavy** and therefore their number density is Boltzmann-suppressed ($n \propto e^{-m/T}$) at freeze-out

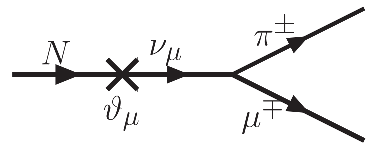
Second alternative: super-WIMP

One can make dark matter interacting **super-weakly** so that their number density never reaches equilibrium value

Sterile neutrino – super-weakly interacting particle

- 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



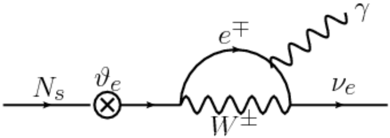


...suppressed by a small parameter U

$$\mathcal{L}_{int} = \frac{g}{\sqrt{2}} W^+_\mu \overline{N^c}\, U^* \gamma^\mu (1-\gamma_5) \ell^-_\alpha + \frac{g}{2\cos\theta_W} Z_\mu \overline{N^c}\, U^* \gamma^\mu (1-\gamma_5)\nu + \ldots$$

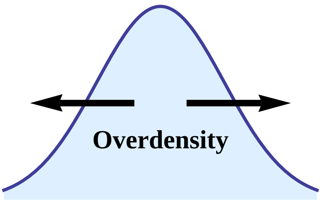
Properties of sterile neutrino dark matter

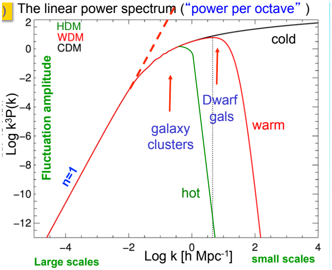
- Can be **light** (down to Tremaine-Gunn bound)
- Can be **decaying** (via small mixing with an active neutrino state)



The decay signal is proportional to $\int \rho_{\mathrm{DM}}(r)$

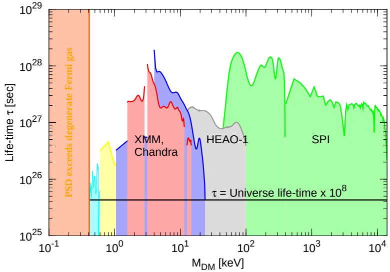
- Can be **warm** (born relativistic and cool down later)

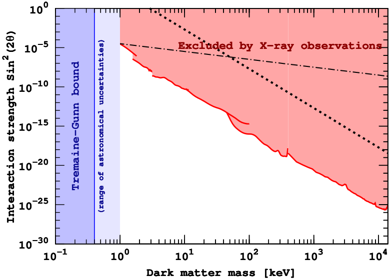


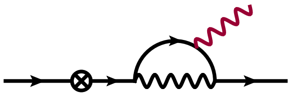


Sterile neutrino – decaying dark matter

See e.g. [1602.04816] "A White Paper on keV Sterile Neutrino Dark Matter"







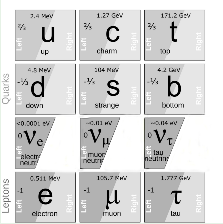
- Non-observation of decay line $N \to \gamma + \nu$
- Lifetime $\gg$ Age of the Universe (dotted line)
- Negligible contribution to neutrino masses [Asaka+'05; Boyarsky+'06]

Sterile neutrino + Okkam razor

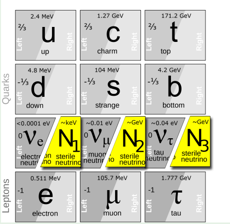
Sterile neutrinos can explain…

- 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: νMSM



$\Longrightarrow$

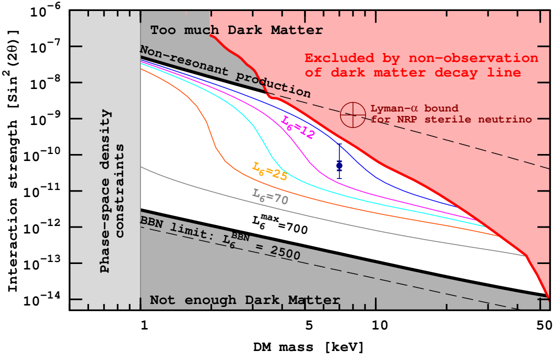


Sharing success of the Standard Model at accelerators and resolving major BSM observational problems

Asaka & Shaposhnikov'05; Review: Boyarsky+'09

νMSM dark matter parameters

Parameter space of sterile neutrino dark matter in the νMSM is bounded on all sides



Is it possible to probe **the whole** parameter space of the νMSM?

Reminder: 3.5 keV line story

Two groups simultaneously reported an unidentified feature in the 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[1,2], MAXIM MARKEVITCH[2], ADAM FOSTER[1], RANDALL K. SMITH[1] MICHAEL LOEWENSTEIN[2], AND SCOTT W. RANDALL[1]

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

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

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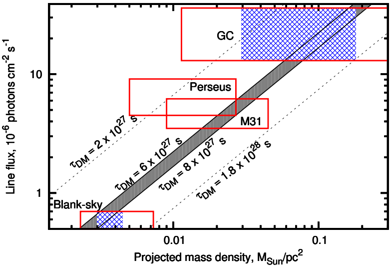
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

PRL (2014) [1402.4119]

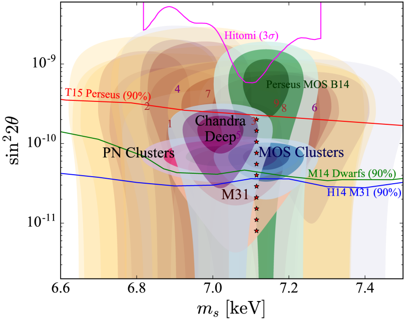
- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay DM $\to \gamma + \nu$ (fermion) or DM $\to \gamma + \gamma$ (boson)

3.5 keV line origin: radiatively decaying DM?

- Many detections and non-detections in different objects
- Consistent with **dark matter decay** hypothesis. Non-trivial check in the Milky Way halo
- Alternative interpretation: conspiracy in the anomalous abundance of Potassium or Sulfur or common systematics in 3 different instruments (XMM, Chandra, Suzaku)
- Should be **careful** when comparing results from different objects – DM content in **each** of them is **uncertain**!



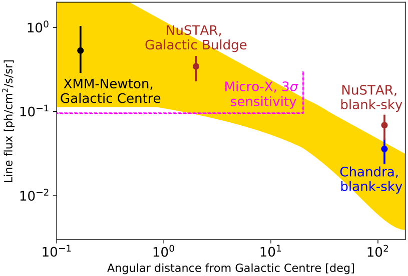
[Boyarsky+, PRL'15]



[Abazajian, Physics Report'17]

Developments in the last year

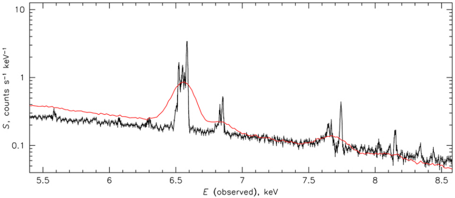
- **11σ detection** by NuSTAR blank-sky **[1607.07328]**
- **3σ detection** by Chandra from **the same region** **[1701.07932]**
- Based on this – expect a ~ 5 times larger signal from the Galactic Center. The signal is there **[1609.00667]**



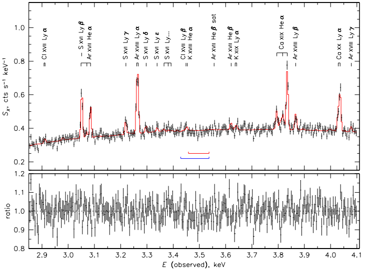
- The 3.5 keV signal has been observed with all **4** existing X-ray telescopes
- The systematic origin of the signal is **highly unlikely**

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 has observed the central part of the Perseus galaxy cluster
- Spectrometer of Hitomi is able to resolve atomic lines, measure their positions and widths (due to Doppler broadening)



X-ray spectrum of Perseus cluster as observed by XMM-Newton (red) and Hitomi (black)



Unfortunately, the satellite was lost few weeks after the launch

Status of Hitomi

(1) On March 26th, attitude maneuver to orient toward an active galactic nucleus was completed as planned.

(2) After the maneuver, unexpected behavior of the attitude control system (ACS) caused incorrect determination of its attitude as rotating, although the satellite was not rotating actually. In the result, the Reaction Wheel (RW) to stop the rotation was activated and lead to the rotation of satellite. 【Presumed Mechanism 1】

(3)In addition, unloading(*) of angular velocity by Magnetic Torquer operated by ACS did not work properly because of the attitude anomaly. The angular momentum kept accumulating in RW. 【 Presumed Mechanism 2】

(4) Judging the satellite is in the critical situation, ACS switched to Safe Hold mode (SH), and the thrusters were used. At this time ACS provided atypical command to the thrusters by the inappropriate thruster control parameters. As a result, it thrusted in an unexpected manner, and it is estimated that the satellite rotation was accelerated. 【 Presumed Mechanism 3】

(5)Since the rotation speed of the satellite exceeded the designed speed, parts of the satellite that are vulnerable to the rotation such as solar array paddles (SAPs), Extensible Optical Bench (EOB) and others separated off from the satellite. <u>There is high possibility that the both SAPs had broken off at their bases and were separated.</u> 【 Presumed Mechanism 4】

Considering the information above, JAXA concluded that the satellites functionality could not be restored and ceased recovery activities (April 28, 2016)

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]**

Status of 3.5 keV line

- Does not seem to be astrophysics (Hitomi spectrum)
- Does not seem to be systematics (4 different instruments)
- **What is this?**

- Hitomi sensitivity to broad line is much weaker
  atomic line broadening: $v_{th} \sim 10^2\,\mathrm{km/sec}$
  decaying dark matter line broadening: $v_{vir} \sim 10^3\,\mathrm{km/sec}$

Future of decaying dark matter searches in X-rays

Another Hitomi (around 2020)

It is planned to send a replacement of the Hitomi satellite

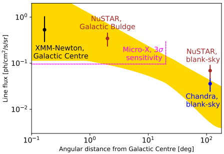
Microcalorimeter on sounding rocket (2019)

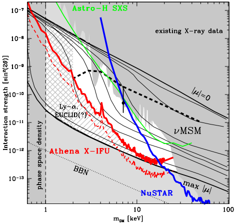
- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line's position and width

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

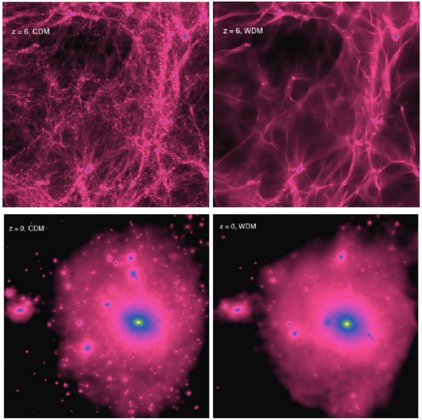
"Dark matter astronomy era" begins?





Sterile neutrino: warm dark matter

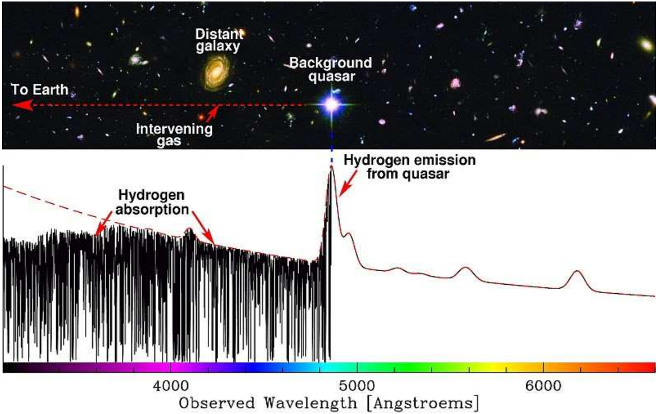
Warm dark matter – less small-scale structures



- Same structures as in **CDM** Universe at Mpc scales and above $\rightarrow$ no signatures in CMB/galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems

Can be probed by the Lyman-α forest data

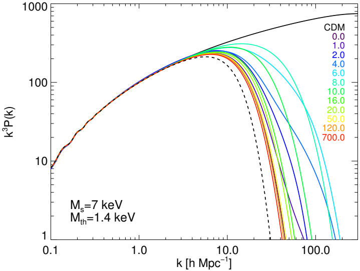
Lyman-α forest

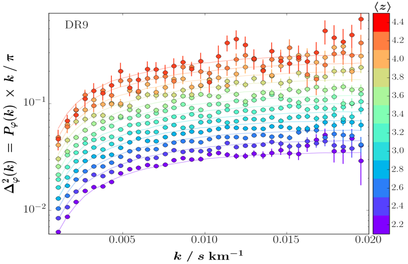


- Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$

  (Ly-α 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)





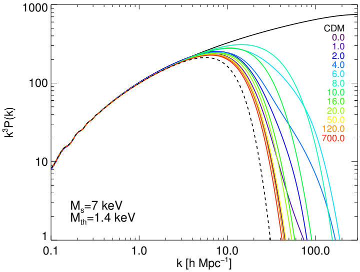
BOSS Ly-α [1512.01981]

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

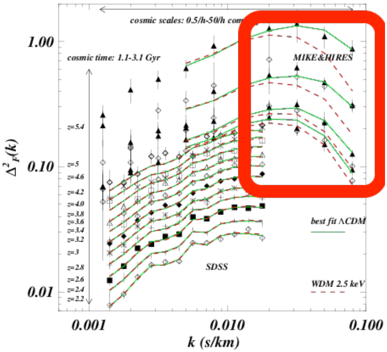
- No suppression of flux power spectrum in SDSS/BOSS datasets
- One can put only lower bound on WDM mass

  [Seljak+'06;Viel+'06;Boyarsky+'08;. . .]

High-resolution Ly-α forest



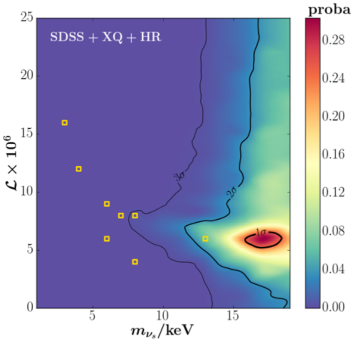
Warm dark matter predicts suppression (cut-off) in the flux power spectrum derived from the Lyman-α forest data

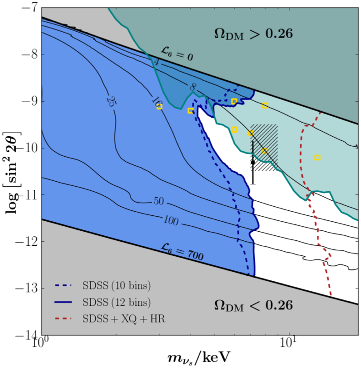


Lyman-α from HIRES data [1306.2314]

- HIRES flux power spectrum **exhibits suppression at small scales**
- This suppression can be explained equally well by thermal history of the Universe (unconstrained at these redshifts) or by **warm dark matter** **[Garzilli, Boyarsky et al. 1510.07006]**

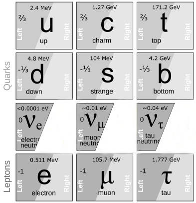
The latest results from Ly-α forest [1706.03118]





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

Conclusions



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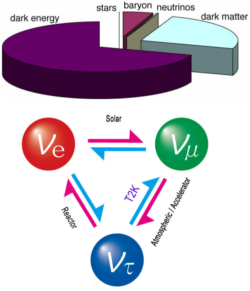

Neutrino oscillation between three generations

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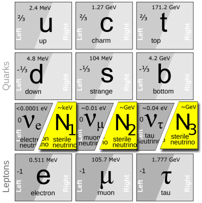
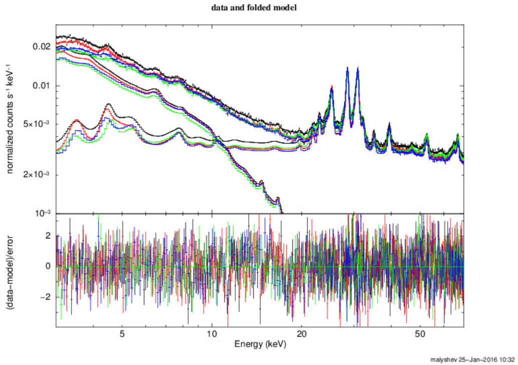


Thank you for your attention!

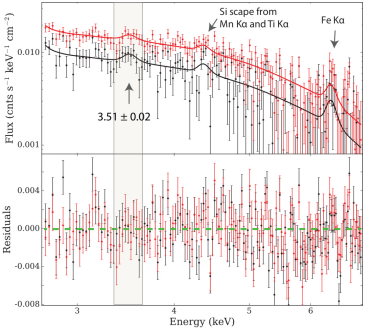
Backup slides:

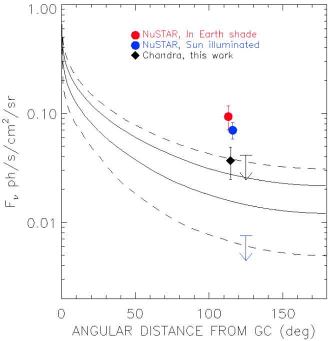
NuSTAR detections: blank-sky [1607.07328]



- **11σ detection** at the level **slightly more than predicted with decaying DM**;
- Located ‘at the edge of energy range, where large uncertainties of response functions are potentially present’.

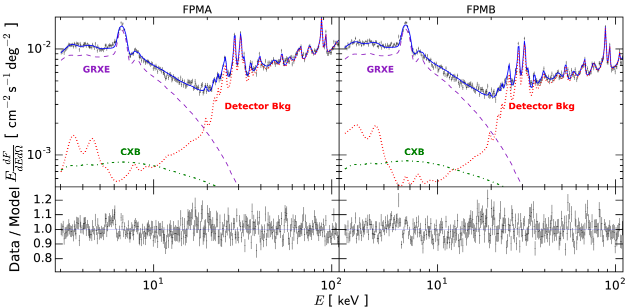
Chandra detections: blank-sky [1701.07932]





- **3σ detection** at the level **consistent with decaying DM**
- **No instrumental features** at these energy (compared with the other instruments)
- Combined with XMM and Suzaku detections, argues **against** systematical origin.

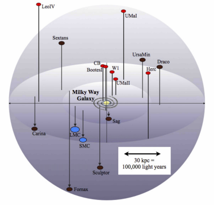
NuSTAR detections: GC [1609.00667]



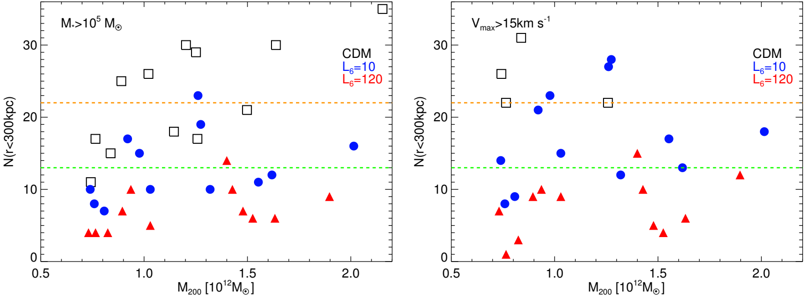
- 3.5 keV line nature ‘is not totally clear’ and ‘its determination is beyond the scope of this work’;
- No numbers are given but from above Fig. one can estimate 3.5 keV line flux that is ~ 5 **times larger** than found by 1607.07328 – **perfectly consistent** with decaying DM!

Satellite number and properties

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
- **Observations**: We do not know how typical Milky Way is



Lovell, Boyarsky, Ruchayskiy et al. [1611.00010]



Current status of structure formation bounds from the Local Universe

- Connection "dark structures" $\leftrightarrow$ "visible structures" depends on (yet unknown) way to implement baryonic feedback
- Simulation to simulation (or even halo-to-halo) scatter is **large** and **affects** the conclusions
- We **do not know** how typical is our Galaxy, our Local Group, etc.
- We **cannot "rule out"** your warm dark matter model with these observations
- Need **statisticically significant** sample instead