WDM, sterile neutrino DM

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Neutrino DM? Tremaine-Gunn bound

In 1979 when S. Tremaine and J. Gunn published in Phys. Rev. Lett. a paper *"Dynamical Role of Light Neutral Leptons in Cosmology"*

- The smaller is the mass of Dark matter particle, the larger is the number of particles in an object with the mass M_{gal}
- Average **phase-space density** of **any fermionic** DM should be **smaller** than density of **degenerate Fermi gas**

$$\frac{2m_{\text{DM}}{}^4}{(2\pi\hbar)^3} \geq \frac{M_{gal}}{\frac{4\pi}{3}R_{gal}^3}\,\frac{1}{\frac{4\pi}{3}v_\infty^3}$$

- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass $M_{\text{DM}} \gtrsim 300 - 400$ eV **[0808.3902]**
- More stringent bounds based on Lioville theorem are **model-dependent** **[Boyarsky, Bondarenko, Fairbain, Read, . . .]**

Neutrino Dark Matter: Tremaine-Gunn bound

Are neutrinos with such a mass are excluded?

- We can compute **contribution to DM density from massive neutrinos**
- The **number density for neutrinos** is given by

$$n_{\nu,0} = \int f_F(p) \frac{d^3p}{(2\pi)^3} \sim T_\nu^3(t_0) \simeq 112 \text{ cm}^{-3}$$

- So the contribution to DM is

$$\Omega_{\nu\text{DM}} h^2 = \frac{1}{\rho_{c,100}} \sum m_\nu n_{\nu,0} = \frac{\sum m_\nu \text{ eV}}{94 \text{ eV}}$$

- For $m_{\text{DM}} = 300$ eV one gets $\Omega_{\text{DM}} h^2 \sim 3$ (**wrong by a factor of 30!**)
- Sum of masses to have the **correct abundance** $\boxed{\sum m_\nu \approx 11 \text{ eV}}$

Massive neutrinos cannot be simultaneously "astrophysical" and "cosmological" dark matter

Neutrino Dark Matter: Structure formation

- Next blow to neutrino DM came around 1983–1985 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 have 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

Consider **heavy** dark matter particles in the thermal equilibrium. Their number density is Boltzmann-suppressed ($n \propto e^{-m/T}$) at freeze-out

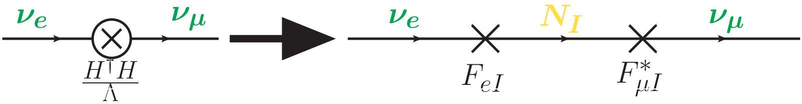
Second alternative: super-WIMP

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

Example of super-WIMPs: sterile neutrino DM I

- Consider a massive particle, N (**"sterile neutrino"**), that interacts with the SM particles like neutrino, but the interaction strength is ϑG_F, where $\vartheta \ll 1$
- The $\vartheta \ll 1$ is so small that N never enters thermal equilibrium. The interaction rate $\Gamma_N \approx \vartheta^2 G_F^2 T^5$ – similar to neutrino, but suppressed by ϑ^2
- Their number density slowly builds up from interaction with the SM particles (inverse process of DM particles converting into the SM ones is not effective while there are too few DM particles, much less than equilibrium)
- As a result their total number density: $n_N \propto \vartheta^2 n_\nu$ and their abundance $\Omega_N \propto m_N \vartheta^2$. For sufficiently small ϑ particles of any mass can produce the correct DM abundance

Example of super-WIMPs: sterile neutrino DM II



- Sterile neutrinos should explain observable neutrino oscillations
- States that propagate (**mass eigenstates**) do not have a definite weak charges – oscillations

- Neutrinos are light because $M_D \ll \boldsymbol{M}$:

$$\boxed{m_\nu \simeq \frac{(M_D)^2}{\boldsymbol{M}}} = U^2 \boldsymbol{M}$$

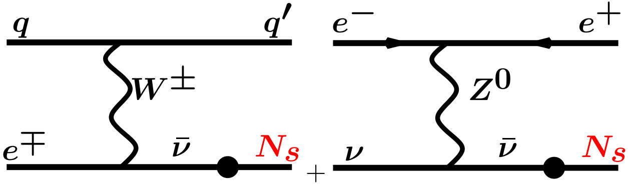
- **active-sterile mixing angle**

$$\boxed{U = \frac{M_D}{\boldsymbol{M}} \ll 1}$$

- Two quasi-degenerate sterile neutrinos may generate masses of active neutrinos even if $U^2 \gg m_\nu / \boldsymbol{M}$ – fine-tuning

Example of super-WIMPs: sterile neutrino DM III

- Sterile neutrino is produced in the primordial plasma via processes like



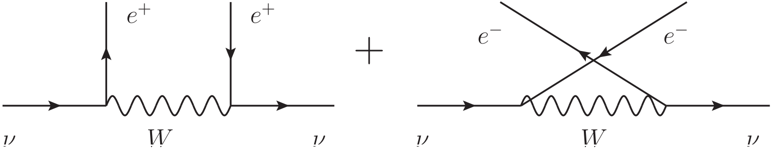
- Let us check first whether sterile neutrinos entered thermal equilibrium: compare the reaction rate Γ_N with the Hubble expansion rate

$$\Gamma_N \sim \vartheta^2 G_F^2 T^5 \gtrless \frac{T^2}{M_*} \tag{1}$$

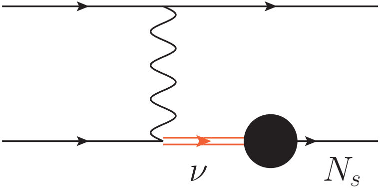
- **Naively**, one may conclude that HNLs were in equilibrium $\Gamma > H$ up until the temperature

$$T_{\text{dec}} \sim \left(M_* G_F^2 \vartheta^2\right)^{-1/3} \approx 90 \text{ MeV} \left(\frac{10^{-5}}{\vartheta^2}\right)^{1/3} \tag{2}$$

Example of super-WIMPs: sterile neutrino DM IV

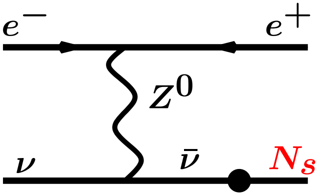


- Equation of motion for neutrinos propagating in thermal medium gets changed



- Neutrinos are an intermediate state in any process with N_s. A change of properties of neutrinos lead to the corresponding change of any matrix element with N_s

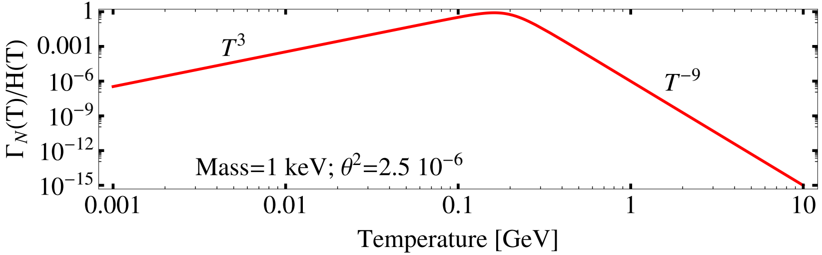
Example of super-WIMPs: sterile neutrino DM V



- Averaging over the particles from the bath, the mixing angle becomes temperature dependent:

$$\vartheta(T) \approx \frac{\vartheta_0}{1 + c\frac{T^6 G_F^2}{\alpha M_N^2}} \tag{3}$$

Example of super-WIMPs: sterile neutrino DM VI

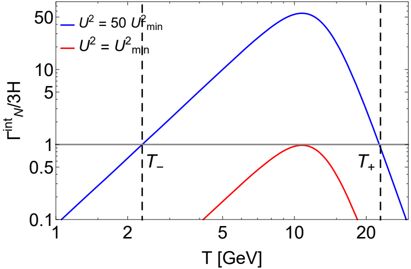


- The reaction rate $\Gamma_N(T) \sim \vartheta^2(T) G_F^2 T^5$ is strongly suppressed at high temperatures
- The production is the most effective at

$$T_{\text{peak}} \sim 150 \text{ MeV} \left(\frac{M_N}{1 \text{ keV}}\right)^{1/3} \gg M_N \tag{4}$$

for M_N in keV–MeV range. Because of the suppression it may turn out that always $\Gamma_N \lesssim H$

Example of super-WIMPs: sterile neutrino DM VII



- Namely, for HNLs with mass in GeV range, the total interaction rate is $\Gamma_N^{\text{int}} = c\vartheta^2 G_F^2 T^5$, where $c = \mathcal{O}(10)$. Then the condition $\Gamma_N^{\text{int}} \lesssim H$ is always satisfied for angles

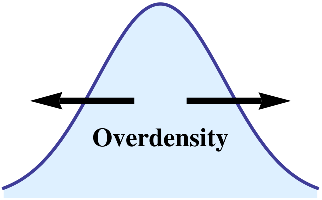
$$U^2 \lesssim U^2_{\text{min}} \simeq 10^{-12}\frac{1\ \text{GeV}}{M_N} \tag{5}$$

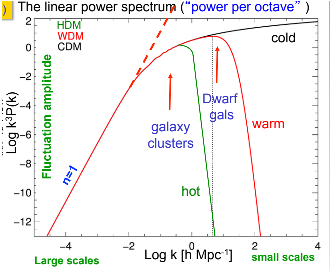
- ... and indeed, HNLs have phase-space distribution

$$f_N(p,t) \sim \frac{\vartheta^2}{\exp(\frac{p}{T_\nu(t)}) + 1} \tag{6}$$

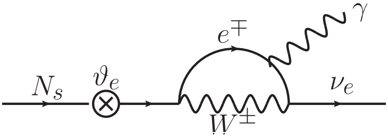
Main sterile neutrino DM signatures

- It is **warm** (born relativistic and cool down later)





- It is **decaying** (via small mixing with an active neutrino state)



Sterile neutrino + Okkam razor I

νMSM: 2 quasi-degenerate GeV-scale Majorana neutrinos $N_{1,2}$ + light keV-scale DM

Sakharov: To generate baryon asymmetry of the Universe **3 conditions** should be satisfied

1. Baryon number should not be conserved
2. C-symmetry and CP-symmetry must be broken
3. Deviation from thermal equilibrium in the Universe expansion

Two quasi-degenerate HNLs with masses $m_N \gtrsim 1$ GeV may provide all Sakharov conditions:

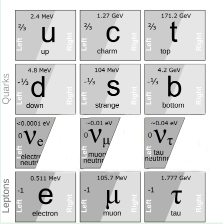
- They may never enter thermal equilibrium
- They violate the lepton number, which then may be transferred to the baryon number via sphalerons
- They introduce additional complex phases to neutrino mass matrices and hence CP violation

Sterile neutrino + Okkam razor II

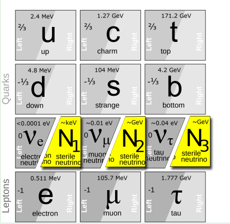
Sterile neutrinos can explain. . .

- 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

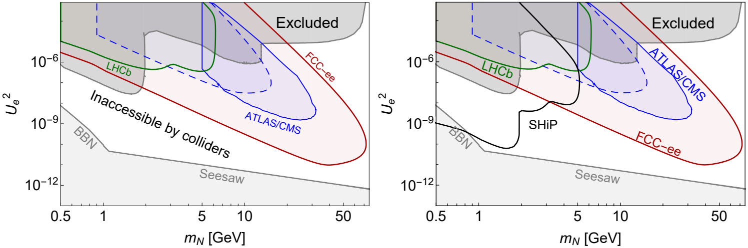


$\Longrightarrow$



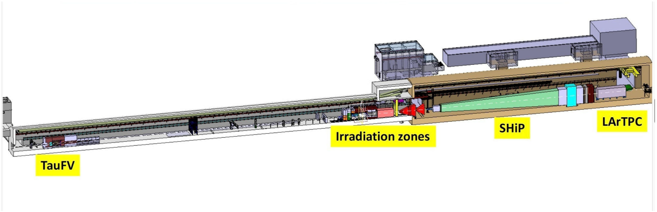
Sharing success of the Standard Model at accelerators and resolving major BSM observational problems Asaka & Shaposhnikov'05; Review: Boyarsky+'09

Sterile neutrino + Okkam razor III

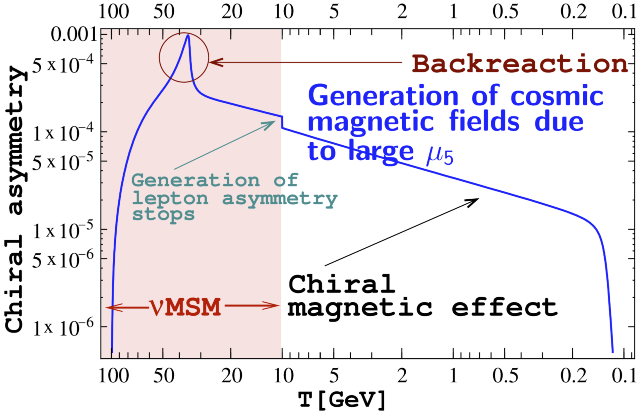


– GeV-scale Majorana neutrinos may be explored at colliders (large masses) and beyond collider experiments (e.g. SHiP)

Bondarenko et al. 2023



Sterile neutrino + Okkam razor IV

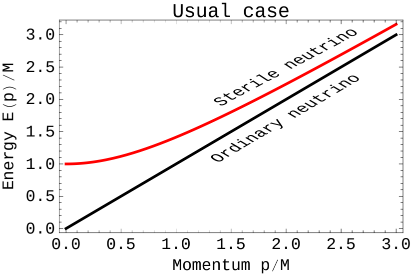


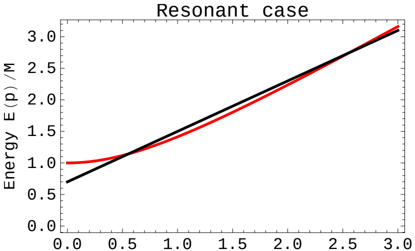
- Sterile neutrinos may also generate primordial magnetic fields

In preparation

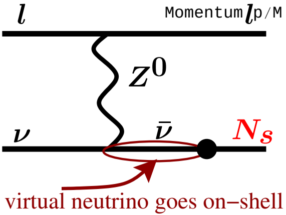
Production through resonant mixing

Shi & Fuller [astro-ph/9810076]; Laine & Shaposhnikov [0804.4543]



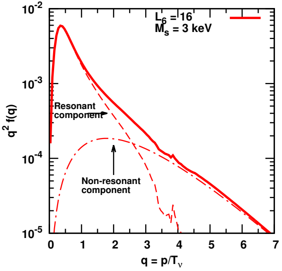


- Conversion of ν to N is enhanced whenever "levels" cross and virtual neutrino goes "on-shell" (analog of MSW effect but for active-sterile mixing)

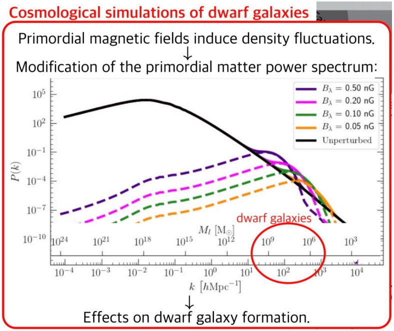


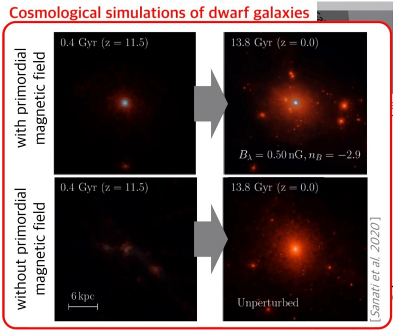
Resonantly produced sterile neutrinos

- In the presence of **large lepton asymmetry** the **MSW resonance** can take place and production of sterile neutrinos becomes much more effective
- The condition for resonance occurs only for specific values of momentum p and during limited period of time
- The resulting sterile neutrino velocity distribution is a mixture of **cold** and **warm** components



- Primordial magnetic field may influence the formation of dwarf galaxies



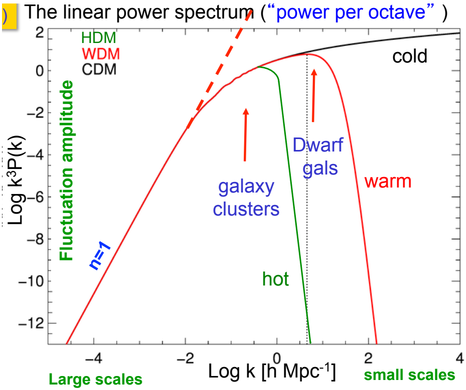


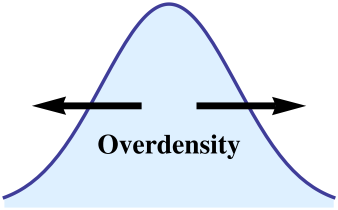
Sanati et al. 2020, Katz 2021

Sterile neutrino as warm dark matter

Warm dark matter

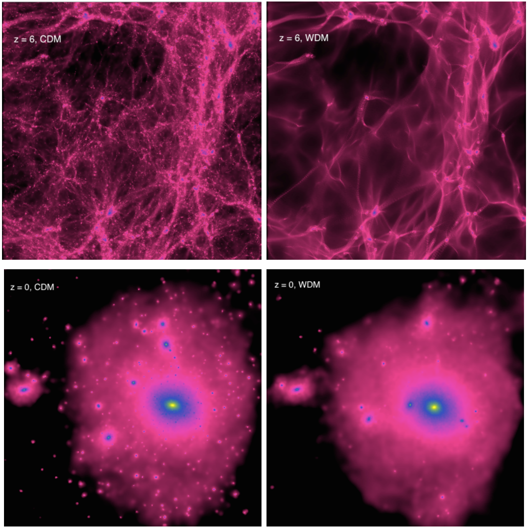
- Particles are born relativistic $\Rightarrow$ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities





– Particle velocities means that warm dark matter has effective **pressure** that prevents small structure from collapsing

What is “warm dark matter” observationally?

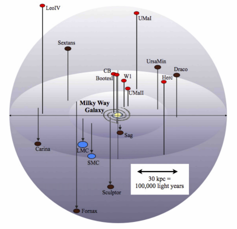


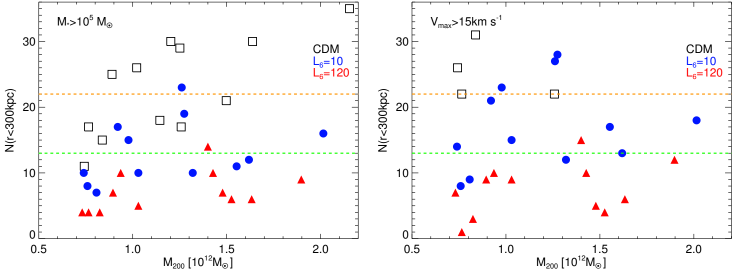
Warm dark matter:

- Same structures as in **CDM** Universe at scales of Mpc and above $\Rightarrow$ 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
- **Can help** with “too big to fail” or “missing satellites” problems

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

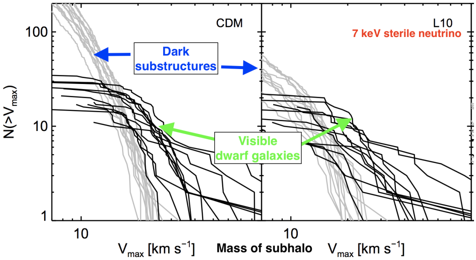


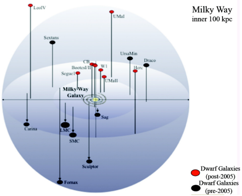


Lovell, Boyarsky+ [1611.00010]

Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]





> The same number of luminous satellites, but different number of **dark** satellites

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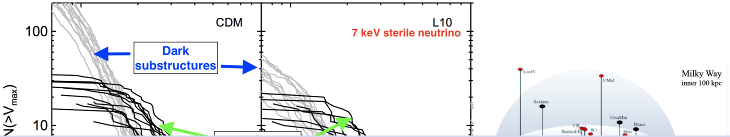
Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]



- The way out is to detect **dark substructures** directly
- This can be done via strong gravitational lensing

The same number of luminous satellites, but different number of **dark** satellites

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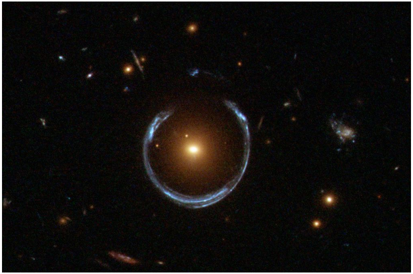
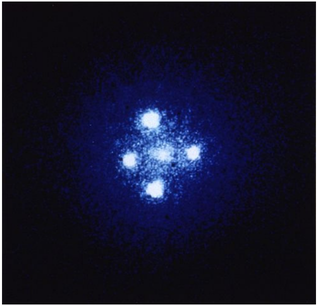
Strong gravitational lensing

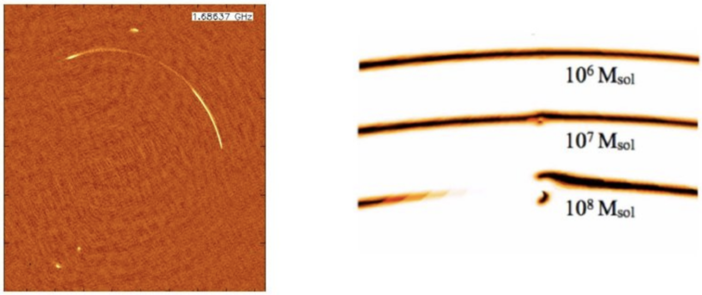


Einstein ring: large red galaxy lenses distant blue galaxy (almost on the line-of-sight).



Einstein cross: 4 images of a distant quasar

Dark substructures detection via arcs

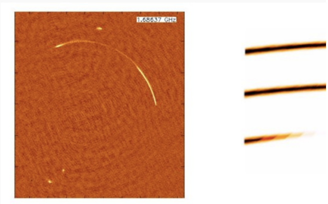


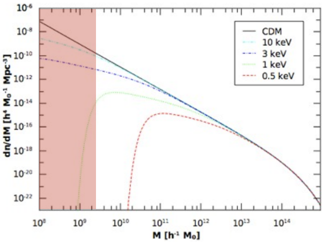
High-resolution gravitational imaging: The image on the left shows VLBI data for the lens system B1938+666. The long arc is a strongly lensed image of a distant background galaxy. The image on the right shows how different mass substructures in the lens galaxy would affect the gravitational arc of B1938+666.

S. Vegetti

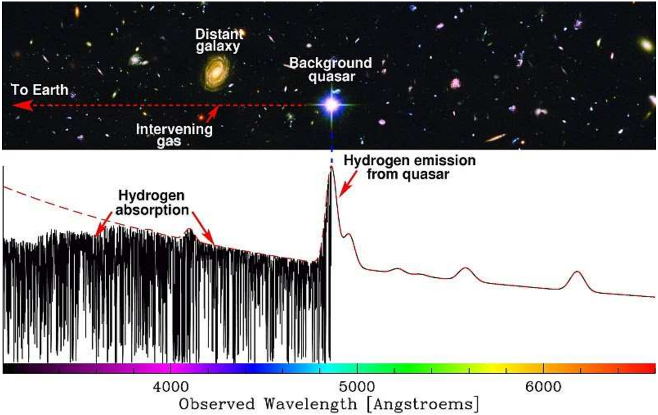
Ruling out cold or warm dark matter

- Current detection limits $M_{sub} \sim 10^9 M_\odot$
- Future surveys (more lenses/arcs) will bring the detection limits $M_{sub} \sim 10^6 M_\odot$
- If now substructures of this size will be found $\Rightarrow$ **CDM is ruled out!** No more direct detection experiments, axion DM searches, etc
- If such substructures are found – WDM strongly disfavoured, no sterile neutrino DM...





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**: $\lambda = (1+z)1215.67\text{Å}$

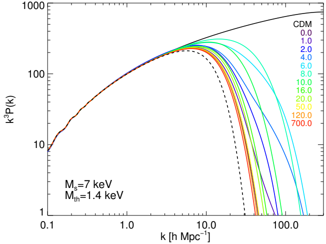
Suppression in the flux power spectrum (SDSS)

What we want to detect

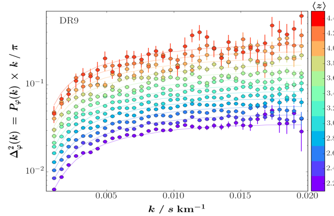
- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the ΛCDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

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

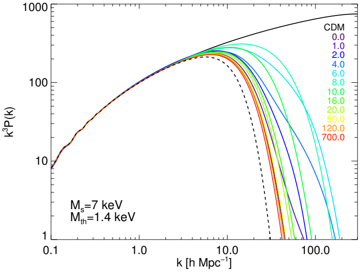


3D linear matter power spectra

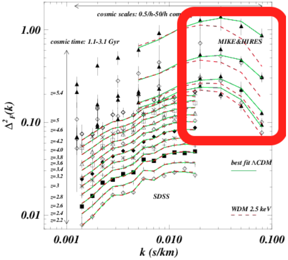


BOSS (SDSS-III) Ly-α [1512.01981]

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?**

But we measure neutral hydrogen!

Lyman-α forest method is based on the underlying assumption

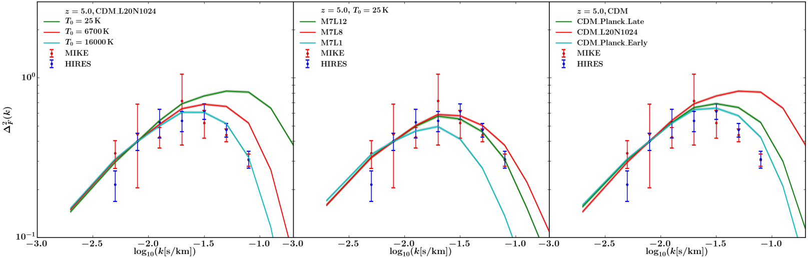
The distribution of neutral hydrogen follows the DM distribution

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)

Temperature? Pressure? WDM?

Garzilli, Magalich, Theuns, Frenk, Weniger, Ruchayskiy, Boyarsky [1809.06585]

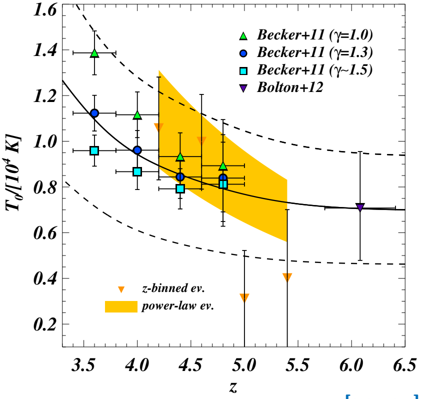


Temperature **WDM** **Pressure**

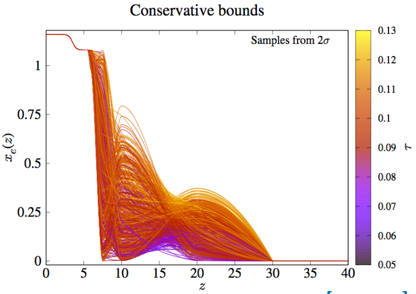
- CDM with the IGM temperature $\sim 10^4$ K is able to explain the MIKE/HIRES flux power spectrum
- Different thermal histories (onset/intensity of reionization) are able to explain power spectra
- ...and so can WDM with a reasonable thermal history

What is known about the IGM thermal history?

Current measurements of IGM temperature



[1306.2314]

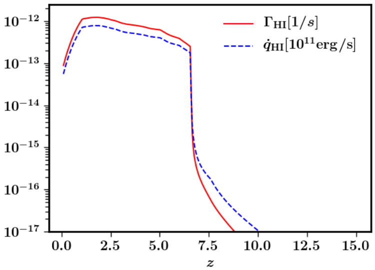


[1708.04913]

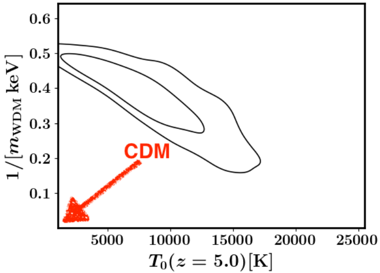
- There are many measurements at $z < 5$
- There is a single measurement **above** $z = 6$
- History of reionization at higher redshifts is poorly constrained

Warm dark matter may have been discovered

Garzilli, Boyarsky, Ruchaiskiy,. . . 2015, 2018, 2019



[Onorbe et al. 2016]



[Garzilli et al. [1912.09397]]

- Universe reionizes late
- CDM is ruled out for such reionization scenario (even if instantaneous temperature is varied)

Sterile neutrino as decaying DM

An unidentified spectral line was detected at energy ~ 3.5 keV I

Boyarsky+ PRL 2014
Bulbul+ ApJ 2014
For a recent review see "Sterile Neutrino Dark Matter " [1807.07938]

Objects

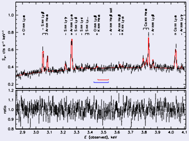
Many detections	Milky way & Andromeda galaxies, Perseus cluster, Draco dSph, distant clusters. COSMOS & Chandra deep fields

Systematics?

Detection with 4 different telescopes:	XMM MOS and PN cameras, Chandra, Suzaku, NuStar

Astronomical line?

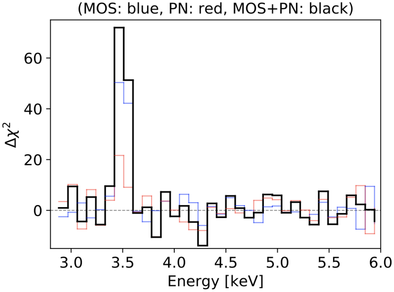
Hitomi observation of the Perseus galaxy cluster ruled out the interpretation as Potassium or any other narrow atomic line. Sulphur ion charge exchange? (Gu+ 2015 & 2017; Shah+ 2016)



Strong line in the Milky Way

Boyarsky, Ruchayskiy, et al. [1812.10488] + update

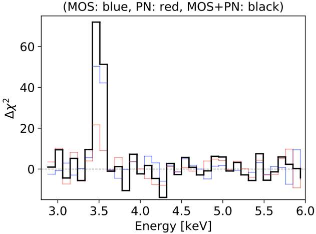
- 41 Msec of quiescent Milky Way regions ($10'$ to $35°$) + extra 8 Msec ($35°$ to $45°$).
- The data split into **6 radial bin**
- Line is detected in 4 bins with $> 3\sigma$ and in 2 bins with $> 2\sigma$ significance
- Good background model in the interval $2.8 - 6$ keV plus $10 - 11$ keV

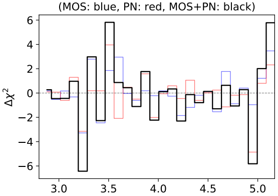


Region	$10' - 14'$ **(Reg1)**	$14' - 3°$ **(Reg2)**	$3° - 10°$ **(Reg3)**	$10° - 20°$ **(Reg4)**	$20° - 35°$ **(Reg5)**	$35° - 45°$ **(Reg6)**
MOS/PN exp.	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1	5.5/2.5
MOS/PN FoV	205/197	398/421	461/518	493/533	481/542	468/561
χ^2/d.o.f.	179/161	184/174	193/184	171/145	139/131	131/128
p-values	0.14	0.29	0.32	0.07	0.31	0.41
3.5 keV position	$3.52^{+0.01}_{-0.01}$	$3.48^{+0.02}_{-0.03}$	$3.51^{+0.02}_{-0.01}$	$3.56^{+0.03}_{-0.02}$	$3.46^{+0.02}_{-0.01}$	$3.48^{+0.03}_{-0.03}$
3.5 keV flux	$0.37^{+0.05}_{-0.08}$	$0.05^{+0.03}_{-0.02}$	$0.06^{+0.02}_{-0.01}$	$0.022^{+0.007}_{-0.004}$	$0.028^{+0.004}_{-0.005}$	$0.016^{+0.006}_{-0.006}$
3.5 keV $\Delta\chi^2$	19.4	4.5	12.4	15.6	25.1	8.1

Is this a dark matter line?

Boyarsky, Ruchayskiy, et al. [1812.10488] + update





Surface brightness profile in the Galaxy

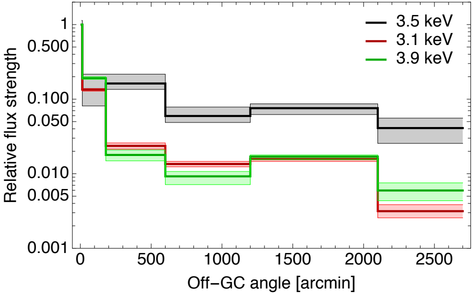
- Assuming any reasonable DM profile we get $\sim 7\sigma$ detection (higher with reg6)
- Radial profile different from nearby astronomical lines

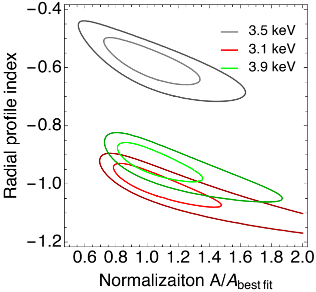
Profile	Significance in σ	Line position [keV]	Decay width Γ $[10^{-28}\,\mathrm{sec}^{-1}]$
NFW [19] $r_s = 20\,\mathrm{kpc}$	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert $r_B = 9\,\mathrm{kpc}$	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto $r_s = 14.8$ kpc $\alpha = 0.2$	6.9σ	$3.494^{+0.002}_{-0.009}$	$0.40^{+0.04}_{-0.06}$

TABLE II. Combined spectral modeling of spatial regions Reg1–Reg5 with the same position of the line and relative normalizations in different regions fixed in accordance with a DM density profile. Two parameters of the line fit are: the energy and the intrinsic decay width, Γ. As intrinsic line width and the normalization of DM density profile are degenerate, when reporting Γ in the last column of the table, we fix the local DM density to $\rho(r_\odot) = 0.4\,\mathrm{GeV/cm^3}$ [20] where the Sun to GC distance $r_\odot = 8.12 \pm 0.03$ kpc [21].

The signal is not astrophysical

Boyarsky, Ruchayskiy, et al. [1812.10488] + update





The radial profile of the 3.5 keV line is significantly more shallow than radial profiles of nearby astrophysical lines

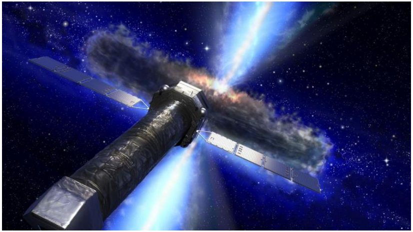
Future: X-ray spectrometers I

- Short flight of **Hitomi** demonstrated that the origin of the line can be quickly checked with spectrometers
- **Hitomi** replacement – XRISM is scheduled to be launched in 2021

With X-ray spectrometer one can

- Check the width of the line (for Perseus cluster the difference in line broadening between atomic lines ($v \sim 180$ km/sec) and DM line ($v \sim 1000$ km/sec) is visible)
- See the structure (doublets/triplets) of lines (if atomic)
- Check exact position of the line (Redshift of the line is Perseus was detected at 2σ with XMM – easily seen by **XRISM**)
- Confirm the presence of the line with known intensity from all the previous detection targets: Milky Way, M31, Perseus, etc.

Future: X-ray spectrometers II



Athena+ (2028)

- Large X-ray missing – combination of spectrometry and imaging
- Era of **dark matter astronomy** begins

Conclusions

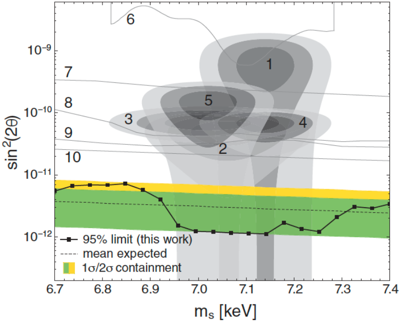
- Sterile neutrino DM remains and interesting, promising and viable DM candidate.
- It is very difficult to be detected directly, but potentially possible with new generation experiments like Ptolemy.
- Astrophysical effects of sterile neutrinos are often degenerate with baryonic effects, any "detections" and "constraints" should be taken with care
- Nevertheless, robust detections/exclusions will be possible in the next 5-10 years
- There are hints consistent with ~ 7 keV sterile neutrinos both in Lyman-α forest and X-ray data
- This claims can be robustly tested with XRISM (2022-2023); DESI, 4MOST . . . . . . SKA; gravitational lensing, stellar streams

Stay tuned

Dessert et al. Science (March 2020) [1812.06976]

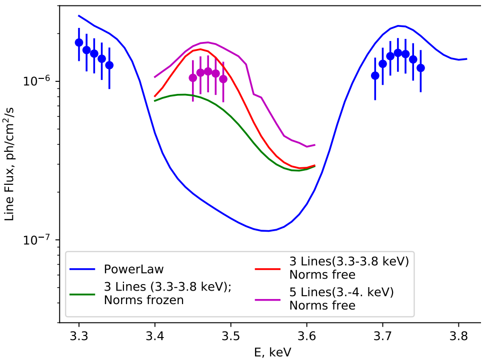
- Quantity $\sin^2(2\theta)$ – sterile neutrino DM mixing angle – is proportional to dark matter decay width
- This mixes physical limit (flux) with their assumptions about DM distribution in the Galaxy
- Ignoring all this, dark matter interpretation has $\sin^2(2\theta) \gtrsim 2\times 10^{-11}$ **give or take a factor of few**

- Deep exposure dataset (30 Msec) of Milky Way regions $5^\circ - 45^\circ$
- Self-invented complicated statistical analysis instead of a standard fitting approach, used by the X-ray community
- **At face value** this rules out dark matter interpretation by a factor ~ 10



Proper modeling at narrow interval

Boyarsky et al. [2004.06601]; also Abazajian [2004.06170]



- The background is **non-monotonic** at the interval of energies 3.3-3.8 keV where they perform search
- There are other lines in this interval
- Not including them into the model **artificially raises the continuum** $\Rightarrow$ reduce any line

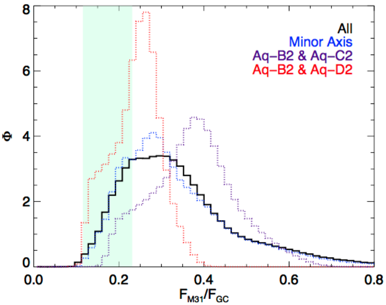
Blue data points: lines with $\geq 3\sigma$ significance

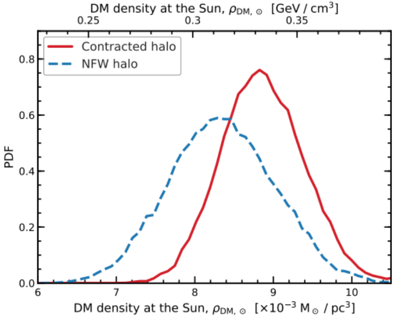
Magenta data points: lines with $\geq 3\sigma$ significance (4σ for $E = 3.48$ keV)

Dark matter content

C. Frenk et al. *The Milky Way total mass profile as inferred from Gaia DR2* [1911.04557]

Lovell et al. [1411.0311]





Dessert et al. assumes
$\rho_\odot = 0.4\,\mathrm{GeV/cm^3}$

- To rule out "mixing angle" as inferred in our work from the center of M31 you should **marginalize** over uncertainties in DM densities of M31 vs. Milky Way