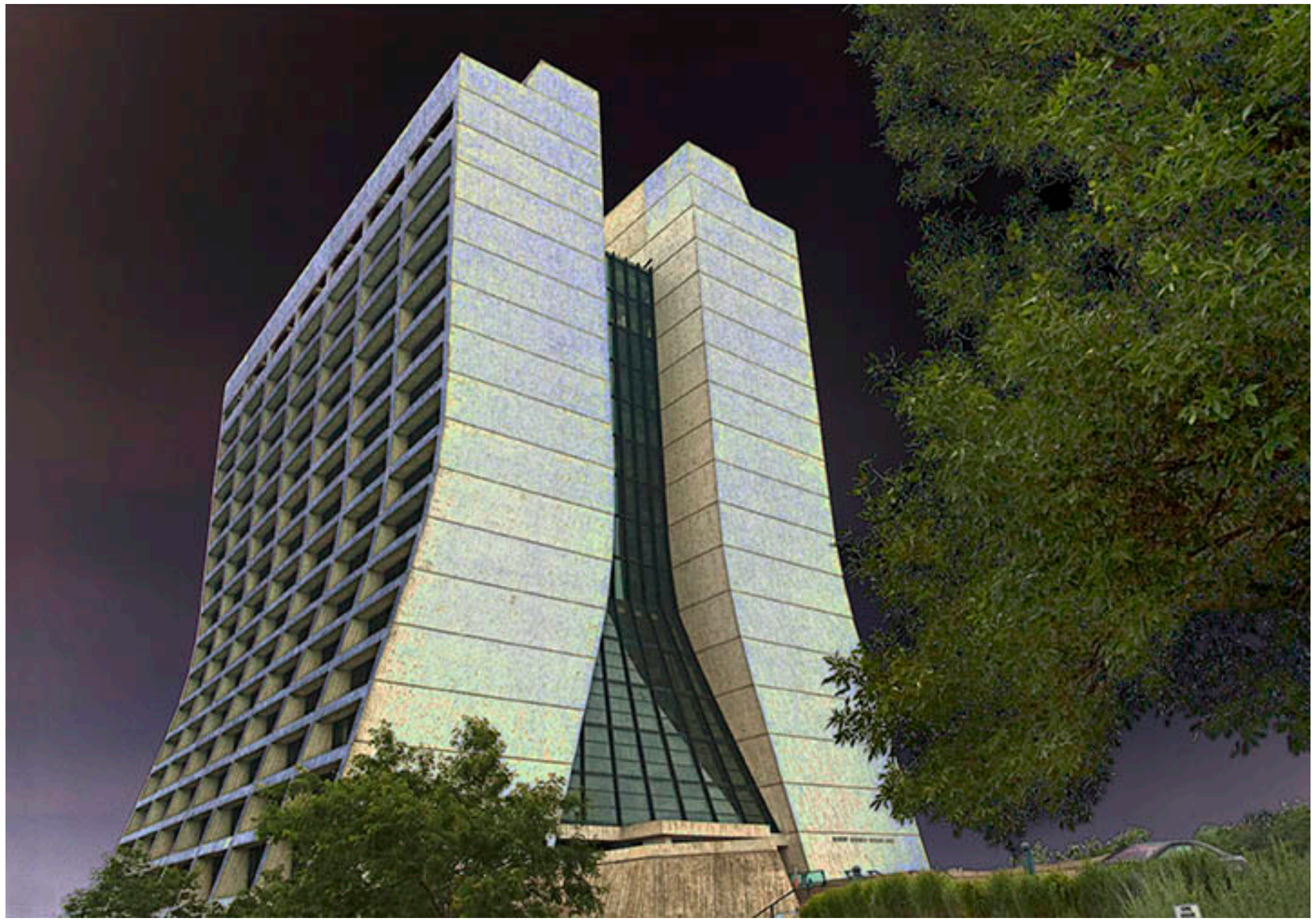
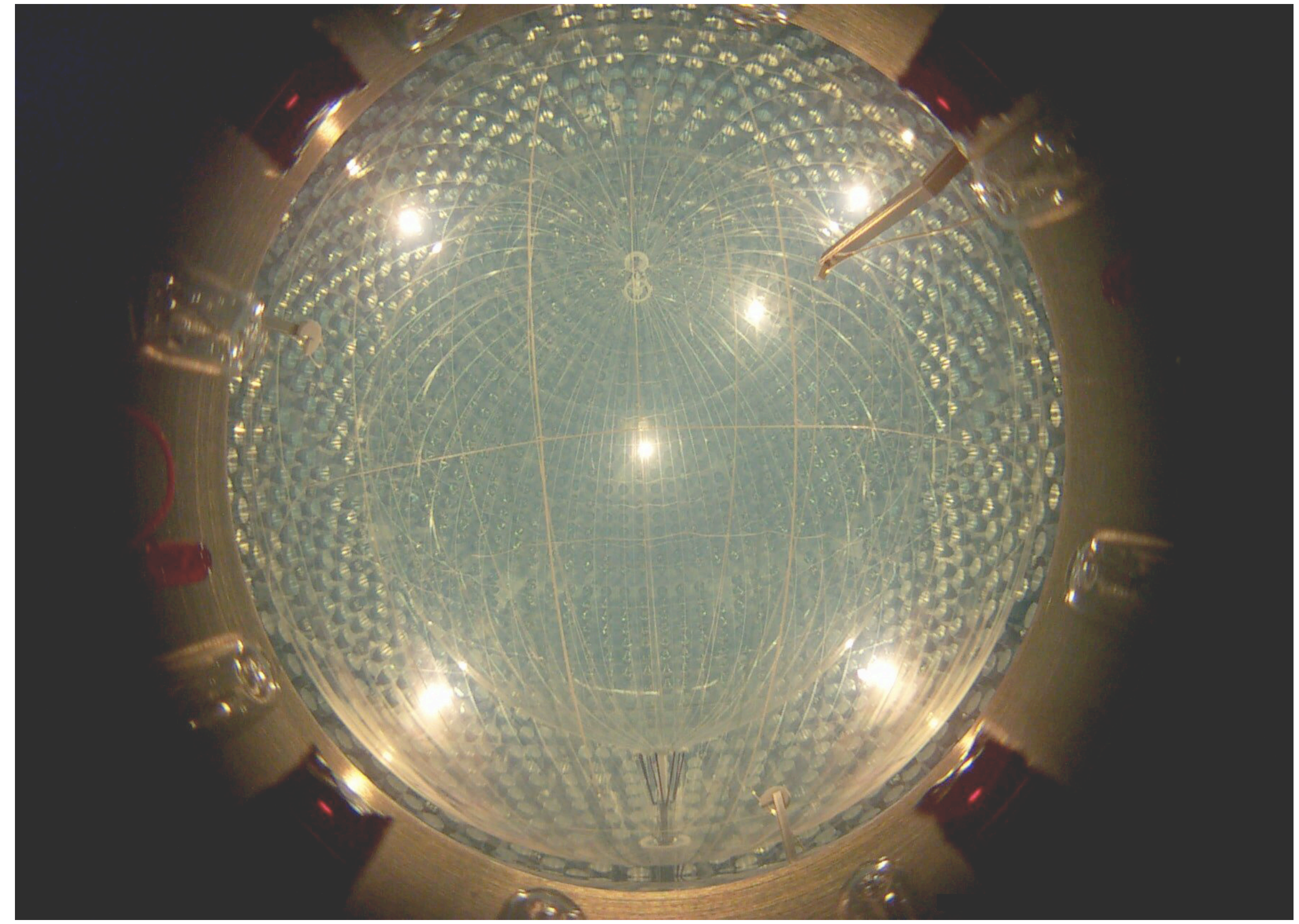




Short base-line ν_e and $\underline{\nu}_e$ oscillations with Borexino

Marco Pallavicini
on behalf of the Borexino Collaboration

FNAL, May 12th-14th, 2011

Talk content

- Short baseline **neutrino anomalies**
- Main features of the **Borexino** experiment
- Why Borexino can be a **powerful tool** to search for short base line electron **neutrino** and **anti-neutrino** disappearance
- Possible neutrino **sources**
- **Sensitivity** of a full program with Borexino
- Sketch of a possible **time schedule**

Introduction

- The possibility to study **neutrino properties** using powerful **radioactive sources** in Borexino has been considered since the 1991 proposal

G. Bellini and R. Raghavan Ed. - 1991

  - At that time, mainly to measure neutrino magnetic moment, calibration and search for possible non-standard interactions: ^{90}Sr, ^{51}Cr mentioned explicitly.

- Recent experimental results have strongly revived this line of research (and triggered a quite impressive flux of papers…):

  - The "Gallium" Anomaly **hep/ex: 1001.2731v1**
  - The "Reactor" Anomaly **hep/ex: 1101.2755v1**
  - The "LSND-MiniBoone" Anomaly (ies ?) **PRD64 112007,2001, PRL 102 101802 (2009), PRL105 181801 (2010)**
  - Indications from Cosmology of more than 3 neutrinos: **astro/ph: 1009.0866v1**
  - Hints of CPT violation from Minos **hep/ex: 1104.0344v2**

- In this talk I will show the result of a very **preliminary** work about the **Borexino sensitivity** with neutrino and anti-neutrino **sources** located **near and inside the detector**

Anomalies

- Fully covered in this workshop, I do not recall them

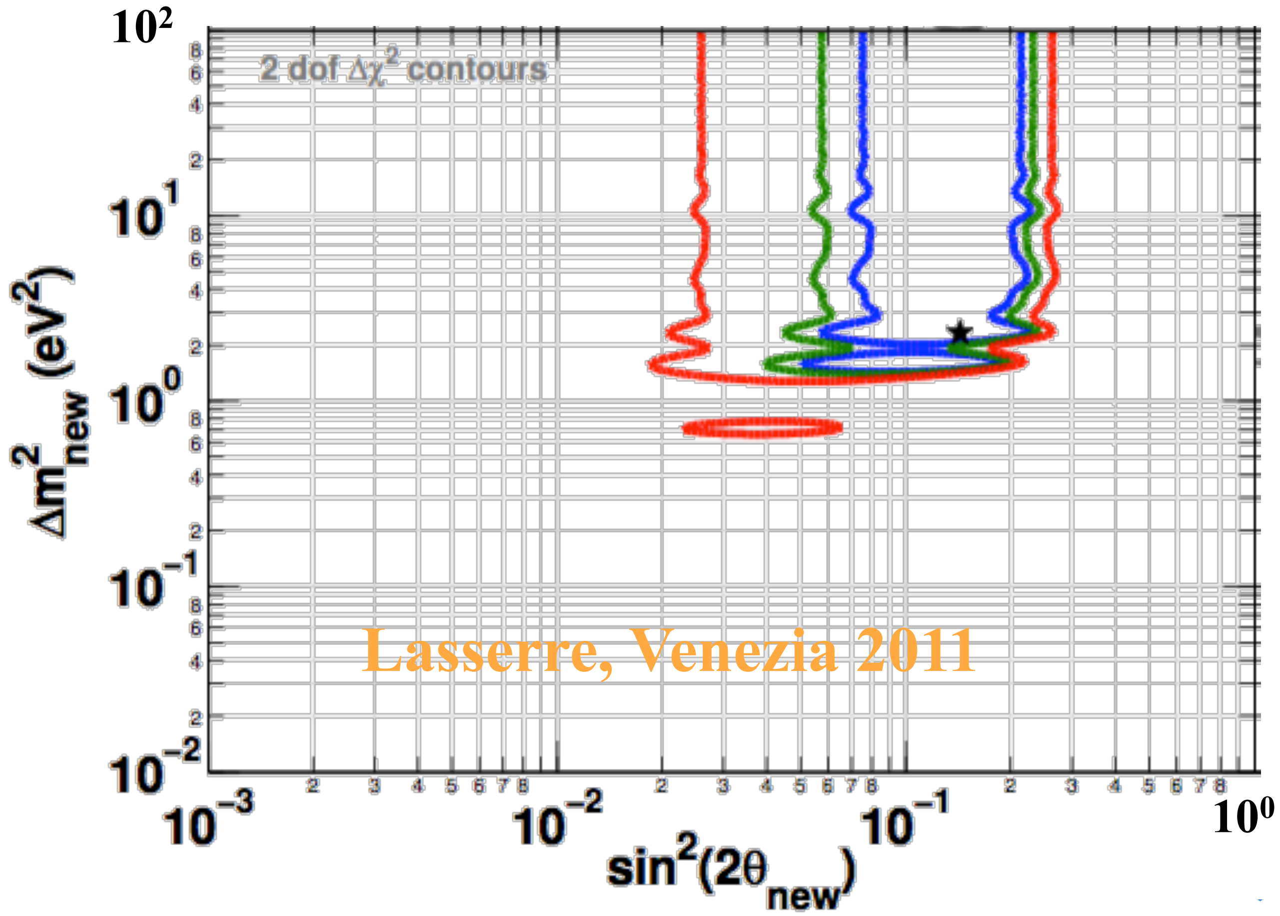
  - The important thing to remember is the order of magnitude of the best fit parameters:

$$\Delta m^2 \approx 1\ eV^2 \qquad \sin^2(2\vartheta_s) \approx 0.1$$

yields, with neutrinos of **energy ≈ 1 MeV, oscillation lengths of the order of 1 m**

  - This is significantly **more that the spatial resolution** of reconstructed events in Borexino **(≈12 cm @ 1 MeV)** and, at the same time, significantly smaller than the detector size (**6.6** m or **9.0 m** or even **12 m**)

    - Oscillations with this parameters might be **SEEN** clearly with a source experiment



The Borexino experiment

- I will just recall the key features relevant for this program.

- Borexino was designed to detect low energy solar neutrinos
  - **~270 t** of **ultra-pure liquid scintillator, shielded against external background**
  - **proved capability** to detect **mono-chromatic neutrino lines below 1 MeV** (see ^{7}Be measurements) and **anti-neutrinos** (geo-neutrinos detection)

- The first phase of the experiment is over:
  - Precision measurement of the ^{7}Be solar neutrinos **hep-ex/1104.1816v1 (sent to PRL)**
  - Absence of day-night asymmetry and global analysis **hep-ex/1104.2150v1**

- **Purification are in progress** for another solar neutrino run with higher sensitivity and hunting for other solar neutrino components
  - **pep, pp, CNO (?)**
  - Solar neutrino phase possibly over in **3 years from now**

The Borexino collaboration

Genova

Milano

Perugia

Princeton University

UMass Amherst (USA)

Virginia Tech. University

Hamburg (Germany)

Dubna JINR (Russia)

Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

Munich (Germany)

Heidelberg (Germany)

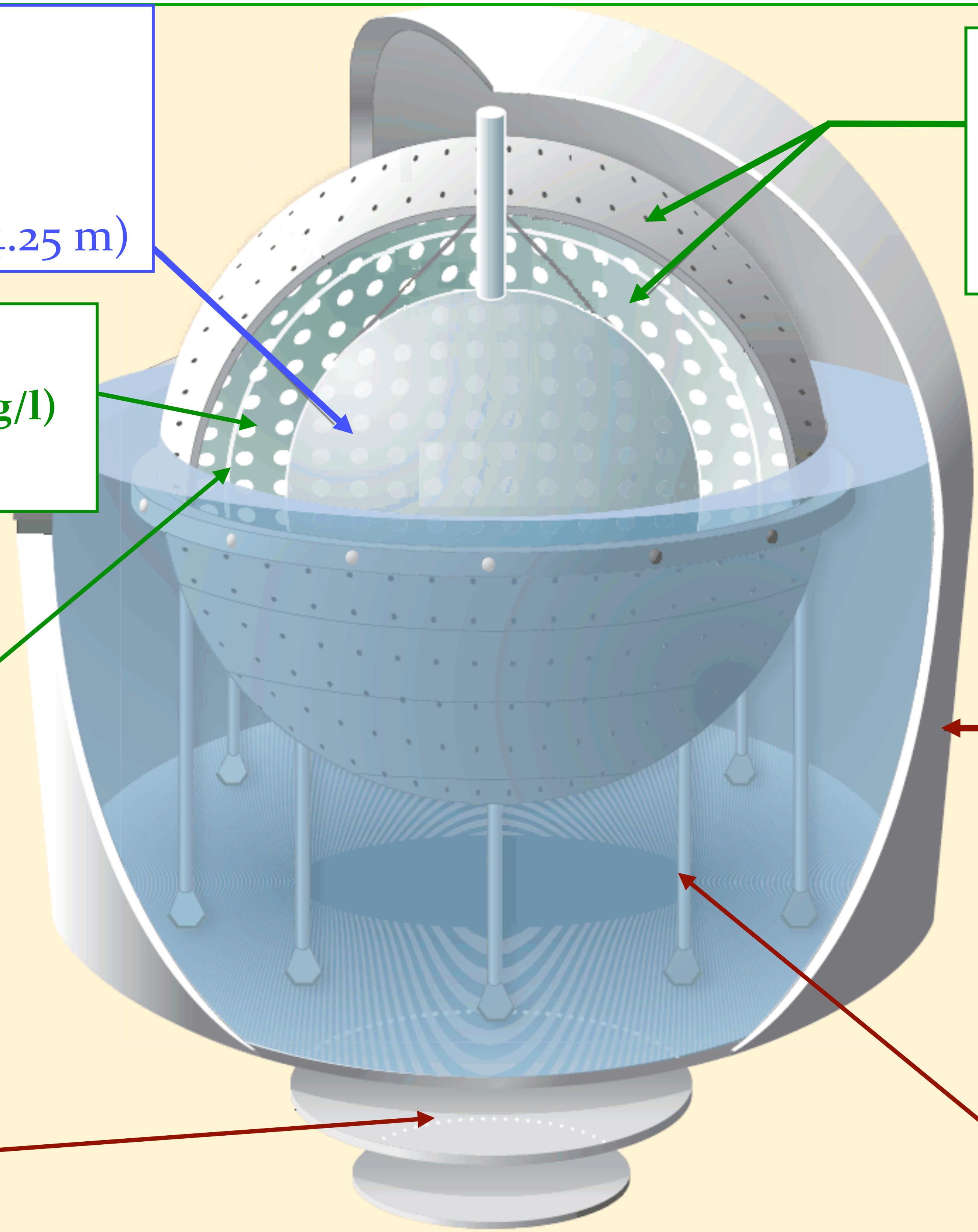
The Borexino detector

Scintillator:
270 t PC+PPO (1.5 g/l)
in a 150 μm thick
inner nylon vessel (R = 4.25 m)

Buffer region:
PC+DMP quencher (5 g/l)
4.25 m < R < 6.75 m

Outer nylon vessel:
R = 5.50 m
(^{222}Rn barrier)

Carbon steel plates

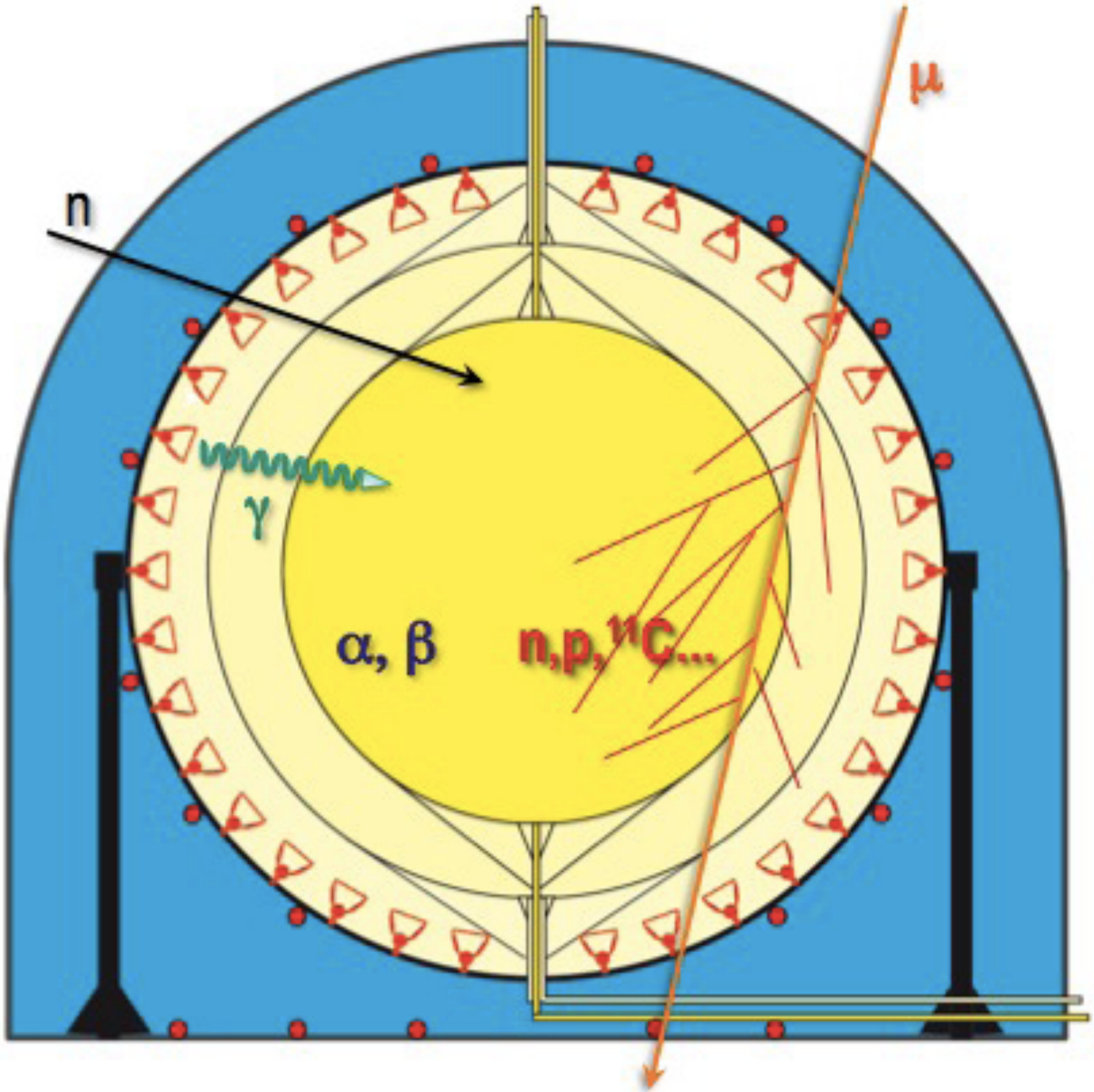


Stainless Steel Sphere:
R = 6.75 m
2212 PMTs
1350 m^3

Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

20 steel legs

The principle of graded shielding

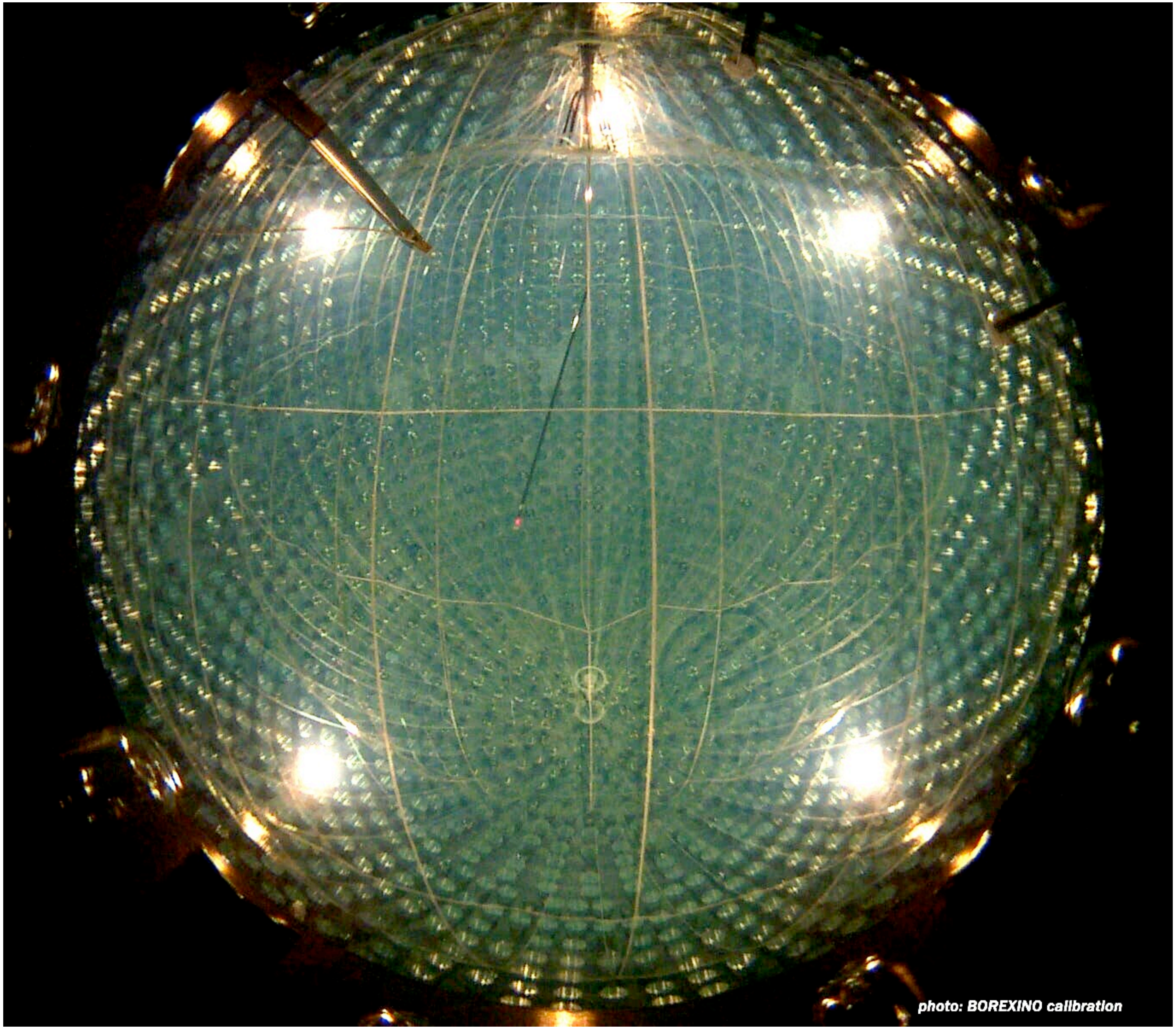


- **Materials** **more and more** **pure** as they get closer to the "core", the Fiducial Volume

- Ultimate background depending on material purity and, mainly, **radioactive traces** in the scintillator at extremely low levels

- **15 years of work to reach required radio-purity**

The detector

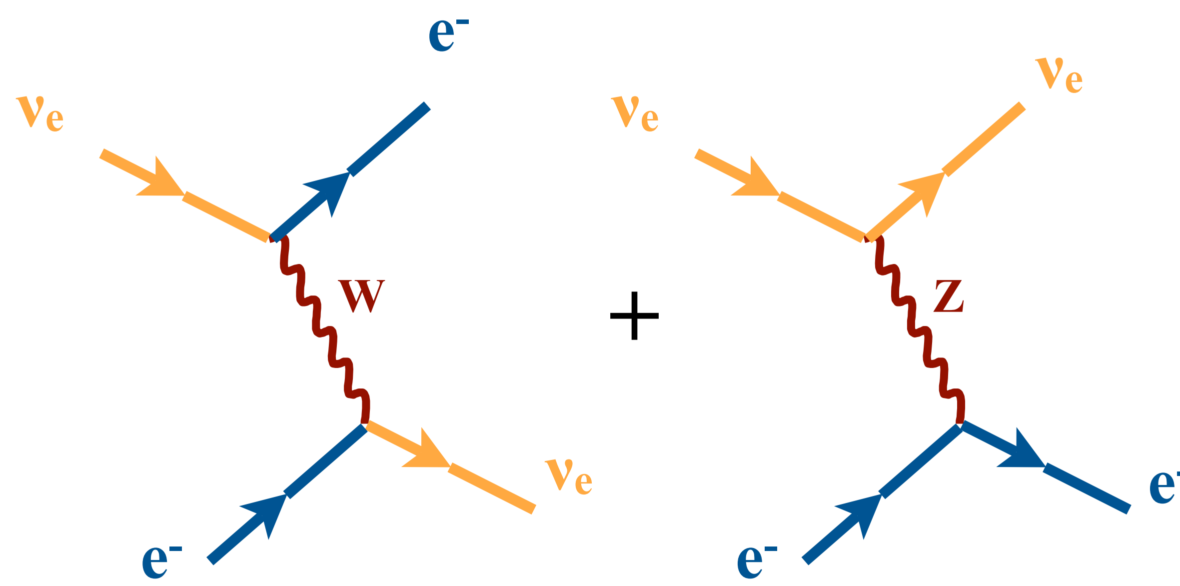


15 years of work in one slide

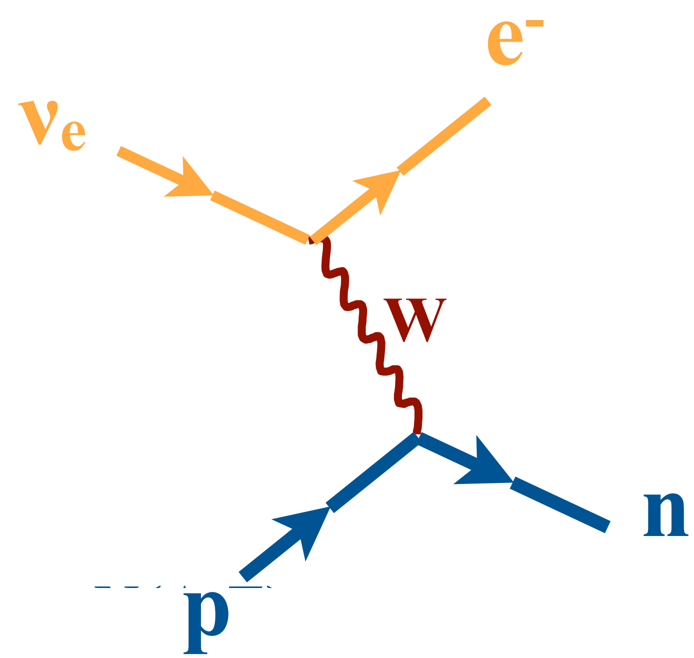
Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	**Achieved**
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	**<$10^{-10}$$s^{-1}$ m^{-2}**	underground water detector	Cerenkov PS analysis	< 10^{-10} eff. > 0.9992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	~10^{-12} g/g	~10^{-18} g/g	selection	threshold	~ 2 10^{-18} g/g
^{238}U **^{232}Th**	dust, metallic	10^{-5}-10^{-6} g/g	**<10^{-16} g/g**	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	**1.6±0.1 10^{-17} g/g** **5.1±1 10^{-18} g/g**
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	<10^{-6} Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	<10^{-18} g/g	distillation,W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		**<1 c/d/t**	distillation, W.E., filtration, cleanliness	fit	**May '07: 70 c/d/t** **Jan '10: ~1 c/d/t**
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	<10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	<1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	**< 1 cpd 100 t**	N_2 stripping	fit	**30 ± 5 cpd/100 t** **NOW: < 5 !**

ν_e and $\bar{\nu}_e$ detection in Borexino

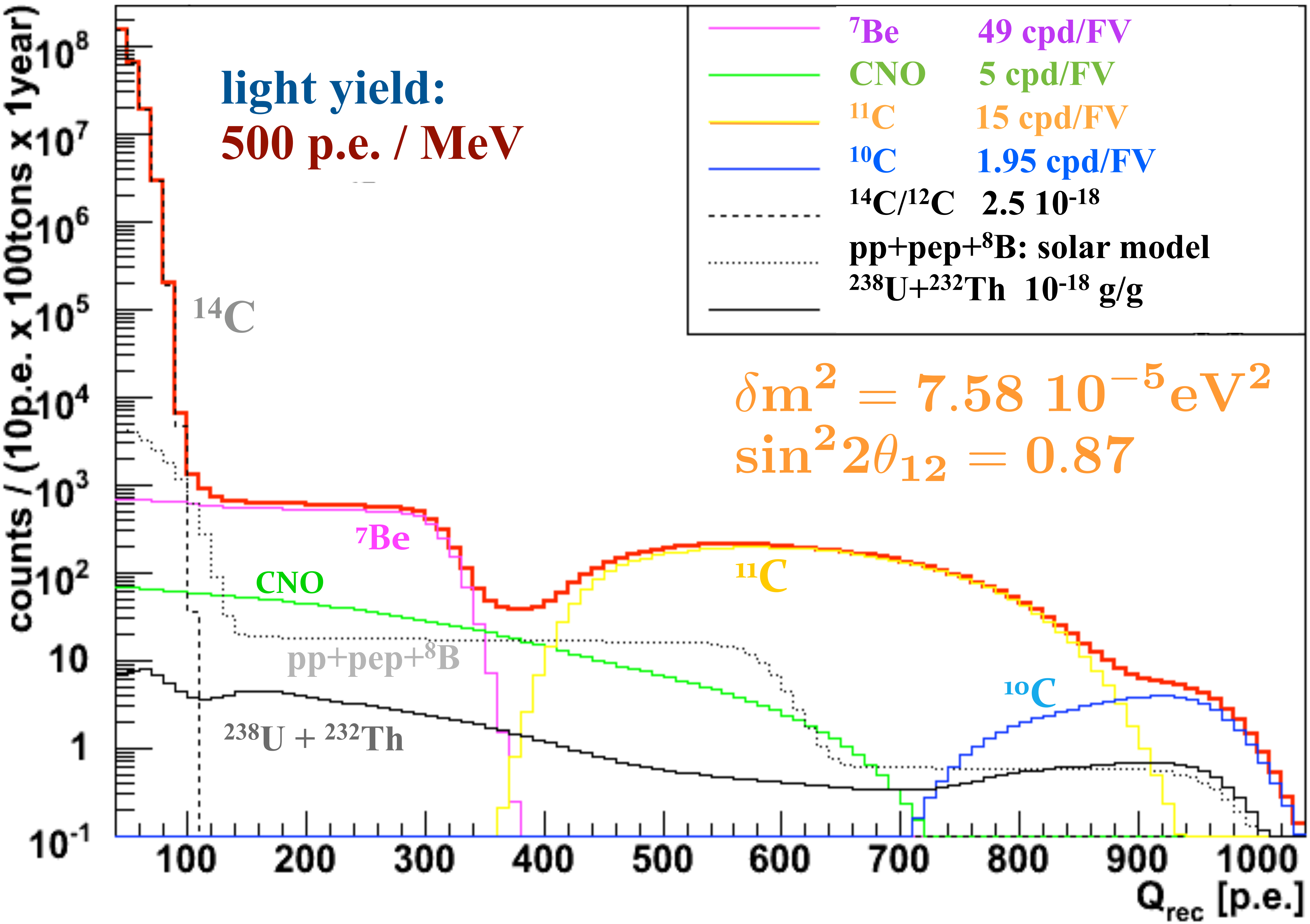
- **Electron neutrinos**
  - Elastic scattering on electrons
  - No directionality
  - Light yield: ≈ **500 p.e. / MeV**
  - Spatial resolution: ≈ **12 cm @ 1 MeV**
  - Powerful **α/β discrimination**
  - Background mainly due to ^{7}Be solar neutrinos !



- **Electron anti-neutrinos**
  - Inverse β decay on protons (E>1.8 MeV)
    - Clean fast coincidence
    - Elastic scattering on electrons not very useful
  - Essentially zero background in the inverse β decay mode



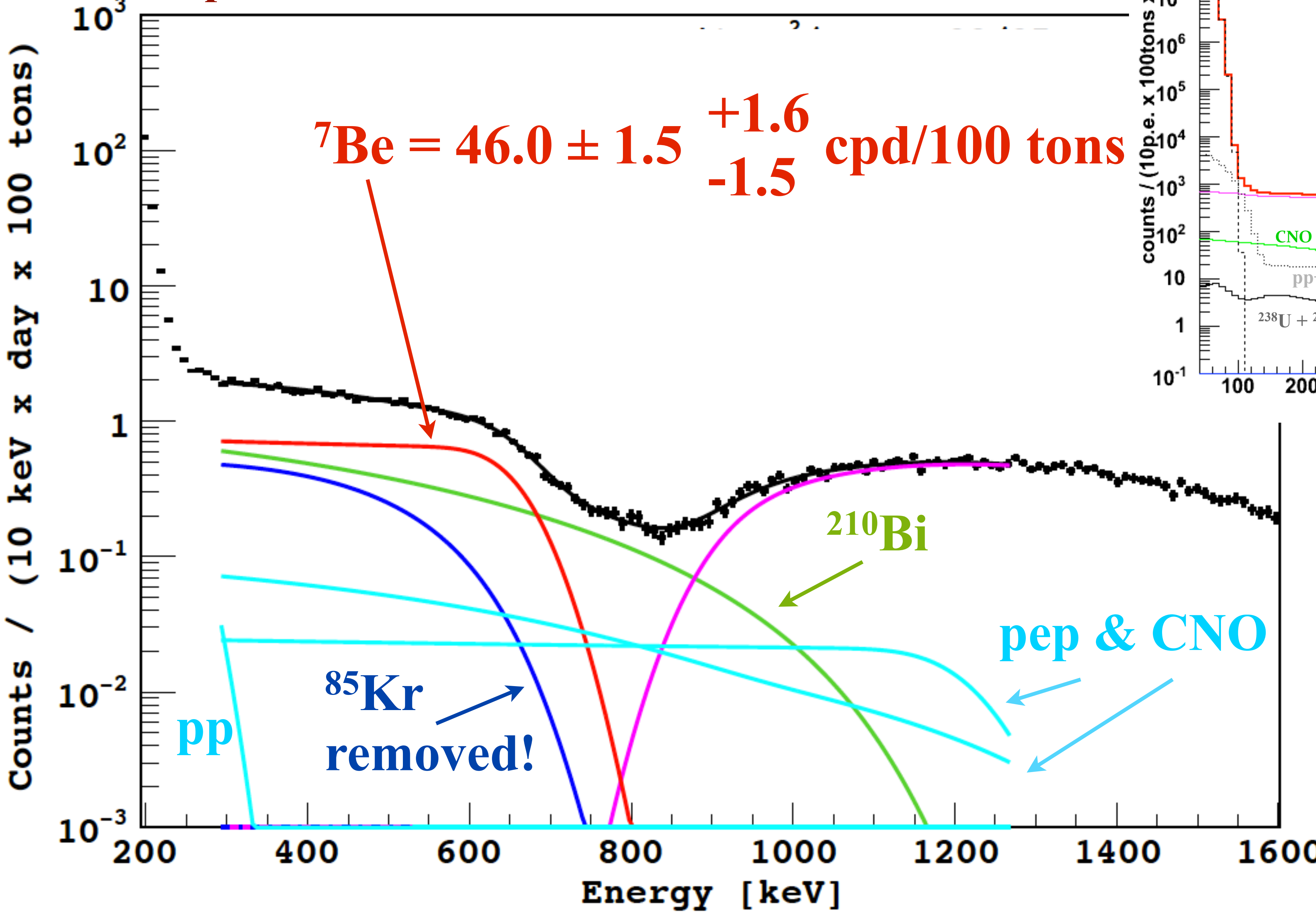
Expected signal in ideal conditions

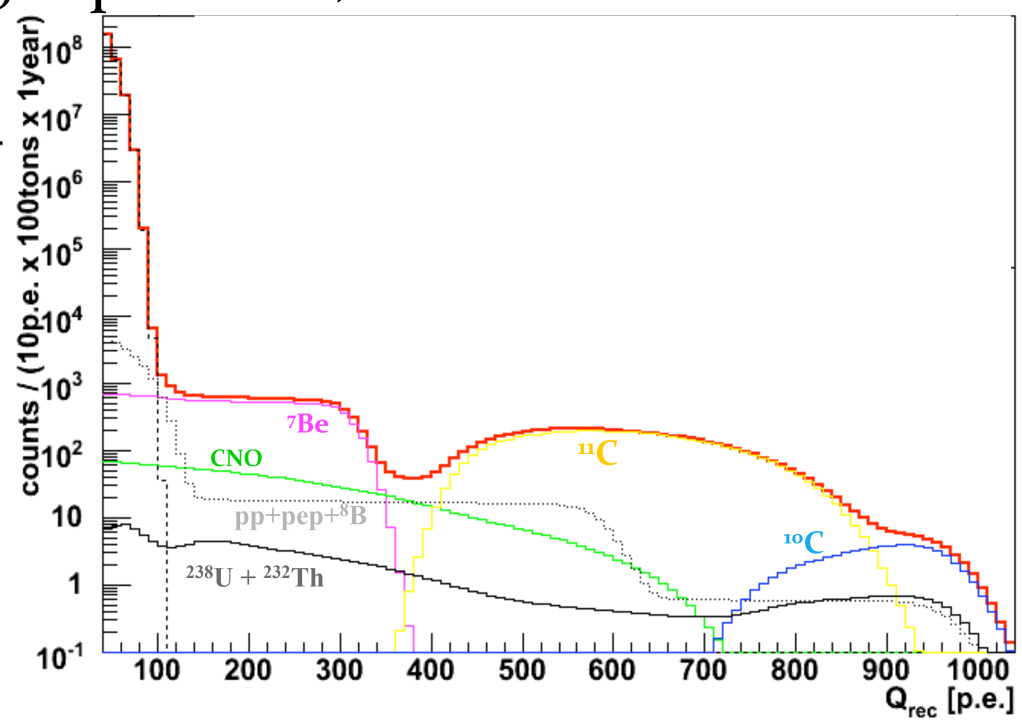


Cabability to detect low energy ν_e – I

- The main goal of the experiment is the **detection of ^{7}Be solar neutrinos**
  - This task was successfully completed this year with the precision measurement
  - A better measurement might possibly be done in the future after further purifications, but the current result is already exceeding design goals (5% precision)

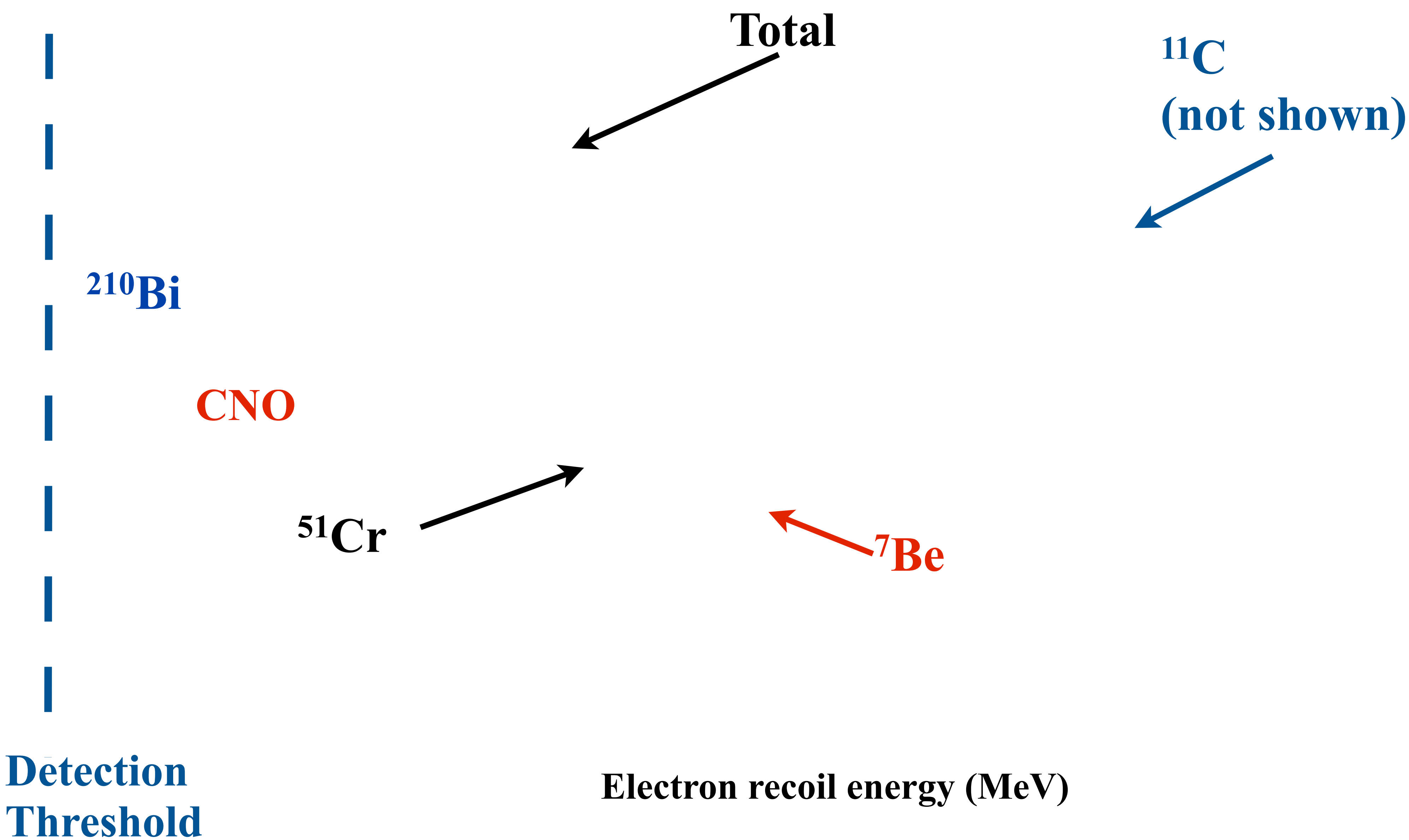
hep-ex/1104.1816v1





Capability to detect low energy ν_e – 2

- **7Be solar neutrinos** are mono-chromatic with energy **0.862 keV**
- **ν_e** from **k - capture radioactive sources** are also mono-chromatic, so the expected spectral shape is identical to ^{7}Be, **but shifted in energy**
  - EXAMPLE: **5 MCi ^{51}Cr** source: **84 ev/day** above detection threshold, **~ twice ^{7}Be**

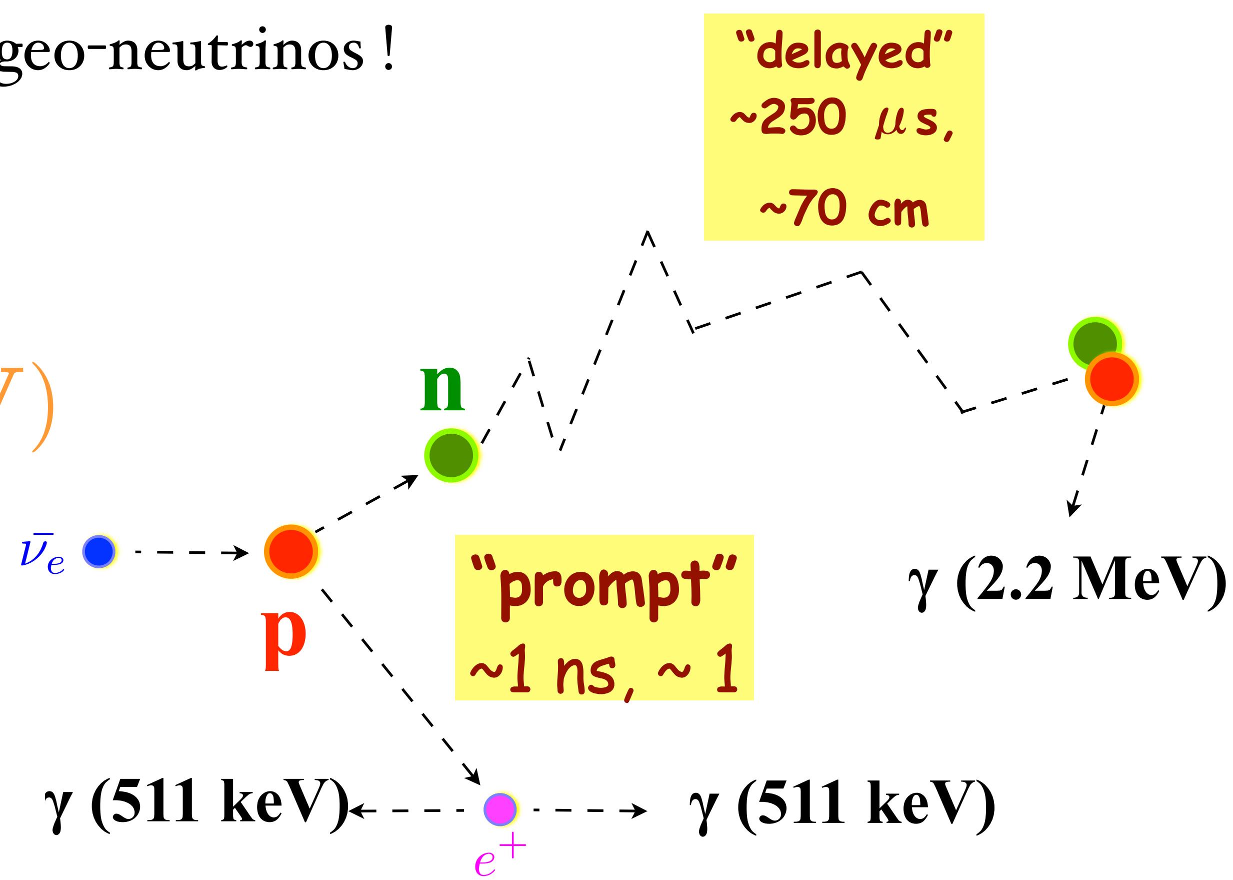


Capability to detect $\overline{\nu}_e$

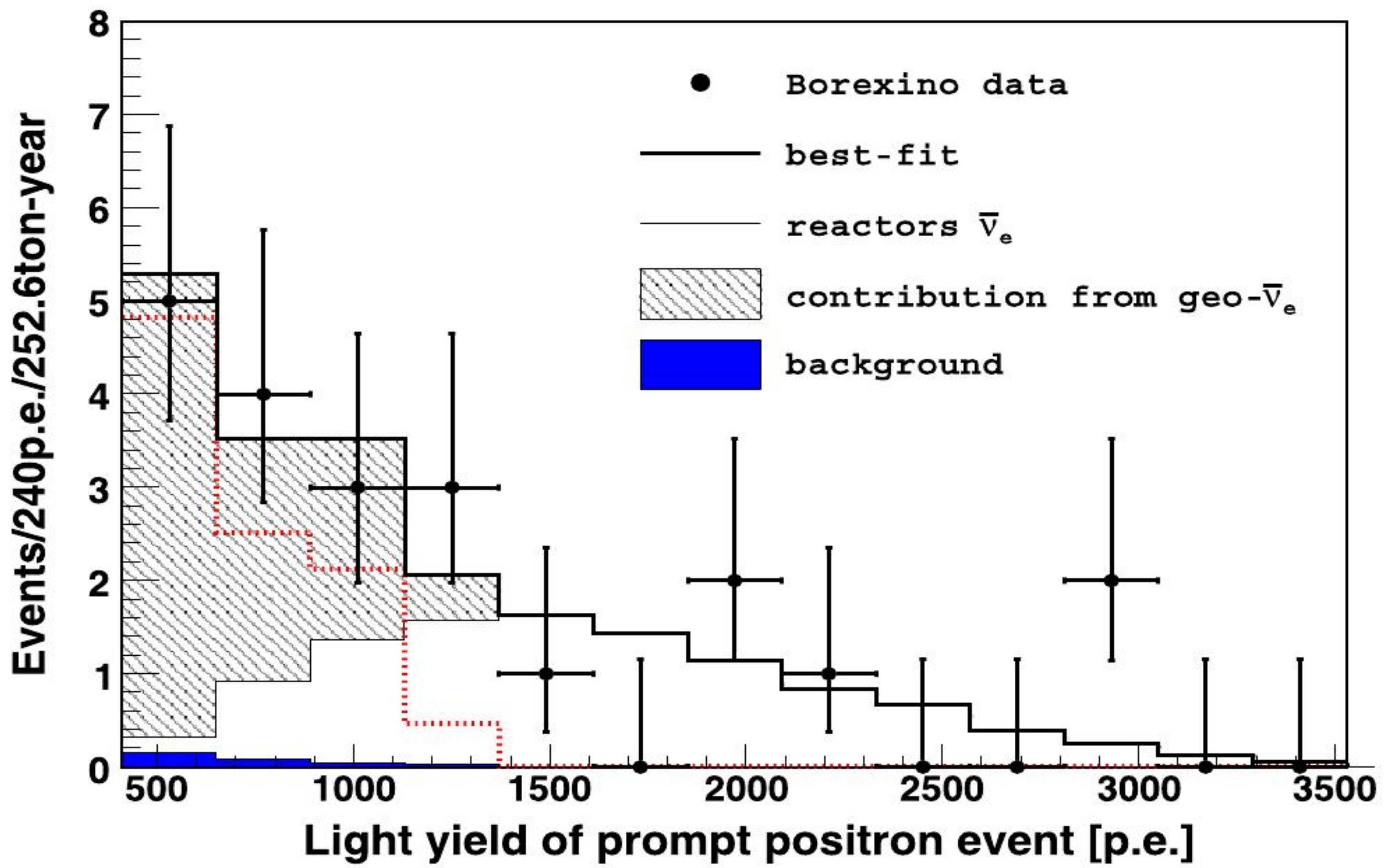
- Inverse β decay on protons yields a super-clean signature in Borexino
  - Background only from reactors in Europe and geo-neutrinos !

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

$$n + p \longrightarrow d + \gamma \ (2.226 \text{ MeV})$$



Phys. Lett. B687:299-304,2010



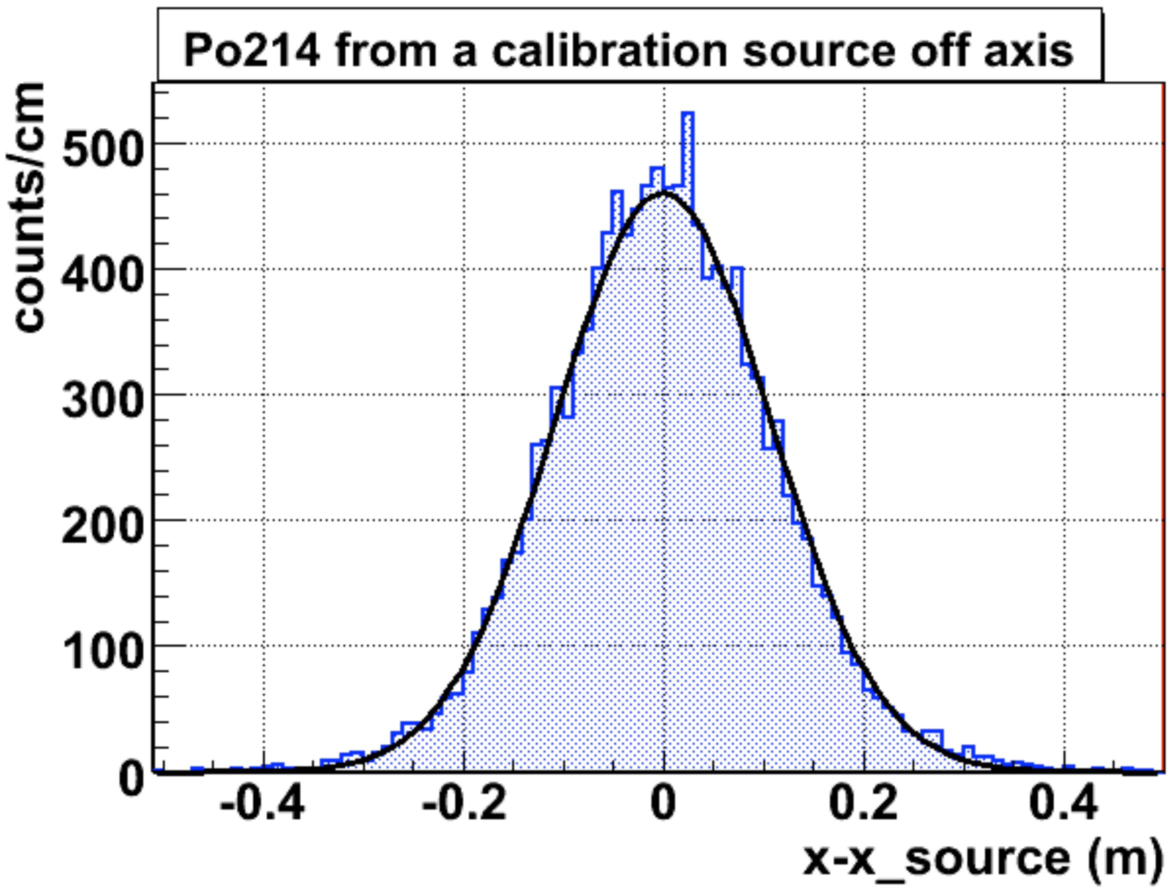
Background to ^{90}Sr source experiment: ~ 5 cpy / 300 t !

Systematic errors

- A big **calibration** effort have reduced the **fiducial volume** and energy scale errors with respect to previous papers
  - The most important for the goal of this talk is **FV determination**

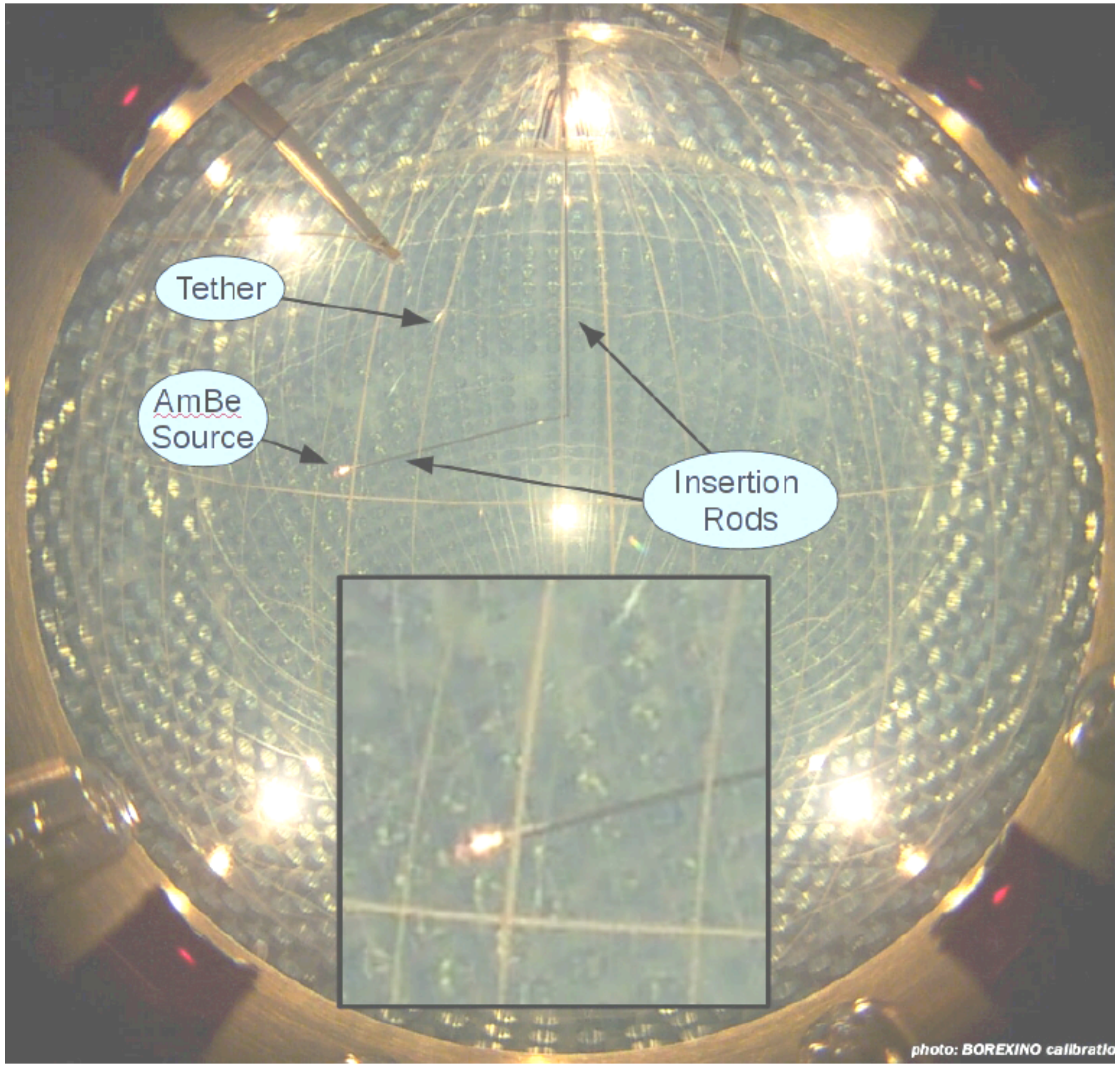
hep-ex/1104.1816v1

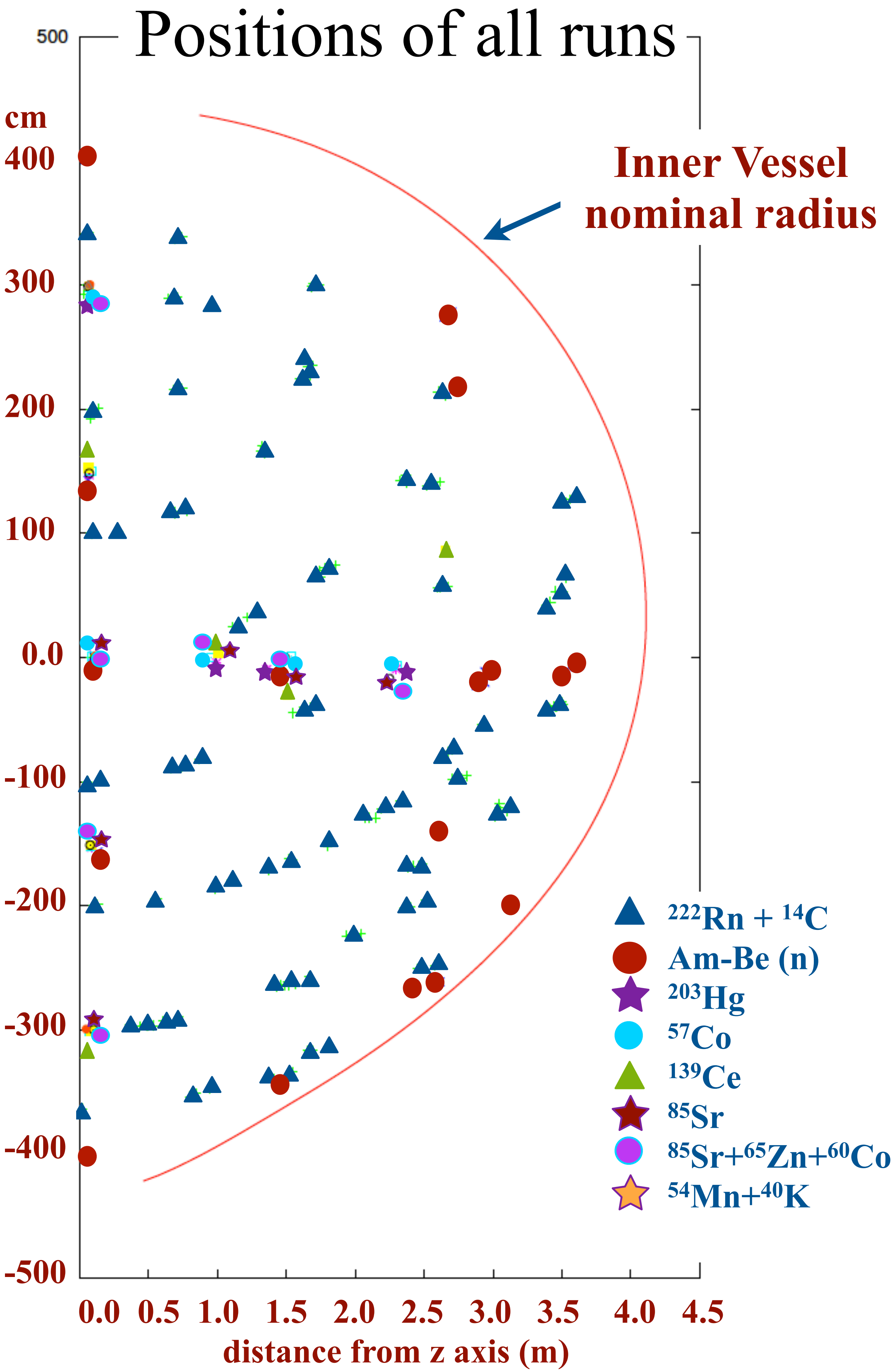
Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Position reconstruction	$^{+1.3}_{-0.5}$
Energy scale	2.7
Fit consistency	1.7
Fit methods	1.0
Total Systematic Error	$^{+3.6}_{-3.4}$



Fiducial volume

- Careful study as a function of the position of the source in the whole Inner Vessel



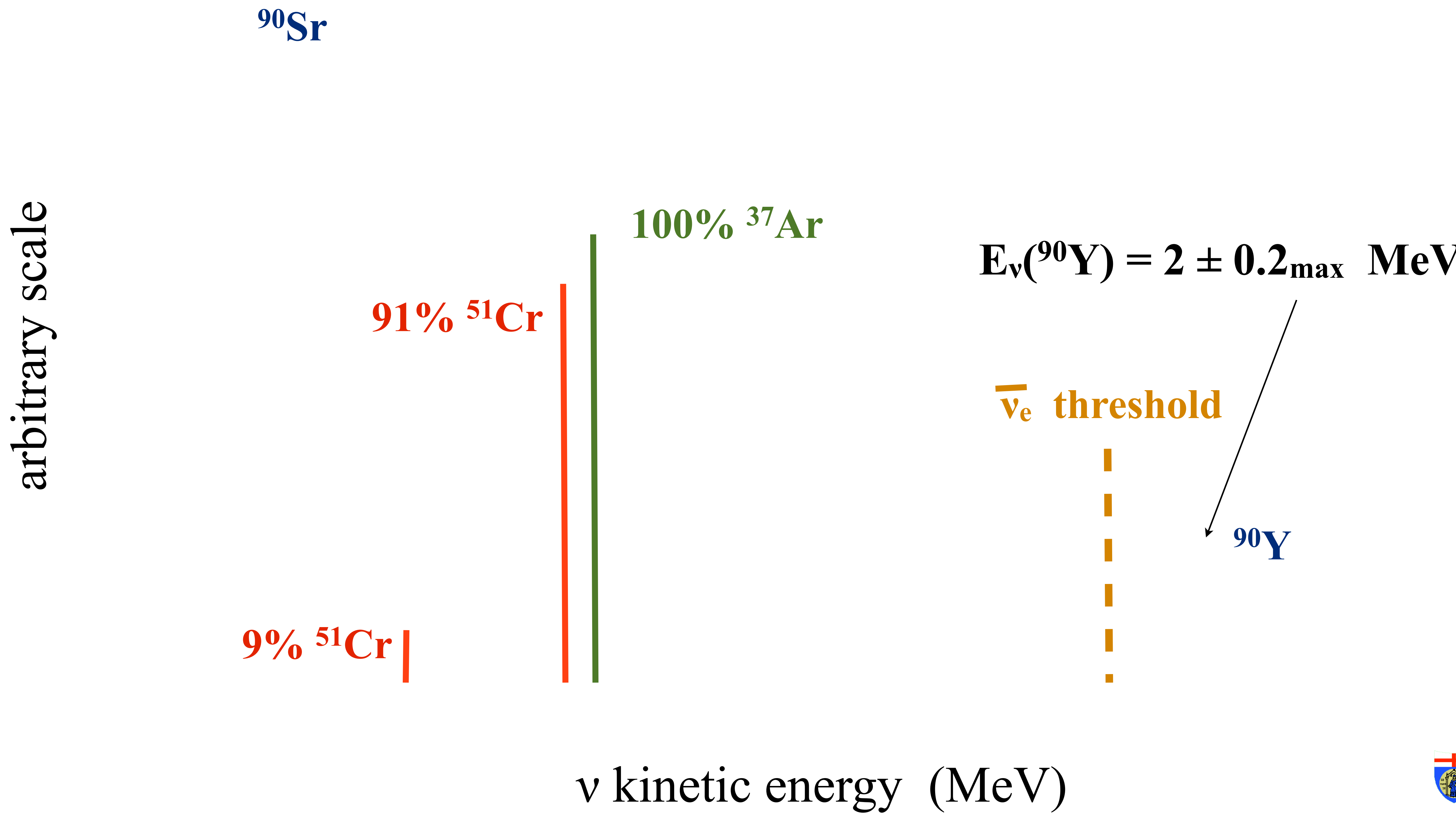


Possible neutrino sources

- We have so far considered **3 sources**
  - many others are possible both for ν and $\bar{\nu}$
- **^{51}Cr**
  - **ν_e from k-capture;**
  - irradiation of enriched ^{50}Cr with thermal neutrons
  - ~35 kg still available at Saclay; 5 - 10 MCi possible with this material.
  - Technique successfully tested twice in Gallex at LNGS **Phys. Lett. B342 440-450, (1995)** **Phys. Rev. C59:2246-2263, (1999)**
- **^{37}Ar**
  - **ν_e from k-capture;**
  - irradiation of enriched ^{40}Ca with fast neutrons
  - Technique successfully tested in Sage. **Abdurashitov et.al. Neutrino Telescopes, Venice (1995)**
- **^{90}Sr - ^{90}Y**
  - $\bar{\nu}_e$ from β decay
  - fission product, abundant as nuclear waste, long life-time
  - Russian company were building heaters for Siberia locations..... not anymore.

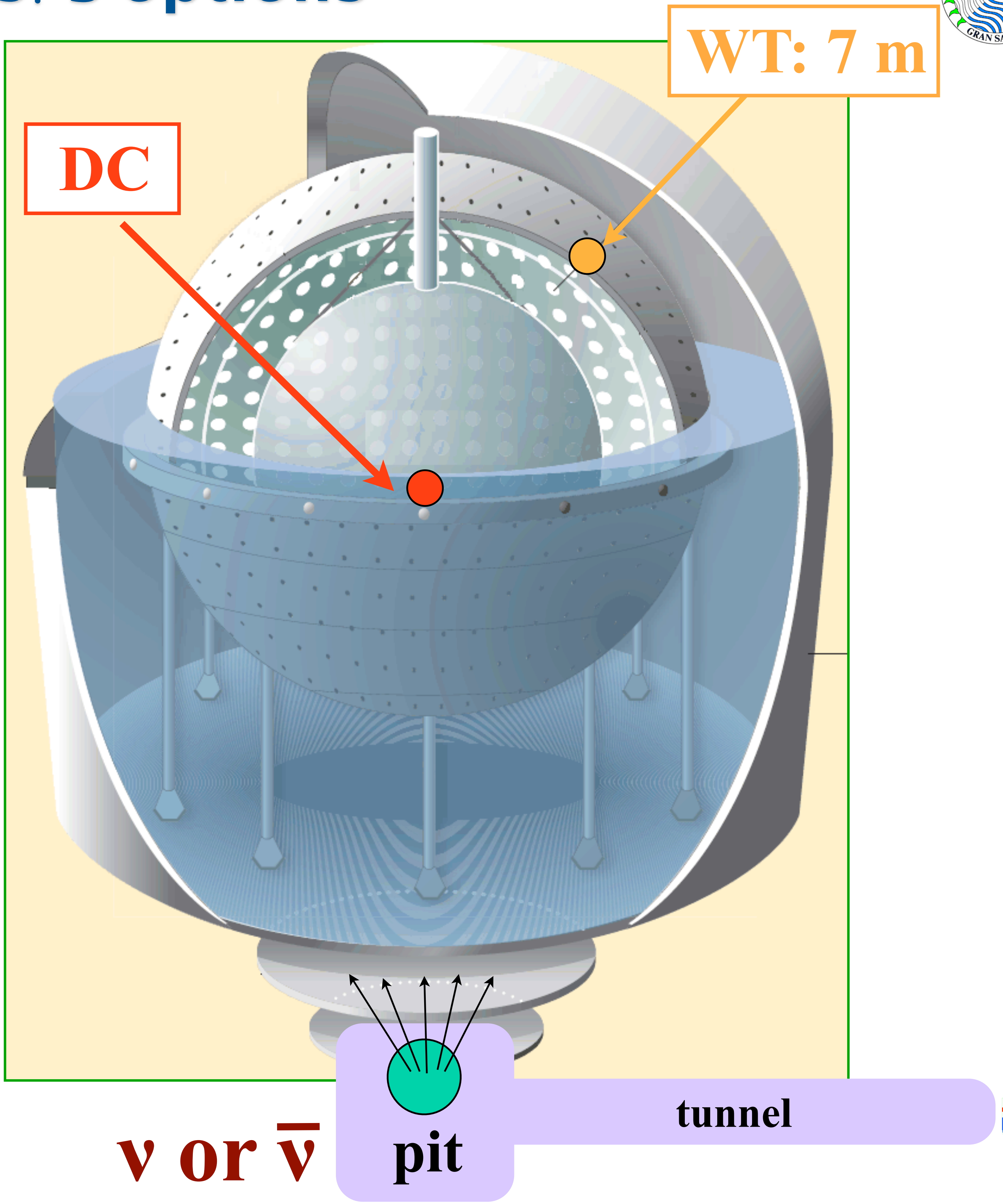
source	τ (days)
^{51}Cr	39.96
^{37}Ar	50.55
^{90}Sr	1.52 E4

Neutrino energy spectra



Source locations: 3 options

- **"Icarus Pit" - IP**
  - A pit built **right below** the W.T.
  - Access tunnel ready
  - **8.25 m** from detector center
- **"Water Tank" - WT**
  - Access from flanges on top
  - Source would be in water
  - **7 m** from detector center
- **"Detector Center" - DC**
  - Possible at the end of Borexino solar neutrino program
  - More effort, but much higher sensitivity



Access to the "icarus pit"

The tunnel to the "icarus pit"

The signal in Borexino

- **Two different techniques** can be used, possibly combined:

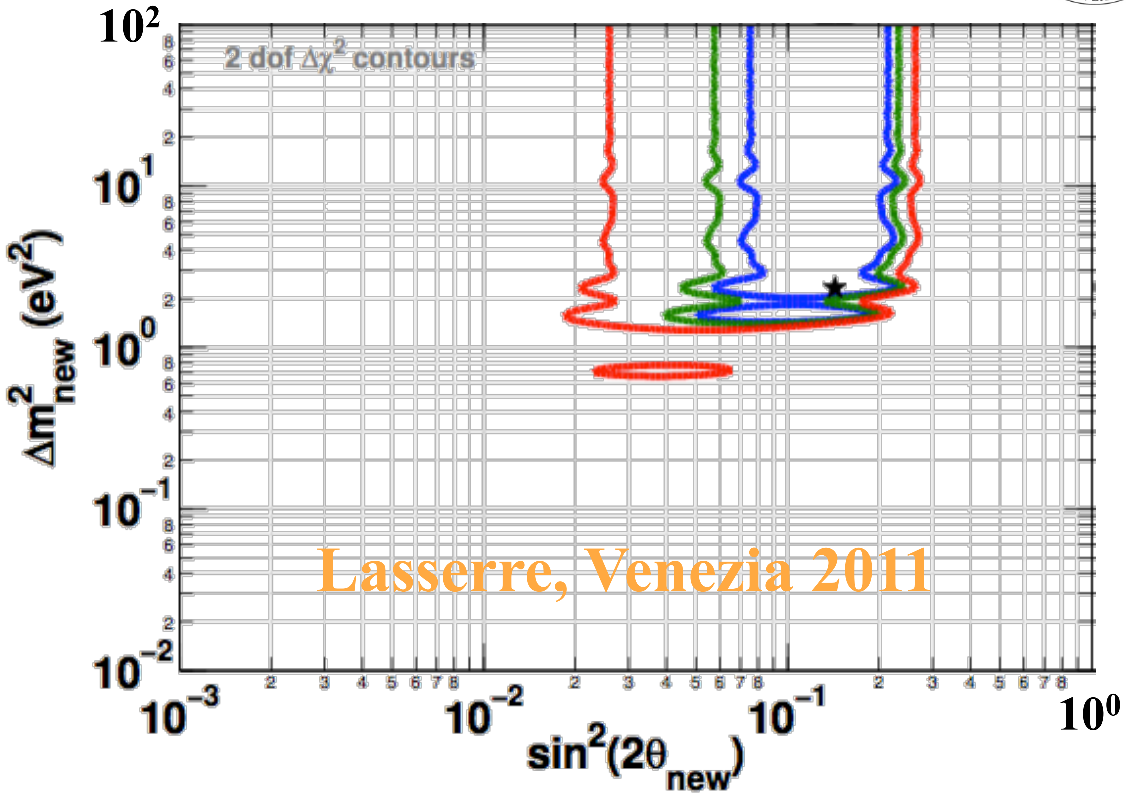
- **Total counts.** i.e. the standard disappearance technique
  - The total number of events depends on θ_s and (very weekly) on Δm^2
  - The sensitivity depends on:
    - Source activity (statistics and signal-to-noise ratio)
    - Systematic on knowledge on source activity
    - Systematic on FV determination

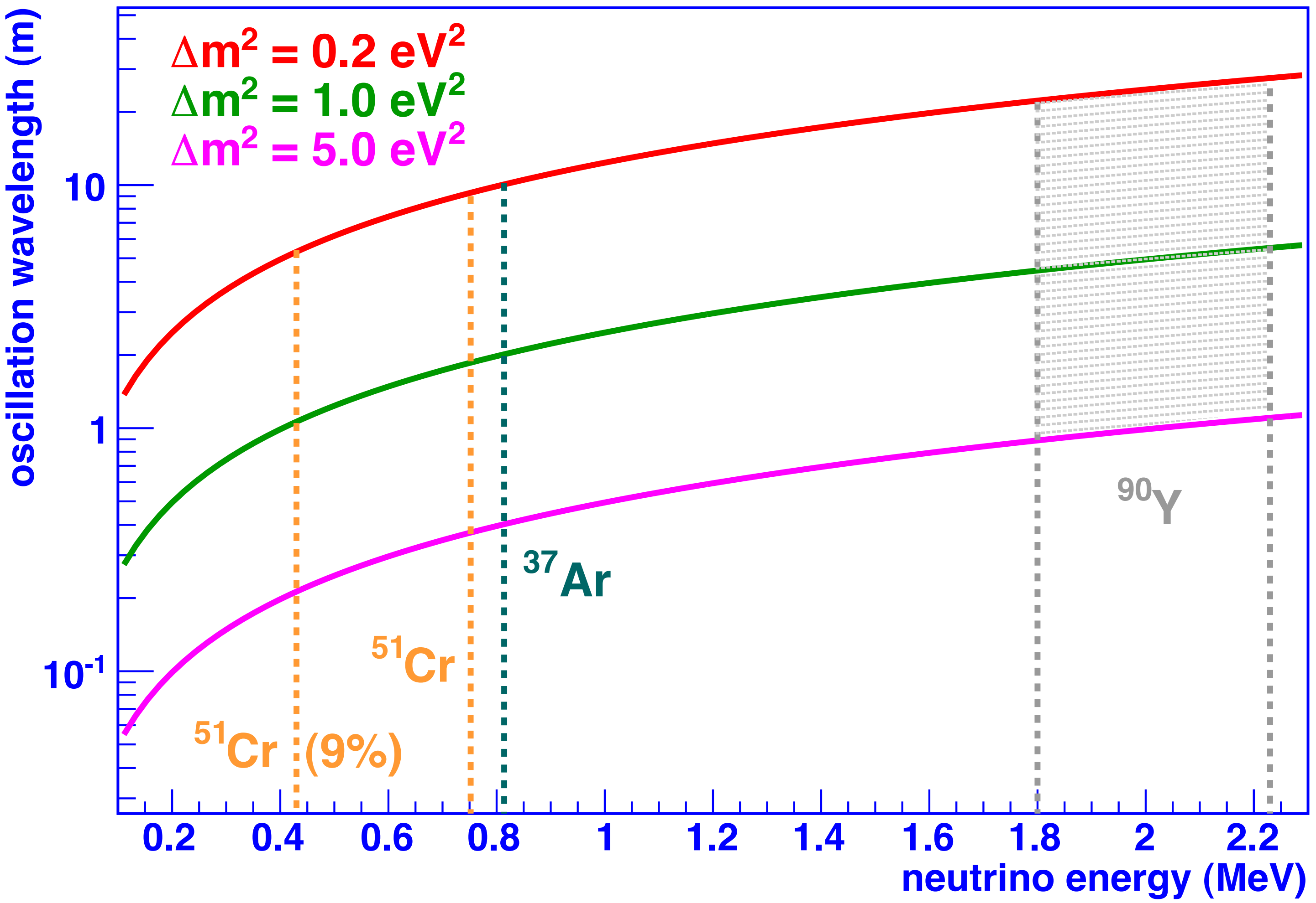
- **Spatial waves.** [C.. Grieb et al., Phys. Rev. D75: 093006 (2007)]
  - In the range of Δm^2 that yields **oscillation wavelength smaller than detector size (~ 7 m)**, but **larger that the spatial resolution (~ 15 cm)**, the distribution of the event distance from the source shows **oscillations**
    - **Direct measurement of Δm^2 and θ_s independently**
    - **Does not depend neither on source activity nor on FV determination**
    - Very powerful complementary approach

Observation of oscillation waves

- **a key feature** of this program is the fact that for many of the parameters indicated by anomalies, **Δm^2** and **$\sin^2(2\vartheta_s)$** can be **measured independently**

$$L_0\ (m) = \frac{\pi\ E\ (MeV)}{1.27\ \Delta m^2\ (eV^2)}$$





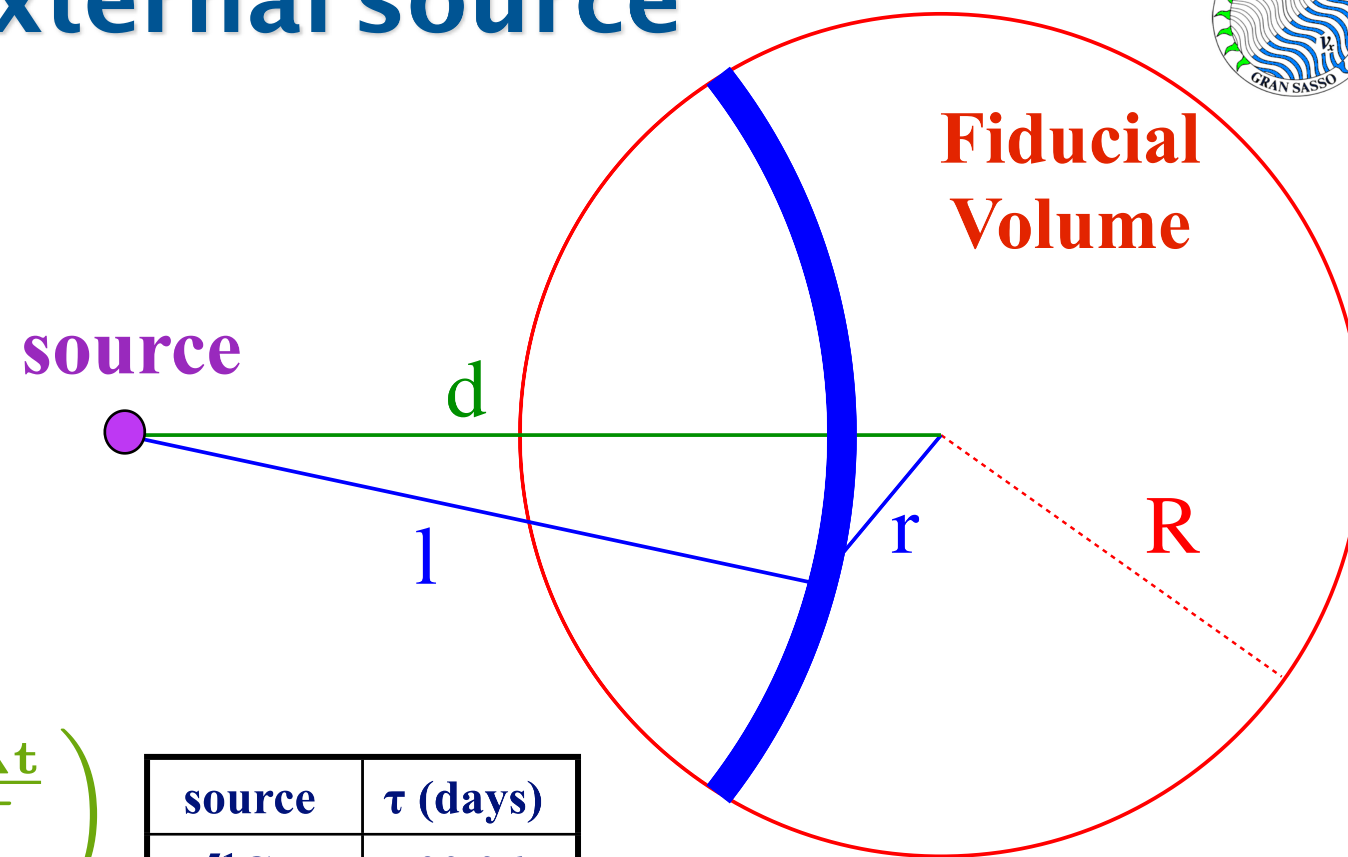
E (MeV)	Δm^2 [eV^2]					Source
	0.1	0.5	1	5	10	
0.747	18.0	3.7	1.8	0.4	0.2	^{51}Cr
0.814	20.0	4.0	2.0	0.4	0.2	^{37}Ar
1.8	45.0	8.9	4.5	0.9	0.4	^{90}Y
2.2	54.0	11.0	5.4	1.1	0.5	^{90}Y

Oscillation Length (m) for various Δm^2 and neutrino energies

Main formulas for external source

- **Volume factor:**

$$V(l) = 2\pi l^2 \left(1 - \frac{d^2 - R^2 + l^2}{2\ d\ l}\right)$$



- **Neutrino flux (and source decay)**

$$\Phi(l) = \frac{I_0}{4\pi l^2}\tau e^{-\frac{t_D}{\tau}}\left(1 - e^{-\frac{\Delta t}{\tau}}\right)$$

source	τ (days)
^{51}Cr	39.96
^{37}Ar	50.55
^{90}Sr	1.52 E4

- **Oscillations (2 flavors)**

$$P_{ee} = 1. - \sin^2(2\theta_s) \cdot \sin^2\left(\frac{1.27\ \Delta m^2\ l}{E}\right)$$

- The expected number of ν_e - induced e^- recoil events collected at distance l from the source, with detection threshold T1 and max recoil energy T2

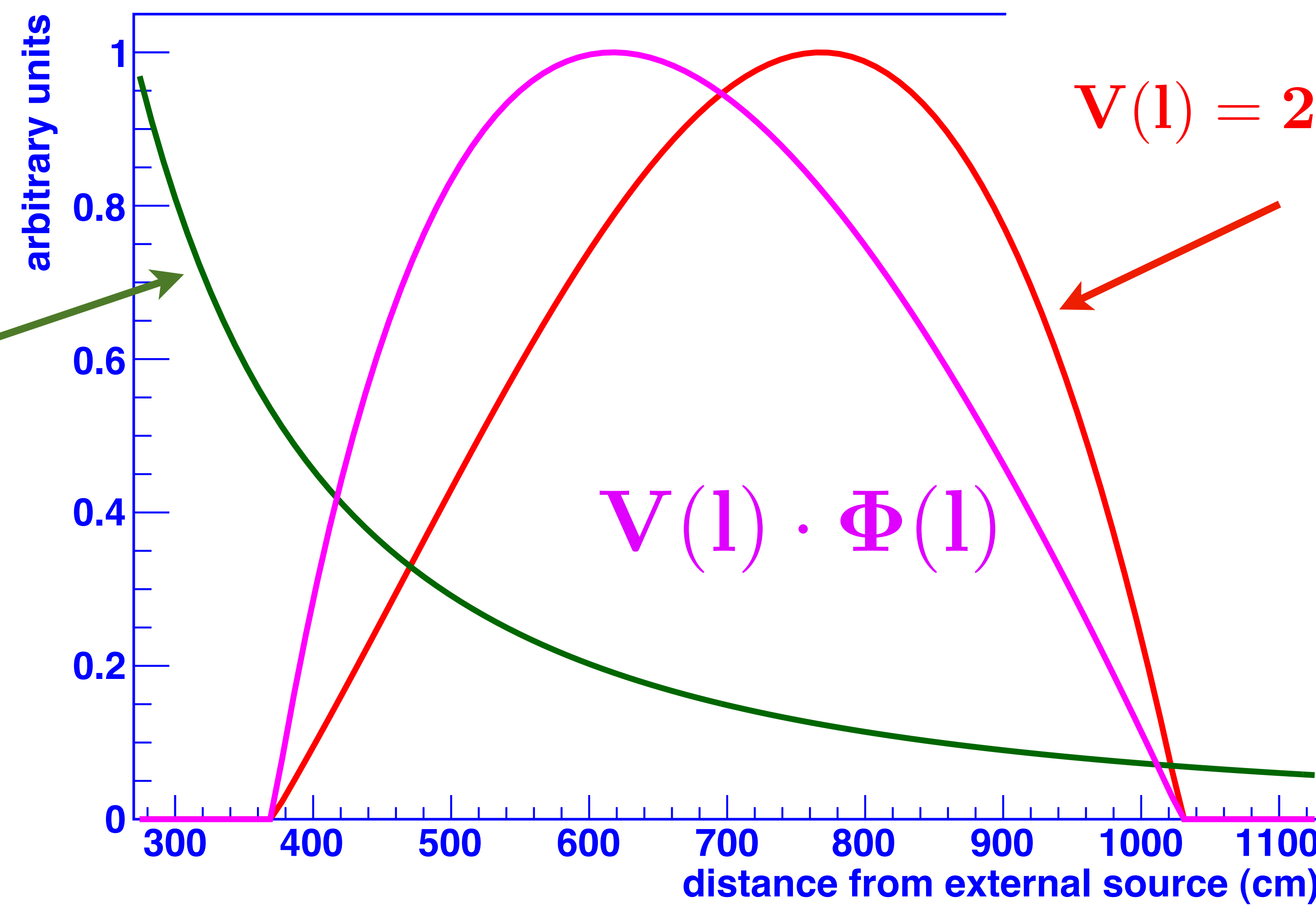
$$N_0(l, T_1, T_2) = n_e\ \Phi(l)\ V(l)\ P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E, T)}{dT} dT$$

Volume and flux effect for external source

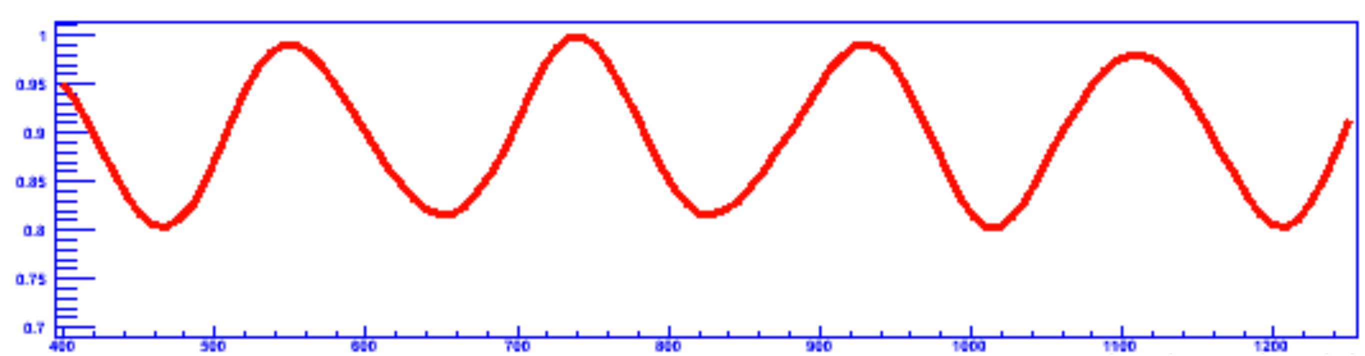
- When the source is located **outside** the detector, the distribution of the events in the F.V. **is not uniform even in absence of oscillations**
  - **Example** with source in W.T. (D=7m) and F.V. radius = 3.3 m

$$V(l) = 2\pi l^2 \left(1 - \frac{d^2 - R^2 + l^2}{2\,d\,l}\right)$$

$$\Phi(l) = \frac{I_0}{4\pi l^2}$$

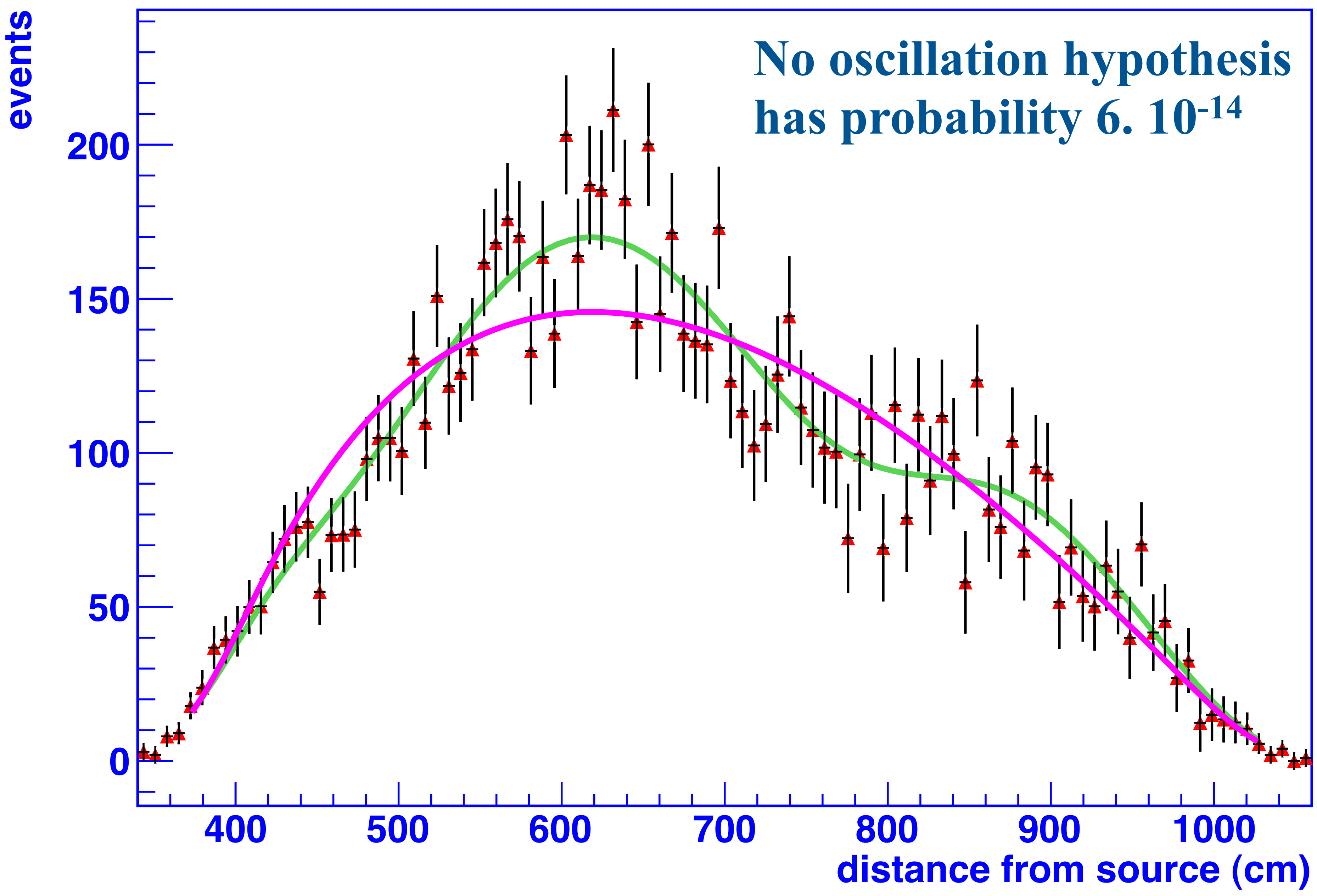


P_{ee} for ^{51}Cr



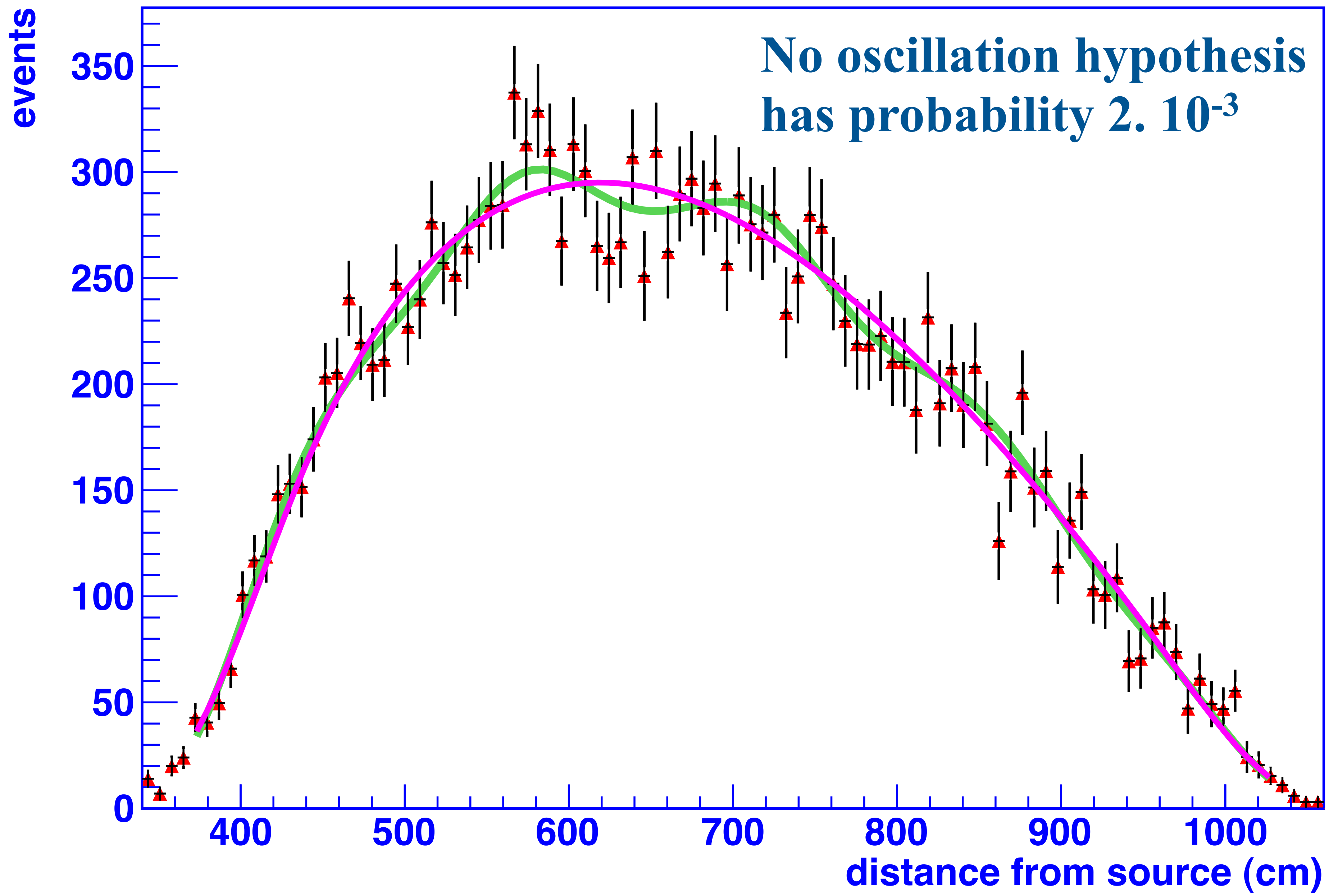
Example: waves with ^{51}Cr source in WT

- **5 MCi ^{51}Cr** source at **7 m** from the source
- 3.3 m F.V. radius
  - **Δm^2 = 0.6 eV^2 $\sin^2(2\vartheta_s)$ = 0.3**



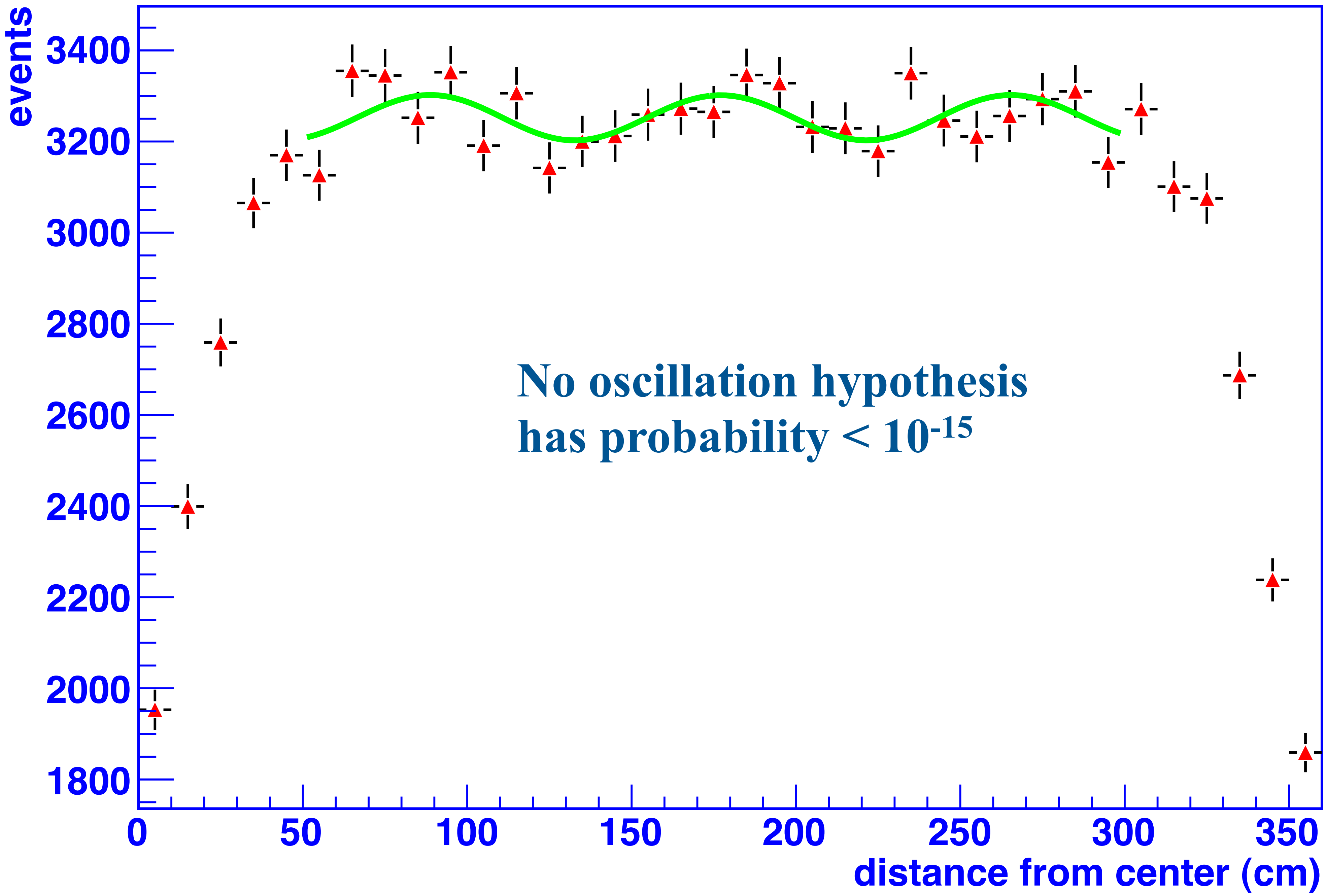
Example: waves with ^{51}Cr source in WT

- **10 MCi ^{51}Cr** source at **7 m** from the source (1 or 2 irradiations)
- 3.3 m F.V. radius
  - **$\Delta m^2 = 1.3\ eV^2$ $\sin^2(2\vartheta_s) = 0.15$**

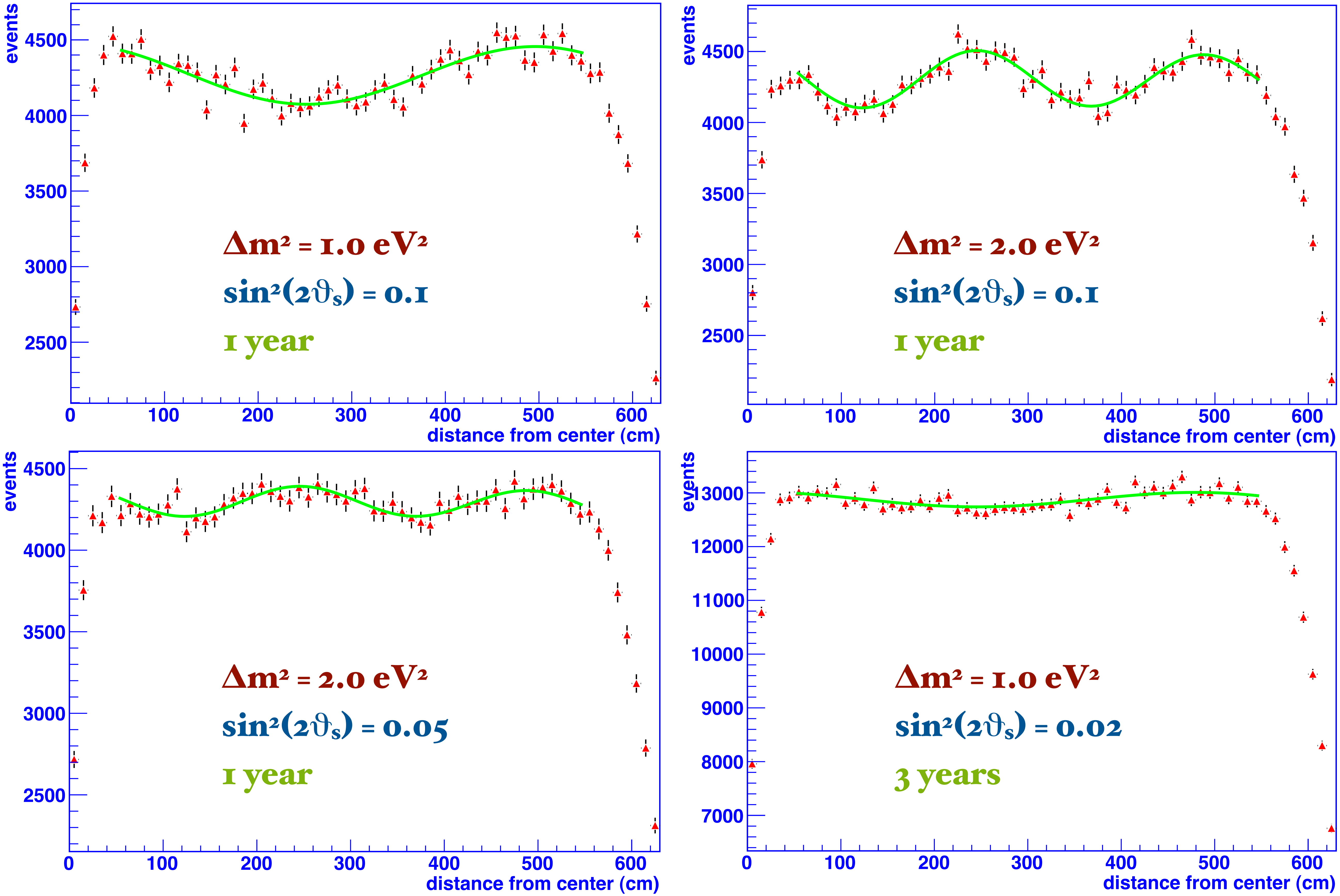


Example: waves with ^{51}Cr in the center

- **5 MCi 51Cr** source in the **center** of Borexino
- 3.3 m F.V. radius
  - **$\Delta m^2 = 2\ eV^2$ $\sin^2(2\vartheta_s) = 0.10$**



Examples with ^{90}Sr in the center



Sensitivity

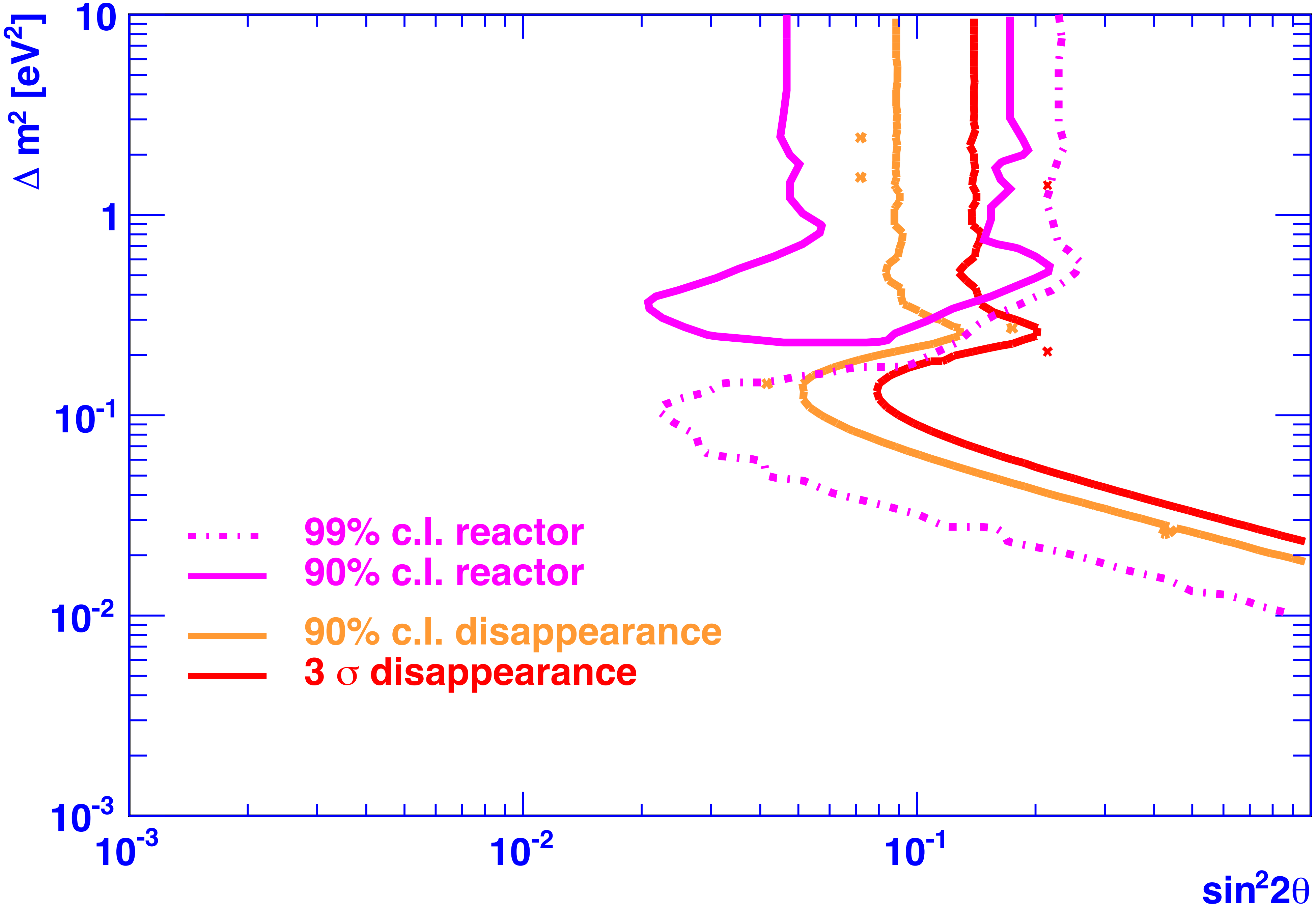
- Having **2 methods**, the sensitivity can be computed for both
- The **total counts** method is not sensitive to $\mathbf{\Delta m^2}$ but has very similar sensitivity to discovering oscillations
  - In the following we will quote **90% c.l.** curves and **3 σ exclusion** curves
    - The curves are computed analytically in this case
- The **wave method** allows to measure both $\mathbf{\Delta m^2}$ and $\mathbf{sin^2(2\vartheta_s)}$
  - We quote 90% c.l. and 3 σ regions
    - In this case MC method was used
- Of course, they can be combined. Not done yet.

Expected number of signal events

Source	Location		
	Icarus Pit	Water Tank	Center
^{51}Cr 5 MCi R=3.3 m	7131	10047	129255
^{51}Cr 10 MCi R=3.3 m	14262	20094	258410
^{37}Ar 2.5 MCi R=3.3 m	6275	8850	113780
^{37}Ar 5 MCi R=3.3 m	12550	17700	227560
^{90}Sr 1 MCi 1y R=4.25 m	17596	25095	187626
^{90}Sr 1 MCi 1y R=6m	56002	79868	265000
^{90}Sr 1 MCi 1y R=6m	162006	238804	795000

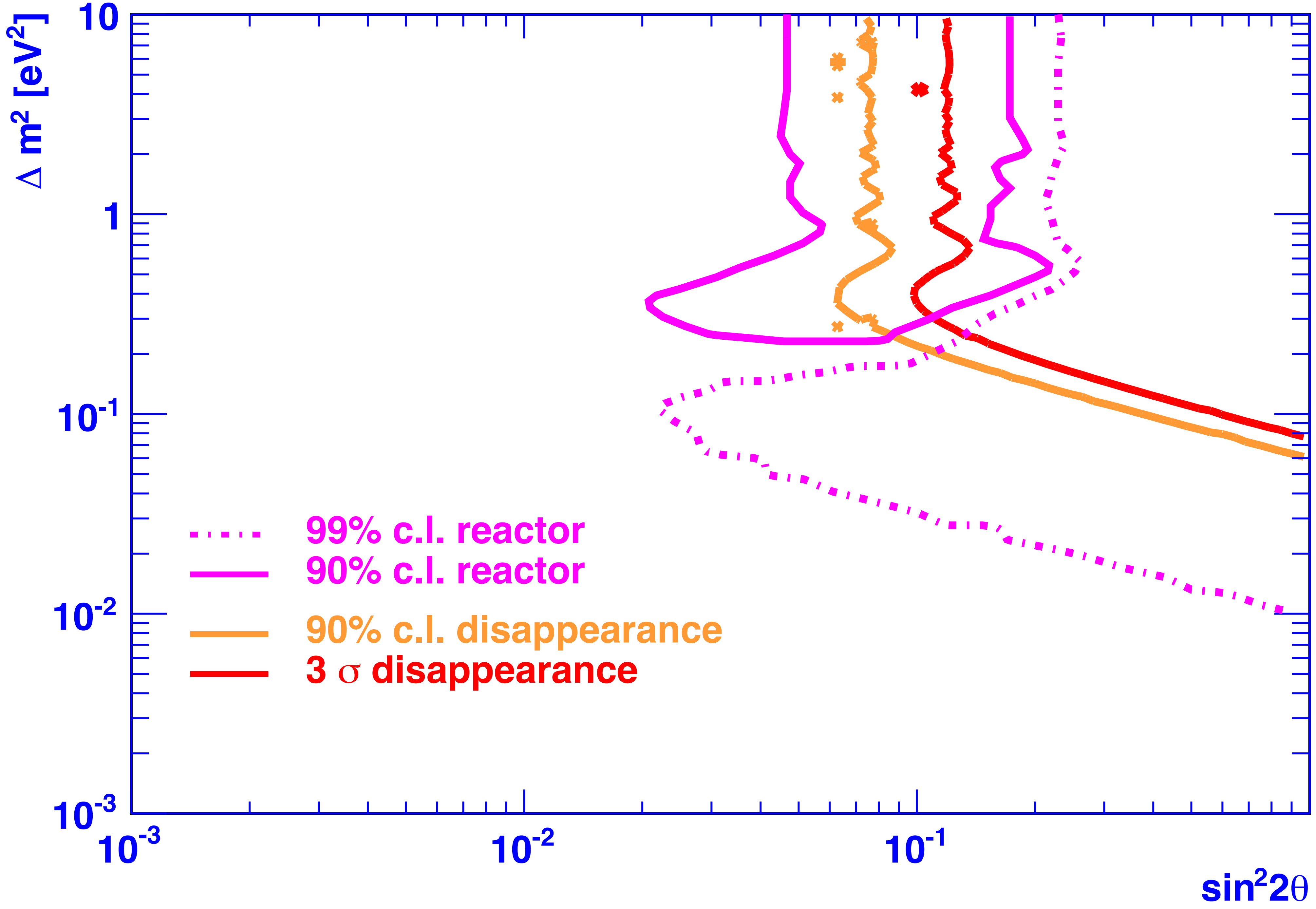
^{51}Cr – TOTAL COUNTS

- **10 MCi ^{51}Cr** source in the **WT**
  - 3.3 m F.V. radius



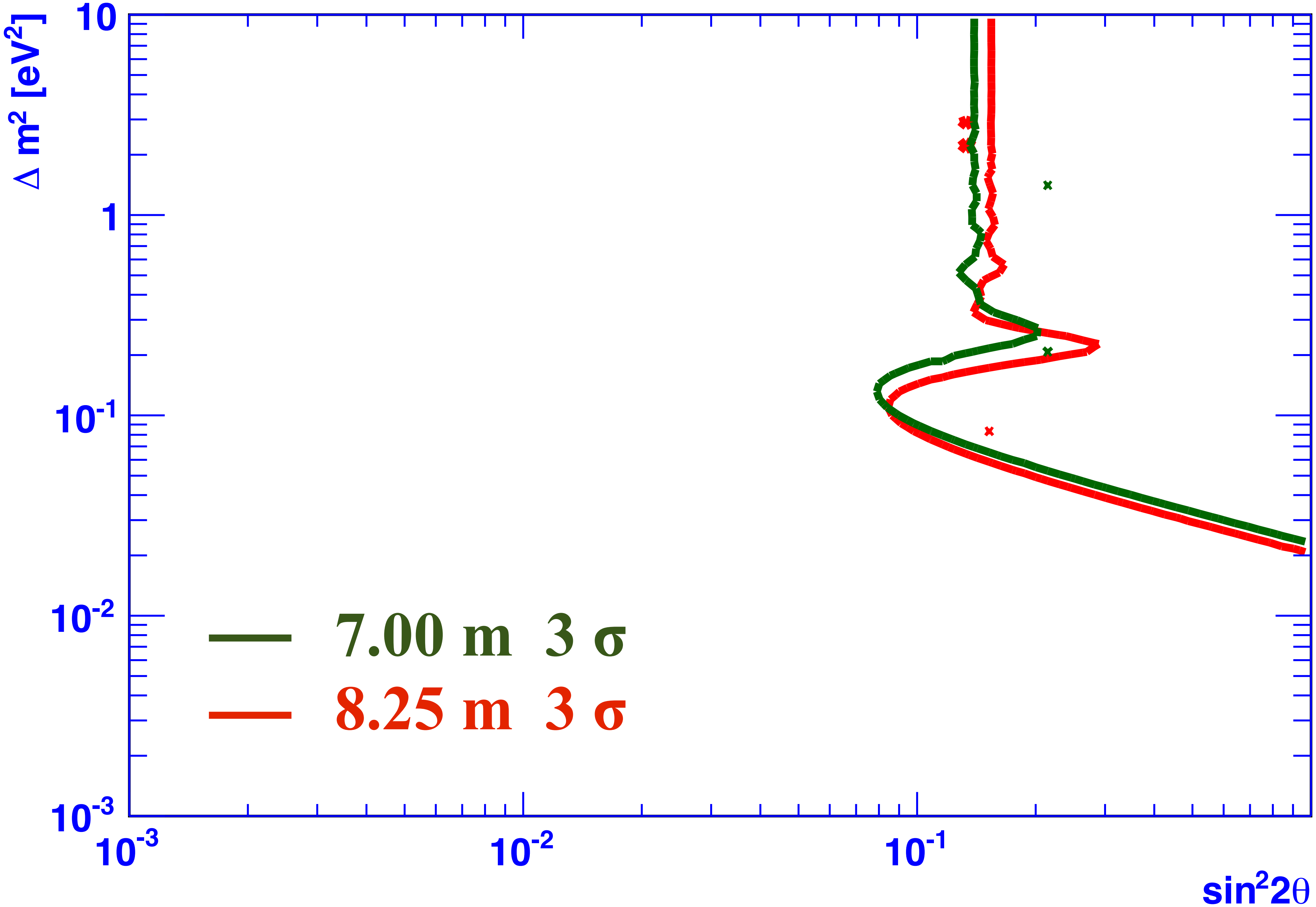
^{51}Cr – TOTAL COUNTS

- **5 MCi** **^{51}Cr** source in the **center** of Borexino
  - 3.3 m F.V. radius - 1% error in source activity - 1% error in F.V.

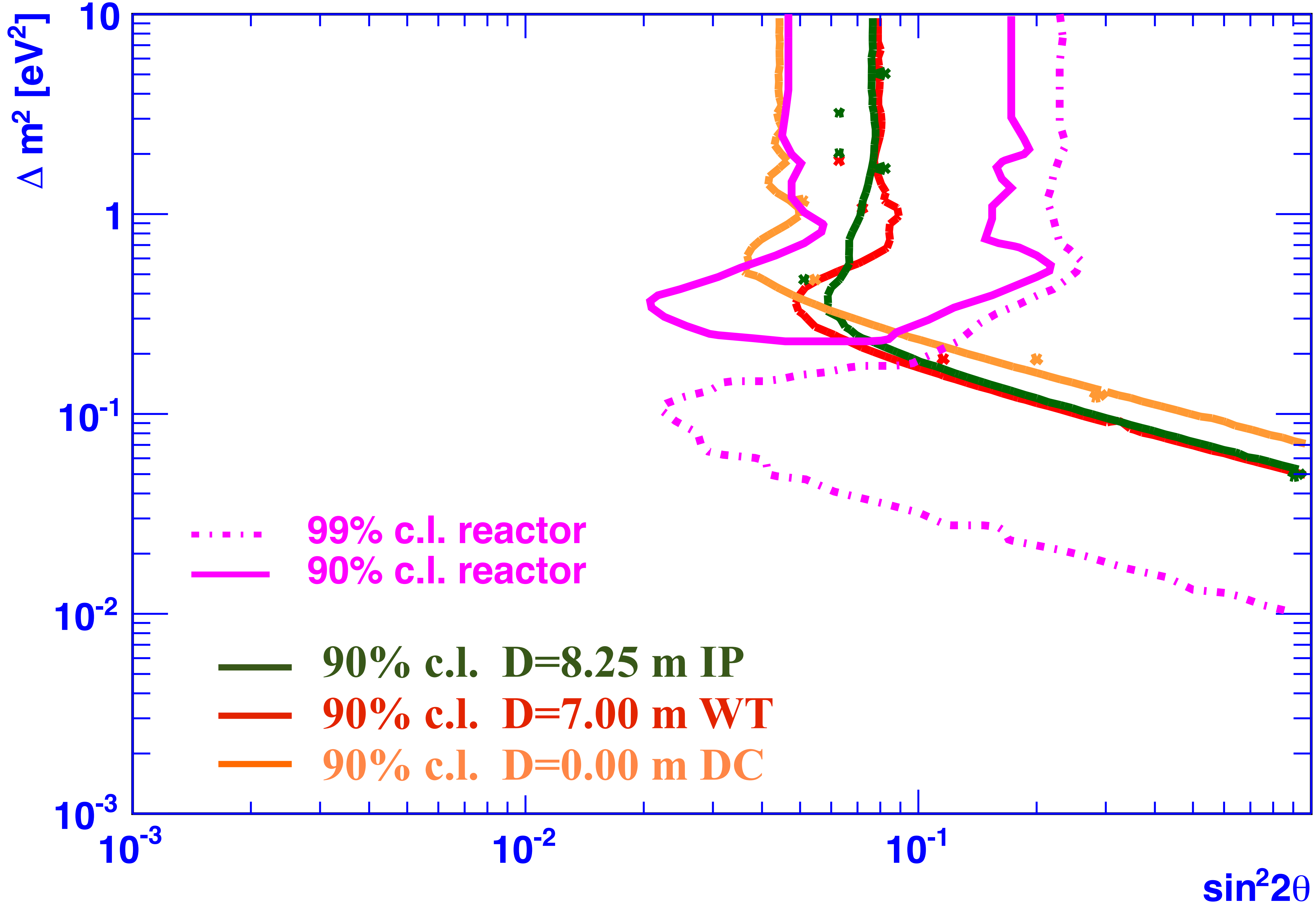


Small difference between IP and WT

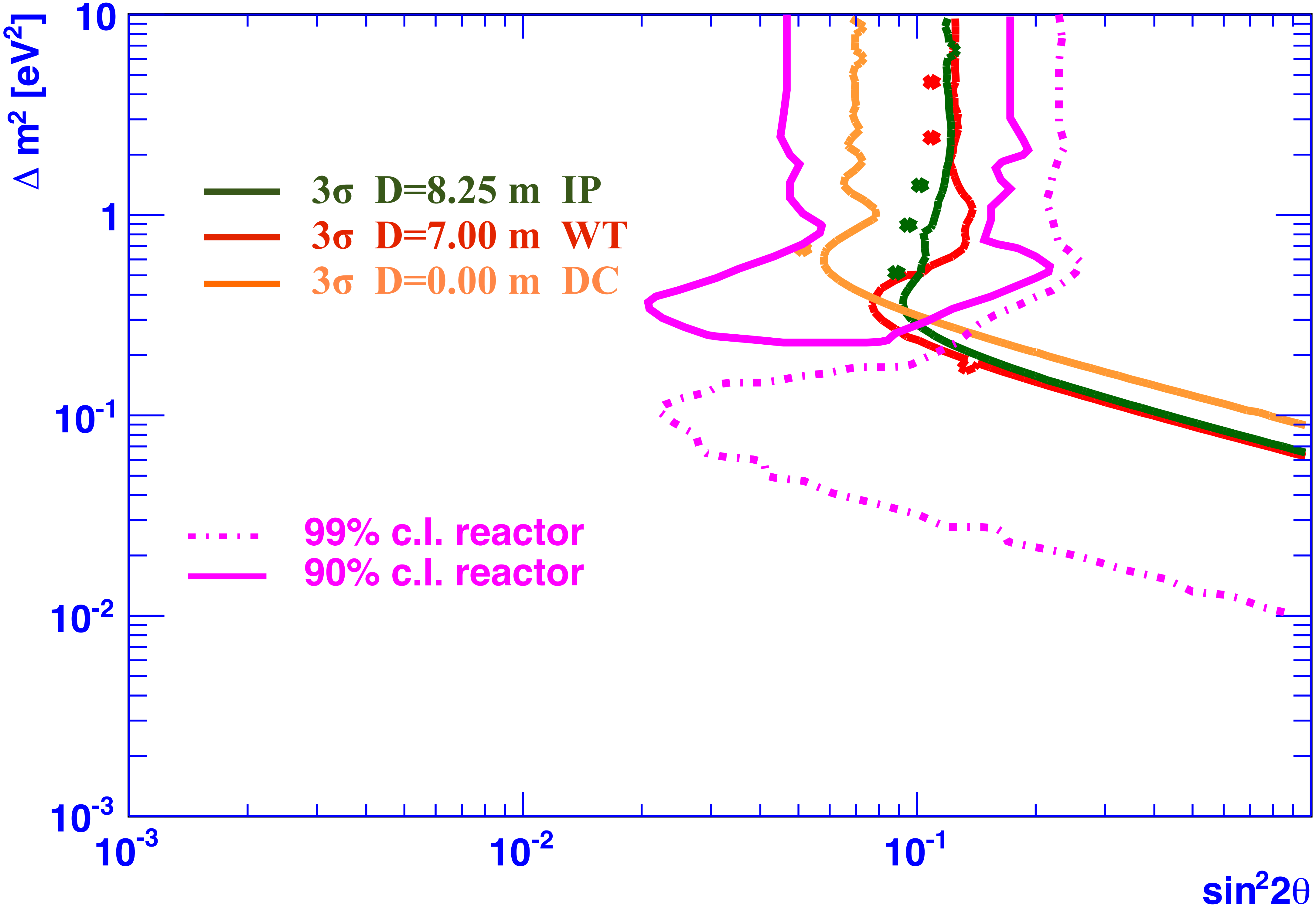
- Comparison between ^{51}Cr source (10 MCi)



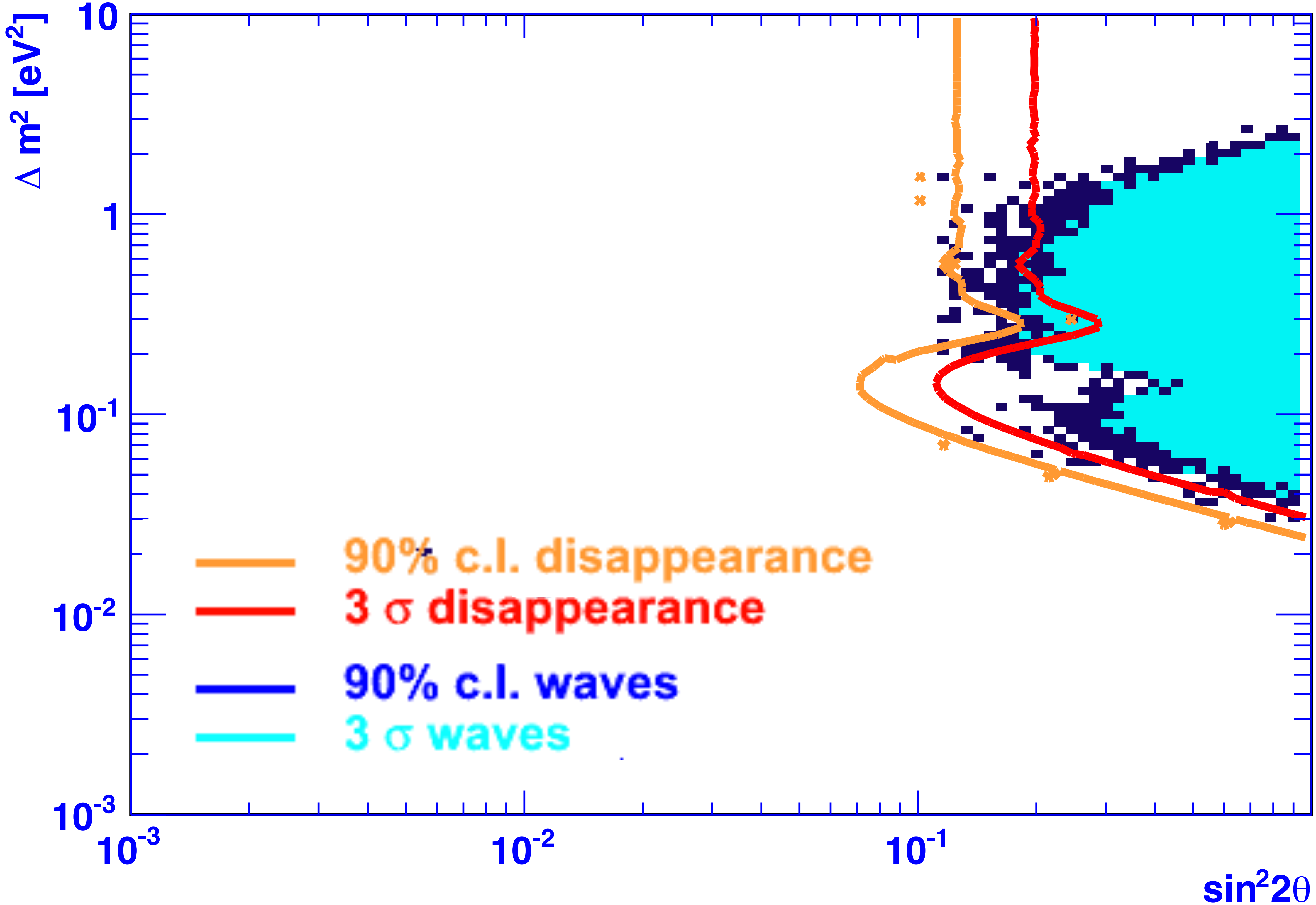
^{90}Sr – 90% c.l. sensitivity



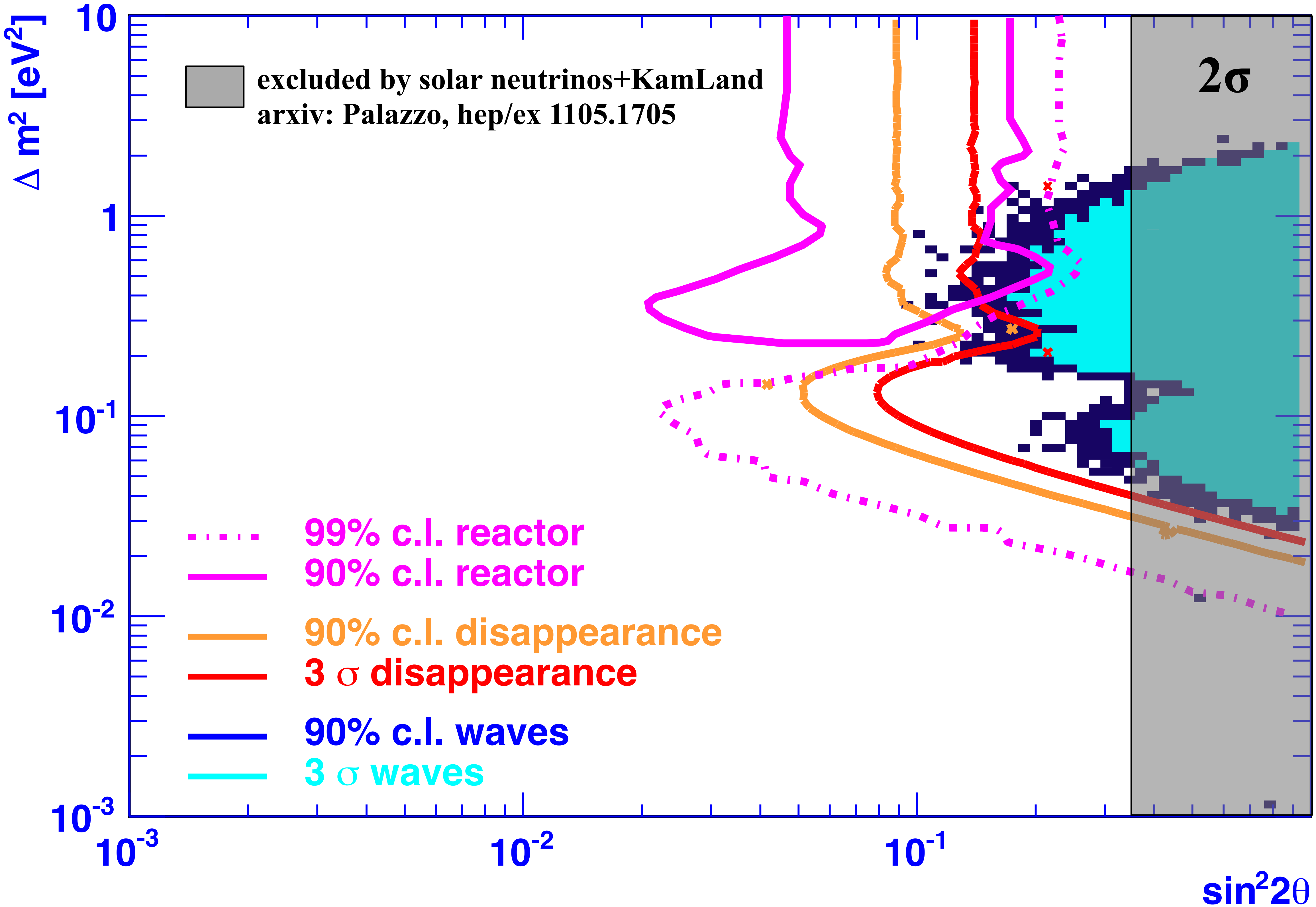
^{90}Sr – 3σ exclusion – 1 MCi



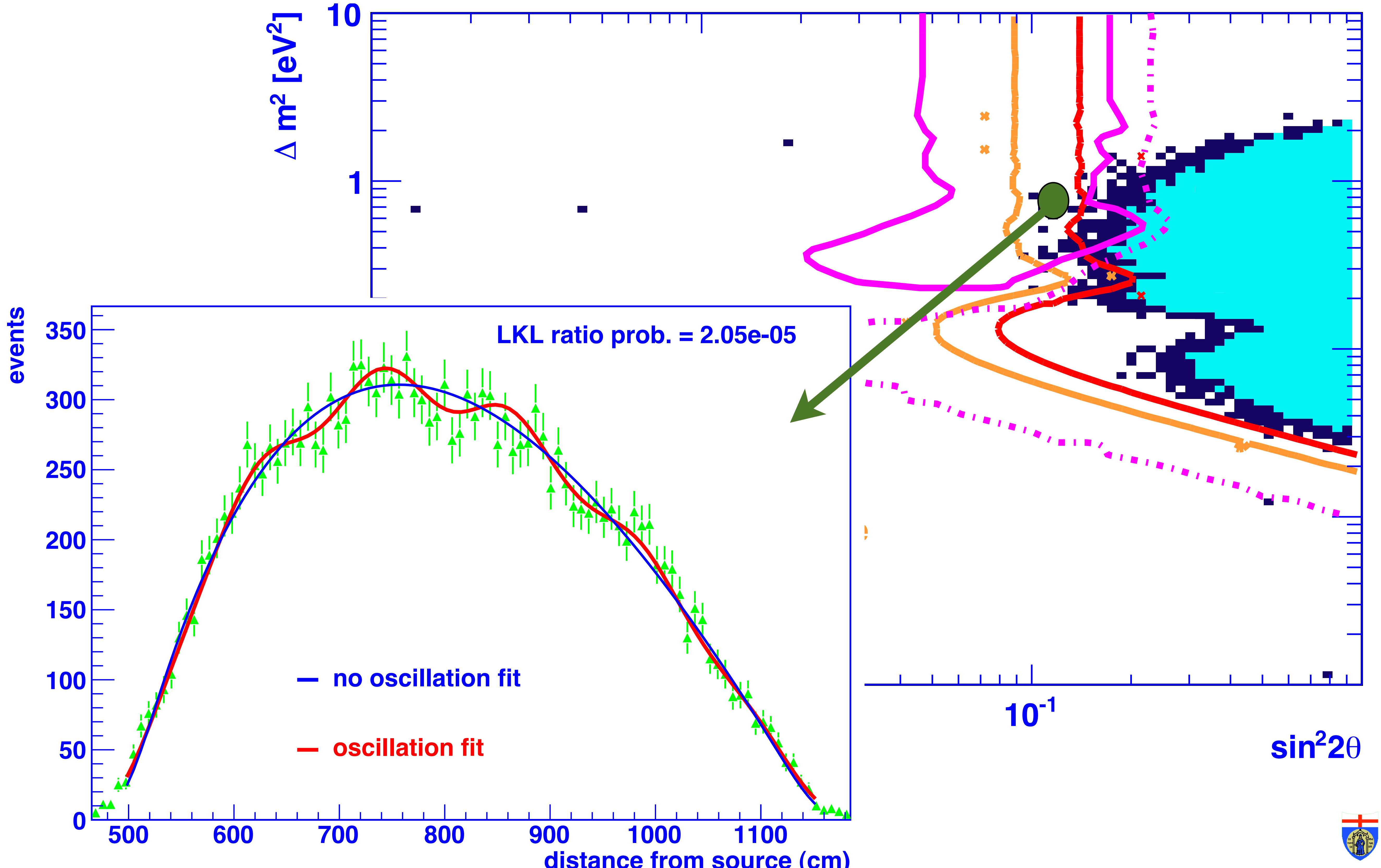
37Ar – 2.5 MCi – External



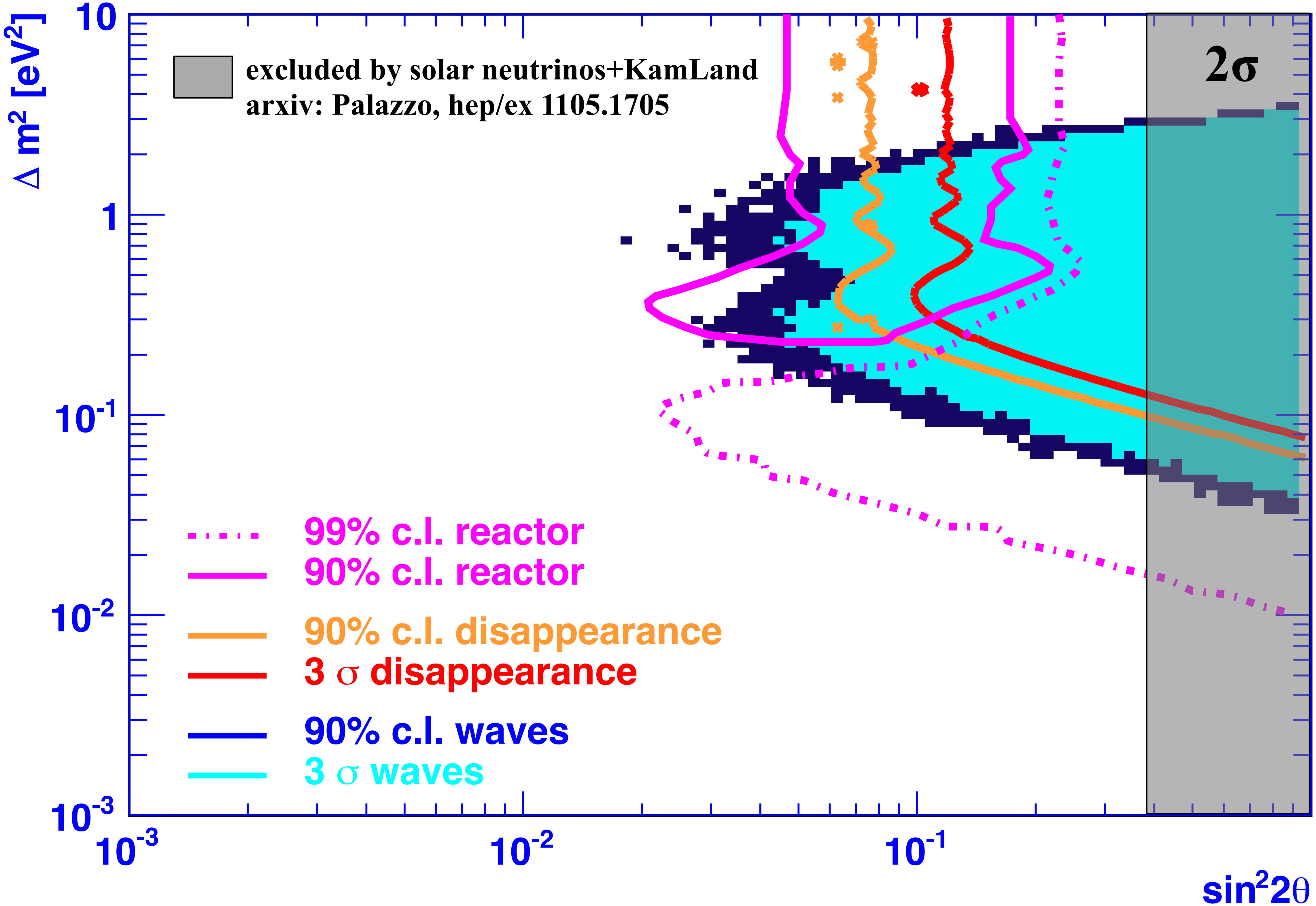
^{51}Cr – 10 MCi – External



^{51}Cr – 10 MCi – External

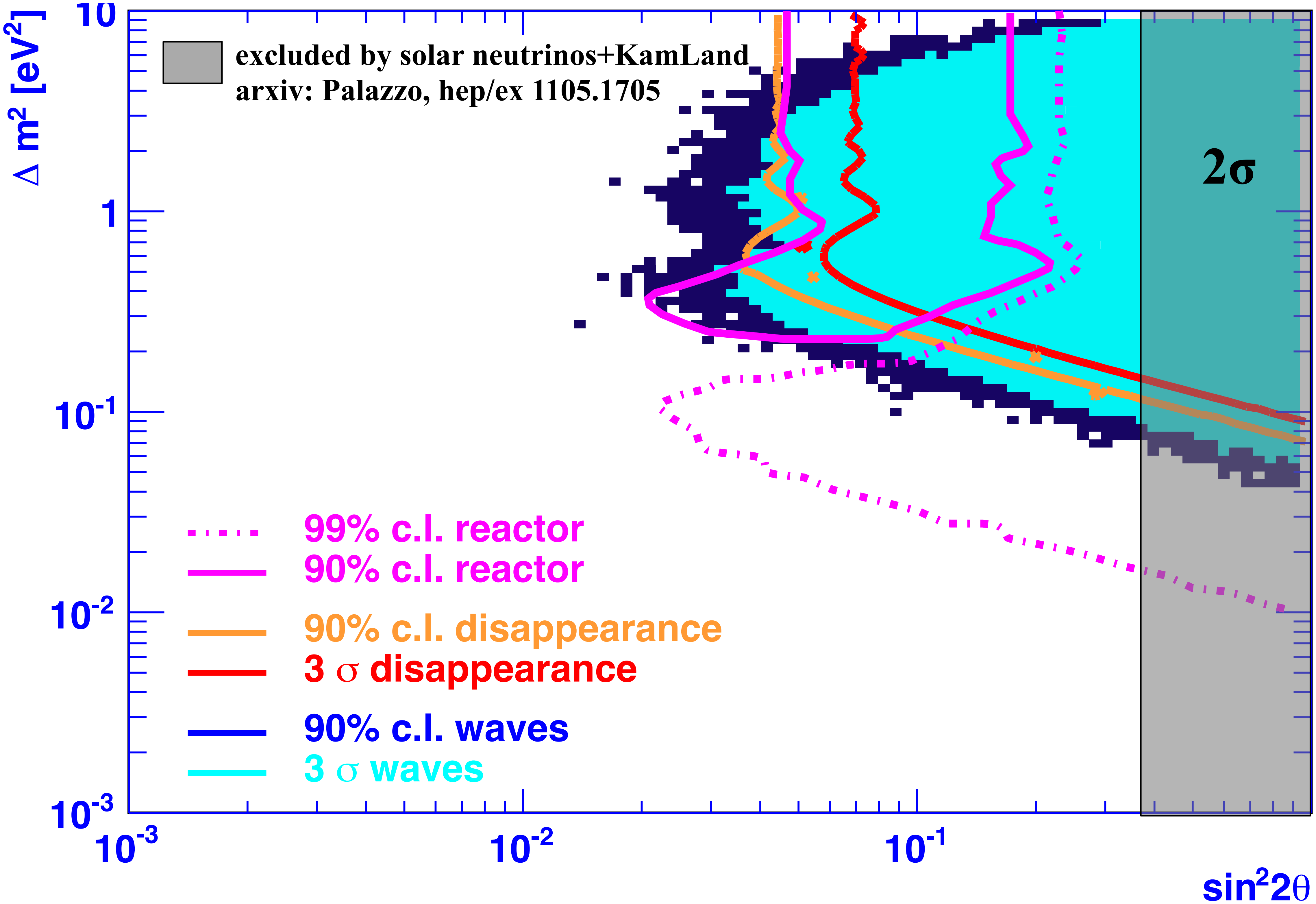


^{51}Cr – 5 MCi source – center

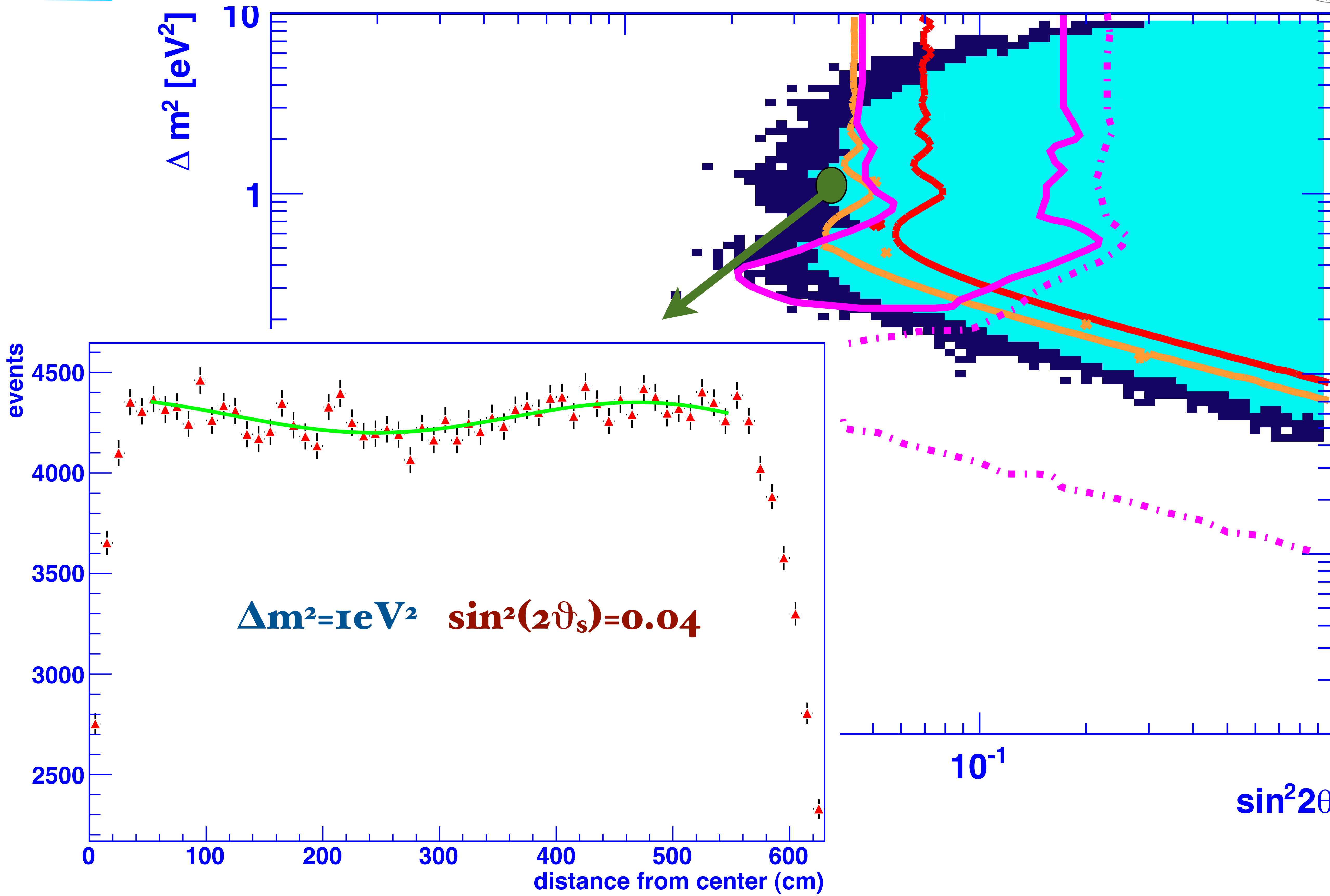


^{90}Sr – Total rate and waves – center – 1 year

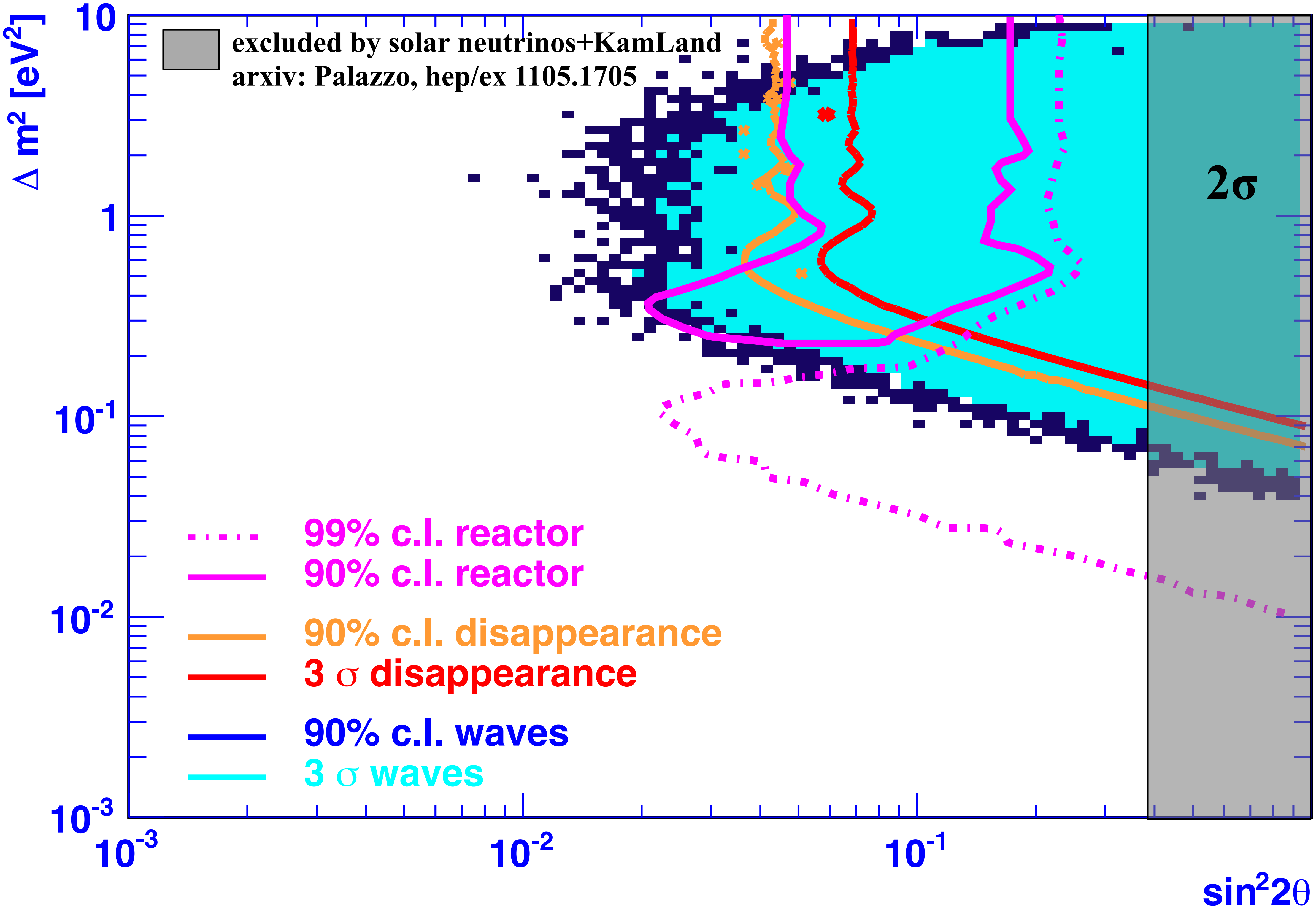
- 1 year, 1 MCi, R = 6 m, source in the center



^{90}Sr – Total rate and waves – center – 1 year

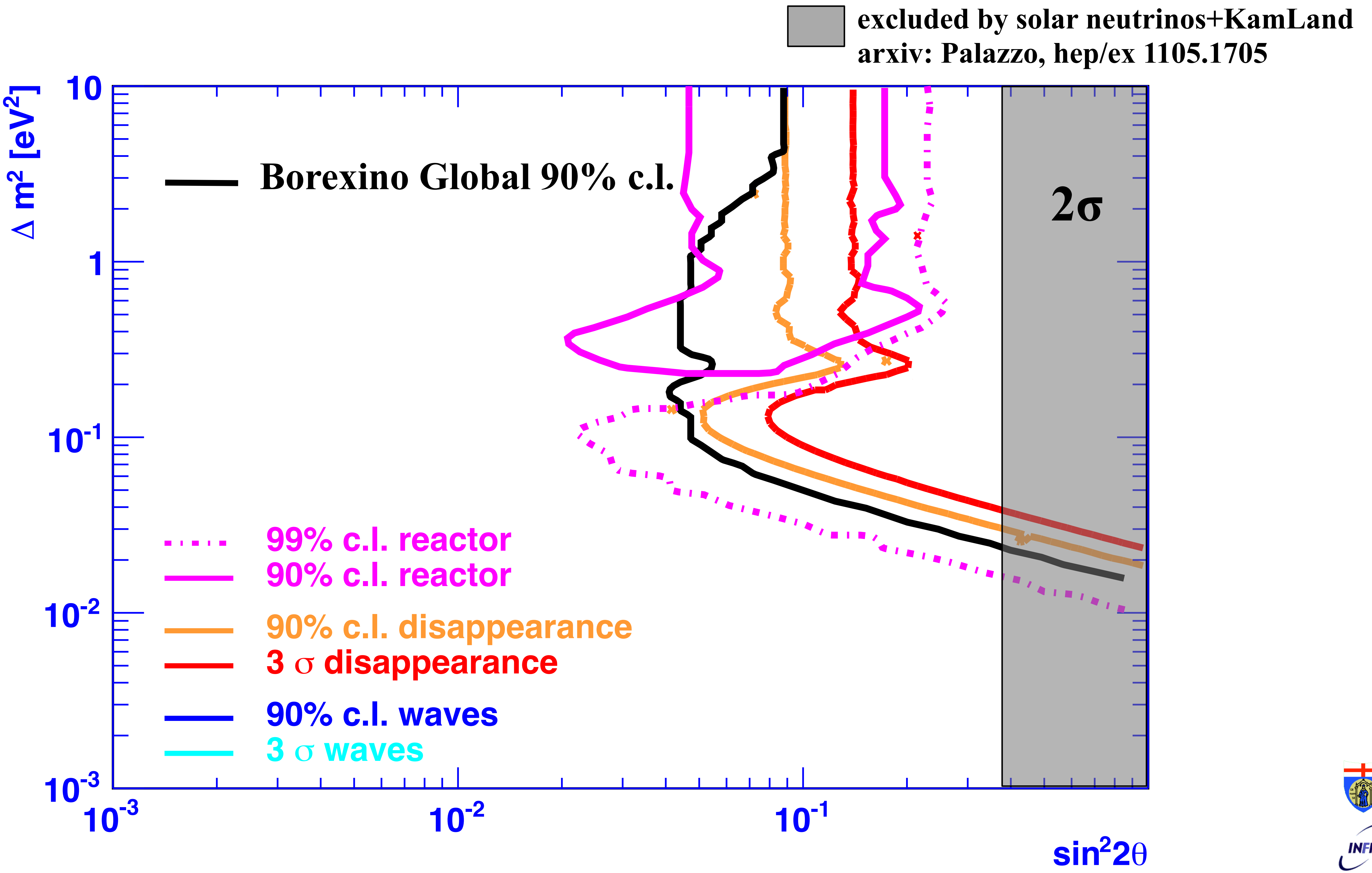


^{90}Sr – 3 years – source in the center

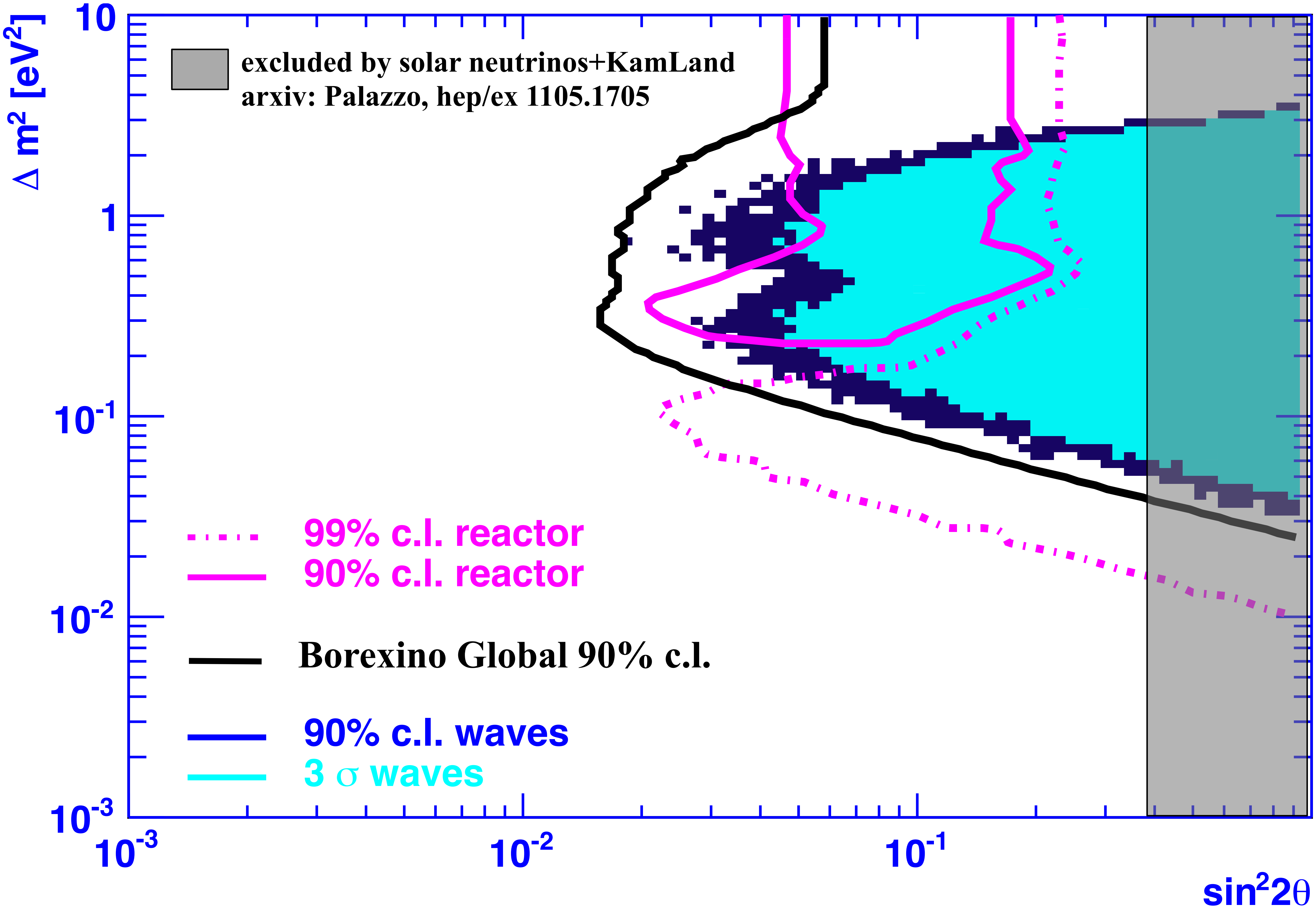


Global analysis: ^{51}Cr – external WT

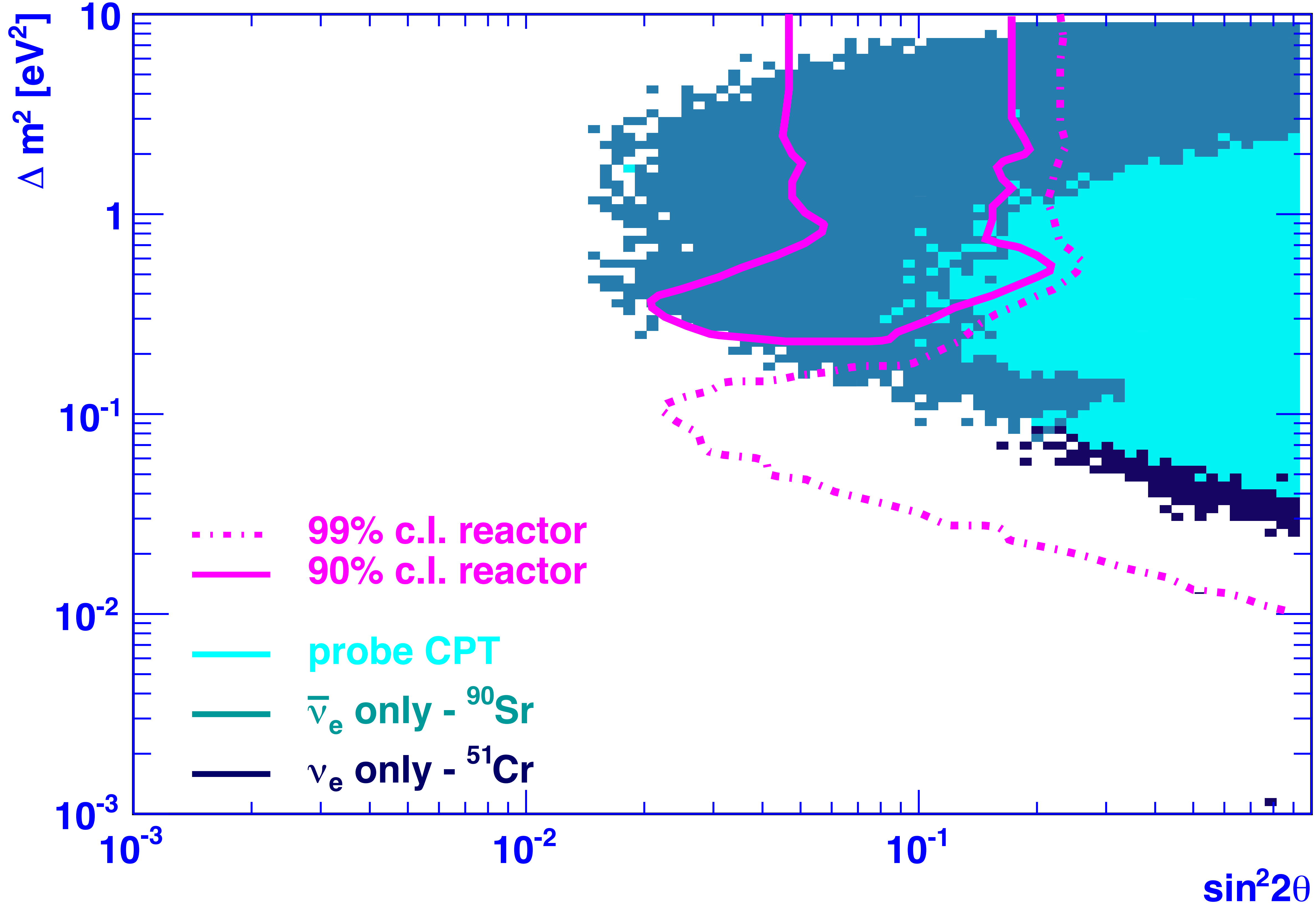
- We have just started to study the sensitivity of a "global analysis", i.e. using waves and total counts in a unique fit



Global analysis: ^{51}Cr in the center – 5 MCi



Probing CPT



Δm^2 [eV^2]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta$
99% c.l. reactor
90% c.l. reactor
probe CPT
$\bar{\nu}_e$ only - ^{90}Sr
ν_e only - ^{51}Cr

Comments on sensitivity

- Our assumptions have been so far **very conservative**
  - We use **3.3 FV for neutrinos.** A larger FV might be considered after careful background subtraction (as done by Lhullier in this workshop who used 6.0 m)
  - We have not yet implemented **L/E analysis** for anti-neutrinos
  - We have not studied yet more energetic sources (^{106}Ru, ^{144}Ce)
- This means that there is **large margin of improvement**
  - WORK IN PROGRESS !

A possible scenario

- **Step 1 - Experiments with external sources**
  - **NEUTRINOS:** **^{51}Cr** or **^{37}Ar** or **similar** in IP or WT, Borexino detector as it is.
    - **No changes anywhere.**
    - **Short runs (a few months),** possible any time as soon as source is ready and as soon as most of **^{210}Po has decayed (2 years from now)**
    - **Compatible with solar neutrino program**
  - **ANTI-NEUTRINOS:** **^{90}Sr** or other more energetic in IP or WT
    - **~ 1 year run**
    - After the end of Borexino solar neutrino program (>3 years from now)
    - Possibly by putting **PPO in the buffers** to get a **larger volume**

- **Step 2 - Experiments with source in the center**
  - The source can go inside, with a fiducial volume of **~ 6 m for ν and ~4 m for ν**
    - ~ 1 year of work to prepare this
  - **Very large sensitivity experiment**
  - The cost is anyway well below the cost of the sources

in 5-6 years from now, very powerful probe of ν_e and $\bar{\nu}_e$ disappearance

Conclusion

- **Borexino is a very good detector for short base line experiments with artificial neutrino sources**
  - **Neutrinos** and **anti-neutrinos** oscillations can be both **probed with high sensitivity**
- **The sensitivity can be very good,** especially with ^{90}Sr sources or similar
- **CPT violation** effects can be probed in a large region where both Δm^2 and $\sin^2(2\vartheta_s)$ can be precisely measured independently
- The measurement can be completed during and after the end of the solar neutrino program
- **The proposal is very cost effective.** The main cost by far due to the sources, even in the case of drain/refill for vessels removal
  - **Borexino is in Hall C, up and running**

Thank you