News about heavy neutral leptons

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Can this be a **unified Standard Model** 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

$$\mathcal{L}_{\text{Seesaw Type I}} = \mathcal{L}_\text{SM} + i \vec{N} \not d \vec{N} + Y \vec{N} (\vec{H} \cdot \vec{L}) + \frac{1}{2} \vec{N} M N^c + \text{h.c.}$$

- Neutrinos are light because $m_{\text{Dirac}} \ll M$:
  $$m_\nu \approx \left(\frac{m_{\text{Dirac}}}{M}\right)^2 = U^2 M$$

- active-sterile mixing angle
  $$U = \frac{m_{\text{Dirac}}}{M} \ll 1$$

The new particle is called “Sterile neutrino” or “heavy neutral lepton” or HNL
HNL parameters and neutrino oscillations

- $N$ HNLs bring $7 \times N - 3$ new parameters
- With the **full knowledge** of PMNS and active neutrino masses/ phases we will be able to determine
  - 7 out of 11 parameters ($N = 2$)
  - 9 out of 18 parameters ($N = 3$)
- Undetermined parameters are: $N$ 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 $I \neq J$)

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

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Properties of sterile neutrinos

Heavy neutral lepton inherits the interactions from neutrinos

Charged current-like: \( \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} U \bar{e} \gamma^\mu (1 - \gamma_5) N^c W_\mu \)

Neutral current-like: \( \mathcal{L}_{NC} = \frac{g}{\cos \theta_W} U \bar{\nu} \gamma^\mu (1 - \gamma_5) N^c Z_\mu \)

Typical values of parameters

Yukawa coupling \( \sim \left( \frac{M_N m_\nu}{\langle \Phi \rangle^2} \right)^{1/2} \approx 4 \times 10^{-8} \left( \frac{M_N}{1 \text{ GeV}} \right)^{1/2} \)

Mixing angles \( U^2 = \frac{m_\nu}{M_N} \approx 5 \times 10^{-11} \left( \frac{1 \text{ GeV}}{M_N} \right) \)
How to search for HNLs

- $M_N < \text{few MeV}$ – only $U_e$ mixing can be probed (kink searches)
- $\mathcal{O}(10)\text{MeV} \lesssim M_N \lesssim M_K$ – intensity frontier experiments (peak searches)
- $\mathcal{O}(100)\text{MeV} \lesssim M_N \lesssim M_B$ – intensity frontier experiments (fixed target experiments)
- $M_N \gtrsim \text{few GeV}$ – LHC searches (displaced vertices; multilepton final states; same sign same flavour leptons, ...)

Helo+’15-’16; Izaguirre & Shuve’15; Ng+’15; Antush+’15-’16; Dib & Kim’15; Gado+’15; Dev+’15; Cvetic+’15-’16

- Z-factories (FCC-ee)
Accidental suppression of mixing angles
Shaposnikov’06; Asaka et al.’11; Ruchayskiy & Ivashko’11; Drewes et al.’16

- Already with two HNLs accidental suppression of some of the flavour mixing angles is possible, given unknown phases in PMNS matrix.
- Therefore it is important to target channels, governed by different mixing angles $U_\alpha$ (at SHiP, NA62, LHC, ...)

\[ T_\mu \equiv \frac{U_\mu^2}{\sum_\alpha U_\alpha^2} \]
Mass of heavy neutral leptons?

- No information from neutrino oscillations
- What can other BSM phenomena tell us about the HNLs mass?
Dark Matter in the Universe

Astrophysical evidence:

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

Expected: mass\text{cluster} = \sum \text{mass}\text{galaxies}
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 all visible structures
Neutrino dark matter

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

**Cosmic neutrinos**

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

**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 $\sim 300 - 400 \, \text{eV}$
- If particles with such mass were weakly interacting (like neutrino) – they would oveclose the Universe ($\Omega \sim 3$!)
Two roads from neutrino dark matter

Dark matter cannot be *light* and *weakly interacting* at the same time

Alternatives:

Light and necessarily *super-weakly* interacting — **HNL**

Heavy and weakly interacting — **WIMP**

... and of course other, completely orthogonal ideas, like axions

**HNLs as dark matter**

- Can be **light** (down to Tremaine-Gunn bound)
- Can be **warm** (born relativistic and cool down later)
- Can be **decaying** (stability is not required)
- Can be **produced** in correct amounts (via mixing with neutrinos)
### Parameter space of HNL dark matter

- Non-observation of decay line $N \rightarrow \gamma + \nu$

- Lifetime $\gg$ Age of the Universe (dotted line)

- Contribution to neutrino masses

$$m_\odot \sim U^2 M$$

[Asaka+'05; Boyarsky+'06]
Parameter space of HNL dark matter II

- Production via non-resonant mixing
  [Dodelson & Widrow’93; Asaka, Laine, Shaposhnikov’06]
- Liouville bound (neglecting feedback from baryons)
  [Boyarsky, O.R. et al.’08; Gorbunov+’08]
- Lyman-α bound
  [Boyarsky, Lesgourgues, O.R., Viel’08]

- Production via mixing and decay signal depend on the same mixing angle $U^2$
- X-ray bounds grow very fast with mass (flux $\sim M_N^5$)
Parameter space of HNL dark matter III

- White region: production via resonant mixing [Shi & Fuller’93; Laine & Shaposhnikov’08]
- Requires: lepton asymmetry exceeding $\eta_{\text{baryon}}$ by many orders of magnitude at $T \sim 100 – 500$ MeV

In summary

- HNL DM is light ($1 – 50$ keV) if there are no other particles
- Yukawa of HNL DM are tiny ($\mathcal{O}(10^{-10})$ or below)
Searches for radiatively decaying dark matter
For overview see e.g. [1602.04816] “A White Paper on keV Sterile Neutrino Dark Matter”

Life-time $\tau$ [sec]  \quad M_{DM}$ [keV]

$10^{-1}$  \quad $10^{25}$

$10^{0}$  \quad $10^{26}$

$10^{1}$  \quad $10^{27}$

$10^{2}$  \quad $10^{28}$

$10^{3}$  \quad $10^{29}$

$10^{4}$  \quad $\tau = \text{Universe life-time} \times 10^8$

“Next decade of sterile neutrino studies”

Essig+’13

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; dSph Loewenstein+’08,’09,’12; Malyshev+’15,…”
Reminder: 3.5 keV line story

Two groups reported an identified feature in the X-ray spectra of dark matter-dominated objets

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul\textsuperscript{1,2}, Maxim Markevitch\textsuperscript{2}, Adam Foster\textsuperscript{1}, Randall K. Smith\textsuperscript{1} Michael Loewenstein\textsuperscript{2}, and Scott W. Randall\textsuperscript{1}

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\textsuperscript{2} NASA Goddard Space Flight Center, Greenbelt, MD, USA.


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

A. Boyarsky\textsuperscript{1}, O. Ruchayskiy\textsuperscript{2}, D. Iakubovskyi\textsuperscript{3,4} and J. Franse\textsuperscript{1,5}

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

PRL (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 – 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor $\sim 3$)
- **Possible origin:** decay $\text{DM} \rightarrow \gamma + \nu$ (fermion) or $\text{DM} \rightarrow \gamma + \gamma$ (boson)
Galactic center – a non-trivial consistency check
Boyarsky, O.R. + PRL 115, 161301

- **4σ+** statistical significance
- Also in S. Riemer-Sorensen’14; Jeltema & Profumo’14
- Observation from M31 puts a **lower** bound on the GC flux
- Non-observations from the Milky Way outskirts puts an **upper** bound on the GC flux
- The observed signal fits into the range

- Line flux, $10^{-6}$ photons cm$^{-2}$ s$^{-1}$
- Projected mass density, $M_{\text{Sun}}$/pc$^2$
- GC
- M31
- Perseus
- Blank-sky

$\tau_{\text{DM}} = 6 \times 10^{27}$ s
$\tau_{\text{DM}} = 8 \times 10^{27}$ s
$\tau_{\text{DM}} = 1.8 \times 10^{28}$ s
Subsequent works

For overview see e.g. [1602.04816] “A White Paper on keV Sterile Neutrino Dark Matter”

- 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+

A common explanation for every detection and non-detection?

- When comparing bounds from different objects one should be careful — dark matter content in each of them uncertain by a factor 2 – 3
The 3.5 keV is present in the spectrum with $11\sigma$ significance.

The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band.

The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure.

However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux.
Most recently: 10 Msec of Chandra observation of Chandra Deep Fields

3σ detection of a line at ~ 3.5 keV

If interpreted as dark matter decay – this is a signal from Galactic halo outskirts (~115° off center)

Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely

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

- Astro-H/Hitomi – new generation X-ray spectrometer with a superb spectral resolution
- Launched February 17, 2016
- Lost few weeks later
- Before its failure observed the center of Perseus galaxy cluster
- The observations was in calibration phase (additional filters block most of X-ray below 3 keV)

Perseus center spectrum [1607.07420]
What did we learn with existing Hitomi data?

- Due to its super energy resolution, *Hitomi* can distinguish between atomic line broadening (thermal velocities $\sim 10^2 \text{km/sec}$) and decaying dark matter line broadening (virial velocity $\sim 10^3 \text{km/sec}$)

- Even the short observation of Hitomi showed that Potassium, Clorium, etc. do not have super-solar abundance in Perseus cluster $\Rightarrow$ 3.5 keV line is **not** astrophysical

- Bounds much weaker for a **broad** (dark matter) line $\Rightarrow$ not at tension with previous detections

This does not seem to be astrophysics (Hitomi spectrum)

This does not seem to be systematics (4 different instruments)

???
Future of decaying dark matter searches in X-rays

Another Hitomi
JAXA is planning to send a replica of Hitomi satellite (within about 2 years)

Microcalorimeter on sounding rocket (2017)
- Large field-of-view and very high spectral resolution
- Can resolve narrow lines from diffuse sources
- Flying time $\sim 10^2$ sec

Athena+
- Large ESA X-ray mission (2028) with X-ray spectrometer (X-IFU)
- Very large collecting area ($10 \times$ that of XMM)
Warm dark matter

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

The linear power spectrum (**“power per octave”**)}

- Overdensity

- Particle velocities means that warm dark matter has effective **pressure** that prevents small structure from collapsing
At non-linear scales

COCO Warm simulation Bose+’15

HNL 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
Current status of structure formation bounds from the Local Universe

- Connection “dark structures” ↔ “visible structures” depends on (yet unknown) way to implement baryonic feedback
- Simulation to simulation (or even halo-to-halo) scatter is quite large and affects the conclusions
- We do not know how typical is our Galaxy, our Local Group, etc.
- You cannot “rule out” your warm dark matter model with these observations
- You can only check that your model fits the data under “reasonable” assumptions about baryonic physics
Lyman-$\alpha$ forest and power spectrum
Warm dark matter predicts suppression (cut-off) in the flux power spectrum derived from the Lyman-\(\alpha\) forest data.

\[ \Lambda CDM \]
\[ \text{WDM 2 keV} \]
\[ \text{WDM 1 keV} \]
No suppression of flux power spectrum in SDSS/BOSS datasets ⇒ only lower bound on WDM mass have been put Seljak+’06; Viel+’06; Boyarsky+’08
Suppression in the flux power spectrum

The suppression of the flux power spectrum is visible in high-resolution HIRES/MIKE dataset.
Suppression in the flux power spectrum may be due to

- 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)
- Warm dark matter

Data prefers cold intergalactic medium around redshift $z = 5$ ⇒ Observed Lyman-$\alpha$ power spectrum suppression is due to something else?
High-resolution Lyman-α forest and HNL dark matter
Garzilli, Boyarsky, Ruchayskiy [1510.07006]

- Best fit thermal relic mass $= 2.1$ keV
- Corresponds to resonantly produced sterile neutrino with $M_N = 7$ keV and lepton asymmetry $L = 11 \times 10^{-6}$
- 3.5 keV line, interpreted as sterile neutrino DM, gives range of lepton asymmetries $L = 8 - 12$

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)
Future of Lyman-\(\alpha\) on

- The high-resolution Lyman-\(\alpha\) spectra show suppression – due to thermal effects or due to warm dark matter
- We have only crude information about the reionization history and temperature of gas at reionization epoch
- The measurement of gas temperatures at redshifts \(z \gtrsim 5\) has high discovery potential
- This can be done (work in progress)

\[
T_{\text{m}}(z) = \frac{2k_B}{m_H} \left(\text{Line width (temperature)}\right)
\]

(Garzilli, Theuns, Schaye'15)
**Summary: Heavy neutral leptons as dark matter**

- HNL DM is **light** (1 – 50 keV)
- Yukawa of HNL DM are tiny ($\mathcal{O}(10^{-10})$ or below)
- Large ($\sim 10^6 \eta_{\text{baryon}}$) late-time lepton asymmetry is required if we want to resolve BSM problems only with **heavy neutral leptons**

Structure formation bounds (satellite counts / Lyman-\(\alpha\)) have still uncontrolled systematics and no numbers from them can be taken “at face value”
Baryogenesis with HNLs

Heavy neutral leptons provide
- Additional sources of CP-violation
- Out-of-equilibrium conditions (decays or oscillations)
- Violation of the lepton number (and $B - L$)

Wide class of scenarios known as leptogenesis

Thermal leptogenesis: $M_N \sim 10^{12}$ GeV

Resonant leptogenesis: $M_{N_1} \approx M_{N_2} > M_W$ and $|M_{N_1} - M_{N_2}| \ll M_N$

Leptogenesis via oscillations: 2 or 3 HNLs, $M_N < M_W$ and $|M_{N_1} - M_{N_2}| \ll M_{N_1,N_2}$

- Fukugita & Yanagida’86
- Pilaftsis, Underwood’04–’05
- Akhmedov, Smirnov & Rubakov’98
- Asaka & Shaposhnikov’05
- ...
**Leptogenesis via oscillations**

Akhmedov+’98; Asaka & Shaposhnikov’05; Canetti & Shaposhnikov’11; Asaka+’08-’16; Canetti+’12; Abada’15; Hernández+’15-’16; Drewes+’12,’15,’16; Hambye & Teresi’16

**Rates:** Laine+’08,’14,’15,’16

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**Shuves & Yavin’14**

- Out-of-equilibrium CP-violating oscillations of HNLs allow to generate effective lepton number in the active neutrino sector
- Generation of lepton asymmetry continues down to $T \sim O(10)\text{GeV}$, reaching levels $\gg \eta_{\text{baryon}}$
Leptogenesis via oscillations can occur for masses down to tens of MeV
Requires degeneracy in masses $\Delta M/\bar{M} \ll 1$
HNL masses from leptogenesis

- HNLs responsible for neutrino masses and leptogenesis can be as light as 10 MeV or as heavy as $10^{12}$ GeV
- There exists only one mechanism (leptogenesis via oscillations) that generates significant lepton asymmetry below sphaleron freeze-out times
- Large lepton asymmetry is required if we want to explain dark matter, baryogenesis and neutrino oscillations with three HNLs only
- The evolution of lepton asymmetry in the primordial plasma is under investigation

We need to identify the parts of the parameter space where not only correct baryon asymmetry but also large lepton asymmetry is produced
SHiP sensitivity to HNL models

- Different baryogenesis models require different patterns of $U_e : U_\mu : U_\tau$
- Existing sensitivity curves (SHiP TP) assumed certain patterns of $U_e : U_\mu : U_\tau$ and cannot be translated to other models

We will generate a grid of simulations and interface that would allow to estimate SHiP sensitivity for any HNL model

A project run by SHiP Theory group (K. Bondarenko, A. Boyarsky, D. Gorbunov, M. Shaposhnikov, O. Ruchayskiy) together with SHiP Physics group (Nico Serra)
How many simulations do we need?

- A model with 2 HNLs has 8 relevant phenomenological parameters \((M_1, M_2, |U_{\alpha 1}|, |U_{\alpha 2}|)\)
- For most of the cases production via different flavours \(|U_{\alpha i}|^2\) is independent
- Number of events in the detector are proportional to \(|U_{\alpha i}|^2\) but never to \(U_{\alpha i} U_{\alpha j}\) (no coherent effects):
- So, for 2 HNLs with \(M_1 \approx M_2\)...

\[
D^- \rightarrow N_{1,2} + e^- \rightarrow \pi^+ + \mu^-
\]

...total number of events in the detector is proportional to

\[
N_{obs} \propto |U_{\mu 1}|^2 |U_{e 1}|^2 + |U_{\mu 2}|^2 |U_{e 2}|^2
\]

\[
= N_{obs,1} + N_{obs,2}
\]

holds when \(\tau \gamma \gg L_{SHiP}\)!

We can simulate 1 HNL and translate the results to all HNL models.
HNL@SHiP project

Summary

- Number of events in the decay volume scales with $|U_\alpha|^2$ as following

$$N_{\text{events}}[M \mid U_e^2, U_\mu^2, U_\tau^2] = \sum_{\alpha,\beta} P_{\alpha\beta}(M) |U_\alpha|^2 |U_\beta|^2$$

holds when $ct\gamma \gg L_{SHiP}$!

- **Grid** $P_{\alpha\beta}(M^{(i)})$ contains all the necessary information
  (scan over $\mathcal{O}(100)\text{MeV} \leq M^{(i)} \leq 5 \text{ GeV}$)

- Interpolate for other sets of HNL parameters $(M_N, U_{\alpha I})$
Neutrinoless double beta decay

- If neutrinos have Majorana mass, the neutrinoless double $\beta$-decay is possible.

- Neutrino oscillations define the value of

$$m_{\beta\beta}^{(\nu)} = \left| \sum_i m_i V^2_{ei} \right|$$

where $V_{ei}$ is the elements of the PMNS matrix, connecting charge (flavour) and mass (propagation) neutrino states:

$$|\nu_\alpha\rangle = \sum_i V_{\alpha i} |\nu_i\rangle$$

$m_i$ are the masses

Effective Majorana mass in type-I seesaw

\[ m^{(\text{seesaw})}_{\beta\beta} = \left| \sum_i m_i V_{ei}^2 + \sum_I f_{\beta}(M_I) \frac{\langle \Phi \rangle^2 Y_{\alpha I}^2}{M_I} \right| \]

- \( f(M_I) \) is the nuclear matrix element, approximately (c.f. Faessler+'14)

\[ f(M_I) \approx \frac{\langle p \rangle^2}{\langle p \rangle^2 + M_I^2}, \quad \langle p \rangle \sim 100 \text{MeV} \]

Seesaw relation in these terms

\[ \sum_{\text{light}} m_i V_{ei}^2 + \sum_{I} \frac{\langle \Phi \rangle^2 Y_{\alpha I}^2}{M_I} = 0 \]
Due to the freedom in active-sterile Yukawa matrix, several HNL (even close in mass) can enhance the rate of $0\nu\beta\beta$ decay as compared to the $m_{\beta\beta}^{(v)}$ while still satisfying requirements of successful baryogenesis.

Hernández+’16. Also Drewes & Eijima’16, Asaka+’16
Conclusions

Neutrino oscillation between three generations
Outline

1. Backup slides
Dwarf spheroidals are “galaxies swallowed by our Galaxy”

Perfect observational targets:
- dense
- dark \((M/L \sim 10^2 - 10^3)\)
- compact (typical sizes \(5' - 30'\))
- nearby (distances \(30 - 100\) kpc)

The line is detected in the spectrum of Draco dSph with low significance \((\Delta\chi^2 = 5.3)\)

Line flux/position are consistent with previous observations

The data is consistent with DM interpretation for lifetime 
\[\tau_{DM} > (7-9) \times 10^{27}\) sec
Standard Model is consistent up to very high scales

Bezrukov+ “Higgs boson mass and new physics” [1205.2893]
Degrassi+ [1205.6497] Buttazzo+ [1307.3536]; Bednyakov [1609.02503]

[1609.02503]

[1411.1923]