

CeSOX sensitivity studies

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CeSOX experimental parameters

	Parameter	Value	Comment
Source	Activity	100 kCi	1.5% uncertainty
	Shape	Cylindrical	Typical caspule geometry
	Size	0.07 m r × 0.14 m h	Typical capsule size
	Isotope	$^{144}\text{Ce} - ^{144}\text{Pr}$	Extracted from spent nuclear fuel
Detector	Shape	Spherical	KamLAND-like, Borexino-like
	Size	4.25 m (radius)	Borexino
	Efficiency	100%	
	Proton density	$5.30 \times 10^{22} \text{cm}^{-3}$	Borexino
	Position resolution	15 cm	Borexino
	Energy resolution	$5\% / \sqrt{E_{\text{vis}}}$	KamLAND-like
Background	-	No background	-
Miscellaneous	Live time	1.5 y	-
	Source distance	8.25 m	To detector center

CeSOX nominal parameters
(CeSOX upgraded – $R < 5.5$ m)

L/E spectrum modeling and χ^2

- Model computes L/E expected anti- ν_e spectrum. It includes:

- Production of anti- ν_e : ^{144}Pr beta spectrum (see M. Durero talk about modeling of ^{144}Pr beta spectrum)+ source finite size effects
- Detection of anti- ν_e : up to date IBD cross-section, number of proton targets, detection efficiency

$$\sigma_{\text{IBD}}(E_e) = \kappa p_e E_e (1 + \delta_{\text{rec}} + \delta_{\text{rad}} + \delta_{\text{WM}})$$

- $\kappa = 9.596 \times 10^{-44} \text{ cm}^2 \text{ MeV}^{-1}$
- Recoil & WM corrections from Fayans (1985)
- Radiative corrections from Vogel (1984)

- Energy and position reconstruction resolutions
- Systematics uncertainties:
 - Fully correlated normalization uncertainty related to source activity uncertainty

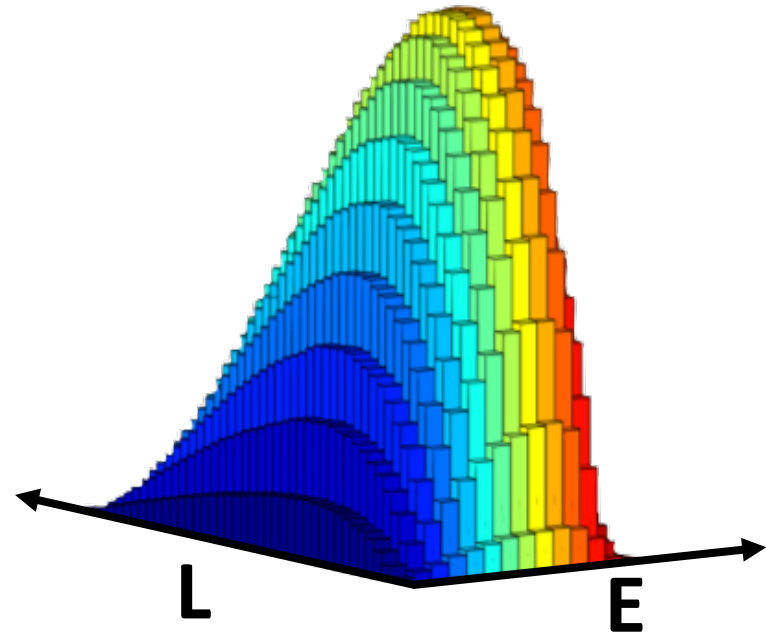
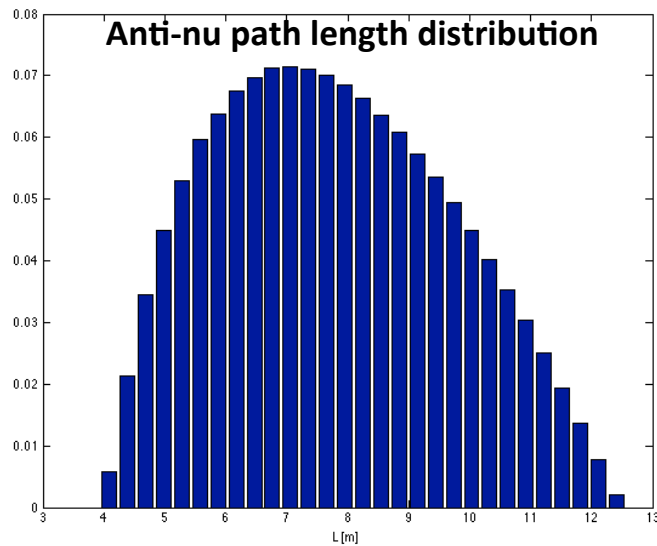
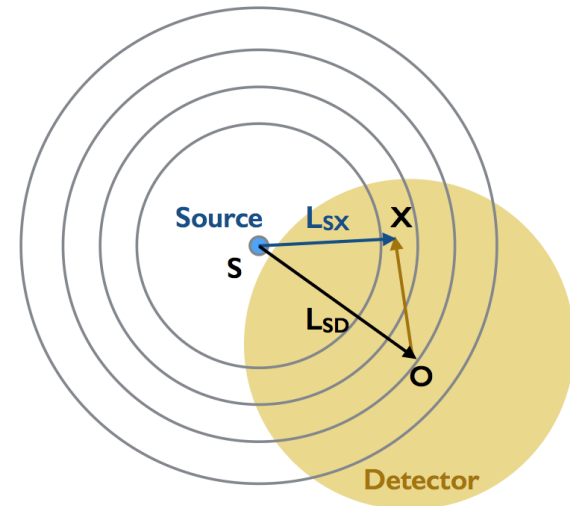
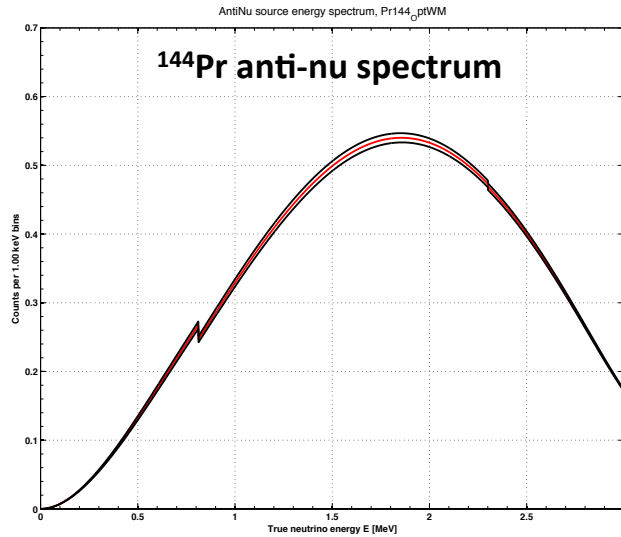
- (3+1) sterile neutrino model

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$

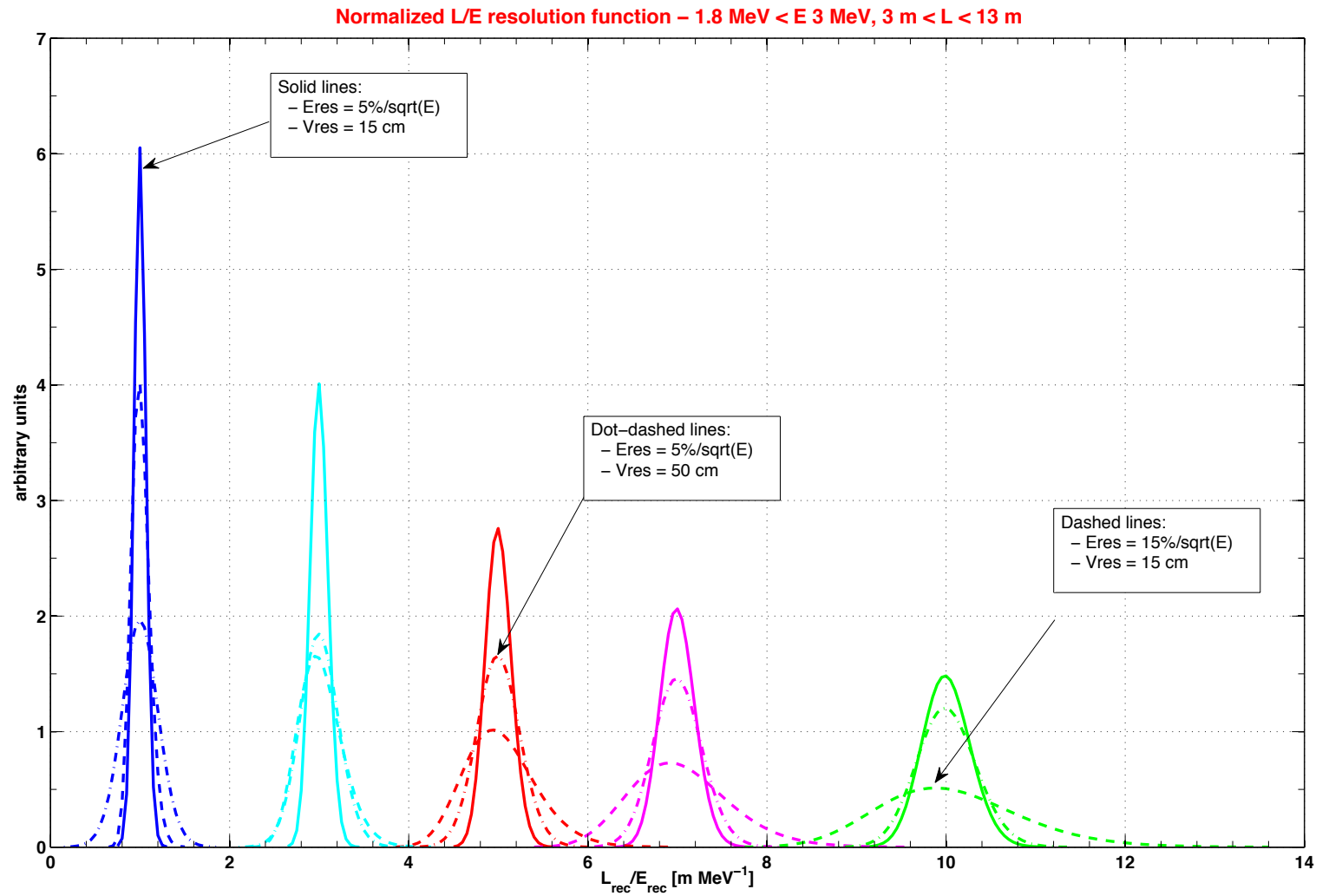
- χ^2 analysis:
$$\sum_i \left(\frac{N_i^{\text{obs}} - (1 + \alpha) N_i^{\text{exp}}(\theta, \Delta m^2)}{\sigma_i^{\text{stat}}} \right)^2 + \left(\frac{\alpha}{\sigma} \right)^2$$

where i runs over (L/E) bins

Model ingredients: L & E distributions

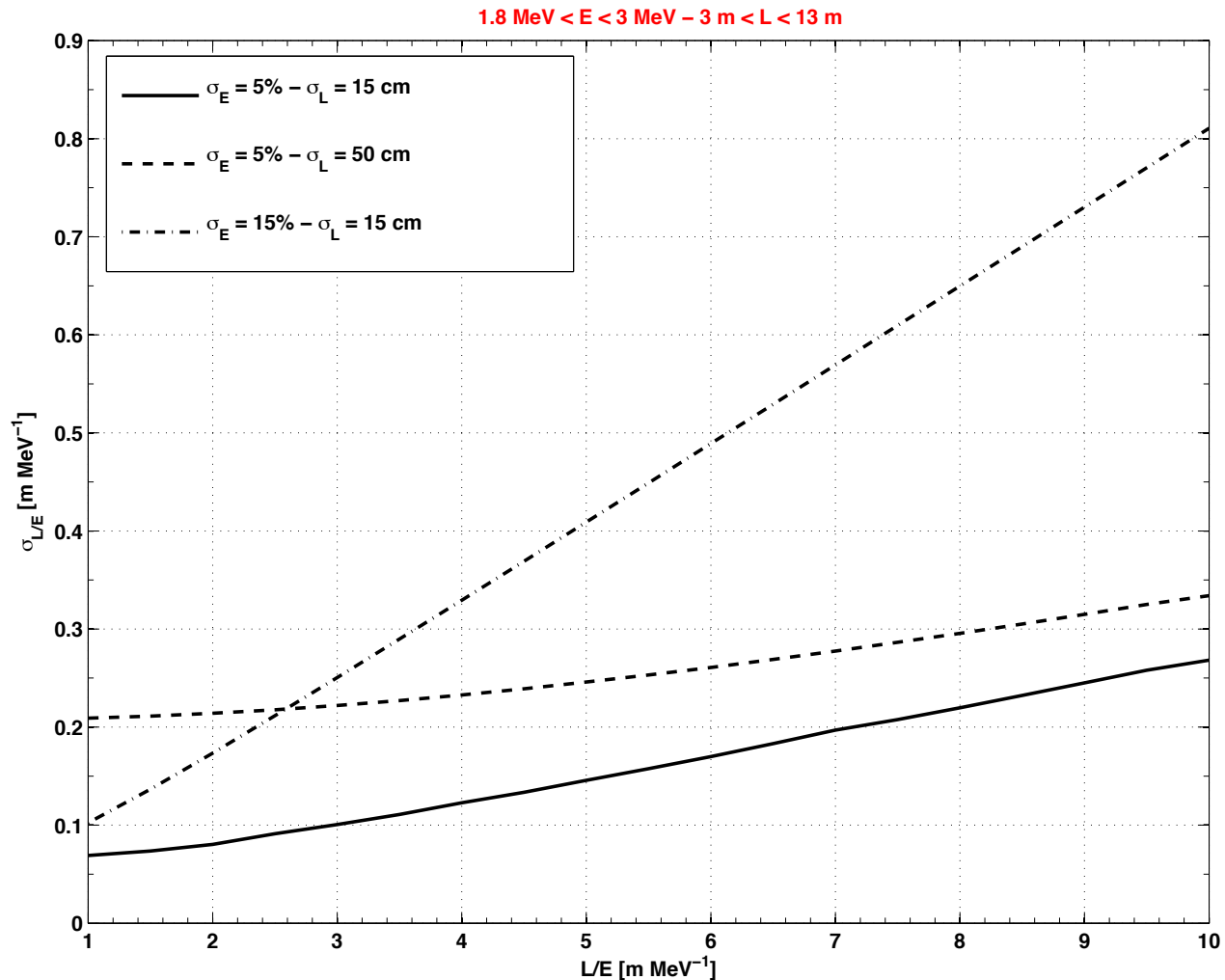


Model ingredients: L/E resolution functions



Model ingredients: L/E resolution

- Width of L/E resolution as a function of L/E:



Number of expected IBD candidates

CeSOX – $R < 4.25$ m

Distance/ Activity	75 kCi	100 kCi	140 kCi
6 m	14230	18970	26580
8.25 m	7060	9410	13180
12 m	3230	4310	6030

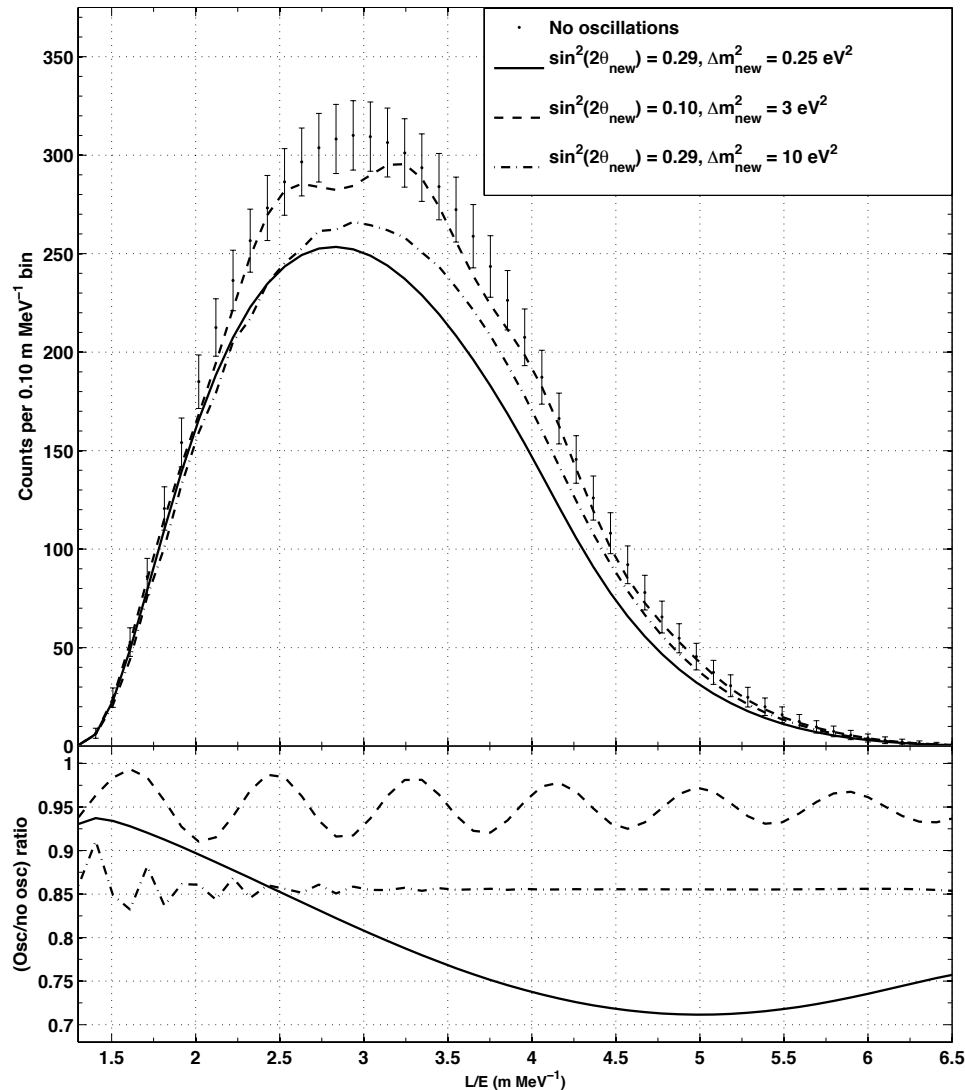
CeSOX nominal

CeSOX – $R < 5.5$ m

Distance/ Activity	75 kCi	100 kCi	140 kCi
6 m	35220	47040	65650
8.25 m	16040	21370	29940
12 m	7140	9520	13320

CeSOX upgraded

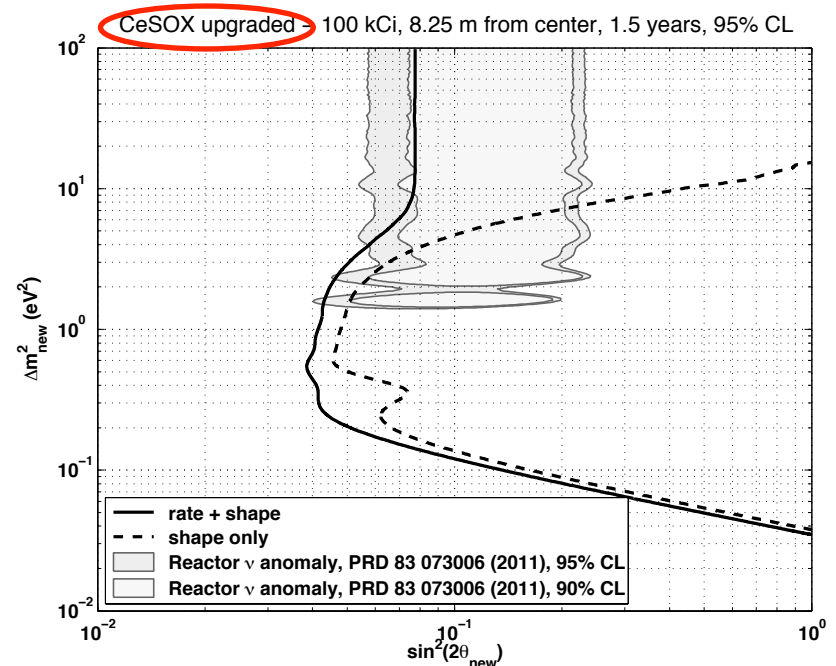
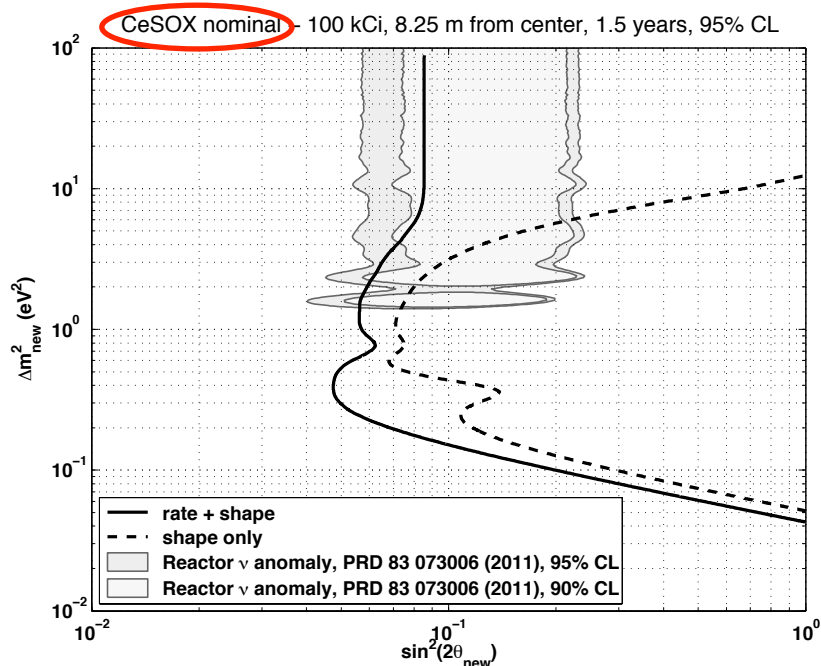
L/E spectrum expected in Borexino



- Statistical error bars only
- Average L/E is around 3.2 m MeV⁻¹: corresponds to resolution of 0.1 m MeV⁻¹
- Exponential damping of oscillations because of detector resolution
- Small Δm^2 ($\leq 0.5 \text{ eV}^2$) hardly visible because of detector size, unless mixing is large
- Good for intermediate Δm^2 (0.5 – 5 eV²)
- High Δm^2 oscillations averaged because binning size > oscillation length + exponential damping: hardly visible unless large mixing angle

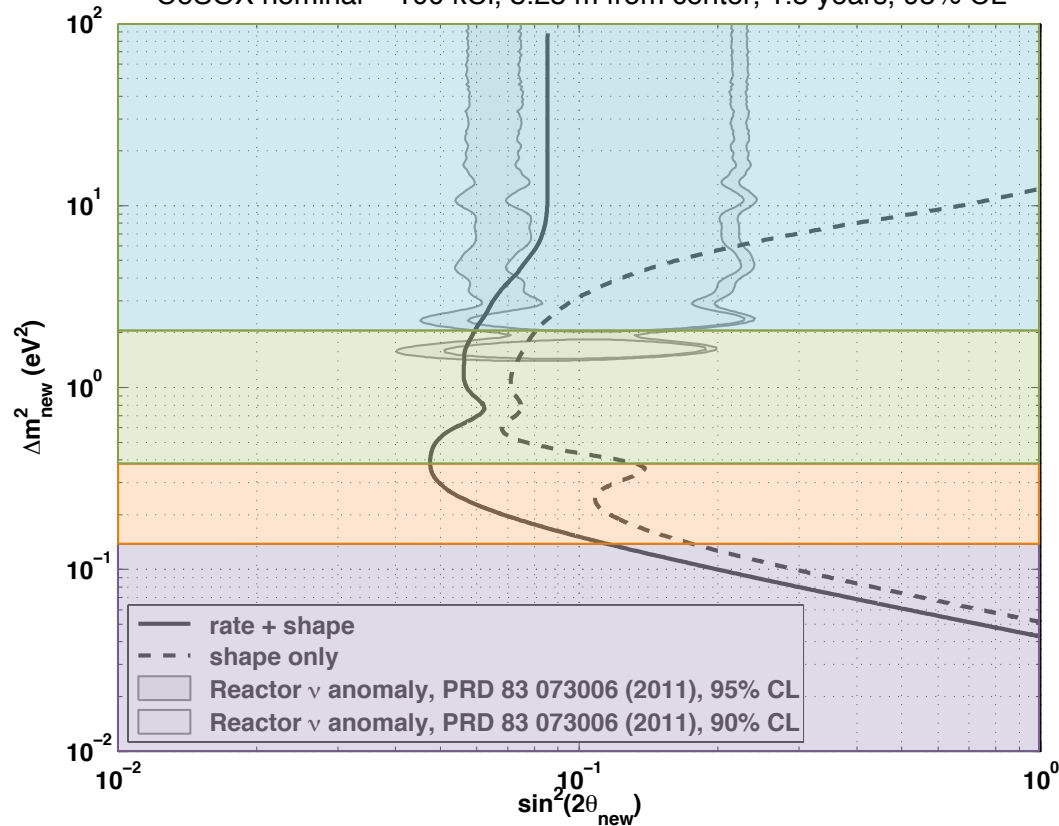
CeSOX χ^2 sensitivity

- Take 0.2 m MeV⁻¹ bins (twice L/E resolution)
- Compute sensitivity to « no oscillation » hypothesis, according to χ^2 formula shown previously
- $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ follows χ^2 distribution with 2 dof
- In next slides, chose 95% CL, $\Delta\chi^2 = 6$
- Reminder:** χ^2 contours are statistically averaged contours. If we perform N realizations, allowing for statistical fluctuations, the average of obtained contours must give the contour displayed on sensitivity plots.



CeSOX contours features

CeSOX nominal – 100 kCi, 8.25 m from center, 1.5 years, 95% CL



Sensitivity to oscillations is degraded because of exponential damping + size of oscillations $<$ binning size. Compensated by rate information: $P \approx 1 - \frac{1}{2} \sin^2(2\theta)$

Detector contains more than 1 oscillation period, best performances are here.

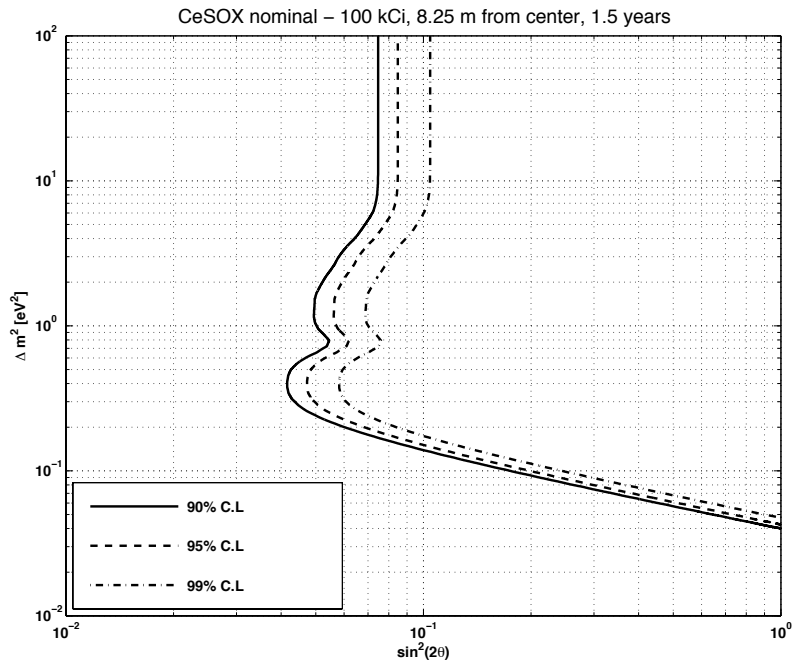
L_{osc} comparable to detector size, but still less than 1 oscillation period is contained in the detector.

L_{osc} much bigger than detector size
 $P \approx 1 - \alpha \sin^2(2\theta) \Delta m^2$

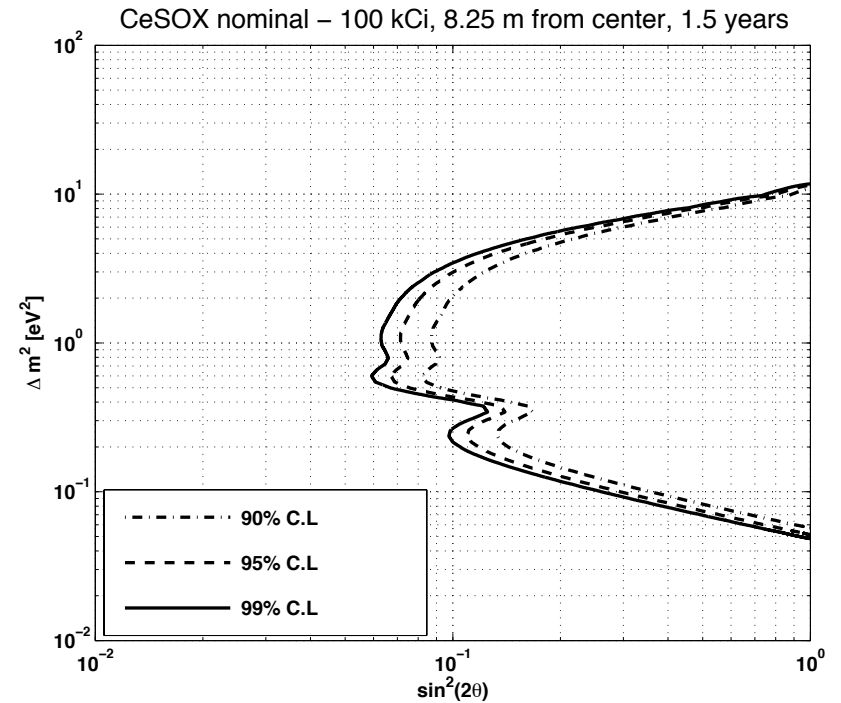
Different confidence levels

- With different confidence level @ 90, 95 and 99 %:

Rate + shape

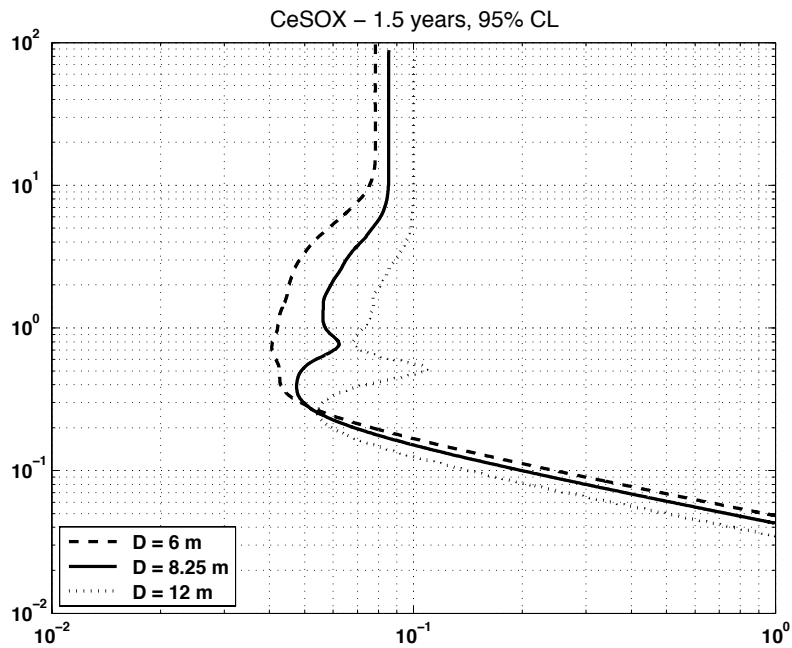


Shape only

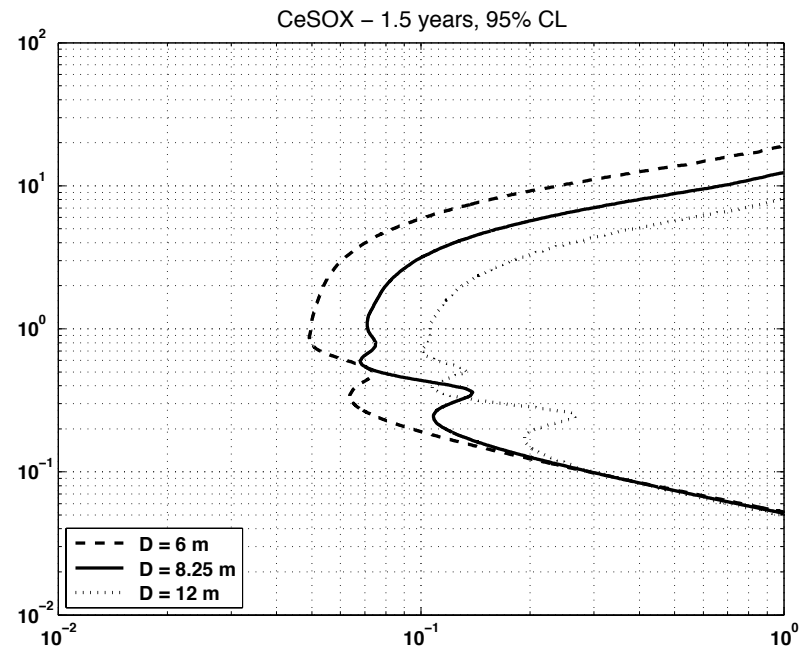


Impact of source-detector distance

Rate + shape



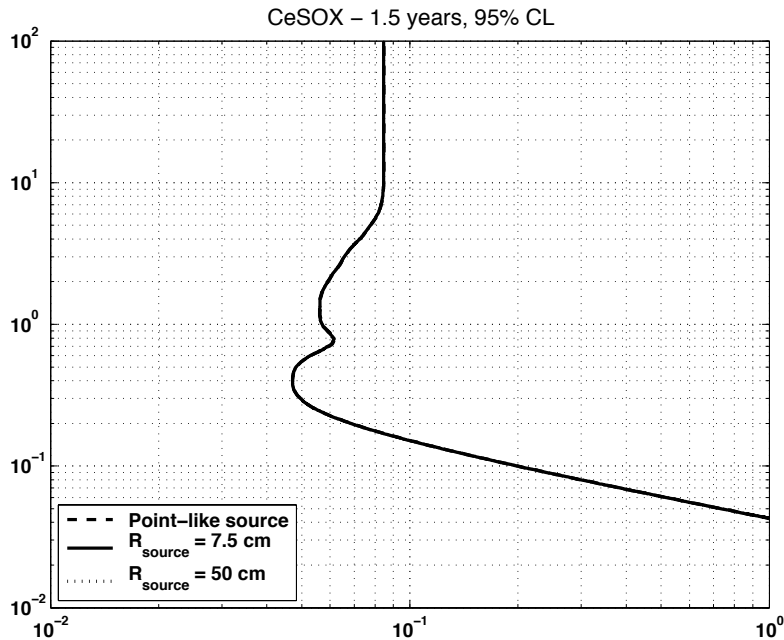
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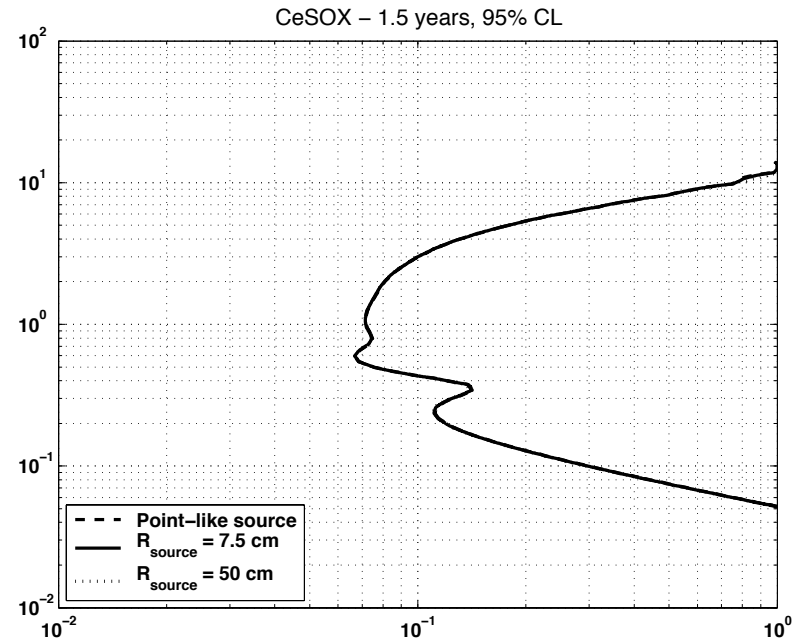
Impact of source extension

- Take a spherical source and increase radius:

Rate + shape



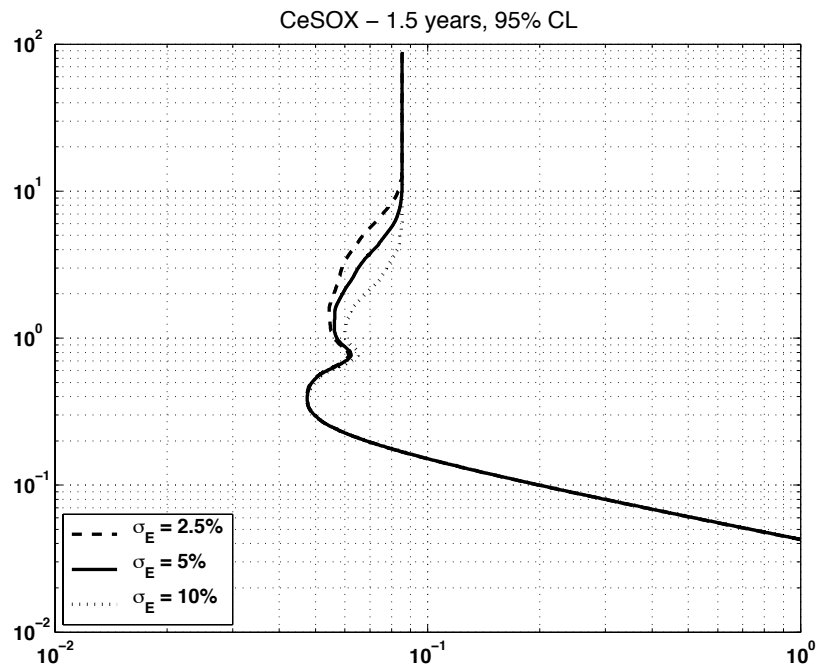
Shape only



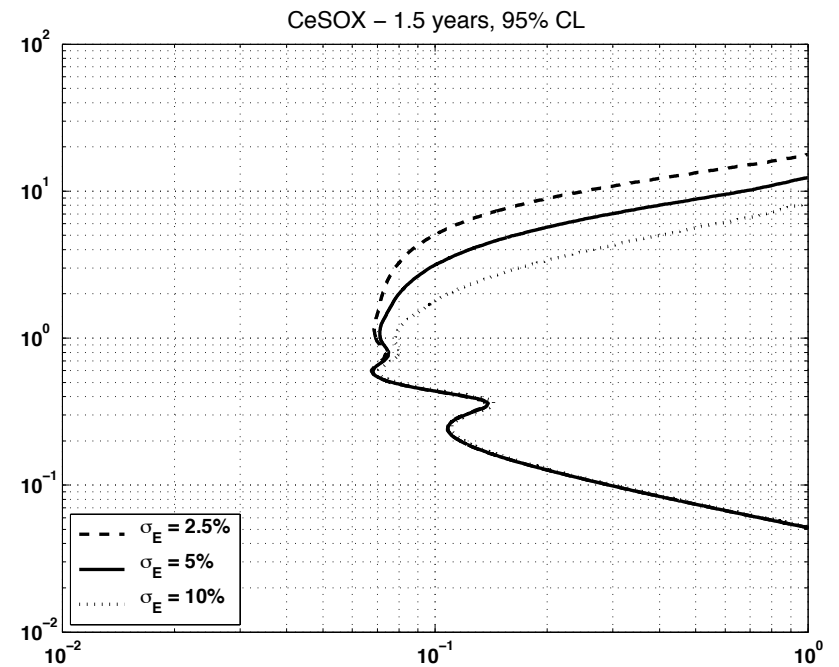
- Source extension doesn't make any differences...

Impact of energy resolution

Rate + shape

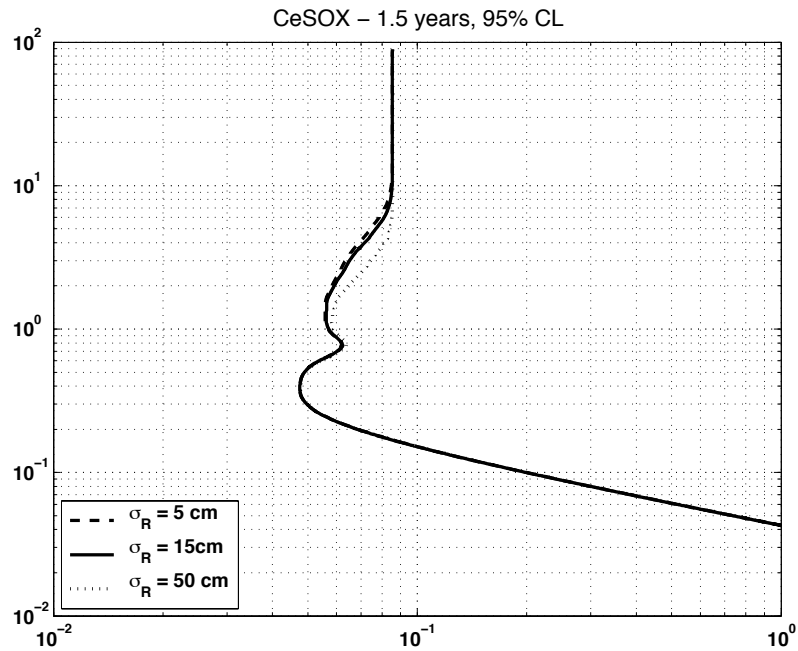


Shape only

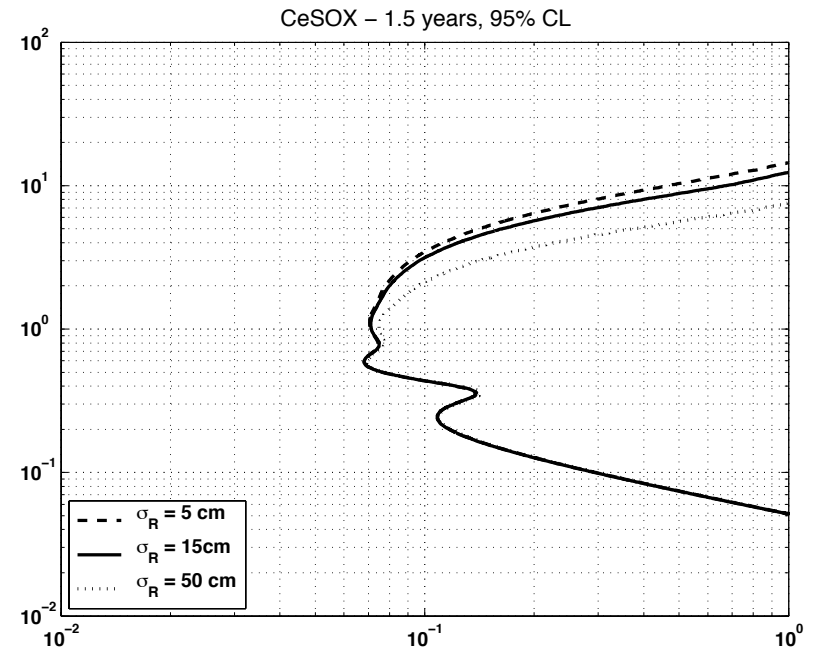


Impact of position resolution

Rate + shape

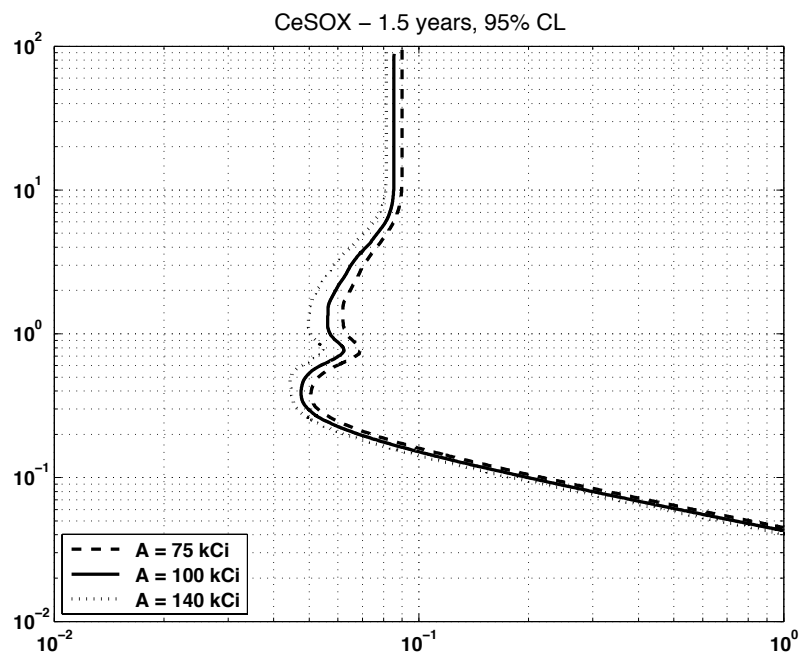


Shape only

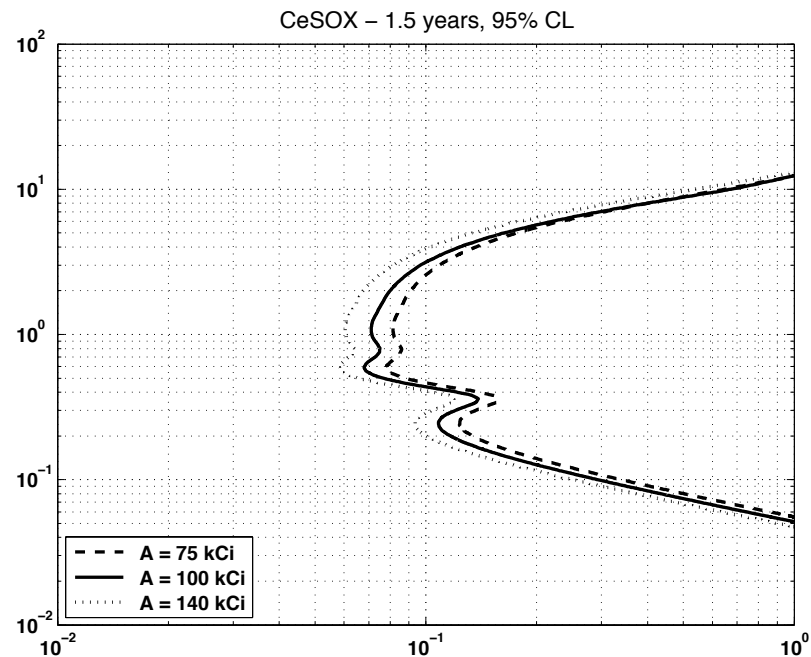


Impact of source activity

Rate + shape

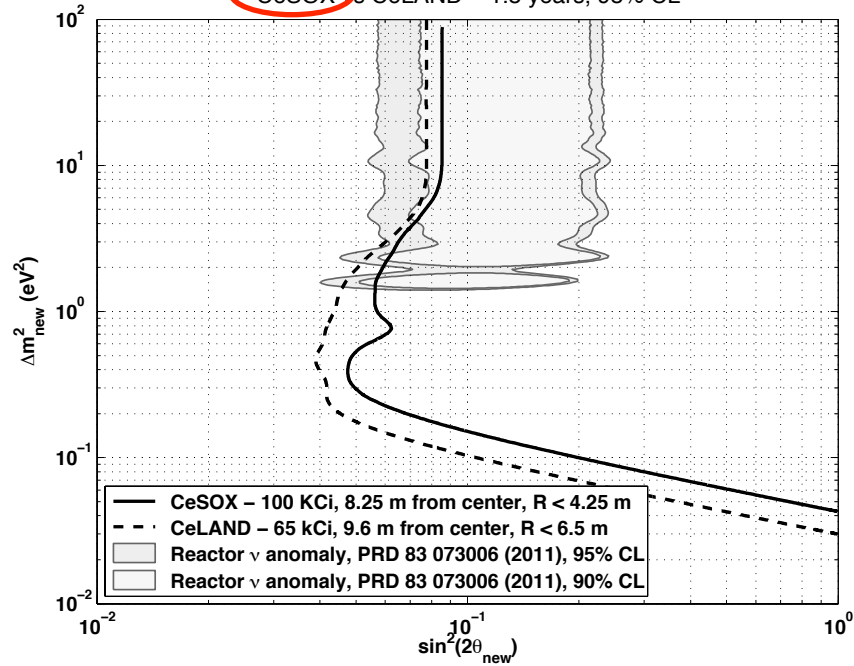


Shape only

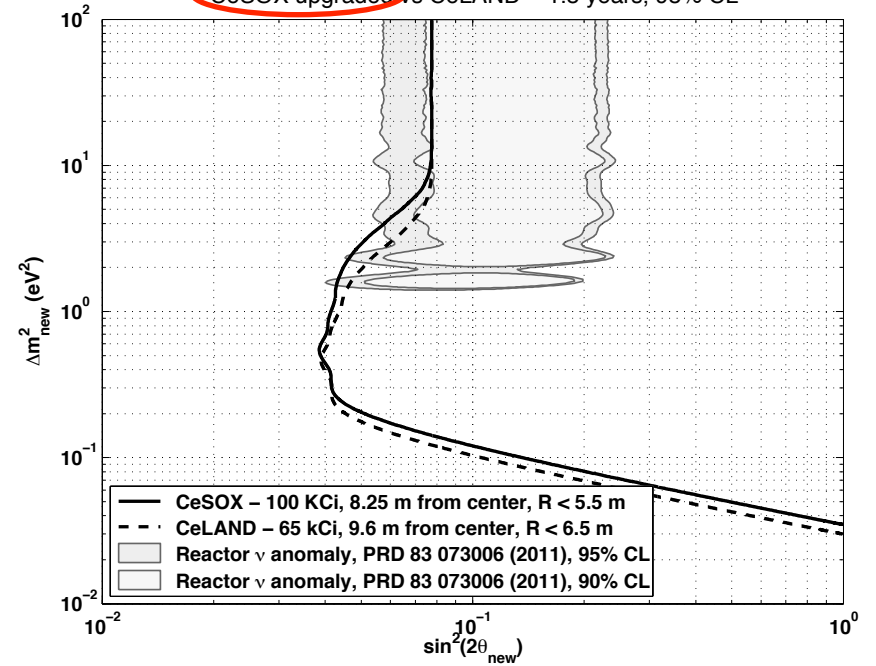


CeSOX vs CeLAND

CeSOX vs CeLAND – 1.5 years, 95% CL

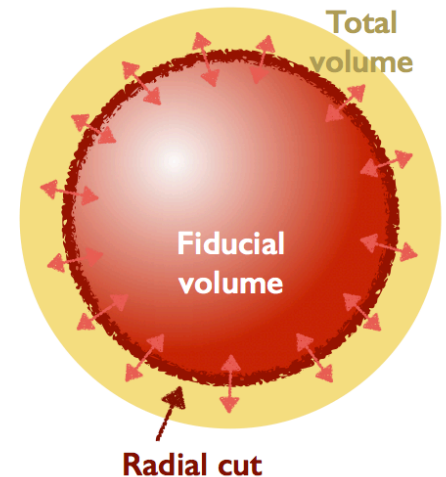


CeSOX upgraded vs CeLAND – 1.5 years, 95% CL



Conclusions

- Competitive limits with CeSOX nominal scenario. Most of the anomaly parameter space is covered at 95% C.L.
- Very good limits with upgraded Borexino detector: better than KamLAND taking into account the transport constraints (higher activity is achievable if deploying at Borexino).
- Contours more sensitive to energy resolution than vertex resolution.
- Source extension does not impact the sensitivity
- Other systematic uncertainty studies ongoing...
 - Effect of fiducial volume uncertainty (what is the fiducial volume uncertainty in Borexino?)
 - Effect of a « radius scale » uncertainty? (Is there any systematic bias associated to the vertex reconstruction in Borexino?) – KamLAND collaboration claimed one in their volume calibration paper (Berger et al. (2009)).
 - Effect of an energy scale uncertainty? (What is the energy scale uncertainty in Borexino?)
 - Any backgrounds systematics that we should include in the sensitivity study? Strongly depends on source impurities content...



Backup slides

KamLAND systematic bias in position reconstruction

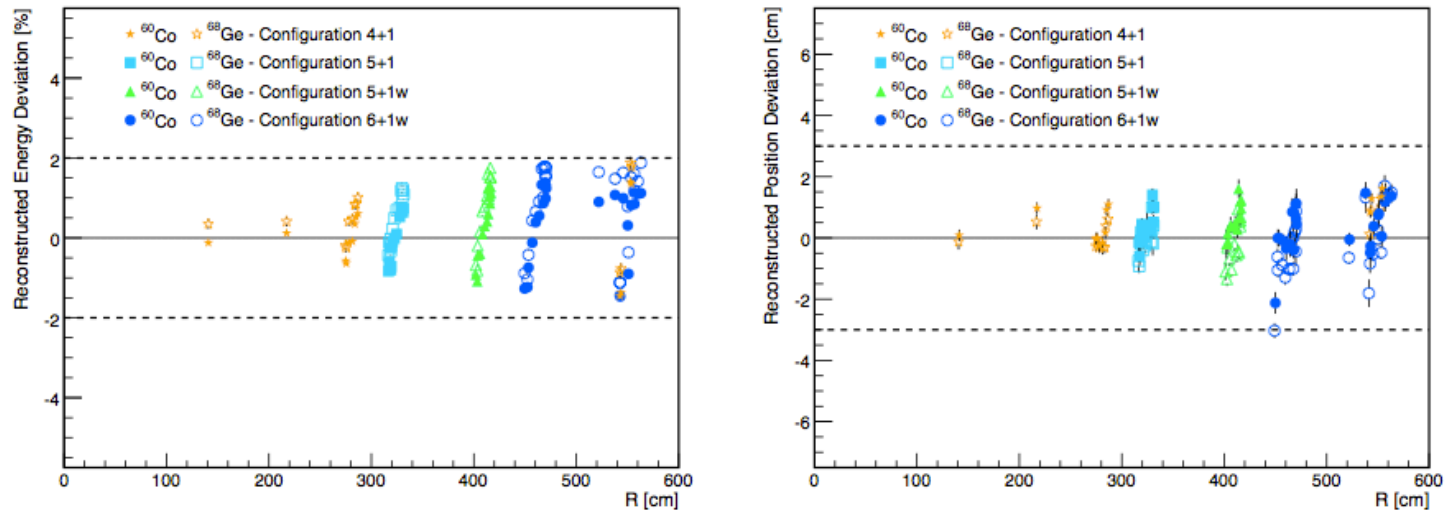


Figure 22. The measured reconstruction deviations as a function of detector radius: The energy deviations were found to be less than 2% (left). The radial position deviations are less than 3 cm (right). The different points correspond to a given pole configuration as follows: yellow stars (4+1), cyan squares (5+1), green triangles (5+1W), blue squares (6+1W). The data with filled points were measured at the 2.506 MeV peak of ^{60}Co . The data with hollow points were measured at the 1.022 MeV annihilation gamma peak of ^{68}Ge .

From Berger et al. (2009): « The KamLAND full-volume calibration system »