Heavy Neutral Lepton searches in Cosmic Ray Beam Dump experiments

Baibhab Pattnaik (IFIC, University of Valencia/CSIC)

-based on “Testing Heavy Neutral Leptons in Cosmic Ray Beam Dump experiments”
O. Fischer, BP, J. Zurita 📕 (arXiv: 2301.07120)

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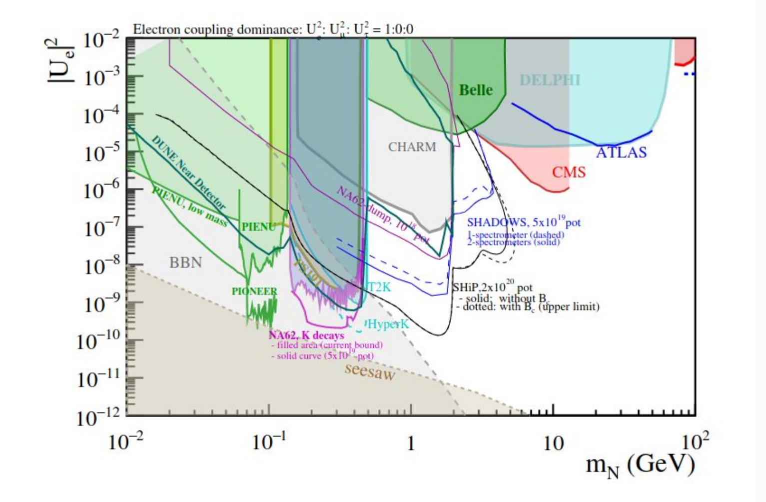
Contents

- Motivation
- HNL model, production and decay
- Signal, background and event count
- SHALON Anomaly (and Mt Thor)
- ANITA Anomaly (and SPYGLASS)
- Conclusions

Motivation

Heavy Neutral leptons

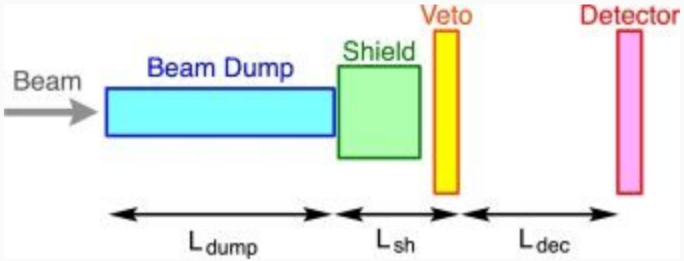
- HNLs are an attractive solution to open problems in neutrino physics
- They can explain observed neutrino oscillation data (masses and mixings)



Abdullahi et al (2203.08039)

Beam dump experiments are well-studied probes of sub GeV HNLs

Eg- MiniBOONE



Replace:
Beam → Cosmic Rays
Beam dump → Atmosphere
Shield+veto → Earth

HNL model, production and decay

Model

We consider a minimal SM extension with one HNL (Minkowski, Phys Lett B 67 (1977)):

$$\mathscr{L} = \mathscr{L}_{SM} + i\overline{N_R}\gamma^\mu \partial_\mu N_R - Y_\alpha \overline{L}_\alpha \tilde{\Phi} N_R - M\overline{N_R^c} N_R + \text{ h. c.}$$

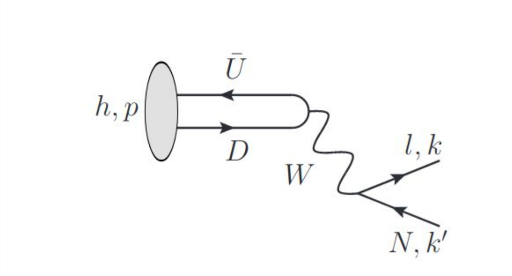
The interactions of the HNL with the three light neutrinos are governed by $U_\alpha \equiv U_{\alpha 4}$, the three mixing parameters to the leptonic generations $(\alpha = e, \mu, \tau)$

HNL production in the atmosphere

Cosmic ray (CR) primaries interact with atmospheric nuclei, resulting in extensive air showers.

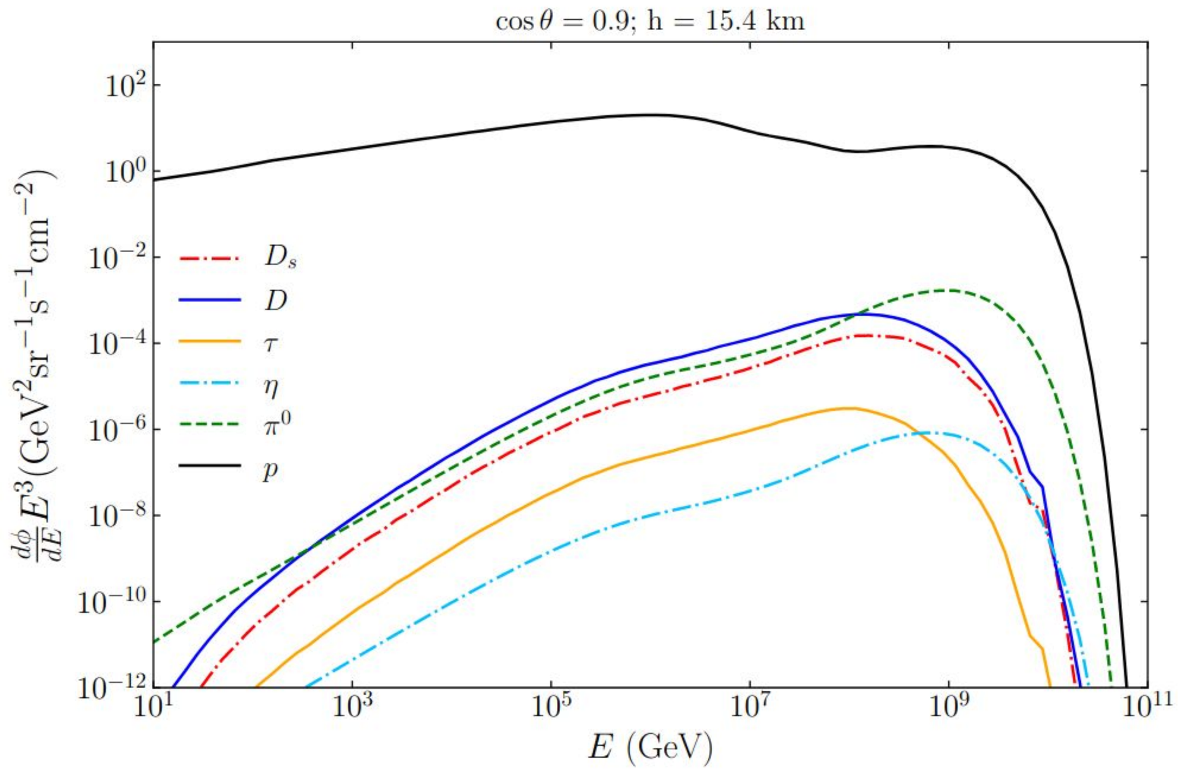
Focus on charged meson as our source of HNLs.

The decay of charged mesons into HNLs are implemented using MCEq (Matrix Cascade Equation). Total HNL flux is the sum of contributions from all mesonic decay channels:



Bondarenko et al: 1805.08567

$$\Phi_N = \sum_{m_i = \pi, K, D, D_s} \Phi_{m_i \to N}$$



Parent meson fluxes in the atmosphere at a height of 15.4 km (Arguelles et al (1910.12839))

HNL production in the atmosphere (contd.)

The production of HNLs from charged mesons is mediated by weak interactions, with a branching ratio given by:

$$\mathrm{Br}(m^{\pm} \to \ell_{\alpha}^{\pm} N) = \mathrm{Br}(m^{\pm} \to \ell_{\alpha}^{\pm} \nu)\, |U_{\alpha}|^2 \frac{\left(x_N^2 + x_\alpha^2 - (x_N^2 - x_\alpha^2)^2\right)}{x_\alpha^2 (1 - x_\alpha^2)^2} \sqrt{\lambda(1, x_\alpha, x_N)}\,,$$

Here $\lambda(1, x_\alpha, x_N) = (1 - (x_N + x_\alpha)^2)(1 - (x_N - x_\alpha)^2)$ and $x_i = m_i / m_m$

We plug the above into MCEq. The obtained output, $\Phi_{m_i \to N}$ thus includes the full kinematic and phase space information for the HNL

HNL decay

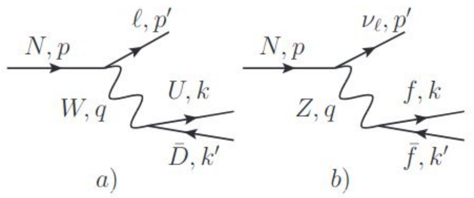
Decays, also, are mediated by weak interactions.

The partial decay widths depend non-trivially on mixing matrix elements. They can be separated into three classes: $|U_e|^2\Gamma_e,\ |U_\mu|^2\Gamma_\mu,\ |U_\tau|^2\Gamma_\tau$

Particle lifetime, for any given mixing:

$$\tau = \left(\sum_{\alpha=e,\mu,\tau} \frac{|U_\alpha|^2}{\tau_\alpha} \right)^{-1}$$

where $\tau_\alpha = \hbar/\Gamma_\alpha$ is the lifetime for pure mixings, i.e. $|U_\alpha|^2 = 1$



Bondarenko et al: 1805.08567

HNL decay (contd.)

This sets the laboratory decay length $\lambda = c\tau\beta\gamma \approx c\tau \frac{E}{m_N}$

Fold MCEq output with decay probability

$$P_{decay}(d, l, \lambda) = e^{-\frac{d}{\lambda}}\left(1 - e^{-\frac{l}{\lambda}}\right)$$

d, l are the distance to the detector and the detector length respectively

Signal, event count and background

Signal

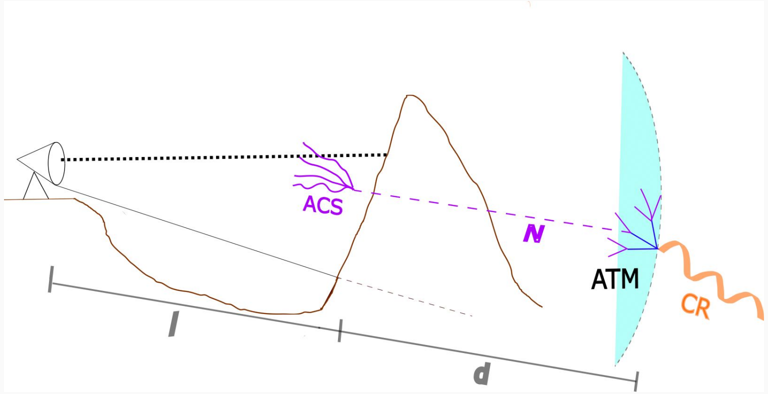
The HNLs emerge from the shield and decay into highly boosted SM charged particles, producing Cherenkov radiation (aka ACS (Appearing Cherenkov Showers))

Differential rate of ACS:

$$\frac{d^3R}{dEdtd\Omega} = \mathrm{Br}(N \rightarrow \mathrm{vis})\ \Phi_N A\, P_{decay}(d, l, \lambda)$$

Integrating over the energy range, runtime

and solid angle gives us the total count



Schematic diagram

Detector specifications

	d [km]	l [km]	A [cm^2]	solid angle [sr]	T [s]	E_1 [GeV]
SHALON	1520	7	7×10^9	0.001	1166400	800
SHALON 10	1520	7	7×10^9	0.001	3.15×10^7	10
ANITA	7000	37	4×10^{12}	2π	5011200	10^8
MtThor	3163.26	5.4	10^{10}	0.024	3.15×10^8	10
SPYGLASS X	12800	35786	10^{16}	8×10^{-4}	3.15×10^7	X=10, 100, 1000

Table 1: Detector specifications: original SHALON and ANITA designs, and the three modifications: a) a SHALON-like experiment with a 10 GeV energy threshold (dubbed SHALON-10), b) an improved SHALON experiment taking as a reference Mt Thor, in Baffin Island, Canada (MtThor) and c) an improved ``Anita'' setup, which we call SPYGLASS

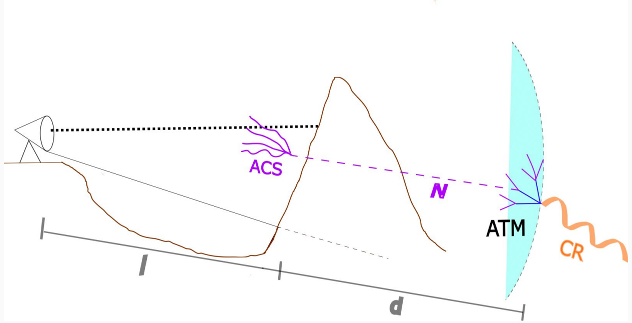
Backgrounds

- Most SM particles produced in CR induced showers have short lifetimes and interaction lengths, decaying well before they reach Earth's surface
- Muons and neutrinos are the most probable background candidates: removed by Earth shield and neutrino flux limits respectively
- Another possible source of background is artificial radiation. e.g.- nuclear reactors and particle accelerators.
- Not relevant for our study: typical energies are well below our energy threshold, and knowing their location, we can point our detector elsewhere

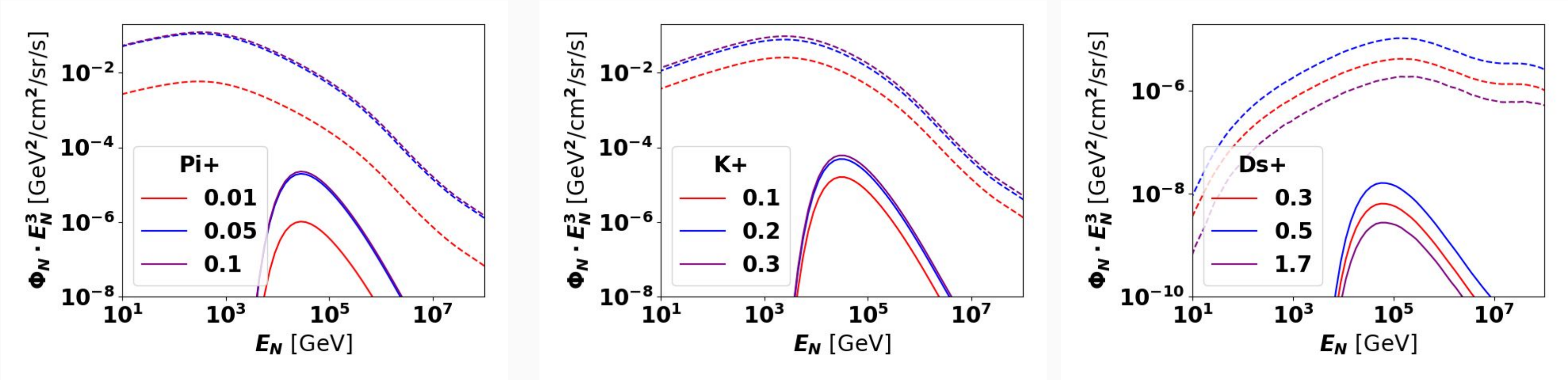
The SHALON Anomaly

SHALON: Experiment and anomaly

- Atmospheric Cherenkov telescope
- Operational energy range: 0.8-100 TeV
- 5 anomalous showers around 10 TeV, no SM explanation: HNLs? (Sinitsyna et al, EPJ Web Conf. 52 (2013) 09010.)
- Background free : neutrino flux limits



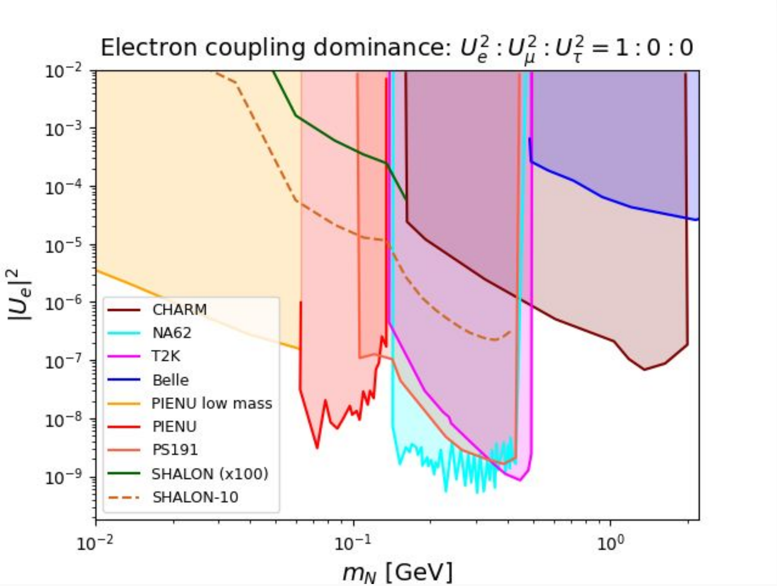
SHALON event rate evaluated with the same methodology as before

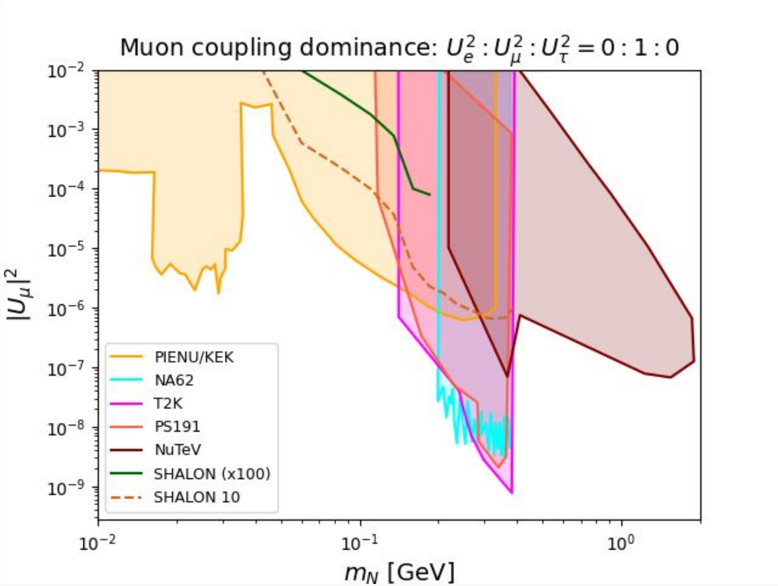


Contributions to the atmospherically produced HNL fluxes from pion (left panel), kaon (middle panel) and Ds meson (right panel) for pure mixing to electron flavour. Solid lines show the HNL spectrum in SHALON after folding with decay probability

- Require large mixings for SHALON to detect HNLs

Exclusion plots



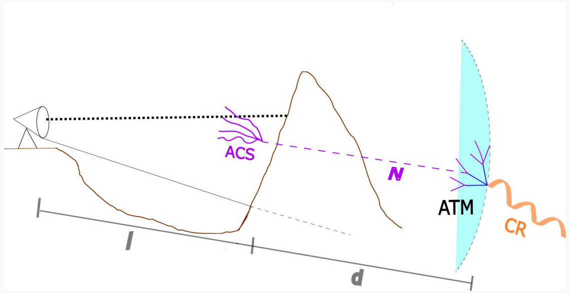


- SHALON is ruled out by existing experiments
- Reducing SHALON threshold to 10 GeV does not work either
- Can we tweak SHALON parameters to detect HNLs?

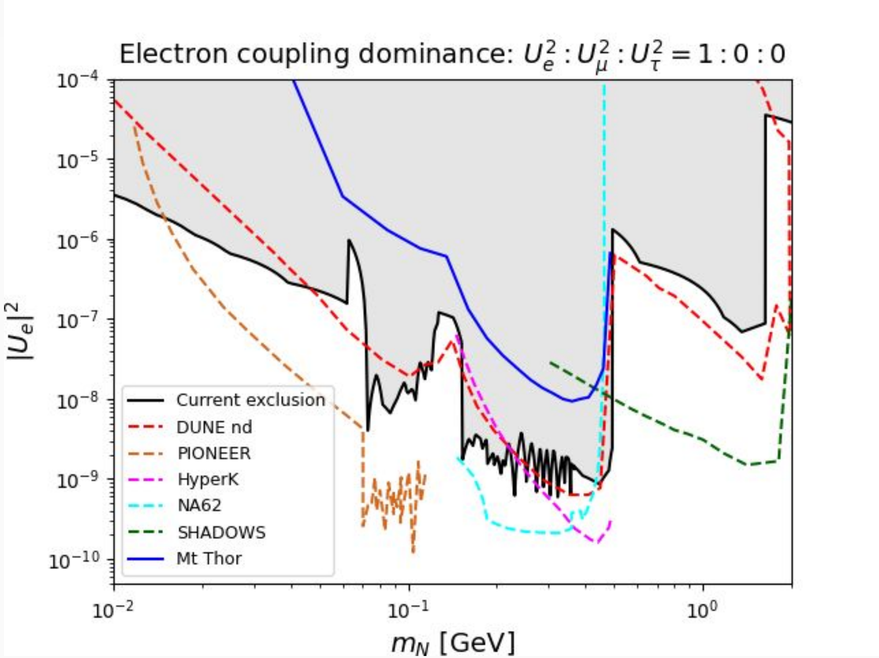
Mt Thor

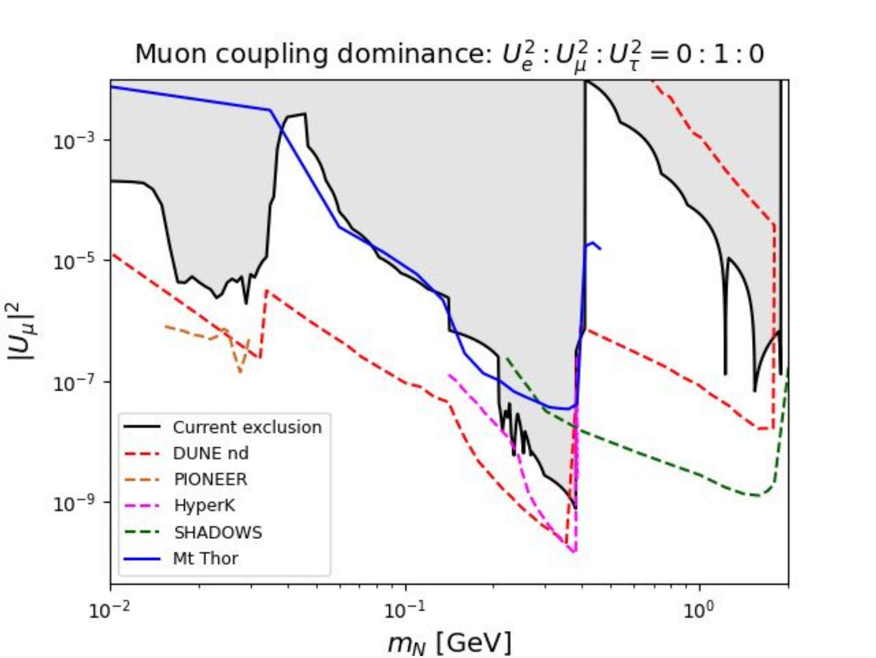
- SHALON-like experiment atop Mt Odin in Canada, pointing at Mt Thor
- Similar systematics to SHALON, with lower threshold
- The vertical drop of Mt Thor leads to increased decay area
- Energy threshold 10 GeV, runtime of 10 years

Above specifications can probe the region of parameter space shown on the next slide (95% C.L.)



Sensitivity limits



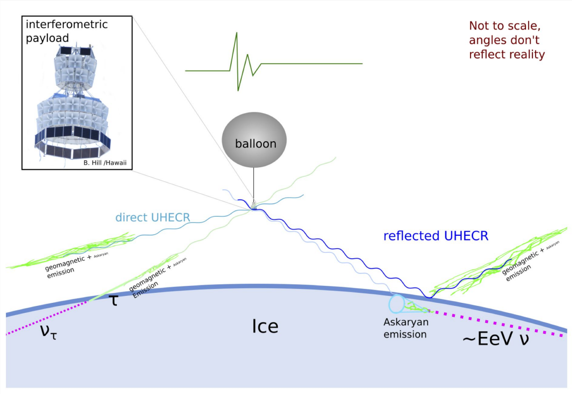


Mt Thor can detect HNLs purely coupled to muon flavour below kaon mass

ANITA Anomaly

ANITA experiment

- Balloon-borne experiment
- 37 km above earth
- Studies diffuse ultrahigh-energy (UHE) neutrino flux



ANITA detection concept (*Cosmin Deaconu*)

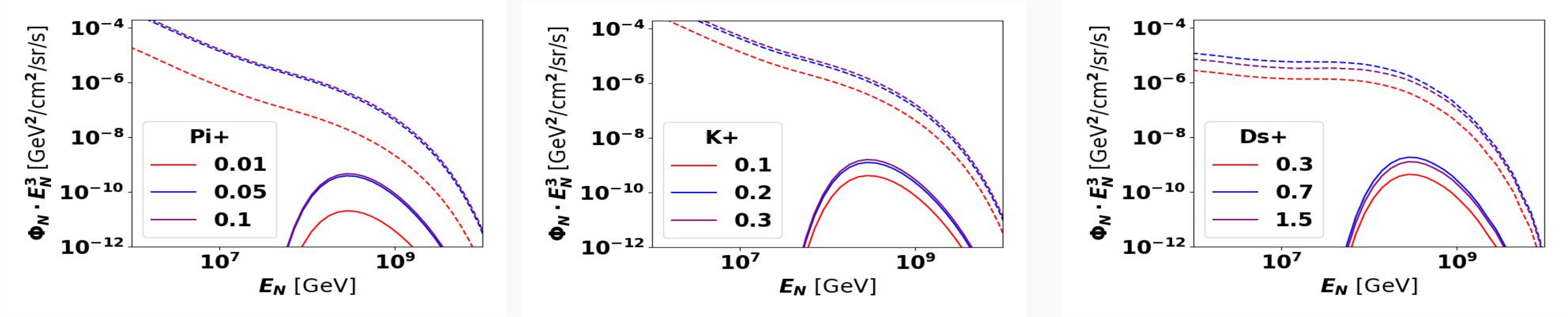
ANITA anomaly

- Two anomalous Earth-emergent UHE showers detected: no SM explanation (ANITA Collaboration, R. Prechelt et al., Phys. Rev. D 105 (2022))
- We explore the possibility of HNL decays as sources for these showers
- Use differential decay rate (from MCEq), fold it with decay probability :

$$\frac{d^3R}{dEdtd\Omega} = \mathrm{Br}(N \rightarrow \mathrm{vis})\ \Phi_N A\, P_{decay}(d, l, \lambda)$$

and integrate using ANITA detector parameters

Results

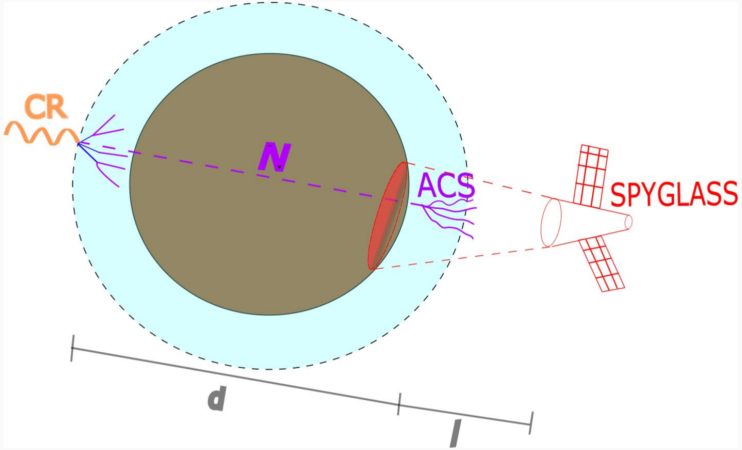


Contributions to the atmospherically produced HNL fluxes from pion (left panel), kaon (middle panel) and Ds meson (right panel) for pure mixing to electron flavour. Solid lines show the HNL spectrum in ANITA after folding with decay probability

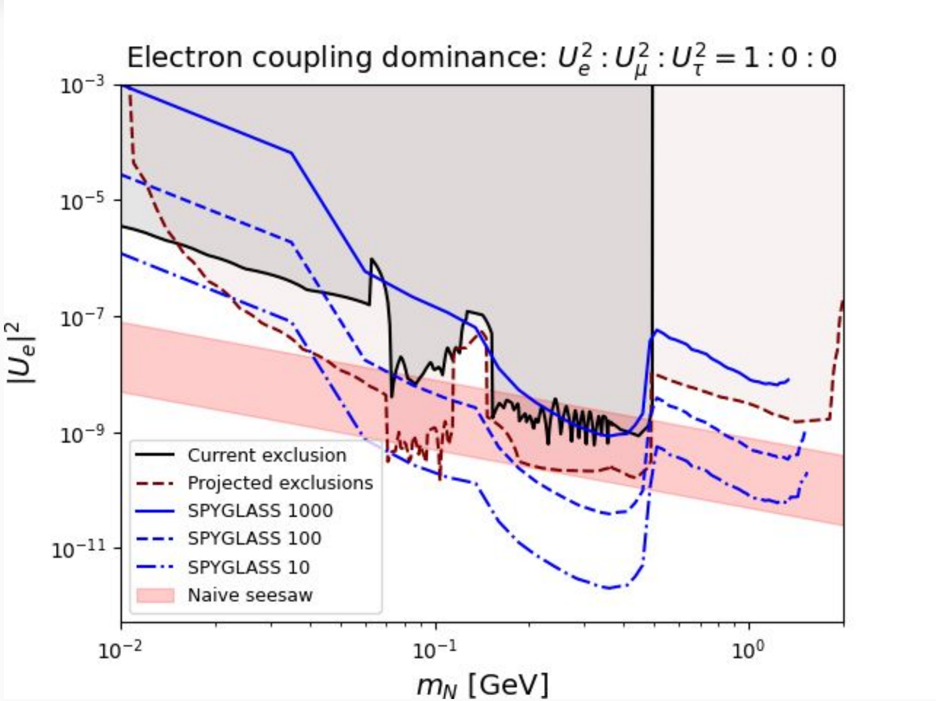
$$R_{\text{ANITA}} \ll 1$$

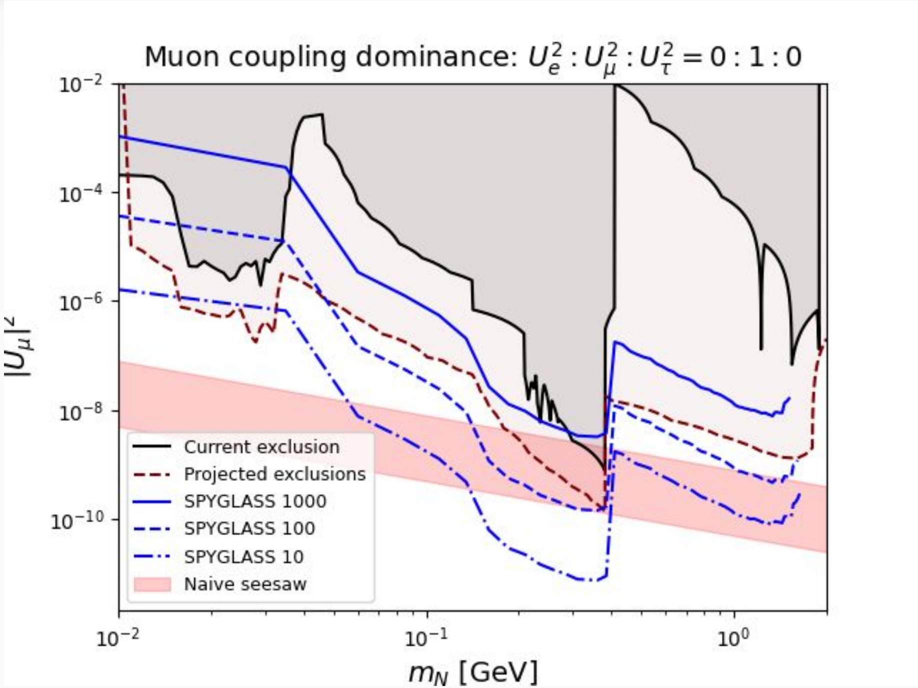
SPYGLASS (Satellite PreYing on Geo Long-lived Appearing ShowerS)

- ANITA-like geostationary satellite, 35786 km above earth surface
- Points at Sahara desert, to minimise possibility of background
- Observes charged particles from HNL decays: similar to other space-borne detectors (e.g. PAMELA)
- Cherenkov radiation can be used as a SM veto
- Runtime: 1 year

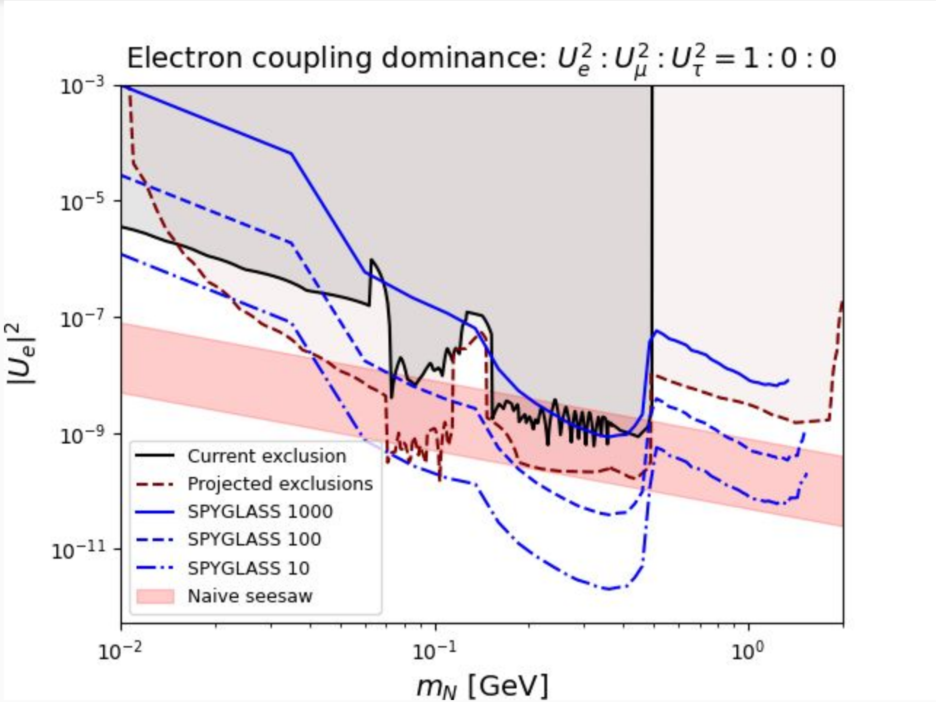


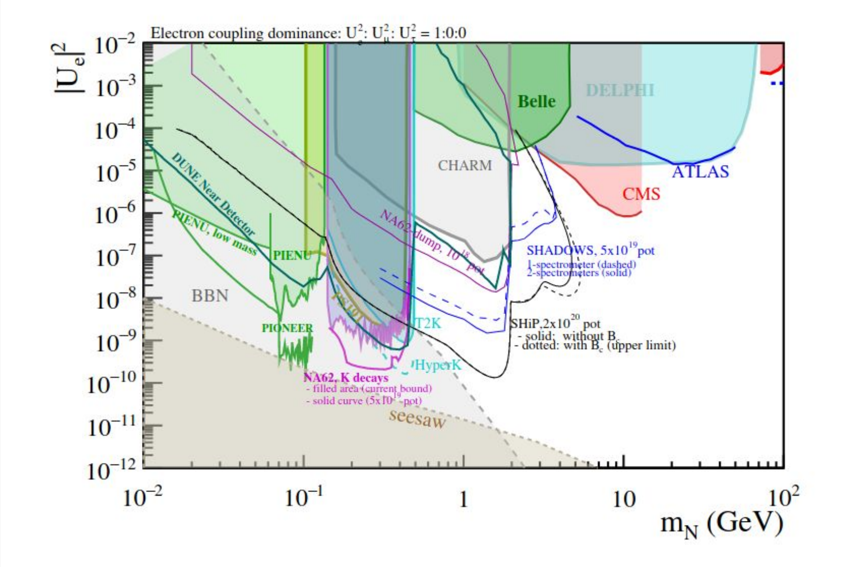
Sensitivity limits





SPYGLASS can probe a significant part of the HNL parameter space!





Abdullahi et al (2203.08039)

The parameter space probed by SPYGLASS is complementary to collider searches

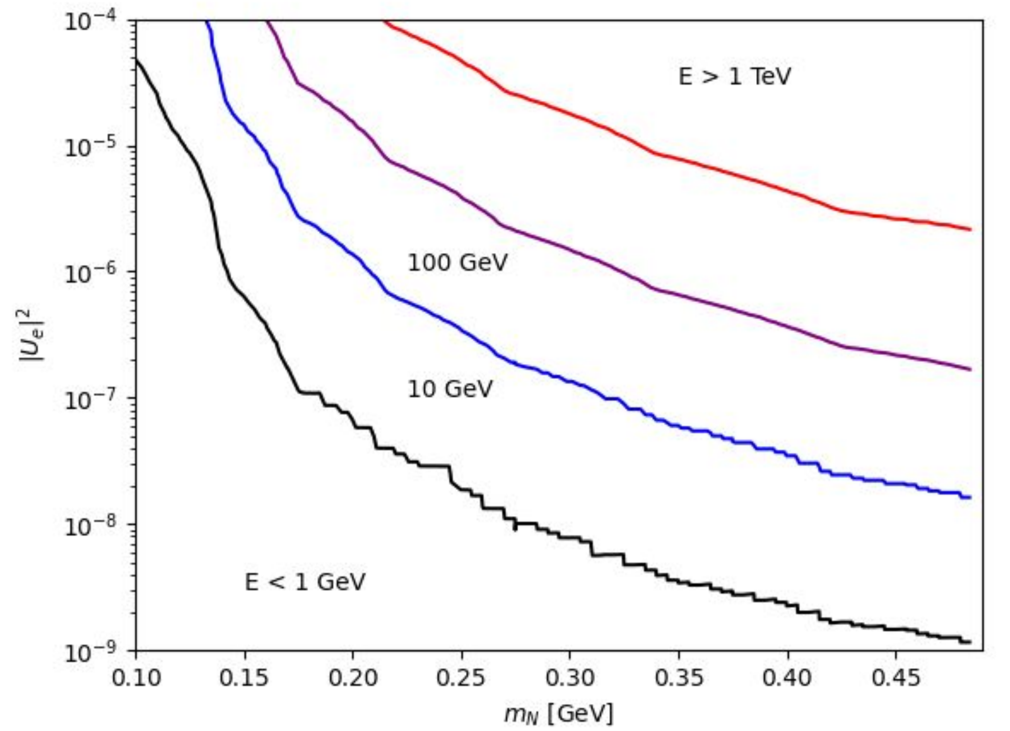
Conclusions

- HNLs can be tested in dedicated “cosmic-ray beam dump" experiments
- Effectively “background-free” scenarios
- Complementary to collider searches
- Mt Thor probes unexplored parameter space below K mass
- SPYGLASS: leading constraints in the 0.1 - 2 GeV mass range for electron coupling and in 10 MeV - 2 GeV mass range for the muon coupling dominated scenario.
- Future possibilities: determine SPYGLASS sensitivity to other light neutral LLPs

Thank you!

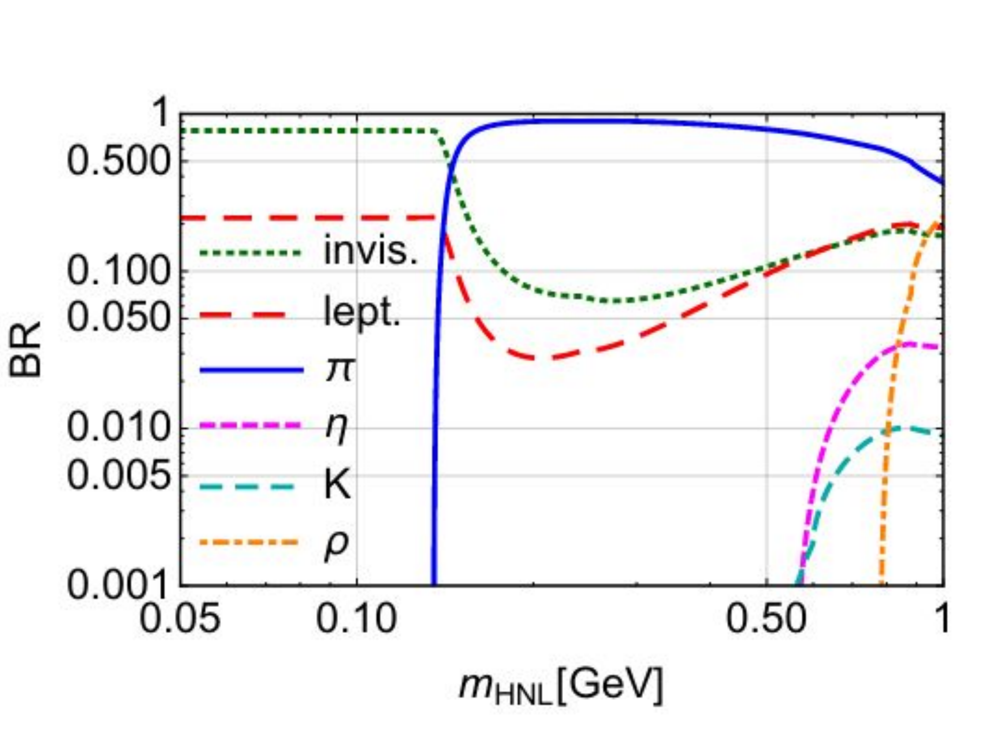
Backup slides

Average energy contours

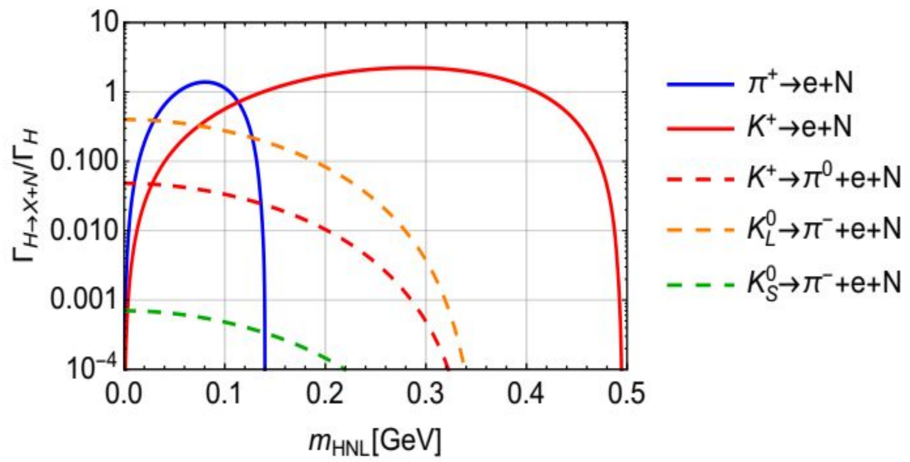


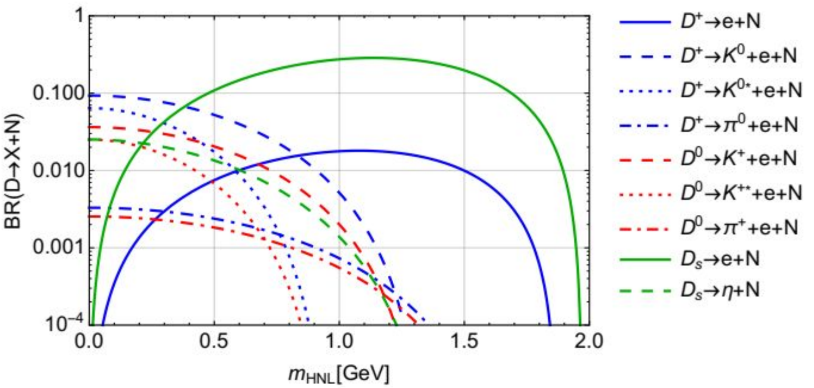
Small mixings favour lower energies

N -> visible branching ratios



Meson branching ratios





Pseudoscalar parent meson branching ratios