Neutrino oscillations and shortcuts in extra dimensions

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APS-DPF/JPS ’06
Honolulu HI, USA

Outline

- Neutrinos in extra dimensions
- Neutrino oscillations & LSND dilemma
- Bulk shortcuts, neutrino oscillations & LSND
- Neutrino bulk shortcuts:
  particle physics, astrophysics & cosmology

H. Päs, S. Pakvasa, T.J. Weiler: PRD 72 (2005) 095017 [hep-ph/0504096]

Large extra dimensions and neutrino masses

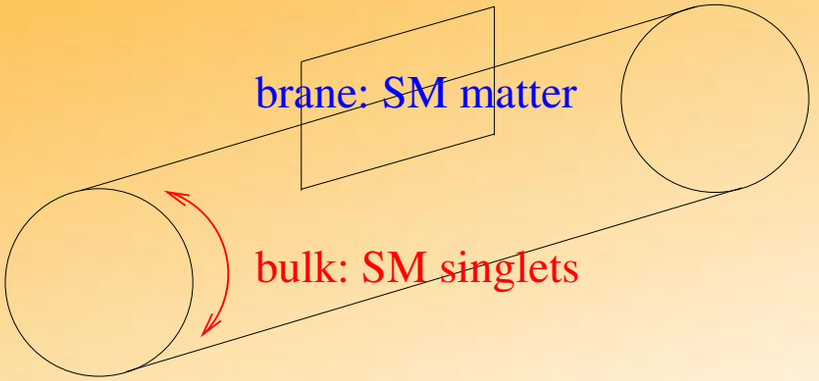
Typical feature of 5d models: Avoiding large gauge hierarchy by lowering the Planck scale

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

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

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

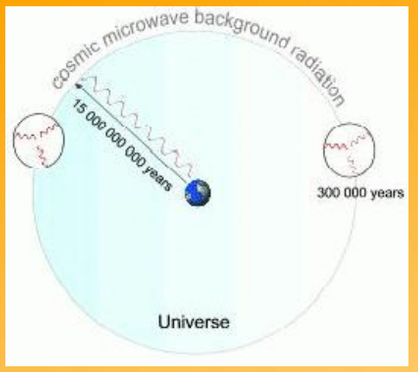
suppression factor: $M_{P\delta d}/M_{P4d}$



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

Bulk shortcuts and the horizon problem

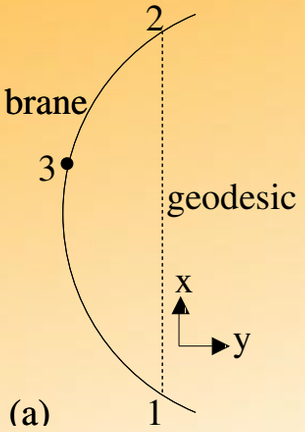
Standard cosmology: Universe homogenous over distances without causal contact (CMB)

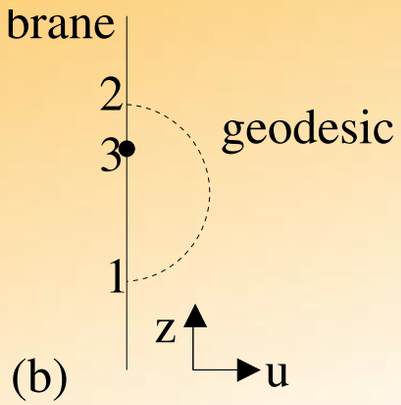


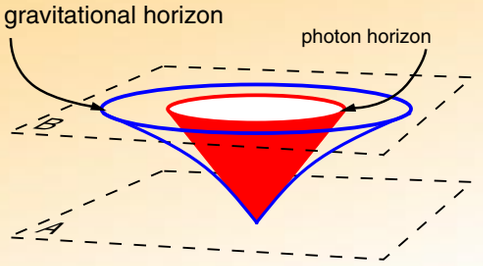
• Conventional solution: Inflationary epoch in the early universe:

$$R(t) \propto \exp(\sqrt{\Lambda/3}t)$$

• Alternative solution: graviton shortcuts in the extra dimension D.J.H. Chung & K. Freese, 1999; G. Kaelbermann & H. Halevi, 1998; R.R. Caldwell & D. Langlois, 2001



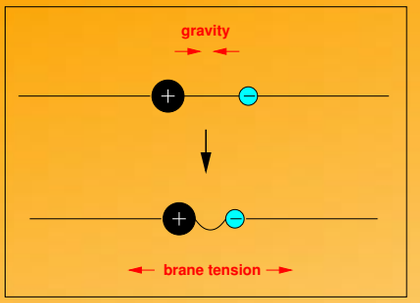




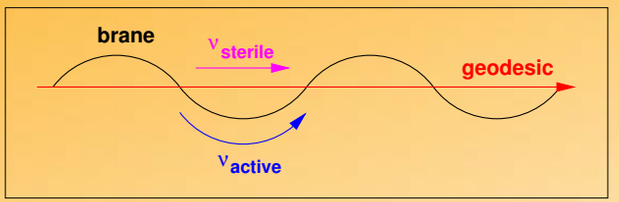
Bulk shortcuts and the horizon problem

3 mechanisms for bulk shortcuts:

- Gravitational self attraction due to brane matter → brane bending
  H. Ishihara, 2000



- Thermal or quantum fluctuations

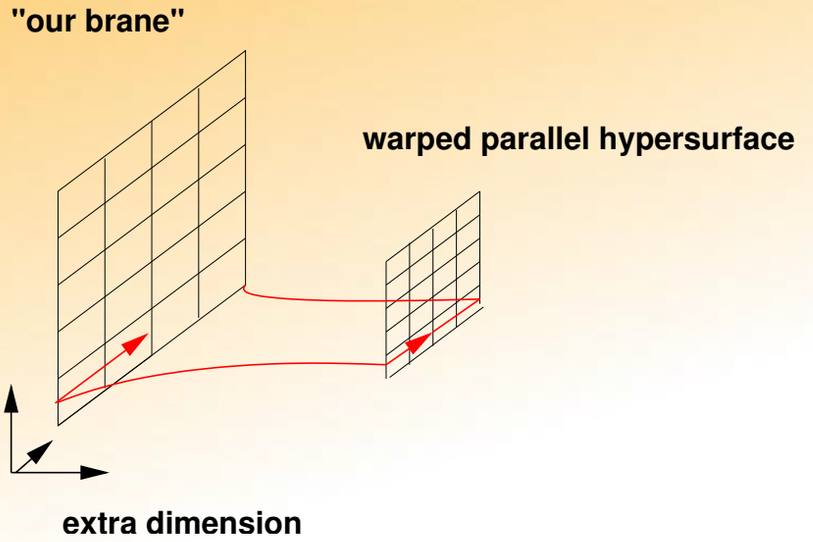


- Asymmetrical warped bulk dimension

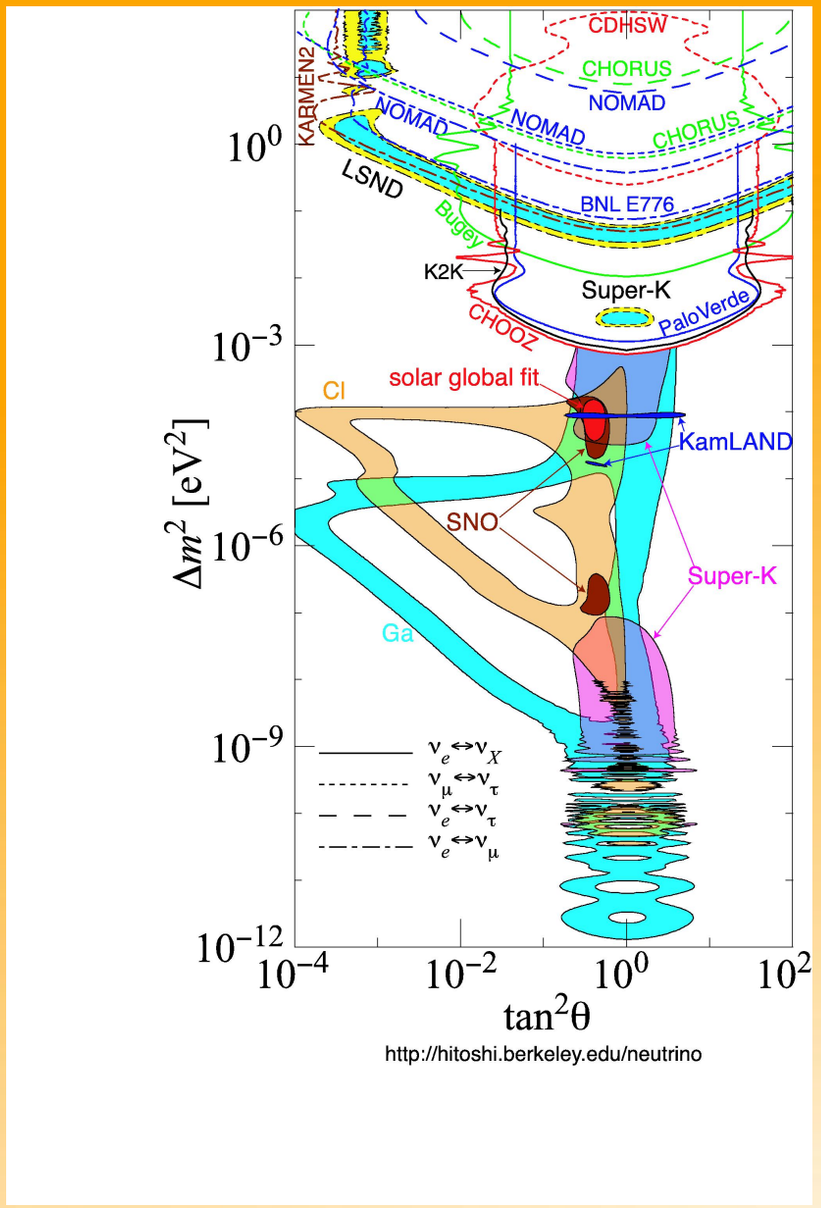
$$ds^2 = dt^2 - [e^{-2ku} a^2(t) d\mathrm{h}^2 + \mathrm{du}^2]$$

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

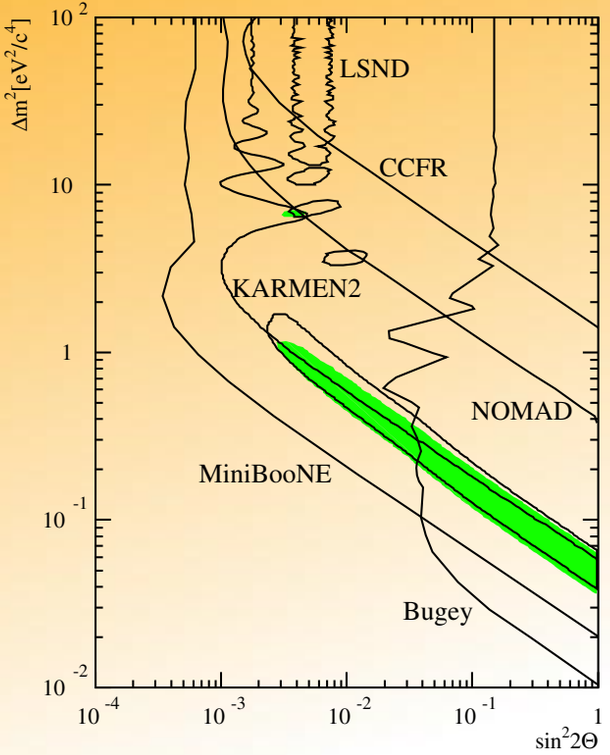
→ sterile neutrinos?



The LSND Dilemma

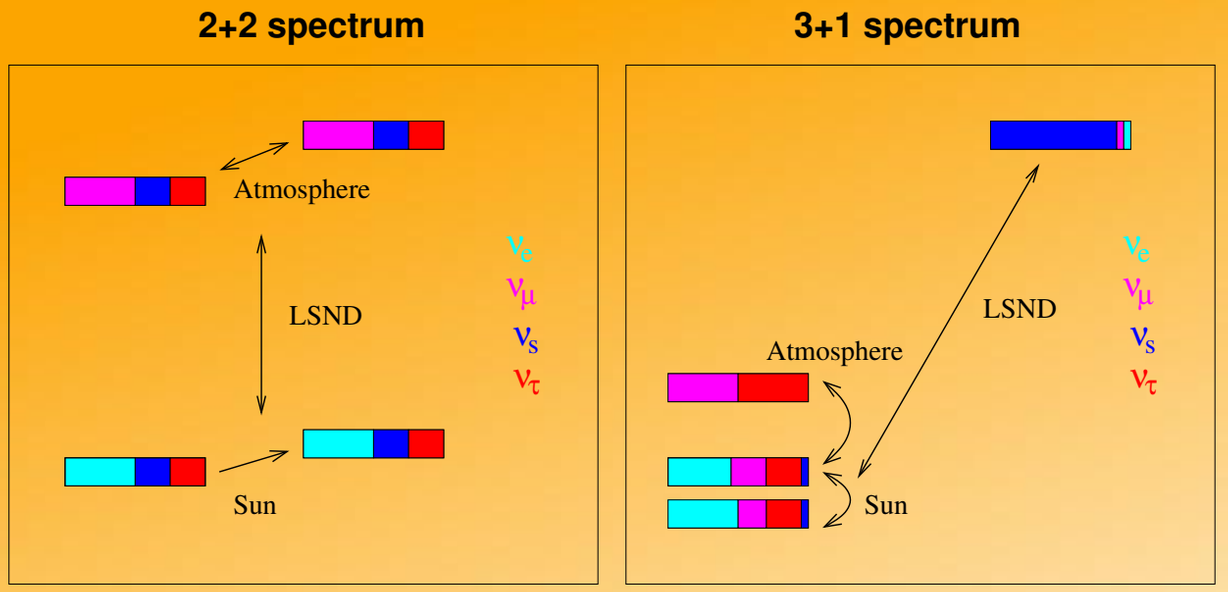


- 3 Δm^2's $\rightarrow$ 4 neutrinos!
- width of the Z-boson (LEP) $\rightarrow$ 3 neutrinos!
- $\rightarrow$ one sterile neutrino?
  (i.e. not coupling to the Z)



LSND and sterile Neutrinos

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 ν's into steriles $\rightarrow$ excluded!

3+1 spectrum: constraints from ν 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 $\rightarrow$ test at MinibooNE (2006)
- may hint towards deviations from the usual oscillation mechanism
- may be a messenger of the mechanism of neutrino mass generation!
- extra dimensions? bulk shortcuts?

Bulk shortcuts and neutrino oscillations

consider bulk shortcuts:

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

Bulk signal gains a time shift Δt

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

$\Delta S = \Delta \int H dt = H \Delta t \rightarrow \Delta H_{\rm eff} T$

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

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

Change in the Hamiltonian:

$\Rightarrow \Delta H_{\rm eff} = H \Delta t / T \rightarrow \epsilon E$

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 $E_{\rm res} = \sqrt{\frac{\delta m^2\,\cos 2\theta}{2\,\epsilon}}$

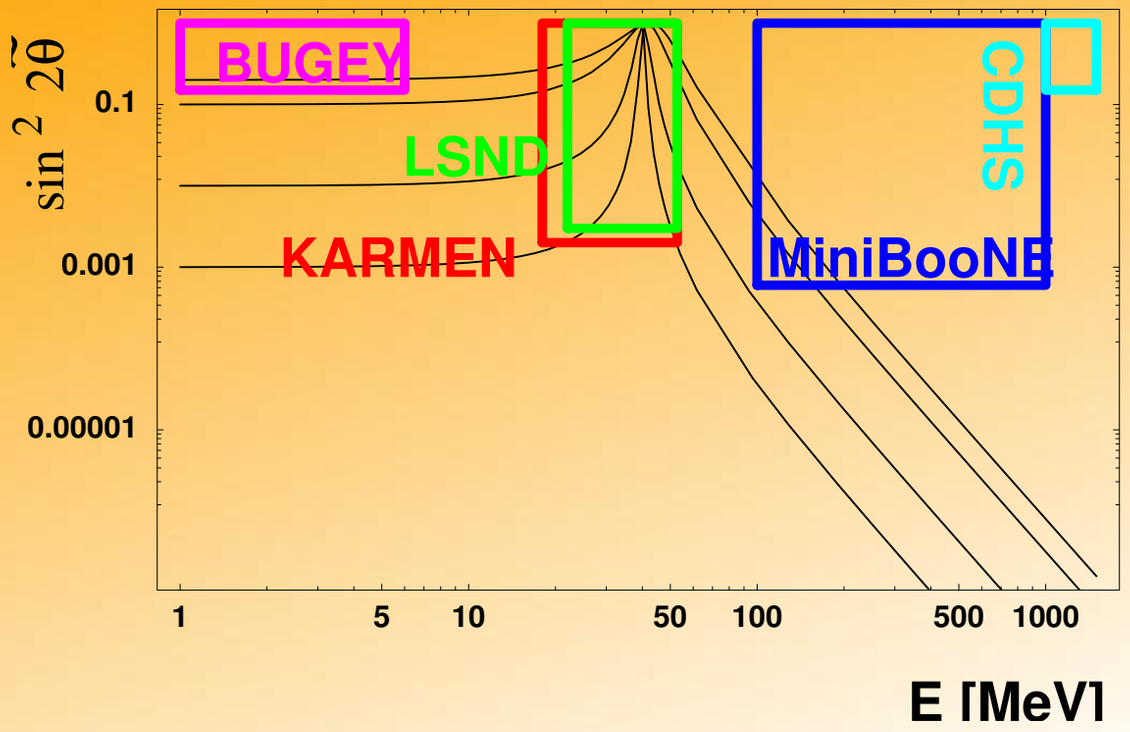
$\rightarrow$ choose $E_{\rm res} = 30 - 400$ MeV $\leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16}$

The active-sterile oscillation probability

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

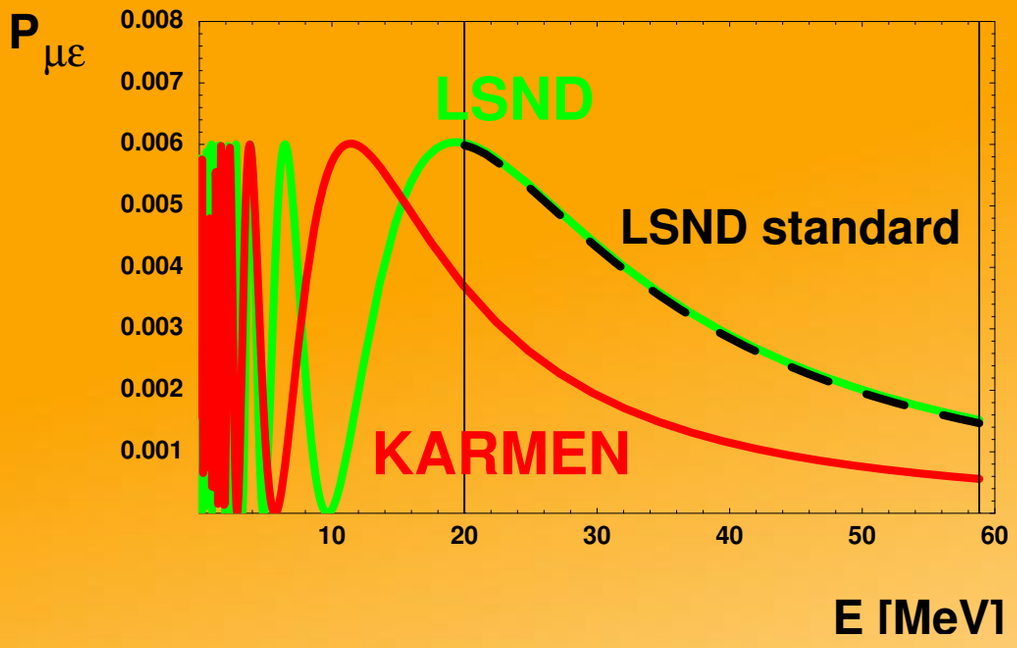
$$\sin^2 2\tilde{\theta} = \left[\frac{\sin^2 2\theta}{\sin^2 2\theta + \cos^2 2\theta (1-A)^2}\right] \qquad \delta H = \frac{\delta m^2}{2\,E}\sqrt{\cos^2 2\theta (1-A)^2 + \sin^2 2\theta}$$

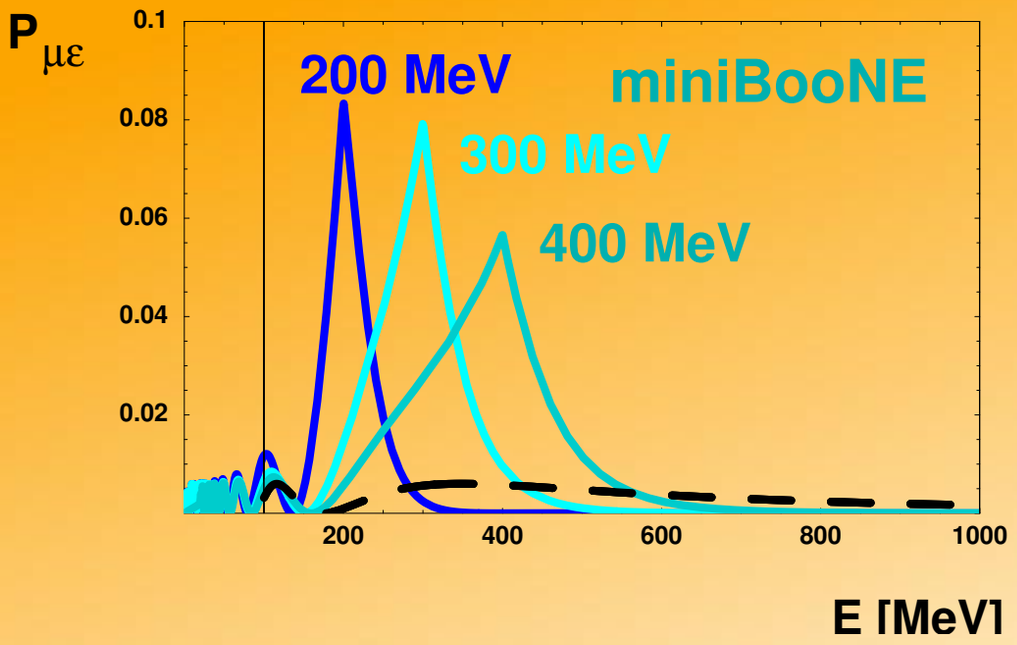
$$A = (E/E_{\rm res})^2$$



Oscillations at $E \gg E_{\rm res}$ (CDHS)are suppressed!
CDHS bound not valid anymore! 3+1 spectrum allowed again!

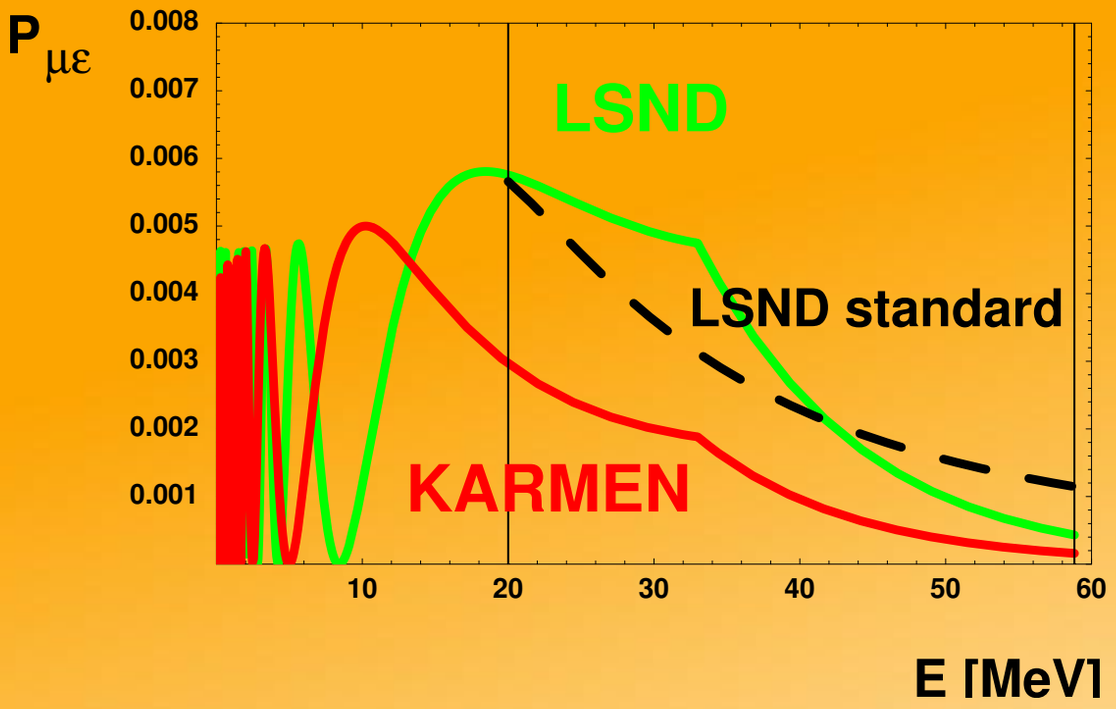
Scenario with high resonance energy

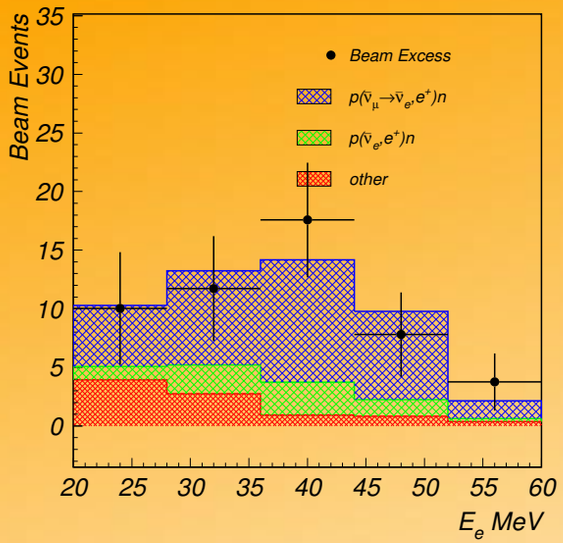




- $E_{\rm res} = 200$ MeV, 300 MeV, 400 MeV; $\sin^2\theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV^2
- good fit to LSND spectrum, $P_{\rm LSND} > P_{\rm KARMEN}$
- enhanced miniBooNE signal in the energy range 100-600 MeV
- strongly enhanced ν_μ disappearance at miniBooNE! (up to 90%!)

Scenario with low resonance energy

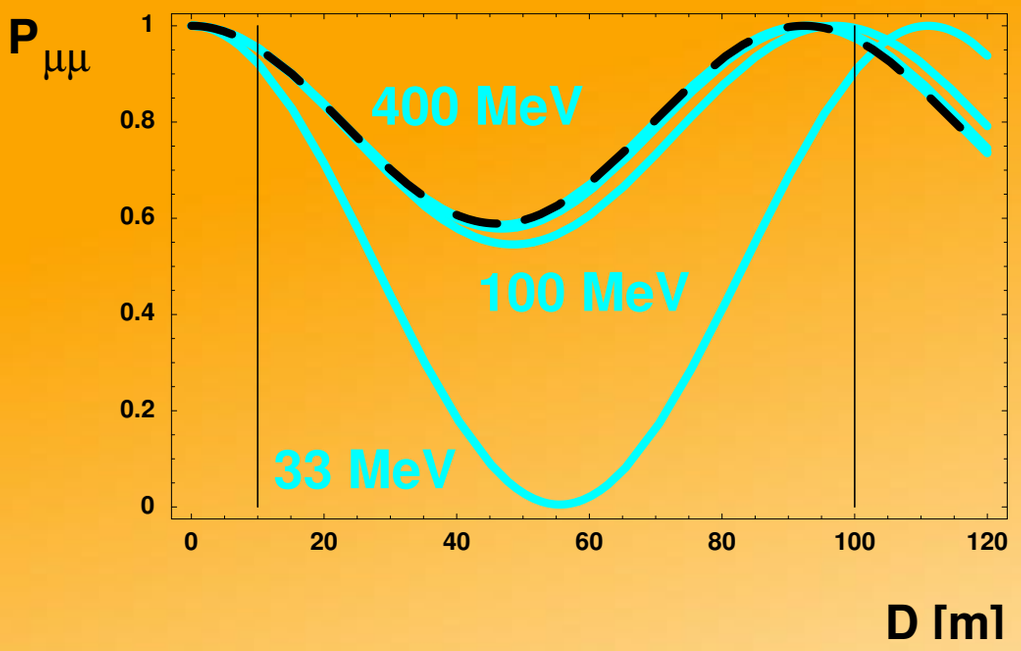




- $E_{\rm res} = 33$ MeV; $\sin^2\theta_* = 0.01$; $\sin^2 2\theta = 0.9$; $\delta m^2 = 0.7$ eV^2
- $P_{\rm LSND} > P_{\rm KARMEN}$

- good (better) fit of LSND spectrum
- no signal at miniBooNE!

Consequences for a stopped pion source at SNS



- Low energy ν_μ disappearance experiment proposed at the Spallation Neutron Source at Oak Ridge or at Fermilab proton driver
- $E_{\rm res} = 33$ MeV; $\sin^2\theta_* = 0.01$; $\sin^2 2\theta = 0.9$; $\delta m^2 = 0.7$ eV^2
- $E_{\rm res} = 100$ MeV, 200-400 MeV; $\sin^2\theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV^2
- strongly enhanced ν_μ disappearance signal

Big Bang Nucleosynthesis

Prediction of primordial abundances of light elements: major success of Big Bang Cosmology

Problem with sterile neutrinos:

ν oscillations populate extra species in early universe:

$$\boxed{\rho_{\nu_s} = \frac{7}{8}\rho_\gamma}$$

- $\rightarrow$ faster expansion of the universe
- $\rightarrow$ higher temperature for weak freezeout
- $\rightarrow$ more neutrons $\rightarrow$ larger ^{4}He abundance

Bulk shortcut scenario:

- higher density: larger brane buckle effect due to gravitational attraction
- higher temperature: more brane fluctuations
- higher density: more scattering off the brane in asymmetrically warped scenarios

All cases: larger $\epsilon \rightarrow$ smaller $E_{\rm res}$

If $E_{\rm res} \lesssim 3$ MeV: oscillations suppressed

Shortcut ν's & Astrophysics

LSND neutrino & dark matter

$\sqrt{\delta m^2_{\rm LSND}} \simeq 1$ eV^2 neutrino:

- erases structure on scales smaller than neutrino horizon
- problem with large scale structure & CMB data
- $\Rightarrow$ Again suppression of active-sterile mixing above $E_{\rm res}$ in the early universe can prevent sterile state from being populated!
- neutrino horizon $\neq$ photon horizon?

keV Warm Dark Matter: lots of nice features!

- Can the eV LSND neutrino be the keV WDM?
- $\delta m^2 \to \delta m^2 \sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta} \ll \delta m^2$?
- However: small $\sin^2 2\theta$ seems not to fit LSND spectrum

Shortcut ν's & Astrophysics

Supernova neutrinos

- Supernova cooling bounds can be avoided by choosing small brane curvature amplitude A and large frequency k without affecting $\epsilon \simeq (Ak/2)^2$
  $\rightarrow$ small compactification radius
  $\rightarrow$ KK states decouple
- Spectra: Bulk shortcut effects: the matter resonant conversion will be cut off above $E_{\rm res}$

Sterile neutrinos & the horizon problem

Are sterile neutrino shortcuts superior to graviton shortcuts?

- Bounds from precision experiments on gravitational square law do not apply
- Sterile neutrinos may couple more strongly (Homogenity problem)

Conclusions

- Bulk shortcuts may arise 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 ($E_{\rm CDHS} \gg E_{\rm res}$)
- $E_{\rm res} \gg 100$ MeV: enhanced oscillations at miniBooNE
- $E_{\rm res} < 100$ MeV: no signal at miniBooNE but distorted LSND spectrum and enhanced oscillations at SNS
- BBN bound may be evaded
- Open questions: BBN, R-process nucleosynthesis, atmospheric ν's, supernova ν's, realistic 3+1 ν fits, warm dark matter, horizon problem,...
- Existence of causality violations depends on exact realization, experimentally testable chronology violations possible, "Neutrino time machine?"
  Päs, Pakvasa, Weiler, gr-qc/0603045