What can particle physics learn from dark matter cosmological observations?

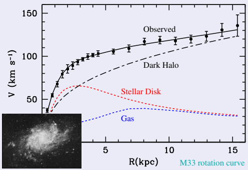
Alexey Boyarsky

Universiteit Leiden

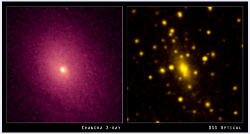
December 16, 2020

Dark Matter

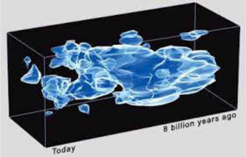
Astrophysical evidence:



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

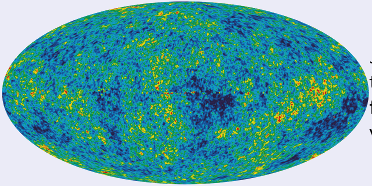


Expected:
$m_{\text{cluster}} = \sum m_{\text{galaxies}}$
Observed: 10^2 times more mass is confining the ionized gas

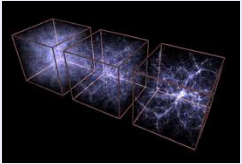


Lensing signal (direct mass measurement) **confirms** other observations

Cosmological evidence:



Jeans instability turned tiny density fluctuations into all visible structures



Cosmological standard model

In the concordance model dark matter is

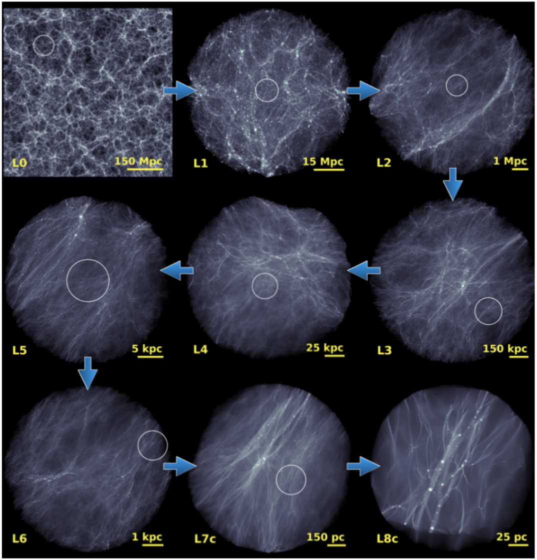
- cold
- stable
- collisionless

Each of these assumptions can turn out to be wrong!

Astrophysics is the key!

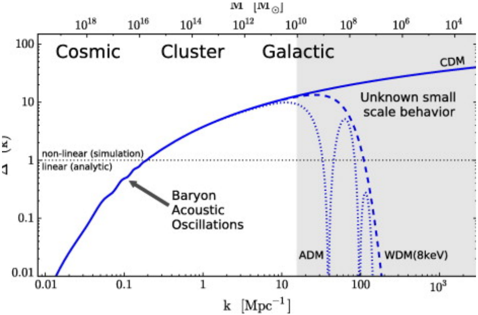
- Only astrophysics can confirm these assumptions
- What shall we do if tomorrow CDM is ruled out?

Cold dark matter – self-similar structure formation

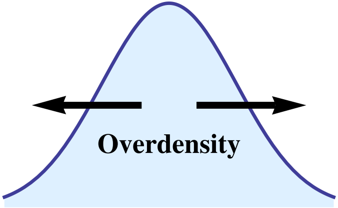


CDM vs. non-CDM

- Example: WDM. Particles are born relativistic ⇒ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

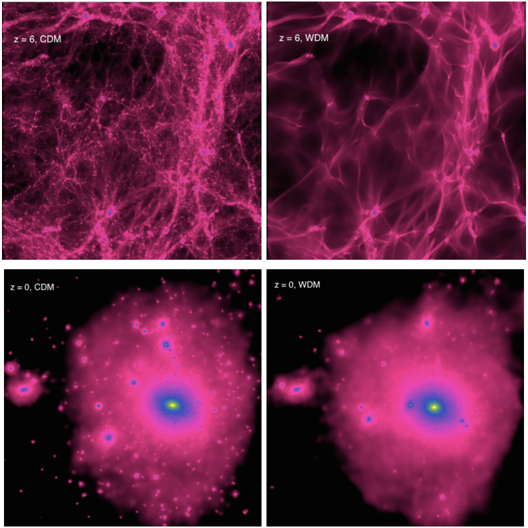


[Kuhlen et al. (2012)]



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

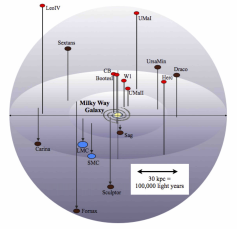
What is “warm dark matter” observationally?



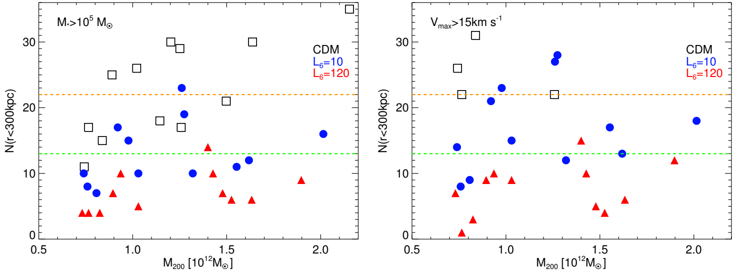
Warm dark matter:

- Same structures as in **CDM** Universe at scales of Mpc and above ⇒ 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



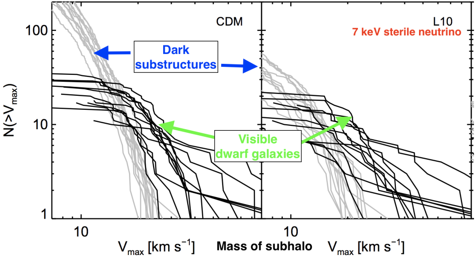
- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
- **Observations**: We do not know how typical Milky Way is

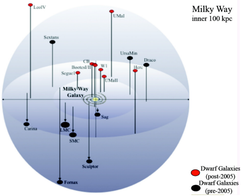


Lovell, Boyarsky+ [1611.00010]

Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]



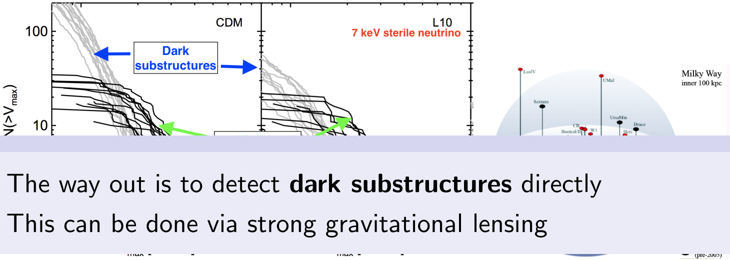


The same number of luminous satellites, but different number of **dark** satellites

- 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

Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]

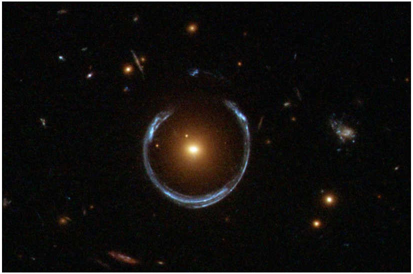


- The way out is to detect **dark substructures** directly
- This can be done via strong gravitational lensing

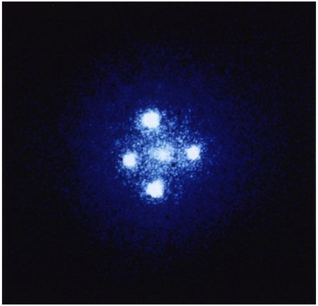
The same number of luminous satellites, but different number of **dark** satellites

- 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

Way 1: 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

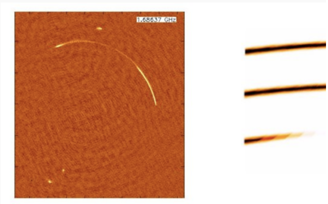
High-resolution gravitational imaging: The image on the left shows VLBI data for the lens system B1938+666. The long arc is a strongly lensed image of a distant background galaxy. The image on the right shows how different mass substructures in the lens galaxy would affect the gravitational arc of B1938+666.

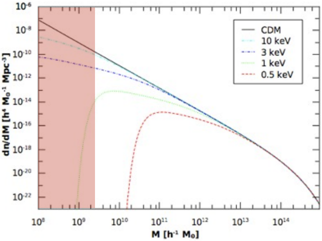
© MPA

S. Vegetti

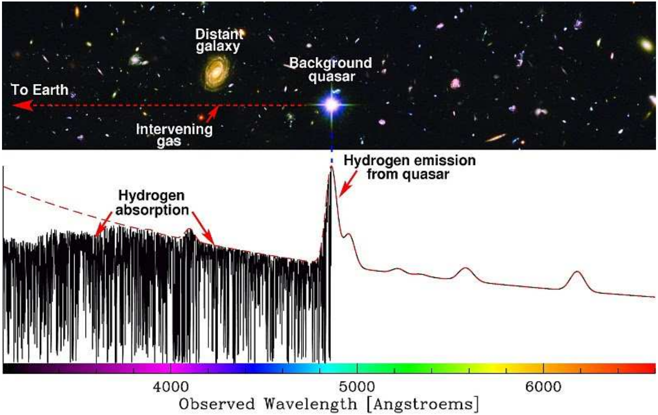
Ruling out cold or warm dark matter

- 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 no substructures of this size will be found $\Rightarrow$ **CDM is ruled out!** Strong impact on direct detection experiments, axion DM searches, etc
- If such substructures are found – WDM strongly disfavoured, no sterile neutrino DM...





Way2: 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**: $\lambda = (1+z)1215.67\text{Å}$

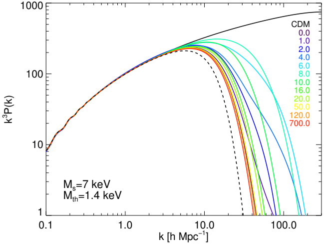
Suppression in the flux power spectrum (SDSS)

What we want to detect

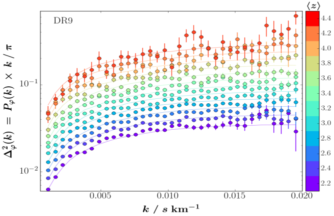
- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the ΛCDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

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

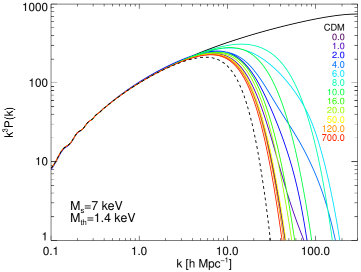


3D linear matter power spectra

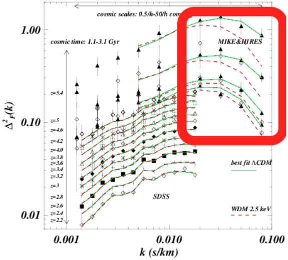


BOSS (SDSS-III) Ly-α [1512.01981]

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

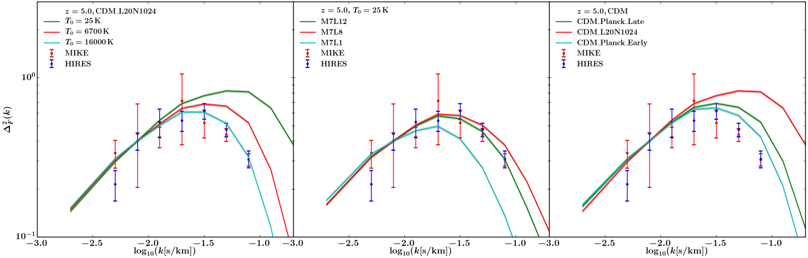
The distribution of neutral hydrogen follows the DM distribution

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]

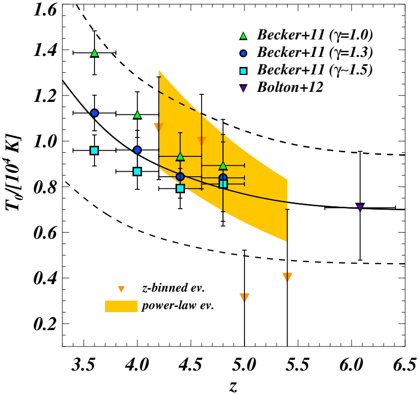


Temperature **WDM** **Pressure**

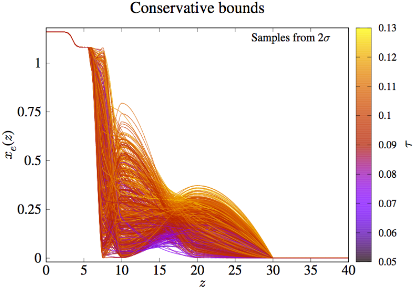
- CDM with the IGM temperature $\sim 10^4$ K is able to explain the MIKE/HIRES flux power spectrum
- Different thermal histories (onset/intensity of reionization) are able to explain power spectra
- . . . and so can WDM with a reasonable thermal history

What is known about the IGM thermal history?

Current measurements of IGM temperature



[1306.2314]

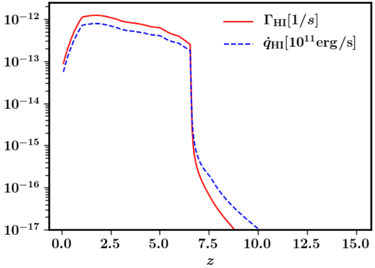


[1708.04913]

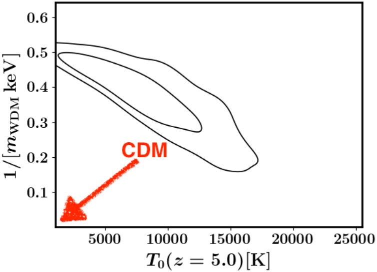
- There are many measurements at $z < 5$
- There is a single measurement **above** $z = 6$
- History of reionization at higher redshifts is poorly constrained

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)

WDM effects and thermal effects have different redshift dependence. More data are on the way, we can distinguish between them!

Future of the Lyman-α forest

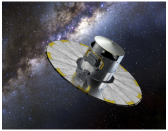
- Degeneracy between astrophysical and dark matter effects on the Lyman-α observables can eventually be resolved via z-dependence
- Future surveys (WEAVE, 4MOST, DESI) and, eventually, SKA will help!

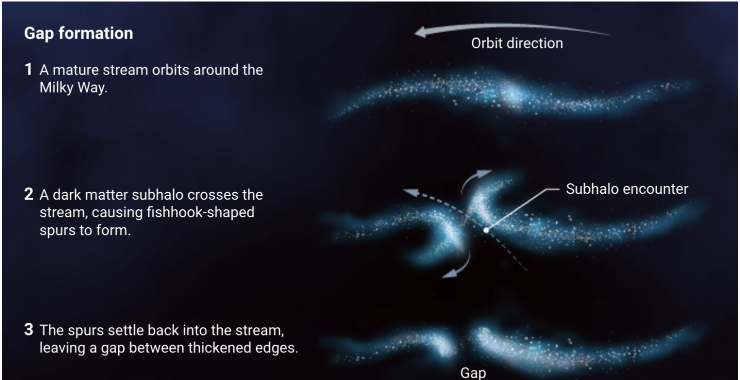
Way 3: Stellar stream gaps

E.Hand, Science (2018)

- Thanks to Gaia we know much better the structure of the Milky Way
- In particular many **stellar streams** – distrupted dwarf galaxies – have been discovered

Gaia Lanfranchi





Gap formation

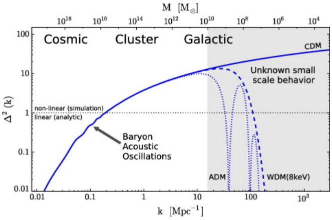
1 A mature stream orbits around the Milky Way.

2 A dark matter subhalo crosses the stream, causing fishhook-shaped spurs to form.

3 The spurs settle back into the stream, leaving a gap between thickened edges.

What does this mean for particle physics?

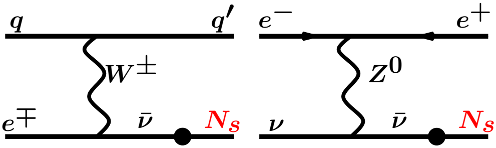
- If one of these methods shows convincing deviation from CDM – what does this mean for particle physics?
- How can particle physics help to identify a microscopic model beyound ”non-CDM”?

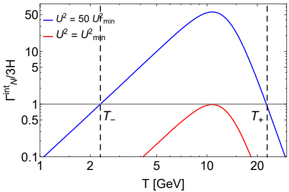


Light new physics

- Although this is not a theorem, but **generically** deviations from CDM would strongly suggest that **new light physics exists**
- This can mean that
  1. Dark matter particles are **light**.
  2. Mediators with the "**dark sector**" are light (mediators)
  3. Both!

Example 1: HNL – "naturally warm" DM. I





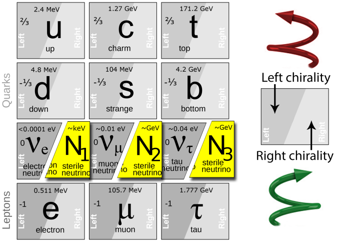
- Heavy neutral lepton (HNL) – part of the **neutrino portal**
- In the early Universe mixing angle is **temperature dependent**
- Produced via freeze-in

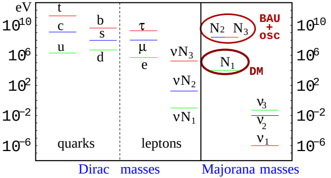
  [Dodelson & Widrow'93; Shi & Fuller'98; Abazajian et al.'00; Asaka, Laine, Shaposhnikov'06-08]
- Production is effective at temperatures

$$T_{max} = 150\,\mathrm{MeV}\left(\frac{M_{dm}}{\mathrm{keV}}\right)^{1/3}$$

- …and average momentum $p \sim T_{max} \gg M_{dm}$ – **warm dark matter**
- Production is sensitive to the presence of lepton asymmetry in the primordial plasma (MSW-like effect)

HNL DM as a part of full model





Heavy neutral leptons can explain . . .

- . . . **neutrino oscillations**

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

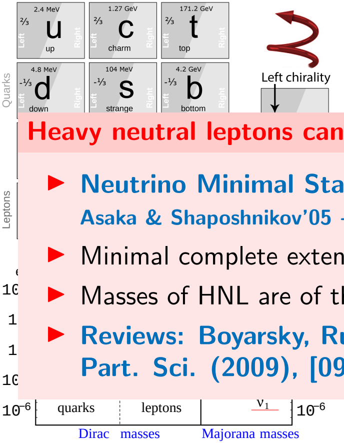
- . . . **Baryon asymmetry**

  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

- . . . **Dark matter**

  Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –

HNL DM as a part of full model



Heavy neutral leptons can explain . . .

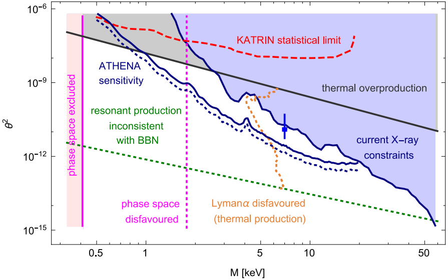
- **neutrino oscillations**

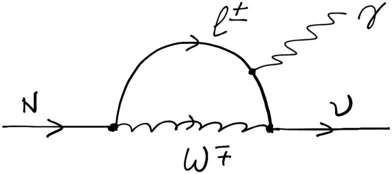
Heavy neutral leptons can explain all of it

- **Neutrino Minimal Standard Model (νMSM)**
  Asaka & Shaposhnikov'05 + . . . hundreds of subsequent works
- Minimal complete extension of the Standard Model
- Masses of HNL are of the order of masses of other leptons
- **Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]**

Searching for keV-scale sterile neutrinos

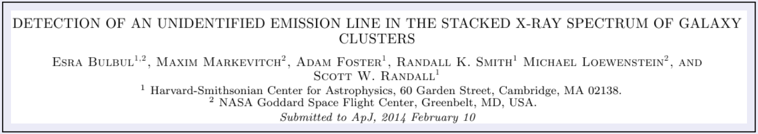
See our review **“Sterile neutrino dark matter”** [1807.07938]





We can search for monochromatic X-ray line originating from sterile neutrinos dark matter decays

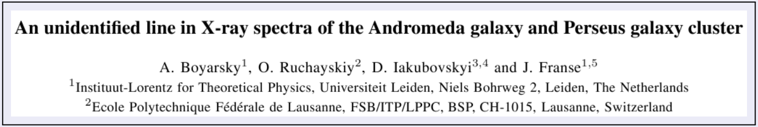
Detection of An Unidentified Emission Line



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

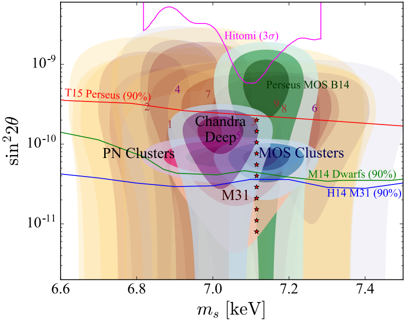
- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{27} - 10^{28}$ sec

Can this be. . .

- . . . (sterile neutrino) decaying dark matter?

Subsequent works

- Subsequent works confirmed the presence of the 3.5 keV line in some of the objects
  Boyarsky O.R.+, Iakubovskyi+; Franse+; Bulbul+; Urban+; Cappelluti+
- challenged it existence in other objects
  Malyshev+; Anderson+; Tamura+; Sekiya+
- argued astrophysical origin of the line
  Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+



[1705.01837]

for reviews see

- *"Sterile neutrinos in cosmology"* [1705.01837]
- *"Sterile Neutrino Dark Matter"* [1807.07938]

What can this be?

Statistical fluctuation? – Detections in many objects

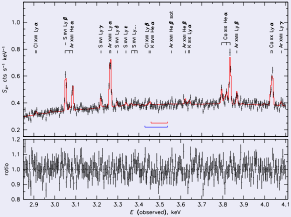
Milky way & Andromeda galaxies, Perseus cluster, Draco dSph, distant clusters. COSMOS & Chandra deep fields

Systematics? – Detection with 4 different telescopes

- Different mirror coating (Au vs. Ir)
- Different detector technologies (CCD vs. Cadmium-Zinc-Telluride)

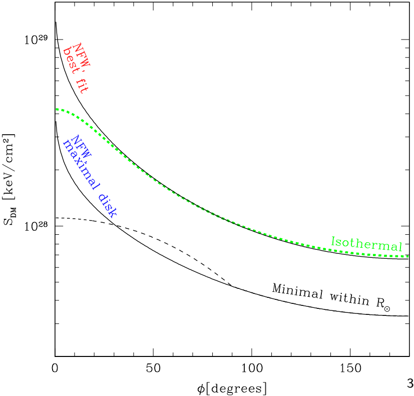
Astronomical line?

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)



Signal from the Milky Way outskirts

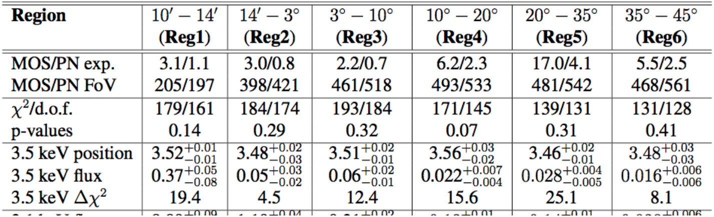
- We are surrounded by the Milky Way halo on all sides
- Expect signal from any direction. Intensity drops with off-center angle
- Surface brightness profile of the Milky Way would be a “smoking gun”



Strong line in the Milky Way

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

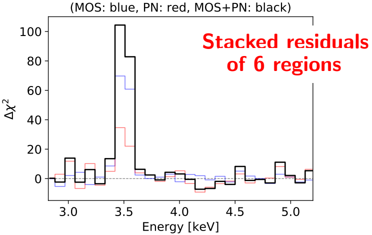
- 49 Msec of quiescent Milky Way regions ($10'$ to 45°)
- The data split into **6 radial bin**
- Line is detected in 4 bins with $> 3\sigma$ and in 2 bins with $> 2\sigma$ significance
- Good background model in the interval $2.8 - 6$ keV plus $10 - 11$ keV

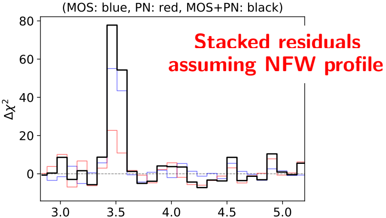


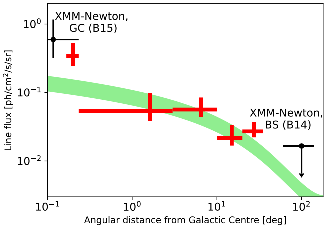
Region	$10' - 14'$ **(Reg1)**	$14' - 3^\circ$ **(Reg2)**	$3^\circ - 10^\circ$ **(Reg3)**	$10^\circ - 20^\circ$ **(Reg4)**	$20^\circ - 35^\circ$ **(Reg5)**	$35^\circ - 45^\circ$ **(Reg6)**
MOS/PN exp.	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1	5.5/2.5
MOS/PN FoV	205/197	398/421	461/518	493/533	481/542	468/561
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

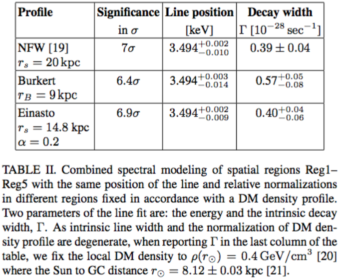
Dark matter profile of the line

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







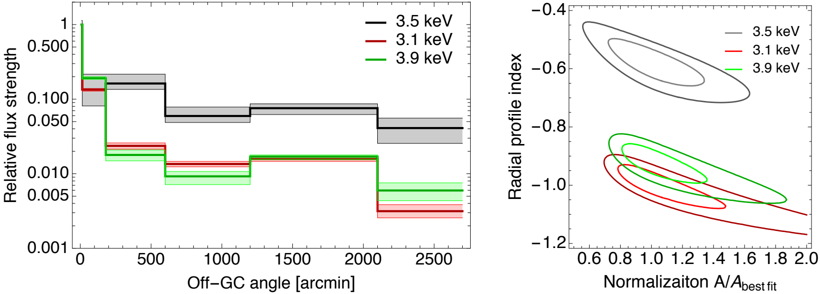


Profile	**Significance** in σ	**Line position** [keV]	**Decay width** Γ $[10^{-28}\,\mathrm{sec}^{-1}]$
NFW [19] $r_s = 20\,\mathrm{kpc}$	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert $r_B = 9\,\mathrm{kpc}$	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto $r_s = 14.8\,\mathrm{kpc}$ $\alpha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

Near future I

XRISM

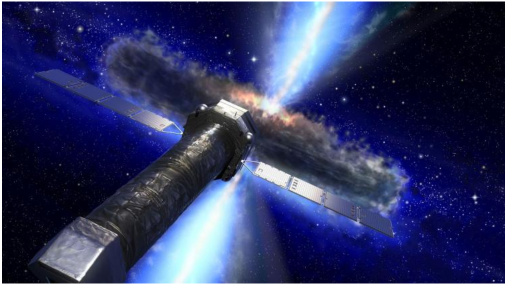
- **Hitomi** demonstrated that the origin of the line can be quickly checked with spectrometers
- **Hitomi** replacement – XRISM is scheduled to be launched in 2021–2022

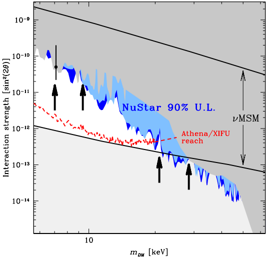
Micro-X

- Microcalorimeter flew on the sounding rocket in July 2018
- Modification for DM searches: increase the field of view from $11'$ to 33°
- Short (300 sec) flight on a sounding rocket can probe the origin of the signal

[1908.09010] see also [1908.08276]

More distant future I





[1607.07328]

Athena+ (2028)

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

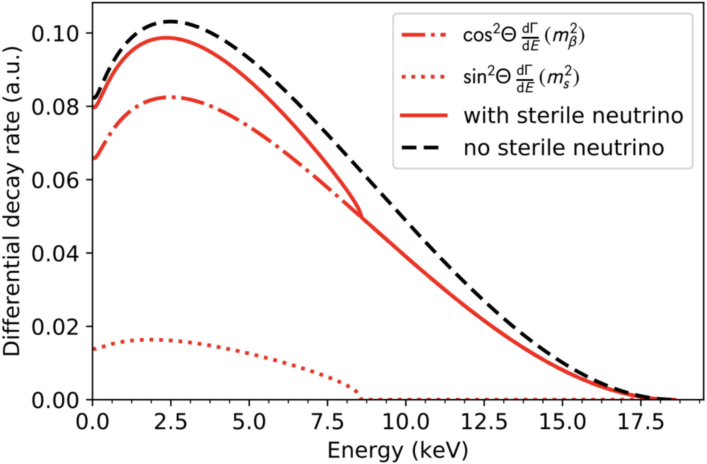
X-ray spectroscopy and future of decaying dark matter searches I

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.
- If confirmed – the era of **dark matter astronomy** begins

Signature of keV sterile neutrino detection

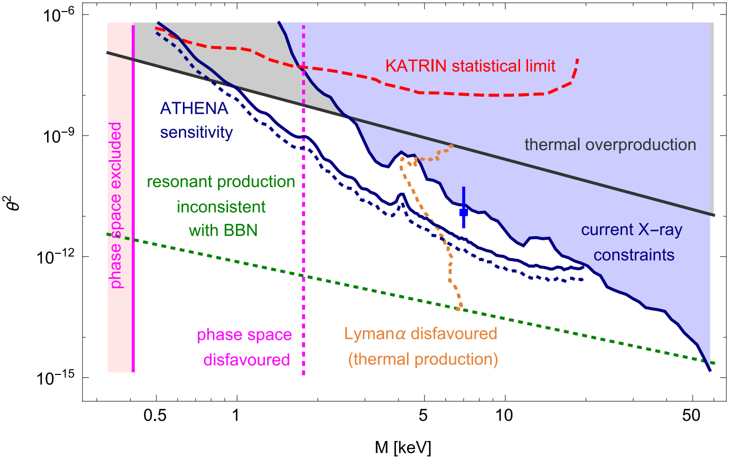
Detection idea: look for a **reaction** T $\rightarrow^3$ He $+ e^- + N$



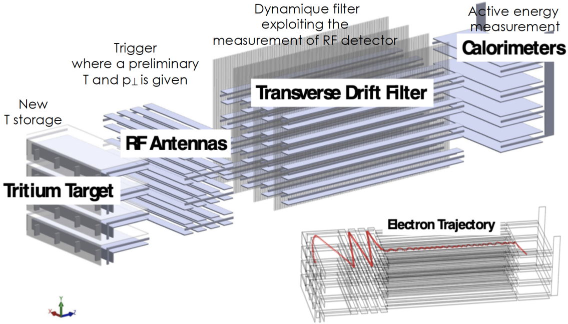
Searching for sterile neutrinos in lab. . .

. . . in the grand scheme of things

Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy [1807.07938]



PTOLEMY experiment



Goals:

1. Detect CNB
2. Accurate measurement of m_ν (anyway necessary before detecting CNB)
3. eV and/or keV sterile neutrino detection (?)

Key challenges:

1. Statistics: extreme amount of tritium
2. Systematics: extreme energy resolution is required
3. Extreme background rates from the target

Subject of the study

CνB detection experiment:

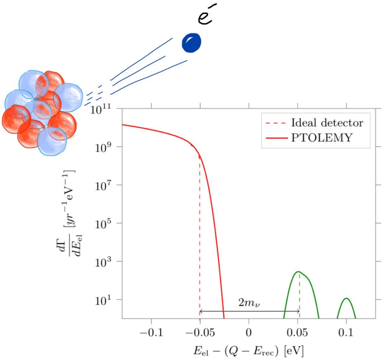
- Challenge - high energy resolution combined with sufficient number of events.

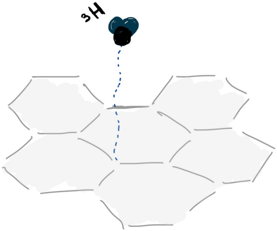
PTOLEMY experiment aims at:

- ≈ 4 CνB events per year.
- Outstanding energy resolution of the apparatus $\approx 10\,\text{meV}$.

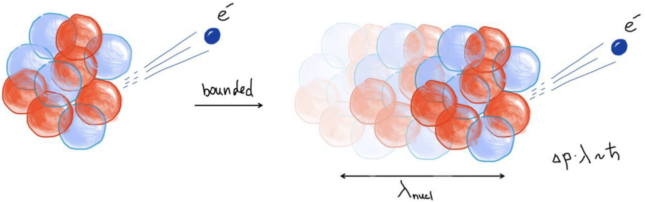
Subject of our study:

- The presence of the substrate introduces additional broadening of the electron spectrum.
- Which leads to intrinsic irreducible limitations on the energy resolution.





General mechanism of the broadening



- For a bonded system, recoil energy of the nucleus is not fixed by the kinematics but has some distribution.
- Uncertainty[1] in the velocity of the centre of mass of the nucleus

$$\Delta u \approx \frac{\hbar}{m_{\text{nucl}}\lambda_{\text{nucl}}}.$$

- The energy of the electron is measured in the laboratory reference frame, where it acquires an uncertainty[2]

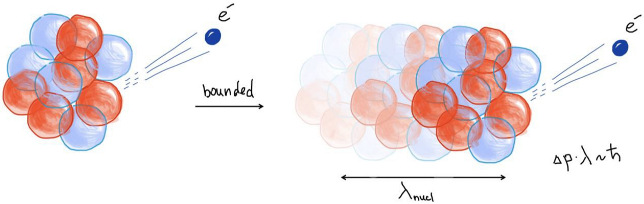
$$\Delta E \approx m_e v_e \Delta u.$$

---

[1] from the Heisenberg uncertainty principle.

[2] ΔE has the same distribution as Δu.

General mechanism of the broadening



$$\Delta E \approx \hbar \frac{m_e v_e}{m_{\text{nucl}} \lambda_{\text{nucl}}},$$

- λ_{nucl} is the spread of the ground state of the nucleus that is defined by the bonding potential.
- One should study the profile of the potential that bonds Tritium to graphene.

Harmonic approximation

For the heavy atom one can expand the potential near its minimum

$$U = \frac{1}{2}\varkappa_{i,j} r_i r_j + U_0$$

- $\varkappa$ defines the stiffness of the potential $\varkappa_{\text{out-of-plane}} \approx 15\varkappa_{\text{lateral}}$
- U_0 defines the strength of the potential $U_{0,\text{lateral}} \ll U_{0,\text{out-of-plane}}$
- Typical wave function spread is

$$\lambda^2_{\text{nucl}} = \frac{\hbar}{\sqrt{m_{\text{nucl}}\varkappa}}$$

.

- We will restrict ourselves to the out-of plane potential.

$$\Delta E \propto \lambda^{-1}_{\text{nucl}} \propto \varkappa^{1/4}$$

Energy broadening for the β-decay of the Tritium on graphene

$$\frac{\Delta E}{\sqrt{\hbar m_e}} \approx \underbrace{\varkappa^{1/4}}_{\text{potential}} \underbrace{\sqrt{\frac{Q}{m_{\text{nucl}}^{3/2}}}}_{\text{nucleus}}$$

The uncertainty in the electron energy ΔE:

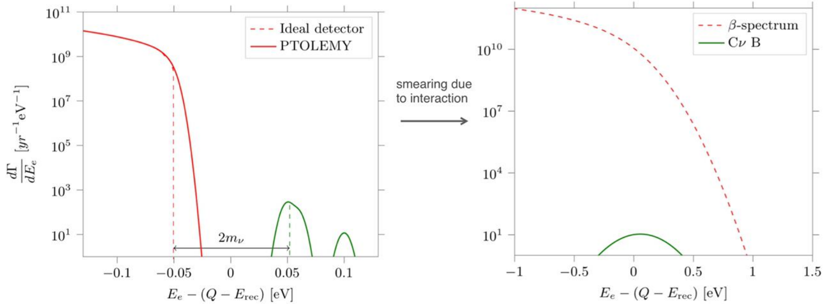
- Is of the order of $200 - 800$ meV (smaller for physisorption).
- Weakly depends on the potential stiffness.
- For molecular tritium ($\varkappa \approx 75$) the estimate is of the same order.
- Strongly depends on the nucleus.
- Is 2 orders of magnitude greater than the resolution needed to see the CνB signal.
- Agrees with the the fully quantum calculation[3]

---

[3] Fermi Golden Rule.

Energy broadening for the β-decay of the Tritium on graphene

$$\frac{\Delta E}{\sqrt{\hbar m_e}} \approx \underbrace{\varkappa^{1/4}}_{\text{potential}} \underbrace{\sqrt{\frac{Q}{m_{\text{nucl}}^{3/2}}}}_{\text{nucleus}}$$



Comment on the in-plane mobility

- The isotropic[4] bonding potential yields $\Delta E_{\text{isotr}} \approx 200 - 800\,\text{meV}$.
- In the ideal case of the full mobility

$$\Delta E(\theta) \approx \sin\theta \Delta E_{\text{isotr}}$$

- Electrons that have the uncertainly in energy $\Delta E \leq \Delta E_{\text{threshold}}$ are emitted in the restricted angle

$$\theta \leq \frac{\Delta E_{\text{threshold}}}{\Delta E_{\text{isotr}}}$$

- The reduction in the rate will be

$$\eta \approx \frac{90^\circ}{\theta_{\text{threshold}}}$$

Example: $\Delta E_{\text{threshold}} = 10\,\text{meV}, \theta_{\text{threshold}} \approx 0.7^\circ - 3^\circ, \eta \approx 30 - 130.$

---

[4] Mobility according to the ab-initio studies of the chemisorbed Tritium.

Conclusions

- There is an intrinsic source of the irreducible uncertainty in the energy of the emitted electron that comes from the bonding of the atom with the substrate.
- This uncertainty weakly depends on the properties of the bonding potential, but strongly depends on the atom itself.
- For the tritium atom chemi- or physisorbed on the graphene the uncertainty in the energy of the electron is two orders bigger that the energy resolution needed to see CνB emission line.
- Changing the stiffness of the bonding $\varkappa$ can not resolve this problem.
- Changing the radioactive atom to minimize the ratio $\frac{Q^2}{m_{\text{nucl}}^3 c^2}$ seems to be more promising.
- Another promising direction of the research is increasing the mobility of the atom along the substrate and narrowing the angle of the detection.

Constraining sterile neutrino

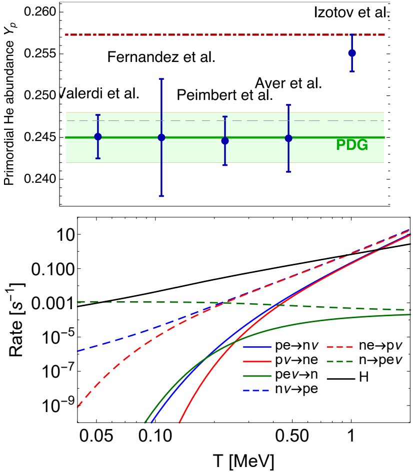
- Constraining sterile neutrino in the lab is more than challenging
- Fortunately, sterile neutrino has a number of distinct astrophysical/cosmological signatures that can be used to explore its properties
- Together with laboratory searches for heavier sterile neutrinos this may allow to explore parameter space of the minimal sterile neutrino model

Primordial nucleosynthesis

- Reminder: primordial Helium-4 abundance is measured with high statistical precision (the measurements are systematics dominated)
- Primordial Helium abundance, Y_p is the interplay of two effects:

$$Y_p = 2X_n e^{-t/\tau_n}$$

where **neutron abundance** X_n is the result of freeze-out of weak reaction (at $t \sim 1$ sec)



HNLs and primordial nucleosynthesis

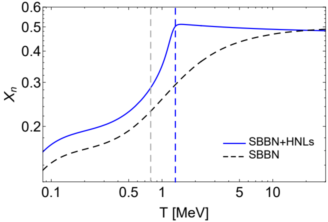
Most recent BBN bounds on HNLs: [2006.07387] (below m_π) and [2008.00749] (above m_π)

- MeV-GeV scale HNLs can be sufficiently long-lived to survive till BBN epoch ($t \sim 0.1 - 10^2$ sec)
- Such HNLs affect primordial Helium production in a number of ways:
  1. Change expansion rate
  2. Change $n \leftrightarrow p$ conversion rates by injecting **weakly** interacting decay products ($e^\pm$, ν_e, $\bar{\nu}_e$)
  3. Change $n \leftrightarrow p$ conversion rates by injecting **strongly** interacting decay products ($\pi^\pm$, K^-, K^0, .etc)
- Strong interaction rates dominate by orders of magnitude ⇒ drives HNL lifetime to be **much below** 0.1 sec

$$\pi^- + p \to n + \pi^0/\gamma$$

$$\pi^+ + n \to p + \pi^0$$

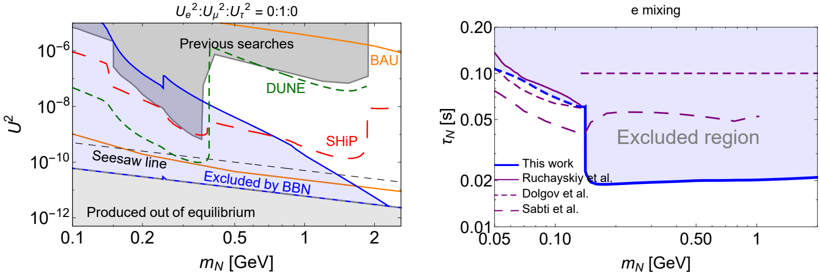
[1006.4172]



[2008.00749]

BBN bounds for HNLs

... and “bottom” line for Intensity Frontier searches

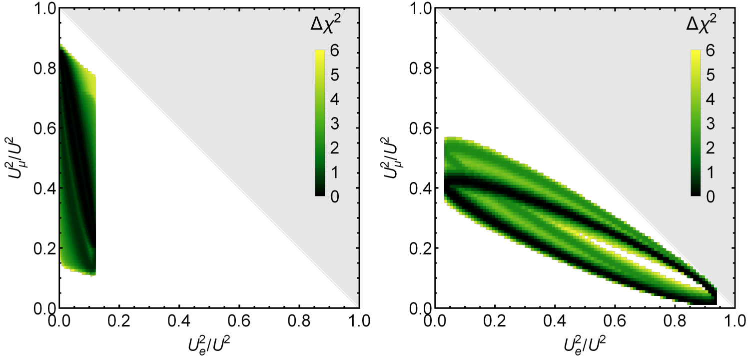


[Boyarsky, Ovchynnikov, Ruchayskiy, Syvolap [2008.00749]]

- BBN bounds about m_π have been untouched for 30 years
- Accounting for strong interactions strengthens them by a factor ~ 5

  [(Similar results for scalar: Pospelov & Pradler [1006.4172])]
- SHiP now can reach the “bottom” for masses below ~ 1 GeV

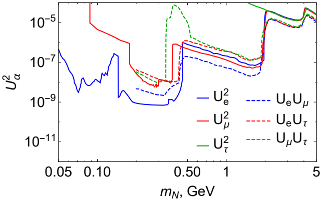
Minimal mass in νMSM I

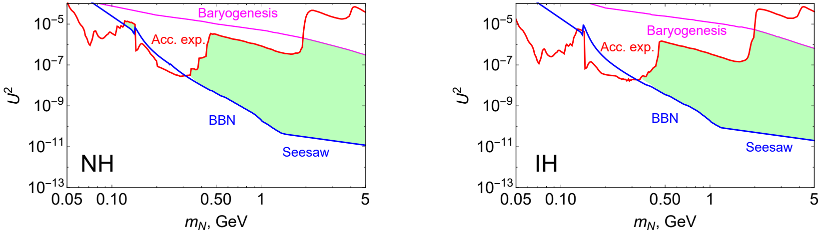


- The allowed region of possible mixings $U_e^2 : U_\mu^2 : U_\tau^2$ in νMSM is quite limited, since only two HNLs have to produce mixings for three active neutrino species
- We can scan over possible mixing patterns to obtain models that do not contradict to any type of constraint: BBN, accelerator experiments, baryogenesis

Minimal mass in νMSM II

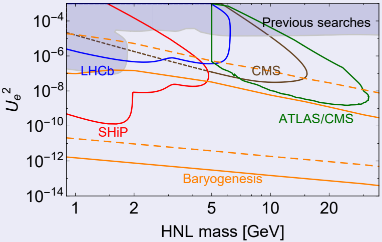
- Accelerator bounds are typically given for pure mixing cases, therefore the actual bounds on U_α^2 need to be reanalyzed in order to be consistent with all bounds



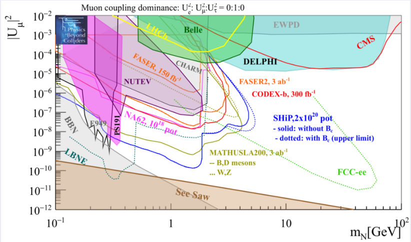


- The green region is points that pass through all the constraints. The blue and red lines are independent bounds. The minimal mass after pion mass is $0.34(0.35)\,\mathrm{GeV}$ for NH (IH).

HNLs are part of the search program of all major particle physics experiments



LHC searches (Boiarska+ [1902.04535])



Beyond LHC (PBC report [1901.09966])

. . .

Back up slides

Example 2: FIPs and WIMPs.

Cosmological mass bound on weakly interacting particles

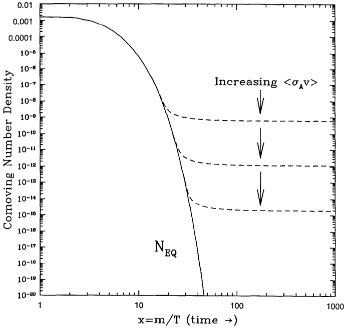
- Original idea of Weakly Interacting Massive Particles (**WIMP** dark matter) goes back to 1977
- **Lee & Weinberg (Phys. Rev. Lett. 1977)**

  "Cosmological lower bound on heavy-neutrino masses"
- **Vysotskii, Dolgov, Zel'dovich (JETP Lett. 1977)**

  "Cosmological limits on the masses of neutral leptons"

- Assume a new **weakly** interacting stable particle (called "heavy neutrino" in the original paper)
- These particles were in **thermal equilibrium** in the early Universe
- They keep the equilibrium number density via annihilation $\chi + \bar{\chi} \leftrightarrow \mathrm{SM} + \mathrm{SM}$
- As Universe expands — DM density drops and annihilation rate decreases
- At some moment **annihilation rate** is not enough to maintain the equilibrium number density $\Rightarrow$ **freeze out**
- WIMP "remembers" density of the Universe at the time of **freeze-out**

Example: light dark matter and light mediators



- The weaker you interact the larger is your number density

$$\Omega_\chi h^2 \sim \frac{3 \cdot 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_{ann} v \rangle} \tag{1}$$

- Annihilation cross-section depends on the interaction strength and on the number of final states

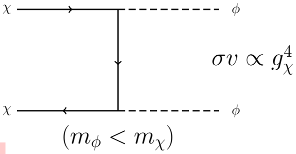
$$\langle \sigma_{ann} v \rangle \sim G_F^2 \; m_\chi^2 \; N_{\text{channels}} \tag{2}$$

For mass $m_\chi \sim \mathcal{O}(1)$ GeV annihilation into the SM channels leads to a **too small** cross-section $\Rightarrow$ **too large** DM abundance

Lee & Weinberg took G_F as an interaction strength and got the lower bound $m_\chi > 5$ GeV

Light WIMP $\Rightarrow$ extra light states

- Light DM requires more **light** states to annihilate into (scalars, vectors, ...)
- **or** light mediators to increase the annihilation cross-section



Examples:

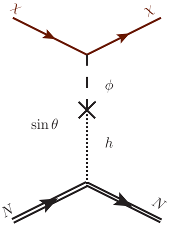
- Light scalar ϕ (scalar portal mediator)

$$\mathcal{L}_{\mathsf{DM}-\phi} = \bar{\chi}\Big(g_\chi + \gamma_5 g'_\chi\Big)\phi\chi$$

- Light vector portal A_μ

$$\mathcal{L}_{\mathsf{DM}-A'} = \bar{\chi}\gamma^\mu A'_\mu\Big(g_\chi + \gamma_5 g'_\chi\Big)\chi$$

- χ – dark matter particle, heavier than (dark) scalar or vector



Light WIMP: extra final states or stronger interaction

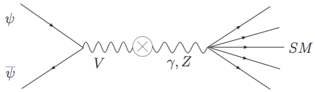
Light Dark matter requires

$\langle \sigma_{ann} v \rangle \sim G_F^2 m_\chi^2 N_{\text{channels}}$

- more **light** states to annihilate to
- increasing the interaction strength to above G_F

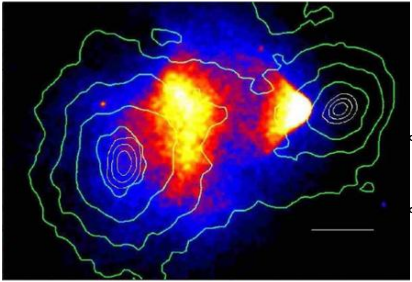
- To increase annihilation rate we need a new **light** mediator $m_{\text{mediator}} \ll m_W$ with a sizeable coupling to the SM sector
- Different mediators are possible: scalars, vectors, pseudoscalars, fermions, etc
- If dark matter is **lighter** than mediator – LDM annihilates into SM states via off-shell mediator

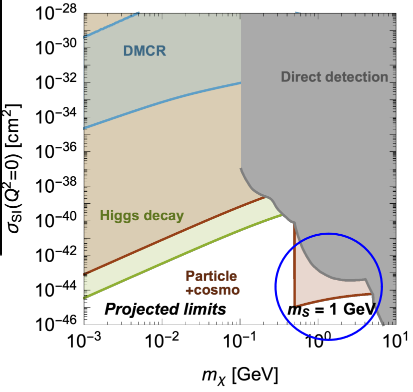
$$G_F \to G_F^{\text{mediator}} = \frac{4\pi\tilde{\alpha}}{m^2_{\text{mediator}}}$$



- Light DM can stay in kinetic equilibrium till low temperatures and in this way suppress the small scale structures [hep-ph/0612238,1603.04884]

Scalar portal to light dark matter





[1909.08632], see also [1512.04119]

- **Bullet cluster** – "Cosmic collider"
- Leads to the self-interaction bound $\sigma/m < 1\,\mathrm{cm}^2/\mathrm{g}$
- Currently we observe ~ 70 of such merger clusters [1610.05327]

non-CDM means new physics

- Thanks to the influx of cosmological data we may learn within the next decade whether dark matter is really
  1. cold (alternatively: warm)
  2. collisionless (alternative: self-interacting)
  3. stable (alternatively: decaying)
- Cosmology can provide unambiguous evidence for/against any of these properties but can tell **little** about particular nature
- non-CDM dark matter likely implies new light (and thus **feebly interacting**) particles
- Particle physics can either discover dark matter particle **or** discover a framework into which we can embed these particles

The synergy of particle physics and cosmology is our way forward if feebly interacting particles exist!

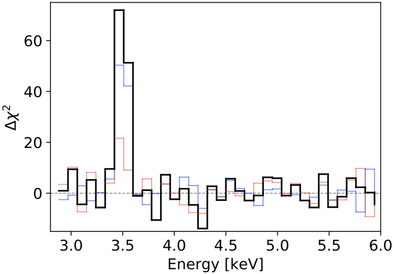
Backup

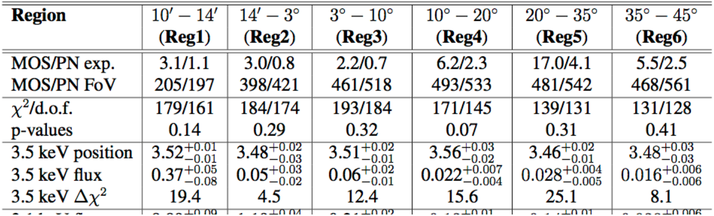
Strong line in the Milky Way

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

(MOS: blue, PN: red, MOS+PN: black)

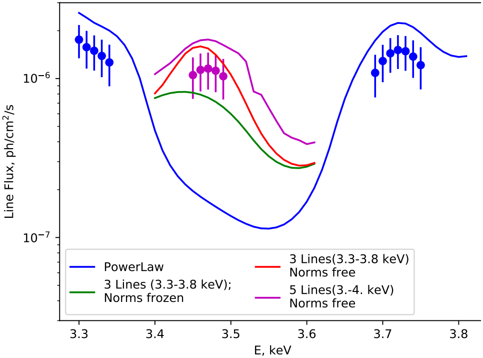




Region	$10' - 14'$ **(Reg1)**	$14' - 3°$ **(Reg2)**	$3° - 10°$ **(Reg3)**	$10° - 20°$ **(Reg4)**	$20° - 35°$ **(Reg5)**	$35° - 45°$ **(Reg6)**
MOS/PN exp.	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1	5.5/2.5
MOS/PN FoV	205/197	398/421	461/518	493/533	481/542	468/561
χ^2/d.o.f.	179/161	184/174	193/184	171/145	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

Proper modeling at narrow interval

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



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

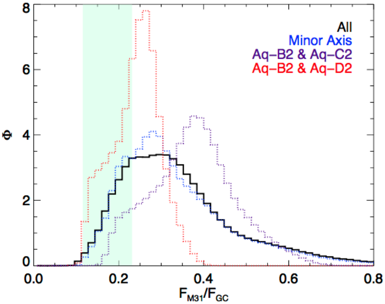
Magenta data points: lines with $\geq 3\sigma$ significance (4σ for $E = 3.48$ keV)

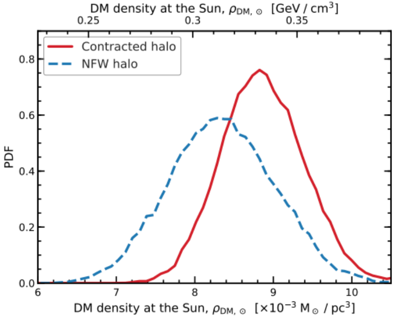
- The background is **non-monotonic** at the interval of energies 3.3-3.8 keV where they perform search
- There are other lines in this interval
- Not including them into the model **artificially raises the continuum** $\Rightarrow$ reduce any line

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]



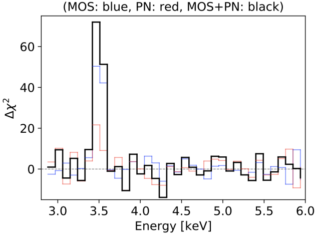


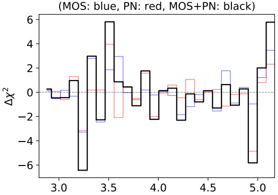
Dessert et al. assumes
$\rho_\odot = 0.4\,\mathrm{GeV/cm^3}$

- 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

Is this a dark matter line?

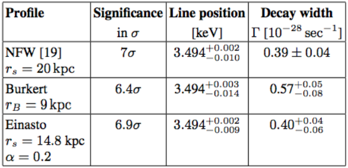
Boyarsky, Ruchayskiy, et al. [1812.10488] + update





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 $r_s = 14.8\,\mathrm{kpc}$ $\alpha = 0.2$	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 $r_\odot = 8.12 \pm 0.03\,\mathrm{kpc}$ [21].