Search for sterile neutrino oscillations with SOX/Borexino

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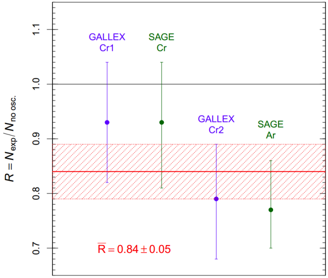
Experimental hints for sterile neutrinos

$\overset{(-)}{\nu}_e$ disappearance:

- SAGE & GALLEX: $\sim 3\,\sigma$ deficit measured-to-expected count rate in calibrations with ^{51}Cr and ^{37}Ar
- reactor anomaly: $\sim 3\,\sigma$ overall deficit measured-to-expected $\bar{\nu}_e$ flux R=0.927 $\pm$ 0.023

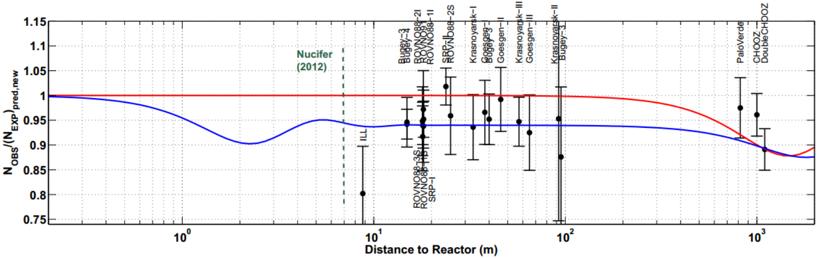


[C. Giunti et al., Phys. Rev. D **86**, 113014]

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance/disappearance:

- LSND: $> 3\,\sigma$ signal for oscillations due to $\Delta m^2_{41} \gtrsim 0.2\,\text{eV}^2$
- MiniBooNE: inconclusive results $\bar{\nu}_\mu \to \bar{\nu}_e$ compatible with LSND / $\nu_\mu \to \nu_e$ in tension

[A. Aguilar et al, Phys.Rev.D **64**, 112007. Aguilar et al, PRL **110** 161801 (2013)]



[G. Mention et al., Phys. Rev. D **83**, 073006. Updated in white paper, arxiv:1204.5379]

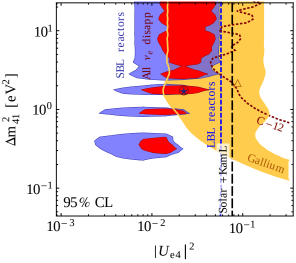
Interpretation in the 3+1 framework

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} , \quad \Delta m^2_{41}$$

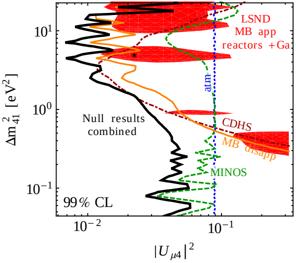
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{\alpha\beta}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

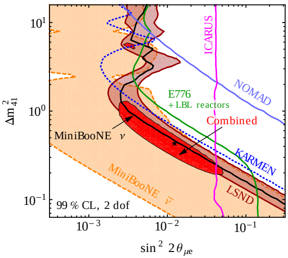
ν_e disappearance
(Gallium & reactor exps)
$\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$



ν_μ disappearance
(MiniBooNE/CDHS/MINOS)
$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$

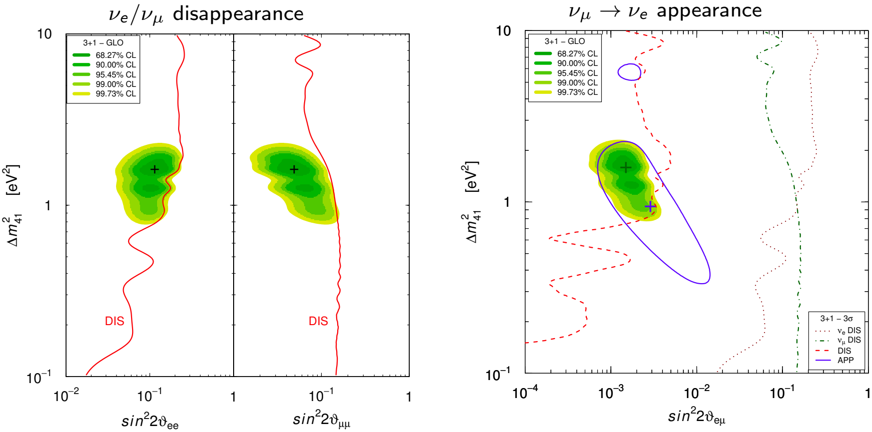


$\nu_\mu \to \nu_e$ appearance
(LSND/MiniBooNE)
$\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$



[J. Kopp, P. A. N. Machado, M. Maltoni and T. Schwetz, JHEP **1305** (2013) 050]

Global oscillation data fit (3+1 scenario)



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

Tension between appearance and disappearance data:

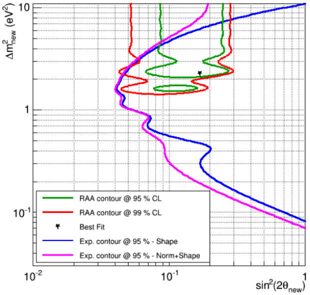
- allowed region: $\Delta m^2_{41} \in [0.8, 2.2]\,\mathrm{eV}^2$ (Giunti et al.)
- stronger tension observed by other groups (Kopp et al., Conrad et al.)
- tension is reduced when considering 3+2 or 3+3 models

Experimental status & perspectives

Many experimental approaches based on neutrinos from radioactive sources, reactors, atmospheric muons, accelerators. . . :

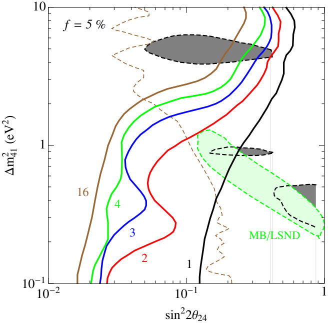
- SOX (first results in 2016): radioactive sources + Borexino LNGS (Italy)
- STEREO (first results in 2016): reactor + Gd-loaded liquid scintillator detector ILL (France)
- IceCube (analysis on-going): MSW effect on atmospheric neutrinos
- FNAL accelerator program
- KATRIN: high-precision measurement of the beta-decay kinematics

STEREO ($\sin^2 2\theta_{ee}$):



[Taken from D. Lhuillier (Neutrino 14)]

IceCube ($\sin^2 2\theta_{\mu e}$):



[A. Esmaili et al., JHEP 1312 (2013)]

SOX: Short distance $\overset{(-)}{\nu}_e$ Oscillations with BoreXino

INFN Milano München Heidelberg Hamburg Mainz

Gran Sasso Perugia Genova Napoli TU Dresden Jagiellonian Kraków

SOX: a project of the Borexino collaboration and CEA

Virginia Tech Houston Paris Moscow JINR Dubna

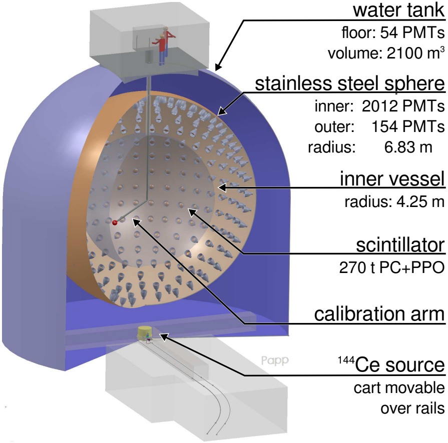
Los Angeles Princeton UMass Amherst St. Petersburg Kurchatov Moscow

SOX: Short distance $\overset{(-)}{\nu}_e$ Oscillations with BoreXino

A project of the Borexino collaboration + CEA. Strong involvement of Germany:

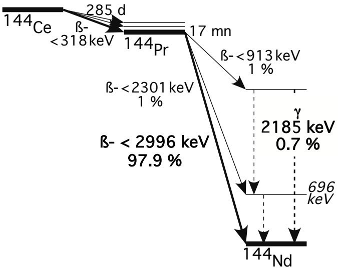
TU München, Univ. Hamburg, Univ. Mainz, Univ. Tübingen

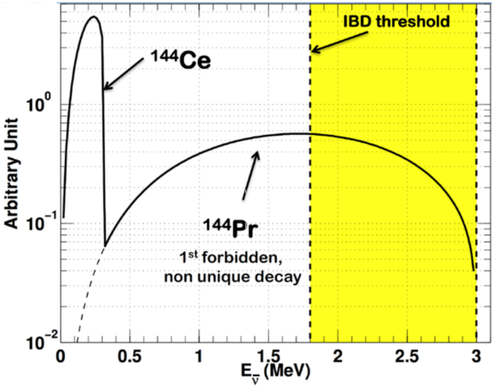
- Borexino detector:
  - 270 t of liquid scintillator
  - 2200 PMTs
  - @ LNGS
- Ultra-intense $\bar{\nu}/\nu$ sources (R=8.5 m):
  - 100 kCi ^{144}Ce-^{144}Pr ($T_{1/2} = 285$ d)
  - 10 MCi ^{51}Cr ($T_{1/2} = 28$ d)
- Project time-schedule:
  - end 2015: beginning data taking with ^{144}Ce source
  - middle 2016: first results
  - beginning 2017: end of ^{144}Ce data taking
  - middle 2017: ^{51}Cr data taking



^{144}Ce-^{144}Pr source – emitted flux

- 100 kCi initial activity
- β^- decay chain:
  $^{144}\text{Ce} \rightarrow ^{144}\text{Pr} + e^- + \bar{\nu}_e$
  $^{144}\text{Pr} \rightarrow ^{144}\text{Nd} + e^- + \bar{\nu}_e$
- $T_{1/2}(^{144}\text{Ce}) = 285\,\text{d}$
- $T_{1/2}(^{144}\text{Pr}) = 17\,\text{m}$





- Q-value(^{144}Ce) $= 0.3\,\text{MeV}$
- Q-value(^{144}Pr) $= 3\,\text{MeV}$
- detection via inverse beta decay

^{144}Ce-^{144}Pr source – detection concept

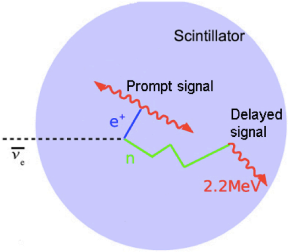
- $\bar{\nu}_e$ interact via inverse beta decay:
  prompt signal: e^+/e^- annihilation
  delayed signal: neutron absorption (2.2 MeV)

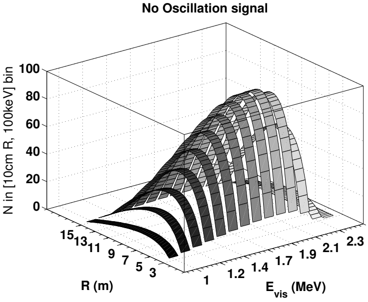
- background free:
  ○ enlarged fiducial volume
  ○ 240 t target mass

- oscillatory pattern in space and energy inside Borexino detector volume:
  Δm^2_{41}=2 eV^2 $\rightarrow$ <3.6 m osc. length

- 10^4 events in 1.5 yr

- event reconstruction accuracy in Borexino:
  ∼ 5% energy resolution
  ∼10 cm spatial resolution





[Cribier et al., PRL 107, 201801 (2011)]

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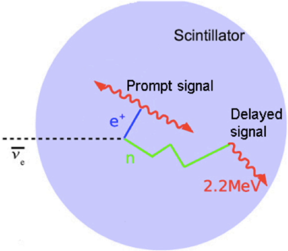
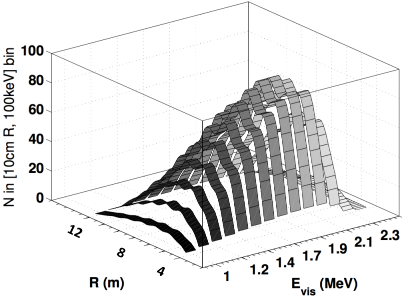




[Cribier et al., PRL 107, 201801 (2011)]

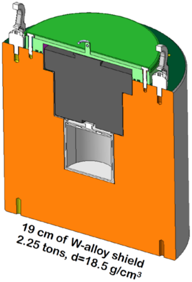
^{144}Ce-^{144}Pr source – production and transport

Produced by chemical extraction of exhausted nuclear fuel (Mayak)

1 t of fuel (KOLA plant) –> 3 kg of Ce –> 32 g of ^{144}Ce –> 100 kCi

Extraordinary safety regulations:

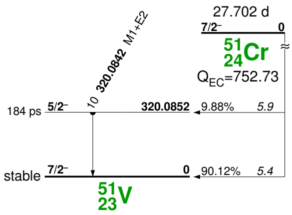
- encapsulation in massive tungstate shielding
- transportation logistic and authorizations
- handling at LNGS

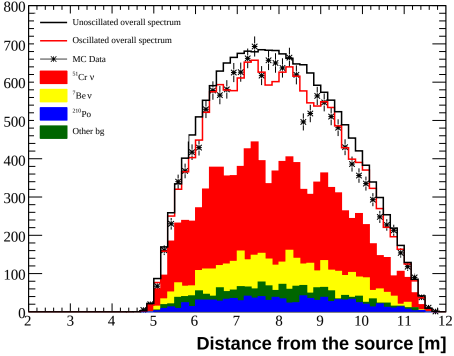


^{51}Cr source – overview

^{51}Cr source features:

- activity of 10 MCi
- electron capture with Q-value of 753 keV:
  - 4 mono-energetic ν_e lines
- $T_{1/2} = 28$ d:
  - $\sim$ 1 week transportation from Oak Ridge (NL)
  - short data taking of the order of 100 d



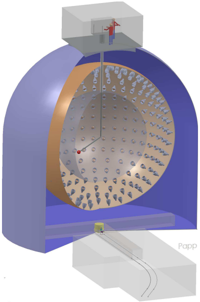


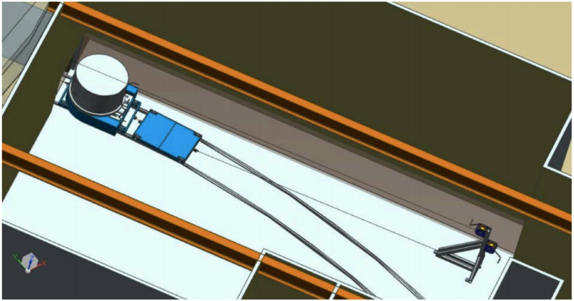
[G. Bellini et al., JHEP 08 (2013) 038]

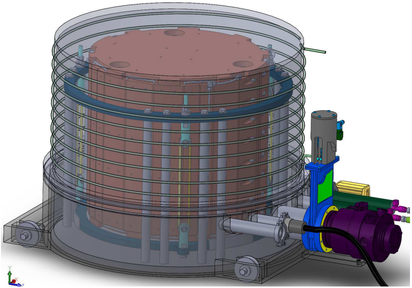
Experimental signature:

- $\nu_e + e^- \to \nu_e + e^-$ (electron recoil)
- expected 10^4 events
- background from solar neutrinos and internal ^{210}Po
- analysis based on count-rate dependence from time & position

Source deployment and characterization



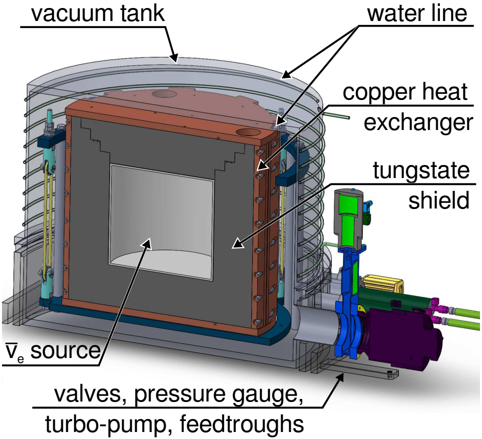




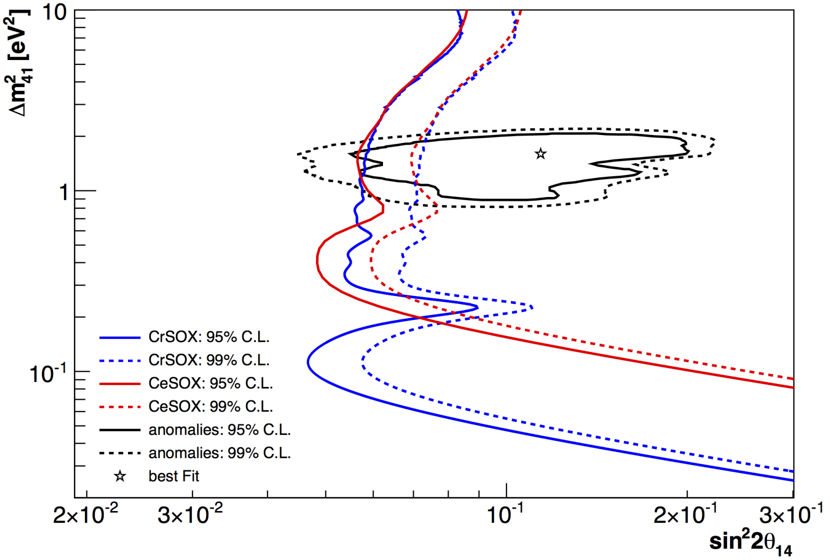
Thermal calorimeter

Source characterization:

- activity measurement with $\sim 1\%$ accuracy
- ^{144}Ce source: measurement prior data taking and then repeated at regular time intervals
- ^{51}Cr source: continuous measurement in the pit during data taking
- TUM/Genova thermal calorimeter:
  - ◦ copper heat-exchanger
  - ◦ vacuum chamber with radiation shields
  - ◦ water line for heat extraction
  - ◦ water temperature and flow: Activity $\propto$ Power $\propto \Delta T \cdot \Phi$
- Mainz/Tübingen: heat source for calibration/mock-up
- alternative setup for first measurement under development at CEA

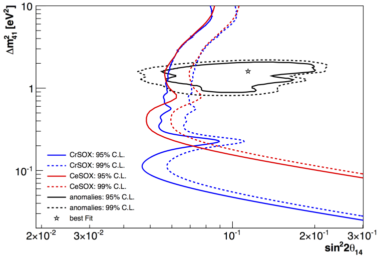


Sensitivity

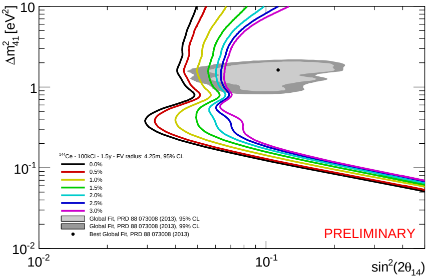


Sensitivity

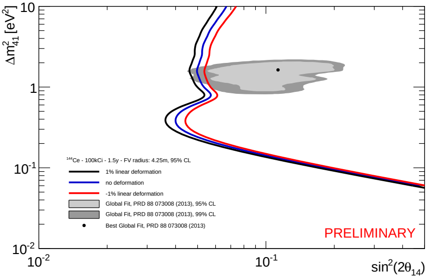
- signal discovery or exclusion in 1.5 yr with ^{144}Ce
- sensitivity enhanced by combining ^{144}Ce with ^{51}Cr
- ^{51}Cr extremely important to confirm signal
- systematic uncertainties dominated by $\overset{(-)}{\nu}_e$ flux:
  - source activity
  - neutrino energy distribution



Source activity uncertainties:



Energy distribution uncertainties:



[From B. Neumair (TUM). Likelihood ratio analysis based on Asimov data sets]

Conclusions

- Sterile neutrinos: complicated field, many datasets, need for conclusive results
- Global fits limit parameter space to: $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$ & $\sin^2 2\theta_{ee} \sim 0.1$
- SOX: direct search for short baseline oscillations in the Borexino detector with $\bar{\nu}_e$ (^{144}Ce) and ν_e (^{51}Cr) radioactive sources
- ^{144}Ce-^{144}Pr data taking starting in fall 2015 to conclusively probe the parameter space of interest. First physics results already in 2016!
- ^{51}Cr data taking conceived in 2017: crucial in case of a positive signal