Neutrino oscillations and shortcuts in the extra dimension

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Physics Colloquium, UH Manoa, April 2005

- Large extra dimensions: particle physics & cosmology
- Neutrinos in extra dimensions
- Neutrino oscillations & LSND dilemma
- Bulk shortcuts, neutrino oscillations & LSND
- Neutrino bulk shortcuts:
  particle physics, astrophysics & cosmology
- Neutrino wormholes: Tales of the Timeless

Work in Collaboration with S. Pakvasa (Hawaii) and T.J. Weiler (Vanderbilt)

- First ideas of extra dimensions: Theodor Kaluza (1921)

  and Oskar Klein (1926) 

- Fundamental ingredient of string theory: consistently formulated in a space-time with 10 or 11 dimensions
- Traditional picture: extra dimensions compatified with radii $\mathcal{O}(l_P) \sim 10^{-33}$ cm
- Large extra dimensions allowed, if observable world constrained on a 4-brane
  P. Horava, E. Witten, 1996

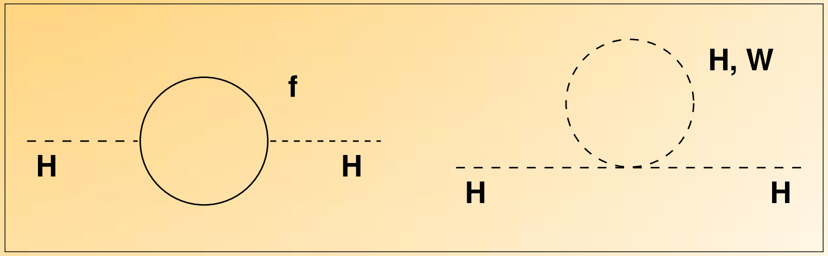
New light
on old problems
in particle physics & cosmology

Hierarchy problem: Why is $m_{EW} \ll M_P$ stable?

Loop corrections to the Higgs mass:

$$\delta m_H^2 = \mathcal{O}\left(\frac{g^2}{16\pi^2}\right) \cdot \int^{\Lambda} d^4k \frac{1}{k^2} = \mathcal{O}\left(\frac{\alpha}{\pi}\right) \Lambda^2 \gg m_H^2$$

for cutoff scale $\Lambda \simeq M_P \gg m_{EW} \simeq$ TeV



Large extra dimensions:

$4d$ Planck scale ($M_P = G_N^{-1/2} \sim 10^{19}$ GeV) $\gg$ fundamental $(4+\delta)d$ Planck scale M_*

Basic idea:

$$\vec{F}_{\rm EM} \propto r^{-2} \text{ in } 3d \leftrightarrow \vec{F}_{\rm grav} \propto r^{-(2+\delta)} \text{ in } (3+\delta)d$$

generalized Gauss law:

$$M_P^2 = M_*^{\delta+2} V_\delta$$

- V_δ: volume of δ-dimensional extra space
- $M_* \sim \mathcal{O}(m_{EW}) \to$ large scale M_P completely avoided

N. Arkhani-Hamed, S. Dimoloulos, G.R. Dvali, 1998; I. Antoniadis, N. Arkhani-Hamed, S. Dimoloulos, G.R. Dvali, 1999; L. Randall, R, Sundrum , 1999

Consequences of large extra dimensions

Gravity is increasing strongly at energies $> R^{-1}$

$R = \sqrt[\delta]{V}/2\pi$ compactification radius

$M_* \sim$ 1 TeV $\rightarrow R \simeq$ mm-fm for $\delta = 2-6$

Consequences:

- Kaluza-Klein States
  - Analogy: particle in a box, momenta of bulk fields are quantized
  - 4d perspective: tower of Kaluza-Klein excitations:
  - $\boxed{m_n^2 = \frac{n^2}{R^2}.}$
- TeV black hole production at the LHC!

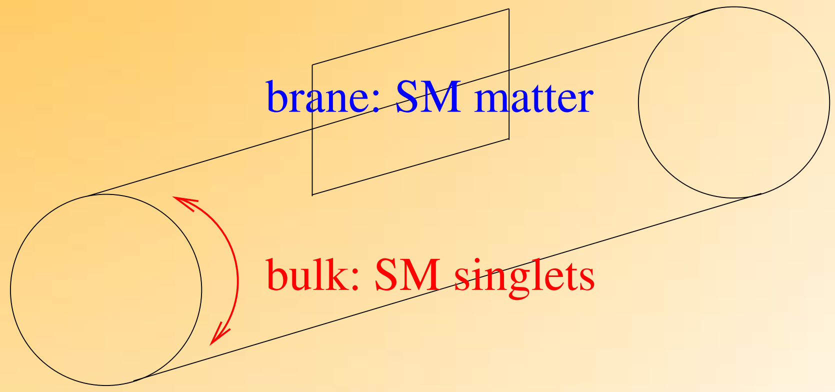
Large extra dimensions and neutrino masses

- 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) $\rightarrow$ ν_R

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

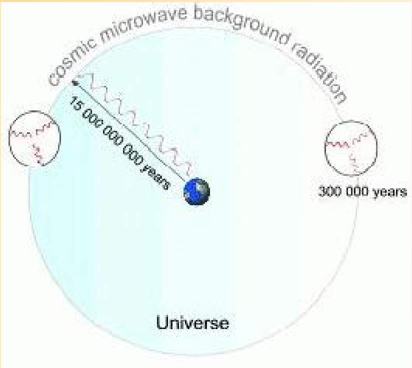
$$m^D = \frac{vY}{\sqrt{2V_\delta M_*^\delta}} = v\frac{Y}{\sqrt{2}}\frac{M_*}{M_P}$$

suppression factor: M_*/M_P



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

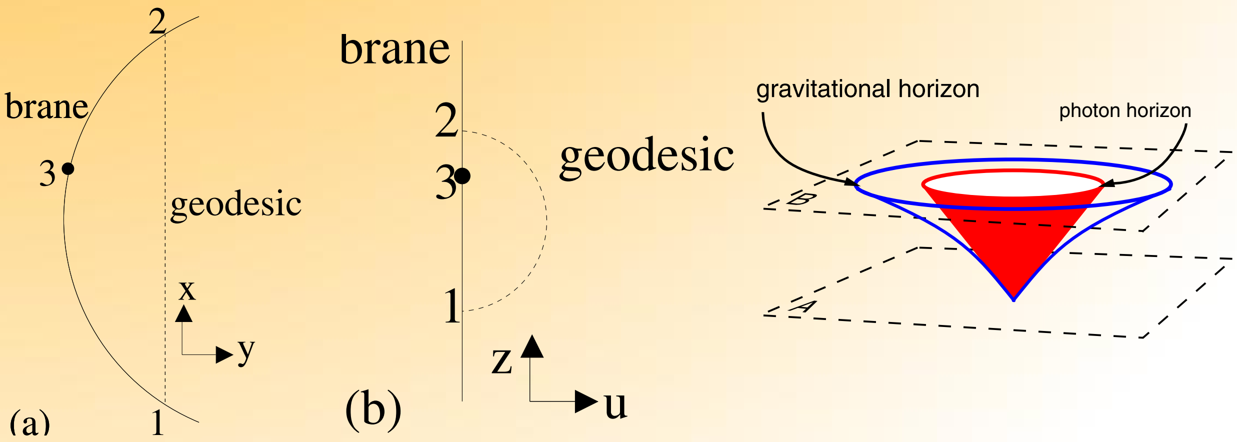
Standard cosmology: Universe homogenous over distances without causal contact (CMB)



- 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



What about

sterile neutrinos

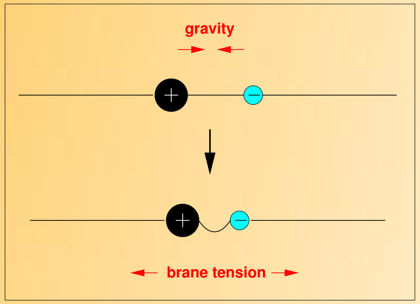
?

SHOrtBreak STERileS?

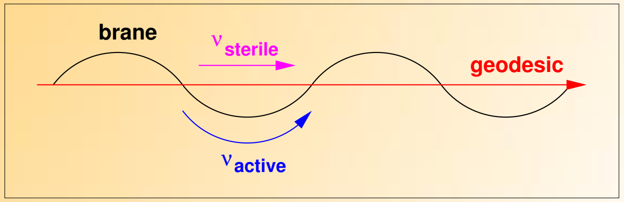
Microsoft: Impossible creatures

3 mechanisms for microscopical brane buckles:

- Gravitational attractions between brane bound systems

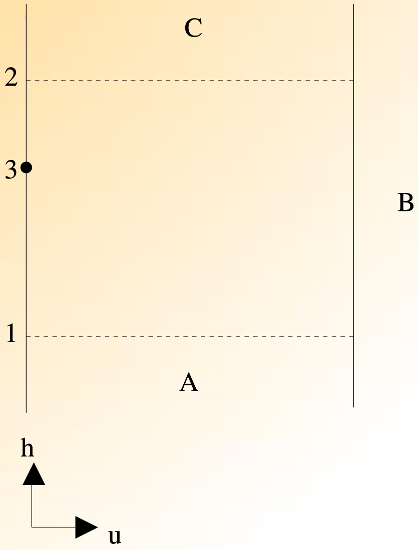


- Quantum fluctuations



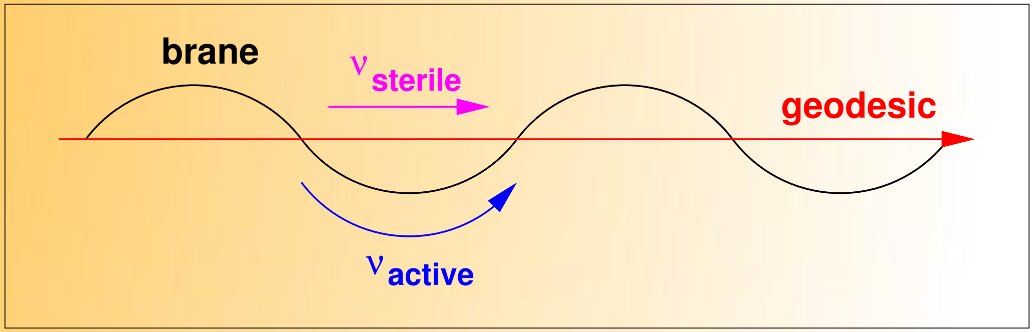
- Chung-Freese 2 brane system

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



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

A toy model:



1+2 d Minkowski spacetime: $ds^2 = dt^2 - dx^2 - dy^2$

Periodic brane: $y = \sin kx$

coordinate transformation $(x, y) \to (u, z)$ straight brane:

$u = y - \sin kx$ and $z = \int \sqrt{1 + k^2 \cos^2 kx}\, dx$

$\to (uz)$-line element: $ds^2 = dt^2 - dz^2 - du^2 - \frac{2 \cos kx(z)}{\sqrt{1+k^2 \cos^2 kx(z)}}\, du\, dz$

γ moving along the brane ((u, z) system): $z_b = t_f$

ν_s bulk geodesic ((x, y) system): $y_g = 0, \quad x_g = t \quad \Rightarrow$

$$u_g = -\sin(kt), \qquad z_g = \int_0^{t_f} \sqrt{1 + k^2 \cos^2 kt}\, dt = \frac{\sqrt{(1+k^2)}}{k} \mathcal{E}\left(kt_f, \sqrt{\frac{k^2}{1+k^2}}\right)$$

$$\boxed{z_g > z_b}$$

Ratio of travel times: $\epsilon = 1 - \frac{k\ t_f}{\sqrt{(1+k^2)}\mathcal{E}\left(k\ t_f, \sqrt{\frac{k^2}{1+k^2}}\right)}$

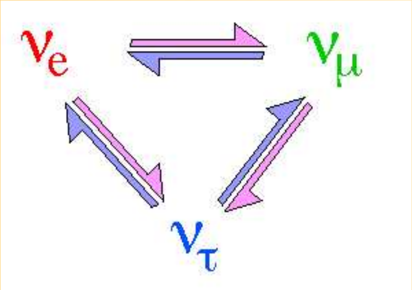
Toy metric allows for apparent superluminal propagation!

How do bulk shortcuts affect neutrino oscillations ?

Quantum mechanics: A system is situated in the coherent superposition of all possible states

- Cats are simultaneously dead and alive
- Neutrinos are simultaneously in different eigenstates

Solar neutrinos
Atmospheric neutrinos
LSND $\Rightarrow$



2 conditions:

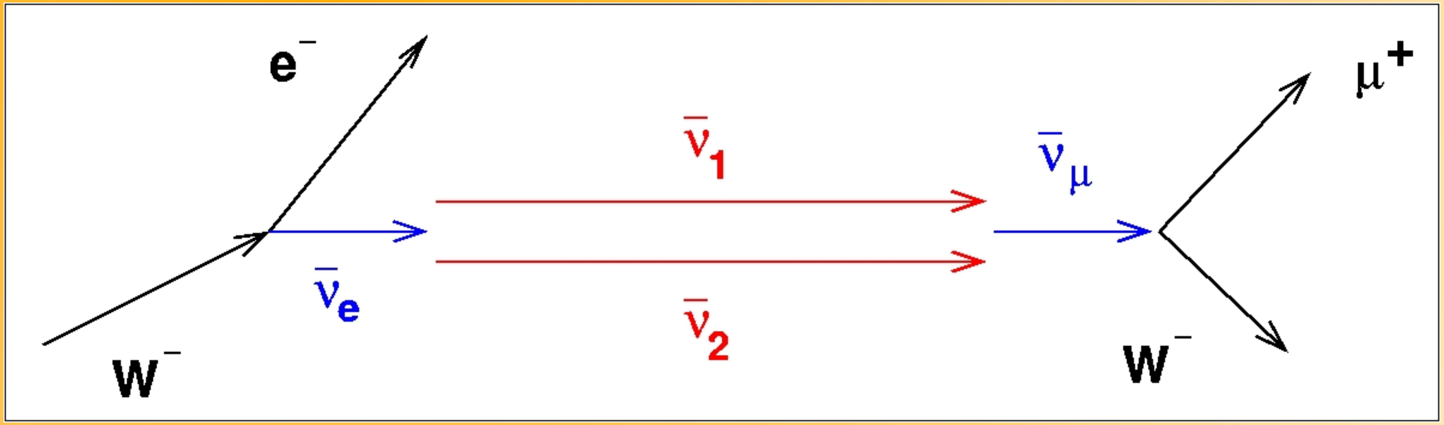
- Neutrinos possess mass
- Masse eigenstates $\neq$ Flavor eigenstates

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_i\rangle$$

2 states system:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \qquad |\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$



Defined energy $\Rightarrow p_i = \sqrt{E^2 + m_i^2} \simeq E - \frac{m_i^2}{2E} \quad (m_i \ll E)$

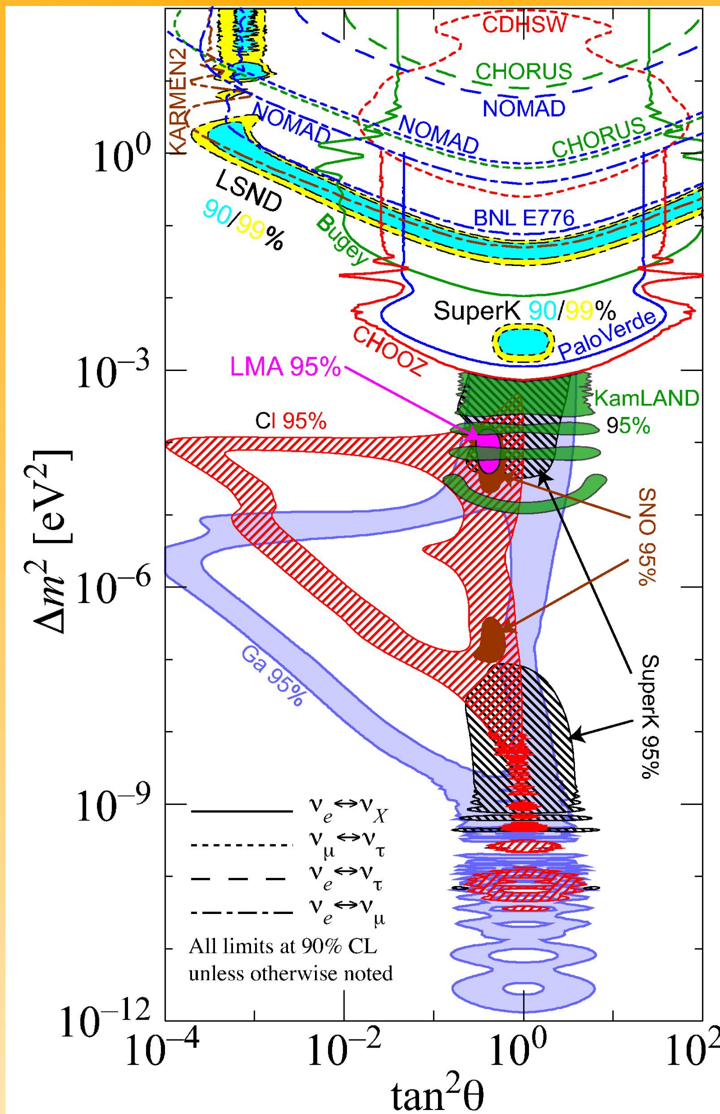
$$|\nu_e(t)\rangle = e^{-iEt+ip_iL}|\nu_e(0)\rangle \qquad (t \simeq L)$$

$$|\nu_e(t)\rangle = \sum_i U_{ei} e^{i\frac{m_i^2}{2E}L}|\nu_i\rangle$$

$$P(\nu_e \to \nu_\mu) = |\langle\nu_\mu|\nu_e\rangle|^2 = |\sum_i U^*_{\mu i} e^{i\frac{m_i^2}{2E}L} U^2_{ei}|^2$$

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2 \frac{L}{4E}), \qquad \Delta m^2 = m_2^2 - m_1^2$$

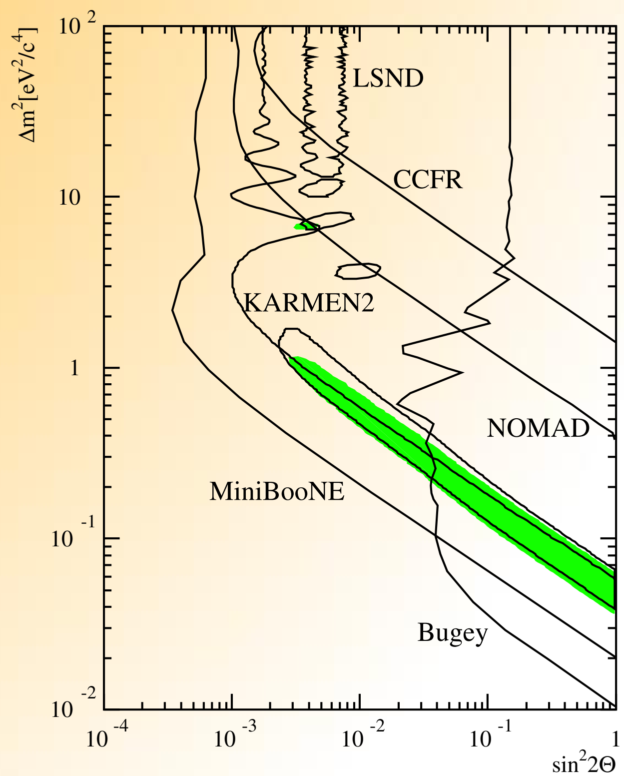
The LSND Dilemma



- 3 Δm^2's → 4 neutrinos!

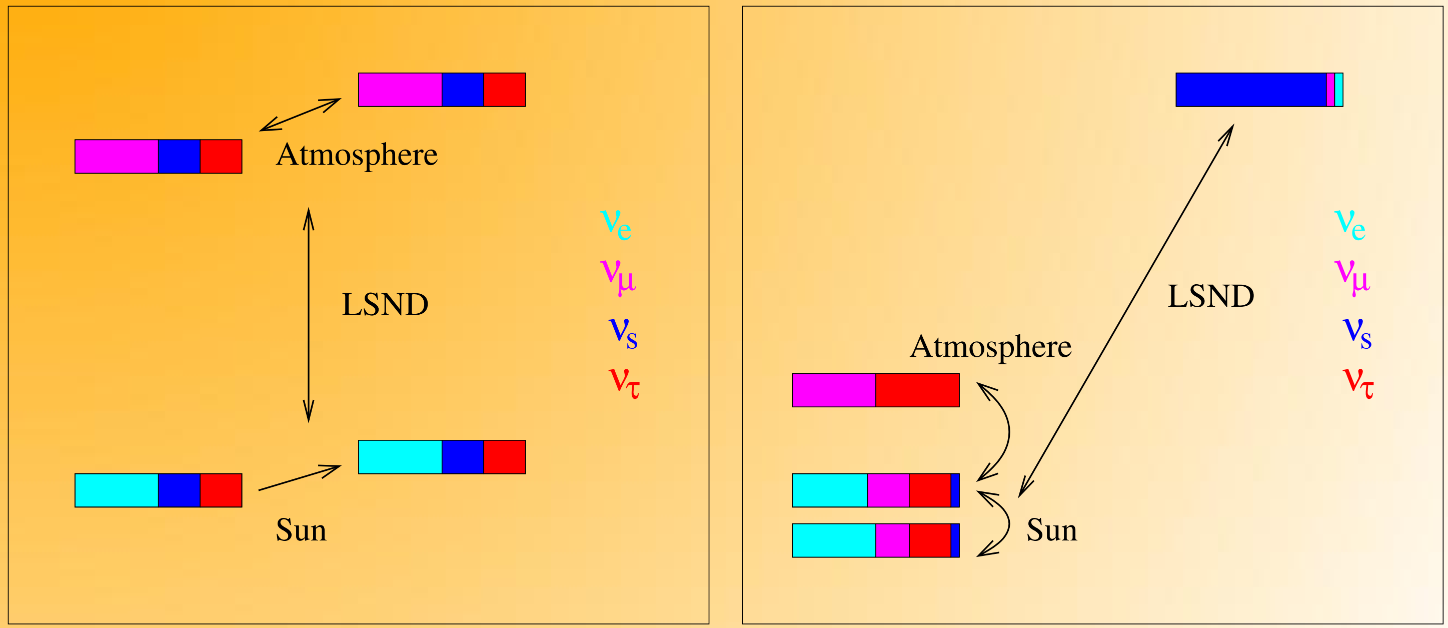
- width of the Z-boson (LEP) → 3 neutrinos!

- → one sterile neutrino? (i.e. not coupling to the Z)



LSND and sterile Neutrinos

2+2 spectrum **3+1 spectrum**



2+2 spectrum:

no oscillations of solar or atmospheric ν's into steriles!

3+1 spectrum:

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

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

LSND: $\sin^2 2\theta_{\mathrm{LSND}} = 4U_{e4}^2 U_{\mu 4}^2$

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

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

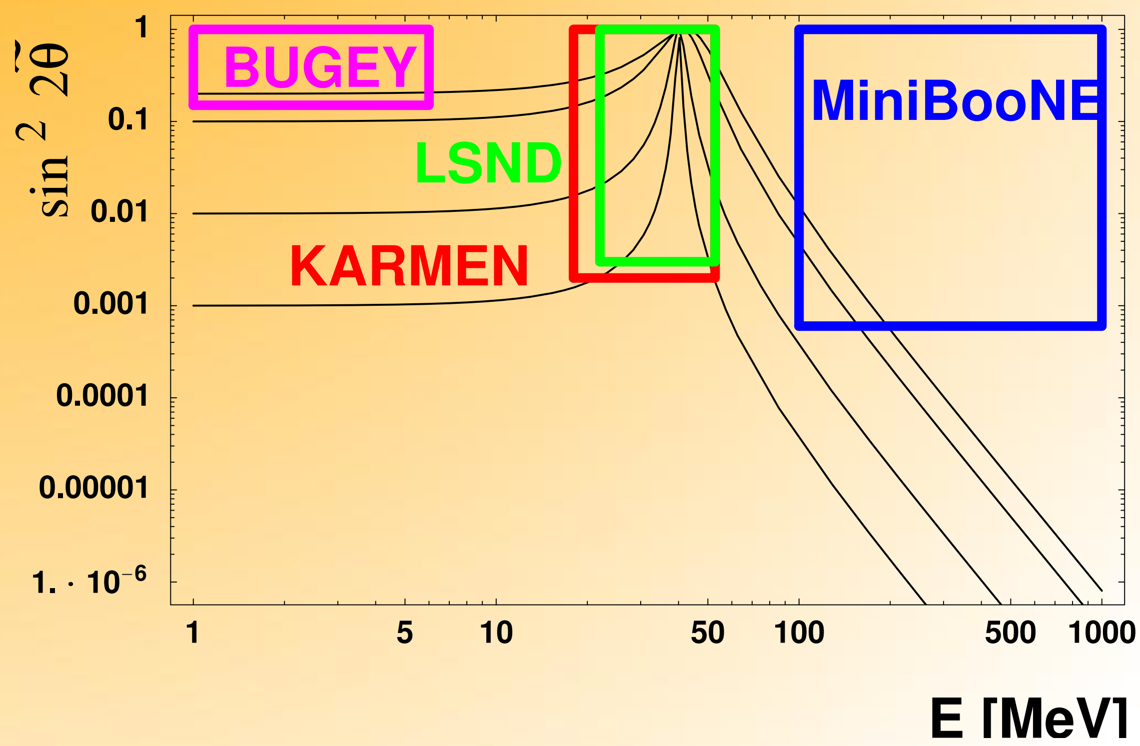
$\rightarrow$ choose $E_{\rm res} = 60 - 500$ MeV $\leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16}$

The active-sterile oscillation probability

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

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

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



Oscillations at $E \gg E_{\rm res}$ are suppressed!

Active-sterile neutrino mixing:

$$|\nu_a >= \cos\theta_* |\nu_\mu > + \sin\theta_* |\nu_e >$$

BUGEY bound ($E_\nu \simeq$ (few) MeV $\ll E_{\text{res}}$):

$$\boxed{\sin^2 2\theta_{e\not e} \simeq 4\, \sin^2\theta\, \sin^2\theta_*}$$

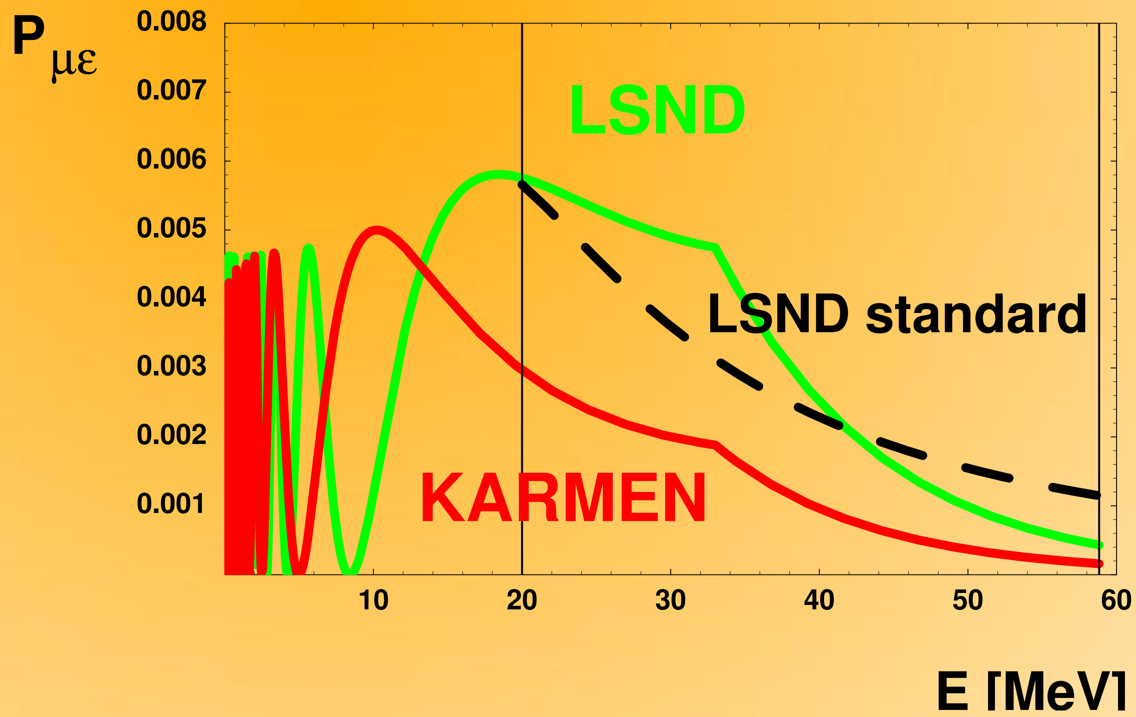
LSND & KARMEN ($E_\nu = 20 - 58.82$ MeV):

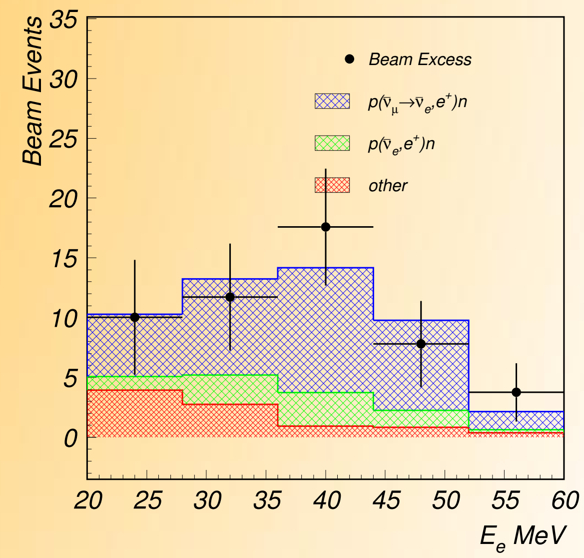
$$\boxed{\sin^2 2\tilde{\theta}_{\text{LSND}} = \frac{1}{4} \sin^2 2\theta_* (1 \mp \cos 2\tilde{\theta})^2}$$

CDHS bound ($E_\nu > 1$ GeV $\gg E_{\text{res}}$):

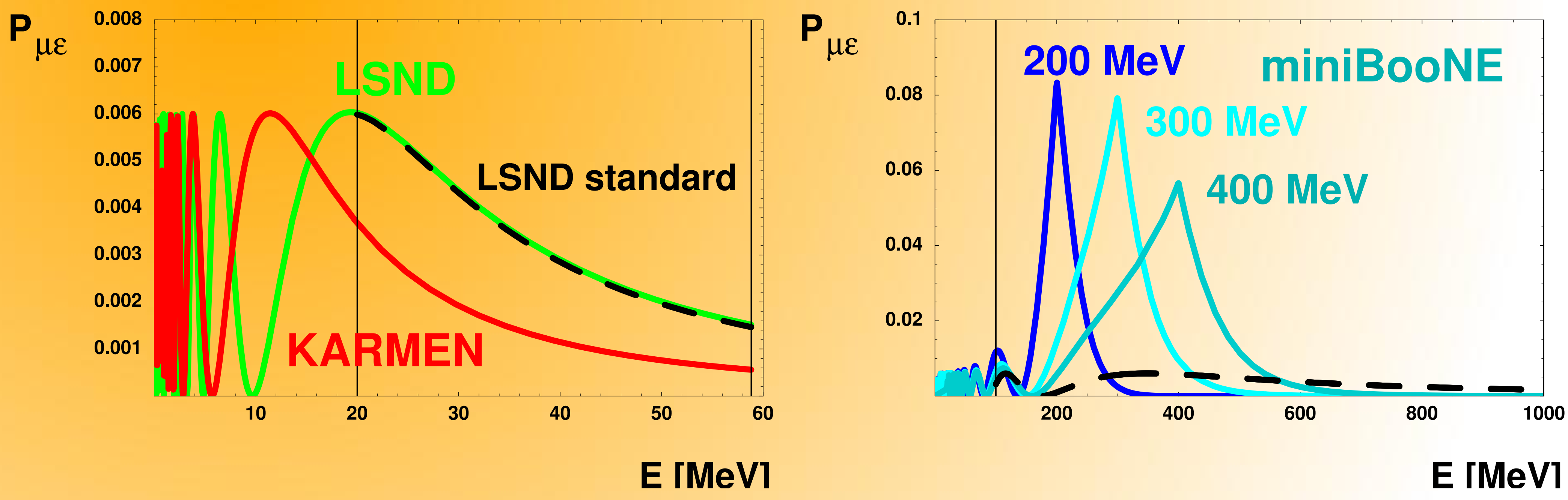
$$\boxed{\sin^2 \tilde{\theta}_{\mu\not\mu} \simeq \cos^2\theta_* \sin^2 2\theta \left(\frac{E}{E_{\text{res}}}\right)^{-4}}$$

The CDHS bound is suppressed by its large 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!



- $E_{\rm res} = 200$ 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

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:

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

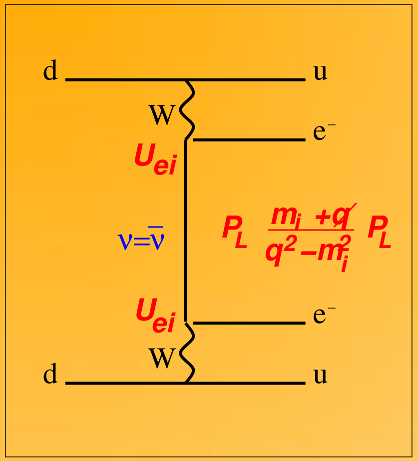
- $\rightarrow$ faster expansion of the universe
- $\rightarrow$ higher temperature for weak freezeout
- $\rightarrow$ more neutrons $\rightarrow$ larger ^4He abundance

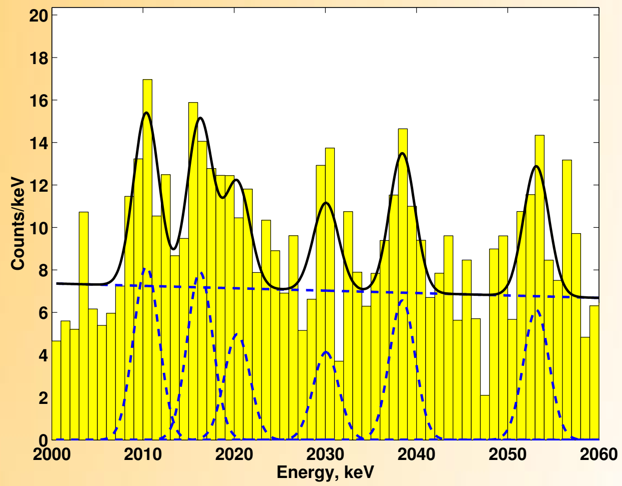
Bulk shortcut scenario:

- higher density: larger brane buckle effect due to gravitational attraction
- higher temperature: more quantum fluctuations
- higher density: more scattering off the brane in Chung-Freese scenario

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

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





$$\Gamma_{0\nu\beta\beta} \propto |m_{ee}|^2 = |\tilde{U}_{e4}^2 \tilde{m}_4 + \sum_{j=1,3} \tilde{U}_{ej}^2\, m_j|^2$$

$m_{ee} = 0.1 - 0.9$ eV? (Klapdor-Kleingrothaus, Krivosheina, Dietz, Chkvorets 2004)

- $p_\nu \sim p_F \sim \mathcal{O}(100)$ MeV
- $p_\nu \sim E_{\text{res}} \Rightarrow \tilde{U}_{e4}$ may become large!
- large signals for $0\nu\beta\beta$ decay!

Tritium β decay ($E_\nu \simeq \mathcal{O}$(MeV)): no enhancement

- r-process nucleosynthesis:

  rapid capture of neutrons on iron-sized seed nuclei:
  prime candidate for the synthesis of nuclei heavier than iron

- prevented from $\boxed{\nu_e n \to pe} \to \alpha$ particles

- $\nu_e n \to pe$ can be suppressed sufficiently by strong $\boxed{\nu_e \to \nu_s}$ oscillations

  G.M. Fuller, 1999

- Bulk shortcut effects: the matter resonant conversion will be cut off above $E_{\rm res}$

LSND neutrino & keV warm dark matter

WDM solves:

- cuspy core problem of cold dark matter
  S.Dodelson, L. Widrow, 1993; X.d. Shi, G.M. Fuller, 1998
- induce observed velocities of radio pulsars
  G.M. Fuller, A. Kusenko, I. Mocioiu, S. Pascoli, 2003

$\delta m^2 \to \delta m^2 \sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta} \ll \delta m^2$?

However: small $\sin^2 2\theta$ seems not to fit LSND spectrum

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 (Homogeinity problem)

If

sterile neutrinos

propagate with superluminal velocity...

possibility of time travel?

Can sterile neutrino shortcuts be interpreted as Wormholes?

“Psycho-ceramics warning: Crackpots are politely requested to refrain from reading this paragraph”
(Matt Visser, Lorentzian Wormholes)

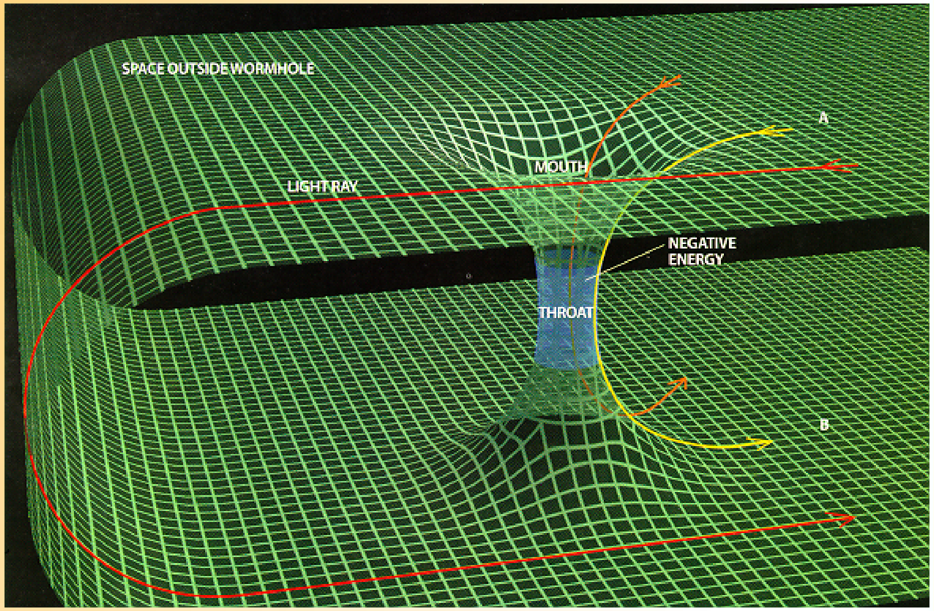
sorry, Matt....

Matt Visser's 3 steps

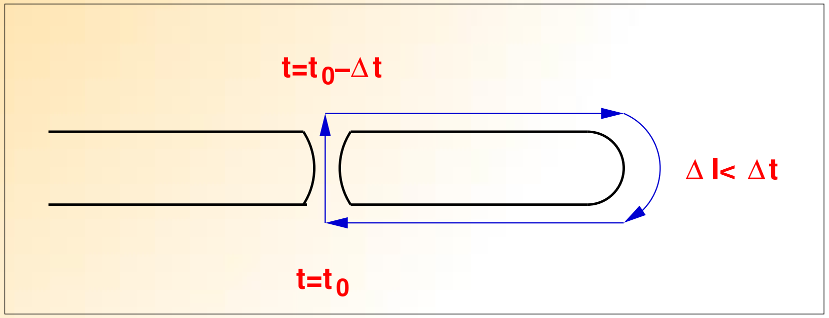
1. Find a wormhole
("recipe for dragon stew")

T. Roman, Scientific American

2. Introduce a time-shift



3. Bring the mouths together



Morris, Thorne, Yurtserver, PRL 61 (1988) 1446

Time machine proposals

- Gödels rotating universe (1949)
- Van Stockums and Tiplers rotating cylinders (1937 & 1974)
- Gott's pair of moving cosmic strings (1991)
- Wheelers space time foam (1962)
- Kerr and Newman geometries (1973)
- Alcubierres warp drive (1994)

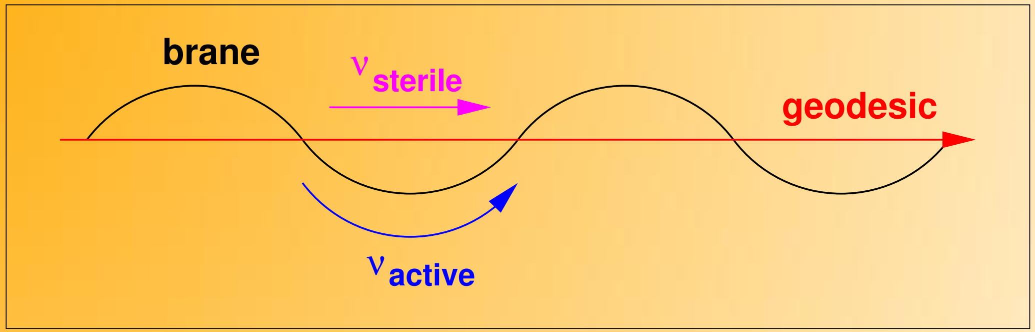
Obstacles:

- exotic energy violating the energy conditions $\longrightarrow$ strong curvature
- unphysically fast rotation $\longrightarrow$ tipping Lorentz cones

"The Time Keepers were born at the end of time, entrusted with the safety of Time by He Who Remains. The Time Keepers were meant to watch over the space time continuum just outside of Limbo, and make sure the universe thrived." Marvel Comics

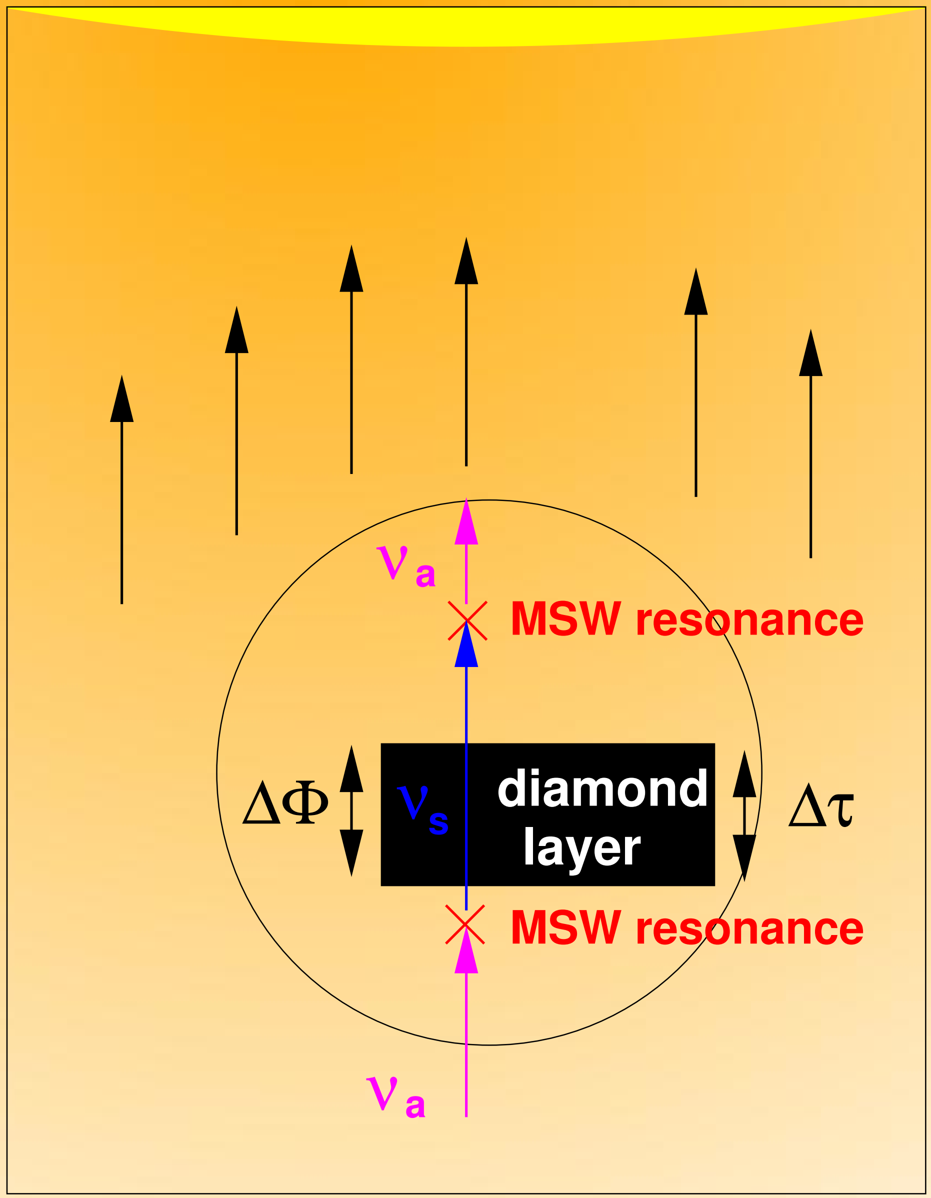
"It seems that there is a chronology protection agency which prevents the appearance of closed time-like curves and so makes the universe safe for historians."
S.W. Hawking, The chronology protection conjecture, Phys. Rev. D 46 (1992) 603-611

Lenny Susskind: *"Wormholes and time travel? Not likely." (gr-qc/0503097)*



Sterile neutrino shortcuts
allow wormhole-like paths
to points with space-like distance
without rotation or strong curvature!

Sterile neutrino physics may allow
and superluminal communication or back-in-time travel
or studies of physics near the chronology horizon!



M. Kuchner, S. Seager, Aspen 2005

$\Delta\tau$ can be of oder seconds!

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 ($E \gg E_{\rm res}$)
- $E_{\rm res} < 100$ MeV: no signal at miniBooNE
- $E_{\rm res} \gg 100$ MeV: enhanced oscillations at miniBooNE
- BBN bound can be evaded
- Neutrinoless double beta decay may be enhanced
- Supernova ν's: $E_{\rm res}$ cutoff for MSW effect
- Dark matter, horizon problem, time travel...