Heavy Neutral Leptons at the GeV scale

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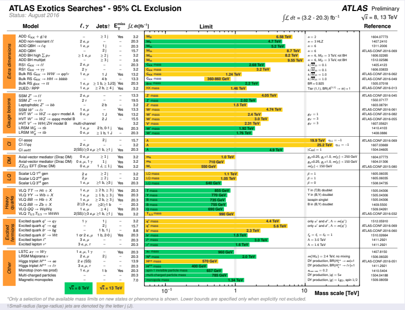
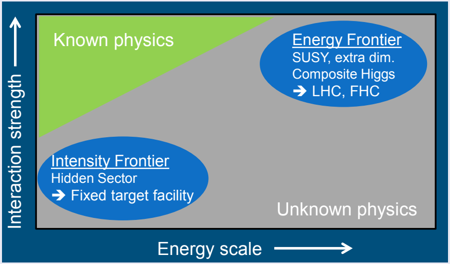
Long-lived particles at Belle II
FSP Workshop
December 11, 2020

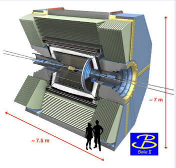
We know that new particles exist

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe



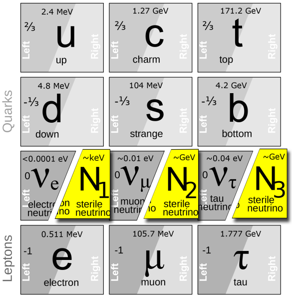
We dont know what they are

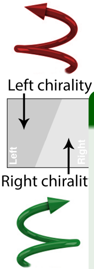


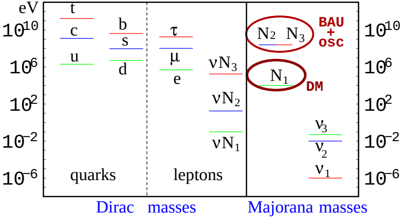


Why heavy neutral leptons

Heavy neutral lepton = HNL = sterile neutrino = heavy Majorana neutrino







HNL can explain ...

- ... **neutrino oscillations**

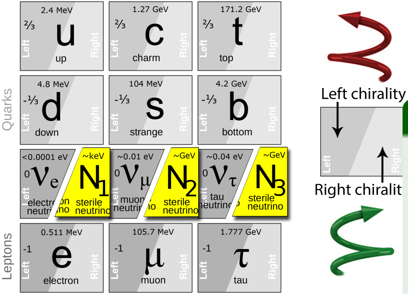
  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

- ... **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 –



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HNL can explain all of it

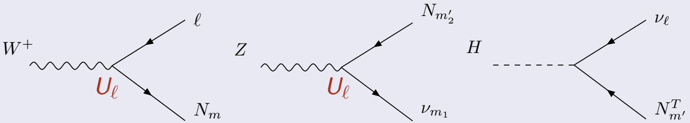
- Neutrino Minimal Standard Model (νMSM)

  Asaka & Shaposhnikov'05 + ...hundreds of subsequent works

- Masses of HNL are of the order of masses of other leptons
- Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

HNL interactions

Neutrino-like interactions



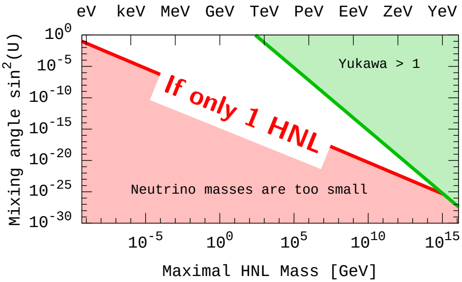
From [0901.3589]

- Naive seesaw formula

$$U^2 \sim \frac{m_{\text{atm}}}{M} \sim 10^{-11}\,\frac{10\,\text{GeV}}{M}$$

- All neutrino experiments would allow to determine

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



HNL interactions

Bottom line

- Several HNLs (as neutrino oscillations or BAU suggest) $\Rightarrow$ U_α^2 can be **orders of magnitude larger**, enabling efficient searches
- Seesaw formula determines a **bottom line** for searches
- Several degenerate in mass HNLs will cancel Lepton Number Violating (LNV) effects – care should be taken when interpreting the results of LNV searches

Shaposhnikov'06; Karsten & Smirnov'07

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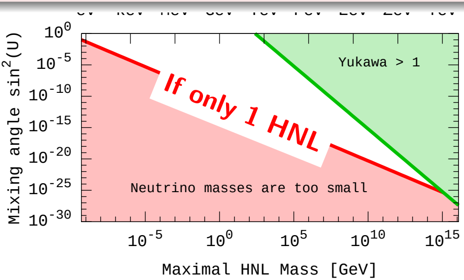
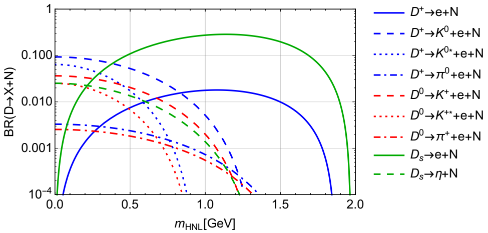
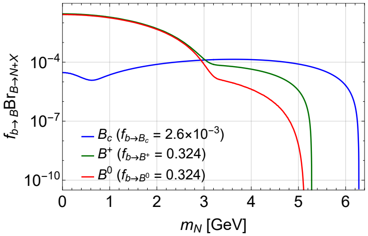


HNL production from mesons

- HNLs are produced from W/Z/Higgs bosons, (semi)leptonic decay of heavy flavoured mesons or τ
- For beam dump experiments the main production channels are production from kaons, D and B mesons (NA62, DUNE, SHiP)
- LHC-based experiment have main sensitivity from the decays of B mesons (FASER, LHCb, MATHUSLA, etc.) as well as Belle II



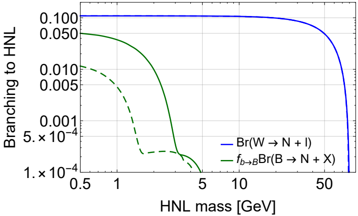
Bondarenko+ [1805.08567]

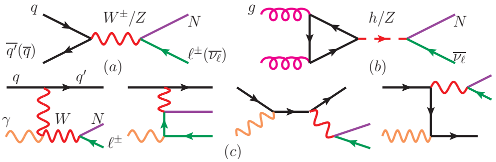


HNL production from W, ...

- Production from W is the main channel for ATLAS and CMS for displaced vertex signature
- For $M_N > M_Z$ prompt production and resonance search at LHC

Degrande+ [1602.06957]

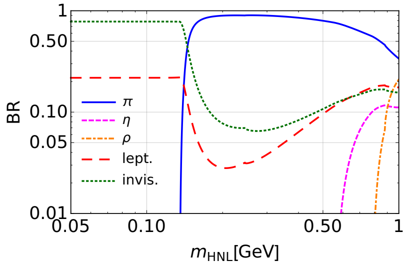


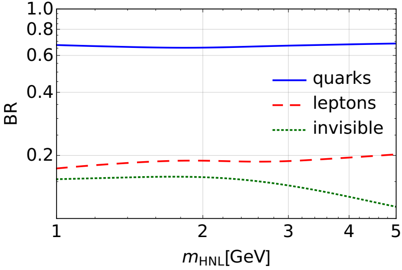


HNL decay

Bondarenko+ [1805.08567]

- Leptonic HNL decays $N \to \ell^+ \ell^- \nu$ – always with MET
- Semi-leptonic HNL decays: $N \to \ell^+ + \text{hadrons}$ or $N \to \nu + \text{hadrons}$





Detailed list can be found in [1805.08567]

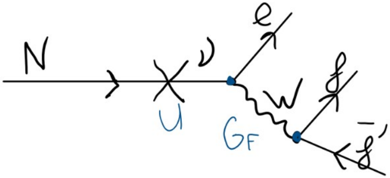
Channel	Open, MeV	Rel. from, MeV	Rel. to, MeV	Max BR, %	Formula
$N \to \nu_\alpha e^+ e^-$	1.02	1.29	—	21.8	(3.4)
$N \to \nu_\alpha \pi^0$	135	136	3630	57.3	(3.7)
$N \to e^- \pi^+$	140	141	3000	33.5	(3.6)
$N \to \mu^- \pi^+$	245	246	3000	19.7	(3.6)

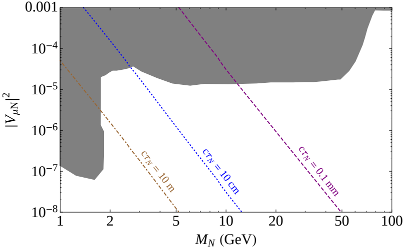
- HNLs decay through weak interaction, so its decay width is suppressed

$$\Gamma_N \sim U^2 G_F^2 m_N^5 \sim U^2 m_N \left(\frac{m_N}{m_W}\right)^4$$

- HNLs can travel quite far before decaying

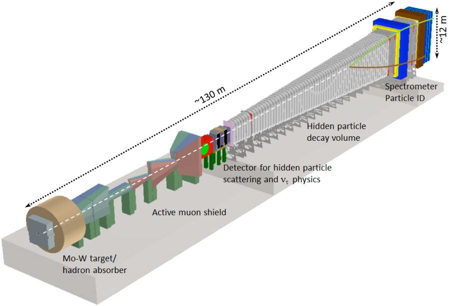
$$c\tau\bar{\gamma} \simeq 3.7\,\mathrm{m}\bar{\gamma}\left(\frac{\mathrm{GeV}}{M}\right)^5\left(\frac{10^{-4}}{U^2}\right)$$

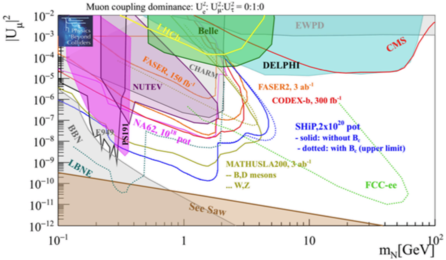




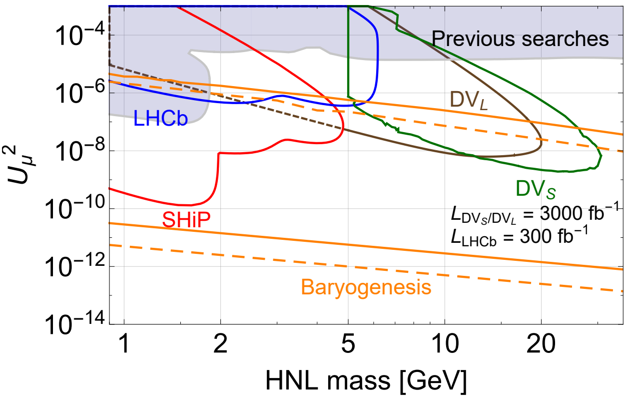
Long lived HNLs at beam dump/LHC based experiments

- Particles that travel long distance can be searched at at beam dump/LHC based experiments
- A lot of proposals, very active community, support from CERN
- One of the best sensitivities are expected from **SHiP** and **MATHUSLA**, but you should be cautious with what sensitivity means





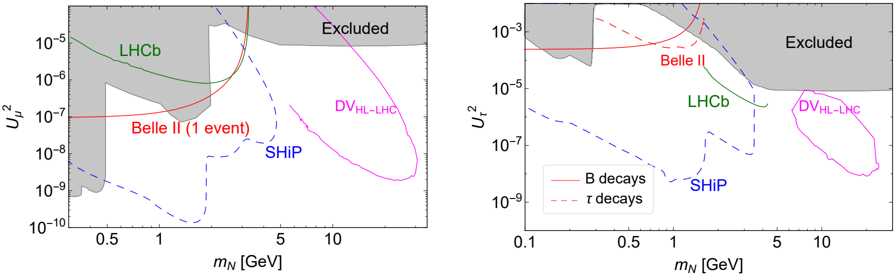
Displaced vertex searches



[1902.04535]

- Displacement btw. few mm and few meters
- Mass of HNLs above $\mathcal{O}(5)$ GeV to kill combinatorial background
- Two or more charged tracks
- Low SM background

HNL search at Belle II

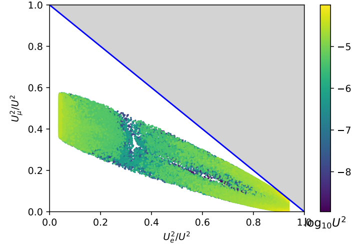


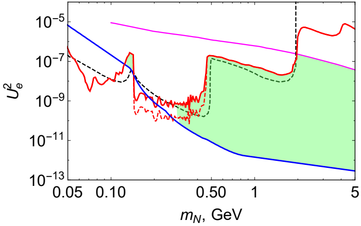
- Belle II can search for HNLs using decays $B \to D\ell N$ **[1908.00376]** and decays of τ leptons **[1908.09719]**. Its sensitivity turns out to be similar to HL LHCb
- Because of large luminocity and possibility to detect event near interaction point, Belle II and LHCb are **complementary** to displace vertex search at ATLAS/CMS and future beam dump/LHC based experiments
- Maximal probed mass could be extended up to 5 GeV if it is possible to use $B^\pm \to \ell^\pm N$ or $B^0 \to \pi^\pm \ell^\mp N$ channels

If HNL has been detected – what can we say?

Imagine that we found HNL with the mass M and the mixings U_α^2

- Contribution of 1 HNL to **neutrino masses $\delta m \sim MU^2$** $\Rightarrow$ at least 2 HNLs exist, their contributions to ν masses cancel each other
- If U^2 in the allowed **BAU** region for 2 HNLs $\Rightarrow$ another HNL exists with the mass degeneracy $\Delta M/M \lesssim m_{atm}$
- For BAU with 3 HNLs $\Rightarrow$ U^2 anywhere below current limits
- Oscillation data forbid some mixing patterns for 2 HNLs
- Combining oscillation data, searches at accelerators, and cosmological bounds leaves limited parameter space of the 2 HNL model, making it **fully testable**





HNL dark matter

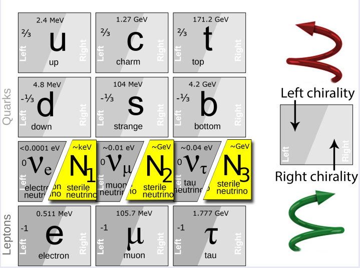
Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy "*Sterile neutrino dark matter*" [1807.07938]

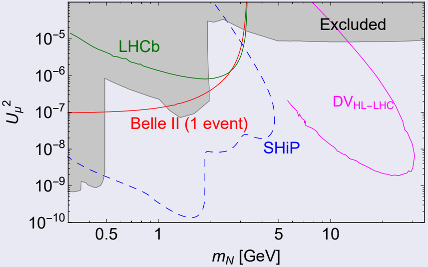
- HNL can be a viable dark matter candidate, if one adds one more HNL
- Such DM is *light* (probably $\mathcal{O}(keV)$), warm(ish) and decaying
- DM HNL contributes **negligibly** to neutrino masses

(Boyarsky+ [hep-ph/0601098])

- To explain neutrino masses **and** dark matter you need **at least 3 HNLs**
- There are several *hints* of DM detection consistent with keV-scale HNL dark matter (3.5 keV line & Lyman-α forest)
- Future data can:
  - Confirm or rule out 3.5 keV line as a tentative DM decay signal
  - Directly probe via gravitational lensing for the presence of dark substructures thus ruling out either **cold** or **warm** dark matter
  - Probe the history of reionization and therefore disentangle warm dark matter and thermal effects in Lyman-α data

Conclusions





- HNLs naturally come as mechanism of neutrino oscillations
- Turns out that the same HNLs can resolve major BSM problems
- Searches at LHC and Intensity Frontier experiments (SHiP, FASER, ...) and Belle II are complimentary to each other
- νMSM shares all the success of the SM while at the same time is a successful cosmological model

...and small parameters become new slightly broken symmetries **Boyarsky [0901.0011]**

Backup slides

$\Delta L = 2$ and accidental suppression of LNV effects

- Processes with $|\Delta L| = 2$ are one of the search targets to-date (due to suppressed Standard Model background)
- However, Majorana mass of HNL does not necessarily mean large LNV effects!
- Often smallness of active neutrino masses is tied to the smallness of lepton number violation (**See e.g. Shaposhnikov (2006); Kersten & Smirnov [0705.3221]**)

Idea:

- Introduce 2 Majorana HNLs N_1 and N_2 with **same mass** per flavour
- Together they form a Dirac particle $\Psi = N_1 + N_2^c$ with the usual Dirac mass $\boldsymbol{M\bar{\Psi}\Psi}$
- Neutrino ν couples to N_1 only $\Rightarrow$ this gives one massive state (combination of ν and N_2^c with the mass $\boldsymbol{M}$) and one orthogonal massless state
- Introduce a small mass-difference ΔM_{12} – the massless state will pick up mass with $m_\nu \propto \Delta M_{12}$

HNLs beyond νMSM

HNL varieties

- Type-III seesaw [Foot et al. Z. Phys. C44 (1989)]
- Inverse seesaw (Mohapatra PRL 56 (1986); Mohapatra & Valle PRD34 (1986))
- Radiative seesaw [Pilaftsis Z. Phys. C55 (1992)]

Interactions with new gauge bosons/scalars

- Left-right symmetric models [Pati & Salam (1974); Mohapatra & Pati (1975); Mohapatra & Senjanovic (1981)]
- HNLs will carry charge w.r.t. $U(1)_{B-L}$ – can be produced via off-shell $B-L$ boson (couples to protons) See e.g. Mohapatra & Marshak (1980); del Aguila & Aguilar-Saavedra [0705.4117]; Huitu et al. [0803.2799]; Batell et al. [1604.06099]
- Majorana mass of HNL can be generated via coupling with a new singlet scalar S (Shaposhnikov & Tkachev (2006); Shoemaker et al. (2010))

$$\boldsymbol{M}\bar{N}^c N \to f_N S \bar{N}^c N$$

where S develops vev

It is possible that sterile neutrino DM
was
already discovered **twice**!

An unidentified spectral line at ~ 3.5 keV I

Boyarsky+ (PRL 2014); Bulbul+ (ApJ 2014); Review "Sterile Neutrino Dark Matter " [1807.07938]

Many detections

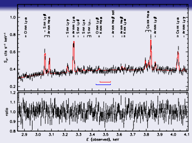
Milky way & Andromeda galaxies, Perseus cluster, Draco dSph, distant clusters. COSMOS & Chandra deep fields

Systematics?

Detection with 4 different telescopes: XMM MOS and PN cameras, Chandra, Suzaku, NuStar

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; Shah+ 2016)

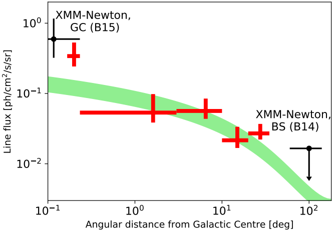


Recent result: Surface brightness profile in the Galaxy

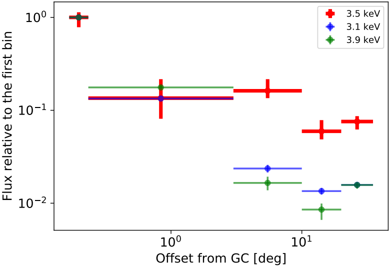
Recent result: Boyarsky, Ruchayskiy et al. [1812.10488]

Surface brightness profile in the Galaxy

- Detected with high significance in 5 spatial bins off Galactic Center
- Consistent with DM interpretation
- Profile different from nearby astronomical lines



Intensity profile consistent with DM density profile



Different from astrophysical lines

Future: X-ray spectrometers I

- 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

With X-ray spectrometer one can

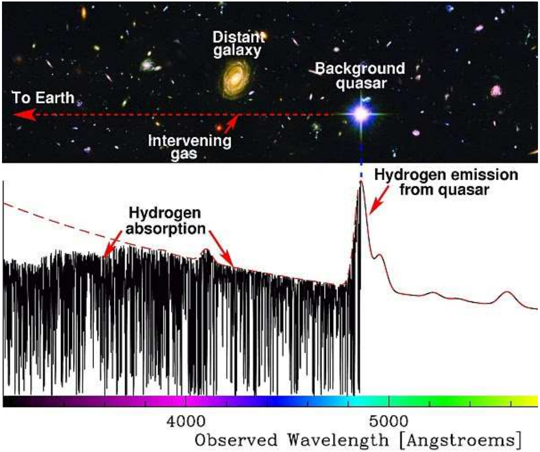
- Check the width of the line (for Perseus cluster the difference in line broadening between atomic lines ($v \sim 180$ km/sec) and DM line ($v \sim 1000$ km/sec) is visible)
- See the structure (doublets/triplets) of lines (if atomic)
- Check exact position of the line (Redshift of the line is Perseus 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.

Future: X-ray spectrometers II

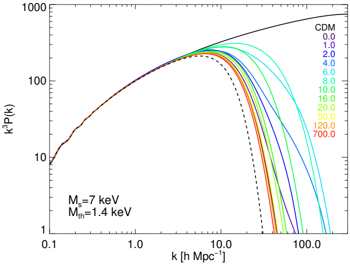
Athena+ (2028)

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

Lyman-α forest



- Neutral hydrogen absorption line at $\lambda = 1215.67\mathring{A}$ (Ly-α absorption $1s \to 2p$)
- Absorption occurs at $\lambda = 1215.67\mathring{A}$ in the **local reference frame** of hydrogen cloud
- Observer sees the **forest**: $\lambda = (1+z)1215.67\mathring{A}$



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