Neutrino anomalies

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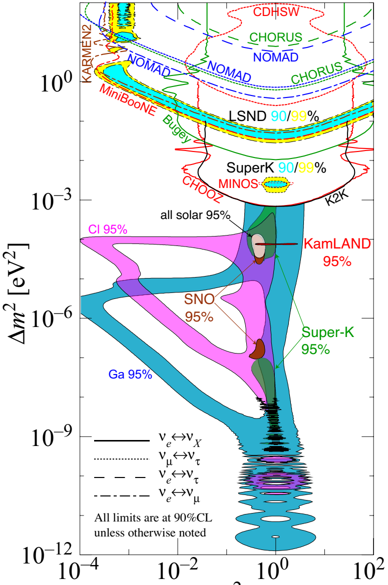
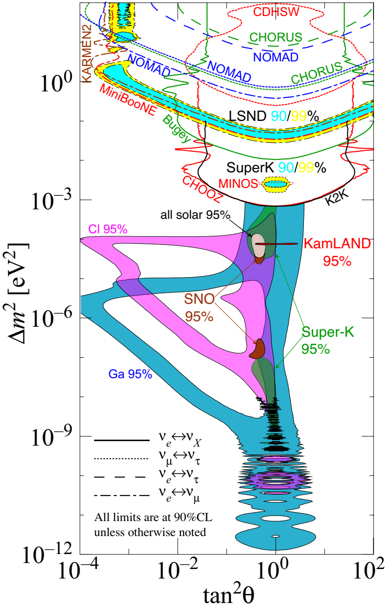
Recap: summary of neutrino oscillation results



http://hitoshi.berkeley.edu/neutrino

- Established theoretical formalism
- Precise measurements of θ_{23}, $|\Delta m^2_{31}|$, θ_{12}, Δm^2_{21}, θ_{13}.

Recap: summary of neutrino oscillation results



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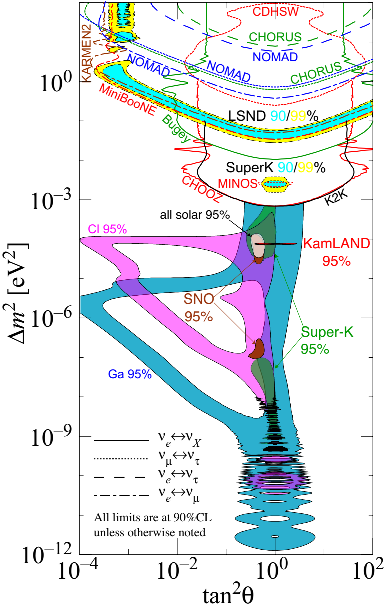
- $\mathrm{sgn}(\Delta m^2_{31})$ unknown
- No sensitivity to δ_{CP} yet
- Absolute neutrino masses not known
- Some open questions regarding coherence properties of neutrinos

Recap: summary of neutrino oscillation results



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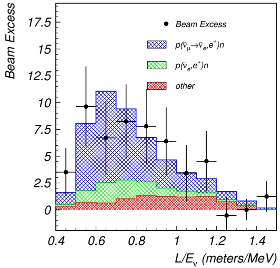
- LSND and MiniBoonE
  - Anomalous $\overset{(-)}{\nu}_e$ appearance at short baseline
- Reactor and gallium anomalies
  - Anomalous $\overset{(-)}{\nu}_e$ disappearance at short baseline

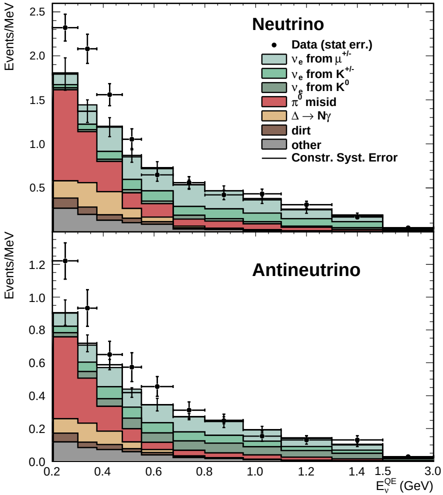
$\rightarrow$ Today's lecture

Oscillation anomalies: LSND and MiniBooNE

- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1$ km/GeV
- MiniBooNE:
  - No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred region
  - but $\bar{\nu}_e$ consistent with LSND
  - Low-E excess not understood



LSND hep-ex/0104049

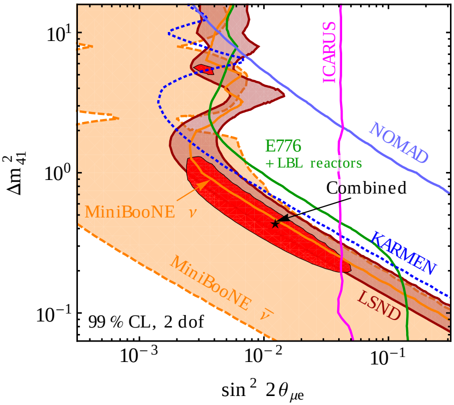


MiniBooNE arXiv:1207.4809

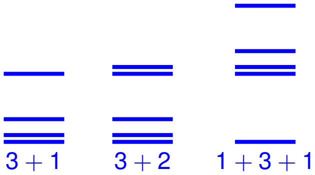
$\nu_\mu \to \nu_e$ oscillations at $L/E \sim 1$ km/GeV?

- Remember: Oscillation maxima for standard oscillations expected at
  - $L/E \sim 500$ km/GeV (from $\Delta m^2_{31} \sim 2.4 \times 10^{-3}$ eV^2)
  - $L/E \sim 15\,000$ km/GeV (from $\Delta m^2_{21} \sim 8.1 \times 10^{-5}$ eV^2)
- Explaining LSND and MiniBooNE requires an additional mass squared difference $\Delta m^2_{41} \sim 1$ eV^2.
- This requires an additional neutrino species.
- LEP measurements of the invisible Z width constrain the number of active neutrinos to three.
- Only possibility: A sterile neutrino ν_s, not coupling to SM gauge interactions.
  - "$3 + 1$ scenario"
- Then: Possibility of $\nu_\mu \to \nu_s \to \nu_e$ oscillations at $L/E \sim 1$ km/GeV

$\overset{(-)}{\nu}_e$ appearance in the 3+1 scenario and beyond



	χ^2_{3+1}/dof	χ^2_{3+2}/dof	χ^2_{1+3+1}/dof
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/66	72.7/63	74.6/63



- Global fit to all appearance data is consistent
- Background oscillations important in MiniBooNE and E776
- Significant improvement in $3+2$ and $1+3+1$

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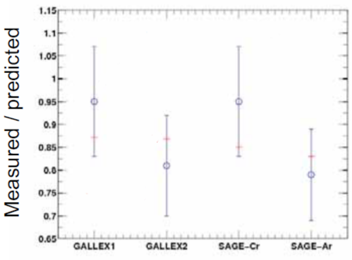
The Gallium anomaly

- Intense radioactive ν_e sources (^{51}Cr and ^{37}Ar) have been deployed in the GALLEX and SAGE solar neutrino detectors
- Neutrino detection via $^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$
- Result: Measurements consistently lower than expectation (2.7σ)



Giunti Laveder arXiv:1005.4599, arXiv:1006.3244
Mention et al. Moriond 2011 talk

- Question: How well are efficiencies of the radiochemical method understood?

The reactor anomaly

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim$ 3.5% higher than previous prediction Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum (for single β-decay: $E_\nu = Q - E_e$)
- Problem: Requires knowledge of Q-values for all contributing decays. $\rightarrow$ take from nuclear databases where available, fit to data otherwise

Old method Schreckenbach 1985	New method Mueller et al. arXiv:1101.2663
30 effective β decays	Uses nuclear databases (90% of $\bar{\nu}_e$ flux)
(fit parameters to ILL data)	5 effective β decays (remaining 10%)
	Error propagation, correlation matrix
	Corrections to the Fermi theory of β decay
	Off-equilibrium corrections
	(not all β-decay chains in equilibrium

- Cross check:
  - Simulate mock e^- spectra using few well-understood β-decays
  - Reconstruct $\bar{\nu}_e$ spectrum using old method: Result is 3% too low
  - Reconstruct $\bar{\nu}_e$ spectrum using new method: Result is exact.

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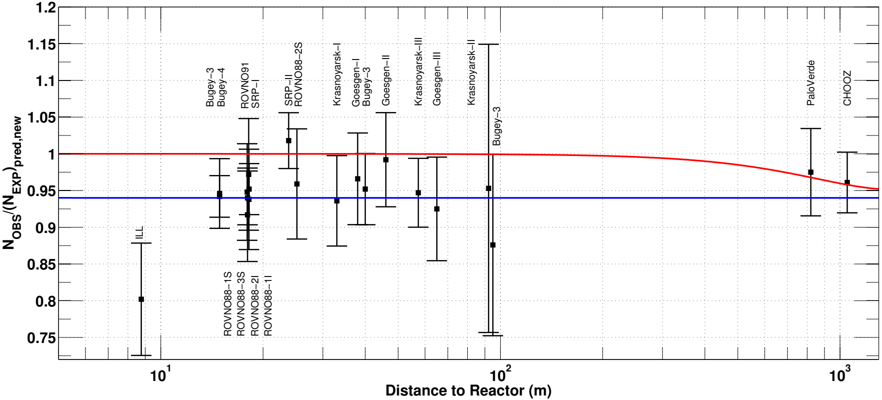
- Possible problems:
  - Poorly understood effects in nuclei with large log *ft*
    Huber arXiv:1106.0687
  - Large systematic uncertainties for non-unique forbidden β decays
    Hayes et al. arXiv:1309.4146

The reactor anti-neutrino anomaly

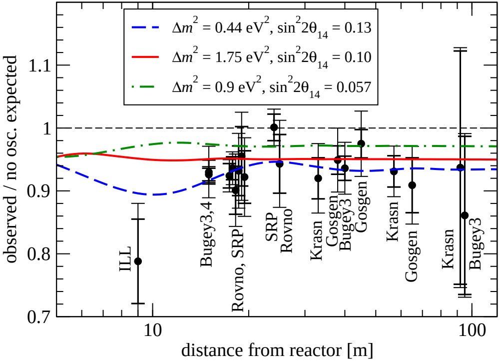
- Have short-baseline reactor experiments observed a $\bar{\nu}_e$ deficit?

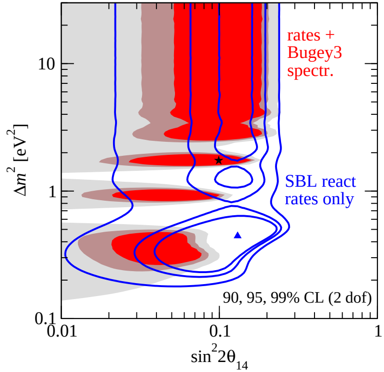


Mention et al. arXiv:1101.2755

red = new reactor $\bar{\nu}_e$ flux prediction
blue = old reactor $\bar{\nu}_e$ flux prediction

$\overset{(-)}{\nu}_e$ disappearance in the 3+1 scenario





	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{no\ osc}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)

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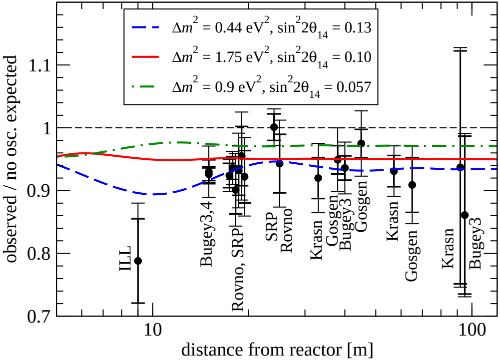

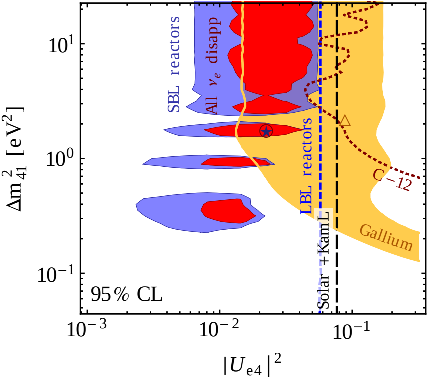

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SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

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Relation between appearance and disappearance

We find: $\overset{(-)}{\nu}_e$ disappearance experiments consistent among themselves, $\overset{(-)}{\nu}_e$ appearance experiments consistent among themselves.

But:

$3 + 1$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\mu\mu} = 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{e\mu} = 2|U_{e4}|^2|U_{\mu 4}|^2$$

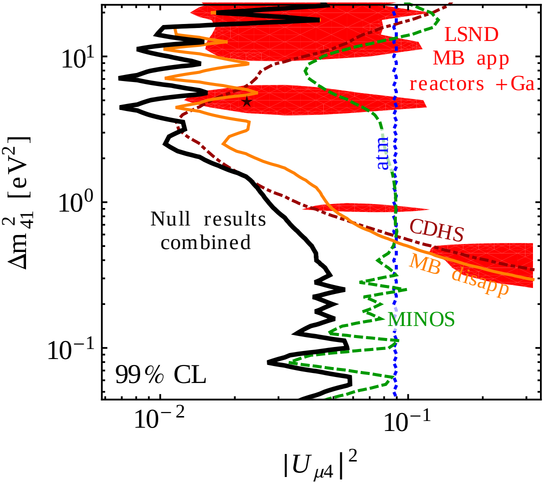
It follows

$$2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu})$$

In the $3 + 1$ case, at large enough baseline, there is a one-to-one relation between the appearance and disappearance probabilities.

$\overset{(-)}{\nu}_\mu$ disappaearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results from $\overset{(-)}{\nu}_\mu$ disappearance searches



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The global oscillation fit

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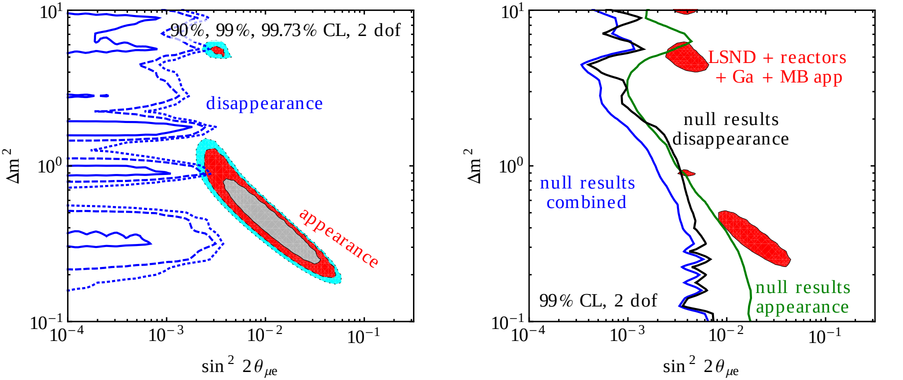

	χ^2_{min}/dof	GOF
3+1	712/(689 − 9)	19%

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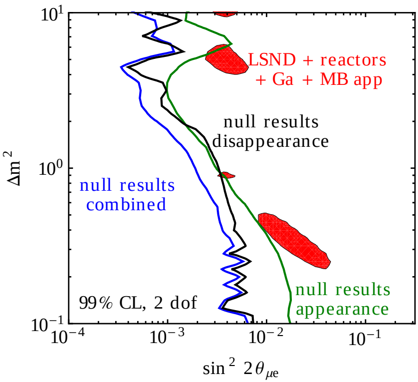
3 + 1 Severe tension between appearance and disappearance and between exp's with and without a signal



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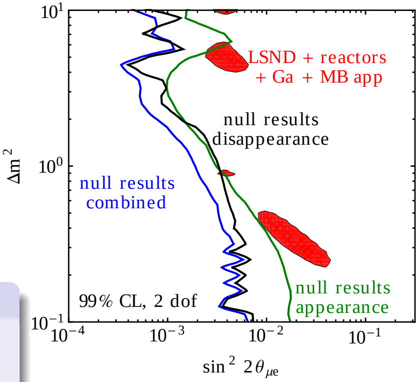

Parameter goodness of fit (PG) test:

Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}

The global oscillation fit

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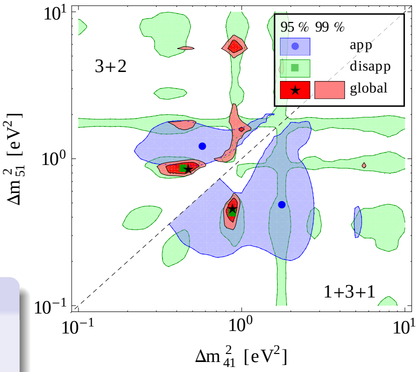
- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Fit improves considerably with two sterile neutrinos



Parameter goodness of fit (PG) test:

Compares $\chi^2_{\rm min}$ from global and separate fits to test compatibility of 2 data sets

	$\chi^2_{\rm min}$/dof	GOF	$\chi^2_{\rm PG}$/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}

The global oscillation fit

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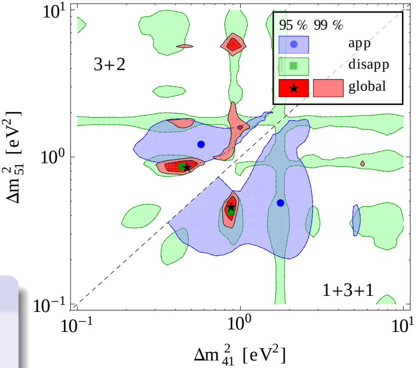
- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Fit improves considerably with two sterile neutrinos
- $1+3+1$ Further improvement, especially in appearance fit



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3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}
1+3+1	694/(689 − 14)	30%	16.8/4	2.1×10^{-3}

Conclusion from oscillation fits:

severe tension

in all cases

Sterile neutrinos in cosmology

Models with $\mathcal{O}$(eV) sterile neutrino(s) constrained by cosmology:

Sum of neutrino masses

$\sum m_\nu \lesssim 0.5$ eV

# of relativistic species

$N_\nu = 4$ mildly disfavored

see e.g. Ade et al. (Planck), arXiv:1303.5076
Gonzalez-Garcia Maltoni Salvado, arXiv:1006.3795
Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276
talks by Krysztof Gorski, Massimiliano Lattanzi, Ninetta Saviano on Monday

Are light sterile neutrinos ruled out by cosmology?

ν_s production in the early Universe through $\nu_{e,\mu,\tau} \to \nu_s$ oscillations at $T \gtrsim$ MeV

Dodelson Widrow 1994

Reconciling sterile neutrinos with cosmology

- Large lepton asymmetry ($\gtrsim 0.01$) $\to$ ν_s production MSW-suppressed
  Foot Volkas hep-ph/9508275, Chu Cirelli astro-ph/0608206, Saviano et al. arXiv:1302.1200
- New gauge interactions between ν_s and dark matter
  $\to$ ν_s production MSW-suppressed
  Dasgupta JK, in preparation
- Couplings to a Majoron field $\to$ suppressed production
  Bento Berezhiani, hep-ph/0108064
- Very low reheating temperature
  Gelmini Palomares-Ruiz Pascoli, astro-ph/0403323
- Entropy production after neutrino decoupling (e.g. due to late decay of heavy sterile neutrinos or other particles) $\to$ neutrinos diluted
  Fuller Kishimoto Kusenko 1110.6479, Ho Scherrer 1212.1689
- > 1 new relativistic degrees of freedom + $w < -1$ + $\mu_\nu \neq 0$
  Hamann Hannestad Raffelt Wong, arXiv:1108.4136