Future Short Baseline Sterile Neutrino Searches with Nuclear Decays

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Outline of the talk

- Why sterile neutrino? Experimental hints;
- How can we confirm or disproof the hints towards sterile nu?;
- SOX: Short Distance neutrino Oscillations with boreXino;

Sterile neutrino search: experimental hints

ν_e, anti-ν_e DISAPPEARANCE

ν_e, anti-ν_e APPEARANCE

Reactor anomaly ~2.5σ

Re-analisys of data on anti-neutrino flux from reactor short-baseline (L~10-100 m) shows a small deficit of R=0.943 ±0.023

G.Mention et al, Phys.Rev.D83, 073006 (2011) , A.Mueller et al. Phys.Rev.C **83**, 054615 (2011)*;*

Gallex/SAGE anomaly ~3σ

Deficit observed by Gallex in neutrinos coming from a ^{51}Cr and ^{37}Ar sources

$$R = 0.76^{+0.09}_{-0.08}$$

C. Giunti and M. Laveder, Phys.Rev. C83, 065504 (2011), arXiv:1006.3244 [hep-ph].

Accelerator anomaly ~3.8σ

Appearance of anti-ν_e in a anti-ν_μ beam (LSND). *A.Aguilar et al. LSND Collaboration Phys.Rev.D 64 112007 (2001).*

Confirmed by miniBooNE (which also sees appearance of ν_e in a ν_μ beam) *A.Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)*

Possible explanation: mixing of the active flavours with a sterile neutrino Δm^2 ~ 1 eV^2

Some observations

- It is not possible to accomodate all the anomalies in a three flavour scenario: we need at least one sterile neutrino;
- (3+1), (3+2), (3+1+1) scenarios fit similarly well the data (but 3+1 maybe preferrable for cosmological reasons);
- However there is a tension between appearance and disappearance data (due to the fact that ν_μ disappearance experiments give no hints for disappearance);

Sterile neutrino search: experimental hints

In the (3+1) scenario,

$$\Delta m^2_{41}, \quad \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

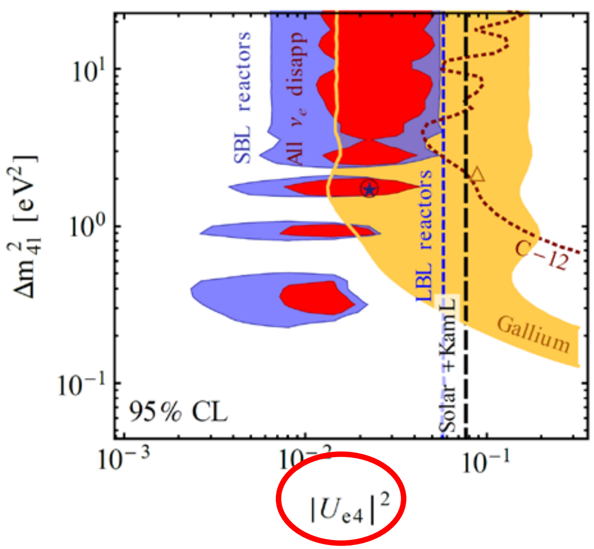
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

$$\Delta m^2_{21} << \Delta m^2_{31} << \Delta m^2_{41} \quad |U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 << 1 \quad |U_{s4}|^2 \cong 1$$

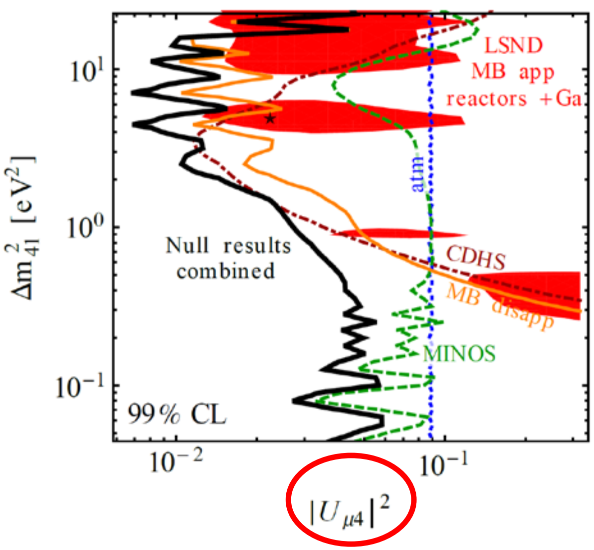
ν_e disappearance (Gallex+Sage+reactors)

$\sin^2 2\theta_{ee} = 4|U_{e4}|^2 (1-|U_{e4}|^2) = \sin^2 2\theta_{14}$



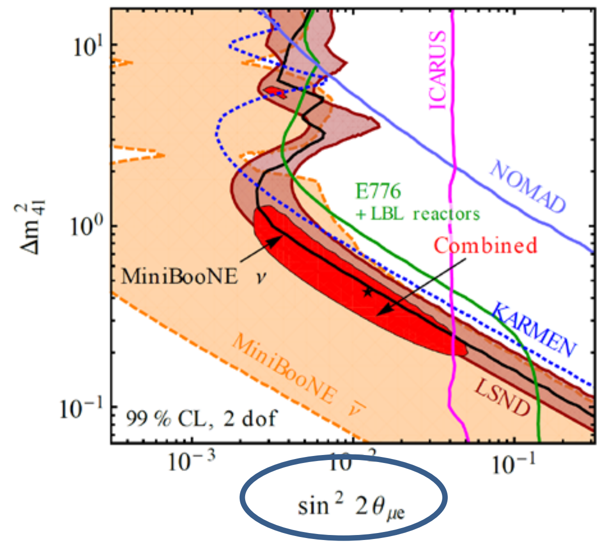
ν_μ disappearance (CDHS,miniBooNE+MINOS..)

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



$\nu_\mu \to \nu_e$ appearance (miniBooNE+LSND.)

$\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2$

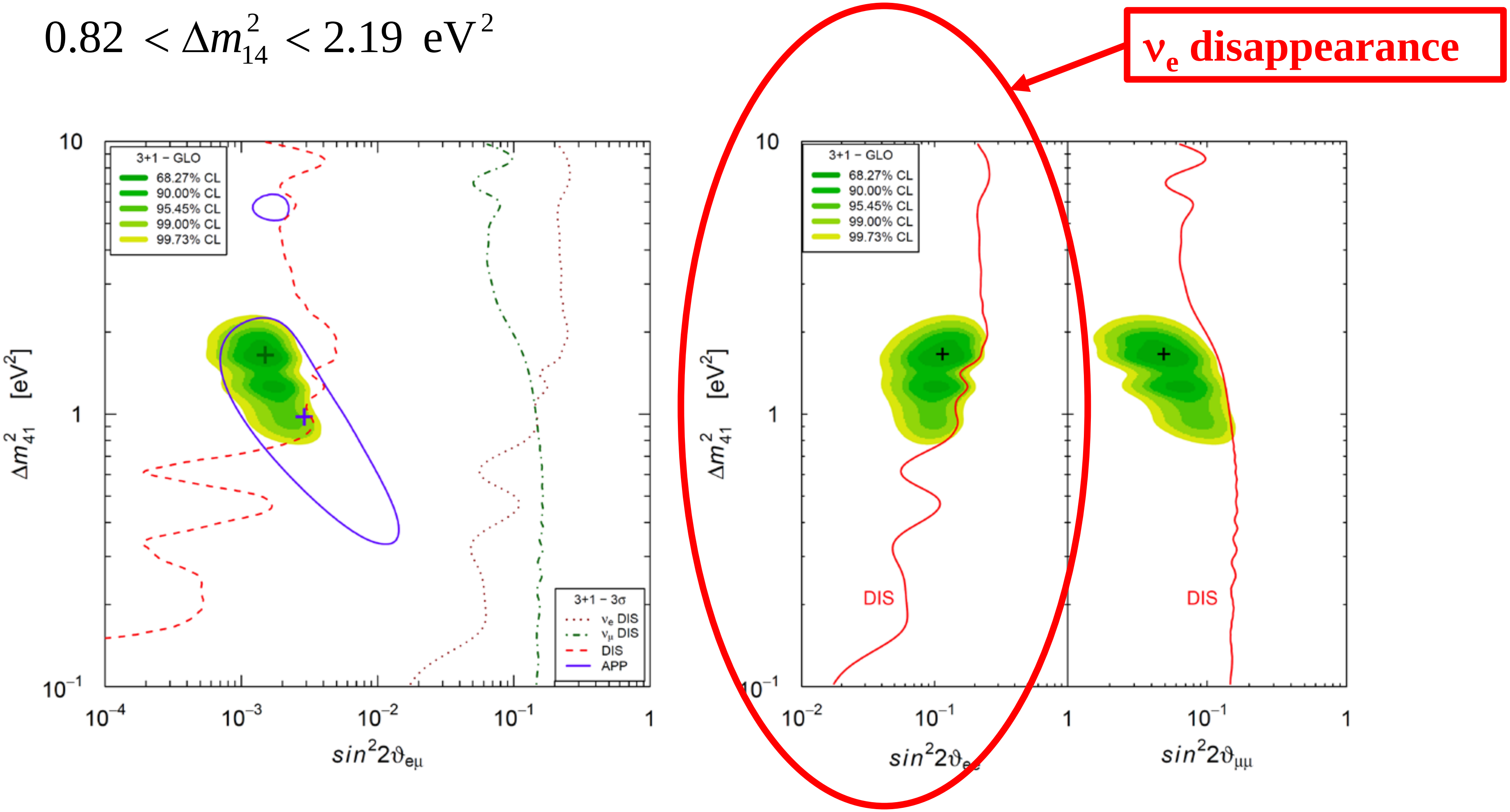


J.Kopp,P.Machado,M.Maltoni, T.Schwetz arXiV:1303.3011v3 [hep-ph]

Sterile neutrino search: experimental hints

- **Global fit of all data isolates a very narrow region of the parameter space**

$$0.82 < \Delta m^2_{14} < 2.19 \text{ eV}^2$$



Fit in the (3 + 1) scenario, including all data (appearance and disappearance) with the exception of the low energy excess by MiniBooNE; *C.Giunti,M.Laveder,Y.F. Li,H.W.Long arXiV:1308.5288 v3 [hep-ph], Phys.Rev.D 88, 073008 (2013)*

Sterile neutrino search using nuclear decays

These experimental anomalies deserve indipendent confirmation or disproval

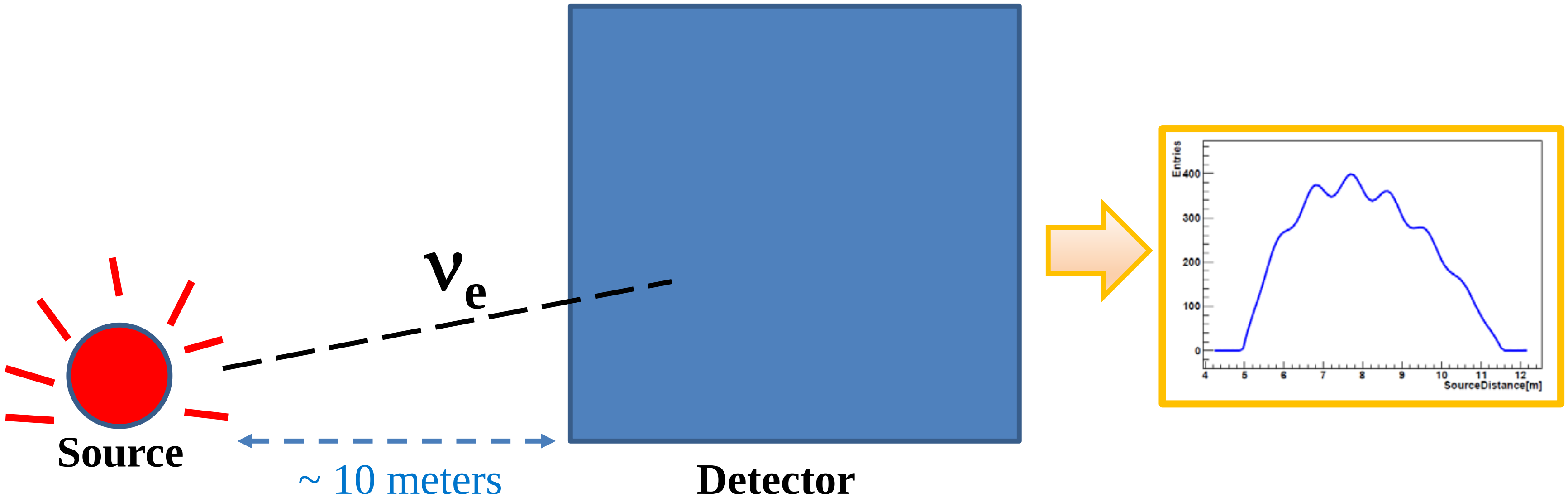
It is possible to investigate the relevant parameter space region by means of neutrinos (or anti-neutrinos) produced in nuclear decays;

In order to be sensitive to $\Delta m^2 \sim 1\ eV^2$

- Need a source with E ~ 1- 10 MeV
- Located at a distance L ~ 1-10 m

1) Look for disappearance of ν_e emitted by the source;

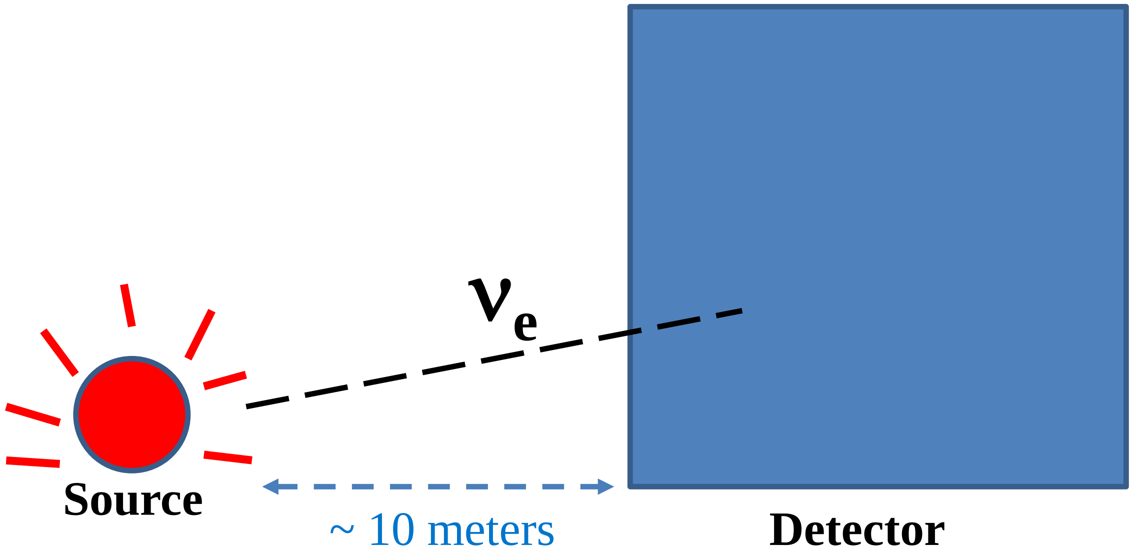
2) Look for oscillation waves within the detector volume (oscillometry);

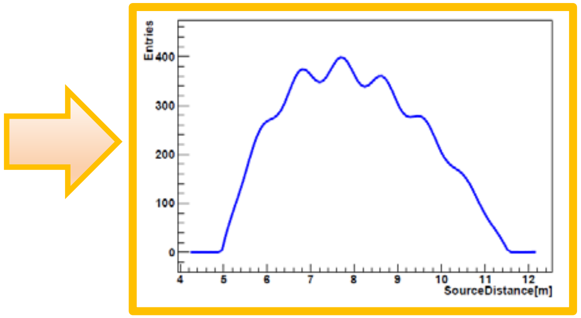


Sterile neutrino search using nuclear decays

Several advantages of using nuclear decays

- Intrinsicly pure ν_e (or anti- ν_e) beam;
- Neutrino spectrum known very precisely;
- Neutrino cross-sections in the ~MeV region known more precisely than at ~ GeV;
- Neutrino flux known with high precision (~1-5 % level);





Possible sources

ν type	Source type	Life τ	Decay mode	Energy [MeV]	Production mode
ν_e	^{51}Cr	40 d	EC	0.75 (90%) 0.43 (10%)	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \geq 5\ 10^{14}\ cm^{-2}\ s^{-1}$
	^{37}Ar	35 d	EC	0.811	Fast neutron irradiation of Ca oxide in reactor
$\bar{\nu}_e$	^{144}Ce-^{144}Pr	411 d	β^-	<2.997	Chemical extraction from spent fuel
	^{90}Sr	40 y	β^-	<2.27	RHS (RadioNuclide Heat Source)
	^{8}Li	868 ms	β^-	<12.9	Beam of neutrons on a ^{7}Li target (ISODAR facility)

neutrino source

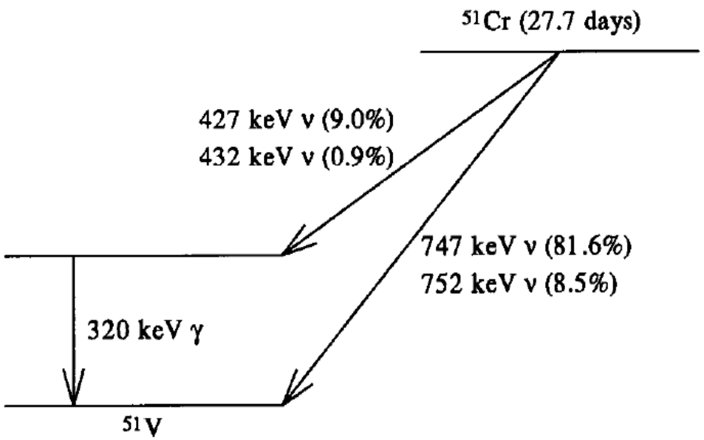
- detecting reaction $\nu + e \rightarrow \nu + e$ radioactive background is a problem; not possible to put the source inside the detector;
- monocromatic; lower energy;

anti-neutrino source

- detecting reaction $\bar{\nu} + p \rightarrow n + e^+$ very little background; may be feasible to put the source inside the detector;
- Continuum spectrum; higher energy;

Possible sources: ^{51}Cr

Source characteristics: ν source, E_ν =750 keV   τ=40 days



Decay scheme of ^{51}Cr to ^{51}V through electron capture.

Production mode

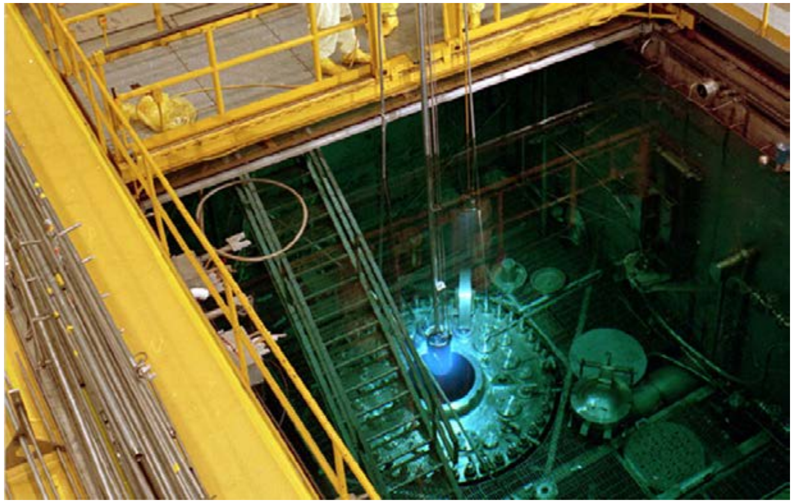
- thermal neutrons impinging on ^{50}Cr (high neutron capture cross-section ~ 17 barn);
- High neutron flux is needed (>**5 10^{14} cm^{-2} s^{-1});**
- **Possibility at the OakRidge High Flux Isotope Reactor (HFIR);**

ADVANTAGES

- γ emitted by the source (E=320 keV) not too difficult to handle;
- Cr used by Gallex still available (36 Kg enriched at 38.6% in ^{50}Cr);

DISADVANTAGES

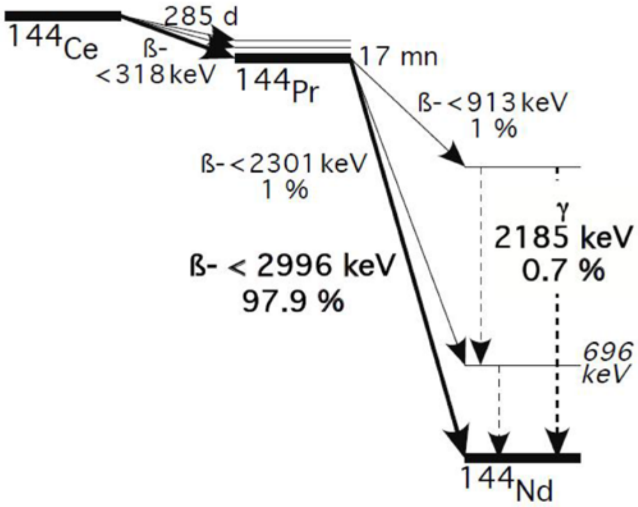
- detecting reaction is $\nu + e^- \rightarrow \nu + e^-$ radioctivity is a serious background (unless reaction with coincidence tag-like in LENS);



Source activity ~ 10 MCi ~370 PBq (3.7 x 10^{17} ν/sec)

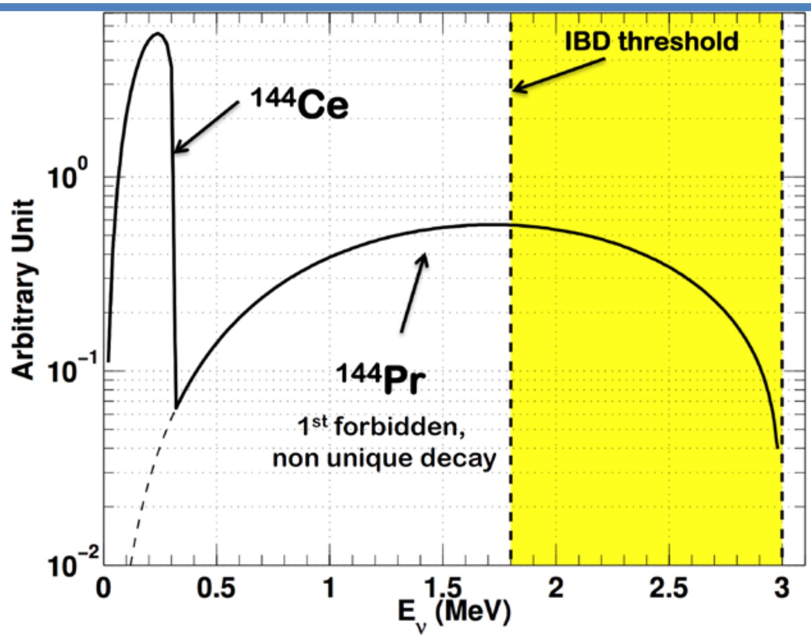
Possible sources: ^{144}Ce-^{144}Pr

Source characteristics: anti-ν source, E_ν <2.99 MeV τ=411 d



Production mode

- extracted from exhausted nuclear fuel;
- **Possibility at the Mayak industrial complex (Russia)**



ADVANTAGES

- detecting reaction is $\bar{\nu} + p \rightarrow n + e^+$ very little background;
- Long lifetime;

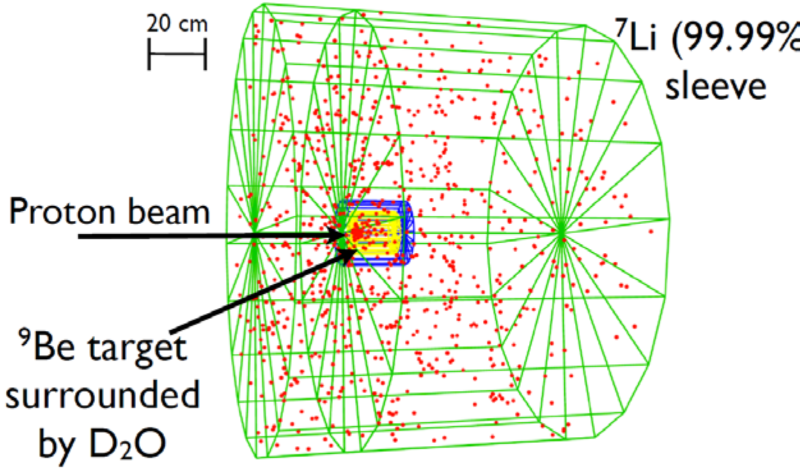
DISADVANTAGES

- high energy γ_s (E=2.2 MeV) emitted by the source are difficult to handle;

Source activity ~100 kCi ~3.7PBq (3.7 x 10 ^{15} ν/sec)

Possible sources: ^{8}Li

Source characteristics: anti-ν source, E_ν <13 MeV τ= 868 ms



Production mode

IsoDAR: Isotropic Decay At Rest

- proton beam (60 MeV) impinging on a ^{9}Be tgt to produce neutrons;
- neutrons moderated and multiplied by a $D_2$0 shield 5 cm thick;
- the Be tgt is surrounded by a sleeve of ^{7}Li (d=200cm, h=150cm)
- ^{8}Li is produced

ADVANTAGES

- Long data taking time possible;
- High Energy;

DISADVANTAGES

- Anti-nu flux known only at ~5% level;
- Production point of ^{8}Li is not point-like (dominated by z uncertainty (150 cm);

Still in the R&D phase:

- Need to produce compact cyclotron with x6 intensity with respect to medical isotope industry;
- Prototype by ~2016

Source activity ~ 8.2 x 10 ^{14} ν/sec

POSTER''Accelerator design and modeling for the decay-at-rest neutrino experiments DAEdALUS and IsoDAR" Dr.WINKLEHNER,Daniel

Candidate detectors

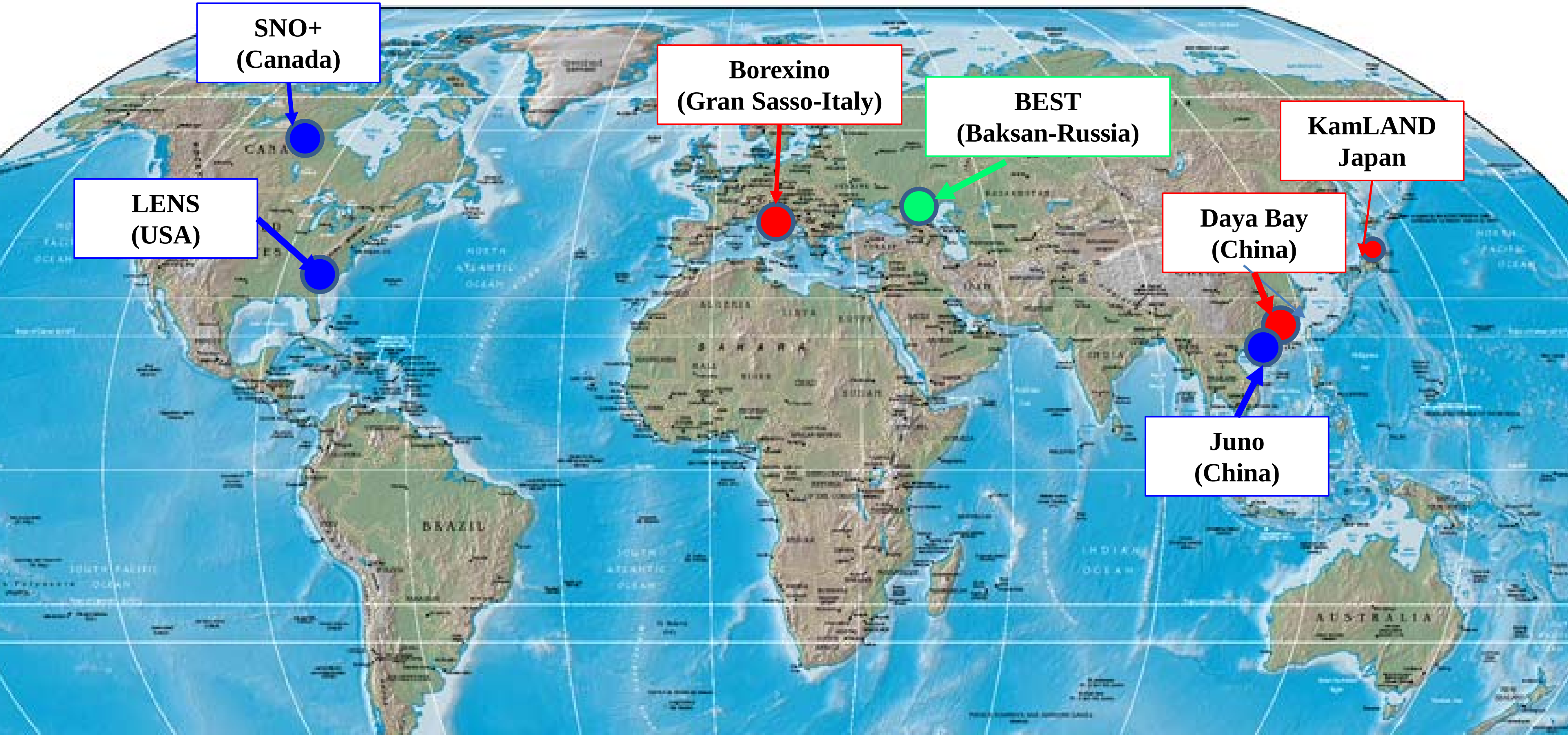
Requirements

- Underground location;
- Large mass, ultra-pure detectors;
- Capability to measure E and L (oscillometry);

Existing large liquid scintillator experiments (Borexino, KamLAND, Daya-Bay)

Future large liquid scintillator experiments (SNO+, LENS, JUNO)

Future experiments based on other techniques (RICOCHET, BEST)

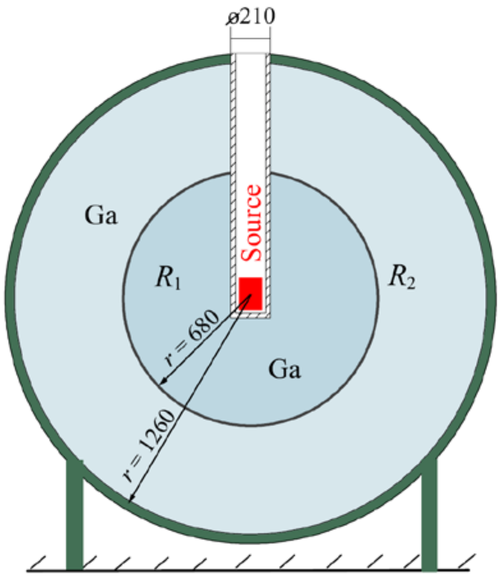


Several papers and ideas

Technique	Detector	Sources	Reaction	Activity	Reference
Large Liquid scintillator detectors	**SOX (Borexino)**	**^{51}Cr,**	**ν+e → ν+e**	**10MCi**	***JHEP08(2013)038,***
		^{144}Ce-^{144}Pr	**ν+p → e^++n**	**100kCi**	*Phys. Rev. Lett. 107, 201801 (2011)*
	KamLAND	**^{8}Li (ISODAR)**	**$\bar{\nu}$+p → e^++n**	**8.2 x 10 ^{14} ν/sec**	***arXiV:1205.4419, arXiV:1310.3857***
		^{144}Ce(CeLAND)	**$\bar{\nu}$+p → e^++n**	**100kCi**	arXiv:1312.0896
	Daya-Bay	**^{144}Ce-^{144}Pr**	**$\bar{\nu}$+p → e^++n**	**500kCi**	***arXiV:1109.6036***
	LENS	**^{51}Cr**	**ν+^{115}In → ^{115}Sn*+e**	**10MCi**	***Phys.Rev.D75 093006(2007)***
	JUNO	**^{8}Li (ISODAR)**	**$\bar{\nu}$+p → e^++n**	**8.2 x 10 ^{14} ν/sec**	***arXiV:1310.3857***
Radiochemical	**BEST**	**^{51}Cr**	**ν+^{70}Ga → ^{71}Ge+e**	**3MCi**	**arXiV:1204.5379**
Bolometers	**Richochet**	**^{37}Ar**	**ν+N → ν+N**	**5MCi**	**Phys. Rev. D85, 013009, (2012)**

Several papers and ideas

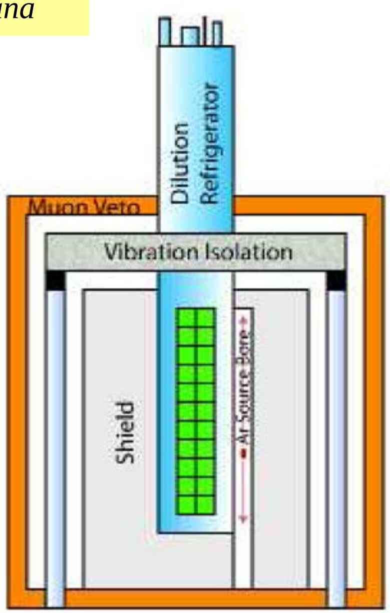
BEST (Baksan experiment on Sterile Transition)



- 50tons of liquid Gallium divided into two separate concentrical regions;
- ^{51}Cr source in the center (3 MCi);
- Radiochemical reaction $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$;
- After exposure of few days, trasfer the liquid and count Ge produced (same as SAGE techinque);
- If no oscillation: ~65 atoms/day of Ge in each region should be produced;

*POSTER'"Status of the BEST *project (Baksan Experiment on Sterile Transitions" Dr.Ibragimova Tattiana*

RICOCHET



- 10000 Si bolometers (total mass 500 Kg) arranged in a column of 0.42m x 2 m ;
- ^{37}Ar source (~5MCi);
- Coherent scattering of neutrinos on Ar nuclei;

Several papers and ideas

Technique	Detector	Sources	Reaction	Activity	Reference
Large Liquid scintillator detectors	**SOX (Borexino)**	**^{51}Cr,**	**ν+e → ν+e**	**10MCi**	***JHEP08(2013)038,***
		^{144}Ce-^{144}Pr	**ν+p → e^++n**	**100kCi**	*Phys. Rev. Lett. 107, 201801 (2011)*
	KamLAND	**^{8}Li (ISODAR)**	**$\bar{\nu}$+p → e^++n**	**8.2 x 10 ^{14} ν/sec**	***arXiV:1205.4419, arXiV:1310.3857***
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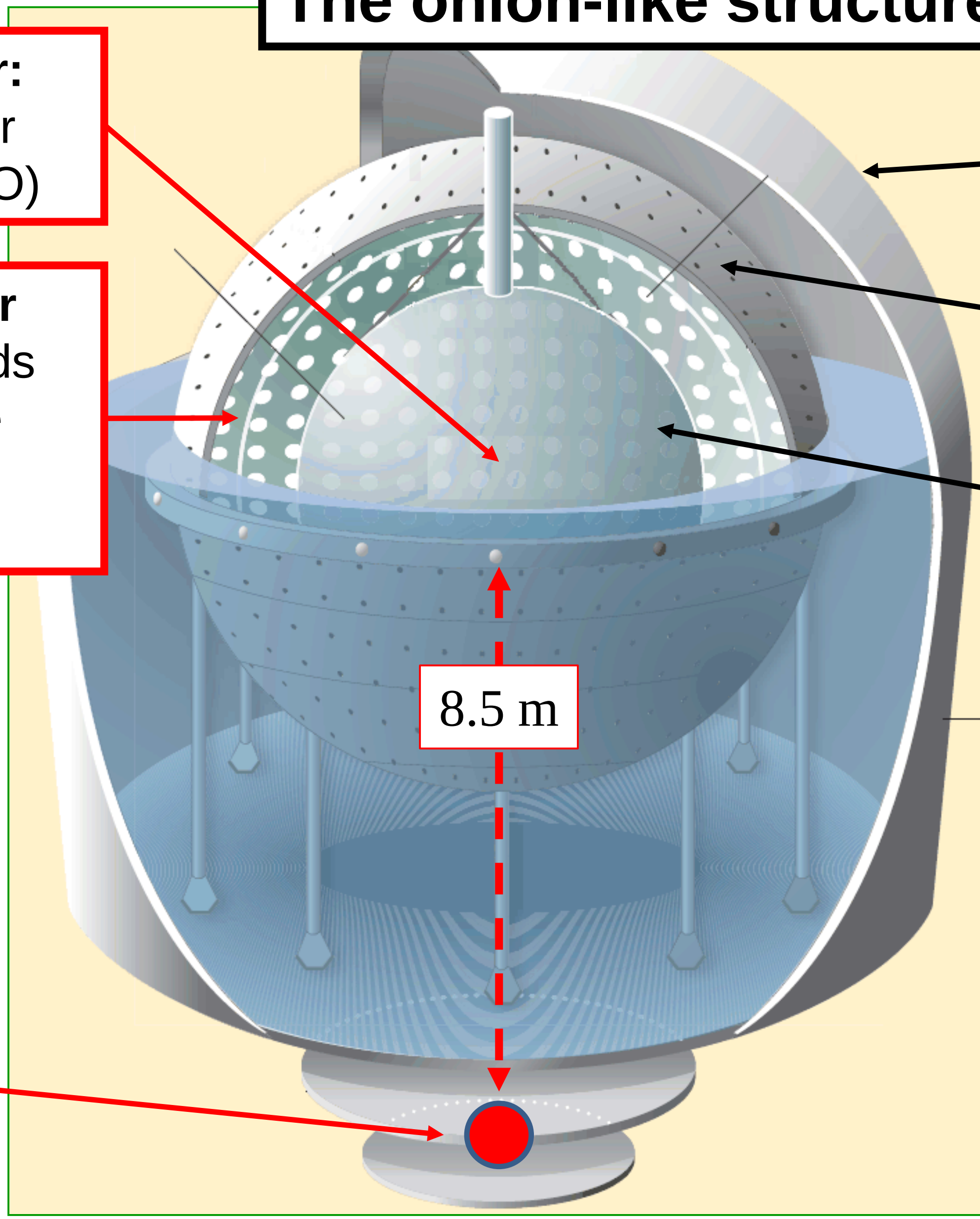
SOX: Short distance ν_e Oscillations with boreXino

The onion-like structure of Borexino



Core of the detector:
300 tons of scintillator
(pseudocumene+PPO)

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

PIT under the detector where the source can be located.

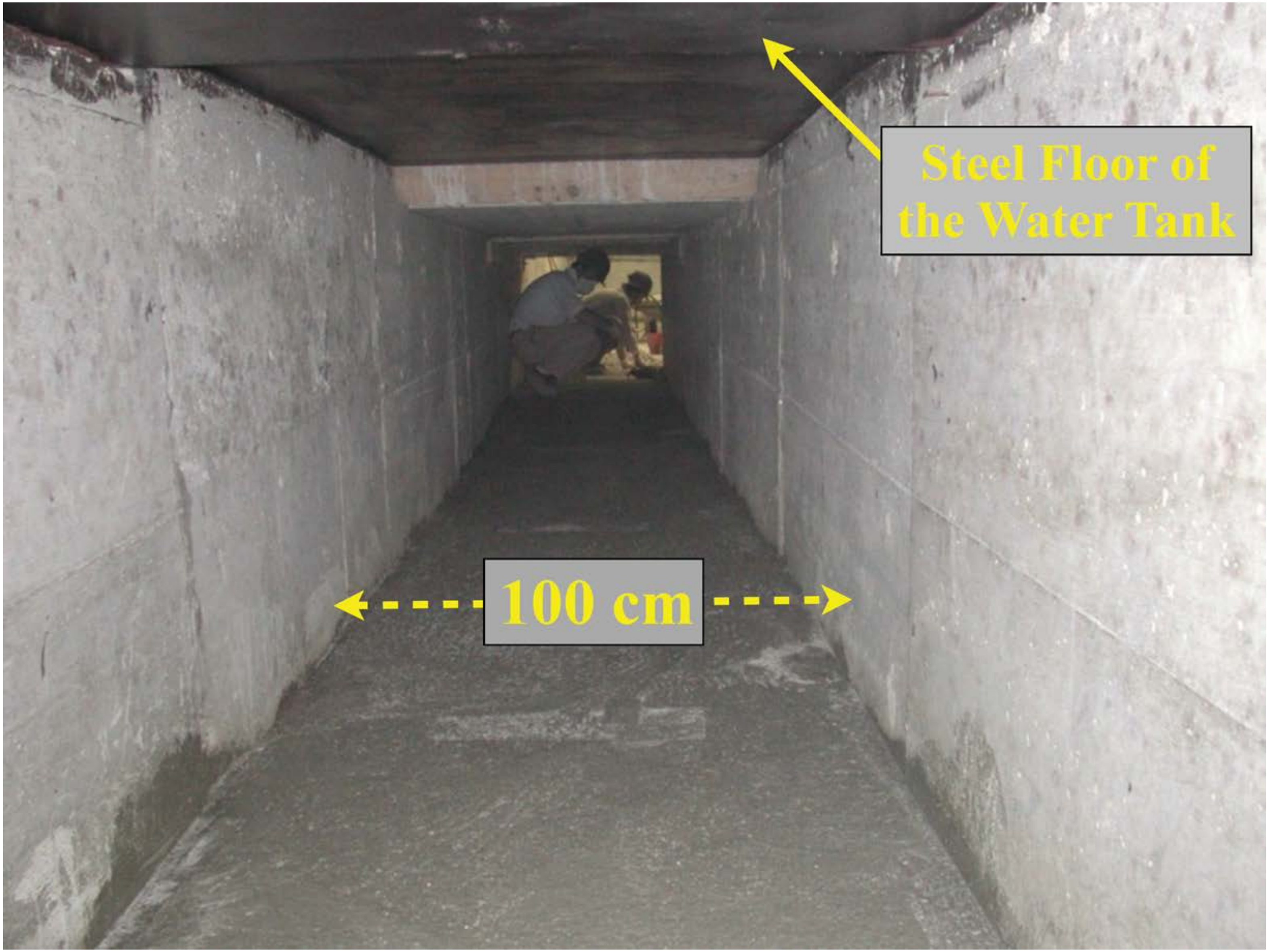
Water tank
R=9m h=16.5m

Stainless Steel Sphere R~ 7 m

Inner Vessel
R=4.25m

Each layer of increasingly pure material protects the core from external radioactivity

SOX: the tunnel under the detector



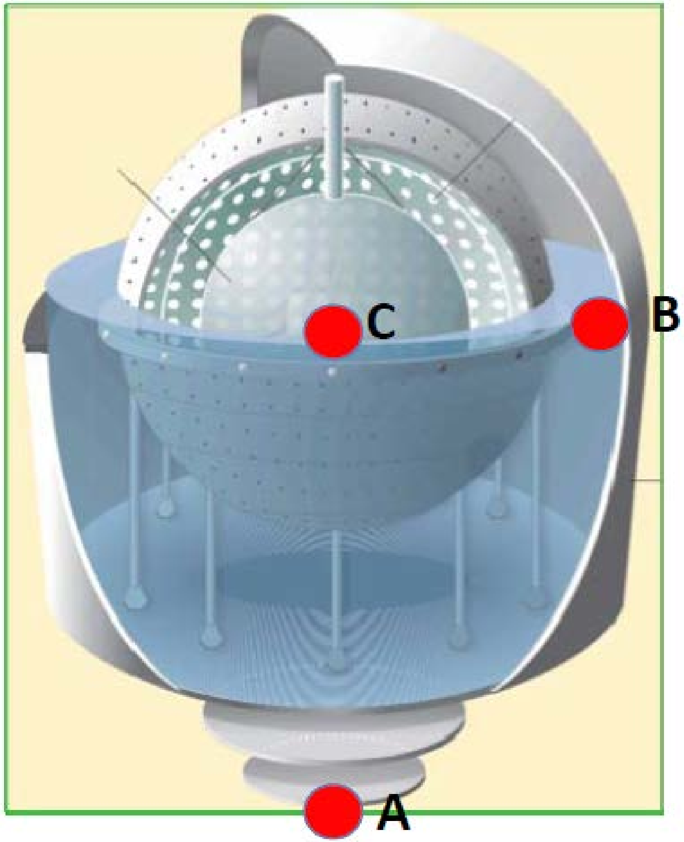
SOX: Short distance ν_e Oscillations with boreXino

The SOX project

- Source in position A: plan to use both ^{51}Cr neutrino and ^{144}Ce-^{144}Pr anti-neutrino sources;
- Future possibility: put the ^{44}Ce-^{144}Pr in the center; more invasive → needs significant refurbishment of the apparatus;

Borexino in a nut-shell

- Borexino is taking data since 2007 in the Gran Sasso Laboratory;
- Capability to detect neutrinos has been demostrated by results on solar neutrinos (see dedicated talk by G.Ranucci);
- Capability to detect anti-neutrinos has been demostrated by results on geo-neutrinos (see poster n. 12 (board 58) by L.Miramonti);



Detection of ~ 500 pe/MeV

Energy resolution σ_E/E ~5% (@1MeV)

Position resolution σ_x ~ 10 cm (@1MeV)

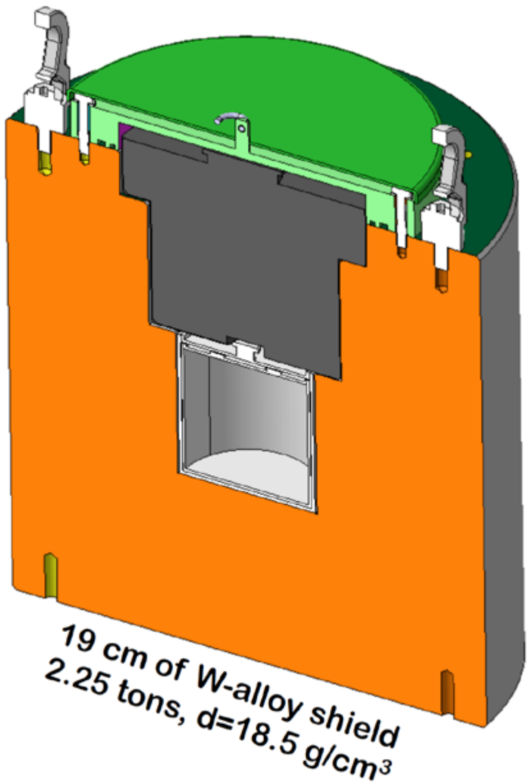
SOX: Short distance ν_e Oscillations with boreXino

It is both a technical and a burocratical challenge

- High activity requires appropriate shielding and suitable transportation containers;
- Many authorizations (transportation, handling, storage) are required;

Source design is driven by

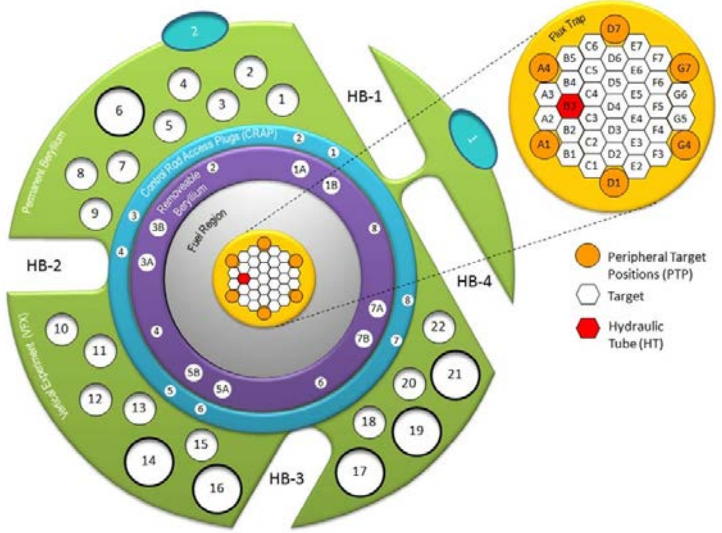
- Production process technique;
- Biological shielding requirements (tungsten alloy shielding);
- Thermal constraints;
- Mechanical constraints (tunnel dimensions, total weight);
- Transportation requirement and containers design and production;
- Hot cell manipulation;
- Handling in the experimental Hall;
- Calorimeter integration (to measure precisely the activity of the source);

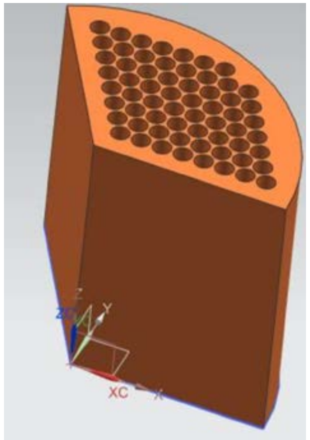


SOX-Cr: production of the ^{51}Cr source

Source characteristics: E_ν =750 keV τ=40 days

- 36 Kg of Cr (enriched in 50Cr (38.6%) used for Gallex calibration is still available;
- Needs to be activated with neutron irradiation;
- OakRidge National Laboratory is the best choice;
- Easiest solution: cast the Cr chips in cylindrical rods;
- Probably need two cycles of the reactor;
- Needs a 10 MCi source (or two 5 MCi sources);

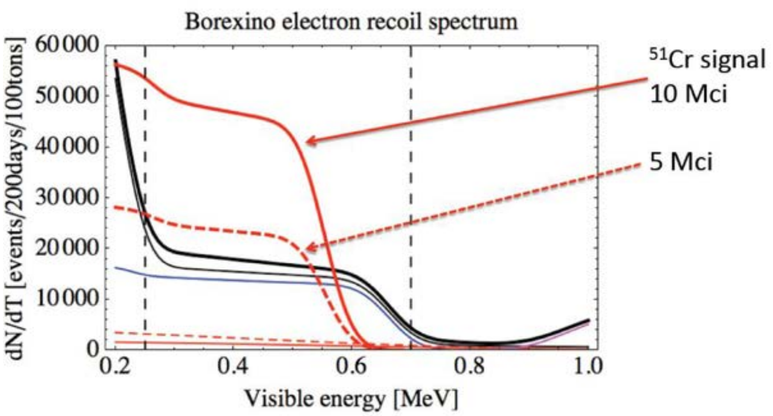




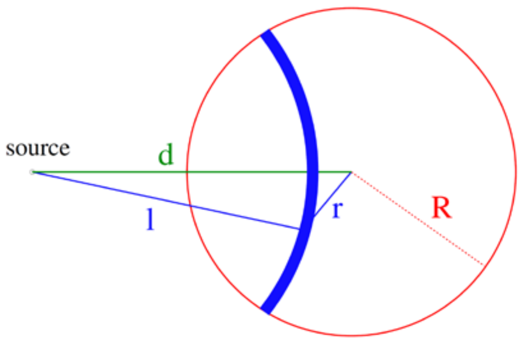
Short data taking period: ~ 2-3 months

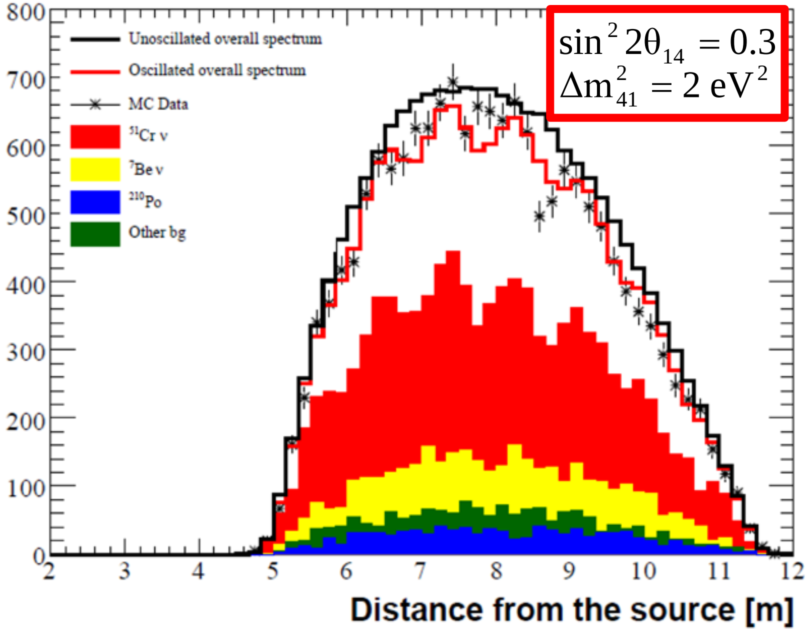
SOX-Cr: sensitivity to sterile neutrino of the ^{51}Cr source

- $\nu_e + e^- \rightarrow \nu_e + e^-$:the signal (electron recoil) is relatively featurless;
- To distinguish signal from radioactive background
  1. use the fact that the source decays while background remains constant;
  2. Also use the position distribution of events;



- Since the source is external the distribution of expected neutrino interaction is not uniform in the volume;





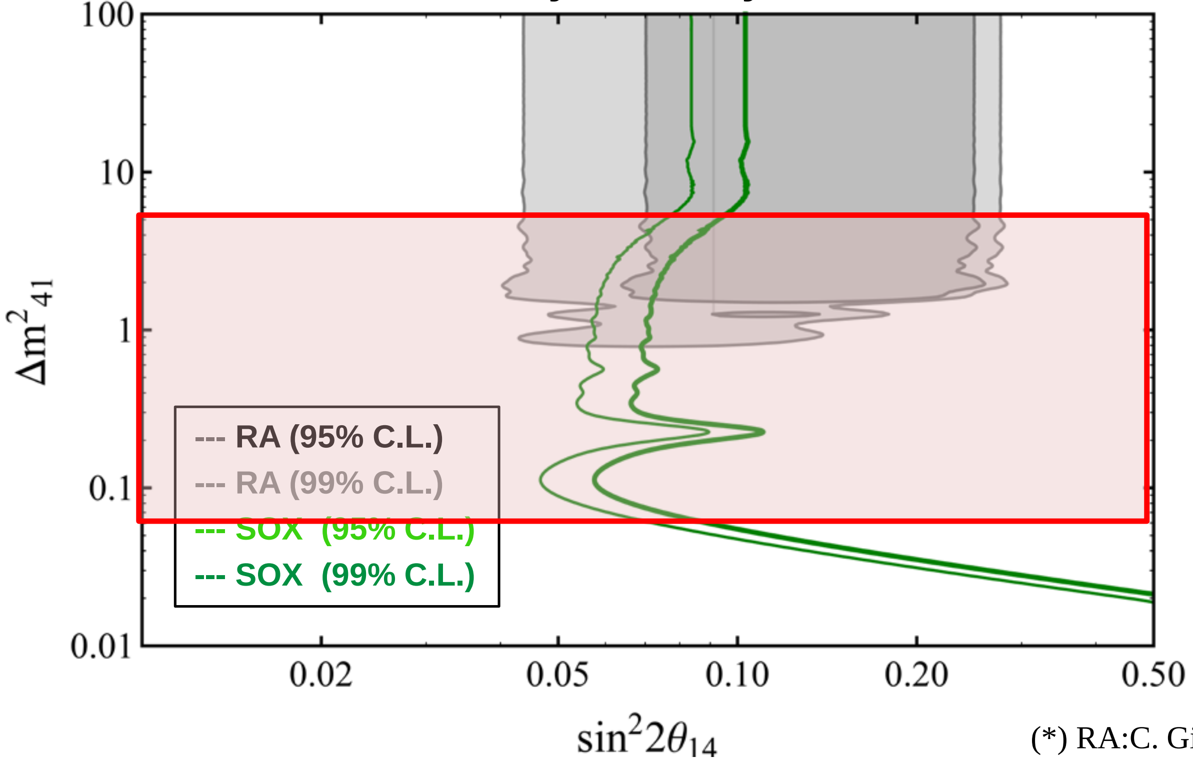
- For some values of the oscillation parameters, waves will be observed;

SOX-Cr: sensitivity to sterile neutrino of the ^{51}Cr source

Source characteristics: E_ν =750 keV τ=40 days

- $\nu_e + e^- \rightarrow \nu_e + e^-$
- Data taking time: 100 days; accumulated neutrino events ~ 14000
- Activity of the source must be known at 1-2 %

^{51}Cr; Time~100 days, activity=10 MCi; R<3.3m



$$L_{osc}(m) = \frac{E(MeV)}{1.27\Delta m^2 (eV^2)}$$

- Δm^2 >10 eV^2 $L_{osc} << \sigma_x$ $P \sim 1/2 \sin^2 2\theta$;
- Δm^2 <0.05 eV^2 L_{osc} >> detector dimensions $P \sim \Delta m^2 \sin^2 2\theta$;
- **0.05 <Δm^2 <5 eV^2 best sensitivity window;**

(*) RA:C. Giunti et al. Physical Review D, vol. 86, 113014, 2012

SOX-Ce: production of the ^{144}Ce- ^{144}Pr source

Source characteristics: E_ν <2.99 MeV τ=411 days

- Spent nuclear fuel (Kola Nuclear Power Plant (Murmansk, Russia);
- Processing of the spent fuel in Mayak complex.
- Possibility to obtain ^{144}Ce-^{144}Pr source with activity ~ 100 kCi;

Kola Nuclear Power Plant

POSTER'Search for a 4th light nu state with a 5 PBq 144Ce-144Pr electron antineutrino generator next to a large liquid scintillator detector" Dr.LASSERRE,Thierry

SOX-Ce: production of the ^{144}Ce- ^{144}Pr source

Complicated transportation logistic in order to comply with safety regulations for transport of radioactive material:

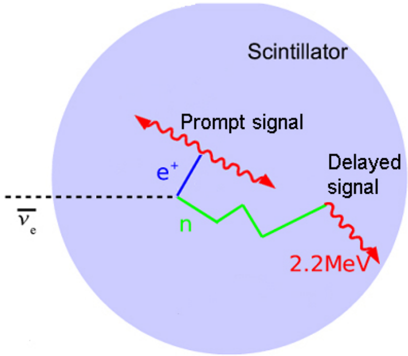
- Spent nuclear fuel will be shipped from Kola reactor to Mayak ~ end of 2014;
- ^{144}Ce source ready for shipment to Gran Sasso by Fall 2015;
- Transportation to Gran sasso in November 2015;

DIFFICULT from Mayak to Gran Sasso; IMPOSSIBLE from Mayak to Japan

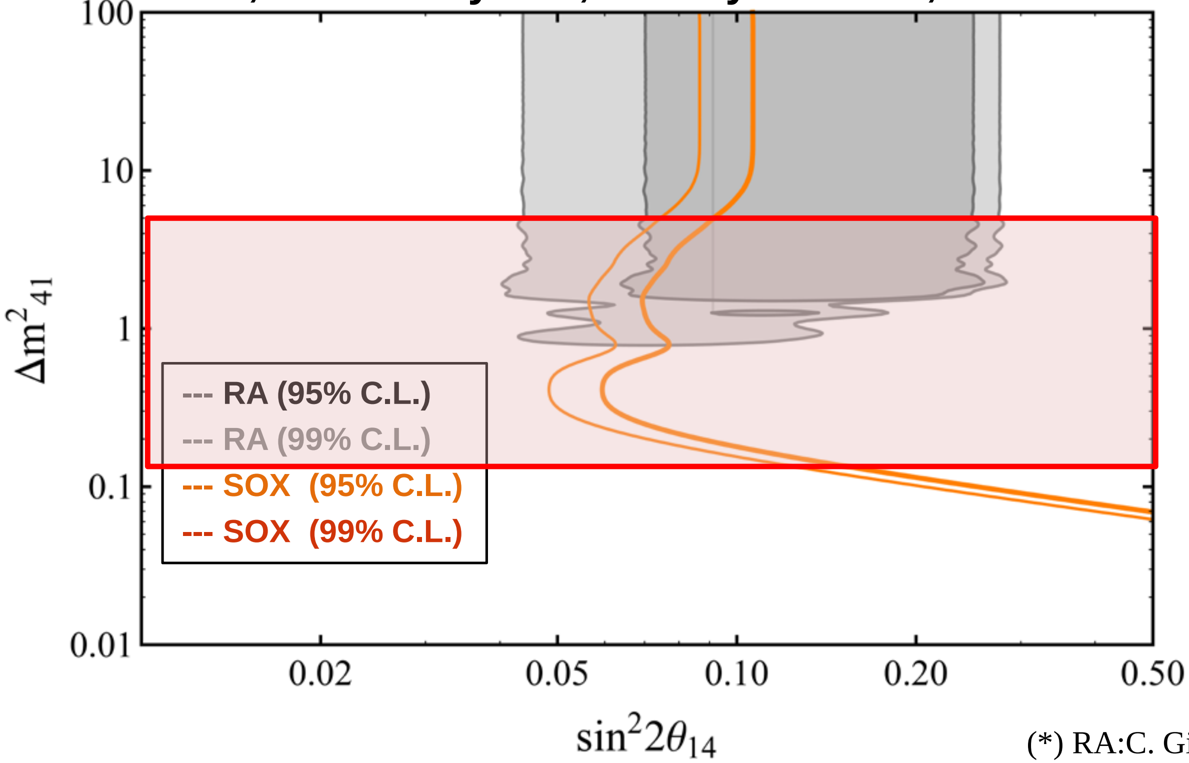
SOX-Ce: sensitivity with the ^{144}Ce- ^{144}Pr source

Source characteristics: E_ν <2.99 MeV τ=411 days

- $\nu_e + p \rightarrow n + e^+$
- Data taking time: 1.5 years; events accumulated ~10000
- Energy resolution more important than position resolution;
- Activity of the source must be known at 1-2 %



^{144}Ce; Time~1.5 years, activity=100 kCi; R<4.25m

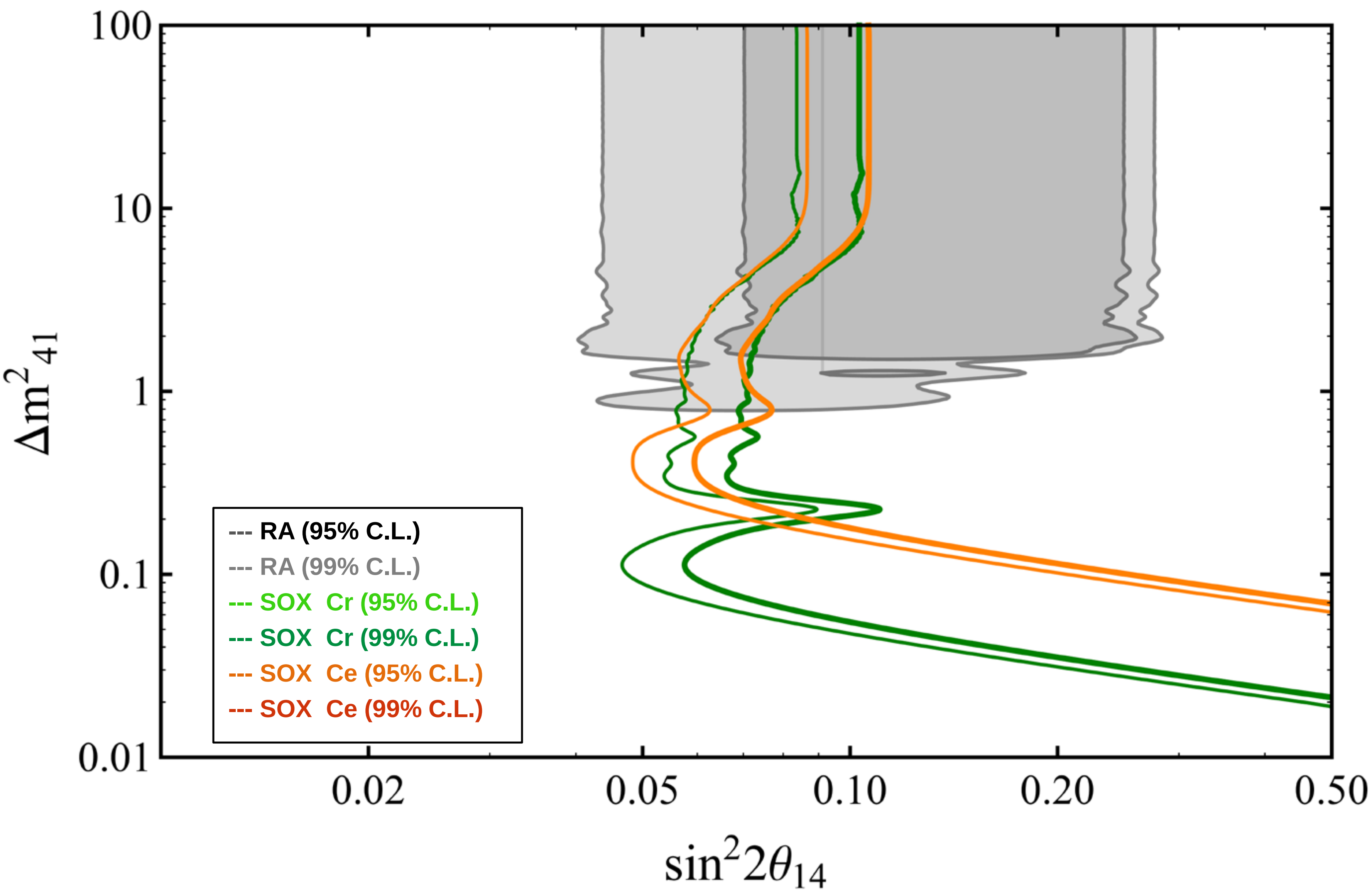


$$L_{osc}(m) = \frac{E(MeV)}{1.27\Delta m^2(eV^2)}$$

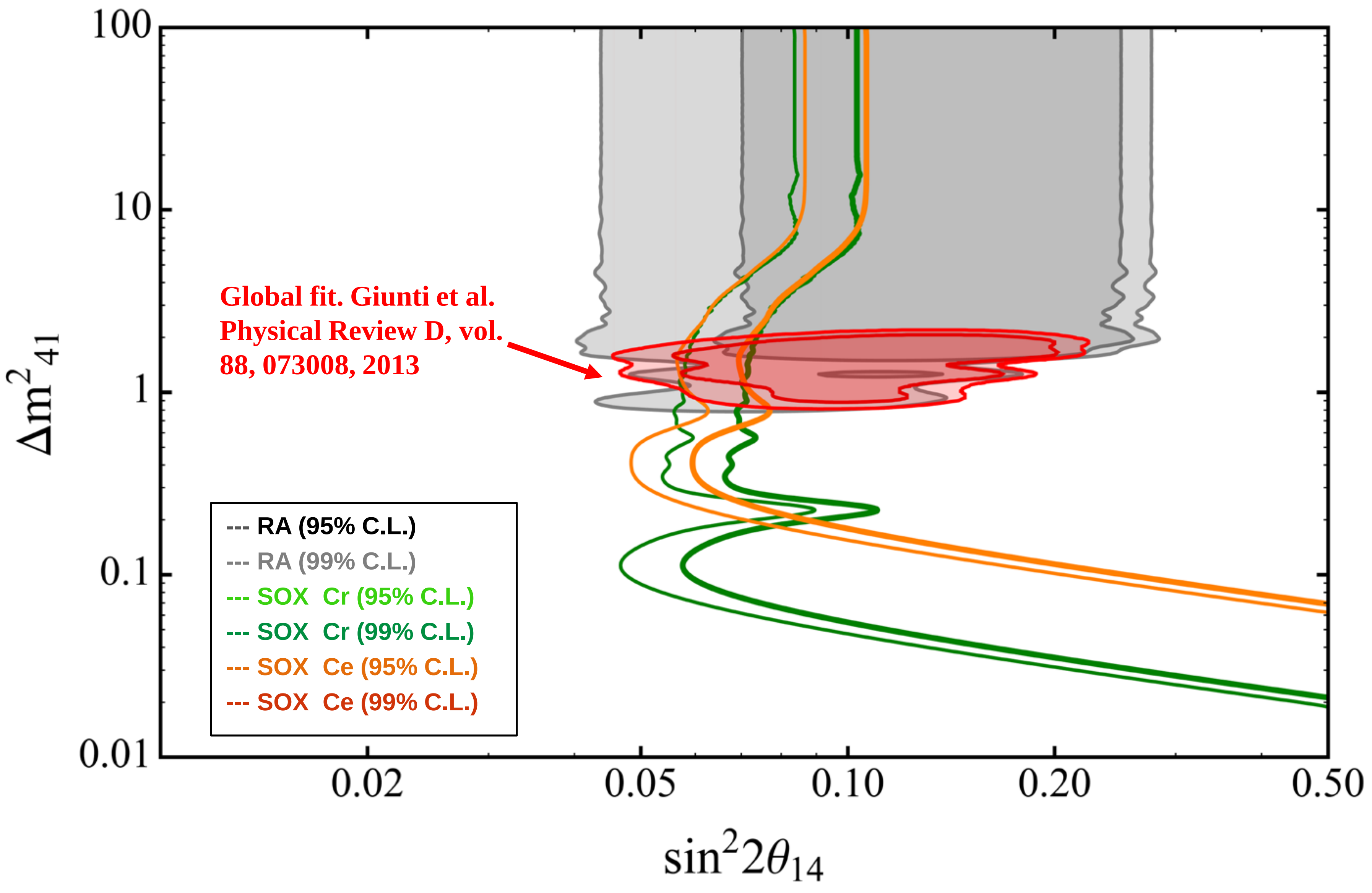
- Δm^2 >5 eV^2 $L_{osc} << \sigma_x$ P~1/2$\sin^2 2\theta$;
- Δm^2 <0.1 eV^2 L_{osc} >> detector dimensions P~ $\Delta m^2 \sin^2 2\theta$;
- **0.1 <Δm^2 <5 eV^2 best sensitivity window;**

(*) RA:C. Giunti et al. Physical Review D, vol. 86, 113014, 2012

SOX: sensitivity to sterile neutrino



SOX: sensitivity to sterile neutrino



Conclusions and perspectives

- Searching for sterile neutrino is a challenging enterprise (high risk/ high gain);
- SBL disappearance experiments with sources have some advantages over SBL reactor/accelerator experiments (better control of neutrino spectra, flux and purity; possibility to do oscillometry);
- Several proposals/ideas of experiments which should address this issue;
- **MOST IMPORTANTLY: first data available with SOX-Ce by the end of 2015 / beginning 2016;**