# Phenomenological analysis related to schemes with sterile neutrinos

## Workshop on Beyond Three Family Neutrino Oscillations

Thomas Schwetz

Max-Planck-Institut für Kernphysik

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# Outline

SBL phenomenology

Active-sterile mixing
- $U_{e4}$
- $U_{\mu 4}$
- $U_{\tau 4}$

Global data

More exotic proposals
- Sterile neutrino + NSI
- Soft decoherence

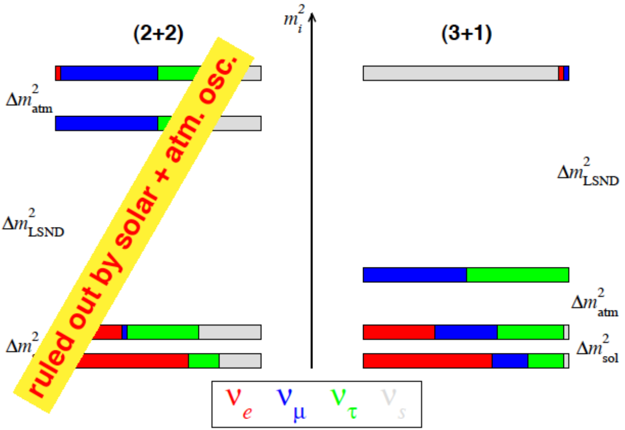
Conclusions

# Short-baseline (SBL) experiments

- $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance searches
  LSND, MiniBooNE, KARMEN, NOMAD
- $\bar{\nu}_e$ disappearance experiments (reactors)
  Bugey-3 (15, 40, 95), Bugey-4, Goessgen, Krasnoyarsk, Rovno, ILL, Chooz, Palo Verde
- $\nu_\mu$ disappearance
  CDHS, MiniBooNE, atmospheric neutrinos, MINOS NC

SBL: $E/L \sim \text{eV}^2 \quad \to \quad$ set $\Delta m^2_{21} \approx \Delta m^2_{31} \approx 0$
exceptions: Chooz, Palo Verde, atmospheric, MINOS NC

# 4-neutrino schemes




3+1: small perturbation to 3-active case

# 3+1 SBL oscillations

appearance

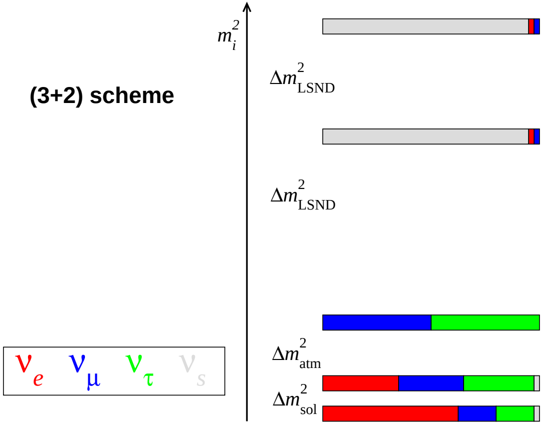
$$P_{\mu e} = \sin^2 2\theta_{\rm app} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm app} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

disappearance

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\rm dis} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm dis} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

- effective 2-flavour oscillations
- no CP violation $\to$ can't reconcile $\bar\nu$ (LSND, MB) and $\nu$ (MB) data
- constraints from $\nu_e$ ($\nu_\mu$) disappearance experiments on $U_{e4}$ ($U_{\mu 4}$) appearance mixing angle quadratically suppressed

# 5-neutrino schemes




Peres, Smirnov, hep-ph/0011054; Sorel, Conrad, Shaevitz, hep-ph/0305255

# 3+2 SBL oscillations

appearance:

$$P_{\nu_\mu\to\nu_e} = 4\,|U_{e4}|^2|U_{\mu 4}|^2\sin^2\phi_{41} + 4\,|U_{e5}|^2|U_{\mu 5}|^2\sin^2\phi_{51} + 8\,|U_{e4}U_{\mu 4}U_{e5}U_{\mu 5}|\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54}-\delta)$$

disappearance:

$$P_{\nu_\alpha\to\nu_\alpha} \approx 1 - 4\sum_{i=4,5}|U_{\alpha i}|^2\sin^2\phi_{i1} - 4\,|U_{\alpha 4}|^2|U_{\alpha 5}|^2\sin^2\phi_{54}$$

$$\left[\phi_{ij}\equiv \Delta m^2_{ij}L/4E\right]$$

- phase $\delta \equiv \arg\left(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5}\right) \to$ CP violation Karagiorgi et al. 06; Maltoni, TS 07
- BUT: constrain $|U_{ei}|$ and $|U_{\mu i}|$ $(i = 4,5)$ from disappearance to be reconciled with appearance amplitudes $|U_{ei}U_{\mu i}|$

# Outline

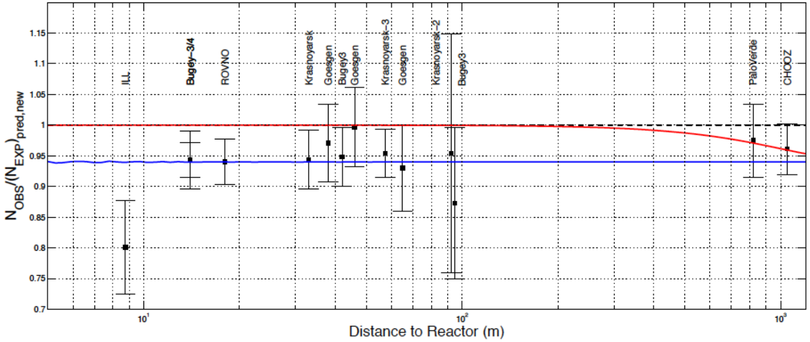
# What do we know about active-sterile mixing?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

independent information on $U_{\alpha 4}$ mainly from disappearance exps

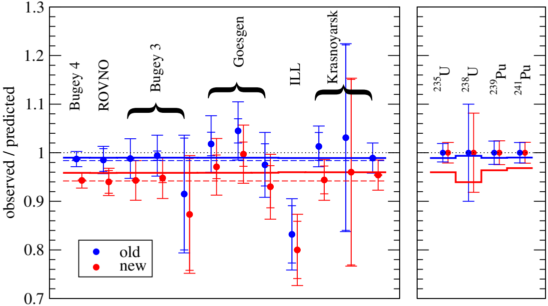
# The "reactor anomaly"

Mention et al., 1101.2755, talk by D. Lhuillier




oscillations with $\Delta m^2 \sim 1$ eV$^2$ may account for disappearance at baselines $L \lesssim 100$ m

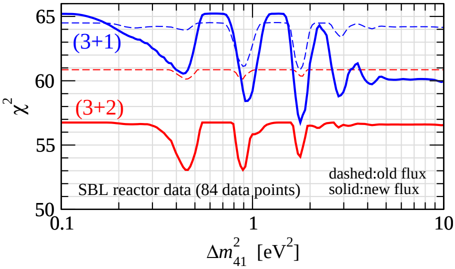
# The “reactor anomaly”




TS, Tortola, Valle 11

- $\chi^2 = 8.1(13.0)/12$ dof for old (new) fluxes $\Rightarrow$ still acceptable fit within errors (P-value: 37%)
- flux free analysis with new fluxes: $f = 0.942 \pm 0.024$, $f = 1$ disfavored with $\Delta\chi^2 = 6.2$ ($2.5\sigma$)

# 3+1 and 3+2 fit to SBL reactor data

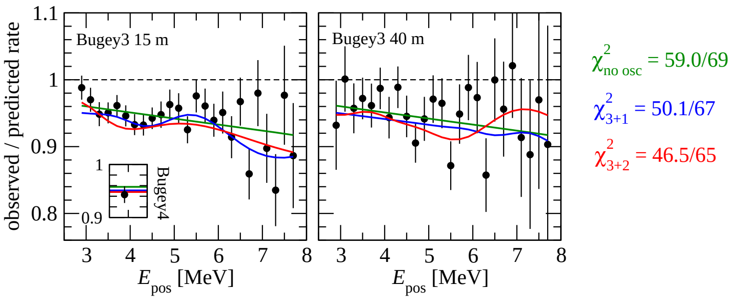



preference for sterile neutrino oscillations with new fluxes

- $\Delta\chi^2(3+1/\text{no-osc}) = 8.5 \to 98.6\%$ CL (2 dof)
- $\Delta\chi^2(3+2/\text{no-osc}) = 12.1 \to 98.3\%$ CL (4 dof)
- old flux: $\Delta\chi^2 = 3.6(4.4)$ for 3+1 (3+2)
- further improvement of fit for 3+2 wrt 3+1 with new fluxes

Kopp, Maltoni, TS, 11

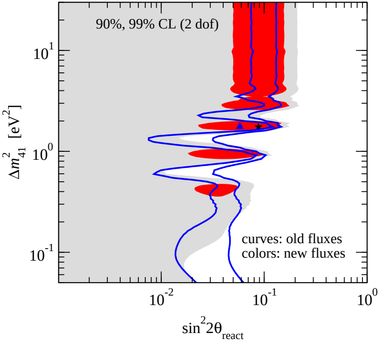
# 3+1 and 3+2 fit to SBL reactor data




| | $\Delta m^2_{41}$ [eV$^2$] | $\lvert U_{e4} \rvert$ | $\Delta m^2_{51}$ [eV$^2$] | $\lvert U_{e5} \rvert$ |
|---|---|---|---|---|
| 3+1 | 1.78 | 0.151 | | |
| 3+2 | 0.46 | 0.108 | 0.89 | 0.124 |

Kopp, Maltoni, TS, 11

# 3+1 and $U_{e4}$ from SBL reactor data




$$\sin^2 2\theta_{react} = 4|U_{e4}^2|(1-|U_{e4}^2|) \approx 4|U_{e4}^2|$$

- previous constraints become now "preferred regions" with $U_{e4} > 0$

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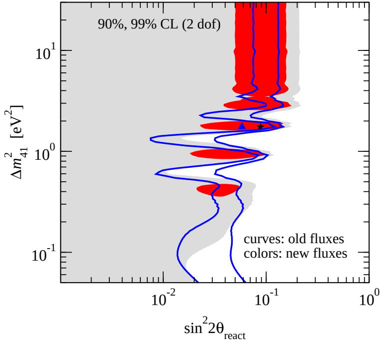


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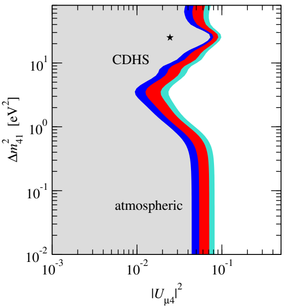
- previous constraints become now "preferred regions" with $U_{e4} > 0$
- "Gallium anomaly" gives additional hint for $U_{e4} > 0$

Acero, Giunti, Laveder, 0711.4222; Giunti, Laveder, 1006.3244; talks by E. Bellotti and C. Giunti

# 3+1 and limits on $U_{\mu 4}$




- $\nu_\mu$ disappearance CDHS (and also MiniBooNE)
- atmospheric neutrinos Bilenky, Giunti, Grimus, TS 99; Maltoni, TS, Valle 01

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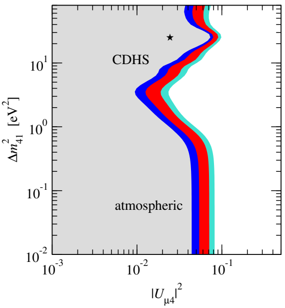


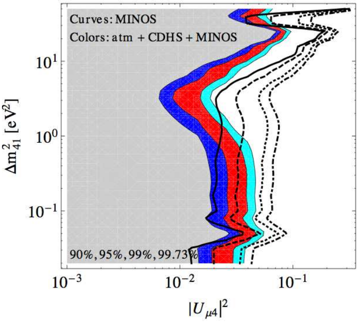


Kopp, Maltoni, TS, in prep

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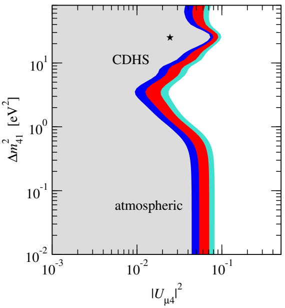


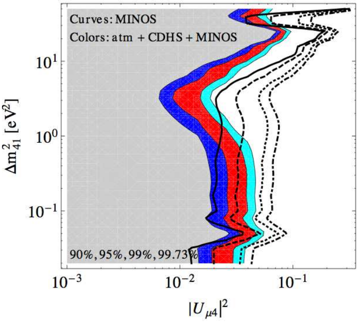


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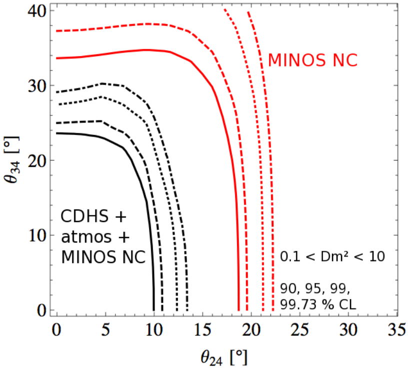
- atmospheric neutrinos Bilenky, Giunti, Grimus, TS 99; Maltoni, TS, Valle 01
- MINOS NC data 1001.0336, 1104.3922; talk by R. Nichol
- additional constraints from MiniB $\nu_\mu(\bar\nu_\mu)$ at $\Delta m^2 \gtrsim 10$ eV$^2$ talk by M. Sorel

# 3+1 and limits on $U_{\tau 4}$




$$|U_{\mu 4}^2| = \sin^2\theta_{24} < 0.03 \qquad |U_{\tau 4}^2| = \cos^2\theta_{24}\sin^2\theta_{34} < 0.16$$

# What do we know about active-sterile mixing?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \approx 0.15 \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & < 0.17 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & < 0.4 \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$|U_{e4}^2| \approx 0.025$$
$$|U_{\mu 4}^2| < 0.03$$
$$|U_{\tau 4}^2| < 0.16$$

for 3+n:

$$\text{limit on } |U_{\alpha 4}^2| \quad \rightarrow \quad \text{limit on } \sum_{i=4}^{3+n} |U_{\alpha i}^2|$$

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for 3+n:

$$\text{limit on } |U_{\alpha 4}^2| \quad \to \quad \text{limit on } \sum_{i=4}^{3+n} |U_{\alpha i}^2|$$

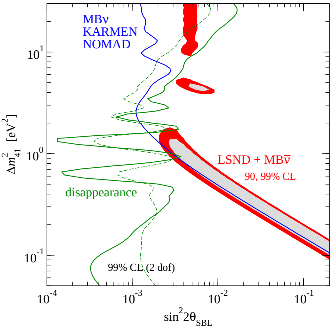
# Outline

# $\nu_\mu \to \nu_e$ data at the $E/L \sim 1$ eV$^2$ scale

- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$, $87.9 \pm 22.4 \pm 6.0$ excess events
  $P = (0.264 \pm 0.067 \pm 0.045)\% \sim 3.8\sigma$ away from zero
- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$, $\sim 2\sigma$ excess
  consistent with LSND in $2\nu$ framework
- MiniBooNE $\nu_\mu \to \nu_e$
  $E > 475$: no excess, $E < 475$: $\sim 3\sigma$ excess
- KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$, tight constraint on LSND region
  (slightly smaller $L/E$ than LSND)

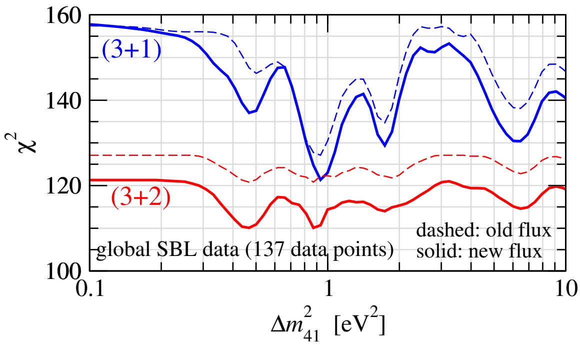
talk by M. Sorel

# 3+1 global fit




- no CP violation $\rightarrow$ LSND+MB$\bar{\nu}$ versus MB$\nu$
- despite relaxed constraints on $U_{e4}$ no improvement of global 3+1 fit
- LSND+MB$\bar{\nu}$ versus rest: $\chi^2_{\mathrm{PG}} = 21.5(24.2)$ for new (old) flux
  $\rightarrow$ compatibility of less than $10^{-5}$

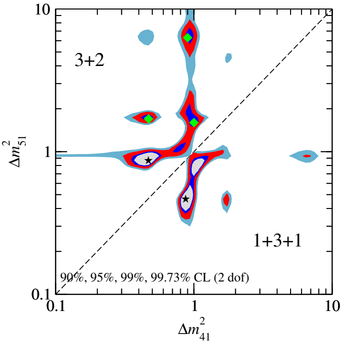
# 3+2 global fit




- $\Delta\chi^2_{3+2}$ (old vs new fluxes) = 11.1
- $\Delta\chi^2$ (3+1 vs 3+2) = 11.2 (97.6% CL, 4 dof)
  6.3 for old flux

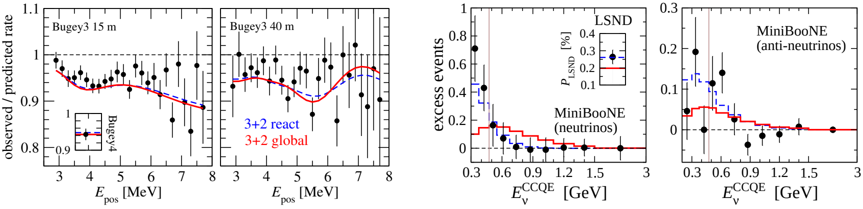
Kopp, Maltoni, TS, 11

# 3+2 global fit



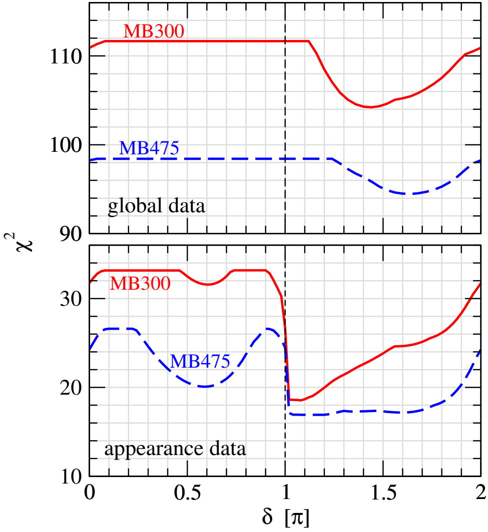

| | $\Delta m^2_{41}$ | $\|U_{e4}\|$ | $\|U_{\mu 4}\|$ | $\Delta m^2_{51}$ | $\|U_{e5}\|$ | $\|U_{\mu 5}\|$ | $\delta/\pi$ | $\chi^2/130$ |
|---|---|---|---|---|---|---|---|---|
| 3+2 | 0.47 | 0.128 | 0.165 | 0.87 | 0.138 | 0.148 | 1.64 | 110.1 |
| 3+2' | 0.47 | 0.117 | 0.201 | 1.70 | 0.151 | 0.101 | 1.39 | 114.4 |
| 3+2' | 1.00 | 0.133 | 0.163 | 1.60 | 0.122 | 0.079 | 1.48 | 114.4 |
| 3+2' | 0.90 | 0.123 | 0.163 | 6.30 | 0.135 | 0.091 | 1.67 | 115.0 |
| 1+3+1 | 0.47 | 0.129 | 0.154 | 0.87 | 0.142 | 0.163 | 0.35 | 106.1 |

# 3+2 global fit




- 3+2 fit to appearance data only (LSND, MB$\nu$, MB$\bar{\nu}$, KARMEN, NOMAD) allows for explanation of MB low energy excess Maltoni, TS, 07
- BUT: this requires large $U_{e4}, U_{e5}, U_{\mu 4}, U_{\mu 5}$ in sever disagreement with disappearance bounds
- MB low-E excess cannot be explained using global data

# CP violation?




Maltoni, TS 07

# Still considerably tension in 3+2 fit

| | LSND+MB($\bar{\nu}$) vs rest | | appearance vs disapp. | |
|---|---|---|---|---|
| | old | new | old | new |
| $\chi^2_{\mathrm{PG},3+2}$/dof | 25.1/5 | 19.9/5 | 19.9/4 | 14.7/4 |
| $\mathrm{PG}_{3+2}$ | $10^{-4}$ | 0.13% | $5 \times 10^{-4}$ | 0.53% |

- explanation of appearance signal requires $U_{ei}$ and $U_{\mu i}$ $(i = 4, 5)$
- no hint for oscillations seen in $\nu_\mu$ disappearance
  $\Rightarrow$ constraints on $U_{\mu i}$ in tension with signals
- MINOS NC data not (yet) included in the fit, slightly change compatibility Kopp, Maltoni, TS, in preparation

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Global data

More exotic proposals
- Sterile neutrino + NSI
- Soft decoherence

Conclusions

# More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying $\nu$ Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile $\nu$s in extra dim Paes, Pakvasa, Weiler 05
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 10
- 2 decaying sterile neutrinos with CPV
- energy dependent quantum decoherence Farzan, TS, Smirnov 07
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile $\nu$ with energy dep. mass or mixing TS 07
- sterile $\nu$ with nonstandard interactions Akhmedov, TS 10

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most of these proposals involve sterile neutrinos

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most of these proposals have problems with some data

# 3+1 + NSI

Akhmedov, TS 10 assume

- a 4th neutrino with $\Delta m^2_{41} \sim 1$ eV$^2$
- a new type of CC-like interaction

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon^{ff'}_{\alpha\beta}(\bar{f} P_{L,R}\gamma^\mu f')(\bar{l}_\alpha P_L \gamma_\mu \nu_\beta) + h.c.$$

$f, f'$ fermions depending on production or detection process

(NC-like NSI will have no relevant effect in short-baseline experiments since matter effect is very small)

# Transition probability in (3+1) NSI

- CP viol and zero-distance effects:

$$P_{\alpha\beta}(L) = \underbrace{4\left[|\alpha_{\alpha\beta}|^2 - \mathrm{Re}(\beta^*_{\alpha\beta}\alpha_{\alpha\beta})\right]\sin^2(\Delta/2)}_{\text{similar to standard oscillations}}$$

$$+ \underbrace{|\beta_{\alpha\beta}|^2}_{\text{zero-distance effect}} + \underbrace{2\mathrm{Im}(\beta^*_{\alpha\beta}\alpha_{\alpha\beta})\sin\Delta}_{\text{NSI-osc interference} \to \text{CP viol}}$$

$\alpha_{\alpha\beta}, \beta_{\alpha\beta}$: functions of $U_{\alpha 4}, \varepsilon_{\alpha\beta}$

# Source and detection processes

- CP viol and zero-distance effects
- can decouple LSND/KARMEN from the rest:

| | source | detection |
|---|---|---|
| LSND/KARMEN | $\mu$ decay | $\nu$-nucl CC ($e$) |
| MiniB/NOMAD | $\pi$ decay | $\nu$-nucl CC ($e$) |
| CDHS (atm) | $\pi$ decay | $\nu$-nucl CC ($\mu$) |
| Bugey/Chooz | $\nu$-nucl CC ($e$) | $\nu$-nucl CC ($e$) |

$|\alpha_{\mu e}^{\rm LK}|, |\beta_{\mu e}^{\rm LK}|, \delta^{\rm LK}$, $\alpha_e, \alpha_\mu, |\beta_{\mu e}|, \delta$, $\Delta m^2_{41}$

$\rightarrow$ 8 parameters (7 for 3+2 osc)

# 3+1 + NSI

CP viol, decouple LSND/KARMEN ⇒

- $\chi^2_{(3+1)\text{osc}} - \chi^2_{(3+1)\text{NSI}} = 18.5 (5\text{ dof}) \quad \rightarrow \quad 99.76\%$ CL
  appearance versus disappearance: PG compatibility of 15%

- $|U_{e4}| \approx 0.116$, $|U_{\mu 4}| \approx 0.205$ (more freedom from new react flux)
  $|\varepsilon^{ud}_{\mu s}| \approx 0.05$, $|\varepsilon^{ud}_{e\mu}| \approx 0.011$, $|\varepsilon^{e\nu}_{\mu s}| \approx 0.03$, $|\varepsilon^{e\nu}_{\mu e}| \approx 0.01$
  strength of new interactions at the level of few % compared to $G_F$
  in agreement with bounds Biggio, Blennow, Fernandez-Martinez, 0907.0097

- if due to dim-6 operator $\varepsilon G_F(\bar{f}f')(\bar{\ell}\nu)$ expect a charged mediator with $m_\phi \sim m_W/\sqrt{\varepsilon} \sim$ TeV → excellent prospect at LHC

- BUT: seems difficult (impossible?) to obtain such operators at dim-6 in gauge invariant way → go to dim-8 and involve some fine tuning

Gavela, Hernandez, Ota, Winter, 0809.3451; Antusch, Baumann, Fernandez, 0807.1003

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  in agreement with bounds Biggio, Blennow, Fernandez-Martinez, 0907.0097

- if due to dim-6 operator $\varepsilon G_F(\bar{f} f')(\bar{\ell}\nu)$ expect a charged mediator with $m_\phi \sim m_W/\sqrt{\varepsilon} \sim$ TeV $\rightarrow$ excellent prospect at LHC

- BUT: seems difficult (impossible?) to obtain such operators at dim-6 in gauge invariant way $\rightarrow$ go to dim-8 and involve some fine tuning
  Gavela, Hernandez, Ota, Winter, 0809.3451; Antusch, Baumann, Fernandez, 0807.1003

# 3+1 + NSI

CP viol, decouple LSND/KARMEN $\Rightarrow$

- $\chi^2_{(3+1)\text{osc}} - \chi^2_{(3+1)\text{NSI}} = 18.5(5 \text{ dof}) \quad \rightarrow \quad$ 99.76% CL
  appearance versus disappearance: PG compatibility of 15%

- $|U_{e4}| \approx 0.116$, $|U_{\mu 4}| \approx 0.205$ (more freedom from new react flux)
  $|\varepsilon^{ud}_{\mu s}| \approx 0.05$, $|\varepsilon^{ud}_{e\mu}| \approx 0.011$, $|\varepsilon^{e\nu}_{\mu s}| \approx 0.03$, $|\varepsilon^{e\nu}_{\mu e}| \approx 0.01$
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# Energy dependent quantum decoherence

Farzan, TS, Smirnov 07

- no sterile neutrino needed
- postulate quantum-decoherence of the mass states $\Rightarrow$ damping of the interference terms in the oscillation probabilities.
- damping affects only oscillations with $\Delta m^2_{31}$ and rapidly decreases with the neutrino energy
- reconcile LSND signal with MB$\nu$ and other null-result exps. (signal in MB$\bar{\nu}$ requires CPT violation decoherence)
- standard explanations of solar, atmos, KamL, MINOS not affected
- LSND signal controlled by the 1-3 mixing: $0.0014 < \sin^2\theta_{13} < 0.034$
- comparison of near and far measurements at reactors: null-result positive signal for $\theta_{13}$ in long-baseline accelerator experiments
- seems to be consistent with reactor anomaly!

# Outline

SBL phenomenology

Active-sterile mixing

- $U_{e4}$
- $U_{\mu 4}$
- $U_{\tau 4}$

Global data

More exotic proposals

- Sterile neutrino + NSI
- Soft decoherence

Conclusions

# Conclusions

- There are a couple of "hints" for sterile neutrinos at the eV scale
- Unfortunately none of these "hints" is convincing by itself
- It is intriguing that they all point to a similar mass range
  BUT, significant tension remains in the global fit
  (non-observation of $\nu_\mu$ disappearance)
- Are these sterile neutrinos consistent with cosmology?
  (CMB, LSS, BBN) see talks by F. Villante, A. Melchiorri

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**Thank you for your attention**