Sterile neutrinos: unifying cosmology with particle physics

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Live Theoretical Physics Colloquium
Once upon a time . . .

. . . the model of particles and interactions was simple

. . . Proton
. . . Electron
. . . Photon
. . . Neutron

\[ \text{Atom} \]

. . . atoms could transform into each other
. . . physicists built quantum theory of radioactivity
. . . the theory described experiments really well but predicted existence of additional heavy particles

- these particles were eventually discovered
- but the structure of the theory dictated existence of yet other particles
- . . .
Once upon a time . . .

. . . the Standard Model was deemed complicated

. . . Of course our model has too many arbitrary features for these predictions to be taken very seriously . . .

S. Weinberg (1967) “A model of leptons”

12’400 citations at the time of writing
Once upon a time . . .

. . . all major predictions of the Standard Model were confirmed.

ATLAS collaboration (2018)
BSM problem I: Neutrino oscillations

What makes neutrinos disappear and then re-appear in a different form? Why they have mass?

- Predicted by Pontekorvko 1957 soon after the kaon oscillation story (why - because neutrinos are neutral)
- Observed in the 1960s as solar neutrino deficit
- Verified by many experiments both in appearance and disappearance

What mediates neutrino oscillations?
BSM problem II: Baryon asymmetry of the Universe

1. Space around us consists of matter with no evidence of primordial antimatter.
2. Standard cosmological scenario predicts symmetrical initial conditions.
3. Physics is (mostly) symmetric w.r.t. particles $\leftrightarrow$ antiparticles.
4. Matter-antimatter symmetric universe would be filled predominantly with photons and neutrinos.
5. Observed CP-violations would lead to many billion times smaller asymmetry.

What particles/processes created tiny matter-antimatter disbalance in the early Universe?
BSM problem III: Dark matter

What is the most prevalent kind of matter in our Universe?

- Gives mass to galaxies
- Does not emit or absorb light

Dense contrast

- Drives cosmological expansion
- Drives formation of structures

What particles is dark matter made of?

![M33 rotation curve](image)
Once upon a time . . .

. . . we thought we knew where to look for BSM phenomena

- We ambitiously wanted to discover new physics alongside the Higgs boson
- Some even thought we have a compelling reason for that
Yet our expectations were proven to be wrong.
So, although we know that new particles exist . . .

we do not know what they are

There are no definitive predictions what kind of new physics we are looking for (although there is no shortage of ideas)

The absence of definite theoretical guidance is our “new normal”

It is the experimental community that guides our forward development
How many particles are needed to solve all BSM problems?
Neutrino masses and oscillations

**Scale of new physics:** from $10^{30}$ GeV to $10^{64}$ GeV

Dark matter

**Scale of new physics:** from $10^{9}$ GeV to $10^{15}$ GeV

Baryon asymmetry of the Universe

**Scale of new physics:** from $10^{3}$ GeV to $10^{15}$ GeV
Neutrino oscillations and new particles

Neutrino oscillations imply new particles

- Type I see-saw
  - extra singlet fermion

- Type II see-saw
  - extra SU(2) triplet scalar

- Type III see-saw
  - extra SU(2) triplet fermion

- Operator of dimension $> 4$ implies new particles
- Naively the masses of these new particles are

$$M_{\text{new states}} \lesssim \Lambda = \frac{v^2}{m_{\text{atm}}}$$

where $v = \langle H \rangle$ – Higgs VEV
Assume one extra fermion $N$

It couples to the “neutrino” combination $\nu = (\tilde{H} \cdot L)$

This combination is $SU(3) \times SU(2) \times U(1)$ gauge singlet

$N$ carries no Standard Model gauge charges!

\[ L_{\text{Seesaw Type I}} = L_{\text{SM}} + i\bar{N} N + \frac{1}{2} \tilde{H} (\tilde{H} \cdot L) + L_{\text{Majorana}}(N) \]  \hspace{1cm} (1)

Majorana mass term $L_{\text{Majorana}}(N) = \frac{1}{2} \tilde{N} M N^c + \text{h.c}$ is possible for $N$

In terms of $\nu$ and $N$ we get ($m_{\text{Dirac}} = F\nu - \text{Dirac mass}$)

\[ L_{\text{Seesaw Type I}} = L_{\text{SM}} + i\bar{N} N + \frac{1}{2} \begin{pmatrix} \tilde{\nu} \\ \tilde{N^c} \end{pmatrix} \begin{pmatrix} 0 & m_{\text{Dirac}} \\ m_{\text{Dirac}} & M \end{pmatrix} \begin{pmatrix} \nu^c \\ N \end{pmatrix} \]  \hspace{1cm} (2)
Particle content

If \( M \gg m_{\text{Dirac}} \) this theory describes two particles:

- Light neutrino with mass \( m_\nu \approx m_{\text{Dirac}} \frac{m_{\text{Dirac}}}{M} \) — seesaw formula

- Heavier particle with mass \( \approx M \)

- Neutrinos are light because \( m_{\text{Dirac}} \ll M \)

- Mixture between states \( \nu \) and \( N \) (difference between weak eigenstate \( \nu \) and massive state \( \tilde{\nu} \)) is parametrized by active-sterile mixing angle

\[
\sin U \approx U = \frac{m_{\text{Dirac}}}{M} \ll 1 \tag{3}
\]
We call this new particle

“Sterile neutrino” or “heavy neutral lepton” or $\text{HNL}$

also “Majorana fermion”, “heavy Majorana neutrino”, “right-handed neutrino”, etc.
Interactions of HNLs

**Interactions**

\[ \mathcal{L}_{\text{int}} = \frac{g}{2\sqrt{2}} W_\mu^+ \bar{N} U^* \gamma^\mu (1 \equiv \gamma_5) \ell_{\alpha} + \frac{g}{2 \cos \theta_W} Z_\mu \bar{N} U^* \gamma^\mu (1 \equiv \gamma_5) \nu + \ldots \]  

- In every process where neutrino appears and where kinematics allows we expect an HNL with probability \( \propto |U|^2 \). For example,

\[ \Gamma(W^+ \rightarrow \mu^+ + N) = |U_\mu|^2 \Gamma(W^+ \rightarrow \mu^+ + \nu_\mu) \]
Feebly interacting HNLs

- HNLs are thus interacting “weaker-than-neutrinos” (by a factor $|U_\alpha|^2$). However, these particles can be detected via other means, thanks to their larger mass [1805.08567]

- Naive seesaw formula tells us

$$U^2 \sim \frac{m_{\text{atm}}}{M} \sim 10^{\equiv 12} \frac{100 \text{GeV}}{M}$$  \hspace{1cm} (6)

- Fortunately, we need more than 1 HNL to explain both $\Delta m_{\text{atm}}^2$ and $\Delta m_{\text{sun}}^2$

- All neutrino experiments would allow to determine

  - 7 out of 11 parameters (2HNL)
  - 9 out of 18 parameters (3HNL)

Seesaw formula (6) provides a bottom line for values of the coupling
Within a model with 2 HNLs any pattern of neutrino oscillations can be snuggly accommodated
How many light particles are needed to solve all BSM problems?

HNL 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 –
How many light particles are needed to solve all BSM problems?

HNL can explain all of it

- **Neutrino Minimal Standard Model (νMSM)**
  Asaka & Shaposhnikov’05 + . . . hundreds of subsequent works

- Masses of HNL are of the order of masses of other leptons


\[ \begin{array}{|c|c|c|}
\hline
10^{-6} & \nu N_1 & 10^{-6} \\
10^{-6} & \nu N_1 & 10^{-6} \\
\hline
\end{array} \]

- **Dirac masses**
- **Majorana masses**

HNL can explain . . .

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HNLs

Oleg Ruchayskiy (NBI)
Baryogenesis in the νMSM

- Two HNLs with GeV masses ($\mathcal{O}(100\,\text{MeV})$ up to $\mathcal{O}(80\,\text{GeV})$)
- Degeneracy in mass $\Delta M/M \ll 1$
- Lepton asymmetry is generated in CP-violating oscillations of two HNLs
- Recent results and comparison with previous works Eijima, Shaposhnikov, Timiryasov [1808.10833]

$$|U|^2 \approx \frac{m_2 + m_3}{2M_N} (X_\omega^2 + X_\omega^{32})$$

- Initial idea: Akhmedov+’98
- Kinetic theory including back-reaction: Asaka, Shaposhnikov’05
- Analysis: Asaka, Shaposhnikov, Canetti, Drewes, Frossard; Abada, Arcadi, Domcke, Lucente; Hernandez, Kekic, Lopez-Pavon, Racker, Salvado; Drewes, Garbrech, Guetera, Klari; Hambye, Teresi; Eijima, Timiryasov; Ghiglieri, Laine
- Recent refs: [1208.4607], [1606.06690], [1609.09069], [1710.03744]
Can these particles be discovered?
What do we have and what do we need?

**Theoretical predictions**
1. Two heavy neutral lepton of $\mathcal{O}(\text{GeV})$ scale
2. Nearly degenerate in mass
3. Possibly CP violation in the active-steirle mixing

**Experimental program**
1. Discover new particle
2. Measure its properties (Mass, spin, branching fractions, flavour structures)
3. Confront with theoretical predictions (from seesaw, BAU, etc)
What experiments can discover HNLs?

- LHC searches ([Boiarska+ [1902.04535]])
- Beyond LHC ([PBC report [1901.09966]])

- HNLs are part of the search program of all major particle physics experiments
What did we discover?

- Boson or fermion?
- If invariant mass $m_{\mu\mu}$ or even $M_{jj}$ has a peak – boson – or is broadly distributed (HNL)
  $\gamma' \to \ell^+ \ell^\mp$ vs. $N \to \mu^+ \mu^\mp \nu$ or $N \to \ell^+ + \pi^\mp$, etc

Plots from [1608.08632; 1805.08567; 1908.04635]
How many of them?

- We discovered HNLs. How many of them?
- If you discovered an HNL signal – you actually discovered two or more particles 😊

- Naive seesaw formula

\[ U_{\text{bottom}}^2 \sim \frac{m_{\text{atm}}}{M} \sim 10 \equiv 11 \frac{10\text{GeV}}{M} \]

- In order to have HNLs with mixings \( U^2 \gg U_{\text{bottom}}^2 \), you need several HNLs that “conspire” to cancel each other’s contribution to neutrino masses

\[ \text{Shaposhnikov}'06; \text{Kersten} \& \text{Smirnov}'07 \]
Do they fit predictions?

- Once HNL parameters are determined, you can check whether they fall into the theory predictions.
- And whether different measurements agree with each other.

  Boiarska+ [1902.04535]
  BAU contours: Eijima+ [1808.10833];
  Short DV: Cottin+ [1806.05191];
  Long DV: Bondarenko+ [1903.11918]
Probing other decay channels

Displaced vertices with the muon tracker

Boiarksa+ [1902.04535]; Bondarenko+ [1903.11918]
Dashed line: Drewes & Hajer [1903.06100]
Lepton number violation in HNL decays?

HNLs are Majorana particles and therefore can violate lepton number conservation.

Lepton number **conserving** (LNC) decay, mediated by HNL: $W^+ \rightarrow \mu^+ \mu^+ \equiv e^+ \nu_e$

Lepton number **violating** (LNV) decay, mediated by HNL: $W^+ \rightarrow \mu^+ \mu^+ e^+ \equiv \bar{\nu}_e$

Many works, see e.g. [1502.05915], [1505.01934], [1509.05981], [1805.11400], [1907.13034]
Can we measure HNL mass splitting at LHC?

- Two HNLs with couplings well above seesaw line\(^a\) suppress LNV effects
- However, two HNLs if sufficiently long-lived can oscillate and undo the suppression

\(^a\)Only those we can probe

- If we measure both LNV and LNC events as well as the total lifetime – we can hope to determine the mass splitting

\[
R_{ll} = \frac{\Delta M^2_{phys}}{2\Gamma_N^2 + \Delta M^2_{phys}}
\]

\(R_{ll}\) — ratio of same-sign to opposite-sign leptons Anamiati\(^+\) [1607.05641]

- \(\Delta M\) can also be measured in SHiP [1912.05520]
In some region of parameter space it is even possible to measure $\Delta M$

Binning events in proper time $\tau$ we can determine $\Delta M$ via $\Delta M \tau = 2\pi$
Holistic view

Accelerator measurements can be confronted with results of other experiments
What about dark matter?

HNL 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 –
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 $n_\nu = 112 \text{cm}^{-3}$ (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 $\sim 300 \equiv 400 \text{eV}$
- If particles with such mass were weakly interacting (like neutrino) – they would overclose the Universe
Two generalizations of neutrino dark matter

- Dark matter cannot be both light and weakly interacting at the same time.
- To satisfy Tremaine-Gunn bound the number density of any dark matter made of fermions should be less than that of neutrinos.
- Neutrinos are light, therefore they decouple relativistic and their equilibrium number density is $\propto T^3$ at freeze-out.

First alternative: WIMP

Heavy but weakly-interacting dark matter – its number density is Boltzmann-suppressed ($n \propto e^{\frac{m}{T}}$) at freeze-out.

Second alternative: sterile neutrino

Light but super-weakly-interacting dark matter so that their number density never reaches equilibrium value.
In particle physics one usually speaks of heavy neutral lepton but in cosmology the same particle is known as sterile neutrino.
Properties of sterile neutrino dark matter

- Can be **light** (down to Tremaine-Gunn bound of 0.5 keV or so)
- Can be **decaying** (with lifetime exceeding the age of the Universe)

Non-observation of decay line

\[ N \rightarrow \gamma + \nu \]

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

Contribution to neutrino masses below \( m_\odot \)

[Asaka+’05; Boyarsky+’06]
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
Challenges: X-ray sky is never “empty”
**Energy:** 3.5 keV. Statistical error for line position $\sim 30 \equiv 50$ eV.

**Lifetime:** $\sim 10^{27} \equiv 10^{28}$ sec

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**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 its existence in other objects
  Malyshev+; Anderson+; Tamura+; Sekiya+
- argued astrophysical origin of the line
  Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+

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*)
Dark matter is universal... but uncertain

- The line is few percents of background
- Challenging to rule out all **systematics** at this level
- But! Dark matter hypothesis means that signal should be present in all galaxies and clusters
- ... and scale accordingly
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”
As usual two independent groups got the idea:

- **The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations** C. Dessert, N. Rodd, B. Safdi
  [1812.06976]
  Submitted on 17 Dec 2018

- **Surface brightness profile of the 3.5 keV line in the Milky Way halo** A. Boyarsky, D. Iakubovskyi, O. Ruchayskiy, D. Savchenko
  Submitted [1812.10488]
  Submitted on 26 Dec 2018
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 $5^\circ \equiv 45^\circ$.

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 $\sim 10$. 
• 49 Msec of quiescent Milky Way regions (10' to 45°)
• The data split into 6 radial bin
• Line is detected in 4 bins with > 3σ and in 2 bins with > 2σ significance
• Good background model in the interval 2.8 ≡ 6 keV plus 10 ≡ 11 keV
Dark matter profile of the line
Boyarsky, Ruchayskiy, et al. [1812.10488] + update

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

Stacked residuals of 6 regions

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

Stacked residuals assuming NFW profile

<table>
<thead>
<tr>
<th>Profile</th>
<th>Significance</th>
<th>Line position [keV]</th>
<th>Decay width $\Gamma$ [$10^{-28}$ sec$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFW [19]</td>
<td>$7 \sigma$</td>
<td>$3.494^{+0.002}_{-0.010}$</td>
<td>$0.39 \pm 0.04$</td>
</tr>
<tr>
<td>Burkert</td>
<td>$6.4 \sigma$</td>
<td>$3.494^{+0.003}_{-0.014}$</td>
<td>$0.57^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>Einasto</td>
<td>$6.9 \sigma$</td>
<td>$3.494^{+0.009}_{-0.008}$</td>
<td>$0.40^{+0.04}_{-0.06}$</td>
</tr>
</tbody>
</table>

Angular distance from Galactic Centre [deg]

Line flux [ph/cm$^2$/s/sr]

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, $\Gamma$. 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
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
- Not including them into the model *artificially raises the continuum* ⇒ reduce any line

Blue data points: lines with $\geq 3\sigma$ significance
Magenta data points: lines with $\geq 3\sigma$ significance (4$\sigma$ 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
Future: X-ray spectrometers

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

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 $2\sigma$ 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.
Sterile neutrinos are born relativistic in the early Universe.
While they cool down with expansion – they homogenize primordial density perturbations.
This translates into the small-scale lack of power that can be observed in the correlation of the Lyman-α absorption lines.

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

Blue: CDM, Orange: 7 keV sterile neutrino
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)

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

1. Baryogenesis with HNLs
2. Lyman-\(\alpha\) forest and sterile neutrino dark matter
3. 3.5 keV line
4. SHiP and other Intensity Frontier experiments
5. SHiP experiment
6. The end
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 $B \equiv L$)

Wide class of scenarios known as leptogenesis

Thermal leptogenesis: $M_N \sim 10^9 \equiv \equiv 10^{12}$ GeV

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

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

- 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

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 $T \sim \mathcal{O}(10)\text{GeV}$, reaching levels $\gg \eta_{\text{baryon}}$
Comparison between works

From Eijima, Shaposhnikov, Timiryasov [1808.10833]
Outline

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Lyman-\(\alpha\) forest and power spectrum
Lyman-\(\alpha\) forest data

Viel+’13

Warm dark matter predicts suppression (cut-off) in the flux power spectrum derived from the Lyman-\(\alpha\) forest data
Suppression in the flux power spectrum

No suppression of flux power spectrum in SDSS/BOSS datasets ⇒ only lower bound on WDM mass have been put \(Seljak+’06;Viell+’06;Boyarsky+’08\)
Suppression in the flux power spectrum

The suppression of the flux power spectrum is visible in high-resolution HIRES/MIKE dataset.

In Lyman-α spectra higher spectral resolution means smaller scales.

BOSS Ly-α [1512.01981]
Warm dark matter or warm hydrogen?
Garzilli, Boyarsky, Ruchayskiy [1510.07006]

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?
Warm dark matter or warm intergalactic medium?
Garzilli et al. (2015, 2018)

- HIRES flux power spectrum exhibits suppression at small scales
- This suppression can be explained equally well by thermal history of the Universe (unconstrained at these redshifts) or by warm dark matter
What is known about the IGM thermal history?

Current measurements of IGM temperature

- There are many measurements at $z < 5$
- There is a single measurement above $z = 6$
- History of reionization at higher redshifts is poorly constrained
What is known about the IGM thermal history?

Current measurements of IGM temperature

- We need to know **when** the Universe was reionized
- We need to know **to what temperature** the gas was heated

- History of reionization at higher redshifts is poorly constrained
Warm dark matter may have been discovered
Garzilli 2015, 2018, 2019 with O.R. and A. Boyarsky

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

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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.

See also discussions in Roach+ [1908.09037], Perez+ [1609.00667]
Line in Chandra
Cappelluti+’17 [1701.07932]

- 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]

![Perseus center spectrum graph]

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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, Chlorium, 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)
- ???
Outline

1. Baryogenesis with HNLs
2. Lyman-$\alpha$ forest and sterile neutrino dark matter
3. 3.5 keV line
4. SHiP and other Intensity Frontier experiments
5. SHiP experiment
6. The end
What we are discussing today


- FASER: ATLAS
- MATHUSLA: CMS or ATLAS
- Codex-b: LHCb
- SHiP: SPS
- NA62++: SPS
- ... (actually, many more)
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Super Proton Synchrotron (SPS)

- High energy proton beam – 400 GeV
- $4 \times 10^{19}$ PoT (protons on target per year).
  $2 \times 10^{20}$ PoT over 5 years
- Beam intensity: $4 \times 10^{13}$ protons/sec
- Produces a lot of $c$-quarks: $X_{c\bar{c}} \sim 10^{3}$
SHiP (Search for Hidden Particles) experiment

Step by step overview
SHiP (Search for Hidden Particles) experiment

Step by step overview
SHiP (Search for Hidden Particles) experiment

Step by step overview

\[ D_s \rightarrow \mu \nu \mu \nabla \mu \rightarrow N \nu \mu \pi^\pm \]

Target/hadron absorber
Active muon shield

Hidden Sector decay volume
Spectrometer
Particle ID

Oleg Ruchayskiy (NBI)
SHiP (Search for Hidden Particles) experiment

Step by step overview
SHiP (Search for Hidden Particles) experiment

Step by step overview
Challenges

- **Background** – many intensity frontier experiments are background free. Many but not all and knowing the background is crucial.

- **PID** – can you identify particles that were produced? Are they only “charged particles”, “hadrons” or something more specific.

- **Mass reconstruction** – if you have a signal, what was the mass particle that decayed? If you have $N$ signal candidate events - do they all reconstruct to the same mass?
All major predictions of the Standard Model have been spectacularly confirmed.

Yet, there are “beyond-the-Standard-model” puzzles of observational nature that lack their explanation.

Particles that are responsible for it are either too heavy (beyond the LHC reach) or too feebly interacting.

There are no theoretical predictions and therefore we need to explore all possible options.

Feebly Interacting Particles can be searched during next LHC runs (or alongside LHC) – results within next decade.
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