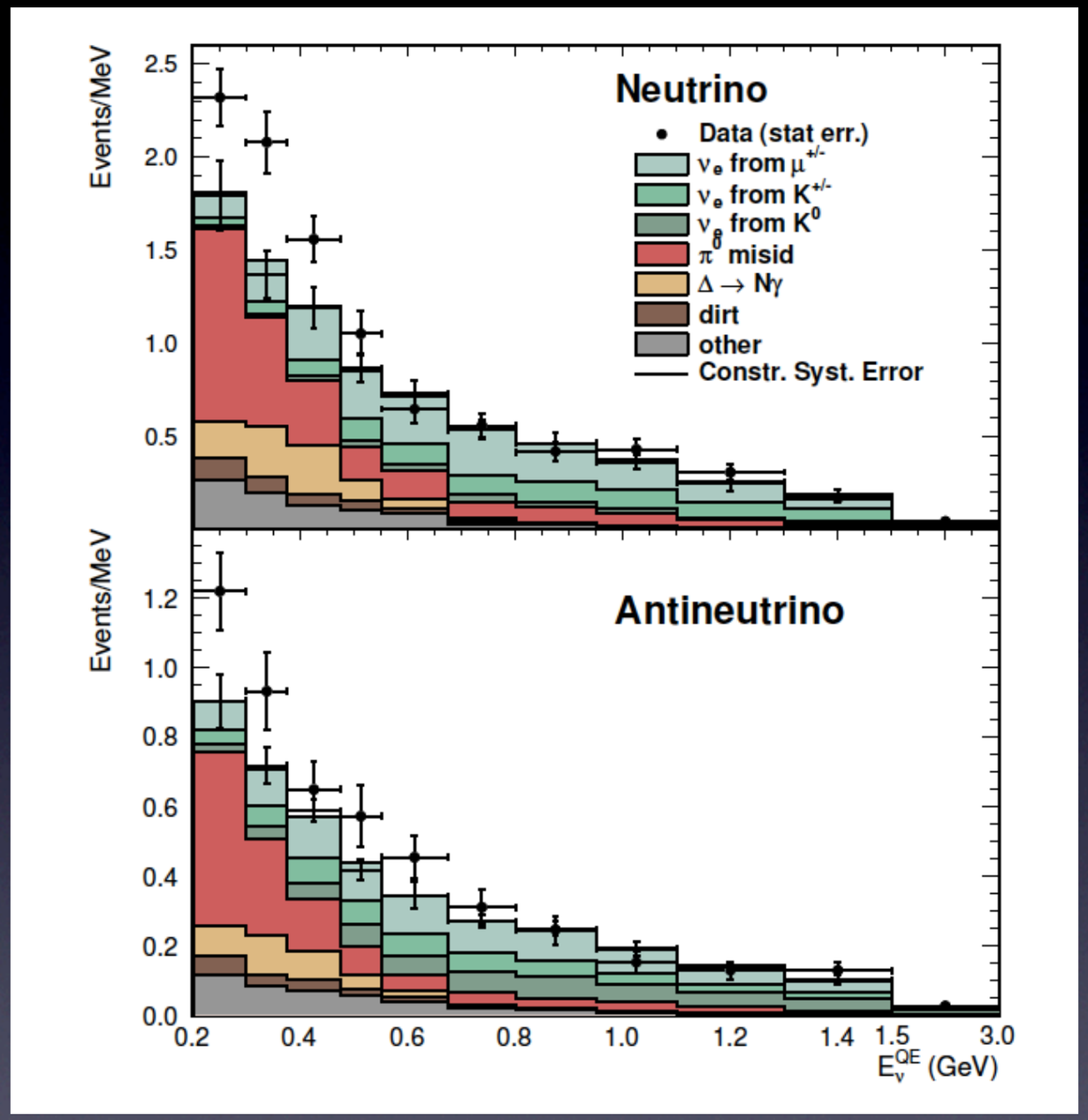
Sterile neutrino oscillations with altered dispersion relations

- Heinrich Päs -
tu dortmund

FLASY 2016, Valparaiso

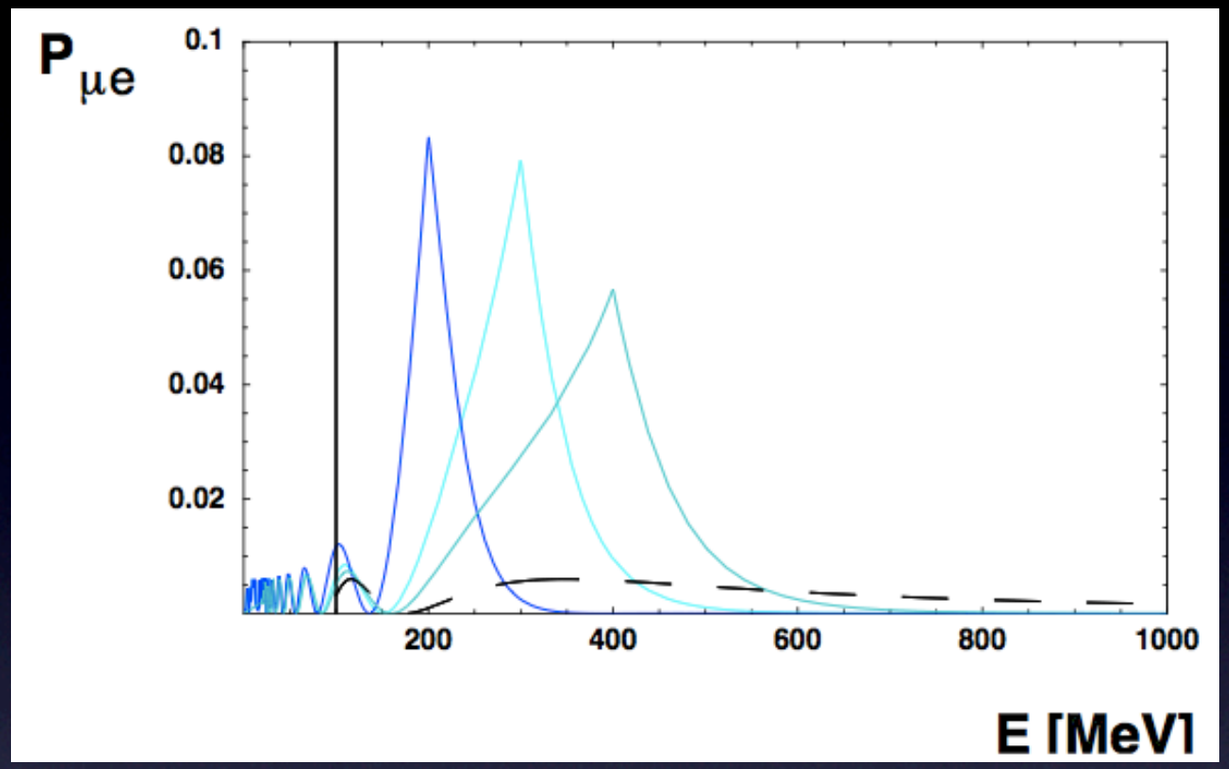
Amo, Valparaiso, cuanto encierras
y cuanto irradias, novia del océano,
hasta más lejos que tu nimbo sordo....
Pablo Neruda

What is this talk about ?



LSND and MiniBooNE oscillation searches

[Conrad, Louis, Shaevitz, 2013]



"Sterile-active neutrino oscillations and shortcuts in the extra dimension"

[HP, Pakvasa, Weiler, 2005]

What is this talk about ?

A very simple idea:

$$E = p + m^2/2E + \textit{new terms}$$

A 4th sterile neutrino ?

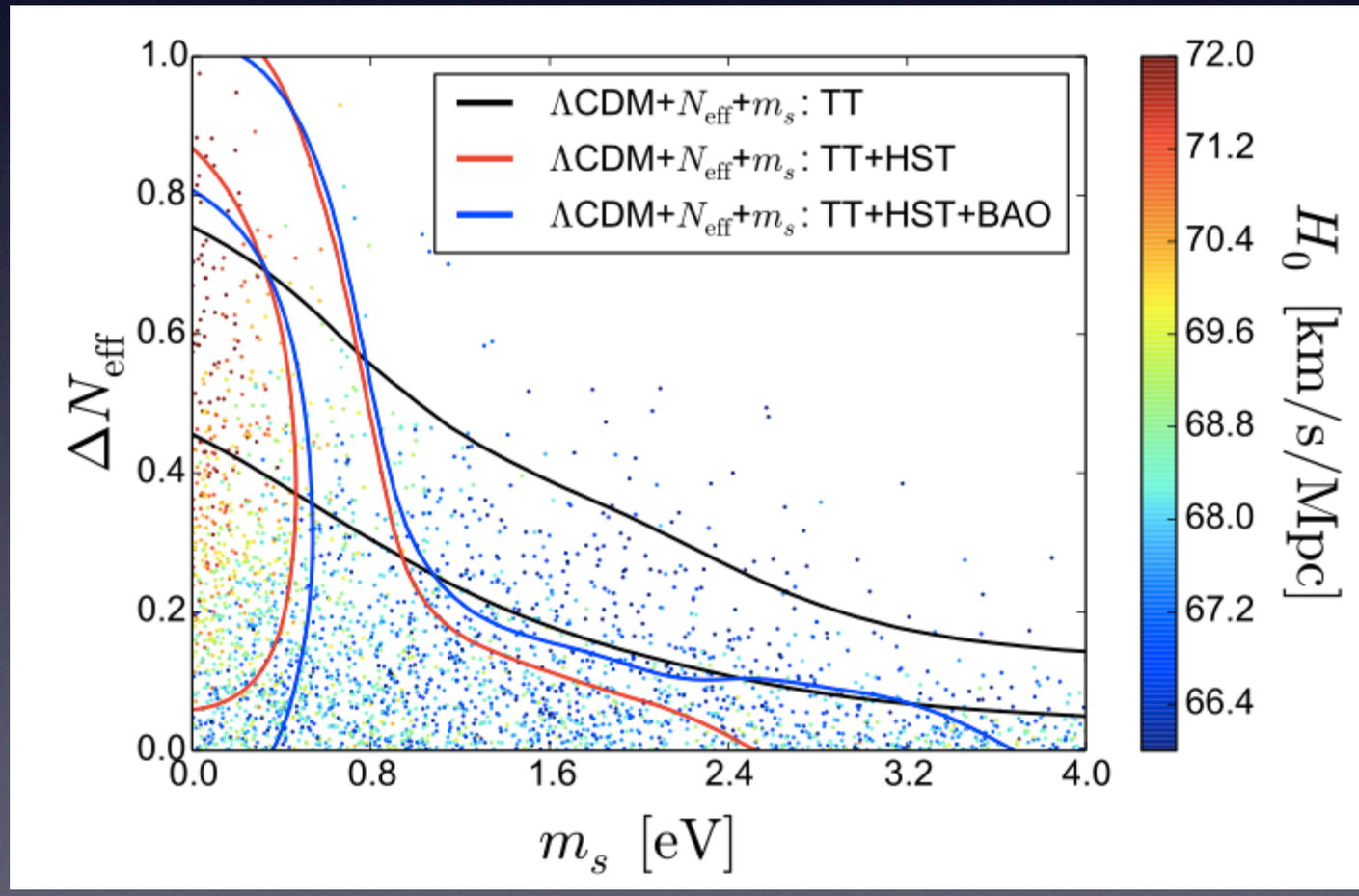
A handful of anomalies with 3-4 σ:

- LSND
- MiniBooNE
- Reactor anomaly
- Gallium anomaly

→ 4th light neutrino with eV-range mass ?

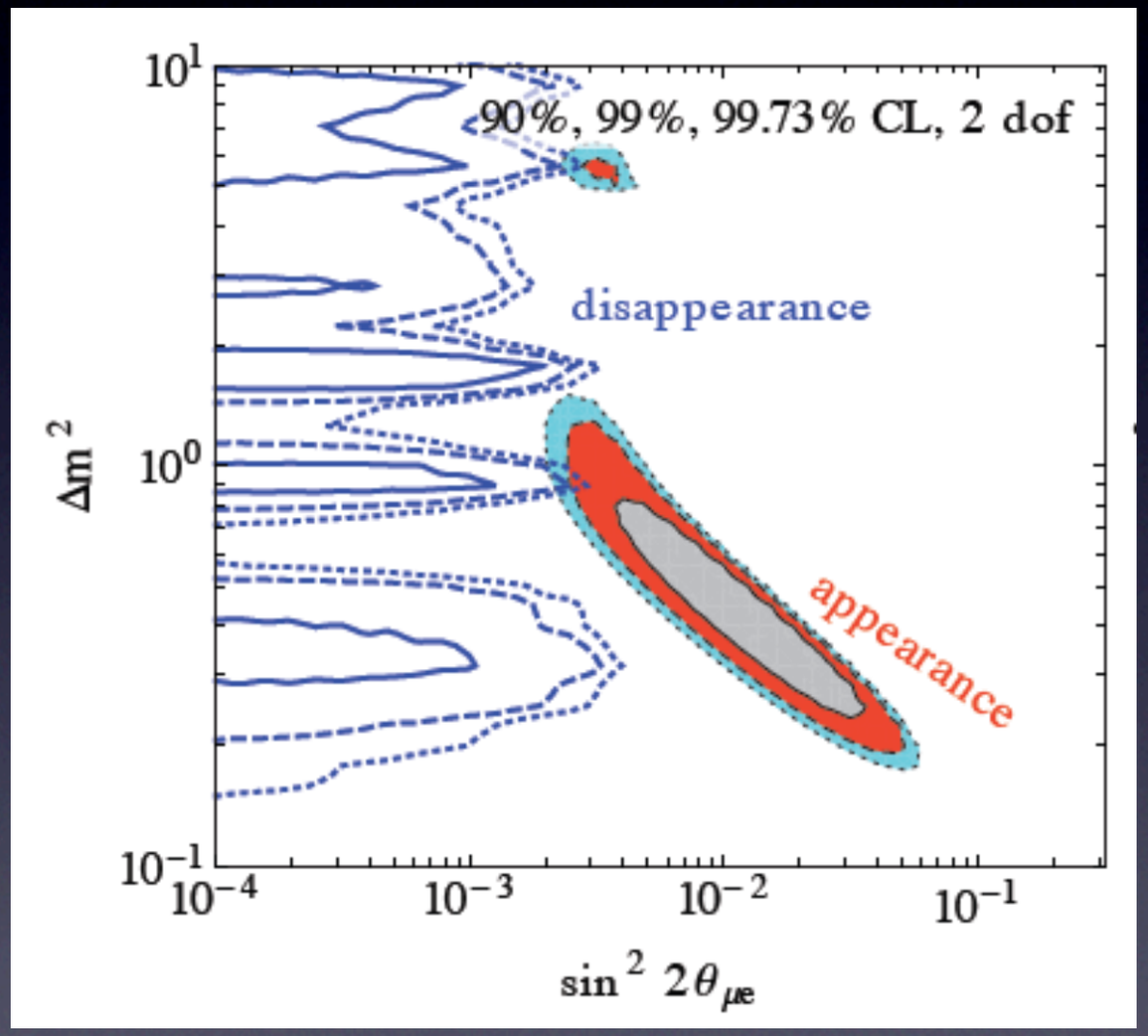
Stringent bounds from cosmology:

[Archidiacono, Gariazzo, Giunti, Hannestad, Hansen, Laveder, Tram, 2016]

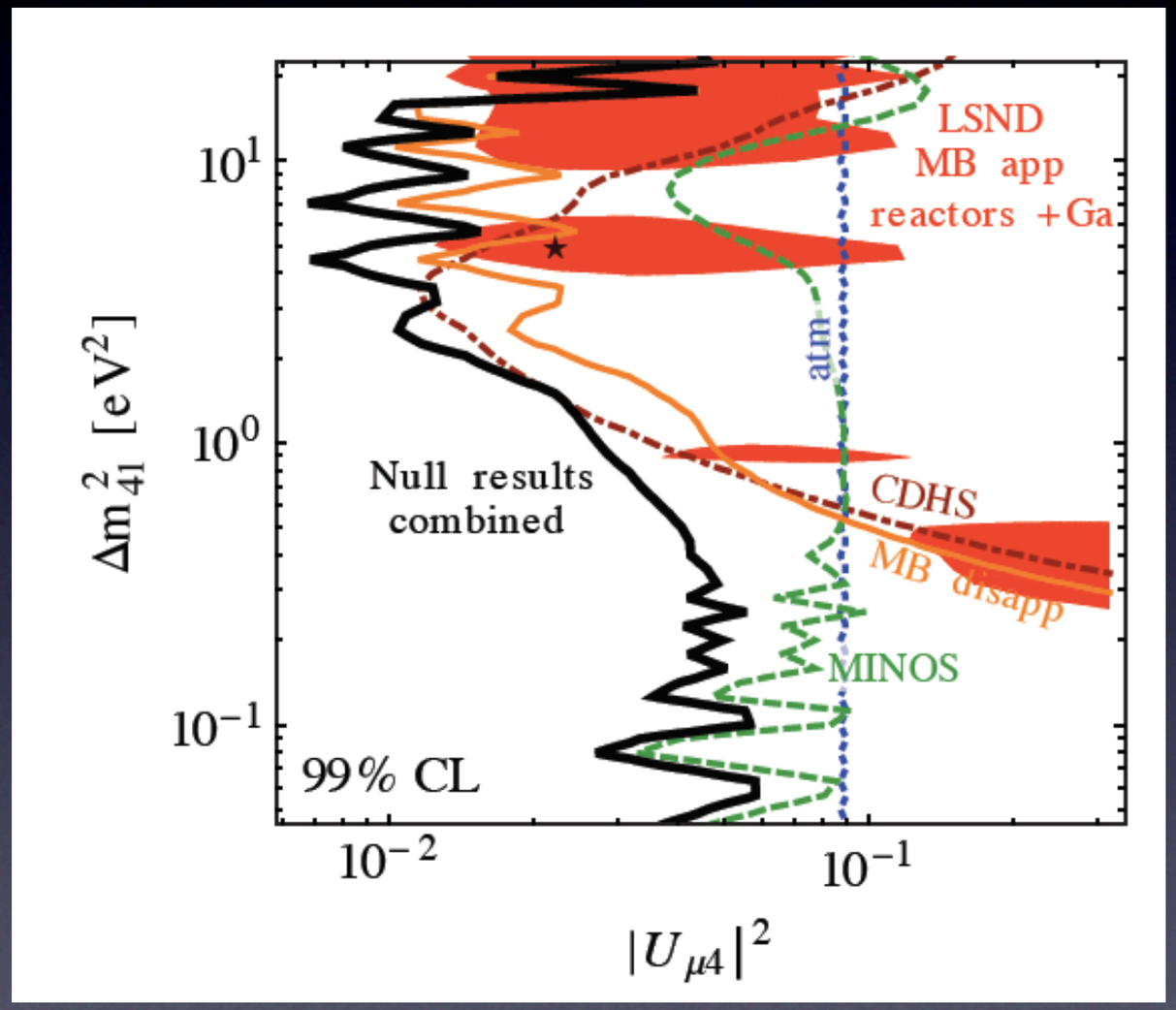


A 4th sterile neutrino ?

Appearance-disappearance tension



Evidences vs. null results combined

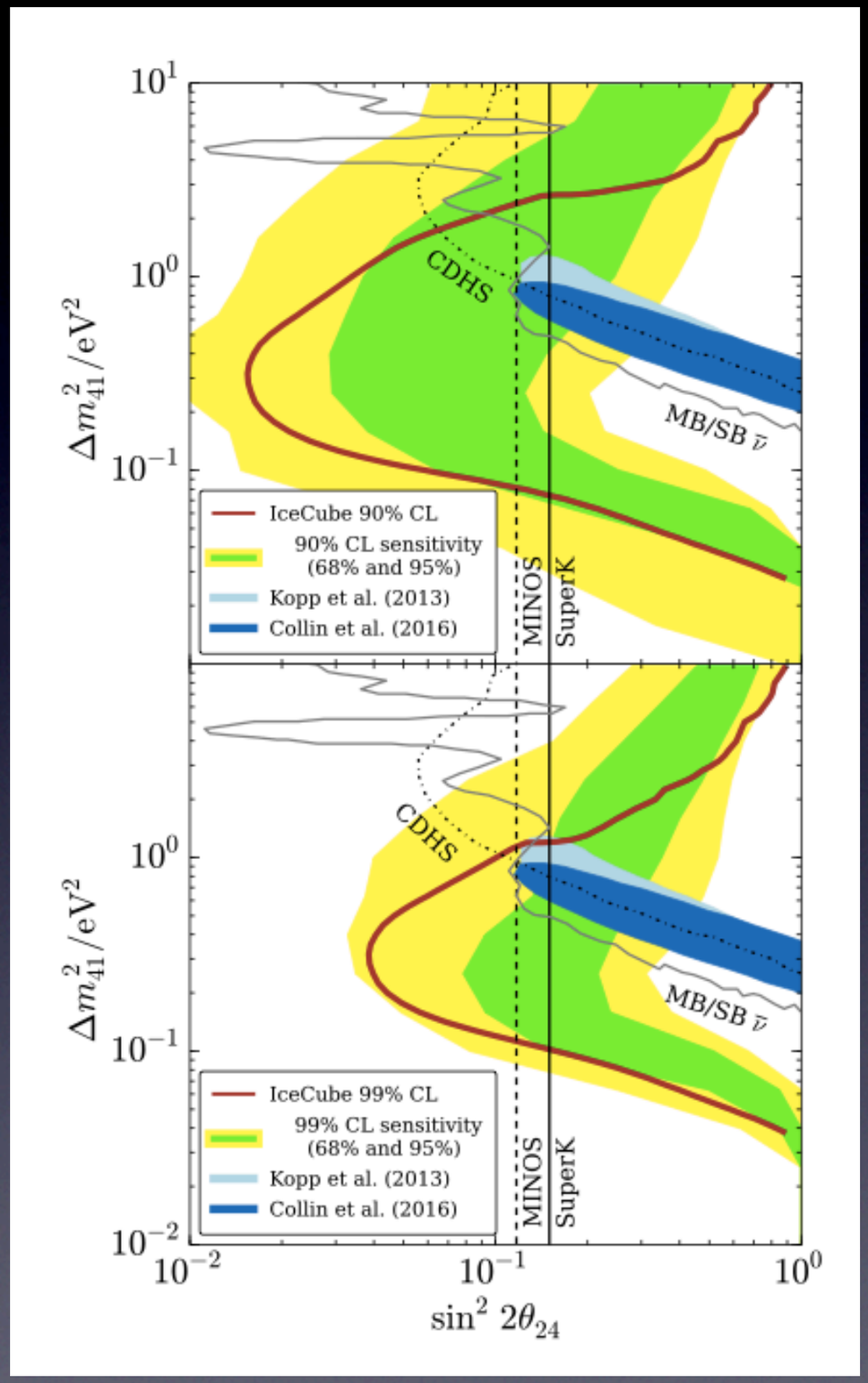


[Kopp, Machado, Maltoni, Schwetz, 2014]

[Kopp, Machado, Maltoni, Schwetz, 2016]

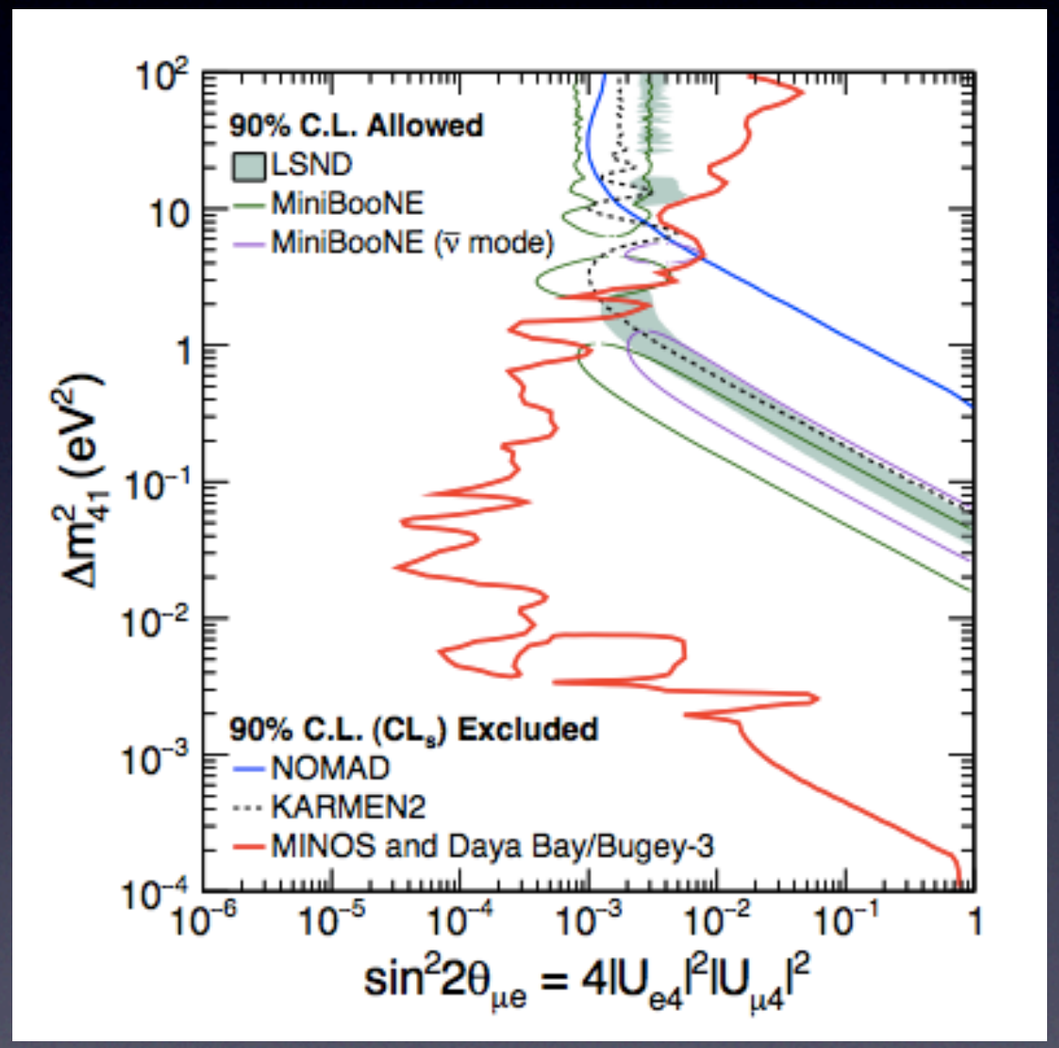
A 4th sterile neutrino ?

IceCube Bounds: (320 GeV - 20 TeV)



[IceCube (Aartsen et al.), 2016]

Daya Bay, MINOS & Bugey-3



[Adamson et al., 2016]

A 4th sterile neutrino ?

Sterile neutrinos can have a very different origin than the SM neutrinos (e.g. superpartners of dilaton, radion or other moduli fields, mirror world fermions, etc...)

There is NO compelling reason to believe that a sterile neutrino should behave just as the SM neutrinos

A 4th sterile neutrino ?

Evidence for light sterile ν is partly conflicting!

- May be wrong!
- May hint towards deviations from the usual oscillation mechanism!
- Sterile neutrinos as messengers of exciting new physics?

Attractive candidate: Altered dispersion relations

$$E = p + m^2/2E + \textit{new terms}$$

- Exotic matter effects, new interactions [Nelson...]
- Lorentz violation [Barenboim, Quigg, Kostelecky....]
- Shortcuts in extra dimensions [Päs, Pakvasa, Weiler...]

A 4th sterile neutrino ?

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Altered dispersion relations: vanilla type

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:

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

$\Rightarrow$ 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 $\leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16}$

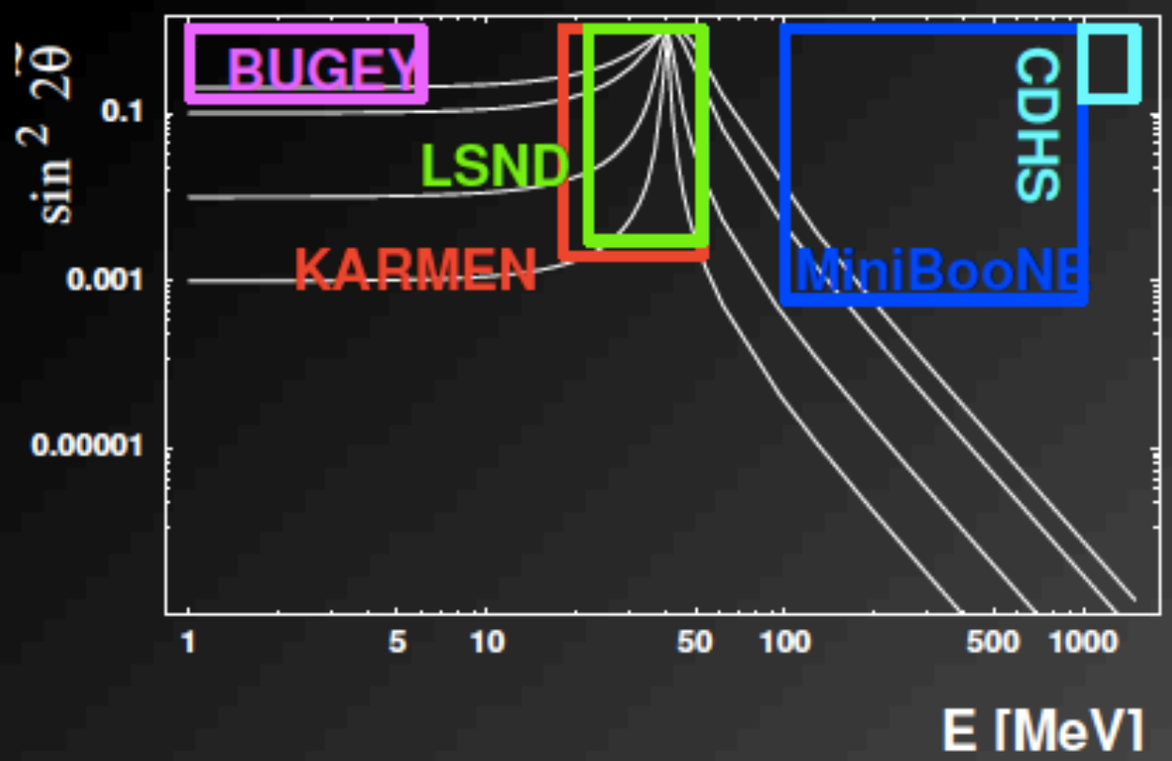
(Päs, Pakvasa, Weiler, 2005)

Altered dispersion relations: vanilla type

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

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

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



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

Altered dispersion relations with 3+1 neutrinos

$$\lambda_{4/3} \equiv \lambda_\pm = \frac{\Delta}{4E}\left(1 - \cos 2\theta_{34}\left(\frac{E}{E_\mathrm{R}}\right)^2 \pm \sqrt{\sin^2 2\theta_{34} + \cos^2 2\theta_{34}\left[1 - \left(\frac{E}{E_\mathrm{R}}\right)^2\right]^2}\right)$$

- 2 mass eigenstates with diverging effective masses!
- Diverging Δm^2's

[Marfatia, HP, Pakvasa, Weiler, 2012]

- Fast oscillations:

$$P(\nu_a \to \nu_b) = 4\, V_{a3}^2\, V_{b3}^2 \times \begin{cases} -\sin^2\left(\frac{L\,(\lambda_+ - \lambda_-)}{2}\right) & \sin^2\tilde{\theta}\,\cos^2\tilde{\theta} \\ +\sin^2\left(\frac{L\,\lambda_+}{2}\right) & \sin^2\tilde{\theta} \\ +\sin^2\left(\frac{L\,\lambda_-}{2}\right) & \cos^2\tilde{\theta}\,. \end{cases}$$

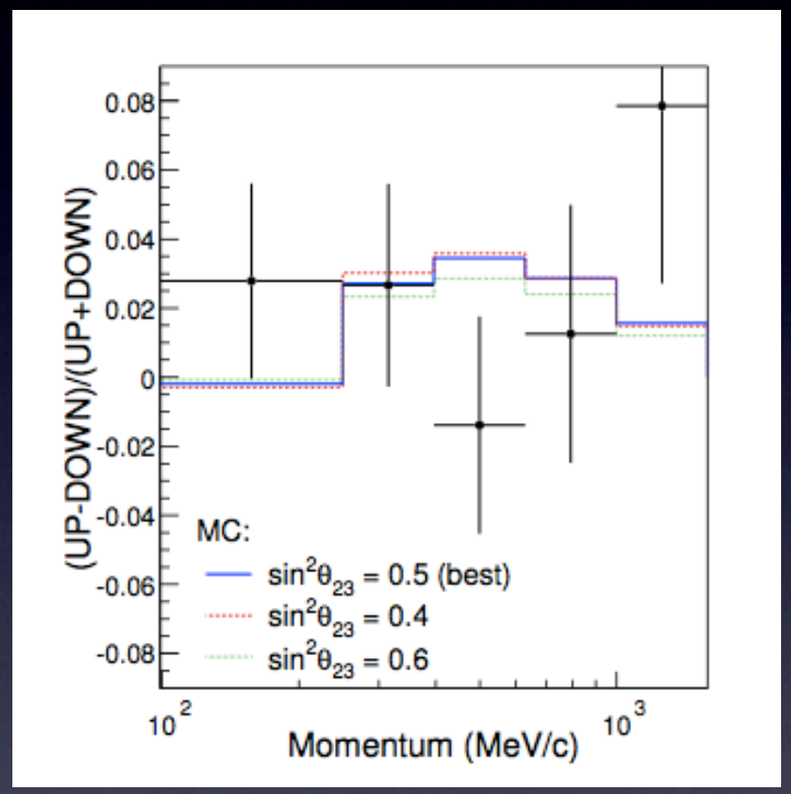
- Contrary to matter effects: Sterile neutrino Lorentz violation strictly constrained by atmospheric ν L/E

[P. Huber, 2007]

Beyond vanilla-type

Closer look at data

[Super-Kamiokande 2010]



Lorentz Violation

[Kostelecky, Mewes 2012]

coefficient	d	CP	T	CPT
$a_L^{\mu\alpha_1\ldots\alpha_{d-3}}$	odd	$-$	$+$	$-$
$c_L^{\mu\alpha_1\ldots\alpha_{d-3}}$	even	$+$	$+$	$+$
$m_l^{\alpha_1\ldots\alpha_{d-3}}$	odd	$+$	$+$	$+$
$e_l^{\alpha_1\ldots\alpha_{d-3}}$	even	$-$	$+$	$-$
$g_l^{\mu\nu\alpha_1\ldots\alpha_{d-3}}$	even	$+$	$-$	$-$
$H_l^{\mu\nu\alpha_1\ldots\alpha_{d-3}}$	odd	$-$	$-$	$+$
$g_{M+}^{\mu\nu\alpha_1\ldots\alpha_{d-3}}$	even	$+$	$-$	$-$
$H_{M+}^{\mu\nu\alpha_1\ldots\alpha_{d-3}}$	odd	$-$	$-$	$+$
$a_l^{\mu\alpha_1\ldots\alpha_{d-3}}$	odd	$-$	$+$	$-$
$c_l^{\mu\alpha_1\ldots\alpha_{d-3}}$	even	$+$	$+$	$+$

Extra-dimensional shortcuts

- Discuss effects of spacetime-geometry

  → effects on baseline and energy dependence!

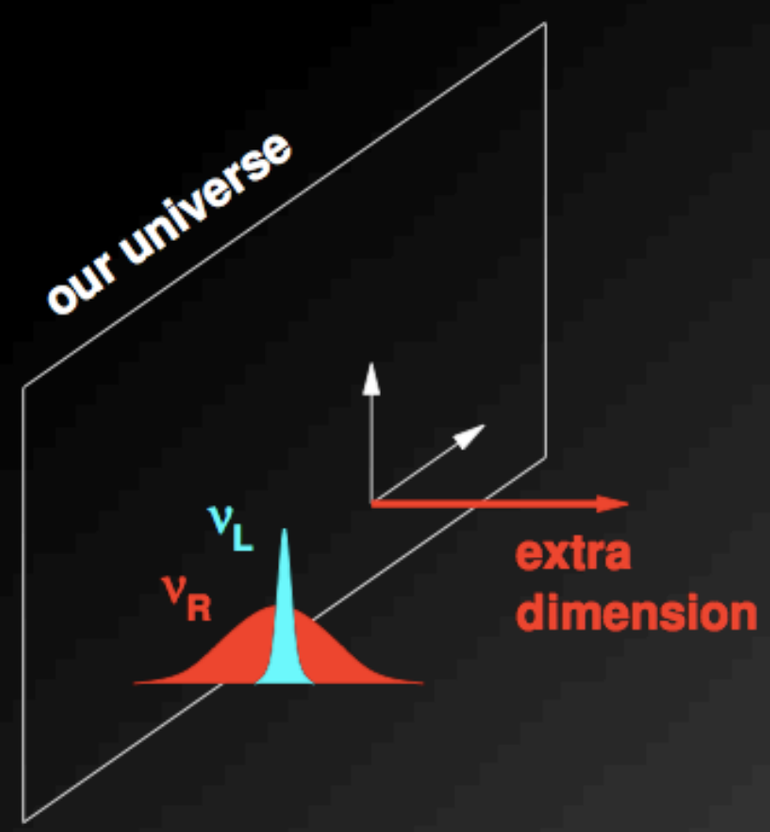
Concrete Model: Neutrinos in extra dimensions

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

→ small Dirac neutrino masses from volume-suppressed couplings to ν_R in the bulk:

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

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

Shortcuts from asymmetrically warped spacetime

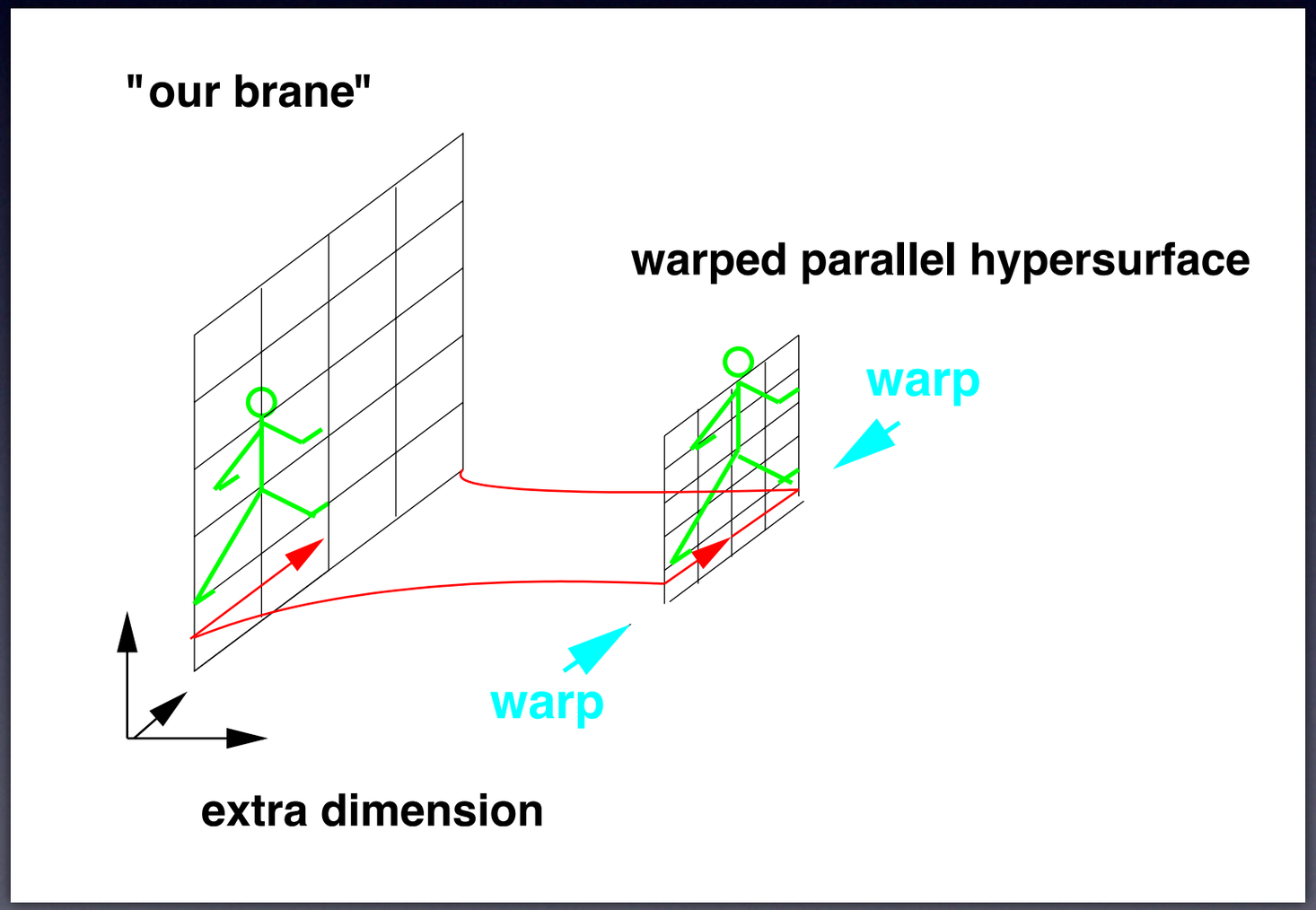
Consider an asymmetrically warped extra dimension with a sterile neutrino in the bulk

$$ds^2 = dt^2 - e^{-2k|u|}dx^2 - du^2$$

[Chung, Freese, 1999, 2000]

[Csaki, Erlich, Grojean, 2001]

- Shrinks space parallel to the brane
- Allows for shortcuts in the extra dimension!



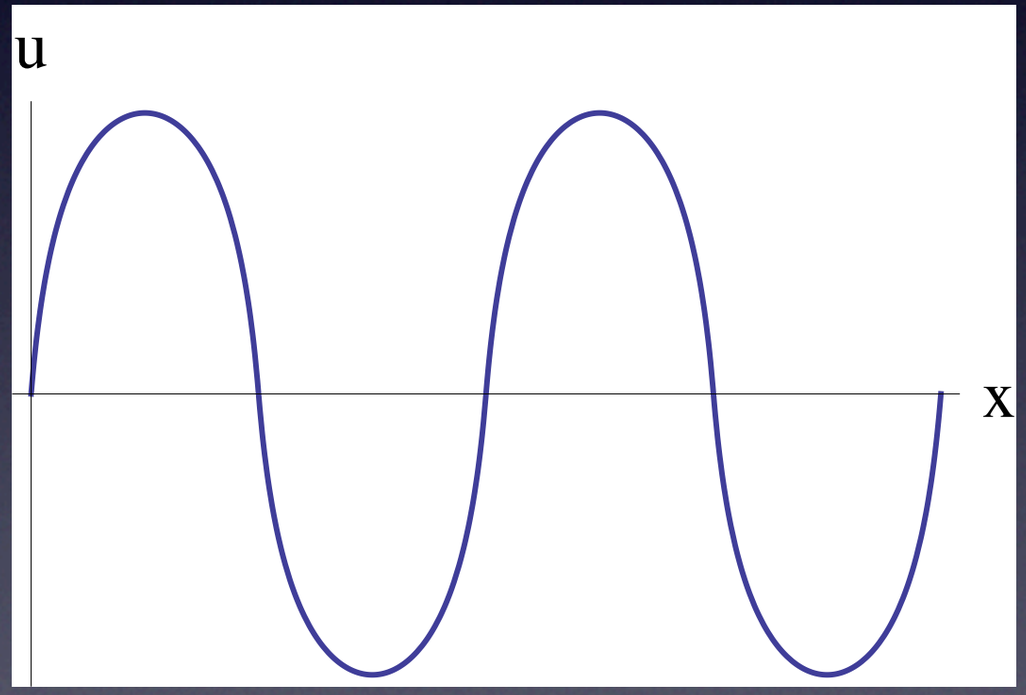
Shortcuts from asymmetrically warped spacetime

Geodesics: oscillating around the brane

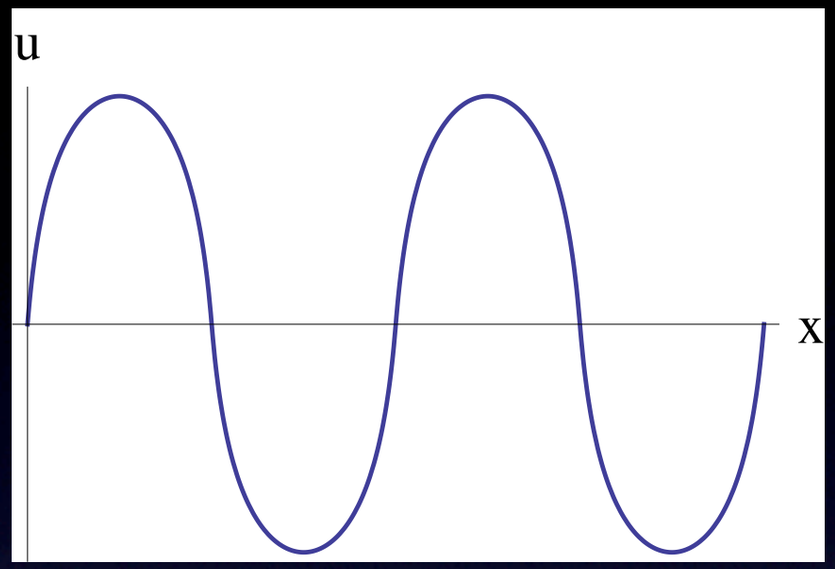
$$u(x) = \pm \frac{1}{2k} ln[1 + k^2 x(l - x)]$$

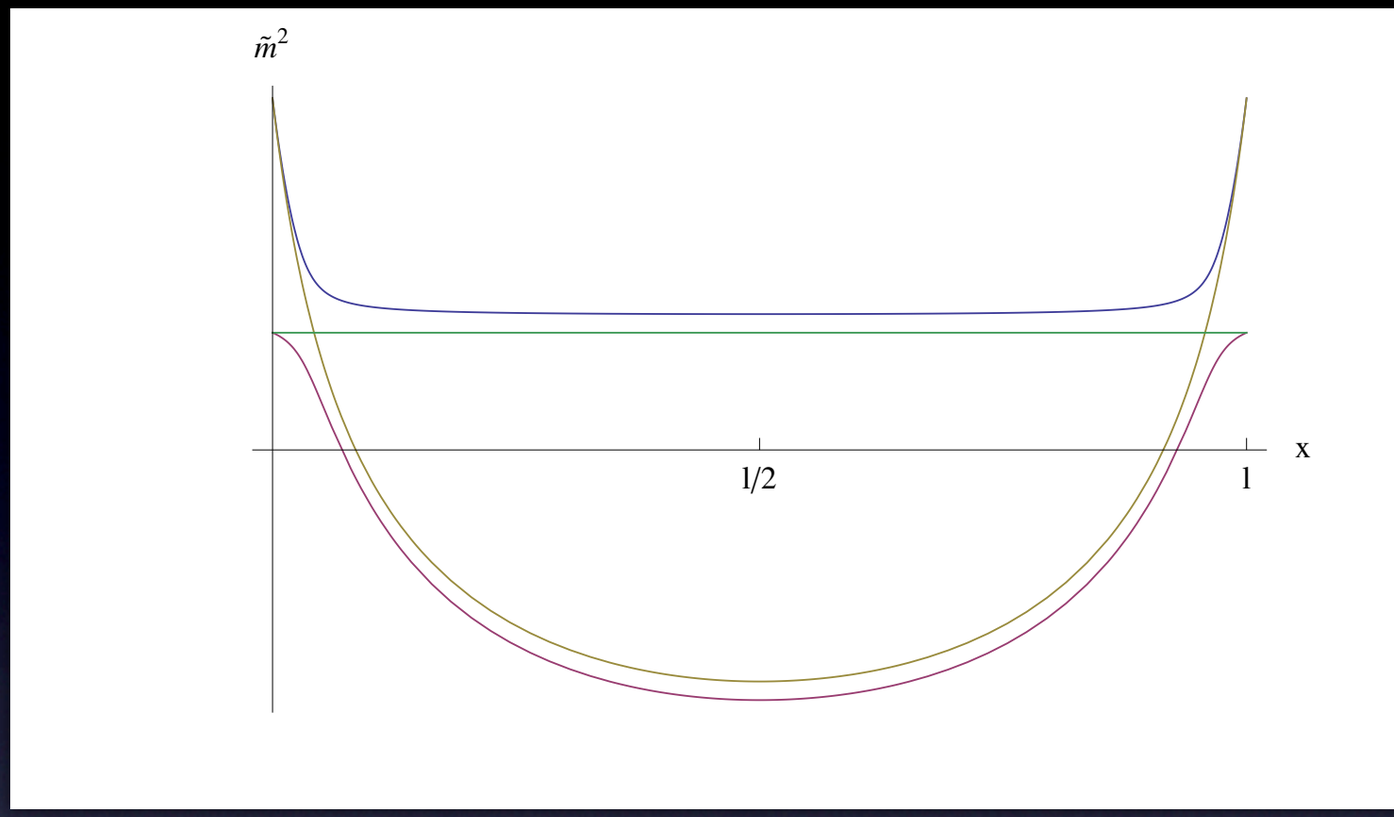
- Shortcut "switched on and off" during propagation

[Hollenberg, Micu, HP, Weiler, 2009]

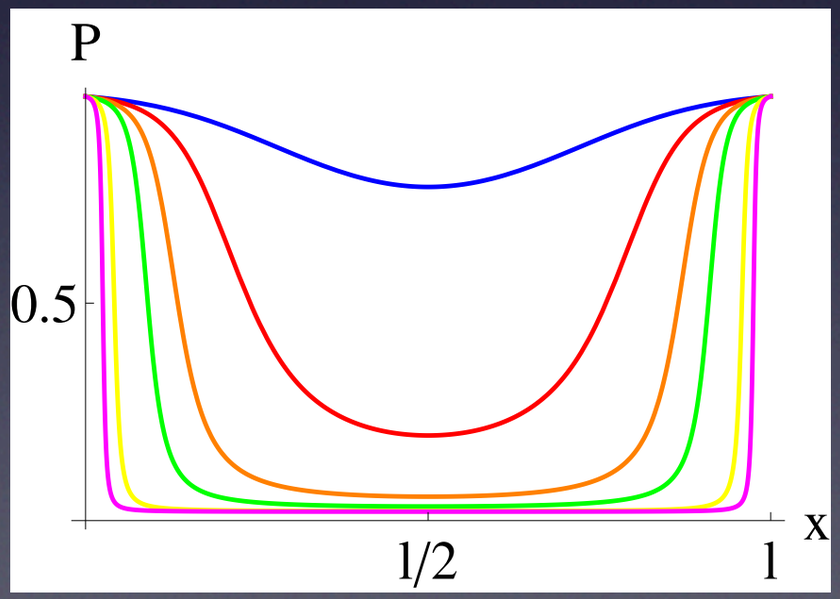


Resonant conversion





- Shortcut "switched on and off"→ new baseline effect
- MSW analogue: resonant conversion



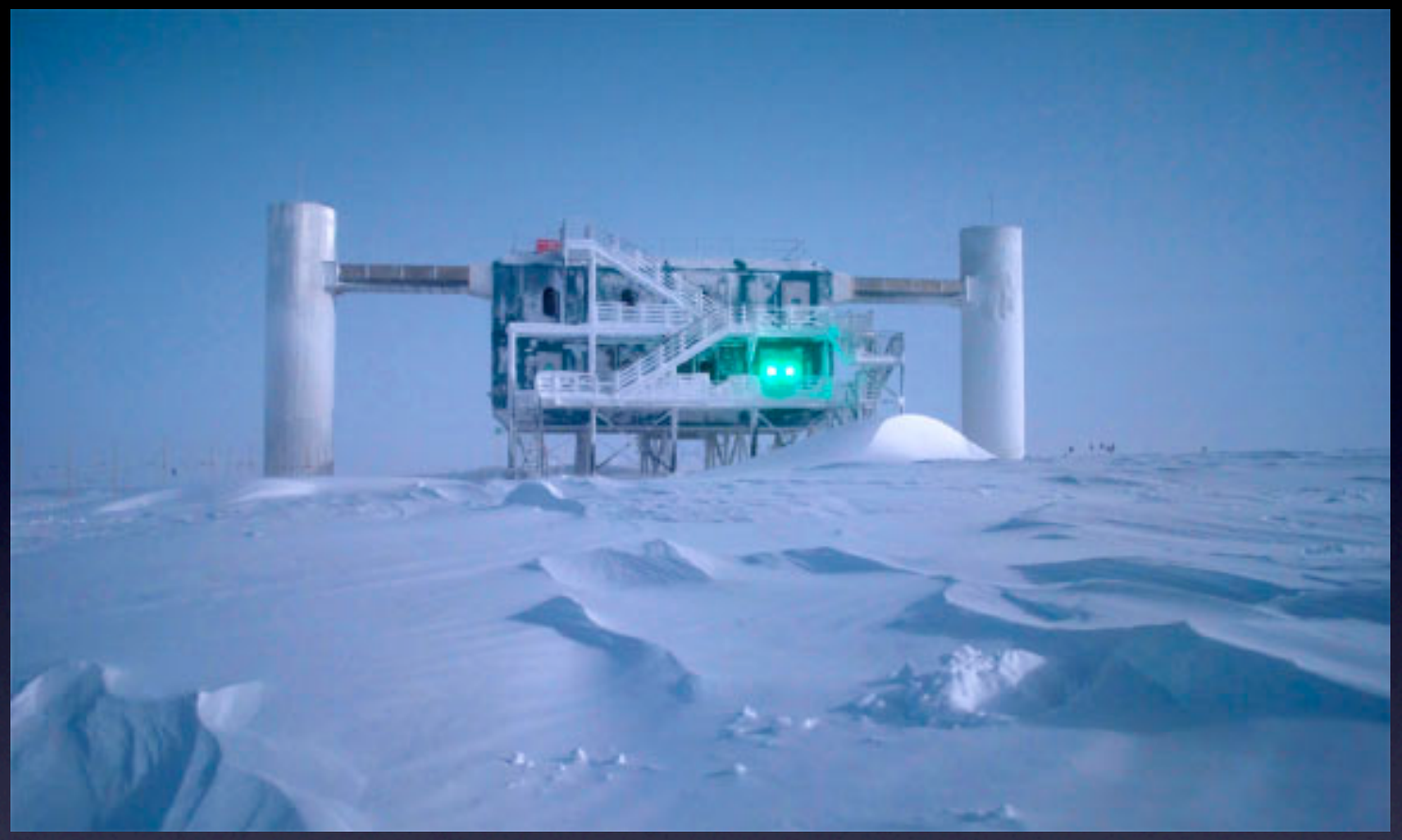
Compatible with atmospheric L/E?

[HP, Sicking, Supsar, work in progress]

Astrophysical Flavor Ratios

Expectation pion source:

$$\begin{array}{ccccccc} \pi^+ & \rightarrow & \mu^+ & + & \nu_\mu & & \\ & & \downarrow & & & & \\ & & e^+ & + & \nu_e & + & \bar{\nu}_\mu \end{array}$$



Flavor Ratio at the source: 1:2:0

Maximal ν_μ-ν_τ mixing: Decoherence →

Flavor Ratio: 1:1:1 at Earth

Altered dispersion relations?

Astrophysical Flavor Ratios

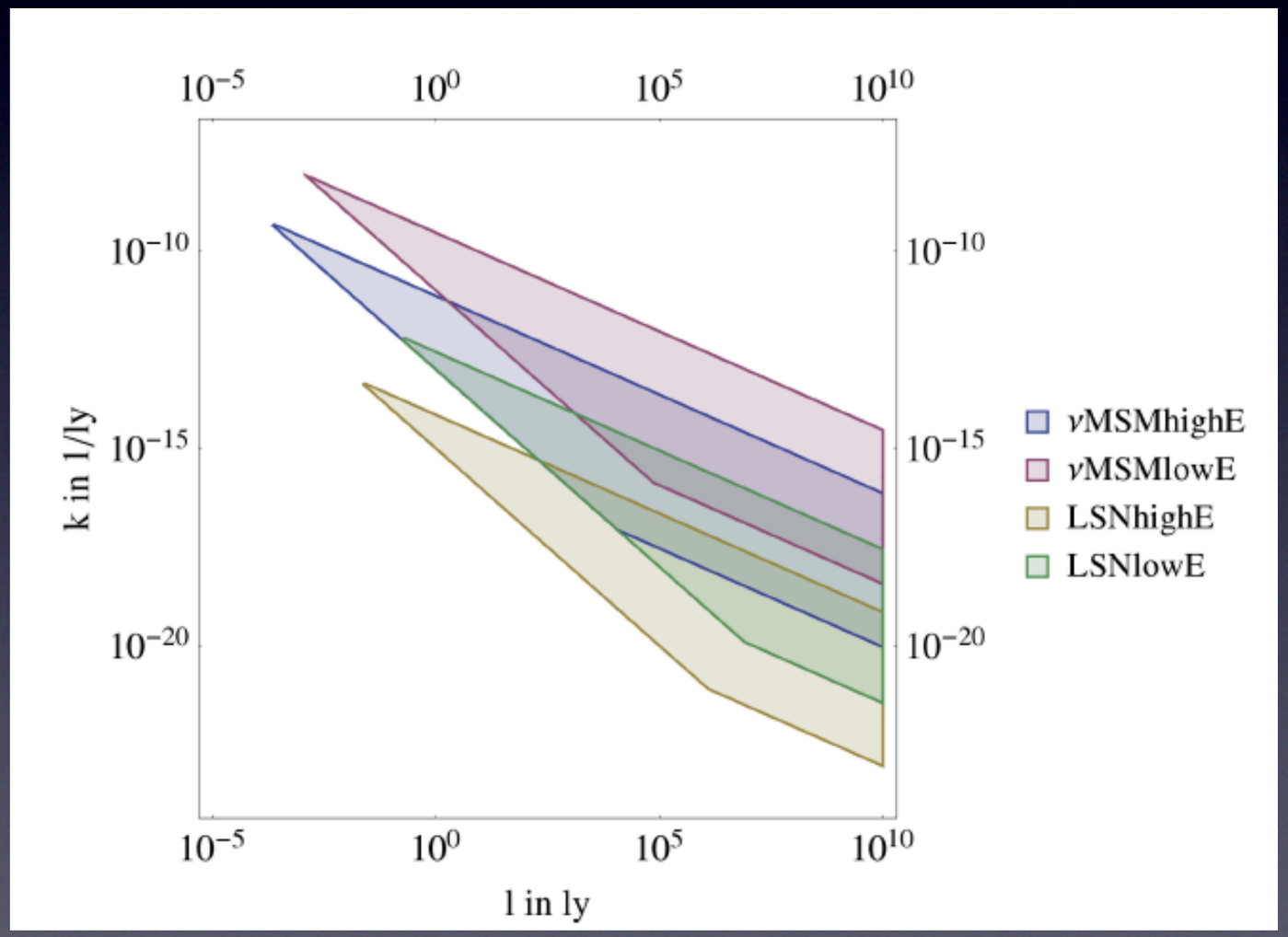
Level crossing: shortcut parameter has to be large enough?

$$\epsilon = 1 - e^{-k|u|} = 1 - \frac{1}{\sqrt{1 + k^2 x(l-x)}}$$

Adiabaticity ?

$$\gamma_{max} = \frac{2E^3}{(\delta m^2)^2 \sin^2(2\theta)} k^2 l \ll 1$$

4:1:1 possible in large regions of parameter space, 0:0:0 possible at high Energies !



[Aeikens, HP, Pakvasa, Sicking, 2014]

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:

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

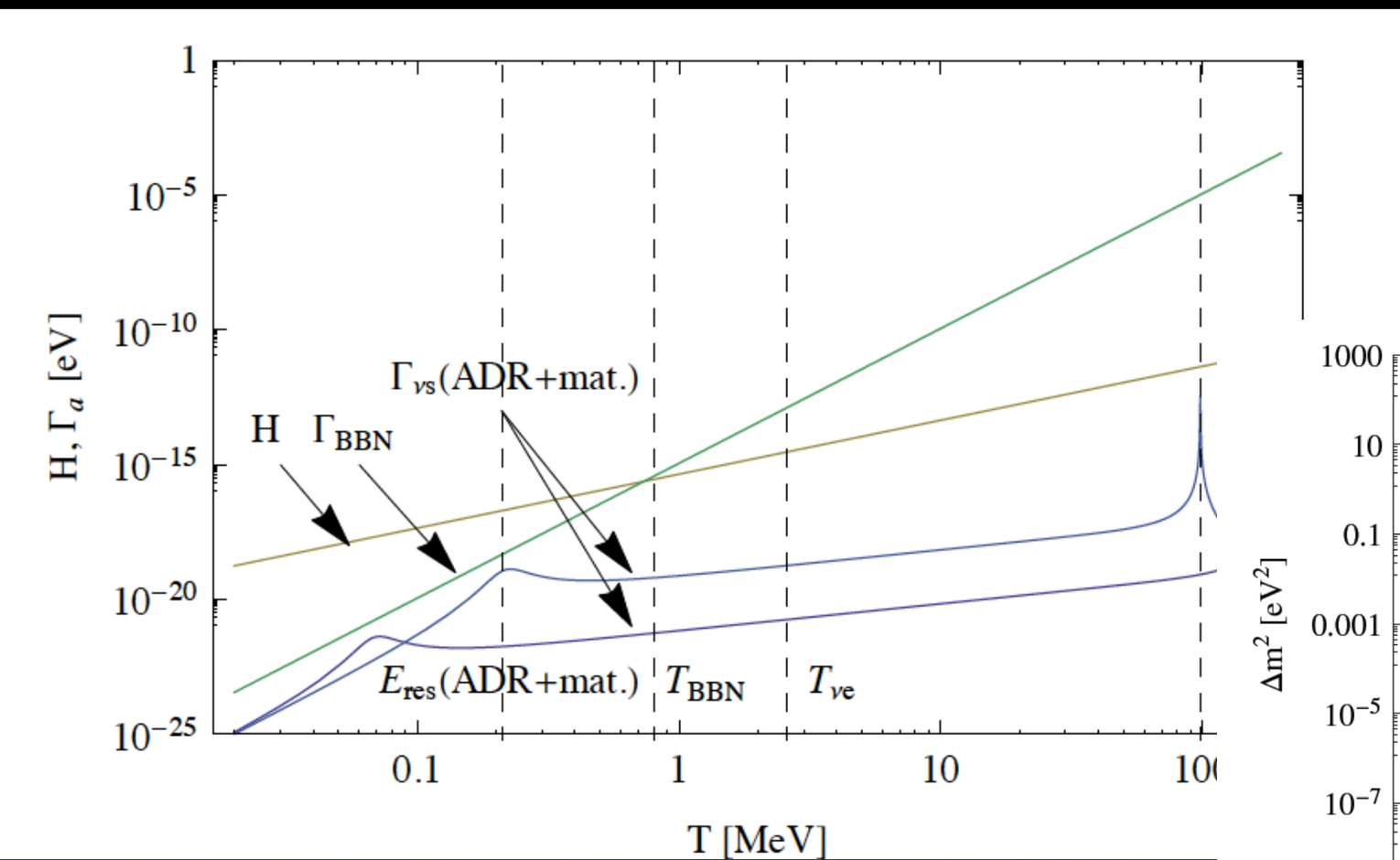
- $\rightarrow$ faster expansion of the universe
- $\rightarrow$ higher temperature for weak freezeout
- $\rightarrow$ more neutrons $\rightarrow$ larger ^4He abundance

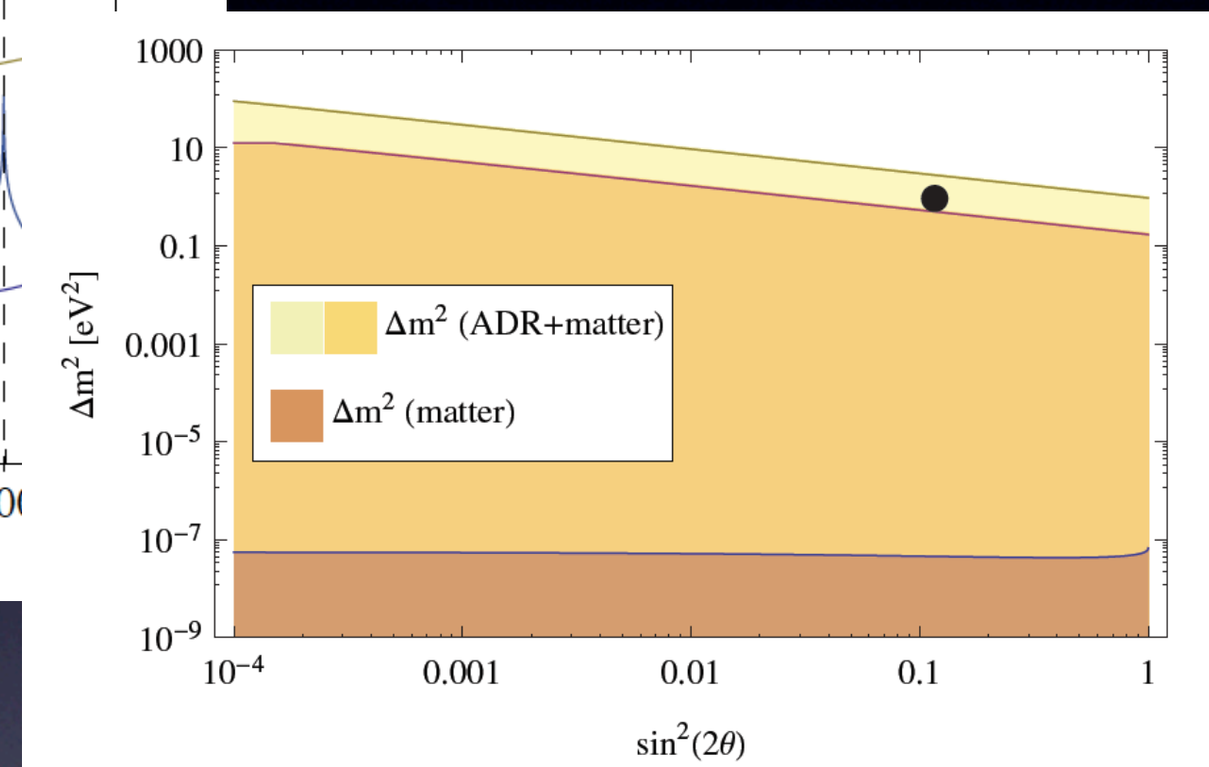
Bulk shortcut scenario:

- higher density: stronger brane bending due to gravitational attraction
- higher temperature: more brane fluctuations
- higher density: more scattering off into the bulk in asymmetrically warped spacetimes

All cases: larger $\epsilon \rightarrow$ smaller $E_{\rm res}$
If $E_{\rm res} \lesssim 3$ MeV: oscillations suppressed (Päs, Pakvasa, Weiler, 2005)

Big Bang Nucleosynthesis





Allowed range increases dramatically!

Similar aguments work for other cosmological bounds!

[Aeikens, HP, Weiler, 2016]

A QFT approach

- Compactify asymmetrically warped 5D QFT
- Kaluza-Klein spectrum = Randall-Sundrum "RS1"
- Corrections to "particle-approximation" ADR

$$E^2 = \left(\lim_{m/k \to 0} \tilde{I}_{00}^{1/2} \right) \vec{p}^2 \approx \left(\frac{e^{kr\pi} r\pi\Delta k}{e^{kr\pi} - 1} + \frac{\Delta k}{k} + 1 \right) \vec{p}^2 \,.$$

- KK states enter oscillation probability
- Rich phenomenology

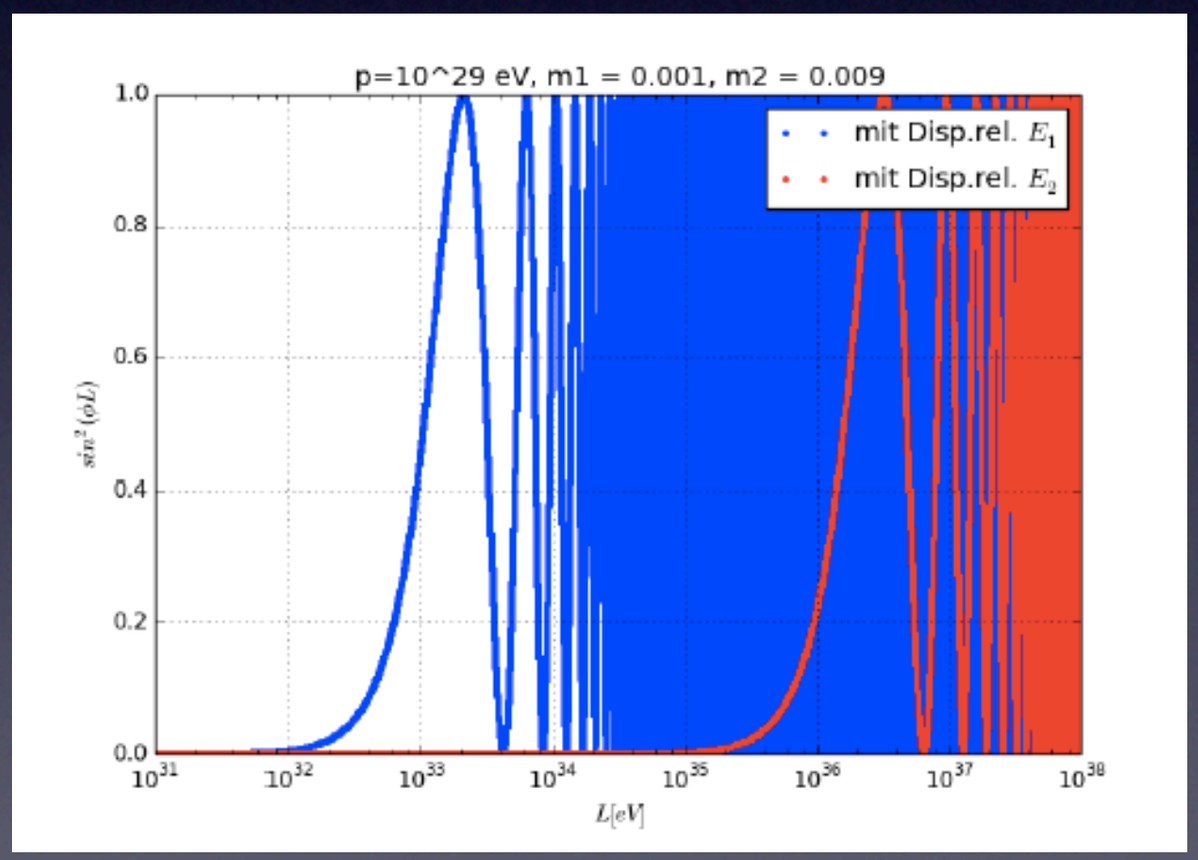
[Döring, HP, Work in Progress]

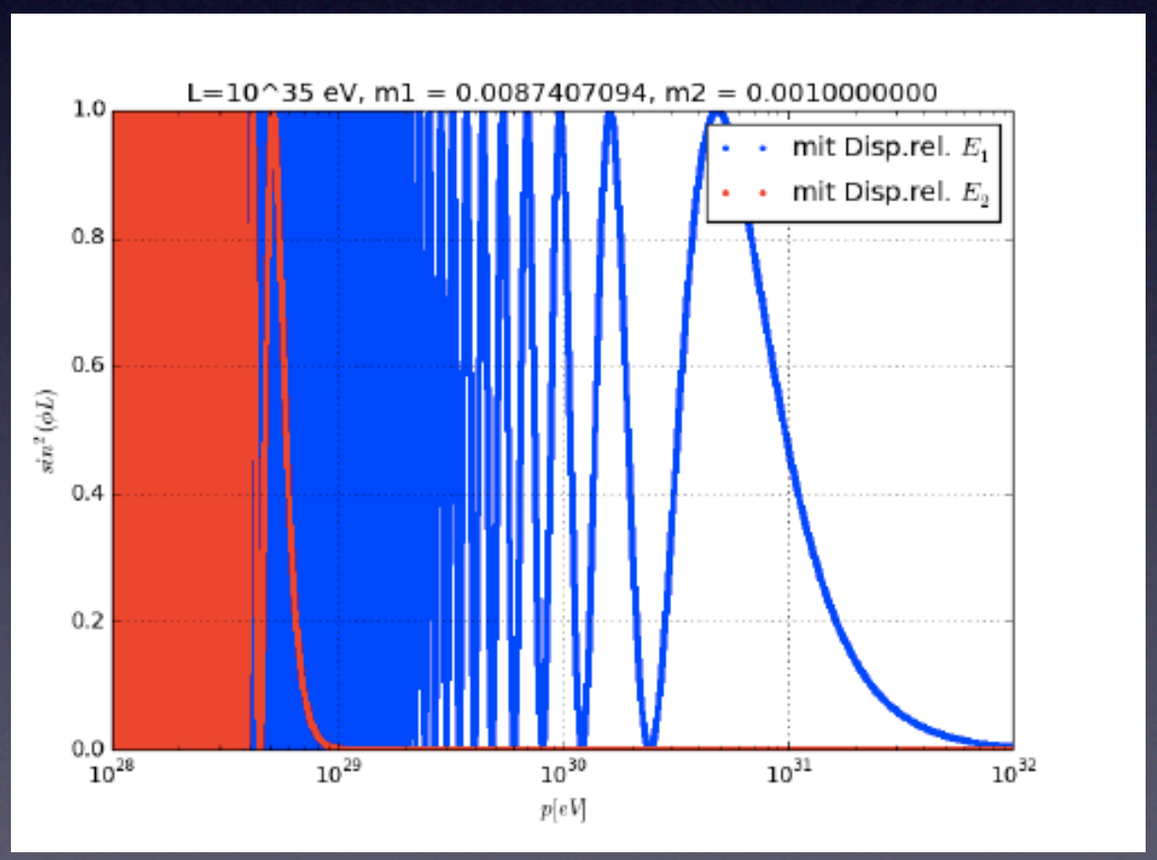
Pseudo-particle Physics

- Motivated by emergent spacetime & analog gravity models [Parentani, Hossenfelder, Liberati, Visser; Wen]
- Inspiration from solid-state physics: periodic ADRs

$$E_1 = \sqrt{p^2 + m^2}$$

$$E_2 = \sqrt{a \sin^2\left(\frac{p}{p_0}\right) + m^2}$$

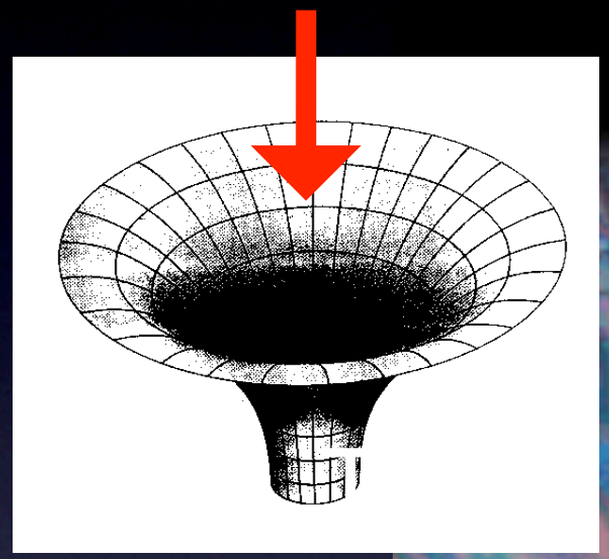


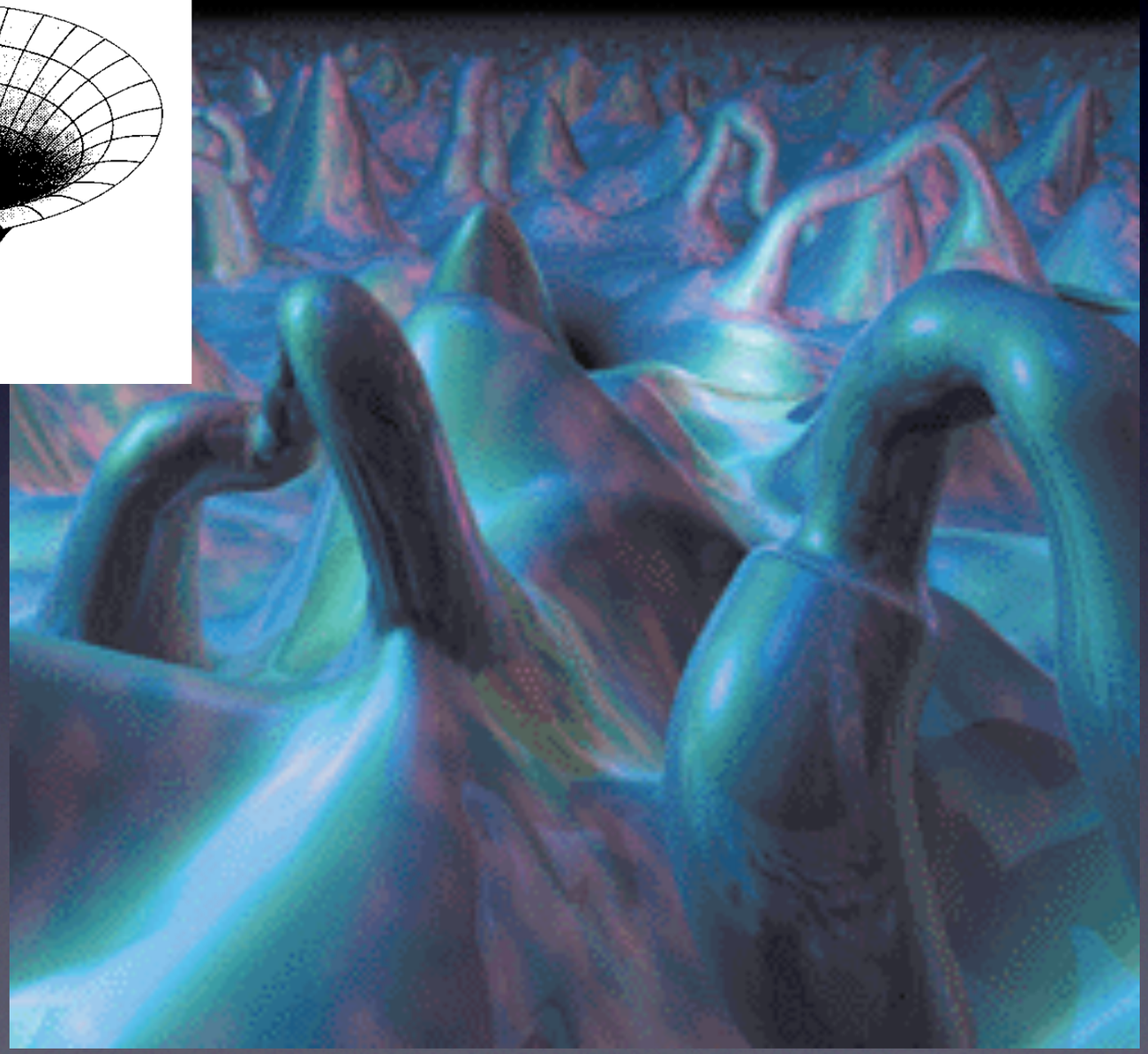


[Kämper, HP, Work in Progress]

Quantum Gravity induced Decoherence

$$|\Psi\rangle \sim \alpha_{\uparrow}|\uparrow\rangle + \beta_{\downarrow}|\downarrow\rangle \rightarrow \text{“mixed”}$$





Quantum Gravity induced Decoherence

$$\frac{d}{dt}\begin{pmatrix}\rho^0\\ \rho^1\\ \rho^2\\ \rho^3\end{pmatrix} = 2\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & 0 & \Delta m^2/(4E) & 0\\ 0 & -\Delta m^2/(4E) & -\alpha & -\beta\\ 0 & 0 & -\beta & -\gamma\end{pmatrix}\begin{pmatrix}\rho^0\\ \rho^1\\ \rho^2\\ \rho^3\end{pmatrix}$$

$$P^{QMV}_{\nu_x\to\nu_{x'}} = Tr[\rho(t)\rho_x] = \frac{1}{2} - \frac{1}{2}e^{-\gamma L}\cos^2 2\theta - \frac{1}{2}e^{-\alpha L}\sin^2 2\theta\cos(\frac{\Delta m^2}{2E_\nu}L)$$

IceCube: extremely sensitive!

$$\gamma < \frac{0.6}{L} \sim 10^{-40} GeV.$$

[Klapdor-Kleingrothaus, HP, Sarkar, 2000]

[Anchordoqui, Goldberg, Gonzalez-Garcia, Halzen, Hoper, Sarkar, Weiler, 2005]

Quantum Gravity induced Decoherence

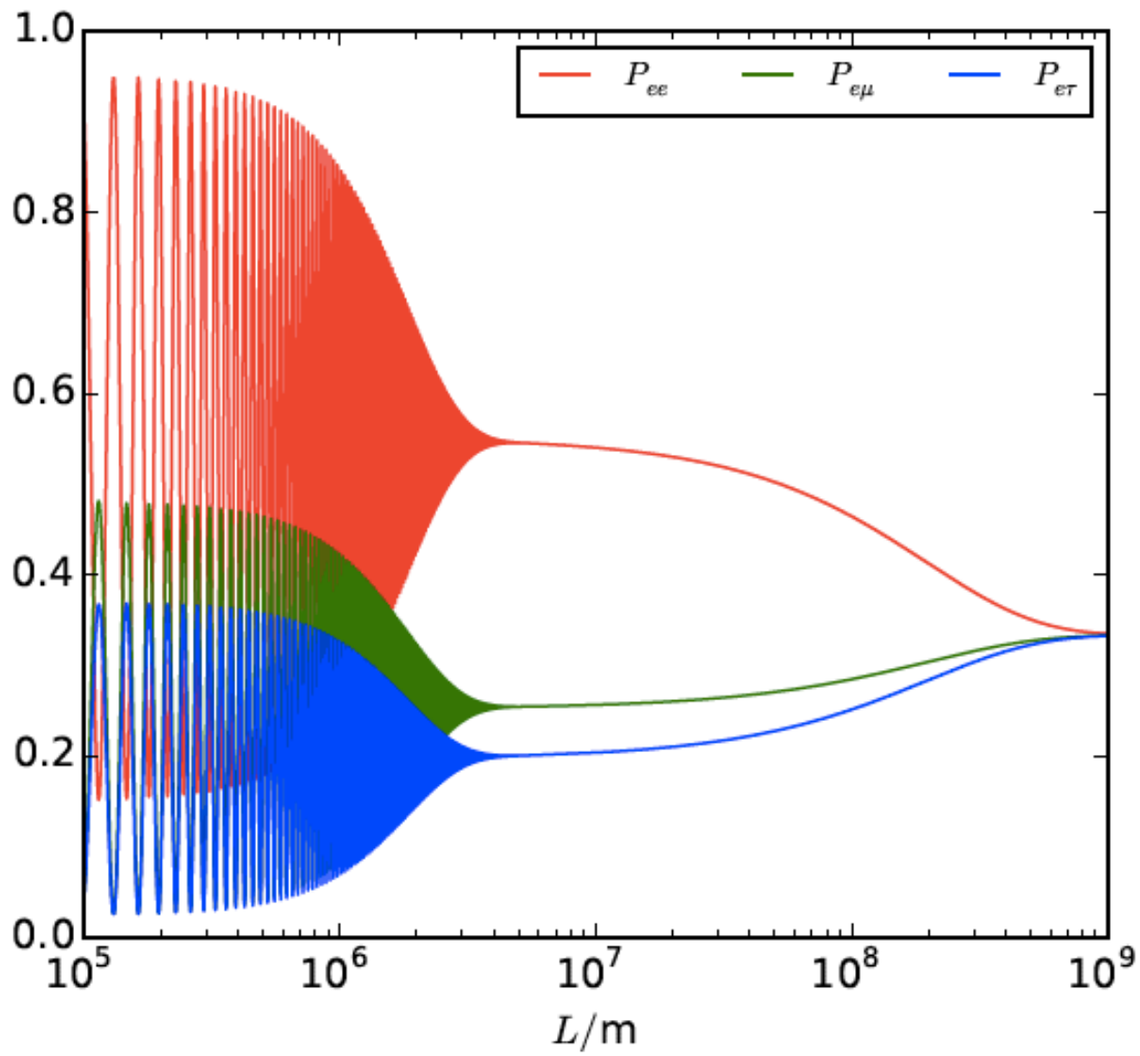


Figure 9: The evolution of the transition probabilities of an initial electron neutrino of energy $E = 1\,\mathrm{MeV}$, taking into account the seperation of wave packets and quantum gravity effects. The propagation distance is plotted logarithmically. The decoherence parameter is choosen as $\gamma = 10^{-24}\,\mathrm{GeV}$

Practical problem: Muon source results in 1:1:1 anyway !

[Büscher, HP, work in progress]

Quantum Mechanics & nothing else

Can the Many-Worlds-Interpretation be probed in Psychology?

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Abstract

A minimal approach to the measurement problem and the quantum-to-classical transition assumes a universally valid quantum formalism, i.e. unitary time evolution governed by a Schrödinger-type equation. As had been pointed out long ago, in this view the measurement process can be described by decoherence which results in a "Many-Worlds" or "Many-Minds" scenario according to Everett and Zeh. A silent assumption for decoherence to proceed is however, that there exists incomplete information about the environment our object system gets entangled with in the measurement process. This paper addresses the question where this information is traced out and - by adopting recent approaches to model consciousness in neuroscience - argues that a rigorous interpretation results in a modern perspective on the von-Neumann-Wigner interpretation – namely that the information that is or is not available in the consciousness of the observer is crucial for the definition of the environment. As such the quantum-to-classical transition while being difficult or impossible to probe in physics may become testable in psychology.

PACS numbers: 03.65

09.04878v1 [quant-ph] 15 Sep 2016

[HP, arXiv:1609.04878 [quant-ph]]

Summary

- Several 3–4 σ evidences for sterile neutrinos
- Partially in conflict with each other & bounds
- Shortcuts in extra dimensions:
  energy & baseline dependence, resonant conversion
- ν oscillation fits?
- Strong effect on astrophysical flavor ratios
- Possibility to avoid cosmology constraints
- Non-standard ν properties should be explored more vigorously while searching for a solution to neutrino anomalies!