A sterile neutrino at MiniBooNE, MicroBooNE and IceCube

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- Gninenko's 50 MeV neutrino at LSND
- A variation of the model at MiniBooNE
- Constraints from T2K, search at MicroBooNE
- Implications at IceCube

Masip, Masjuan, Meloni, JHEP 01 (2013) 106

Bellaterra, April 2014

• Homestake, GALLEX, SAGE,... IMB, Kamiokande, Super K, ... KEK, K2K,...

SNO, KamLAND,... **Neutrinos have masses and mixings (!)**

$$\begin{cases} \Delta m^2_{12} \approx 7.9 \times 10^{-5}\ \mathrm{eV}^2 \\ \Delta m^2_{23} \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2 \\ \qquad \approx \Delta m^2_{13} \end{cases} \qquad \begin{cases} \sin^2\theta_{12} \approx 0.30 \\ \sin^2\theta_{23} \approx 0.50 \\ \sin^2\theta_{13} \approx 0.025 \end{cases}$$

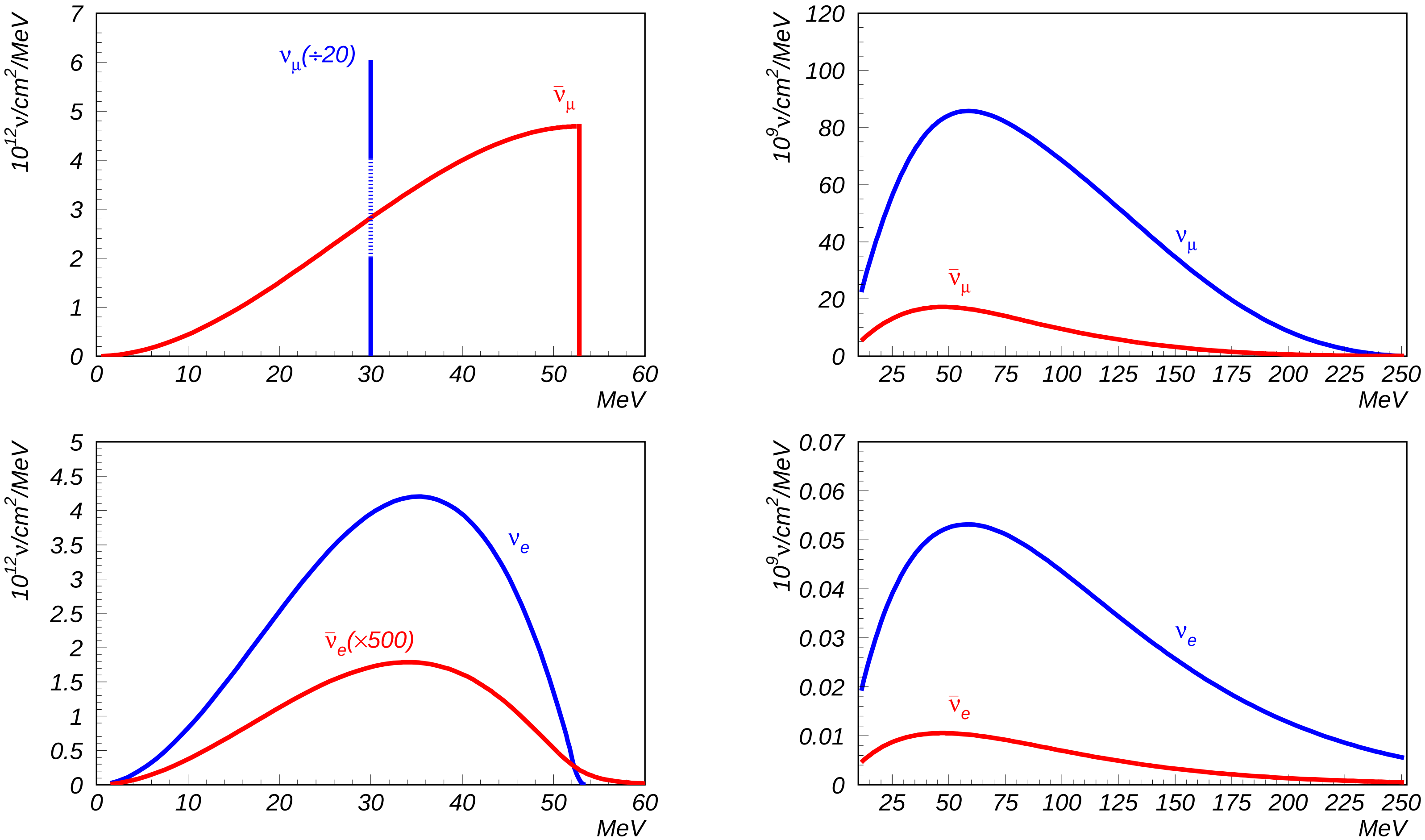
Is it $y_\nu\, H L \nu^c$ or $\dfrac{1}{\Lambda_\nu} HHLL$?

• *Persistent* anomalies in several experiments with neutrino beams from particle accelerators. Excess of 3 events with an electron in the final state per 1000 ν_μ CC-interactions. $\nu_\mu \to \nu_e$ oscillations unconsistent with ν-mass parameters (2 sterile neutrinos of $m \approx 1$ eV?).

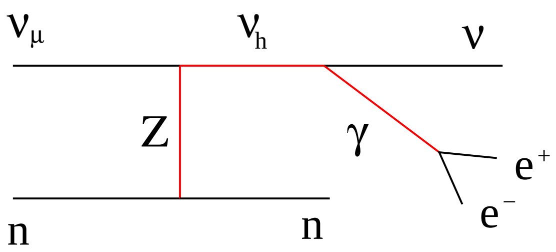
LSND, KARMEN, MiniBooNE, TRIUMF, T2K, NOMAD, IceCube

● LSND observed **3** electron events per **1000** $\overline{\nu}_\mu$ CC interactions. Interpreted as $\bar{\nu}_\mu \to \bar{\nu}_e$ then $\bar{\nu}_e p \to e^+ n$, with a 2.2 MeV photon from neutron capture.

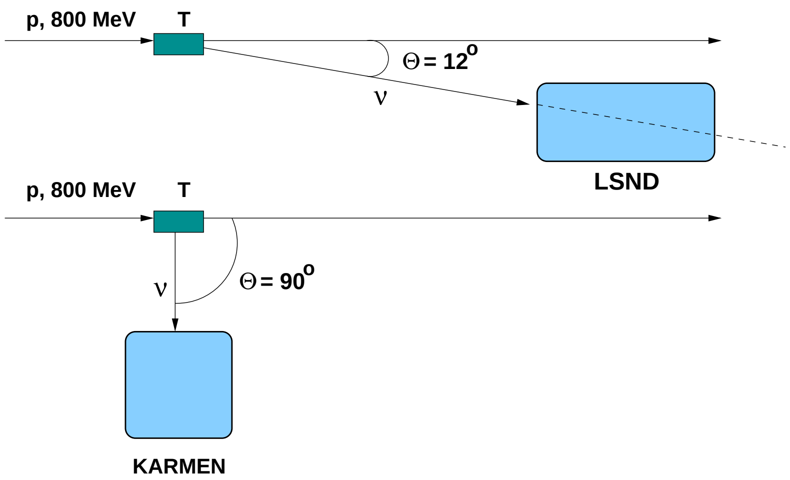
Fluxes: DAR (left) and DIF (right) $\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$; $\pi^+ \to \mu^+ \nu_\mu$

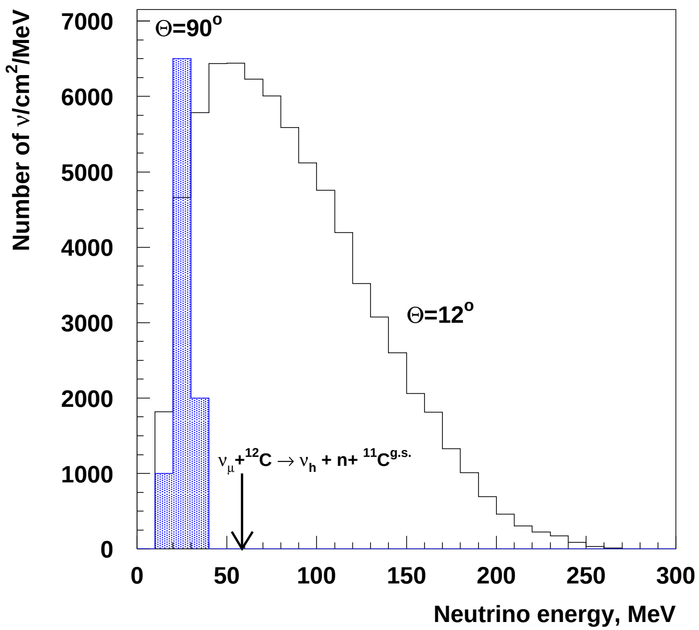


Gninenko's 50 MeV neutrino hypothesis to explain LSND



- Sterile ν_h with $|U_{\mu h}|^2 \approx 10^{-3}$–$10^{-2}$, $\nu_h \to \nu\gamma$ with $\tau_h \lesssim 10^{-8}$ s
- KARMEN did not confirm... ν_h would be above threshold there!





ν_h would appear in up to 1% of muon and kaon decays!

$$\mu^- \to e^- \, \bar{\nu}_e \, \nu_h \to e^- \, \bar{\nu}_e \, \gamma \, \nu \; , \qquad K^- \to \mu^- \, \bar{\nu}_h \to \mu^- \, \gamma \, \bar{\nu}$$

- Usual searches are based on decay modes with charged particles

$$\nu_h \to ee\nu, \mu e\nu, \mu\pi\nu \quad \text{not} \quad \nu_h \to \nu\gamma$$

- If ν_h is long lived ($\tau_h > 10^{-9}$ s) but light ($m_h \approx 50$ MeV), $|U_{\mu h}|^2 \approx 0.003$ does not change significantly the kinematics in μ and K decays.

- If it is short lived, muons and kaons have decay modes with photons

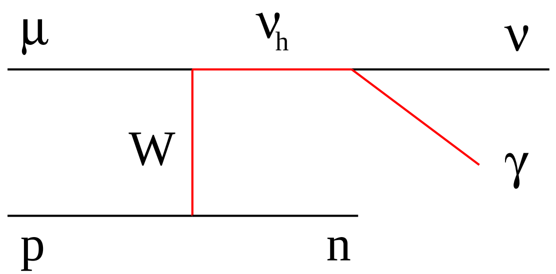
$\mu^- \to e^- \, \bar{\nu}_e \, \nu_\mu \, \gamma$	$1.4 \pm 0.4\%$
$K^- \to \mu^- \, \bar{\nu}_\mu \, \gamma$	$0.62 \pm 0.08\%$
$K^- \to \mu^- \, \bar{\nu}_\mu \, \pi^0$	$3.35 \pm 0.03\%$

A recent analysis of ISTRA+ data seems to disfavor this possibility

• Gninenko proposed that ν_h can also explain the MiniBooNE anomaly (see below) if its lifetime is reduced to $\tau_h \leq 10^{-9}$ s (versus $\tau_h \leq 10^{-8}$ s at LSND).

• McKeen & Pospelov noticed that Gninenko's ν_h is unconsistent with data on muon capture plus photon at TRIUMF

$$R_\gamma = \left.\frac{\Gamma_{RMC}}{\Gamma_{\text{tot}}}\right|_{E_\gamma > 60\ \text{MeV}}$$

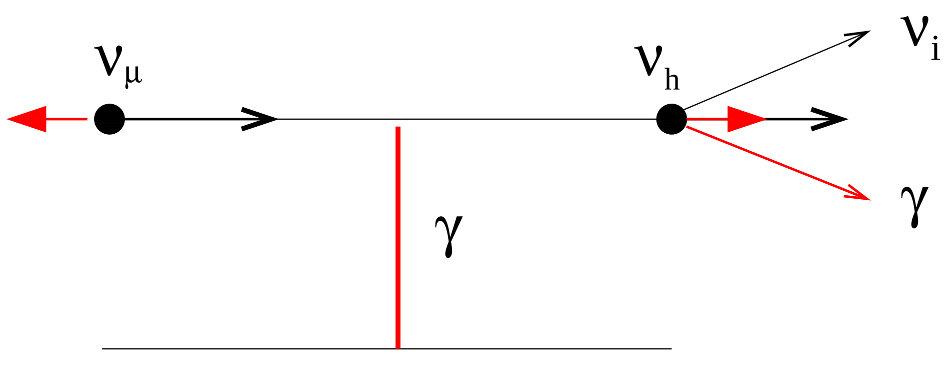


$$|U_{\mu h}|^2 \leq (2\text{–}8) \times 10^{-4} \;\; \text{for} \;\; m_h = 40\text{–}80\ \text{MeV} \;\; \text{and} \;\; \tau_h < 10^{-9}\ \text{s}$$

ν_h: factor of 3 excess   TRIUMF data: 30% excess (again a 2.5σ dev.!)

• The cut $E_\gamma > 60$ MeV and the small size of the target volume (≈ 15 cm) make this experiment very sensitive to the lifetime: $\tau_h \geq 3 \times 10^{-9}$ s fits.

- Our variation of Gninenko's model: (i) keep a longer lifetime, $\tau_h \approx 5 \times 10^{-9}$ s. (ii) include ν_h production through photon exchange. (iii) ν_h a Dirac fermion.



- $\nu_h \equiv \{N_1, N_1^c\}$; N_1 mixed with ν_μ, $|U_{\mu h}|^2 \approx 0.003$; EM dipole transitions $\mu_{\rm tr}^{ih}$ to describe ν_h production ($i = \mu$) and decay ($i = \mu, \tau, \ldots$):

$$L_{eff} \subset \frac{1}{2}\,\mu_{\rm tr}^{ih}\left(\overline{\nu}_h\,\sigma_{\mu\nu}\,(1-\gamma_5)\,\nu_i + \overline{\nu}_i\,\sigma_{\mu\nu}\,(1+\gamma_5)\,\nu_h\right)\partial^\mu A^\nu$$

$\tau_h = 5 \times 10^{-9}$ s implies $\sqrt{\sum_i (\mu_{\rm tr}^{ih})^2} = 7 \times 10^{-6}\ {\rm GeV}^{-1} = 2 \times 10^{-8} \mu_B$

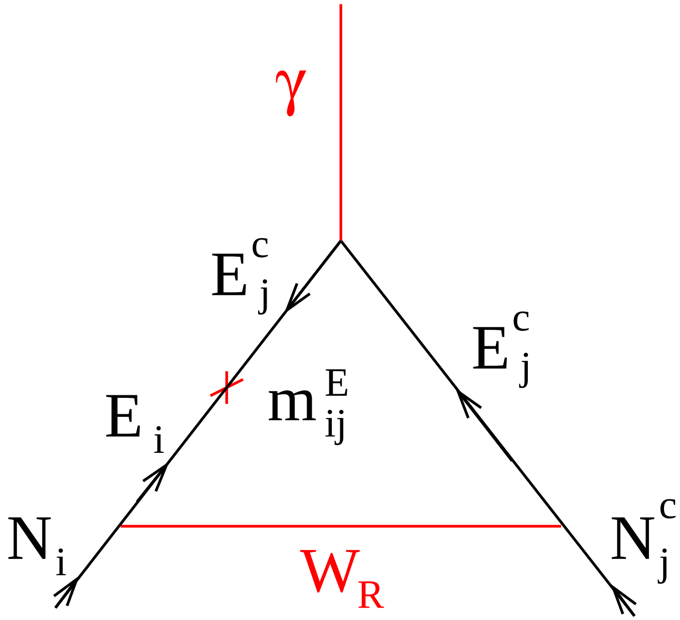
MiniBooNE will require $\mu_{\rm tr}^{\mu h} = 2 \times 10^{-9} \mu_B$

$$SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y \;:\; \chi = \begin{pmatrix} \langle\chi^0\rangle \\ \chi^- \end{pmatrix} \quad \chi^c = \begin{pmatrix} \chi^{c+} \\ \langle\chi^{c\,0}\rangle \end{pmatrix}$$

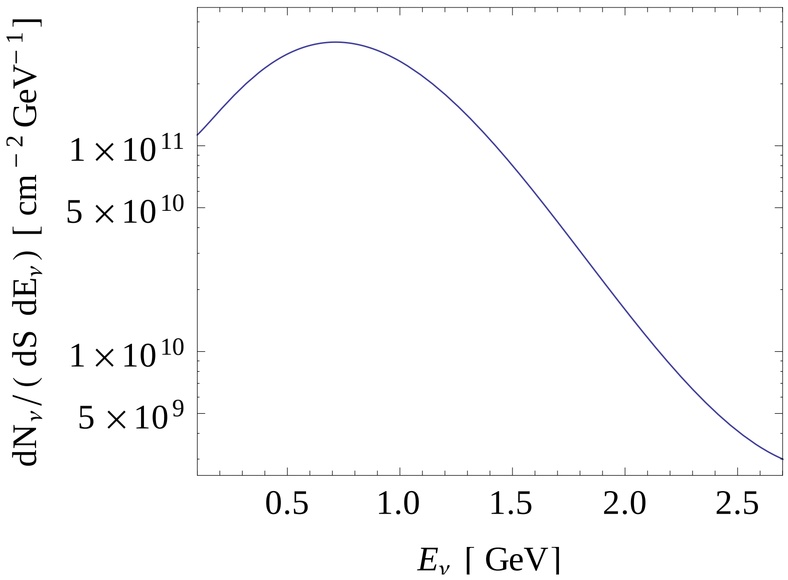
$Y = T^3_R + B - L$

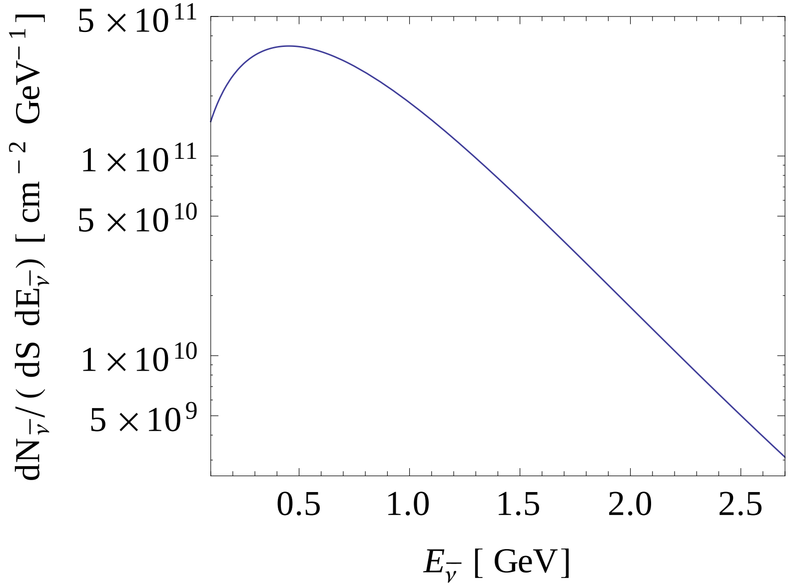
$Q = T^3_L + Y$

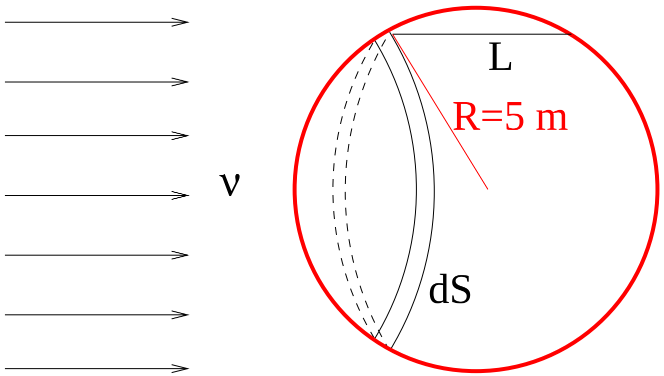
$\nu_\mu' = c_\alpha\, \nu_\mu + s_\alpha\, N_1$



$$L_1 = \begin{pmatrix} N_1 \\ E_1 \end{pmatrix} \quad L_1^c = \begin{pmatrix} E_1^c \\ N_1^c \end{pmatrix} \qquad W \subset m_h\, L_1 L_1^c + \frac{1}{\Lambda_1}\,(L_1^c \chi^c)\,(L_1 \chi)$$

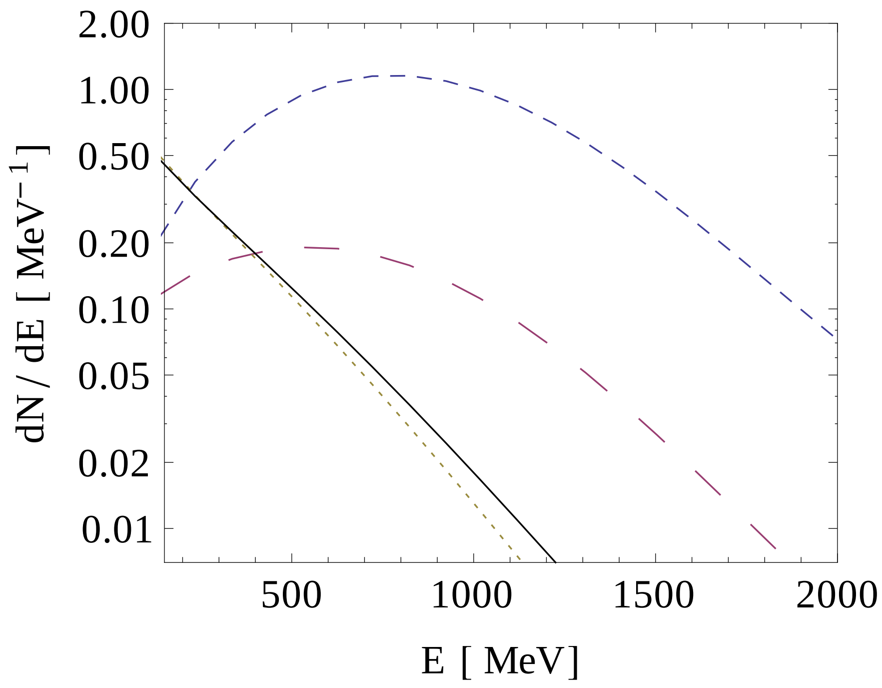


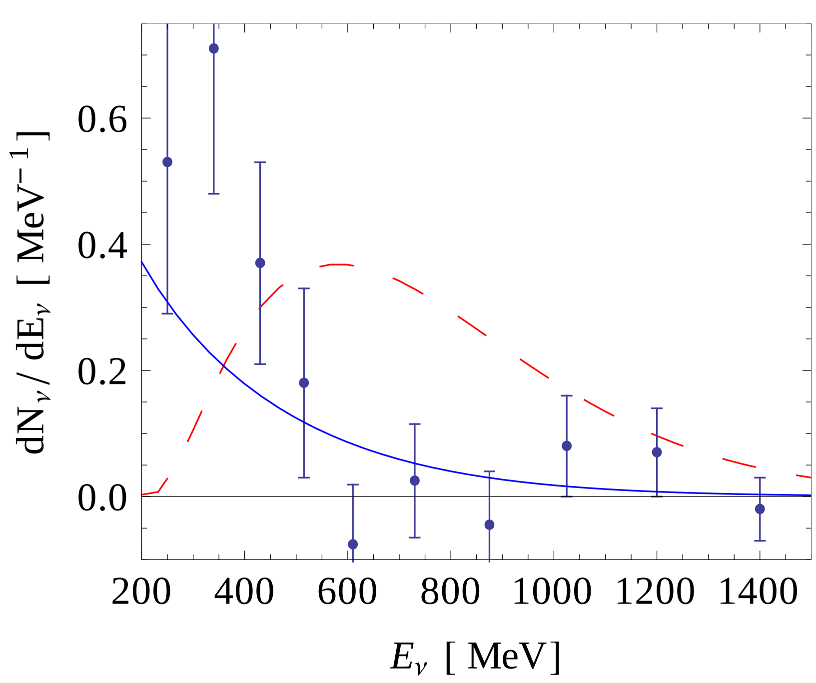




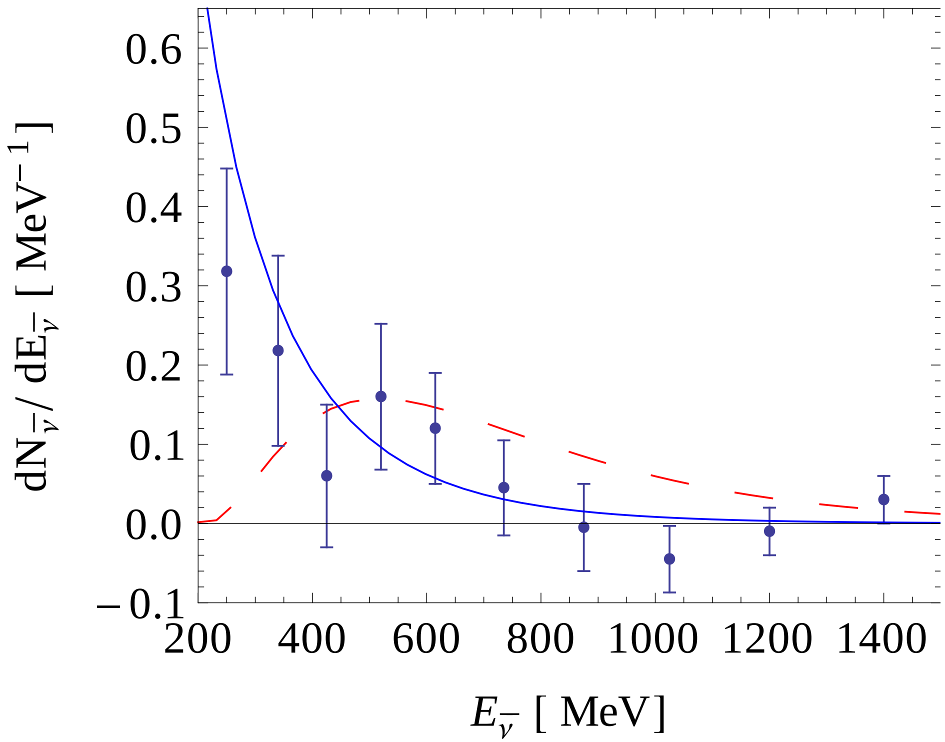
$$p_{\mathrm{i}} = \frac{\sigma\, \rho\, L}{m_{CH_2}}$$

$$p_{\mathrm{i+d}} = \frac{\sigma\, \rho\, L}{m_{CH_2}} \left(1 - \frac{\lambda_d}{L}\left(1 - e^{-\frac{L}{\lambda_d}}\right)\right)$$





Left: Energy distribution of ν_h produced in the detector (dashes), of ν_h decaying inside the detector (long dashes), of photons from $\nu_h \to \nu_i \gamma$ (dots), and of ν_h events reconstructed as CC interactions (solid). Right: Energy distribution of ν_h events reconstructed as CC interactions (solid), of events from neutrino oscillations for $\sin^2(2\theta) = 0.004$ and $\Delta m^2 = 1\ \mathrm{eV}^2$ (long dashes), and excess at MiniBooNE in the neutrino mode (5.58×10^{20} POT)



Antineutrino mode (11.27×10^{20} POT)

- The decay length ($\lambda_{dec} > R$) and the helicity ($+$ for ν_h, $-$ for $\bar{\nu}_h$) imply that the MiniBooNE excess concentrates at low energies, just as it is observed.

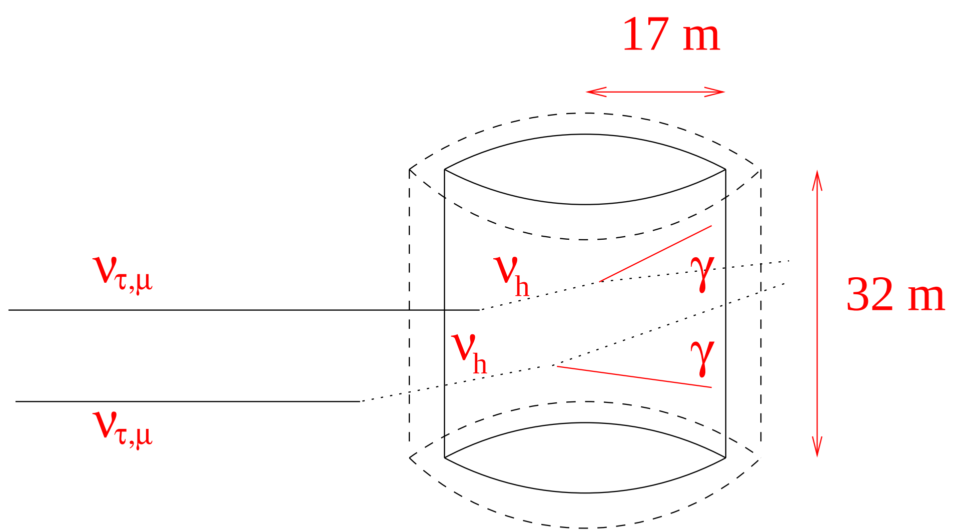
If BR$(\nu_h \to \nu_\mu \gamma) \approx 1\%$, is BR$(\nu_h \to \nu_\tau \gamma) \approx 99\%$?

At T2K we expect some ν_e,

$$p_{\nu_\mu \to \nu_e} \approx \sin^2 \theta_{23} \; \sin^2 2\theta_{13} \; \sin^2 \frac{1.27 \; \Delta m^2_{23}(\mathrm{eV}^2) \; L(\mathrm{km})}{E_\nu(\mathrm{GeV})}$$

but most neutrinos are ν_τ,

$$p_{\nu_\mu \to \nu_\tau} \approx \sin^2 2\theta_{23} \; \sin^2 \frac{1.27 \; \Delta m^2_{23}(\mathrm{eV}^2) \; L(\mathrm{km})}{E_\nu(\mathrm{GeV})}$$

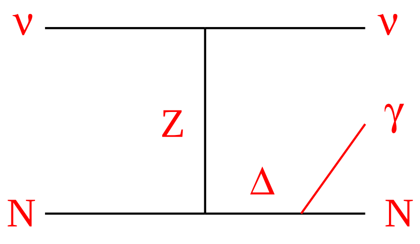


- $\nu_\mu \to \nu_e$ oscillations with $\sin^2 2\theta_{13} = 0.1$: 6 events
- $\nu_\mu Z \to \nu_h Z$: 1.1 events (75% from ν_h produced outside).
- ν_h must decay 99% of the times into another sterile neutrino!

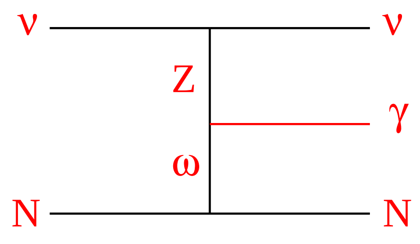
$$\mu_{\rm tr}^{\tau h} < \mu_{\rm tr}^{\mu h} \qquad \text{and} \qquad \text{BR}(\nu_h \to \nu_{h'}\gamma) = 0.99$$

- Initial events seem to be distributed near the point of entrance into the detector. $\nu_\tau Z \to \nu_h Z$ events could explain that: When ν_h is produced outside the detector $\lambda_{dec} \approx d$
- The tracking system in the near detector (ND280) can distinguish electrons from photons: we expect 3 ν_h events per 1000 ν_μ CC interactions

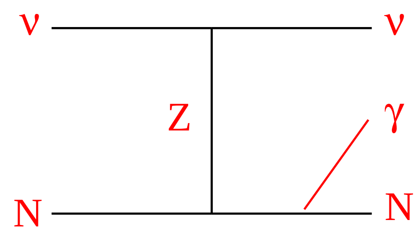
- **MicroBooNE** (liquid Argon TPC) will investigate whether the low-energy excess at MiniBooNE is cause by electron or by photon events,



Delta resonance

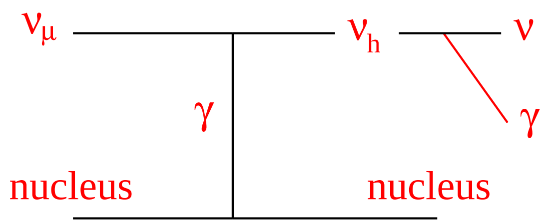


pseudo Chern−Simons



Compton

or



50 MeV sterile neutrino

?

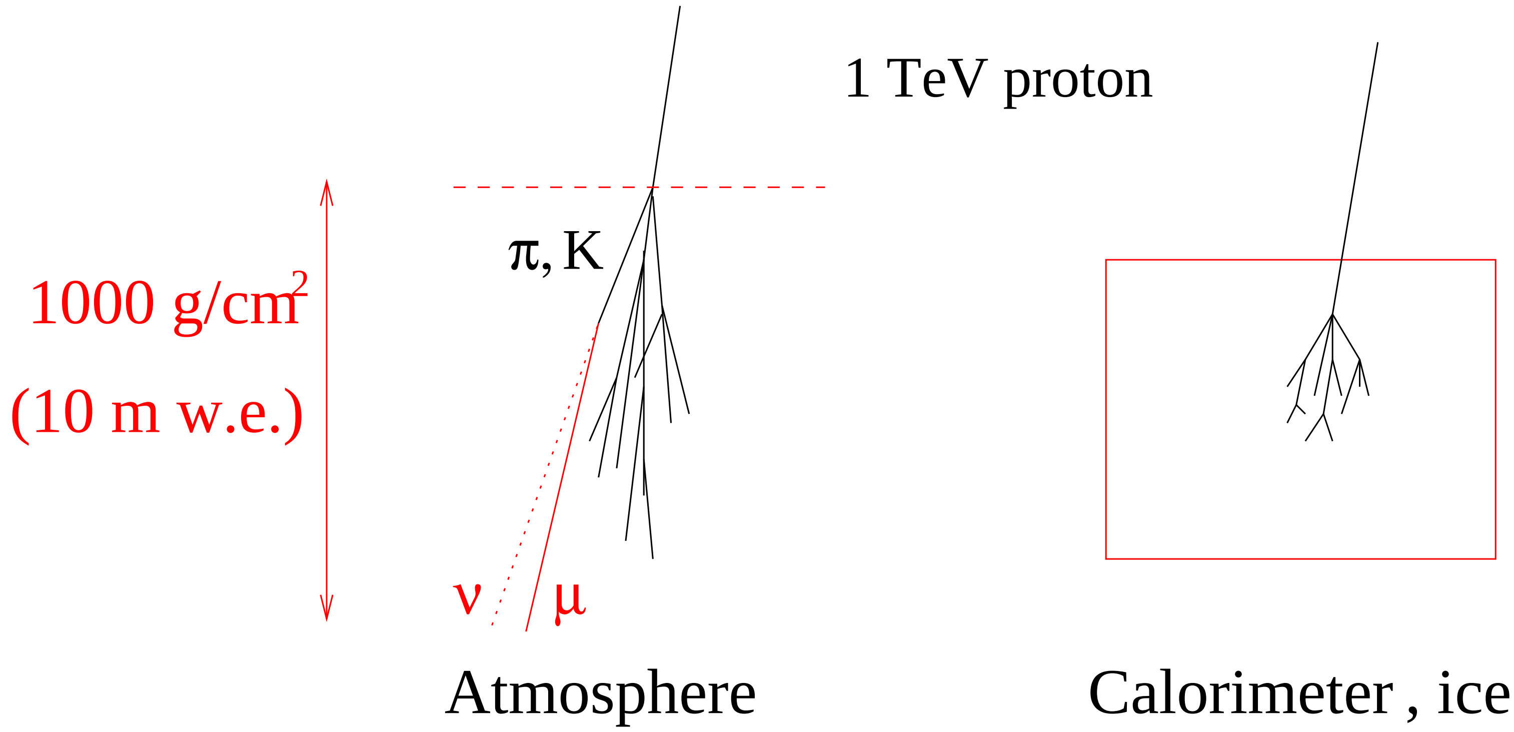
- This background may be distinguished from the $\nu_h \to \gamma \nu_{h'}$ hypothesis:

The event distribution inside the detector is flat for the background events, but $\propto \left(1 - e^{-z/\lambda_d}\right) \approx \frac{z}{\lambda_d}$ for heavy neutrino events.

LSND: anomaly at $L \approx 30$ m for $E \approx 40$ MeV

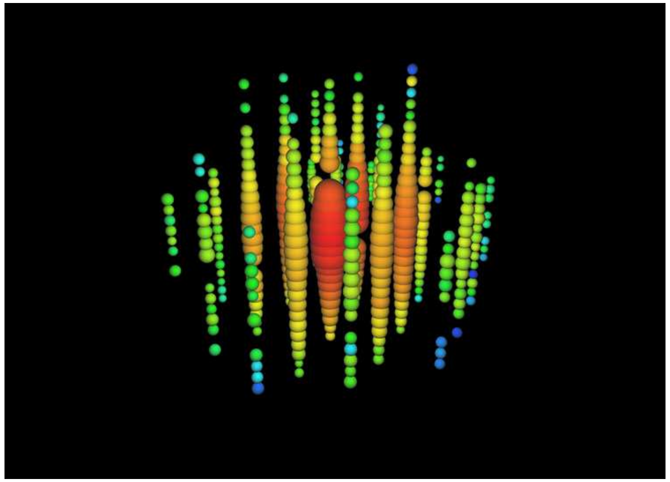
MiniBooNE: anomaly at $L \approx 500$ m for $E \approx 300$ MeV

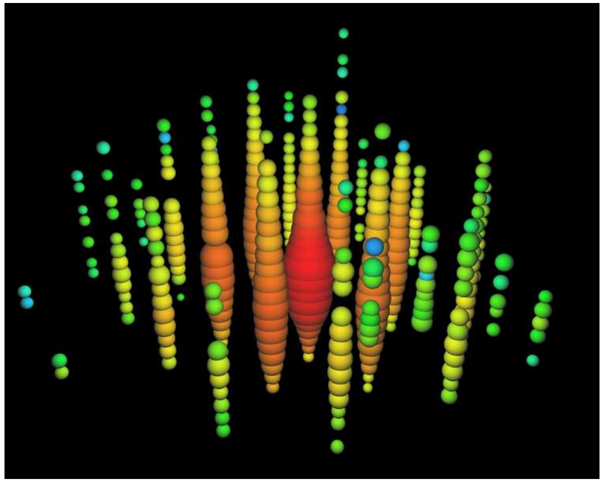
ν telescopes: anomaly at $L \approx 10$–100 km for $E \approx 1$ TeV ??

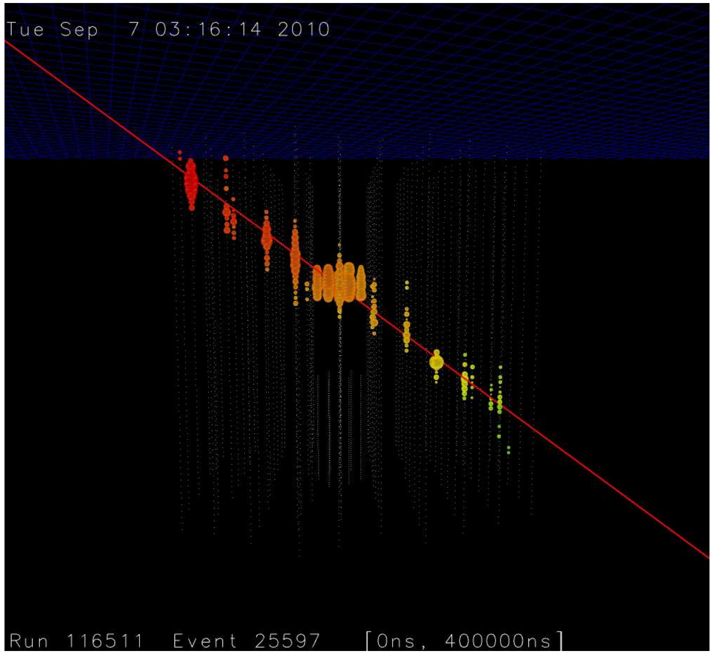


- Atmospheric muons and neutrinos can be seen at IceCube

- Bert, Ernie & Muon







• Analytical meson and lepton fluxes [*Z–moment* method, Gaisser, Lipari]

Set of coupled differential equations that describe the evolution with the atmospheric depth t (in g/cm^2) of the fluxes of *parent* hadrons (ϕ_H with $H = p, n, \pi^\pm, K^\pm, K_L$) and of any particles that may result from their decay or their collision with an air nucleus: [$\phi_H(E,\theta,t)$]

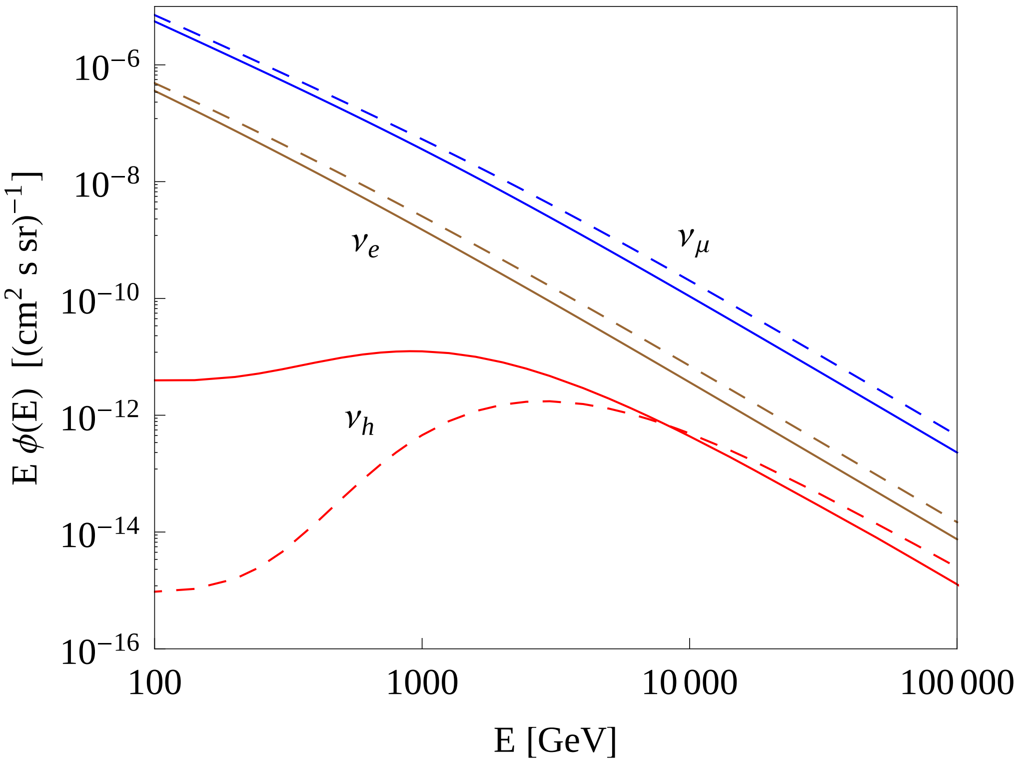
$$\frac{\partial \phi_H}{\partial t} = -\frac{\phi_H}{\lambda^H_{\rm dec}} - \frac{\phi_H}{\lambda^H_{\rm int}} + \sum_{H'} S_{H'H}$$

$$\text{Source:}\ \ S_{H'H} = \frac{\phi_{H'}}{\lambda^{H'}_{\rm int}} Z_{H'H} \qquad \text{Z}-\text{factors:}\ \ Z_{H'H} = \int_0^1 {\rm d}x\; x^{\alpha-1} F_{H'H}$$

$F_{H'H}(x)$: distribution of the fraction of energy taken by H after a H'–air collision ($x = E_H/E_{H'}$). Primary all nucleon flux: $\Phi_N \propto E^{-\alpha}$

$$B(K^+ \to \mu^+ \nu_h) \approx B(K^+ \to \mu^+ \nu) \times |U_{\mu h}|^2 \; \bar{\rho}_h \qquad \bar{\rho}_h \approx 1 + \frac{m_h^2}{m_\mu^2}$$

- Neutrino fluxes ($\nu_i + \bar{\nu}_i$) at sea level for $\theta = 0$ (solid) and $\theta = 60^o$ (dashes)



Z–moment method

$m_h = 60$ MeV

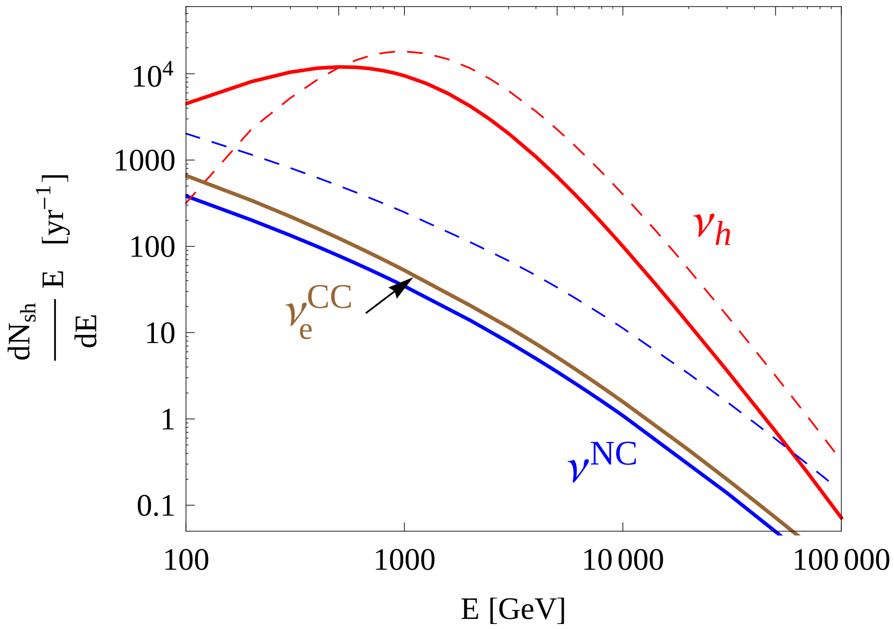
$|U_{\mu h}|^2 = 0.005$

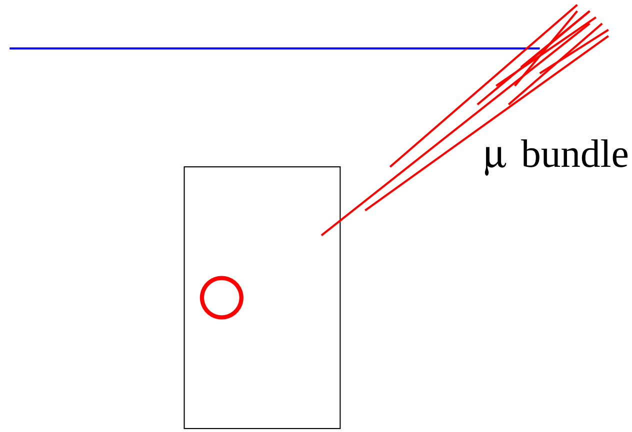
$\tau_h = 10^{-9}$ s

$\lambda_{dec} = 5$ km at $E = 1$ TeV

[PRD83(2011)091301]

• Contained events at ANTARES and the DeepCore in IceCube. In dashes the energy distribution of the parent neutrino.





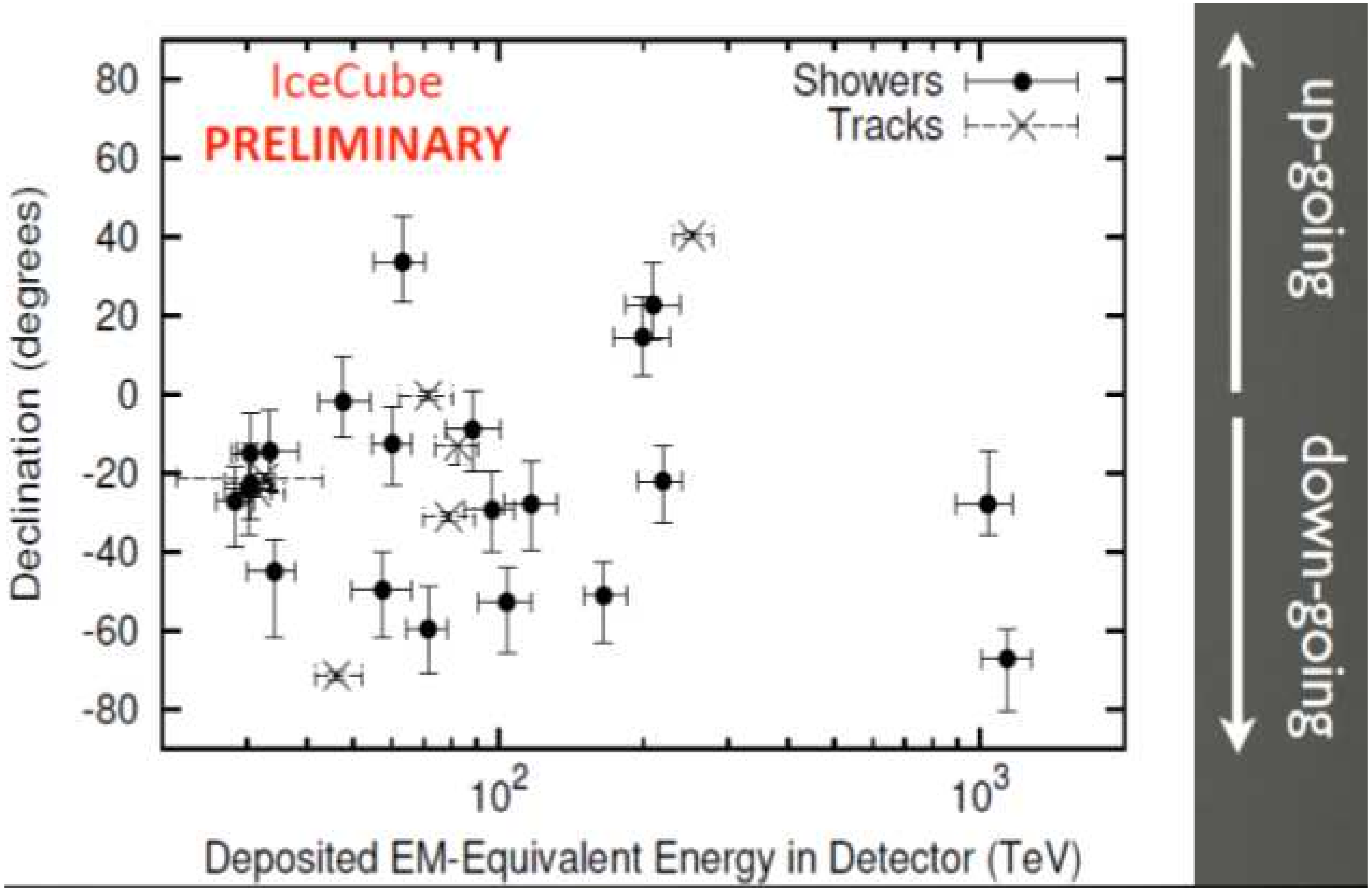
• 14000 $\nu_h \to \gamma\nu$ events of energy above 500 GeV per year, versus 220 standard events ($\nu_e N \to eX$ and $\nu_{\mu,e} N \to \nu_{\mu,e} X$)

• At energies below 100 GeV ν_h does not reach the telescope, above 1000 TeV its decay length becomes too large and the signal vanishes.

- Neutrinos ν_h produced in the atmosphere and decaying inside IceCube would produce an excess of contained events (similar to ν_e CC interactions or inelastic NC collisions) at energies 1–1000 TeV

- This excess would only appear in downgoing or near-horizontal events (no ν_h upgoing events)

- Most of these events (specially the ones from small zenith angles) would be contaminated with muons. Excess of muons plus contained cascade recent data from IceCube (at IPA 2013 ...)



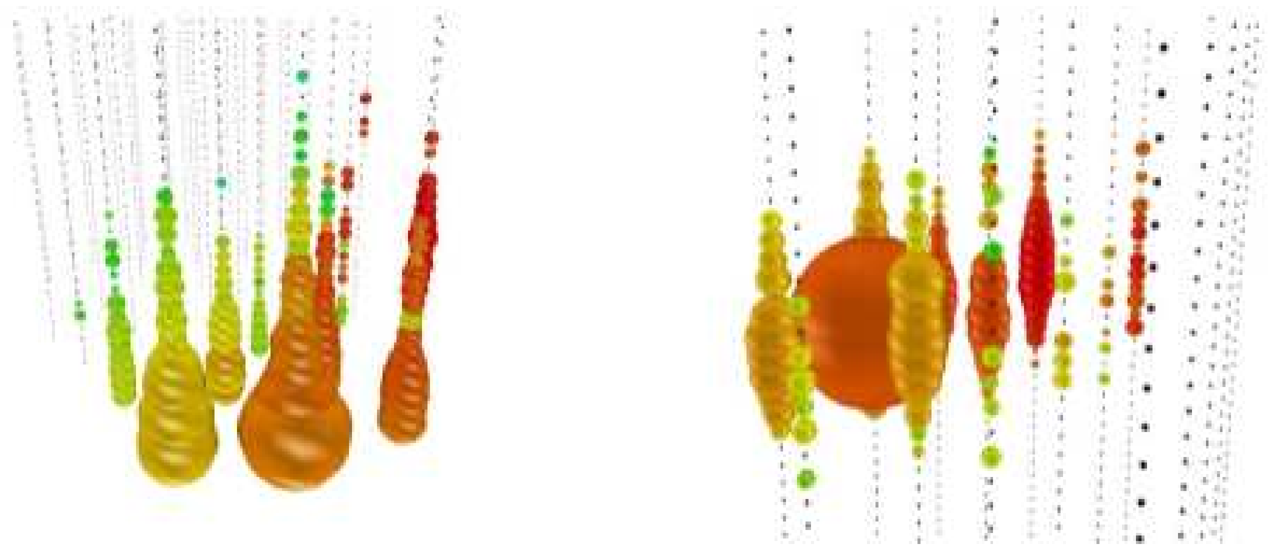
- 28 events (21 showers + 7 tracks), 4 tracks consistent with muons entering the detector (not neutrino events), spectrum $\approx E^{-2}$
- We expect 10.6 atmospheric events (1.8 showers + 8.8 tracks) with a spectrum $\approx E^{-3.7}$

First evidence of cosmic neutrinos (!?)

- If they are cosmic $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 1)$, there is an excess of showers versus tracks. Atmospheric neutrinos from charm decays $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 0.1)$ could not explain this excess.
- In any case, there is an excess of events from down-going directions. The Earth is not fully opaque (from zenith angles between 90^o and 150^o) to neutrinos of energy below 100 TeV.

... from an IceCube presentation at *Exotics with neutrino telescopes 2013* ...

Observed Events (High Light Density)



Expected BG Events:	0.14
Observed Events:	2

SUMMARY

- Neutrino physics has progressed a great deal during the past 20 years, but (i) basic questions are still unanswered and (ii) some *persistent* anomalies should be clarified (MicroBooNE this year?)

- A 50 MeV neutrino ν_h mixed with the muon flavor ($|U_{\mu h}|^2 \approx 0.003$) with a lifetime $c\tau = 1.5$ m, produced $\nu_\mu Z \to \nu_h Z$ and decaying $\nu_h \to \nu_{h'} \gamma$ through electromagnetic dipole transitions could explain LSND, KARMEN, TRIUMF, MiniBooNE.

- An excess of contained events at IceCube could be correlated with the LSND and MiniBooNE anomalies. These events would only be downgoing and quasi-horizontal, possibly *contaminated* by muons from the parent air shower.