The Reactor Antineutrino Anomaly
and
Large Extra Dimensions

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Based on MNZ arXiv:1101.0003 and MNPZ in preparation

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Planck 2011 - IST, Lisbon

Outline

- Basics of ν oscillations

- Neutrinos and large extra dimensions

- Reactor antineutrino anomaly

Basics of

ν

oscillations

Smirnov, Feruglio and Valle talks...

Basics of ν oscillations

Formalism

Neutrinos oscillate: $$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\, \nu_{iL}$$

Basics of ν oscillations

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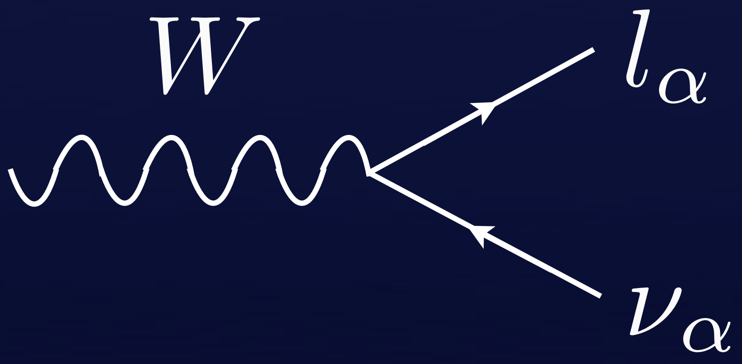

Flavor eigenstates

mass eigenstates

mixing matrix: $U = U_{23} P_\delta\, U_{13}\, P_{-\delta}\, U_{12}$

Basics of ν oscillations

Formalism

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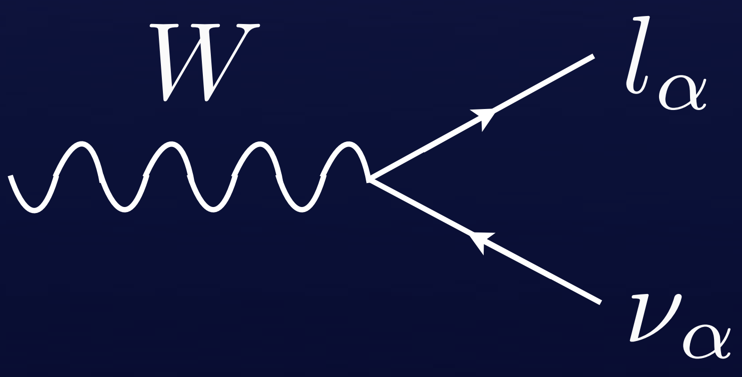


Flavor eigenstates

mass eigenstates

mixing matrix: $U = U_{23} P_\delta U_{13} P_{-\delta} U_{12}$

diagonal?

$$P_{\pm\delta} = \mathrm{diag}(\,1\;\;1\;\;e^{\pm i\delta}\,)$$

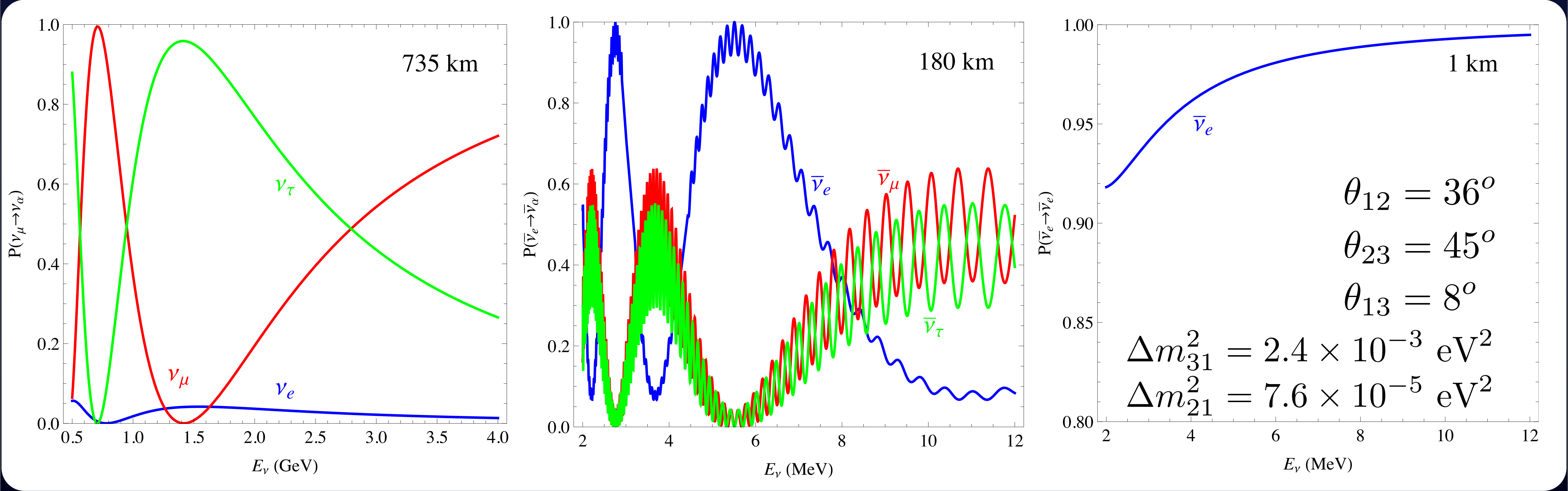
$$U_{12} = \left(\begin{array}{ccc} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{array}\right), \ldots$$

Basics of ν oscillations

Probabilities

$$P\left(\nu_\alpha \to \nu_\beta; L\right) = \left|A\left(\nu_\alpha \to \nu_\beta; L\right)\right|^2$$

$$A\left(\nu_\alpha \to \nu_\beta; L\right) = \sum_i U_{\alpha i} U^*_{\beta i} \exp\left(-i\frac{m_i^2 L}{2E_\nu}\right)$$



Neutrinos

and

Large Extra Dimensions

Arkani-Hamed, Dimopoulos, Dvali, March-Russel, PRD65 2002
Dienes, Dudas, Gherghetta, Nucl.Phys.B557 1999
Dvali, Smirnov, Nucl.Phys.B563 1999
Barbieri, Creminelli, Strumia, Nucl.Phys.B585 2000
Davoudiasl, Langacker, Perelstein, PRD65 2002
PANM, Nunokawa, Zukanovich Funchal, arXiv:1101.0003

Large Extra Dimensions

Motivation

Suppose n compactified extra dimensions (n≥2)

The hierarchy problem:

$$m_{EW} = 1 \text{ TeV} \longleftrightarrow M_{Pl} = 10^{18} \text{ GeV}$$

Large Extra Dimensions

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The hierarchy problem:

$$m_{EW} = 1\ \text{TeV} \longleftrightarrow M_{Pl} = 10^{18}\ \text{GeV}$$

We can generate small Dirac masses for the neutrinos introducing 3 bulk fermion singlets

These masses arrive from Yukawa couplings

The smallness of the neutrino masses comes from a volume suppresion

Large Extra Dimensions

The model

In the end of the day, we have to diagonalize the following matrix in the KK space, which introduces mixing

size of ex. dim.

↑

$$a^2 M_i^\dagger M_i = \lim_{N\to\infty} \begin{pmatrix} (N+1/2)\,\xi_i^2 & \xi_i & 2\xi_i & \dots & N\xi_i \\ \xi_i & 1 & 0 & \dots & 0 \\ 2\xi_i & 0 & 4 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ N\xi_i & 0 & 0 & \dots & N^2 \end{pmatrix}$$

$$\boxed{\xi_i = \sqrt{2}\, m_i\, a}$$

$$P\left(\nu_\alpha^{(0)} \to \nu_\beta^{(0)}; L\right) = \left| A\left(\nu_\alpha^{(0)} \to \nu_\beta^{(0)}; L\right)\right|^2$$

Large Extra Dimensions

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$$A\left(\nu_\alpha^{(0)} \to \nu_\beta^{(0)}; L\right) = \sum_{i,j,k} \sum_{N=0}^{\infty} U_{\alpha i} U_{\beta k}^* W_{ij}^{(0N)*} W_{kj}^{(0N)} \exp\left(i \frac{\lambda_j^{(N)2} L}{2Ea^2}\right)$$

STANDARD

$$A\left(\nu_\alpha \to \nu_\beta; L\right) = \sum_i U_{\alpha i} U_{\beta i}^* \exp\left(-i \frac{m_i^2 L}{2E_\nu}\right)$$

Large Extra Dimensions

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Large Extra Dimensions

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Almost diagonal (ij): $\nu_\alpha \to \nu_{\mathrm{s}}$ ✓

$\nu_\alpha \to \nu_\beta$ ✗ (induced by LED)

Large Extra Dimensions

The model

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LED effect ~$\sum_i \xi_i^2 \left|U_{\alpha i}\right|^2$ at first order in ξ_i^2

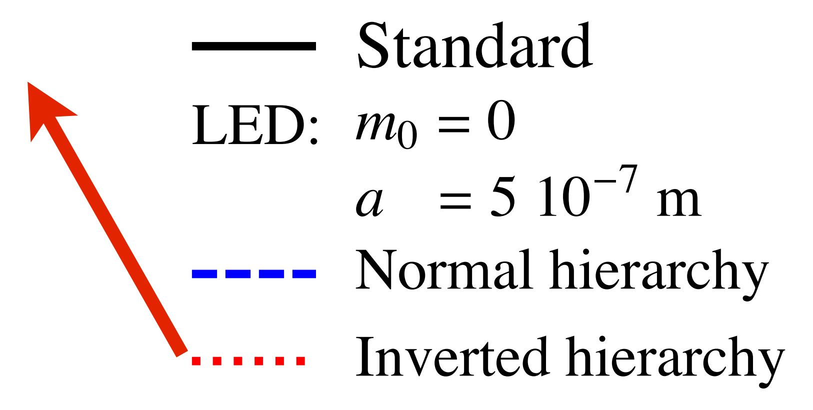
$$\xi_i^2 = 2\, m_i^2\, a^2 \sim 0.1 \Rightarrow a \sim 5\, {\rm eV}^{-1} = 1\, \mu m$$

$$\nu_e \to \nu_e \neq \nu_\mu \to \nu_\mu$$

Large Extra Dimensions

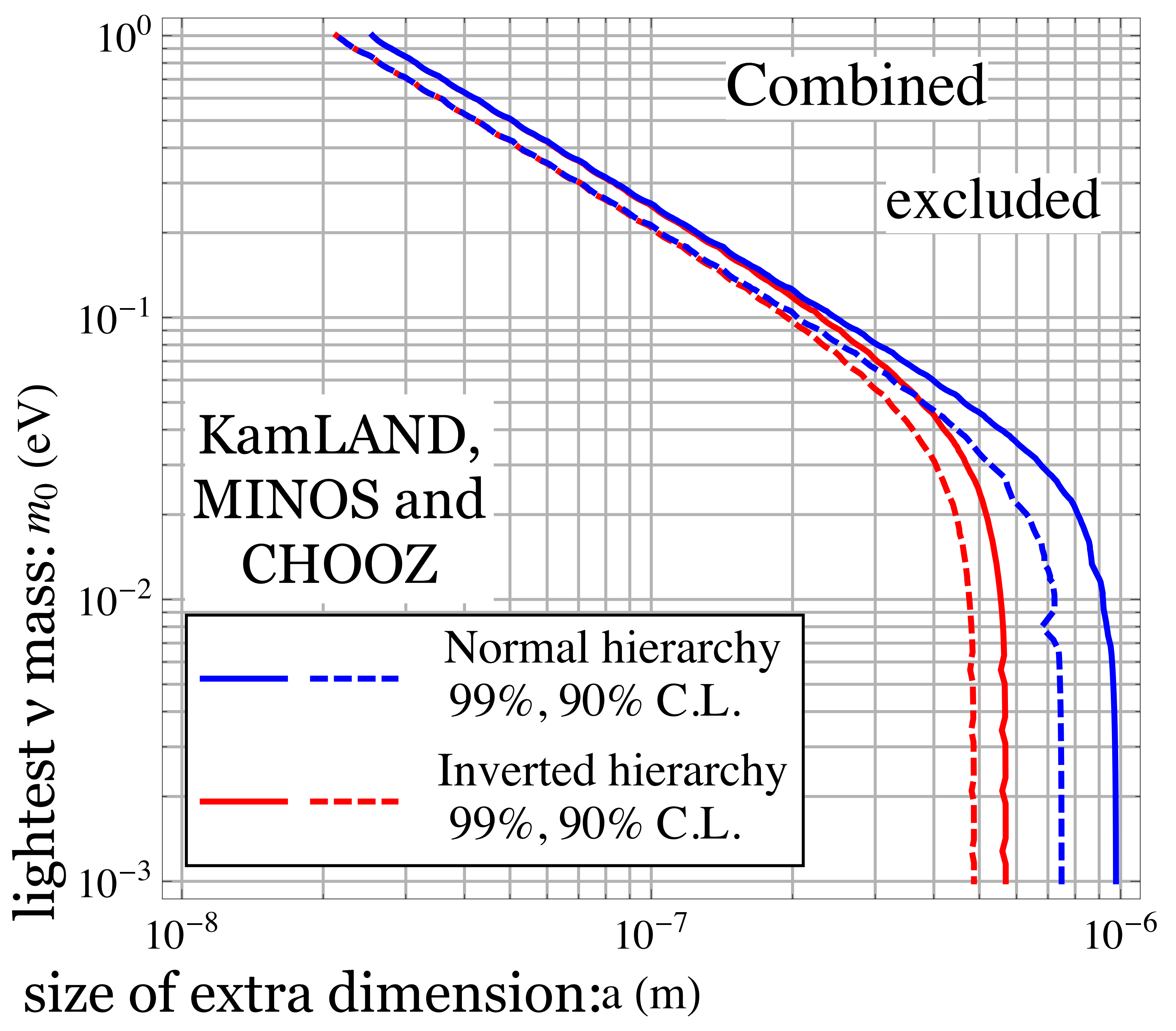
Probability

Reactor experiments channel



Large Extra Dimensions

Limits



Large Extra Dimensions

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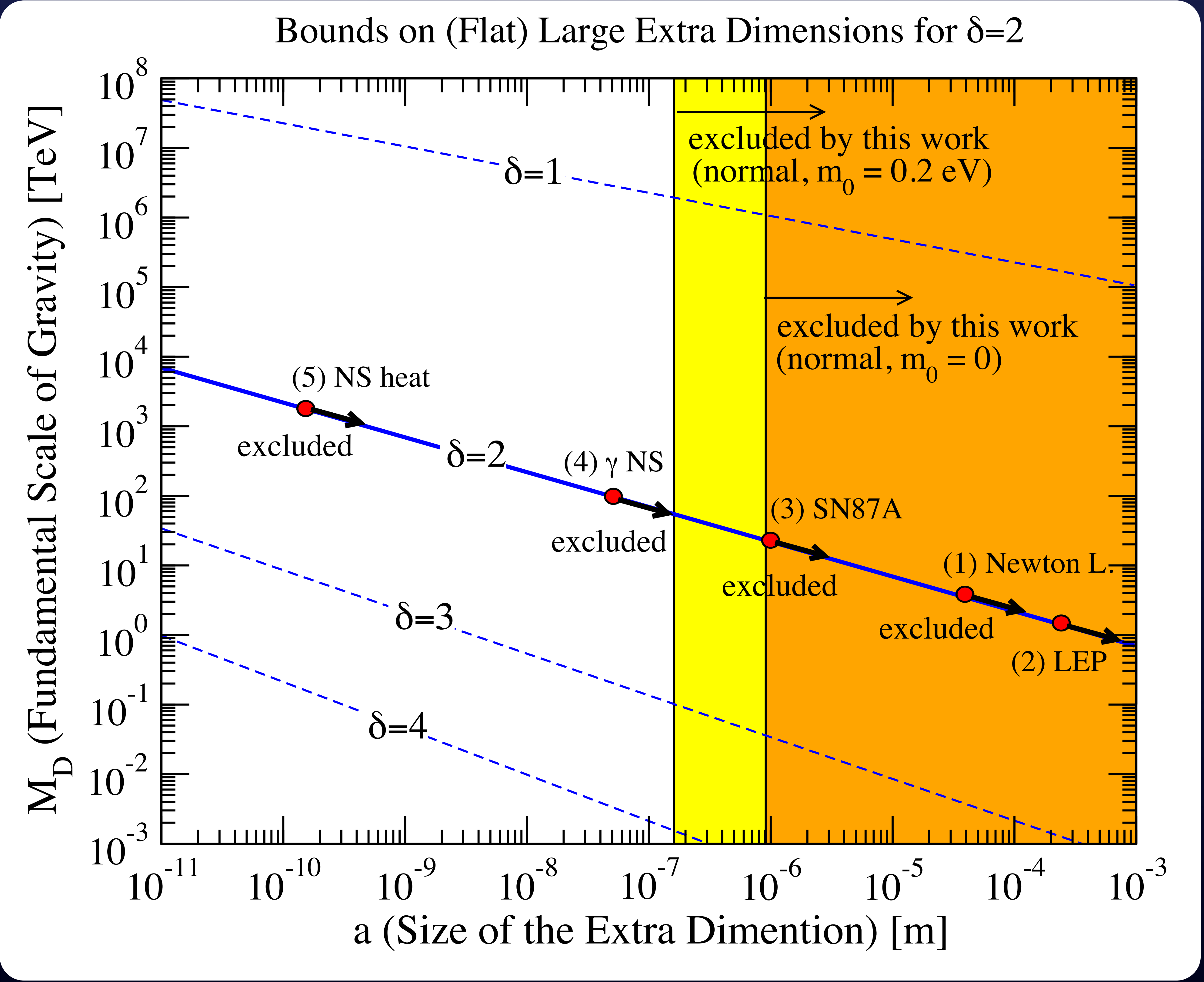

$$M_D^{\delta+2} = \frac{M_{Pl}^2}{8\pi a^\delta}$$

PDG 2010

Hannestad, Raffelt PRD67 2003

Hannestad, Raffelt PRD69 2004

Large Extra Dimensions

Discussion

Constraints from CHOOZ, KamLAND and MINOS:

m_0=0, NH: a<0.75 (0.98) μm @ 90% (99%) CL

m_0=0, IH: a<0.49 (0.57) μm@ 90% (99%) CL

m_0=0.2 eV: a<0.10 (0.12) μm@ 90% (99%) CL

Large Extra Dimensions

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Although model dependent, our bounds for $\delta=2$, $M_D > 22$ TeV, are stronger than LHC bounds

Francheschini et al 1101.4919

Large Extra Dimensions
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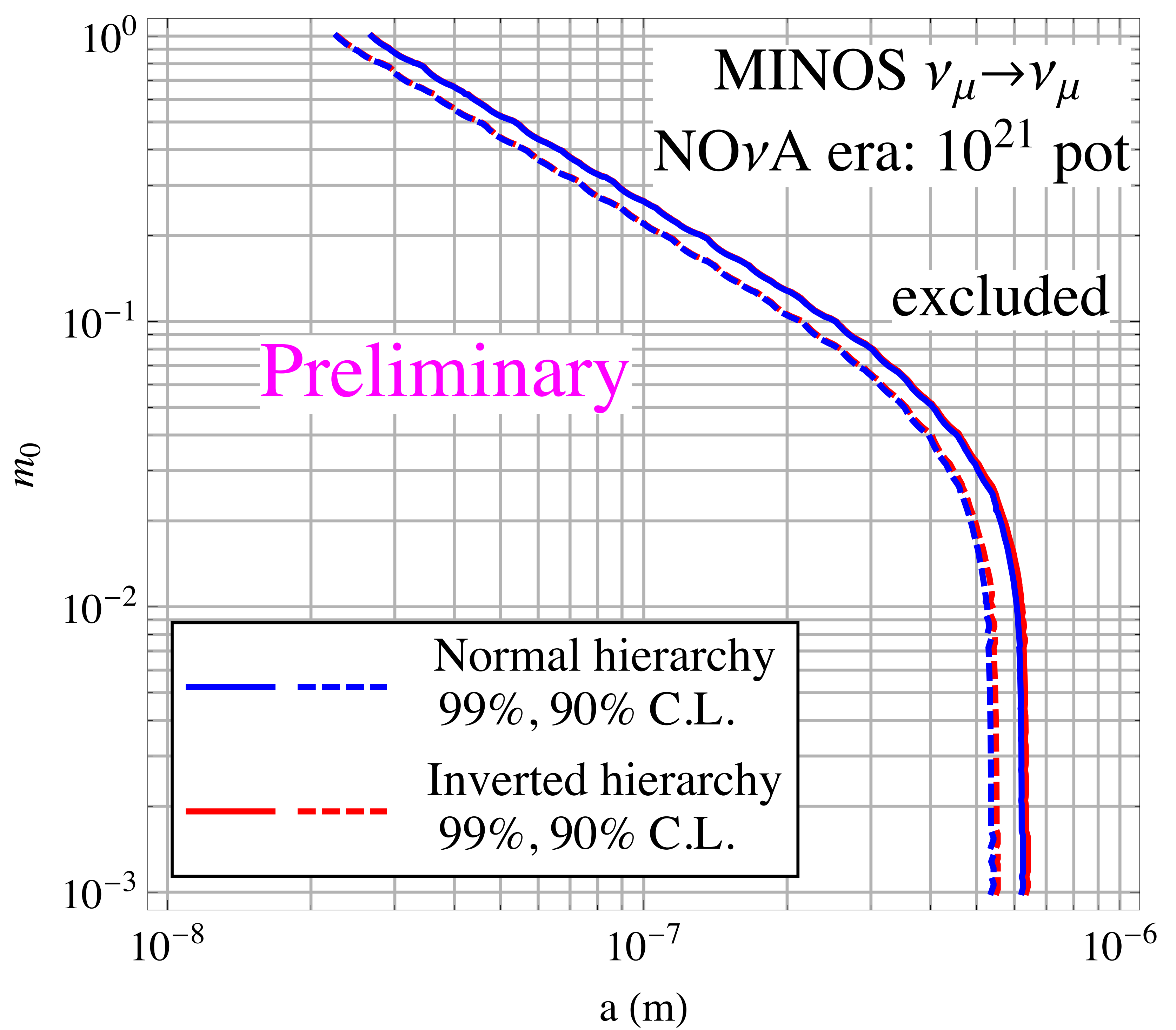
Francheschini et al 1101.4919

1101.0003: T2K and NOvA will not be able to significantly improve this limits.
MINOS in NOvA era (MINOS+)?...

Large Extra Dimensions

MINOS+



The Reactor

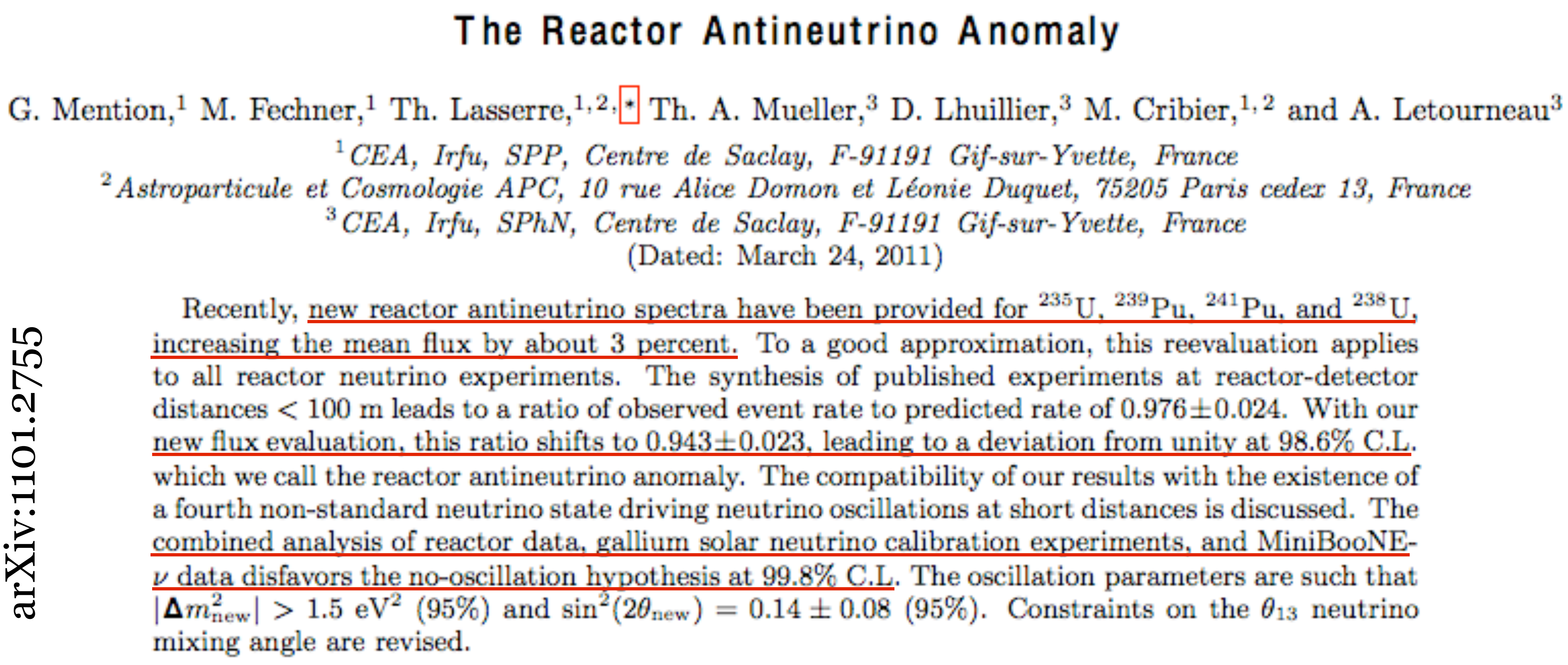
Antineutrino

Anomaly

Mueller *et al*, 1101.2663
Mention *et al*, PRD83 2011
PANM, Nunokawa, Pereira dos Santos,
Zukanovich Funchal in preparation…

Reactor Antineutrino Anomaly

A new analysis



arXiv:1101.2755

The Reactor Antineutrino Anomaly

G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]
[1] *CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
[2] *Astroparticule et Cosmologie APC, 10 rue Alice Domon et Léonie Duquet, 75205 Paris cedex 13, France*
[3] *CEA, Irfu, SPhN, Centre de Saclay, F-91191 Gif-sur-Yvette, France*

(Dated: March 24, 2011)

Recently, new reactor antineutrino spectra have been provided for ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U, increasing the mean flux by about 3 percent. To a good approximation, this reevaluation applies to all reactor neutrino experiments. The synthesis of published experiments at reactor-detector distances < 100 m leads to a ratio of observed event rate to predicted rate of 0.976 ± 0.024. With our new flux evaluation, this ratio shifts to 0.943 ± 0.023, leading to a deviation from unity at 98.6% C.L. which we call the reactor antineutrino anomaly. The compatibility of our results with the existence of a fourth non-standard neutrino state driving neutrino oscillations at short distances is discussed. The combined analysis of reactor data, gallium solar neutrino calibration experiments, and MiniBooNE-ν data disfavors the no-oscillation hypothesis at 99.8% C.L. The oscillation parameters are such that $|\Delta m^2_{\rm new}| > 1.5$ eV^2 (95%) and $\sin^2(2\theta_{\rm new}) = 0.14 \pm 0.08$ (95%). Constraints on the θ_{13} neutrino mixing angle are revised.

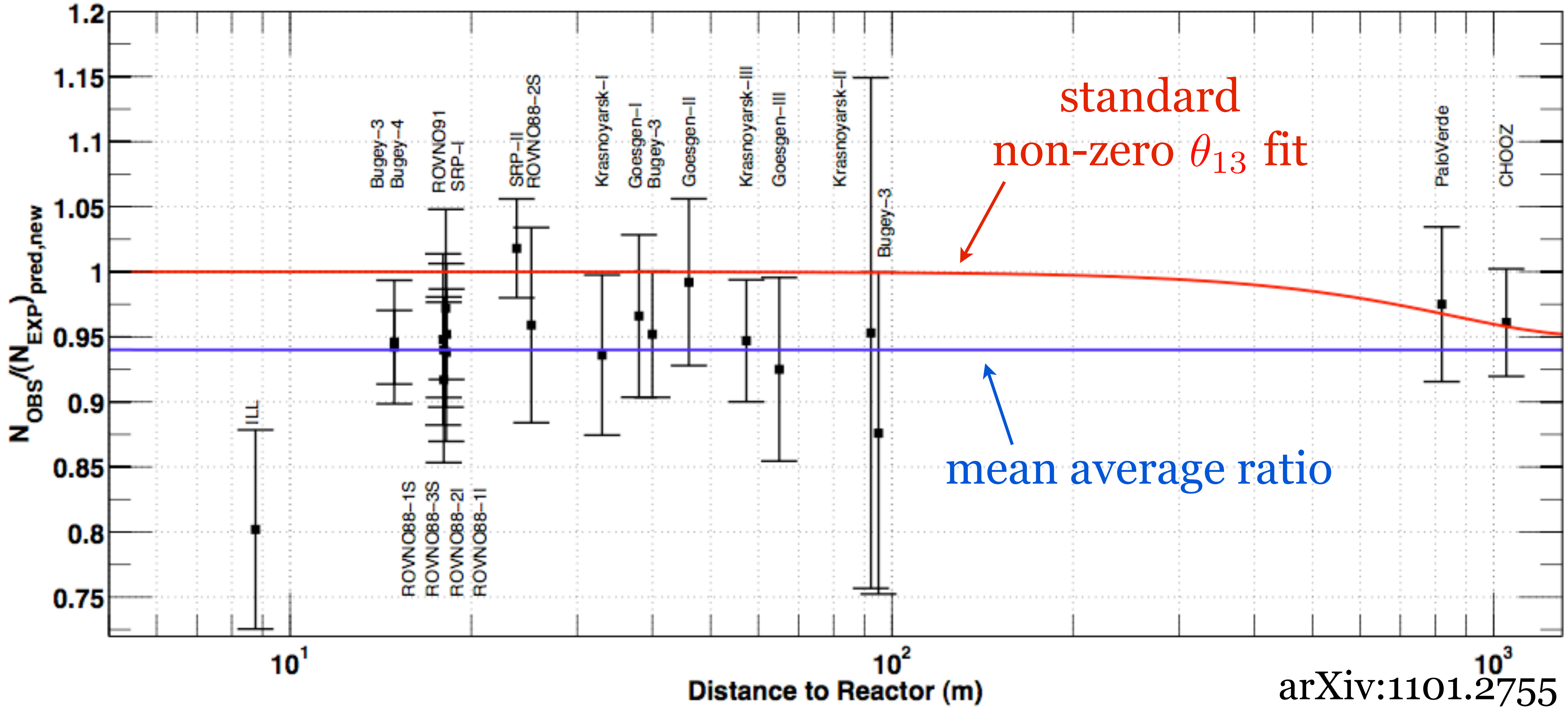
Correlation between experiments

Gallex ^{51}Cr and Sage ^{51}Cr and ^{37}Ar included

MiniBooNE data do not contribute significantly

Reactor Antineutrino Anomaly

A new analysis



standard non-zero θ_{13} fit

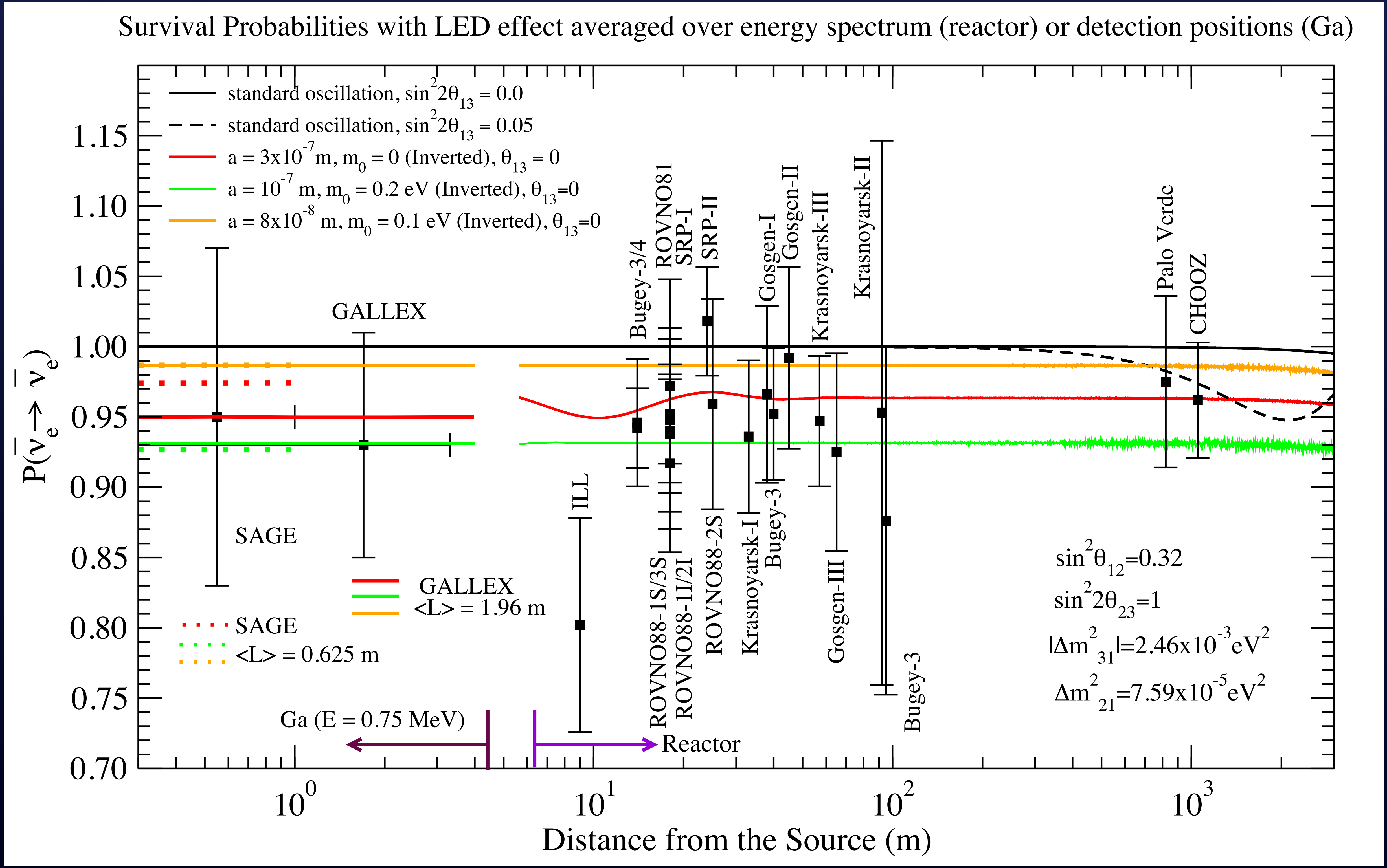
mean average ratio

arXiv:1101.2755

Could the anomaly be due to LED effects?

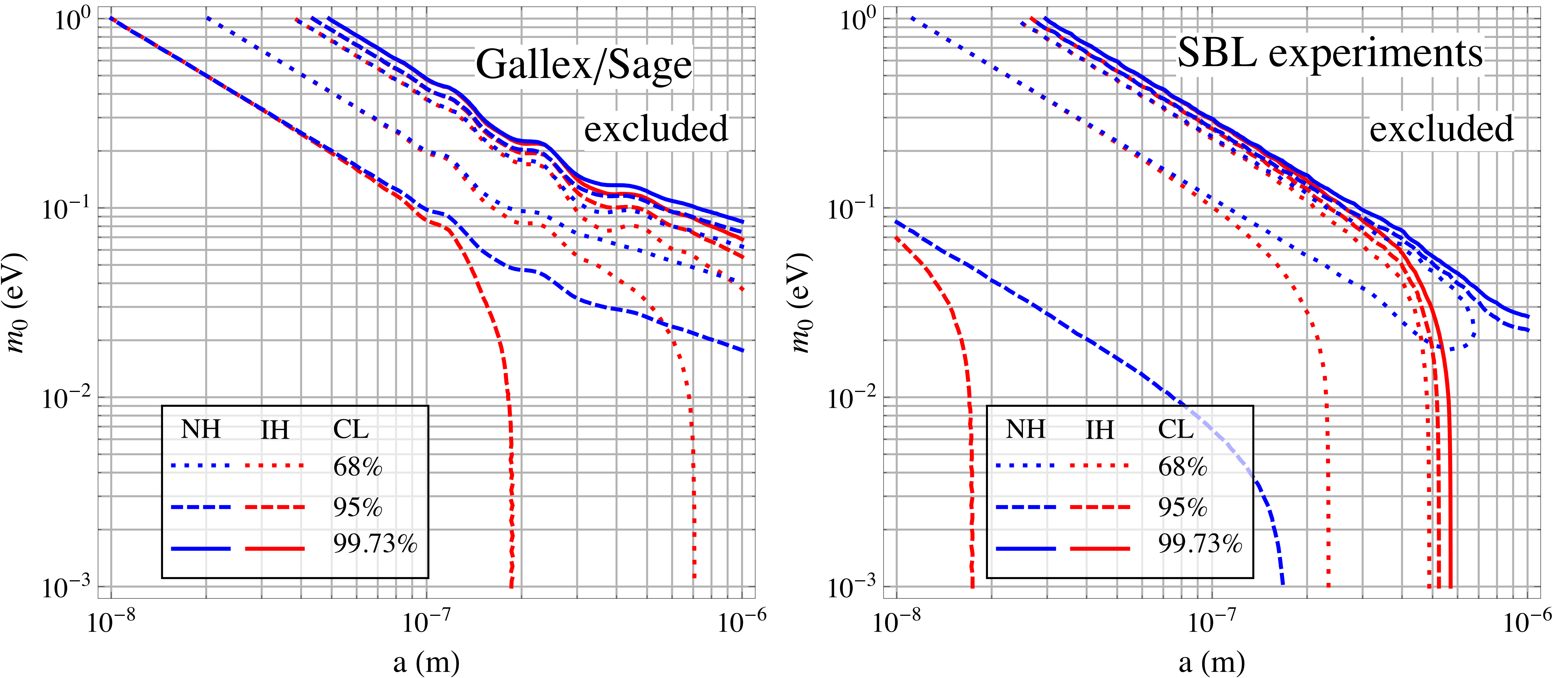
Reactor Antineutrino Anomaly

Our analysis



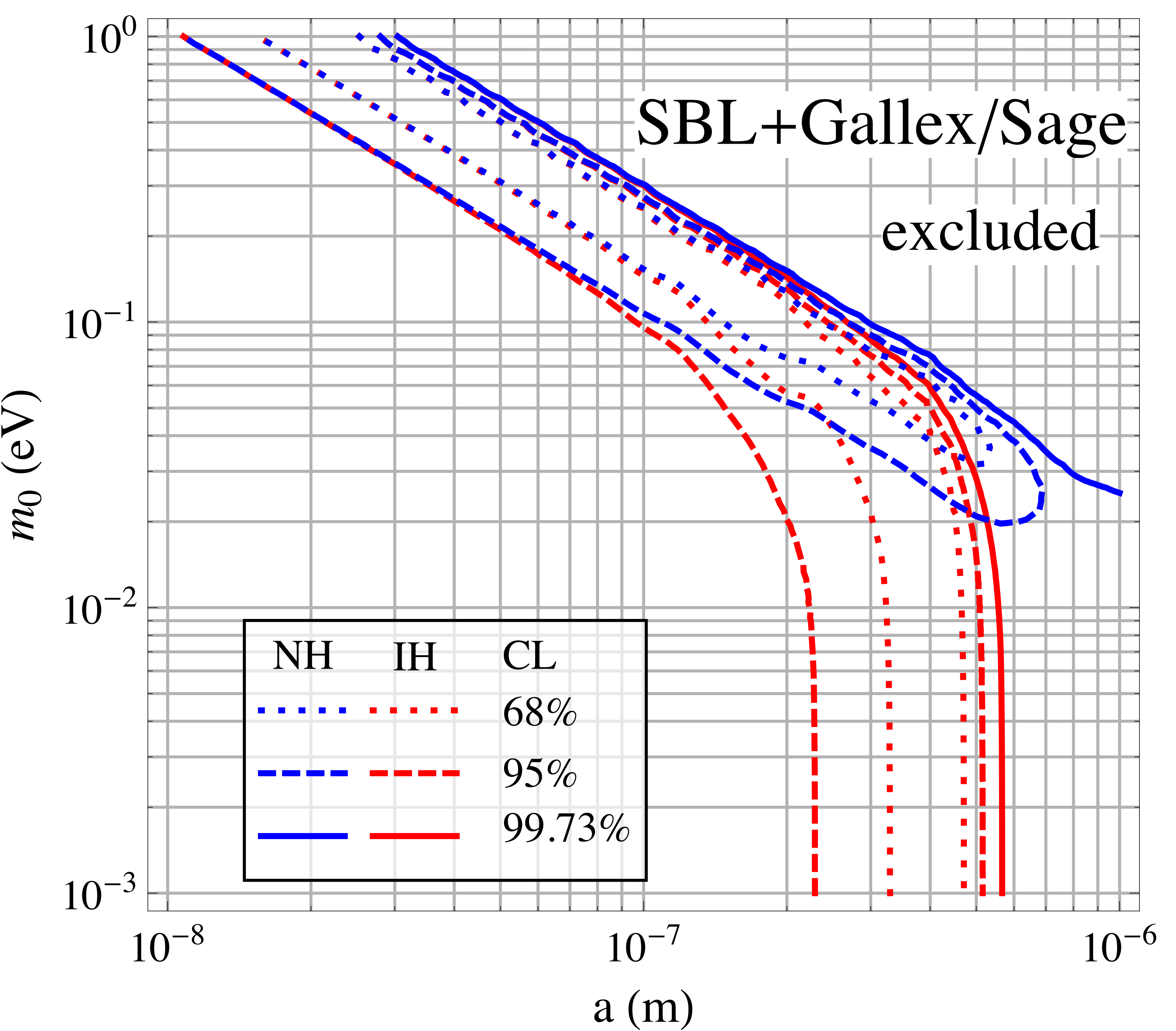
Reactor Antineutrino Anomaly

Gallex/Sage and SBL reactors



Reactor Antineutrino Anomaly

Combined analysis



2.9 σ from a = 0

Reactor Antineutrino Anomaly

Discussion

The anomaly could originate
from a LED model

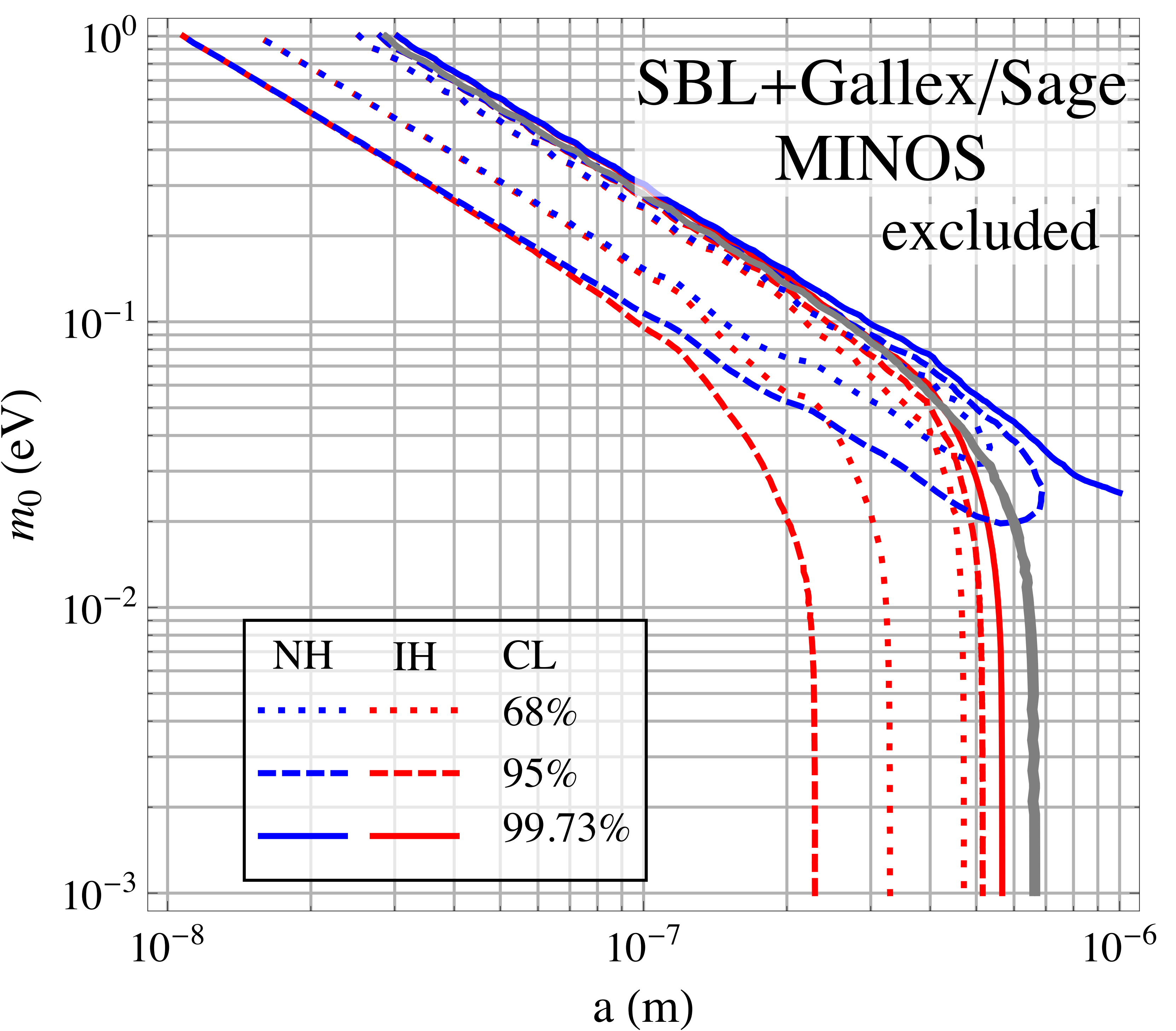
Double CHOOZ will help solving the anomaly

Again, MINOS+ could also contribute to solve it...

EXTRA SLIDES

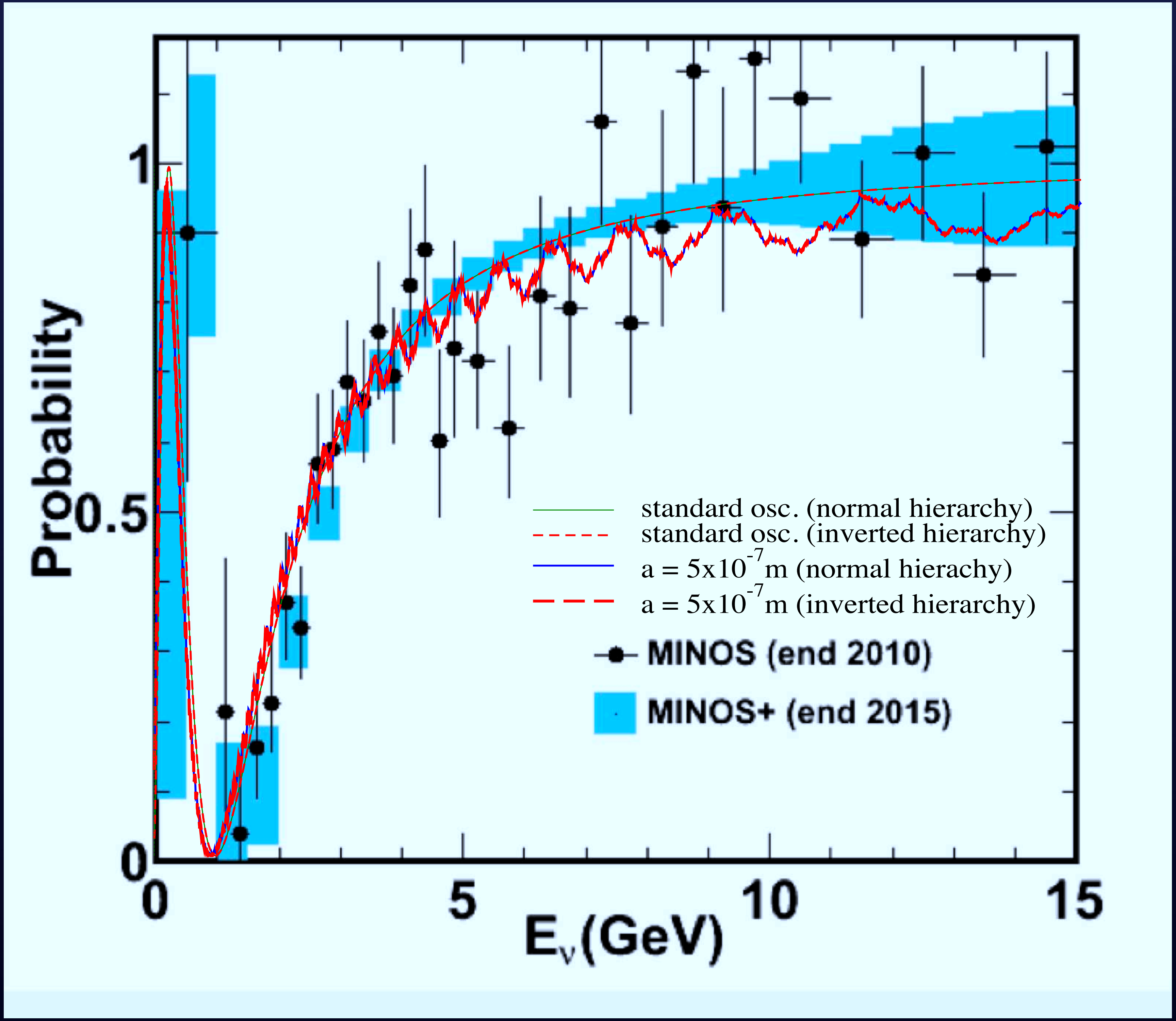
Reactor Antineutrino Anomaly

Discussion



Large Extra Dimensions

MINOS+



Large Extra Dimensions

The model

bulk singlets

$$S = \int d^4x dy\, i\overline{\Psi}^\alpha \Gamma_A \partial^A \Psi^\alpha$$

5-D Dirac matrices

$$+ \int d^4x \left(i\overline{\nu}_L^\alpha \gamma_\mu \partial^\mu \nu_L^\alpha + \lambda_{\alpha\beta} H \overline{\nu}_L^\alpha \Psi_R^\beta (x, 0) + \text{h.c.} \right)$$

SM neutrinos

$$\frac{h_{\alpha\beta}}{\sqrt{M_{Pl(4+n)}^{2+n}}}$$

Higgs

Large Extra Dimensions

The model

Decompose $\Psi^{\alpha}\left(x,y\right)$ in KK modes

$$\Psi^{\alpha}\left(x,y\right)=\frac{1}{\sqrt{2\pi a}}\sum_{N=-\infty}^{\infty}\psi^{\alpha(N)}\left(x\right)e^{iNy/a}$$

$$\nu_L^{\alpha(0)}=\psi_L^{\alpha(0)} \qquad \nu_L^{\alpha(N)}=\frac{1}{\sqrt{2}}\left(\psi_L^{\alpha(N)}-\psi_L^{\alpha(-N)}\right)$$

$$\nu_R^{\alpha(0)}=\psi_R^{\alpha(0)} \qquad \nu_R^{\alpha(N)}=\frac{1}{\sqrt{2}}\left(\psi_R^{\alpha(N)}+\psi_R^{\alpha(-N)}\right)$$

$$N=1,\ldots,\infty$$

Large Extra Dimensions

The model

$h_{\alpha\beta}\,\langle H\rangle\, M_{Pl(4+n)}/M_{Pl}$

$$\mathcal{L}_{\rm mass} = \sum_{\alpha,\beta=e,\mu,\tau} m^D_{\alpha\beta}\left[\overline{\nu}^{\alpha}_{L}\nu^{\beta(0)}_{R} + \sqrt{2}\sum_{N=1}^{\infty}\overline{\nu}^{\alpha}_{L}\nu^{\beta(N)}_{R}\right] + \sum_{\alpha=e,\mu,\tau}\sum_{N=1}^{\infty}\frac{N}{a}\overline{\nu}^{\alpha(N)}_{L}\nu^{\alpha(N)}_{R} + \text{h.c.}$$

Size of extra dimension

Diagonalizing in flavor subspace

$$\nu^{(0)}_{\alpha L} = \sum_i U_{\alpha i}\,\nu^{(0)}_{iL}$$

$$\nu^{(0)}_{\alpha R} = \sum_i R_{\alpha i}\,\nu^{(0)}_{iR}$$

$$\nu^{(N)}_{\alpha R,\alpha L} = \sum_i R_{\alpha i}\,\nu^{(N)}_{iR,iL}$$

Basics of ν oscillations

Parameters

Gonzalez-Garcia, Maltoni, Salvado 1001.4525

Mixing angles

$$\theta_{12} = 34,4 \pm 1,0^o$$

$$\theta_{23} = 42,8(^{+4,7}_{-2,9})^o$$

$$\theta_{13} = 5,6(^{+3,0}_{-2,7})^o$$

Masses

$$\Delta m^2_{21} = 7,59 \pm 0,20 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = 2,46 \pm 0,12 \times 10^{-3}\ \mathrm{eV}^2$$

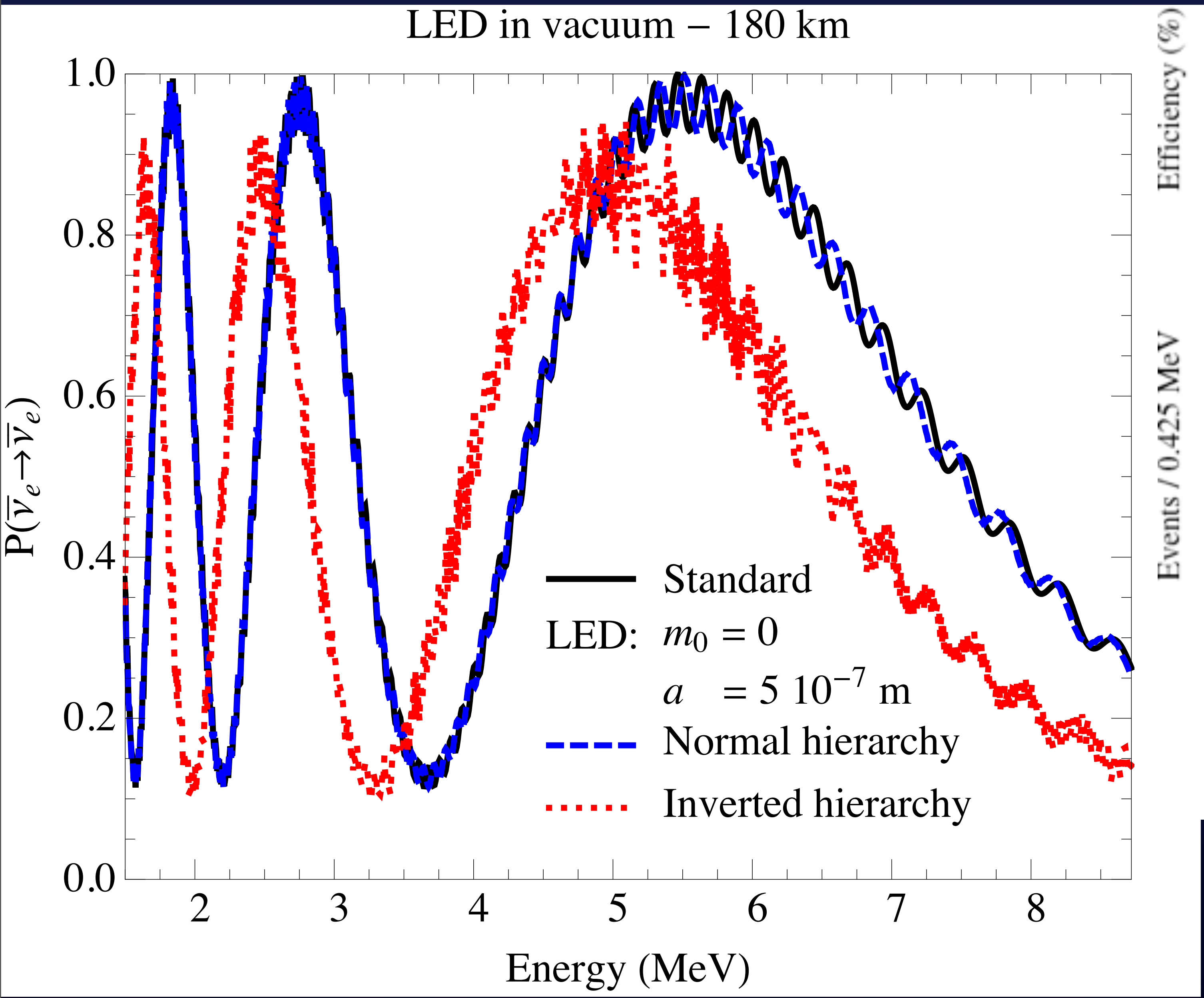
or

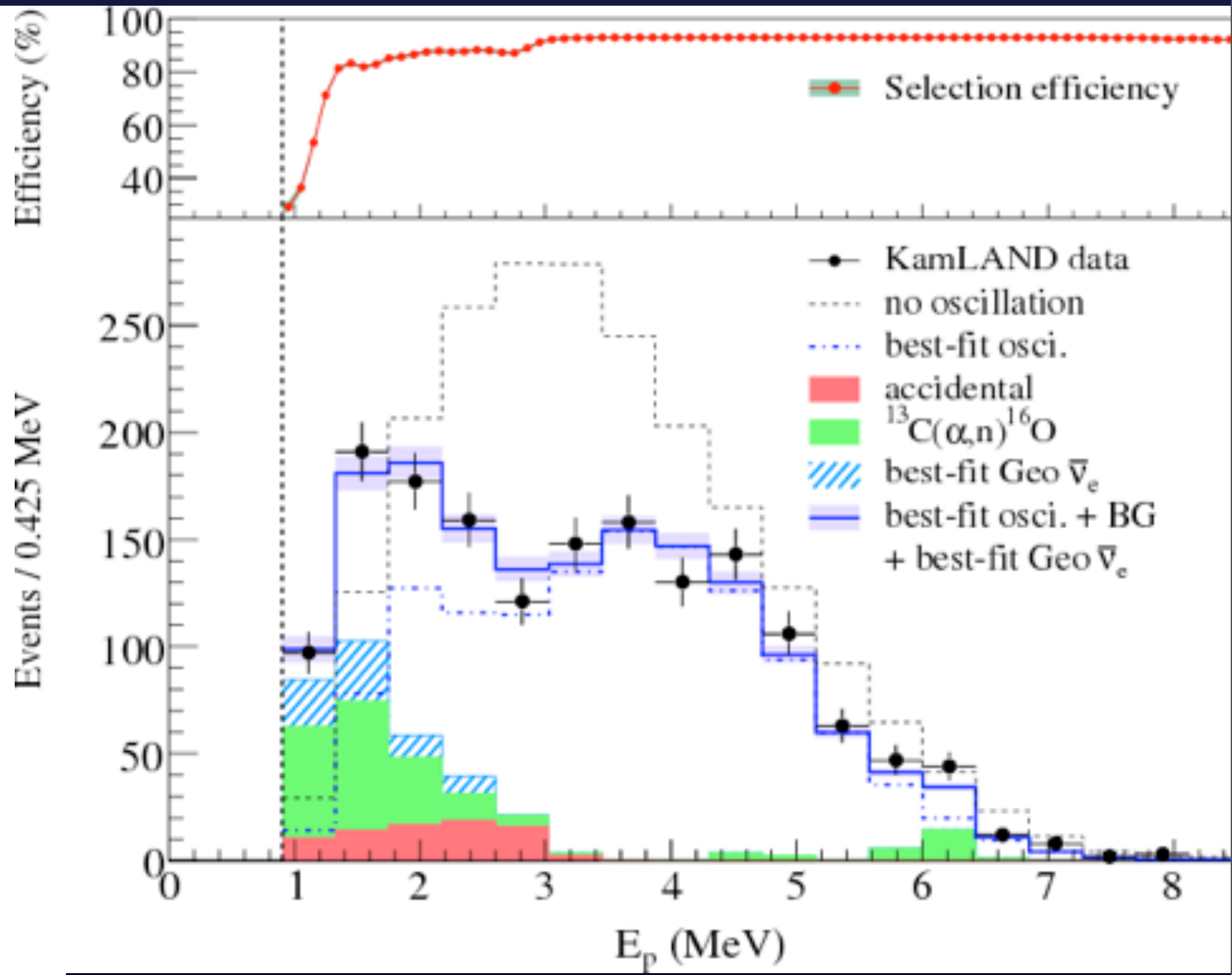
$$\Delta m^2_{31} = -2,36 \pm 0,11 \times 10^{-3}\ \mathrm{eV}^2$$

$$*\delta_{CP} \in [0, 2\pi]$$

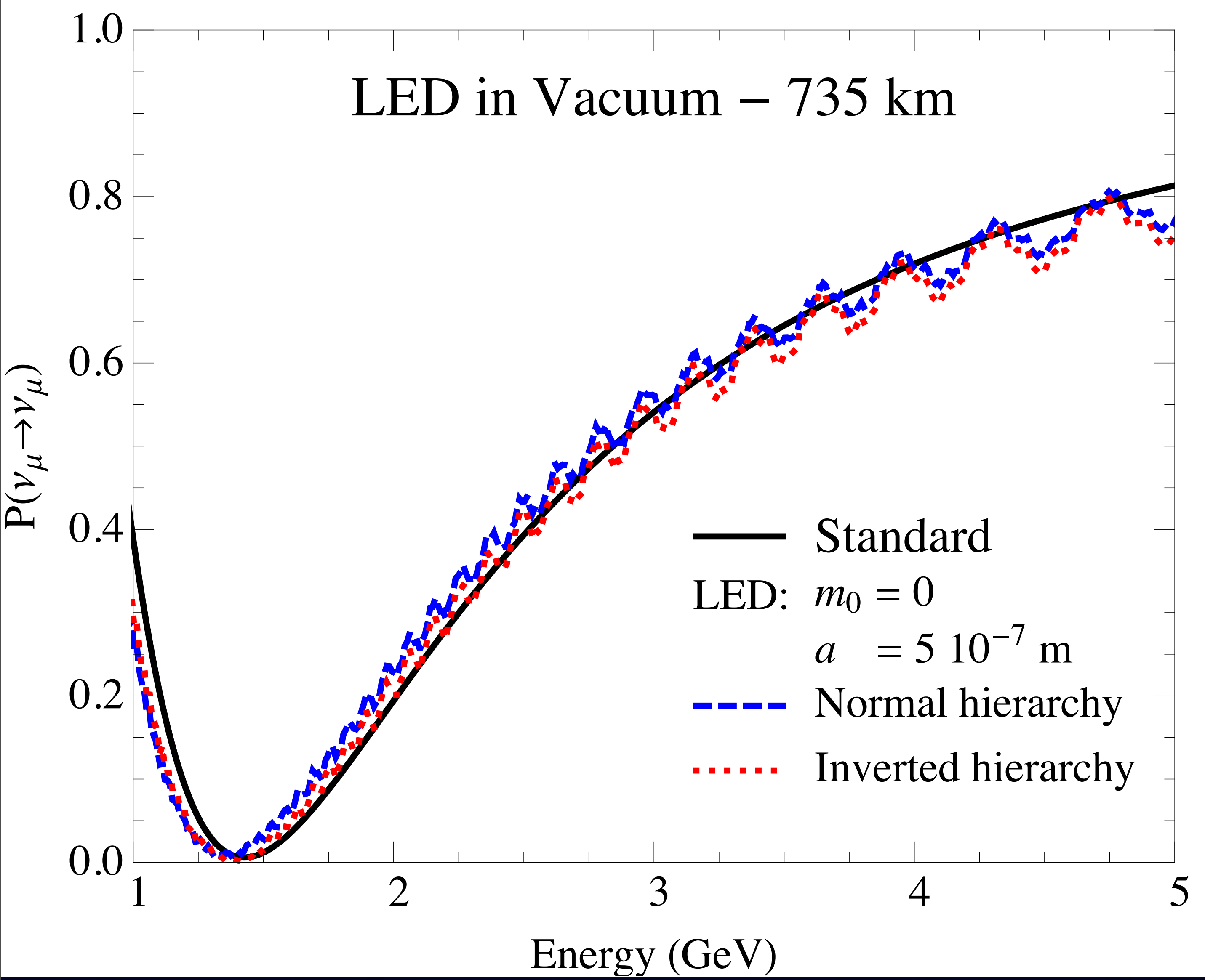
Large Extra Dimensions

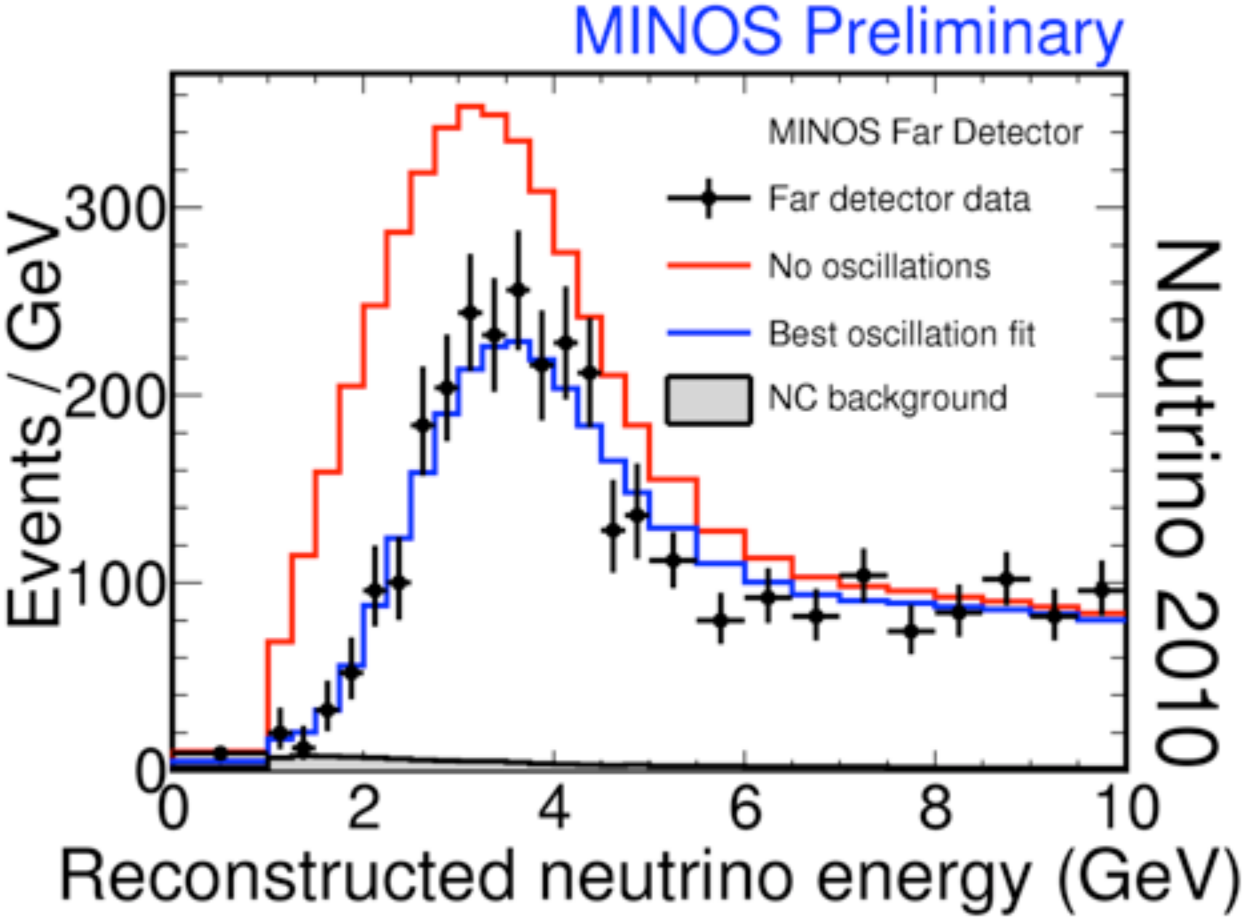
KamLAND





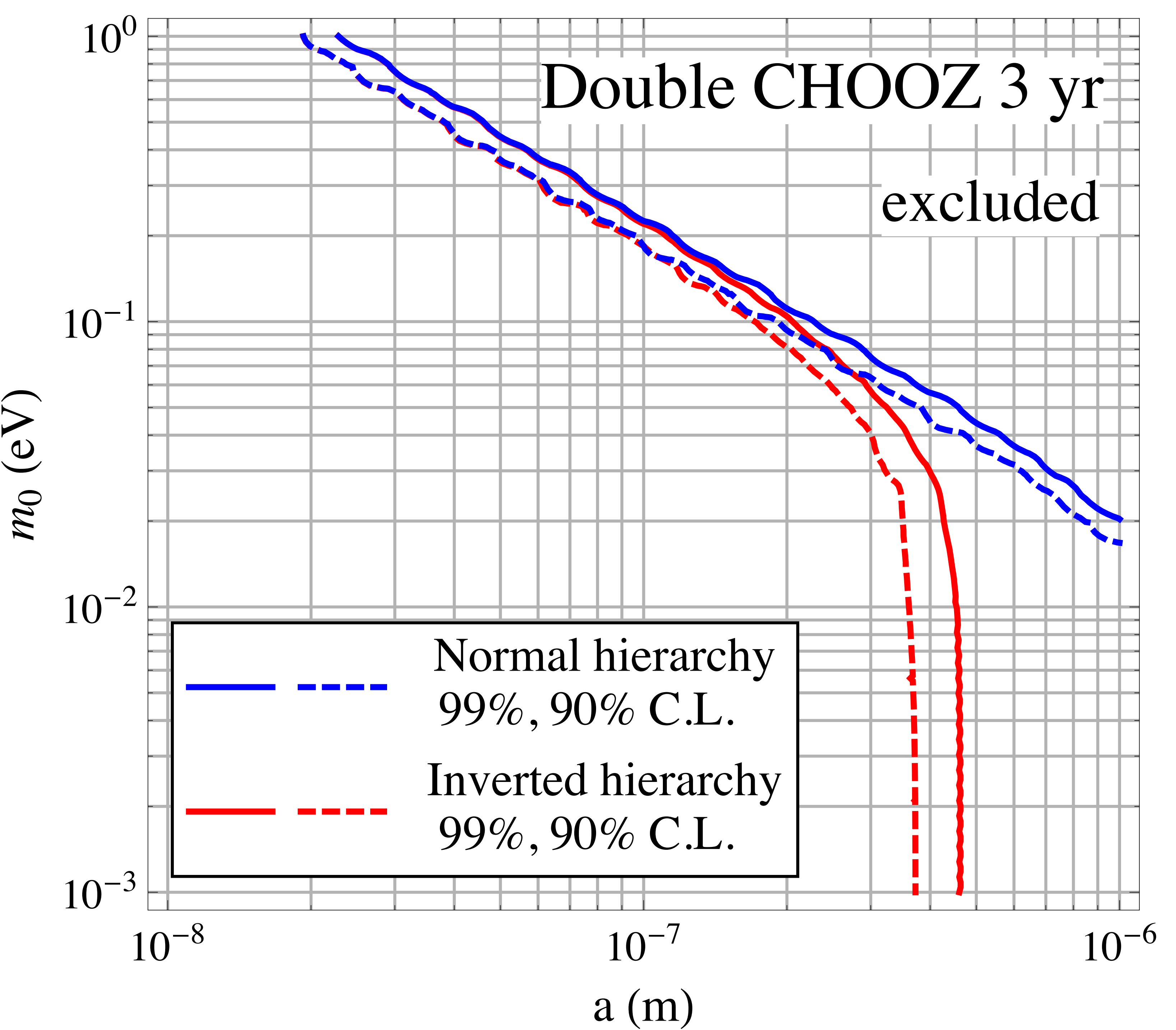
Large Extra Dimensions
MINOS





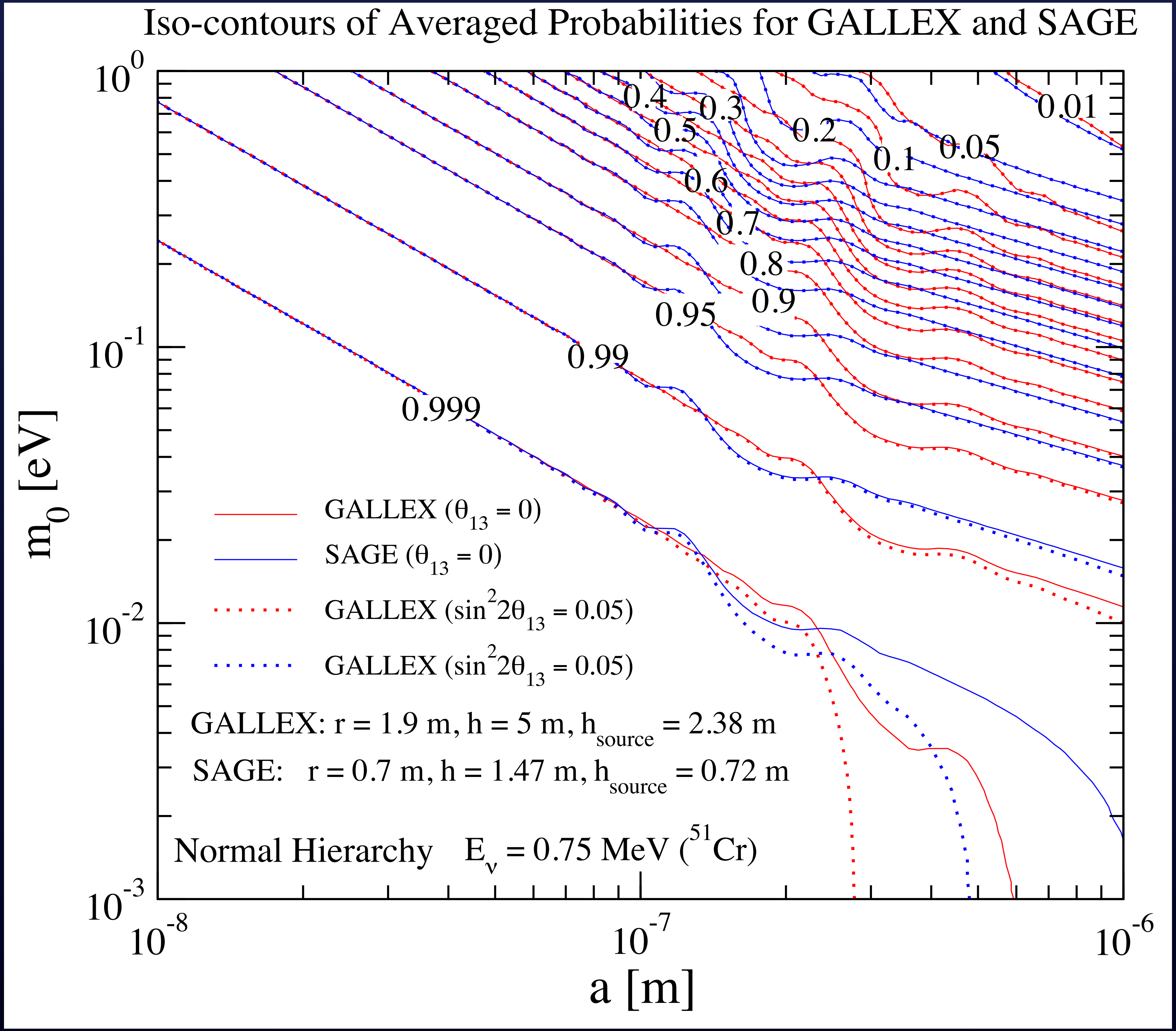
Large Extra Dimensions

Double CHOOZ



Reactor Antineutrino Anomaly

Our analysis



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