Large Extra Dimensions at IceCube and DUNE

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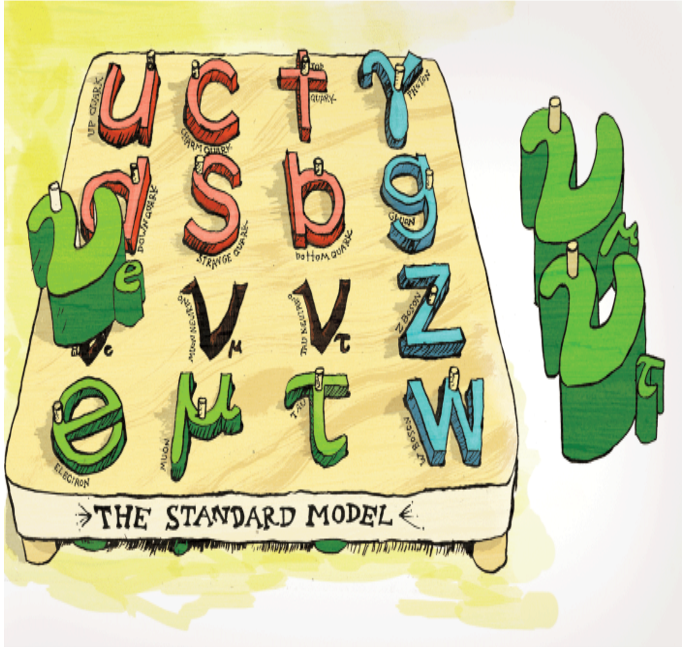
Neutrinos in the SM

$$\mathcal{L} = \sum_{\alpha=e,\mu,\tau} i\bar{\nu}_L^\alpha \partial\!\!\!/ \nu_L^\alpha$$ (neutrino Kinetic term)

$$- \frac{g}{2\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_L^\alpha \gamma^\rho (1-\gamma^5) l_\alpha W_\rho + h.c.$$ (Charged Current Interaction)

$$- \frac{g}{4\cos\theta_w} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_L^\alpha \gamma^\rho (1-\gamma^5) \nu_L^\alpha Z_\rho$$ (Neutral Current Interaction)

$$- \sum_{\alpha=e,\mu,\tau} \bar{l}_L^\alpha M^l l_R^\alpha + h.c.$$ (leptonic mass term)



$$\mathbf{L_e} = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$$

$$\mathbf{L}_\mu = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$$

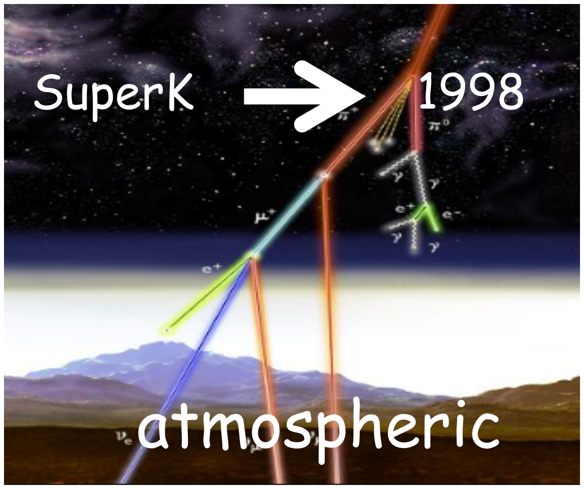
$$\mathbf{L}_\tau = \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

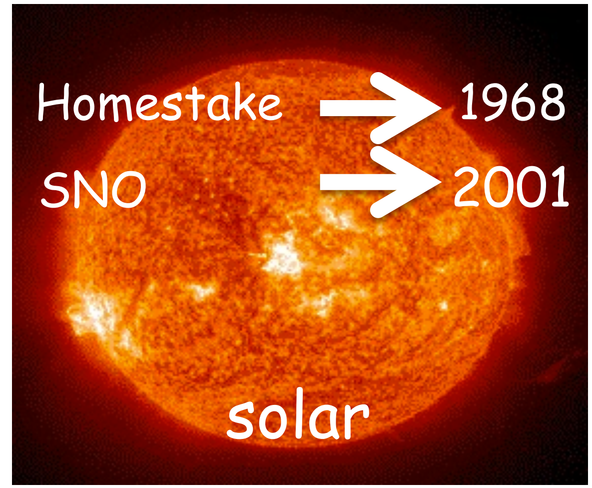
No right handed neutrinos in the SM, hence no mass!!!

Neutrinos have no mass in the SM!

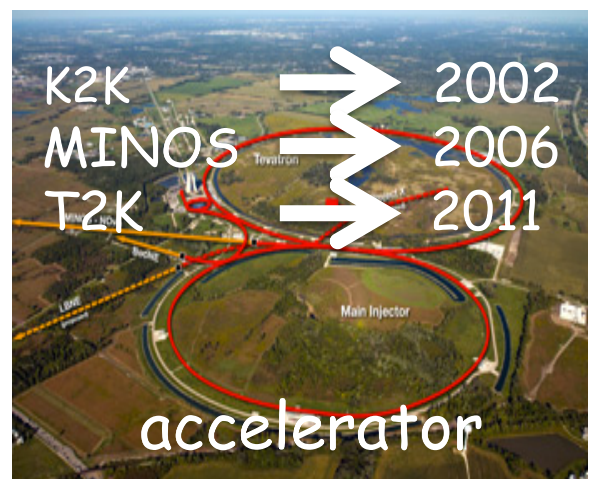
Surprise!!!

However in nature.....





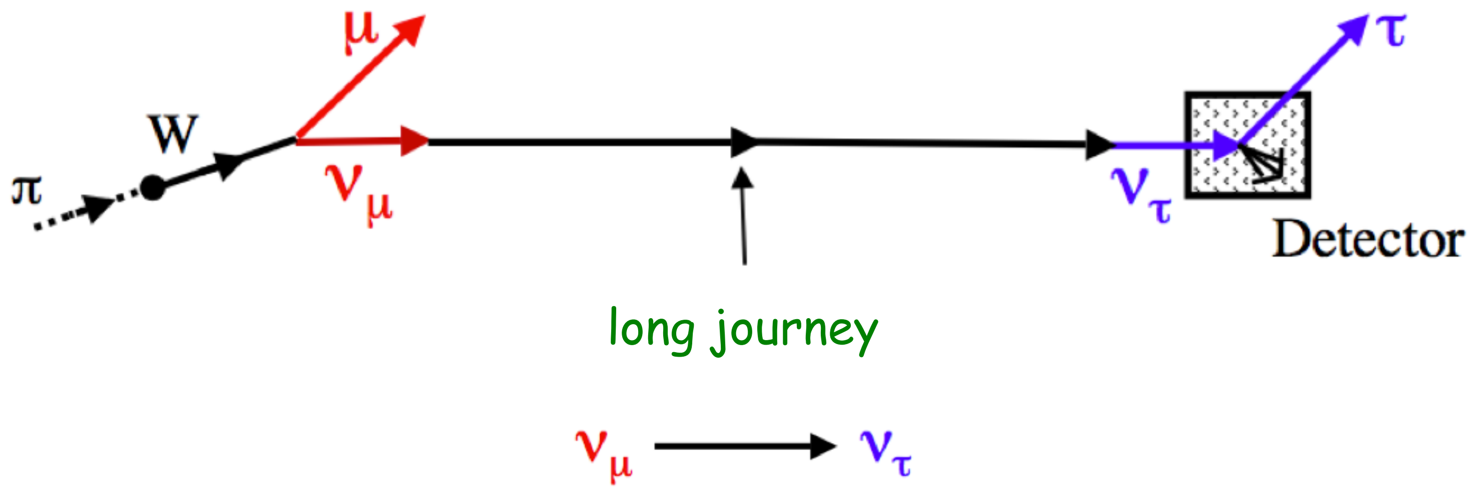
Neutrino oscillation needs masses and mixing!



The oscillation is described by the "PMNS" matrix!

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\overline{\ell^i_L}\gamma^\mu \boxed{U_{PMNS}} \nu_j W^+_\mu + h.c.$$

If neutrinos have mass, and leptons mix, we can have neutrino oscillation:



Neutrino experiments performed in the last 2 decades have proved that such flavor changes actually occur!

Two Flavors

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

One mixing angle
No CP phase

$$\Delta m^2 = \Delta m^2_{21} = m^2_2 - m^2_1$$

One mass-squared difference

$$P(\nu_\alpha \to \nu_\beta) = \frac{1}{2}\sin^2 2\theta \left[1 - \cos\left(\frac{\Delta m^2 L}{2E}\right)\right]$$

$$= \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Transition probability

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Survival probability

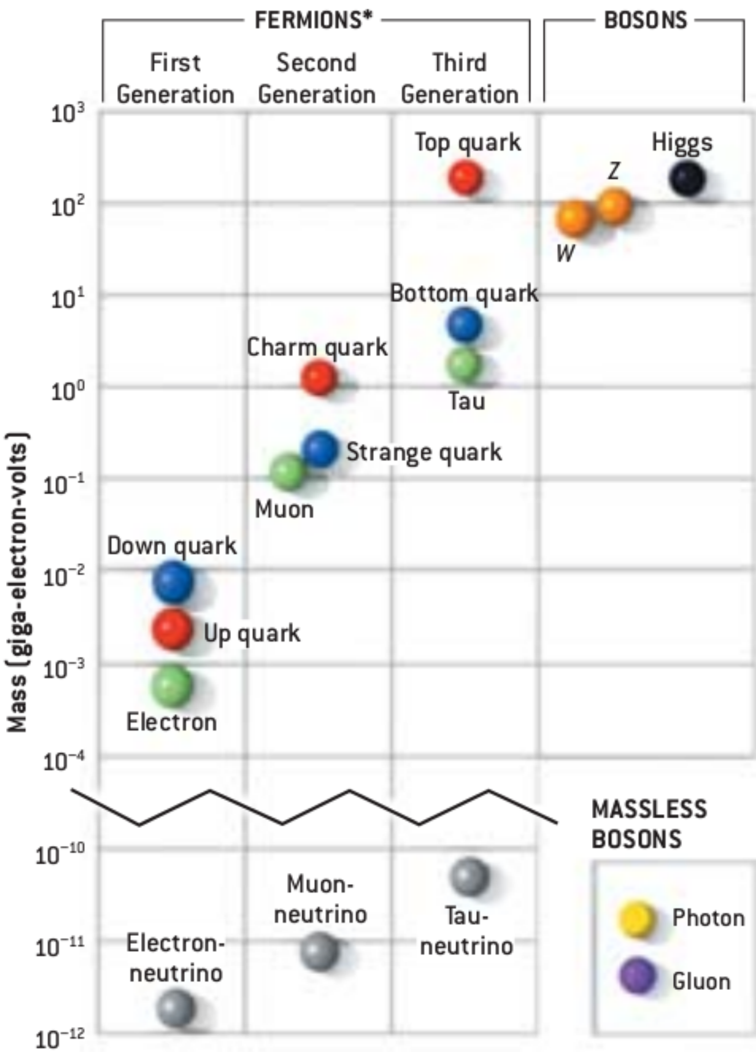
Standard picture of neutrinos

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i$$

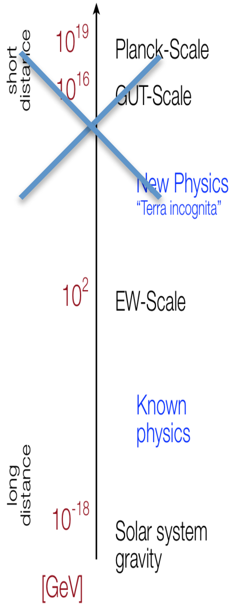
$$\alpha = e, \mu, \tau$$

$$U_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Smallness of Neutrino Masses



How can we explain it?!!



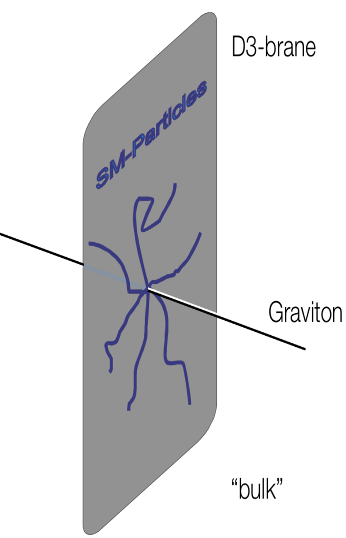
LED: One solution to the hierarchy problem

[Arkani-Hamed, Dimopoulos and Dvali, 1998]

Idea: Graviton propagates in the extra dimension

$$4D \rightarrow (4+n)D$$
$$\Lambda_{Pl} \rightarrow M \sim m_{ew}$$

- ✓ "n" compactified extra space dimensions with size R.
- ✓ Gravity in all "3+n" space dimensions
- ✓ SM interactions and all matter particles (including ν_L) have to be confined to our 4-dimensional world.



$$M^2_{Pl} = V_n M_f^{2+n}$$
$$V_n = (2\pi)^n R^n$$

- ✓ At least 2 extra dimensions are needed:

$$n \geq 2$$

Kaluza-Klein Theory

- Extra dimensions should be compact. Simplest case is periodic with radius R.

$$\phi(x^\mu, y) = \phi^0(x^\mu) + \sum_{n=1}^{\infty} \phi^{(n)}(x^\mu) e^{i\frac{n}{R}y} + h.c.$$

- Consider the 5-dimensional Klein-Gordon eq.:

$$\partial_M \partial^M \phi = 0,$$
$$\partial_\mu \partial^\mu \phi - \partial_y \partial^y \phi = 0,$$
$$(\partial_\mu \partial^\mu + (n/R)^2)\phi^{(n)} = 0.$$

- This is a tower of states with: $m_n^2 = (n/R)^2$.

Formalism

If a SM singlet fermion (such as the sterile neutrino) is present, it can also propagate to more than 4-dimensions.

[Arkani-Hamed, Dimopoulos and Dvali, Russell 1998]

$$S = \int d^4x\, dy\, i\bar{\Psi}^\alpha \Gamma^A \partial_A \Psi_\alpha + \int d^4x\, \left(i\bar{\nu}_{\alpha L}\bar{\sigma}^\mu \partial_\mu \nu_L^\alpha + \lambda_{\alpha\beta} H \bar{\nu}_L^\alpha \psi_R^\beta(x,0) + h.c.\right)$$

The 5-dimensional fermion

The SM neutrinos

After compactification:

$$\nu_R^{\alpha(0)} \equiv \psi_R^{\alpha(0)},$$

$$\nu_R^{\alpha(n)} = \frac{\psi_R^{\alpha(n)} + \psi_R^{\alpha\ (n)}}{\sqrt{2}}, \ n = 1, ..., \infty,$$

$$\nu_L^{\alpha(n)} = \frac{\psi_L^{\alpha(n)} + \psi_L^{\alpha\ (n)}}{\sqrt{2}}, \ n = 1, ..., \infty,$$

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The 5-dimensional fermion

The

Flavor neutrinos

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$$\nu_R^{\alpha(0)} \equiv \psi_R^{\alpha(0)},$$

$$\nu_R^{\alpha(n)} = \frac{\psi_R^{\alpha(n)} + \psi_R^{\alpha\ (n)}}{\sqrt{2}},\ n = 1, ..., \infty,$$

$$\nu_L^{\alpha(n)} = \frac{\psi_L^{\alpha(n)} + \psi_L^{\alpha\ (n)}}{\sqrt{2}},\ n = 1, ..., \infty,$$

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

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

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

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

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

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

The free parameters are "m_1" and "R"

The equivalence between the LED and (3+3n) sterile models

The relation between flavor and mass eigenstates:

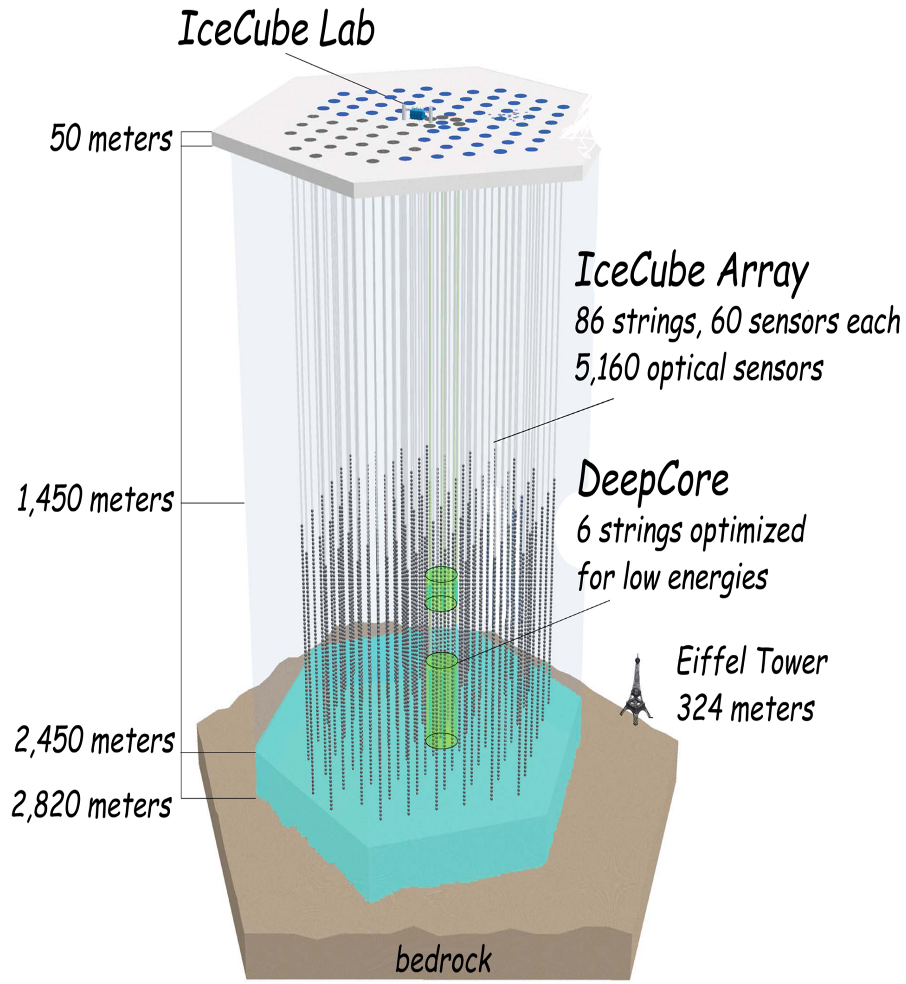
$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \sum_{n=0}^{N} S_i^{0n} \nu_{iL}^{\prime(n)} = \sum_{i=1}^{3} \sum_{n=0}^{N} W_{\alpha(i+3n)} \nu_{iL}^{\prime(n)}, \qquad (\alpha = e, \mu, \tau)$$

In (3+3n) model:

$$W_{\alpha(i+3n)} \;=\; U_{\alpha i} S_i^{0n}, \qquad (i = 1, 2, 3), \qquad (\alpha = e, \mu, \tau), \qquad (n = 0, 1, \cdots, N)$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} \;-\; 4 \sum_{l>m} \Re\left[W_{\alpha l} W_{\beta l}^* W_{\alpha m}^* W_{\beta m}\right] \sin^2\left(\frac{\Delta m_{lm}^2 L}{4E_\nu}\right)$$
$$+\; 2 \sum_{l>m} \Im\left[W_{\alpha l} W_{\beta l}^* W_{\alpha m}^* W_{\beta m}\right] \sin\left(\frac{\Delta m_{lm}^2 L}{2E_\nu}\right),$$

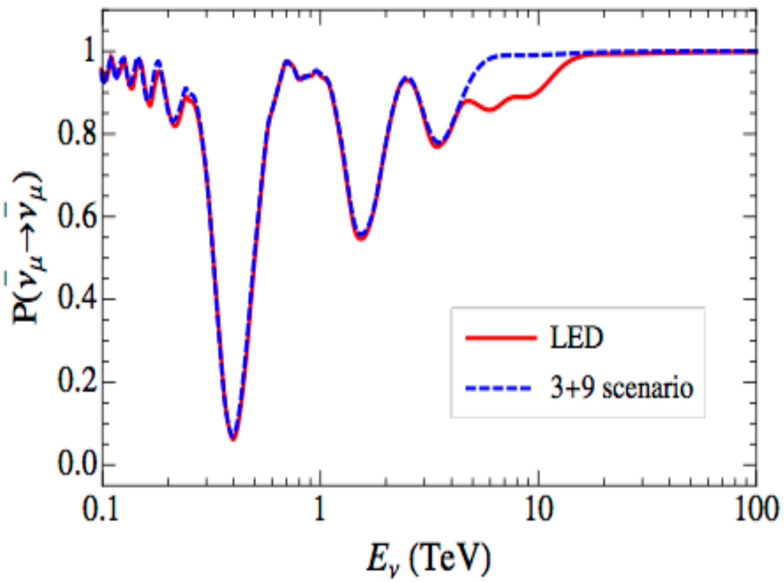
- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 120 m string spacing
- Angular resolution $\sim 1^o$
- Completed 2010



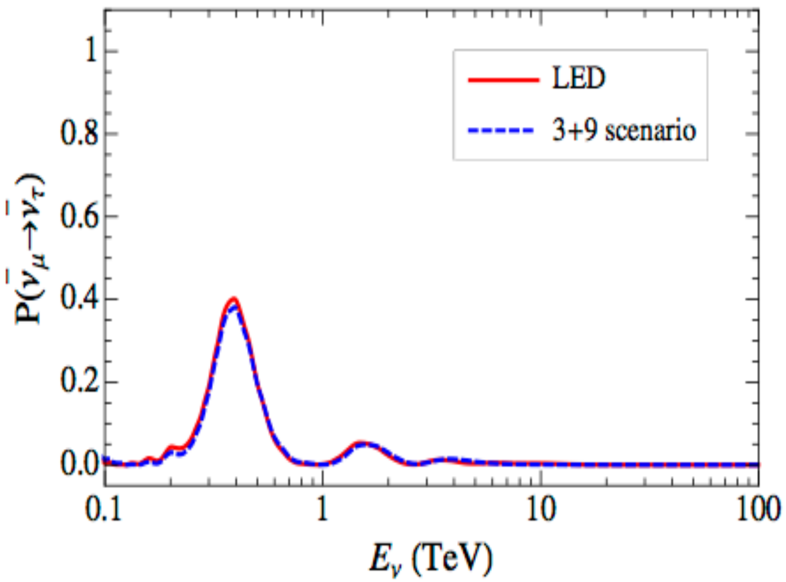
The Oscillation Probabilities

- For 3 KK modes:

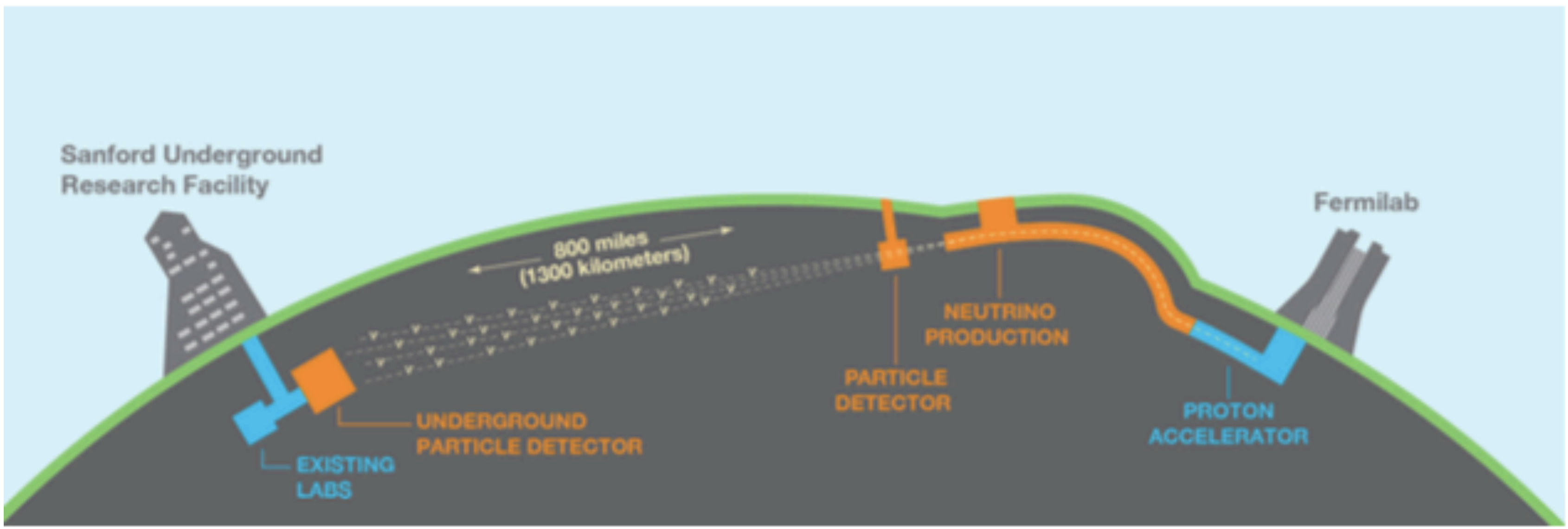
$$m_1^D = 0.01 \text{ eV and } R_{\text{ED}} = 5 \times 10^{-5} \text{ cm}$$



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

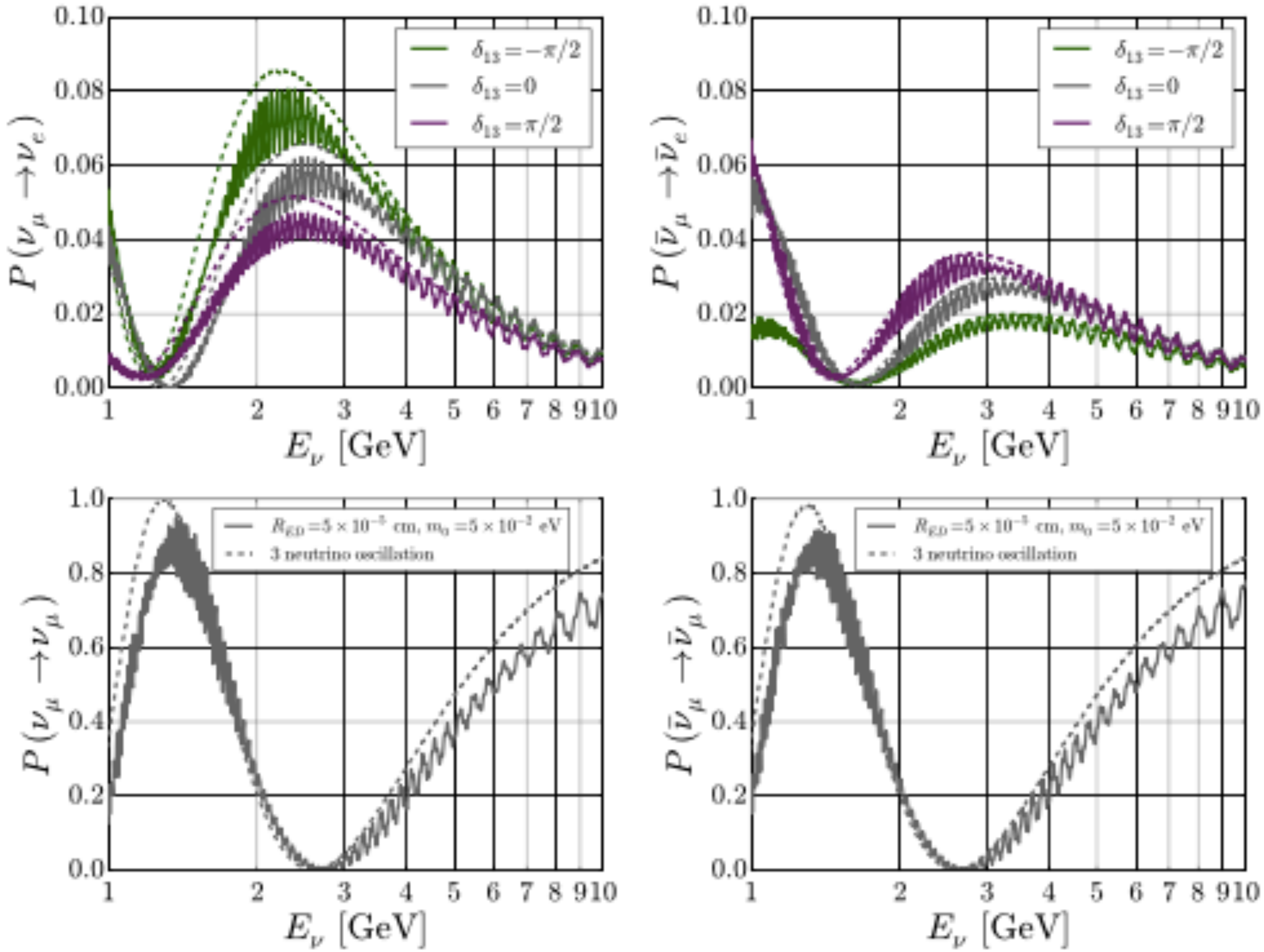


(b) $P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$



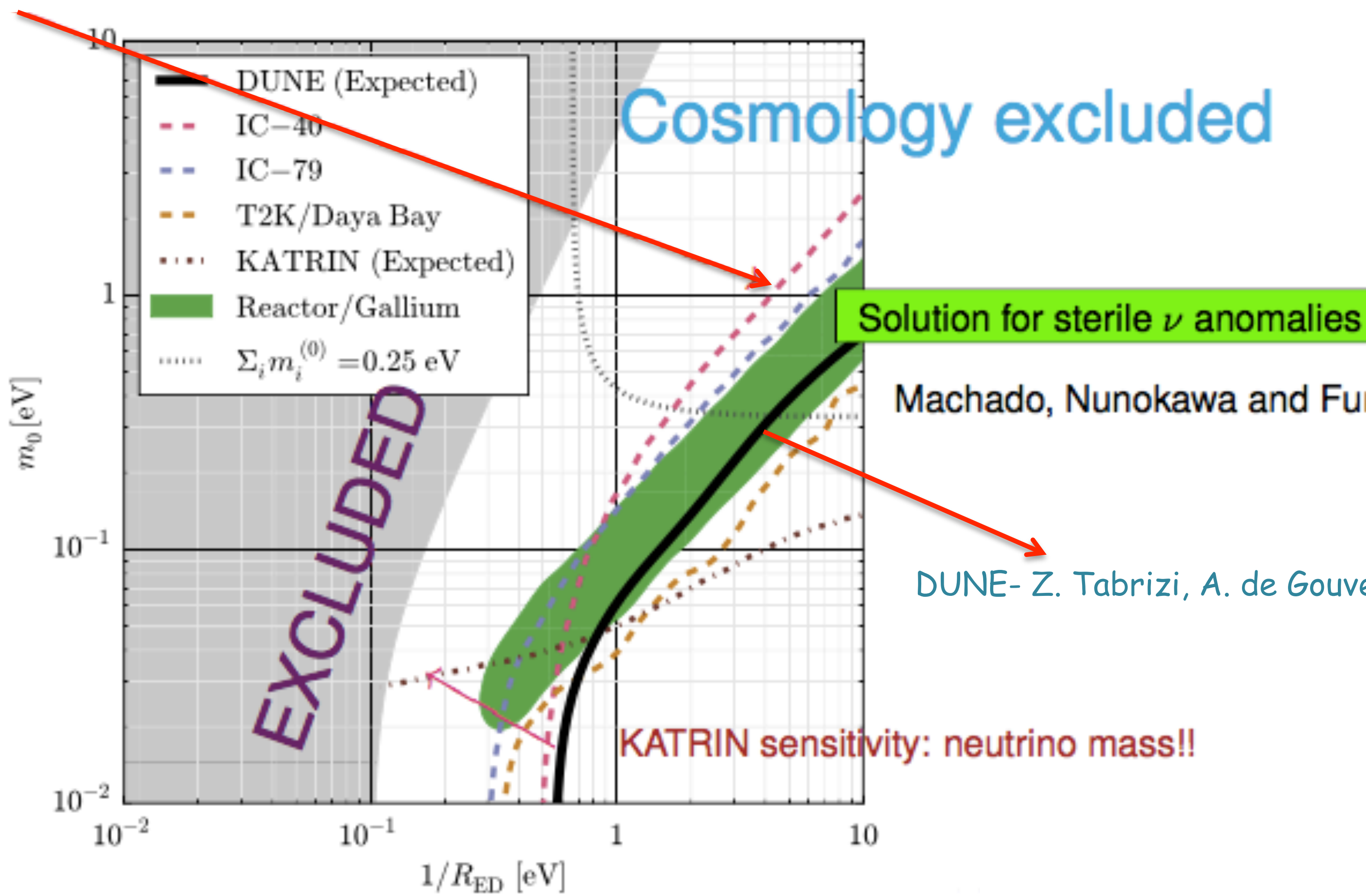
Measure μ (e) events: Test of P($\nu_\mu \to \nu_\mu$)($P(\bar{\nu}_\mu \to \bar{\nu}_\mu$) and P($\nu_\mu \to \nu_e$)(P($\bar{\nu}_\mu \to \bar{\nu}_e$))

The Oscillation Probabilities



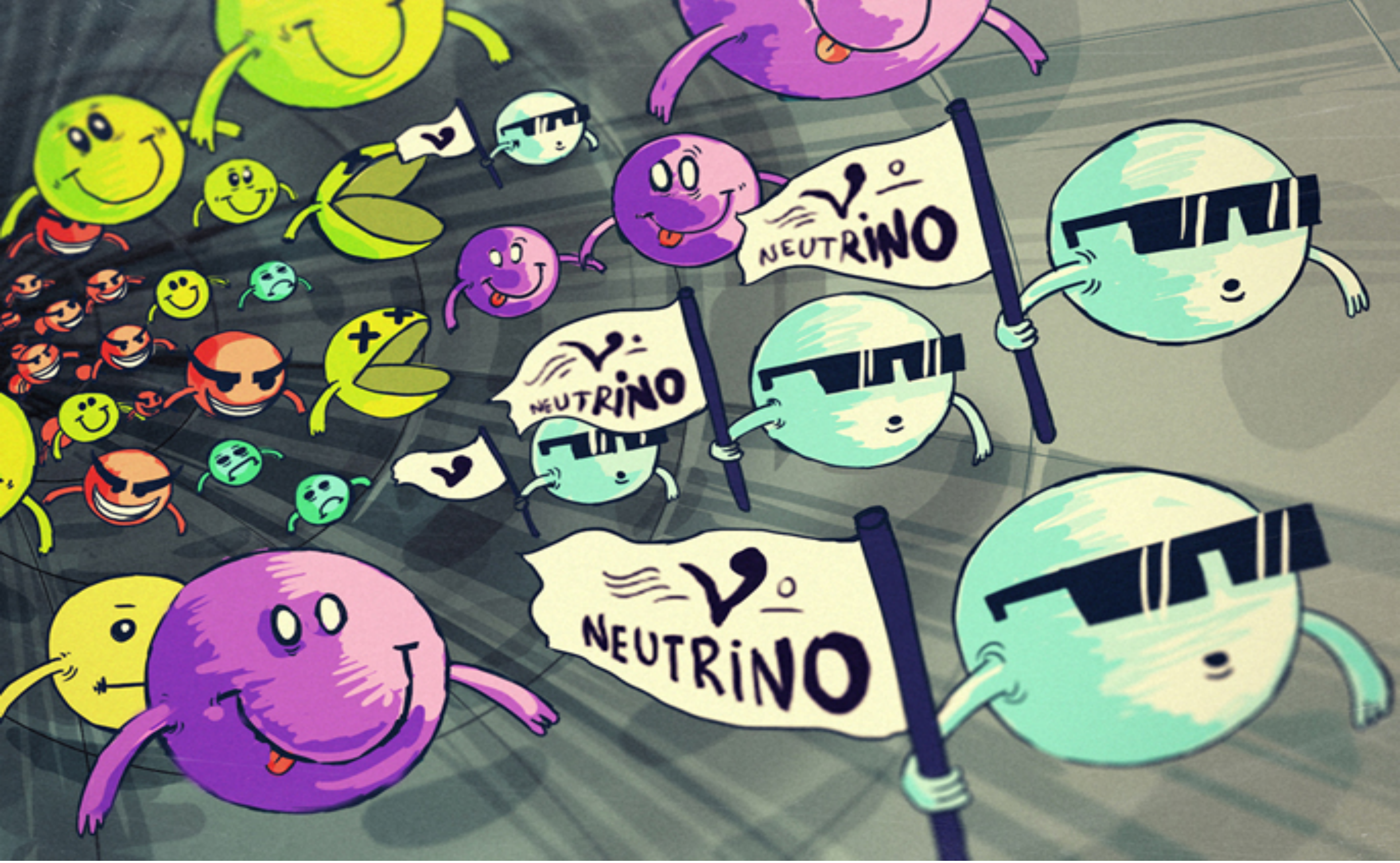
Constraining "LED"

IceCube- Z. Tabrizi, A. Esmaili, O.L.G. Peres



Machado, Nunokawa and Funchal

DUNE- Z. Tabrizi, A. de Gouvea, et al



Thanks for your attention