Sterile Neutrinos
with
Altered Dispersion Relations
as an **Explanation** for
MiniBooNE, LSND, Gallium & Reactor Anomalies

- Heinrich Päs -

tu dortmund

Fermilab August 22, 2019

2018/19: What's new?

- MiniBooNE anomaly: 4.8σ (+LSND: 6.1σ)
  arXiv:1805.12028
- A working phenomenological framework
  arXiv:1808.07734
- An extra-dimensional model yielding the phenomenology as 4D EFT limit
  arXiv:1808.07460
- Fits to MiniBooNE & LSND data
  Work in progress with Dominik Döring, En-Chuan Huang & Bill Louis

Outline

- Neutrino Physics Overview
- The case for sterile neutrinos
- Altered dispersion relations: The basic idea
- A phenomenological framework
- An extra-dimensional model
- Cosmological bounds & consequences

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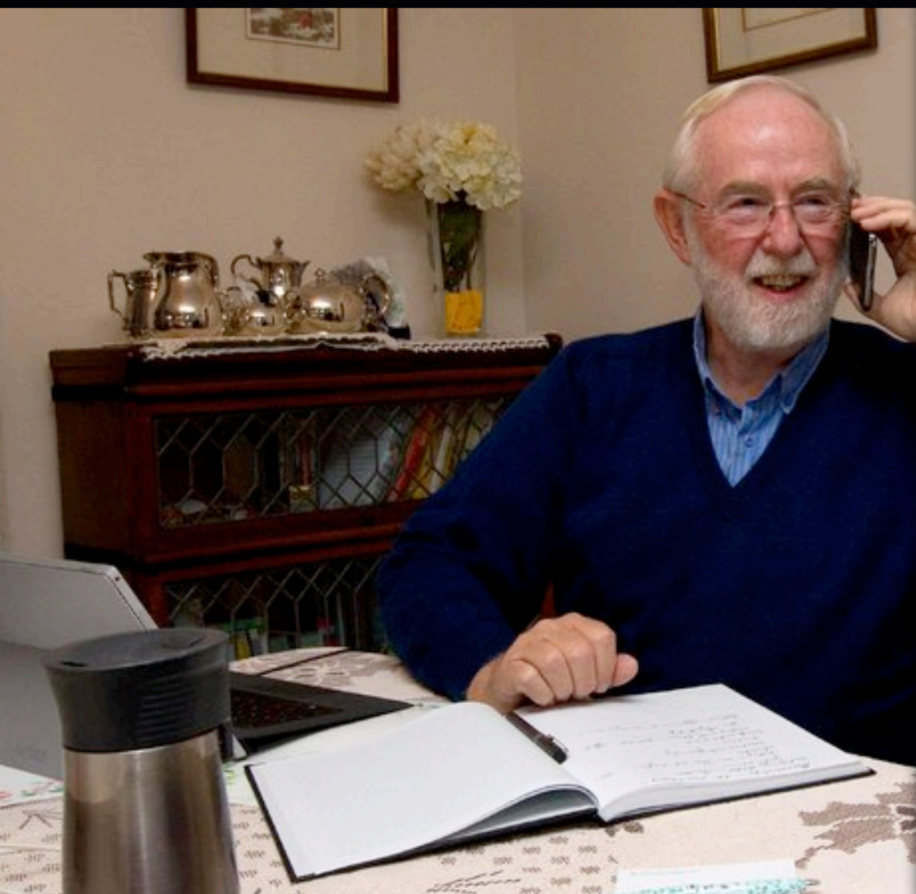
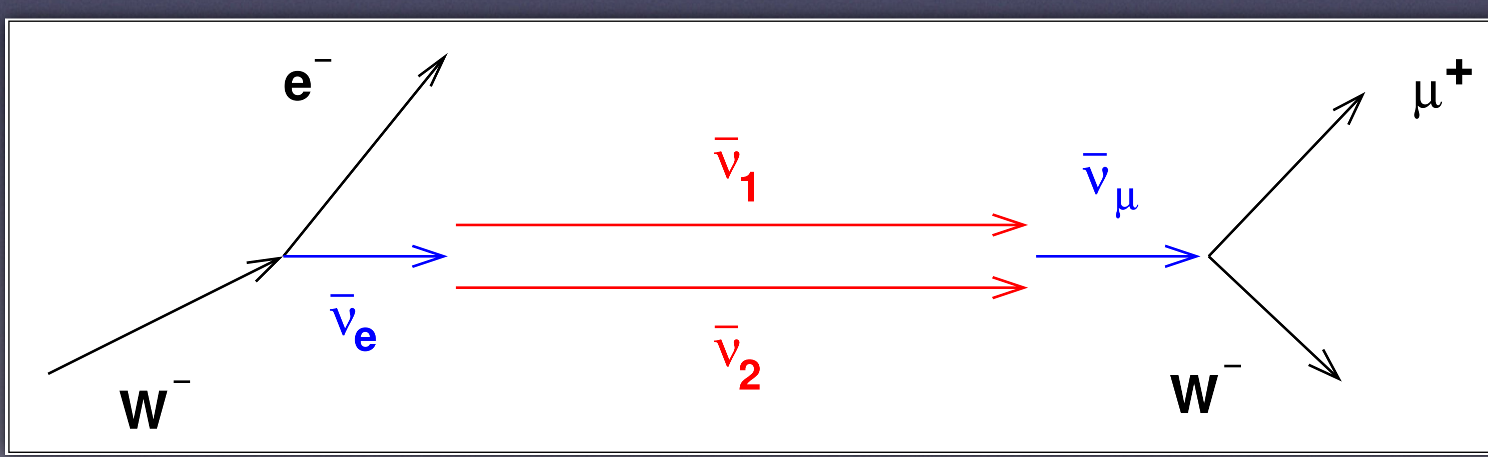
4 years ago...



The New York Times

Takaaki Kajita of the University of Tokyo and Arthur B. McDonald of Queen's University in Ontario were awarded the Nobel Prize in Physics on Tuesday for discovering that the enigmatic subatomic particles known as neutrinos have mass.



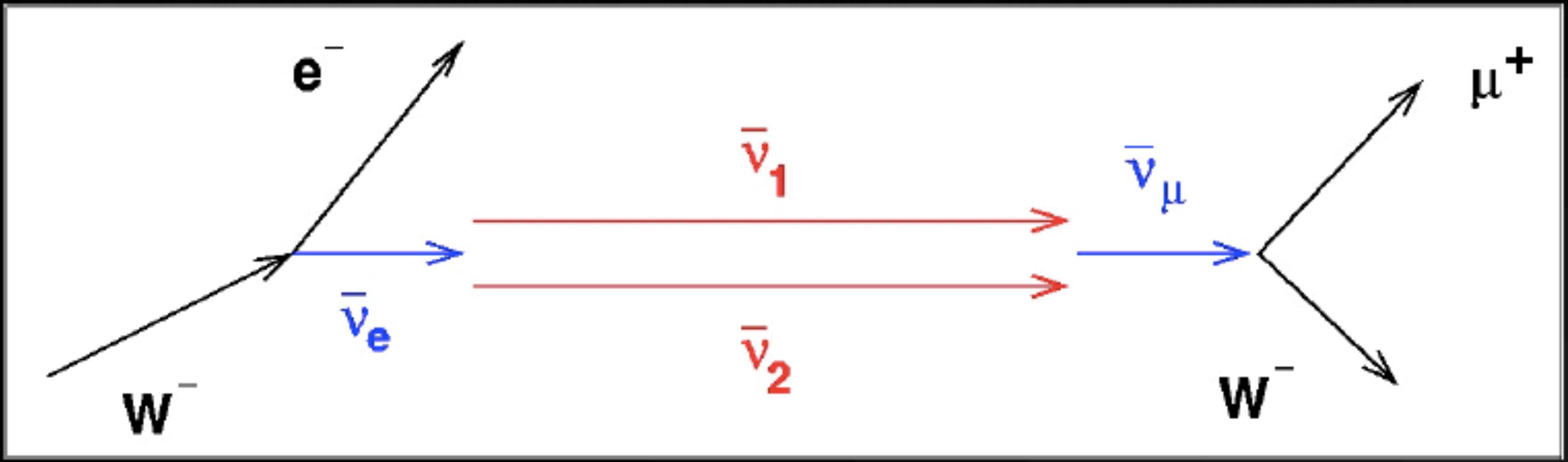
$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

Neutrino Oscillations: 2 Flavor Case

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

Neutrino Oscillations: 2 Flavor Case



2 conditions:

- Neutrinos possess mass
- Mass eigenstates $\neq$ Flavor eigenstates $|\nu_e\rangle = \sum_{i=1}^{3} U_{ei}|\nu_i\rangle$

2 states system: $U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$

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

Neutrino Oscillations: 2 Flavor Case

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

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

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

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

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

…2018/19: Precision Science

$$U_{3\times 3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

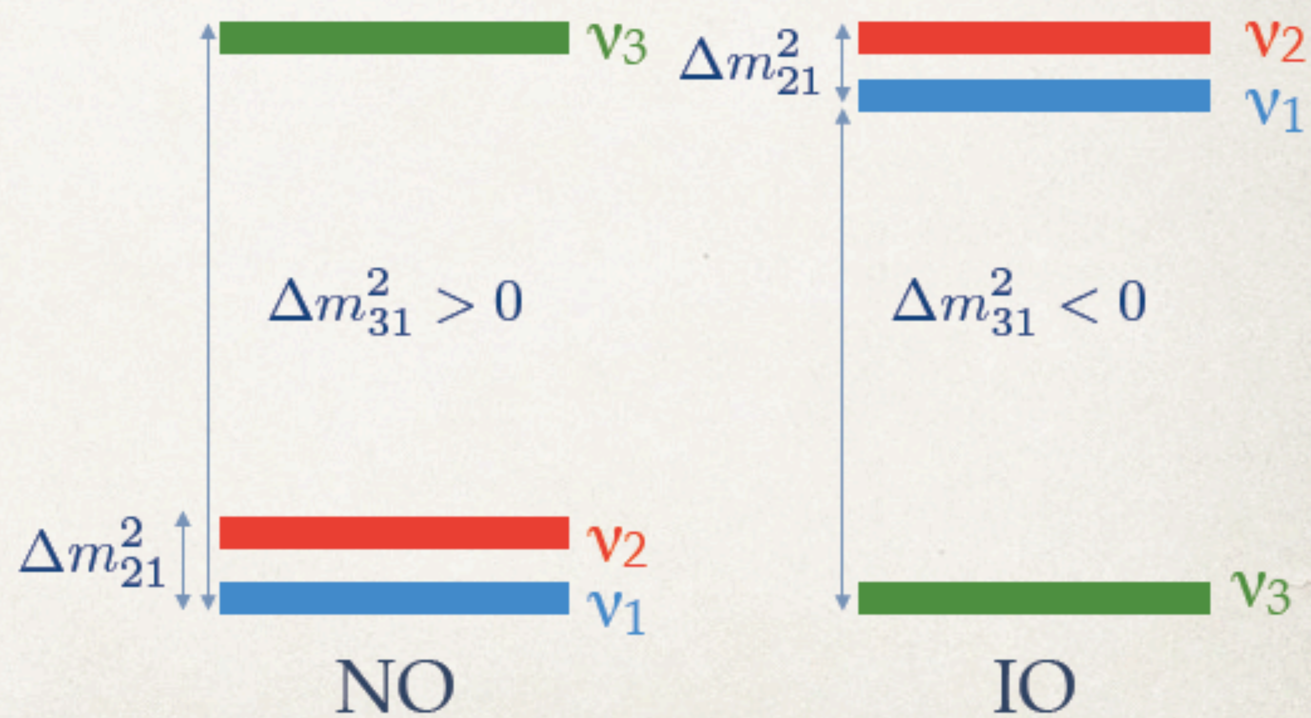
- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- three CP phases: 1 Dirac + 2 Majorana
- three masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$\Delta m^2_{21}, \Delta m^2_{31}$

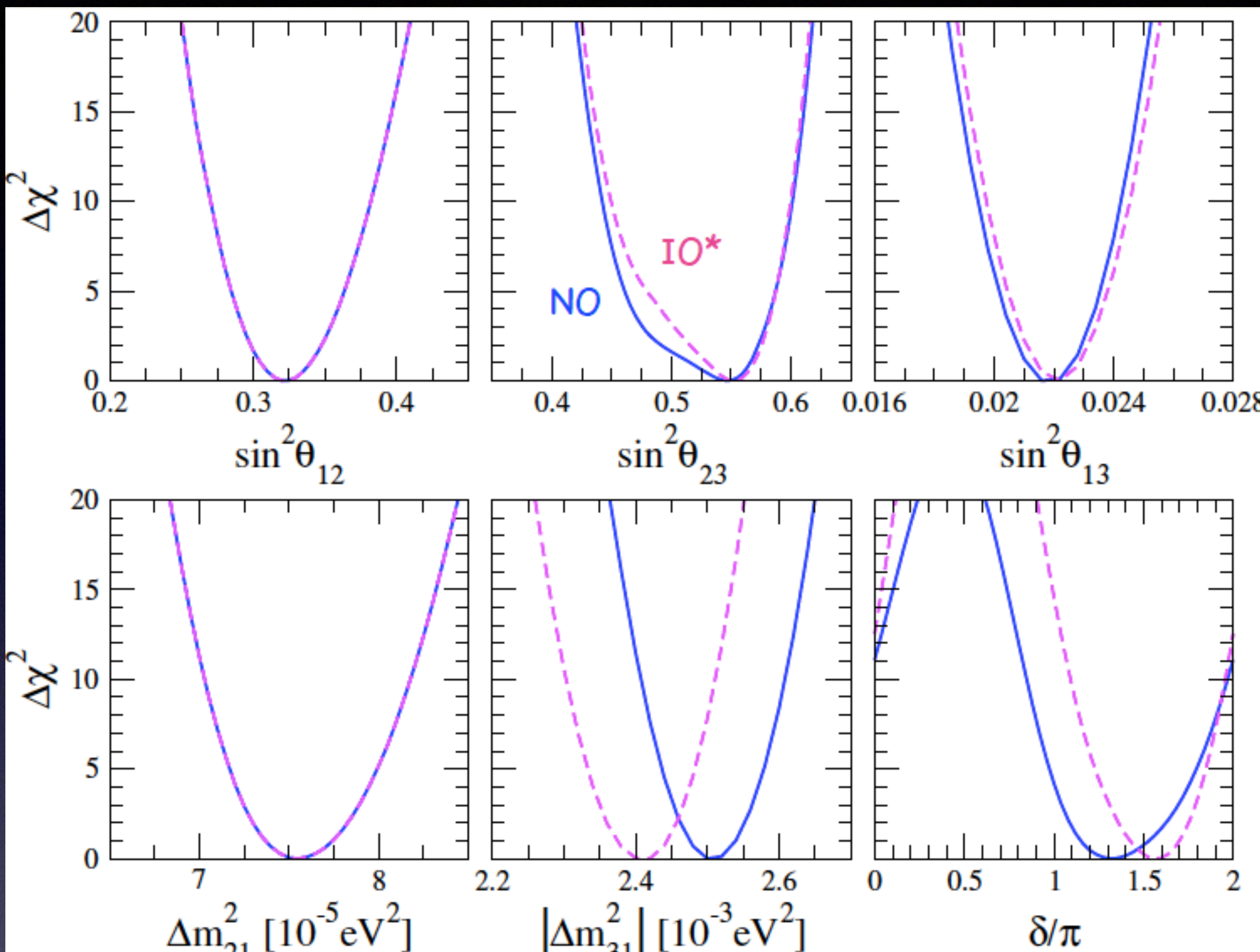
neutrino mass spectrum



$$|\Delta m^2_{31}|_{NO} > |\Delta m^2_{31}|_{IO}$$

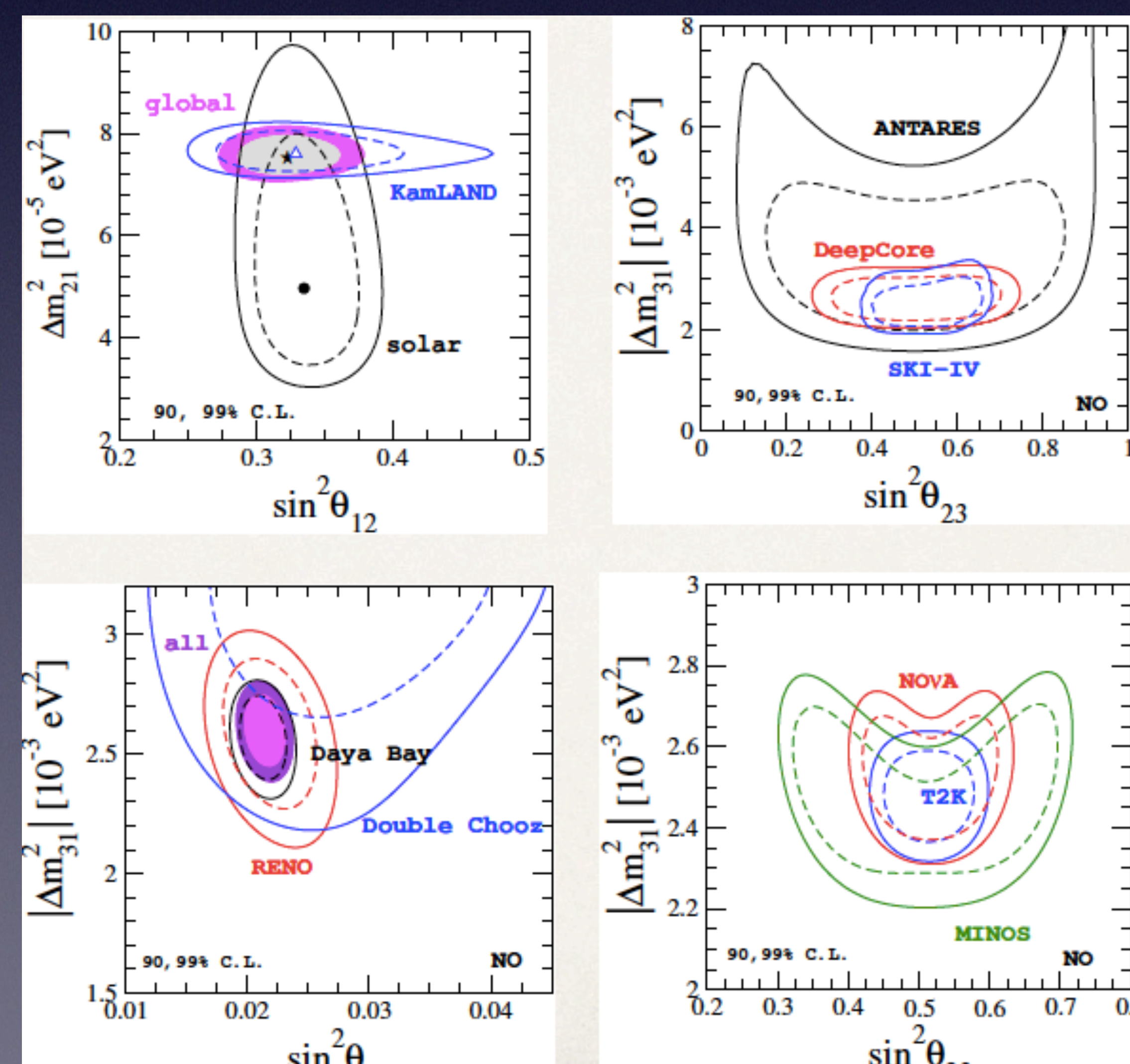
Mariam Tortola, Talk at Neutrino2018

Global data fits



Consistent picture of 3-neutrino mixing

Mariam Tortola, Talk at Netrino2018



Δm^2's and mixing angles determined at the few-% Level

Open Questions

- Absolute Mass Scale?
  →KATRIN, Cosmology, 0vBB Decay
- Mass Hierarchy?
  →3σ preference for NO
- CP Violation?
  →2σ (NO)/3.8σ (IO) evidence for CPV
  →Best fit 3π/2
- Mechanism of Neutrino Mass Generation?
- Dirac or Majorana?
  →Lepton Number Violation?, 0vBB Decay
- More than 3 Neutrinos?
  →Reactor, Gallium, LSND & MiniBooNE anomalies

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Sterile Neutrinos?

Physics ABOUT BROWSE PRESS COLLECTIONS CELEBRATING 10 YEARS

Viewpoint: The Plot Thickens for a Fourth Neutrino

Joachim Kopp, Theoretical Physics Department, CERN, Geneva, Switzerland, and PRISMA Cluster of Excellence, Mainz, Germany

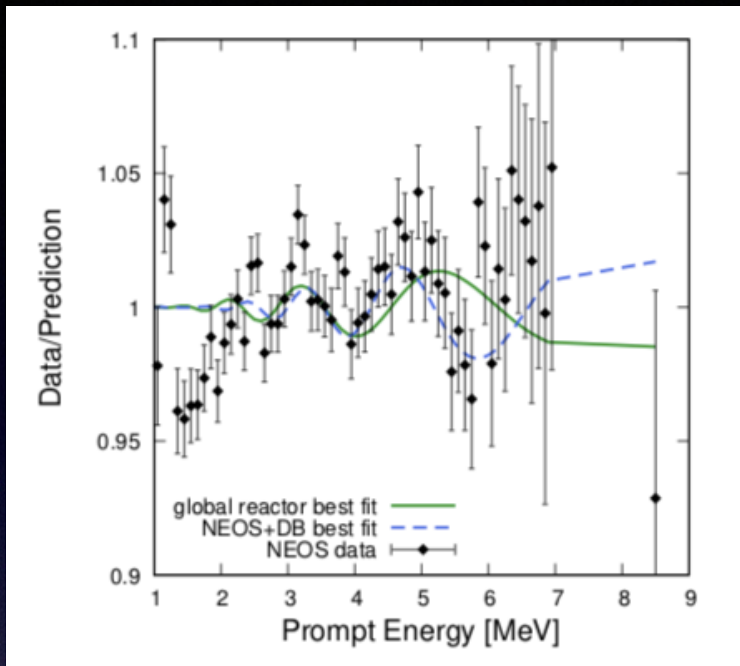
November 26, 2018 • *Physics* 11, 122

Confirming previous controversial results, the MiniBooNE experiment detects a signal that is incompatible with neutrino oscillations involving just the three known flavors of neutrinos.

Physics, American Physical Society, November 26, 2018

Sterile Neutrinos?

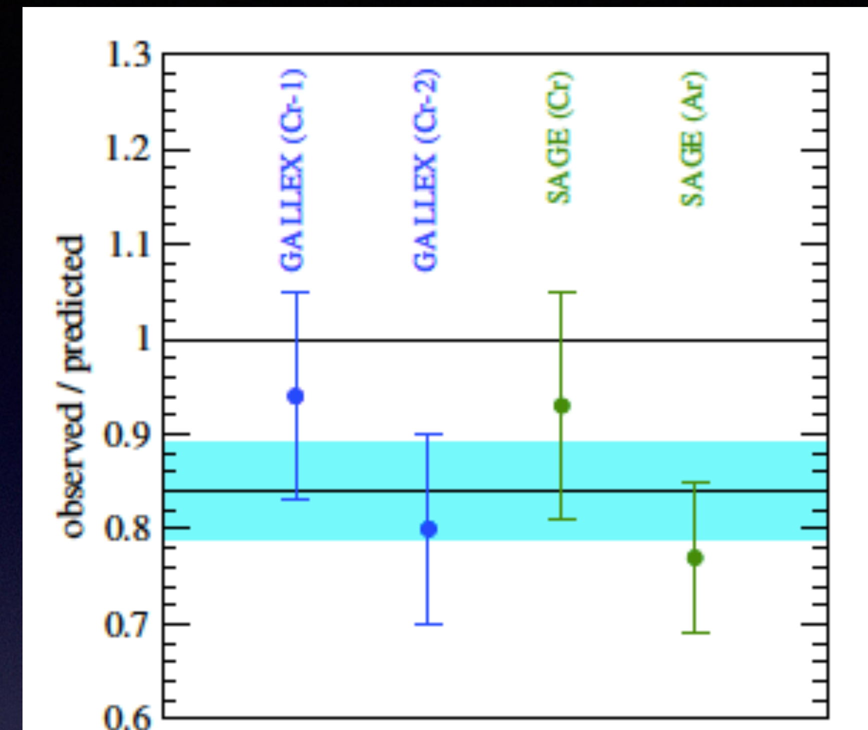
Reactor Anomaly



$\nu_e \rightarrow \nu_e$

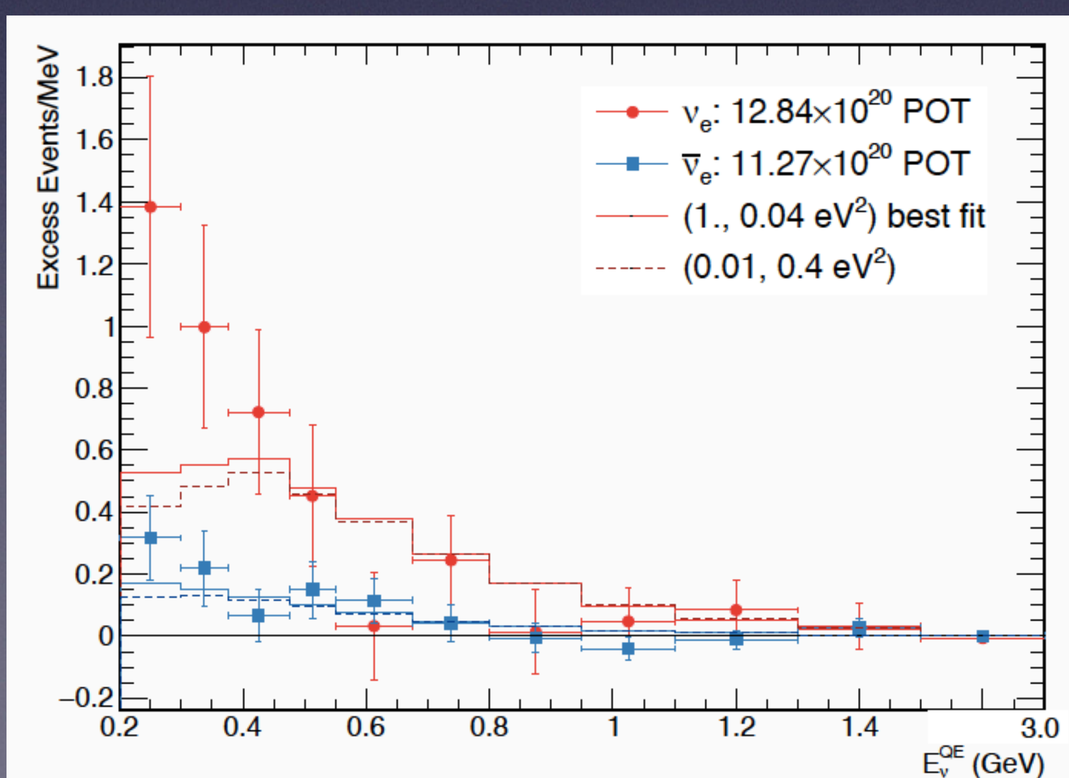
All pointing towards a 1 eV sterile neutrino!

Gallium Anomaly



$\nu_e \rightarrow \nu_e$

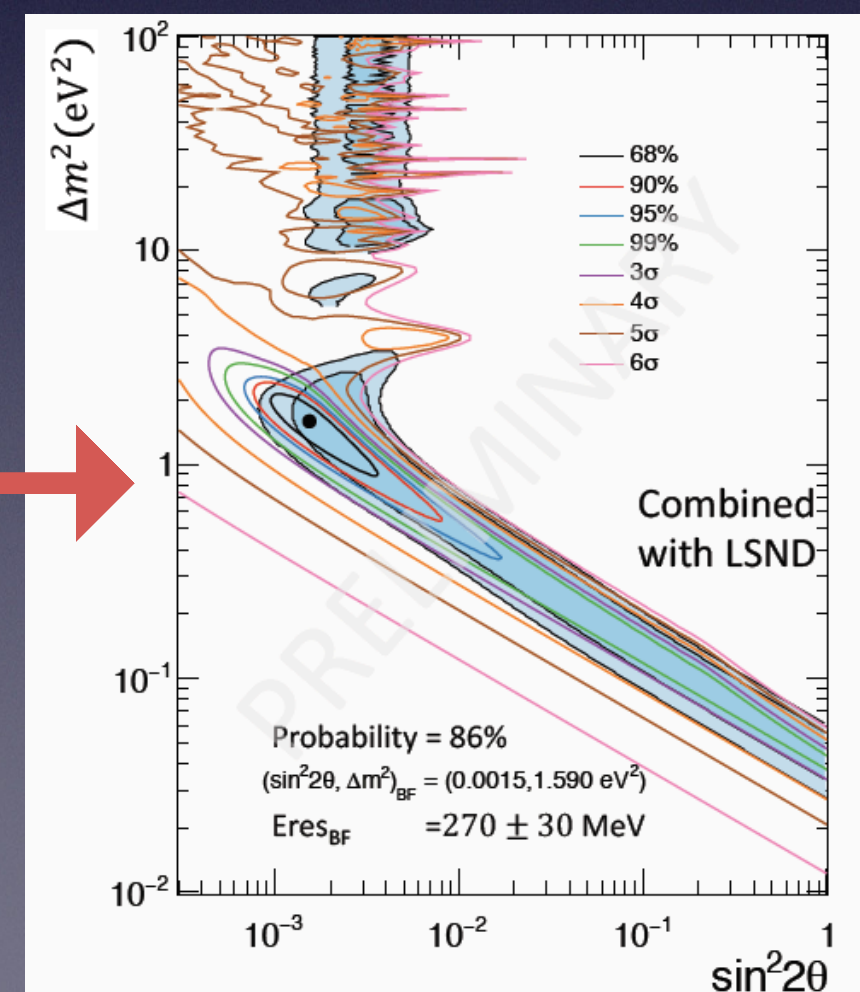
LSND/MiniBooNE Anomaly



$\nu_\mu \rightarrow \nu_e$

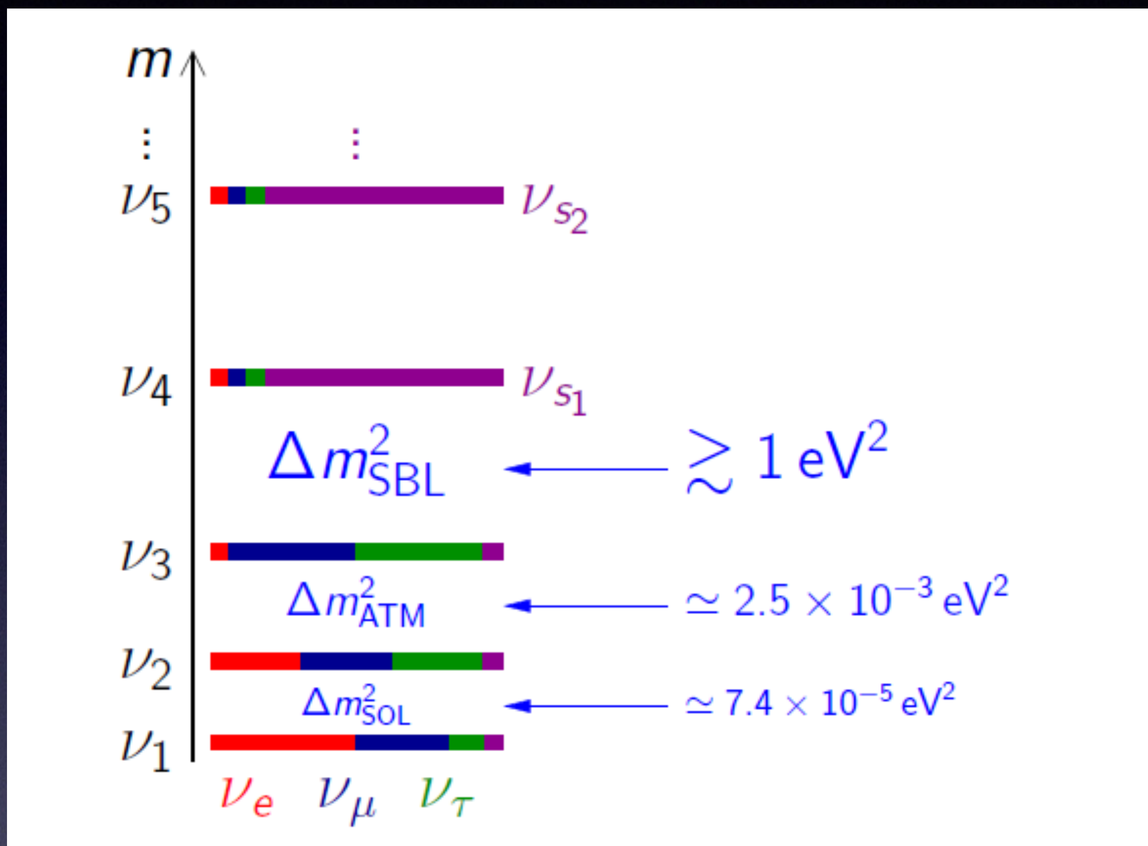
"Hypothetical MSW-like resonance model"

En-Chuan Huang, Talk at Netrino2018



Sterile Neutrinos?

→ Add a sterile neutrino with $\Delta m^2 \sim 1\ eV^2$



Conrad/Shaevitz

To explain LSND/MiniBooNE:

ν_s -mixing with both ν_e and ν_μ :

$$\sin^2 2\theta_{\mu e} = 4\,|U_{\mu 4}|^2 |U_{e4}|^2 = \frac{1}{4}(\sin^2 2\theta_{\mu\mu} + 4\,|U_{\mu\mu}|^4)(\sin^2 2\theta_{ee} + 4\,|U_{ee}|^4)$$

$$\simeq \frac{1}{4}\sin^2 2\theta_{\mu\mu}\sin^2 2\theta_{ee},$$

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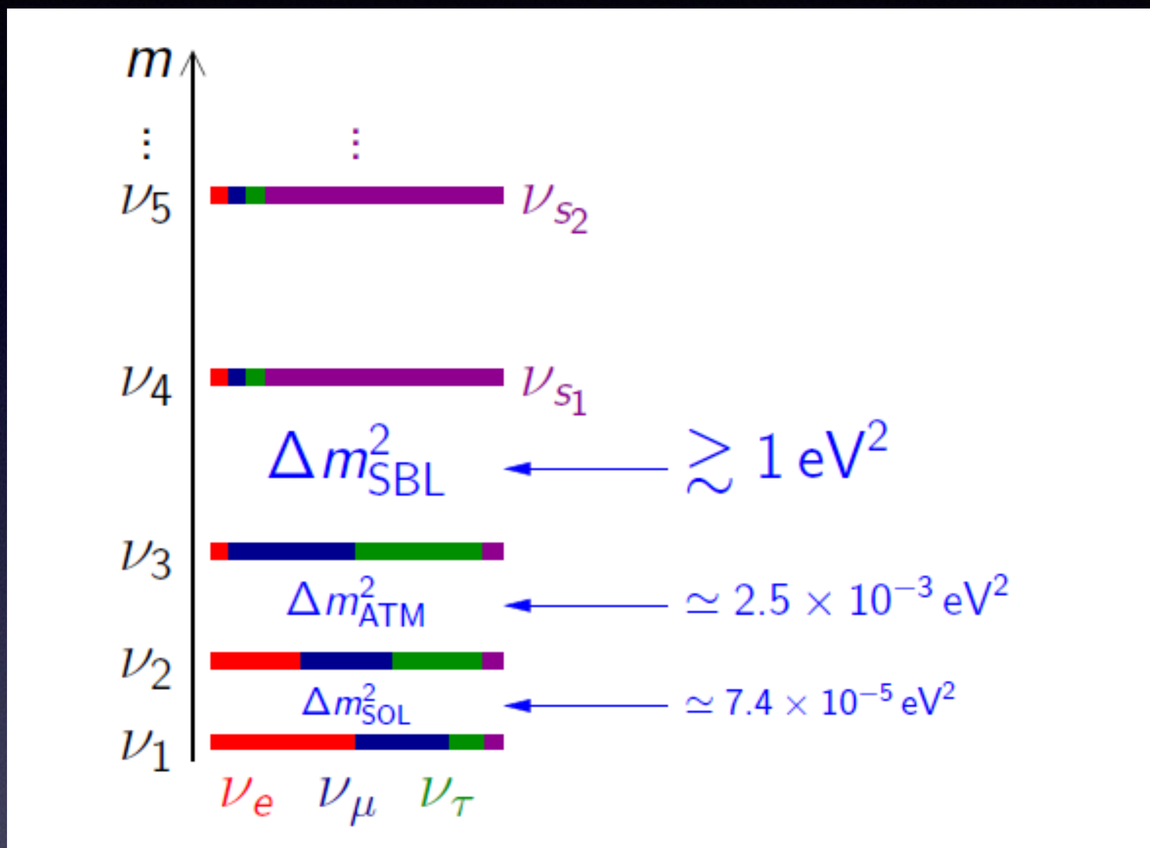

Conrad/Shaevitz

constrained by ν_μ disappearance

constrained by ν_e disappearance

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Giunti, Zavanin, 2015

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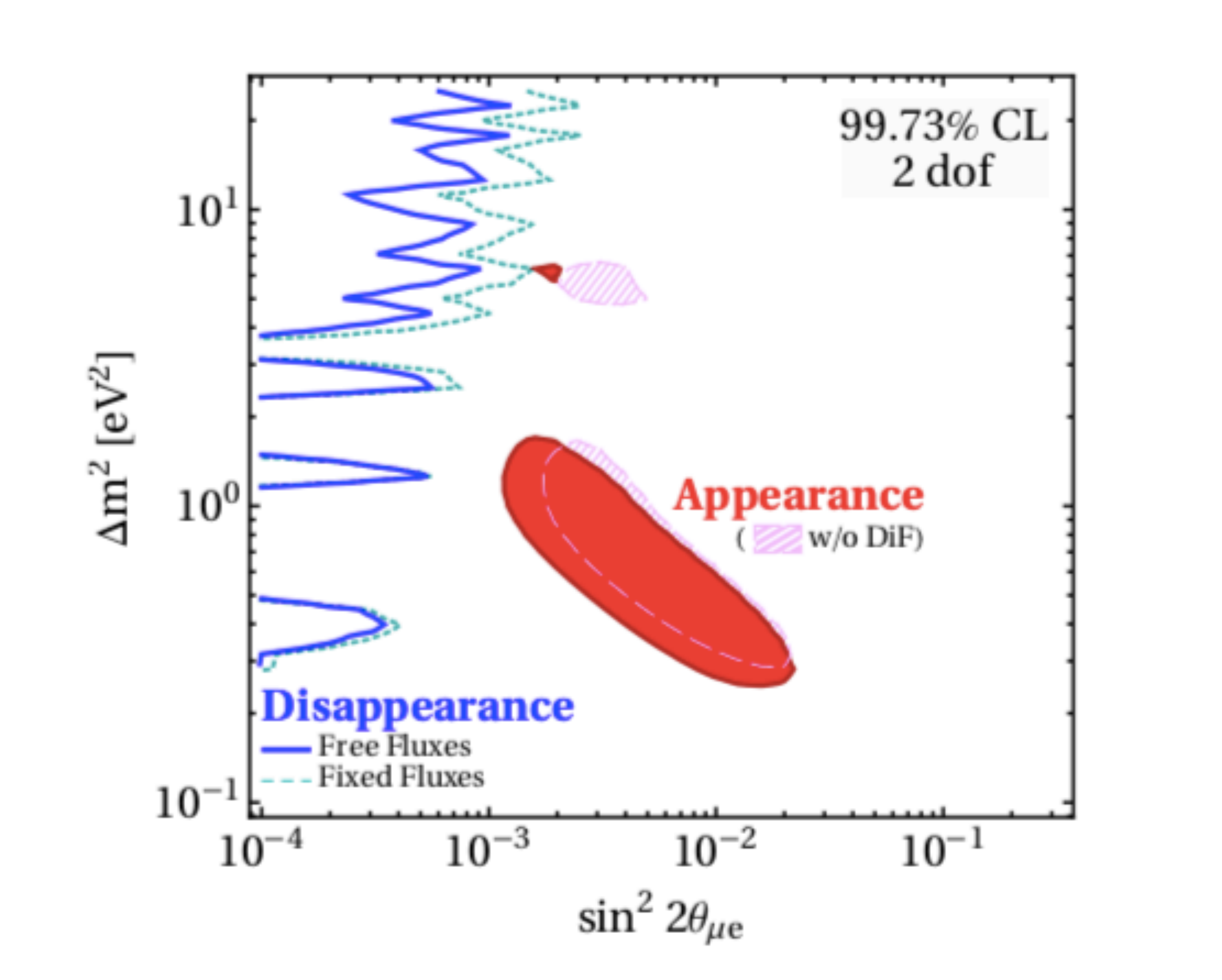
Sterile Neutrinos?

Appearance versus Disappearance Experiments



Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, 2018

Neutrino Oscillation evidence for energies <1 GeV & no evidence for energies >1 GeV!

Bill Louis, TomFest, august 2019

Alternative Explanations?

- Heavy particle decay
  Bertuzzo, Jana, Machado, Zukanovich Funchal, 2018;
  Ballett, Pascoli, Ross-Lonergan, 2018
  →Reactor and Gallium anomalies?
  → severely constrained by MiniBooNE electron-like event energy and angular distributions in the full MiniBooNE data-set *Jordan et al., 2018*

- Non-Standard Interactions
  Liao, Marfatia, Whisnant, 2018;
  Denton, Farzan, Shoemaker, 2018
  →resonant-like structure in MiniBooNE?

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

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Sterile neutrino Altered Dispersion Relations

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

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

→ novel energy dependence!

HP, Pakvasa, Weiler 2005

Sterile neutrino Altered Dispersion Relations

Attractive candidate: Altered dispersion relations

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

- Exotic matter effects, new interactions *[Nelson...]*
  →relevant for either ν or anti-ν !
- Lorentz violation *[Barenboim, Quigg, Kostelecky....]*
- Shortcuts in extra dimensions *[HP, Pakvasa, Weiler...]*

Sterile neutrino Altered Dispersion Relations

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Altered dispersion relations: vanilla type

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:

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

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

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

Change in the Hamiltonian: $\Rightarrow \Delta H_{\text{eff}} = H \Delta t / T \rightarrow \varepsilon E$

(Päs, Pakvasa, Weiler, 2005)

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

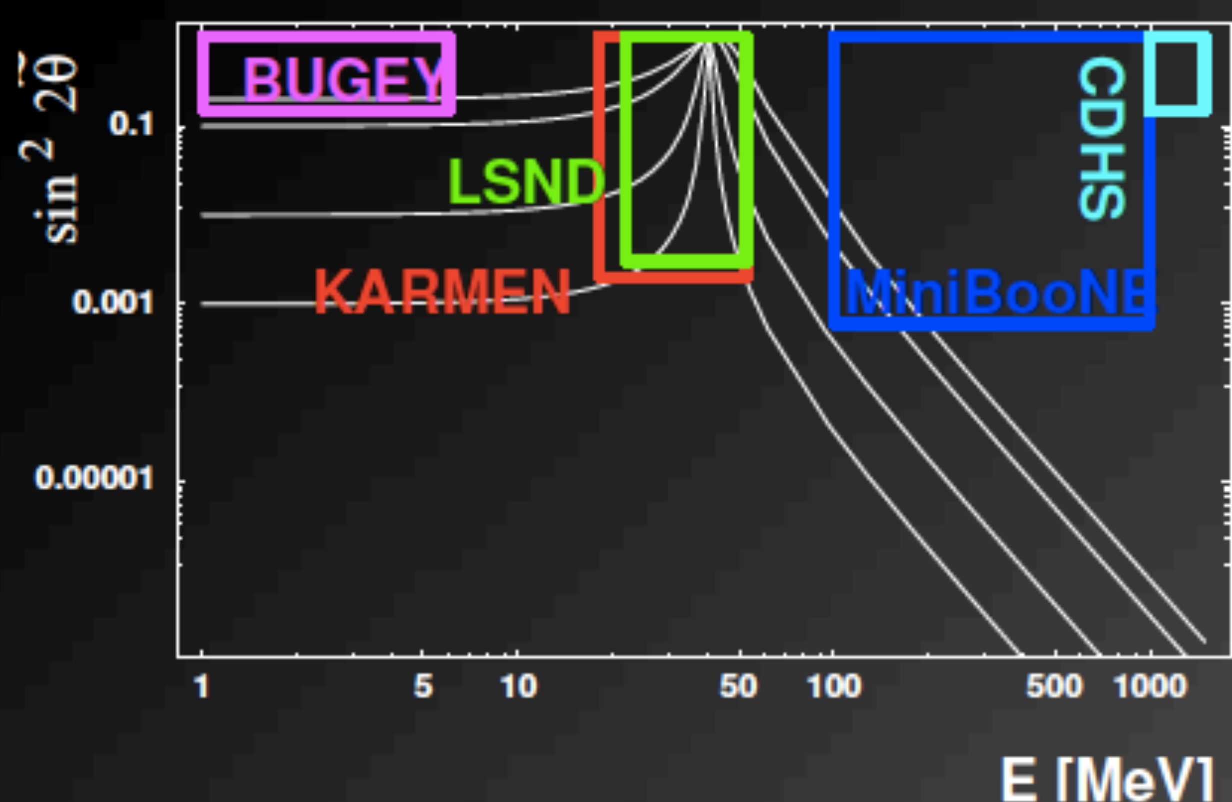
(Päs, Pakvasa, Weiler, 2005)

Altered dispersion relations: vanilla type

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

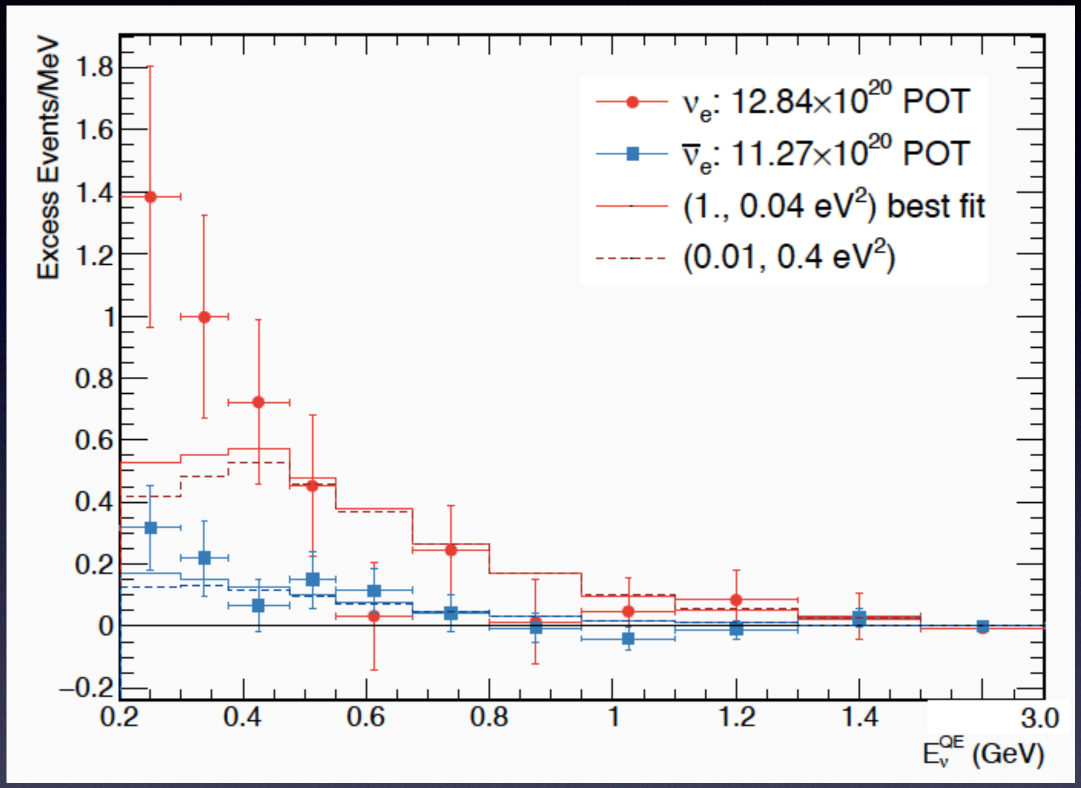
$$\sin^2 2\tilde{\theta} = \left[\frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}\right] \qquad \delta H = \frac{\delta m^2}{2E}\sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta}$$

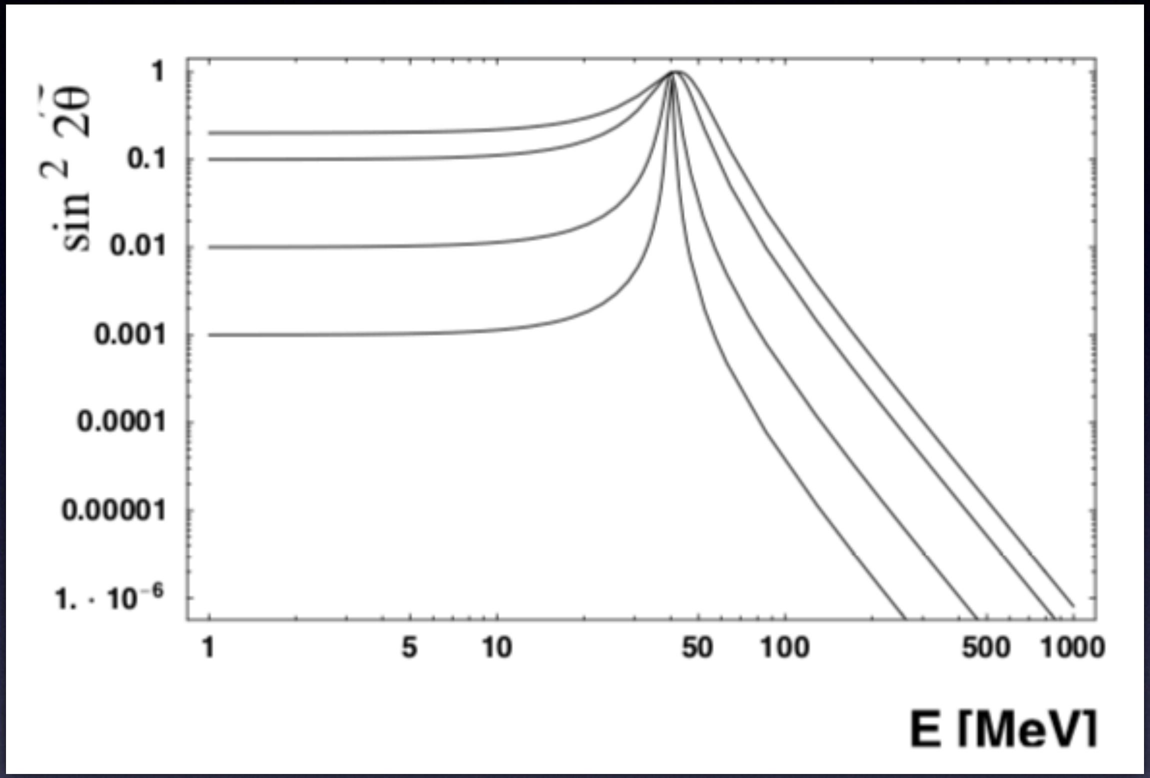
$$A = (E/E_{\rm res})^2$$



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)

Altered dispersion relations: vanilla type



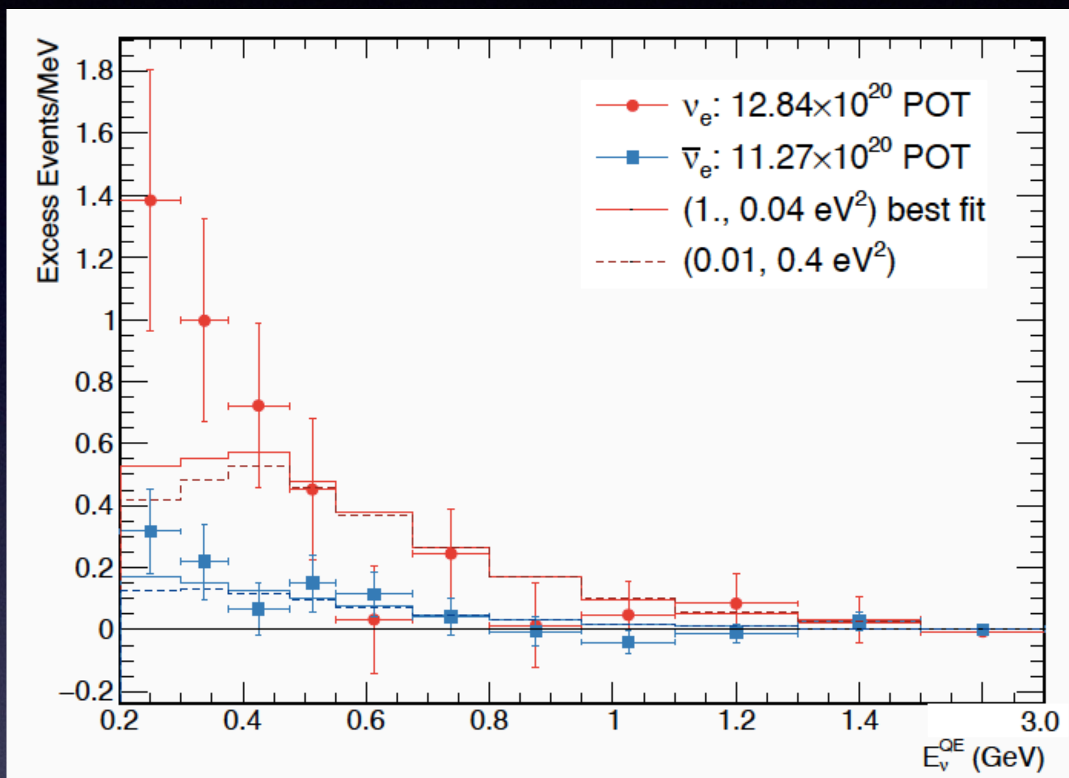


MiniBooNE 2018

HP, Pakvasa, Weiler 2005

→ resonance-like features!

Altered dispersion relations: vanilla type



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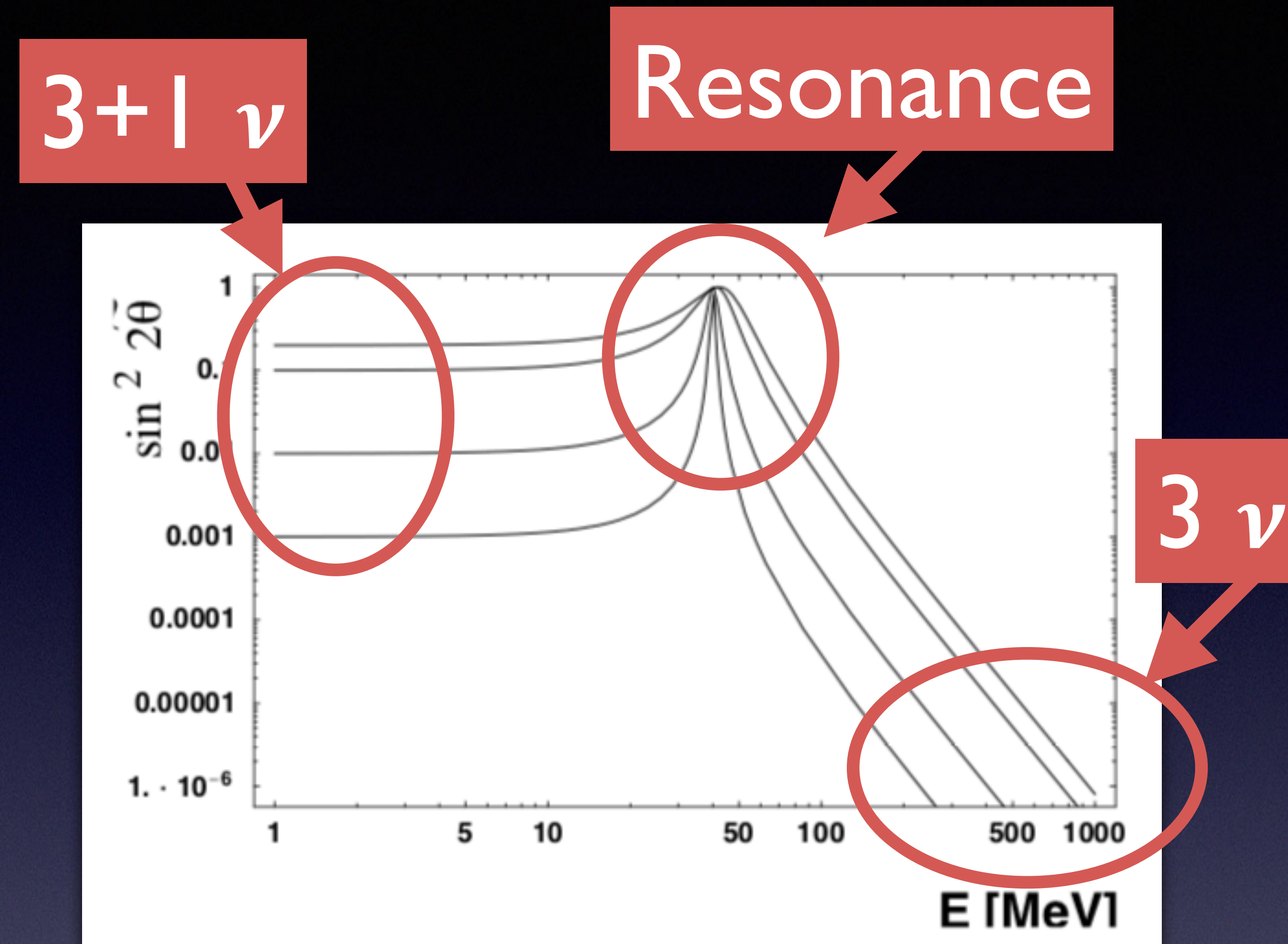


HP, Pakvasa, Weiler 2005

→ resonance-like features!

Altered dispersion relations: vanilla type

"A nice model -
but unfortunately it doesn't work"

P. Huber, 2007

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 large effective masses!
- Large Δm^2's

[Marfatia, HP, Pakvasa, Weiler, 2012]

- Fast oscillations:

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

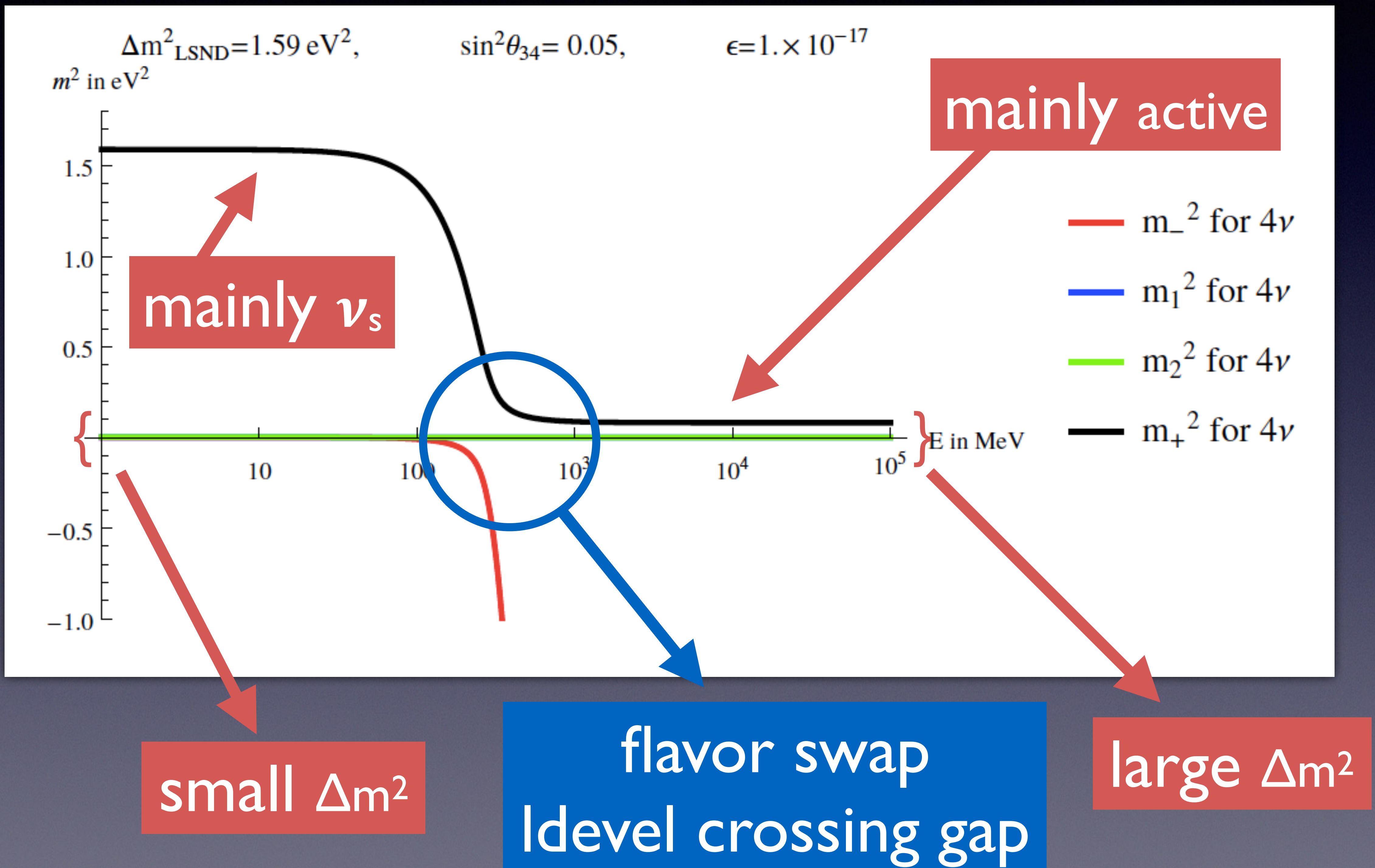
Fast Oscillations!

- Sterile neutrino ADR's excluded by atmospheric ν L/E !!!

[P. Huber, 2007]

Altered dispersion relations with 3+1 neutrinos

So what's the problem?



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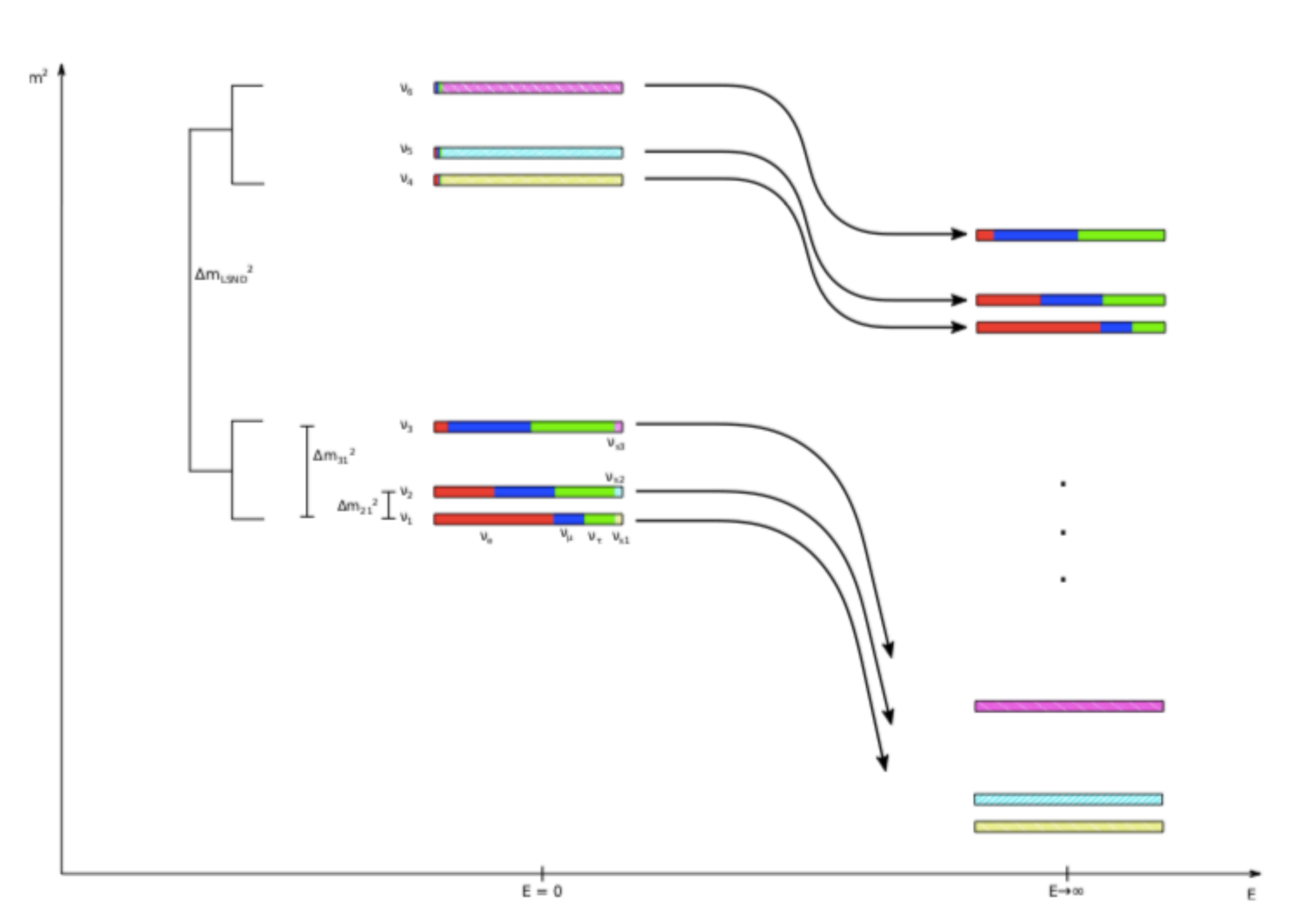
Solution ?

→ Promote the model to 3+3

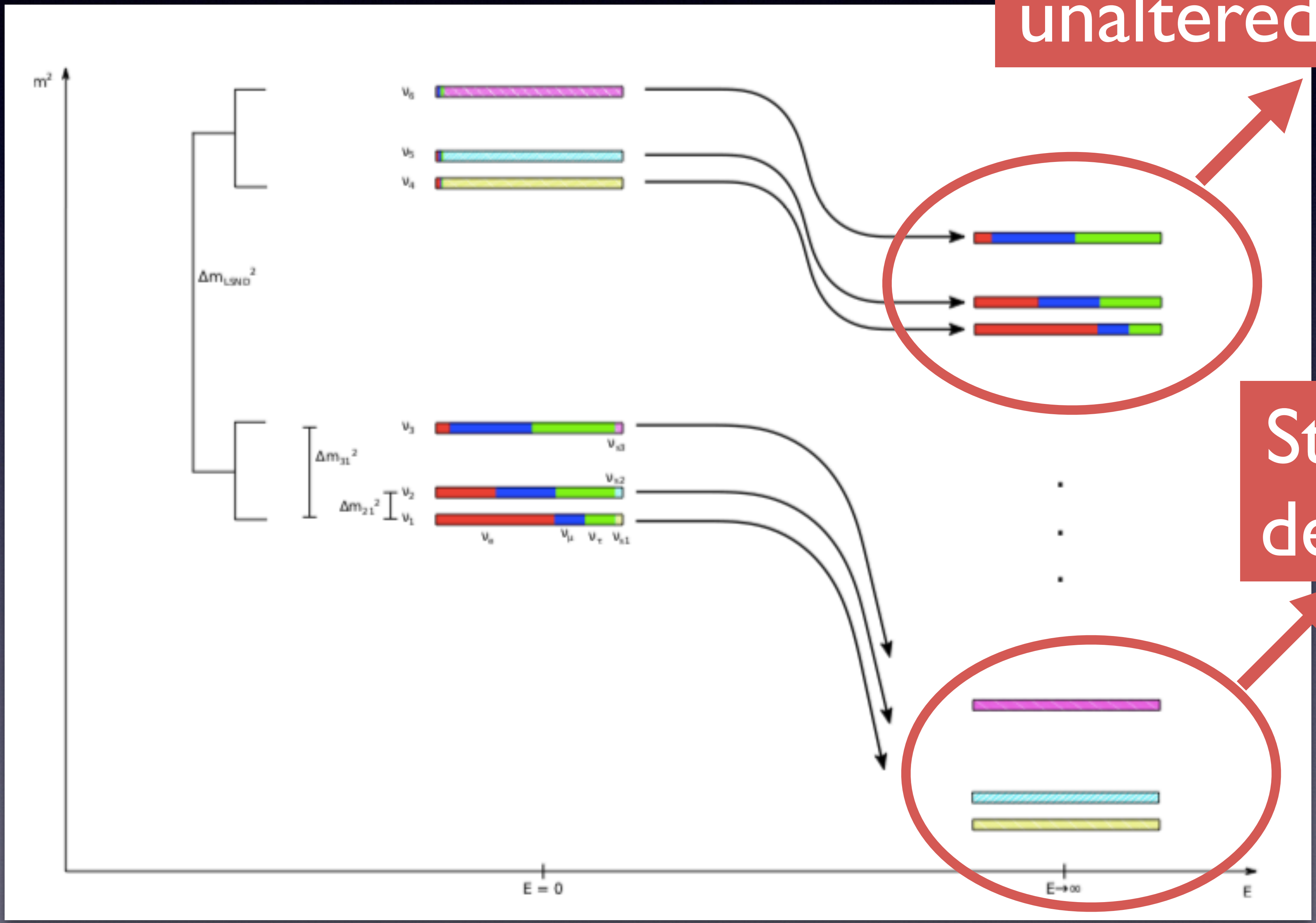


Döring, HP, Sicking, Weiler, arXiv:1808.07460

Solution ?

→ Promote the model to 3+3

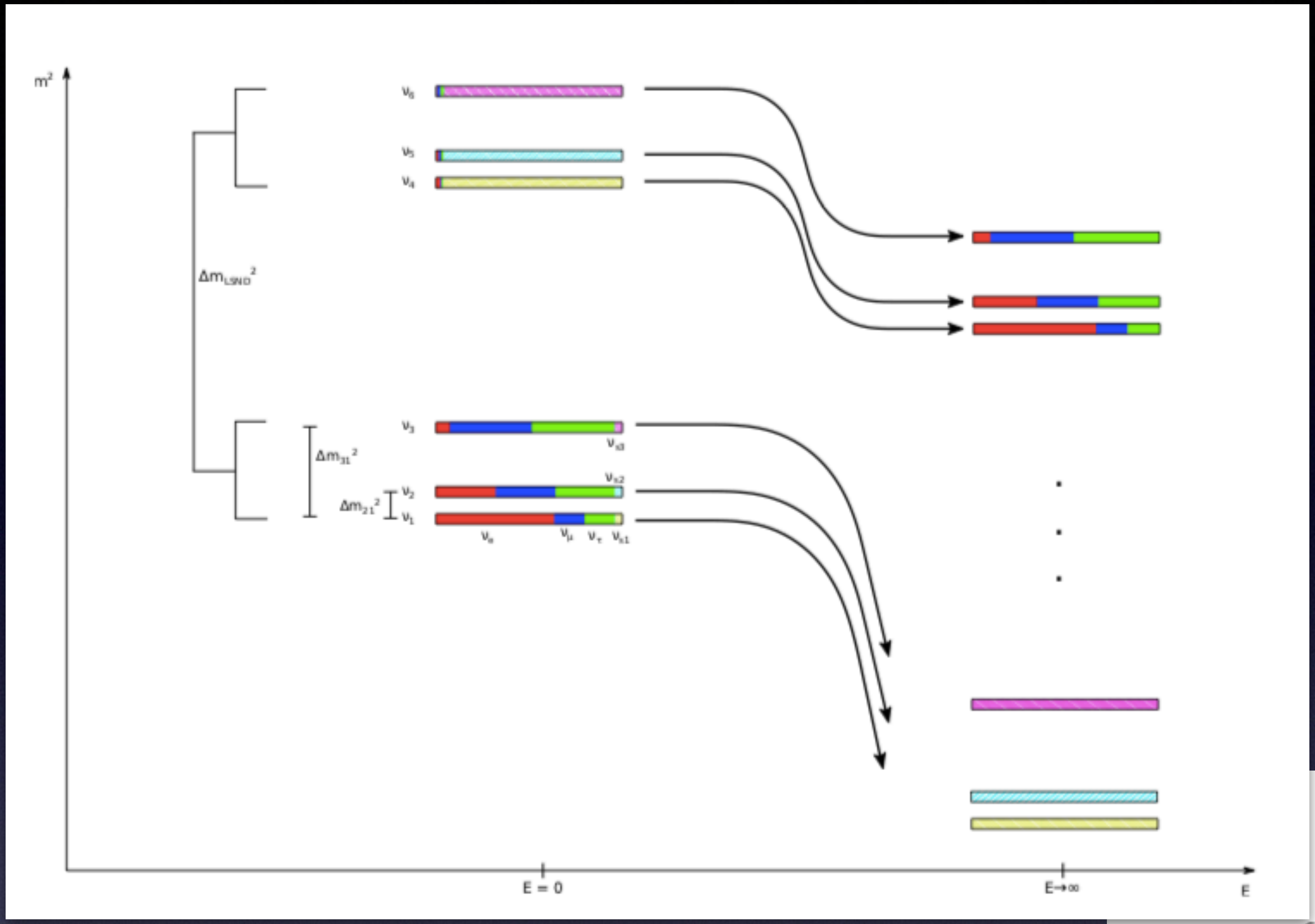
3ν scheme with unaltered's Δm^2's



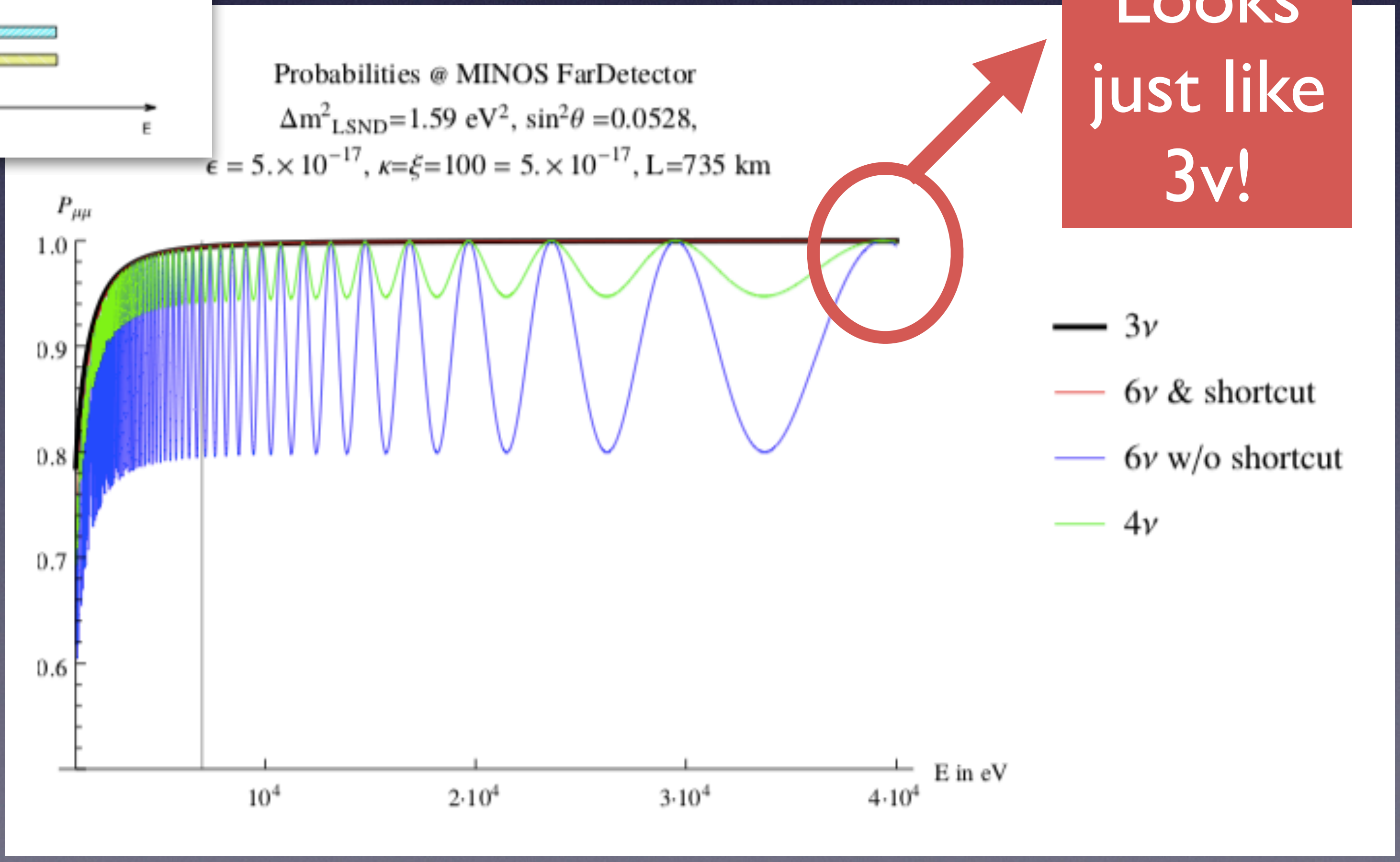
Sterile ν's decouple!

Döring, HP, Sicking, Weiler, arXiv:1808.07460

Sterile Neutrinos?



In a 3+3 model with democratic mixing the sterile neutrino decouples completely at high energies



Looks just like 3ν!

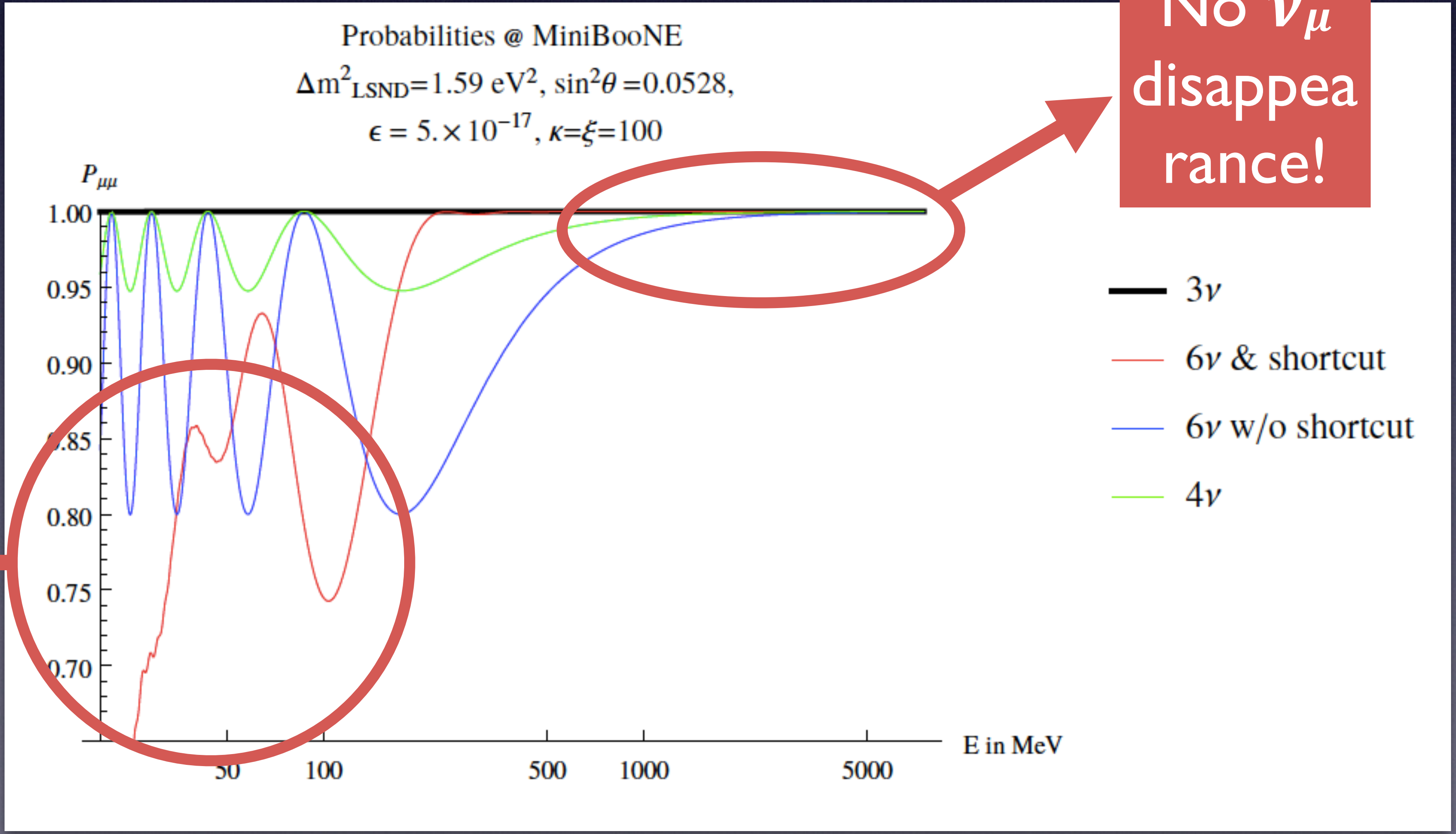
Döring, HP, Sicking, Weiler, arXiv:1808.07460

Altered dispersion relations with 3+3 neutrinos

Necessary: Different resonance energies for 3 sterile neutrinos to avoid unitarity cancellation!

$$V_{\text{eff}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \varepsilon E & 0 & 0 \\ 0 & 0 & 0 & 0 & \kappa \cdot \varepsilon E & 0 \\ 0 & 0 & 0 & 0 & 0 & \xi \cdot \varepsilon E \end{pmatrix}.$$

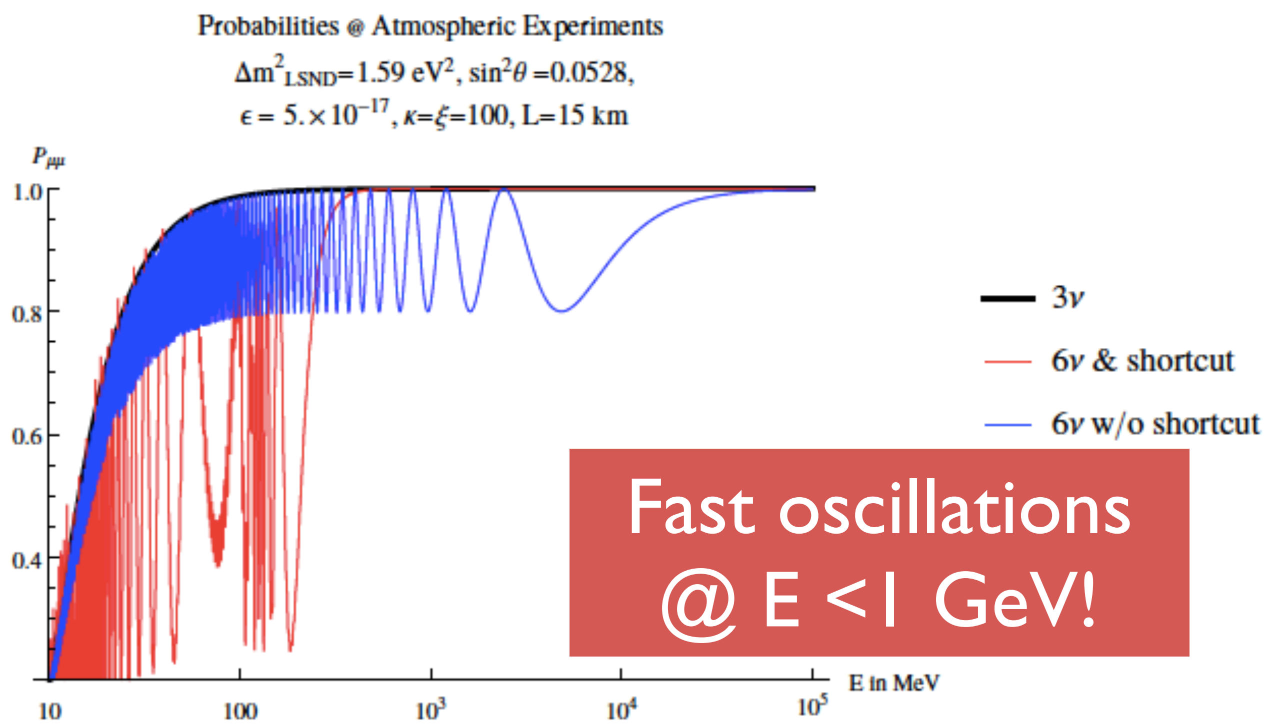
Döring, HP, Sicking, Weiler, arXiv: 1808.07460



No ν_μ disappearance!

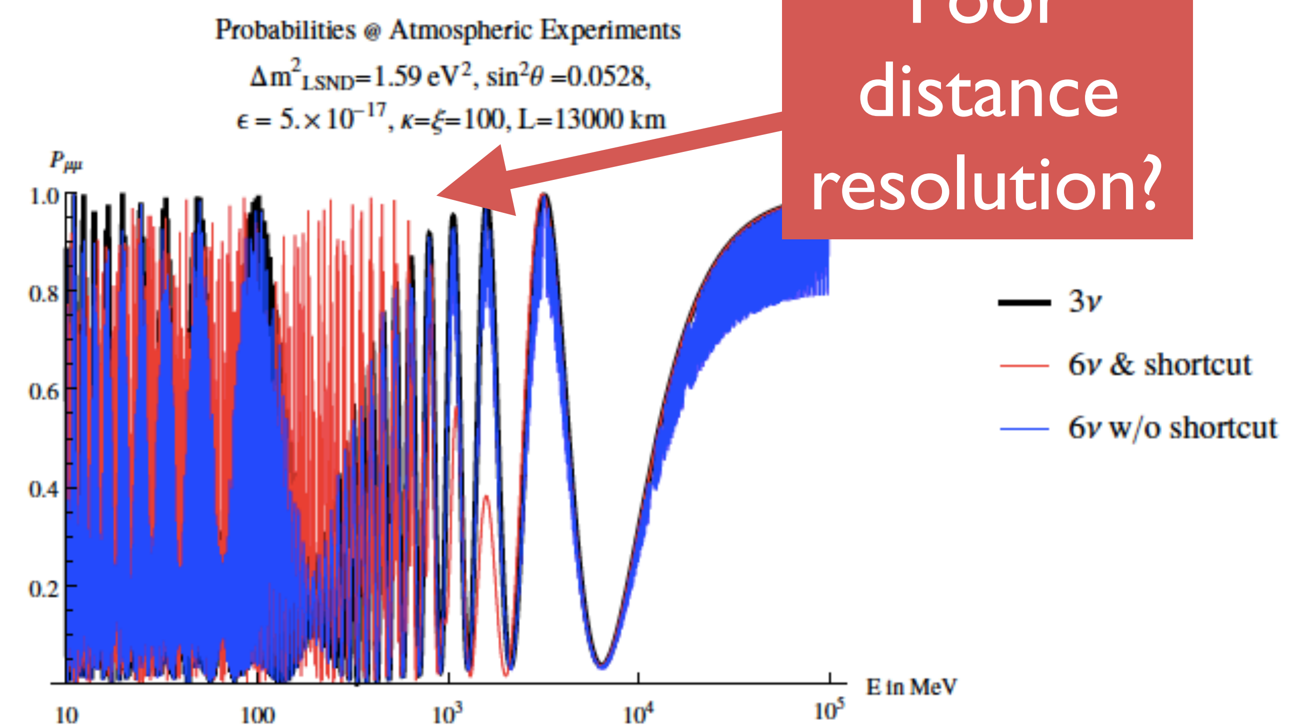
Huge ν_μ disappearance! Test: SBN, CCM

Super-K sub-GeV data?



Fast oscillations @ E < 1 GeV!

(a)Downward going neutrinos

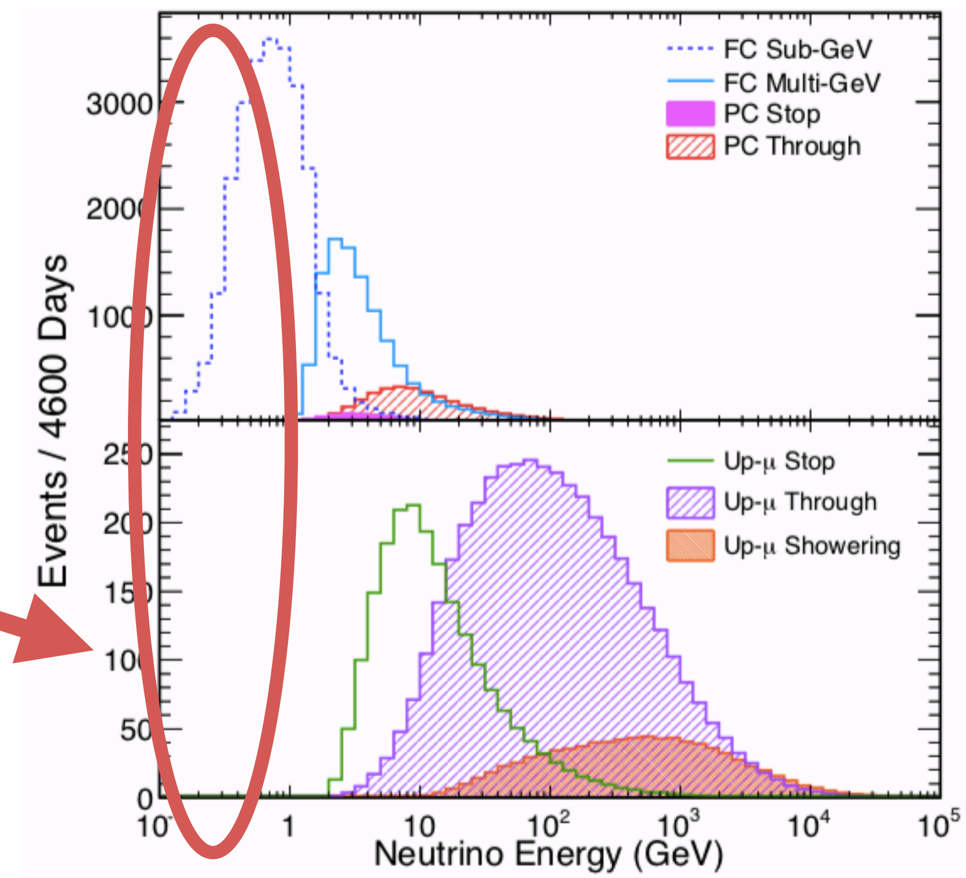


Poor distance resolution?

(b)Upward going neutrinos

Döring, HP, Sicking, Weiler, arXiv:1808.07460

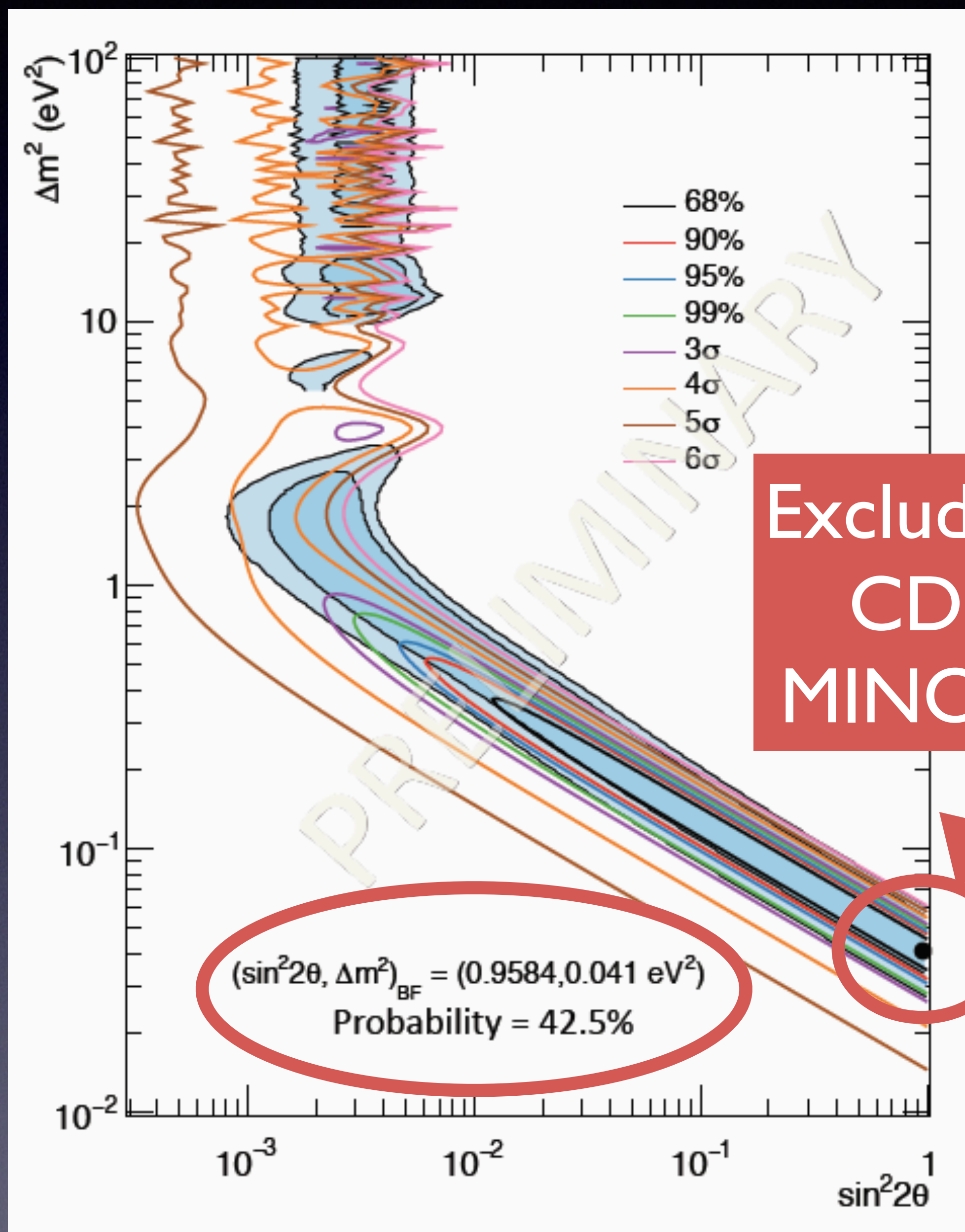
Limited statistics!



Super-K, arXiv:1410.2008

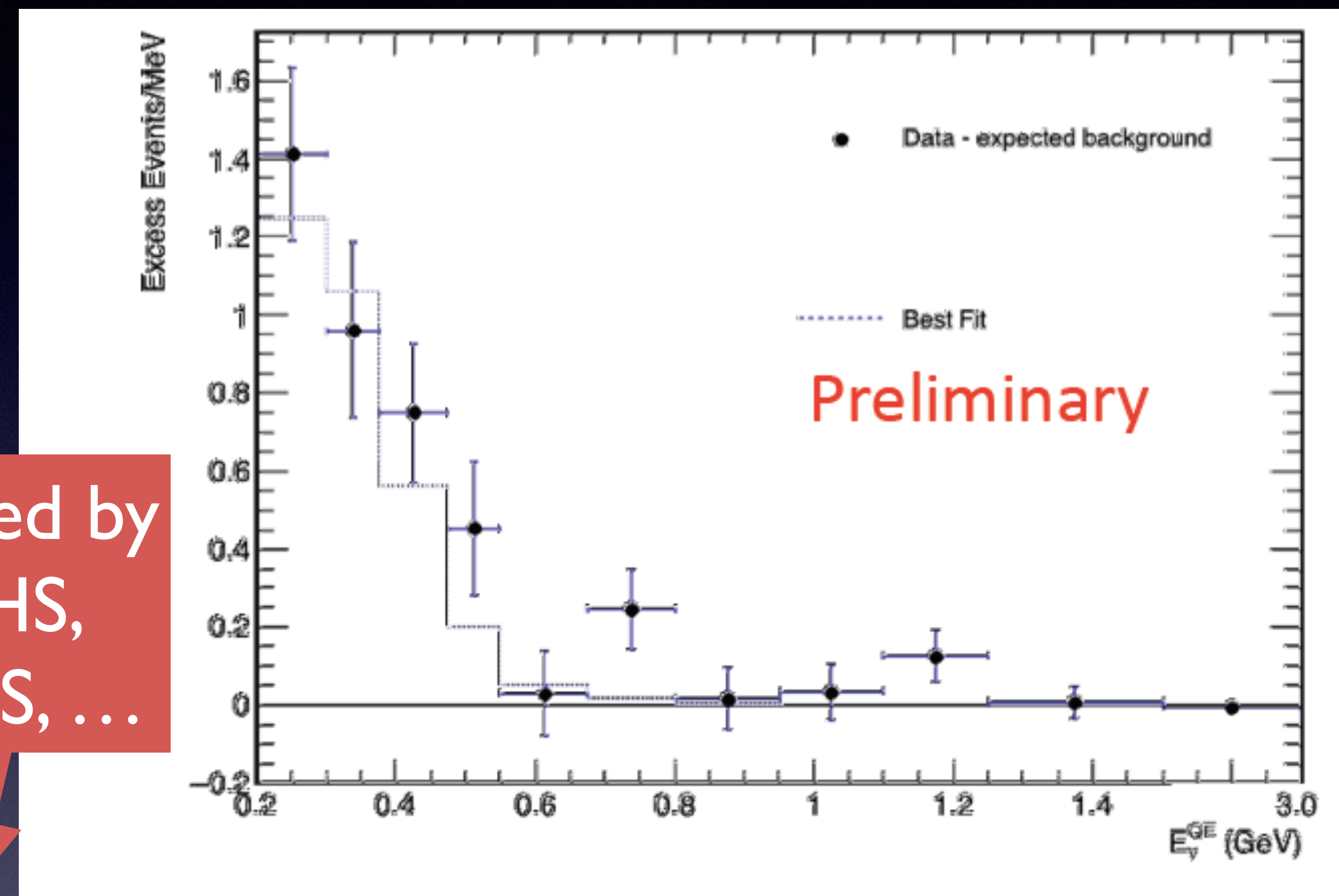
Fitting LSND & MiniBooNE

2ν Fit



Excluded by CDHS, MINOS, …

3+3 ADR Fit



$\sin^2 2\theta = 0.0564$

$\Delta m^2 = 1.75\ eV^2$

$\varepsilon = 7.6 \times 10^{-18}$

$\kappa, \xi = 127.5$

$\chi^2 = 19.5/22$ dof (P = 61.4%)

Not excluded!

Fits Courtesy of En-Chuan Huang

Bill Louis, Talk @ TomFest, August 14, 2019

Fitting LSND & MiniBooNE

3+3 ADR Fit: Resonance Energies

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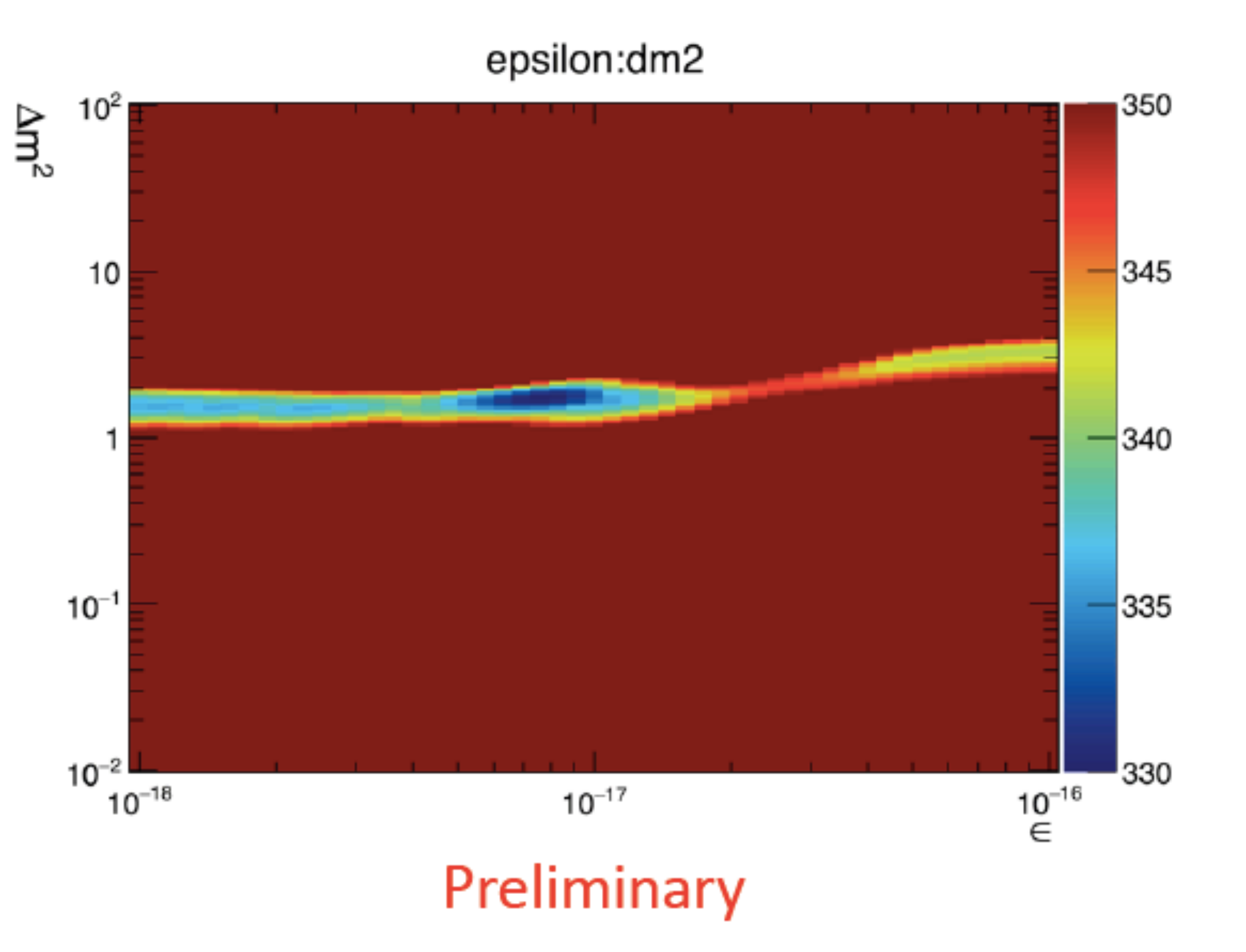

Fit Courtesy: En-Chuan Huang

Bill Louis, Talk @ TomFest, August 14, 2019

Resonant energies result at:
$E_{Res}^{1,2}$=30 MeV
E_{Res}^{3}=330 MeV

Fitting LSND & MiniBooNE

3+3 ADR Fit & Reactor Anomaly

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$\Delta m^2 = 1.75\ eV^2$
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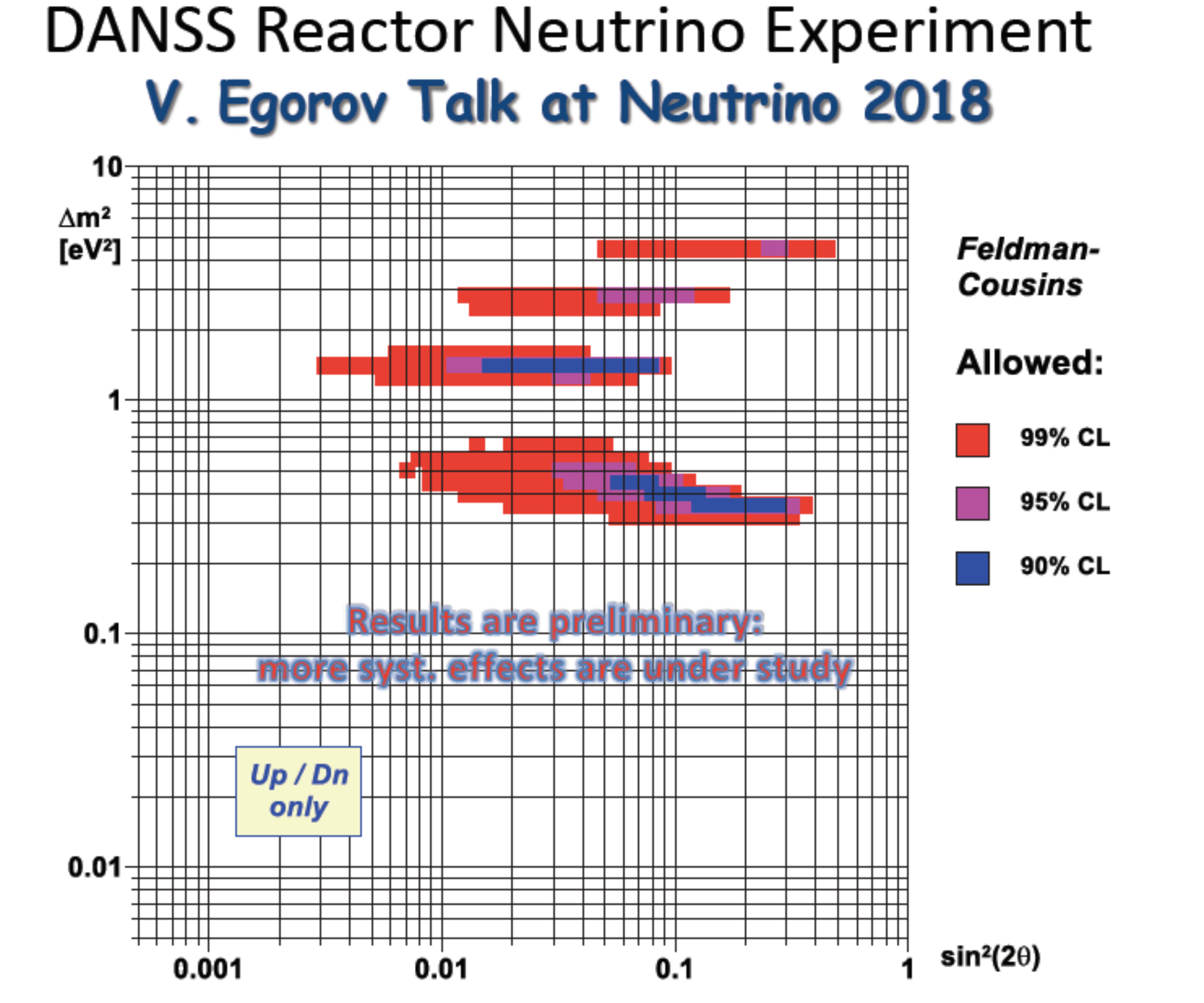


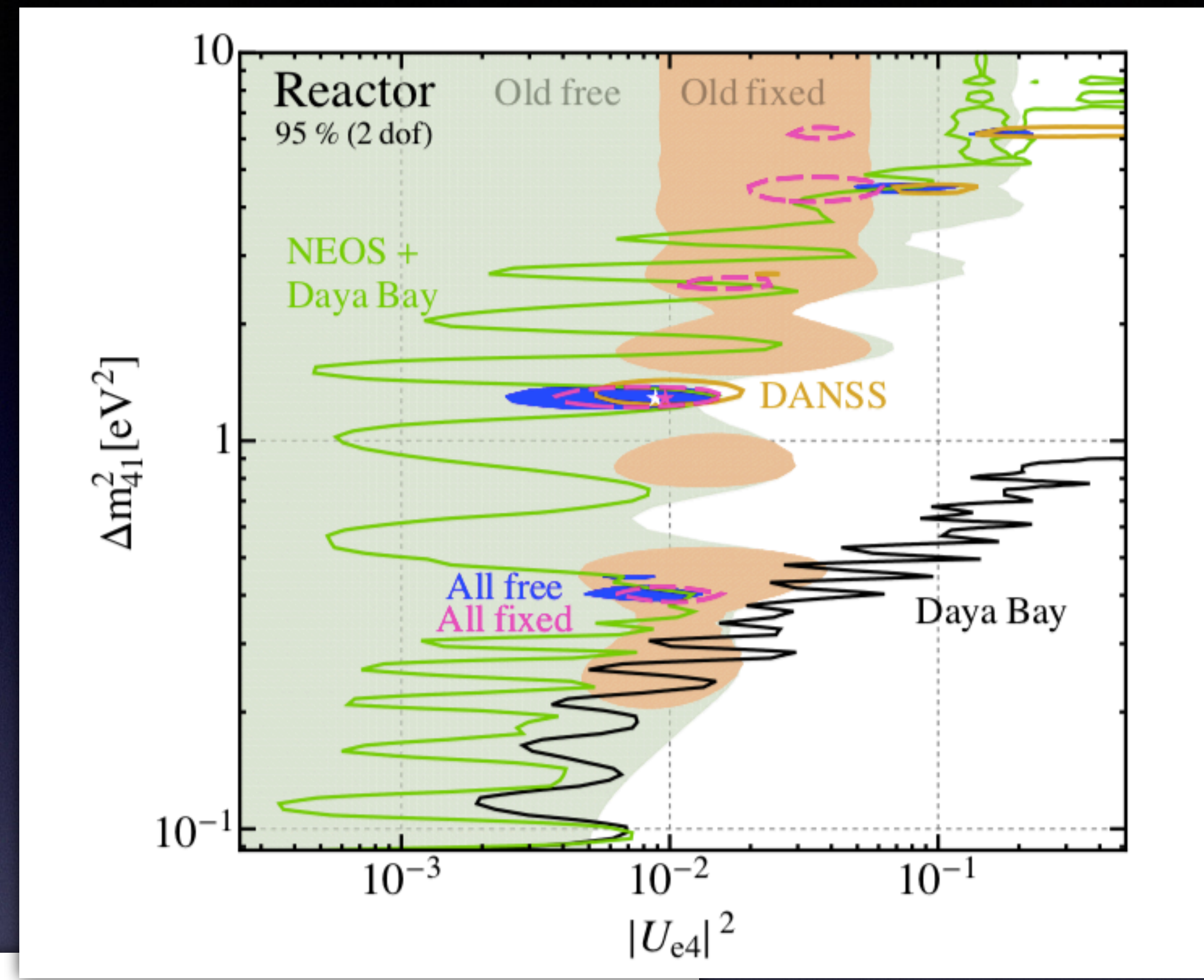
DANSS best fit at $(\sin^2 2\theta, \Delta m^2) = (0.05, 1.4\ eV^2)$ is 2.8σ better than null

Perfect agreement with reactor results!

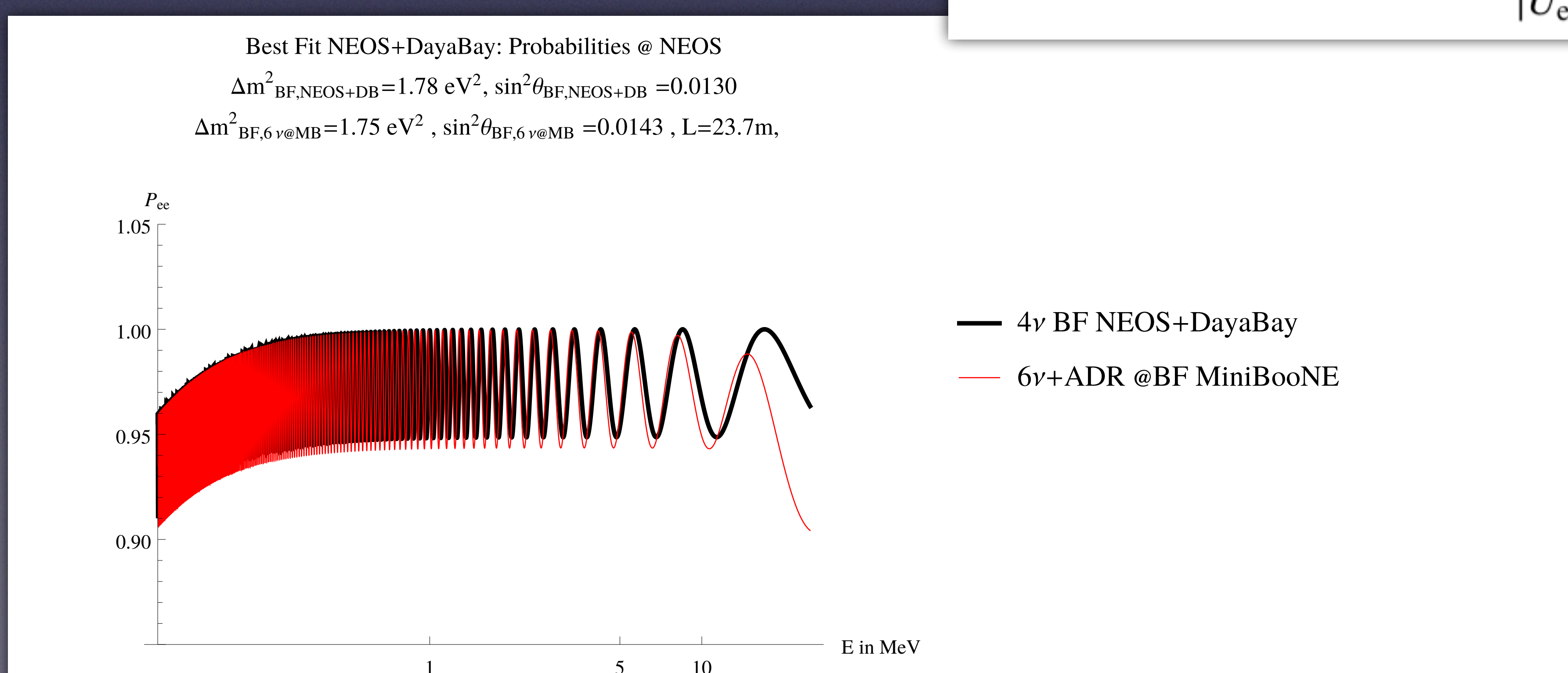
Fitting LSND & MiniBooNE

3+3 ADR Fit & Reactor Anomaly

Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, 2018

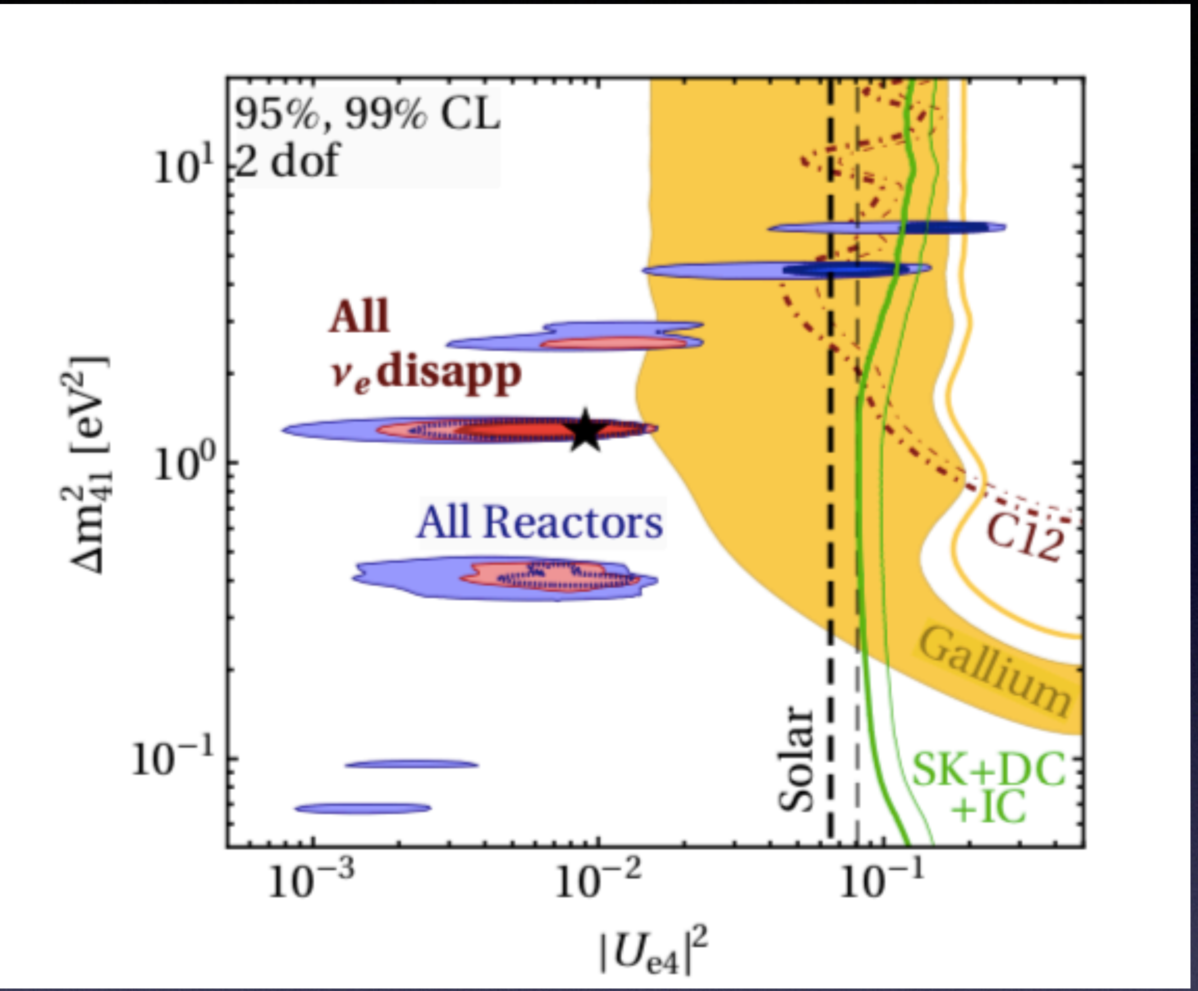


Perfect agreement with reactor results!

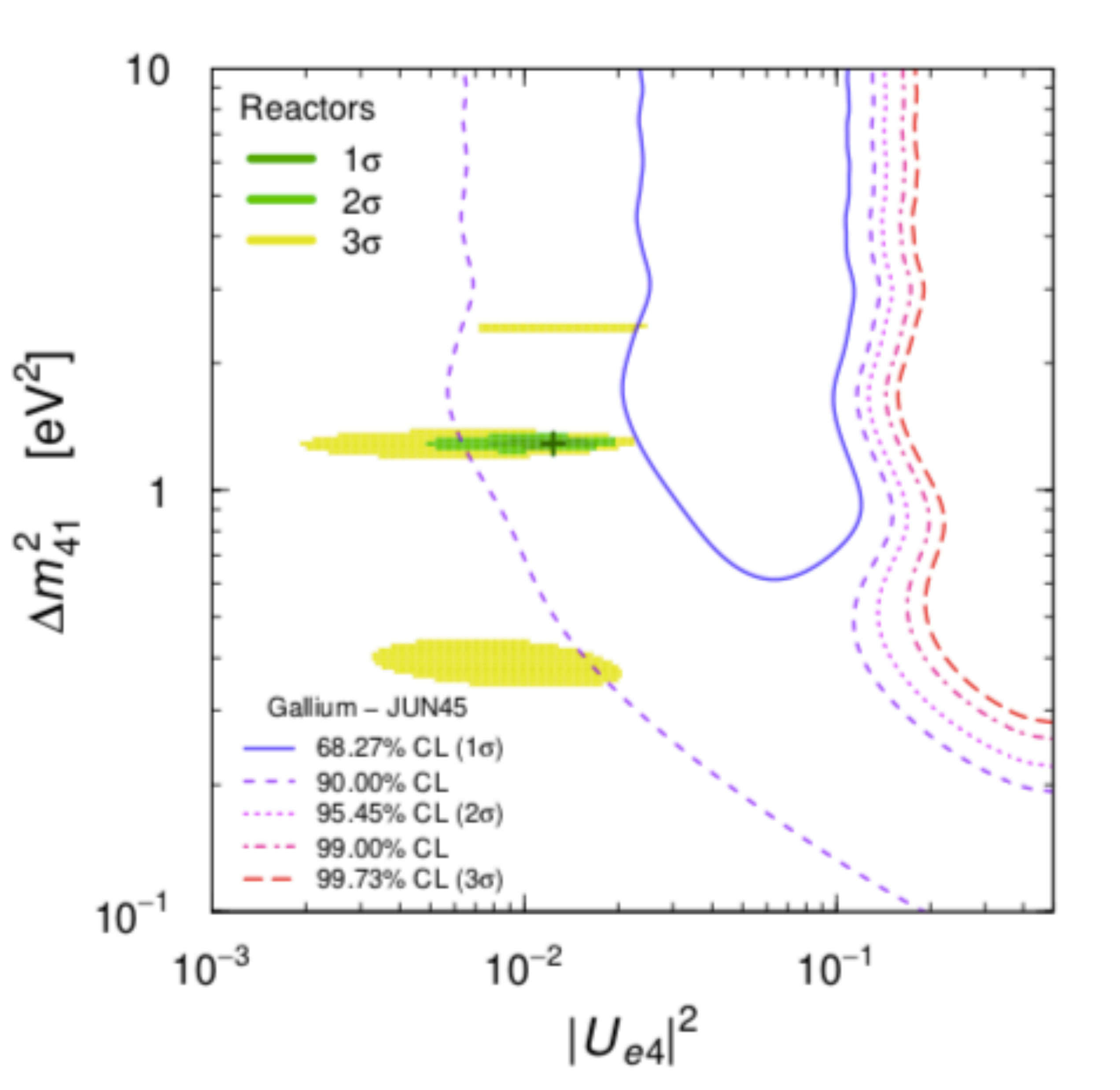


Fitting LSND & MiniBooNE

as with the Gallium anomaly…



Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, 2018



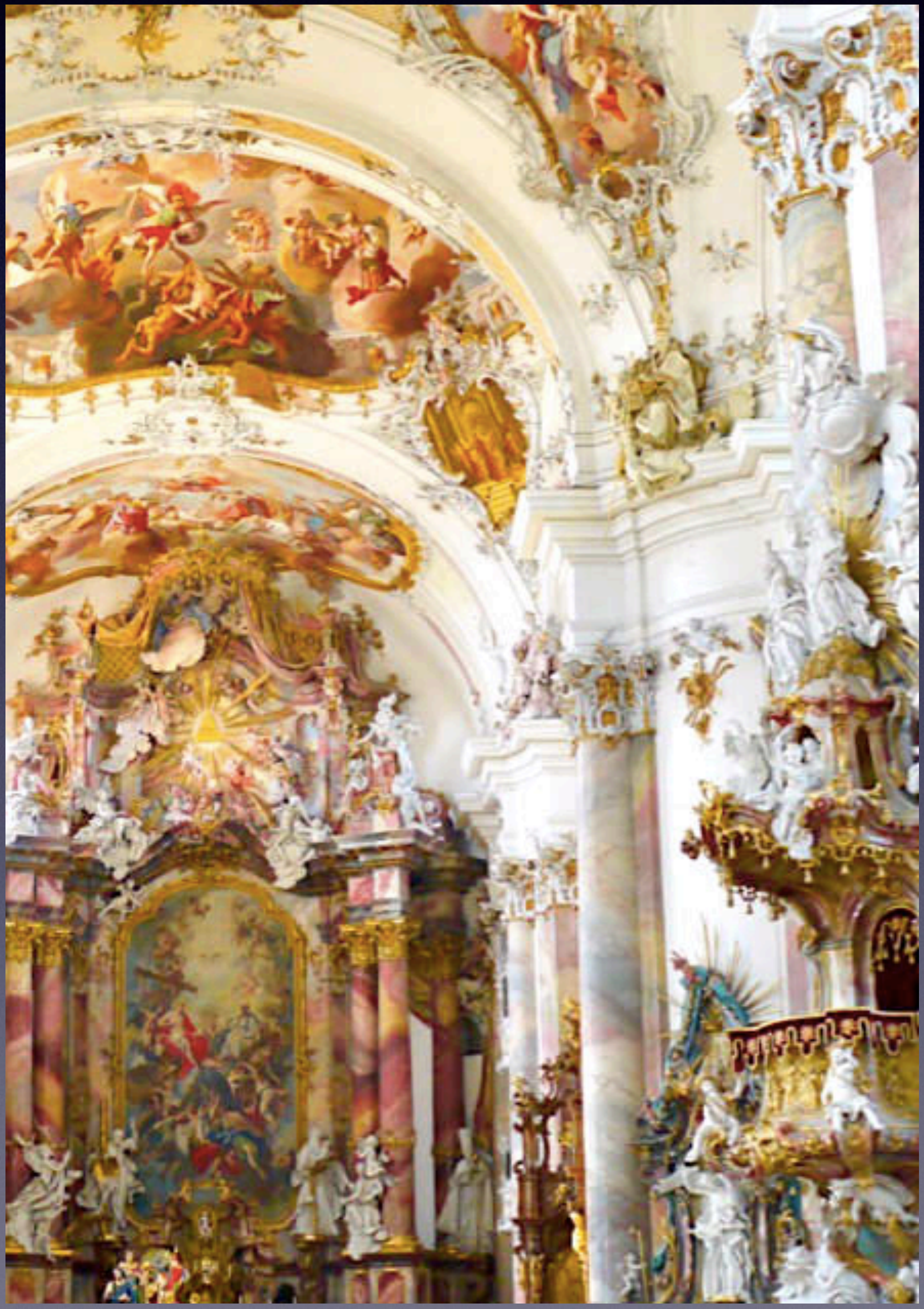
Kostensalo, Suhonen, Giunti, Srivastava, 2019

Baroque?

MiniBooNE, MINOS+ and IceCube data imply a baroque neutrino sector

Jiajun Liao,[1,2] Danny Marfatia,[1] and Kerry Whisnant[3]

- Required: ADRs
- 3 active flavors - 3 steriles
- symmetry: democratic Δm^2's & mixing angles for all steriles
- 3 space dimensions - 3 extra dimensions
- No finetuning!
- Resonance predicted and MiniBooNE/LSND fit yields reactor/Gallium best fit!



Outline

- Neutrino Physics Overview
- The case for sterile neutrinos
- Altered dispersion relations: The basic idea
- A phenomenological framework
- An extra-dimensional model
- Cosmological bounds & consequences

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

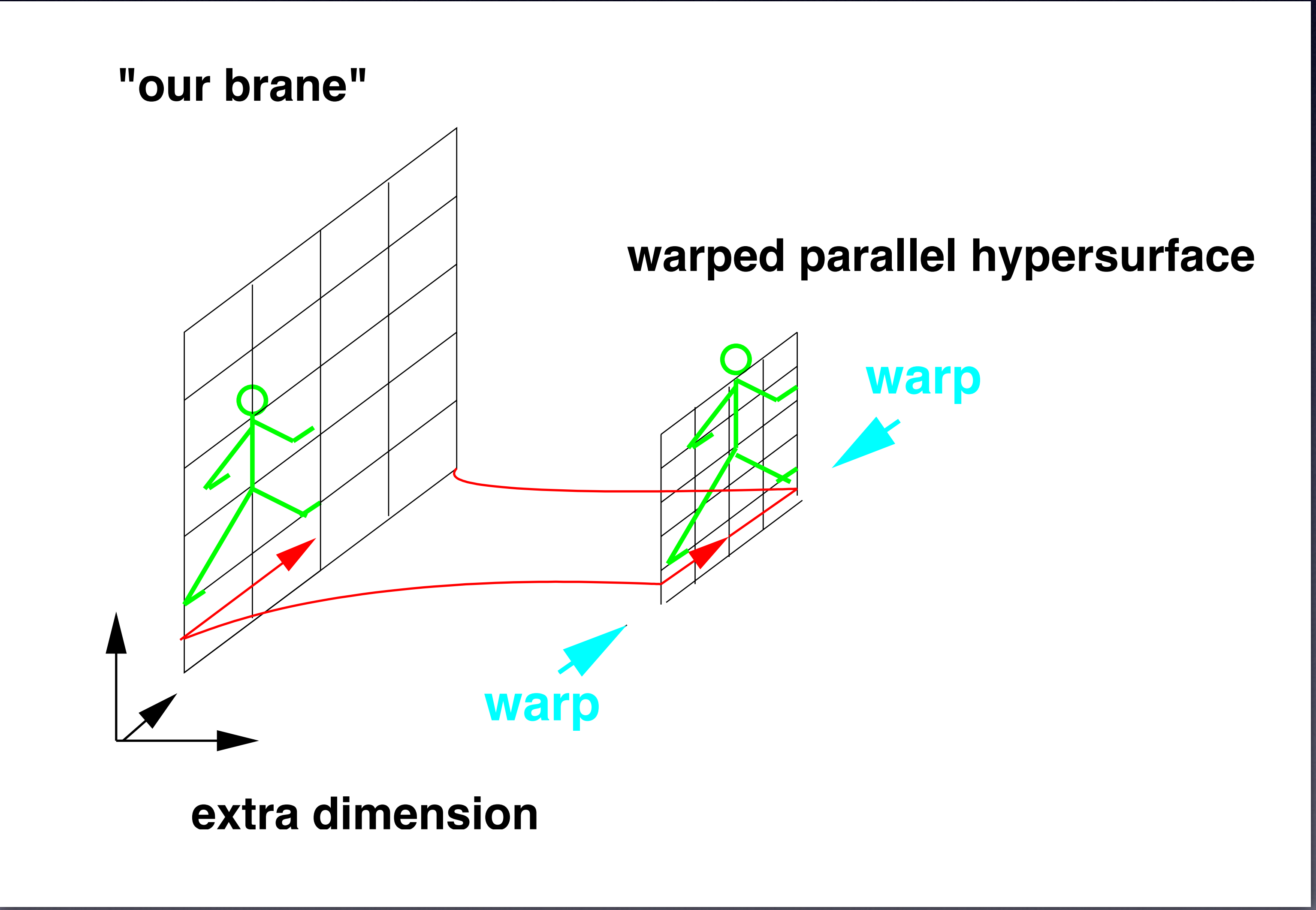
$$ds^2 = dt^2 - e^{-2k|u|}dx^2 - du^2$$

Chung, Freese, 1999, 2000
Csaki, Erlich, Grojean, 2001

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

[HP, S. Pakvasa, T. Weiler, PRD72 (2005) 095017]

[D. Döring, HP, arXiv:1808.07734]



Sterile ν's in asymmetrically warped extra dimensions

[Döring, HP, arXiv:1808.07734]

- 2 gauge singlet neutrinos:
  mass generation & propagation in extra dimensions
- Compactification on S^1/Z_2:
  Kaluza-Klein spectrum & effective 4D ν_s ADR

as in RS-1 scenarios

$$S = \int d^4x \left(\overline{\nu_L}\,,\ \overline{\Psi^0_L}\,,\ \overline{N}\right) \begin{pmatrix} i\partial\!\!\!/ & 0 & y_0 v \\ 0 & i\partial\!\!\!/ + i\tilde{I}_{00}\partial_k\gamma^k & \kappa \\ y_0 v & \kappa & i\partial\!\!\!/ \end{pmatrix} \begin{pmatrix} \nu_L \\ \Psi^0_L \\ N \end{pmatrix}$$

Propagation Eigenstates:

$$E^2_\phi = \vec{p}^{\,2}\,,$$

$$E^2_{\chi/\xi} = \kappa^2 + \vec{p}^{\,2} \underbrace{\left[\left(1 + \frac{\tilde{I}_{00}}{2}\right)^2 - \frac{\tilde{I}^2_{00}}{4}\right]}_{f(\tilde{I}_{00})}$$

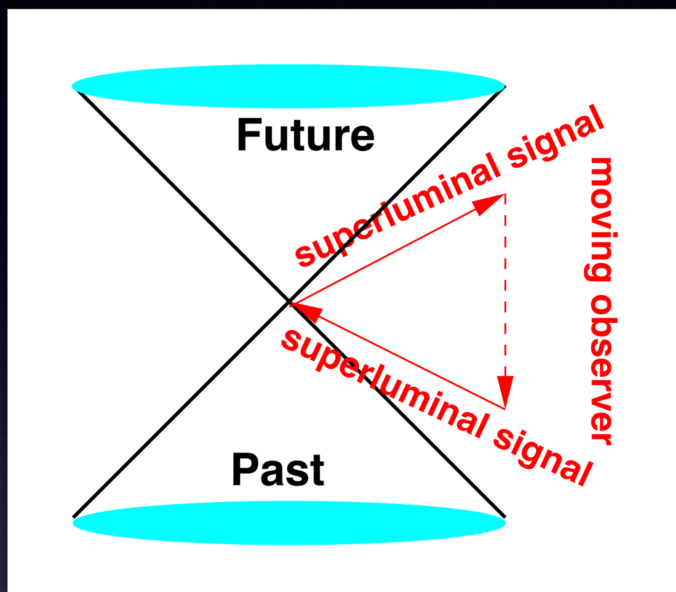
$$p_{\chi/\xi} \approx E - \frac{\kappa^2}{2E} - \frac{E^2}{2E}\tilde{I}_{00} + \mathcal{O}(\tilde{I}^2_{00}) + \mathcal{O}(\kappa^2 \tilde{I}_{00})$$

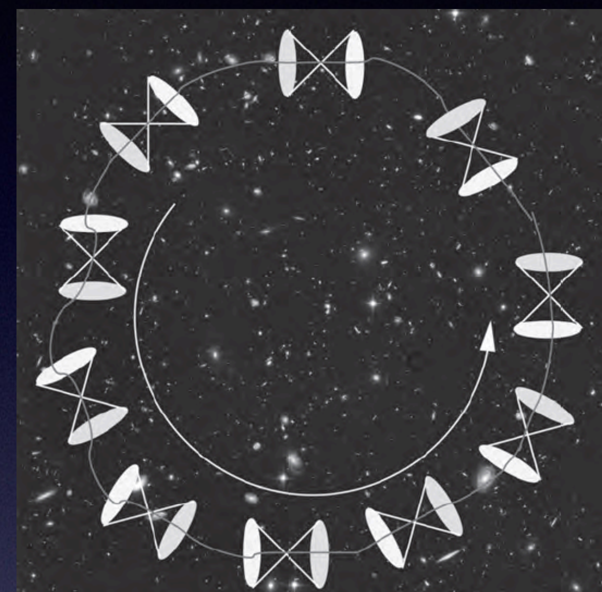
ADR: 4D EFT limit!

Causality?

Neutrino Time Travel ?

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





No: Globally hyperbolic, defined time direction

$$ds^2 = \gamma_{uv}^2 \left\{ [1 - \beta_{uv}^2 \eta^2(v)]\, dt^2 + 2\beta_{uv}\alpha(u)[1 - \eta^2(v)]\, dx\, dt - \alpha^2(u)[\eta^2(v) - \beta_{uv}^2]\, dx^2 \right\} - du^2 - dv^2$$

But: 2 asymmetrically warped extra dimensions with a relative boost can do the job!

[HP, S. Pakvasa, J. Dent, T. Weiler, PRD 80 (2009) 044008]

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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:

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

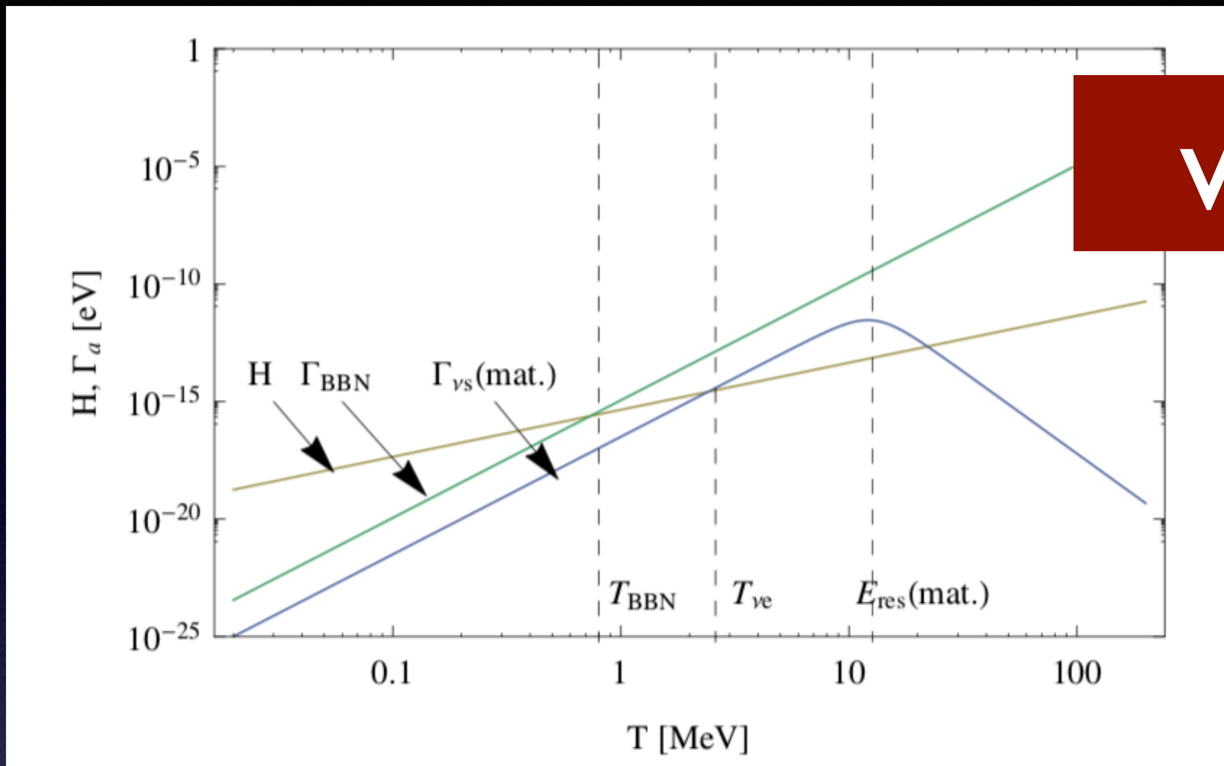
- $\rightarrow$ faster expansion of the universe
- $\rightarrow$ higher temperature for weak freezeout
- $\rightarrow$ more neutrons $\rightarrow$ larger ^4He abundance

<u>Bulk shortcut scenario:</u>

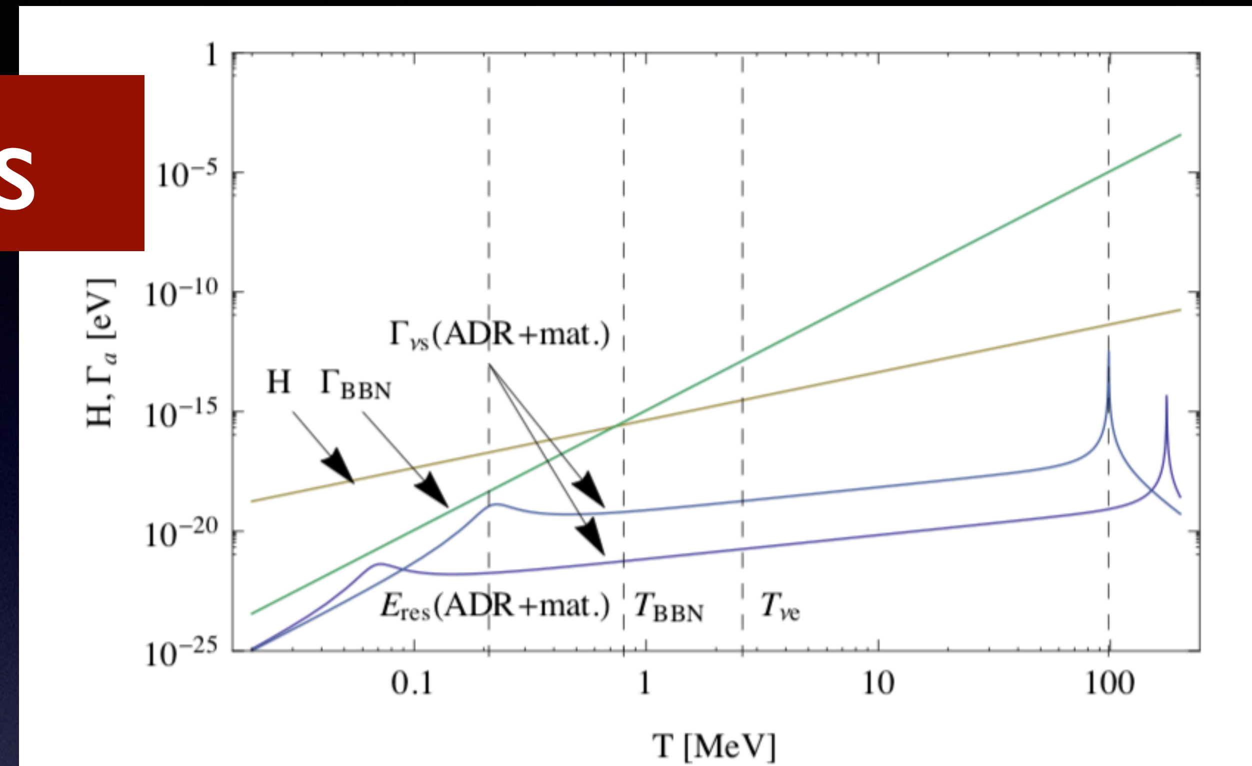
- higher density: stronger brane bending due to gravitational attraction
- higher temperature: more brane fluctuations
- higher density: more scattering off into the bulk in asymmetrically warped spacetimes

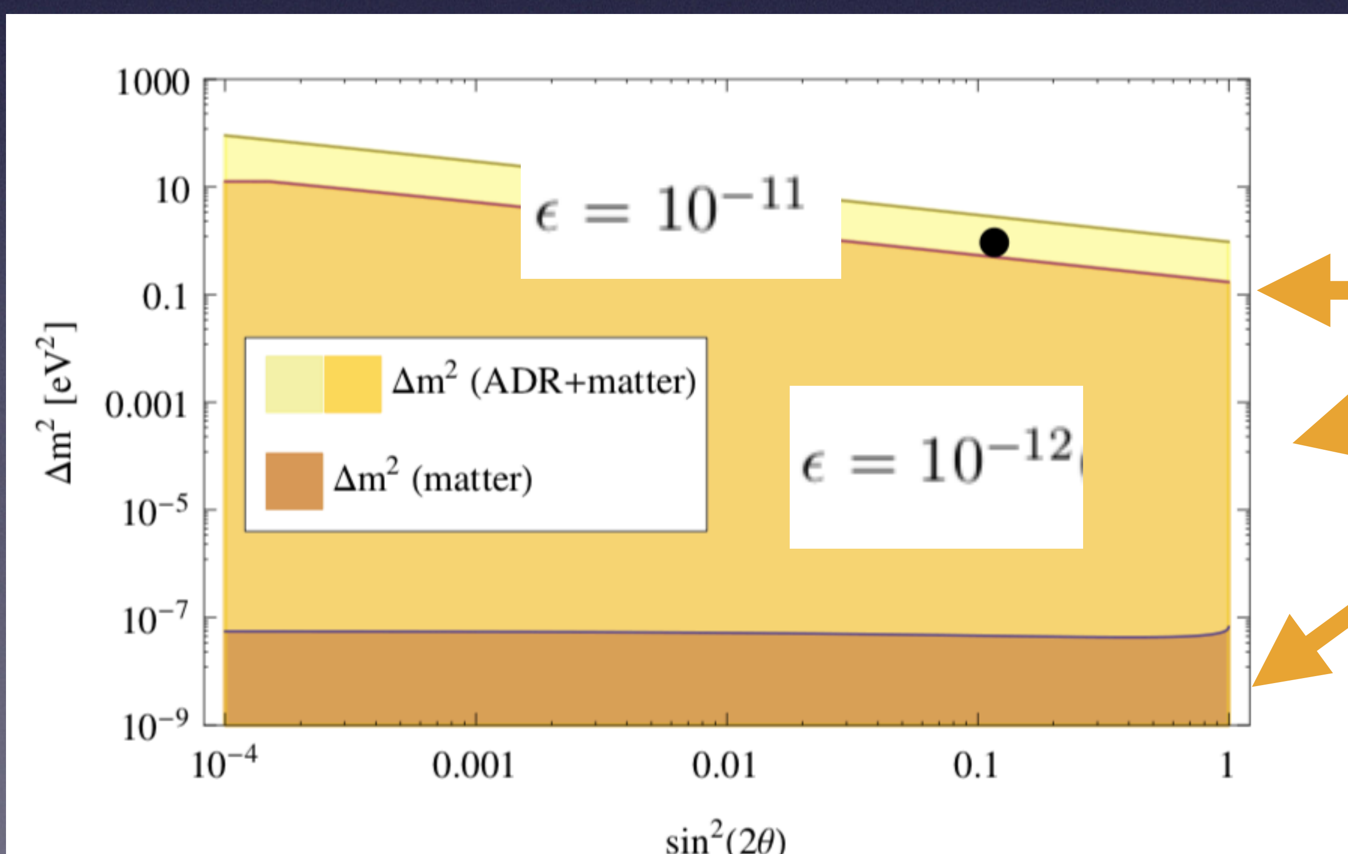
All cases: larger $\epsilon \rightarrow$ smaller $E_{\rm res}$
If $E_{\rm res} \lesssim 3$ MeV: oscillations suppressed (Päs, Pakvasa, Weiler, 2005)

Big Bang Nucleosynthesis



VS





Aeikens, HP, Pakvasa, Weiler, 2016

allowed regions

Similar aguments work for other cosmological bounds!

Astrophysical Flavor Ratios

Expectation pion source:

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

Flavor Ratio at the source: 1:2:0

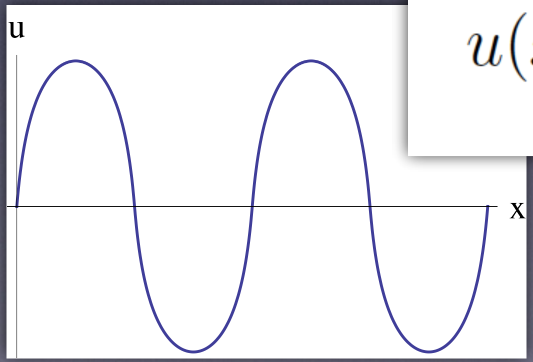
Maximal ν_μ-ν_τ mixing: Decoherence →

Flavor Ratio: 1:1:1 at Earth

- Geodesics: oscillating around the brane
- Shortcut "switched on and off"→ new baseline effect
- MSW analogue: resonant conversion

Hollenberg, HP, Micu, Weiler, 2009

Aeikens, HP, Pakvasa, Sicking, 2014



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

Astrophysical Flavor Ratios

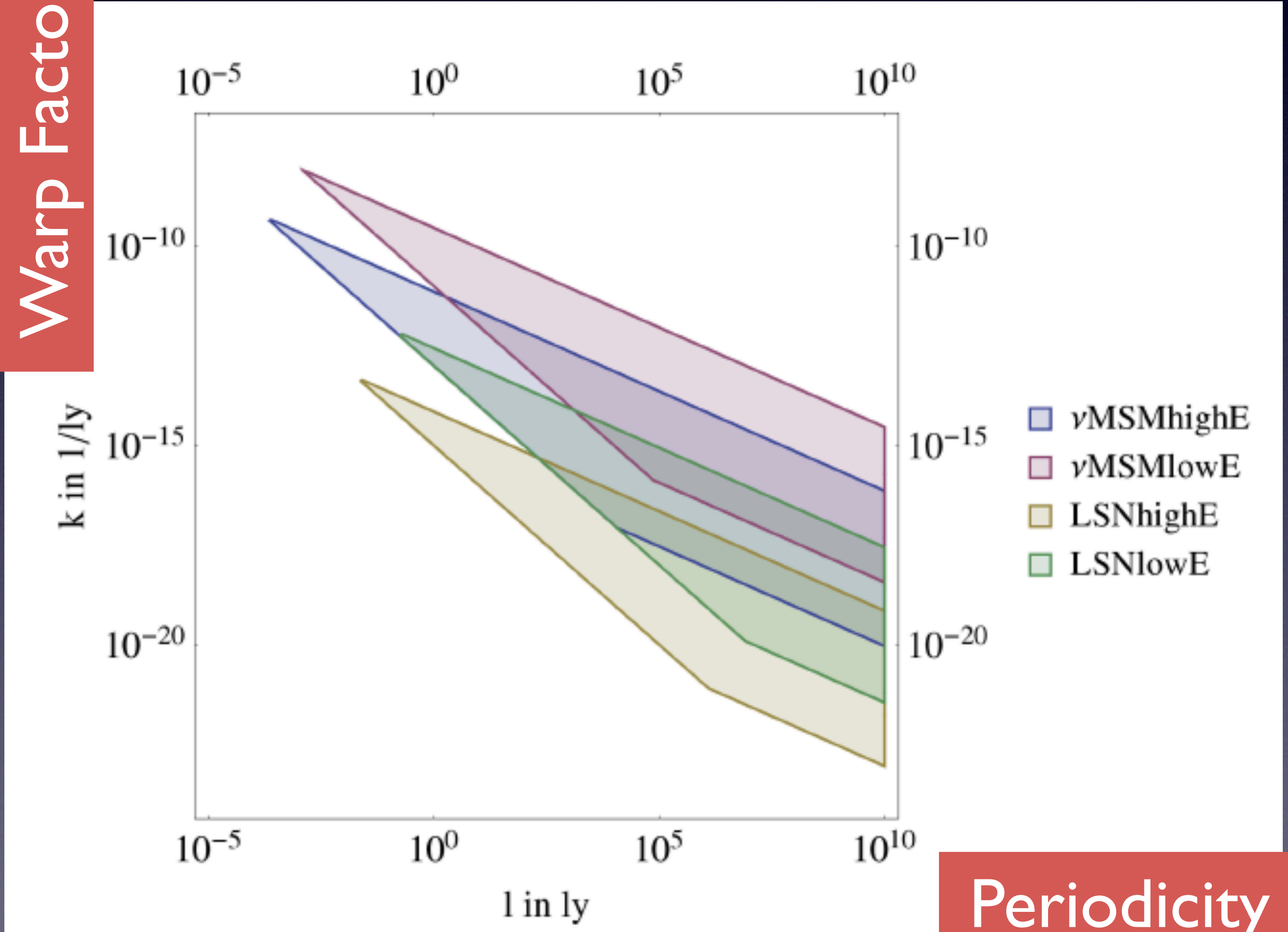
Level crossing: shortcut parameter has to be large enough?

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

Warp Factor

Adiabaticity ?

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



Periodicity

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

Aeikens, HP, Pakvasa, Sicking, 2014

Lorentz violation & multi-messenger astronomy

Selected for a Viewpoint in *Physics*
PRL **119,** 251301 (2017) PHYSICAL REVIEW LETTERS week ending 22 DECEMBER 2017

Strong Constraints on Cosmological Gravity from GW170817 and GRB 170817A

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(Received 16 October 2017; published 18 December 2017)

The detection of an electromagnetic counterpart (GRB 170817A) to the gravitational-wave signal (GW170817) from the merger of two neutron stars opens a completely new arena for testing theories of gravity. We show that this measurement allows us to place stringent constraints on general scalar-tensor and vector-tensor theories, while allowing us to place an independent bound on the graviton mass in bimetric theories of gravity. These constraints severely reduce the viable range of cosmological models that have

$$c_T^2 = 1 + \alpha_T\,.$$

...rger peak and the peak optical brightness. An arrival delay of $\Delta t \simeq 1.7$ seconds implies that

$$|\alpha_T| \lesssim 1 \times 10^{-15}. \quad (3)$$

Necessary for LSND/ MiniBooNE

$\varepsilon = 7.6 \times 10^{-18}$

Summary

- Quite possible: MiniBooNE & other anomalies due to backgrounds or systematics
- Simple oscillation models: conflict with CDHS, MINOS…
- But keep in mind "1 eV^2 miracle"
- ADR ν oscillations: energy dependence & resonance
- Excellent fit to MiniBooNE & LSND
- Fits also reactor & Gallium anomalies
- No conflict with high energy ν_μ disappearance (CDHS…)
- Crucial tests: CCM, SBN, ICARUS, MicroBooNE
- One possible ADR model: shortcuts in extra dimensions
- Interesting cosmological consequences