Sensitivity studies and systematics of the SOX project

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Sterile neutrinos in a 3+1 model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

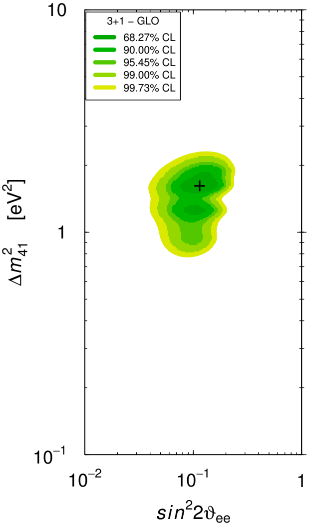
$\Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{32}$
Δm^2_{41}

standard oscillations almost untouched:
large mass splitting & small admixtures among active and sterile neutrinos

$\rightarrow$ survival probability P_{ee} of $\bar{\nu}_e$

$$P_{ee} \approx 1 - \sin^2(2\theta_{14}) \sin^2\left(\frac{1.27 \Delta m^2_{41}(\text{eV}^2) L(\text{m})}{E(\text{MeV})}\right) \quad @ \quad \frac{L}{E} \approx \frac{1\,\text{m}}{1\,\text{MeV}}$$

Where to look for sterile neutrinos?



- global analysis of all anomalies in a 3+1 model
- best fit point: $\Delta m^2_{41} \sim 1.5 eV^2$ & $\sin^2(2\theta_{14}) \sim 0.1$

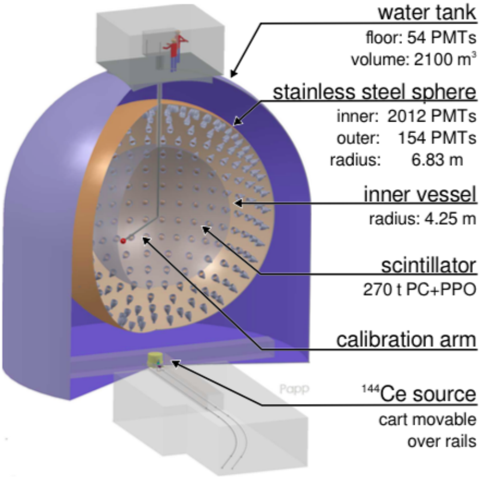
$\rightarrow$ oscillation length $\sim$ O(m)

- source next to detector

C. Giunti, M. Laveder, Y. F. Li, and H. W. Long, Phys. Rev. D **88**, 073008

Experimental setup

The Borexino detector



- radius of active volume: 4.25 m
- distance: 8.5 m

→ neutrino flux $\sim \frac{1}{r^2}$

- detection via inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

→ spatial and time coincidence

→ almost background free

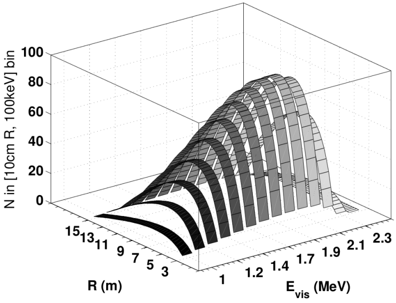
Expected signal

$$N(E,L,t) \sim A(t) \cdot \sigma_{IBD}(E) \cdot S_{\nu}(E) \cdot f(L) \cdot P_{ee}(E,L)$$

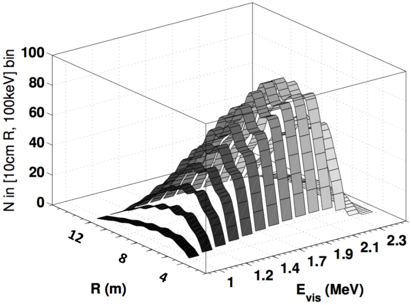
- $A(t)$: activity
- $\sigma_{IBD}(E)$: IBD cross section
- $S_{\nu}(E)$: neutrino spectrum
- $f(L)$: geometrical factor
- $P_{ee}(E,L)$: survival probability

- 10^4 events for 100 kCi & 1.5 y
- spatial resolution: 10 cm
- energy resolution: 5% at 1MeV

→ smoking gun signature



no oscillations

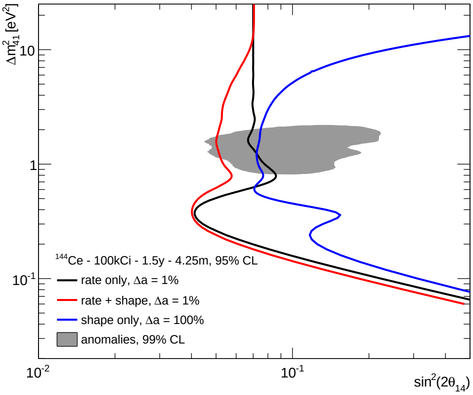


$\Delta m^2_{41} = 2\text{eV}^2$ & $\sin^2(2\theta_{14}) = 0.15$

Likelihood function:

$$\mathscr{L}\left(\sin^2(2\theta), \Delta m^2, u_i\right) = \text{Poiss}\left(\text{data}(E,L) | \text{signal}(E,L | \sin^2(2\theta), \Delta m^2, u_i)\right) \cdot \text{Gauss}\left(u_i | \bar{u}_i, \sigma_{u_i}\right)$$

- test statistic: profile likelihood ratio using Asimov data set
- experimental uncertainties u_i in pull terms



shape analysis:

- $\Delta m^2 \approx 0.5$ - $5\,\text{eV}^2$
- good energy and spatial resolution

rate analysis:

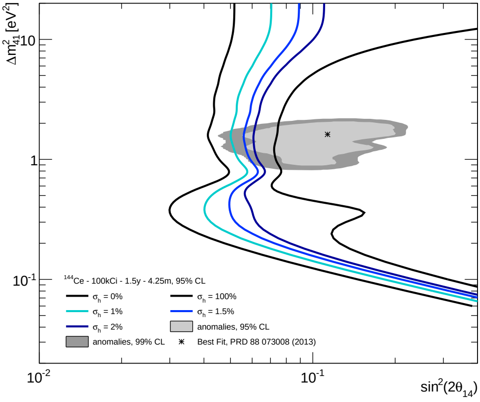
- $\Delta m^2 \approx 0.2$ - $0.5\,\text{eV}^2$ & $>5\,\text{eV}^2$
- accurate activity measurement

Source related uncertainties: power

$$N(E,L,t) \sim A(t) \cdot \sigma_{IBD}(E) \cdot S_\nu(E) \cdot f(L) \cdot P_{ee}(E,L)$$

$$\downarrow$$

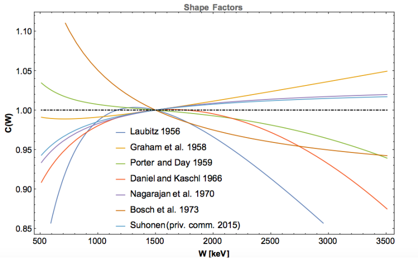
$A(t) \sim$ P(t) (calorimetric measurements)

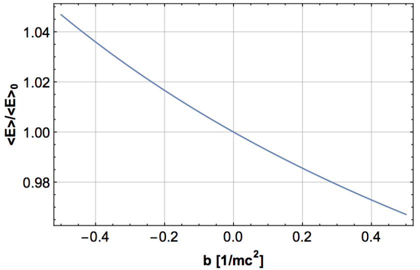


→ aim of 1% accuracy excludes almost the whole region of 99% CL of anomalies

Source related uncertainties: neutrino spectrum

- first non-unique forbidden transition
- $S_\beta \sim C(W)$ W: total energy of electron
- shape factor: $C(W) = 1 + a \cdot W + \dfrac{\mathbf{b}}{W} + c \cdot W^2$



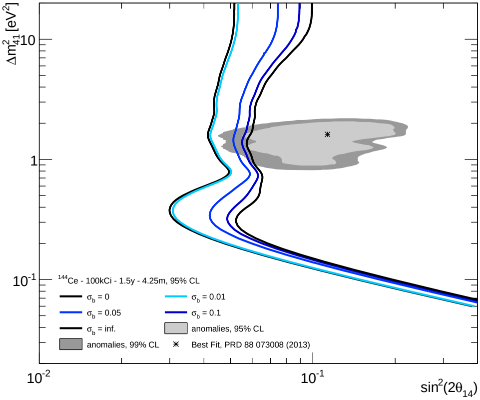


- shape factors
  - deform neutrino spectrum → mimic shape oscillations
  - change mean emitted energy → mimic rate deficit
- new measurements needed

$$N(E,L,t) \sim A(t) \cdot \sigma_{IBD}(E) \cdot S_\nu(E) \cdot f(L) \cdot P_{ee}(E,L)$$

$$\downarrow \qquad \searrow$$

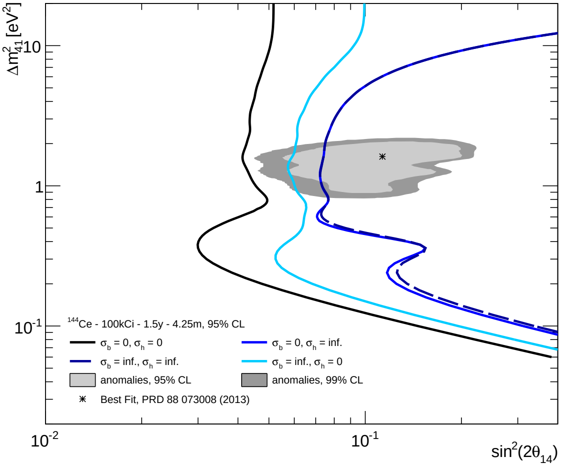
$$A(t) \sim \frac{1}{< E(a,\mathbf{b},c) >} \qquad S_\nu(E,a,\mathbf{b},c)$$



→ rate info not completely lost

→ aim is to determine b with 5% accuracy

Interplay of uncertainties



$\rightarrow$ b can mimic oscillation only for $\Delta m^2_{41} < 1\mathrm{eV}^2$

$\rightarrow$ shape only analysis almost unaffected

Conclusions

- global fit of anomalies with a 3+1 model expects $\Delta m^2_{41} \sim 1.5 eV^2$ & $\sin^2(2\theta_{14}) \sim 0.1$
- SOX could observe oscillations within the detector volume
- sensitivity shown obtained with a profile likelihood ratio
  - rate analysis
  - shape analysis
- source related uncertainties studied:
  - power measurement $\rightarrow$ $<$1% accuracy
  - shape factor b $\rightarrow$ $<$5% accuracy

$\rightarrow$ best fit value is excluded in all studies with $>$95% CL