Extra Dimensions in Atmospheric Neutrinos

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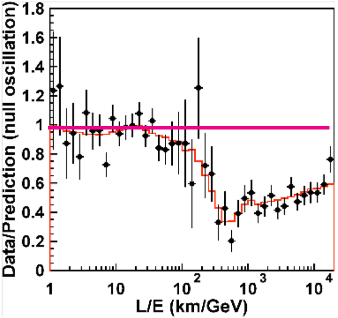
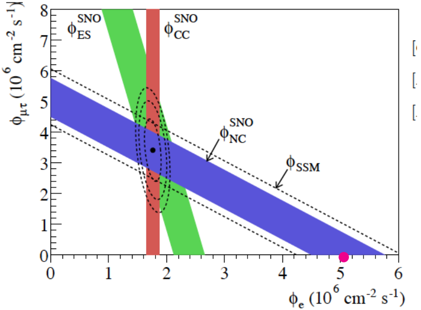
[1] In collaboration with Arman Esmaili and Zahra Tabrizi

- In the latest years there are stronger evidences for neutrino oscillation



Super-Kamiokande Experiment

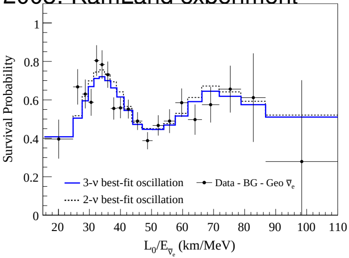


SNO experiment

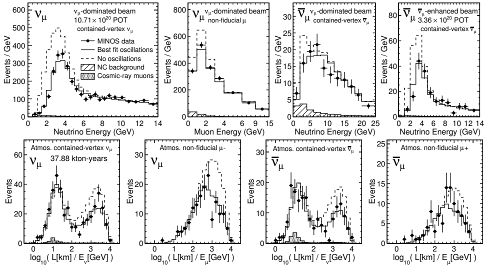
All evidences point to non-zero neutrino masses: Nobel prize in 2015!!

Oscillation discover in other expts

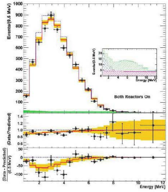
2008: KamLand experiment



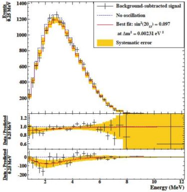
MINOS experiment: UFG/USP/UNICAMP



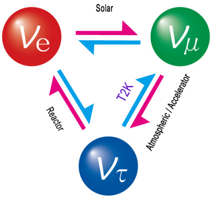
Double CHOOZ: UNICAMP/UFABC/CBPF



Gd-capture

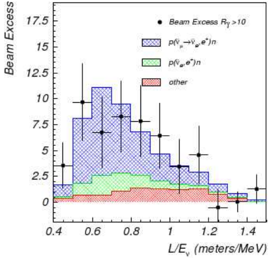


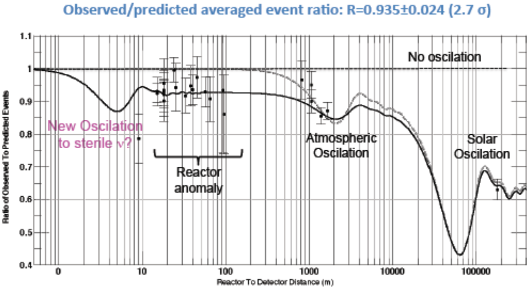
H-capture

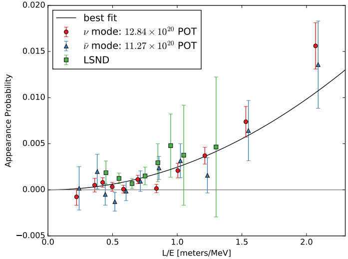


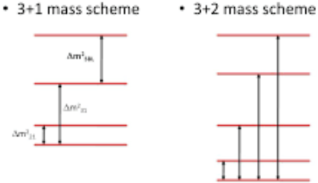
Neutrino oscillation between three generations

- LSND, Mini-BooNE (2018) and Reactor anomaly

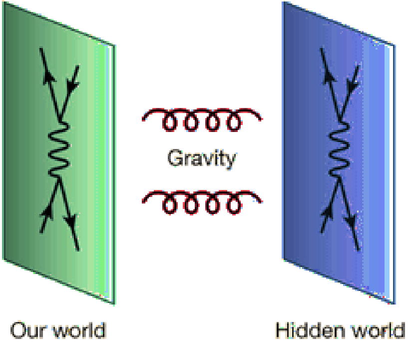








- Proposed by Arkani-Hamed, Savas Dimopoulos and Dvali (ADD)

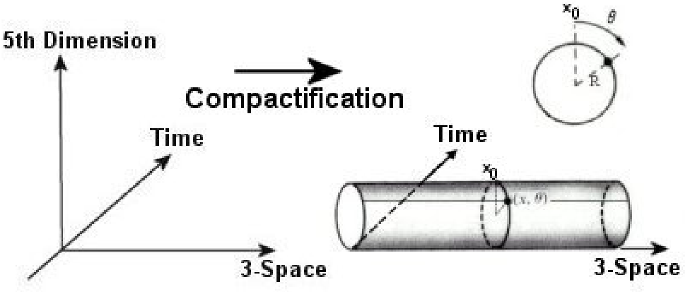


- Gauss law: $V \sim \dfrac{m_1 m_2}{M_D^{\delta+2} R_{\mathrm{ED}}^{\delta} r} = \dfrac{m_1 m_2}{M_{\mathrm{Pl}} r}$

Constrains from $1/r$ tests $R_{\mathrm{ED}} > 1$ mm

Large extra dimension model

Compactification: explanation of smallness of gravity: $\propto \dfrac{1}{V_{\rm ED}} \propto \dfrac{1}{R_{\rm ED}}$



One of extra dimensions have $R_{\rm ED}$ much greater then the other dimensions (5D) .

Neutrino in Large Extra Dimension Models

$$S_i = \int d^4x \, dy \, i\overline{\Psi}_i \Gamma^A \partial_A \Psi_i + \int d^4x \, \left[i\bar{\nu}_{iL} \, \partial\!\!\!/ \nu_{iL} + \lambda_{ij} h \bar{\nu}_{iL} \psi_{jR}(x, y = 0) \right]$$

<ins>Smallness of neutrino mass</ins>: $m_\nu \propto \dfrac{\lambda_{ij}}{R_{\rm ED}} \sim 1\text{eV}$

- Fourier modes: infinite number of states

Neutrino in Large Extra Dimension Models

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Mass terms

$$\sum_{n=-\infty}^{\infty} m_i^D \bar{\nu}_{iL} \psi_{iR}^{(n)} + \sum_{n=1}^{\infty} \frac{n}{R_{\rm ED}} \left(\overline{\psi_{iL}^{(n)}} \psi_{iR}^{(n)} - \overline{\psi_{iL}^{(-n)}} \psi_{iR}^{(-n)} \right) + \text{h.c.},$$

$$M_i = \lim_{n\to\infty} \begin{pmatrix} m_i^D & \sqrt{2}m_i^D & \sqrt{2}m_i^D & \sqrt{2}m_i^D & \dots & \sqrt{2}m_i^D \\ 0 & 1/R_{\rm ED} & 0 & 0 & \dots & 0 \\ 0 & 0 & 2/R_{\rm ED} & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & n/R_{\rm ED} \end{pmatrix}.$$

Only two free parameters $m_i^{\rm D}$ and $R_{\rm ED}$.

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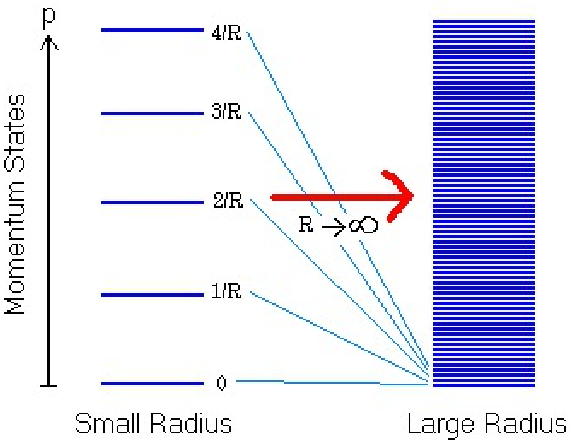
Neutrino in Large Extra Dimension Models

Depending on radius we can have oscillation on short and long scale



Flavor neutrinos

$$\frac{1}{R^2} >> \Delta m^2_{31}$$

$$\frac{1}{R^2} \sim \Delta m^2_{31}$$

Neutrino in Large Extra Dimension Models

The flavor eigenstates are written as

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL}^{(0)} = \sum_{i=1}^{3} U_{\alpha i}\sum_{n=0}^{\infty} S_i^{0n}\nu_{iL}'^{(n)} \;, \qquad (\alpha = e, \mu, \tau),$$

The eigenvalues are solution of

$$\lambda_i^{(n)} - \pi\left(m_i^D R_{\rm ED}\right)^2 \cot\left(\pi\lambda_i^{(n)}\right) = 0.$$

with solution

$$m_i^{(n)} = \frac{\lambda_i^{(n)}}{R_{\rm ED}} \simeq \frac{n}{R_{\rm ED}}, \qquad (n = 0, 1, \cdots),$$

- If $\underline{\Delta m_{31}^2 = m_3^2 - m_1^2} \sim \frac{n^2}{R_{\rm ED}^2}$: Stronger changes in neutrino oscillation

- If the radius $R_{\rm ED}$ is larger also stronger non-unitarity effects

$$\boxed{U_{\alpha i} \to U_{\alpha i} S_i^{0n}}$$

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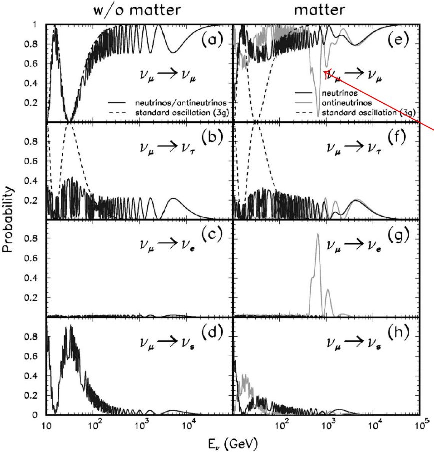
Matter effects for sterile ν

H. Nunokawa, O.L.G.P. and R. Zukanovich Funchal. Phys.Lett. B562 (2003)



Stronger muon disappearance.

Also: A. Nicolaidis, *et al.* hep-ph/9904415 and Osamu Yasuda, hep-ph/0102166

Stronger bound on $|U_{\mu 4}|^2$, A. Esmaili, F. Halzen and O.L.G.P. JCAP 1211, 041(2012)

Matter effects in Large extra dimensions

Matter potential in mass basis

$$
i\frac{d}{dt}\begin{pmatrix}\nu_1^{(0)}\\ \nu_2^{(0)}\\ \nu_3^{(0)}\\ \nu_1^{(1)}\\ \nu_2^{(1)}\\ \nu_3^{(1)}\\ \nu_1^{(2)}\\ \nu_2^{(2)}\\ \nu_3^{(2)}\\ \vdots\\ \nu_1^{(N)}\\ \nu_2^{(N)}\\ \nu_3^{(N)}\end{pmatrix}=\frac{1}{2ER_{\rm ED}^2}\left(\begin{array}{ccc|ccc|ccc|c|ccc}
\eta_1+V_{11} & V_{12} & V_{13} & \xi_1 & 0 & 0 & 2\xi_1 & 0 & 0 & \dots & N\xi_1 & 0 & 0\\
V_{21} & \eta_2+V_{22} & V_{23} & 0 & \xi_2 & 0 & 0 & 2\xi_2 & 0 & \dots & 0 & N\xi_2 & 0\\
V_{31} & V_{32} & \eta_3+V_{33} & 0 & 0 & \xi_3 & 0 & 0 & 2\xi_3 & \dots & 0 & 0 & N\xi_3\\ \hline
\xi_1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0\\
0 & \xi_2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0\\
0 & 0 & \xi_3 & 0 & 0 & 1 & 0 & 0 & 0 & \dots & 0 & 0 & 0\\ \hline
2\xi_1 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & \dots & 0 & 0 & 0\\
0 & 2\xi_2 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & \dots & 0 & 0 & 0\\
0 & 0 & 2\xi_3 & 0 & 0 & 0 & 0 & 0 & 4 & \dots & 0 & 0 & 0\\ \hline
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots\\ \hline
N\xi_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & N^2 & 0 & 0\\
0 & N\xi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 & N^2 & 0\\
0 & 0 & N\xi_3 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 & 0 & N^2
\end{array}\right)\begin{pmatrix}\nu_1^{(0)}\\ \nu_2^{(0)}\\ \nu_3^{(0)}\\ \nu_1^{(1)}\\ \nu_2^{(1)}\\ \nu_3^{(1)}\\ \nu_1^{(2)}\\ \nu_2^{(2)}\\ \nu_3^{(2)}\\ \vdots\\ \nu_1^{(N)}\\ \nu_2^{(N)}\\ \nu_3^{(N)}\end{pmatrix}
$$

For neutrinos

Mass eigenstates

$$\eta_i = (N+1/2)\,\xi_i^2\,, \qquad V_{ij} = 2ER_{\rm ED}^2 \sum_{\alpha=e,\mu,\tau} U^*_{\alpha i}U_{\alpha j}V_\alpha$$

$$\xi_i = \sqrt{2}m_i^D R_{\rm ED}$$

For anti-neutrinos: $\overline{V}_\mu < 0$ then $\overline{\nu}_\mu \to \nu_s$ transition

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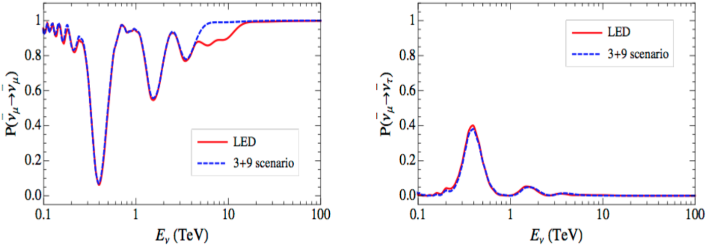
The Oscillation Probabilities

$$\Delta m^2 \sim \frac{1}{R^2} \sim 0.16\text{eV}^2$$

$$\sin^2\theta \sim (mR)^2 \sim 2.5\times 10^{-2}$$

- For 3 KK modes:

$$m_1^D = 0.01 \text{ eV and } R_{\text{ED}} = 5\times 10^{-5} \text{ cm}$$



(a) $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ (b) $P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$

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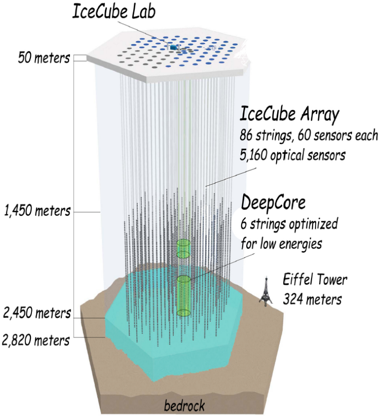
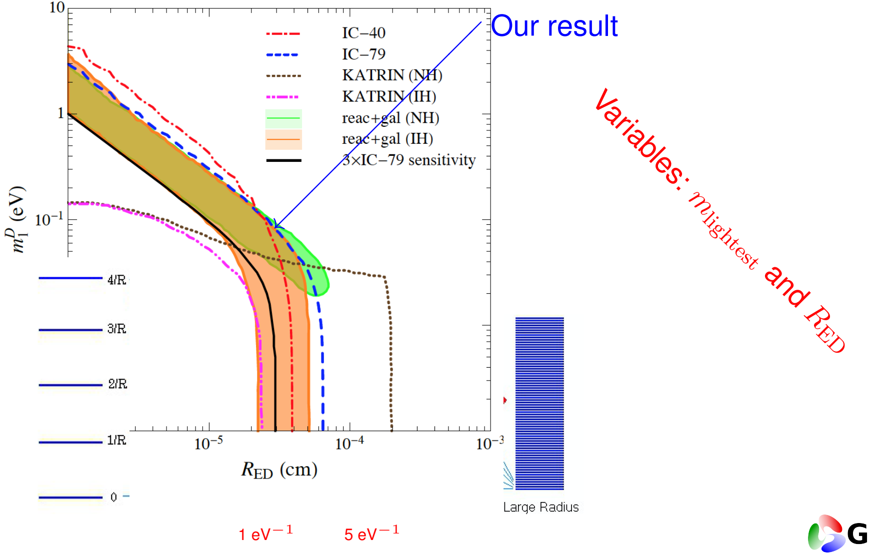
ICECUBE experiment

- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 120 m string spacing
- Angular resolution $\sim 1^o$
- Completed 2010



χ^2 analysis of muon disaepparance data of ICECUBE



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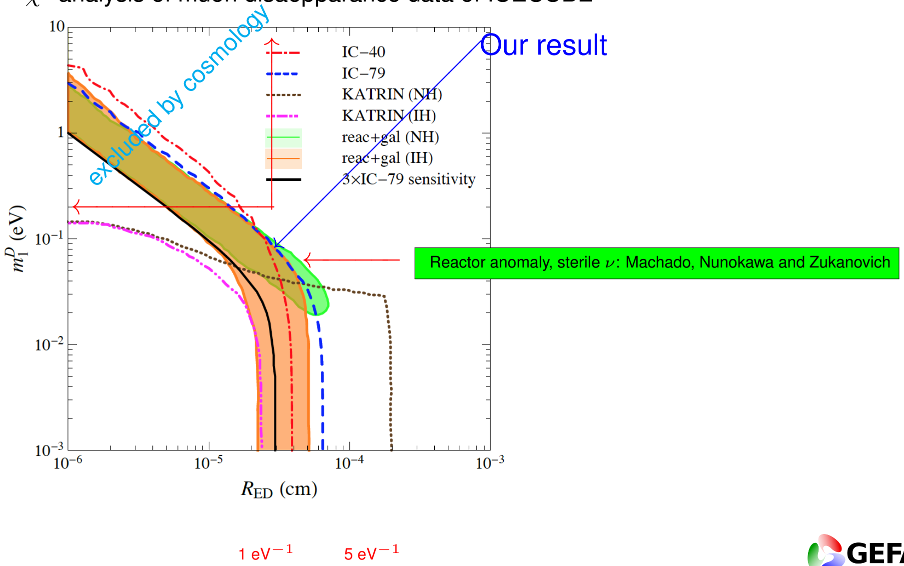
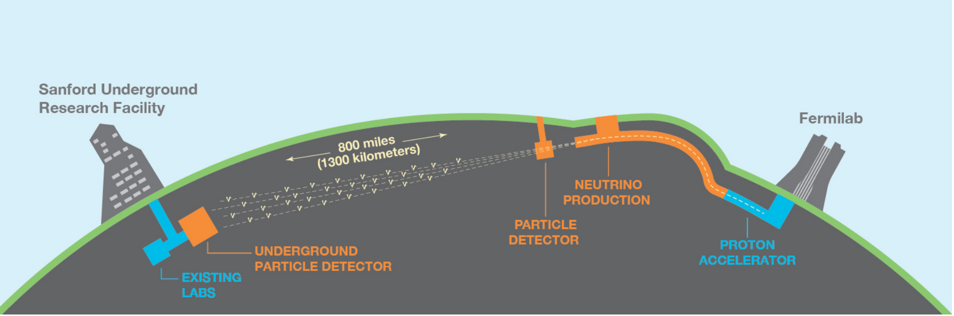


Test in longbaseline experiments: DUNE



Measure μ (e) events: Test of P($\nu_\mu \to \nu_\mu$)($P(\bar{\nu}_\mu \to \bar{\nu}_\mu$) and P($\nu_\mu \to \nu_e$)(P($\bar{\nu}_\mu \to \bar{\nu}_e$))

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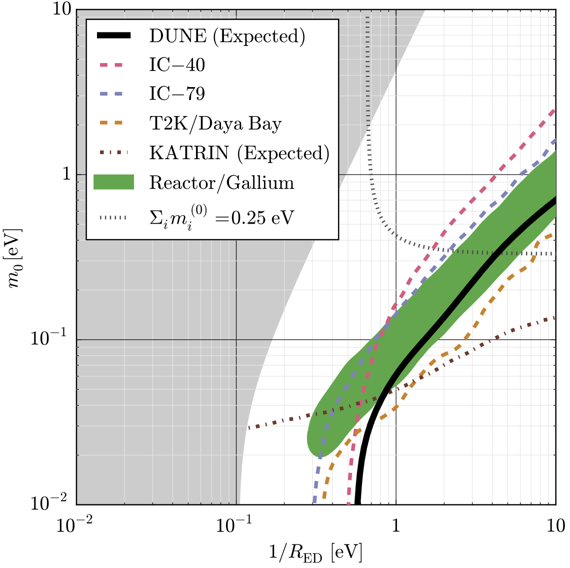
Constrains on large extra dimensions



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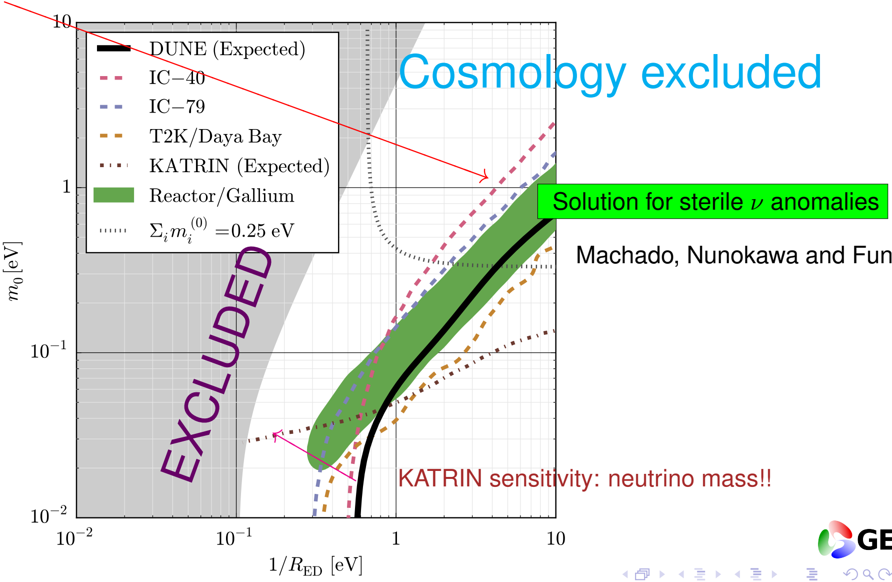
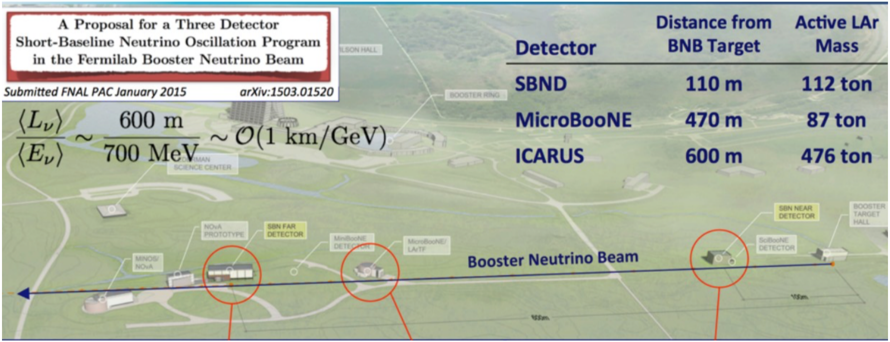
Constrains on large extra dimensions

IC-40/IC-79: ICECUBE analysis by O. L. G. P., Esmaili and Tabrizi (USP)

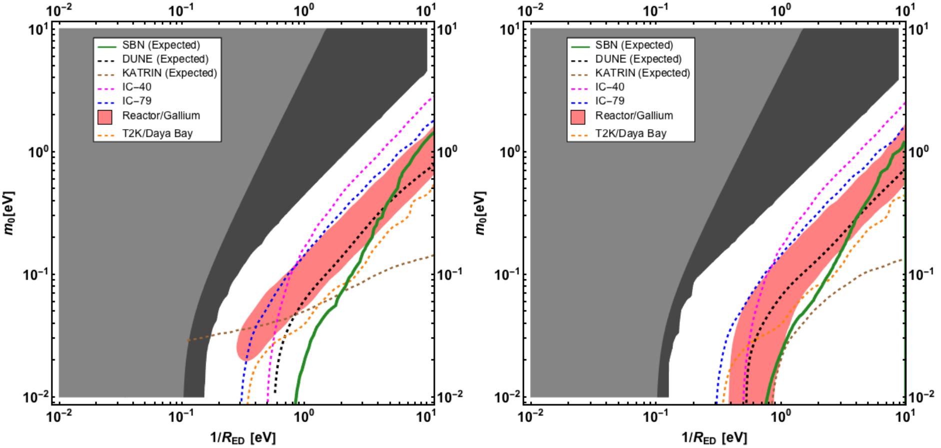


Machado, Nunokawa and Funchal

Short Baseline program for FERMILAB



Sensitivity region for SBN

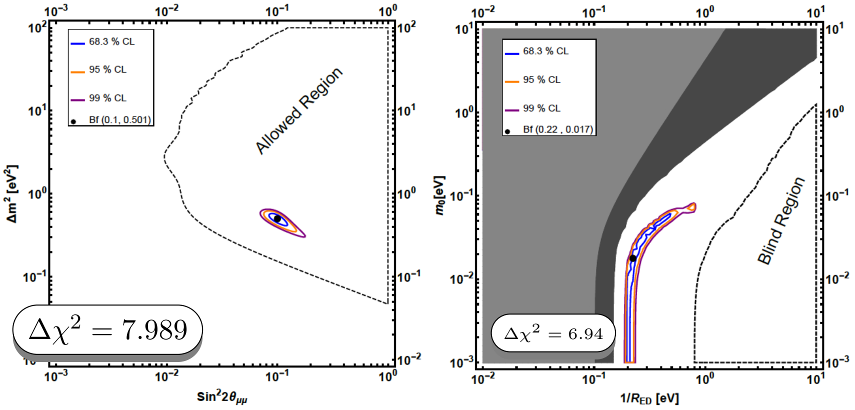


Work in progress, G. Stenico, D. Vanegas Forero and O.L.G.P.

Discrimination power

TRUE LED: $\rightarrow$ 3+1 scenario

TRUE 3+1 model : $\rightarrow$ LED scenario



Conclusions

1. Smallness of neutrino mass: motivated by large extra dimension models?
2. Neutrinos in large extra dimension models: oscillation pattern and non-unitarity
3. Future experiments can provide very good constrains on size of extra dimension
4. Full discrimination between the extra dimension oscillation model and the usual three neutrino theory
5. ICECUBE ($3\times$ IC-70) $R_{\rm ED} > 2,5(3,0) \times 10^{-5}$ cm for small m_0

Support : Projeto Temático FAPESP 2014/19164-6.

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