Experimental searches on sterile neutrinos

XIIth International Conference on

Heavy Quarks and Leptons

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Michael Wurm

JGU Mainz

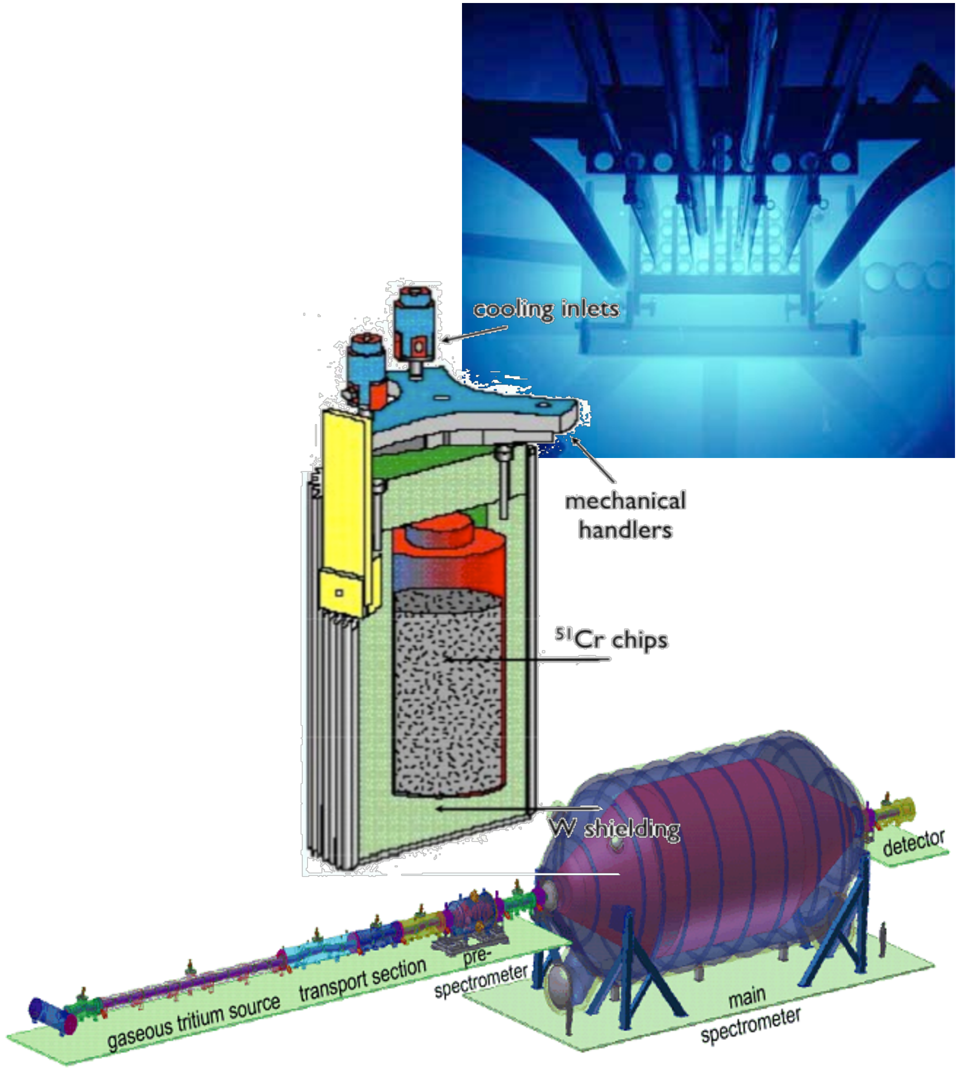
JG|U PRiSMA

Outline

Motivation for experimental sterile neutrino searches on eV mass scale

Experimental approaches:

- disappearance searches at nuclear reactors
- disappearance searches with radioactive ν sources
- appearance/disappearance with accelerator beams
- search for distortion of β-decay end-point



Experimental hints for sterile neutrinos

Several experiments see unexpected signals at ~3σ level:

- **Accelerator anomaly (3.8σ)**
  LSND and MiniBOONE results for ν_μ neutrino beam observed excess in low-energy ν_e-like events

LSND Collaboration, Phys.Rev.D 64 (2001) 112007
MiniBooNE Collaboration, PRL 110 (2013) 161801

→ *appearance signal at new (short) baseline?*

- **Gallium anomaly (2.8σ)**
  Calibration runs with radioactive neutrino sources at solar radiochemical experiments Gallex/SAGE
  → deficit in the detected ν_e rate: R = 0.76 ± 0.09

e.g. C. Giunti and M. Laveder Phys.Rev.C 83 (2011) 065504

- **Reactor antineutrino anomaly (~2.5σ)**
  re-evaluation of reactor neutrino spectra results
  → rate deficit in all short-baseline (L=10-100m) reactor neutrino experiments: R = 0.927 ± 0.23

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

→ *disappearance of electron into sterile neutrinos $\nu_e \rightarrow \nu_s$?*

Mixing of active with sterile neutrinos

Additional **light** (m_Z<45 GeV) **sterile neutrinos** will not couple to Z^0 (LEP), but might mix with the three active neutrino flavors.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} & U_{14} & \dots \\ U_{21} & U_{22} & U_{23} & U_{24} & \dots \\ U_{31} & U_{32} & U_{33} & U_{34} & \dots \\ U_{41} & U_{42} & U_{43} & U_{44} & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

+ additional Δm^2's: $\Delta m^2_{21},\ \Delta m^2_{31},\ \Delta m^2_{32},\ \Delta m^2_{41} \dots$

Flavor mixing allows for new **active→sterile** and **active→active oscillations**

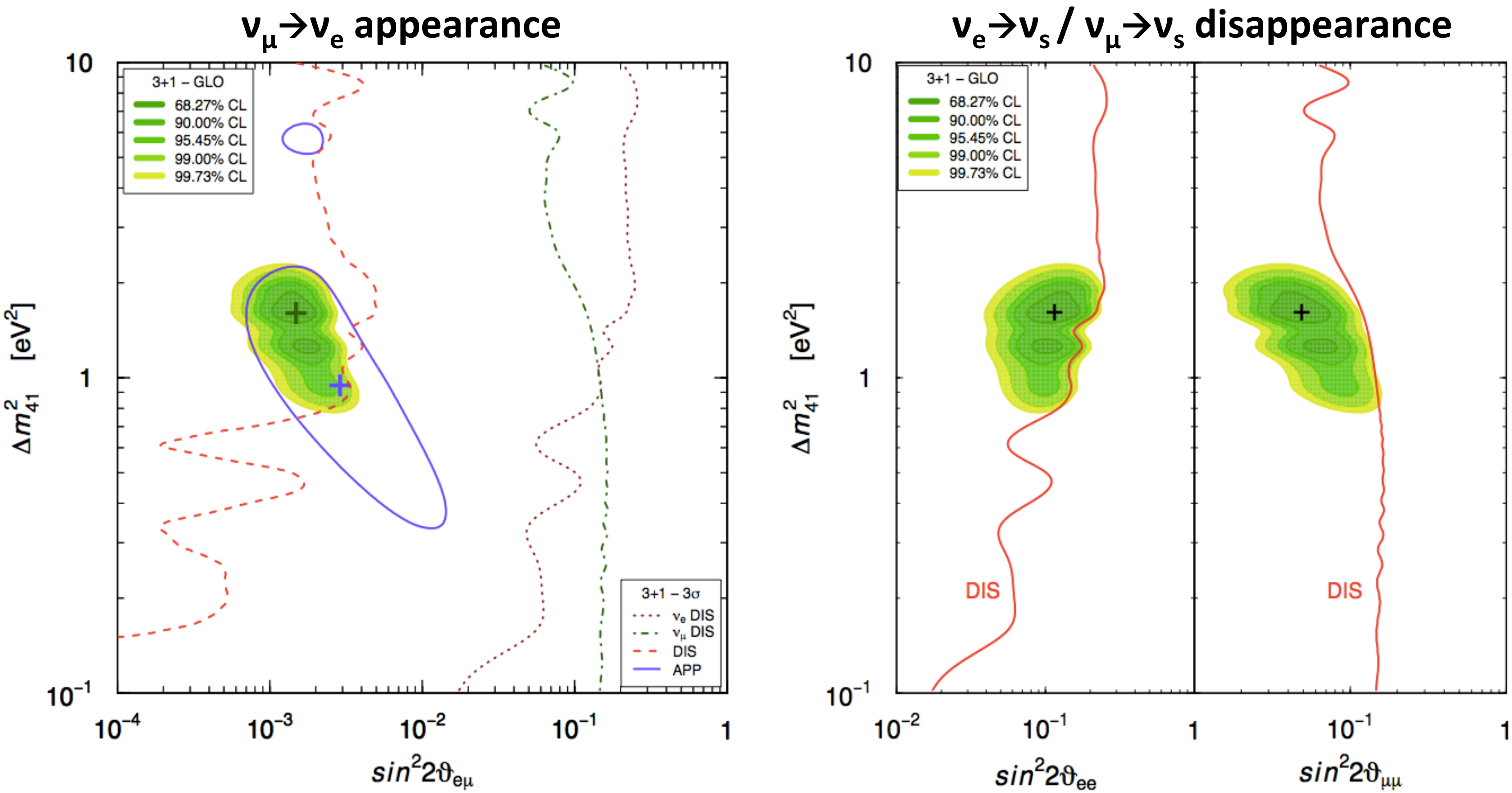
e.g.

$$P(\nu_e \to \nu_s) = \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right); \qquad \sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{e\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right); \qquad \sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

→ new oscillation baselines! *→ new mixing amplitudes!*

Global oscillation data in a (3+1) scenario



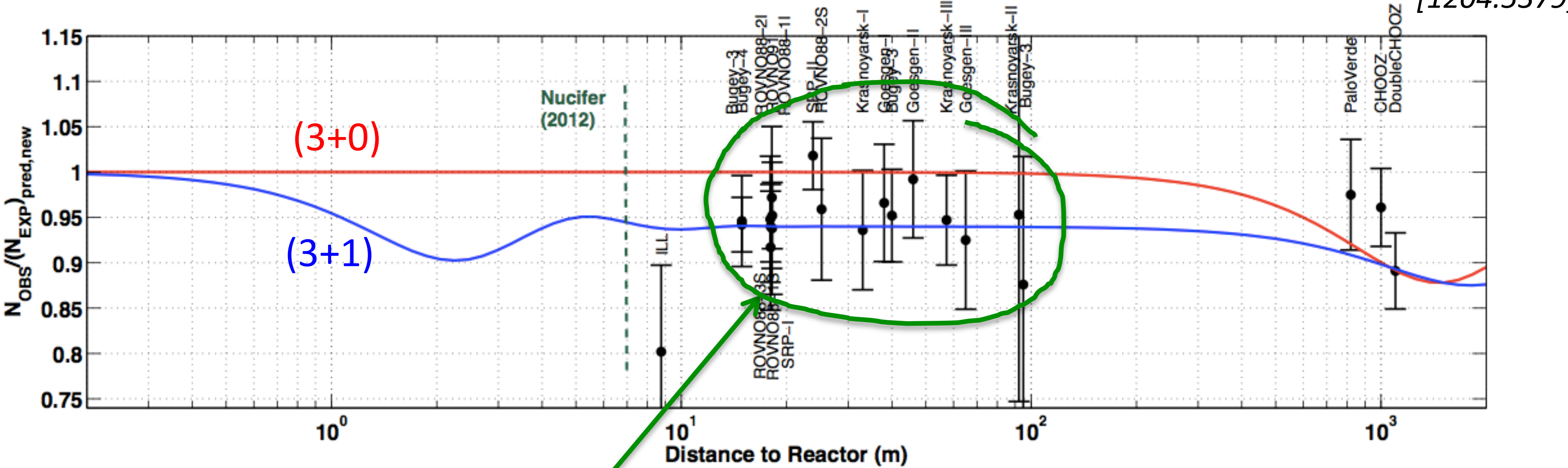
→ Possible value of new Δm^2 limited to ~1eV^2 regime (in some conflict with cosmological limits on total ν mass)

→ Sterile neutrino hypothesis is not reflected by ν_μ disappearance data

New disappearance searches at nuclear reactors

Current status: Observed vs. expected $\bar{\nu}_e$ rate as function of baseline

[1204.5379]

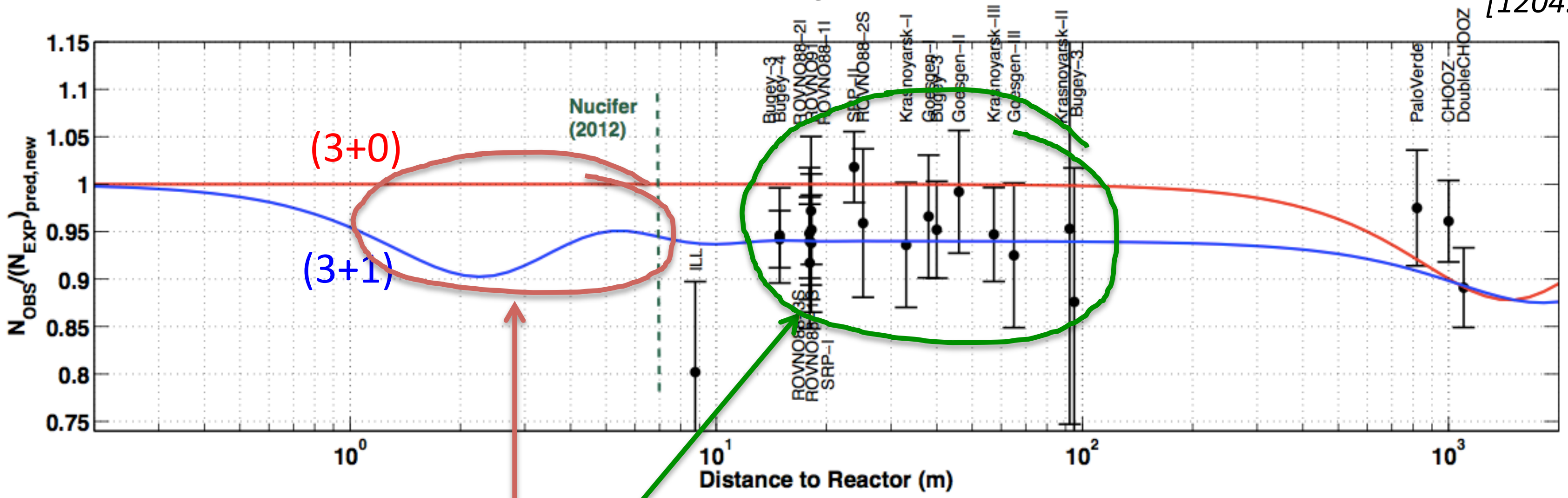


Up to now: rate deficit only

New disappearance searches at nuclear reactors

Current status: Observed vs. expected $\bar{\nu}_e$ rate as function of baseline

[1204.5379]



Up to now: rate deficit only

New approaches

- test rate dependence at short baselines
  → segmented/movable detectors

New disappearance searches at nuclear reactors

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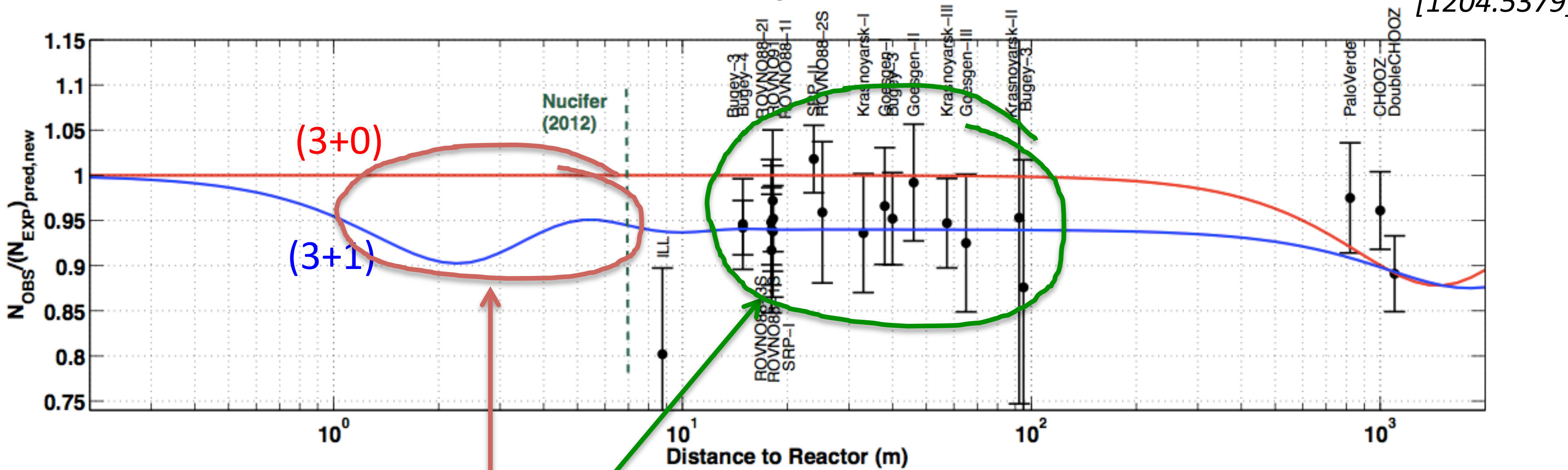
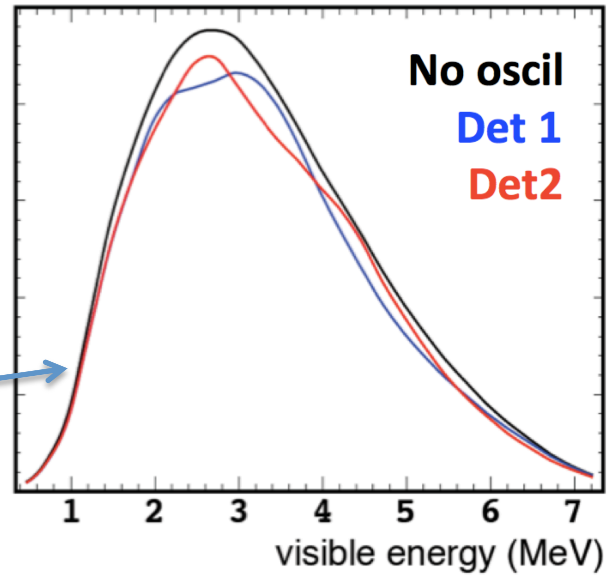


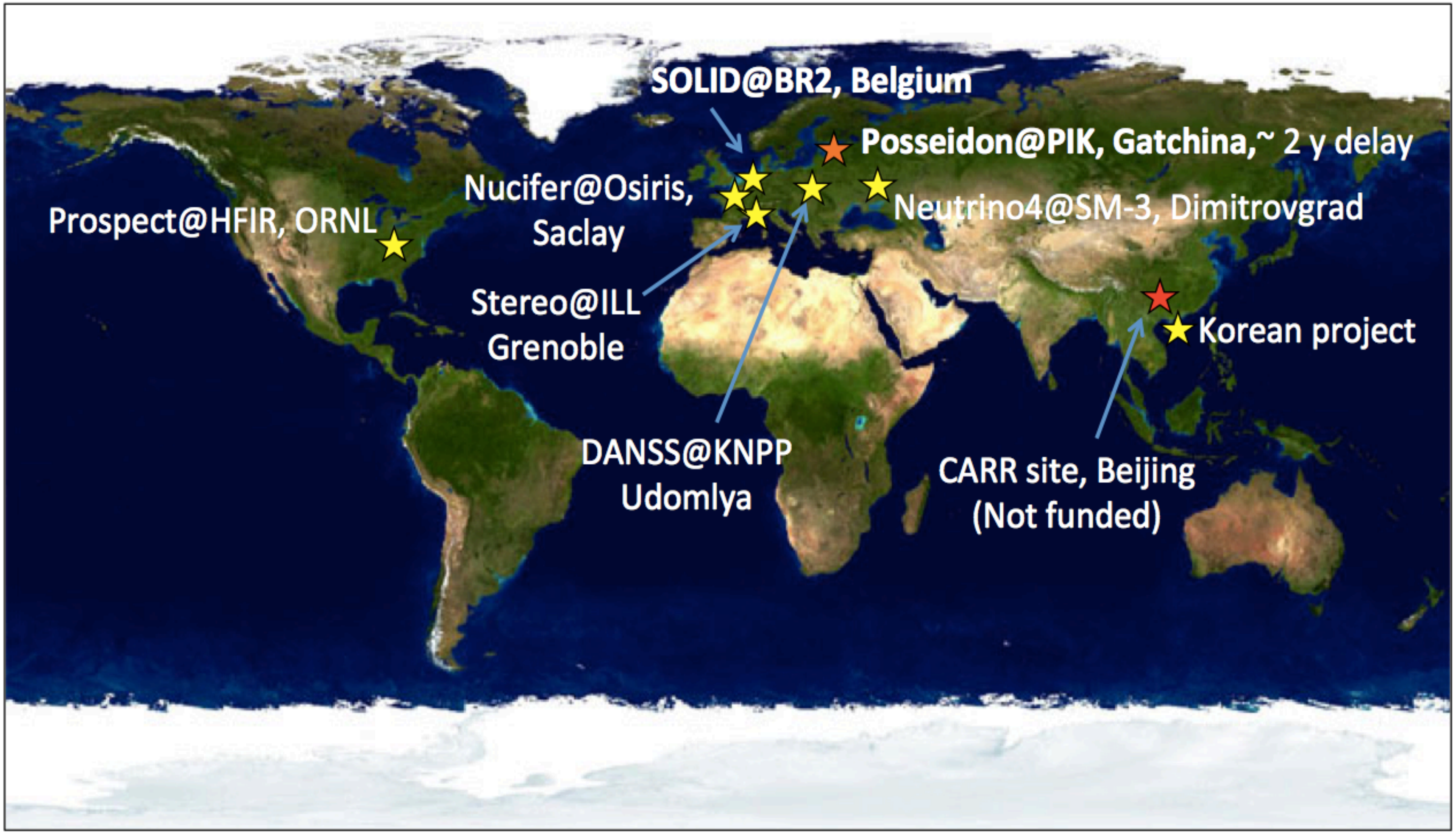
Up to now: rate deficit only

New approaches

- test rate dependence at short baselines
  → segmented/movable detectors
- search for (distance-dependent) spectral deformation

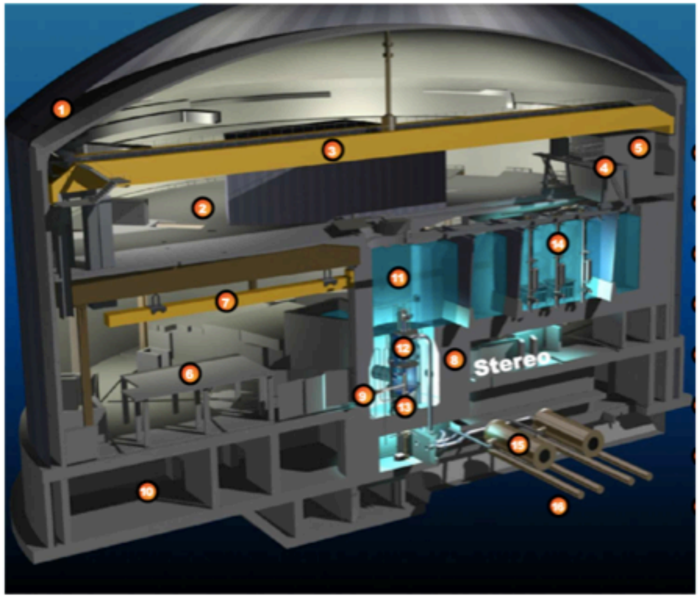


Planned reactor neutrino experiments



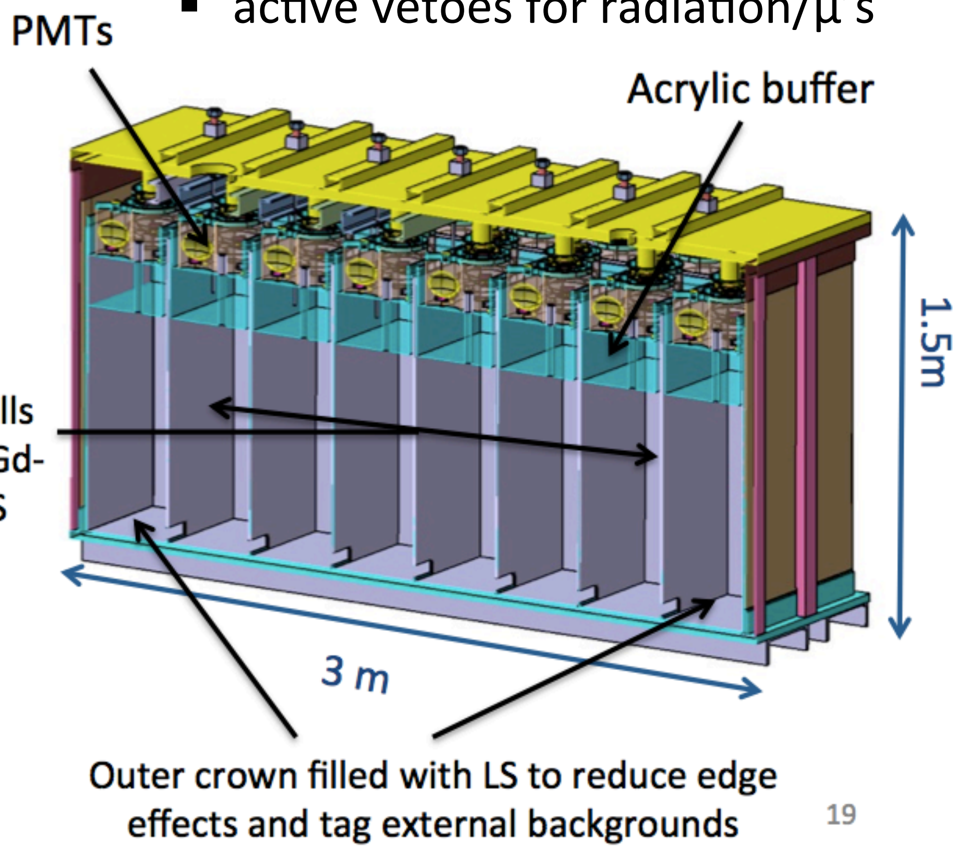
courtesy of D. Lhuillier (Neutrino 2014)

STEREO at ILL Grenoble



Detector

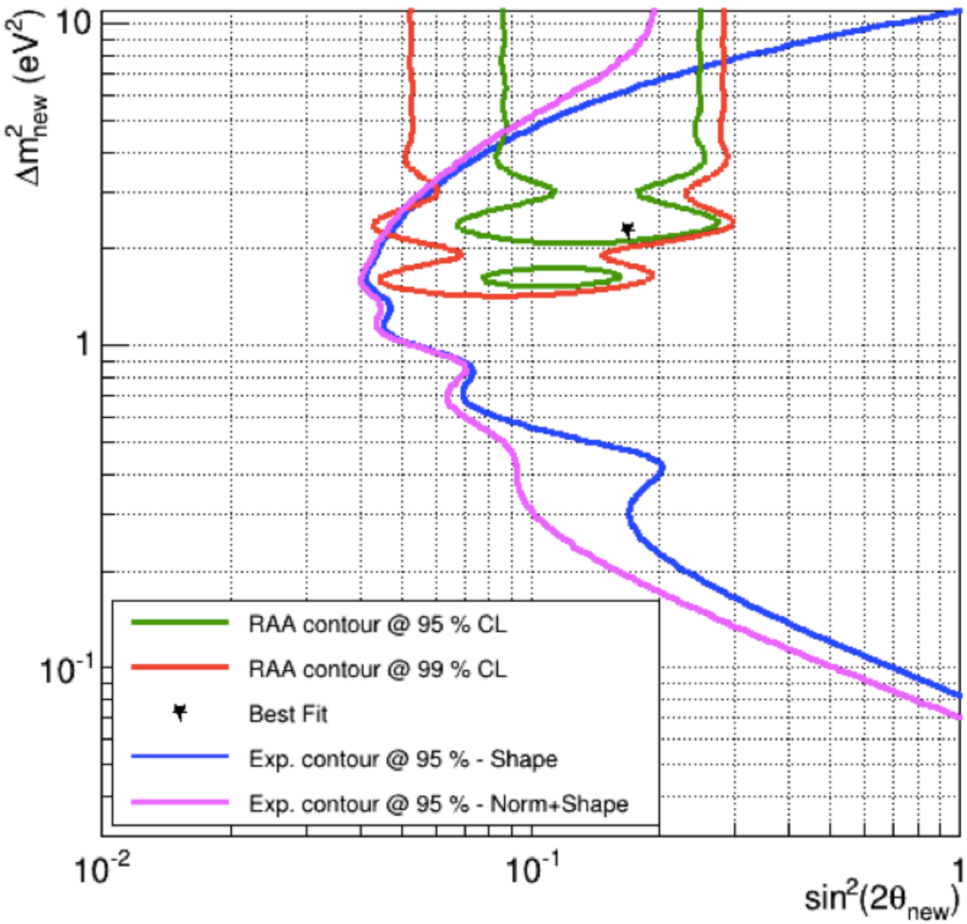
- Gd-doped liquid scintillator for $\overline{\nu}_e$ detection
- segmented
- active vetoes for radiation/μ's



ILL reactor

- 57 MW, compact core (<1m)
- experiment [9-11] m from core
- 15 mwe overburden
- high level of reactor background

STEREO – Expected sensitivity

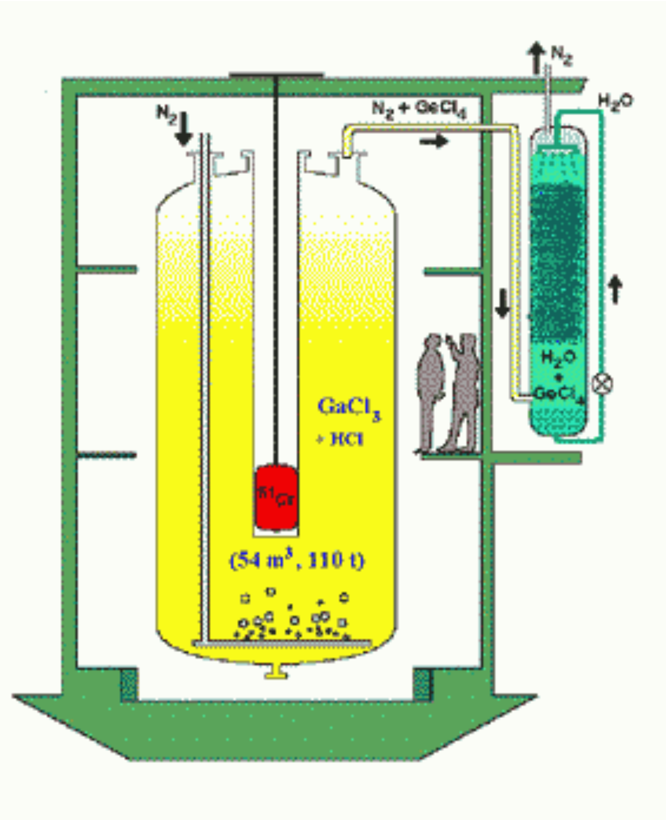


Experimental parameters

- 300 days, L_0 = 10 m
- E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
- ~410ν_e/day
- δE_{scale} = 2%
- All syst. of predicted spectra
- S/B = 1.5, 1/E+flat model
- Norm 4%
- Start data taking in 2015

from D. Lhuillier's talk @ Neutrino 2014

New searches with radioactive $\overset{(-)}{\nu}_e$ sources



Gallex/SAGE results

- integral rate deficit
- no spectral/spatial information

→ search for distance /energy dependence induced by $\nu_e \rightarrow \nu_s$ oscillation pattern

→ use as well antineutrino sources

Experimental requirements

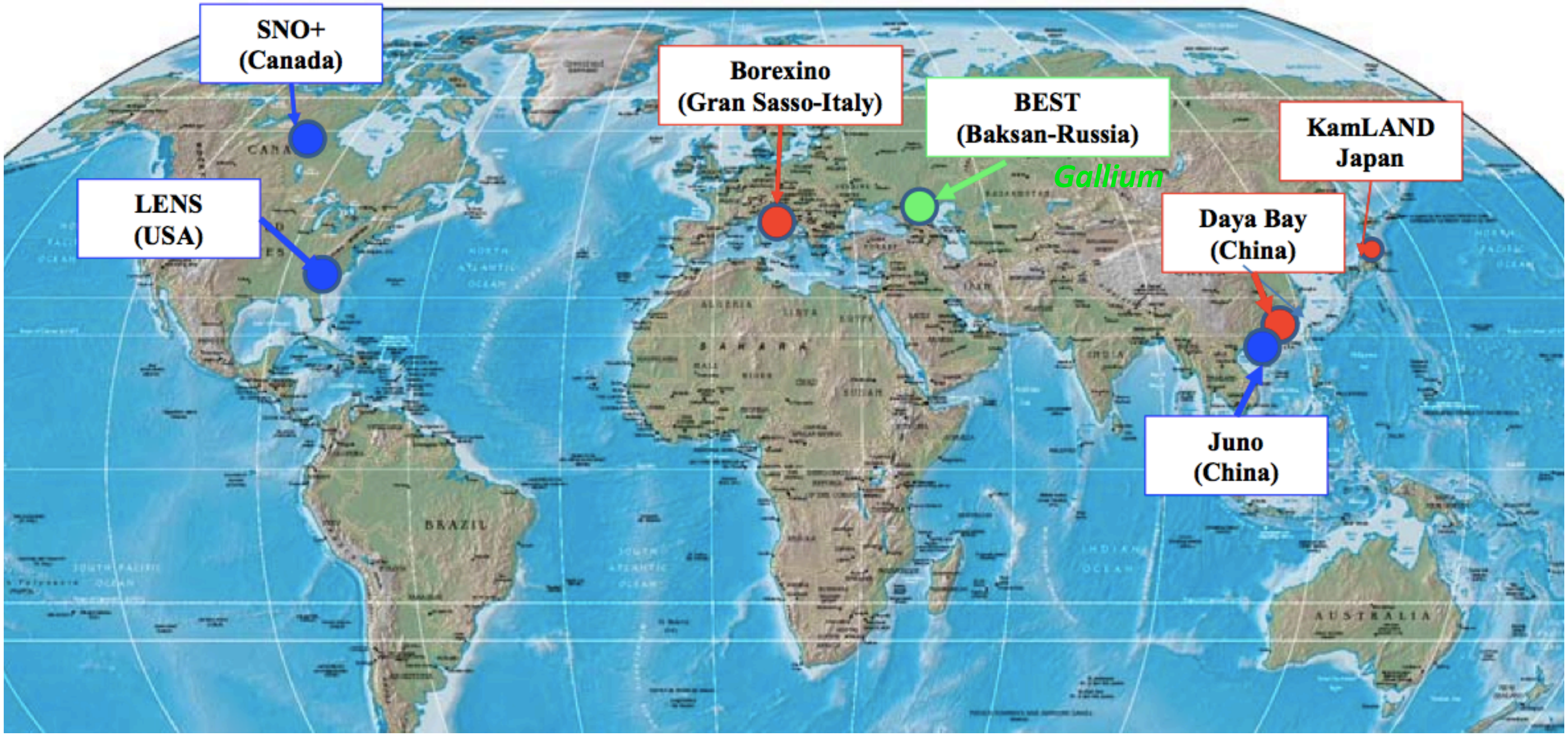
- large source intensity: ~1MCi and target mass
- low threshold: ~1MeV
- low radioactive/cosmic background

Proposed experiments

- segmented Ga detector
- source inside or very close to existing large liquid-scintillator detectors
- bolometers for coherent neutrino-nucleus scattering

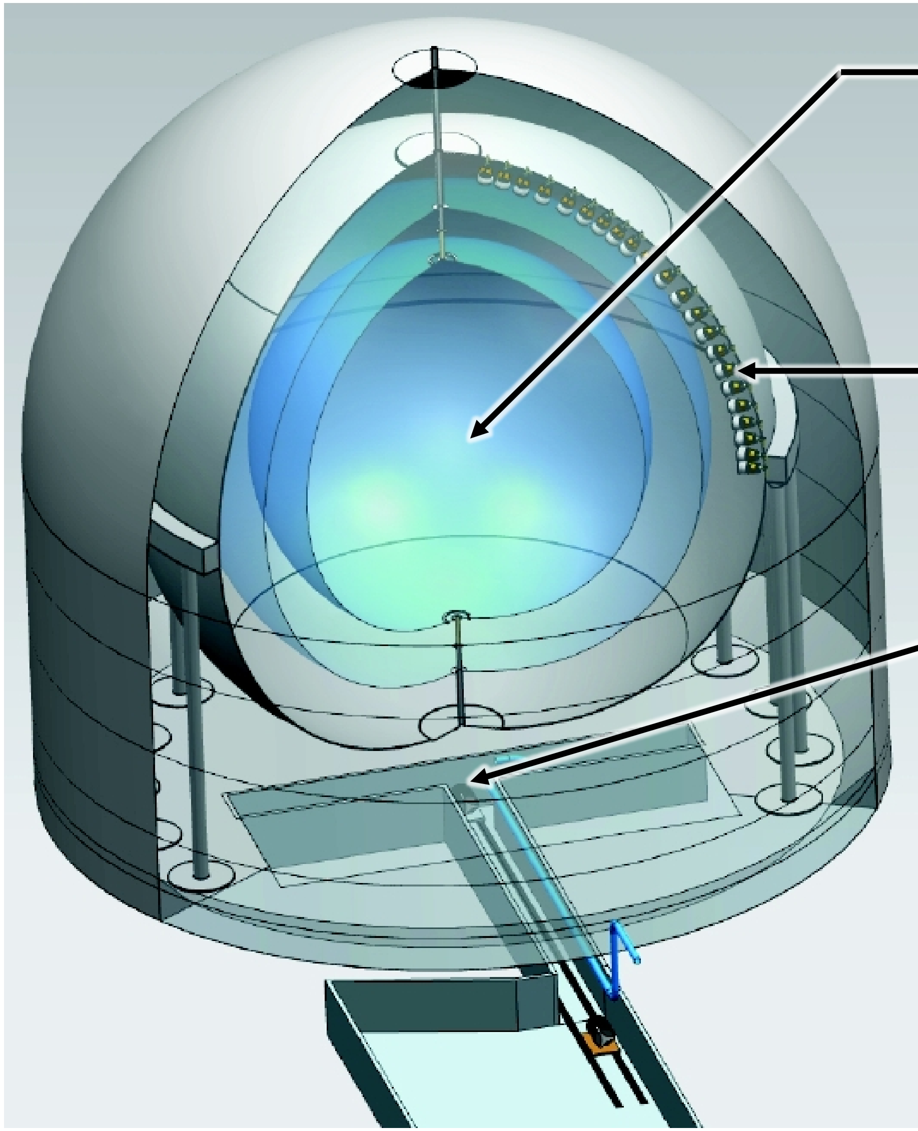
Source neutrino experiments

Projects mostly related to existing/up-coming liquid-scintillator detectors:



courtesy of B. Caccianiga (Neutrino 2014)

SOX: Short-distance ν_e Oscillations with boreXino



Active volume
270t of liquid scintillator (PC)
in nylon vessel of R=4.25 m
radiopurity: U/Th < 10^{-17} g/g

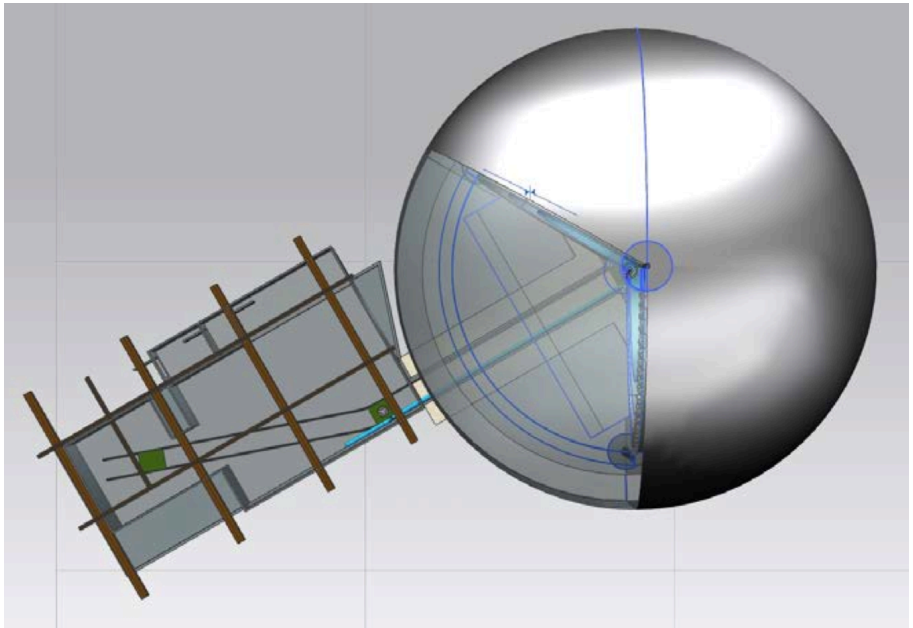
Stainless steel sphere
radius: 6.85 m
2,200 inward-facing PMTs

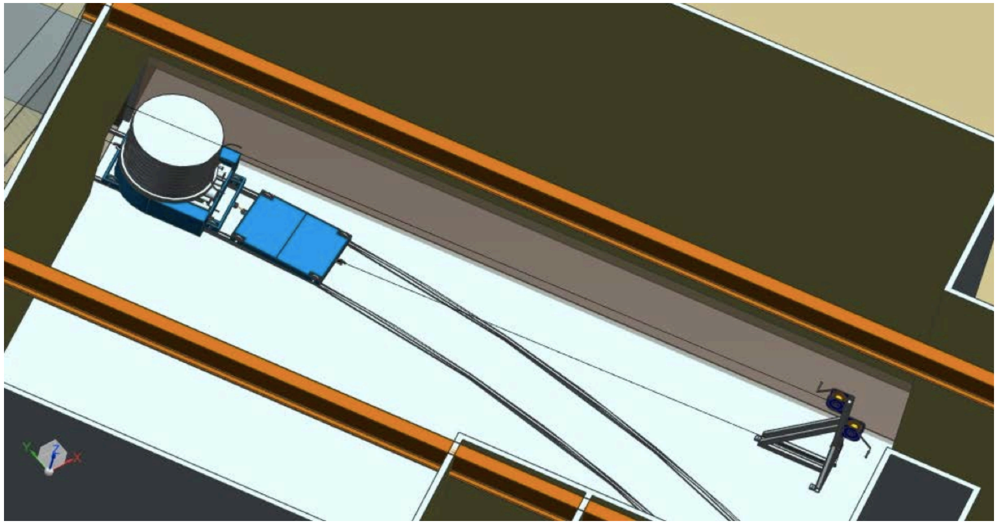
SOX Pit
Position of **ν source**, R=8.25m

Neutrino detection
ν_e by elastic ν-e-scattering
$\overline{\nu}_e$ by inverse β-decay on H

Detector specs @ 1 MeV
Energy resolution: 5 %
Spatial resolution: 10 cm

SOX Pit



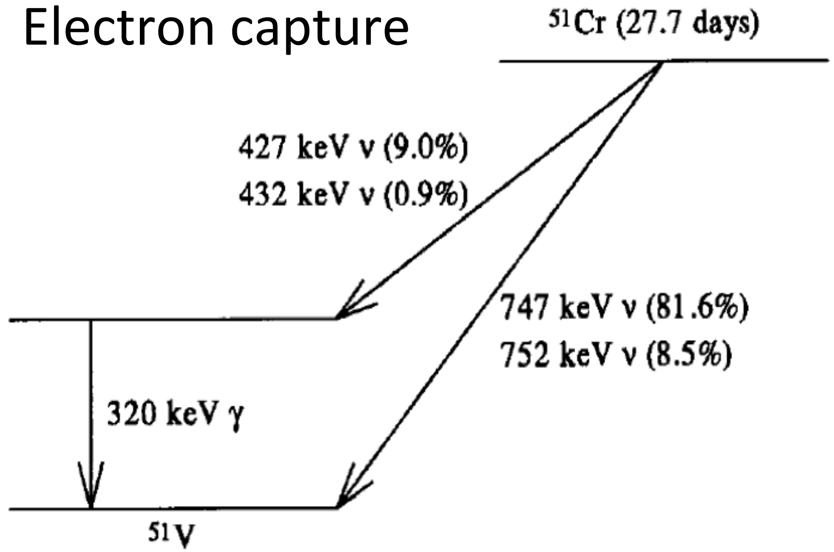


CrSOX: Electron neutrinos from ^{51}Cr

Source	^{51}Cr
Production	n-activation of ^{50}Cr at reactor
Decay mode	EC
Neutrino energy	747 keV
Initial activity	2-4 x 10^{17} Bq (5-10 MCi)
Half life	28 d
Exposure	100-180 d
Fiducial mass	130 tons
Events (180 d)	1.1 x 10^4
Oscillation length (Δm^2 = 2 eV^2)	0.9 m
Generated heat	190 W/MCi

Decay scheme

Electron capture



→ emission of mono-energetic ν_e's

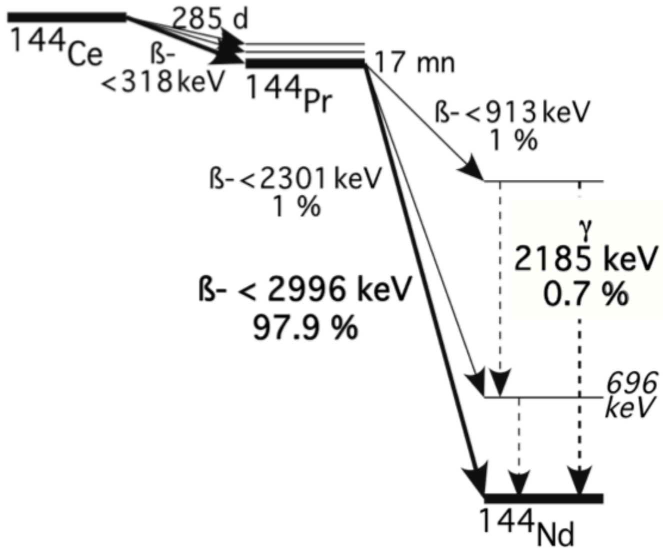
→ low-energy γ-ray in 10% of decays (shielding/activity measurement)

→ short half-life: Fast transport (~1 week) to LNGS is crucial

CeSOX: Electron antineutrinos from $^{144}Ce/Pr$

Source	$^{144}Ce/Pr$
Production	extraction from spent nuclear fuel
Decay mode	β^-
Neutrino spectrum	< 3.0 MeV
Initial activity	4×10^{15} Bq (100 kCi)
Half life	285 d
Exposure	1-1.5 yrs
Fiducial mass	240 tons
Oscillation length ($\Delta m^2 = 2\ eV^2$)	< 3.6 m
Events (1.5yrs)	10^4
Generated heat	7.6 W/kCi

Decay scheme

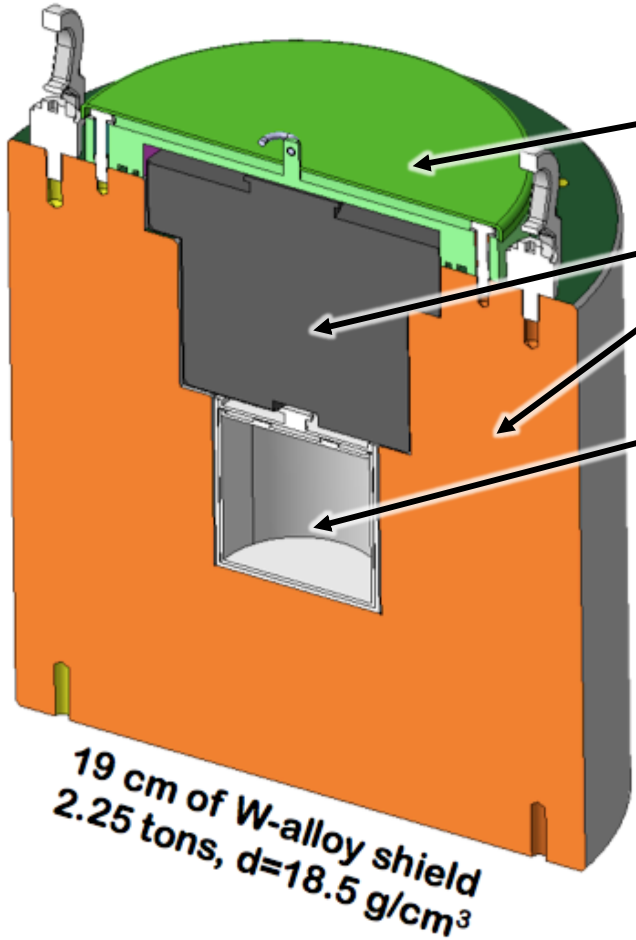


→ tests also energy dependence, but knowledge on spectral shape needed

→ long half life: more time for transport, longer exposure

→ less background for detection but maybe source-intrinsic γ's/n's

SOX Source Design: Cerium



Stainless-steel top flange

Tungsten shielding
(width of 19 cm)

Stainless steel container
→ contains CeO_2

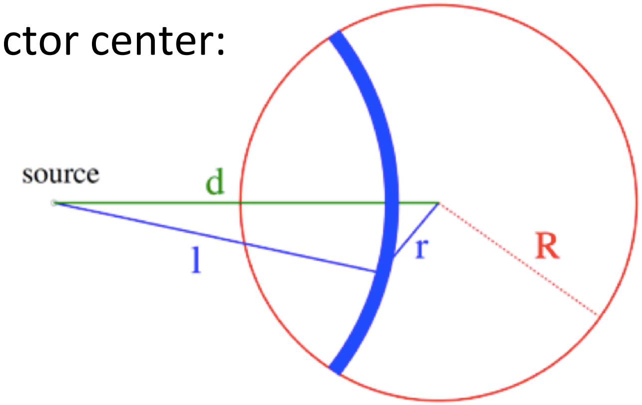
Source diameter: 15cm
Shielding diameter: 54cm

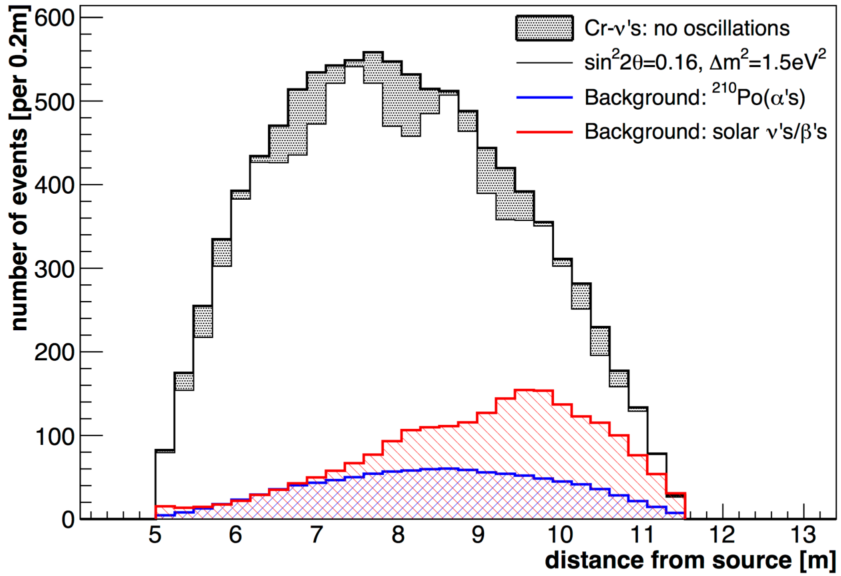
Determining factors for design

- *production:* sealing/manipulation
- *high activity:* appropriate radiation shielding and transportation
- *decay heat:* sufficient cooling
- *mechanics:* dimensions of the tunnel/ calorimeter for heat measurement

Expected signal for CrSOX

Source 8.25m below detector center:



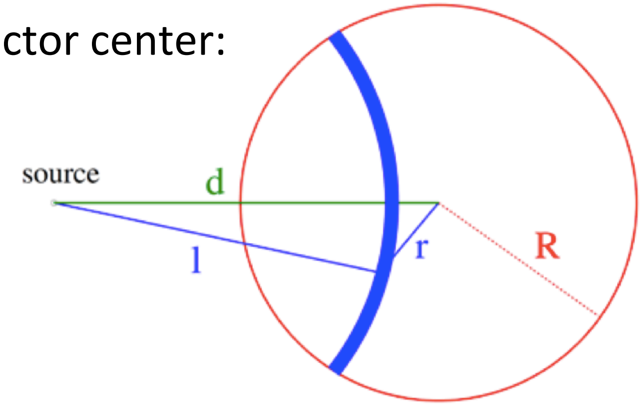


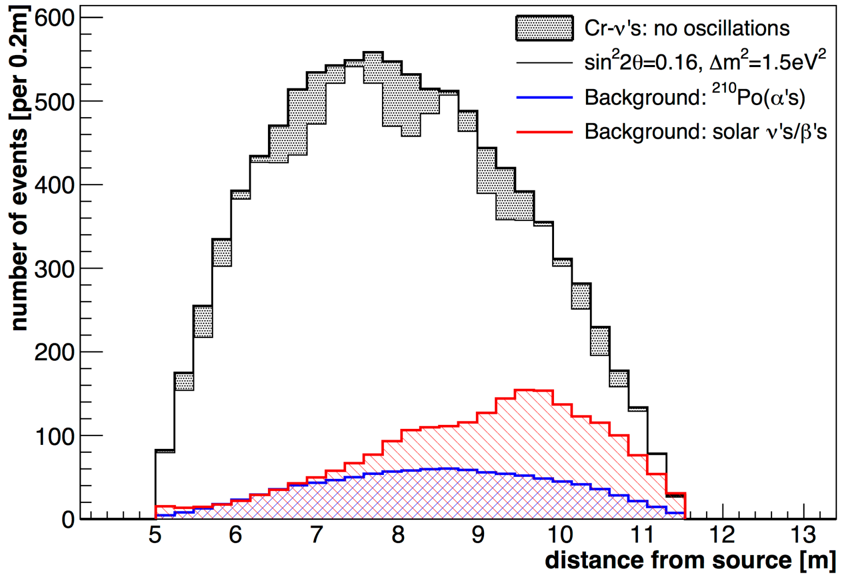
Expected distance distribution:

- geometry x $1/r^2$ dependent flux
- oscillations shown for best-fit values → waves discernible
- spatial resolution: ~20 cm

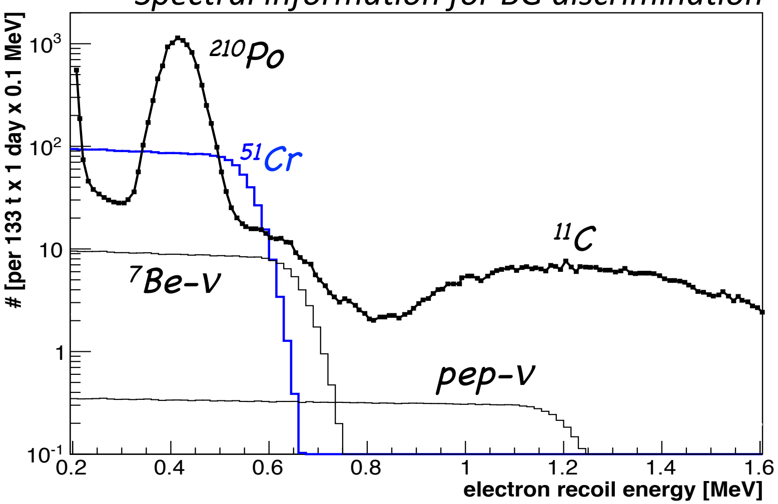
Expected signal for CrSOX

Source 8.25m below detector center:





Spectral information for BG discrimination

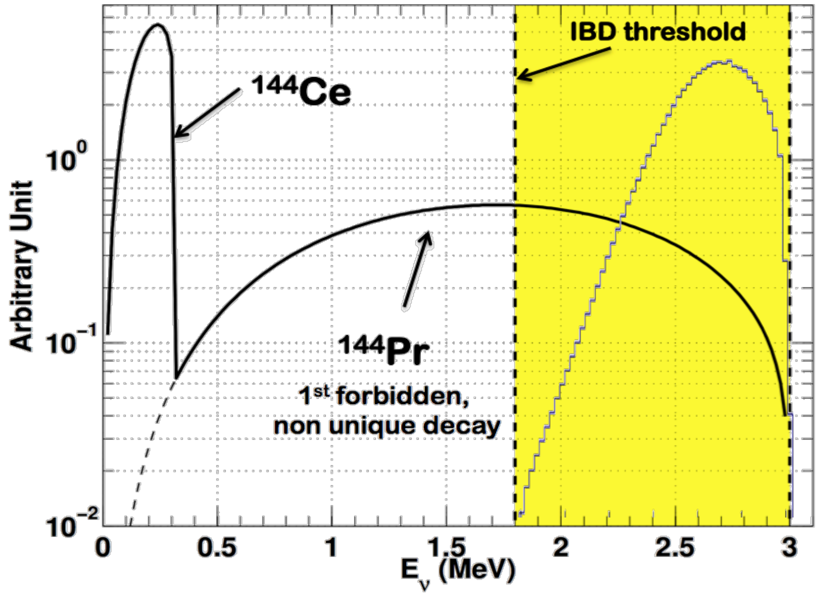


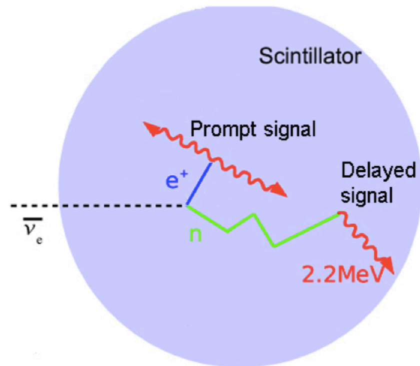
Expected distance distribution:

- geometry x $1/r^2$ dependent flux
- oscillations shown for best-fit values → waves discernible
- spatial resolution: ~20 cm

Expected signal for CeSOX

Extended energy spectrum



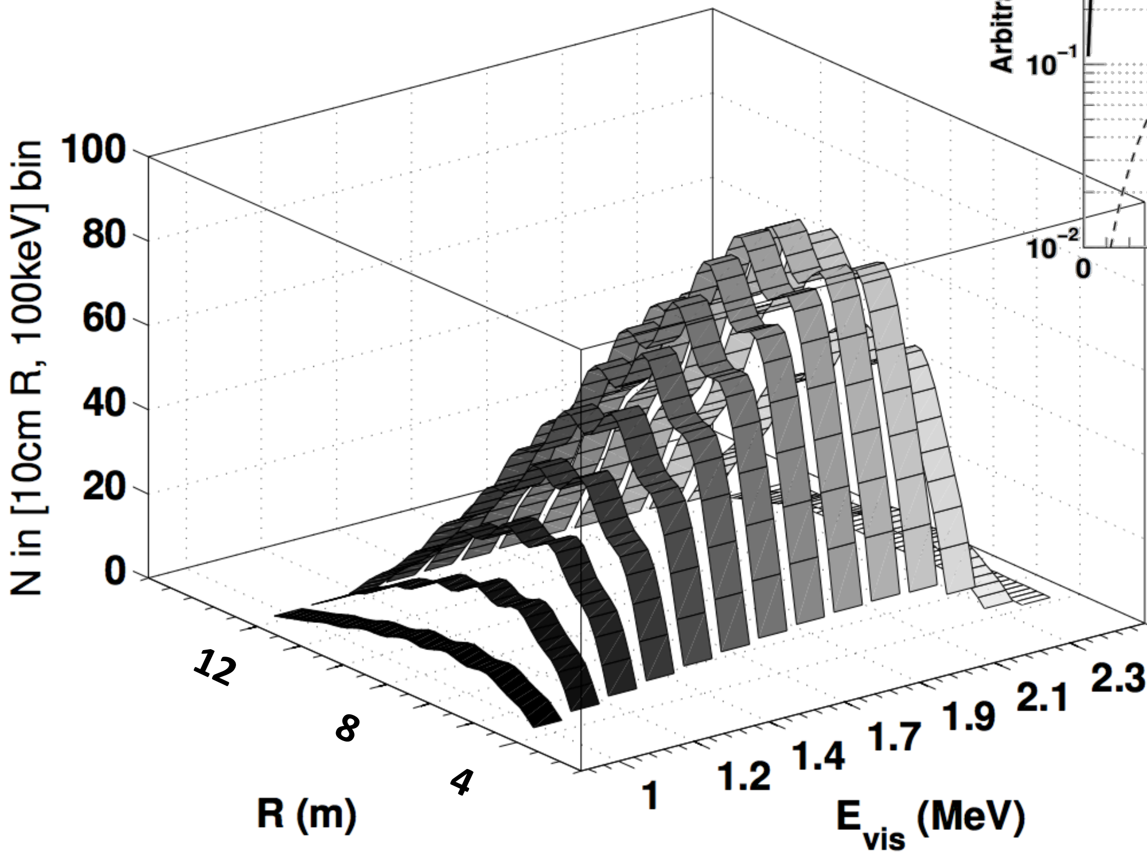


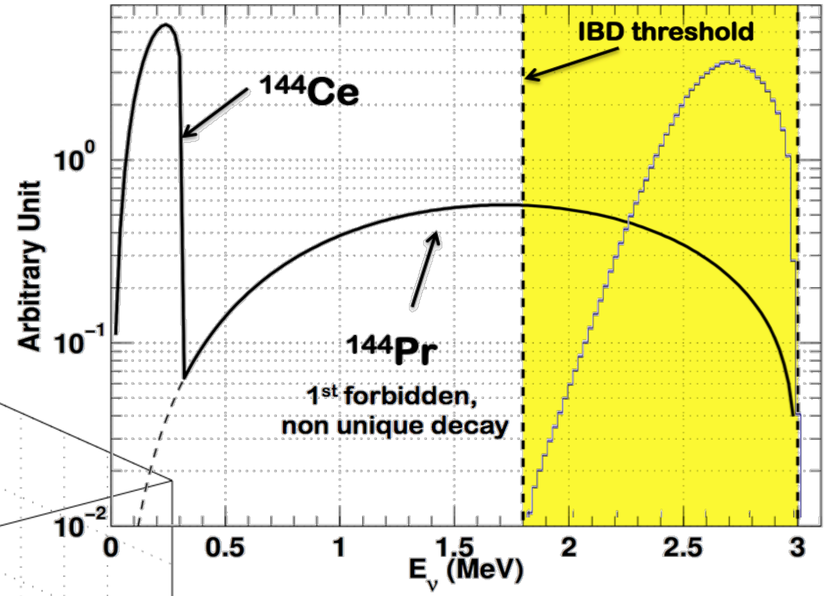
IBD coincidence signature
→ almost background-free

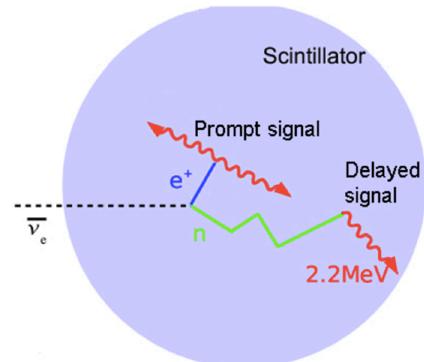
Expected signal for CeSOX

Extended energy spectrum

→ distance + energy dependence of oscillation pattern is observed

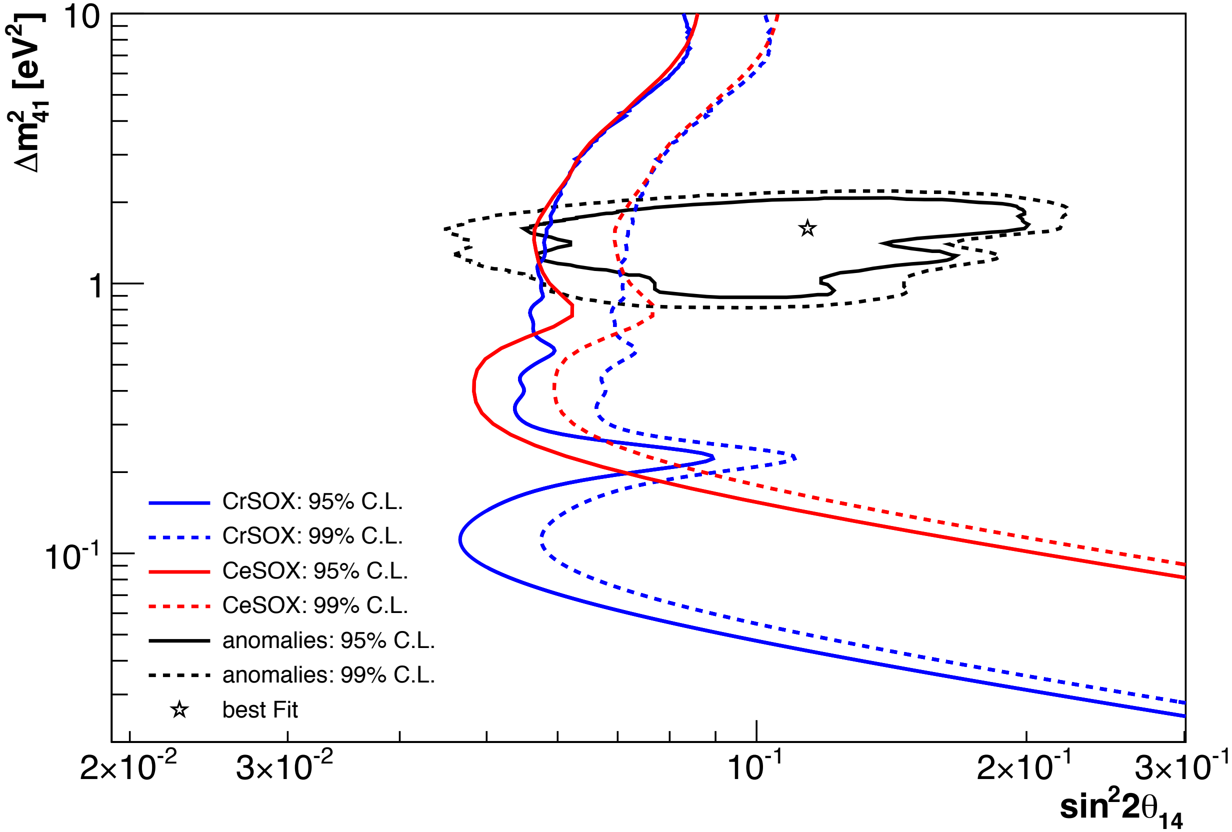






IBD coincidence signature
→ almost background-free

Projected sensitivity of CrSOX/CeSOX



CrSOX

Activity: 10 MCi

Fiducial radius: 3.3 m

1% source error

1% FV error

1% background error

CeSOX

Activity: 100 kCi

Fiducial ra dius: 4 m

1% source error

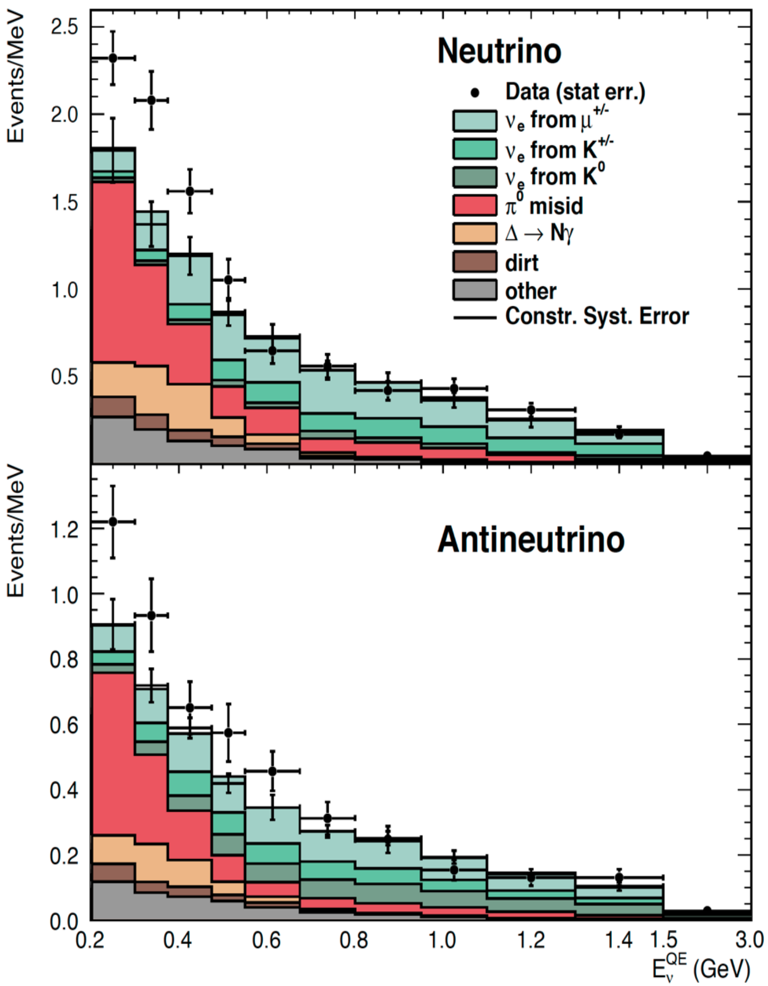
1% FV error

no relevant background

→ SOX could discover/exclude best fit value at ~5σ

→ 95% C.L. region of anomalies can be covered

Future neutrino beam experiments



MiniBooNE data:
electron-like excess at low energies

How to improve?

- better knowledge of beam spectrum, cross-sections, energy scale …
  → addition of near detector
- better control of backgrounds
  → Liquid-Argon TPCs
- better sensitivity
  → stronger beams/larger detectors

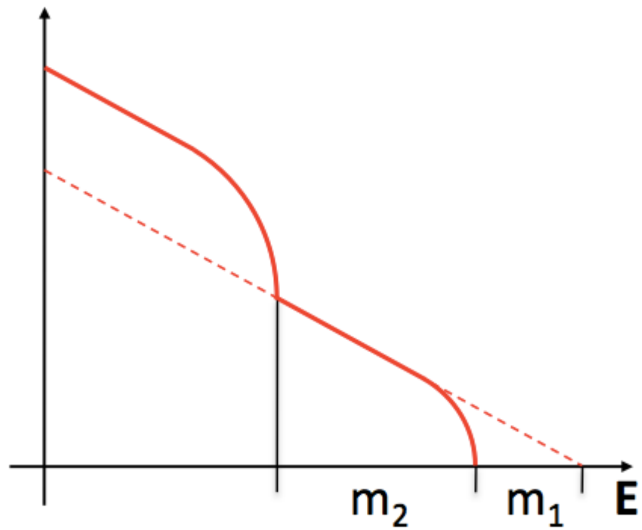
What projects are discussed?

- MicroBooNE running at Fermilab
  → too small for sterile ν search
- Addition of LAr1 as near detector or ICARUS T-600 as far detector

Spectroscopy of beta-decay end point

Measuring the ν_e mass

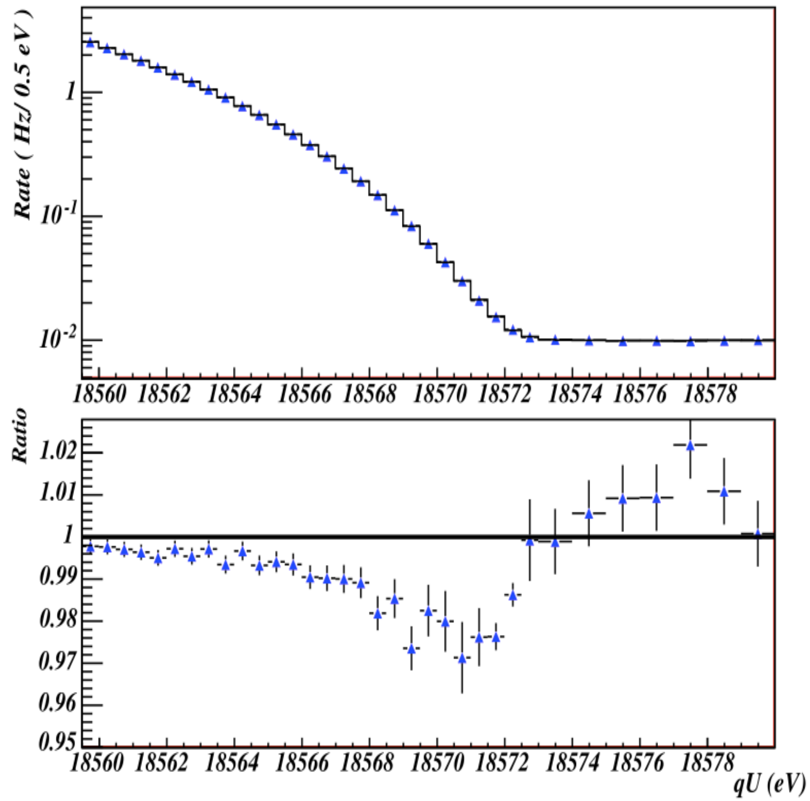
- Effect of mass is a shift of the endpoint/spectral deformation
- 3 known mass eigenstates could in principle be resolved
  but mass differences very small
  $\Delta m_{31} < 50$ meV



Spectroscopy of beta-decay end point

Measuring the ν_e mass

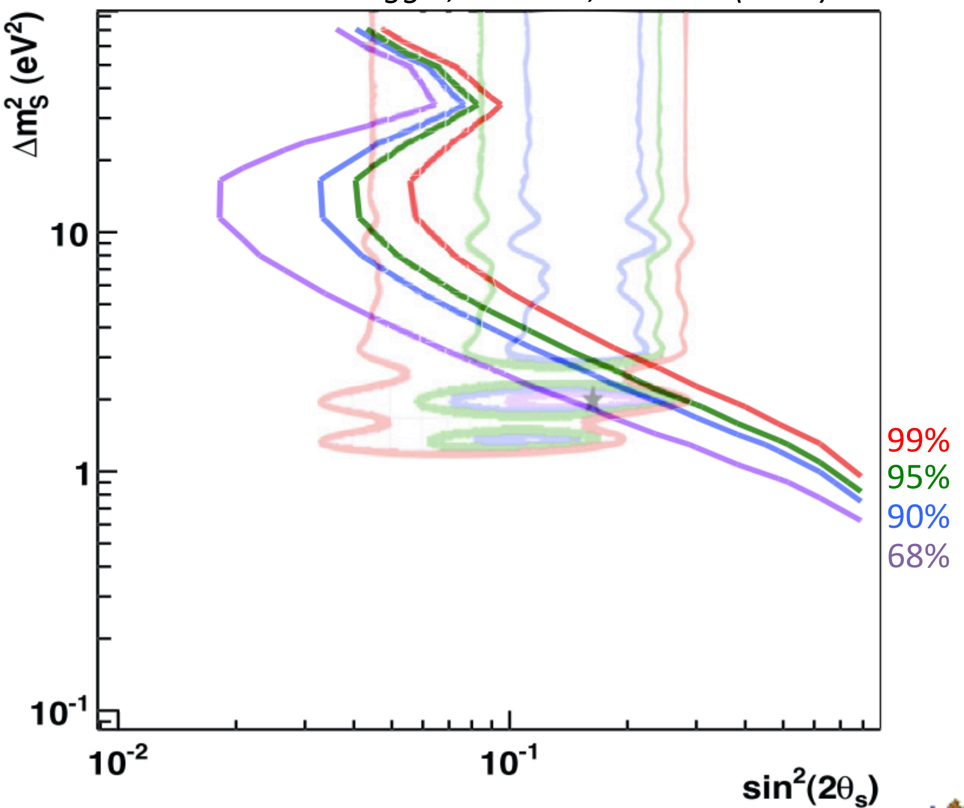
- Effect of mass is a shift of the endpoint/spectral deformation
- 3 known mass eigenstates could in principle be resolved
  but mass differences very small
  $\Delta m_{31} < 50$ meV
- sterile mass splitting much larger
  $\Delta m_{41} \sim 1$eV
  → *observable in tritium decay?*
- size of effect depends on size of sterile neutrino mixing



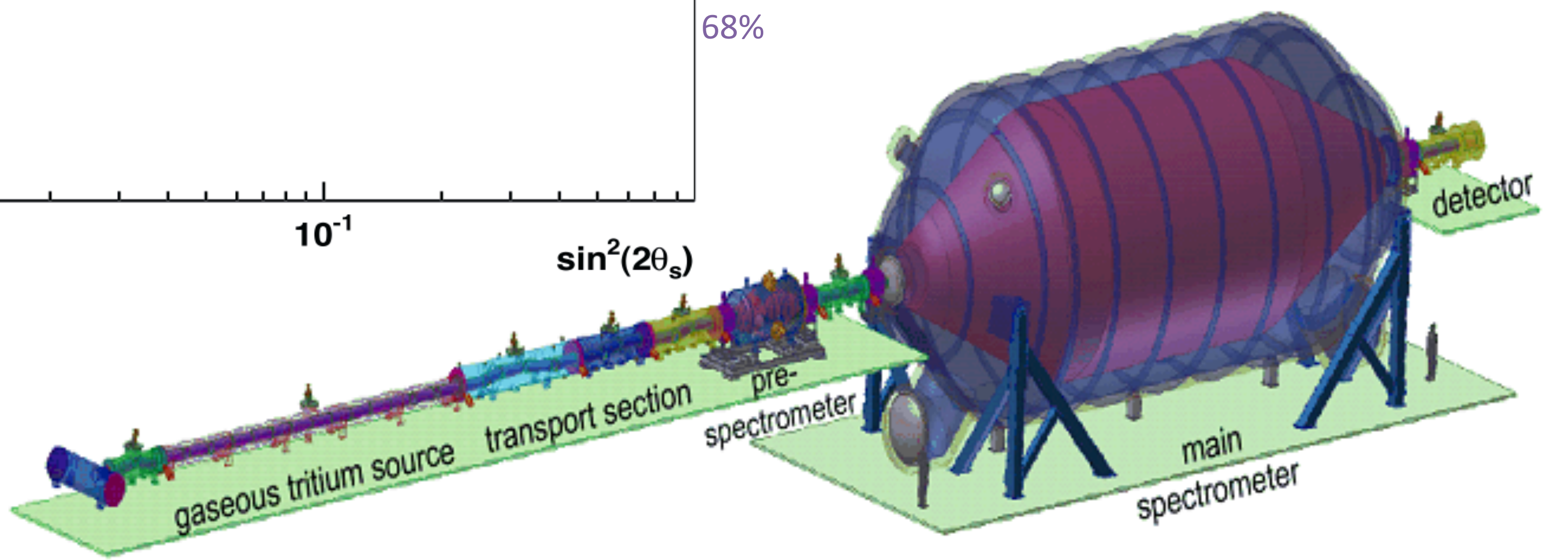
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
Spectral deformation of tritium decay spectrum
(3-year measurement in KATRIN)
Sterile ν parameters: $\Delta m^2 = 2$ eV^2, $|U_s|^2 = 0.067$

First sensitivity estimates for KATRIN

J. A. Formaggio, J. Barret, PLB 706 (2011) 68



- sensitivity will reach into the region of interest
- methodically independent from oscillation searches
- studies on systematics are on-going



Conclusions

- Several experimental hints for sterile neutrinos not conclusive → for sure worth testing
- New generation of oscillation experiments is sensitive to spectral deformation and distance dependence
  → much more conclusive results expected
- When to expect new data?
  → STEREO and SOX will start data taking in 2015
- KATRIN has the potential to provide complementary data from tritium decay endpoint measurement

Backup Slides

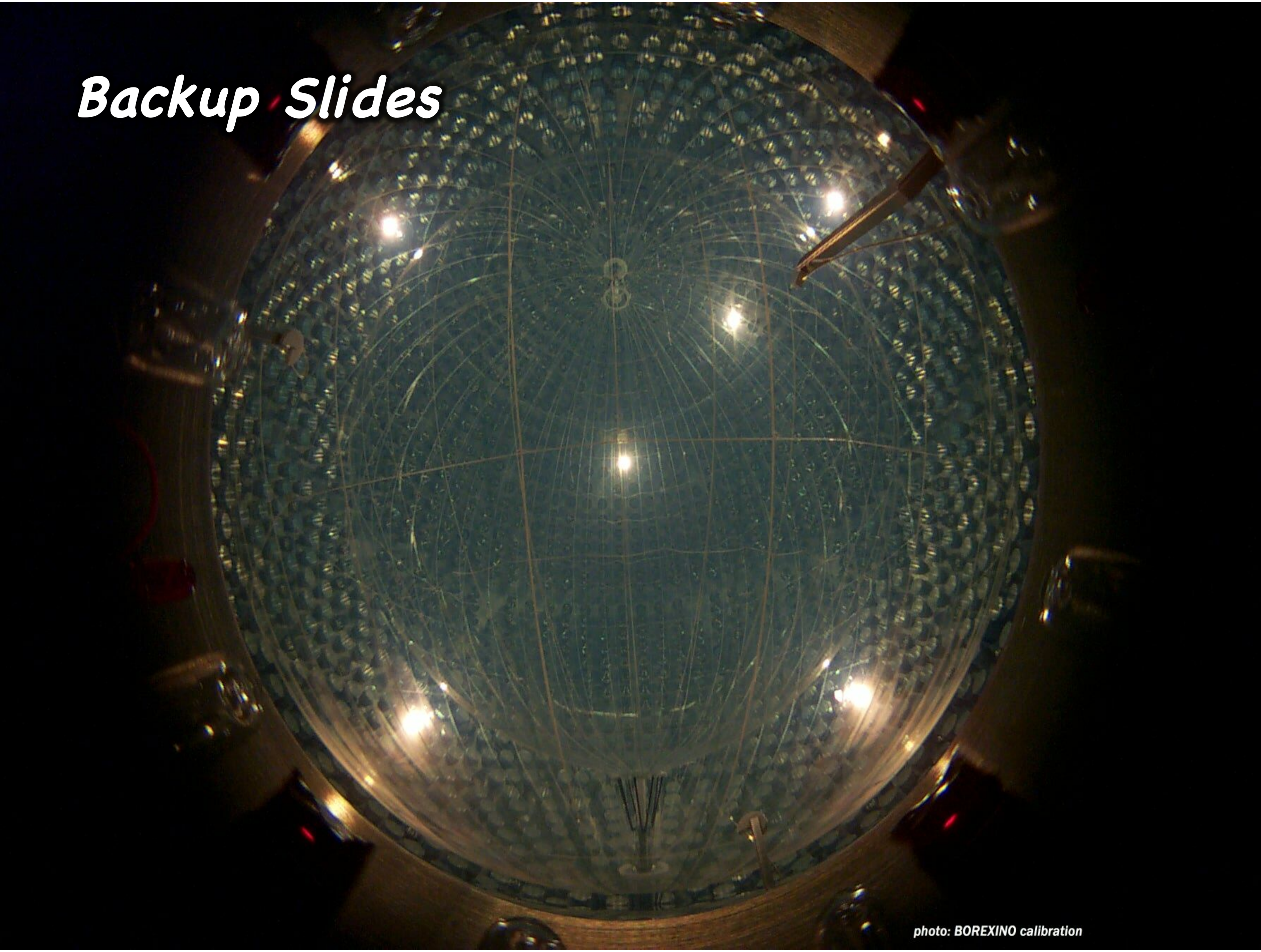
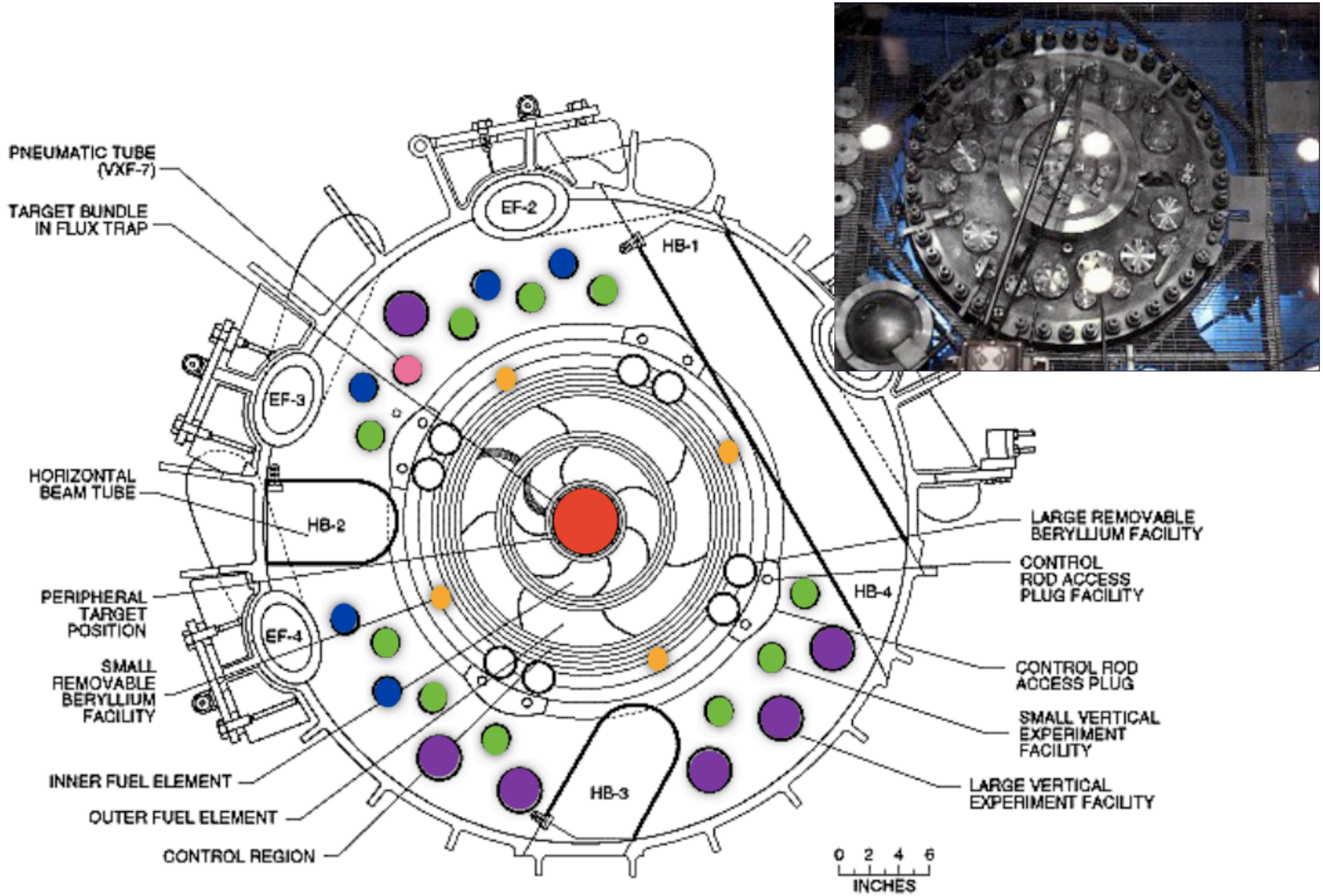
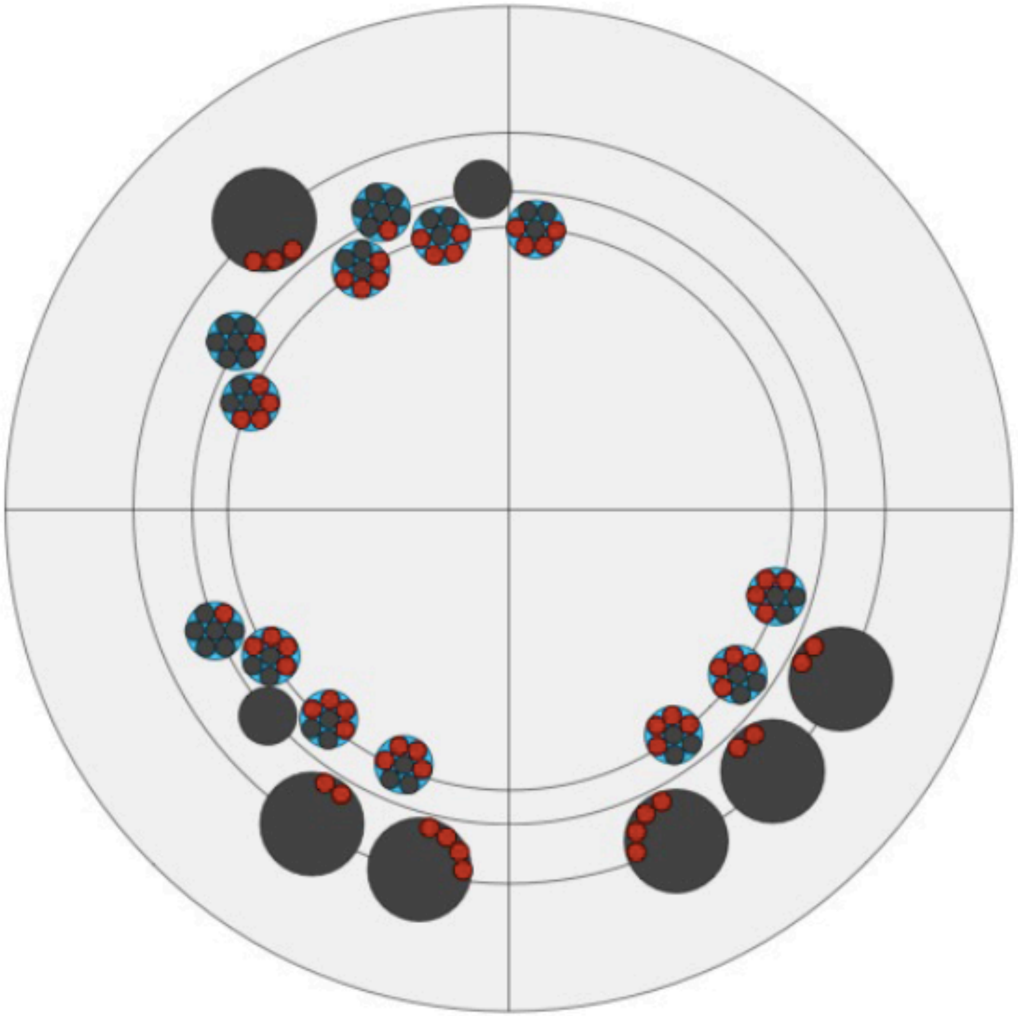


photo: BOREXINO calibration

Neutron activation to ^{51}Cr @ Oak Ridge NL



Optimized configuration for irradiation material



Source Material

- 36 kg in chips
- ^{51}Cr: 38%

Chromium rods

→ reduced self-shielding of material

Irradiation

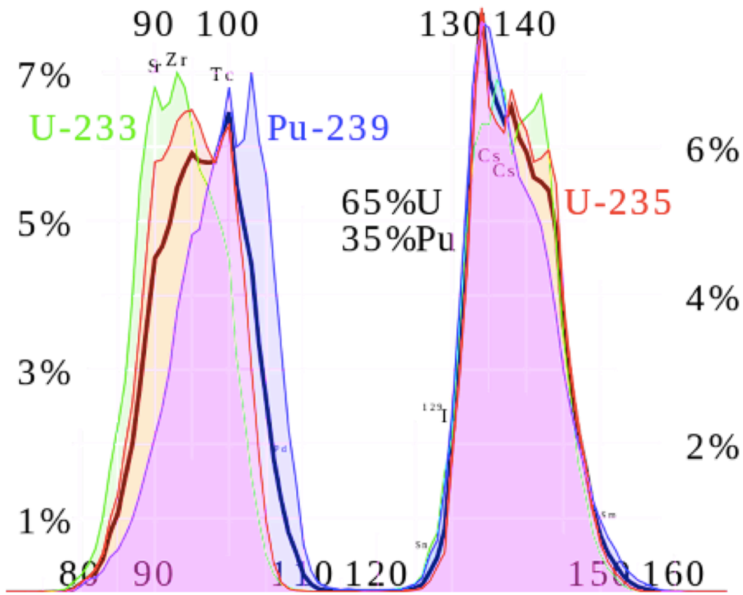
2 cycles of 24 days
w/ 8 days down-time

Expected activity

>5 MCi

Cerium: Abundant fission product

Composition	Before	After
^{235}U	3.2 %	0.7%
^{238}U	96.8 %	94.2%
^{239}Pu	--	0.95%
^{237}Np	--	0.05%
Fission products	--	3.7%
Ce	--	0.22%



→ Main cerium isotopes in spent nuclear fuel:

^{140}Ce	stable	
^{142}Ce	stable	
^{144}Ce	$T_{1/2}$=285 d	all at ~ 0.06%

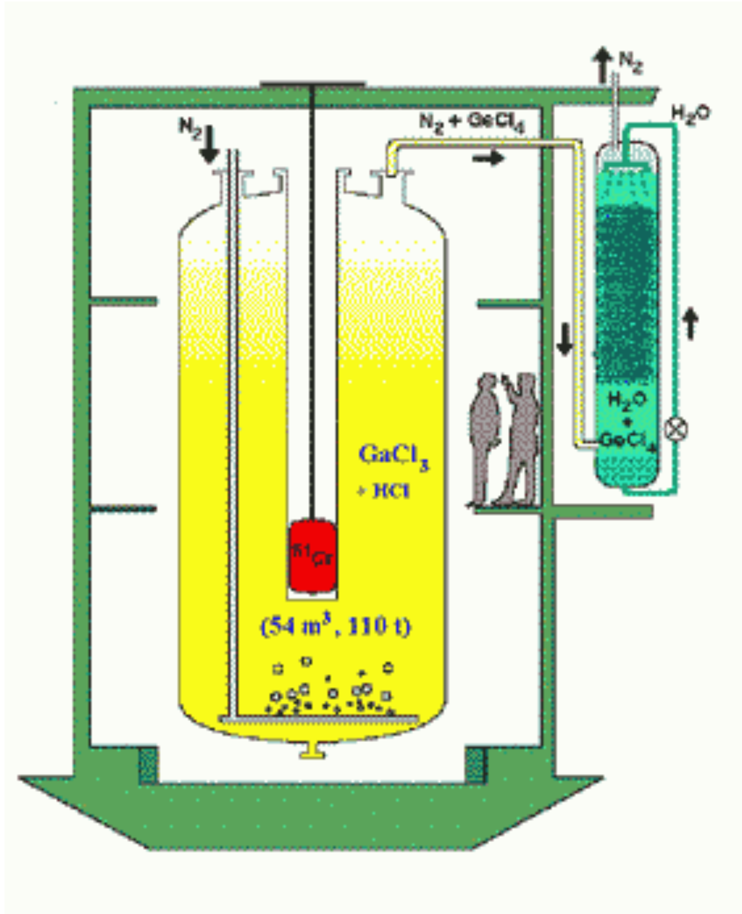
→ after 4 years: $^{144}Ce/Ce$ ~ 0.5%

Experimental hints for sterile neutrinos

Source calibration runs at Ga radiochemical detectors:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

→ observed signal rates below expectation (2.8σ)



[1204.5379]

Exp	Source	Ratio (Exp/Th)*
Gallex	^{51}Cr	0.95 ± 0.11
	^{51}Cr	$0.81^{+0.10}_{-0.11}$
SAGE	^{51}Cr	0.95 ± 0.12
	^{27}Ar	0.79 ± 0.08
total		**0.86 ± 0.05**

** cross-sections as calculated by J. Bahcall*

Best fit values for $\nu_e \rightarrow \nu_s$:
$\sin^2 2\theta = 0.5$, $\Delta m^2 = 2.24\ \mathrm{eV}^2$

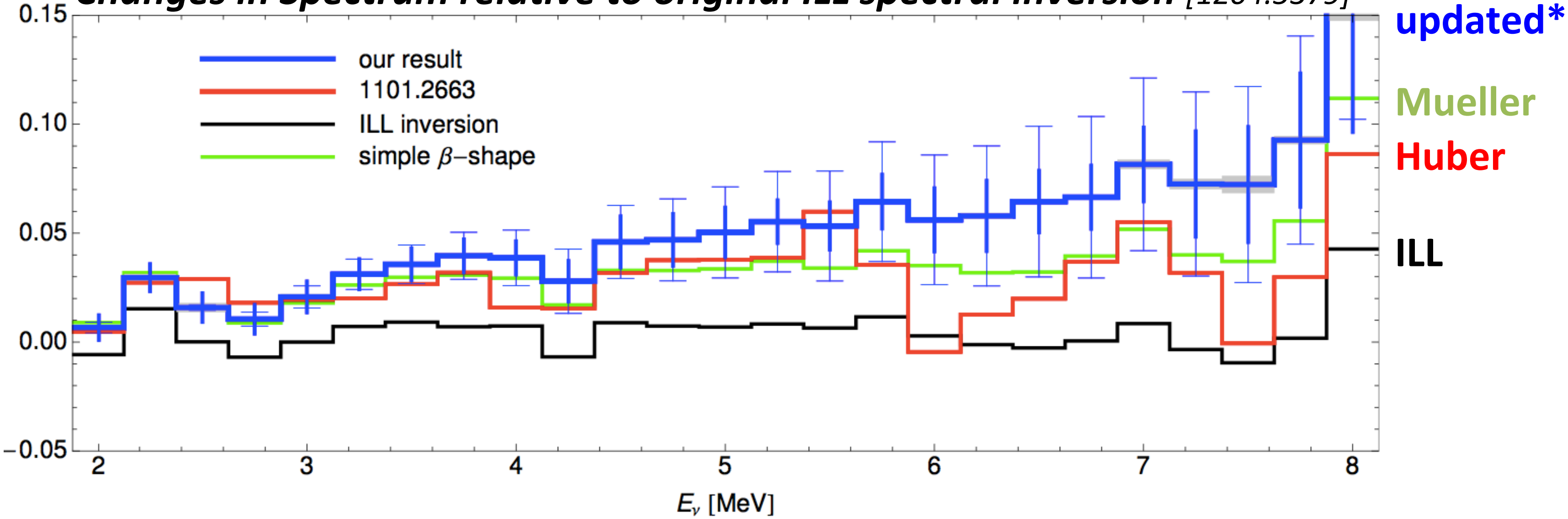
Reactor antineutrino anomaly

Re-evaluation of the β-decay spectra of fission products measured in ILL experiment *(Schreckenbach et al.)*

→ shift of spectrum to higher energies

→ **increase of expected event rates by ~4.5%** in reactor ν experiments

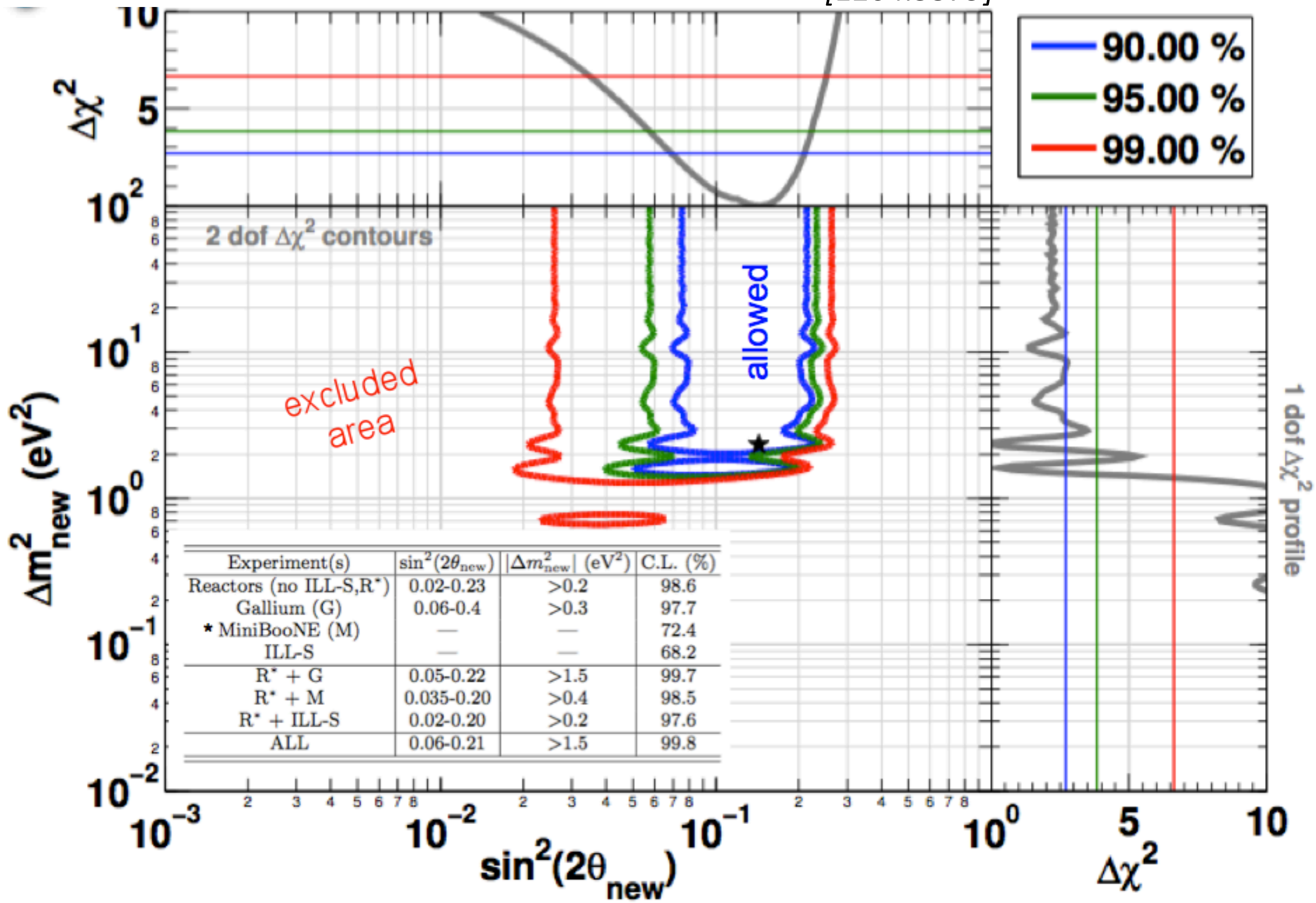
Changes in Spectrum relative to original ILL spectral inversion *[1204.5379]*



** updated: Mueller spectrum + new corrections from Fermi theory (ν_s whitepaper)*

Global fit to sterile neutrino data

[1204.5379]



Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
★ MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

→ Best fit values: $\sin^2 2\theta_{14} \approx 0.16$, $\Delta m^2_{41} \approx 2$ eV^2

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TU Dresden

Jagiellonian Kraków

BOREXINO/SOX Collaboration

CEA Saclay

JINR Dubna

Virginia Tech

Houston

Paris

SINP MSU

Moscow

Princeton

Los Angeles

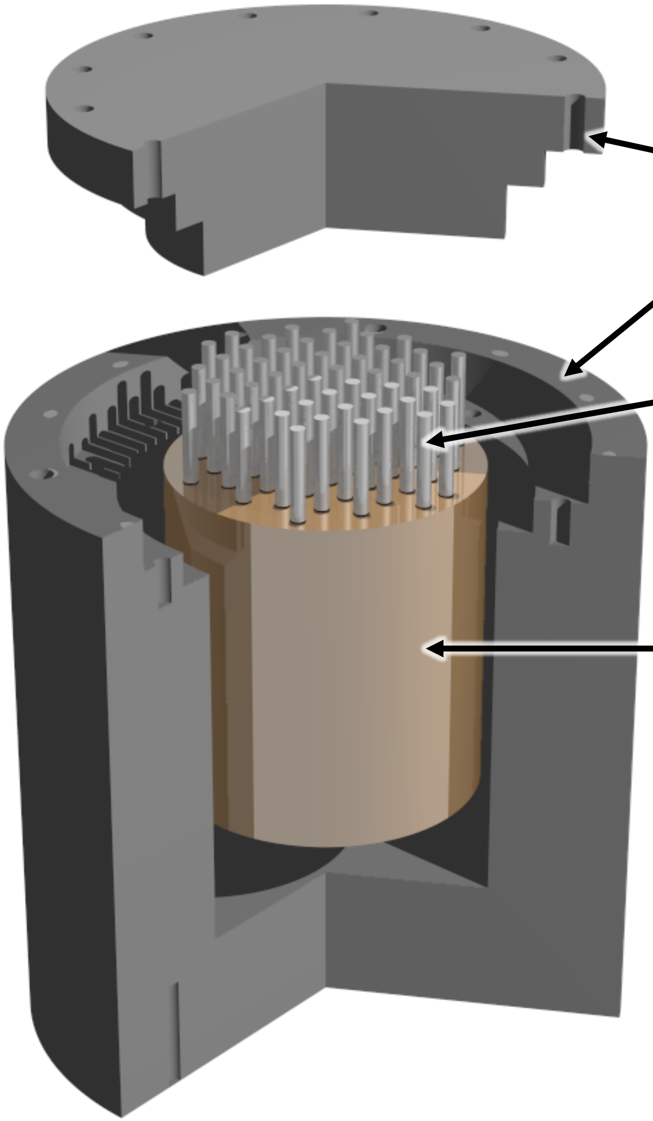
UMass Amherst

St. Petersburg

Kurchatov Moscow

Source enriched in ^{50}Cr (GALLEX)

Envisaged CrSOX Source Design



Total dimensions: 50 cm x 50 cm

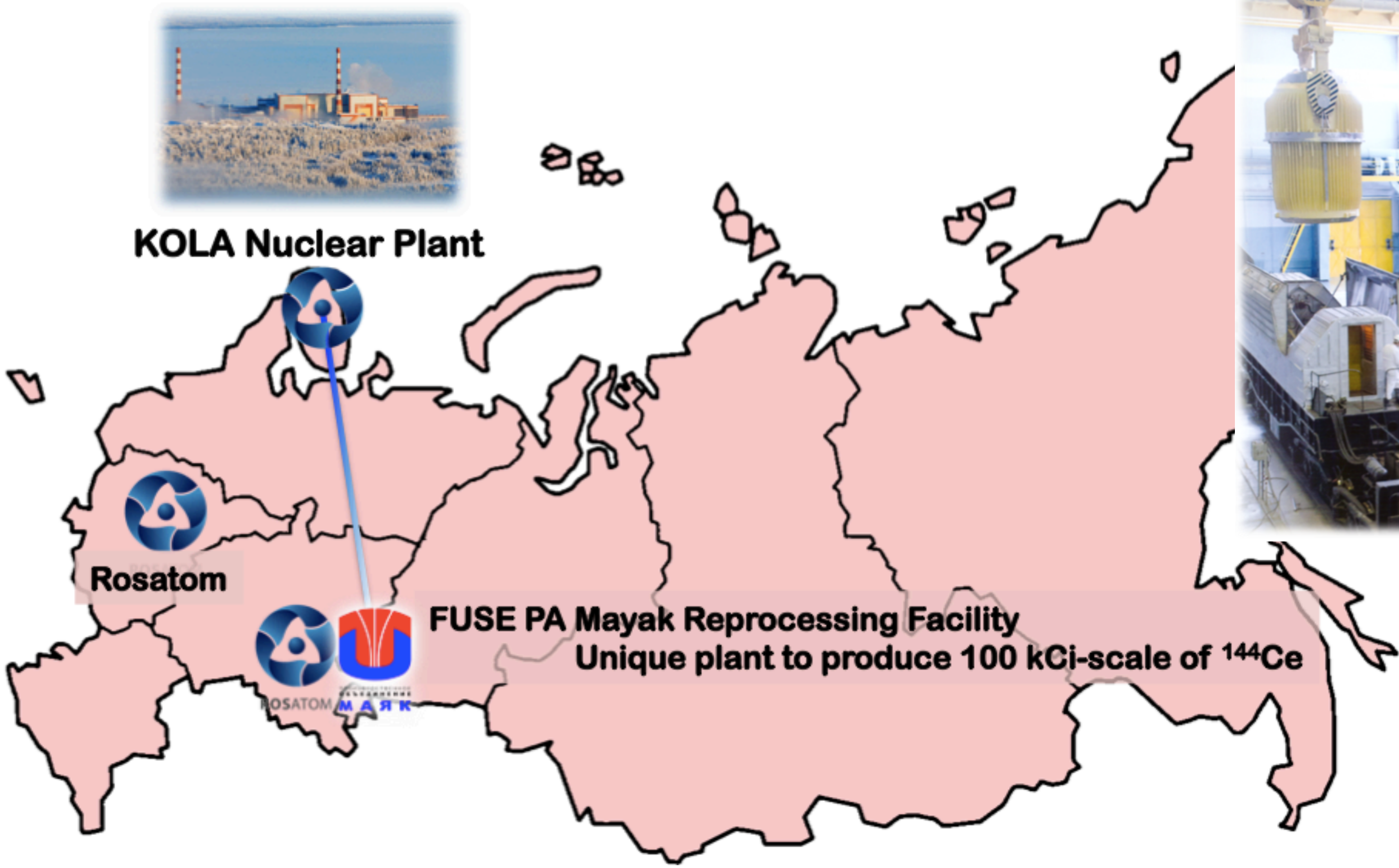
Tungsten (W) shielding (15 cm)
→ reduces γ-radiation to save level

Cr rods
→ enriched in ^{50}Cr
→ neutron-activated in reactor

Copper matrix (Φ=30 cm)
→ encloses source rods
→ heat conduction

Initial temperature profile
@ rods: 350°C
@ W surface: 70°C

Ce Source production @ FUSE PA Mayak



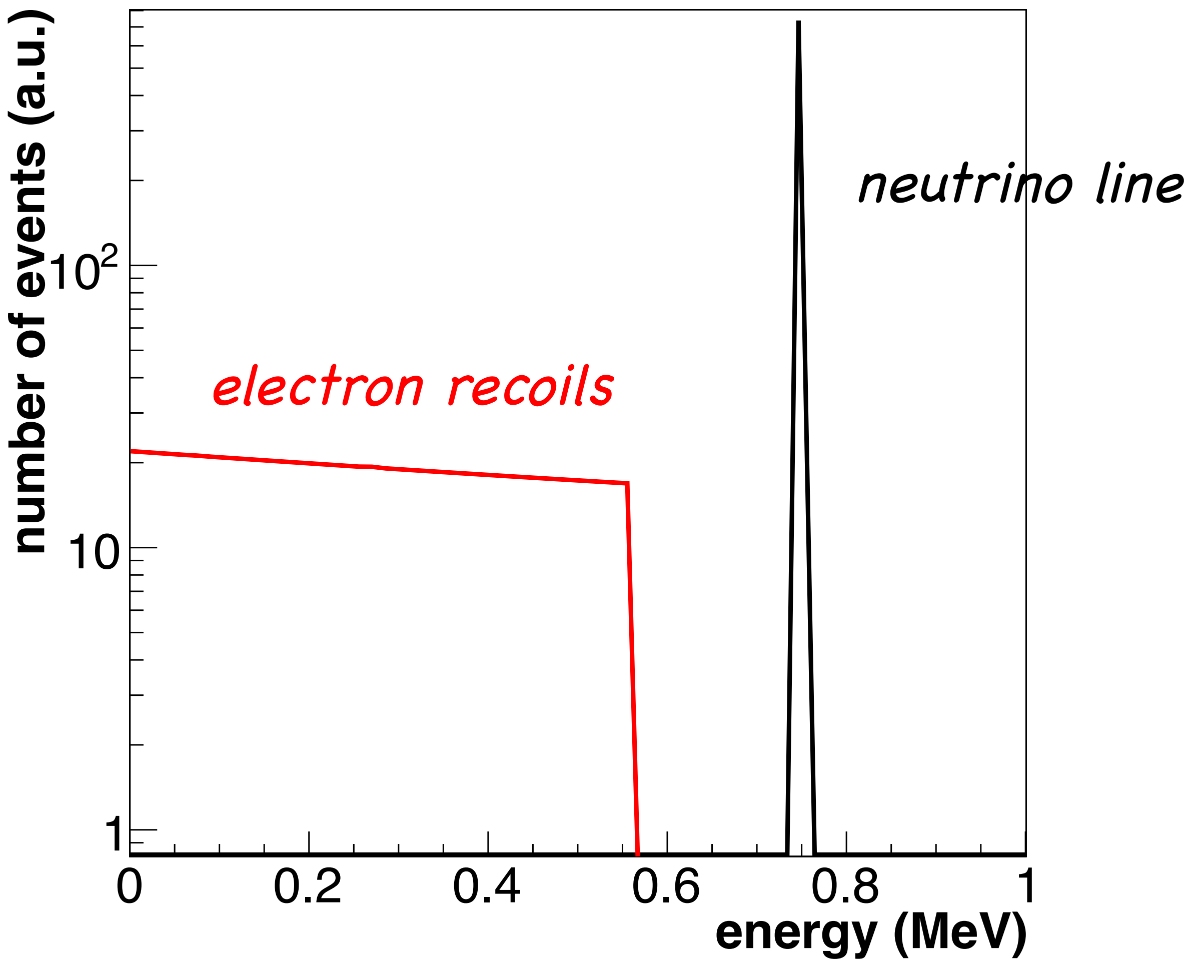
→ based on 10 ton of specially selected fuel from KOLA Nuclear Plant

→ Radiochemical extraction: 7.8 kg CeO_2 → 31.4 g ^{144}Ce → ~100 kCi

Transport from Mayak to LNGS

CrSOX: Electron Recoil Signal

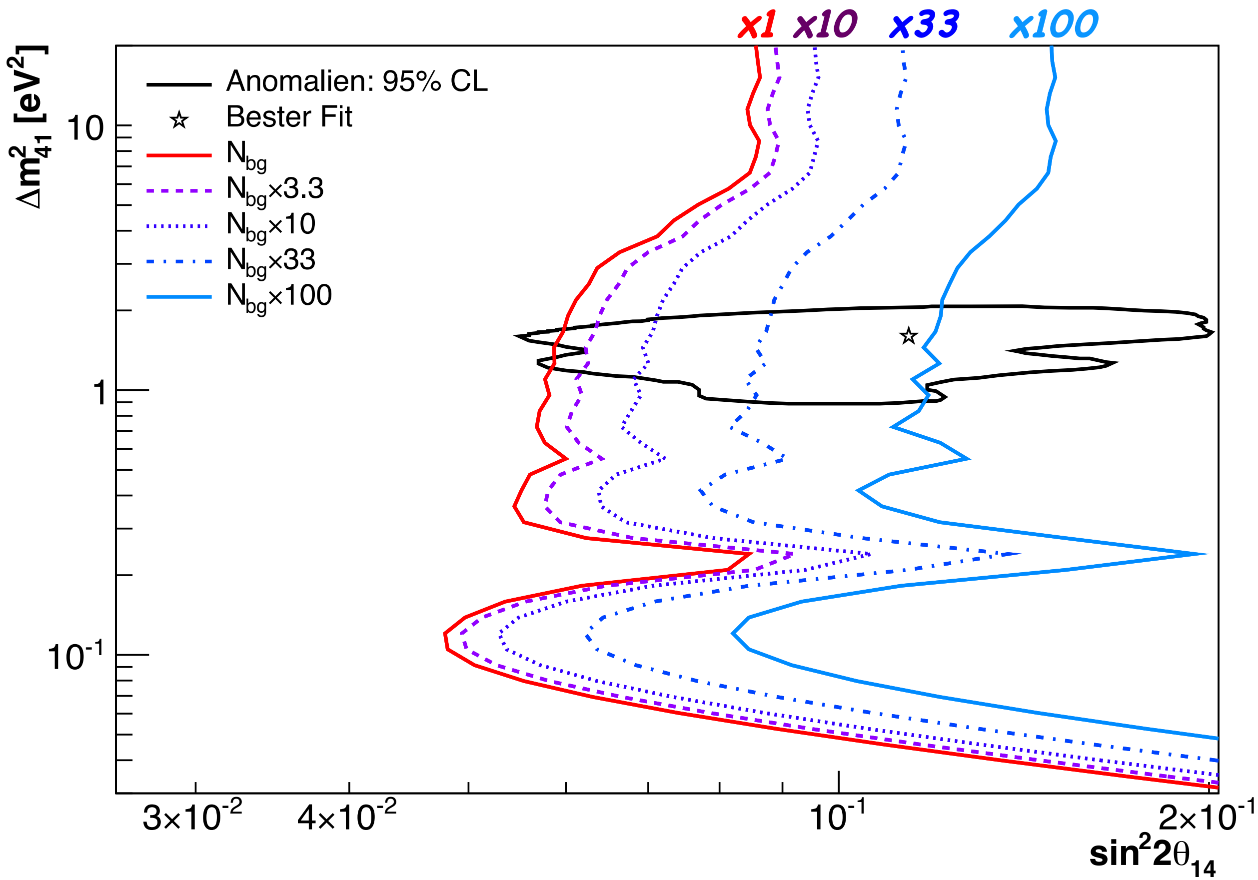
$$\nu_e + e \to e + \nu_e$$



Greater level of radioactive backgrounds

Analysis extrapolates background levels based on current data (including further decay of ^{210}Po)

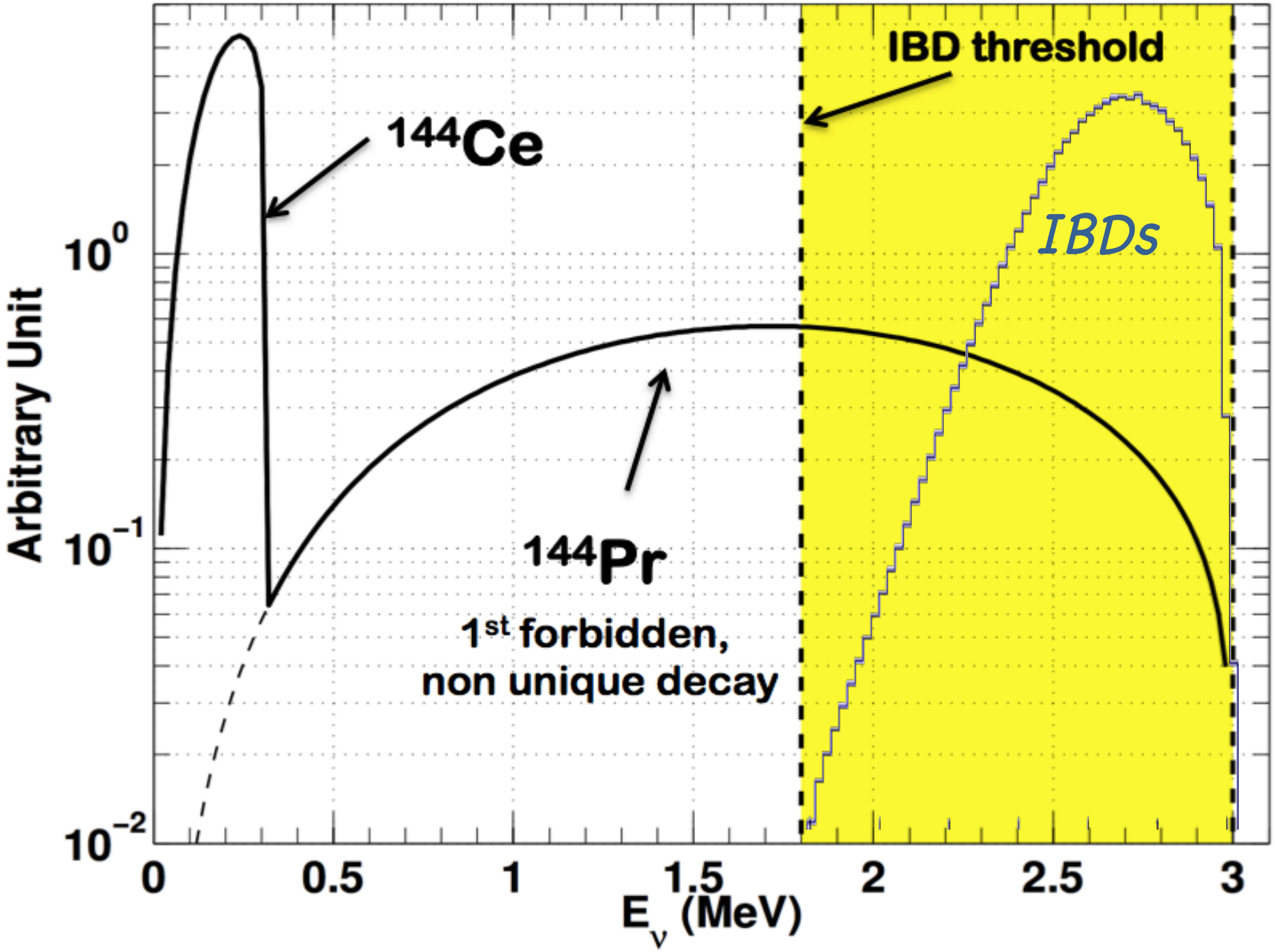
→ Detector operations (calibration, purification) might affect purity levels



→ *only a large increase might compromise sensitivity*

CeSOX Antineutrino Spectrum

$$\mathrm{IBD}: \bar{\nu}_e + p \rightarrow n + e^+$$

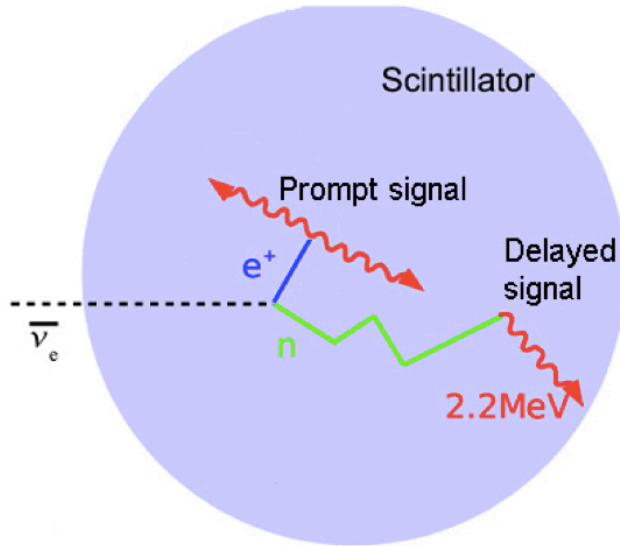


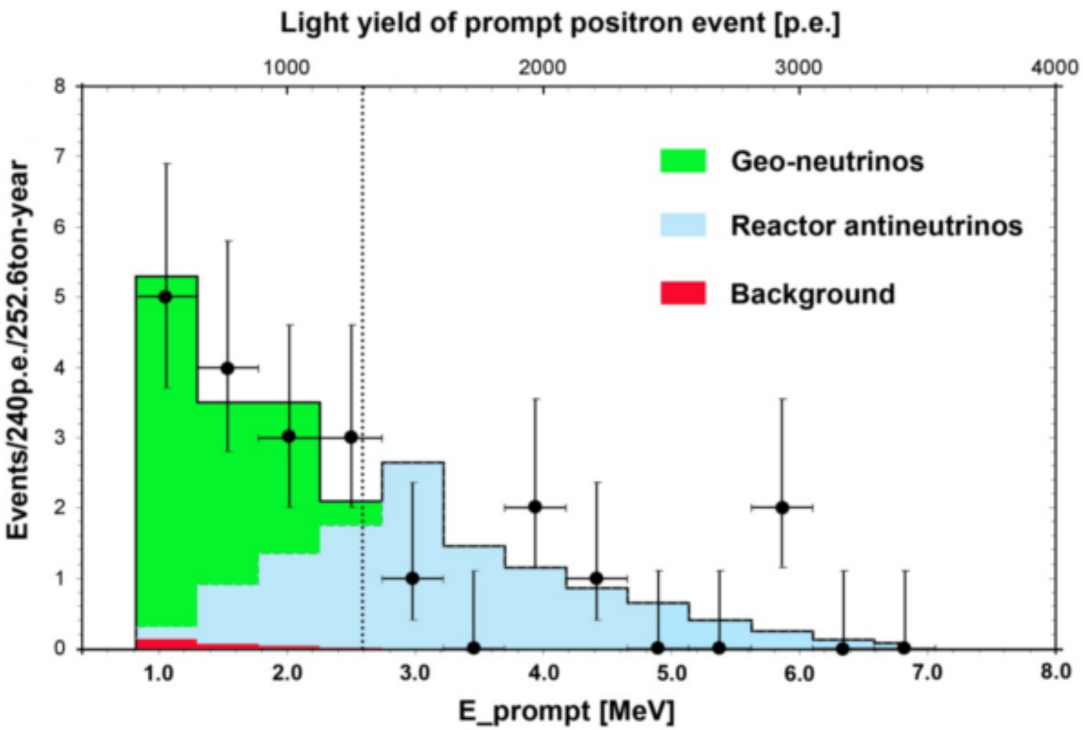
CeSOX Backgrounds

IBD: Coincidence signature

→ greatly reduced background:
single events suppresses

→ larger fiducial volume (r_{FV} ≈ 4m → 240t)





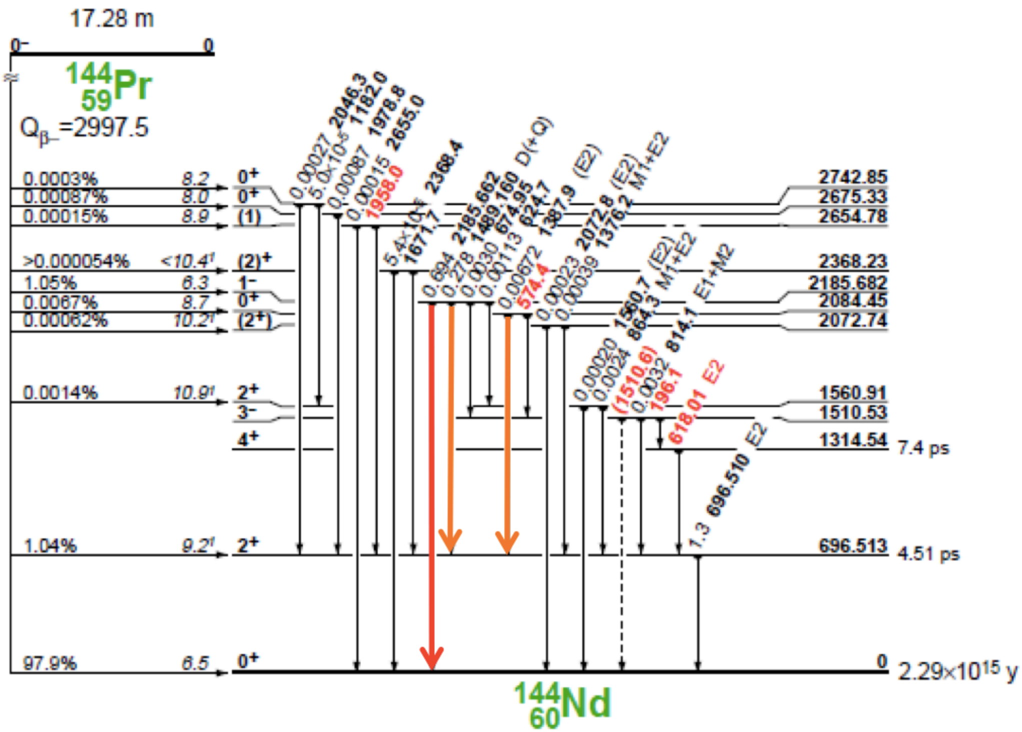
Remaining backgrounds

→ geoneutrinos

→ reactor neutrinos

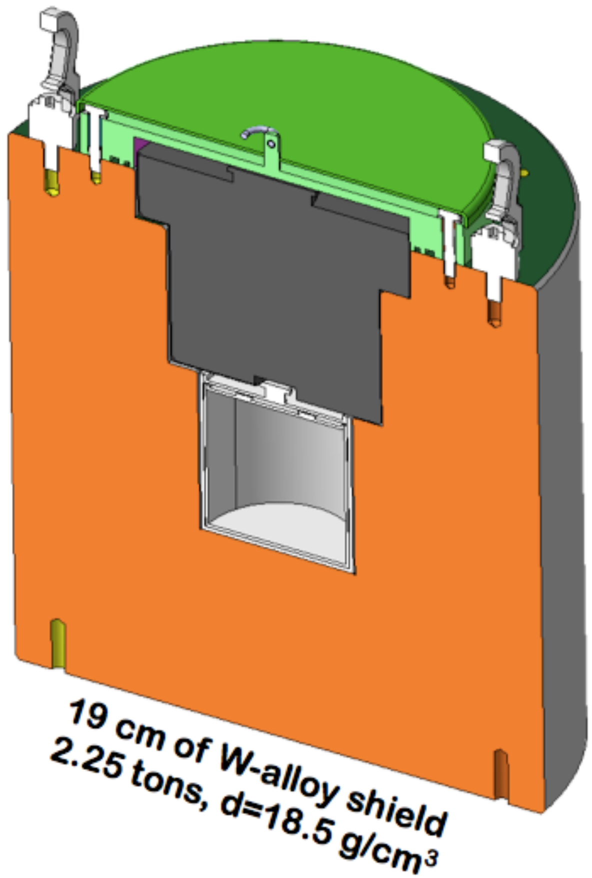
→ accidental coincidences

CeSOX source: γ Activity and Shielding

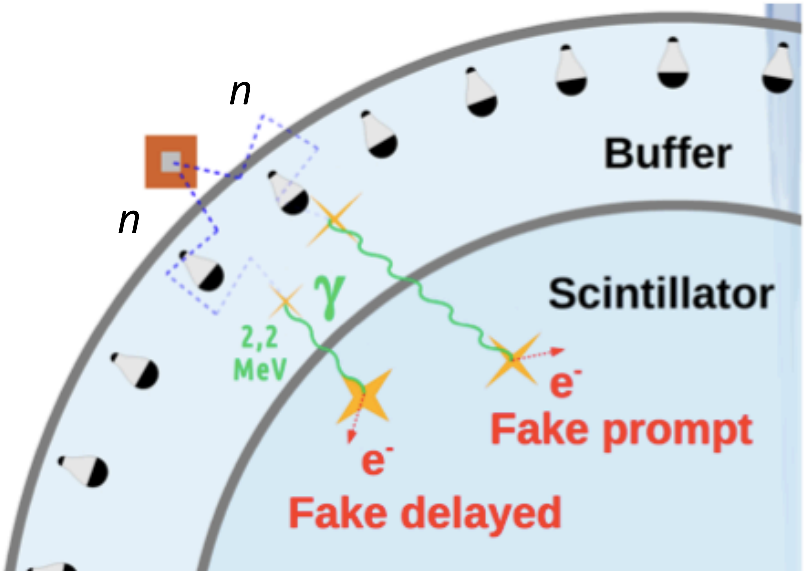


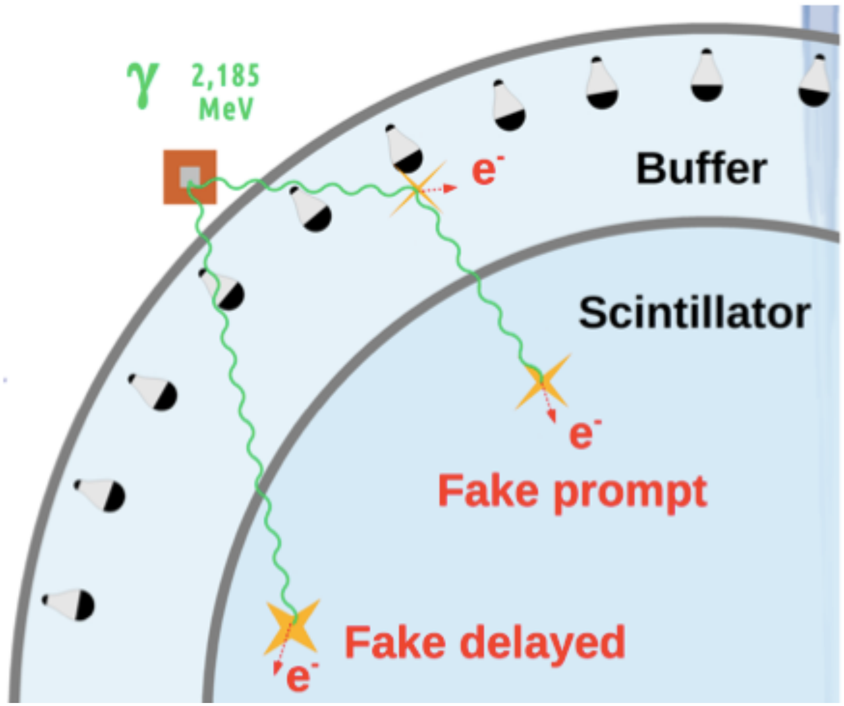
E_γ [keV]	Branching
1380	0.007%
1489	0.3%
2185	0.7%

→ **2 x 10^{10} Bq @ 100 kCi**



CeSOX: Accidental Coincidences





→ still under investigation

→ additional shielding (?)

CrSOX: Likelihood-based analysis

Profile likelihood based on

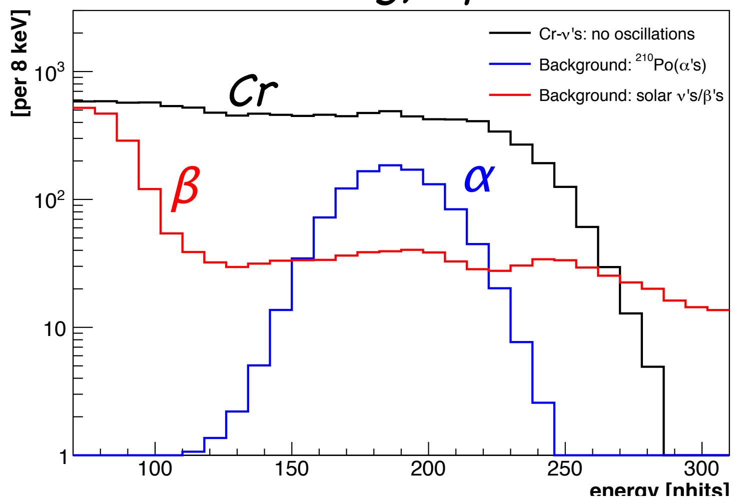
- energy spectrum
- distance from source
- time profile

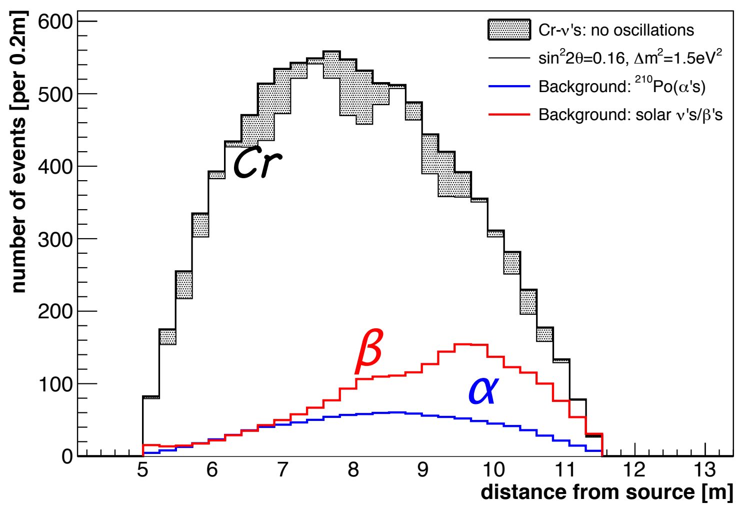
Nuisance parameters:

- signal/bg normalizations

→ prior knowledge included via pull terms

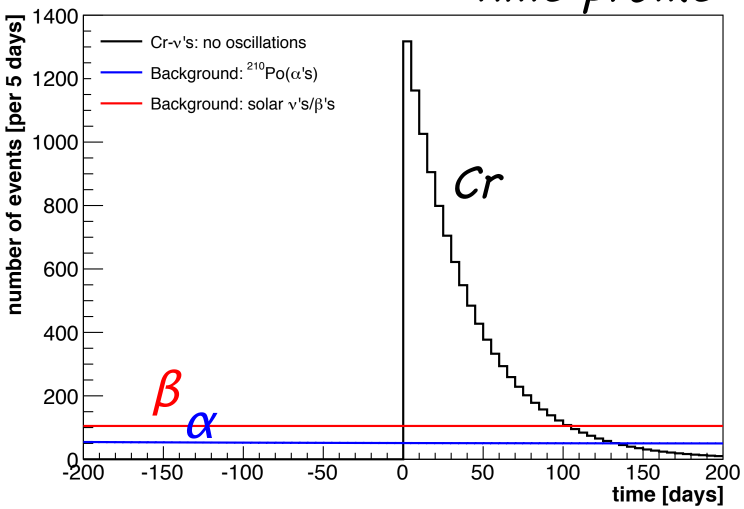
visible energy spectrum





distance distribution

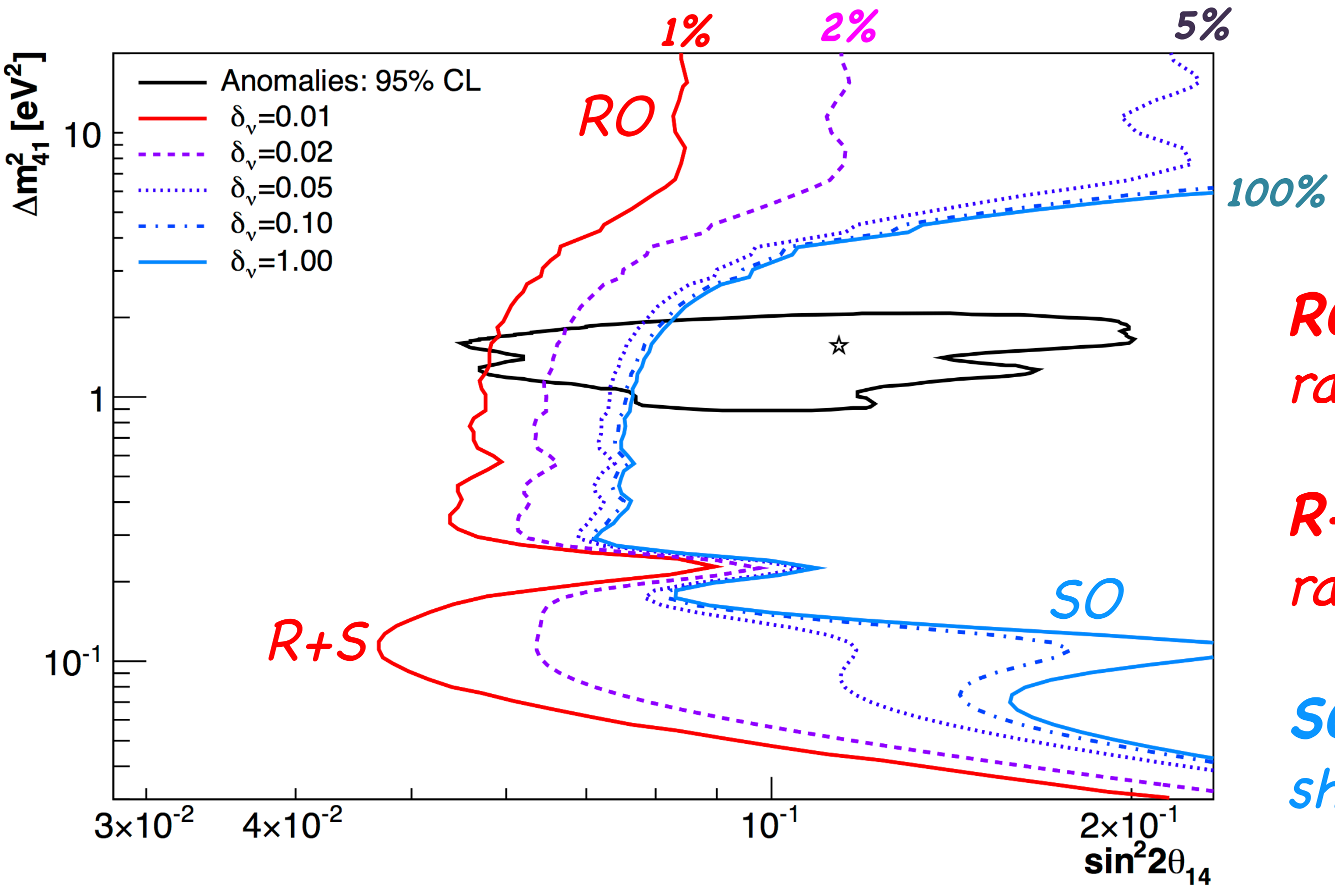
time profile



Impact of Cr-rate normalization uncertainty

Present analysis uses estimate on expected event rate

- Uncertainty on **fiducial volume**: ~1% from interal source calibration
- Uncertainty on **source activity**: ~1% Cr-source calorimetry

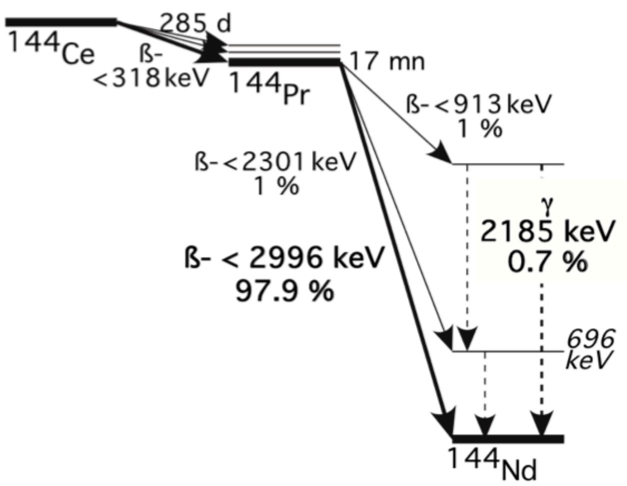


RO
rate only

R+S
rate+shape

SO
shape only

$^{144}Ce/Pr$ decay spectrum

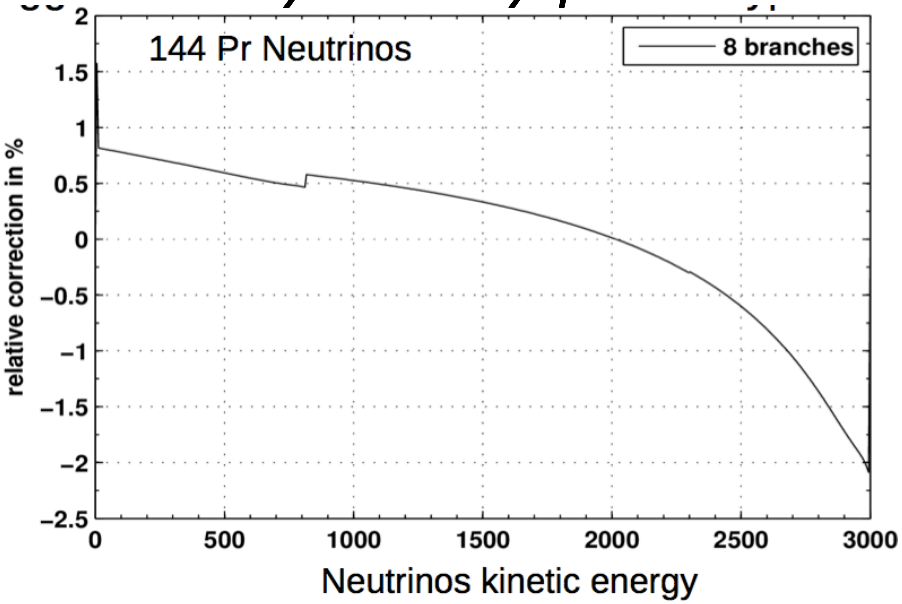


→ ^{144}Ce below IBD threshold

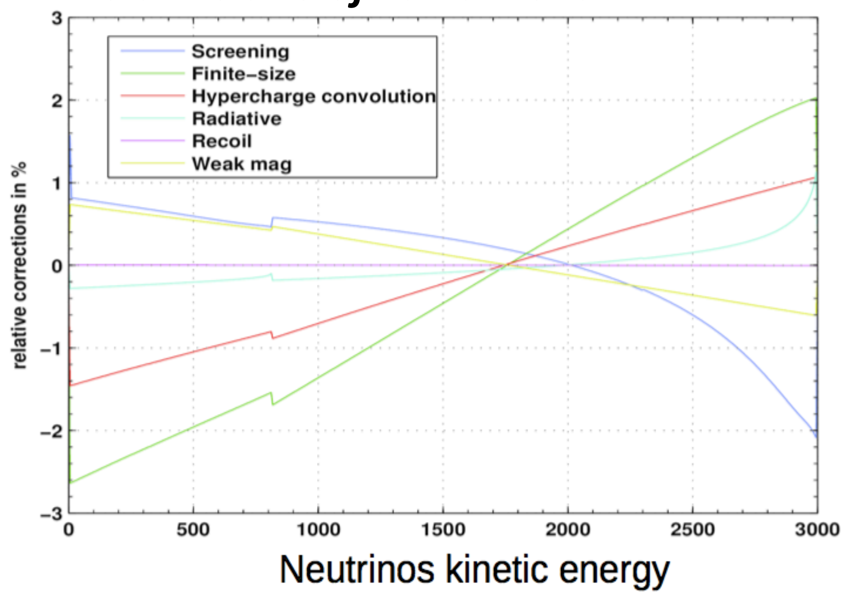
→ ^{144}Pr: complicated decay spectrum
- 9 relevant transitions
  (2 above IBD threshold)
- several %-level corrections
  to be applied to the spectrum

→ needs detailed calculations
+ lab measurements of β-spectrum

Praesodynium decay spectrum



Relative size of corrections



Calorimetric measurement of source power

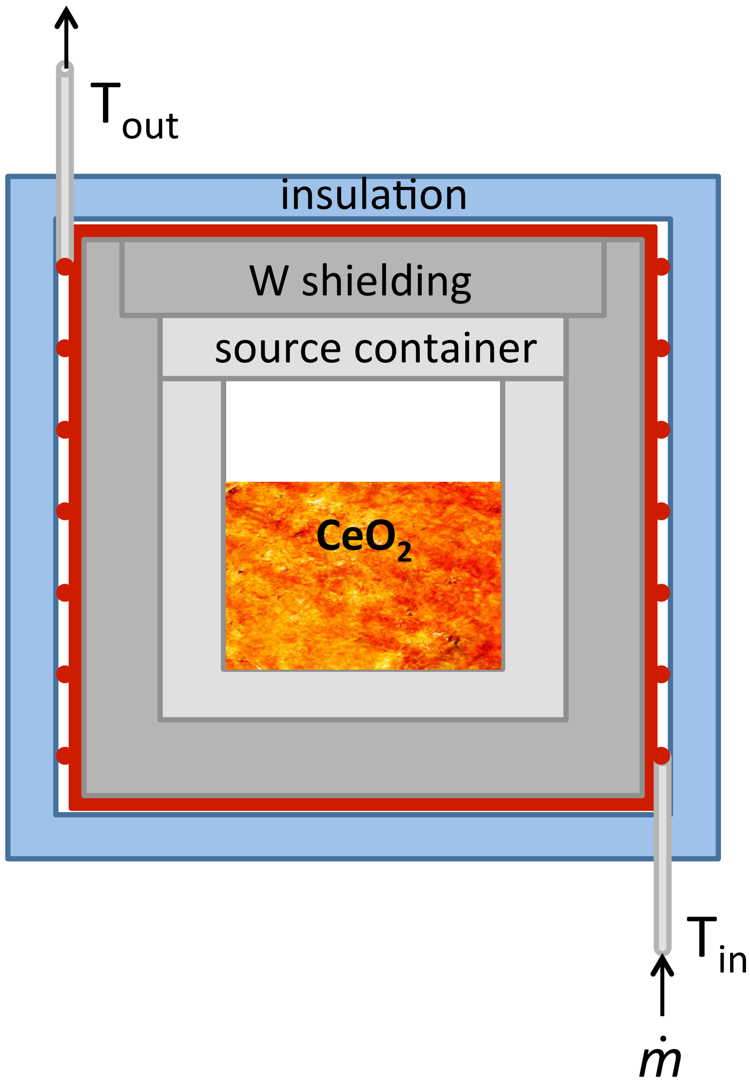
Thermal power output

- CrSOX: γ-rays (E≈320keV, BR≈10%)
- CeSOX: β+γ's

→ power deposited mostly inside the source

Measurement principle

- Isolate source from environment
- Heat transfer to water serpentine in jacket attached to W-shielding
- Measurement of H_2O mass flux and temperature increase
  → power emitted by source



Calorimeter for source power measurement

TUM design
(to go into SOX-Pit)