Neutrinos & Large Extra Dimensions

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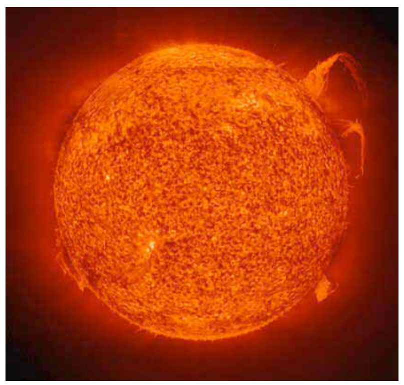
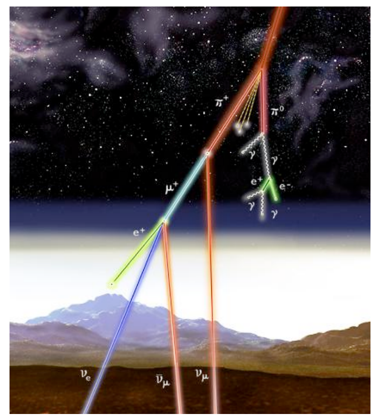
ν Masses & Mixings



solar



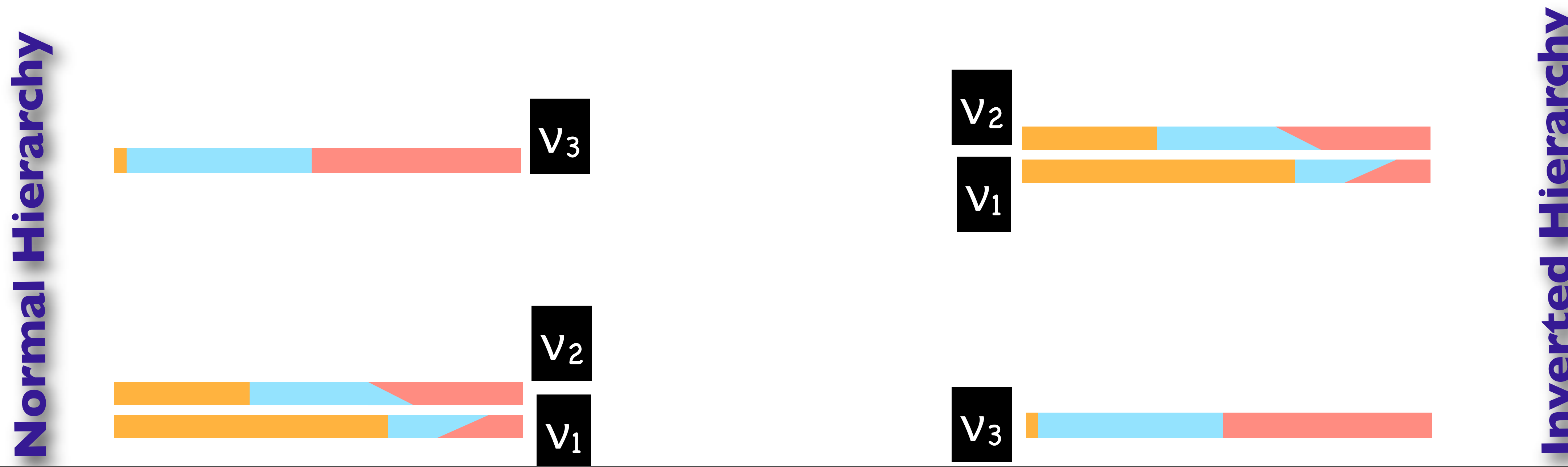
atmospheric

accelerator

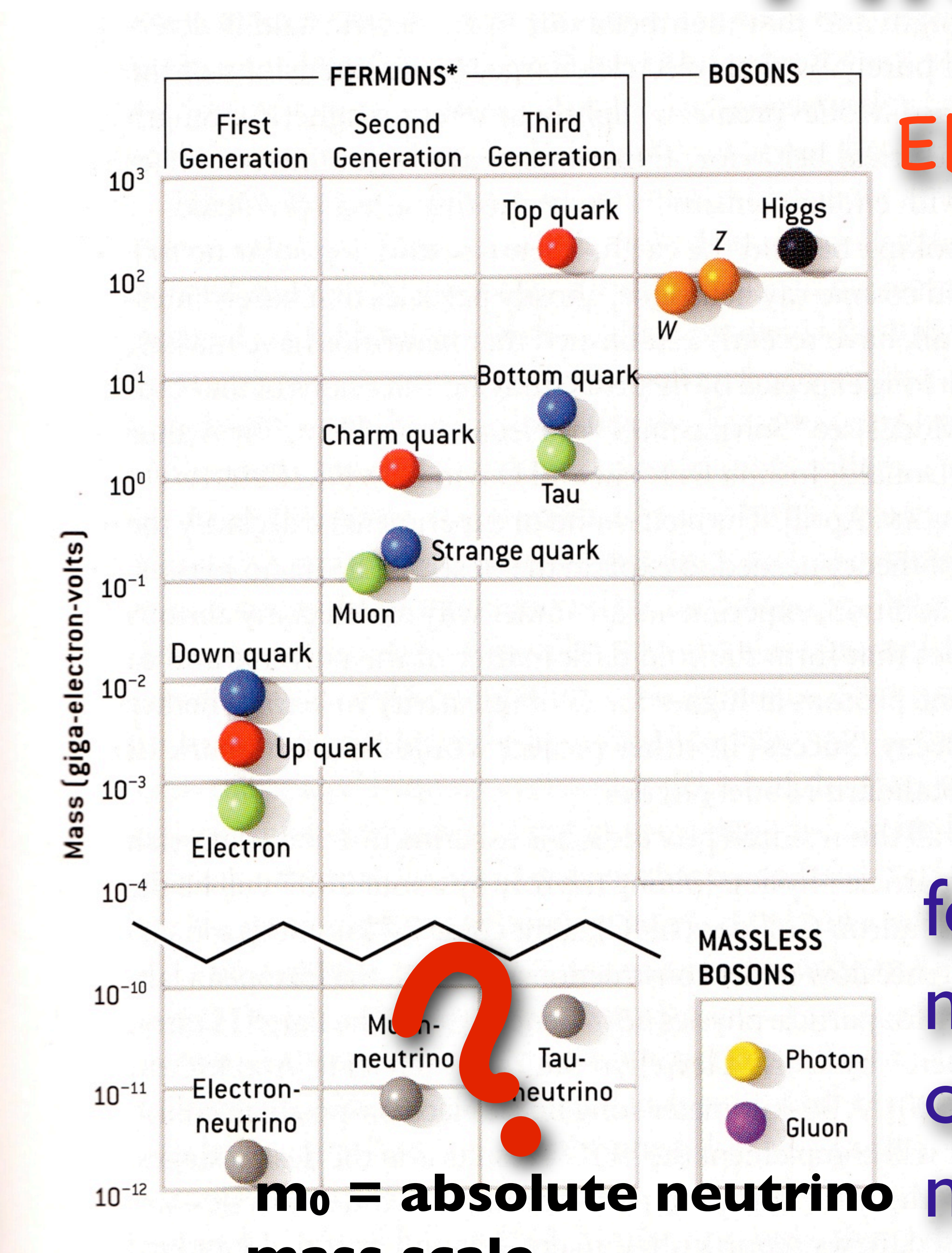
reactor

$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2$ $\quad |\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\ eV^2$

$\sin^2\theta_{12} \approx 0.31$ $\quad \sin^2\theta_{23} \approx 0.5$ $\quad \sin^2\theta_{13} \approx 0.025$



Fermions Mass Hierarchy



m_0 = absolute neutrino mass scale

Elementary Particle Masses Span ≥ 11 orders of magnitude !

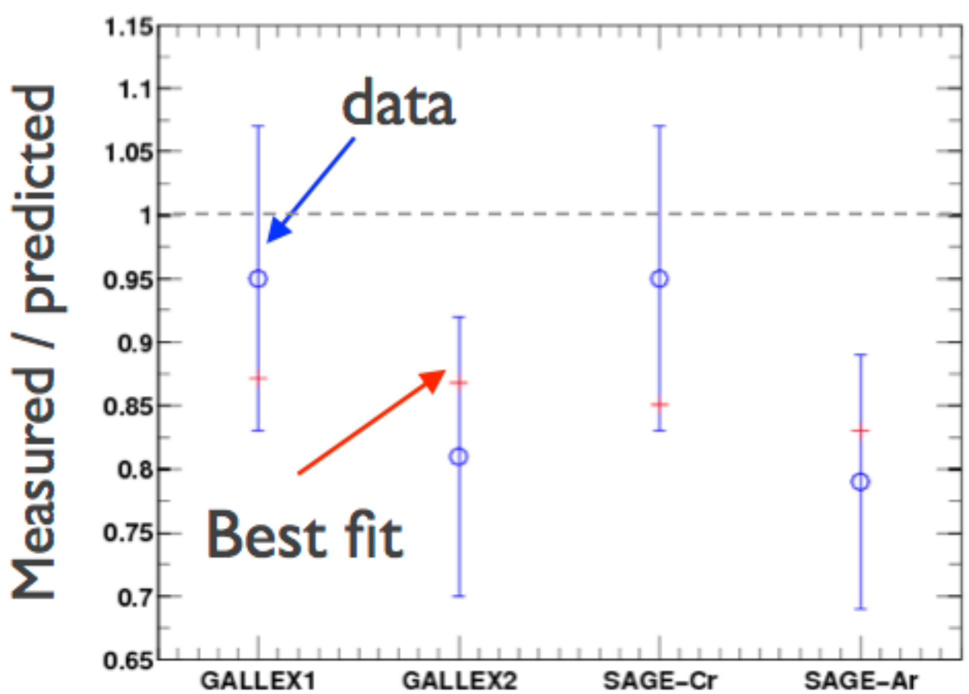
for neutrinos the well motivated seesaw mechanism can provide an *understanding* of the smallness of neutrino mass if neutrinos are *Majorana fermions*

Neutrino *Anomalies*

seem to indicate the need of extra species

(see Steve Brice)

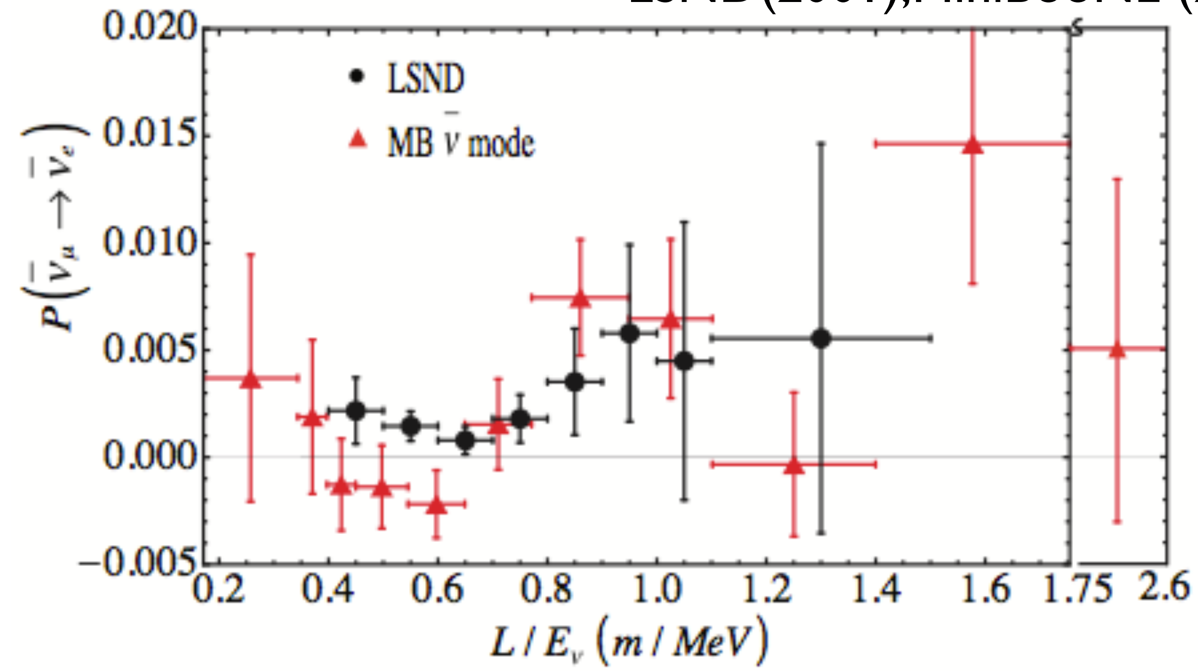
Gallium Anomaly



Gallex (2010), SAGE (2009)

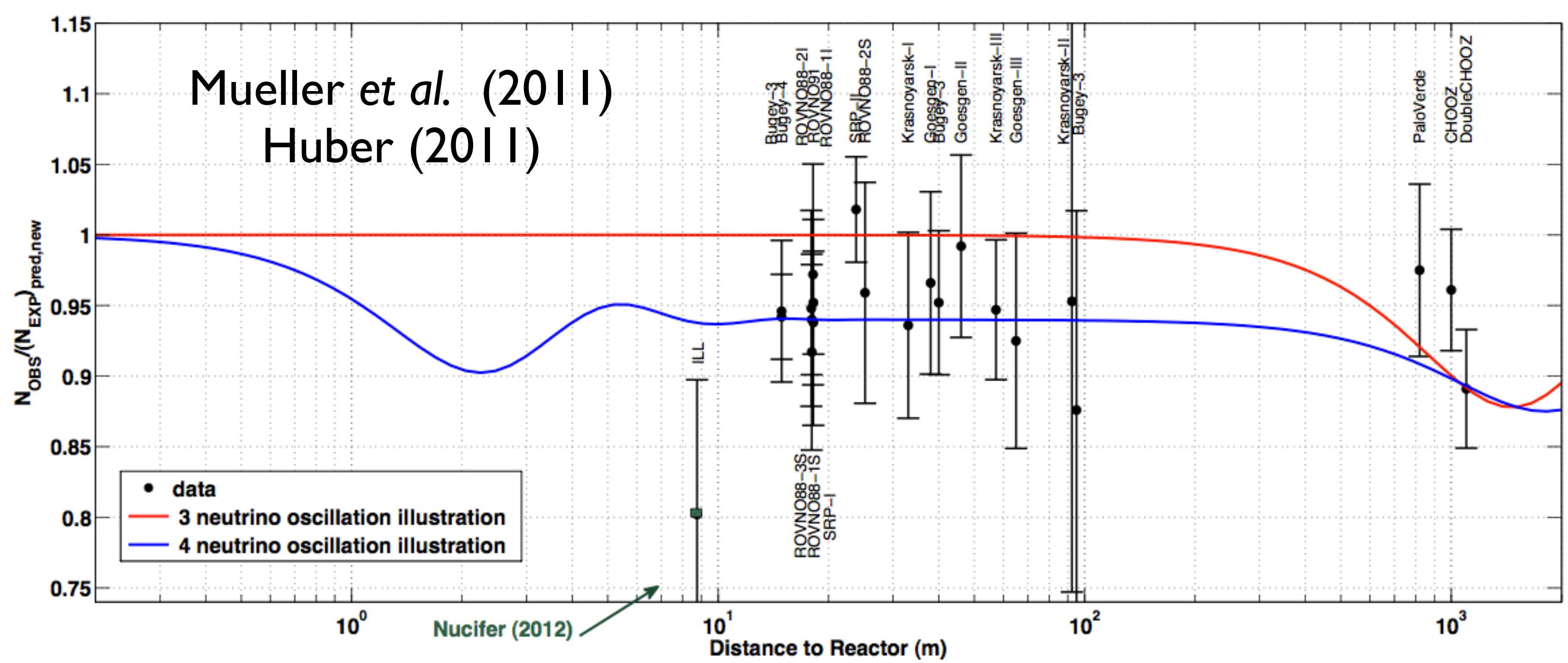
LSND/MiniBooNE Anomaly

LSND(2001),MiniBooNE (2012)



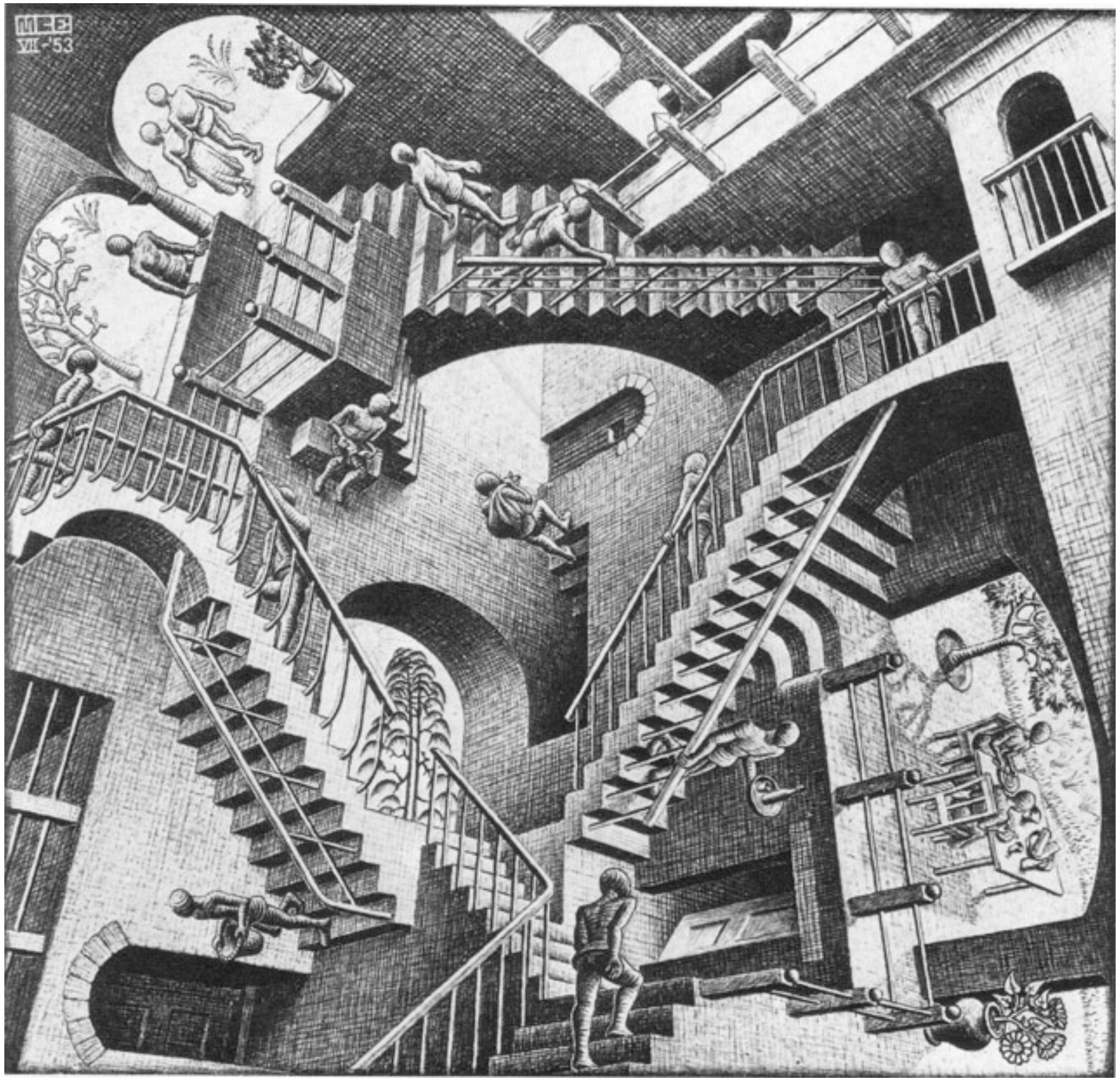
Reactor Anomaly

Mueller *et al.* (2011)
Huber (2011)



Menton *et al.* (2011)

Extra Dimensions



T. Kaluza (1919)

O. Klein (1926)

Extra Dimensions

more recently this was revisited by *string inspired* ideas designed to address the hierarchy problem

flat extra dimensions

Large Extra Dimensions (LED) : only gravity (and SM singlets) in the bulk

Arkani-Hamed, Dimopoulos, Dvali (1998)

Universal Extra Dimensions (UED): all SM particles can propagate in the bulk

Appelquist, Cheng, Dobrescu (2001)

Warped Extra Dimensions (WED): extra dimensions are curved

Randall, Sundrum (1999)

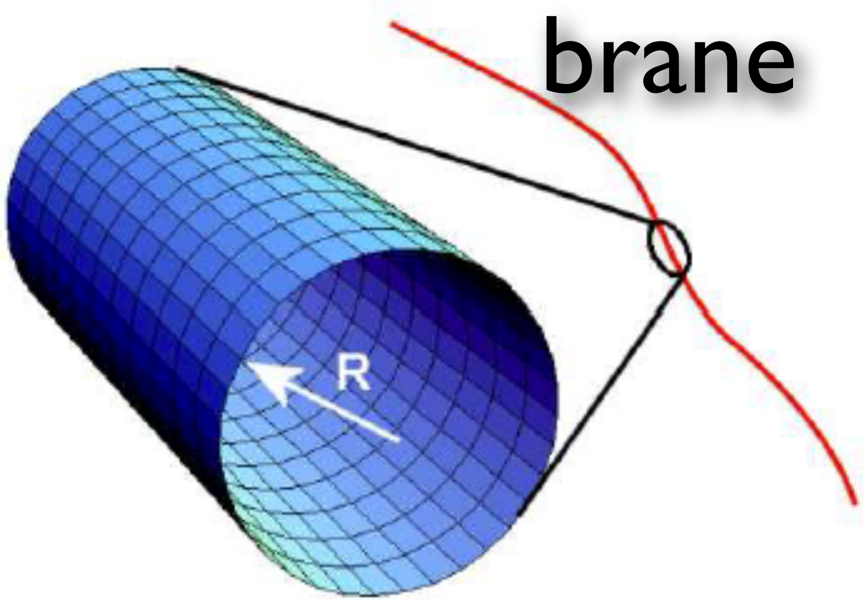
Large Extra Dimensions

assuming toroidal compactification of the δ extra dimensions of the same size R

bulk

1+3+δ

$$\mathbf{M_{PL} = \frac{1}{\sqrt{8\pi\, G_N}} \sim 10^{16}\, TeV}$$



$$\mathbf{M^* = \left(\frac{M_{PL}^2}{(2\pi R)^\delta}\right)^{1/(2+\delta)}}$$

new fundamental scale of gravity

$$\mathbf{ds^2 = g_{\mu\nu} dx^\mu dx^\nu - \delta_{ab} dy^a dy^b}$$

δ≥2

largest extra dimension < 0.2 mm

LED & Neutrinos

Dienes, Dudas, Gherghetta (1999)

Dvali, Smirnov (1999)

Mohapatra, Nandi, Perez-Lorenzana (1999)

Davoudiasl, Langacker, Perelstein (2002)

$\delta \geq 2$ but only one $R_1 = a >> R_2$, R_3, ... (effectively 1+3+1 D)

$$S = \int d^4x\, dy\, i\, \Psi^\alpha \Gamma_J \partial^J\, \Psi^\alpha +$$

$$\int d^4x\, dy\, (i\bar{\nu}_L^\alpha \gamma_\mu \partial^\mu \nu_L^\alpha + \lambda_{\alpha\beta} H \bar{\nu}_L^\alpha \Psi_R^\beta(x,y)\delta(y) + \text{h.c.})$$

bulk-brane coupling

SM particles propagate in the 1+3D brane

3 families of SM singlets propagate in the 1+4D bulk

$\Gamma_J \;\; J = 0, ..., 4$: the 5-D Dirac gamma matrices

Ψ^α : SM singlet bulk fermion fields

ν_L^α : SM neutrinos

$$\lambda_{\alpha\beta} = h_{\alpha\beta}/\sqrt{M^*}$$

➥ Dimensionless coupling

LED & Neutrinos

to get chiral fermion compactify on an orbifold (S^1/Z_2)

periodicity condition : $y = y + 2\pi a$ allows a Fourier decomposition

$$\Psi^{\alpha}(x,y) = \frac{1}{\sqrt{2\pi a}} \sum_{n=-\infty}^{\infty} \Psi^{\alpha(n)}(x)\, e^{iny/a}$$

$$\nu_{\alpha R}^{(0)} \equiv \Psi_R^{\alpha(0)}$$

Kaluza-Klein modes

$$\nu_{\alpha R}^{(n)} \equiv \frac{1}{\sqrt{2}} \left(\Psi_R^{\alpha(n)} + \Psi_R^{\alpha(-n)} \right) \qquad n = 1, ..., \infty$$

even under Z_2

$$\nu_{\alpha L}^{(n)} \equiv \frac{1}{\sqrt{2}} \left(\Psi_L^{\alpha(n)} - \Psi_L^{\alpha(-n)} \right) \qquad n = 1, ..., \infty$$

odd under Z_2

Effective Mass Lagrangian

$$\sum_{\alpha,\beta} m^D_{\alpha\beta}\left[\overline{\nu}_{\alpha L}\,\nu^{(0)}_{\beta R} + \sqrt{2}\sum_{n=1}^{\infty}\overline{\nu}_{\alpha L}\,\nu^{(n)}_{\beta R}\right] + \sum_{\alpha}\sum_{n=1}^{\infty}\frac{n}{a}\,\overline{\nu}^{(n)}_{\alpha L}\,\nu^{(n)}_{\alpha R}$$

➥ SM neutrinos

KK modes

sterile neutrinos

$$\mathbf{m^n_{KK} = \frac{n}{a}}$$

mass of KK modes

$$\mathbf{m^D_{\alpha\beta} = h_{\alpha\beta} v \frac{M^*}{M_{PL}}}$$

naturally small Dirac masses

Neutrino Mass Matrix

$$M_i^\dagger M_i = \lim_{N\to\infty} \begin{pmatrix} m_i^2 & 2am_i & 2am_i & 2am_i \dots & 2m \\ 2am_i & (1/a)^2 & 0 & \dots & 0 \\ 2am_i & 0 & (2/a)^2 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 2am_i & 0 & 0 & \dots & (N/a)^2 \end{pmatrix}$$

$$\lambda_i - \pi a^2 m_i^2 \cot(\pi\lambda_i) = 0$$

$$(W_i^{(n)})^2 = \frac{2}{1 + \pi^2 (a\,m_i)^2 + \lambda_i^{(n)2}/(a\,m_i)^2}$$

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}^* \sum_{n=0}^{\infty} W_i^{(n)} \nu_{iL}^{(n)}$$

Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta; L, E) = |\mathcal{A}_{\nu_\alpha \to \nu_\beta}(L, E)|^2$$

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{i=1}^{3} U_{\alpha i} U^*_{\beta i} \, A_i(L, E)$$

PMNS mixing

a single extra parameter

standard oscillation

$$A_i(L, E) \approx (1 - \frac{\pi^2}{6} m_i^2 a^2)^2 \exp\left(i \frac{m_i^2 L}{2E}\right)$$

$$\mathbf{m}^{\mathbf{n}}_{\mathrm{KK}} = \frac{\mathbf{n}}{\mathbf{a}}$$

$$+ \sum_{n=1}^{\infty} 2 \left(\frac{m_i}{m^n_{\mathrm{KK}}}\right)^2 \exp\left[i \frac{(2m_i^2 + m^{n2}_{\mathrm{KK}})L}{2E}\right]$$

depends on : absolute neutrino mass scale
mass hierarchy

Neutrino Oscillations

can be probed by current experiments

$$P(\nu_\alpha \to \nu_\beta; L, E) = |\mathcal{A}_{\nu_\alpha \to \nu_\beta}(L, E)|^2$$

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{i=1}^{3} U_{\alpha i} U^*_{\beta i}\, A_i(L, E)$$

in order to affect the standard probability by ~10% (since at least one m_i ~ 0.05 eV)

⇒ a ~ 5 eV^{-1} = 1μm

$$A_i(L, E) \approx (1 - \frac{\pi^2}{6} m_i^2 a^2)^2 \exp\left(i \frac{m_i^2 L}{2E} \right)$$

$$+ \sum_{n=1}^{\infty} 2 \left(\frac{m_i}{m^n_{\rm KK}} \right)^2 \exp\left[i \frac{(2m_i^2 + m^{n2}_{\rm KK})L}{2E} \right]$$

$$\mathbf{m}^{\mathbf{n}}_{\rm KK} = \frac{\mathbf{n}}{\mathbf{a}}$$

depends on : absolute neutrino mass scale

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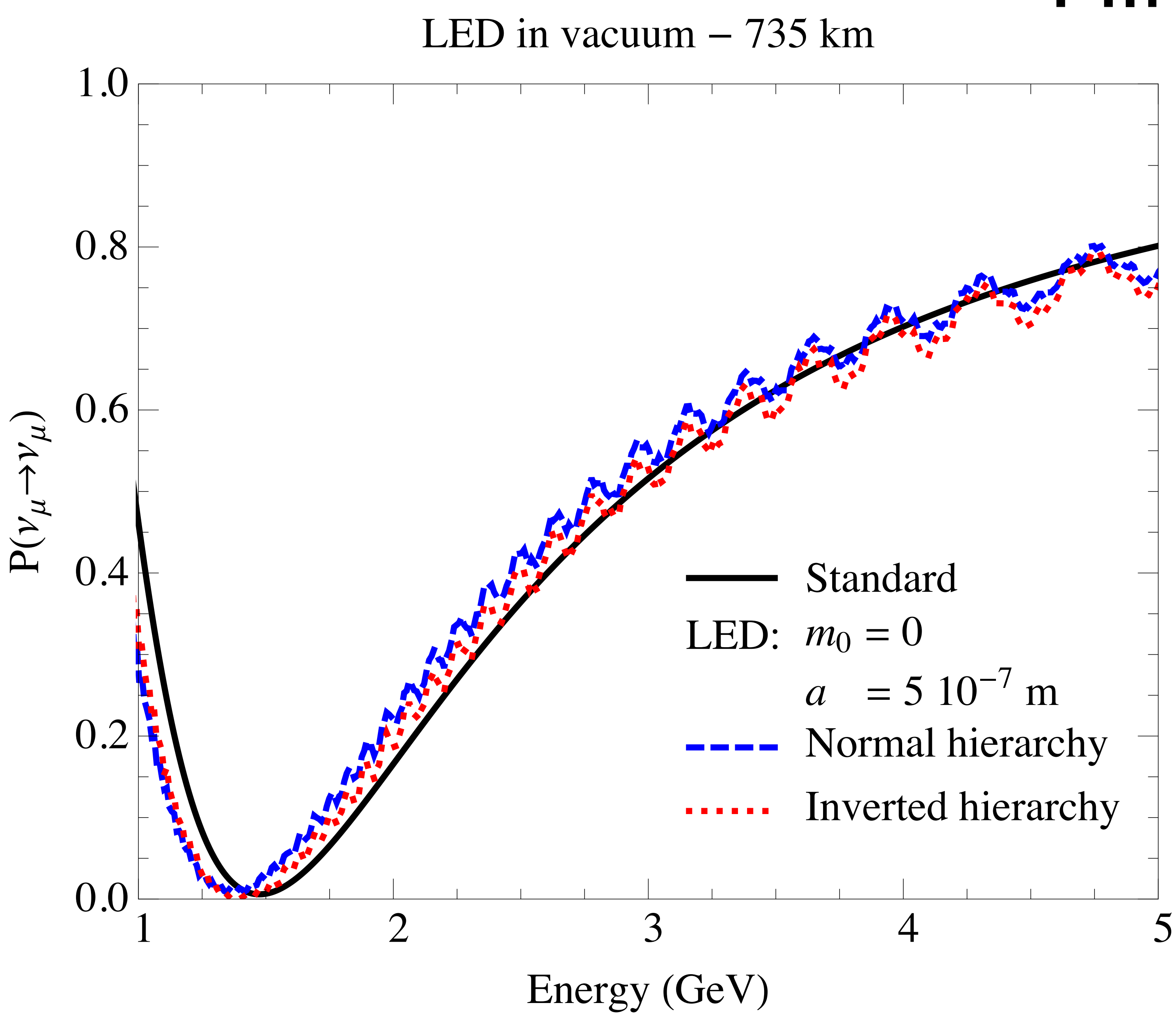
Neutrino Oscillations

MINOS



$$\sin^2\theta_{12} = 0.319$$

$$\sin^2 2\theta_{13} = 0.07$$

$$\sin^2 2\theta_{23} = 1$$

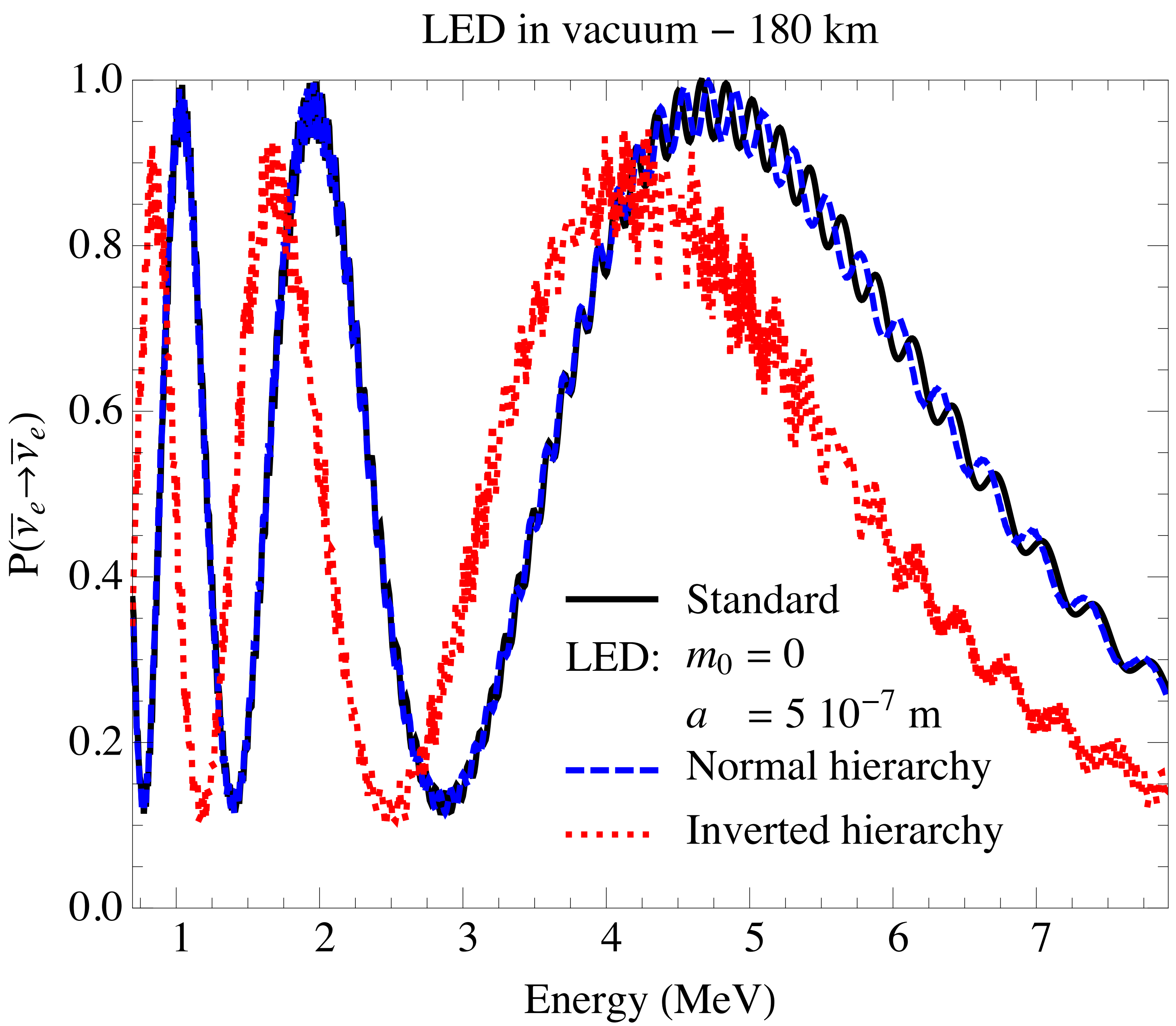
$$\Delta m^2_{21} = 7.59 \times 10^{-5}\,\mathrm{eV}^2$$

$$|\Delta m^2_{32}| = 2.46 \times 10^{-3}\,\mathrm{eV}^2$$

$m_0 = m_1$ normal hierarchy (NH)
$m_0 = m_3$ inverted hierarchy (NH)

Neutrino Oscillations

KamLAND



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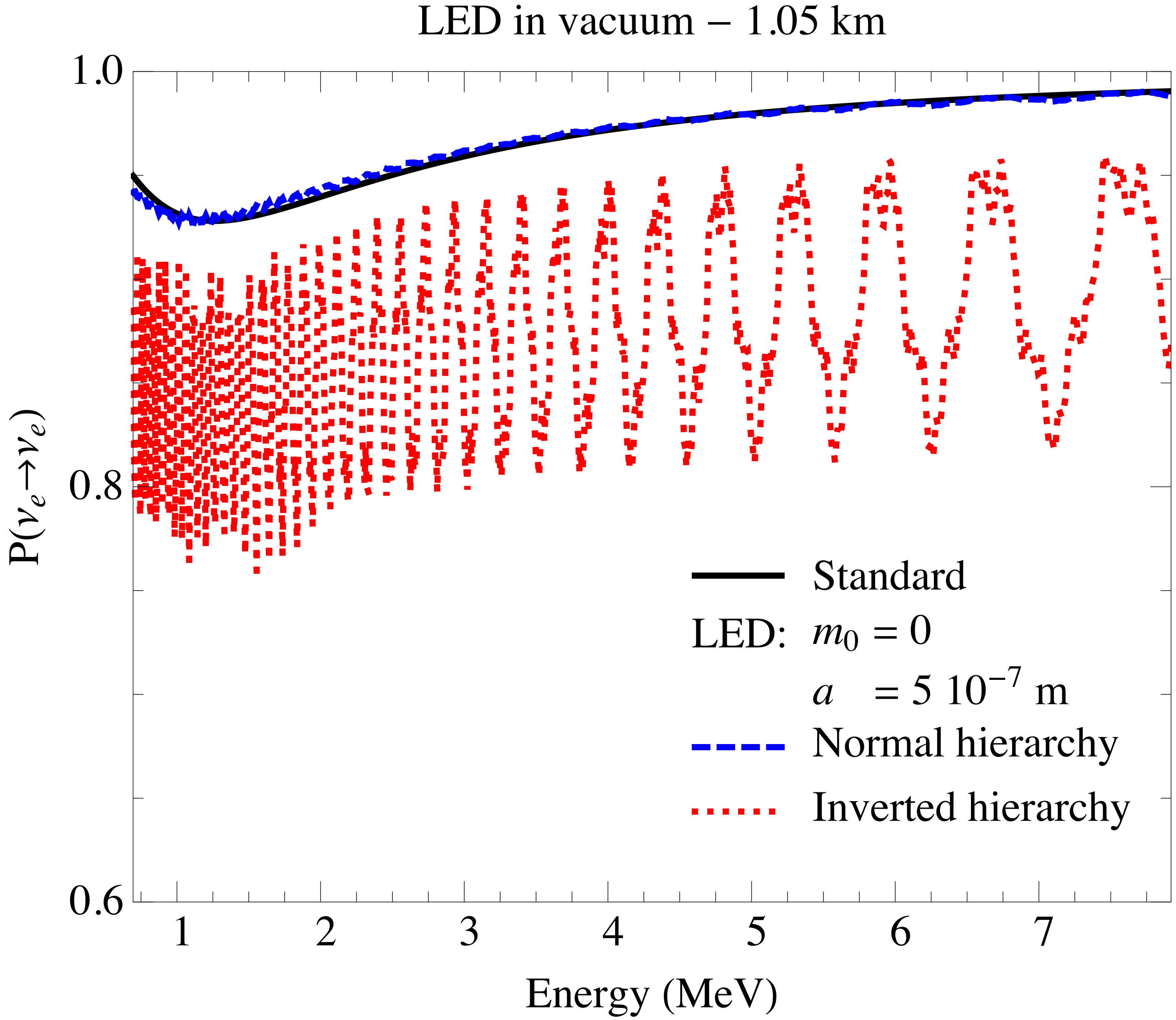
Neutrino Oscillations

CHOOZ/DC/RENO/Daya Bay



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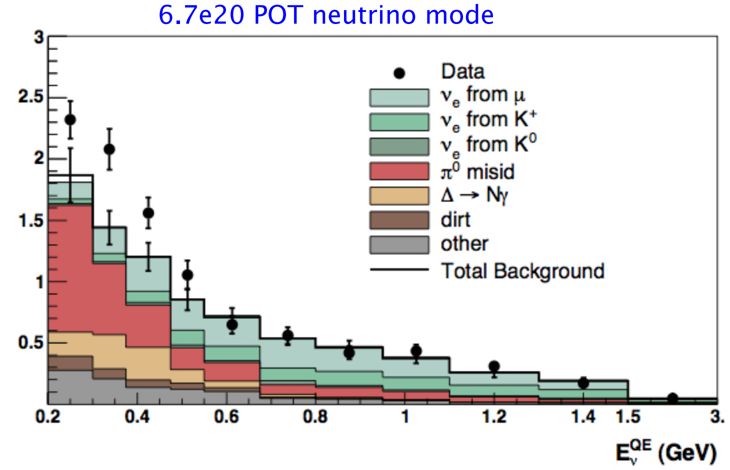
Neutrino Oscillations

No sizable effect in disappearance

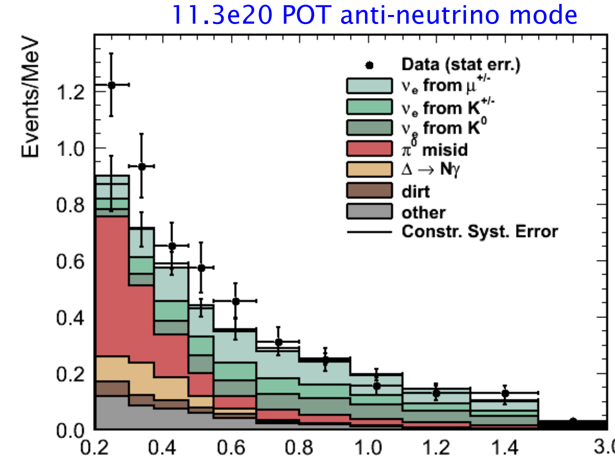
$$\nu_\mu \longrightarrow \nu_s^{(n)} \longrightarrow \nu_e \qquad\qquad \bar{\nu}_\mu \longrightarrow \bar{\nu}_s^{(n)} \longrightarrow \bar{\nu}_e$$

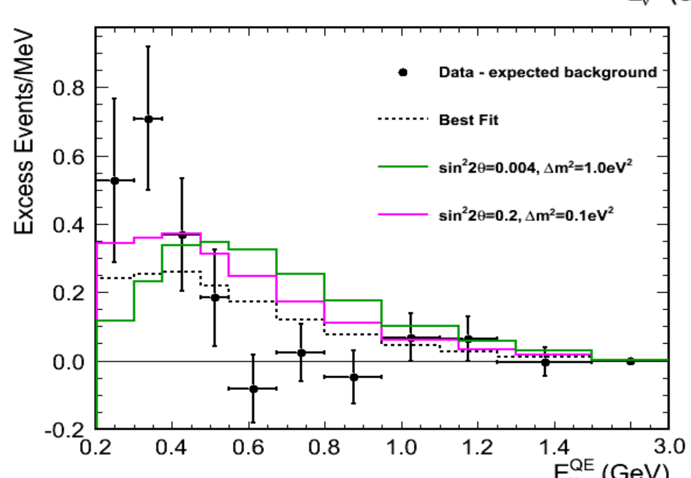
Comparing neutrino to anti-neutrino mode

6.7e20 POT neutrino mode

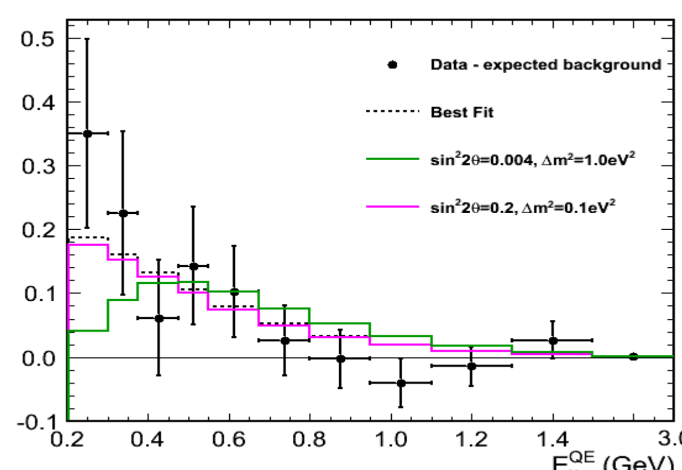


11.3e20 POT anti-neutrino mode





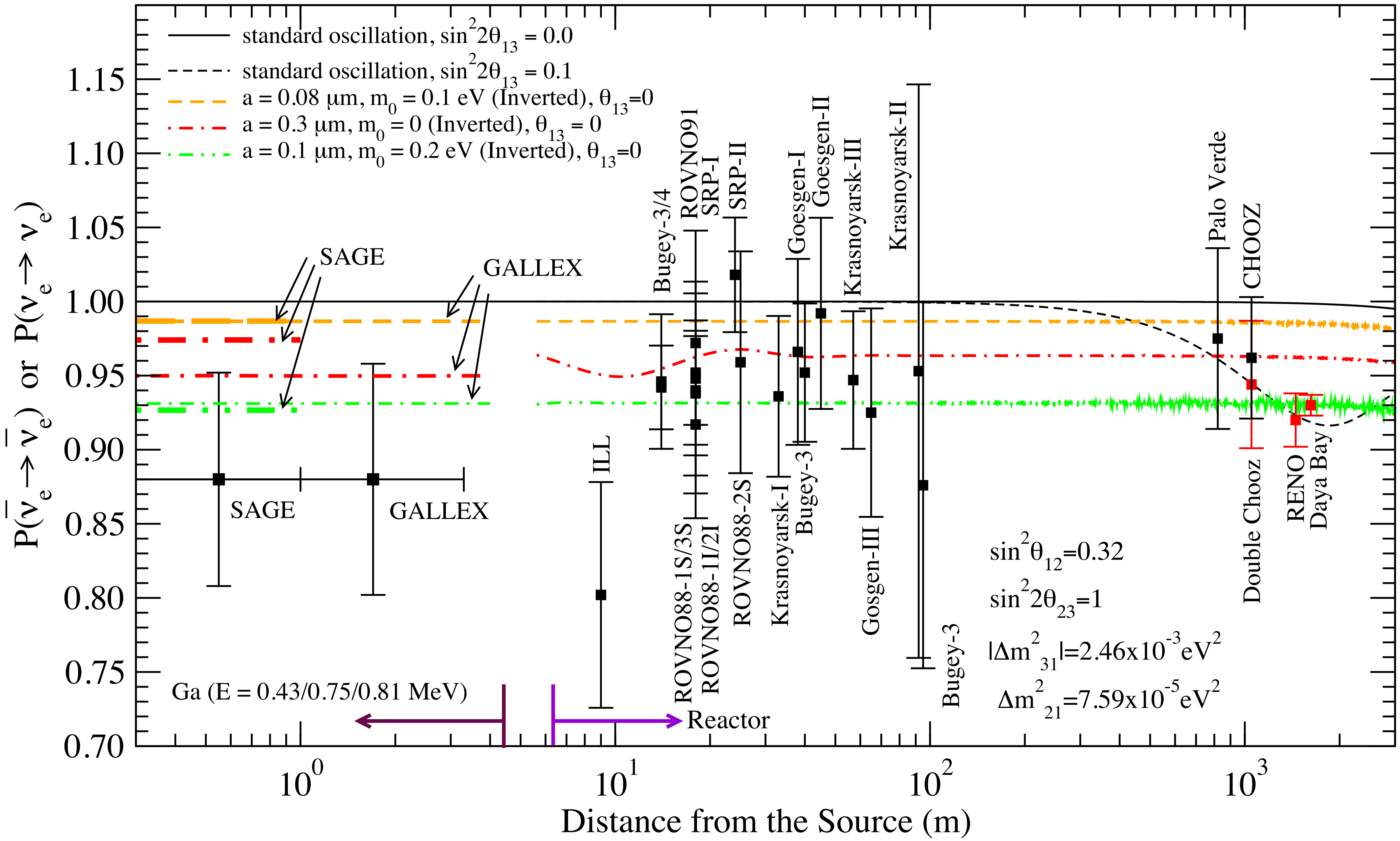
Excess: 146.3 ± 28.4 ± 40.2



Excess: 77.8 +/- 20.0 +/- 23.4

Cannot explain MiniBooNE/LSND

Survival Probability

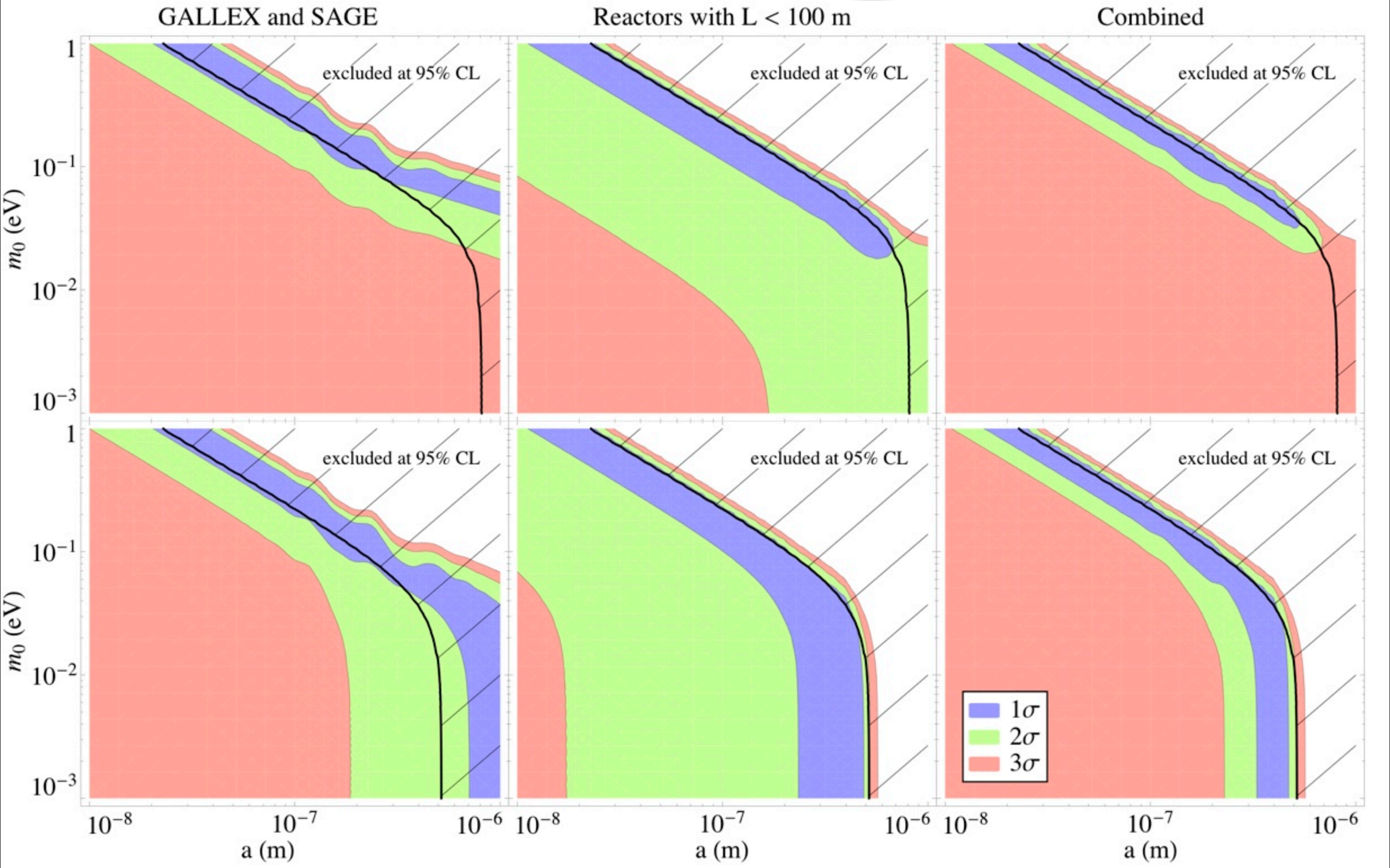


averaged survival probability

To illustrate how LED can “explain” the short baseline anomalies

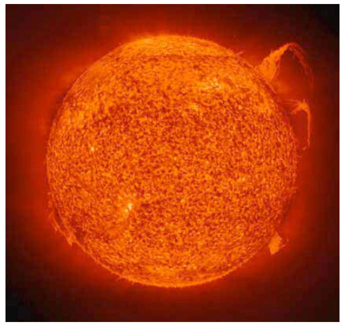
PAN Machado, H. Nunokawa, F.A. Pereira dos Santos, RZF (2012)

Allowed Regions



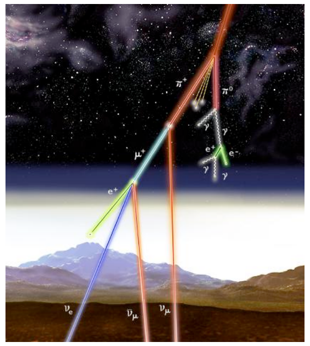
PAN Machado, H. Nunokawa, F.A. Pereira dos Santos, RZF (2012)

Some Comments



if $1/a >> \sqrt{\Delta m^2_{21}}$ LED matter effects are not important, but LED can reduce the overall ν_e survival probability

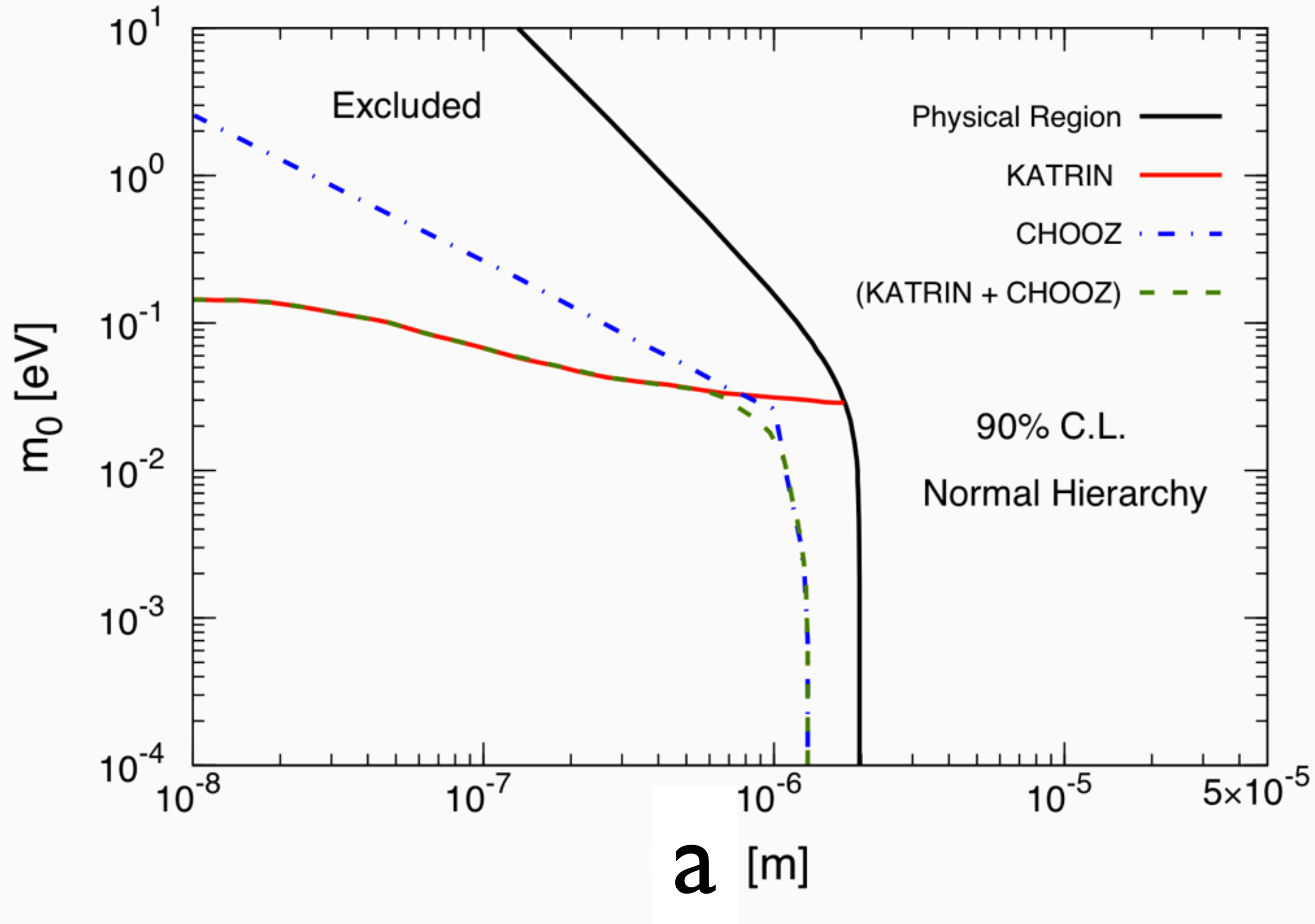
Terrestrial bounds imply very small reduction



As long as we consider the terrestrial bounds LED does not observably affect the atmospheric neutrino oscillations

Effective ν_e Mass

V. S. Basto-Gonzalez, A. Esmaili, O.L.G. Peres (2012)



$$^3\mathrm{H} \to {}^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

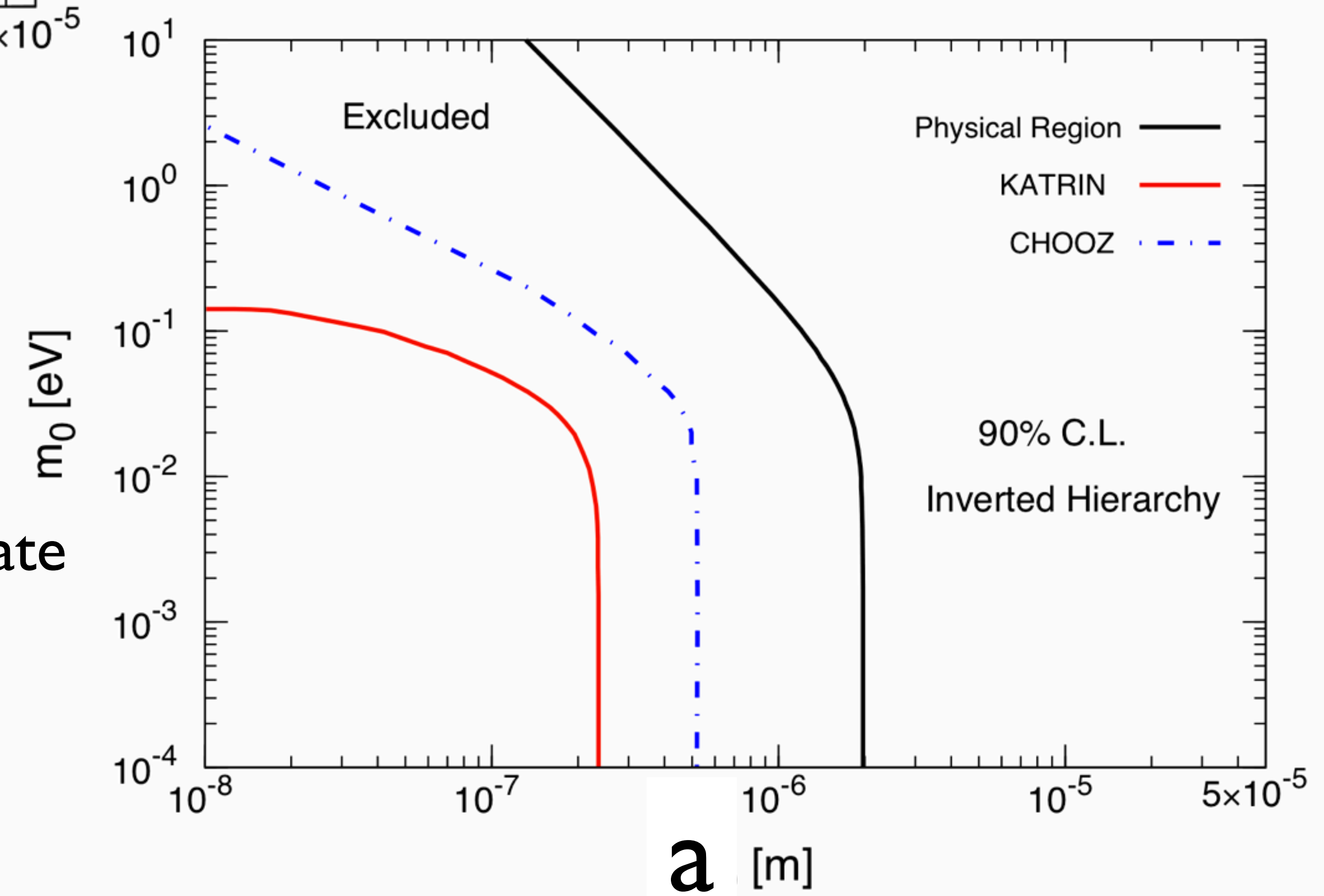
KATRIN

$$K(T_e, m_0, a) =$$
$$\sum_k p_k E_k \sum_{n=1}^{3} |U_{ei}|^2 \sum_{n=0}^{\infty} (W_i^{(n)})^2 \sqrt{E_k^2 - (\lambda_i^{(n)}/a)^2}$$

p_k = transition probability of the kth excited state of the daughter nucleus

$$E_k = Q - W_k - T_e$$

excitation energy



Conclusions

- LED framework can provide "naturally" small Dirac masses

- LED framework can provide sterile neutrinos

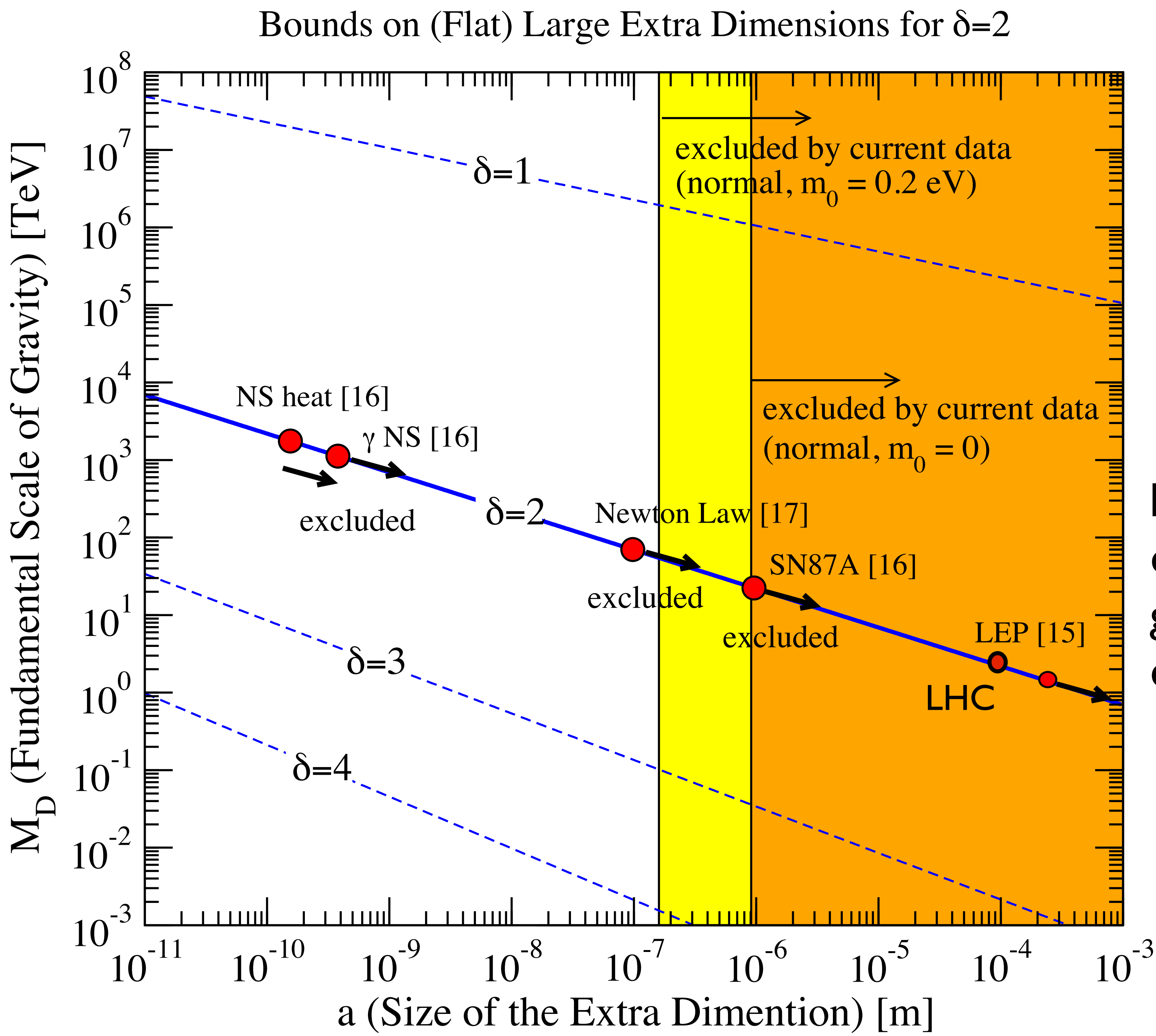
- LED framework is testable (a single new parameter)

- LED can accommodate all current neutrino oscillation data (except for MiniBooNE/LSND)

Other Bounds

model dependent

KK gravitons



LEP (LHC): from KK graviton emission and exchange

best bounds:
due to over production/decays of KK gravitons in astrophysical environments

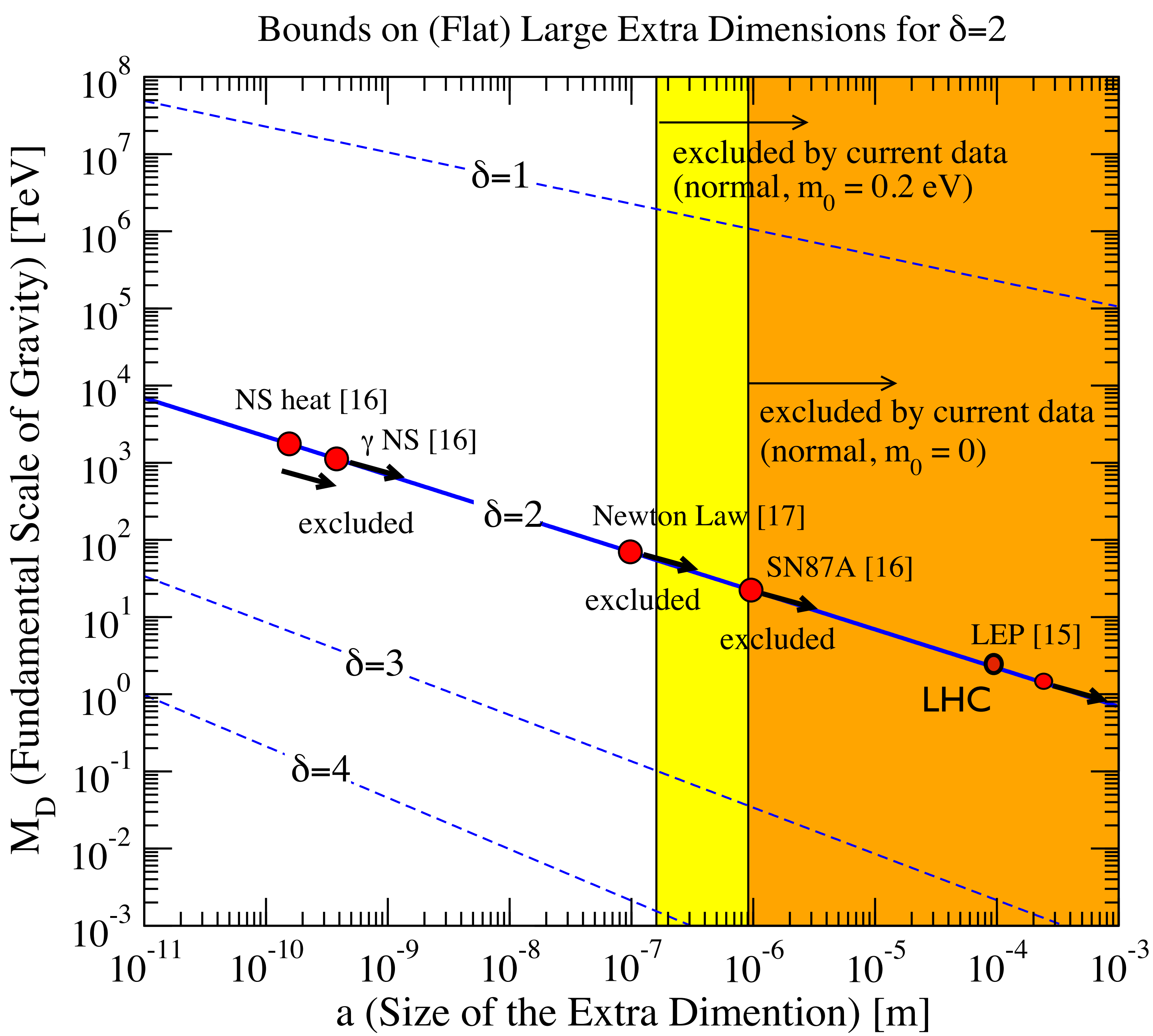
Hall, Tucker-Smith (1999) Hannestad (2001, 2004)

Hannestad, Raffelt (2003)

$$\mathbf{M^* = M_D = \left(\frac{M_{PL}^2}{(2\pi\, a)^\delta}\right)^{1/(2+\delta)}}$$

Other Bounds

model dependent



$$M^* = M_D = \left(\frac{M_{PL}^2}{(2\pi\, a)^\delta} \right)^{1/(2+\delta)}$$

KK neutrinos

BBN Goh, Mohapatra (2002)

weaker than our bounds

Cosmology Abazajian, Fuller, Patel (2003)

very strong bounds from CMB, diffuse γ backgrounds, LSS

but can be evaded


Thank you !