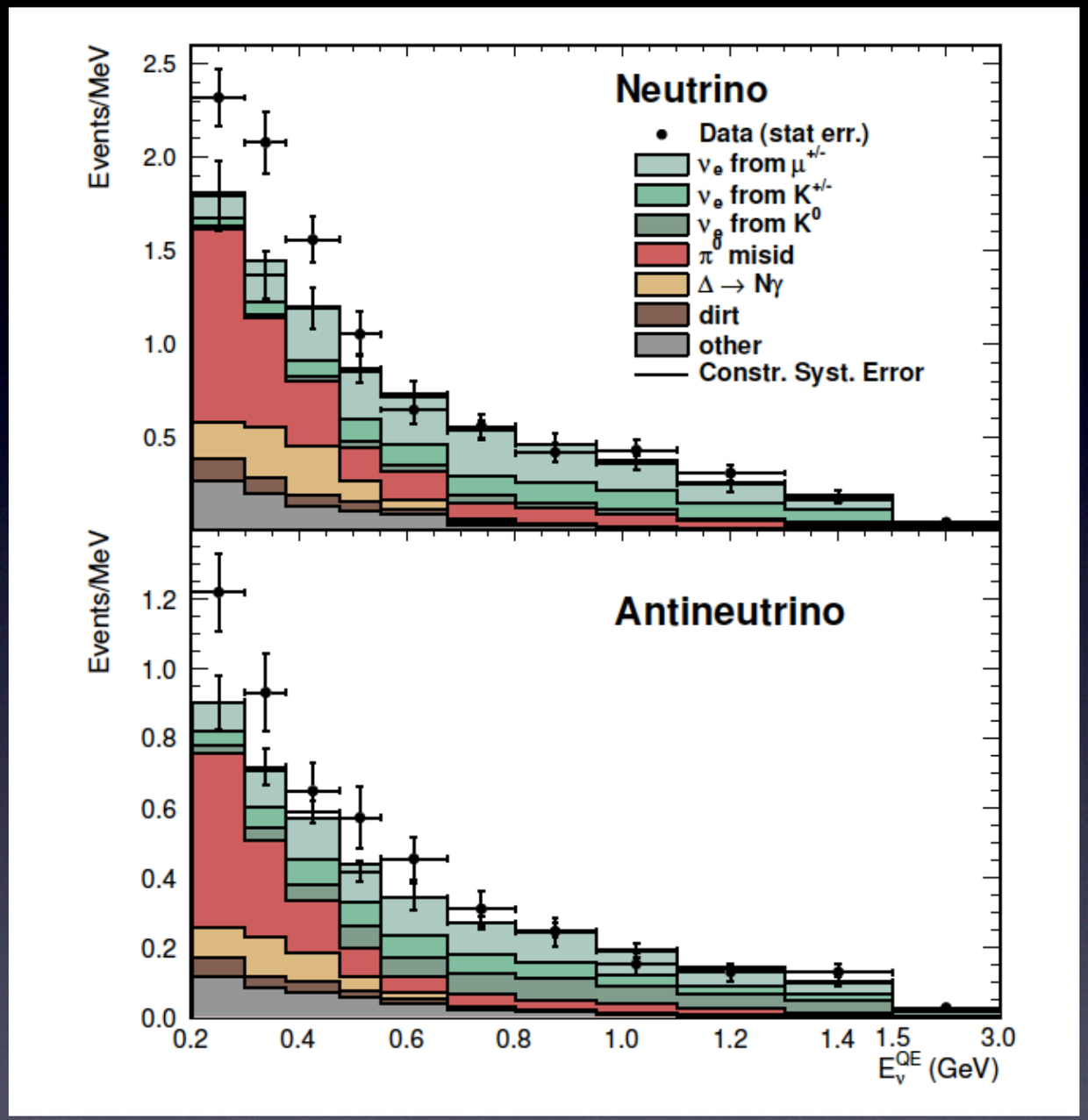
Sterile neutrino oscillations with altered dispersion relations

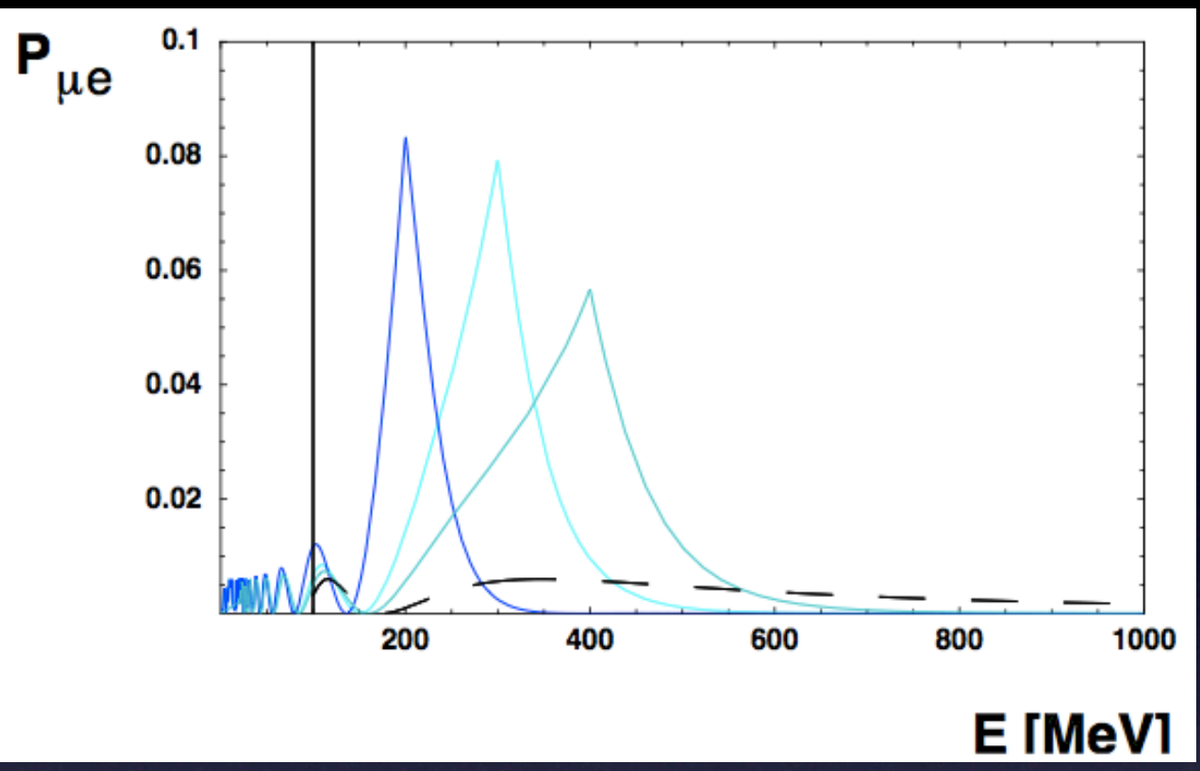
Heinrich Päs

Nu@Fermilab 2015

What is this talk about ?



[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 ?

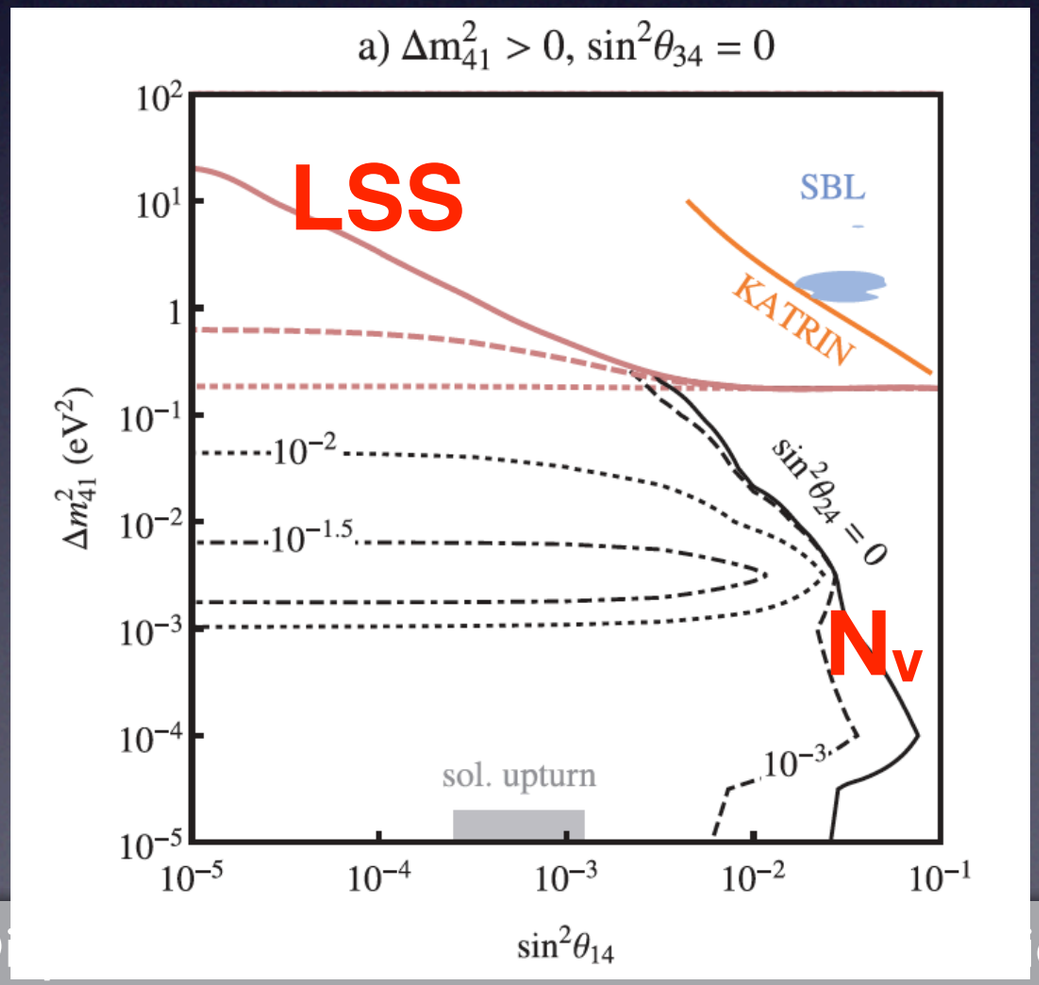
A handful of anomalies with 3-4 σ:

- LSND
- MiniBooNE
- Reactor anomaly
- Gallium anomaly

→ 4th light neutrino with eV-range mass ?

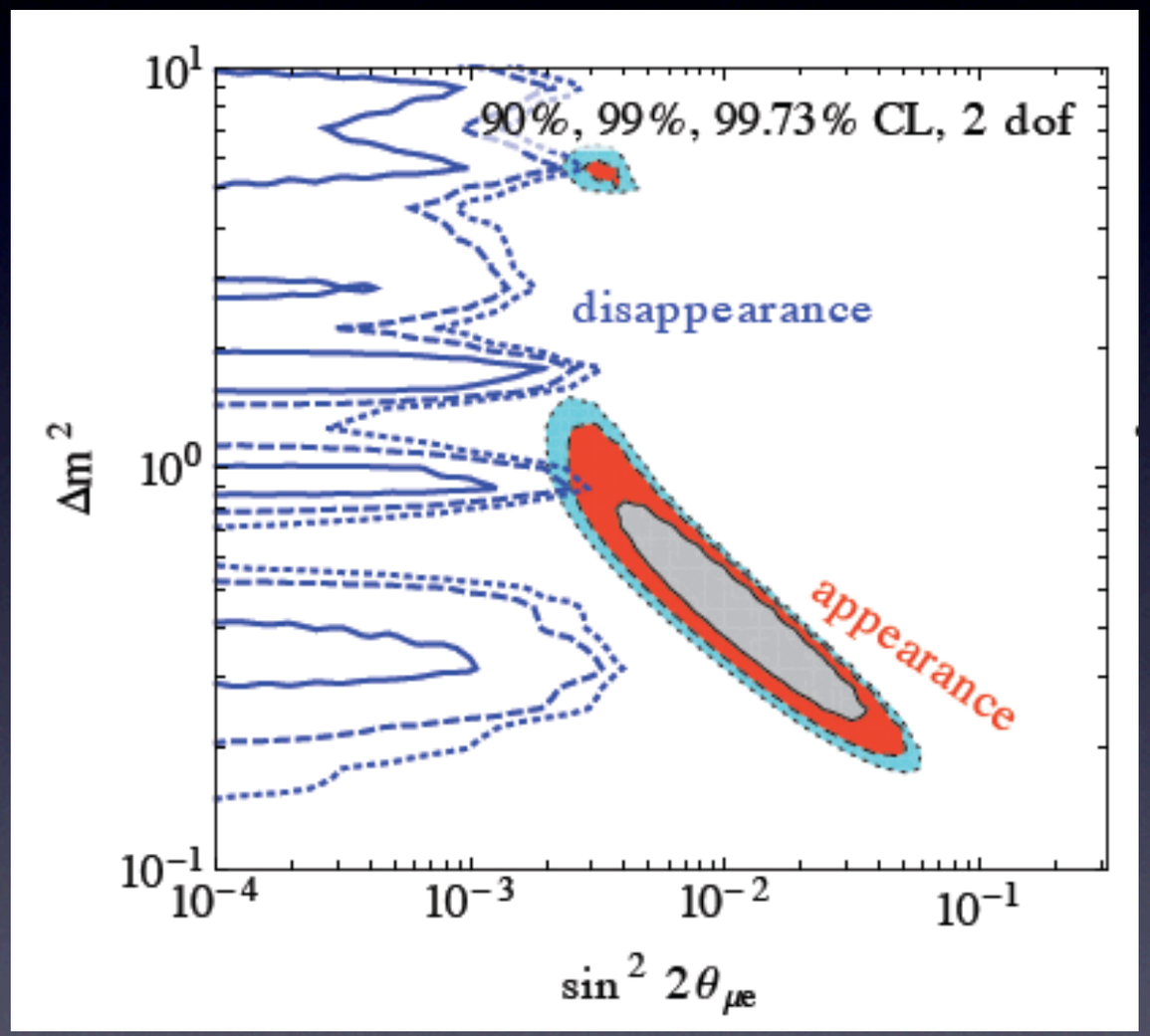
Stringent bounds from cosmology:

[Saviano 2015]

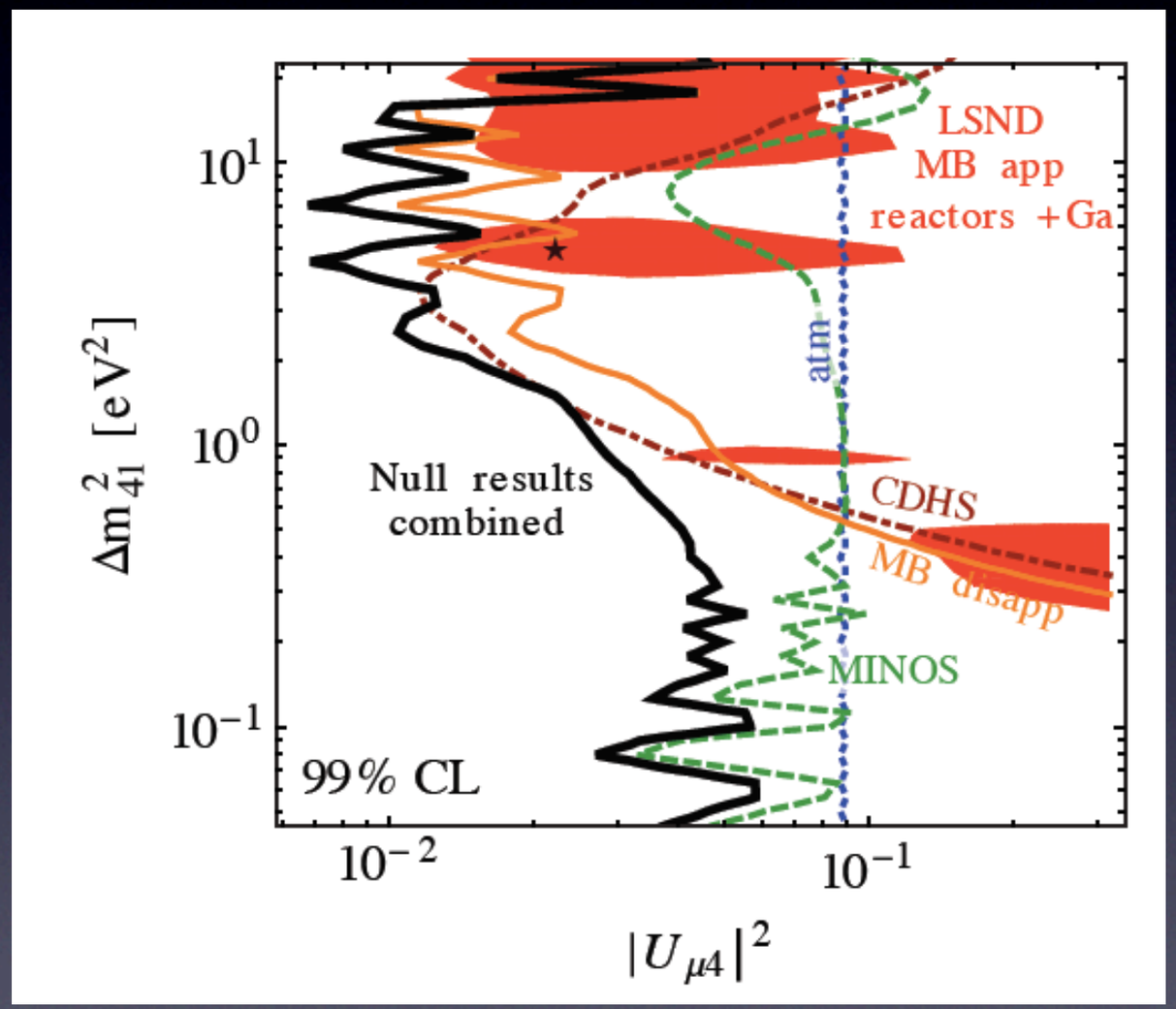


A 4th sterile neutrino ?

Appearance-disappearance tension



Evidences vs. null results combined



[Kopp, Machado, Maltoni, Schwetz, 2014]

[→ Talk by Georgia Karagiorgi]

A 4th sterile neutrino ?

Sterile netrinos 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...]

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

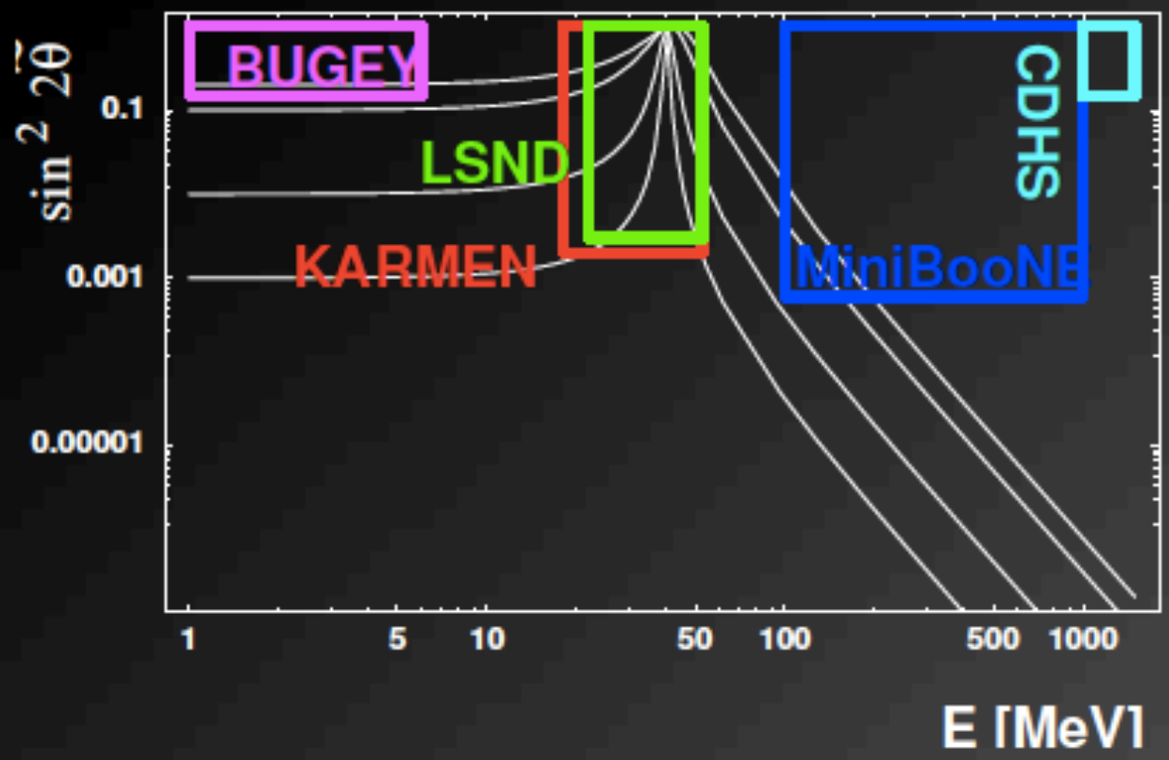
(Päs, Pakvasa, Weiler, 2005)

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
- Fast oscillations:

[Marfatia, HP, Pakvasa, Weiler, 2012]

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

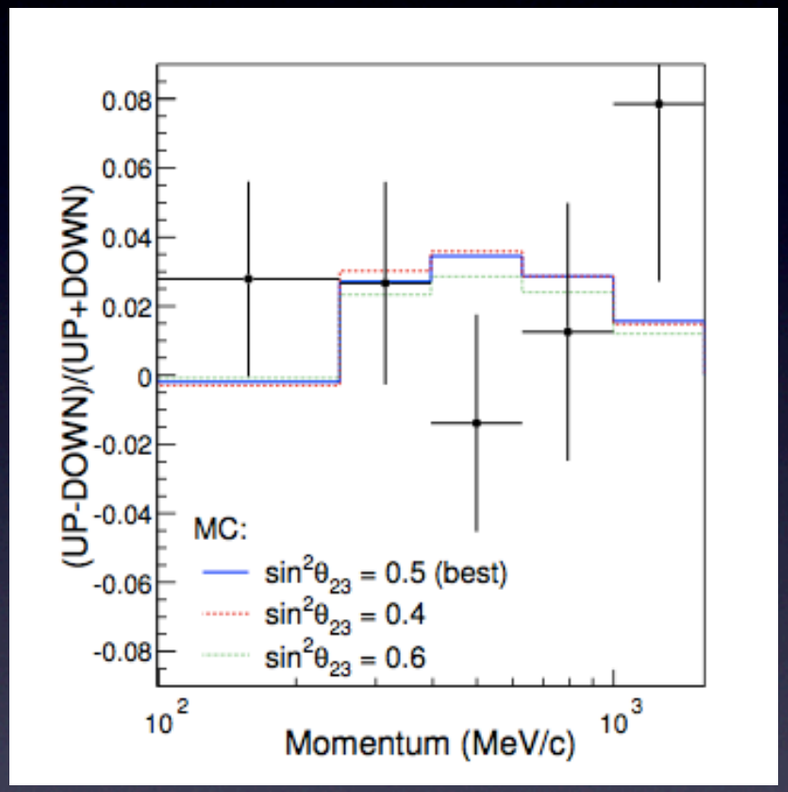
- Contrary to matter effects: Sterile neutrino Lorentz violation strictly constrained by atmospheric ν L/E

[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!

Shortcuts from asymmetrically warped spacetime

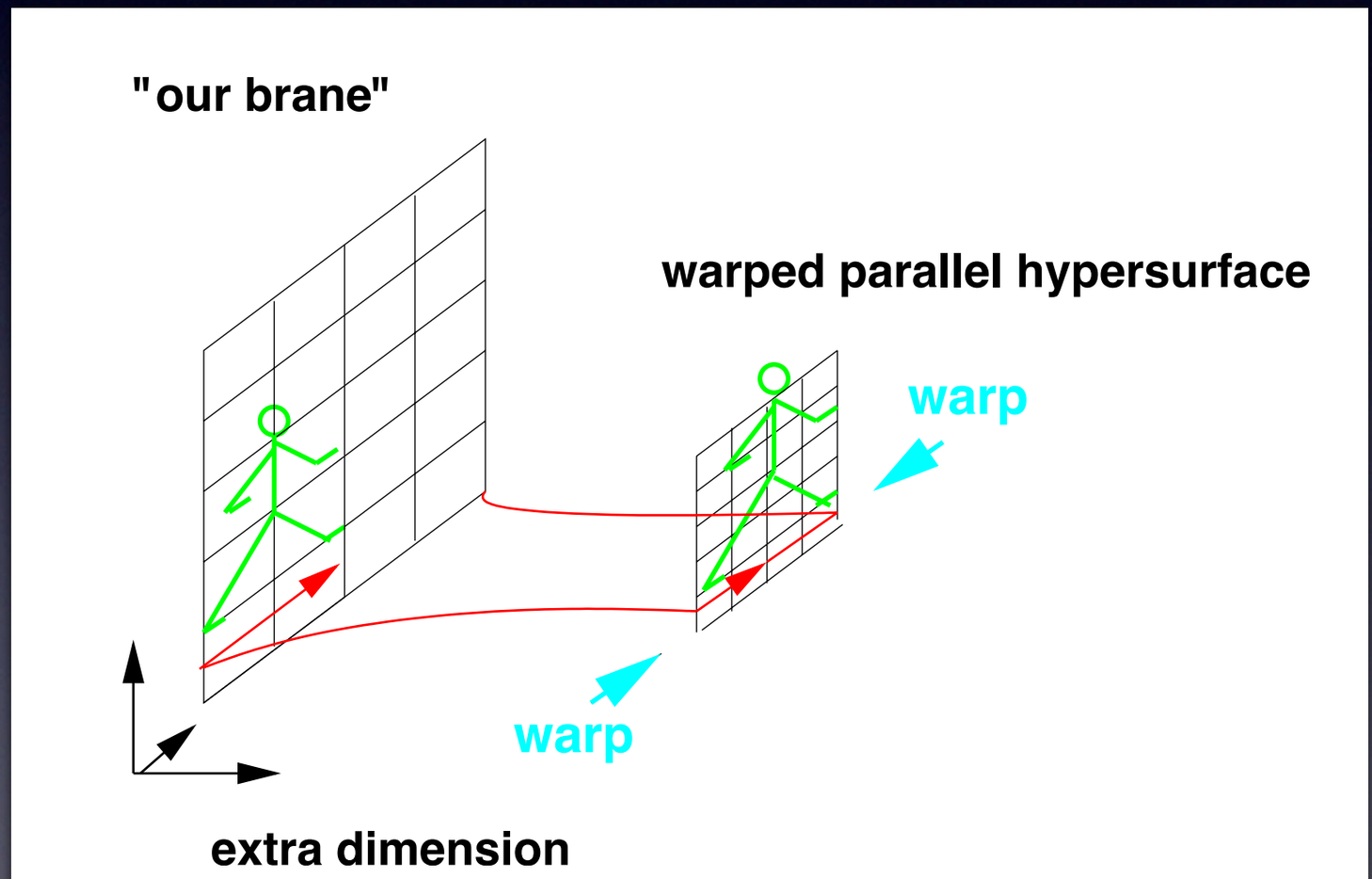
Consider an asymmetrically warped extra dimension with a sterile neutrino in the bulk

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

[Chung, Freese, 1999, 2000]

[Csaki, Erlich, Grojean, 2001]

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



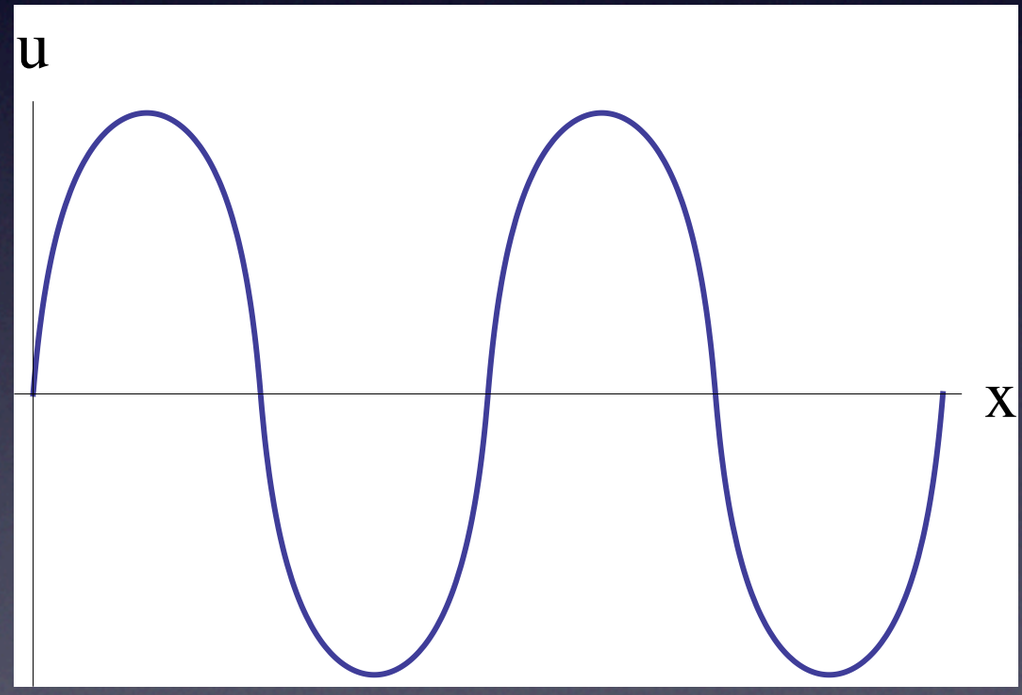
Shortcuts from asymmetrically warped spacetime

Geodesics: oscillating around the brane

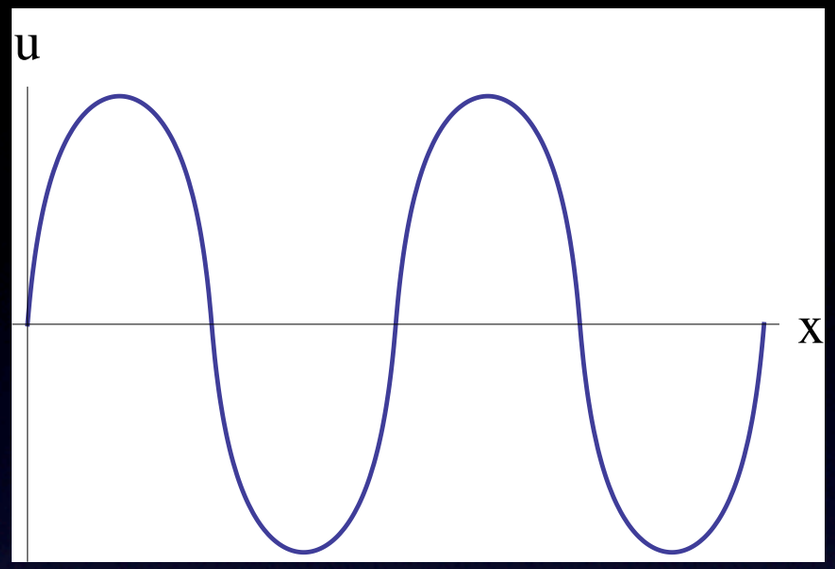
$$u(x) = \pm \frac{1}{2k} ln[1 + k^2 x(l - x)]$$

- Shortcut “switched on and off” during propagation

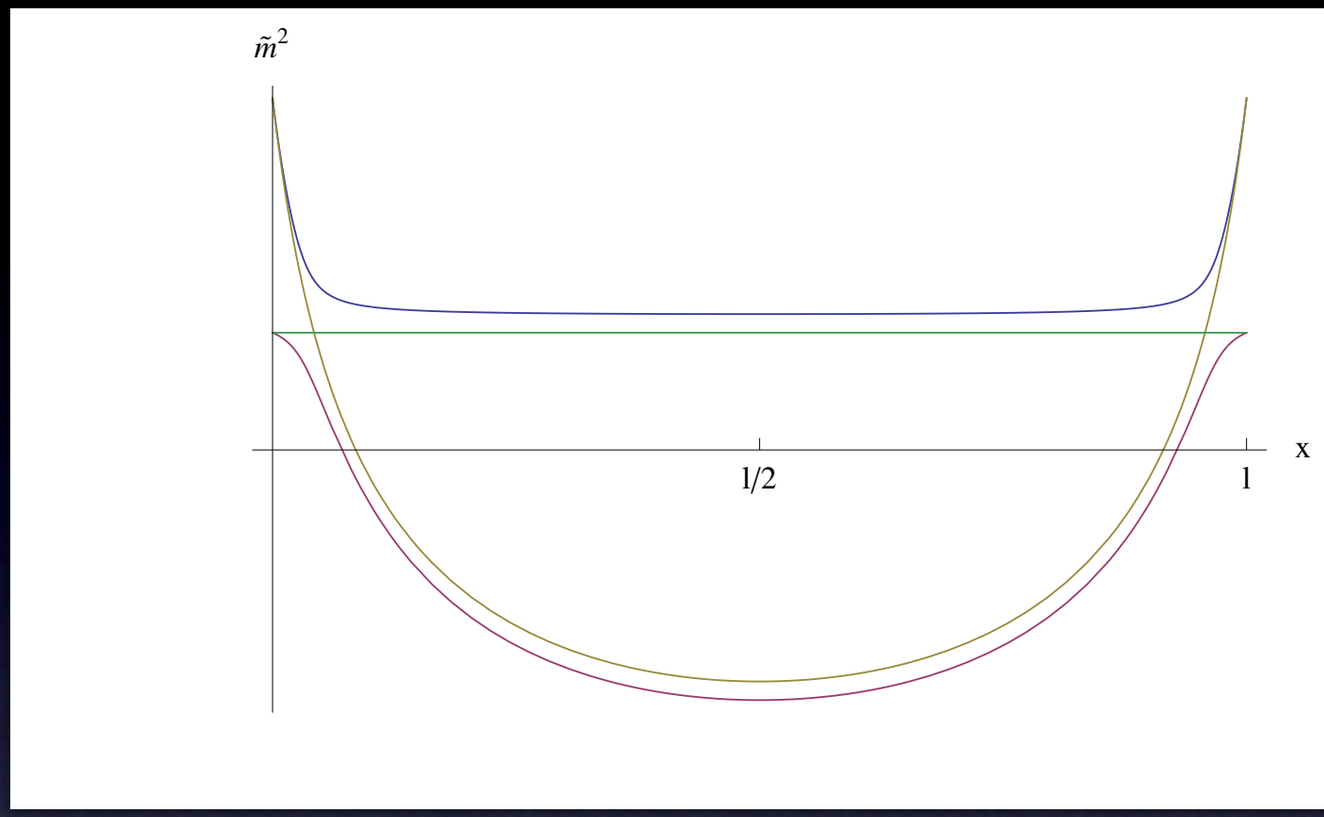
[Hollenberg, Micu, HP, Weiler, 2009]

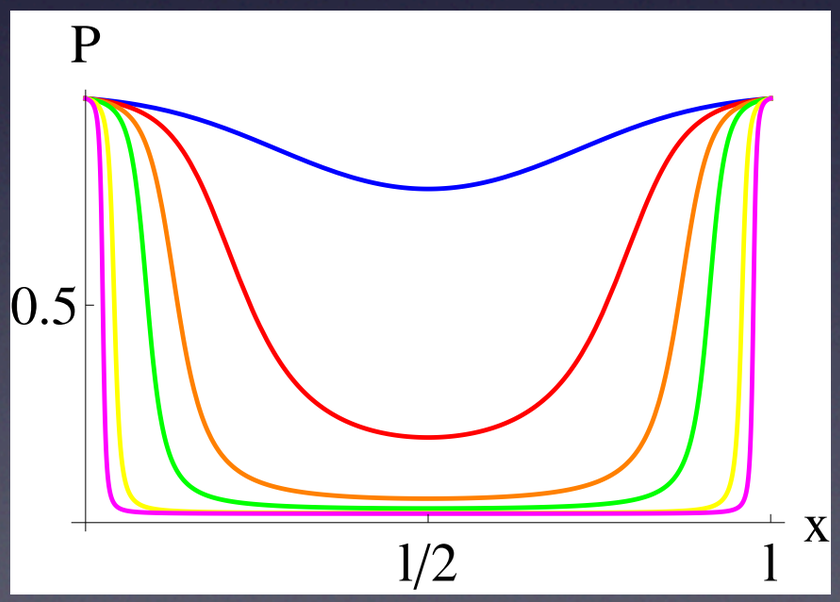


Resonant conversion



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





[HP, Sicking, Supsar, work in progress]

Compatible with atmospheric L/E?

Astrophysical Flavor Ratios

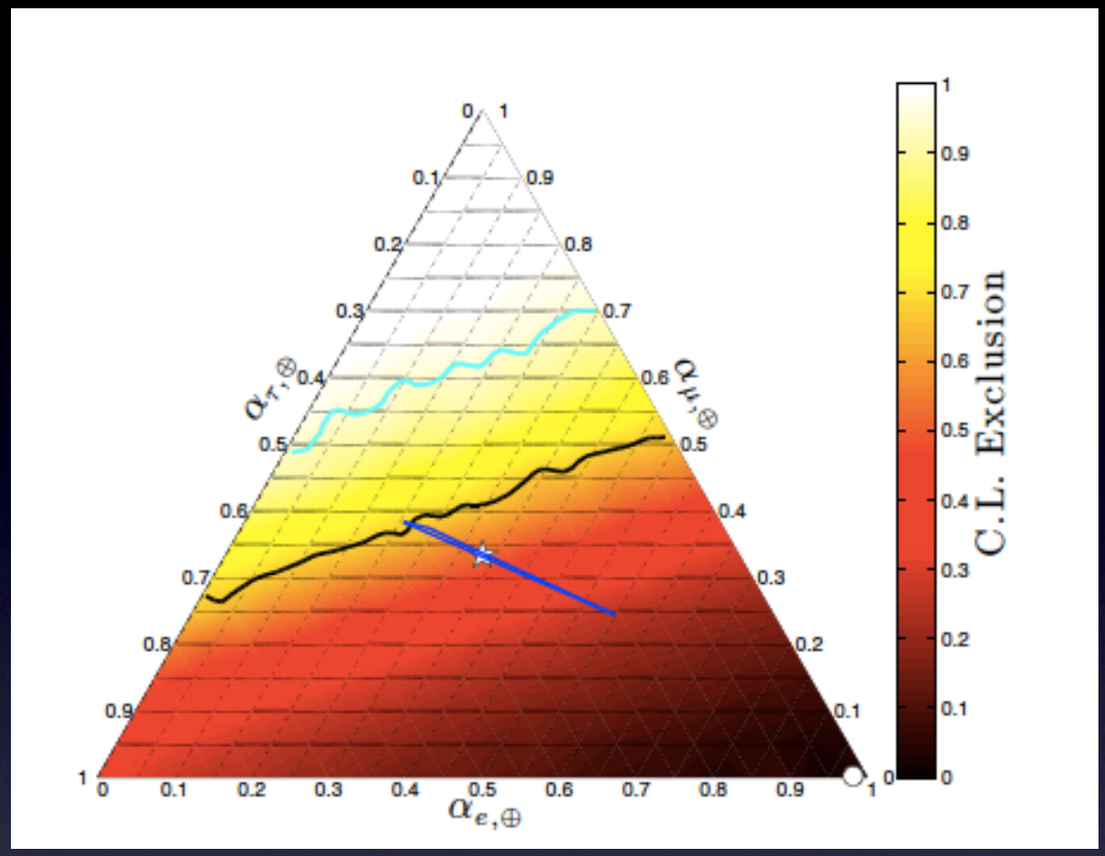
Expectation pion source:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

Flavor Ratio at the source: 1:2:0

Maximal ν_μ-ν_τ mixing: Decoherence →

Flavor Ratio: 1:1:1 at Earth



Energy interval: 60 TeV – 3 PeV

[Palomares-Ruiz, Vincent, Mena, 2015]

Flavor Ratio Best Fit: 1:0:0

Altered dispersion relations?

Astrophysical Flavor Ratios

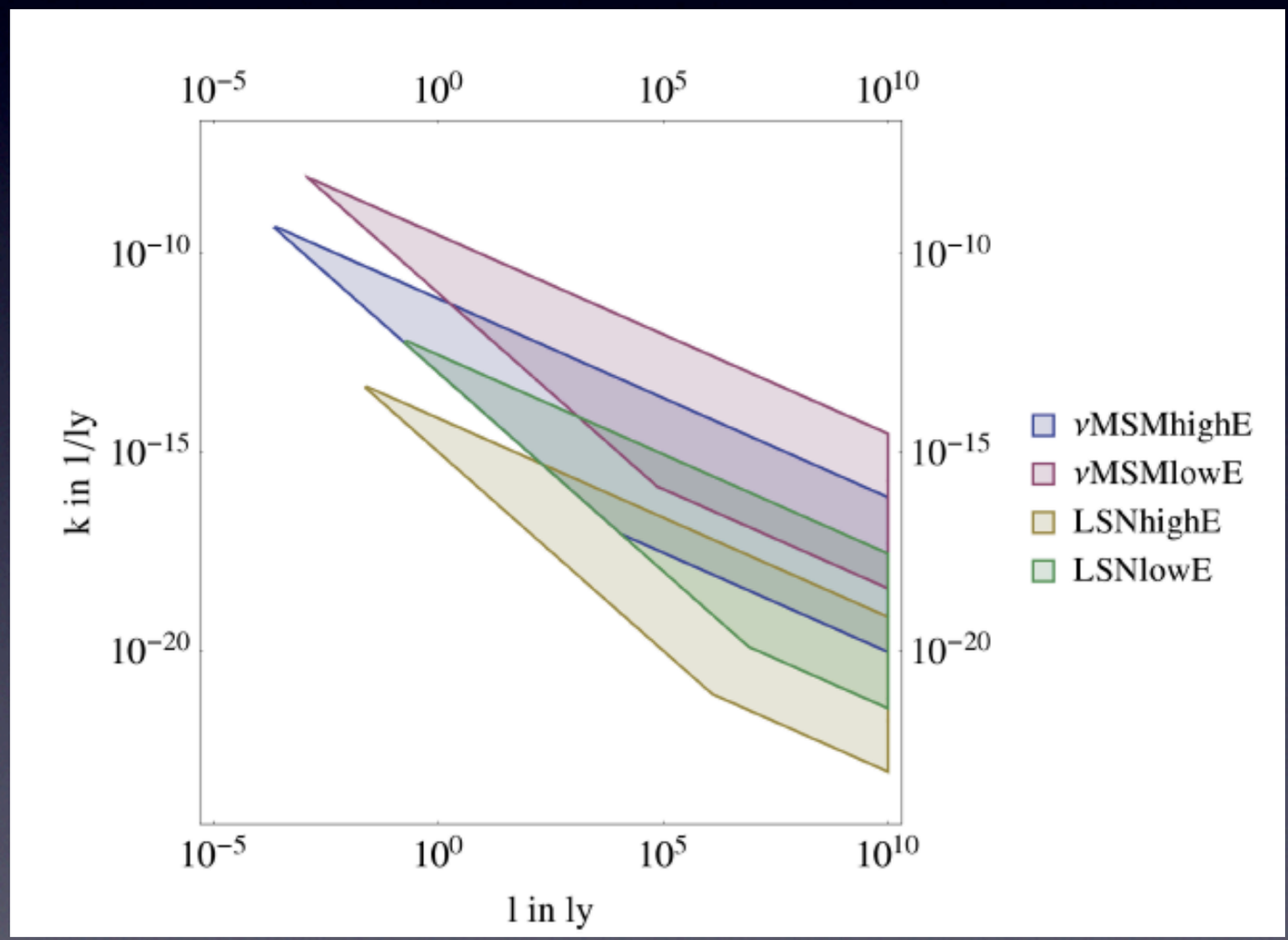
Level crossing: shortcut parameter has to be large enough?

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

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:

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

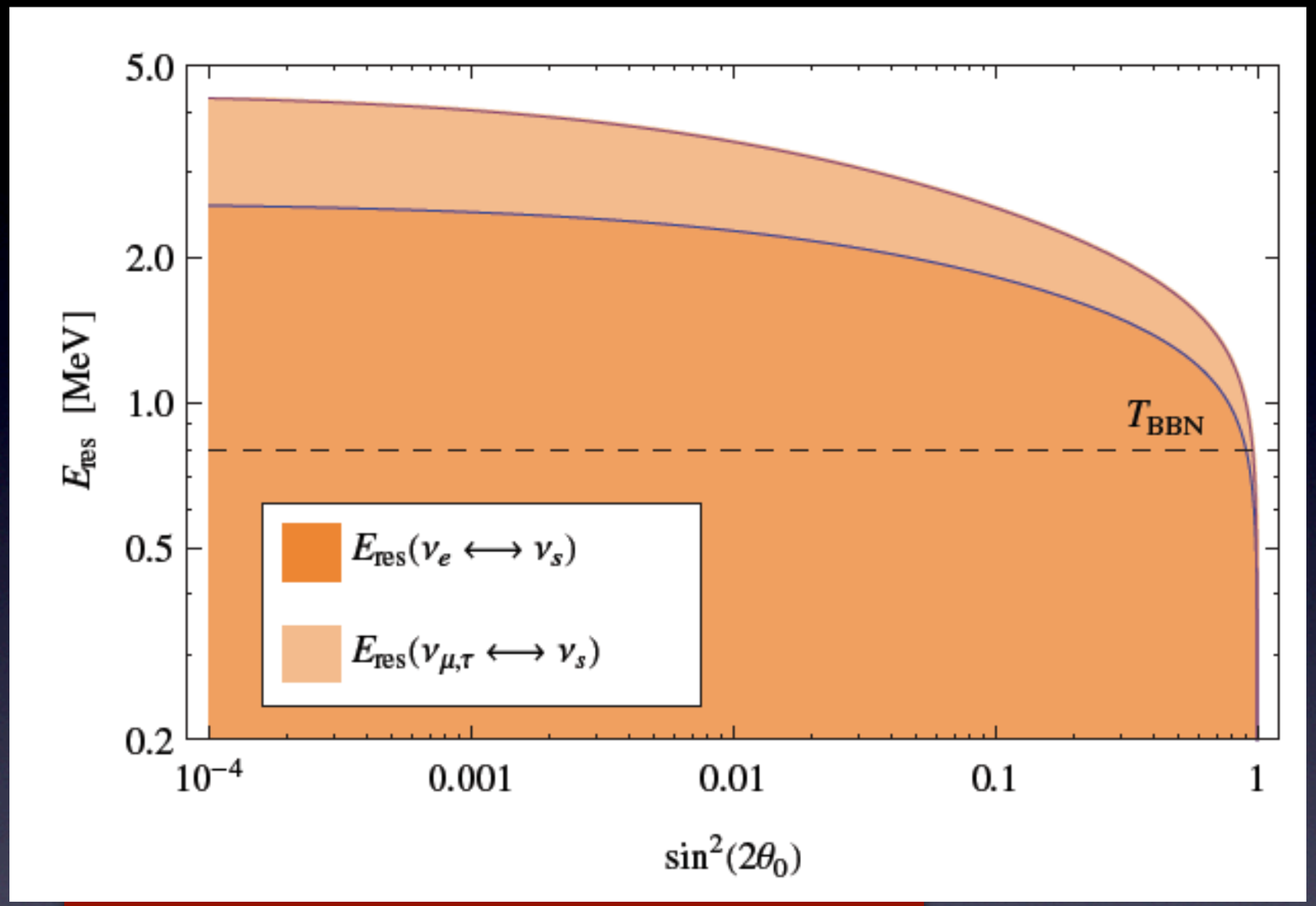
- $\rightarrow$ faster expansion of the universe
- $\rightarrow$ higher temperature for weak freezeout
- $\rightarrow$ more neutrons $\rightarrow$ larger ^4He abundance

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_{res}
If $E_{\text{res}} \lesssim 3$ MeV: oscillations suppressed (Päs, Pakvasa, Weiler, 2005)

Big Bang Nucleosynthesis



Small E_{Res} allows for large mixing!

Similar aguments work for other cosmological bounds!

[Aeikens, HP, Weiler, work in progress]

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!