Sterile neutrinos as dark matter

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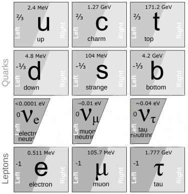
Borexino10 Workshop, Gran Sasso, September 7, 2017.

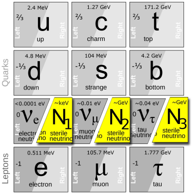
νMSM: SM extension with 3 sterile neutrinos

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

- 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**



$\Longrightarrow$



A **unified SM** of particle physics and cosmology

Sharing success of the Standard Model at accelerators and resolving major BSM problems:
Neutrino masses and oscillations; Baryon asymmetry of the Universe; Dark matter

Type I seesaw model

- Left-handed neutrino is **not** truly neutral; we can write

$$\text{Neutrino Majorana mass} = \frac{\boldsymbol{c}(\bar{L}\cdot\tilde{H}^\dagger)(L^c\cdot\tilde{H})}{\boldsymbol{\Lambda}}$$

but it violates unitarity! Alternative: **see-saw mechanism**,

$$\mathcal{L}_{\text{Seesaw Type I}} = \mathcal{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + \bar{N}(\tilde{H}\cdot L) + \frac{1}{2}\bar{N}\boldsymbol{M}N^c + \text{h.c.}$$

- Contains both Dirac and Majorana mass terms
- Neutrinos are light because $m_{\text{Dirac}} \ll \boldsymbol{M}$:

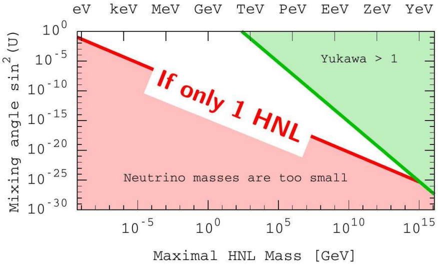
$$m_\nu \simeq \frac{(m_{\text{Dirac}})^2}{\boldsymbol{M}} = U^2\boldsymbol{M}$$

- **active-sterile mixing angle**

$$U = \frac{m_{\text{Dirac}}}{\boldsymbol{M}} \ll 1$$

The new particle is called "Sterile neutrino" or "heavy neutral lepton" or **HNL**

HNL parameters and neutrino oscillations



For every point in the white region, HNLs with such mass/interaction that can explain the phenomenology of neutrino oscillations

- $\mathcal{N}$ HNLs bring $7 \times \mathcal{N} - 3$ new parameters
- With the **full knowledge** of PMNS and active neutrino masses/phases we will be able to determine

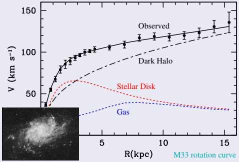
  7 out of 11 parameters $(\mathcal{N} = 2)$
  9 out of 18 parameters $(\mathcal{N} = 3)$

- Undetermined parameters are: $\mathcal{N}$ Majorana masses + some ratios of Yukawas (for example, one replace $Y_{\alpha I} \leftrightarrow Y_{\alpha J} (M_I/M_J)^{1/2}$ for some pairs $I \neq J$.)

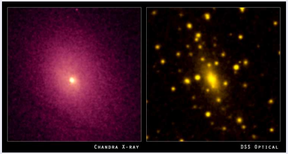
What can **dark matter** tell us about the HNLs mass?

Dark Matter in the Universe

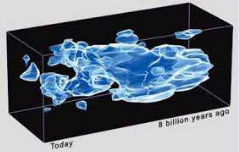
Astrophysical evidence:



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

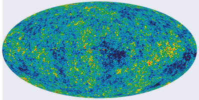


Expected:
$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{gals}}$
Observed: 10^2 times more mass confining ionized gas

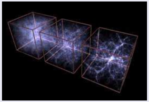


Lensing signal (direct mass measurement) **confirms** other observations

Cosmological evidence:



Jeans instability turned tiny density fluctuations into visible structures



Neutrino dark matter

Neutrino seems to be a perfect dark matter candidate: neutral, long-lived, massive, abundantly produced in the early Universe

Cosmic neutrinos

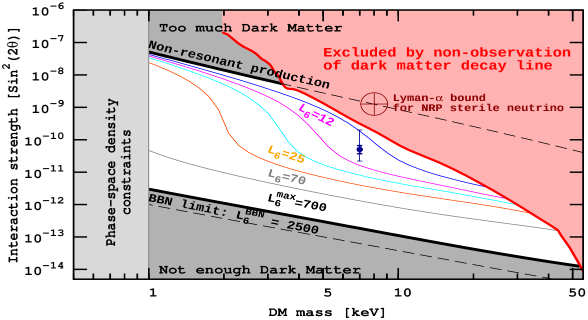
- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 112\,\mathrm{cm}^{-3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$

Tremaine-Gunn bound (1979)

- Such light neutrinos **cannot form small galaxies** – one would have to put too many of them and violated Pauli exclusion principle
- Minimal mass for fermion dark matter $\sim 300 - 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would **overclose the Universe** ($\Omega h^2 \sim 3\,!$)

νMSM dark matter parameters

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



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

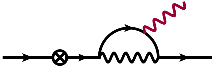
A smoking gun signature: DM decay line

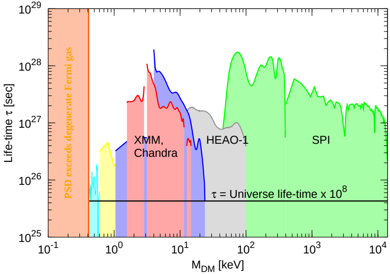
MW (HEAO-1) Boyarsky+'05; **Coma and Virgo clusters** Boyarsky+'06; **Bullet cluster** Boyarsky+'06;

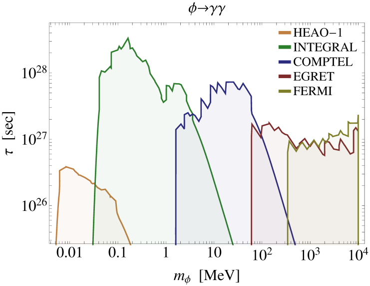
LMC+MW(XMM) Boyarsky+'06; **MW** Riemer-Sørensen+'06; Abazajian+'06; **MW (XMM)** Boyarsky+'07;

MW (INTEGRAL) Yuksel+'07; Boyarsky+'07; **M31** Watson+'06; Boyarsky+'07; Horiuchi+'13; **dSphs**

Loewenstein+'08,'09,'12; Malyshev+'15,. . .





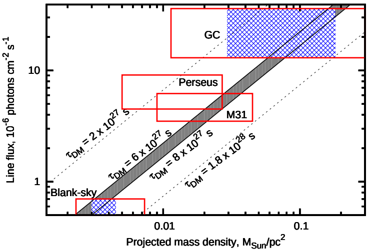


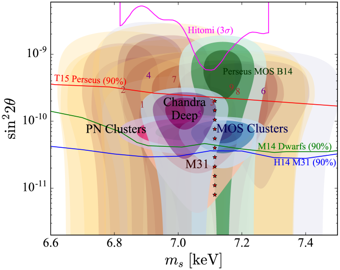
See e.g. [1602.04816] **"A White Paper on keV Sterile Neutrino Dark Matter"**

3.5 keV line origin: radiatively decaying DM?

3.5 keV line: **Bulbul et al, ApJ'14; Boyarsky, Ruchayskiy, DI, Franse, PRL'14**

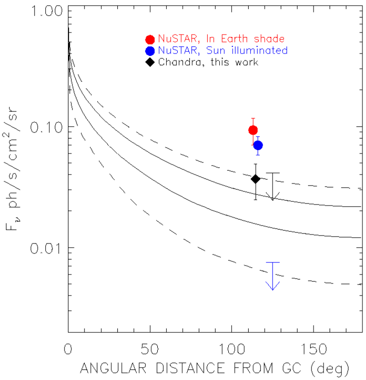
- **Observations** point to $\tau_{DM} = (6-8)\times 10^{27}$ s **[1408.2503, 1508.05186]**;
- Many detections and non-detections in different objects;
- Should be **careful** when comparing results from different objects – DM content in **each** of them is **uncertain**!





Boyarsky, Franse, DI, Ruchayskiy, PRL'15 **Abazajian, PhysRep'17**

New detections

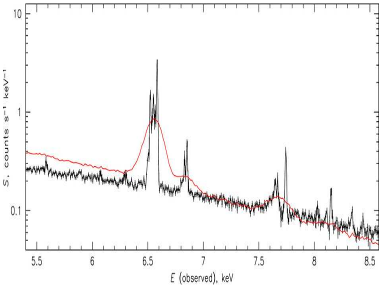


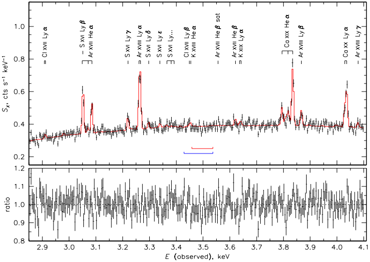
- **11σ detection** by NuSTAR blank-sky **1607.07328**
- **3σ detection** by Chandra from the same region **1701.07932**
- 5 times larger signal than blank-sky from Galactic Center **1609.00667**

Combined with previous detections, argues **against** systematical origin

Next step for 3.5 keV line: resolve the line

- A new microcalorimeter with a superb spectral resolution – Hitomi (Astro-H) launched February 17, lost March 26, 2016;
- Before its loss, **observed** Perseus cluster core in calibration phase (additional filters block most of X-ray below 3 keV)





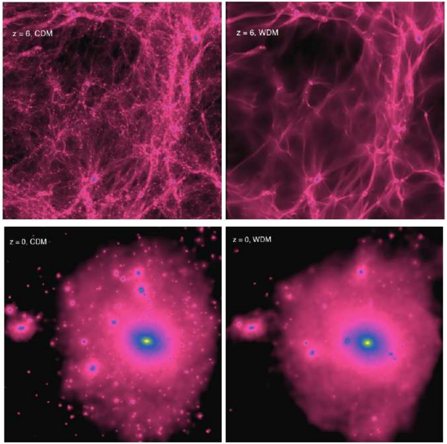
What did we learn with existing Hitomi data?

- Due to its superior energy resolution, *Hitomi* can distinguish between **atomic line broadening** (thermal velocities $\sim 10^2\,\mathrm{km/sec}$) and **decaying dark matter line broadening** (virial velocity $\sim 10^3\,\mathrm{km/sec}$)
- Bounds much weaker for a **broad** (dark matter) line $\to$ not at tension with previous detections
- Even the short observation of Hitomi showed **no nearby astrophysical lines** in Perseus cluster $\to$ 3.5 keV line is **not astrophysical** Hitomi collaboration, 1607.04487

- **This does not seem to be astrophysics** (Hitomi spectrum)
- **This does not seem to be systematics** (4 different instruments)
- **???**

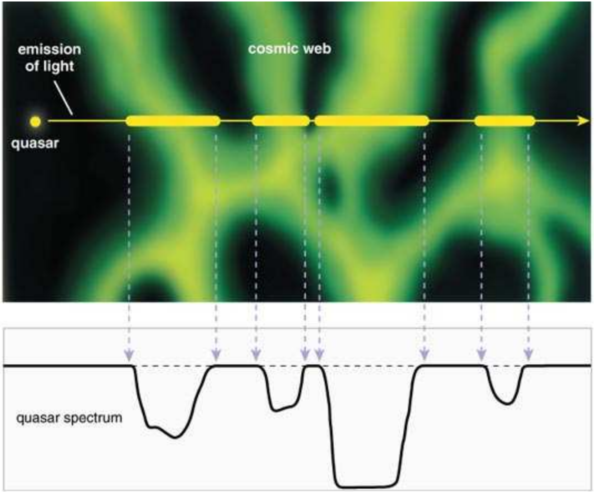
Sterile neutrino: warm dark matter

COCO Warm simulation Bose+'15. HNL dark matter:

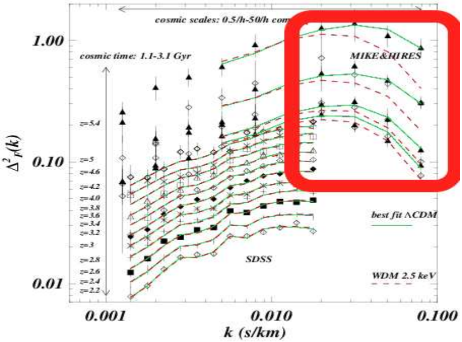


- Same structures as in **CDM** Universe at Mpc scales and above → no signatures in CMB/galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems

Lyman-α forest and power spectrum



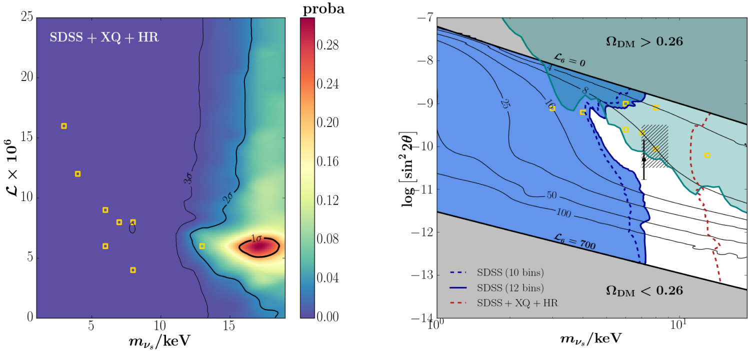
High-resolution Ly-α forest and νMSM DM



- Best fit **thermal relic** mass $= 2.1$ keV
- Corresponds to resonantly produced sterile neutrino with $M_N = 7$ keV and lepton asymmetry $L_6 = 11$
- 3.5 keV line, interpreted as sterile neutrino DM, gives range of lepton asymmetries $L_6 = 8 - 12$

By accident (or maybe not?) the HNL dark matter interpretation of 3.5 keV line predicts **exactly** the amount of suppression of power spectrum observed in HIRES/MIKE (and **fully consistent** with all other structure formation bounds), see Garzilli, Boyarsky, Ruchayskiy [1510.07006]

The latest results from Ly-α forest [1706.03118]



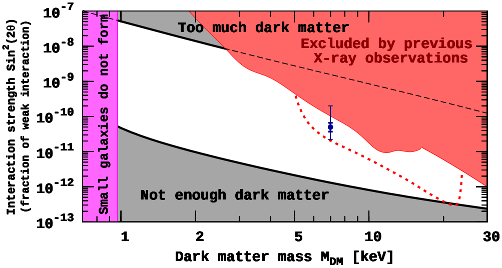
Data from SDSS-III (BOSS) + X-Shooter + HIRES

Hatched rectangle indicates 3σ 'island' in νMSM parameter space

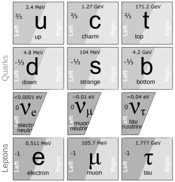
Similar result from reionization (**DI et al., in progress**) and high-z luminosity function (**1611.05892**)

Future X-ray observations:

- **Micro-X** sounding rocket experiment (2019+) – large field-of-view, large energy resolution, very small exposure – will probe Galactic Center+Bulge region (ApJ'15 [1506.05519]);
- **Hitomi-2** – planned to launch by NASA during 2020-2021;
- **Athena** – large ESA mission (2028+), very large resolution and collecting area (each 10×XMM-Newton) – will probe individual DM haloes (e.g. galaxy clusters).



Conclusions



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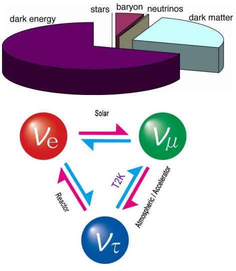

Neutrino oscillation between three generations

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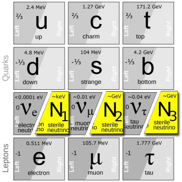


Thank you for your attention!

Backup slides:

DM decay line: basic properties

- Signature of 2-body radiative decay (e.g. DM$\to \gamma + \gamma$, DM$\to \gamma + \nu$): **monochromatic line** from **all** DM overdensities.
- Due to small ($v \sim 10^{-4} - 10^{-2}$) Doppler broadening the line is **narrow**.
- Observed line position should **evolve** with redshift.
- Line position from nearby objects $E_\gamma = \frac{1}{2} m_{\rm DM} c^2$
- Flux from DM decay:

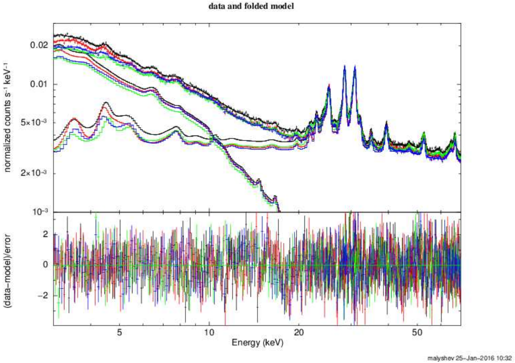
$$F_{\rm DM} = \frac{E_\gamma}{m_{\rm DM}\tau_{\rm DM}} \int\limits_{\text{fov cone}} \frac{\rho_{\rm DM}(\vec{r})}{4\pi|\vec{D}_L + \vec{r}|^2} d^3\vec{r} \approx \frac{\Omega_{\rm fov}}{8\pi m_{\rm DM}\tau_{\rm DM}} \mathcal{S}$$

- **DM column density**

$$\mathcal{S} = \int\limits_{\Omega_{\rm fov}} \rho_{\rm DM}(r) dr$$

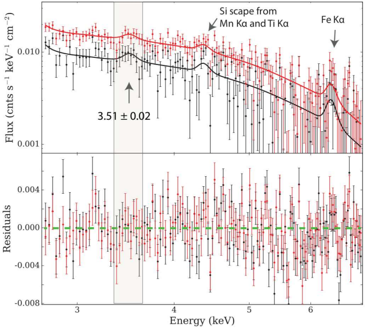
– integral along the line-of-sight, averaged within the instrument's field-of-view – **slowly** grows with halo mass ($\sim M^{0.2}$) – 0911.1774.

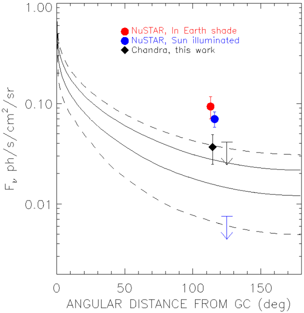
NuSTAR detections: blank-sky [1607.07328]



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

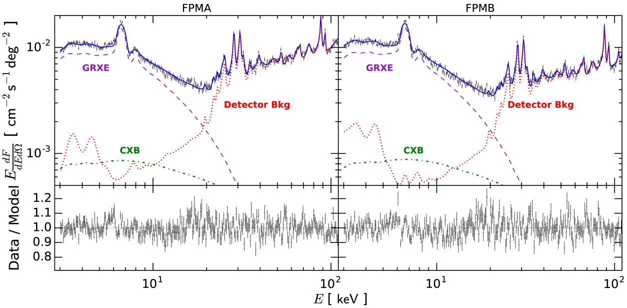
Chandra detections: blank-sky [1701.07932]





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

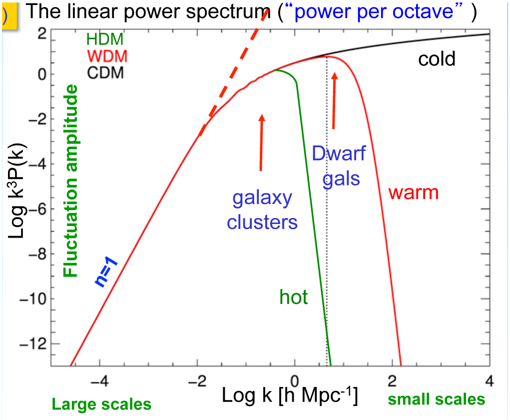
NuSTAR detections: GC [1609.00667]



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

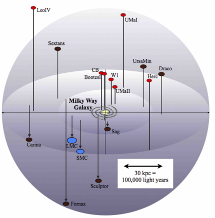
Sterile neutrino: warm dark matter

- keV sterile neutrinos are born **relativistic**
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

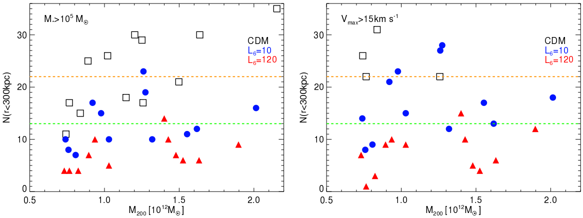


Satellite number and properties

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



Lovell, Boyarsky, Ruchayskiy et al. [1611.00010]



Current status of structure formation bounds from the Local Universe

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