A sterile neutrino at MiniBooNE and IceCube

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

Masip, Masjuan, PRD 83 (2011) 091301

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

Saint Petersburg, October 2013

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

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

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

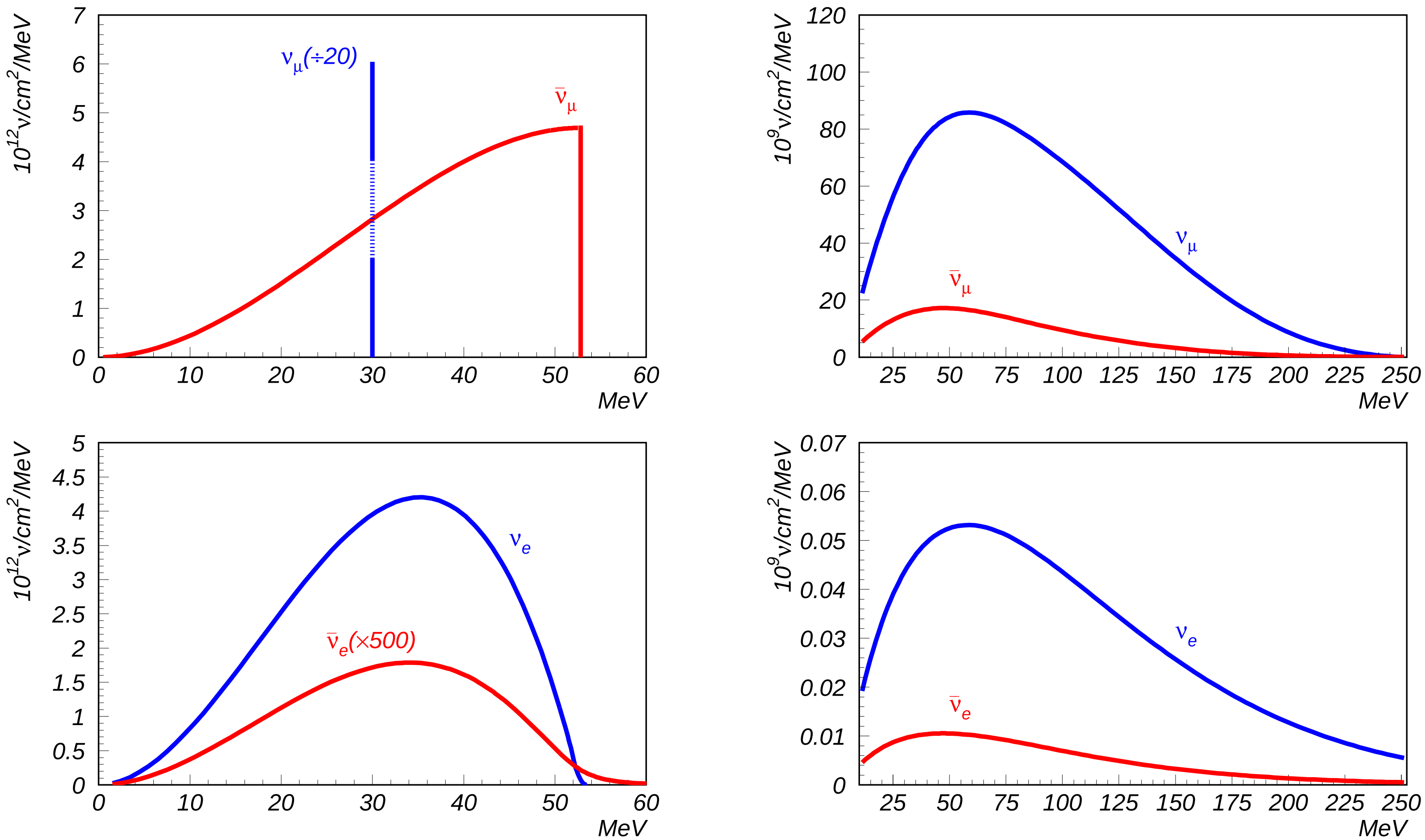
Is it $y_\nu\, HL\nu^c$ or $\dfrac{1}{\Lambda_\nu} HHLL$?

• *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?).

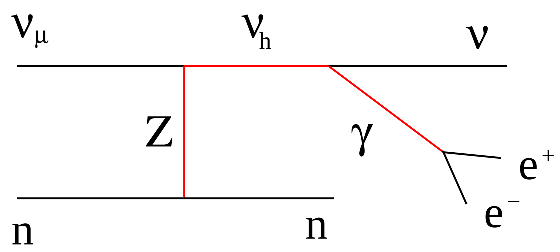
LSND, KARMEN, MiniBooNE, TRIUMF, T2K, NOMAD, IceCube

● 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.

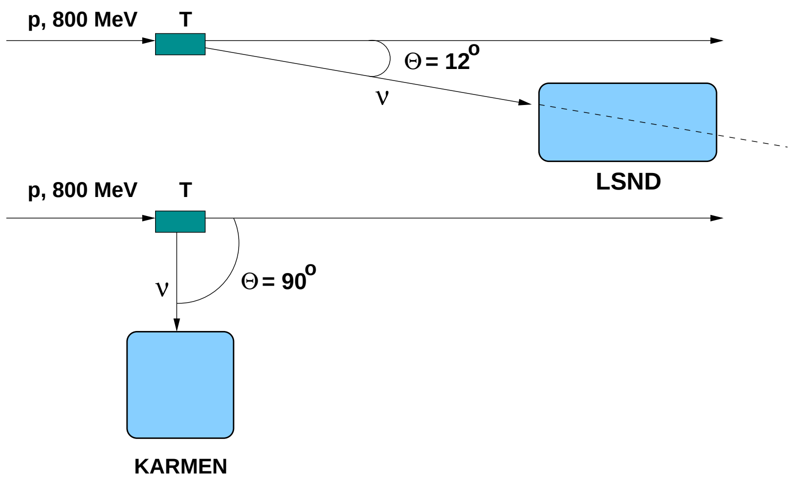
Fluxes: DAR (left) and DIF (right) $\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$; $\pi^+ \to \mu^+ \nu_\mu$

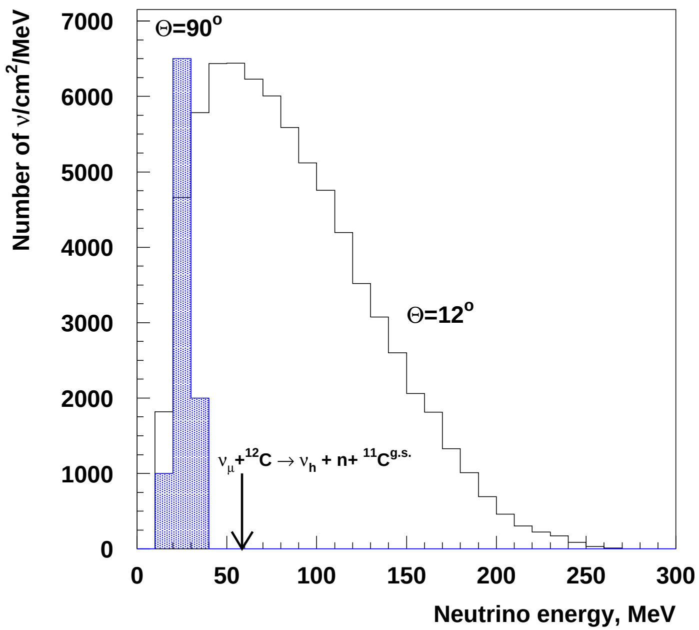


Gninenko's 50 MeV neutrino hypothesis to explain LSND



- 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

$$\mu^- \to e^- \, \bar{\nu}_e \, \nu_\mu \, \gamma \qquad 1.4 \pm 0.4\%$$

$$K^- \to \mu^- \, \bar{\nu}_\mu \, \gamma \qquad 0.62 \pm 0.08\%$$

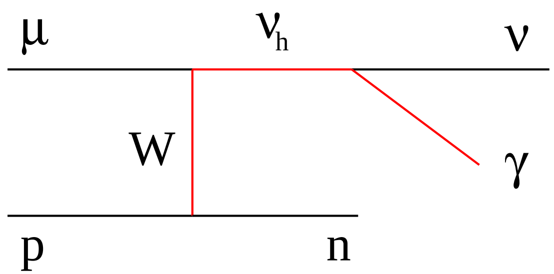
$$K^- \to \mu^- \, \bar{\nu}_\mu \, \pi^0 \qquad 3.35 \pm 0.03\%$$

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

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

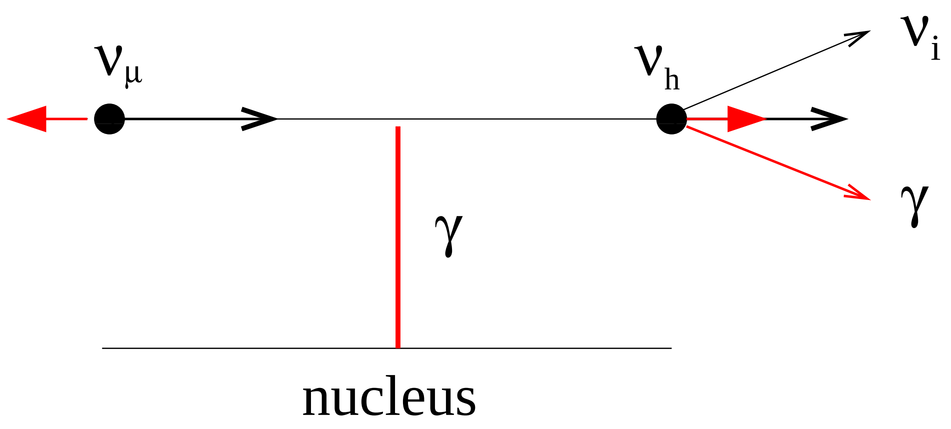


$$|U_{\mu h}|^2 \leq (2-8) \times 10^{-4} \ \text{ for } \ m_h = 40-80\ \rm MeV \ \text{ and } \ \tau_h < 10^{-9}\ \rm s$$

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

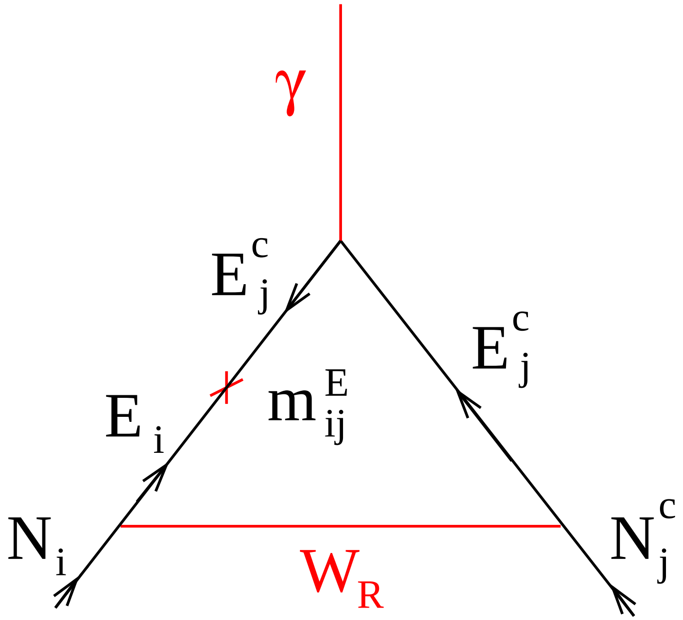
MiniBooNE will require $\mu_{\rm tr}^{\mu h} = 2 \times 10^{-9}\mu_B$

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

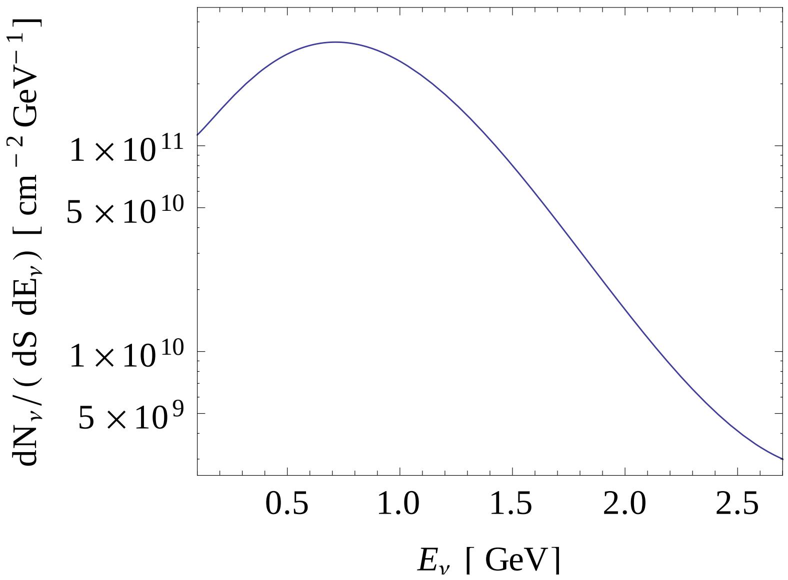
$$Y = T^3_R + B-L$$

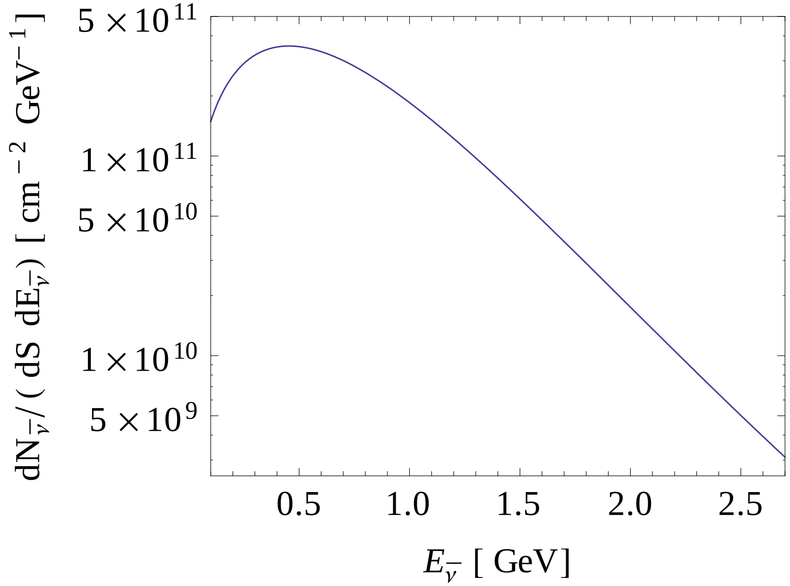
$$Q = T^3_L + Y$$

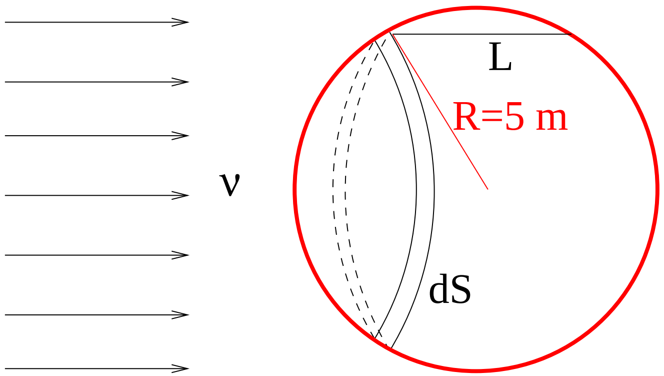
$$\nu_\mu' = c_\alpha \, \nu_\mu + s_\alpha \, N_1$$



$$L_1 = \begin{pmatrix} N_1 \\ E_1 \end{pmatrix} \quad L^c_1 = \begin{pmatrix} E^c_1 \\ N^c_1 \end{pmatrix} \qquad W \subset m_h \, L_1 L^c_1 + \frac{1}{\Lambda_1} \, (L^c_1 \chi^c) \, (L_1 \chi)$$

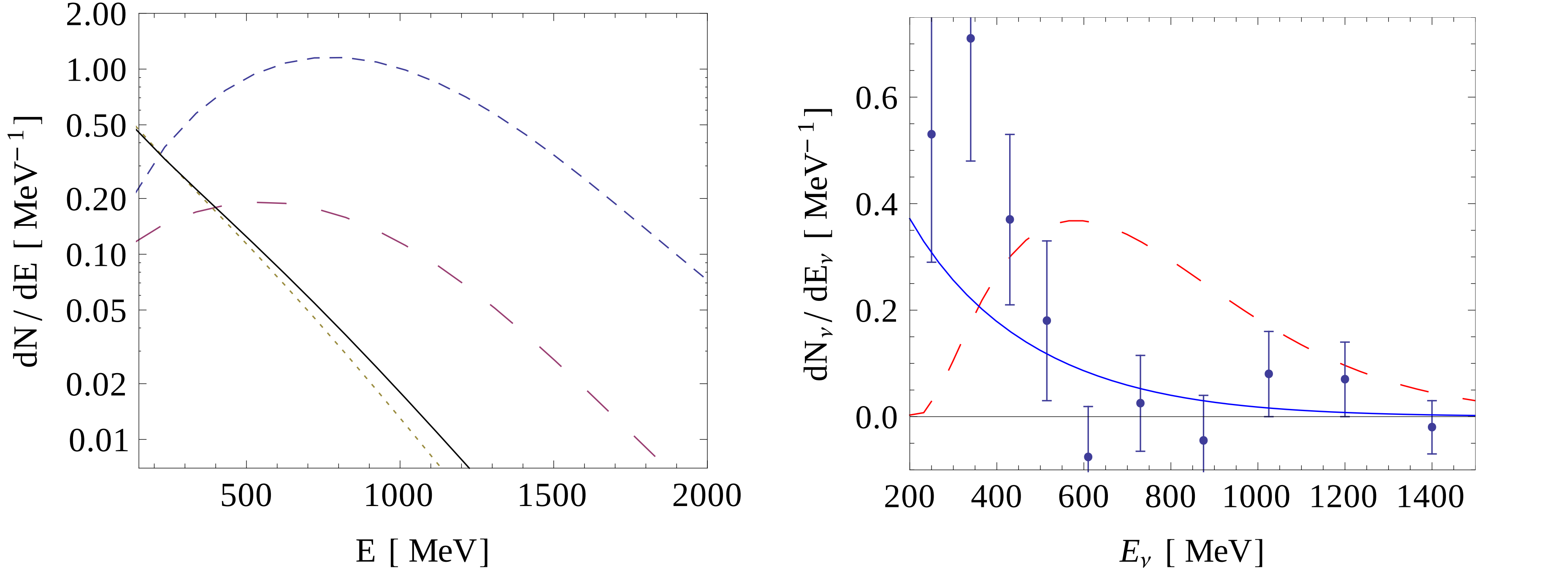




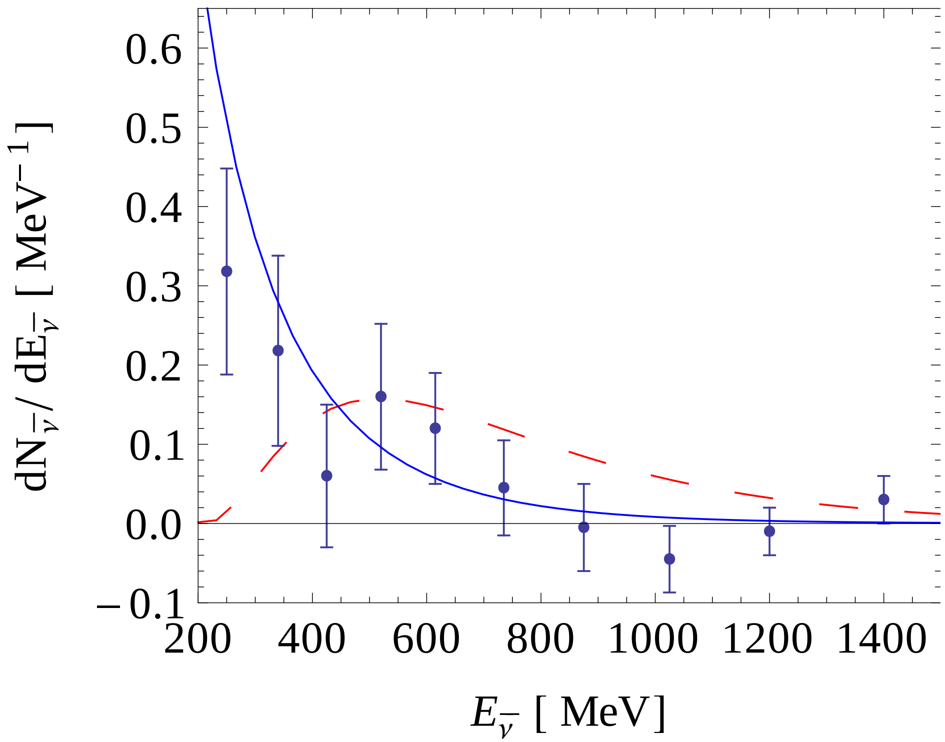


$$p_{\rm i} = \frac{\sigma\,\rho\,L}{m_{CH_2}}$$

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



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.

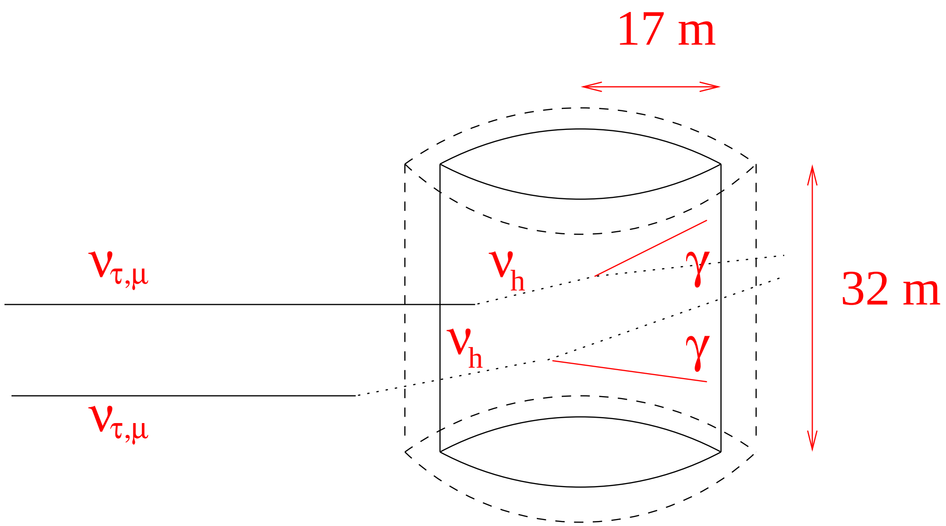
If BR$(\nu_h \to \nu_\mu \gamma) \approx 1\%$, is BR$(\nu_h \to \nu_\tau \gamma) \approx 99\%$?

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,

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

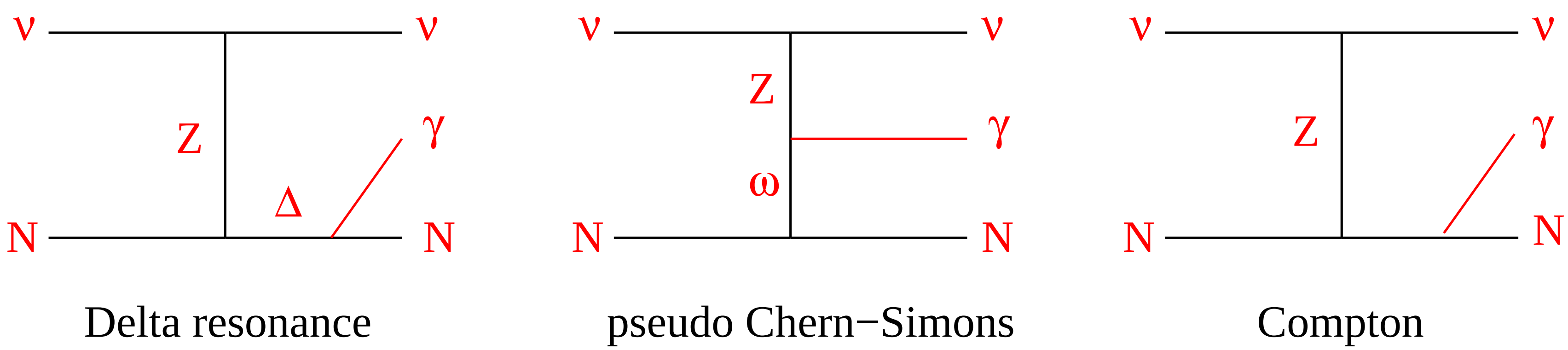


- $\nu_\mu \to \nu_e$ oscillations with $\sin^2 2\theta_{13} = 0.1$: 6 events
- $\nu_\mu Z \to \nu_h Z$: 1.1 events (75% from ν_h produced outside).
- ν_h must decay 99% of the times into another sterile neutrino!

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

- 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 will investigate whether the low-energy excess at MiniBooNE is cause by electron or by photon events,



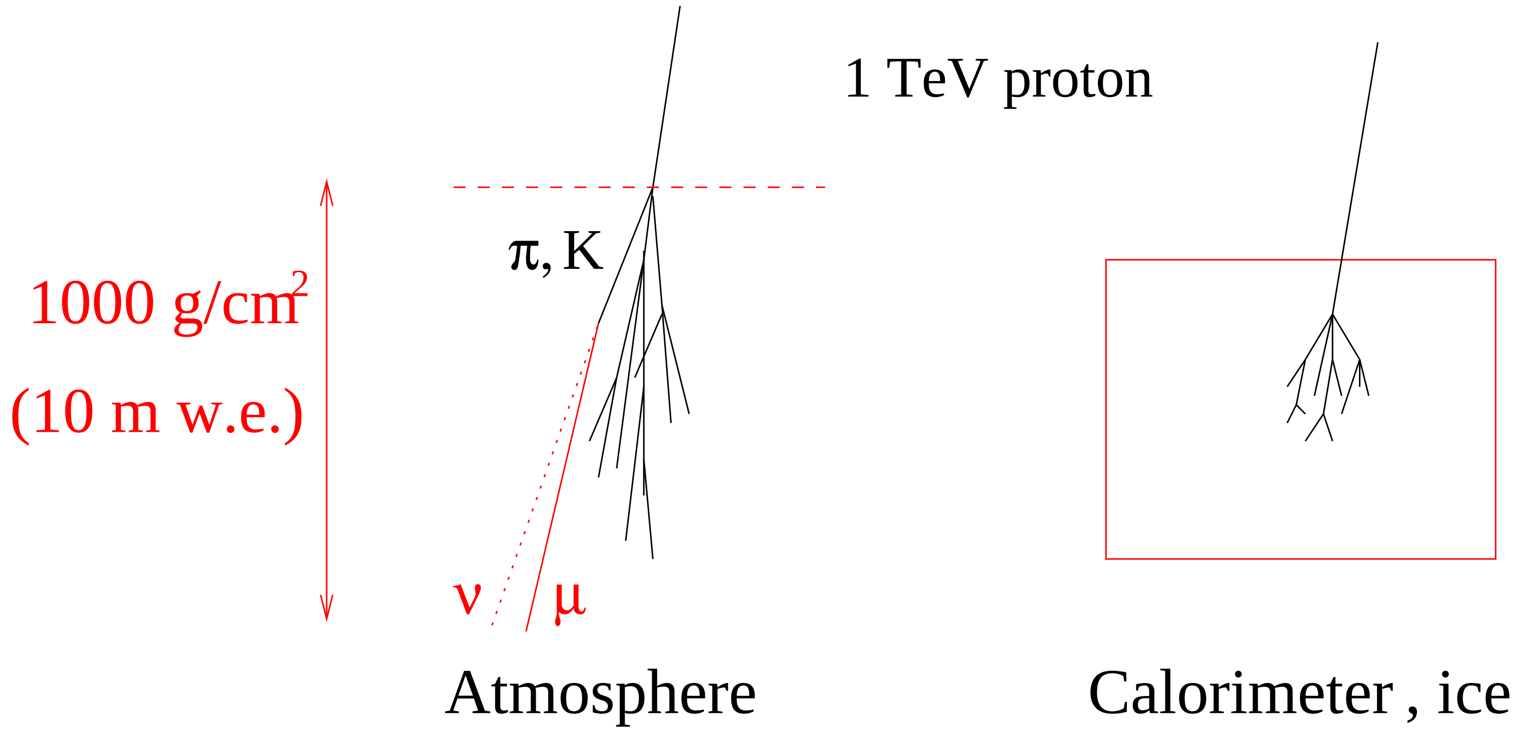
• There are observables that may distinguish this photon background from the $\nu_h \to \gamma \nu_{h'}$ hypothesis:

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

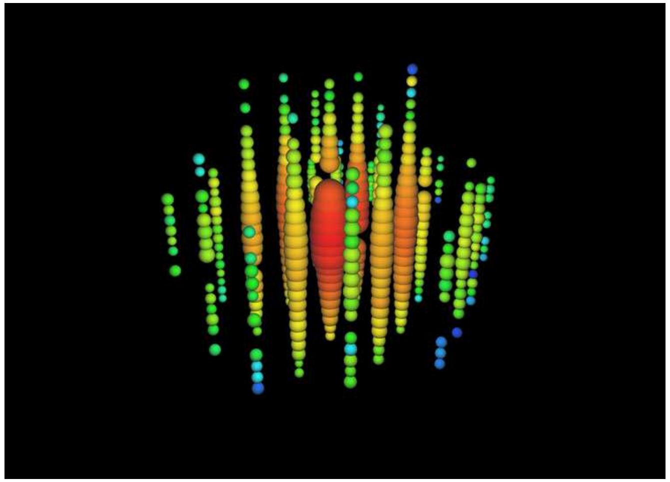
MiniBooNE: anomaly at $L \approx 500$ m for $E \approx 300$ MeV

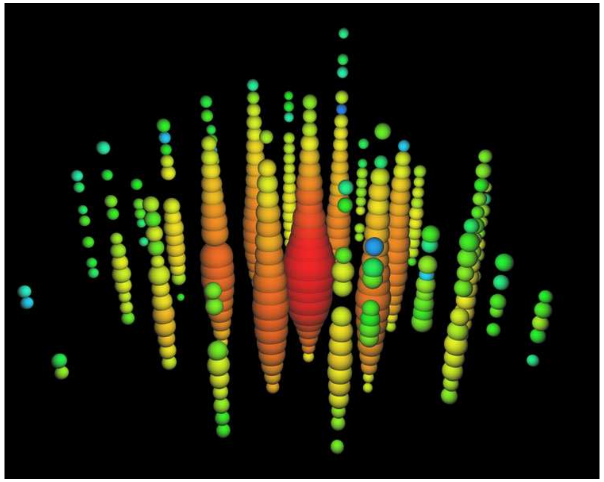
ν telescopes: anomaly at $L \approx 10$–100 km for $E \approx 1$ TeV ??

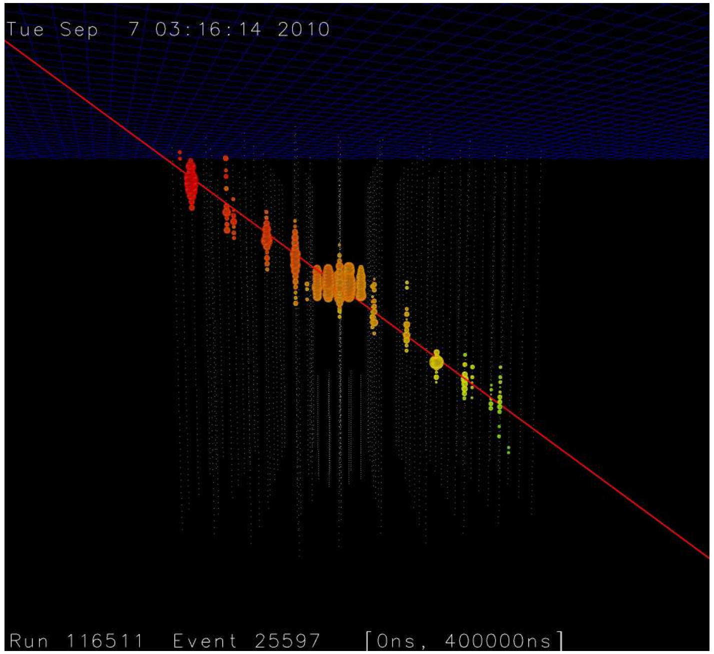


- Atmospheric muons and neutrinos can be seen at IceCube

- 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: [$\phi_H(E, \theta, t)$]

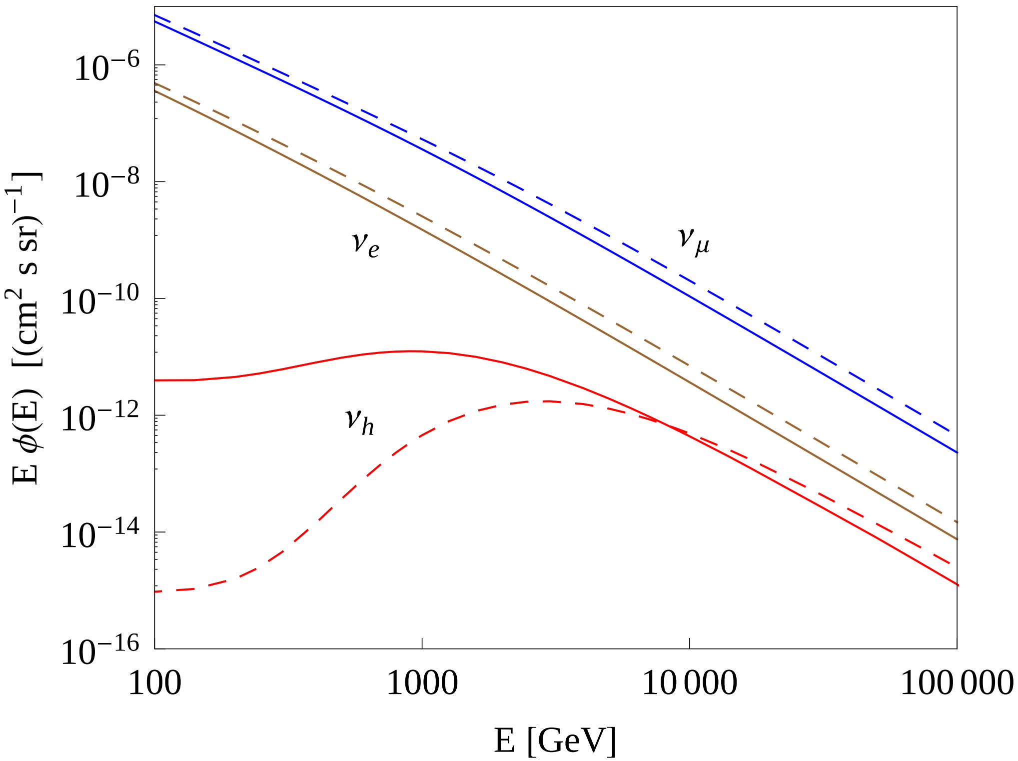
$$\frac{\partial \phi_H}{\partial t} = -\frac{\phi_H}{\lambda^H_{\rm dec}} - \frac{\phi_H}{\lambda^H_{\rm int}} + \sum_{H'} S_{H'H}$$

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

$F_{H'H}(x)$: 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

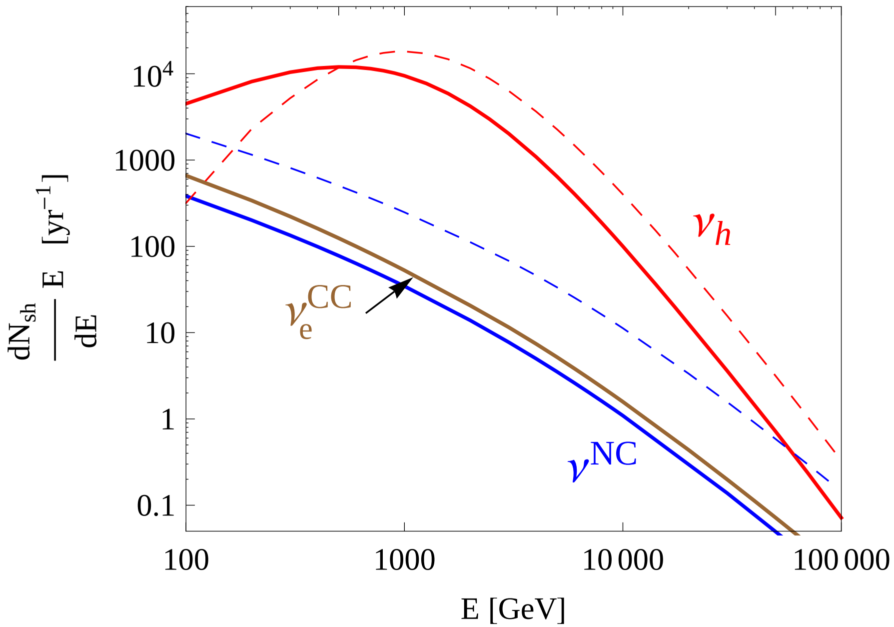
$|U_{\mu h}|^2 = 0.005$

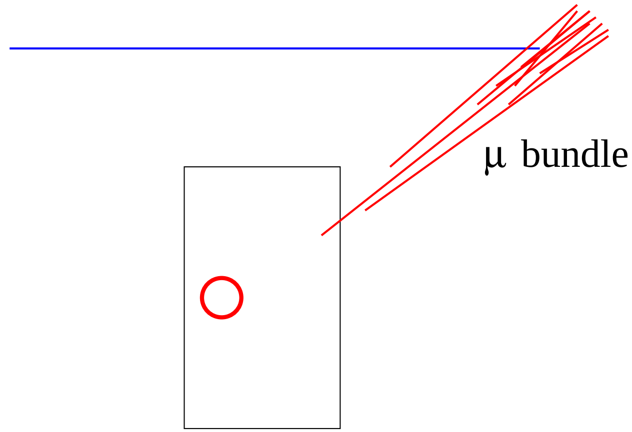
$\tau_h = 10^{-9}$ s

$\lambda_{dec} = 5$ 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.





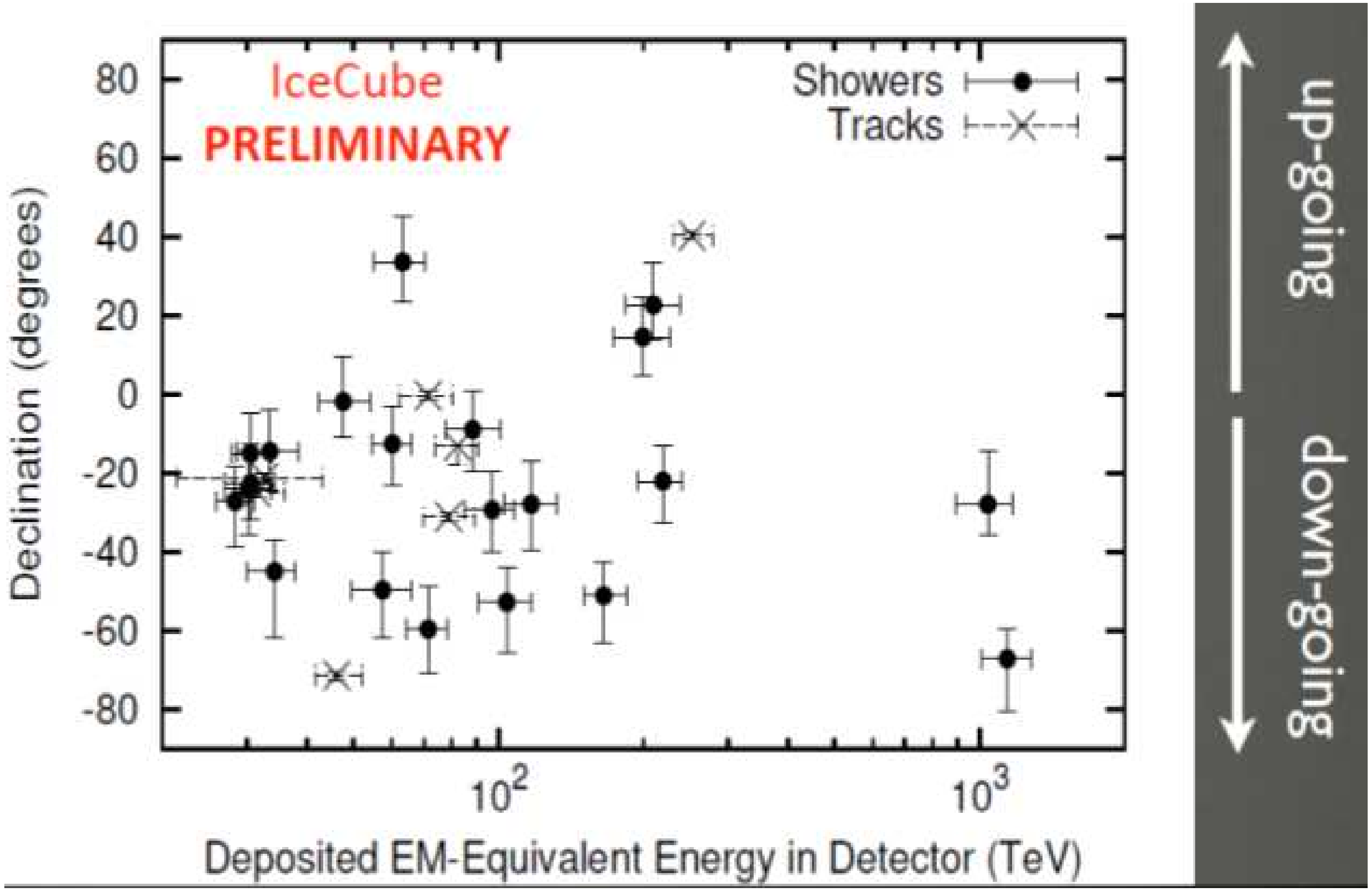
• 14000 $\nu_h \to \gamma\nu$ events of energy above 500 GeV per year, versus 220 standard events ($\nu_e N \to eX$ and $\nu_{\mu,e} N \to \nu_{\mu,e} X$)

• 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

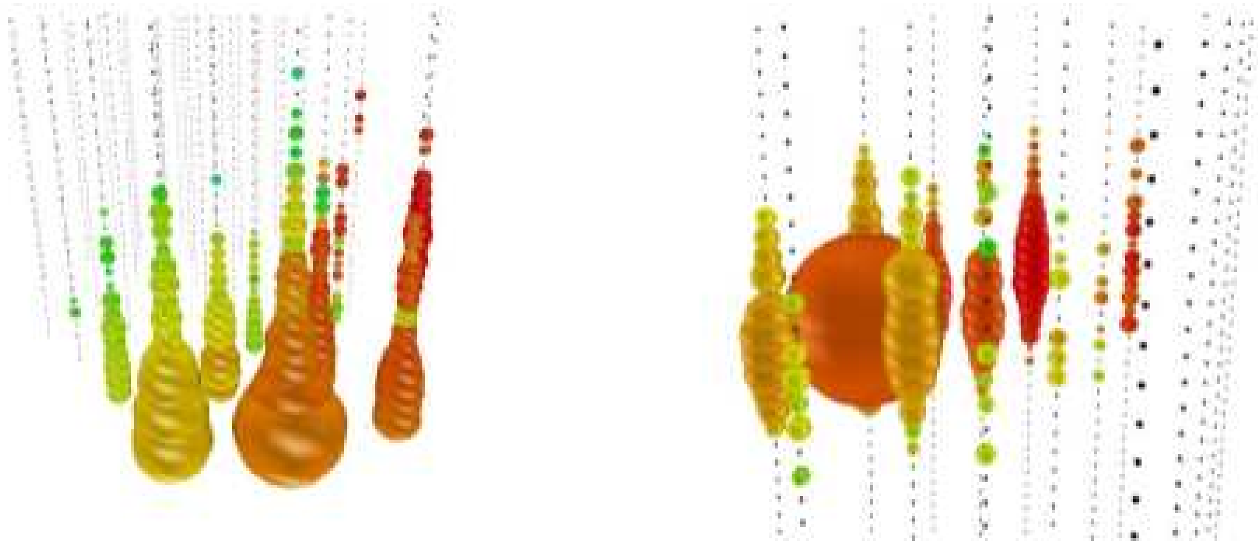
• This excess would only appear in downgoing or near-horizontal events (no ν_h upgoing events)

• 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 ...



... 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 next 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.