# MiniBooNE and shortcuts in extra dimensions: explaining the World neutrino data

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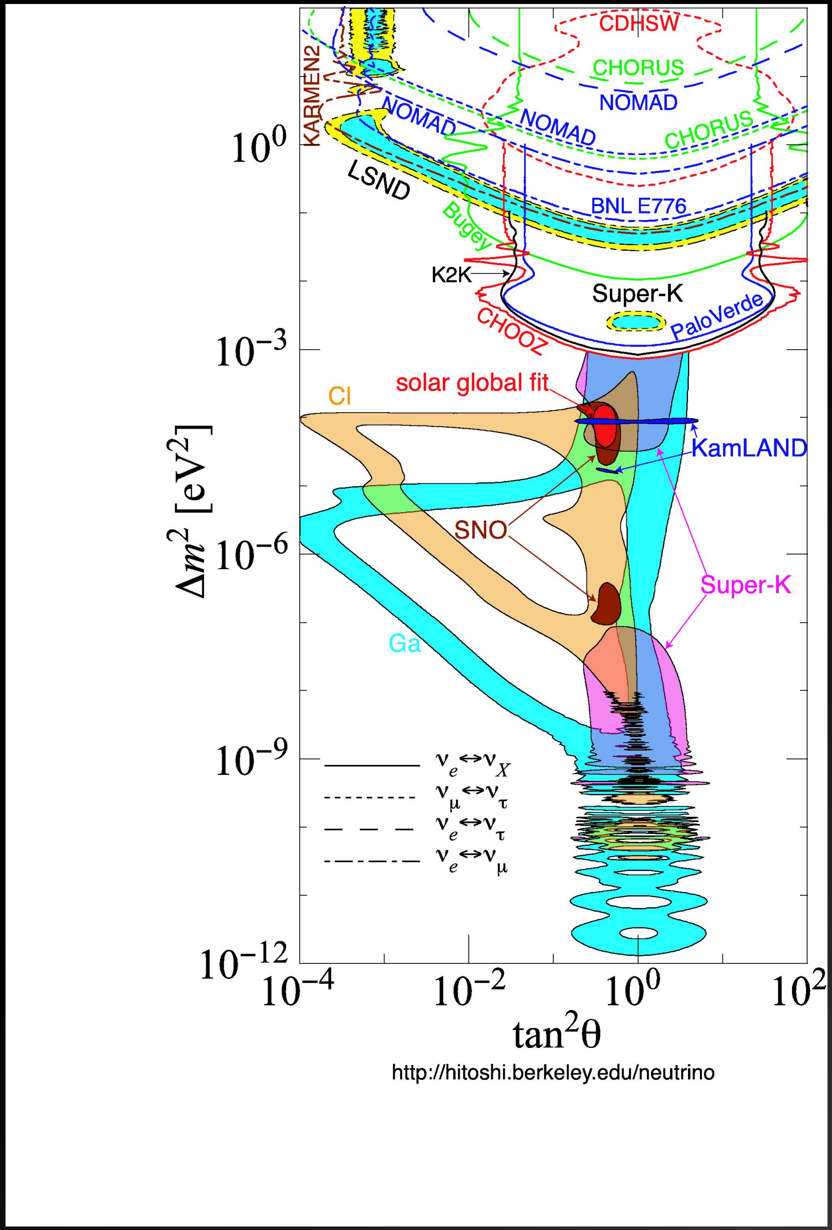
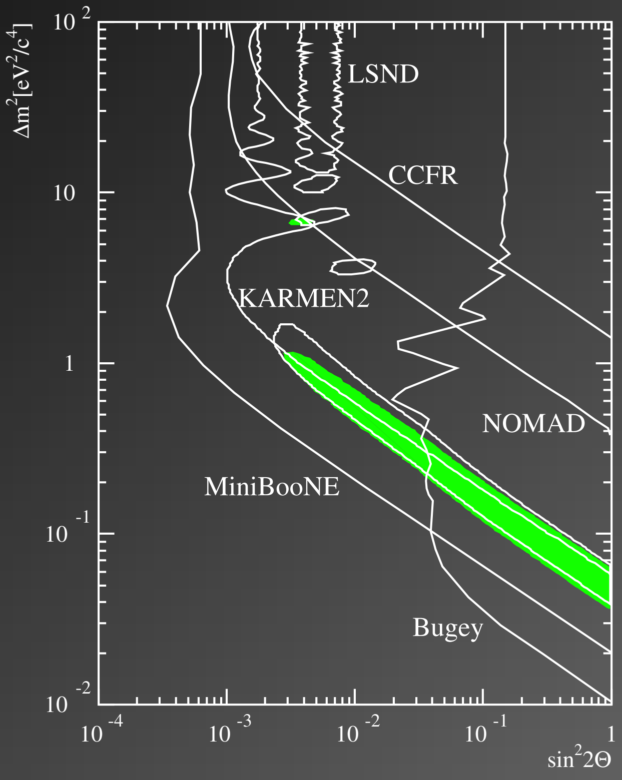
# Outline

- Summary of neutrino data & LSND dilemma
- Neutrinos in extra dimensions
- Bulk shortcuts, neutrino oscillations & LSND
- MiniBooNE & the World neutrino data:
  Towards a realistic 3+1 neutrino fit

# Summary of neutrino data

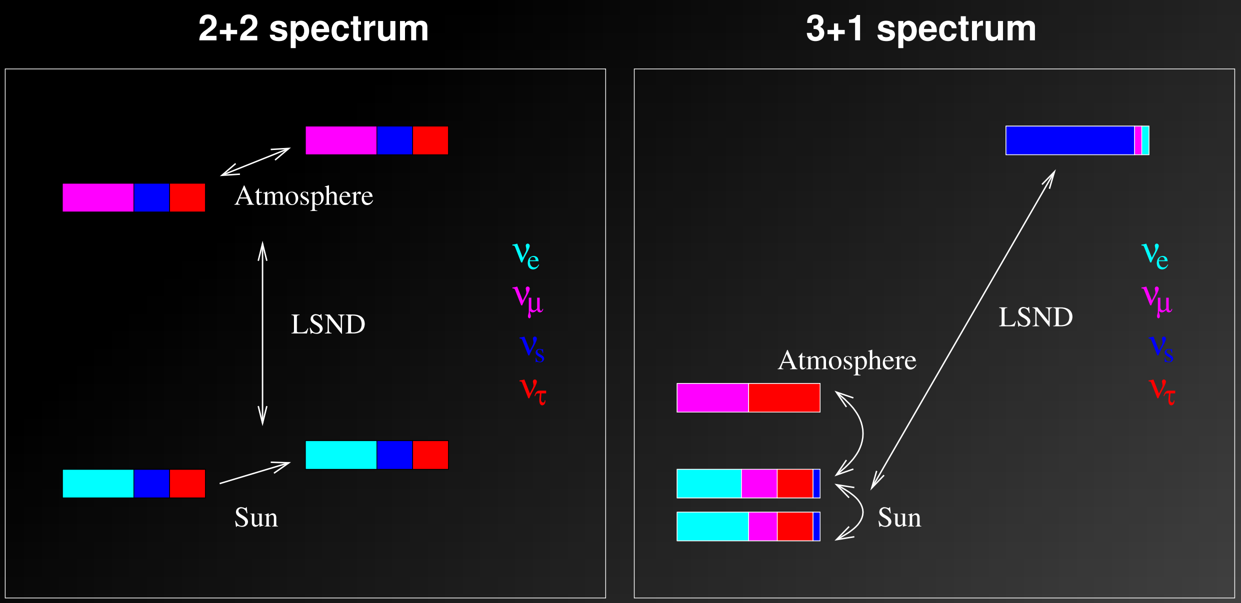



- 3 $\Delta m^2$'s $\rightarrow$ 4 neutrinos!
- width of the Z-boson (LEP) $\rightarrow$ 3 neutrinos!
- $\rightarrow$ one sterile neutrino? (i.e. not coupling to the Z)



# The LSND Dilemma

LSND: $\overline{\nu}_\mu - \overline{\nu}_e$ oscillations over $\Delta m^2 \simeq 1$ eV$^2$




2+2 spectrum:
no oscillations of solar or atmospheric $\nu$'s into steriles $\rightarrow$ excluded!

3+1 spectrum: constraints from $\nu$ disappearance experiments

BUGEY bound ($\nu_e \rightarrow \nu_{\not e}$): $\sin^2 2\theta_{e\not e} = 4\,U_{e4}^2\,(1 - U_{e4}^2)$

CDHS bound ($\nu_\mu \rightarrow \nu_{\not\mu}$): $\sin^2 2\theta_{\mu\not\mu} = 4\,U_{\mu 4}^2\,(1 - U_{\mu 4}^2)$

LSND ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$): $\sin^2 2\theta_{\rm LSND} = 4U_{e4}^2 U_{\mu 4}^2$

LSND is doubly suppressed! $\sin^2 2\theta_{\rm LSND} \simeq \frac{1}{4}\sin^2 2\theta_{e\not e} \sin^2 2\theta_{\mu\not\mu} \rightarrow$ excluded!

# LSND:

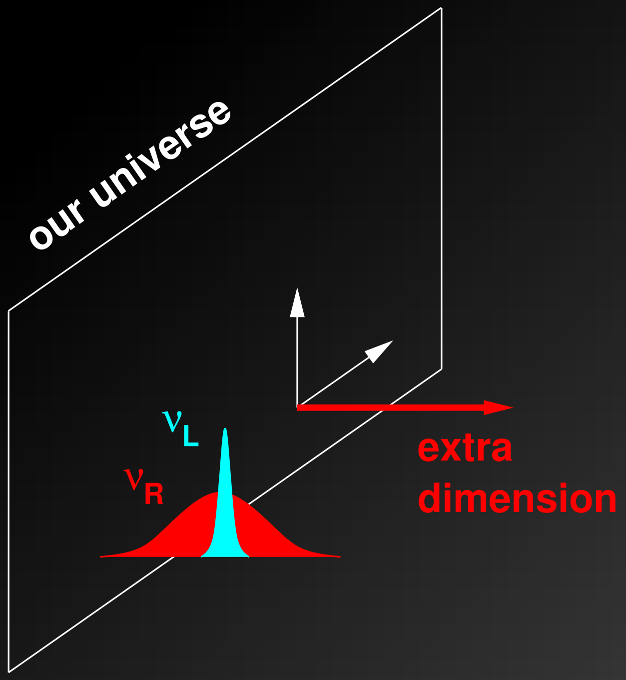
- might be wrong
- may hint towards deviations from the usual oscillation mechanism
- may be a messenger of the mechanism of neutrino mass generation!
- extra dimensions? bulk shortcuts?

- No large scale $\longrightarrow$ no seesaw suppression of neutrino masses
- However: string theories $\longrightarrow$ singlet fermions in the bulk (e.g. superpartners of moduli fields) $\longrightarrow \nu_R$

$\longrightarrow$ small Dirac neutrino masses from volume-suppressed couplings to $\nu_R$ in the bulk:

$$m^D = \frac{vY}{\sqrt{2V_\delta M_{P\delta d}^\delta}} = v\frac{Y}{\sqrt{2}}\frac{M_{P\delta d}}{M_{P4d}}$$

suppression factor: $M_{P\delta d}/M_{P4d}$




N. Arkhani-Hamed, S. Dimoloulos, G.R. Dvali, J. March-Russel, 1998; K.R. Dienes, E. Dudas, T. Gherghetta, 1999; Y. Grossman, M. Neubert, 2000; S.J. Huber, Q. Shafi, 2002; G. Bhattacharyya, H.V. Klapdor-Kleingrothaus, H. Päs, A. Pilaftsis, 2002

What about:

Non-trivial

brane properties

?

Brane bending ?

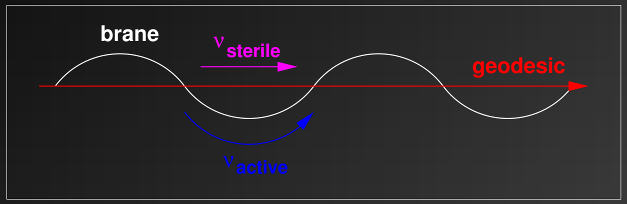
Asymmetrical warping?

3 mechanisms for bulk shortcuts:

- Gravitational self attraction due to brane matter

H. Ishihara, 2000

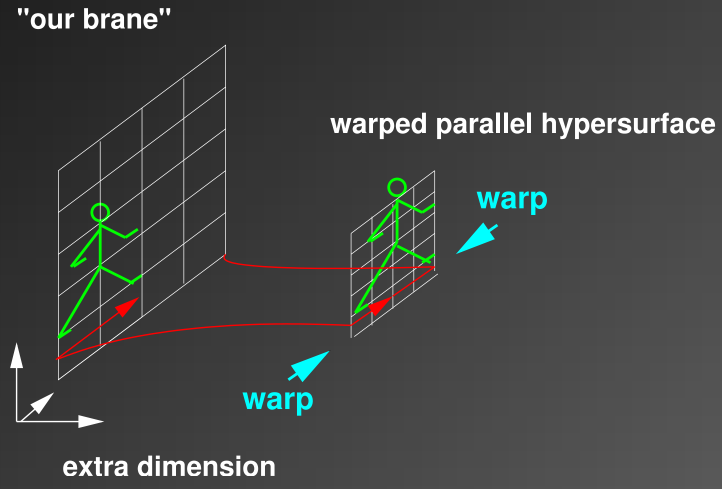
- Thermal or quantum fluctuations




- Asymmetrically warped bulk dimension

$$ds^2 = dt^2 - \alpha^2(u)dx^2 - du^2$$

D.J.H. Chung & K. Freese, 1999




→ bulk shortcuts as a solution to the cosmological horizon problem

Brane bending or asymmetrical warping allows
for
apparent superluminal propagation!

How
do bulk shortcuts
affect
neutrino oscillations ?

consider bulk shortcuts:

Evolution factor in path integral: $\sim e^{iS}$ with $S = \int H dt$

Bulk signal gains a time shift $\Delta t$

$\Rightarrow$ Phase difference in evolution factor due to shortcut:

$\Delta S = \Delta \int H dt = H \Delta t \to \Delta H_{\text{eff}} T$

$\Rightarrow \Delta H_{\text{eff}} = H \Delta t / T$

Introduce shortcut parameter: $\epsilon \equiv (t_{\text{brane}} - t_{\text{bulk}})/t_{\text{brane}} = \Delta t/T$

Change in the Hamiltonian:

$\Rightarrow \Delta H_{\text{eff}} = H \Delta t / T \to \epsilon E$

(Päs, Pakvasa, Weiler, 2005)

## Evolution equation in flavor space:

$$i \frac{d}{dt} \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix} = H_F \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix}$$

## Hamiltonian in the presence of bulk shortcuts:

$$H_F = + \frac{\delta m^2}{4\,E} \begin{pmatrix} \cos 2\theta & -\sin 2\theta \\ -\sin 2\theta & -\cos 2\theta \end{pmatrix} + E\,\frac{\epsilon}{2} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

$\Rightarrow$ A Resonance exists at $E_{\mathrm{res}} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\,\epsilon}}$

$\longrightarrow$ choose $E_{\mathrm{res}}$=30-400 MeV $\leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16}$

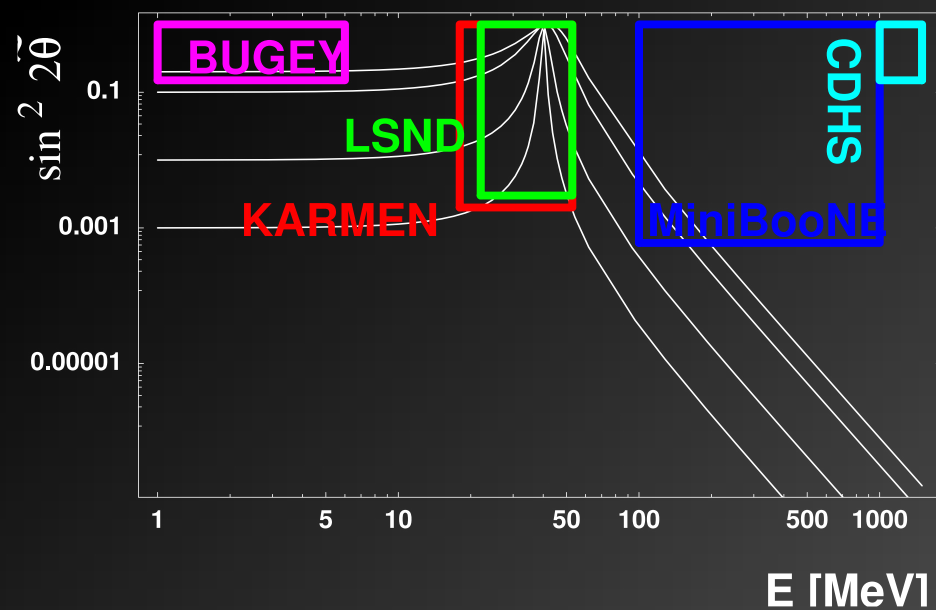
(Päs, Pakvasa, Weiler, 2005)

# The active-sterile oscillation probability

$$P_{as} = \sin^2 2\tilde{\theta}\ \sin^2(\delta H\ D/2)$$

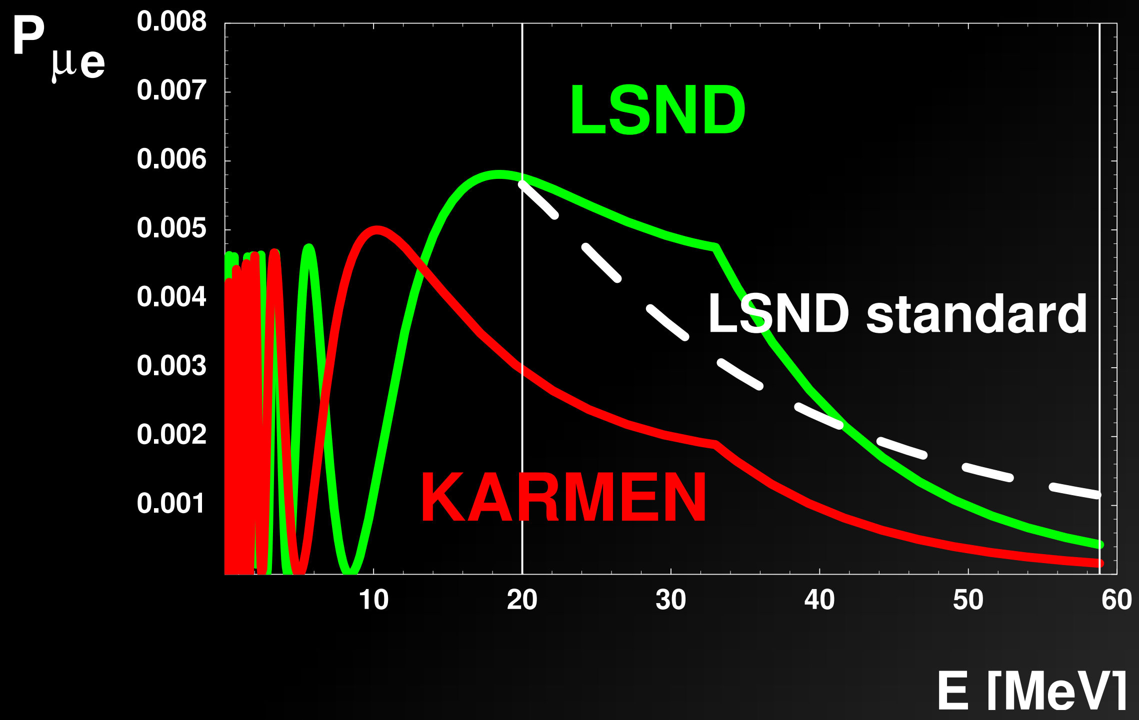
$$\sin^2 2\tilde{\theta} = \left[\frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}\right] \qquad \delta H = \frac{\delta m^2}{2\,E}\sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta}$$

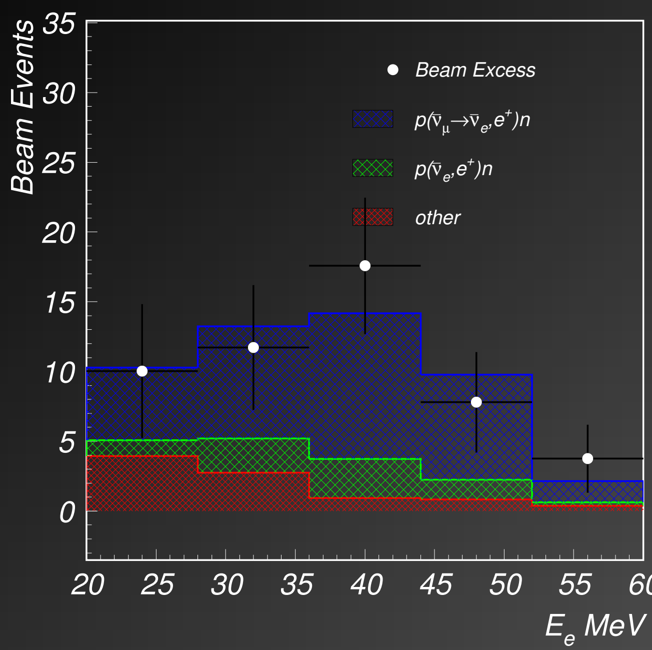
$$A = (E/E_{\rm res})^2$$




Oscillations at $E \gg E_{\rm res}$ (CDHS)are suppressed!
CDHS bound not valid anymore! 3+1 spectrum allowed again! $\rightarrow$ choose
$E_{\rm LSND} < E_{\rm res} \ll E_{\rm CDHS}$ (Päs, Pakvasa, Weiler, 2005)

# Scenario with low resonance energy

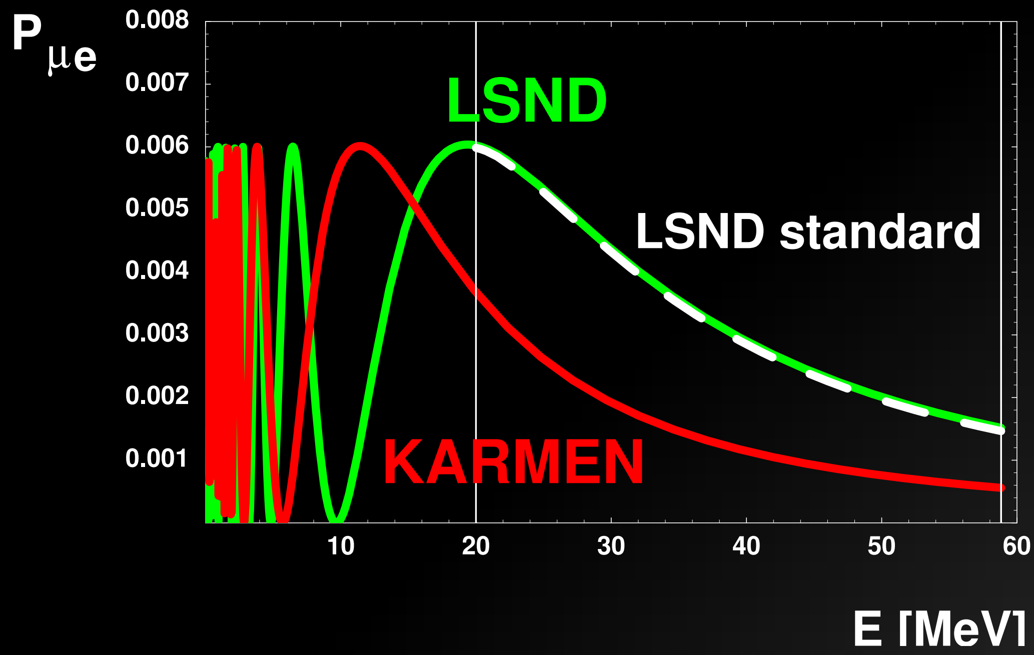


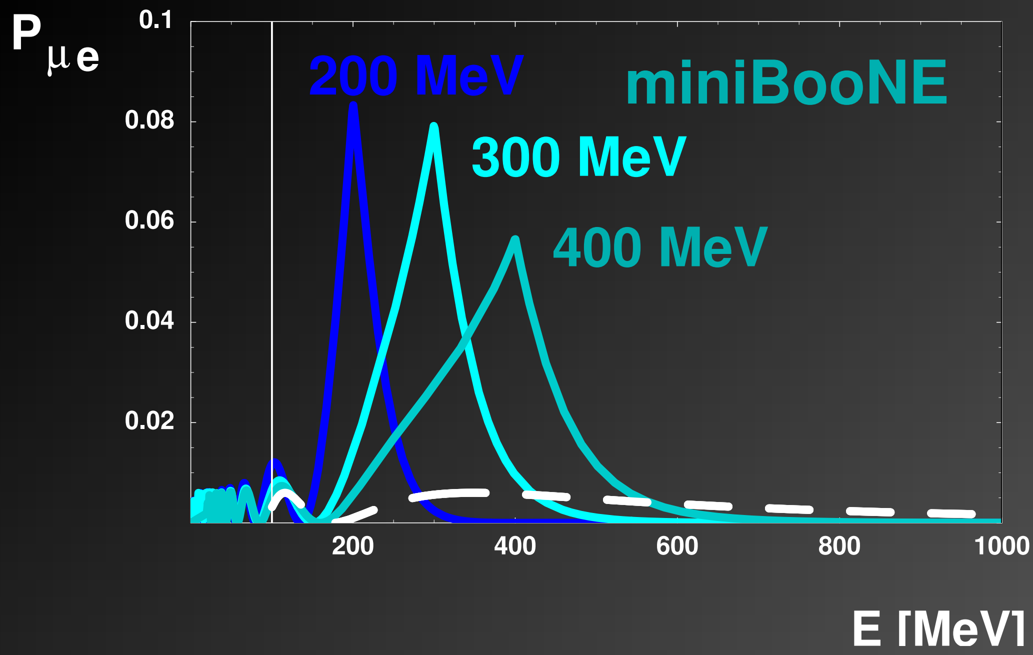




- $E_{\rm res} = 33$ MeV
- $P_{\rm LSND} > P_{\rm KARMEN}$
- good (better) fit for LSND spectrum
- no signal at MiniBooNE!
- strongly enhanced $\nu_\mu$ depletion at SNS stopped $\pi$ source

(Päs, Pakvasa, Weiler, 2005)

# Scenario with high resonance energy



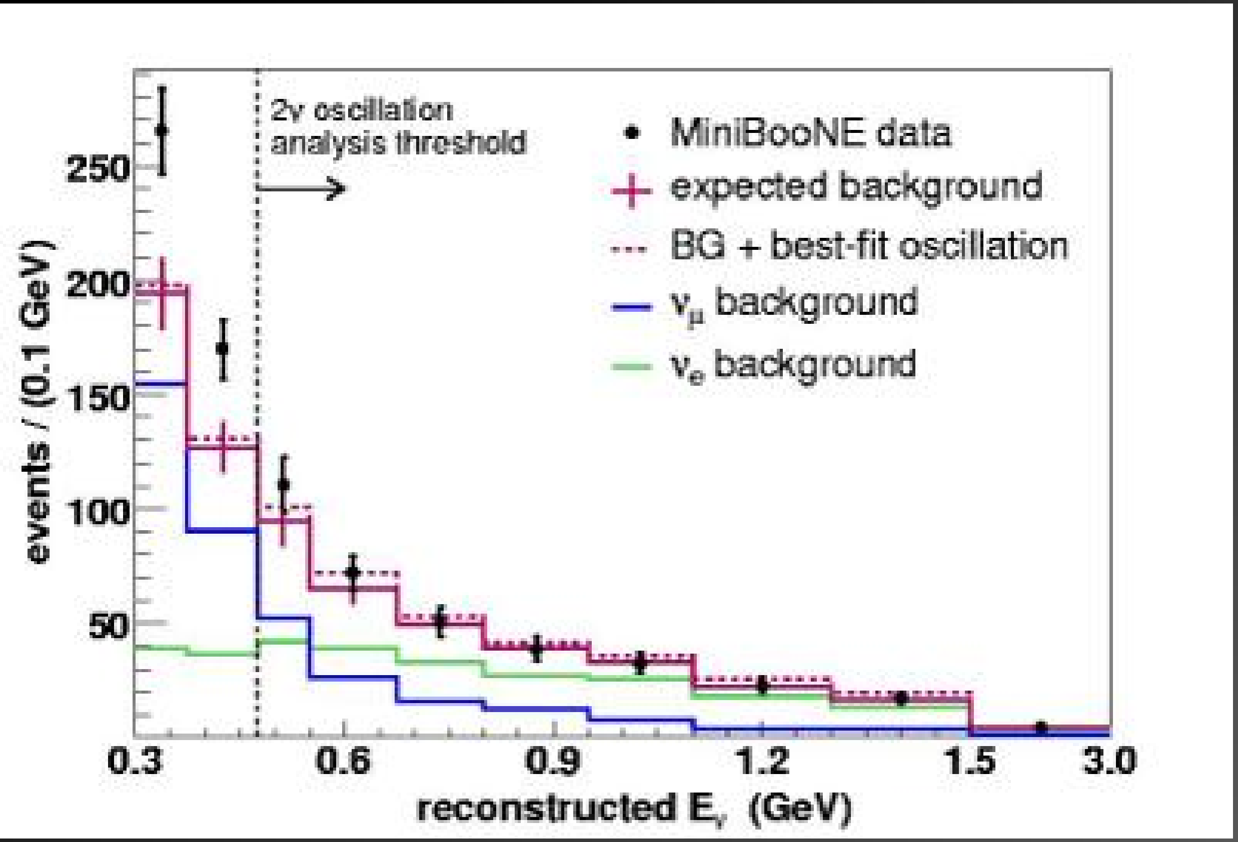




- $E_{\rm res} = 200$ MeV, 300 MeV, 400 MeV; $\sin^2\theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV$^2$
- good fit to LSND spectrum, $P_{\rm LSND} > P_{\rm KARMEN}$
- enhanced miniBooNE signal in the energy range 100-600 MeV

(Päs, Pakvasa, Weiler, 2005)

The MiniBooNE result:

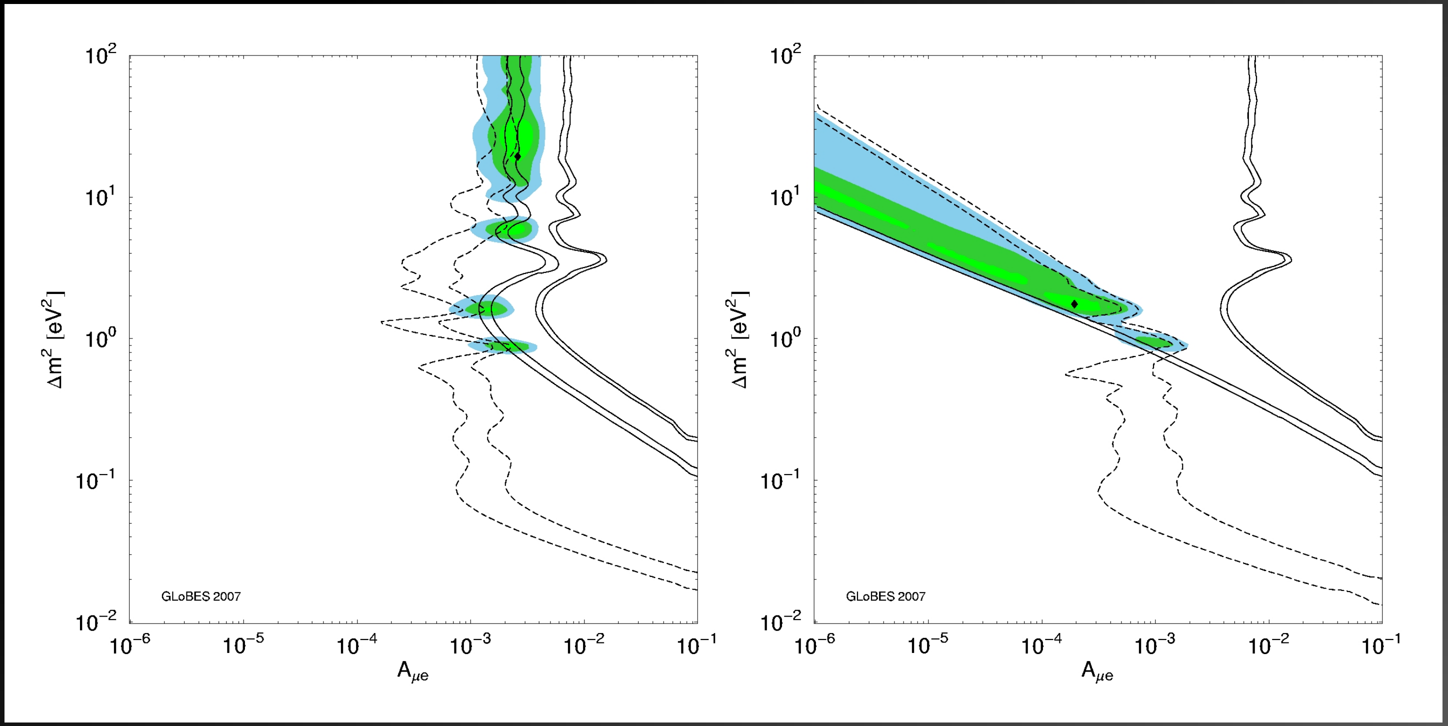
- excludes standard neutrino oscillations as an explanation for LSND
- sees a 3.7 $\sigma$ excess of $\nu_e$ events at low energies $<$ 475 MeV (background?)



# Realistic 3+1 fits: Good news

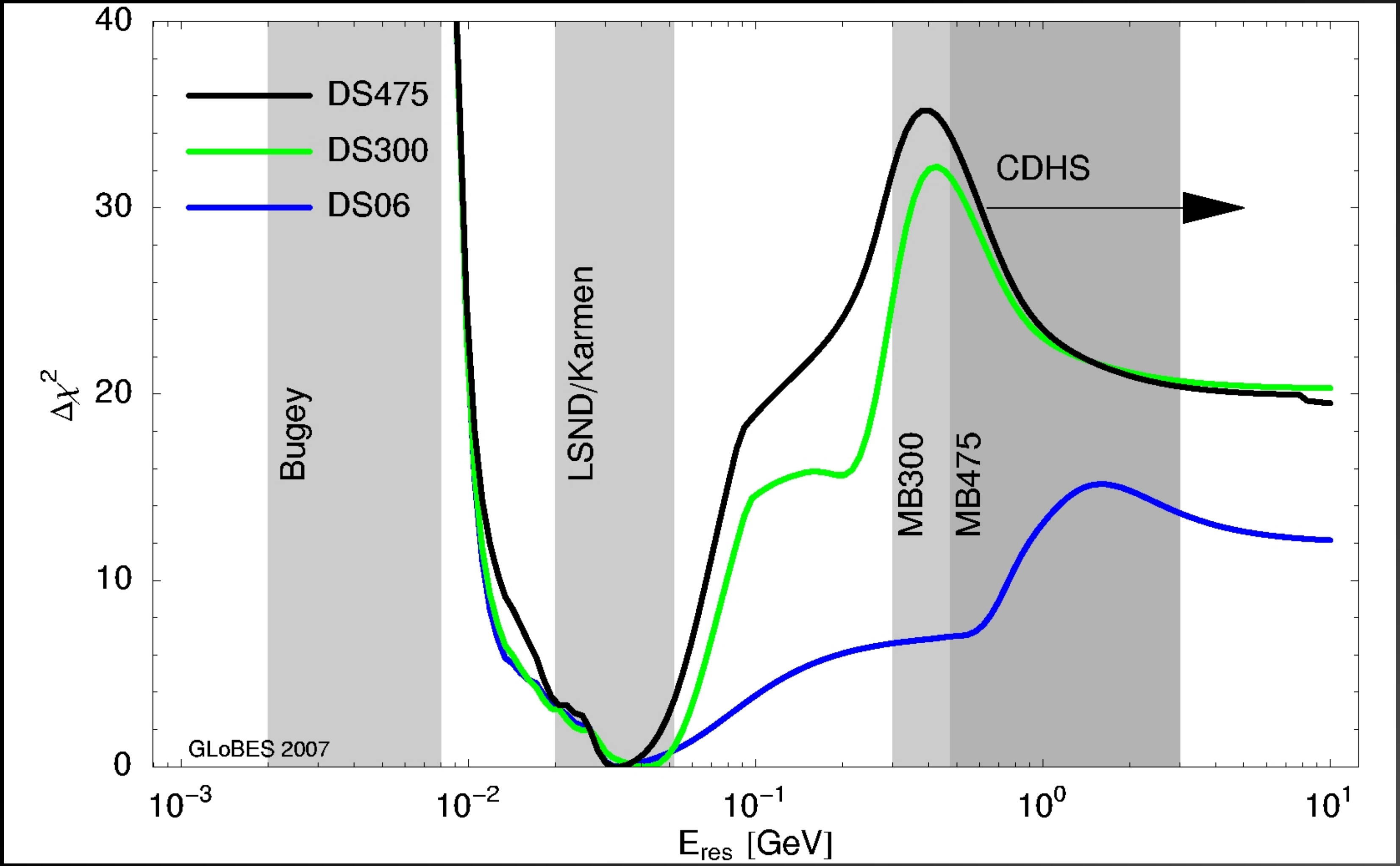
- Päs, Pakvasa, Weiler: 2-flavor approximation
- Barger, Huber, Learned, Marfatia, Päs, Pakvasa, Weiler: realistic 3+1 neutrino fits

standard $\nu$ oscillations vs $\nu$ shortcut scenario




(MiniBooNE $>$ 475 MeV, LSND, KARMEN, CDHS, BUGEY)

preliminary fit courtesy by Patrick Huber




fit courtesy by Patrick Huber

- best fit at $E_{\rm res} = 33$ MeV
- MiniBooNE low-E anomaly: local minimum in the $E_{\rm res} = 100 - 200$ MeV range

# MiniBooNE summary

Results of a 3-parameter fit: $\theta_{as}$, $\Delta m^2_{41}$, $E_{\rm res}$

- standard neutrino oscillations are disfavored at 4 $\sigma$ level
- sterile neutrinos with a modified dispersion relation (shortcuts) are compatible at the 1 $\sigma$ level with all data (both MiniBooNE $>$ 300 GeV and MiniBooNE $>$ 475 GeV)
- the best-fit resonance energy lies in the small energy range
- large $E_{\rm res}$ creates tension between
  - small active-sterile mixing $\longrightarrow$ suppressed LSND signal
  - large active-sterile mixing $\longrightarrow$ too much $\nu_e$ events in MiniBooNE high-E sample
- New data to come:
  - SciBooNE as a near detector
  - anti-neutrino data
  - detection of MINOS neutrinos
  - lower energy data $>$ 100 GeV
- If MiniBooNE low-E anomaly is confirmed with smaller error bars (work in progress):
  - switch on more mixing angles
  - introduce a second sterile neutrino (maybe KK mode) with small mixing $\longrightarrow$ large $E_{\rm res}$ and small contribution to LSND and high-E MiniBooNE

# Conclusions

- Bulk shortcuts can arise naturally in extra dimensional theories
- Bulk shortcuts affect neutrino mixing and imply a new resonance
  - Neutrino oscillations are suppressed for $E \gg E_{\rm res}$
  - LSND becomes compatible with BUGEY and CDHS ($E_{\rm CDHS} \gg E_{\rm res}$)
- Excellent (only?) fit to the World's neutrino data with 3 parameters: $\theta_{as}$, $\Delta m^2_{41}$, $E_{\rm res}$
  - More pronounced MiniBooNE low-E anomaly may require 2nd mixing angle or 2nd sterile neutrino
  - BBN and other cosmological bounds may be evaded
  - May explain Heidelberg-Moscow double beta decay claim?
  - Large signals expected in future MiniBooNE data (NEW DATA TO COME!), reactor, SNS, LENS experiments
- All simple realizations are causally stable but... if you are desparate to have a neutrino time machine I'll get you one