MeV-scale Sterile Neutrinos at Short Baseline Experiments

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Neutrinos: the quest for a new physics scale, CERN
27 March 2017

A theory in search of a scale

Where to find a sterile neutrino and what to expect if we find one

A minimal Type I Lagrangian

- We add new gauge singlet fermions to the SM
- Most general renormalizable coupling: Yukawa interaction with lepton doublet

$$\mathcal{L}_N = \mathcal{L}_{\mathrm{SM}} + \overline{N} i \partial\!\!\!/ N + \left(\frac{m_N}{2} \overline{N^c} N + y_\alpha \overline{L}_\alpha H N + \mathrm{h.c.} \right) ,$$

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- "Sterile" states at new mass scale
- Light Majorana mass terms:

$$m_\nu \approx v^2 y_\nu^{\rm T} m_N^{-1} y_\nu$$

- Weak interactions, suppressed by mixing between light-heavy states:

$$|U_{\alpha 4}|^2 \approx \frac{m_\nu}{m_N} \approx 5 \times 10^{-8} \left(\frac{\rm MeV}{m_N} \right)$$

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- Natural Type I
  - Order 1 yukawa couplings
  - New scale around GUT scale
  - Very suppressed mixing
- Low-scale Type I
  - Small yukawa couplings (y<<1)
  - N kinematically accessible
  - Mixing still very small
- Type I-like
  - Gives up on naive seesaw formulae
  - Perhaps new symmetries (à la ISS)
  - N kinematically accessible
  - Larger mixing possible

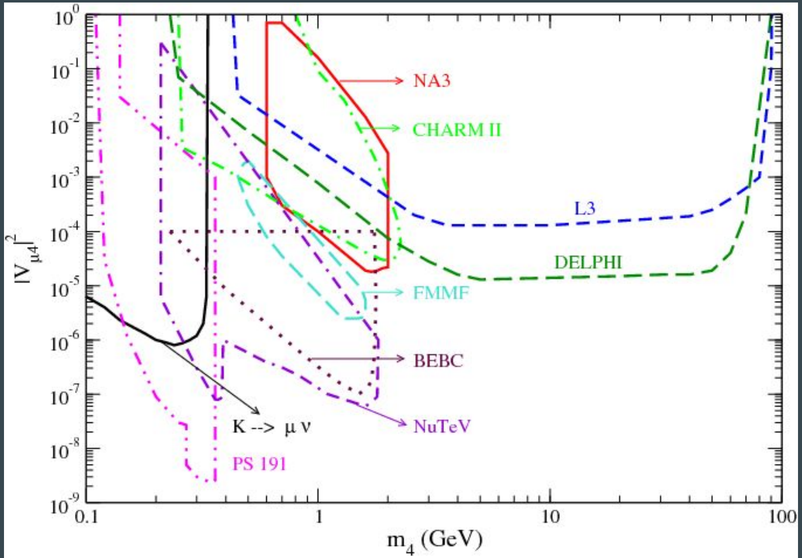
Constraints on Type I variants

Atre, Han, Pascoli, Zhang 0905.3389

- Searching for these states is a viable way to investigate the neutrino sector

- The heavy state retains its mixing mediated weak interactions, allowing for observable effects in many processes

- These models are constrained by many sources
  - Beam dumps
  - Peak searches in meson decay
  - Rare decays/LFV/LNV
  - Colliders
  - ...



- Cosmological bounds can be very strong [See e.g. Hernandez et al. 1311.2614; 1406.2961]

But...

- Even if we found N below the GeV scale, it would be unsatisfying if there were no other sign of new physics. Even if the new states were in the seesaw prefered region.

A more general "Type I"?

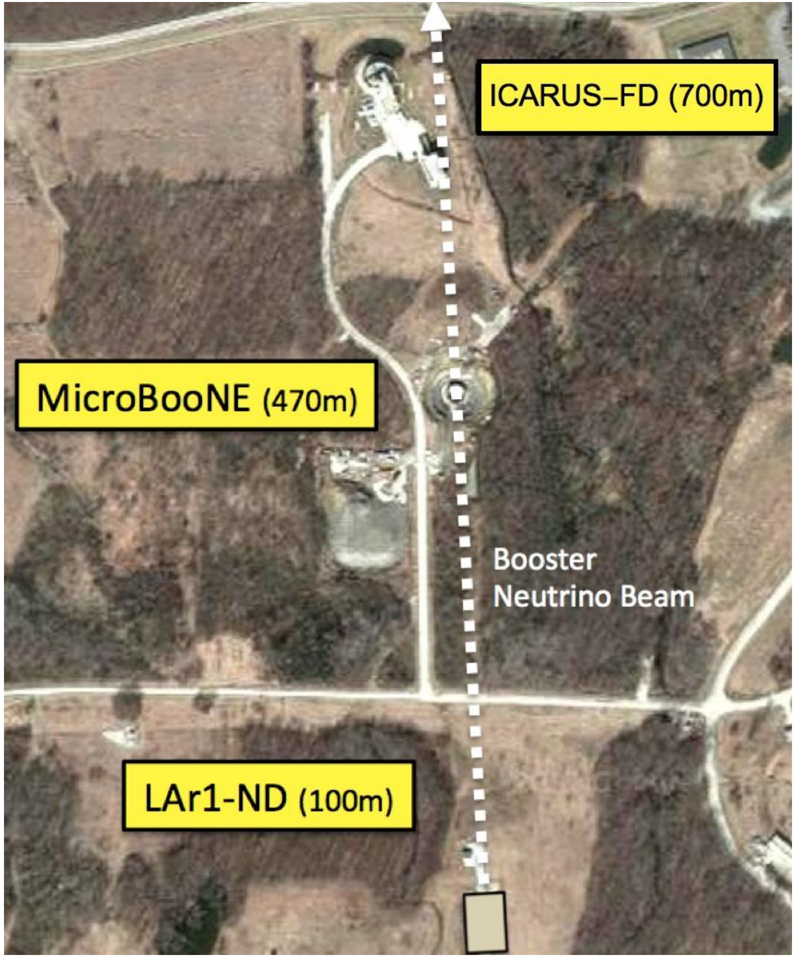
"We argue that the mere presence of these particles would be a signal of physics beyond the minimal seesaw mechanism"

From del Aguila, Bar Salom, Soni, Wudka 0806.0876

- This has lead some to consider the light neutral states as having a possibly richer phenomenology
  - (Quasi-?)Model independent bounds (e.g. peak searches, non-unitarity) [e.g. de Gouvea et al. 1511.00683, E. Fernandez-Martinez's talk]
  - Heavy neutrino Effective Field Theory [del Aguila et al. 0806.0876; Aparici et al. 0904.3244]
  - Additional low-scale physics (possibly in a simplified set-up)
    - U(1) B-L + sterile states [Batell et al. 1604.06099; Farzan et al. 1607.07616]
    - Secret interactions [N. Saviano's talk]
    - And many more...
- In this context, we'll discuss MeV sterile searches at upcoming neutrino beam experiments with a particular focus on Fermilab's SBN program.

MeV-scale steriles at SBN

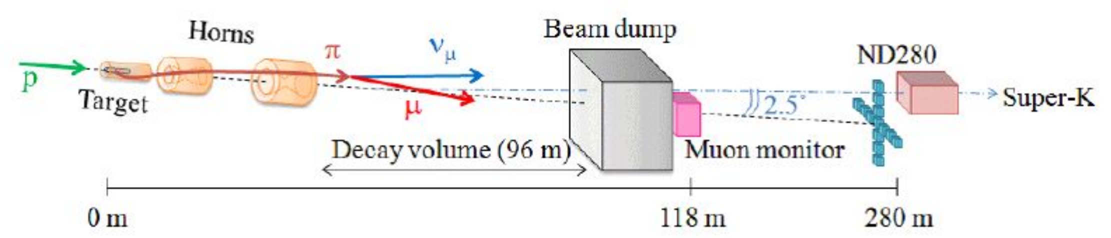
Potential sensitivities of Fermilab's SBN and the role of timing information



Based on 1610.08512 by S. Pascoli, M. Ross-Lonergan and PB

MeV steriles in neutrino beams

- In general production mechanisms can vary, but assuming only mixing-suppressed weak interactions, meson decays will generate a flux:



From Matsuoka et al. 1008.4077

- Moreover, modern neutrino beams are now crossing the exposure thresholds set by PS-191, and naively expect to improve on its sensitivities

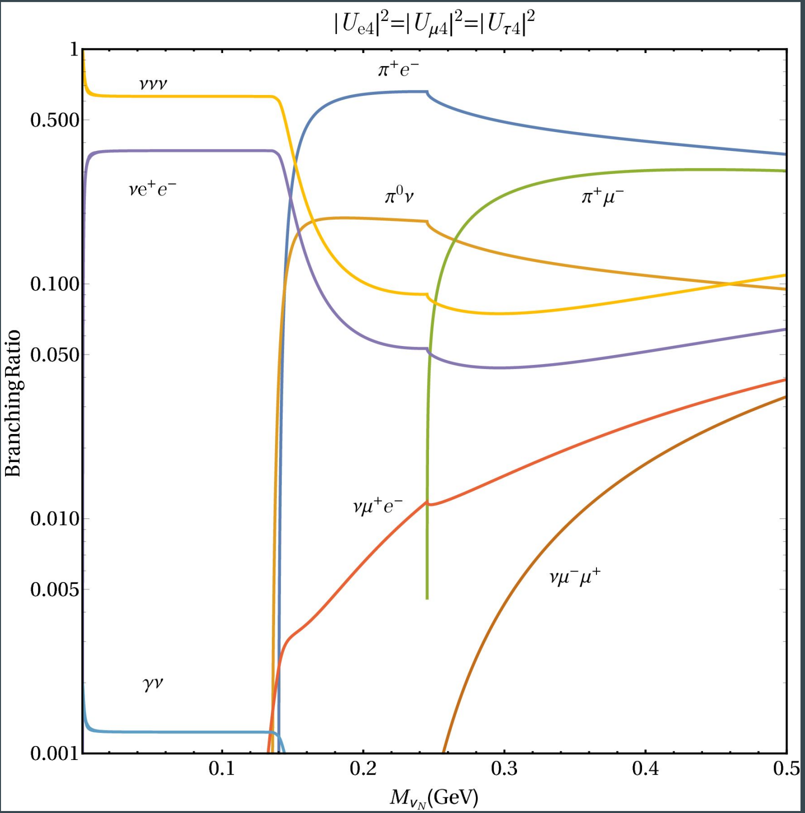
From Asaka, Eijima, Watanabe 1212.1062

	PS191 [19]	T2K [23]	MINOS [24]	MiniBooNE [25]	SciBooNE [26]
POT	0.86×10^{19}	10^{21}	10^{21}	10^{21}	10^{21}
$(\text{Distance})^{-2}$	$(128\,\text{m})^{-2}$	$(280\,\text{m})^{-2}$	$(1\,\text{km})^{-2}$	$(541\,\text{m})^{-2}$	$(100\,\text{m})^{-2}$
Volume	$216\,\text{m}^3$	$88\,\text{m}^3$	$303\,\text{m}^3$	$524\,\text{m}^3$	$15.3\,\text{m}^3$
Events	1	9.9	2.7	15.8	13.5

- However, key differences in design: decay in flight needs large low-density detectors, oscillation/cross-section measurements needs high SM scattering rates.

- To estimate sensitivity we need to think about backgrounds and background suppression.

Decay channels of interest

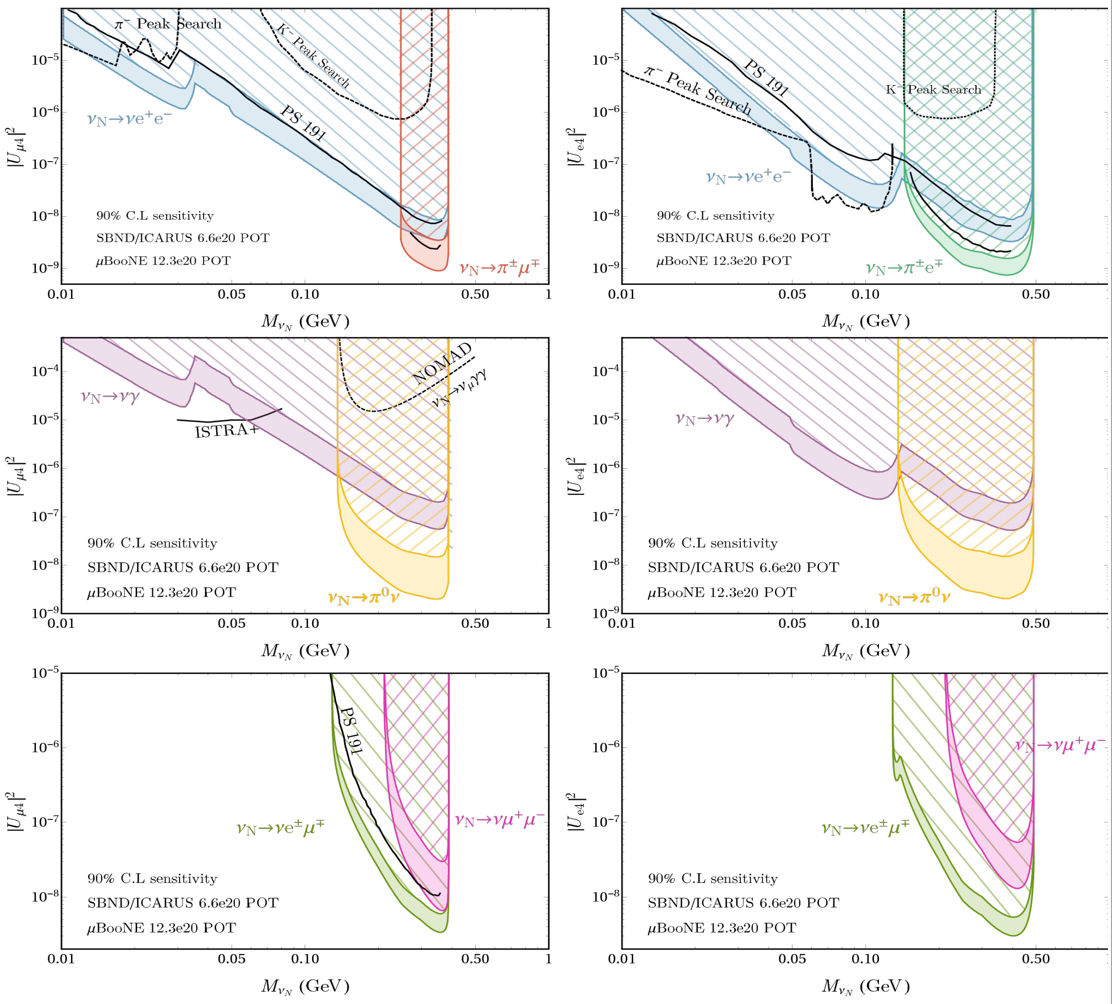


- Below muon mass
  - Invisible three neutrino decay
  - Three-body electron-positron-neutrino
  - Loop and GIM suppressed radiative
- Above muon/pion below muon+pion
  - Semileptonic charged pion + electron
    - BG: CC1pi with mis-id
  - Semileptonic neutral pion + neutrino
    - BG: NC1pi
  - Three-body muon-electron-neutrino
- Above pion+muon (below Kaon)
  - Semileptonic charged pion + muon
    - BG: CC1pi
  - Three-body muon-muon-neutrino

From Ballett, Pascoli, Ross-Lonergan 1610.08512

Projected sensitivities

- Performed a MC simulation of SBN's signal and background, applying reasonable analysis cuts to the samples.
- Coloured band shows potential sensitivity if analysis is improved.
- We see that in all channels, SBN can achieve at least as good sensitivity as PS-191.
- Many channels have no directly equivalent bound e.g. π^0 ν. But can be quite competitive at SBN.



PB, Pascoli, Ross-Lonergan 1610.08512

Non-minimal models

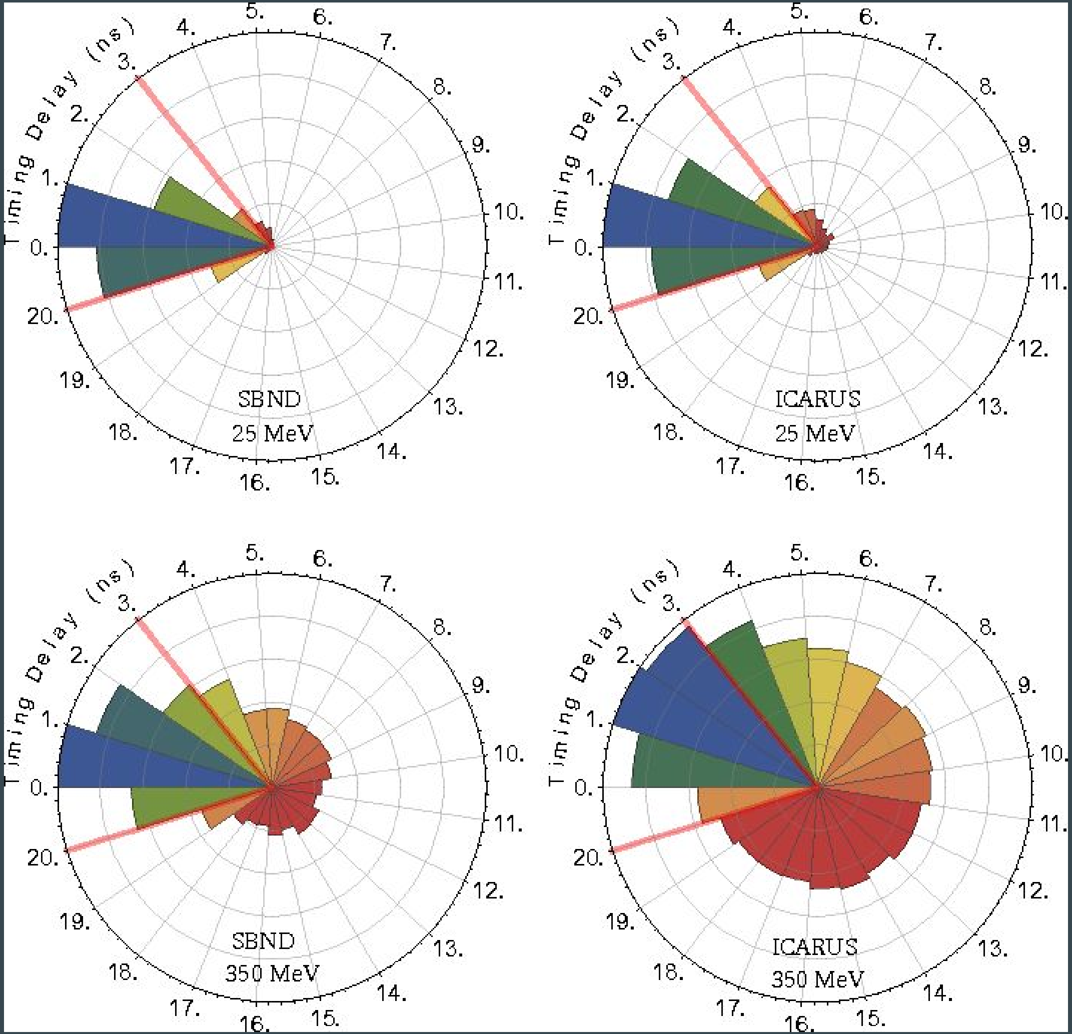
- In a non-minimal model, the possible final states and thresholds are the same (kinematics!) but their rates may be different.
- But a bound on one channel cannot be translated into a bound on another. Each decay needs to be considered independently.
- In a simplified scheme, all that matters for beam dumps is:

$\sigma(pp \to N)$	Production rate. Could be direct, or via meson decay depending on the model.
Γ_{T}	Total decay rate, affects likelihood of particles reaching the detector and decaying inside it.
$\Gamma_{\mathrm{c}}/\Gamma_{\mathrm{T}}$	Branching ratio into channel of interest. Governs number of events observed of a certain type.

- Beam experiments are quite robust: they are multi-channel direct-observation experiments, and generally their detection prospects improve with non-minimality.

Event timing at SBN

- At the MeV scale, events starrt to arrive over a wide range of timing bins.
- The beam is structured into buckets of ~2 ns duration, separated by gaps of ~19 ns. We studied the events against this periodic notion of time.
- This leads to a big difference between e.g. ICARUS and SBND. A smoking gun signature of heavy particle propagation.
- Can be used to suppress beam related backgrounds, to improve parameter reconstruction, and to discover heavy propagation in a model independent way.



In summary

- MeV sterile neutrinos can be searched for in neutrino beam experiments, and can be an additional goal for exps. focused on oscillations or cross-section measurements
- Background suppression is key. However, we have shown that SBN can extend the current bounds, and test channels for which no comparable published bounds exist
- We should consider the possibilities of non-minimal behaviour: channels become uncorrelated, but beam bounds quite robust
- Event timing information can also be very useful. This can improve sensitivities, and parameter estimation. A significant time delay would be strong model independent evidence of heavy particle propagation

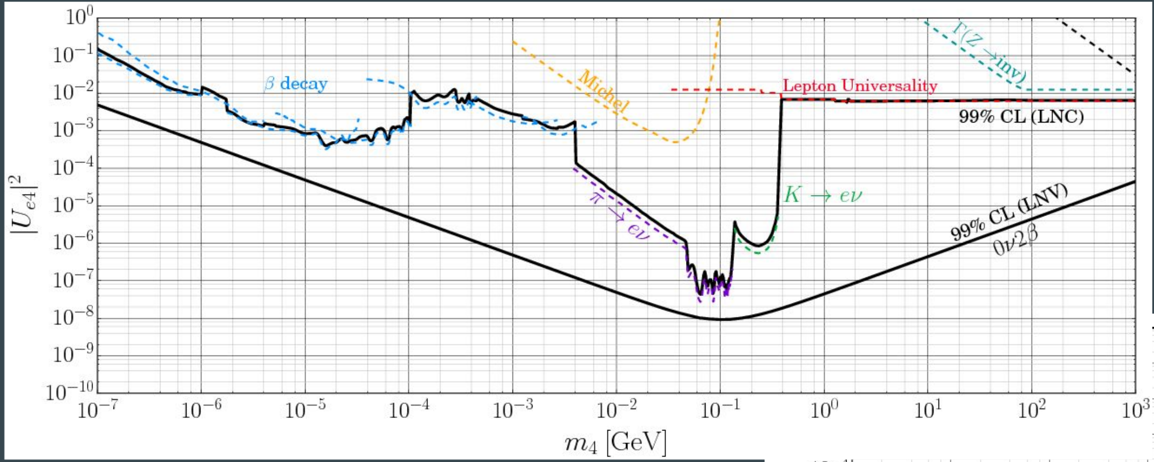
Thank you

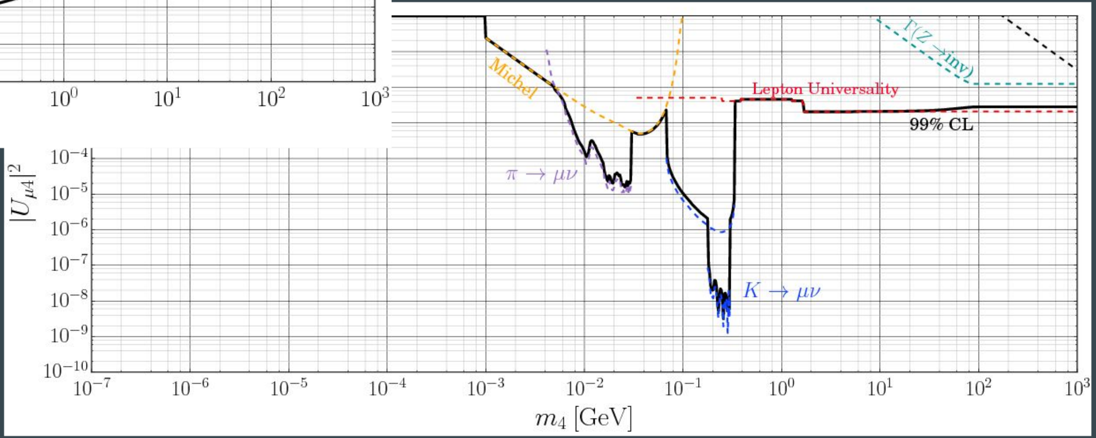
And thanks to...

Model independent bounds

From de Gouvea and Kobach 1511.00683

- Assumes large invisible decays of N
- All searches for final states become ineffective, but non-unitarity and peak searches remain





Projected sensitivities: DUNE

- Estimates suggest DUNE's ND could do these measurements well for the minimal model. But as far as I know, there is no detailed public study. Final sensitivity will depend on ND design and channels studied.

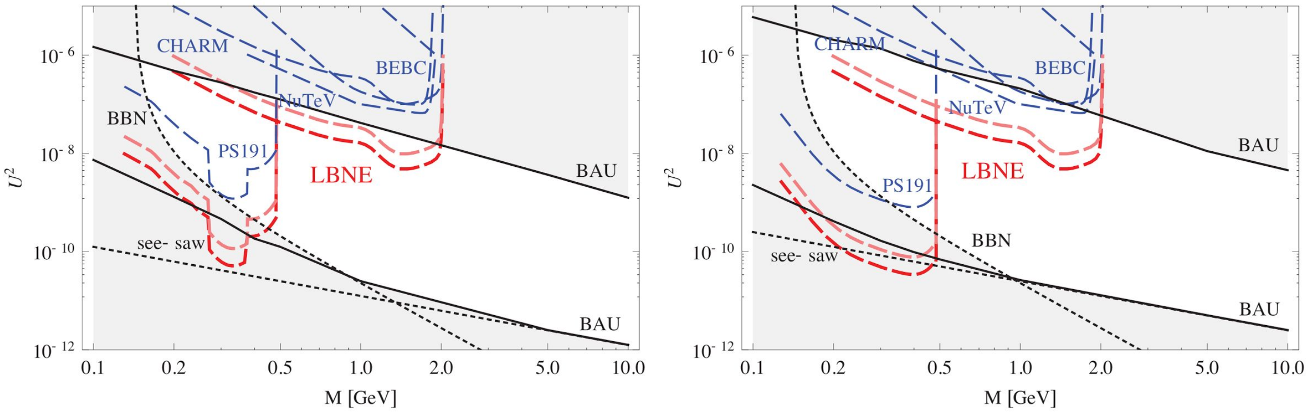


Figure 7.5: Upper limits on U^2, the mixing angle between heavy sterile neutrinos and the light active states, coming from the Baryon Asymmetry of the Universe (solid lines), from the seesaw mechanism (dotted line) and from the Big Bang nucleosynthesis (dotted line). The regions corresponding to different experimental searches are outlined by blue dashed lines. Left panel: normal hierarchy; right panel: inverted hierarchy (adopted from [297]). Pink and red curves indicate the expected sensitivity of the LBNE near detector with an exposure of 5×10^{21} POT ($\sim$ 5 years) with the 1.2−MW reference beam at 120 GeV for detector lengths of 7 m and 30 m , respectively (see text for details).

From LBNE physics paper 1307.7335