HNLs from cosmos

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A model of HNLs

Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

Heavy neutral leptons

- Heavy neutral leptons (HNLs) are particles with neutrino-like interactions suppressed by flavour-dependent **mixing angles** $U_e, U_\mu, U_\tau \ll 1$
- HNLs are a natural generalization of neutrino dark matter

  (Dodelson&Widrow'93; Shi&Fuller'98; Abazajian+'00; Asaka,Laine&Shaposhnikov'06; Shaposhnikov&Tkachev'06; Kusenko+'06; Laine&Shaposhnikov'08; . . .)
- HNLs responsible for neutrino masses are **not** dark matter

  (Asaka & Shaposhnikov'05; Boyarsky+'06)
- Minimal model should include **at least** 3 HNLs
- The same model can be responsible for leptogenesis $\Rightarrow$ **Neutrino Minimal Standard Model (νMSM)**

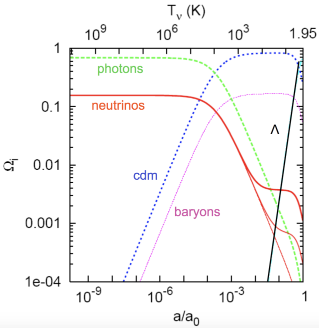
  (Asaka & Shaposhnikov'05; Asaka, Blanchet, Shaposhnikov'05)

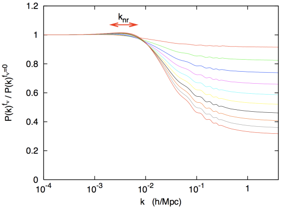
Predictions of the νMSM

Predictions of the νMSM

1. Lightest neutrino mass is (almost) zero and therefore sum of the neutrino masses is equal $(1-2)m_{atm}$ (depending on mass ordering)
2. Warm and decaying dark matter in keV range
3. Two HNLs with masses in MeV–GeV region and lifetimes that can be as long as seconds
4. No new physics above electroweak scale

- Neutrinos act as radiation in the early Universe and later as matter $\Rightarrow$ affect background evolution of the Universe at late times
- While relativistic – neutrinos **free stream** erasing primordial density perturbations $\Rightarrow$ **affect CMB peaks** and **slow down growth of structures**



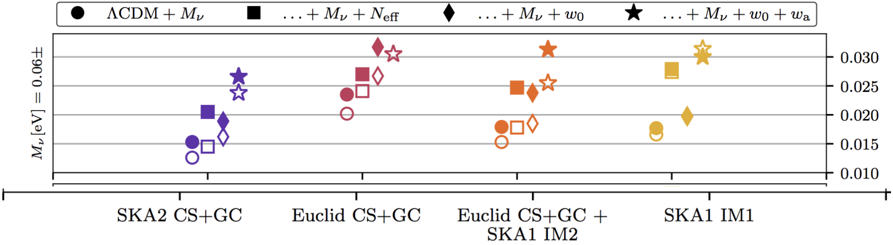


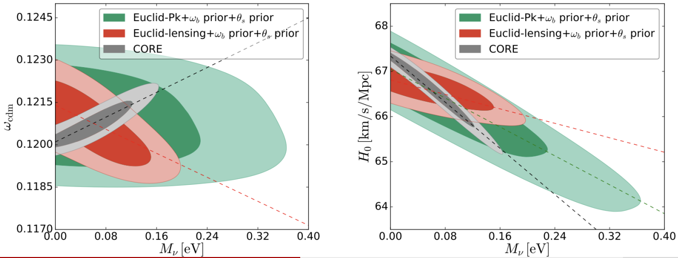
From top to bottom: effect of neutrinos with $\sum m_\nu = 0.05 \ldots 0.5$ eV

- You need $\mathscr{O}(5\%)$ precision measurement of the matter power spectrum in the range from $0.1 \ldots 10$ 1/Mpc

Ultimate neutrino mass measurement

Recall: to detect $\sum m_\nu = 0.06$ eV at 3σ you need precision $\sigma_{m_\nu} \sim 0.02$ eV. See [1801.08331]





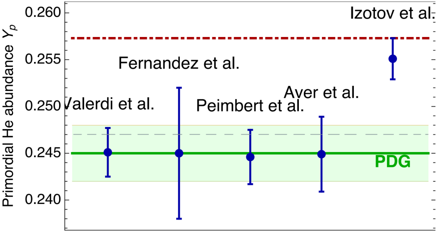
[1610.09852]

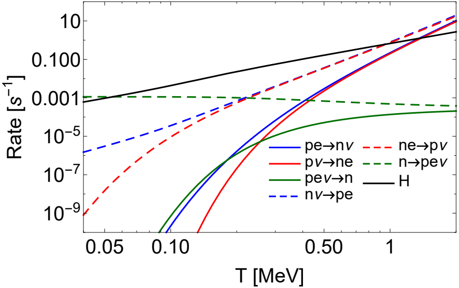
Primordial nucleosynthesis

- 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)





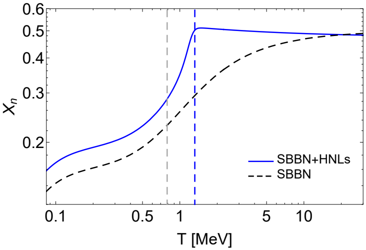
HNLs and primordial nucleosynthesis

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 $\Rightarrow$ drives HNL lifetime to be **much below** 0.1 sec

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

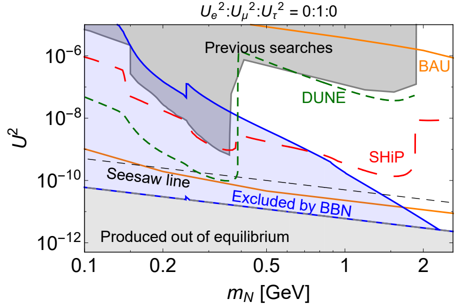
[1006.4172]

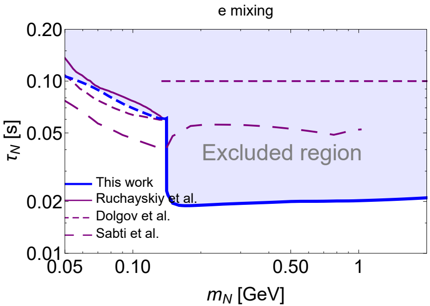


[2008.00749]

BBN bounds for HNLs

...and "bottom" line for Intensity Frontier searches



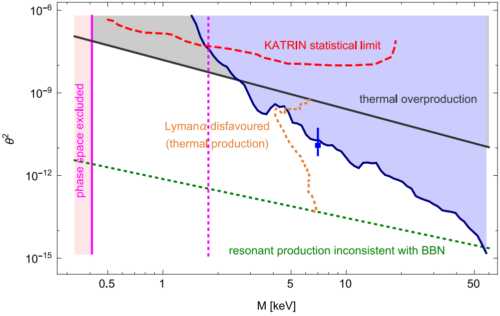


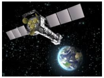
Boyarsky, Ovchynnikov, Ruchayskiy, Syvolap [2008.00749]

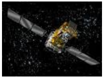
- BBN bounds about m_π have been untouched for 30 years
- Accounting for strong interactions strengthens them by a factor ~ 5
  (Similar results for scalar: Pospelov & Pradler [1006.4172])
- SHiP now can reach the "bottom" for masses below ~ 1 GeV

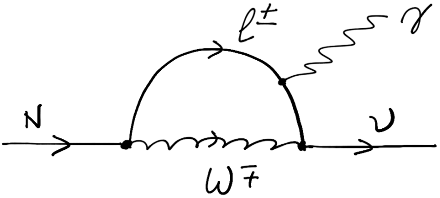
Searching for keV-scale sterile neutrinos

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

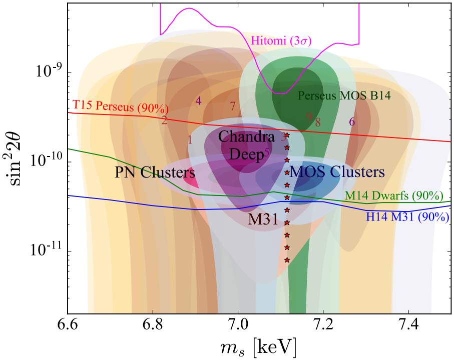
  Boyarsky O.R.+, Iakubovskyi+; Franse+; Bulbul+; Urban+; Cappelluti+

- 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

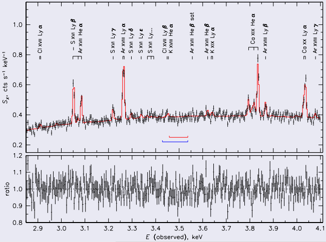
Milky way & Andromeda galaxies, Perseus cluster, Draco dSph, distant clusters. COSMOS & Chandra deep fields

Systematics? – Detection with 4 different telescopes

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

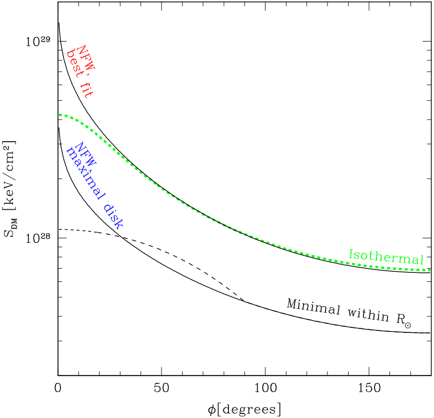
Astronomical line?

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

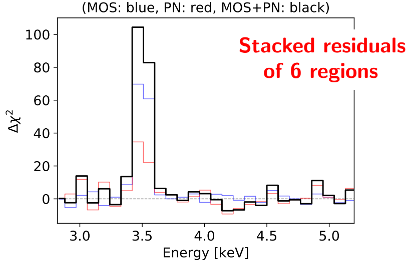
Boyarsky, Ruchayskiy, et al. [1812.10488] + update

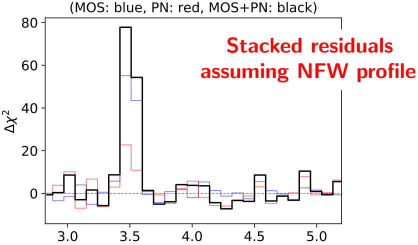
- 49 Msec of quiescent Milky Way regions ($10'$ to 45°)
- The data split into **6 radial bin**
- Line is detected in 4 bins with $> 3\sigma$ and in 2 bins with $> 2\sigma$ significance
- Good background model in the interval $2.8 - 6$ keV plus $10 - 11$ keV

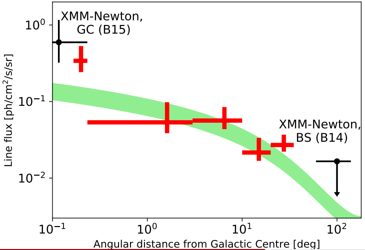
Region	$10' - 14'$ **(Reg1)**	$14' - 3^\circ$ **(Reg2)**	$3^\circ - 10^\circ$ **(Reg3)**	$10^\circ - 20^\circ$ **(Reg4)**	$20^\circ - 35^\circ$ **(Reg5)**	$35^\circ - 45^\circ$ **(Reg6)**
MOS/PN exp.	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1	5.5/2.5
MOS/PN FoV	205/197	398/421	461/518	493/533	481/542	468/561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





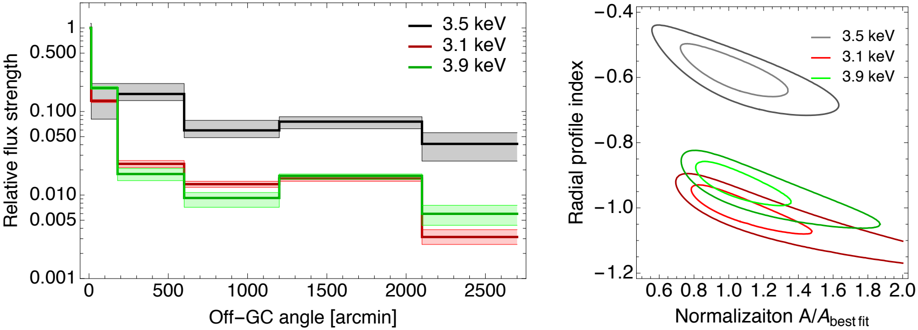


Profile	Significance in σ	Line position [keV]	Decay width Γ $[10^{-28}\,\mathrm{sec}^{-1}]$
NFW [19] $r_s = 20\,\mathrm{kpc}$	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert $r_B = 9\,\mathrm{kpc}$	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto $r_s = 14.8$ kpc $\alpha = 0.2$	6.9σ	$3.494^{+0.002}_{-0.009}$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

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 den-

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

XRISM

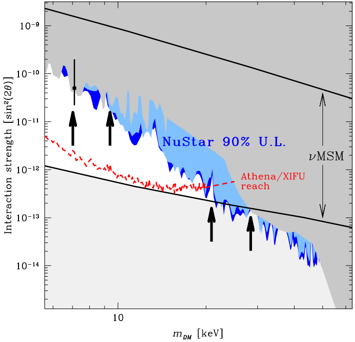
- **Hitomi** demonstrated that the origin of the line can be quickly checked with spectrometers
- **Hitomi** replacement – XRISM is scheduled to be launched in 2021–2022

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



[1607.07328]

Athena+ (2028)

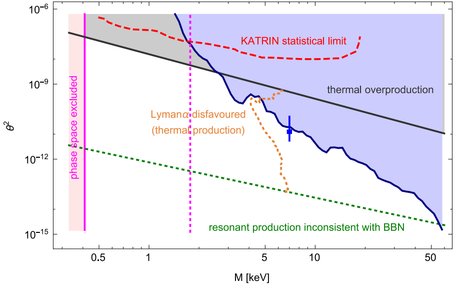
- Large X-ray missing – combination of spectrometry and imaging
- Era of **dark matter astronomy** begins

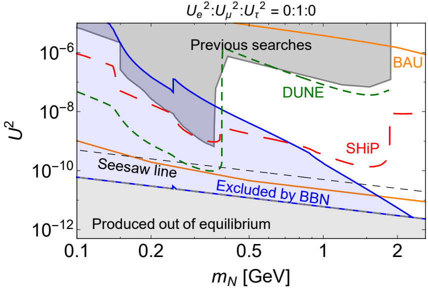
X-ray spectroscopy and future of decaying dark matter searches

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

Conclusion





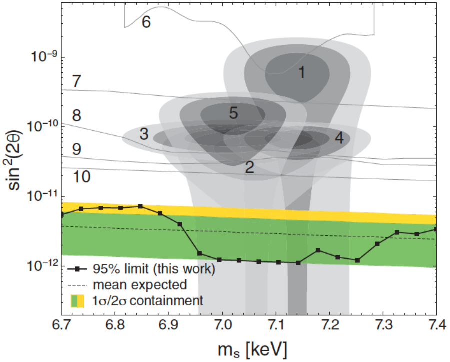
Cosmology and astrophysics can tell us a lot about particle physics and in particular about HNLs ☺

Backup slides

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



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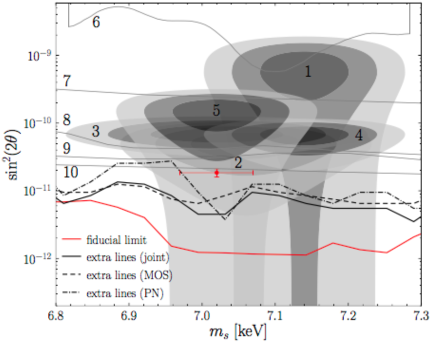
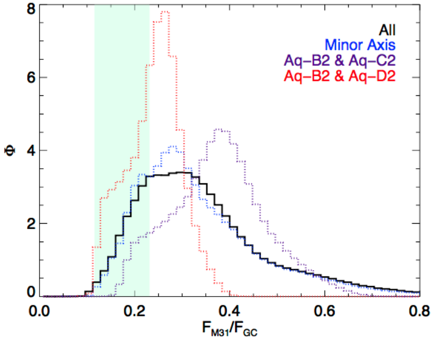
- Deep exposure dataset (30 Msec) of Milky Way regions $5^\circ - 45^\circ$
- Self-invented complicated statistical analysis instead of a standard fitting approach, used by the X-ray community
- **If you read inside the paper** the do not rule out dark matter interpretation at all



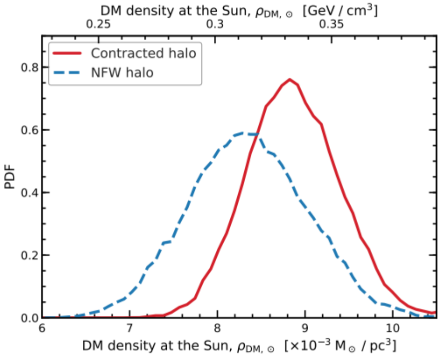
(A)

Dark matter content

[1411.0311]



[1911.04557]

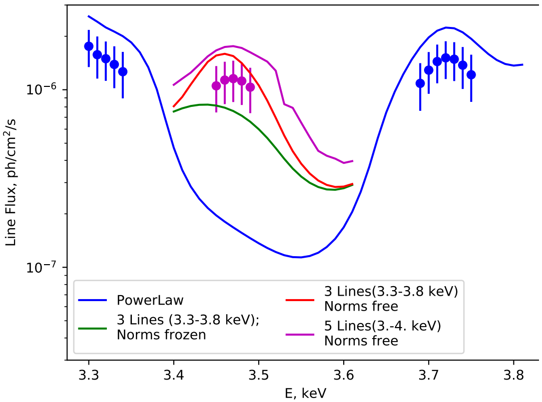


Dessert et al. assumes $\rho_\odot = 0.4\,\mathrm{GeV}/\mathrm{cm}^3$

- 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

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

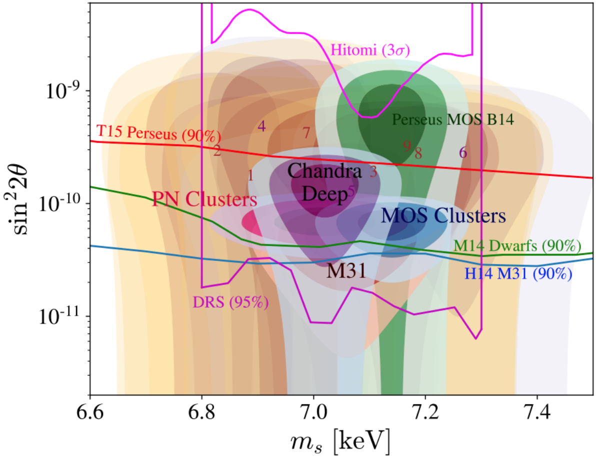
  As shown by [1812.10488; 2004.06601] and most recently by [2008.02283]
- Not including them into the model **artificially raises the continuum** $\Rightarrow$ reduce any line

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

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

Bounds are consistent with previous detections

Abazajian [2004.06170]



- Does not include proper modeling of effective area
- Does not account for wider interval of energies
- Should be correct within a factor of few