MeV-Scale Heavy Neutrino Decay in Super-Kamiokande

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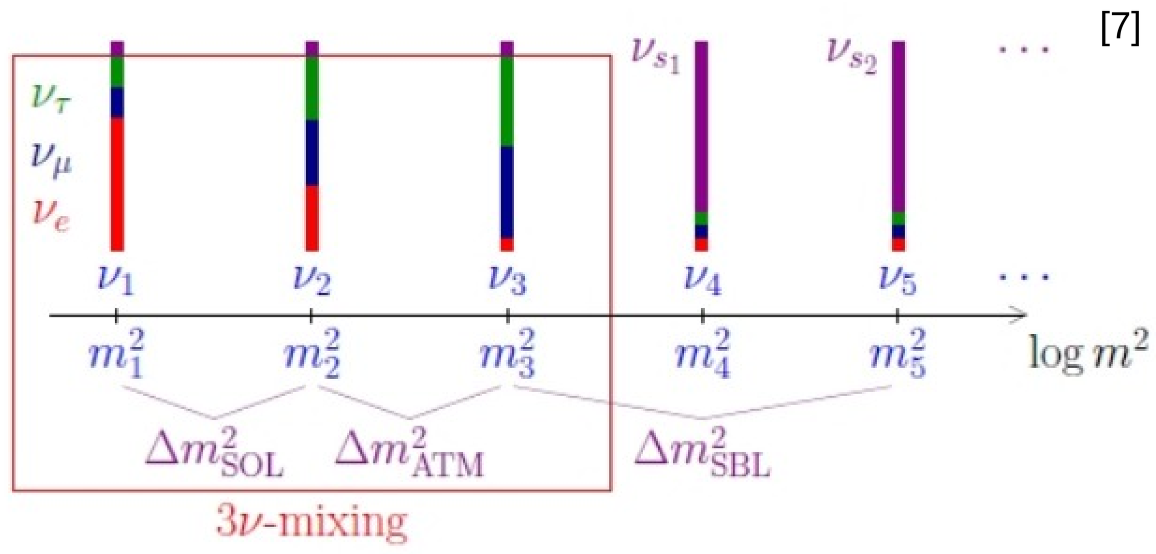
Sterile Neutrino Theory

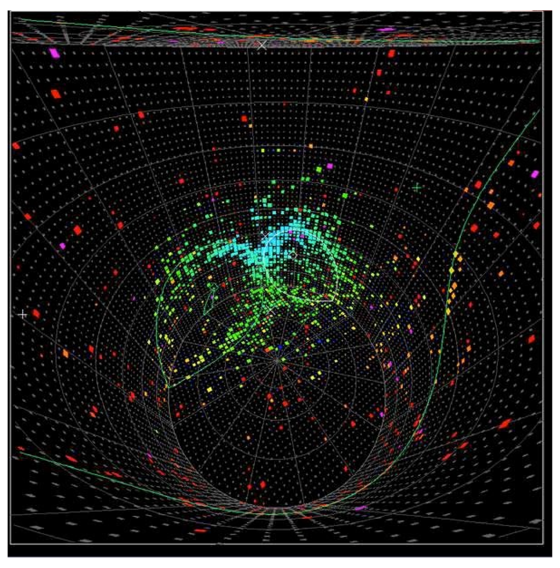
• Neutrino mass is unexplained by the Standard Model due to absence of right-handed neutrinos.
→ basic modifications to the SM are Dirac and Majorana masses for neutrinos
→ the heavy-neutrino mass scale is unknown (some ideas are keV, EW-scale, GUT-scale...)

• According to SM right-handed neutrinos must be **sterile** (completely non-interacting, except for gravity).
• However, heavy-mass-states (mostly sterile) may contain small amounts of the flavour-states (neutrino **mixing**).
→ For < keV-scale states, their participation in and effect on neutrino oscillation may be observed
→ For > keV-scale they are separated from the oscillation effects, but may undergo weak interactions, for example creating observable **decay products**
→ As the phenomenology varies by mass and neutrino flavour, a patchwork of various experiments [1][2] is needed to explore the parameter-space of **sterile mass** and **mixing-matrix-parameters**.

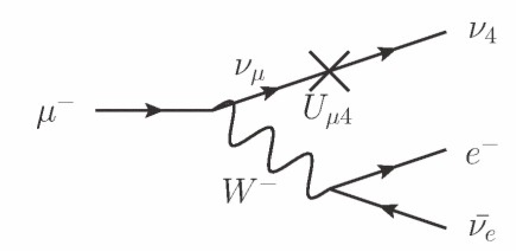
[7]



Atmospheric Heavy Neutrinos

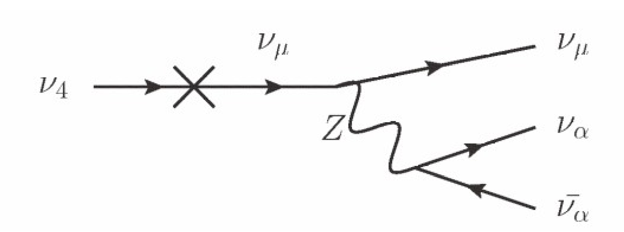


• Neutrinos are copiously produced in **cosmic ray** collisions in the atmosphere, by the decay of Pions, Muons and Kaons.
→ A small fraction of decays may produce sterile neutrinos instead, for example, in the case of Muon decay:

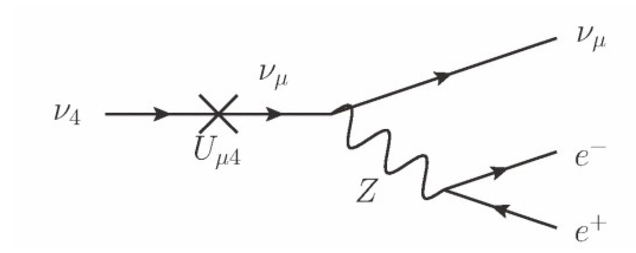


$$\frac{\Gamma(\mu\to e^-\nu_e\nu_s)}{\Gamma(\mu\to e^-\nu_e\nu_\mu)} = |U_{\mu s}|^2(1-8r+8r^3-r^4-24r^2\ln(r)) \qquad r=\left(\frac{m_s}{m_\mu}\right)^2$$

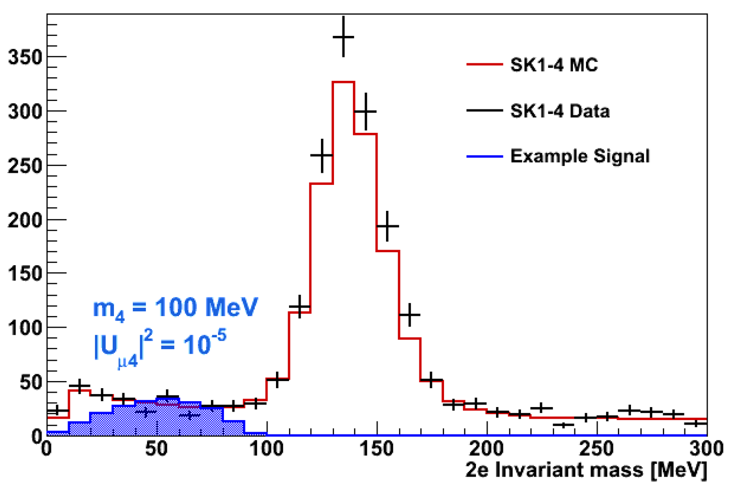
→ after propagation through the atmosphere, some of these steriles may **decay inside Super-Kamiokande** by e.g.



or



$$\Gamma(\nu_s\to 3\nu)=\frac{G_F^2 m_s^5|U_{\mu s}|^2}{192\pi^3} \qquad \Gamma(\nu_s\to e^+e^-\nu)=\Gamma(\nu_s\to 3\nu)\left(\frac{1}{4}-\sin^2\theta_W+2\sin^4\theta_W\right)$$

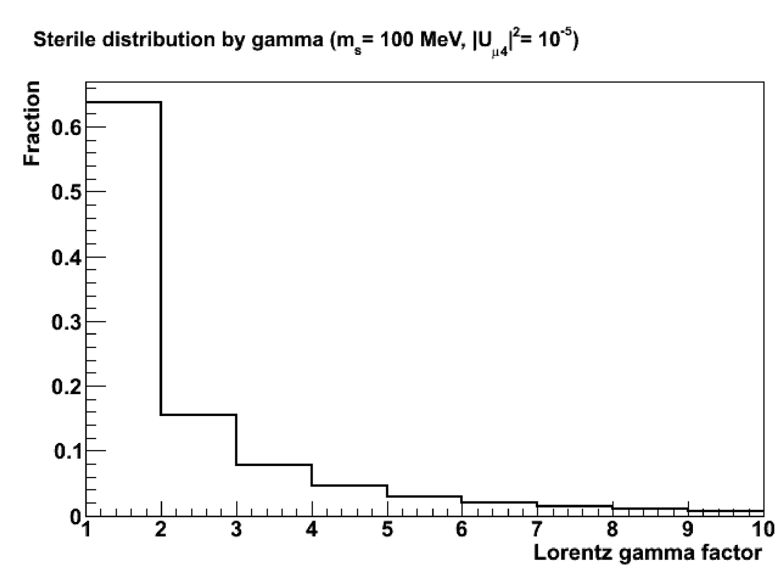


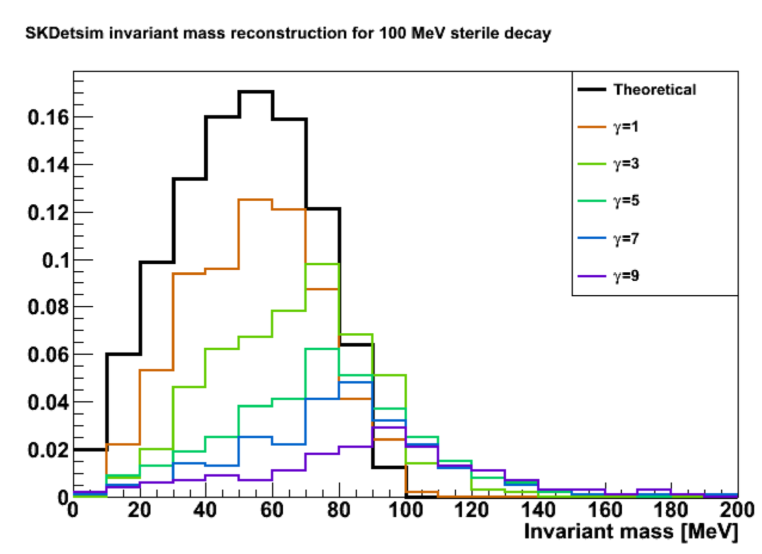
• We see that the second decay can produce a **double electron signal** in Super-K
→ With branching ratio ~10%, this signal is helpful for a heavy neutrino with mass O(10) MeV
→ to separate from atmospheric background (neutral pion decay, etc.), we can consider e.g. **invariant mass**
→ due to the undetectable energy carried away by the final-state neutrino, we should perform a spectrum fit

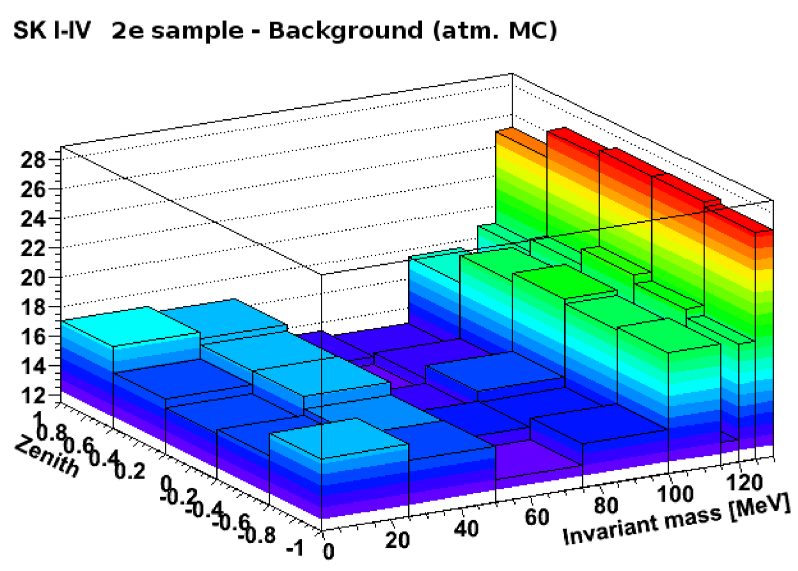
Search Strategy

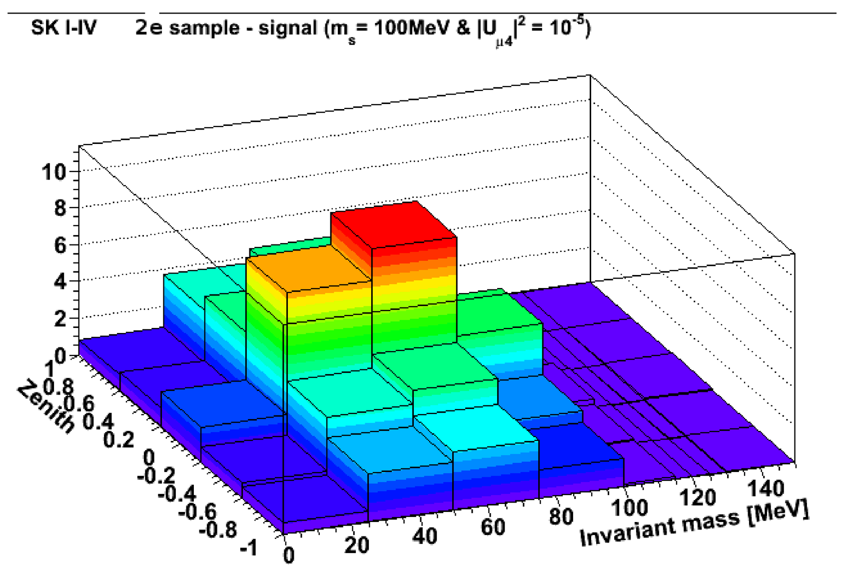
• For **atmospheric flux prediction**, Honda-flux [3] code is used to obtain a simulation of atmospheric interactions that may create sterile neutrinos.
→ The steriles from each interaction are propagated through the atmosphere, and the probability to decay inside of Super-Kamiokande is calculated.
→ Each weighted is event summed into distributions of **sterile energy** and **zenith angle**, and also distributions of the **decay electron properties** (momentum, invariant mass, inner angle)

• Realistic **detector response** is obtained from the Super-K official Monte-Carlo simulation.
• A full **systematic error treatment** is performed (flux errors, cross-sections, reconstruction etc.).





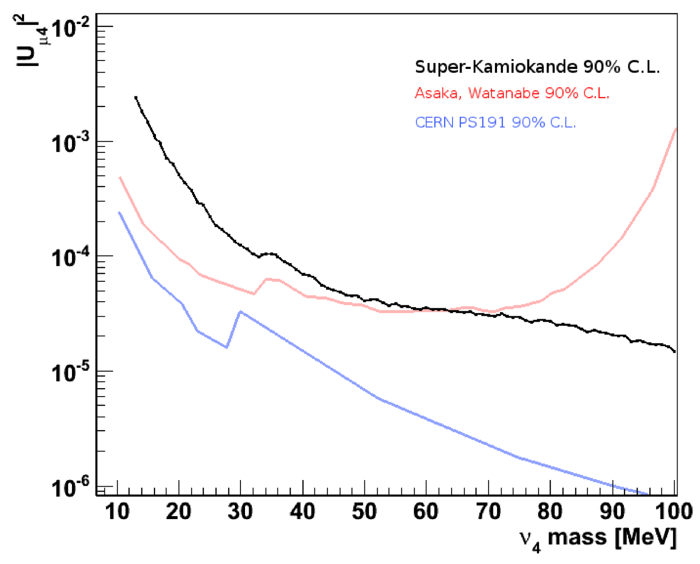




Fitting & Results

• Using an optimized invariant-mass / zenith-angle binning, considering each heavy-neutrino-mass as a separate case, the min. χ^2 is obtained fitting the systematic errors with penalty "pull terms", and then scanning to get $\Delta\chi^2$ (90% C.L. limits shown).

• Compared to previous studies about SK [4] our study includes:
→ better flux predictions
→ full SK I-IV dataset
→ directional information
→ steriles produced by decay of cosmic-ray Kaons
→ realistic reconstruction and systematic errors



• Although there are many improvements, a realistic knowledge of SK reconstruction means our final data limit is similar to the previous study
→ we don't beat the world-best limits [5] in this area
• Improving best limits may be possible with ~10 years of Hyper-K data.
• Extending the mass range may be effective with T2K near detector [6].

[1] Wong (Doctoral thesis) - http://etheses.dur.ac.uk/4931/ [2] Kuzenko, Pascoli, Semikoz - http://arxiv.org/abs/hep-ph/0405198 [3] M. Honda et. al. - http://arxiv.org/abs/1102.2688 [4] Asaka, Watanabe - http://arxiv.org/abs/1202.0725
[5] CERN PS191 - http://www.nu.to.infn.it/exp/all/cern-ps-191/ [6] Asaka, Eijima, Watanabe - http://arxiv.org/abs/1212.1062 [7] Giunti - arxiv:1206.0294