Probing large extra dimensions with neutrino oscillations

Pedro A N Machado[1,2]

in collaboration with:
H Nunokawa[3], F A Pereira dos Santos[3],
and R Zukanovich Funchal[1]

[1]Universidade de São Paulo, [2]CEA-Saclay, [3]PUC-RIO

Based on 1101.0003 and MNPZ in preparation

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and an interpretation for the reactor and gallium anomalies

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Outline

- Neutrino oscillations

- Neutrinos and large extra dimensions

- Reactor and gallium anomalies

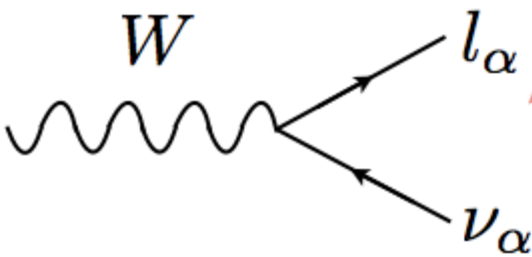
- Conclusions

Neutrino oscillations

Neutrino oscillations

Neutrinos oscillate:

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



mass eigenstates

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

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

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

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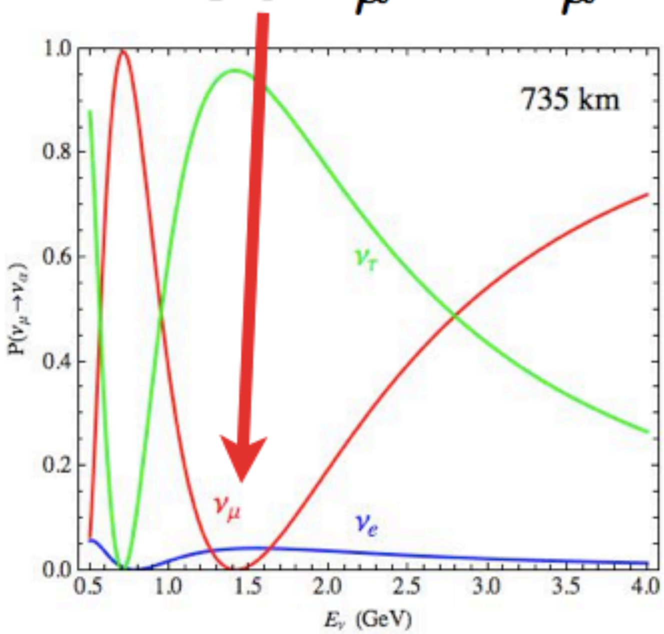
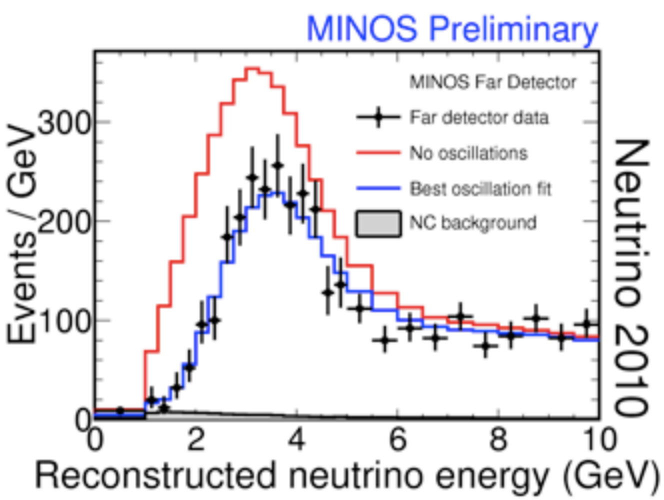
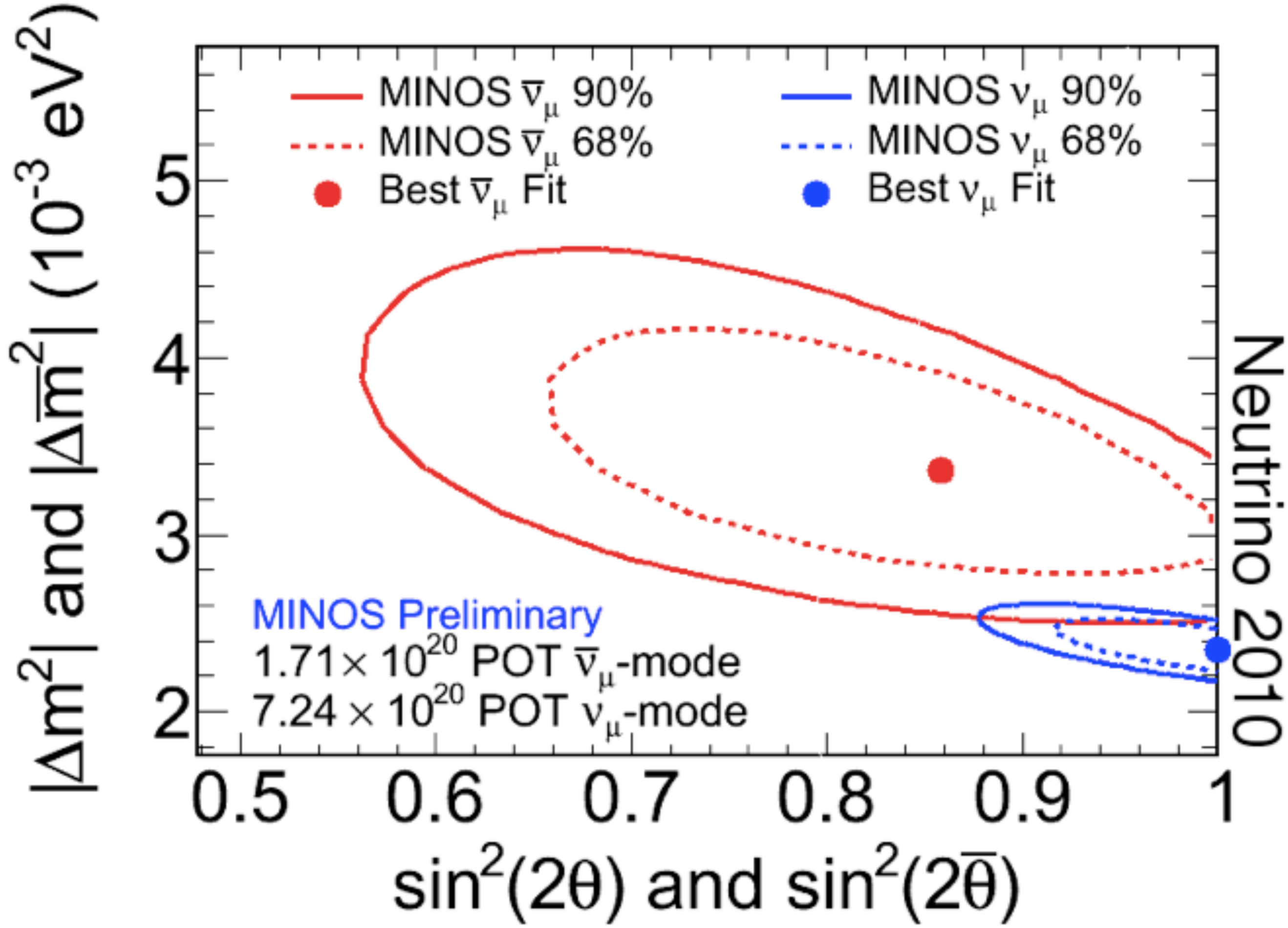
Neutrino oscillations

MINOS $\nu_\mu \to \nu_\mu$

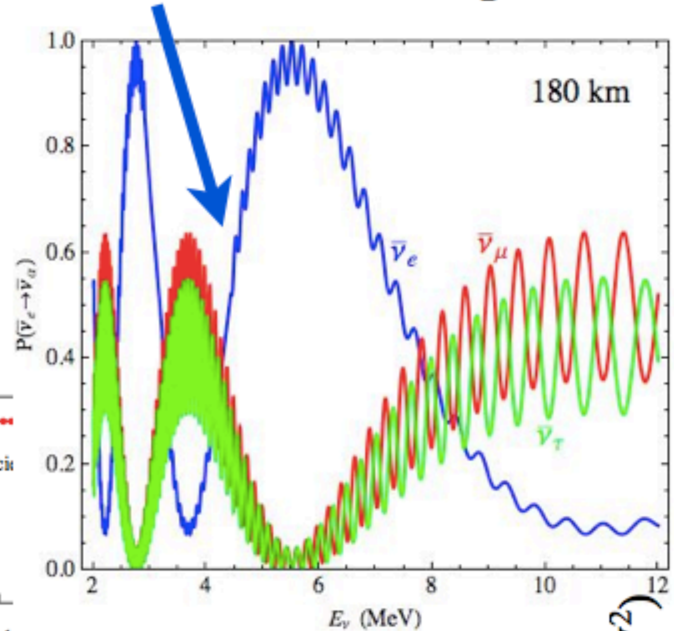


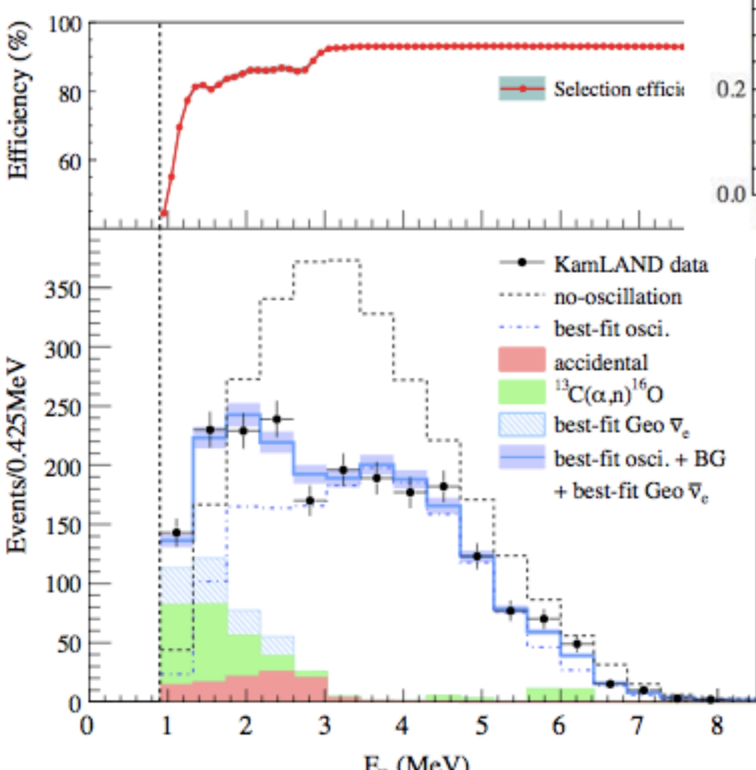


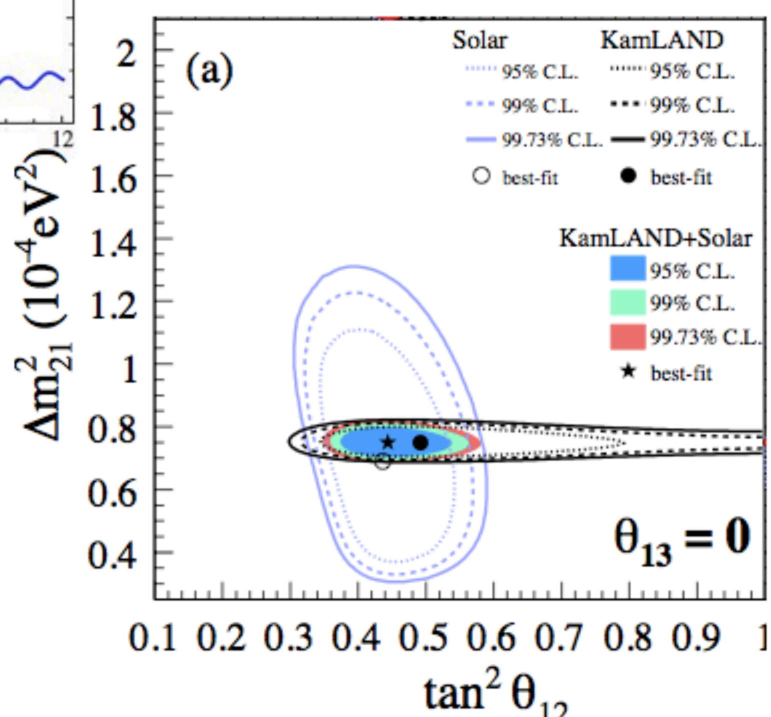


Neutrino oscillations

KamLAND $\bar{\nu}_e \to \bar{\nu}_e$

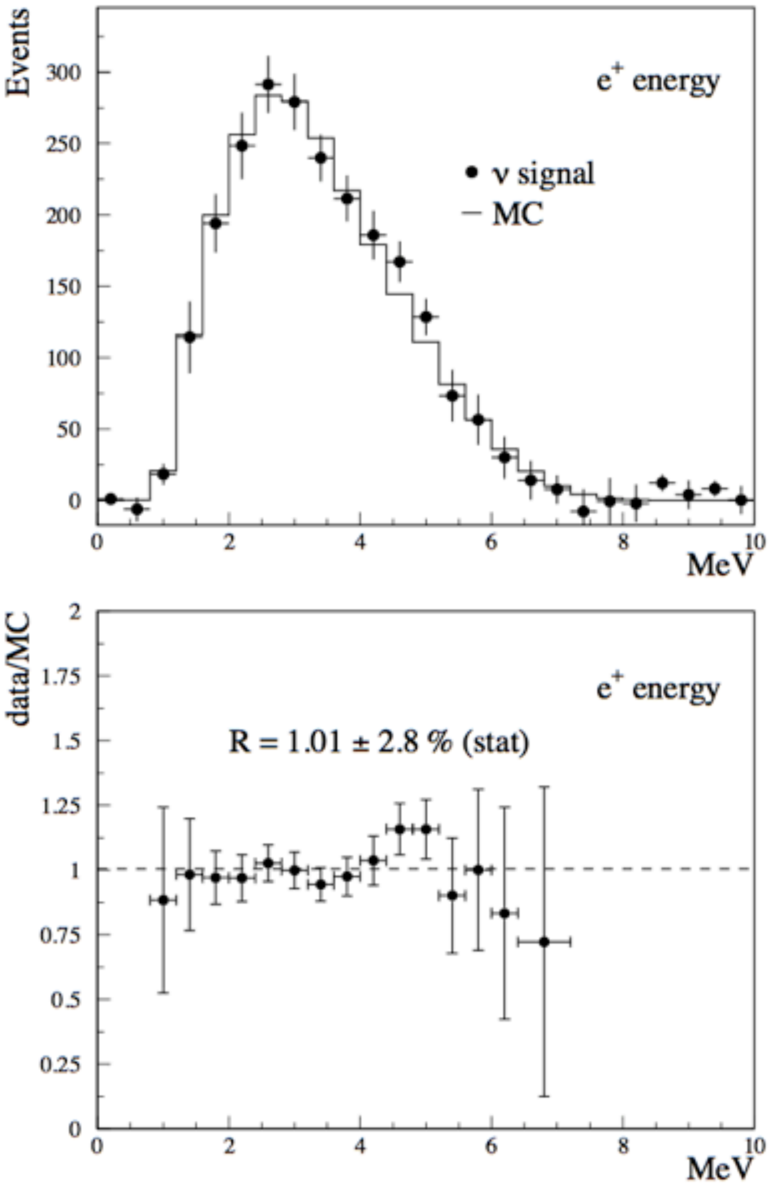


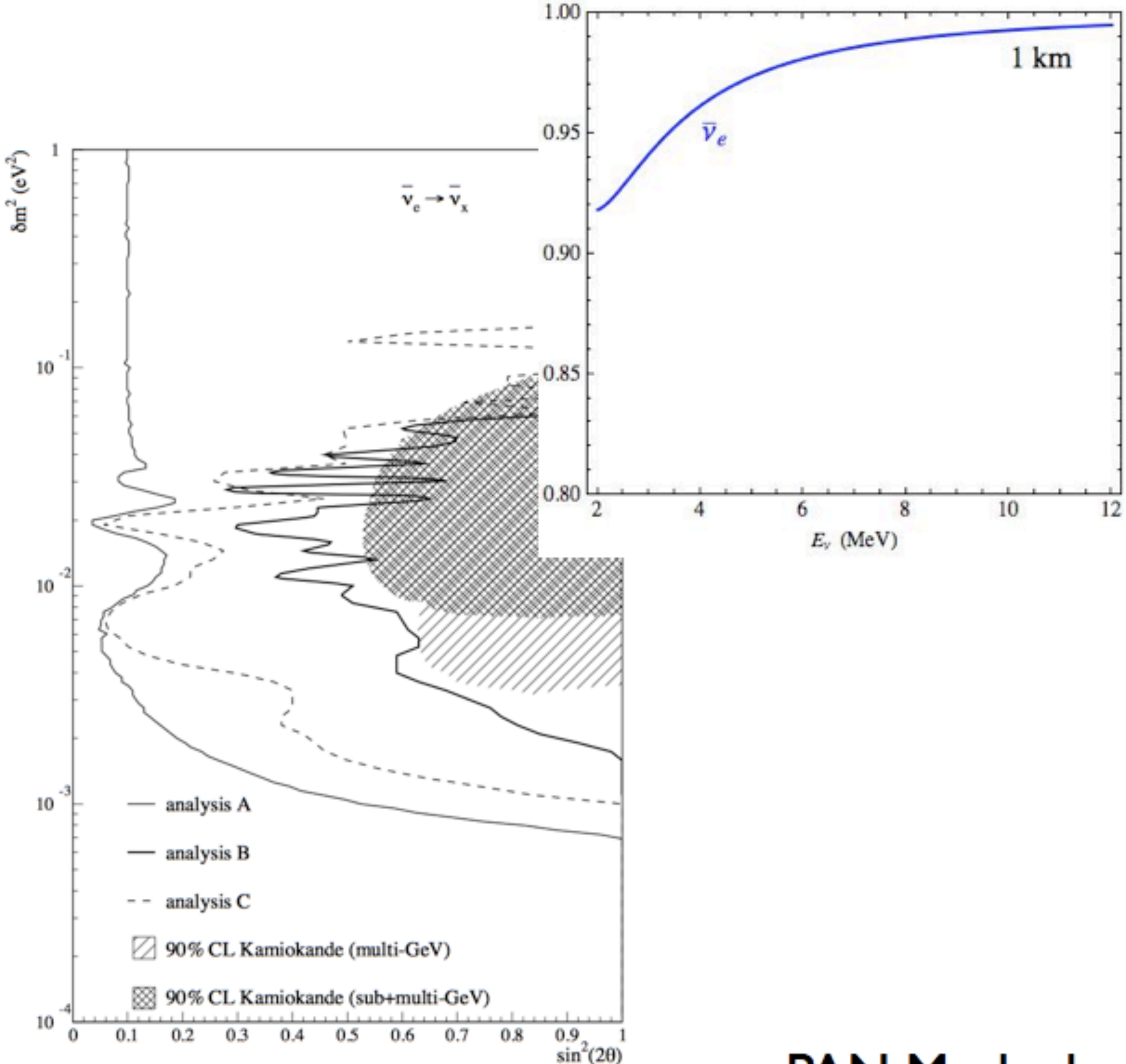




Neutrino oscillations

CHOOZ $\bar{\nu}_e \to \bar{\nu}_e$





Fermilab Jul-07-2011

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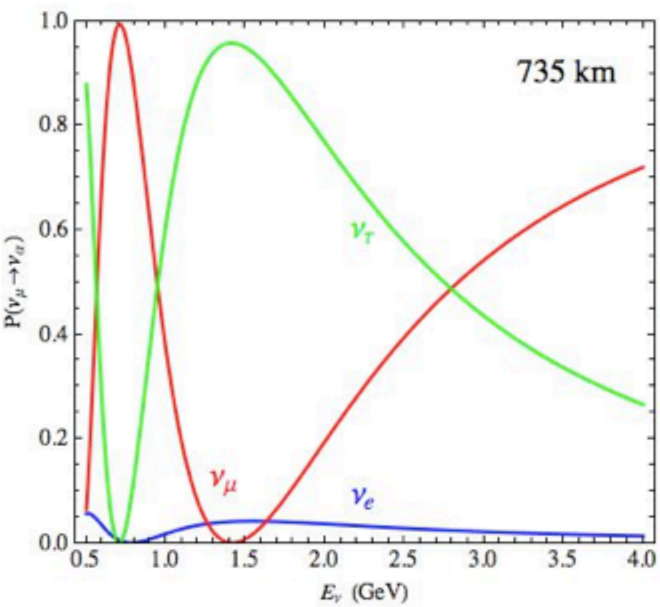
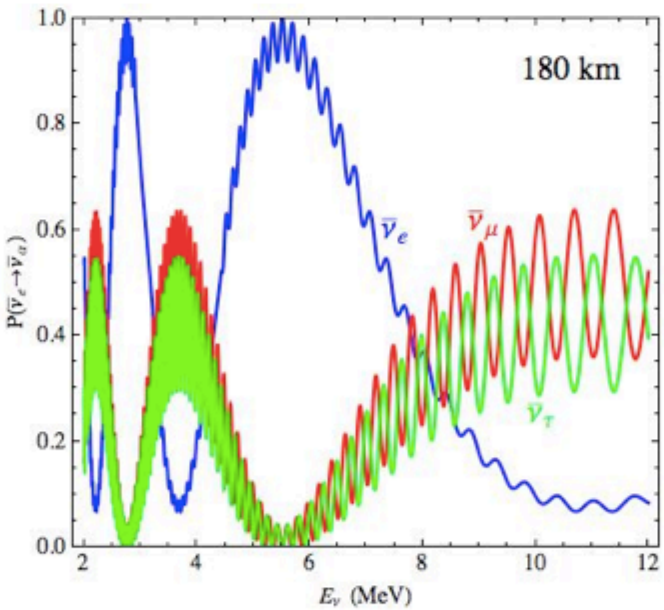
Neutrino oscillations

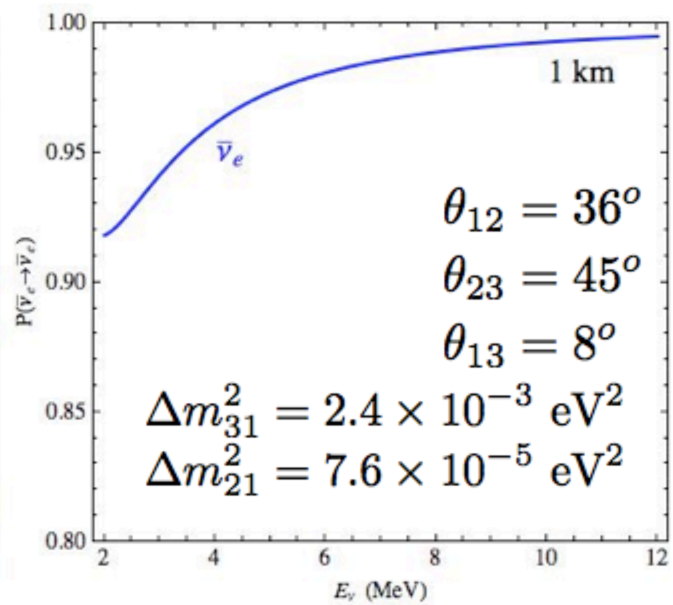
MINOS $\nu_\mu \to \nu_\mu$



KamLAND $\bar{\nu}_e \to \bar{\nu}_e$



CHOOZ $\bar{\nu}_e \to \bar{\nu}_e$



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

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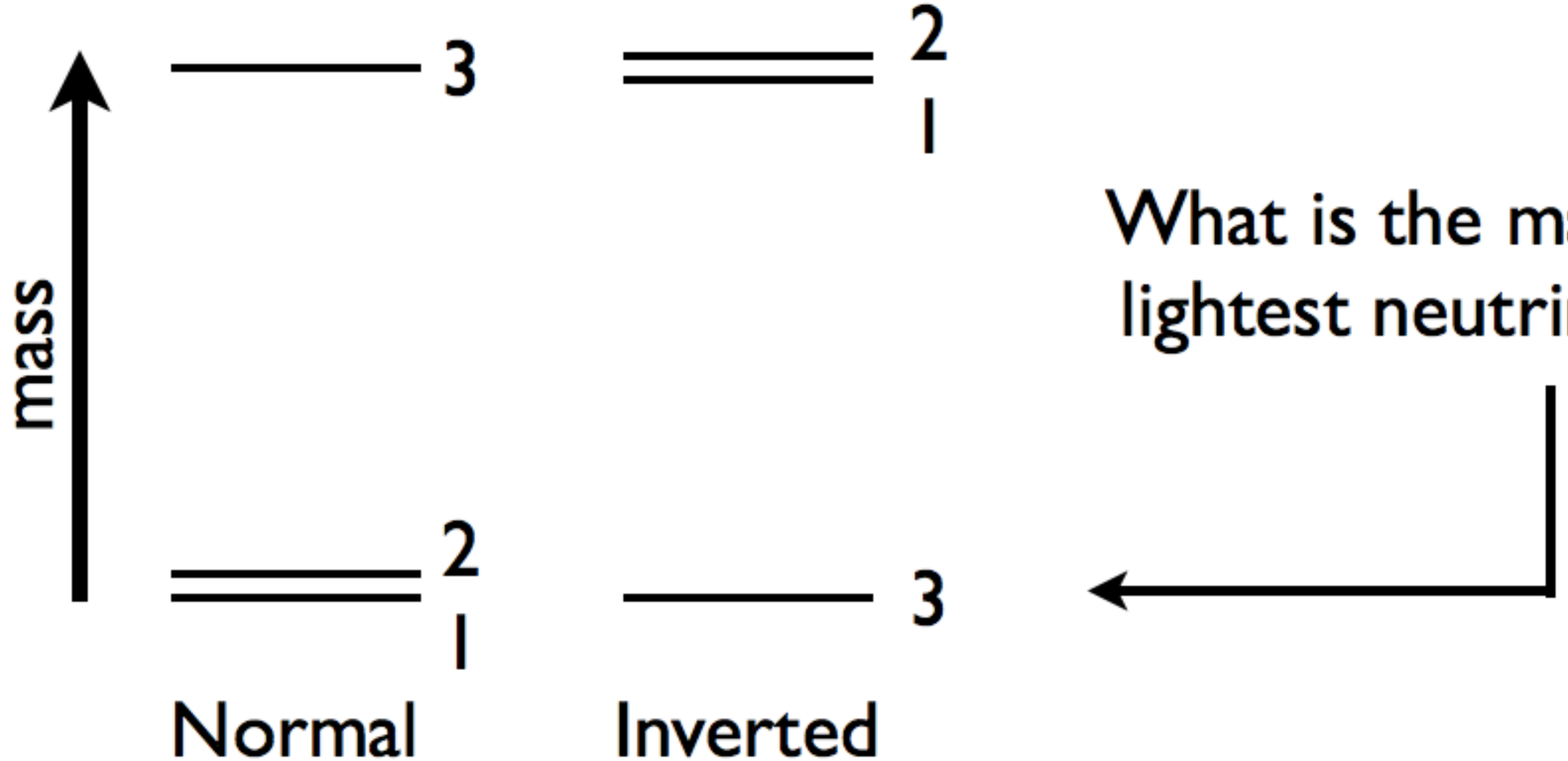
Neutrino oscillations

What is the mass hierarchy?



What is the mass of the lightest neutrino (m_0)?

Neutrinos and Large extra dimensions

Arkani-Hamed, Dimopoulos, Dvali, PRD59 1999
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

Why LED?

Why LED?

Lower energy scales - GUT, Planck and string scales

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Lower energy scales - GUT, Planck and string scales

- GUT - EDs felt by all forces, gauge and gravitational
- Planck - EDs felt by gravitation only
- Combining both, the string scale can be lowered

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- GUT - EDs felt by all forces, gauge and gravitational
- Planck - EDs felt by gravitation only
- Combining both, the string scale can be lowered

Just for fun, let's lower the Planck scale

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

Suppose δ flat extra dimensions, each compactified on a circle of radius a

Why LED?

The gravitational potential in this theory is described as

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+\delta)}^{\delta+2}\, r^{\delta+1}}$$

$r \ll a$

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$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+\delta)}^{\delta+2}\, r^{\delta+1}} \longleftrightarrow V(r) \sim \frac{m_1 m_2}{M_{Pl(4+\delta)}^{\delta+2}\, a^{\delta}\, r}$$

$r \ll a$ $\qquad\qquad$ $r \gg a$

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$r \ll a$ $\qquad\qquad$ $r \gg a$

Hence, the relation between the effective 4D Planck scale and the true Planck scale is $M_{Pl}^2 \sim M_{Pl(4+\delta)}^{2+\delta} a^{\delta}$

If we impose $M_{Pl(4+\delta)} \sim m_{EW}$, then

$$a \sim 10^{\frac{30}{\delta}-17}\text{cm} \times \left(\frac{1\text{TeV}}{m_{EW}}\right)^{1+\frac{2}{\delta}}$$

Why LED?

The gravitational potential in this theory is described as

$$V(r) \sim \frac{m_1 m_2}{M^{\delta+2} \ldots}$$

$r \ll a$

$$V(r) \sim \frac{m_1 m_2}{M^{\delta+2}_{Pl(4+\delta)} a^\delta \, r}$$

Ok, but what about neutrinos?

Hence, the r... D Planck scale and the true Planck scale is $M^2_{Pl} \sim M^{2+\delta}_{Pl(4+\delta)} a^\delta$

If we impose $M_{Pl(4+\delta)} \sim m_{EW}$, then

$$a \sim 10^{\frac{30}{\delta} - 17} \mathrm{cm} \times \left(\frac{1 \mathrm{TeV}}{m_{EW}} \right)^{1 + \frac{2}{\delta}}$$

Why neutrinos?

Small neutrino masses point to another high scale

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Small neutrino masses point to another high scale

We can lower GUT and Planck scales. Can we generate small ν masses without introducing another high scale?

Why neutrinos?

Small neutrino masses point to another high scale

We can lower GUT and Planck scales. Can we generate small ν masses without introducing another high scale?

For simplicity, assume that one of them is compactified in a circle of radius a, much larger than the size of the others (5D treatment)

Now, introduce 3 bulk fermion singlets

Why neutrinos?

Take a look at the 5D action with the bulk singlets

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

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

Why neutrinos?

Take a look at the 5D action with the bulk singlets

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

5D 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

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

(dimension analysis)

Higgs

Why neutrinos?

Decompose the singlet in KK modes (Fourier modes)

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

Integrate in y and redefine the fields

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

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

$$n = 1, \ldots, \infty$$

Why neutrinos?

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

Why neutrinos?

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

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

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

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The neutrino masses are naturally suppressed!

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The neutrino masses are naturally suppressed!

Why neutrinos?

$\mathcal{L}_{\rm m}$ … $n)\Big]$

$+ \sum_{\alpha=e,\mu,\tau} \sum_{n=1}$ … $+ \text{h.c.}$

But then, what will happen
to the neutrino sector?
How this affects oscillation?

The neutrino masses are
naturally suppressed!

What now?

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

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

$$+\sum_{\alpha=e,\mu,\tau}\sum_{n=1}^{\infty}\frac{n}{a}\overline{\nu}^{\alpha(n)}_{L}\nu^{\alpha(n)}_{R} + \text{h.c.}$$

Diagonalize in flavor subspace $\quad \nu_{\alpha L} = \sum_i U_{\alpha i}\,\nu_{iL}$

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

What now?

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

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

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

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

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

STANDARD

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

What now?

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Almost diagonal (kj): $\nu_\alpha \to \nu_s$ ✓

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

What now?

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

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

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

What now?

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$$\nu_e \to \nu_e$$

What now?

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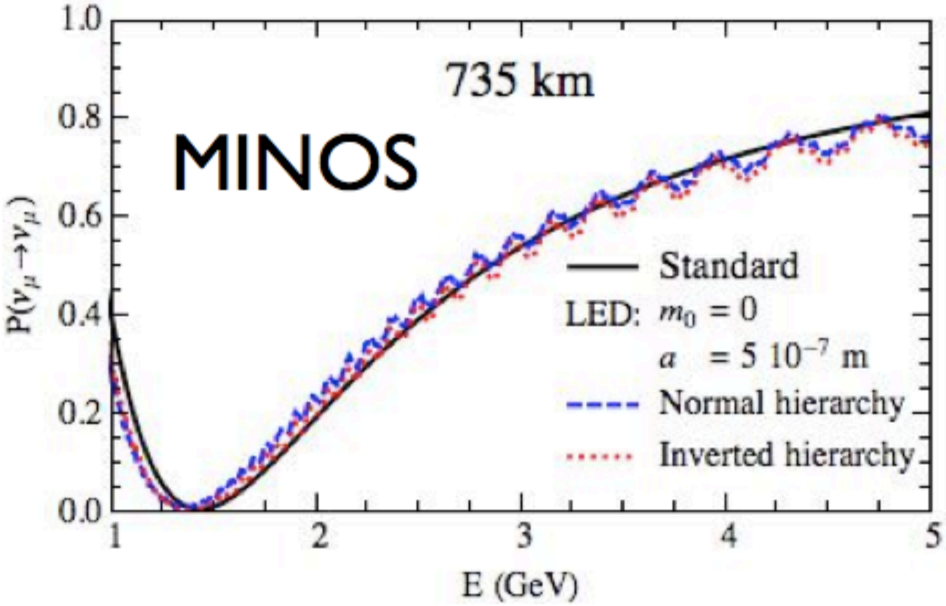
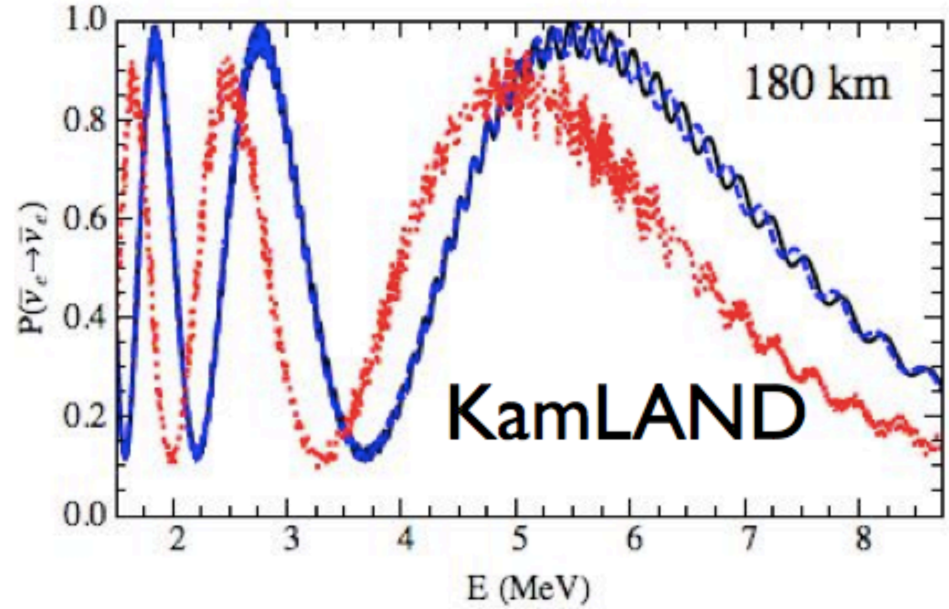
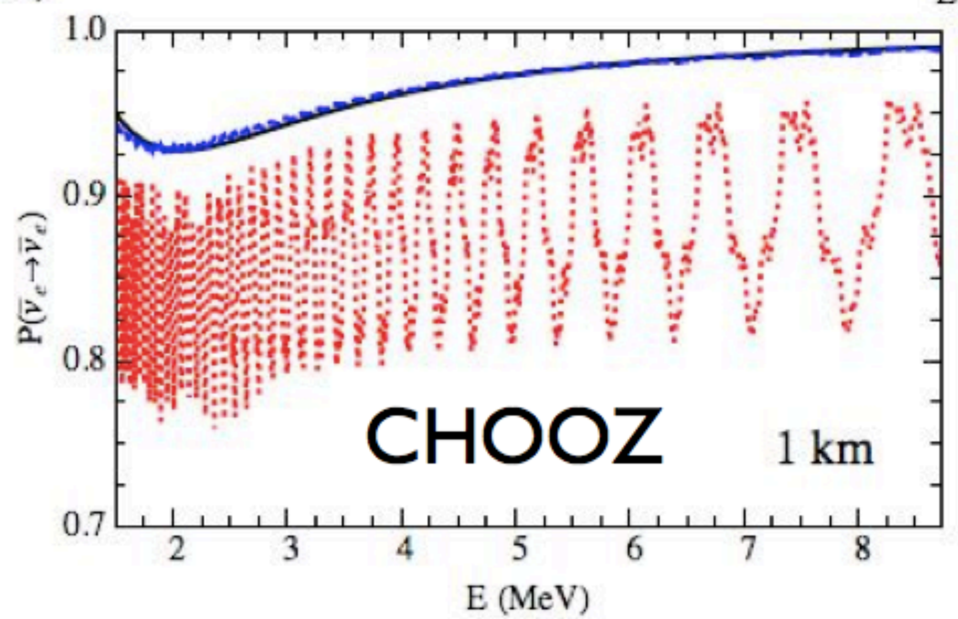
$$\nu_e \to \nu_e \neq \nu_\mu \to \nu_\mu$$

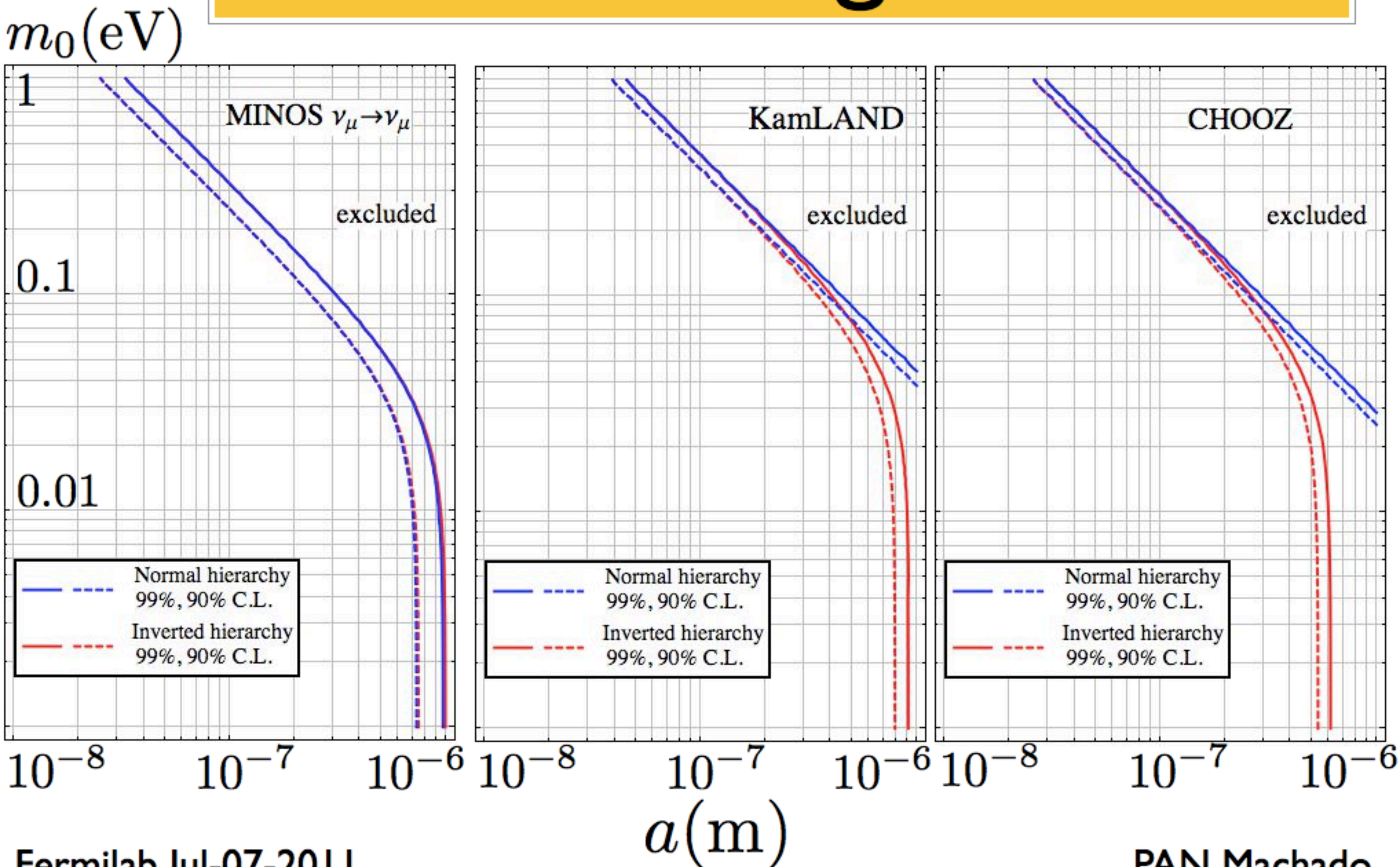
Searching for LED



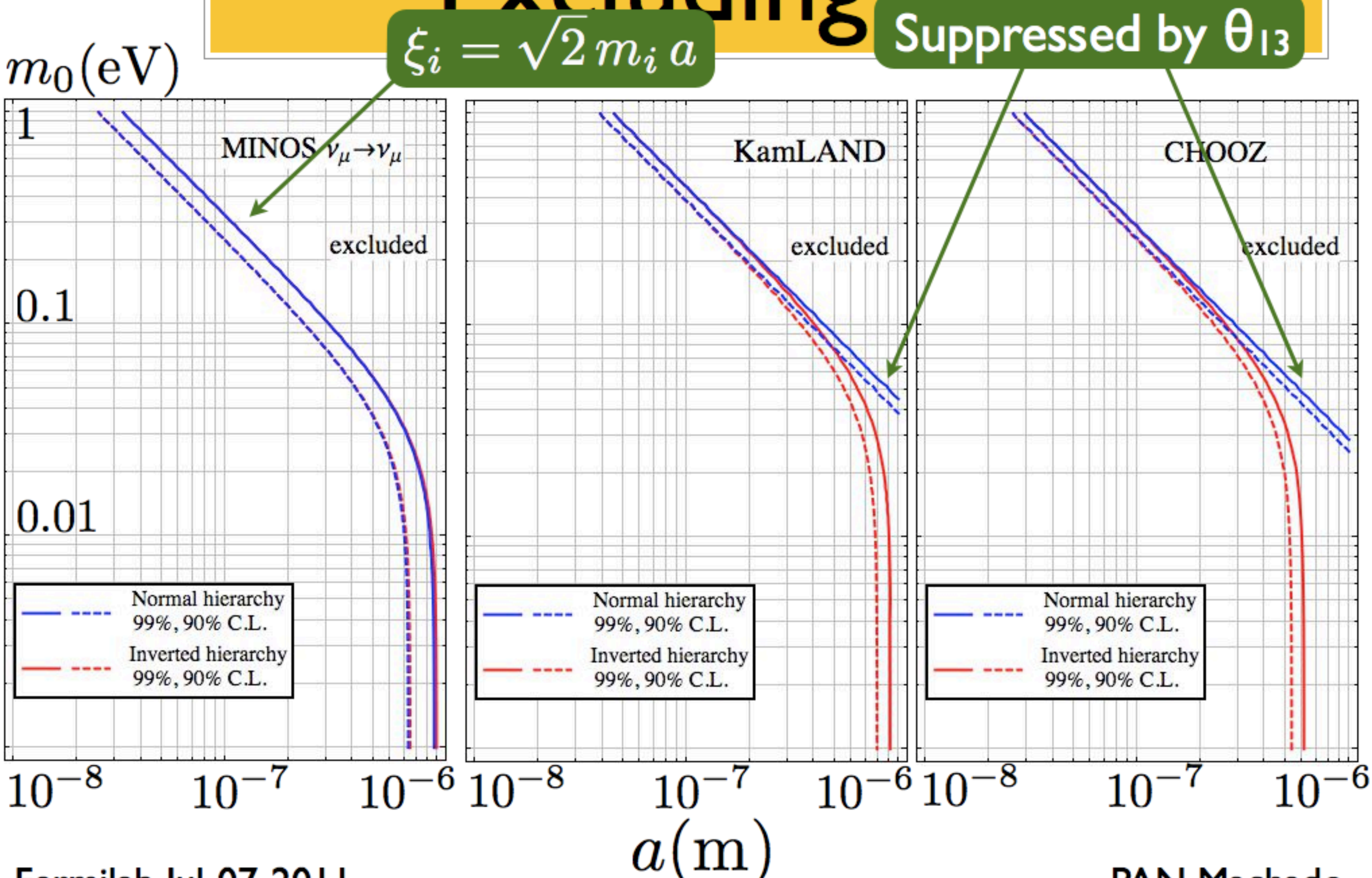




Excluding LED



Excluding LED



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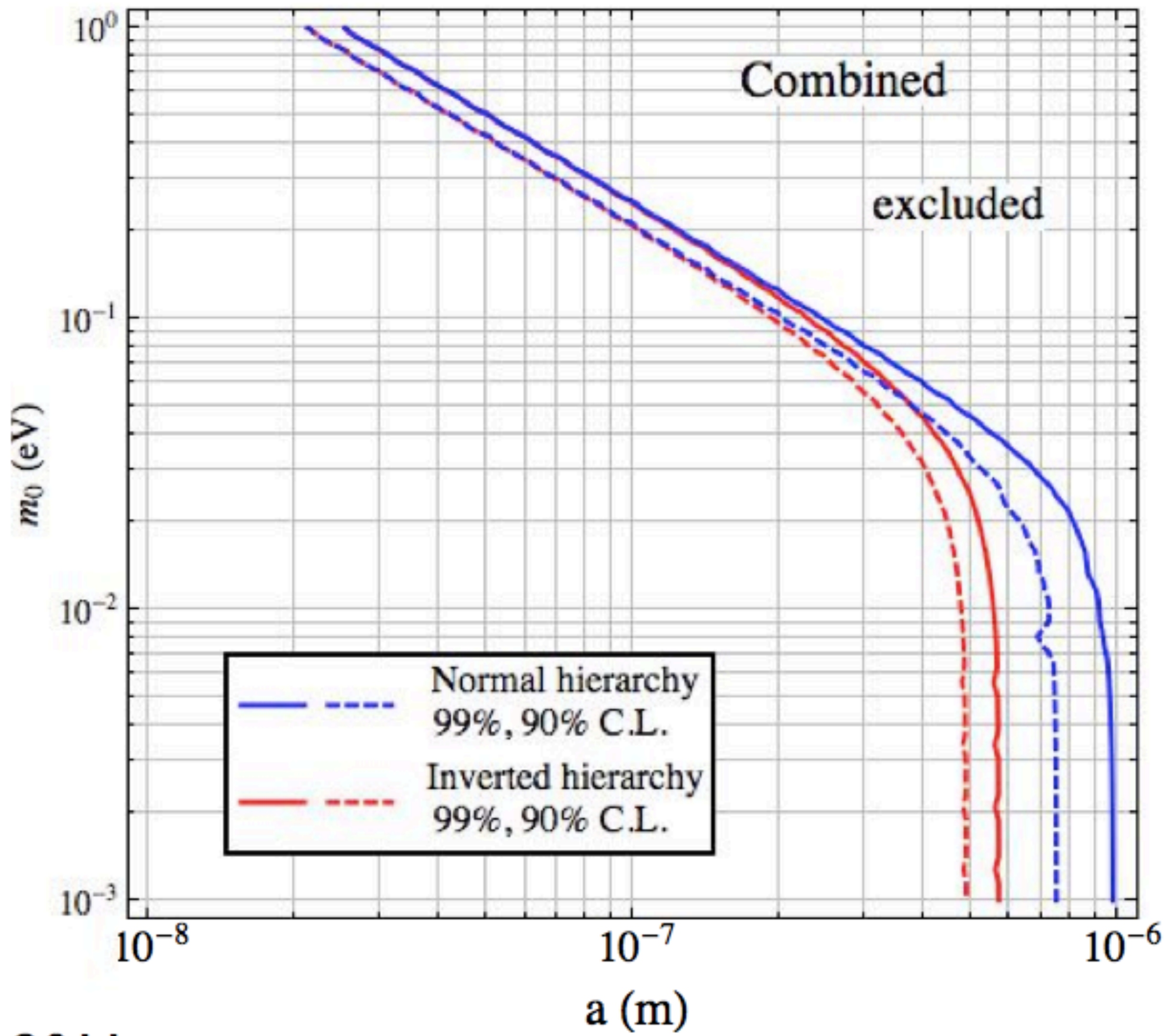
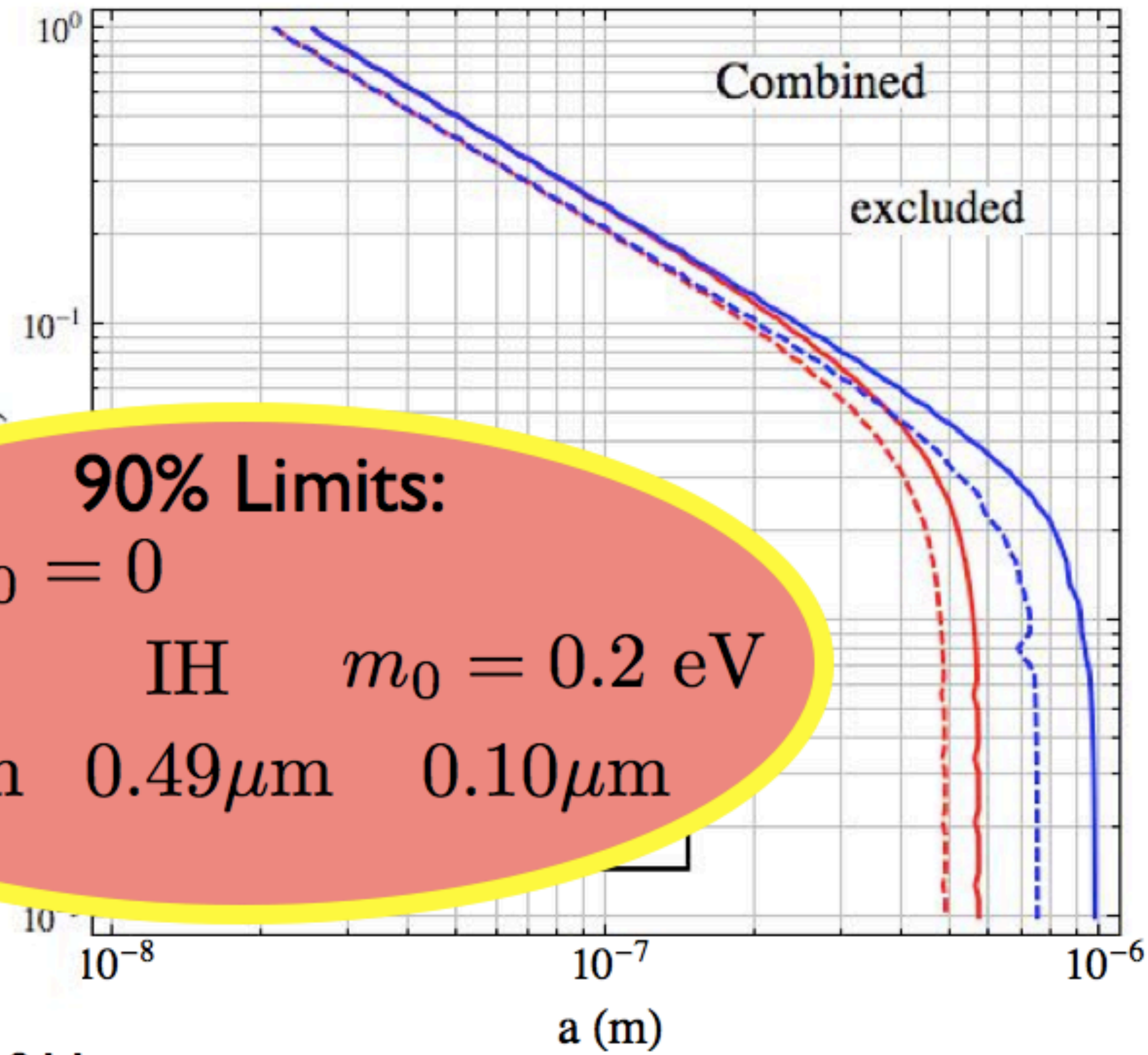


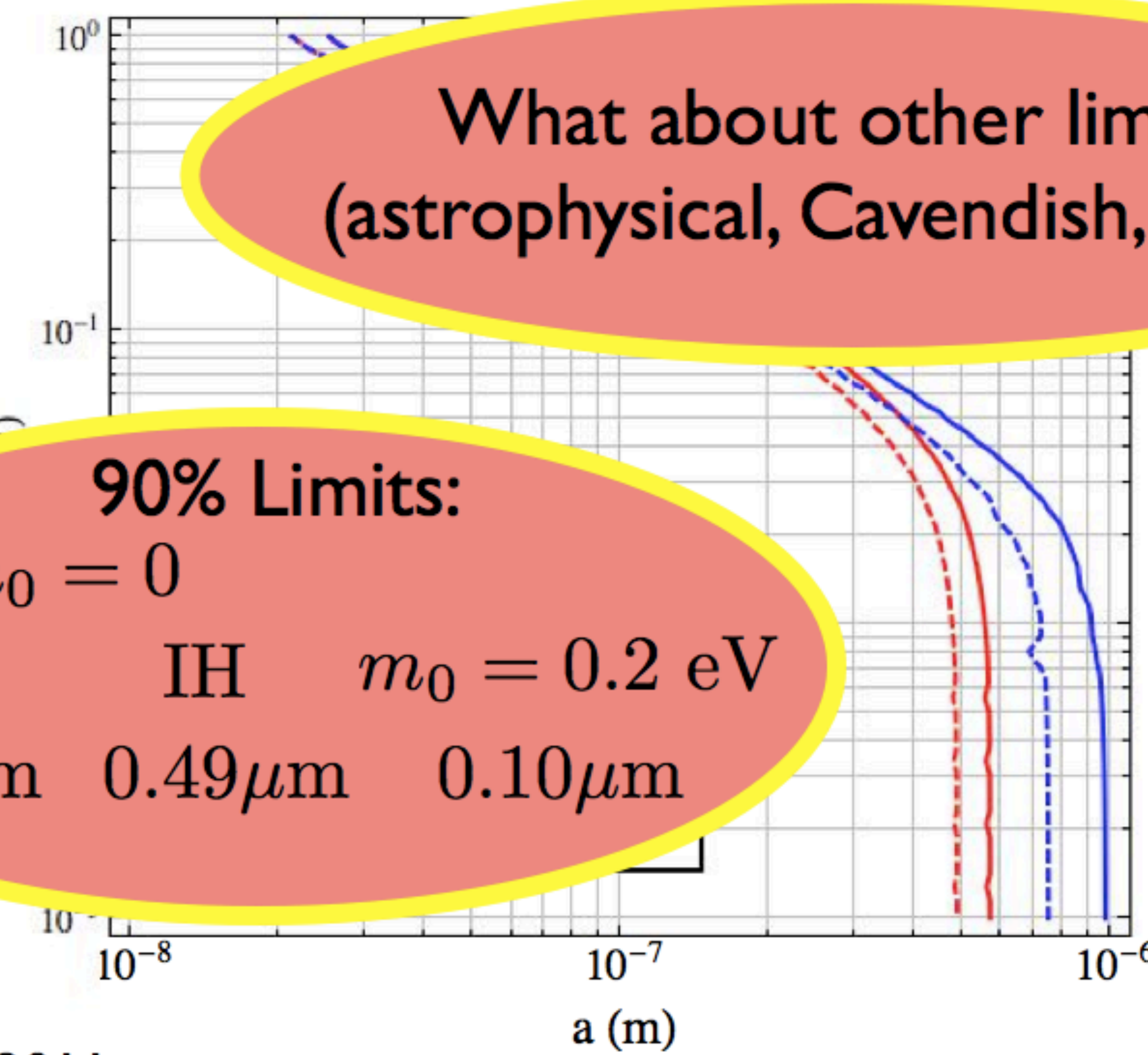
Excluding LED



90% Limits:

$m_0 = 0$		
NH	IH	$m_0 = 0.2$ eV
0.75μm	0.49μm	0.10μm

Excluding LED



What about other limits?
(astrophysical, Cavendish, LEP, ...)

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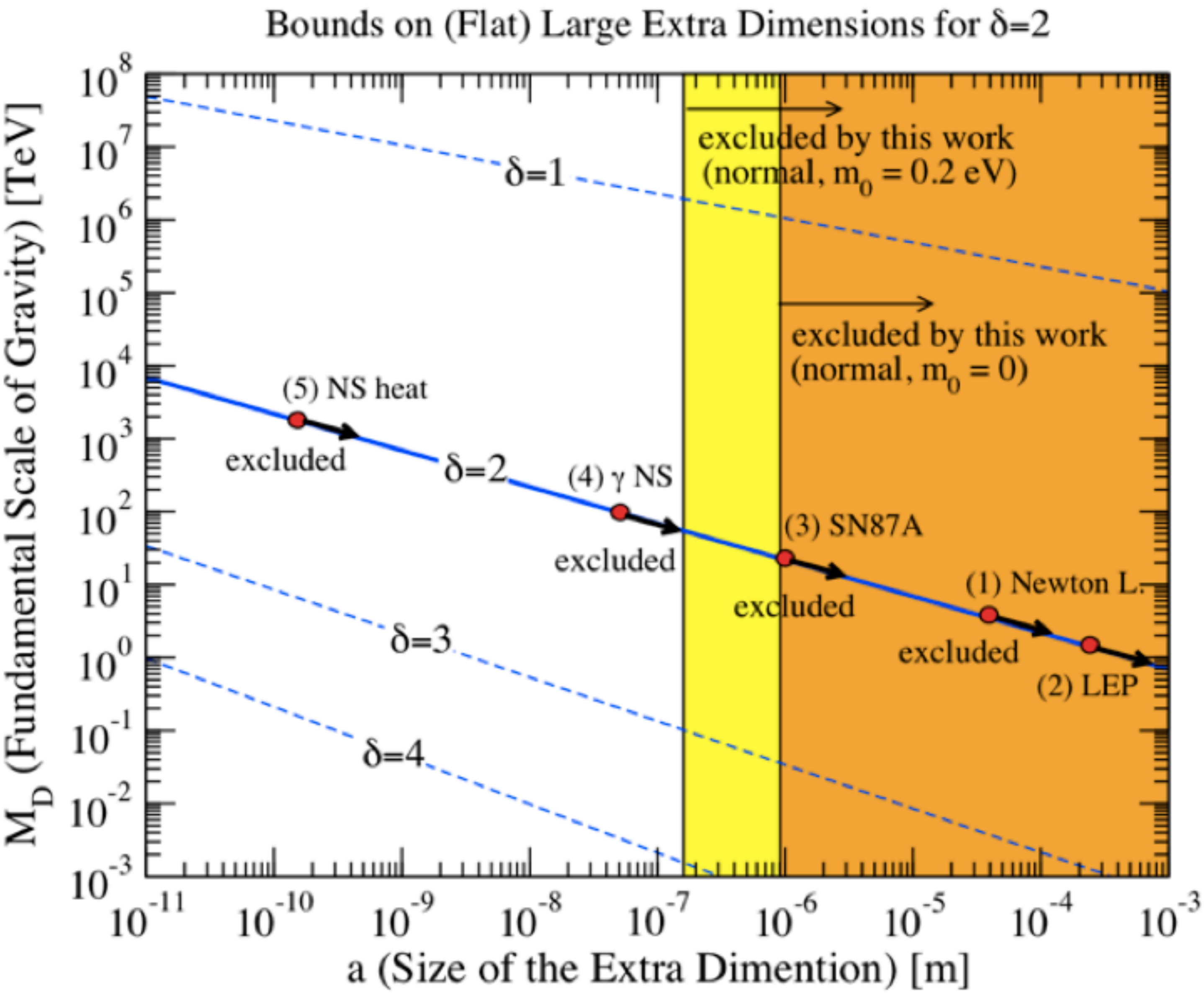
NH	IH	$m_0 = 0.2$ eV
0.75μm	0.49μm	0.10μm

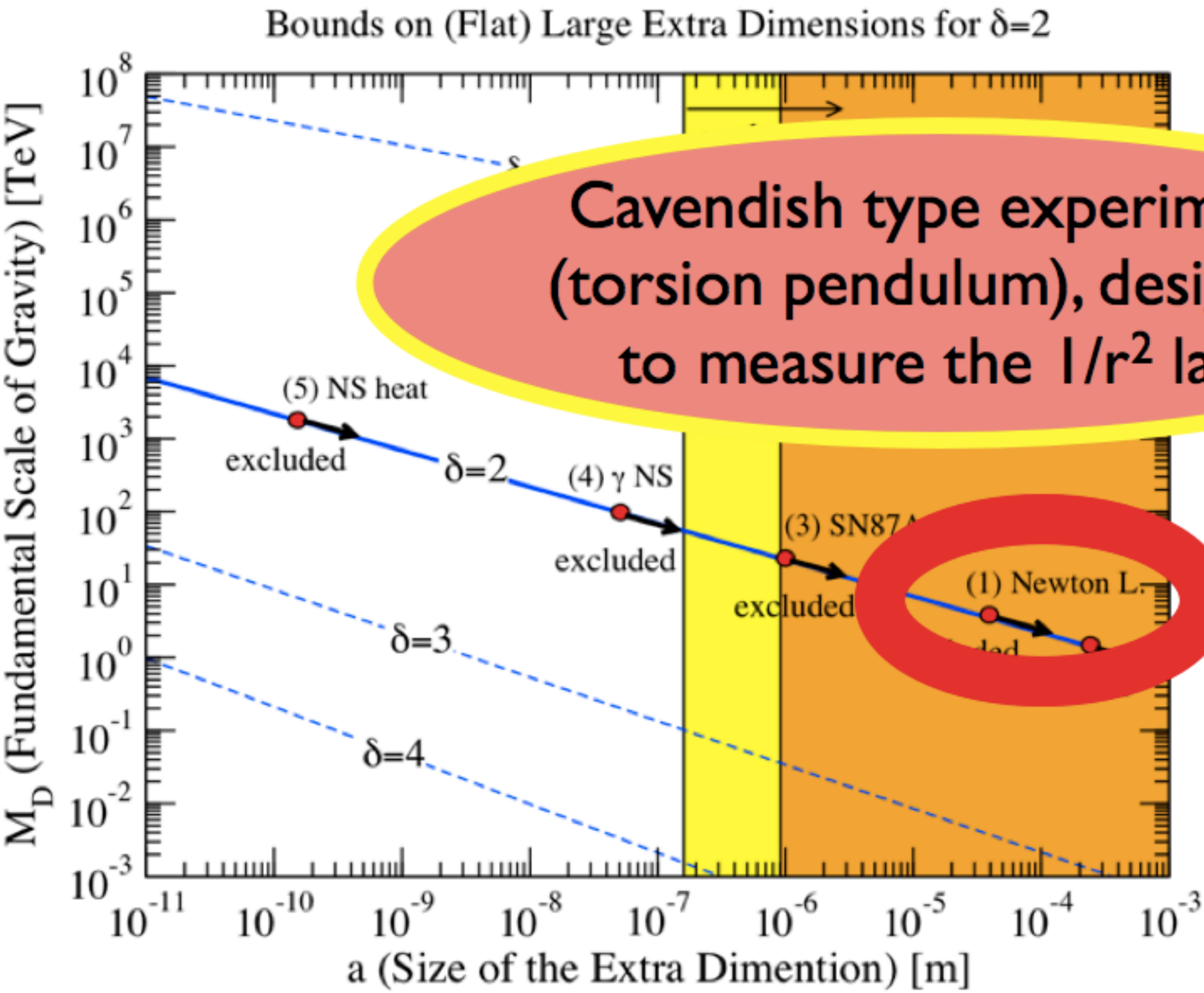
Excluding LED



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

PDG 2010
Hannestad, Raffelt PRD67 2003
Hannestad, Raffelt PRD69 2004

Excluding LED



Cavendish type experiment (torsion pendulum), designed to measure the $1/r^2$ law

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

PDG 2010
Hannestad, Raffelt PRD67 2003
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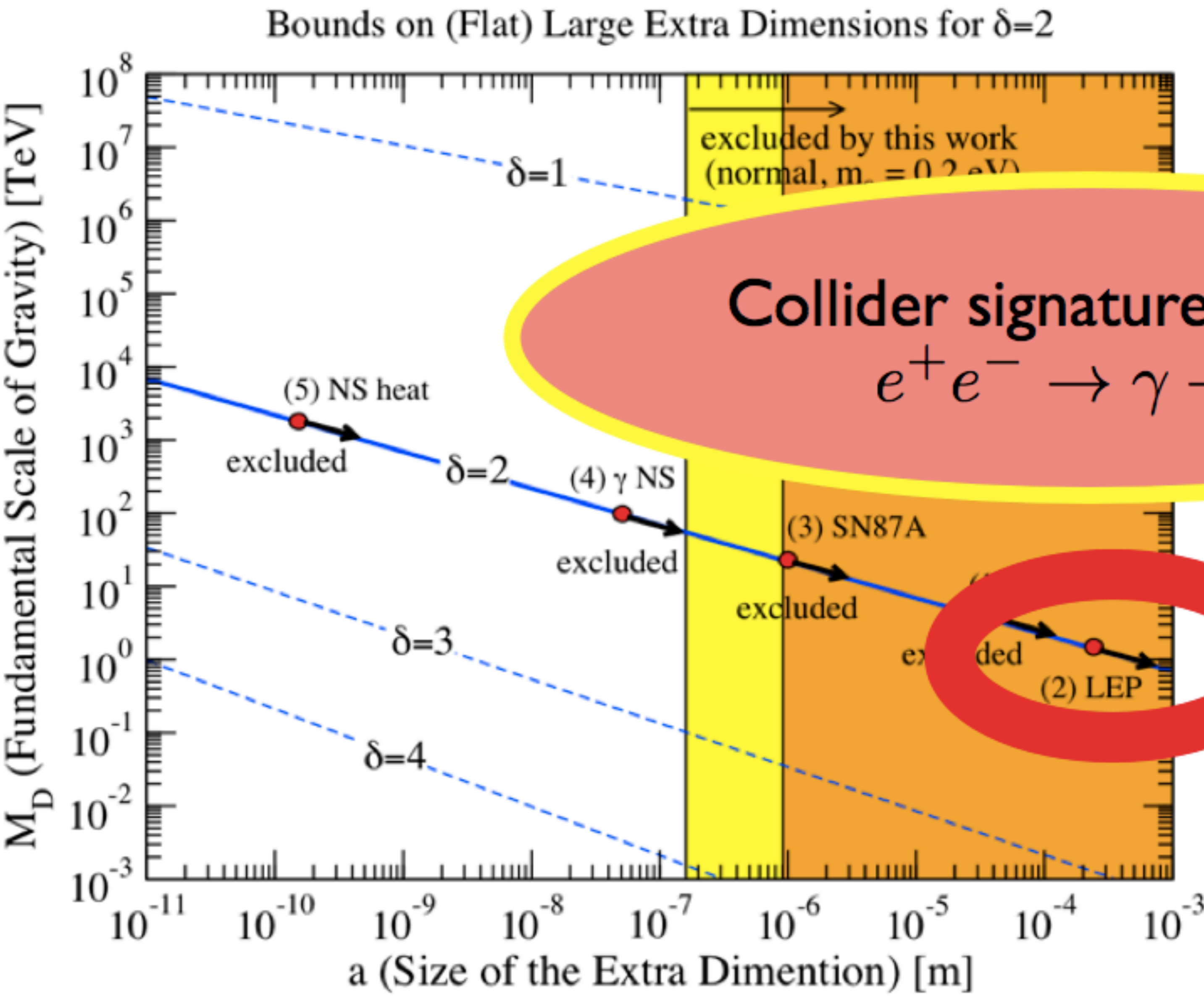
Excluding LED



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

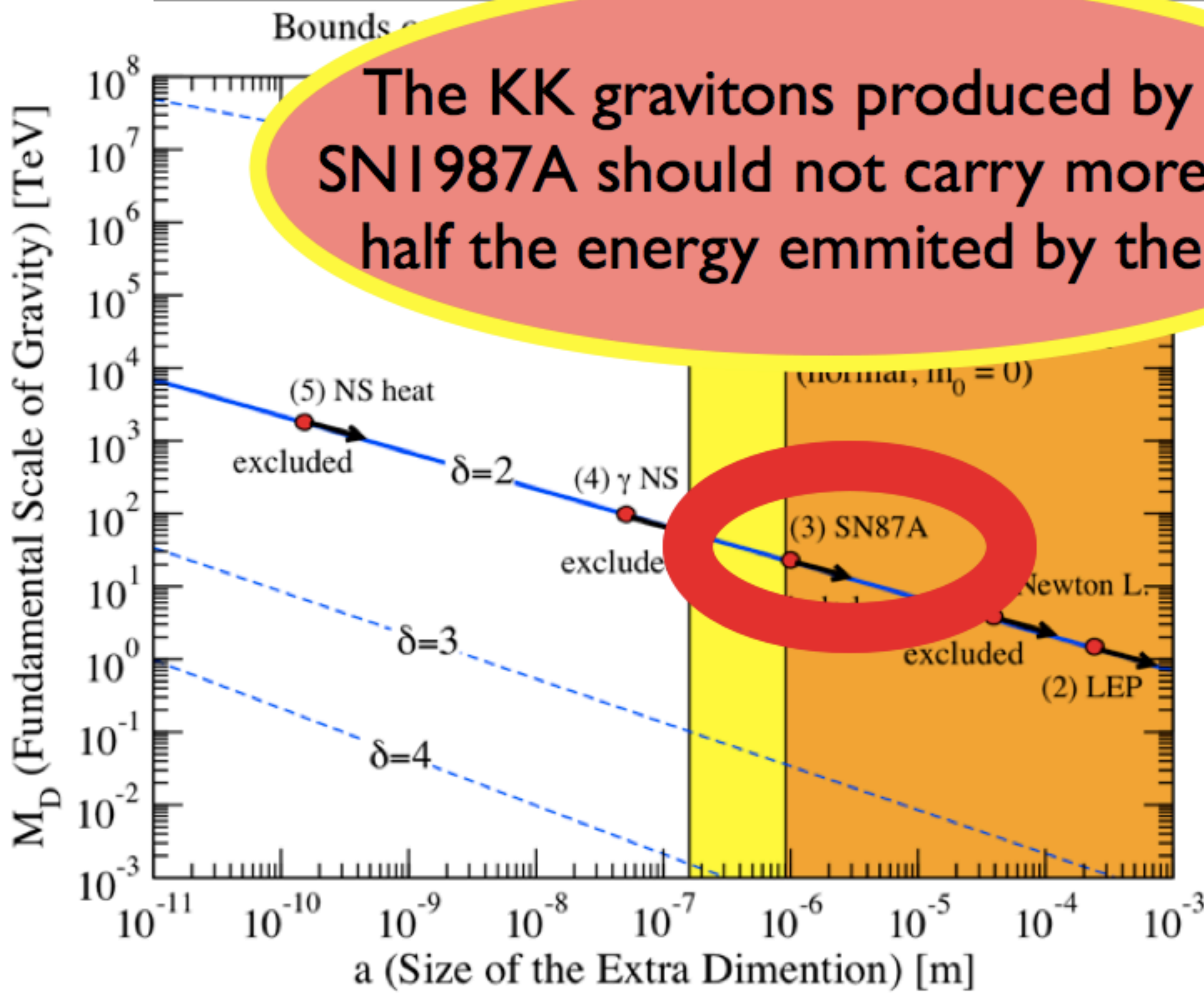
Collider signatures such as
$e^+e^- \to \gamma + \not{E}$

PDG 2010
Hannestad, Raffelt PRD67 2003
Hannestad, Raffelt PRD69 2004

Excluding LED

The KK gravitons produced by the SN1987A should not carry more than half the energy emmited by the SN

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

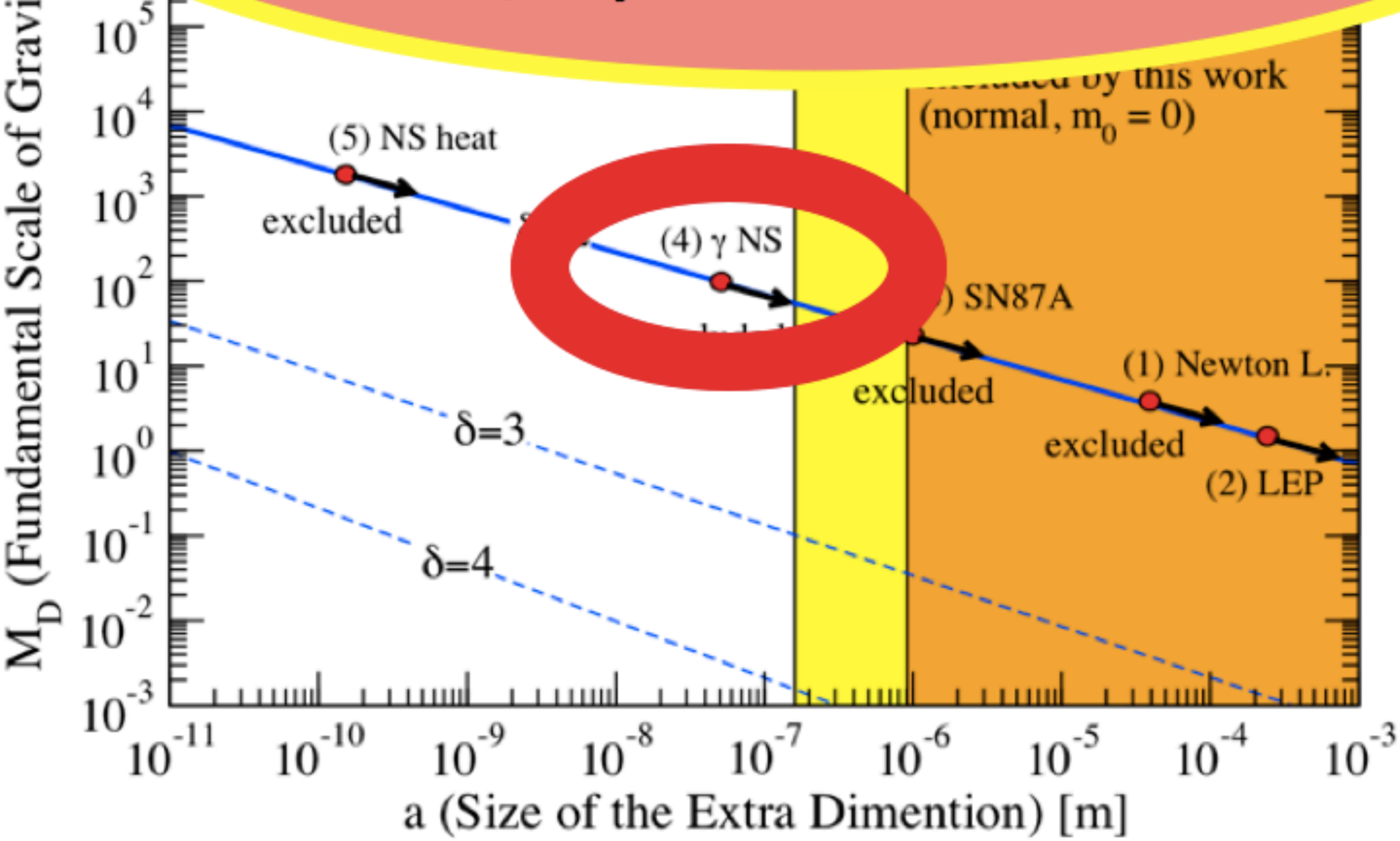


PDG 2010
Hannestad, Raffelt PRD67 2003
Hannestad, Raffelt PRD69 2004

Excluding LED

KK gravitons emmited by SN remnants and neutron stars gets trapped, form a halo and decay emmiting photons. Limit comes from γ rays from neutron stars.

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



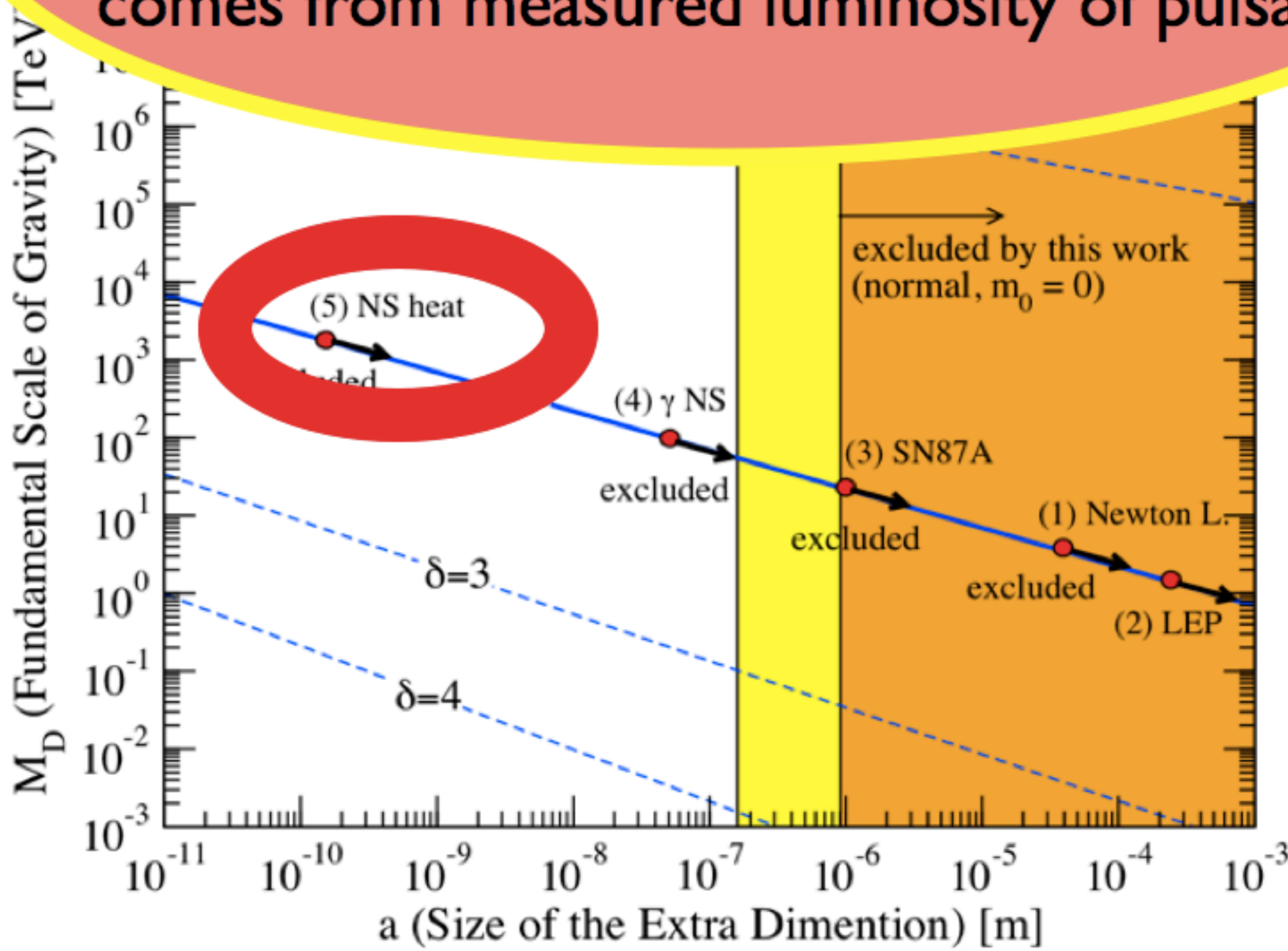
PDG 2010

Hannestad, Raffelt PRD67 2003

Hannestad, Raffelt PRD69 2004

KK gravitons from this halo decay and the products heat up neutron stars. The limit comes from measured luminosity of pulsars

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



PDG 2010
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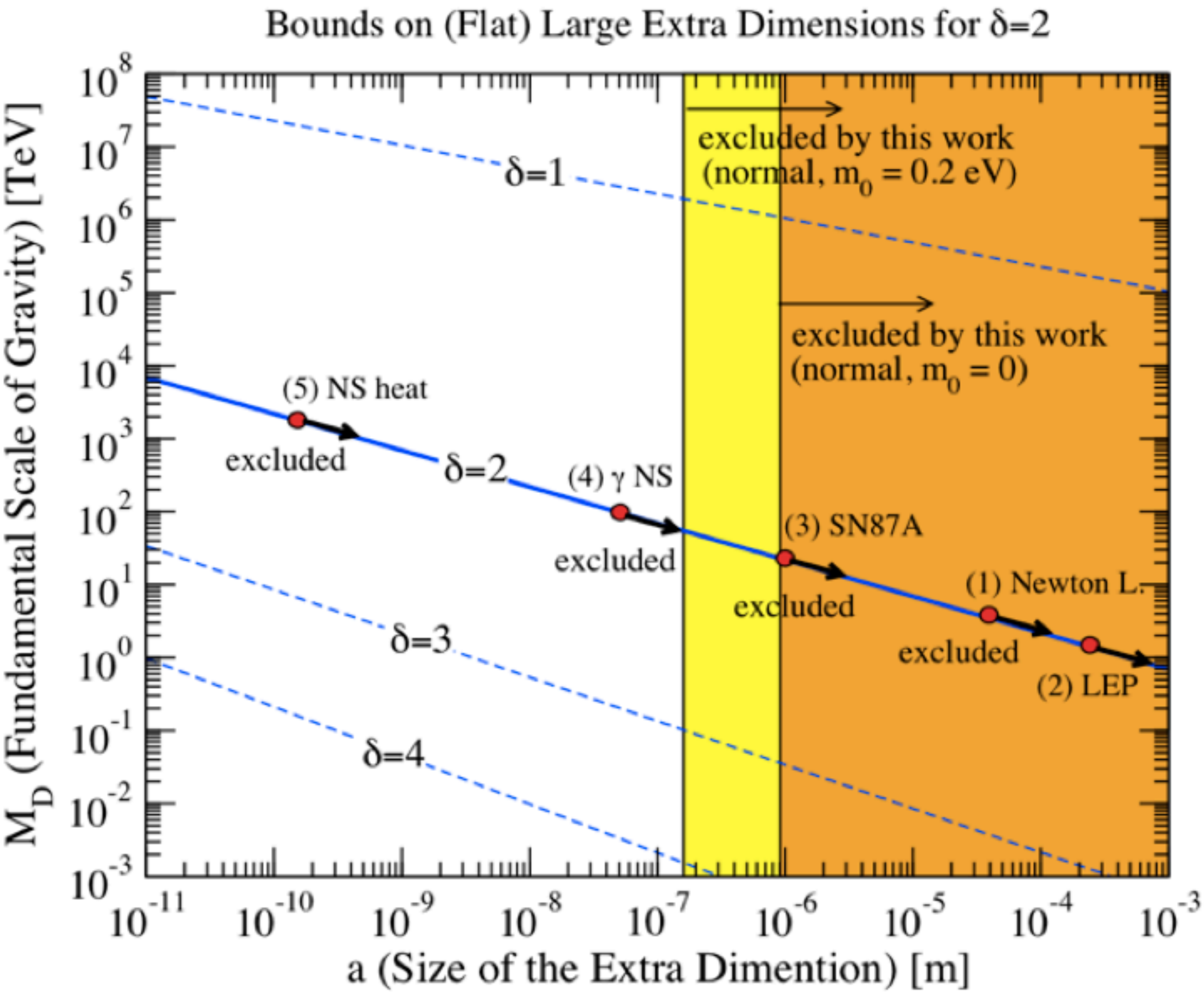
Excluding LED



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PDG 2010
Hannestad, Raffelt
PRD67 2003
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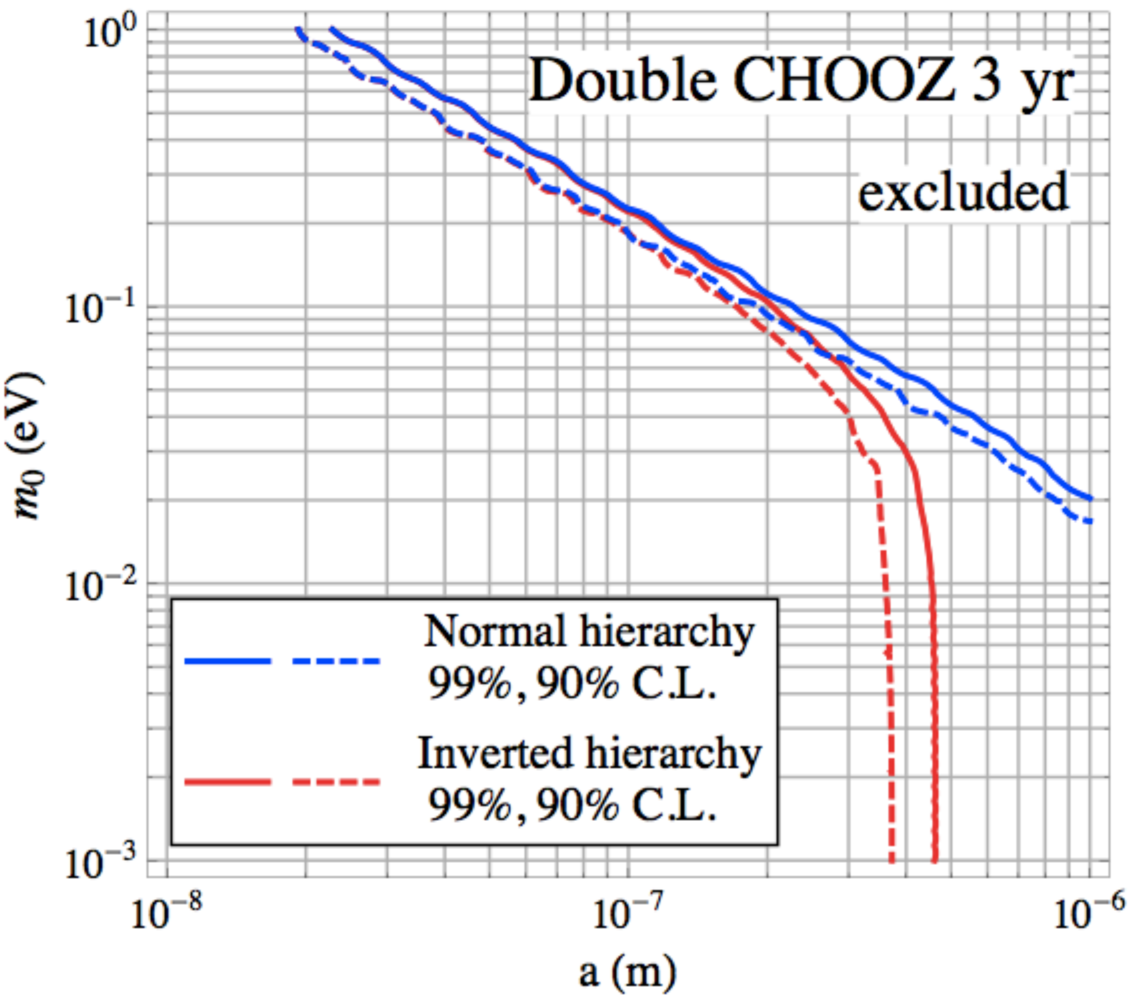
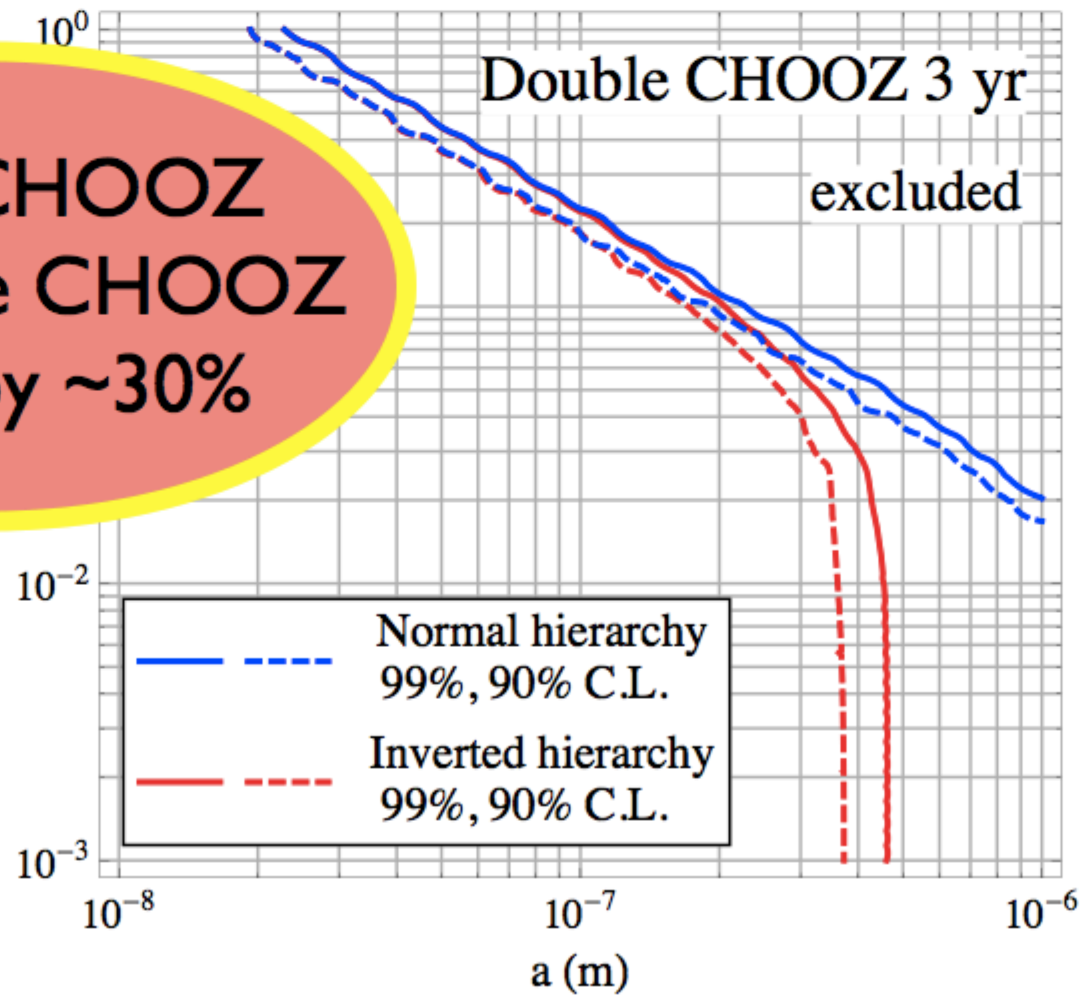
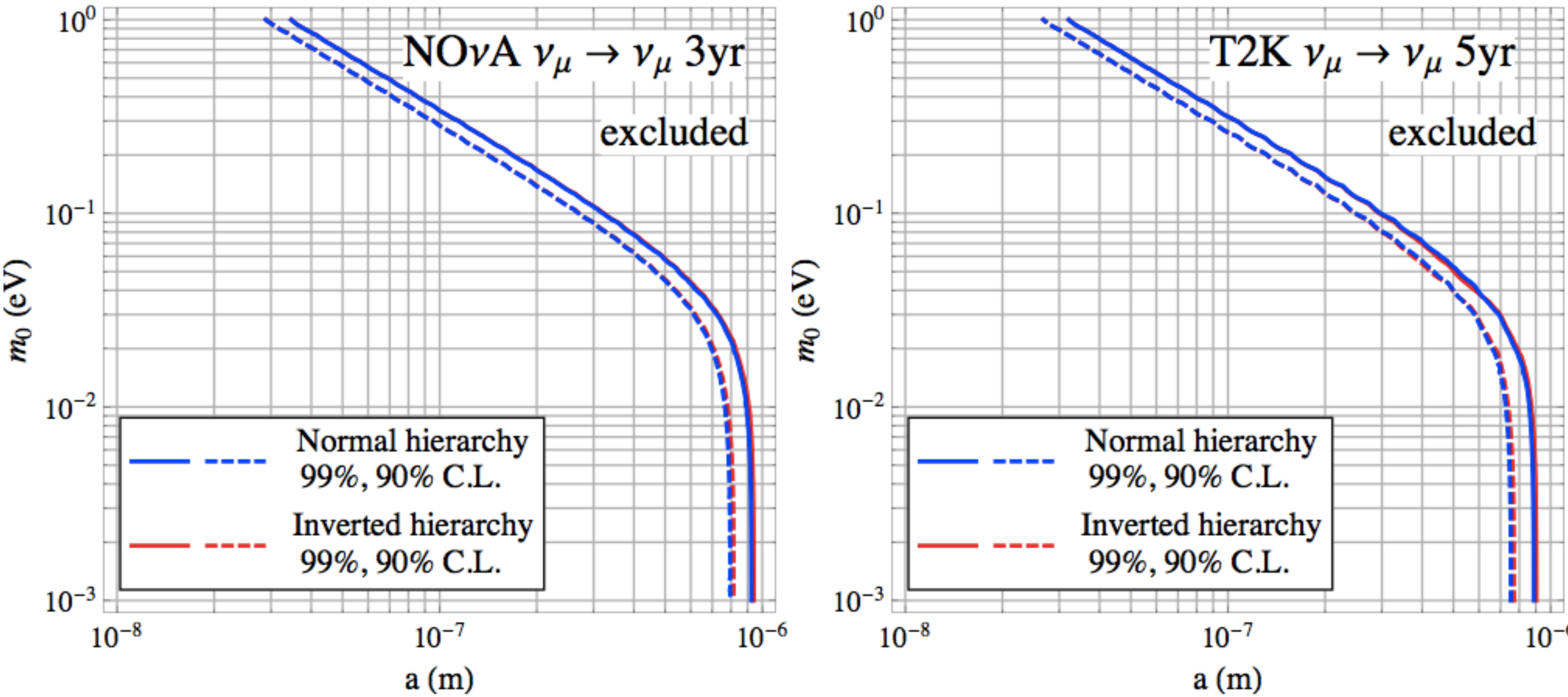


Excluding LED

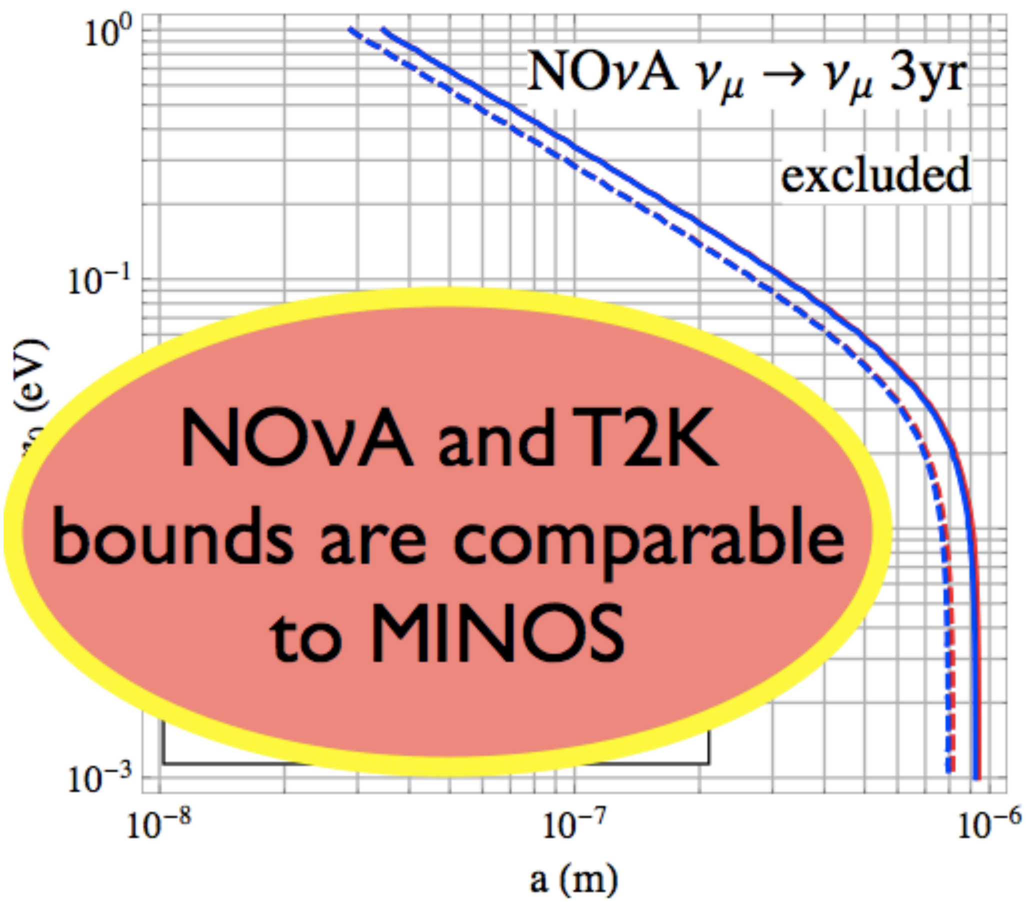
Double CHOOZ can improve CHOOZ bounds by ~30%



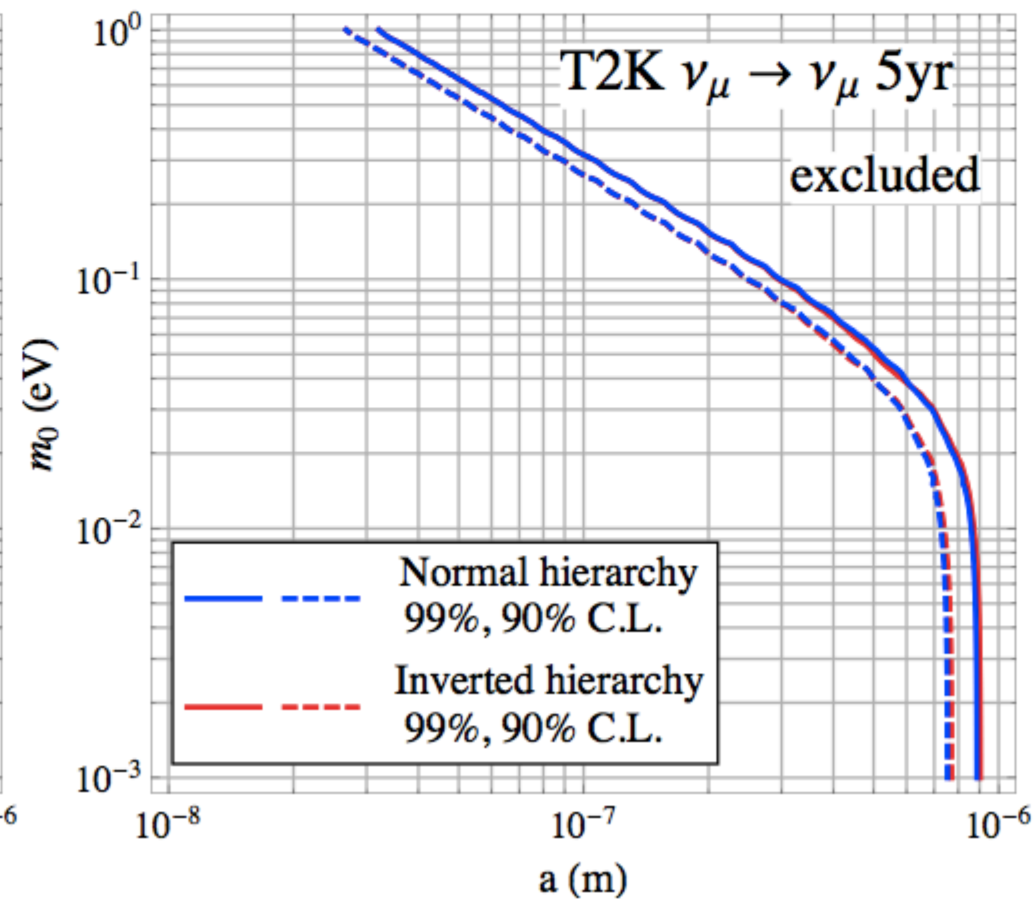
Excluding LED

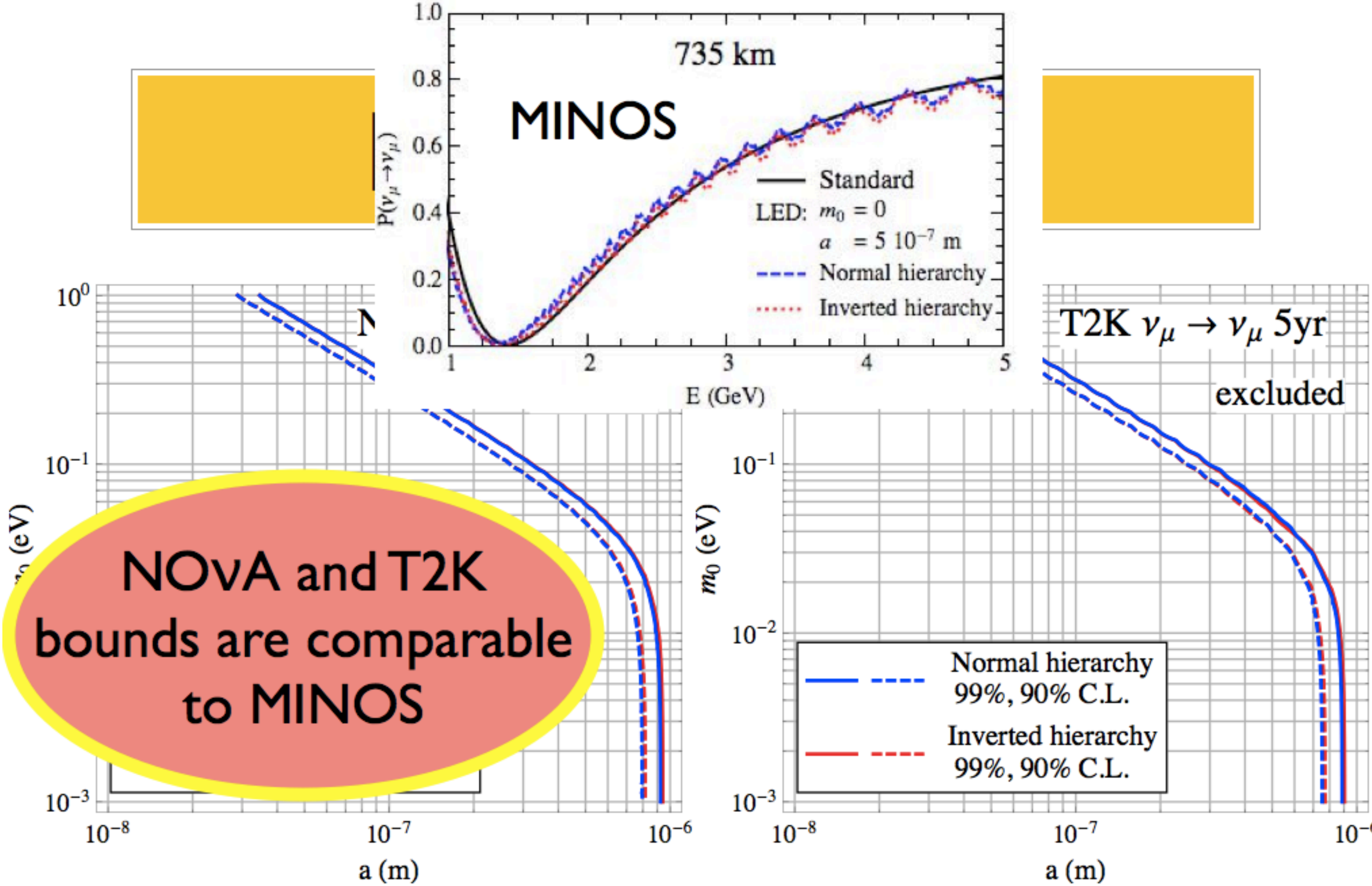


Excluding LED

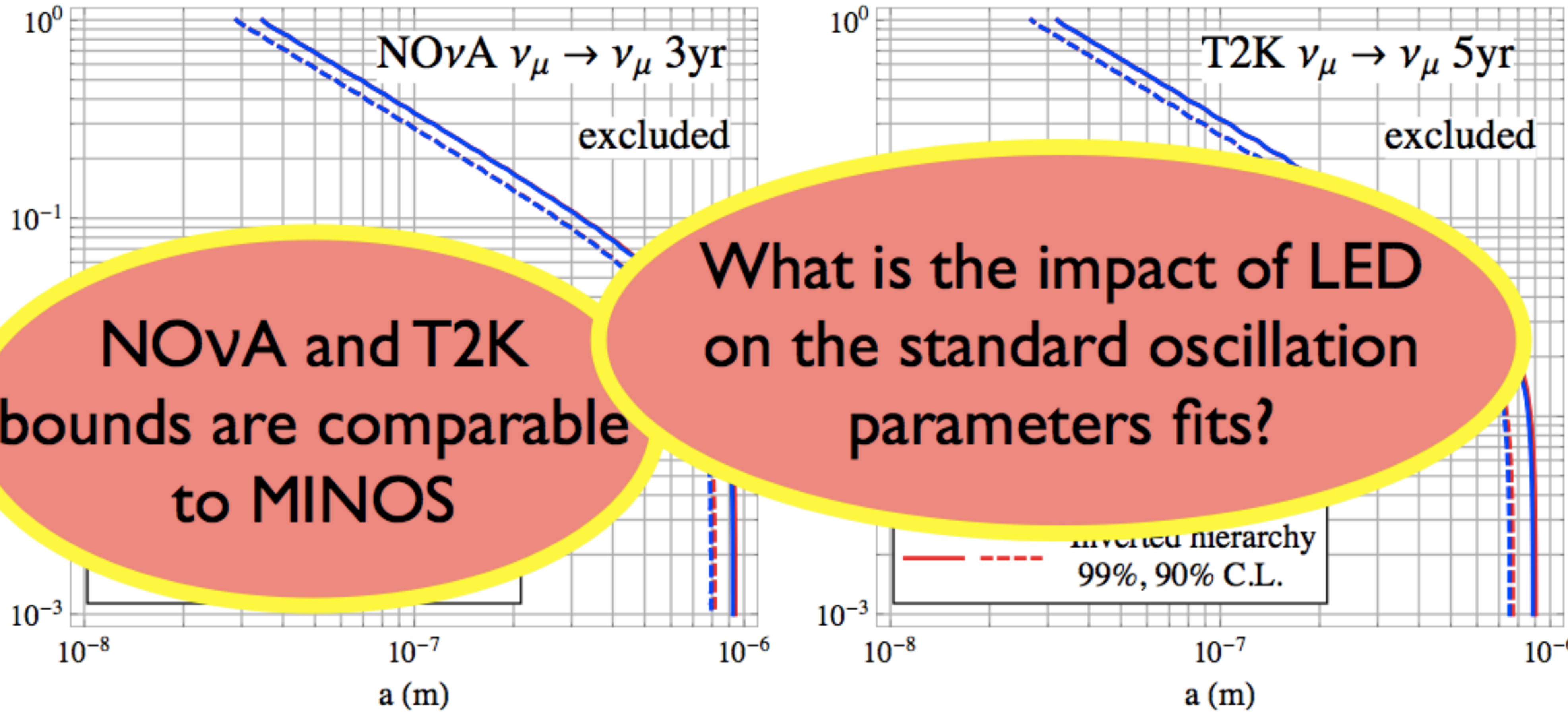


NOvA and T2K bounds are comparable to MINOS




735 km
MINOS
Standard
LED: m_0 = 0
a = 5 10^{-7} m
Normal hierarchy
Inverted hierarchy
$P(\nu_\mu \to \nu_\mu)$
E (GeV)
T2K $\nu_\mu \to \nu_\mu$ 5yr
excluded
Normal hierarchy 99%, 90% C.L.
Inverted hierarchy 99%, 90% C.L.
m_0 (eV)
a (m)
NOvA and T2K bounds are comparable to MINOS

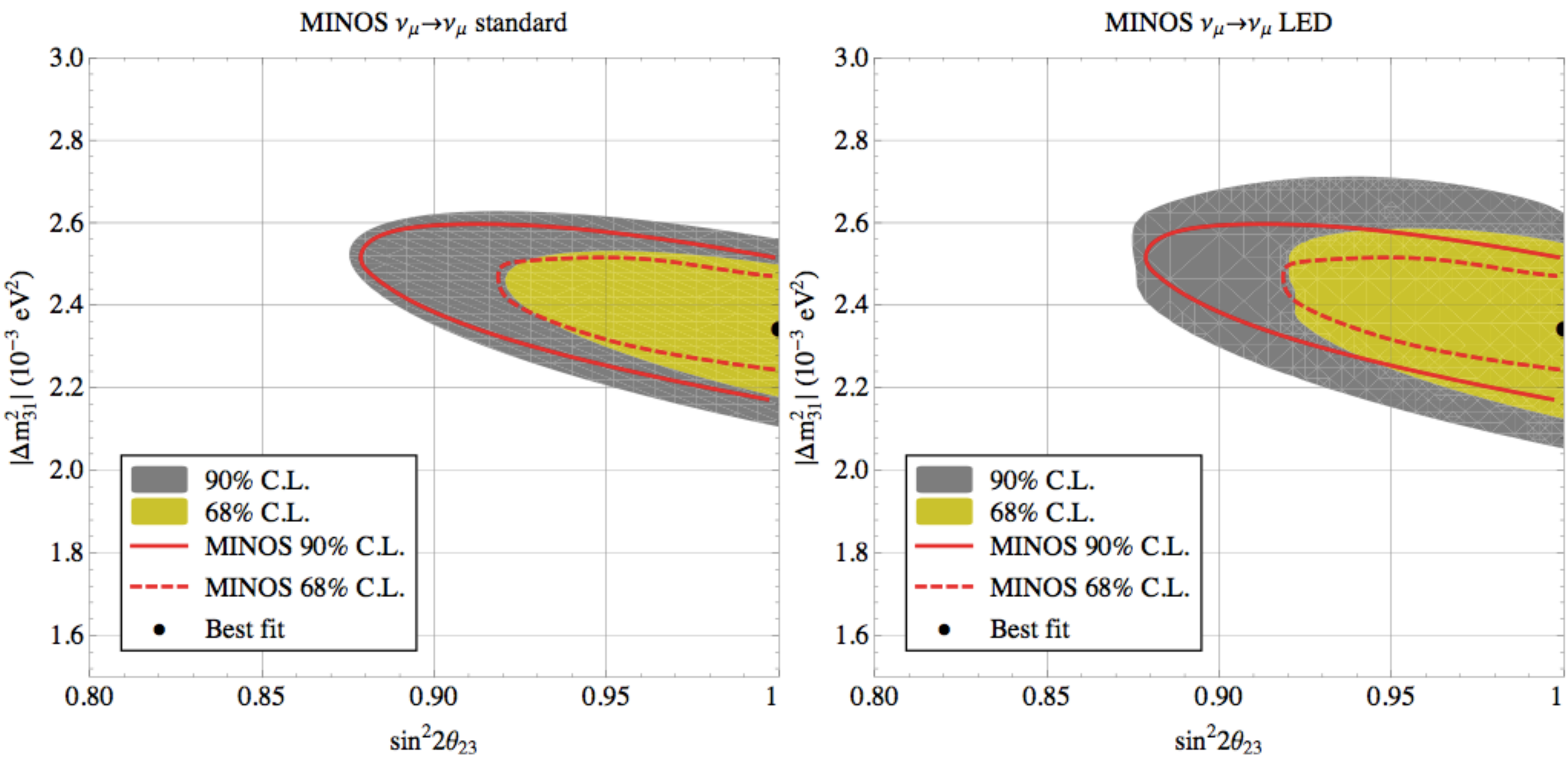
Excluding LED



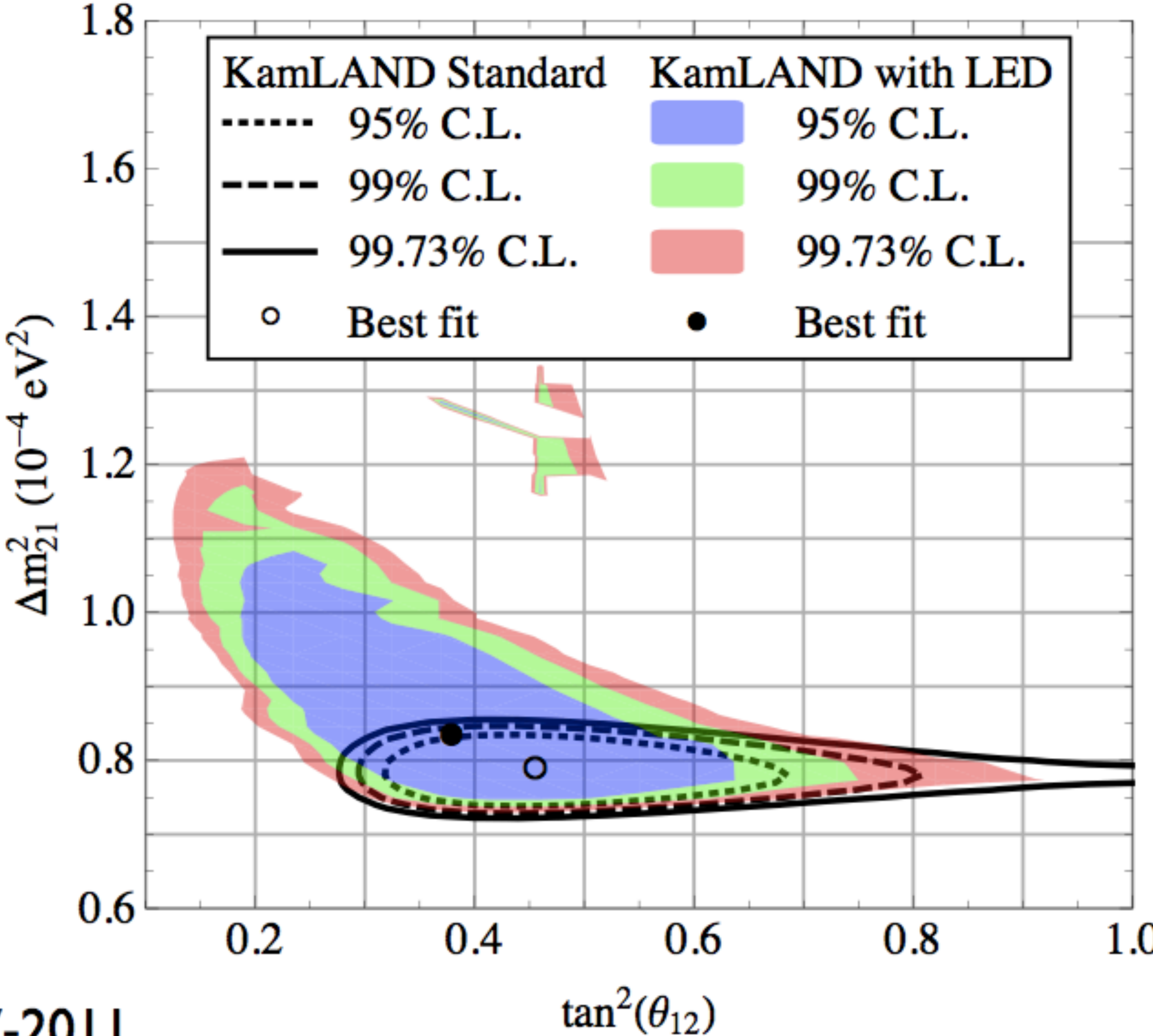
NOνA and T2K bounds are comparable to MINOS

What is the impact of LED on the standard oscillation parameters fits?

Impact of LED



Impact of LED



Discussion

We derived submicrometer bounds on large extra dimension

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Although model dependent, ours bounds for $\delta=2$, $M_D > 22$ TeV, are stronger than LHC bounds ($M_D >$ few TeV)
Francheschini et al 1101.4919

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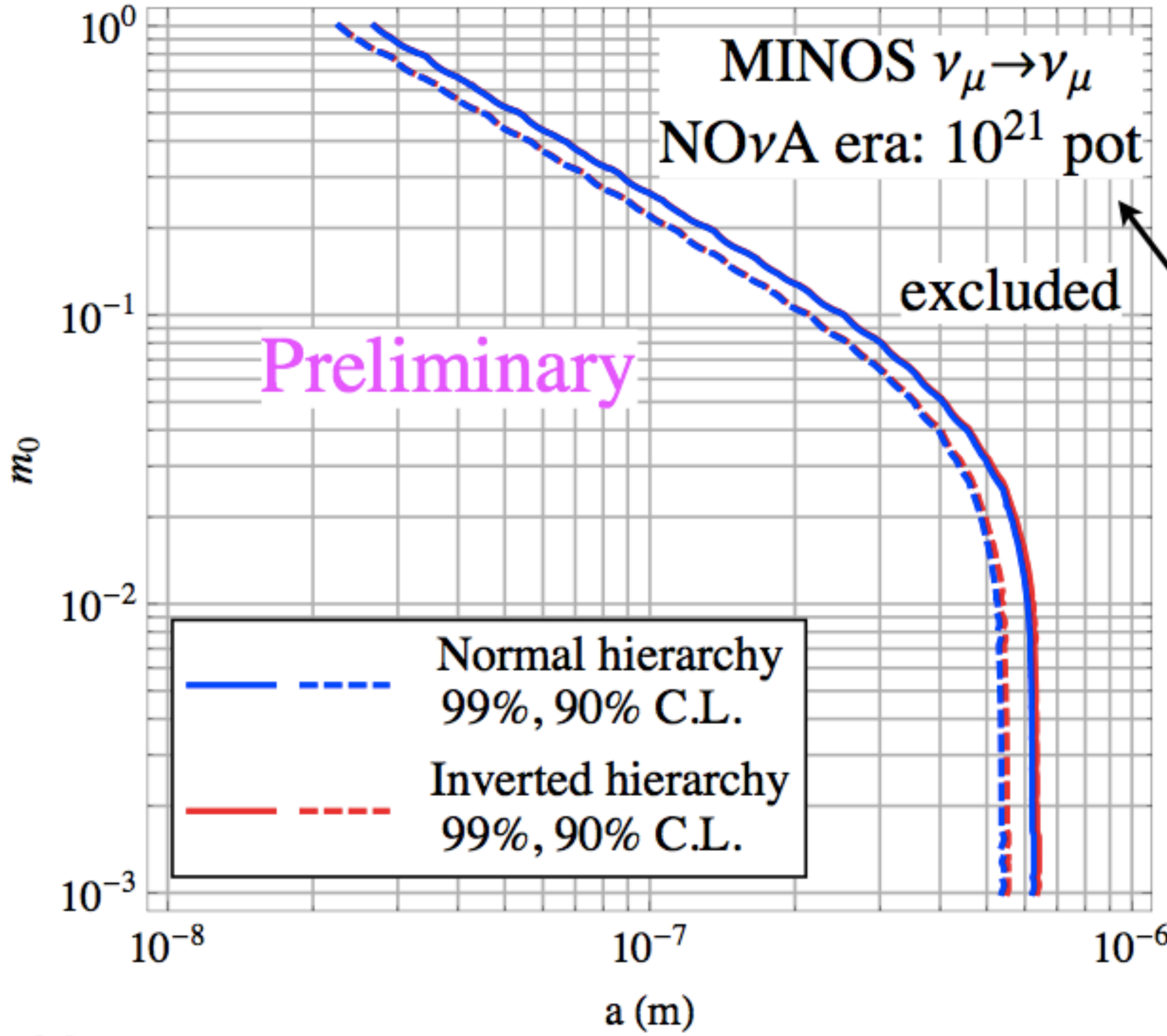
Francheschini et al 1101.4919

T2K and NOvA will not be able to significantly improve these limits.

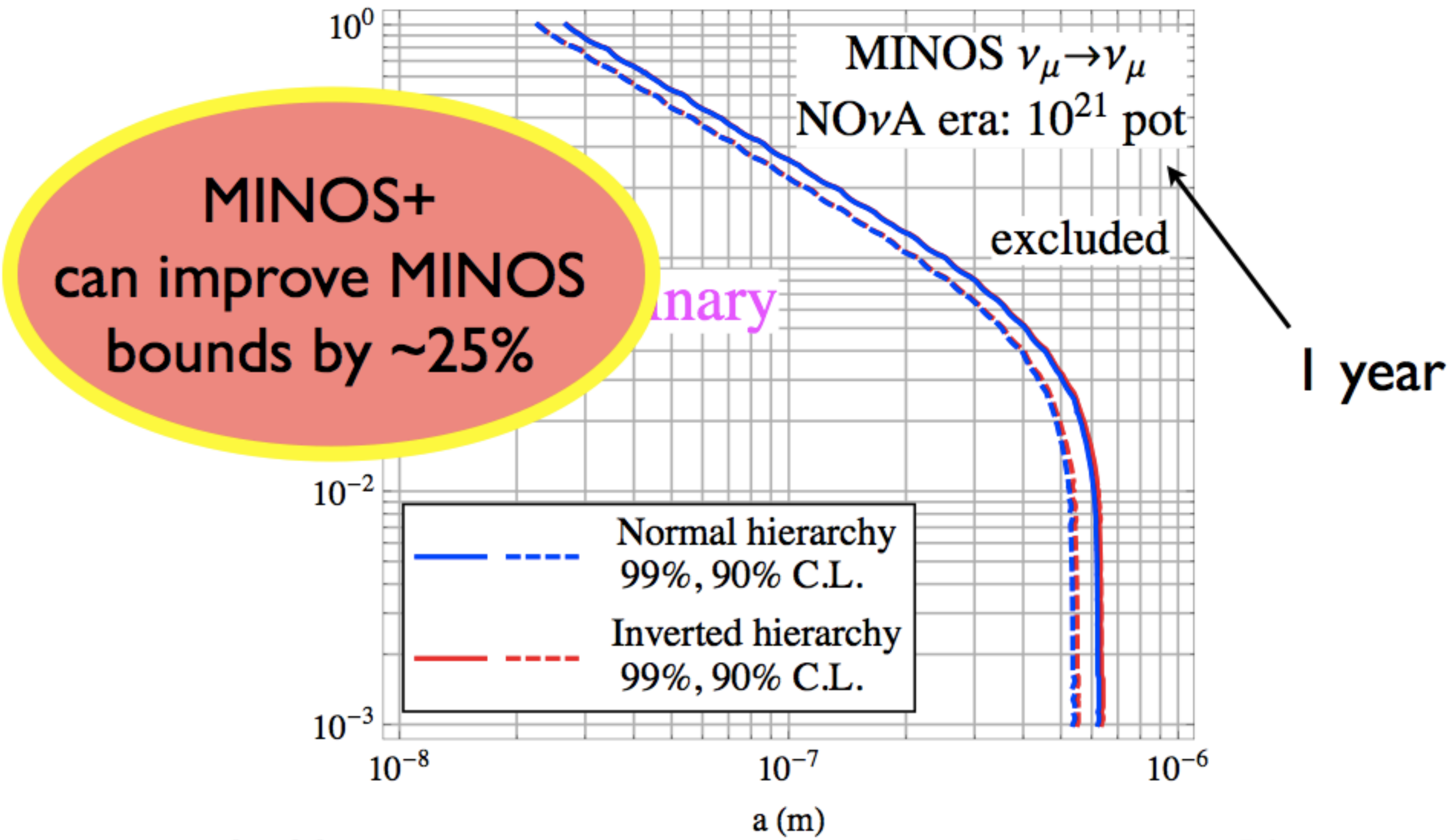
What about MINOS in NOvA era (MINOS+)?...

Excluding LED



1 year

Excluding LED



An interpretation for the reactor and gallium anomalies

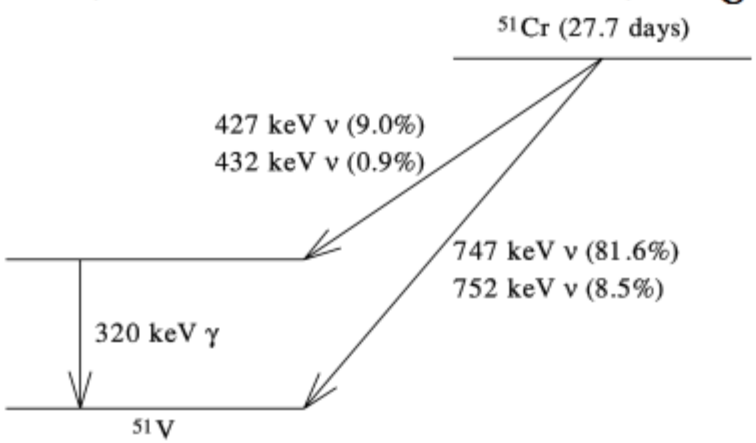
Mueller et al, PRC83 2011
Mention et al, PRD83 2011
SAGE, PRC59 1999
SAGE, PRC73 2006
PANM, Nunokawa, Pereira dos Santos, Zukanovich Funchal in preparation...

What are the anomalies?

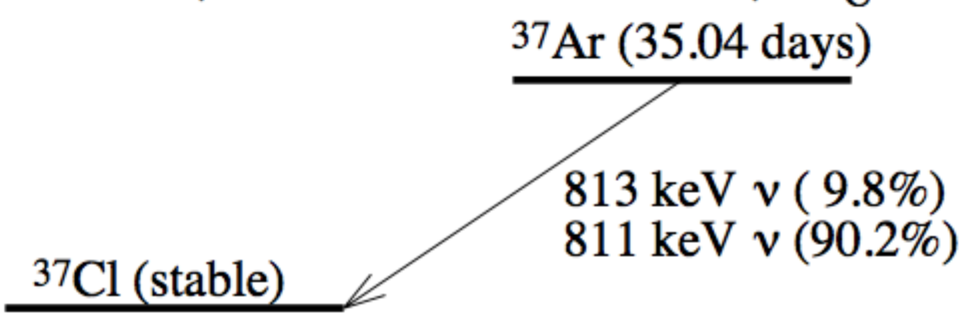
the gallium anomaly

Sources:

$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$$

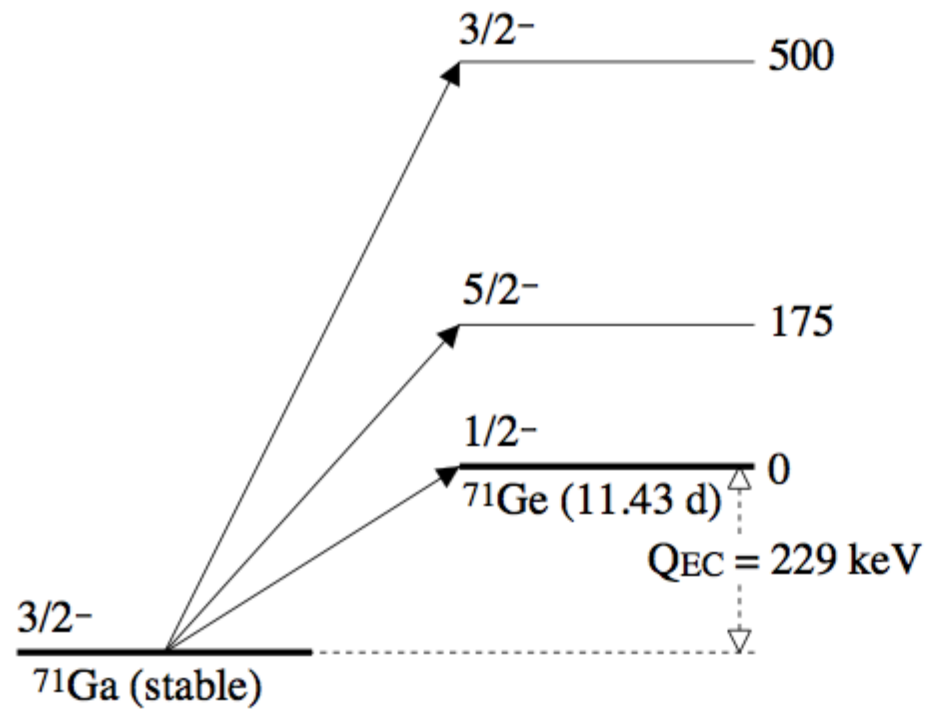


$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$



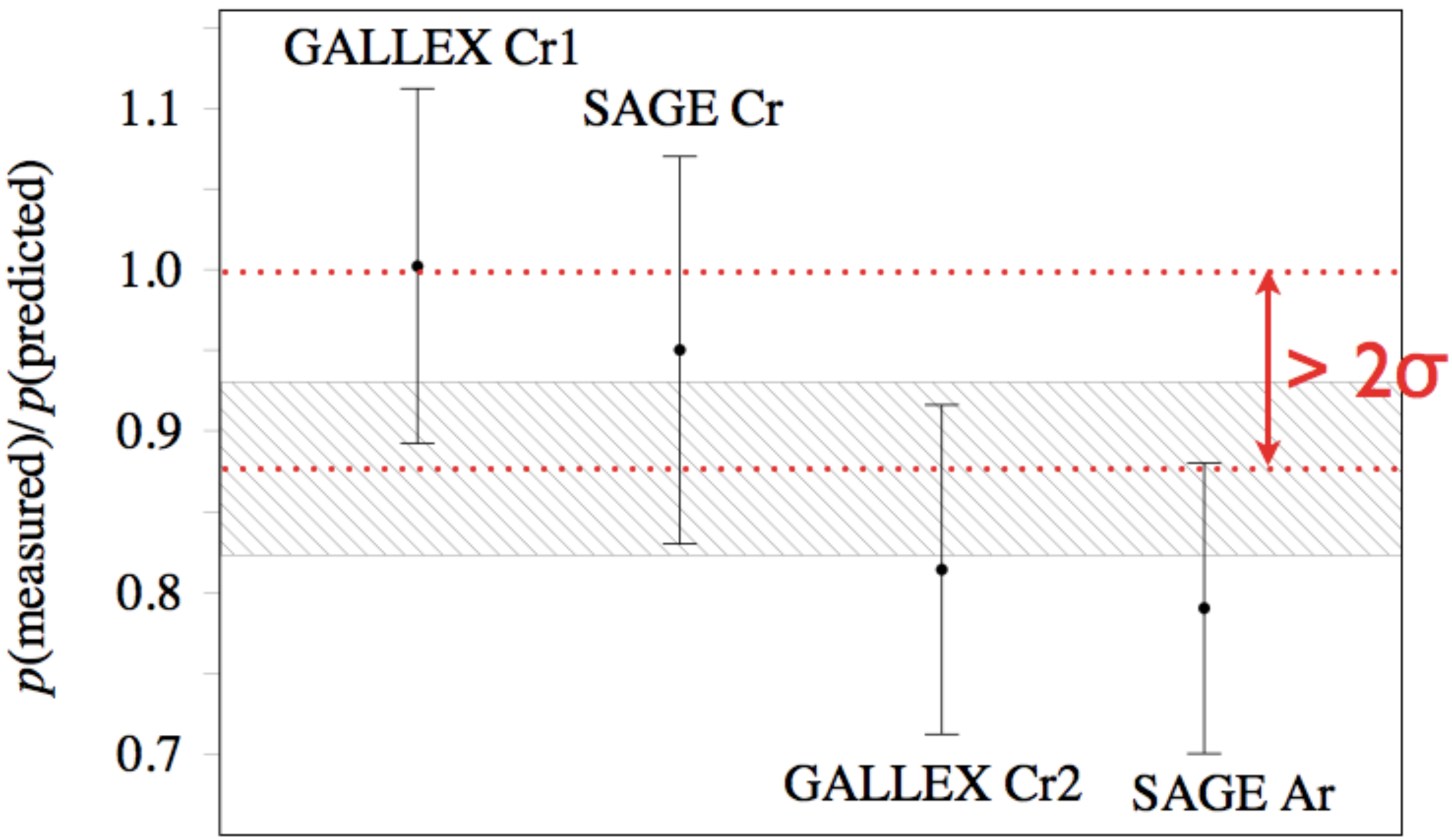
Detection:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$$



What are the anomalies?

the gallium anomaly



What are the anomalies?

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)

arXiv:1101.2755

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 $|\Delta m^2_{\text{new}}| > 1.5$ eV^2 (95%) and $\sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.08$ (95%). Constraints on the θ_{13} neutrino mixing angle are revised.

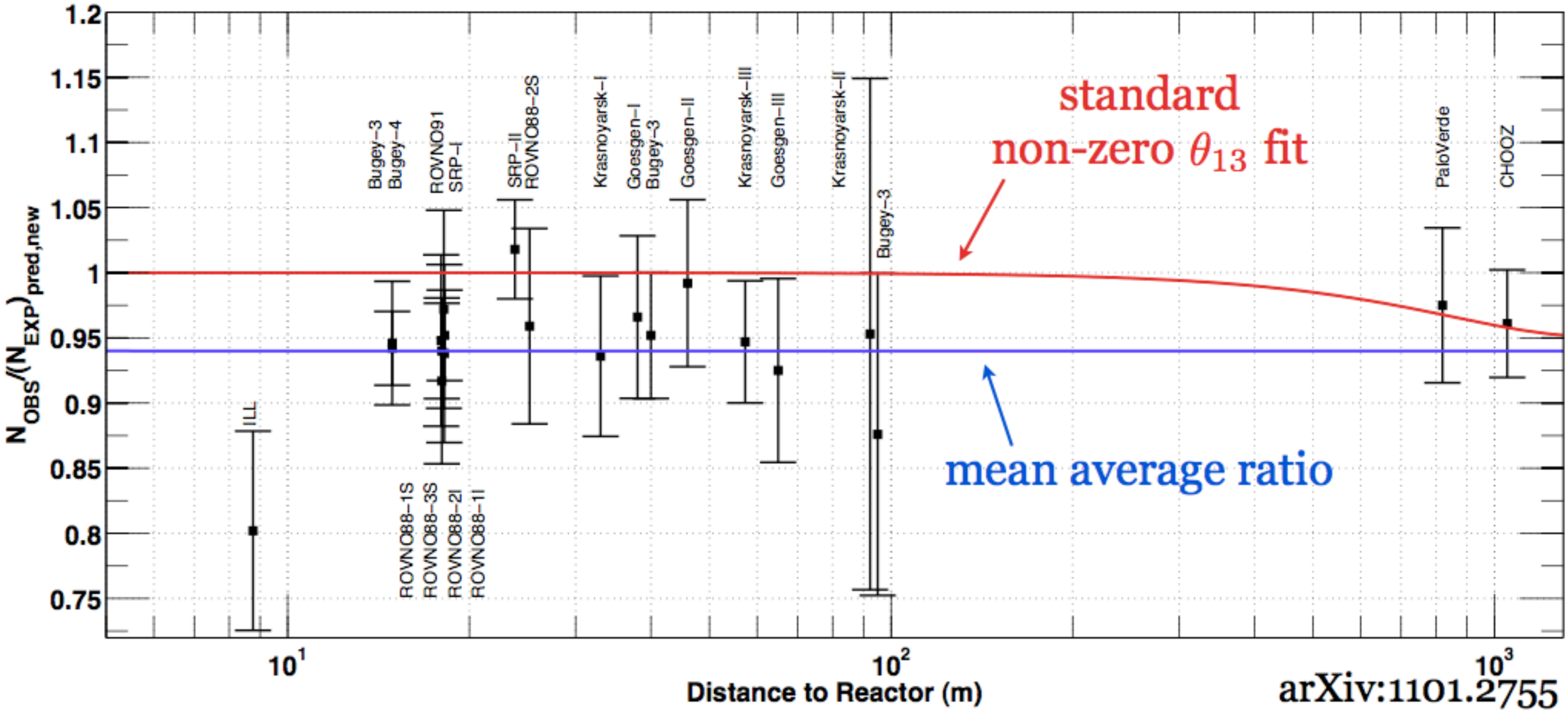
2.2 σ

> 3 σ

Correlation between experiments

MiniBooNE data do not contribute significantly

What are the anomalies?

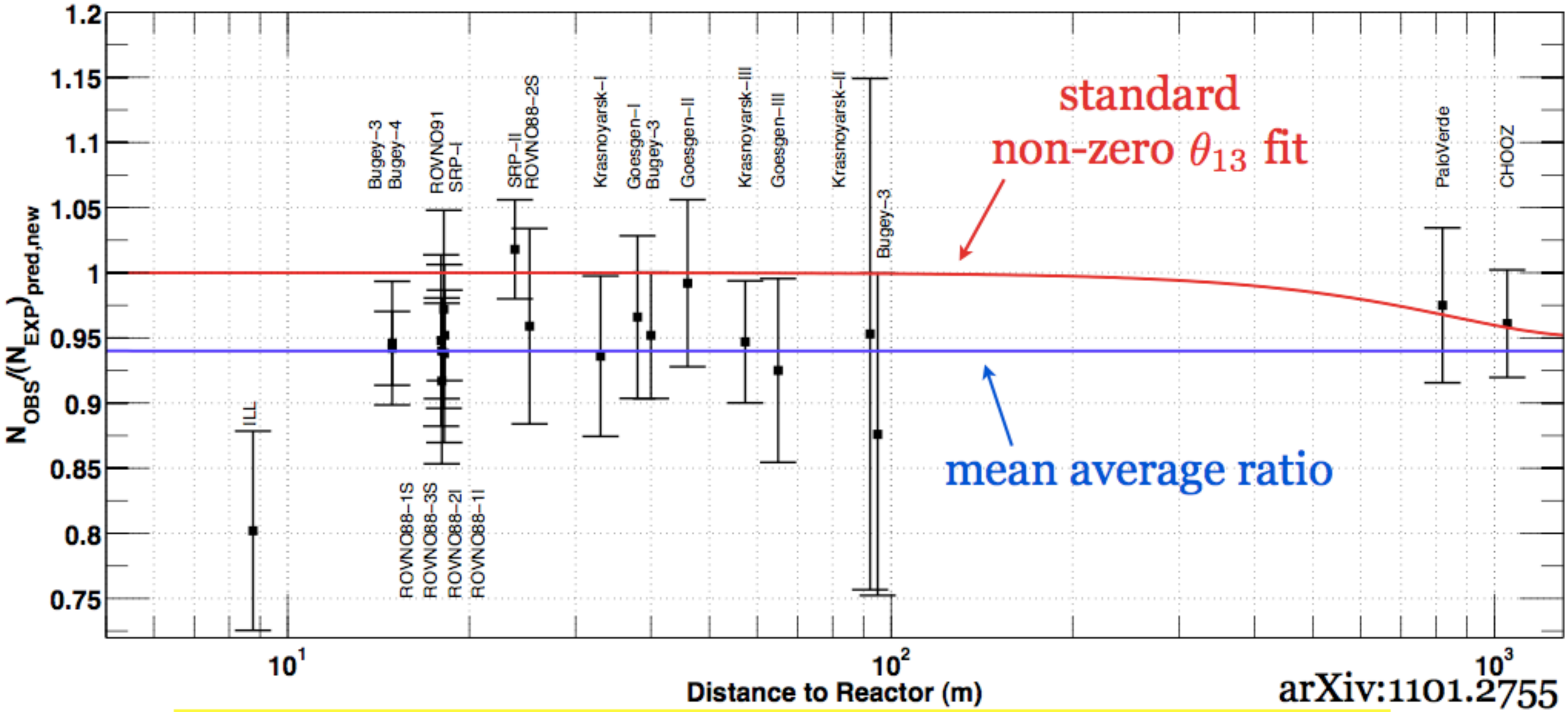


arXiv:1101.2755

Fermilab Jul-07-2011

PAN Machado

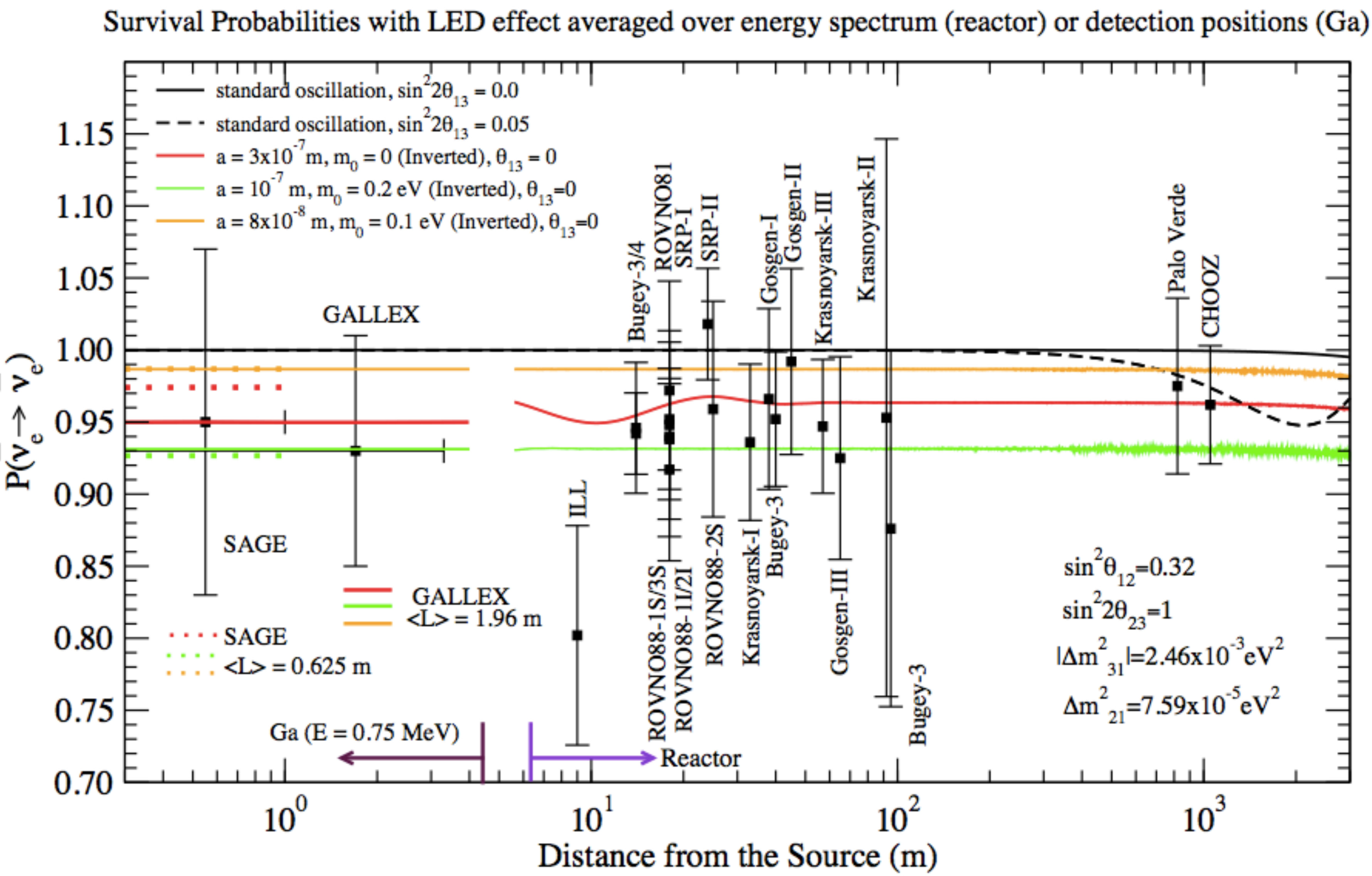
What are the anomalies?



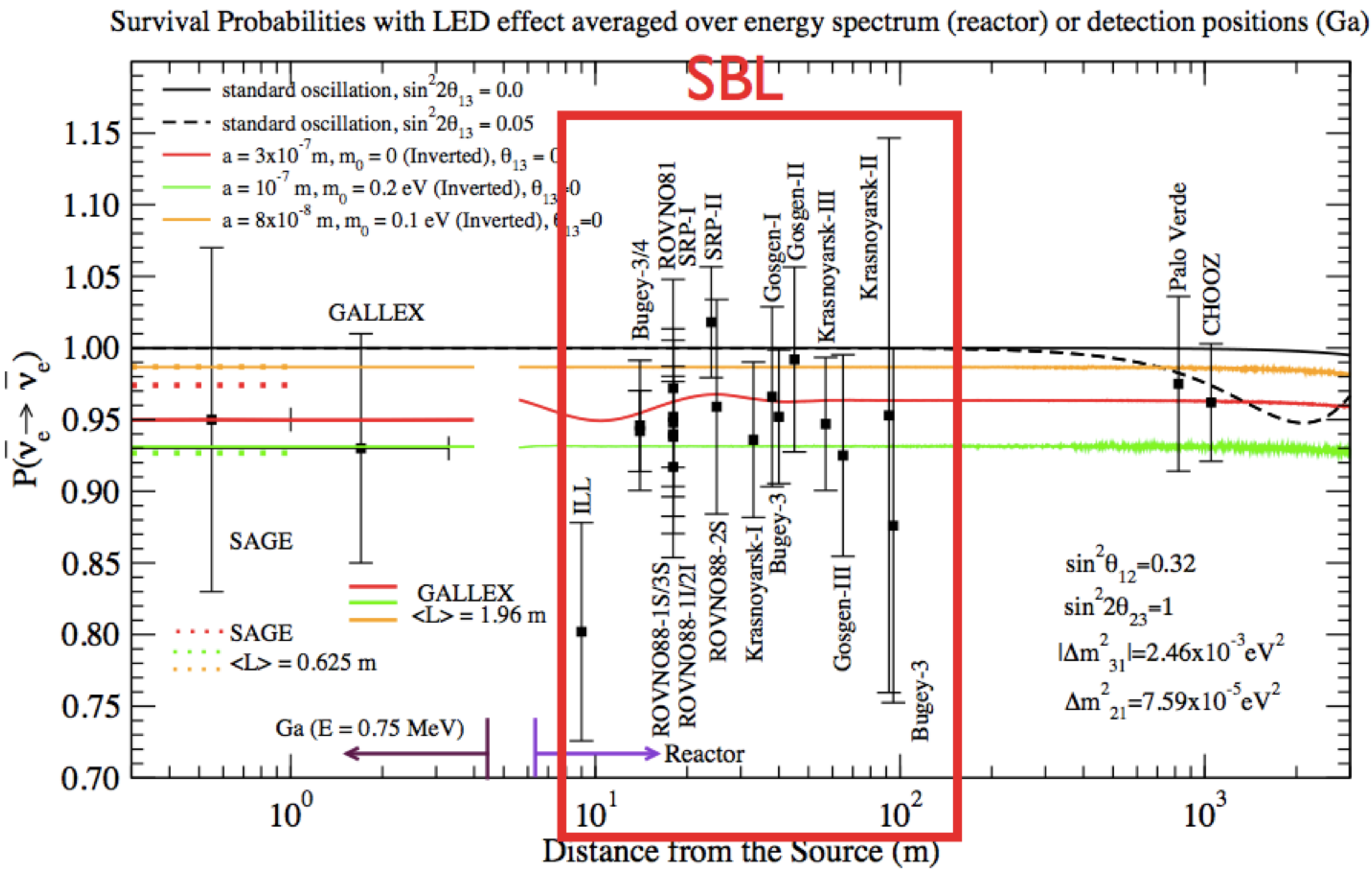
arXiv:1101.2755

Could these anomalies be due to LED effects?

Interpreting the anomalies



Interpreting the anomalies



PAN Machado

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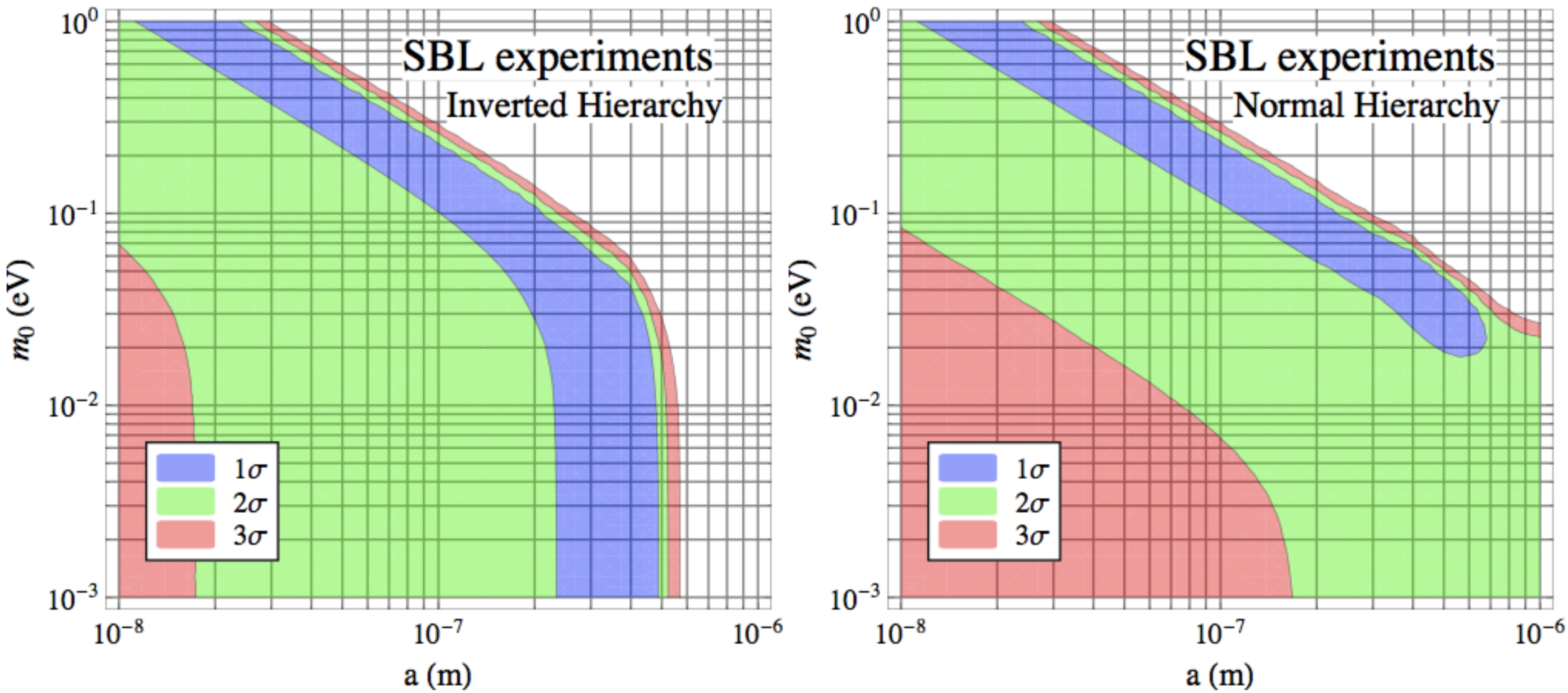

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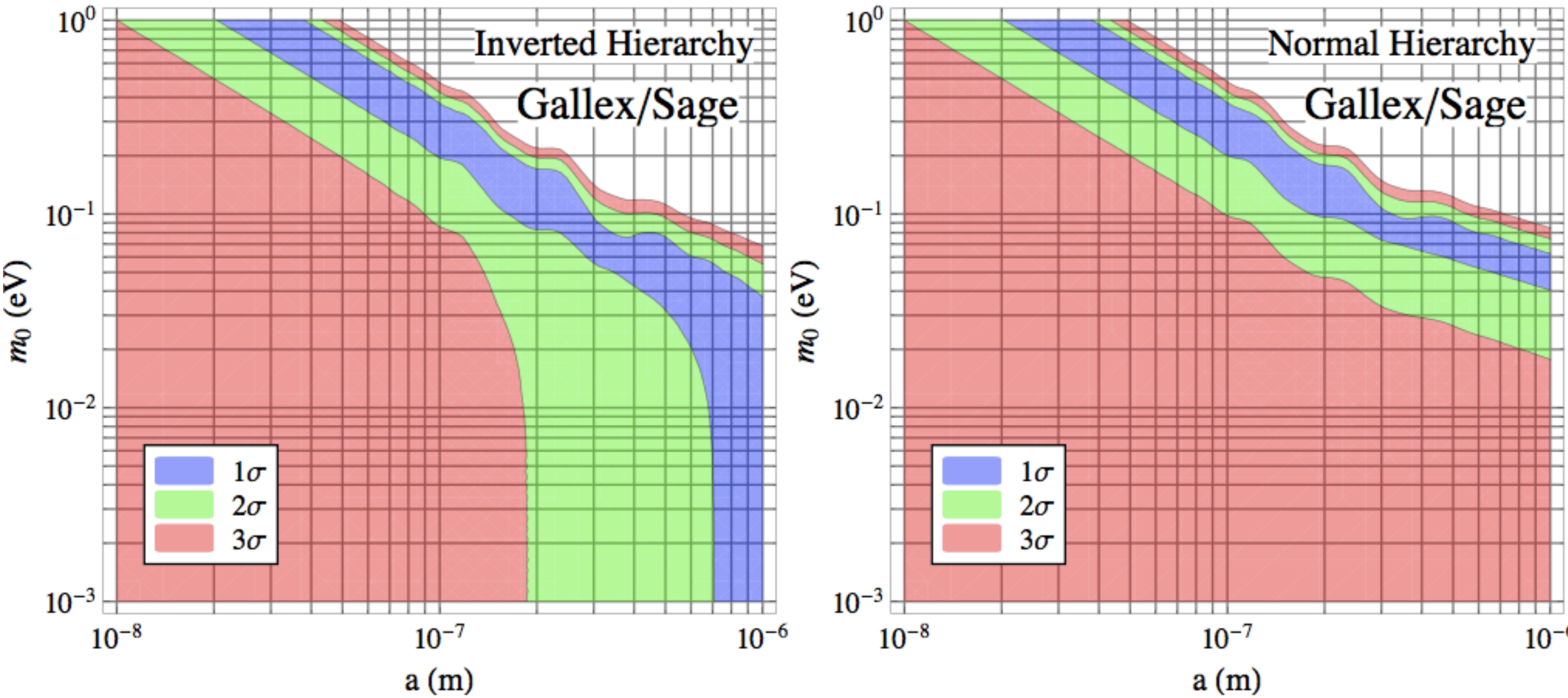

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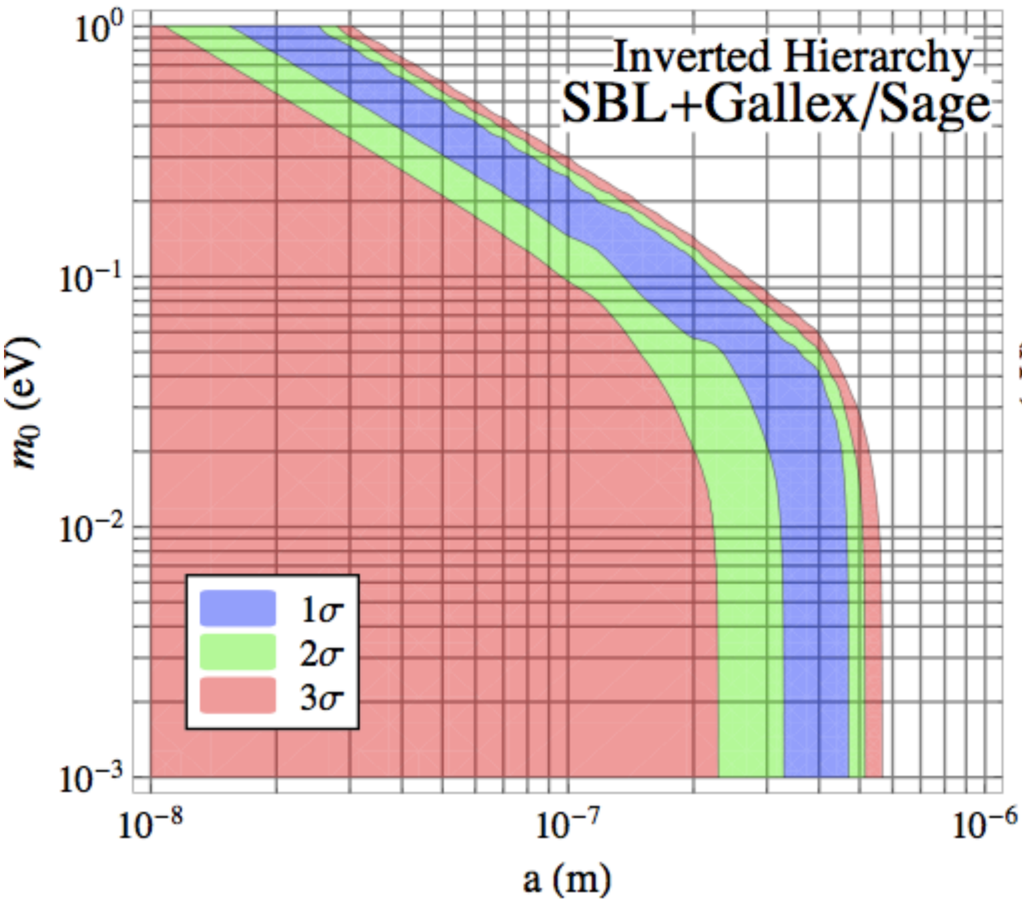
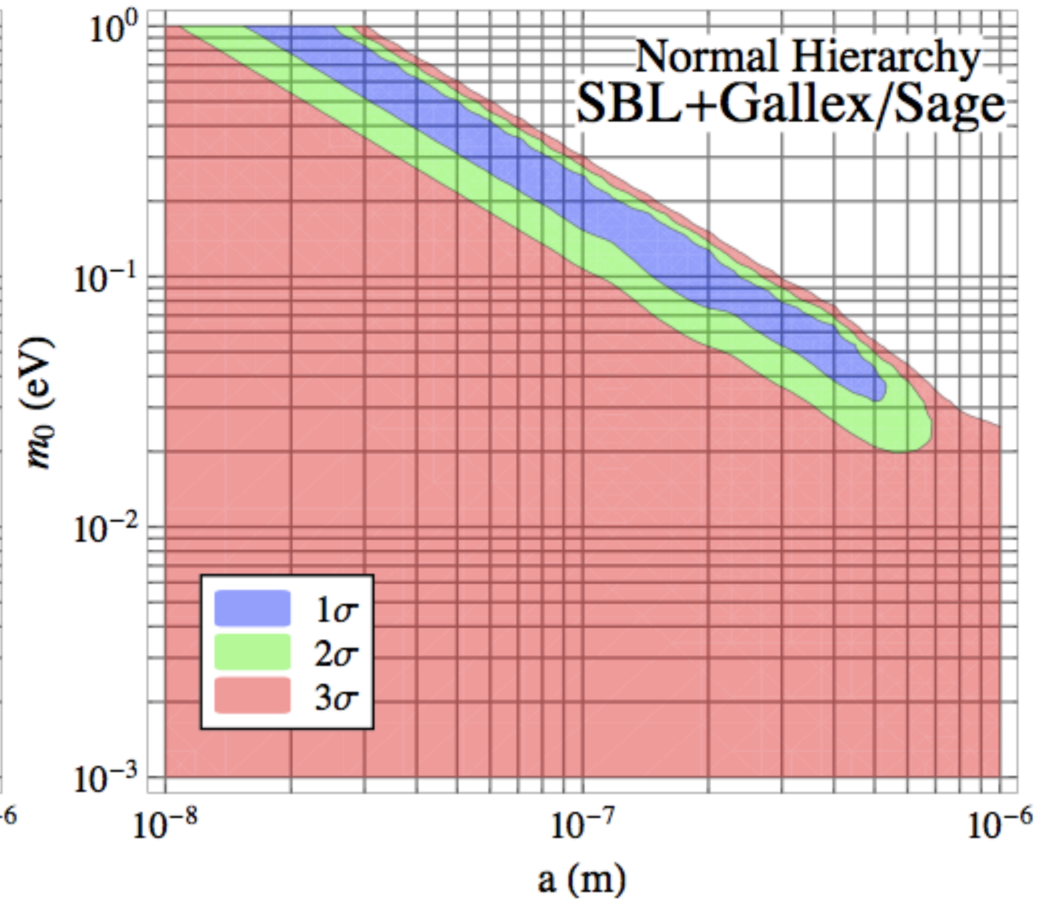
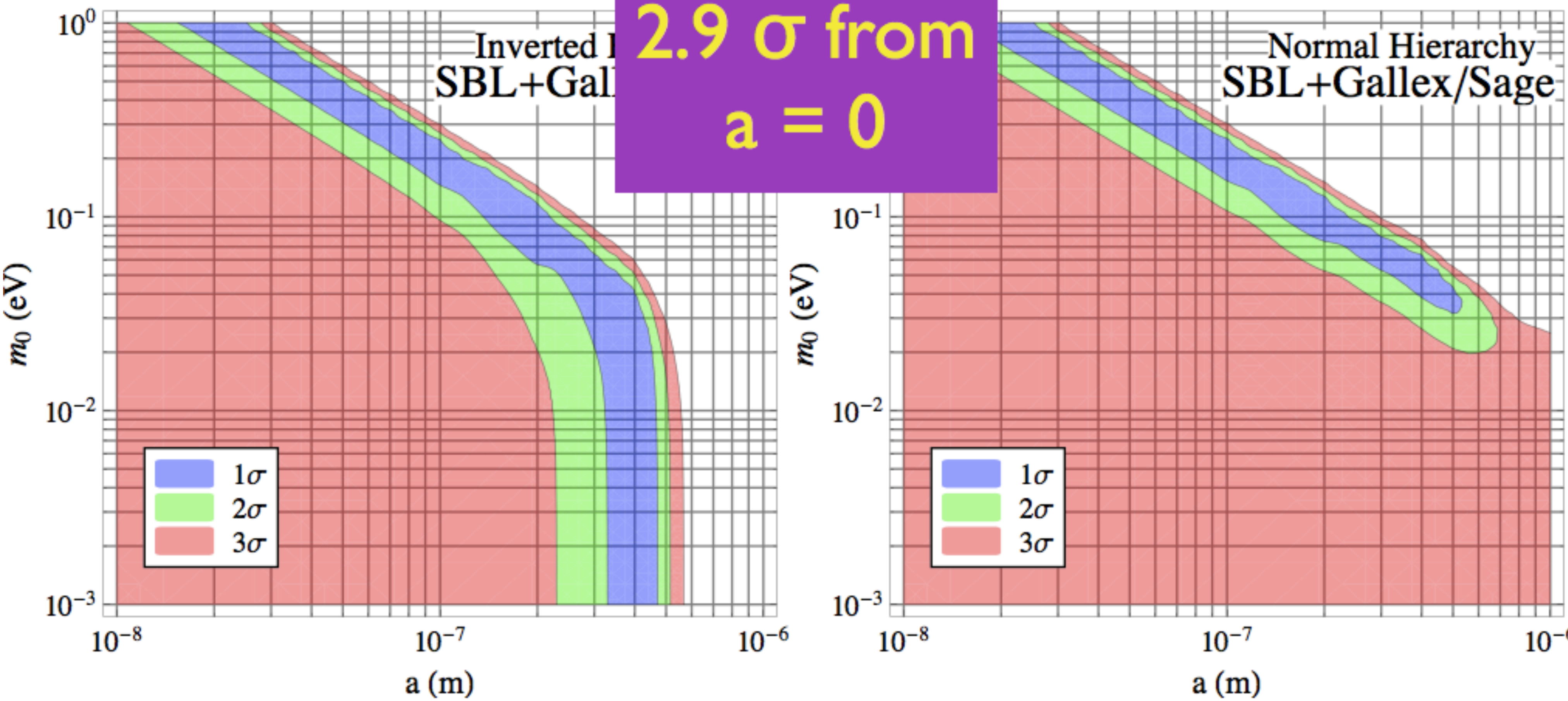


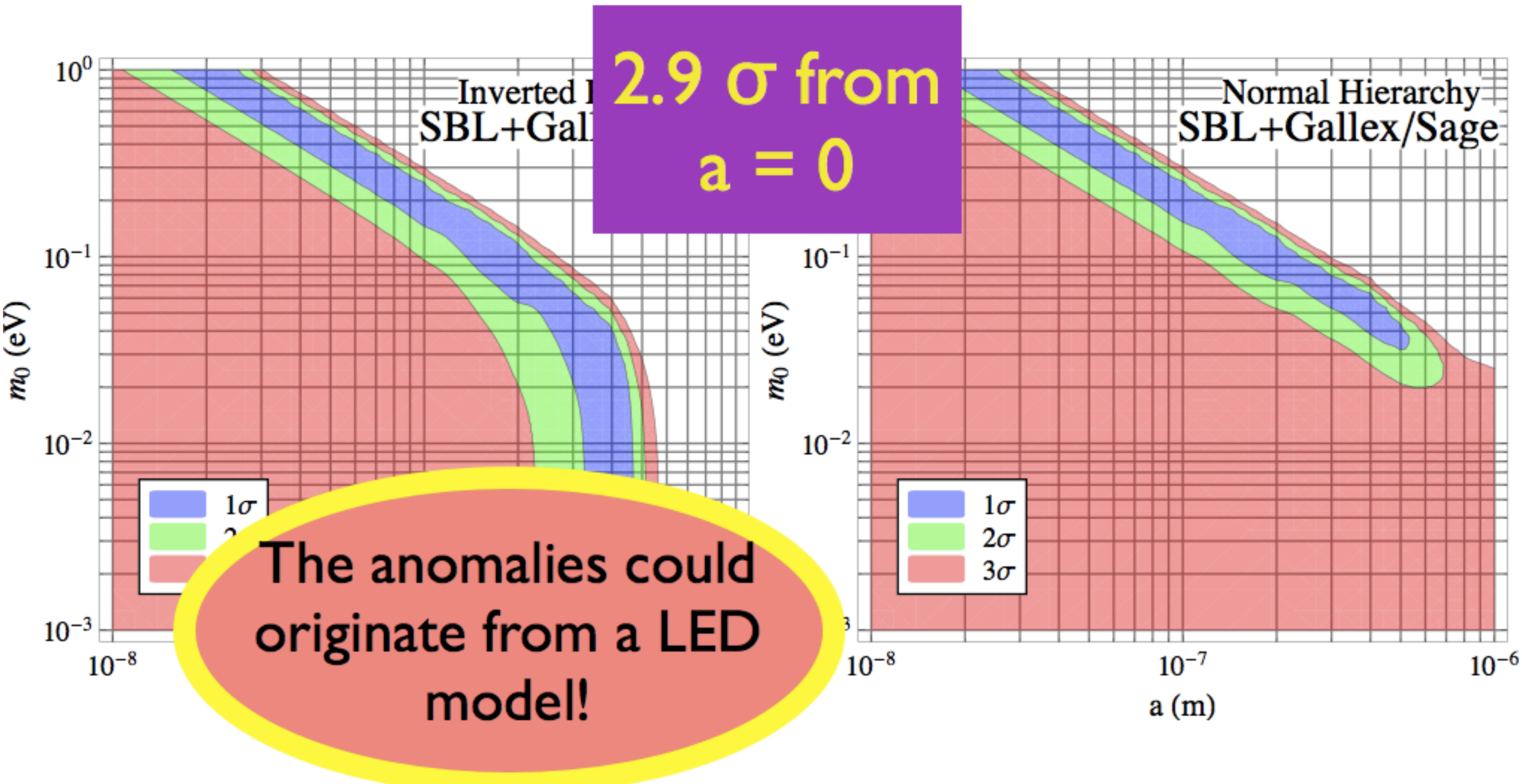


Interpreting the anomalies

2.9 σ from a = 0



Interpreting the anomalies



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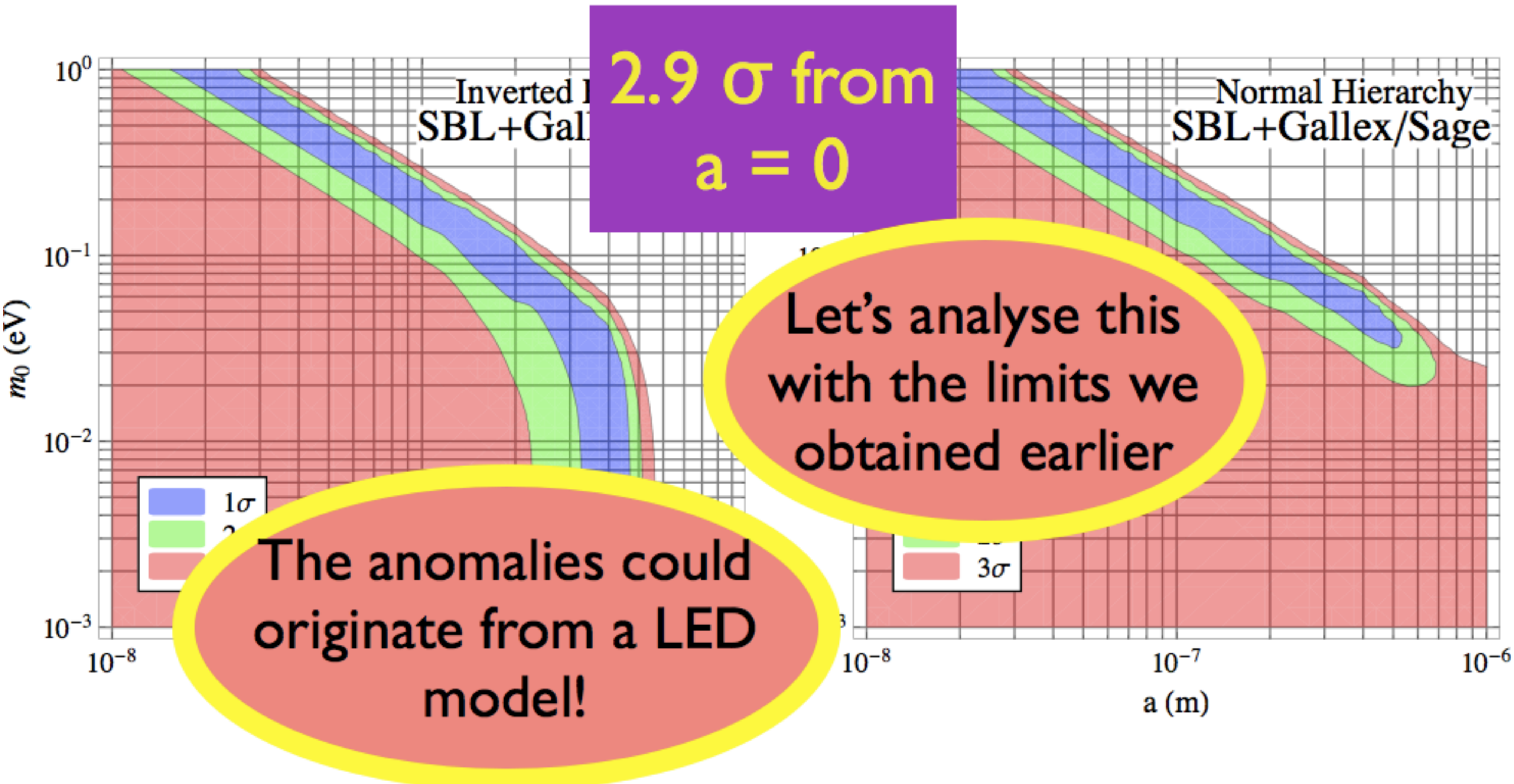

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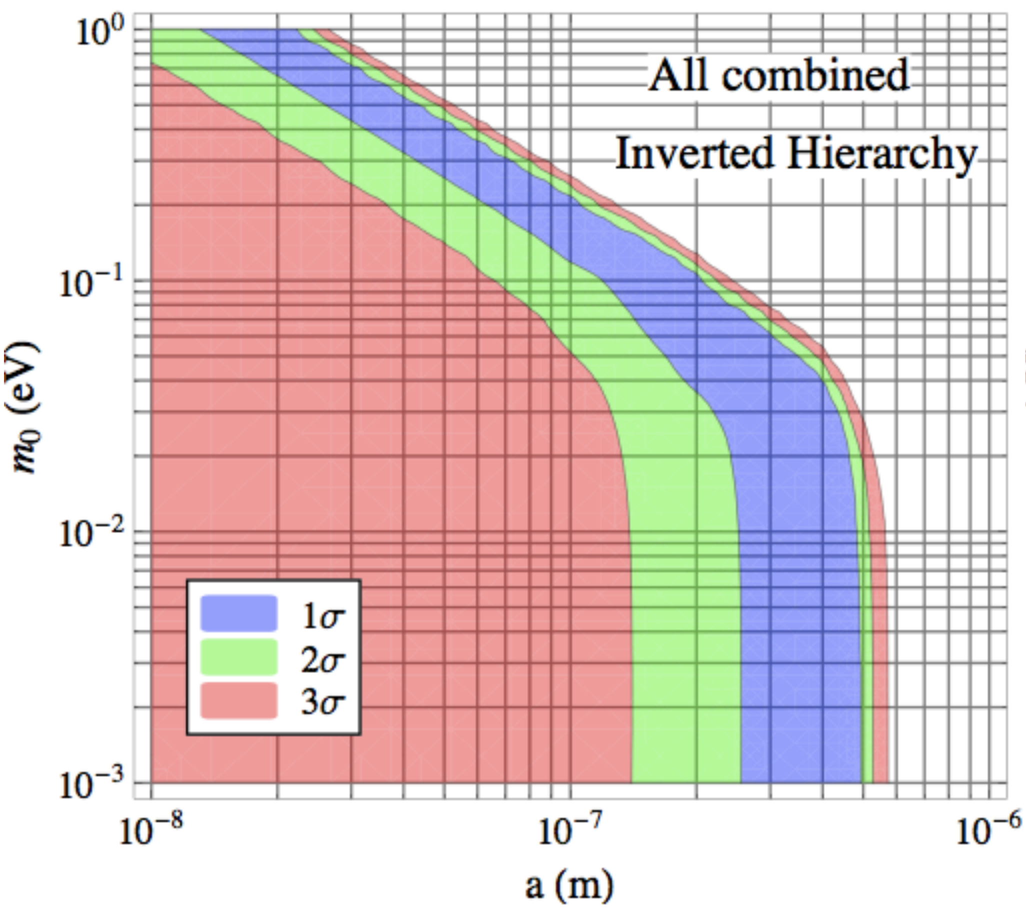

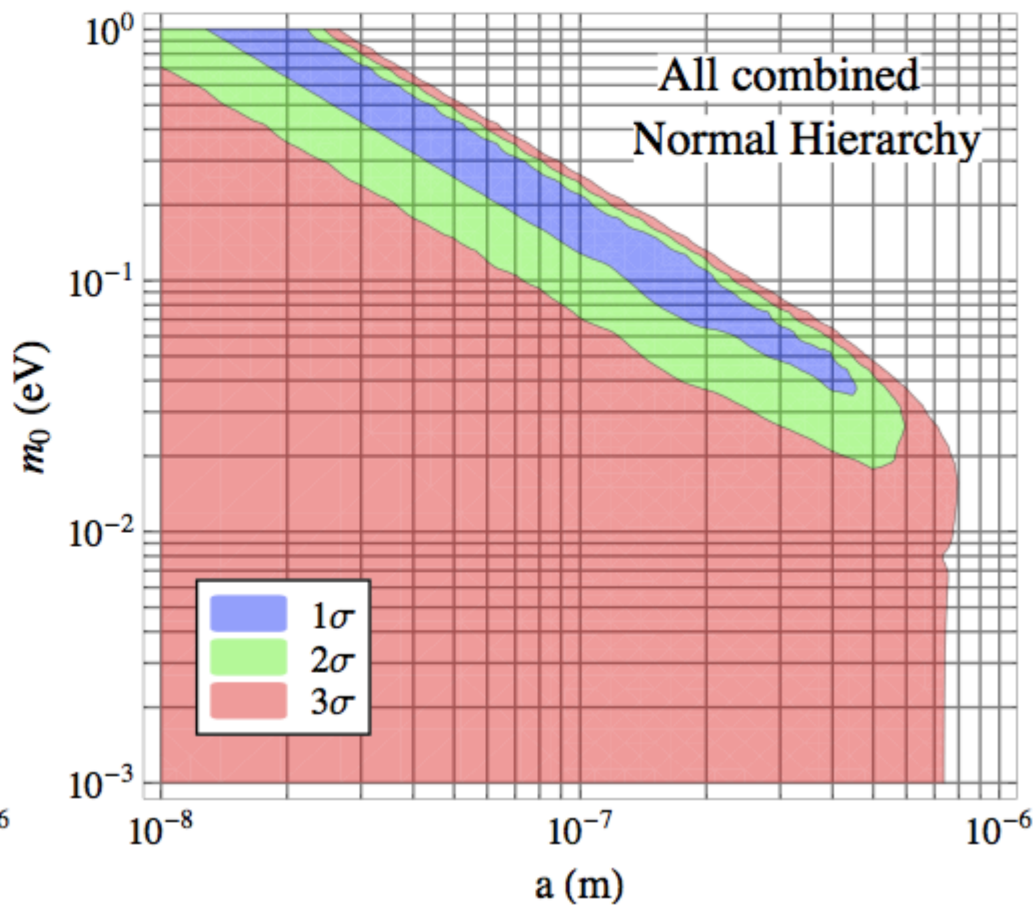

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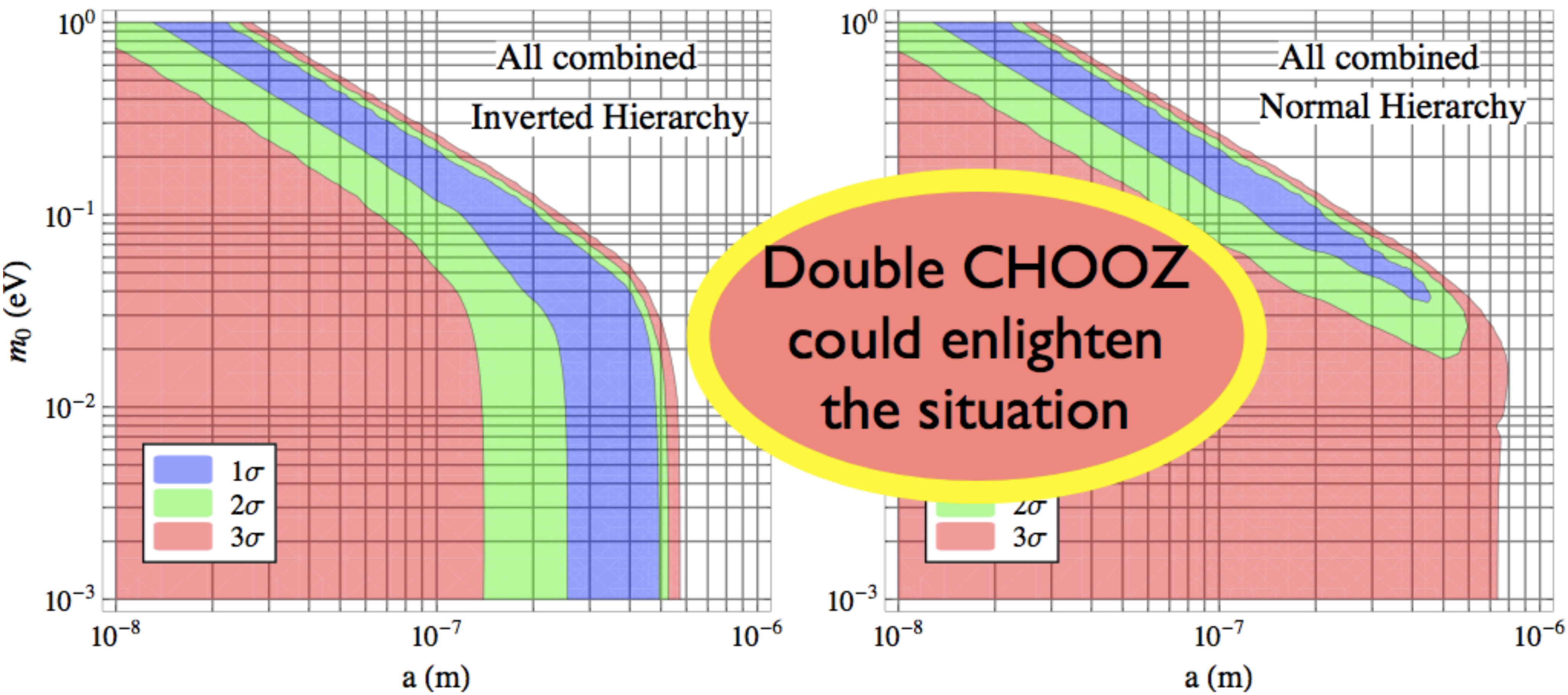

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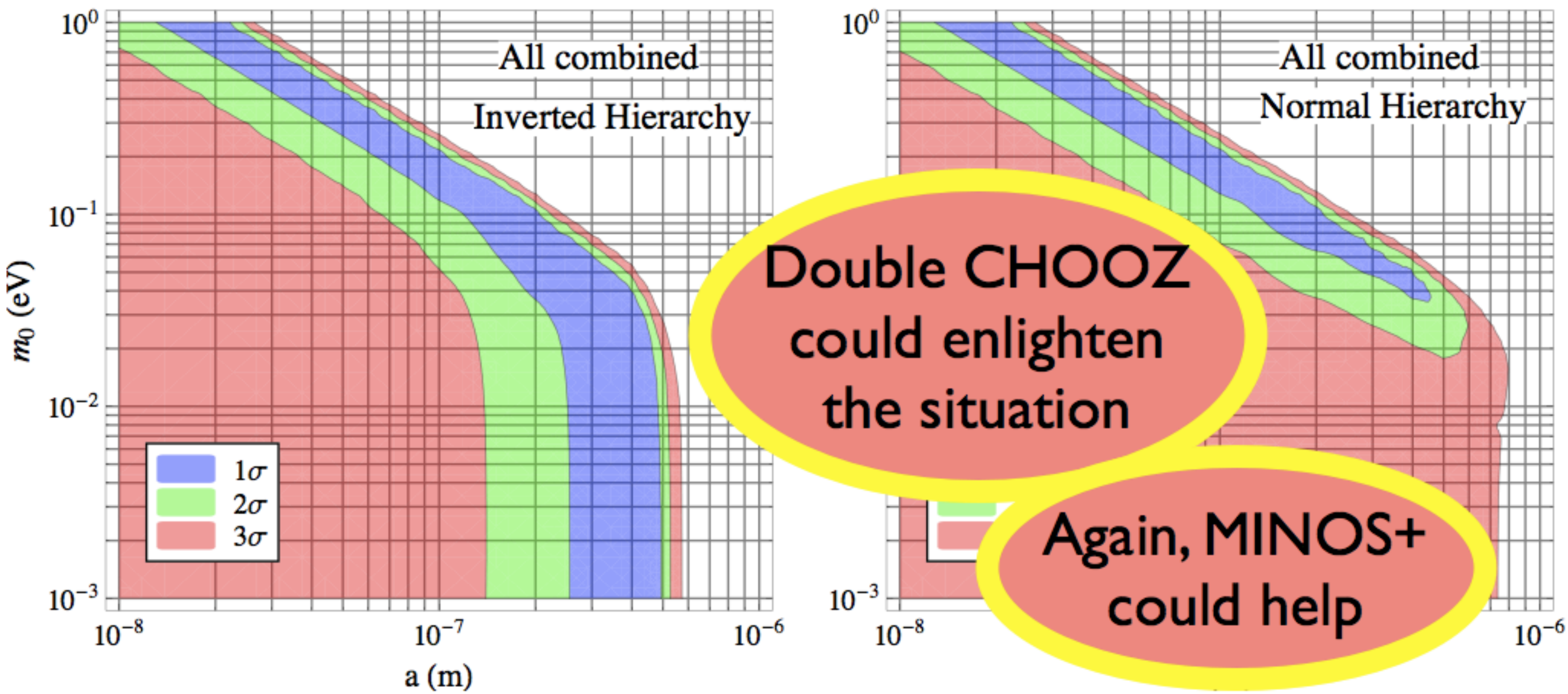

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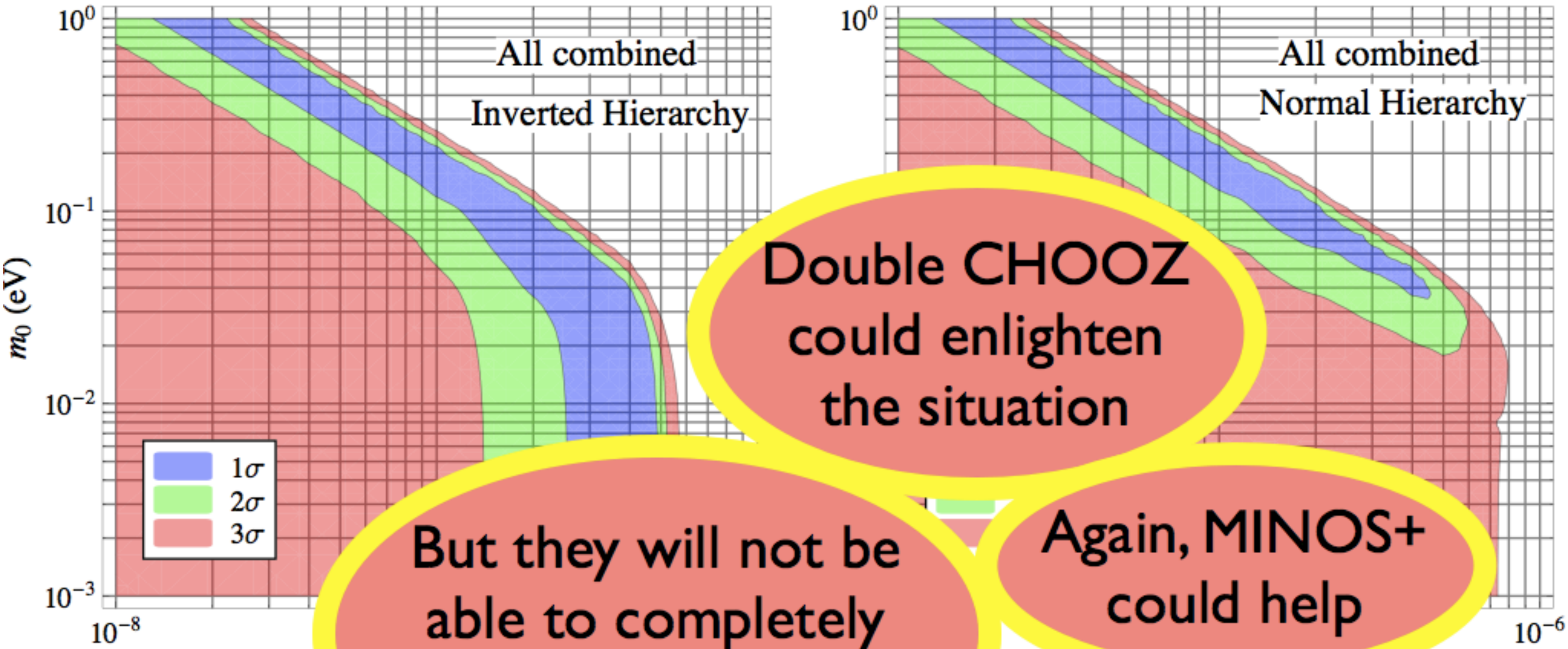

Double CHOOZ could enlighten the situation

But they will not be able to completely exclude the preferred region

Again, MINOS+ could help

Conclusions

We studied an interesting extra dimensions model and derived bounds on the largest ED from ν experiments

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We shown that future reactor experiments can improve the current limits, but NOvA and T2K will not contribute significantly

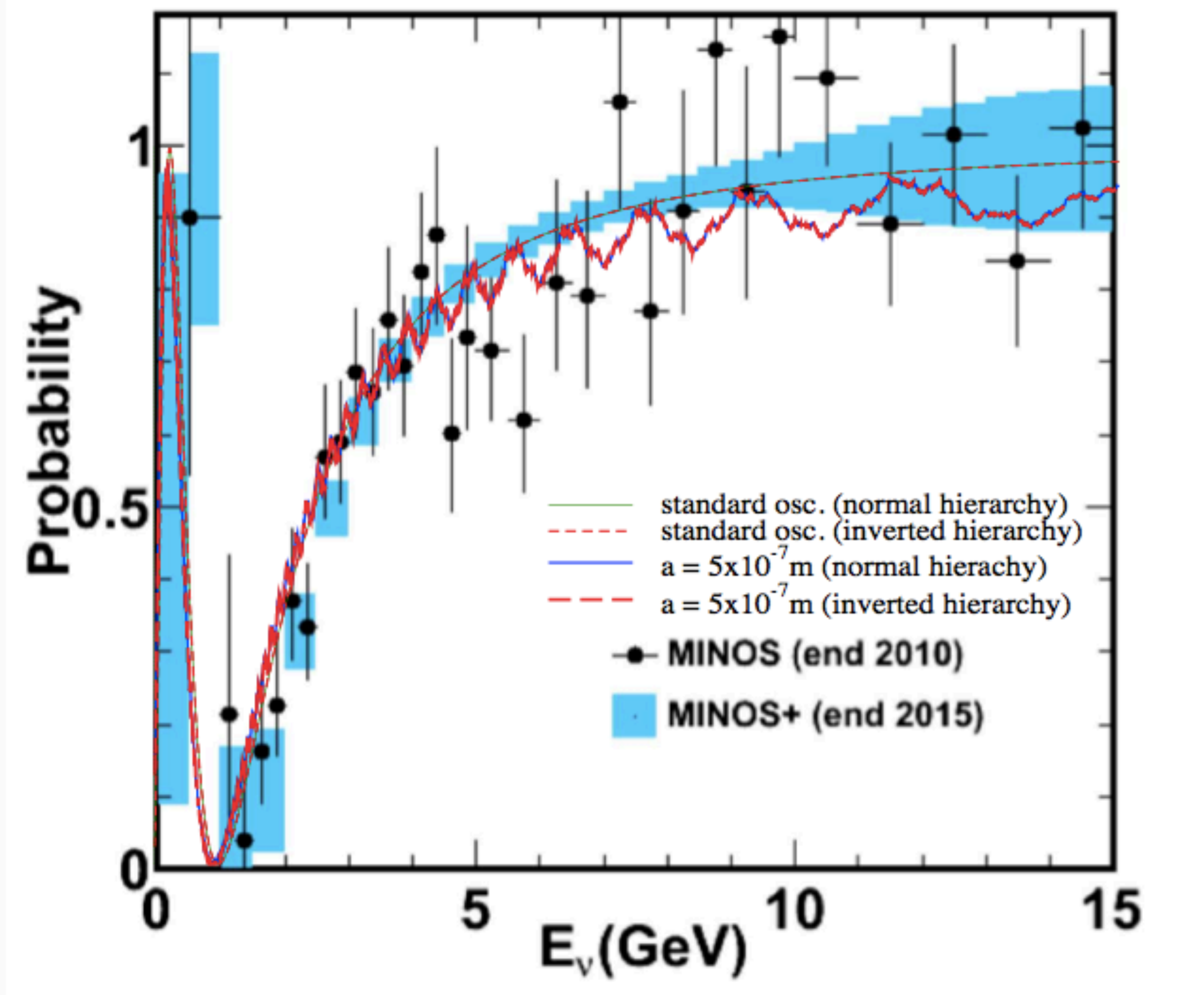
On the other hand, MINOS+ seems promising

Finally, LED is a possible interpretation for the gallium and reactor antineutrino anomalies

Thank you!

Backup slides

MINOS+



Probability
1
0.5
0
0
5
10
15
Eν(GeV)
standard osc. (normal hierarchy)
standard osc. (inverted hierarchy)
a = 5x10-7m (normal hierachy)
a = 5x10-7m (inverted hierarchy)
MINOS (end 2010)
MINOS+ (end 2015)

Solar neutrinos

If 1/a >> $\sqrt{\Delta m^2_\odot}$ then the effect of LED is basically to induce vacuum like oscillations from active to sterile

This would simply reduce the overall survival probability

In order to introduce a strong distortion of the solar spectra, the size of the ED should be ~ (60-100) μm