Sterile neutrino dark matter

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PPC 2018
Zurich
August 23, 2018

~~Sterile~~ 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

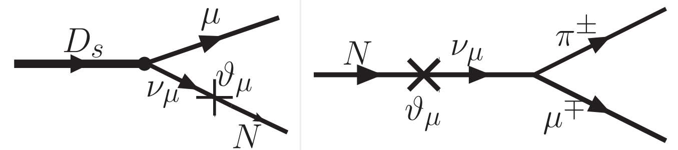
One can make dark matter **heavy** and therefore their number density is Boltzmann-suppressed $(n \propto e^{-m/T})$ at freeze-out

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

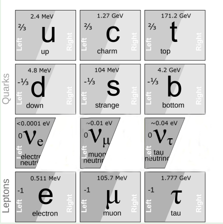
$$\mathcal{L}_{int} = \frac{g}{\sqrt{2}} W_\mu^+ \overline{N^c}\, U^*\, \gamma^\mu (1-\gamma_5) \ell_\alpha^- + \frac{g}{2\cos\theta_W} Z_\mu \overline{N^c}\, U^*\, \gamma^\mu (1-\gamma_5) \nu + \dots$$

Sterile neutrino + Okkam razor

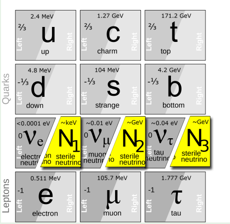
Sterile neutrinos can explain...

- 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



$\Longrightarrow$

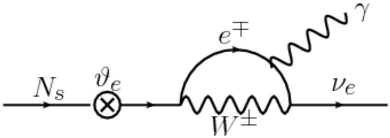


Sharing success of the Standard Model at accelerators and resolving major BSM observational problems

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

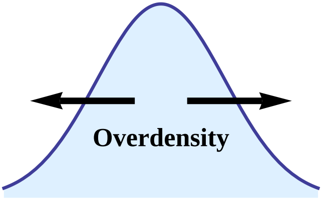
Properties of sterile neutrino dark matter

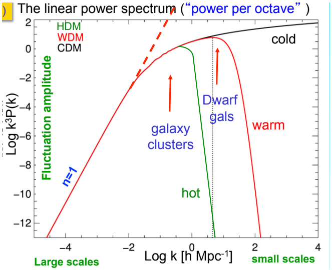
- Can be **light** (down to Tremaine-Gunn bound)
- Can be **decaying** (via small mixing with an active neutrino state)



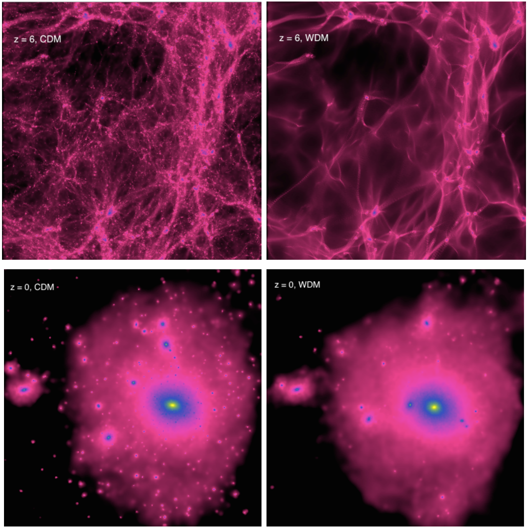
The decay signal is proportional to $\int \rho_{\rm DM}(r)$

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





At non-linear scales



COCO Warm simulation Bose+'15

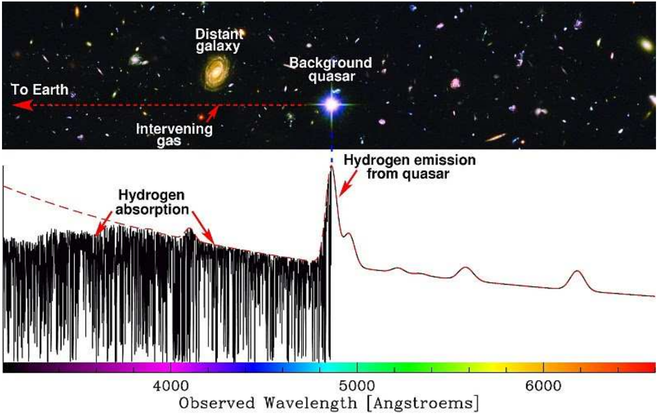
HNL dark matter:

- No signatures in CMB or galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo

. . . WDM was "ruled out" many times

In reality WDM may have been discovered 5 years ago. . .

Lyman-α forest



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

  (Ly-α absorption $1s \to 2p$)
- Absorption occurs at $\lambda = 1215.67\text{Å}$ in the **local reference frame** of hydrogen cloud.
- Observer sees the **forest**: $\lambda = (1+z)1215.67\text{Å}$

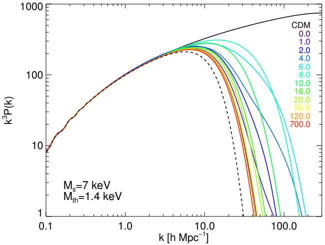
Suppression in the flux power spectrum (SDSS)

What we want to detect

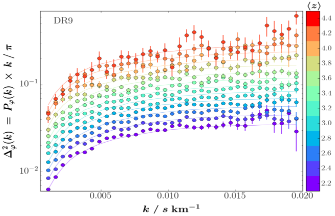
- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the ΛCDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

- We observe **flux power spectrum** – projected along the line-of-sight power spectrum of neutral hydrogen absorption lines

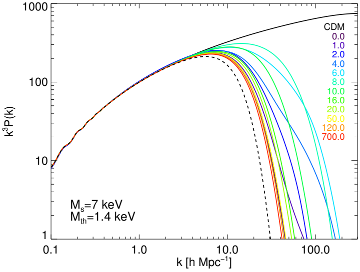


3D linear matter power spectra

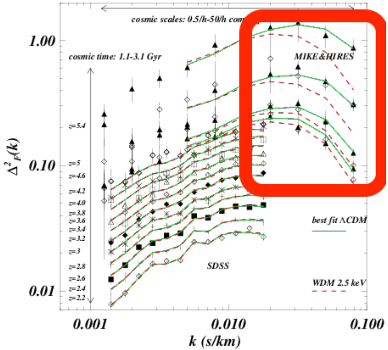


BOSS (SDSS-III) Ly-α [1512.01981]

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]

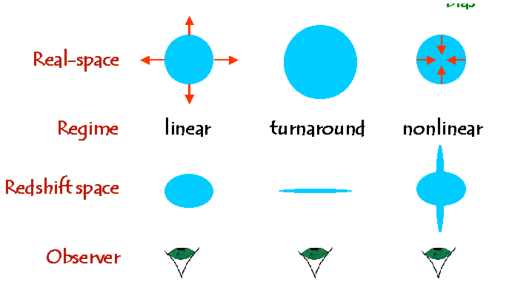
- HIRES flux power spectrum **exhibits suppression at small scales**

Is this warm dark matter?

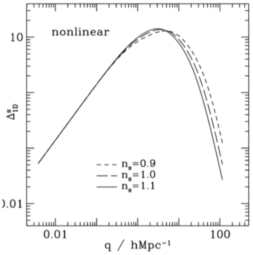
Cut-off in CDM: Redshift-space distortion

- Lyman-α forest measures **absorption features** – power spectrum in **redshift space**

$$z_{obs} = z_{true} + \frac{v_{pec}}{c}$$



[Matthew Colless, 2dF]



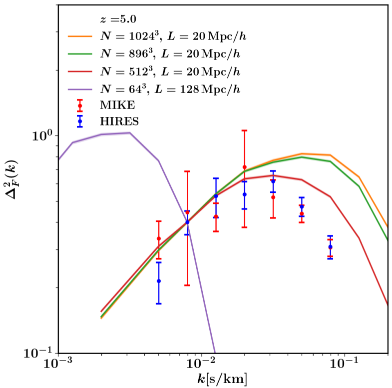
[Desjacques & Nusser'04]

Even for ΛCDM the non-linear power spectrum (measured from the redshifts space) has a suppression at small scales (matter falls towards overdensities)

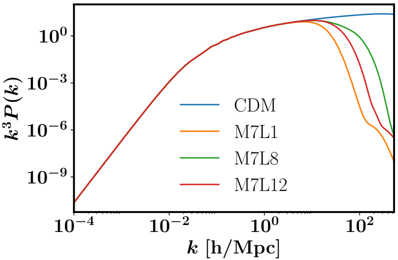
Redshift distortion effect. Resolution studies

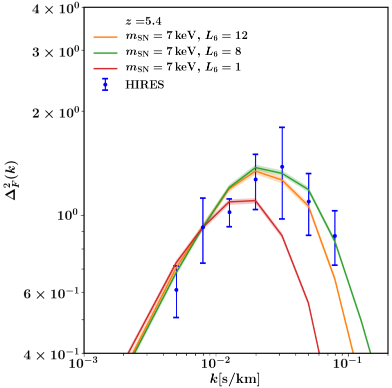
Garzilli, Magalich, Frenk, Theuns, Weniger, Ruchayskiy, Boyarsky (2018) To appear

- Increasing resolution of simulation shows that the effect happens at **too small scales to affect Ly-α spectra**



Can the observed suppression be warm dark matter?





- The shape of the flux power spectrum can be explained by resonantly produced sterile neutrinos with $M = 7\,\mathrm{keV}$ and $L_6 \sim 12$

Garzilli, Magalich, Frenk, Theuns, Weniger, Ruchayskiy, Boyarsky (2018) To appear

If baryons follow dark matter on all scales – warm dark matter fits perfectly the high resolution Lyman-α forest data (and CDM **does not** fit)

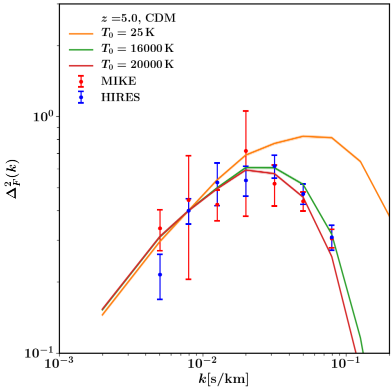
Do baryons follow dark matter?

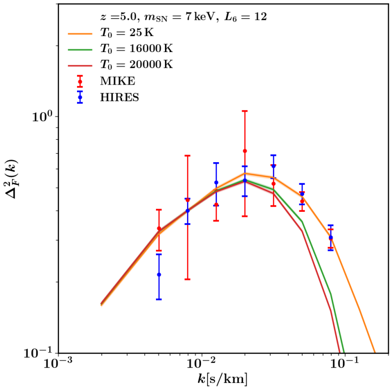
- Universe was completely ionized by $z \sim 6$
- Gas had become **hot**

Baryonic effects

- Temperature at redshift z (Doppler broadening) – **increases hydrogen absorption line width**
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)

Baryonic effects: Doppler broadening





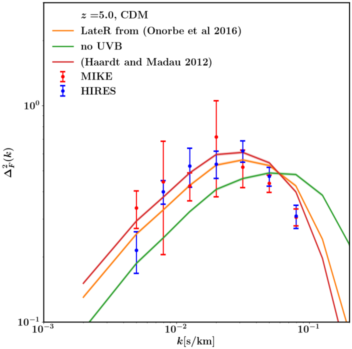
Garzilli, Magalich, Frenk, Theuns, Weniger, Ruchayskiy, Boyarsky (2018) To appear

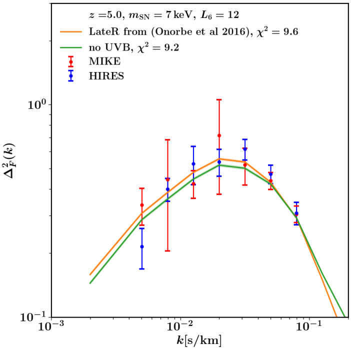
Doppler broadening can also explain the observed suppression of flux power spectrum

Gas pressue effects on Lyman-α flux power spectrum

Garzilli, Magalich, Frenk, Theuns, Weniger, Ruchayskiy, Boyarsky (2018) To appear

- Reionization heats the gas
- Gas **pressure** increases
- Pressure opposes collapse of structures below the **Jeans scale**
- Jeans length evolves in the Universe





Pressure effects can also explain the observed suppression of flux power spectrum

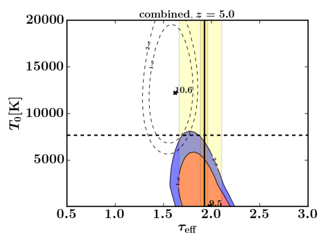
So, what is the origin of the cut off?

Garzilli, Magalich, Frenk, Theuns, Weniger, Ruchayskiy, Boyarsky (2018) To appear

Both WDM and thermal effects can explain the cut-off:

- The shape of the flux power spectrum can be explained by WDM (e.g. 7 keV sterile neutrino)
- Can also be explained by CDM + (combination of) pressure and temperature effects
- we need to work much more to decide, did we discovered or ruled out WDM

14 d.o.f



PRELIMINARY

Garzilli, Magalich, Frenk, Theuns, Weniger, Ruchayskiy, Boyarsky (2018) To appear

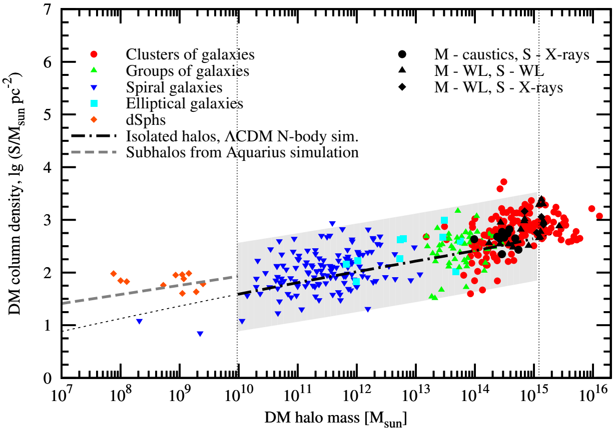
Prediction

If the shape of the HIRES/MIKE flux power spectrum is explained by the DM free-streaming, we **predict** IGM medium with $T_{IGM} \lesssim 8\,000$ K at $z \sim 5$ and the start of reionization at $z \sim 7$

Decaying Dark Matter and 3.5 kev line

Signal from different DM-dominated objects

Boyarsky, Ruchayskiy et al. Phys. Rev. Lett. 97 (2006); Phys. Rev. Lett. 104 (2010)



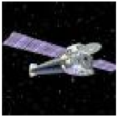
Signal:

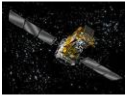
$$\mathcal{S} = \int \rho_{dm}(r) dr$$

(Column density)

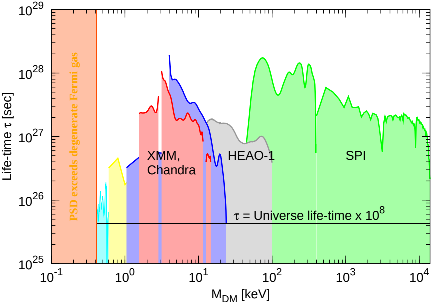
Search for Dark Matter decays in X-rays

See “Next decade in sterile neutrino studies” by Boyarsky et al. [Physics of the Dark Universe, 1 (2013)]





Available X-ray satellites: Suzaku, XMM-Newton, Chandra, INTEGRAL, NuStar



MW (HEAO-1) Boyarsky+ 2005; Coma and Virgo clusters (XMM) Boyarsky+ 2006 ; Bullet cluster (Chandra) Boyarsky+ 2006; LMC&MW(XMM) Boyarsky+ 2006; MW (XMM/Chandra) Riemer-Sørensen+ (2006); Abazajian+ 2006; MW (SPI) Yuksel+ (2007); Boyarsky+ (2007); M31 (XMM) Watson+ 2006; Boyarsky+ 2007

$$\text{Signal-to-noise} \propto \overbrace{\mathcal{S}_{\text{DM}}}^{signal} \underbrace{\sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E}}_{signal-over-background}$$

Detection of An Unidentified Emission Line

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

Bulbul et al. ApJ (2014) [1402.2301]

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

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

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

Boyarsky et al. Phys. Rev. Lett. (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{27} - 10^{28}$ sec (uncertainty: factor $\sim 3 - 5$)

Decaying dark matter?

Interpretations I

There are 4 classes of interpretations

- Statistical fluctuation (there is nothing there at all!)
- Unknown astrophysical emission line (emission line of some chemical element)
- Instrumental feature (systematics) (We do not know our telescopes well enough)
- Dark matter decay line

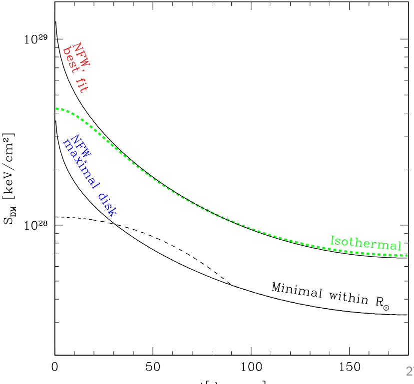
Significance of the original signal

[Boyarsky et al. Phys. Rev. Lett. (2014) [1402.4119]]		
M31 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.
M31 + Perseus (MOS)	$\Delta\chi^2 = 25.9$	4.4σ for 3 d.o.f.
Global significance of detecting the same signal in 3 datasets: 4.8σ		
[Bulbul et al. ApJ (2014) [1402.2301]]		
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 center (XMM, MOS)	$\Delta\chi^2 = 12.8$	3.1σ for 2 d.o.f.
Perseus center (Chandra, ACIS-S)	$\Delta\chi^2 = 11.8$	3.0σ for 2 d.o.f.
Perseus center (Chandra, ACIS-I)	$\Delta\chi^2 = 6.2$	2.5σ for 1 d.o.f.

More detections followed!

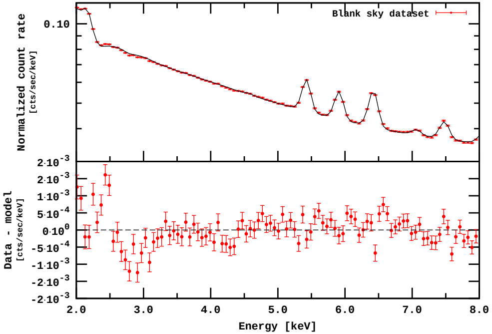
Consistency check: Milky Way outskirts

- We are surrounded by the Milky Way halo on all sides
- Expect signal from any direction. Intensity drops with off-center angle
- Surface brightness profile of the Milky Way would be a "smoking gun"



Consistency check: Milky Way outskirts

Phys. Rev. Lett. (2014) [1402.4119]

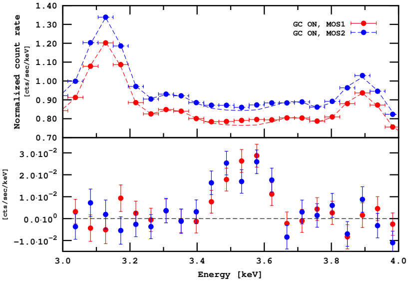


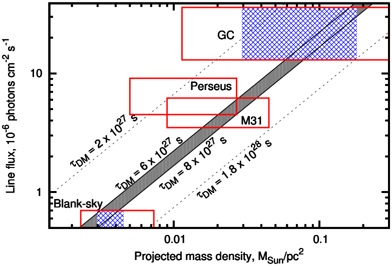
- No line is seen in 16 Msec observations of off-center Milky Way
- Confirmed by
  - **[(Sekiya et al. [1504.02826])]** with Suzaku
  - **[(Figueroa-Feliciano et al. [1506.05519])]** with XQC

Is this the end of the story?

Galactic center – a non-trivial consistency check

Boyarsky+ Phys. Rev. Lett. 115, (2014)



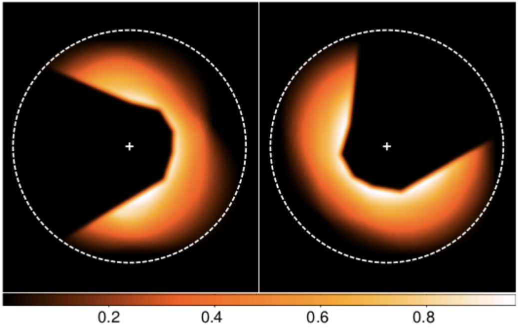


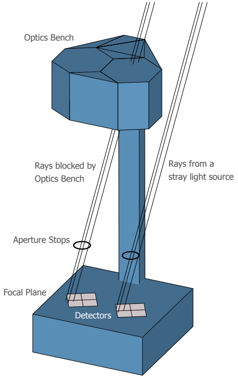
- $4\sigma+$ statistical significance
- Also in **S. Riemer-Sorensen'14; Jeltema & Profumo'14**

The observed signal fits into the predicted range

Another X-ray satellite: NuStar

- Has small field of view, would not be competitive with XMM, Chandra or Suzaku
- **But!** NuStar has a specical **0-bounce photons** mode where FoV is $30\,\mathrm{deg}^2$

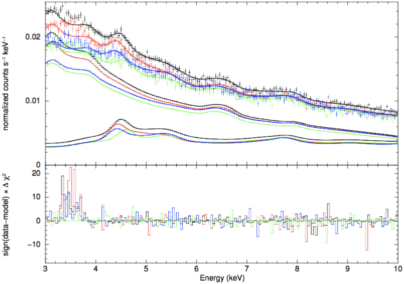




3.5 keV line in NuStar spectrum

Milky Way halo. Neronov & Malyshev [1607.07328]. Also Ng+ [1609.00667]

- The 3.5 keV is present in the 0-bounce spectrum of the Cosmos field and CDFS (total cleaned exposure $7.5\,\mathrm{Msec}$)
- Combined detection has 11σ **significance**
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band

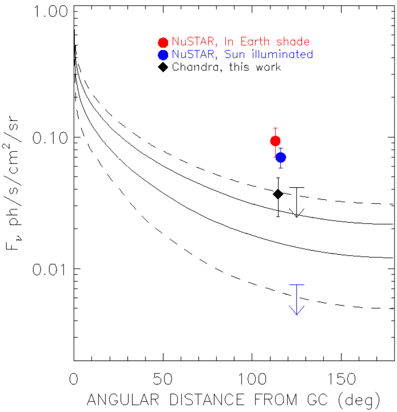


- The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure
- However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux

Line in Chandra from the same region of the sky

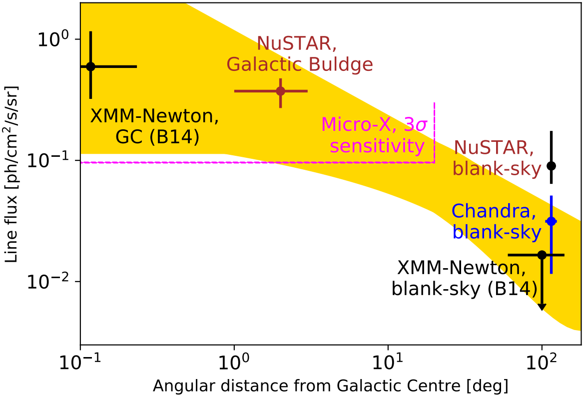
Cappelluti+'17 [1701.07932]

- Combined 10 Msec of Chandra observation of COSMOS and CDFS fields (same as NuStar)
- 3σ detection of a line at ~ 3.5 keV
- Flux is compatible with NuStar
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115°$ off center)



Surface brigthness profile of the 3.5 keV line in the Milky Way. PRELIMINARY

Boyarsky, Iakubovskyi, Ruchayskiy. To appear (2018)



All detection in the Milky Way follow the same trend

Not systematics!

By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

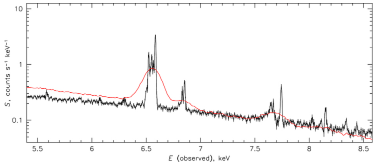
- Line is changing with redshift
- ACIS-I is a silicon CCD while the imagers of NuSTAR are two Cadmium-Zinc-Telluride detectors
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely
- Different orbits of satellites – cosmic ray origin is unlikely
- Datasets accumulated over different periods (15yrs for Chandra vs. 3yrs for Nustar) – not related to, e.g. solar activity

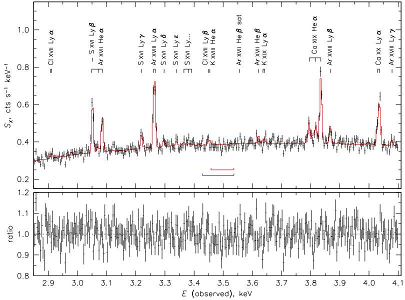
Is this a line from atomic transition(s)?

As argued by **[Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+]**

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 observed the central part of the Perseus galaxy cluster where strong line was detected by XMM & Suzaku
- Spectrometer of Hitomi is able to resolve atomic lines, measure their positions and their Doppler broadening

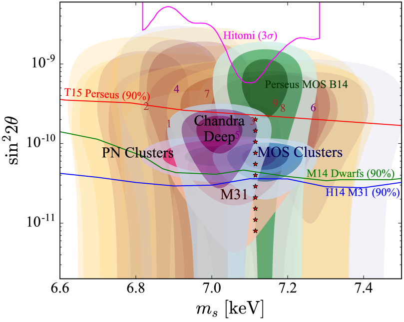




Unfortunately, the satellite was lost few weeks after the launch

What did we learn with existing Hitomi data?

- Even the short observation of Hitomi showed **no nearby astrophysical lines** in Perseus cluster $\to 3.5$ keV line is **not astrophysical [Hitomi collaboration, 1607.04487]**
- Astrophysical lines in the center are Doppler broadened with velocity $v_{th} \sim 10^2\,\mathrm{km/sec}$ (as measured by Hitomi collaboration)
- Decaying dark matter line broadening is determined by the virial velocity of the Perseus galaxy cluster, $v_{vir} \sim 10^3\,\mathrm{km/sec}$
- For XMM/Chandra/Suzaku/Nustar there was no difference – they resolution did not allow to distinguish broad from narrow lines
- Hitomi sensitivity to broad line is much weaker



[1705.01837]

Future of decaying dark matter searches in X-rays

Another Hitomi (around 2020)

It is planned to send a replacement of the Hitomi satellite

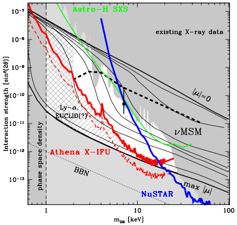
Microcalorimeter on sounding rocket (2019)

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

Athena+ (around 2028)

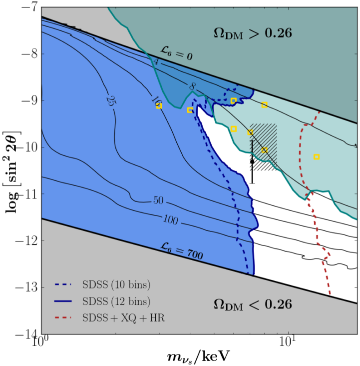
- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution

"Dark matter astronomy era" begins?



The latest results from Ly-α forest [1706.03118]

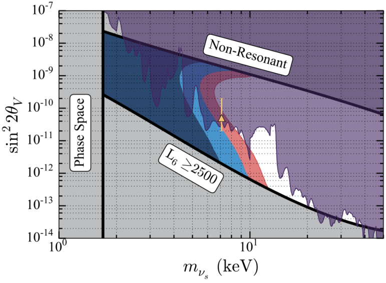
By accident (or maybe not) sterile neutrino dark matter interpretation of 3.5 keV line predicts exactly the amount of suppression of power spectrum observed in HIRES/MIKE (and fully consistent with all other structure formation bounds)



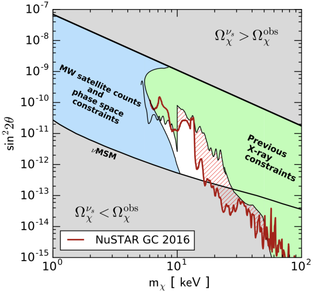
- Data from SDSS-III (BOSS) + X-Shooter + HIRES
- Limited set of thermal histories

Warm dark matter has been "ruled out" many times

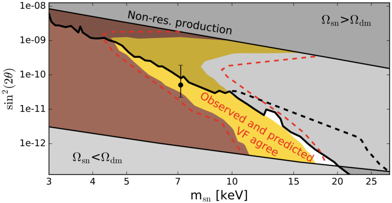
We keep seeing such plots. . .



[1701.07674]



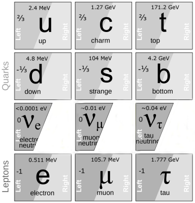
[1609.00667]



[1704.01832]

However, these structure formation bounds should be understood differently that bounds in particle physics

Conclusions



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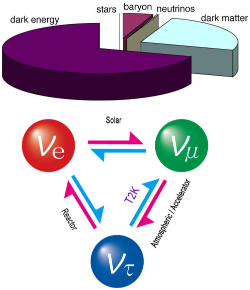

Neutrino oscillation between three generations

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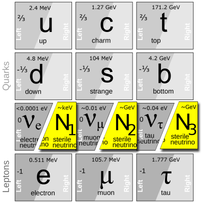
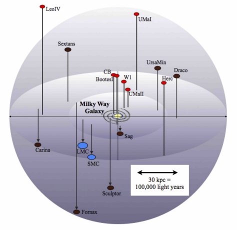


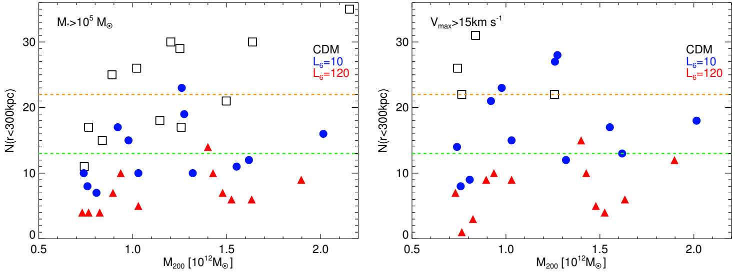
Thank you for your attention!

Backup slides

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+ [1611.00010]

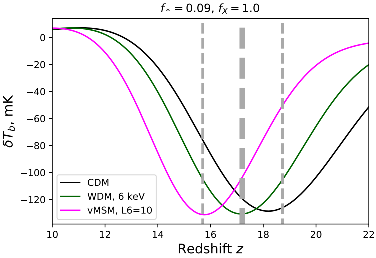
Current status of structure formation bounds from the Local Universe

- 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 quite large and affects the conclusions
- We do not know how typical is our Galaxy, our Local Group, etc

- You cannot "rule out" your warm dark matter model with these observations
- You can only **check** that your model **fits the data under "reasonable" assumptions about baryonic physics**

WDM and 21cm line

- EDGES signal means that stars already existed by $z \simeq 17$
- Does this limit models with delayed structure formation (e.g. WDM)? **[1805.00021]**
- **No!** Details of star formation are not known and the results of analytical/numerical estimates are controlled by parameters about which we have little knowledge



[Boyarsky et al. to appear]

- These parameters were never determined for WDM cosmologies where star formation **is known to be different** from CDM
- WDM (rather than CDM) can easily produce enough star light by $z \simeq 17$ **[Boyarsky et al. to appear]**