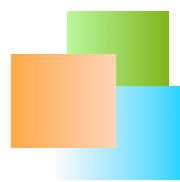


Short base-line ν_e and $\bar{\nu}_e$ oscillations with Borexino

Marco Pallavicini
on behalf of the Borexino Collaboration

LNGS, May 3rd and 4th, 2011

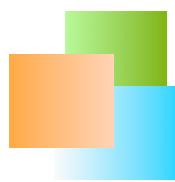


Talk content



- 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

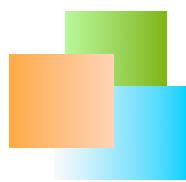


- The possibility to study **neutrino properties** using powerful **radioactive sources** in Borexino has been considered since the 1991 proposal

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 ?)
 - 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:

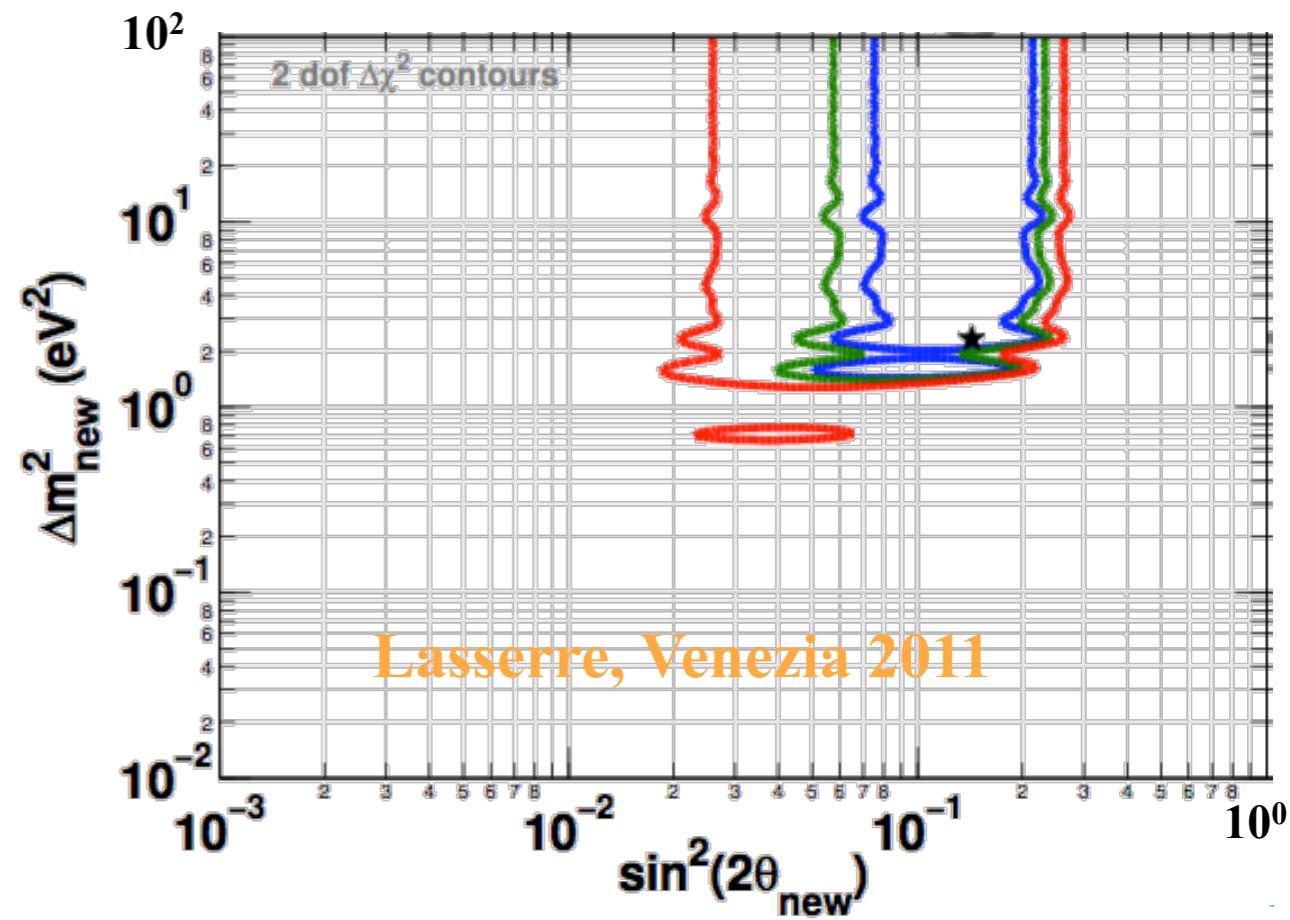
$$\Delta m^2 \approx 1 \text{ eV}^2$$

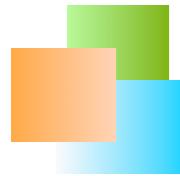
$$\sin^2(2\vartheta_s) \approx 0.1$$

yields, with neutrinos of **energy $\approx 1 \text{ MeV}$** , **oscillation lengths of the order of 1 m**

- This is significantly **more than the spatial resolution** of reconstructed events in Borexino (**$\approx 12 \text{ cm}$ @ 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 these parameters might be **SEEN** clearly with a source experiment



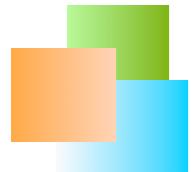


The Borexino experiment



- I assume that the experiment is reasonably well known. 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 $^{7\text{Be}}$ measurements) and **anti-neutrinos** (geo-neutrinos detection)
- The first phase of the experiment is over:
 - Precision measurement of the $^{7\text{Be}}$ solar neutrinos **hep-ex/1104.1816v1**
 - 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



Dubna JINR
(Russia)



**Kurchatov
Institute**
(Russia)



**Jagiellonian U.
Cracow**
(Poland)



Munich
(Germany)



Heidelberg
(Germany)



Princeton University



Virginia Tech. University

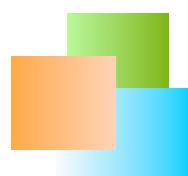


UMass Amherst
(USA)



Hamburg
(Germany)





The Borexino detector



Scintillator:

270 t PC+PPO (1.5 g/l)

in a 150 μm thick

inner nylon vessel ($R = 4.25 \text{ m}$)

Buffer region:

PC+DMP quencher (5 g/l)

$4.25 \text{ m} < R < 6.75 \text{ m}$

Outer nylon vessel:

$R = 5.50 \text{ m}$

(^{222}Rn barrier)

Carbon steel plates

Stainless Steel Sphere:

$R = 6.75 \text{ m}$

2212 PMTs

1350 m^3

Water Tank:

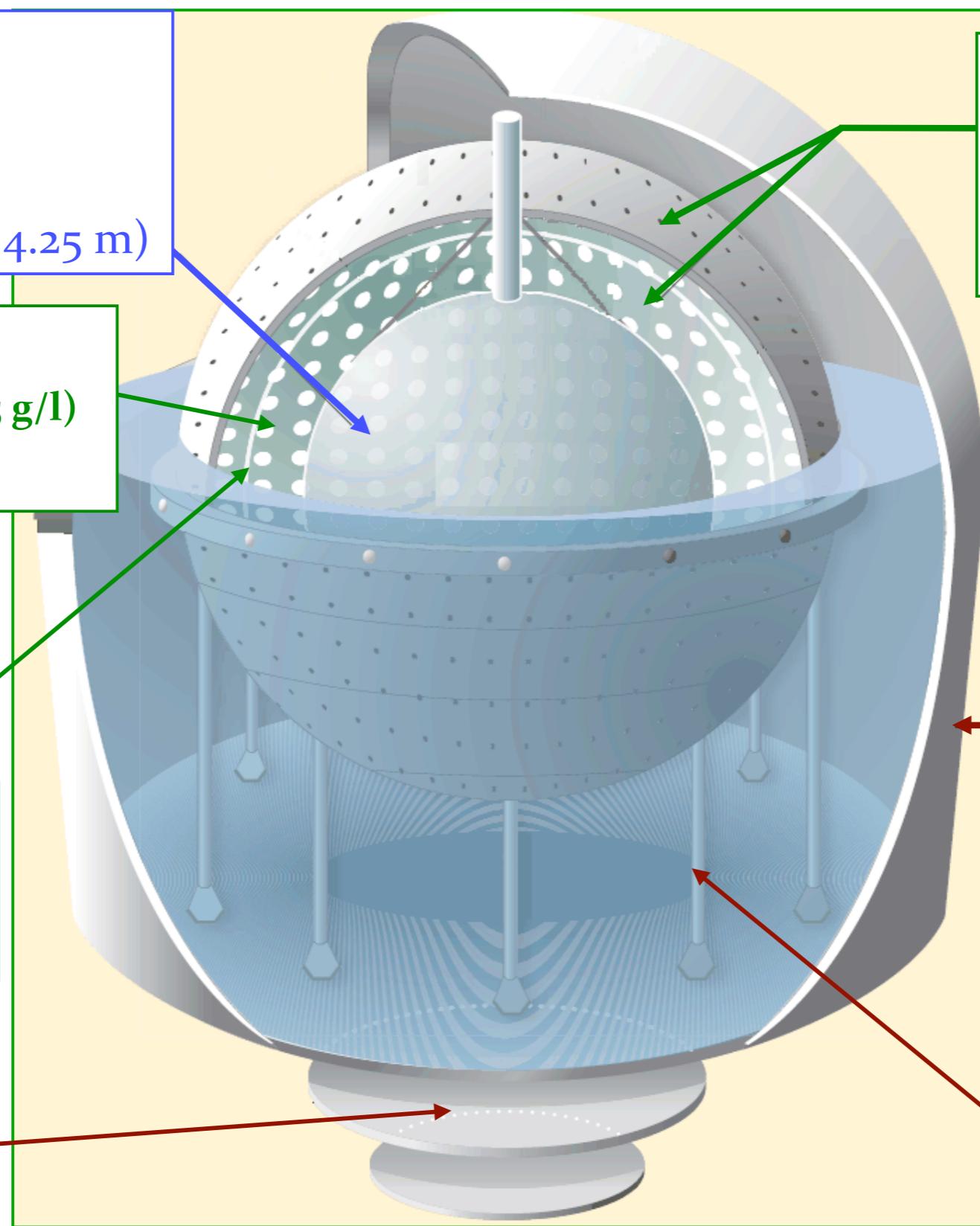
γ and n shield

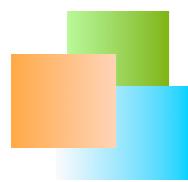
μ water Č detector

208 PMTs in water

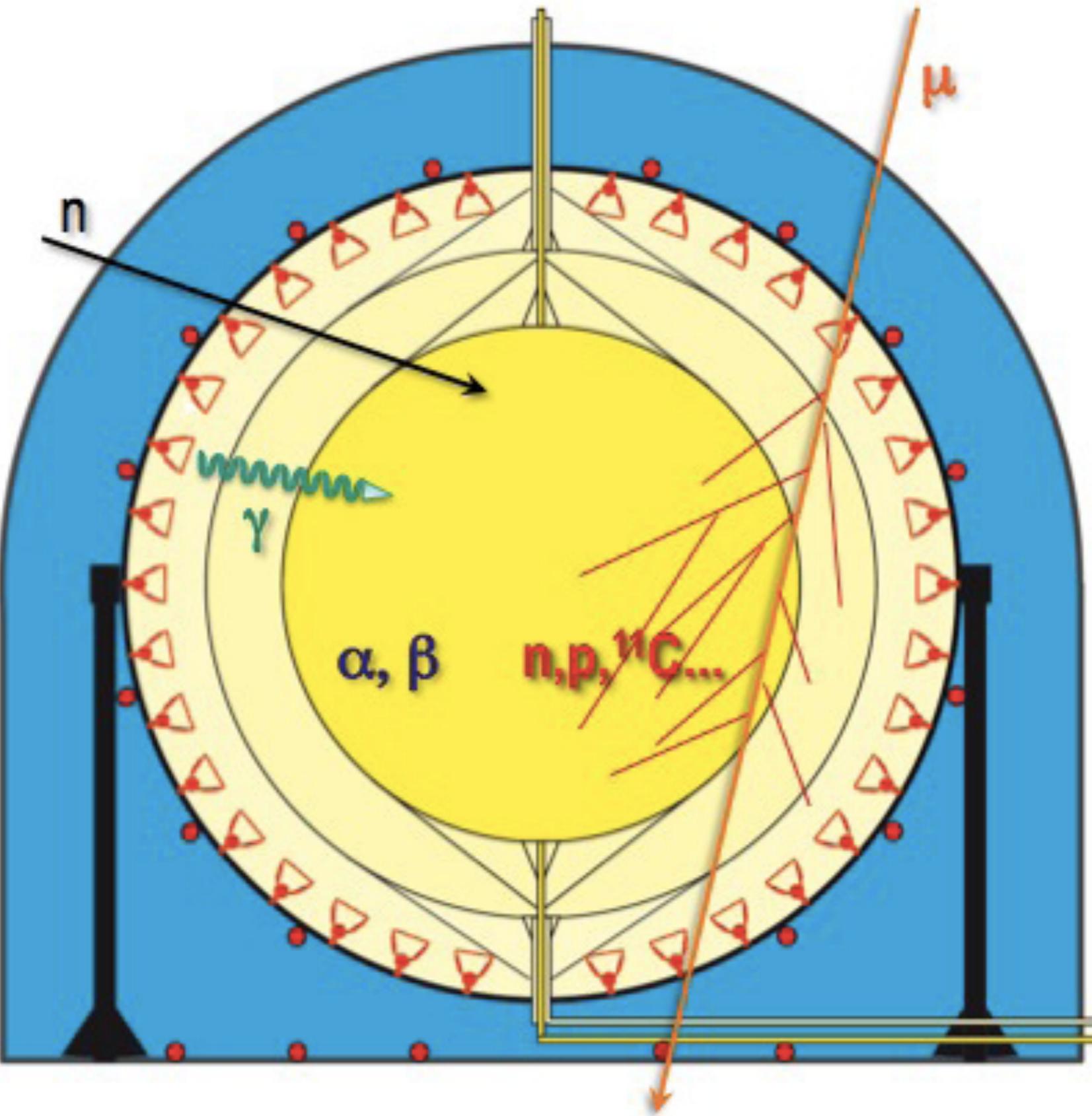
2100 m^3

20 steel legs

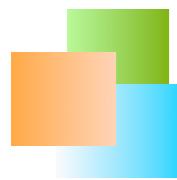




The principle of graded shielding



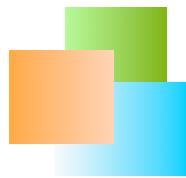
- Materials **more and more pure** as they get closer to the “core”, the Fiducial Volume
- Ultimate background depending on material purity and, mainly, **radioactive traces** in the scintillator at extremely low levels
- **15 years of work to reach required radio-purity**



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	$\sim 200 \text{ s}^{-1} \text{ m}^{-2}$ @ sea level	$< 10^{-10} \text{ s}^{-1} \text{ m}^{-2}$	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	$\sim 10^{-12} \text{ g/g}$	$\sim 10^{-18} \text{ g/g}$	selection	threshold	$\sim 2 \cdot 10^{-18} \text{ g/g}$
^{238}U ^{232}Th	dust, metallic	$10^{-5}\text{-}10^{-6} \text{ g/g}$	$< 10^{-16} \text{ g/g}$	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	$1.6 \pm 0.1 \cdot 10^{-17} \text{ g/g}$ $5.1 \pm 1 \cdot 10^{-18} \text{ g/g}$
^{7}Be	cosmogenic	$\sim 3 \cdot 10^{-2} \text{ Bq/t}$	$< 10^{-6} \text{ Bq/t}$	distillation	--	not seen
^{40}K	dust, PPO	$\sim 2 \cdot 10^{-6} \text{ g/g}$ (dust)	$< 10^{-18} \text{ g/g}$	distillation, W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		$< 1 \text{ c/d/t}$	distillation, W.E., filtration, cleanliness	fit	May '07: 70 c/d/t Jan '10: $\sim 1 \text{ c/d/t}$
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	$< 10 \text{ cpd } 100 \text{ t}$	N_2 stripping cleanliness	tagging, α/β	$< 1 \text{ cpd } 100 \text{ t}$
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	$< 1 \text{ cpd } 100 \text{ t}$	N_2 stripping	fit	$<< ^{85}\text{Kr}$
^{85}Kr	air, nuclear weapons	$\sim 1 \text{ Bq/m}^3$ (air)	$< 1 \text{ cpd } 100 \text{ t}$	N_2 stripping	fit	$30 \pm 5 \text{ cpd/100 t}$ NOW: $< 5 !$

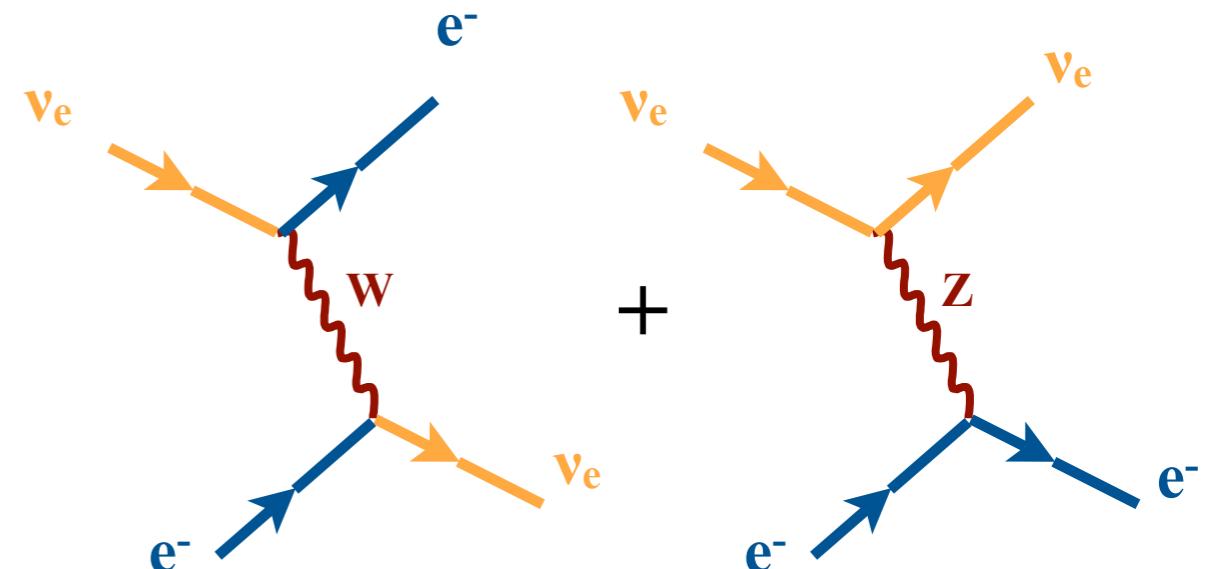


ν_e and $\bar{\nu}_e$ detection in Borexino



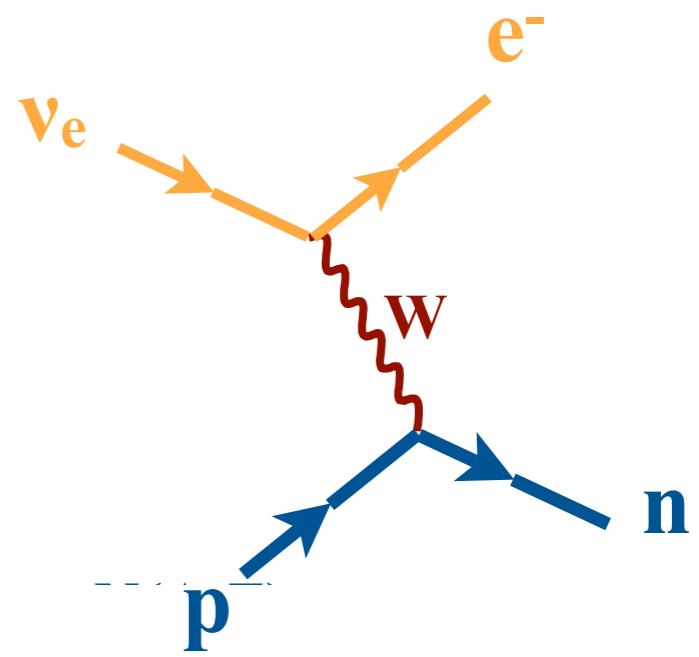
● Electron neutrinos

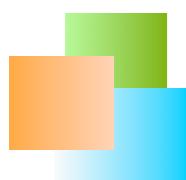
- Elastic scattering on electrons
- No directionality
- Light yield: ≈ 500 p.e. / MeV
- Spatial resolution: ≈ 12 cm @ 1 MeV
- Powerful α/β discrimination
- Background mainly due to ^7Be solar neutrinos !



● 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

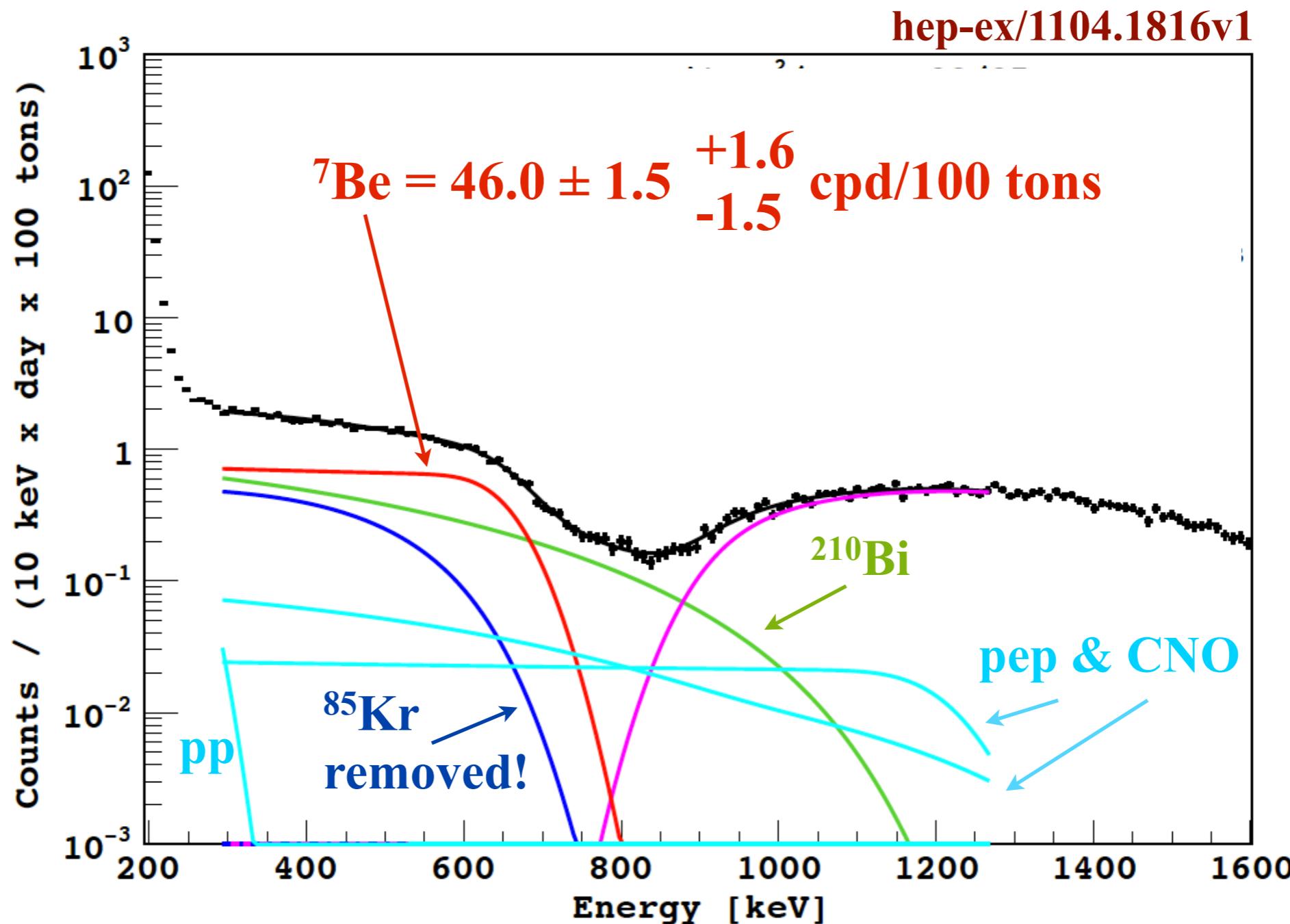


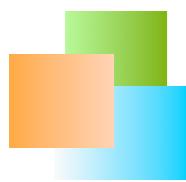


Capability to detect low energy ν_e – I



- The main goal of the experiment is the **detection of ^7Be 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)

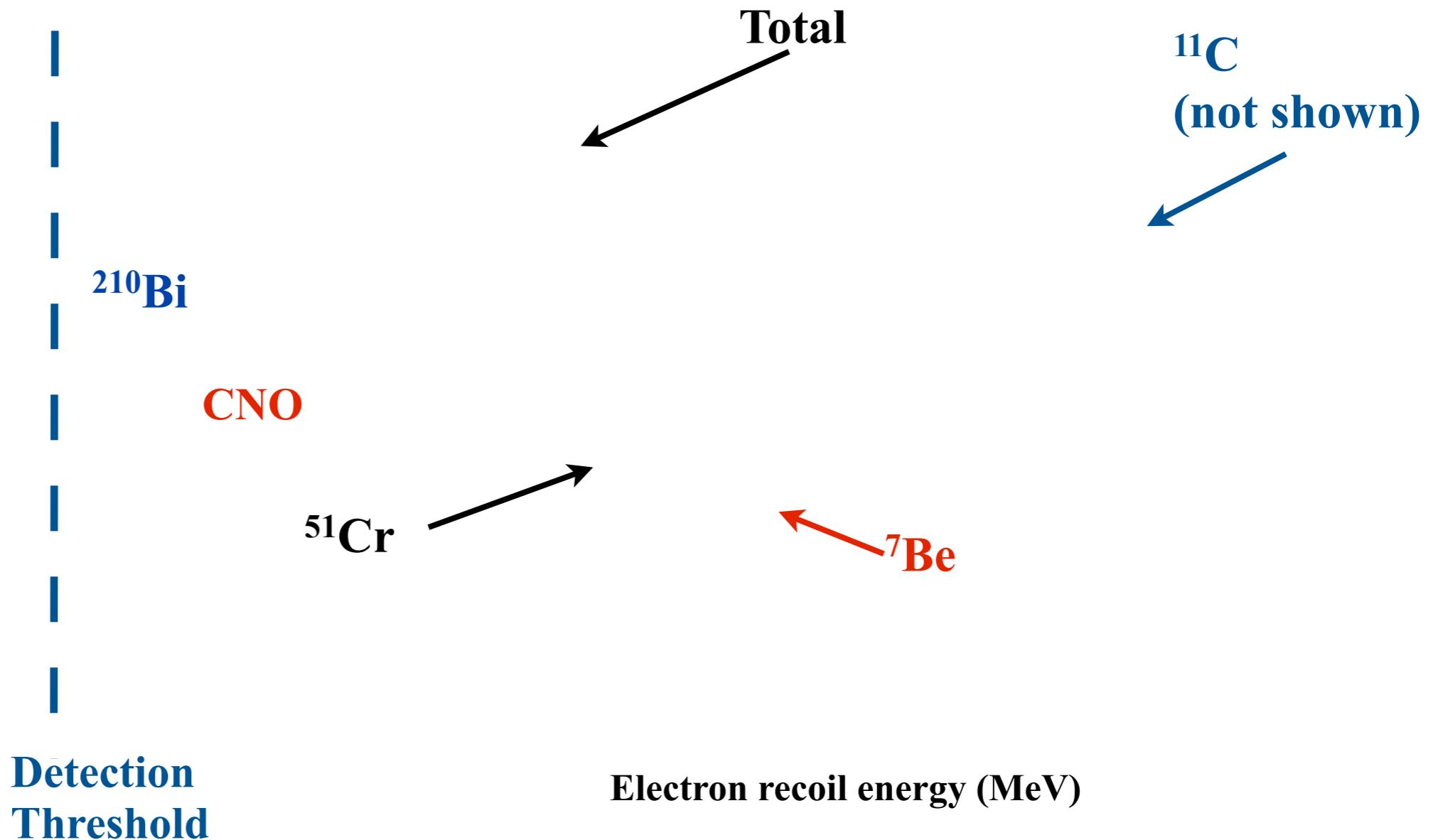


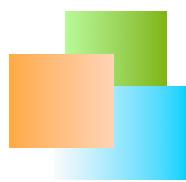


Capability to detect low energy ν_e – 2



- **${}^7\text{Be}$ 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 ${}^7\text{Be}$, **but shifted in energy**
- EXAMPLE: **5 MCi ${}^{51}\text{Cr}$** source: **84 ev/day** above detection threshold, **~ twice ${}^7\text{Be}$**





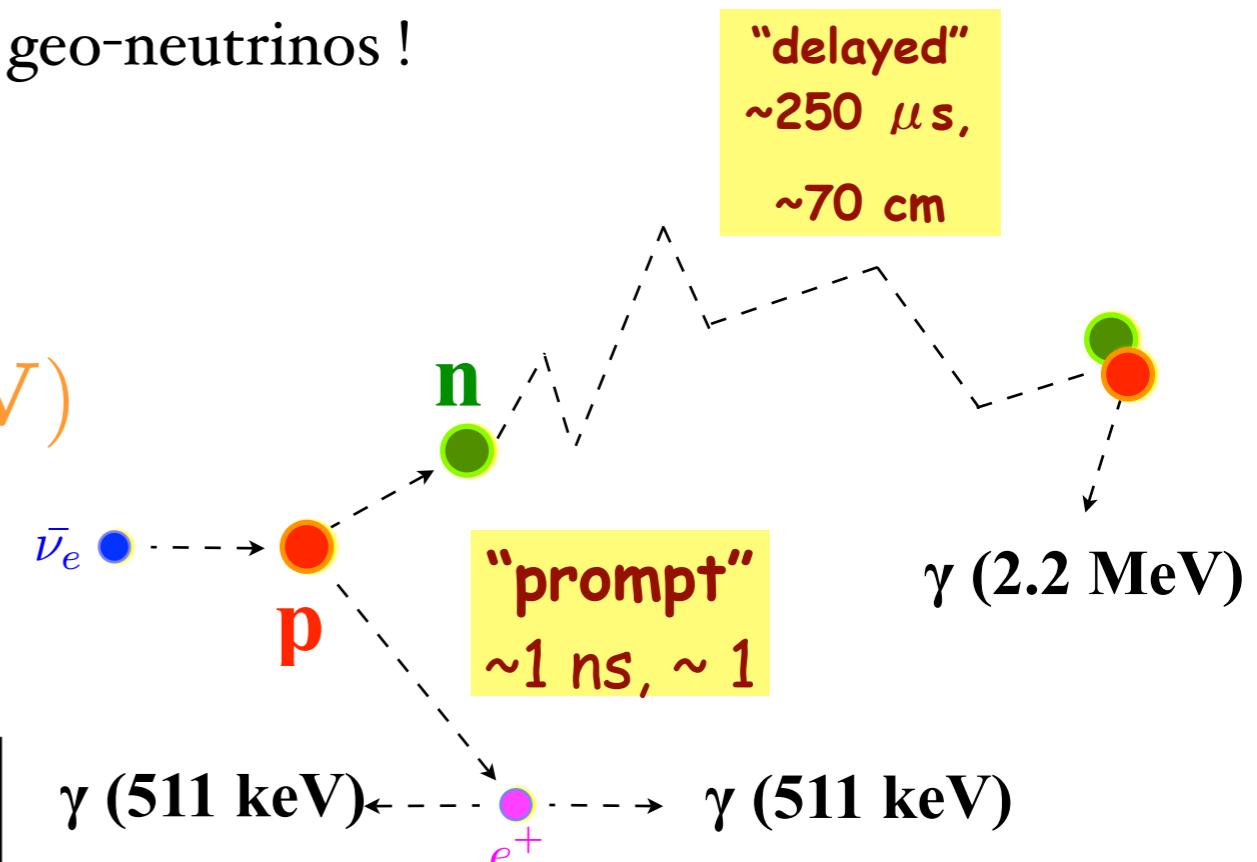
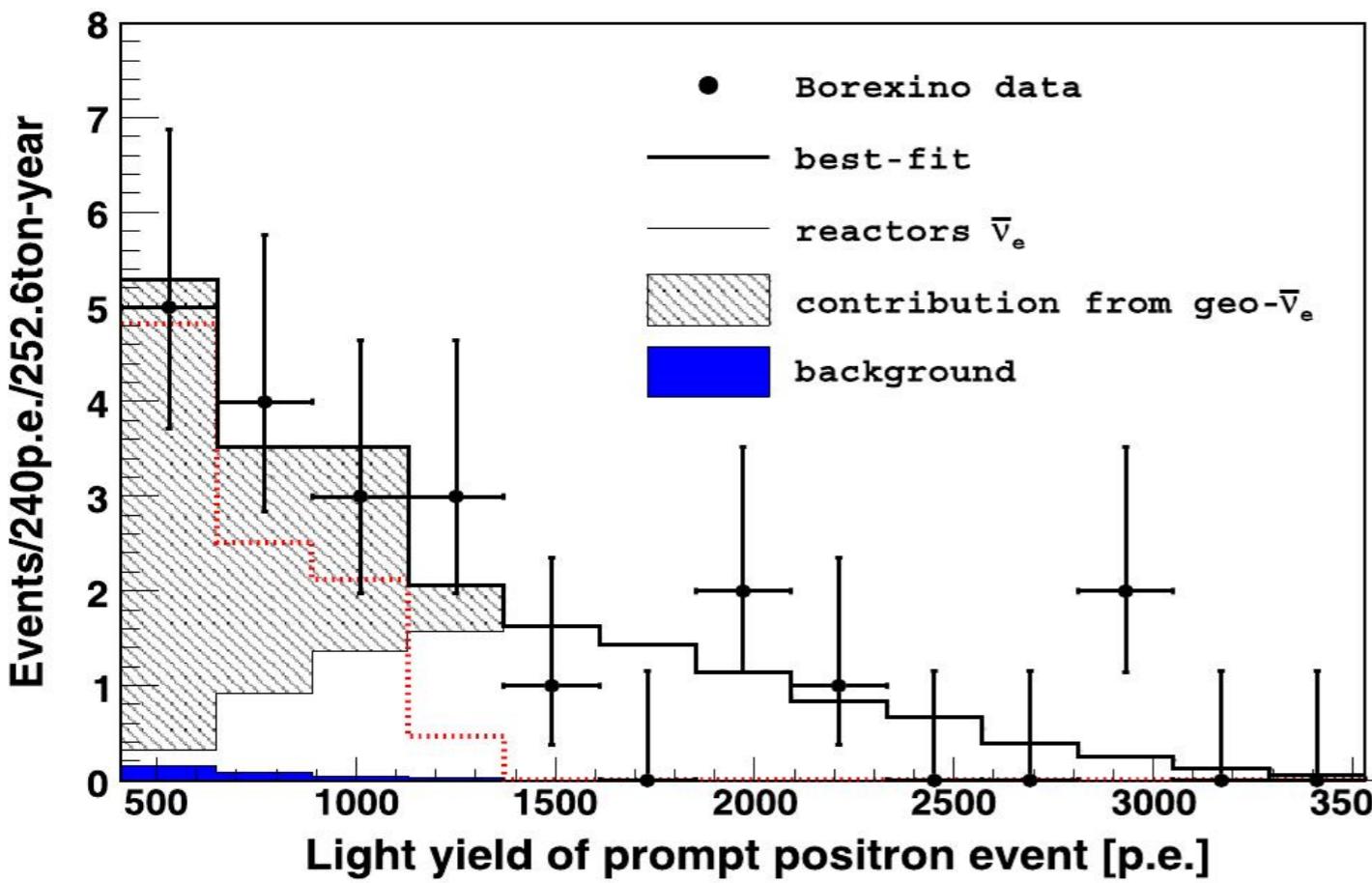
Capability to detect $\bar{\nu}_e$



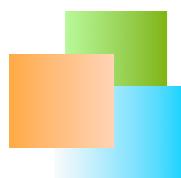
- Inverse β decay on protons yields a super-clean signature in Borexino
 - Background only from reactors in Europe and geo-neutrinos !



Phys. Lett. B687:299-304, 2010



Background to ^{90}Sr
source experiment:
 $\sim 5 \text{ cpy} / 300 \text{ t} !$



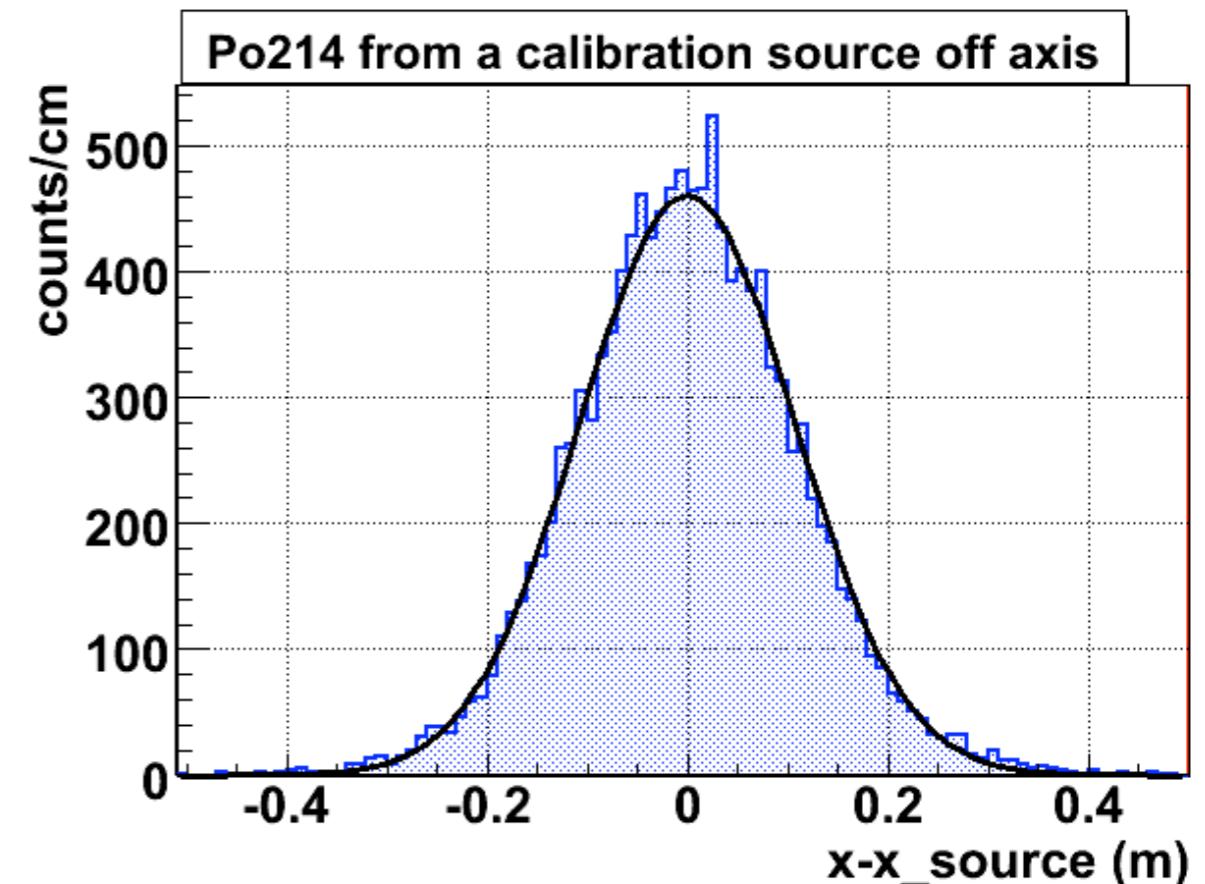
Systematic errors

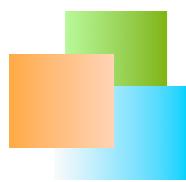


- A big **calibration** effort have reduced the **fiducial volume** and energy scale errors with respect to previous papers
 - The most important for the goal of this talk is **FV determination**

[hep-ex/1104.1816v1](#)

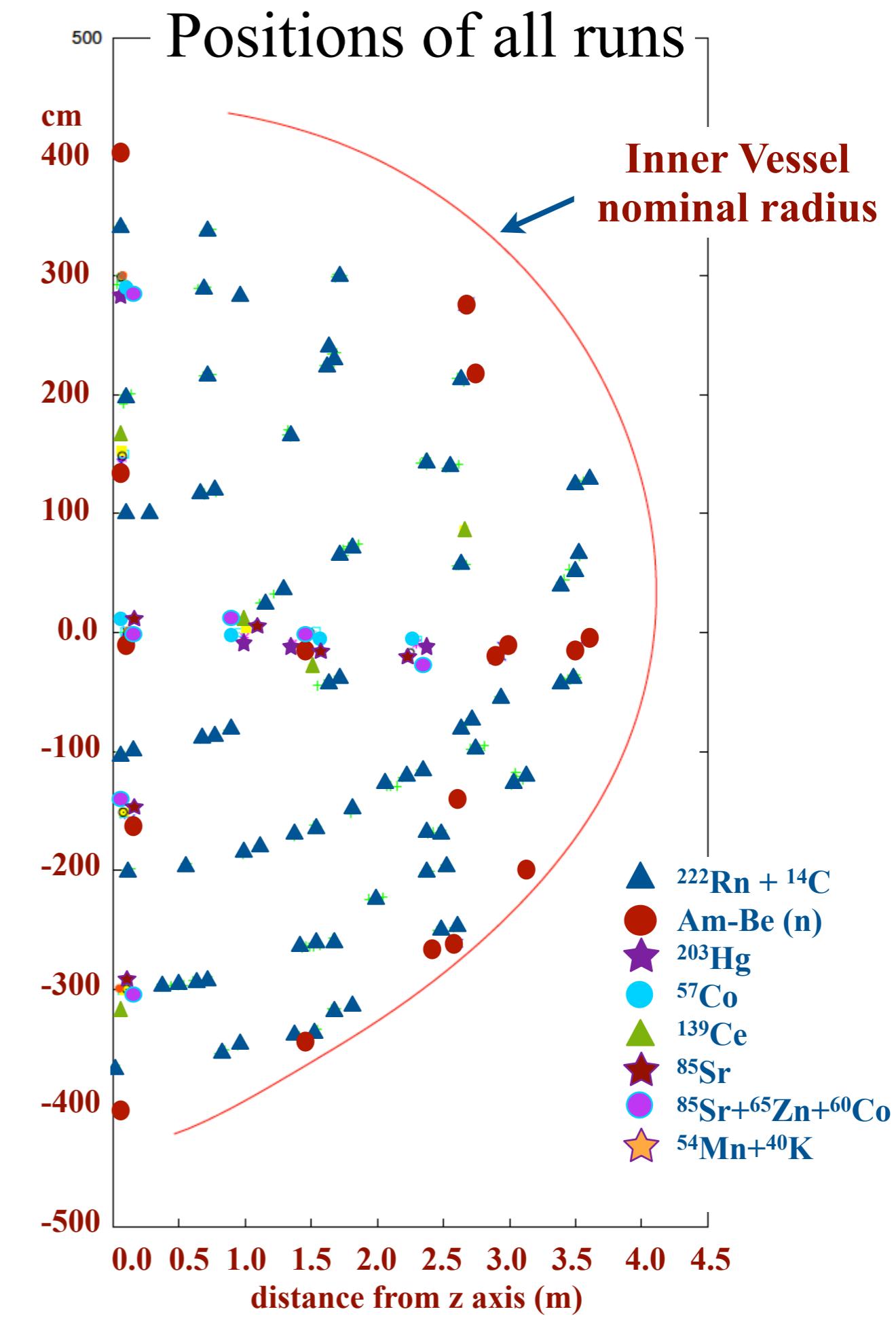
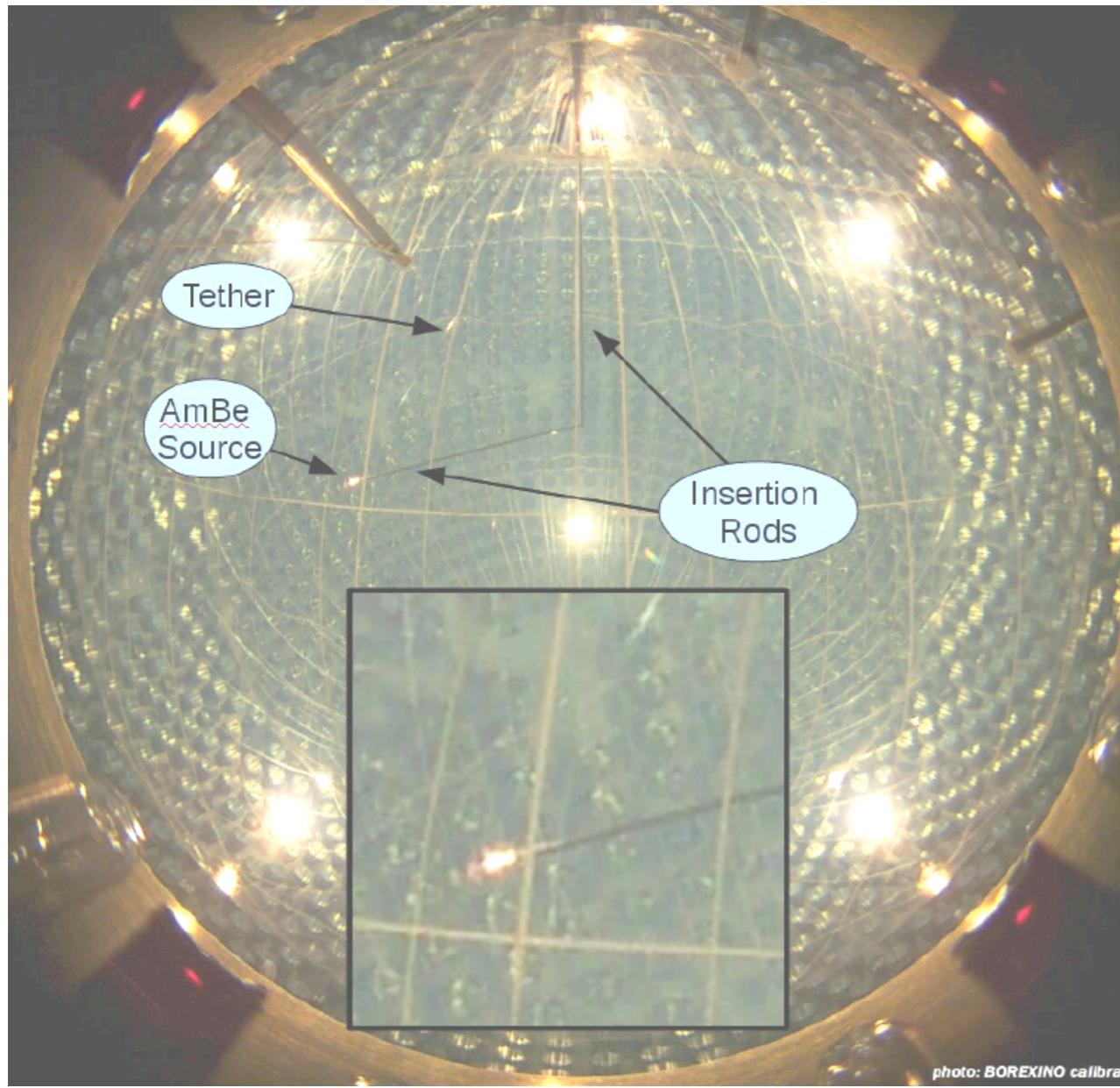
Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Position reconstruction	+1.3 -0.5
Energy scale	2.7
Fit consistency	1.7
Fit methods	1.0
Total Systematic Error	+3.6 -3.4

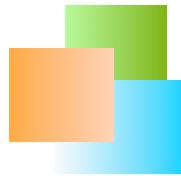




Fiducial volume

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





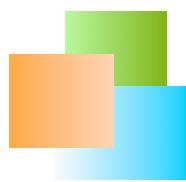
Possible neutrino sources



- 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)**
- **$^{90}\text{Sr} - ^{90}\text{Y}$**
 - **$\bar{\nu}_e$ 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



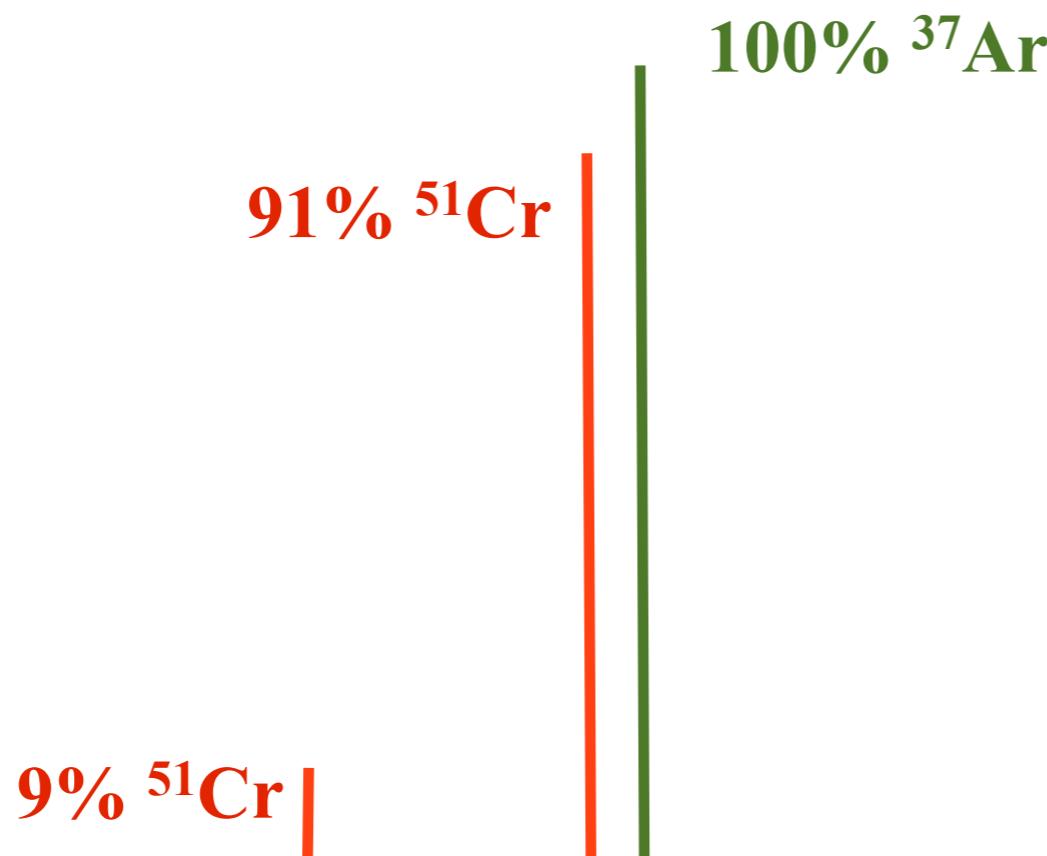


Neutrino energy spectra



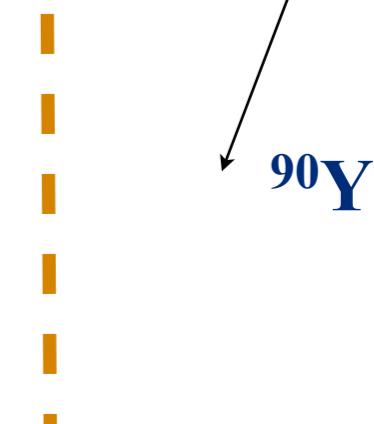
arbitrary scale

^{90}Sr



$$E_{\nu}(^{90}\text{Y}) = 2 \pm 0.2_{\max} \text{ MeV}$$

$\bar{\nu}_e$ threshold



^{90}Y

ν kinetic energy (MeV)



Source locations: 3 options



● “Icarus Pit” - IP

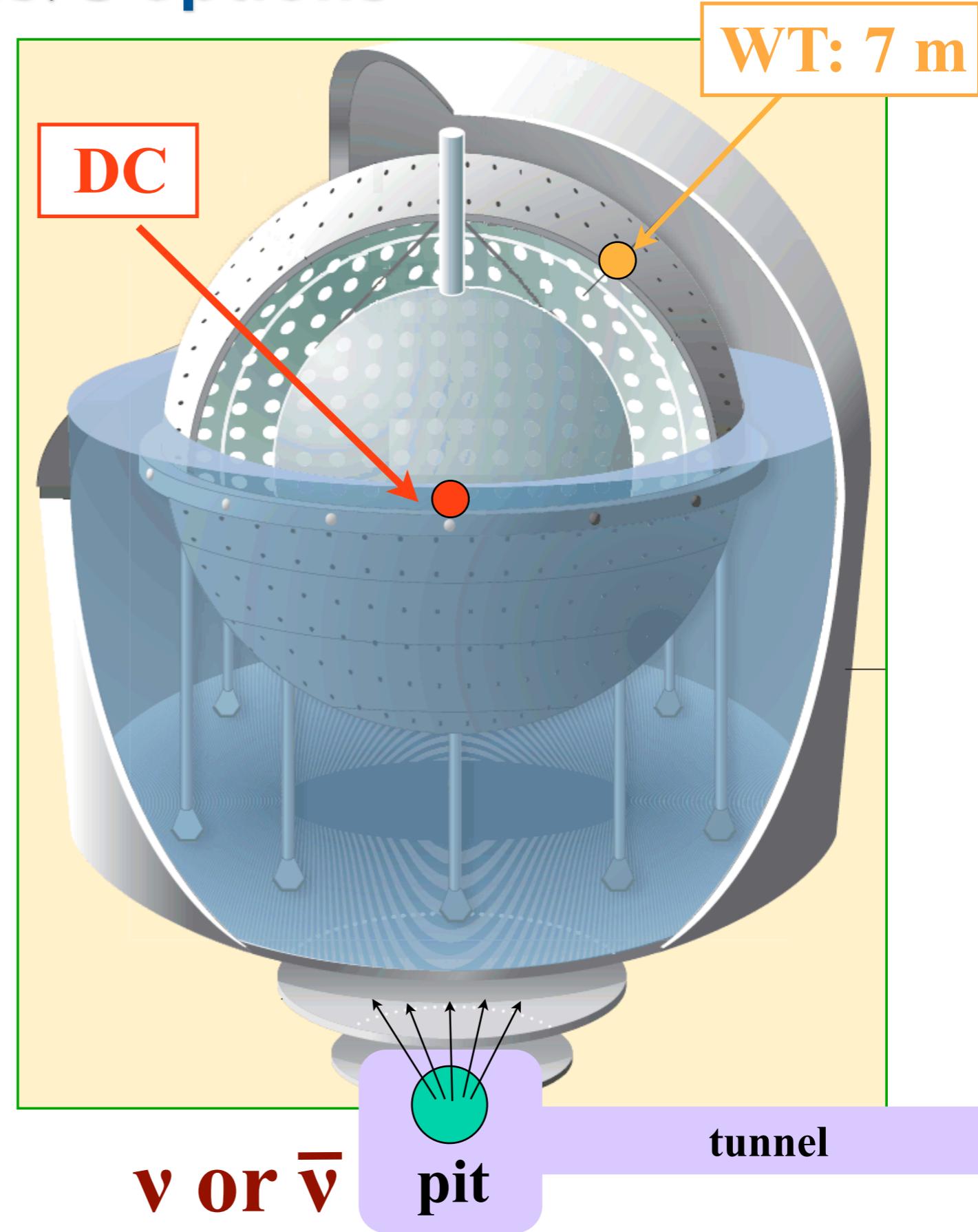
- A pit built **right below** the W.T.
- Access tunnel ready
- **8.25 m** from detector center

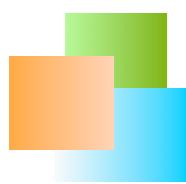
● “Water Tank” - WT

- Access from flanges on top
- Source would be in water
- **7 m** from detector center

● “Detector Center” - DC

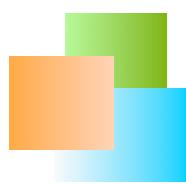
- Possible at the end of Borexino solar neutrino program
- More effort, but much higher sensitivity





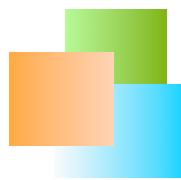
Access to the “icarus pit”





The tunnel to the “icarus pit”

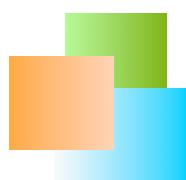




The signal in Borexino



- **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 weakly) 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 than 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

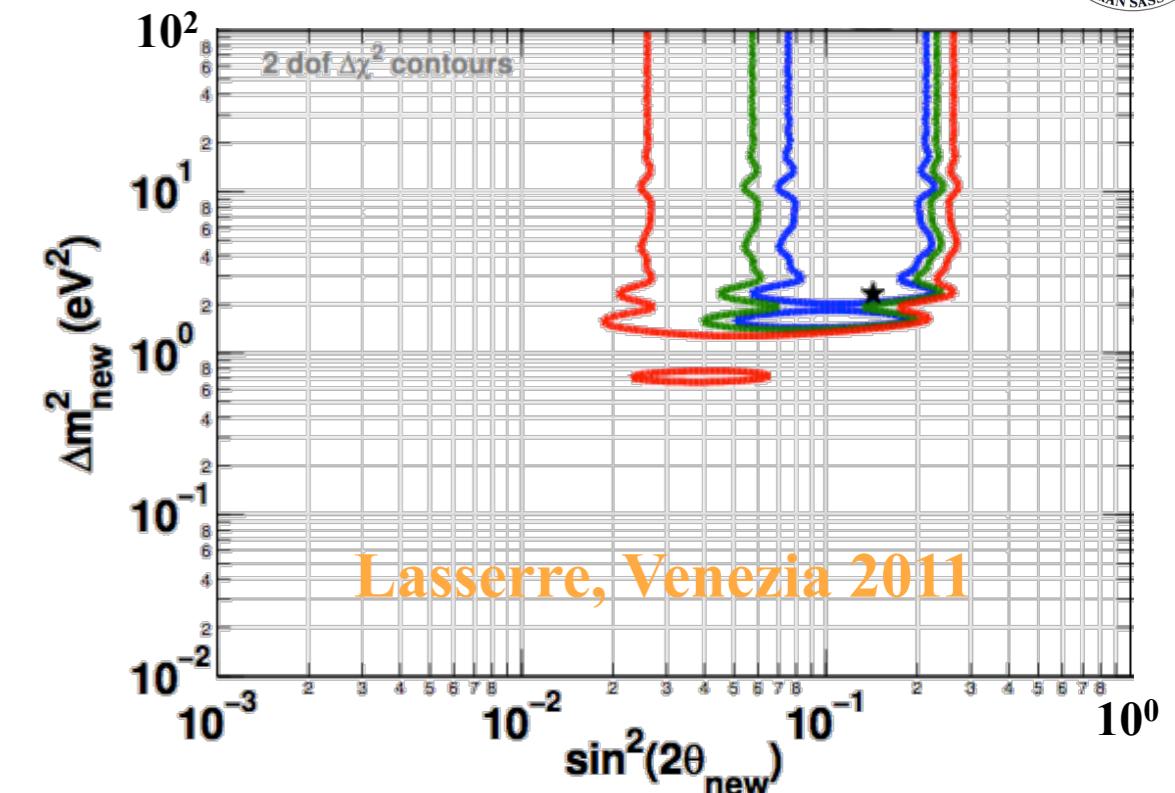
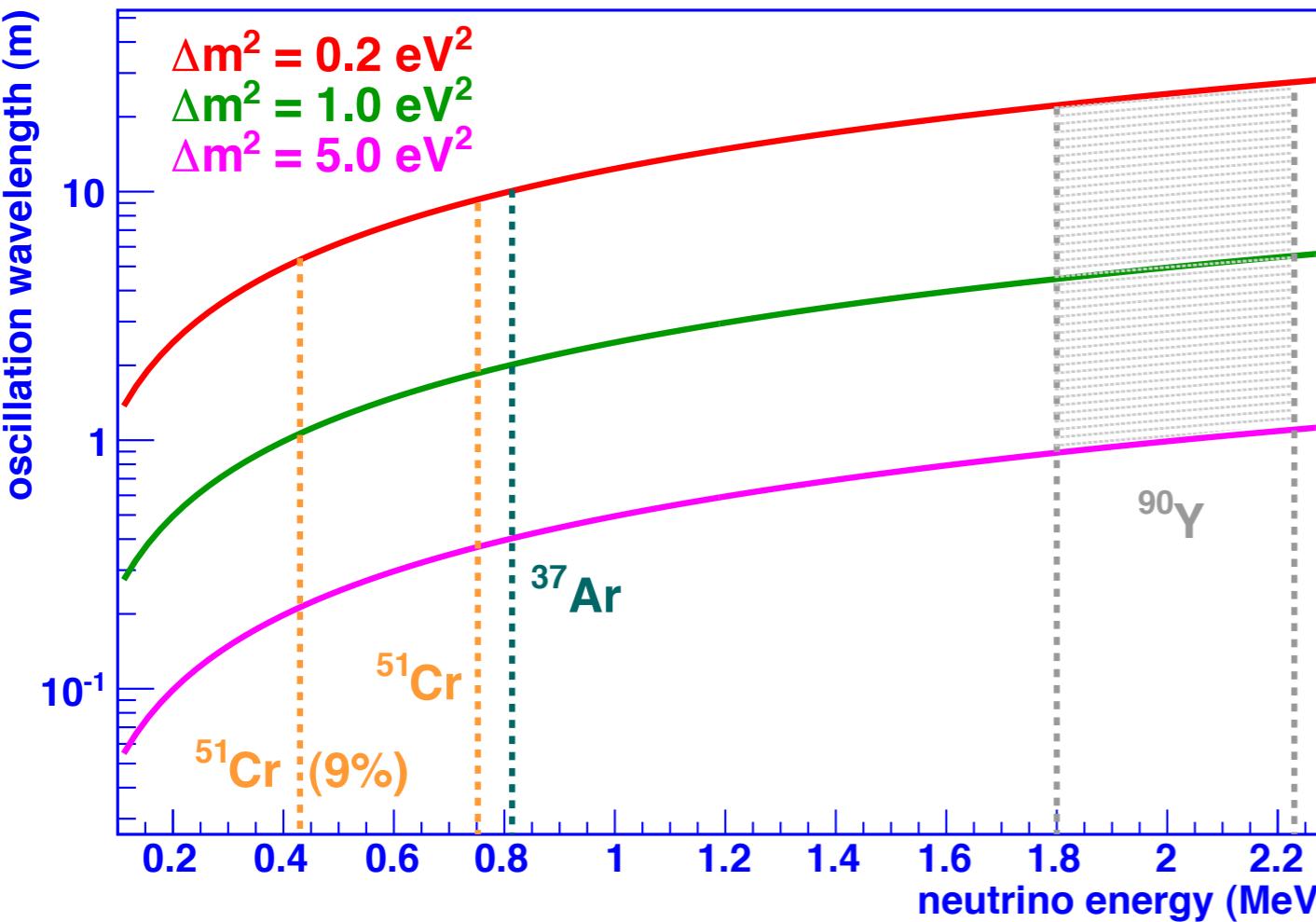


Observation of oscillation waves



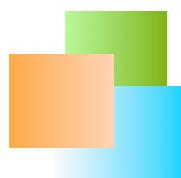
- a key feature of this program is the fact that for many of the parameters indicated by anomalies, Δm^2 and $\sin^2(2\vartheta_s)$ can be measured independently

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



E (MeV)	$\Delta m^2 \text{ [eV}^2]$					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

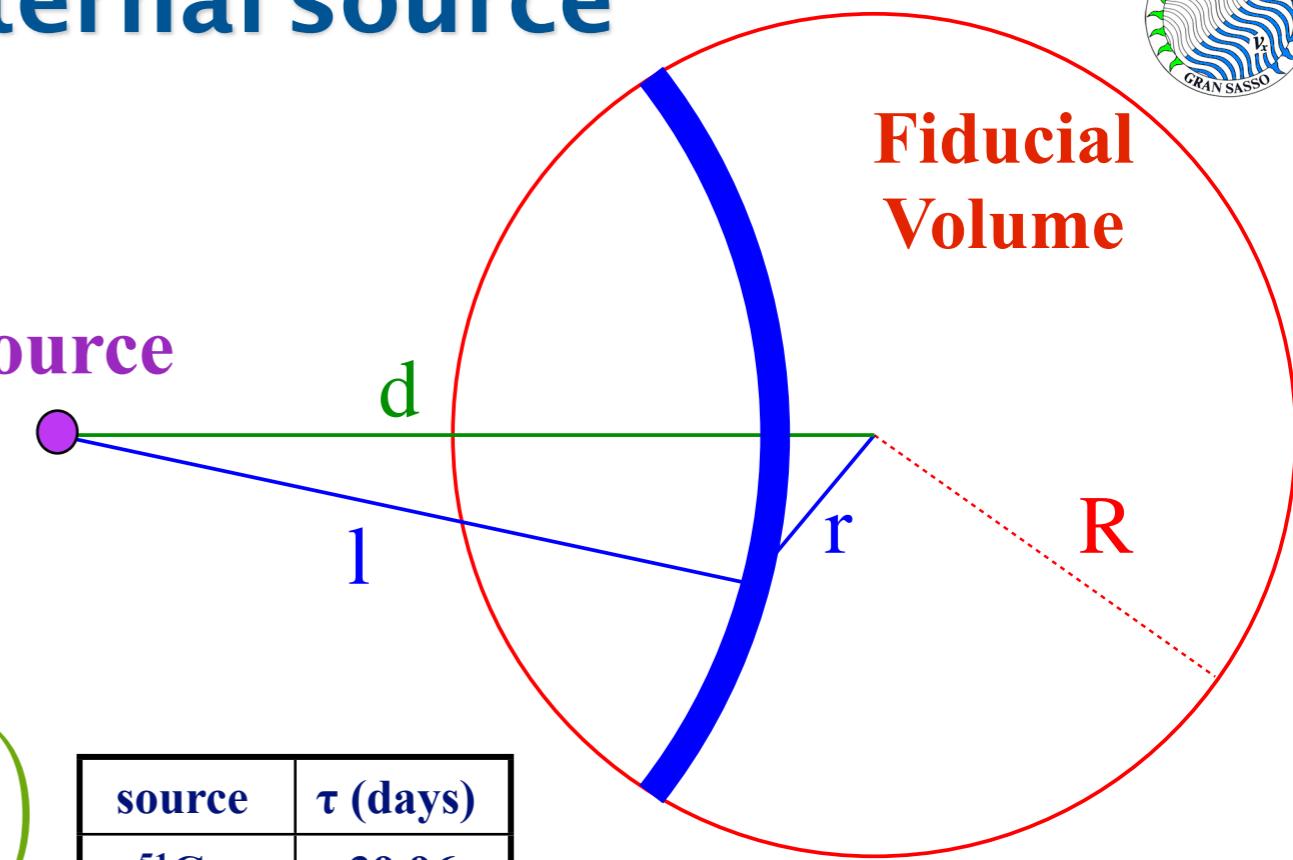


Main formulas for external source



- **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)**

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

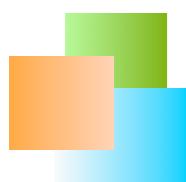
source	τ (days)
^{51}Cr	39.96
^{37}Ar	50.55
^{90}Sr	1.52 E4

- **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 T_1 and max recoil energy T_2

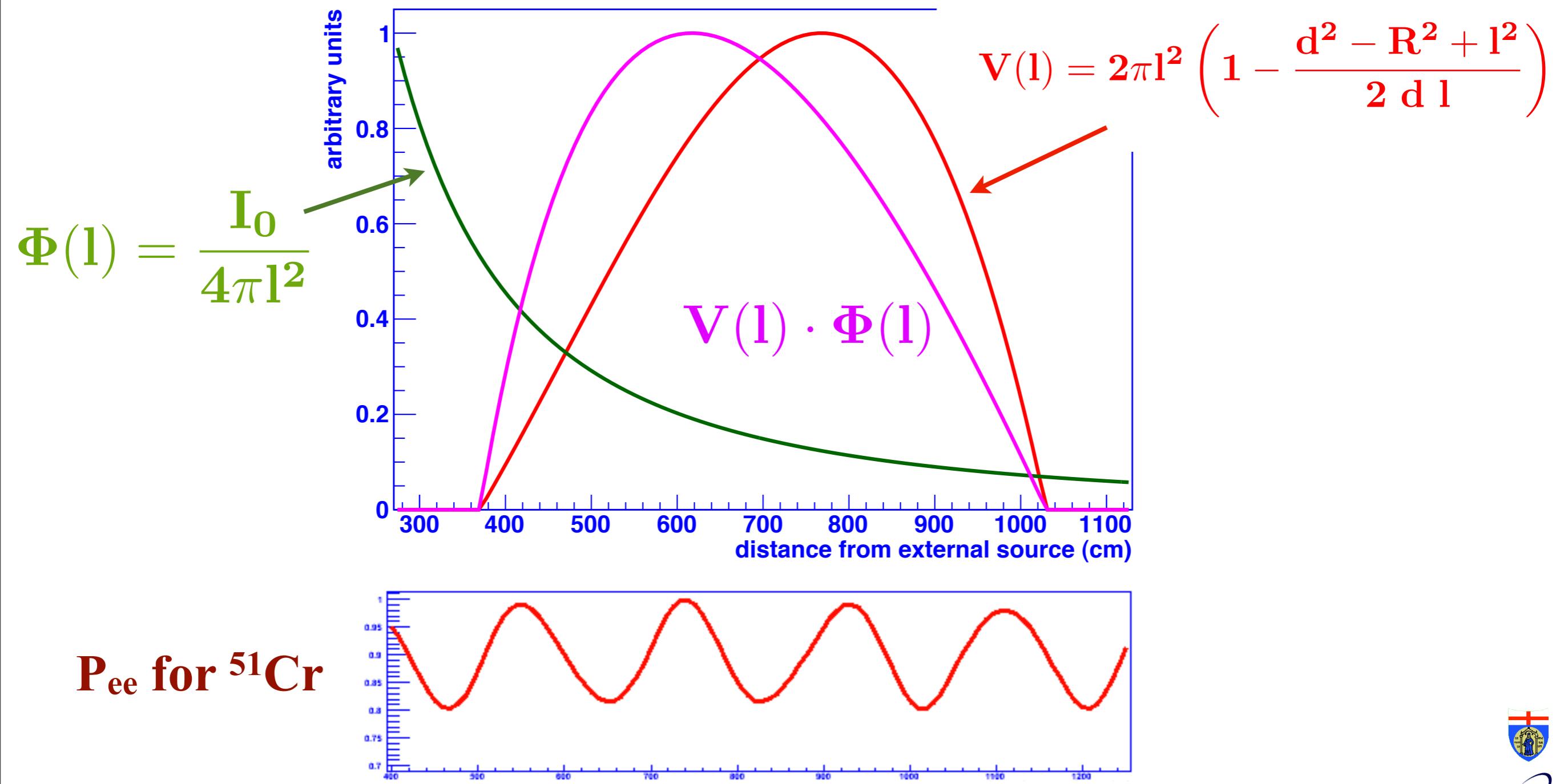
$$N_0(l, T_1, T_2) = n_e \Phi(l) V(l) P_{ee}(l, E) \int_{T_1}^{T_2} \frac{d\sigma_e(E, T)}{dT} dT$$

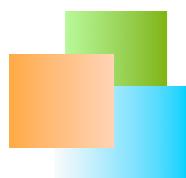


Volume and flux effect for external source



- 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. ($D=7\text{m}$) and F.V. radius = 3.3 m

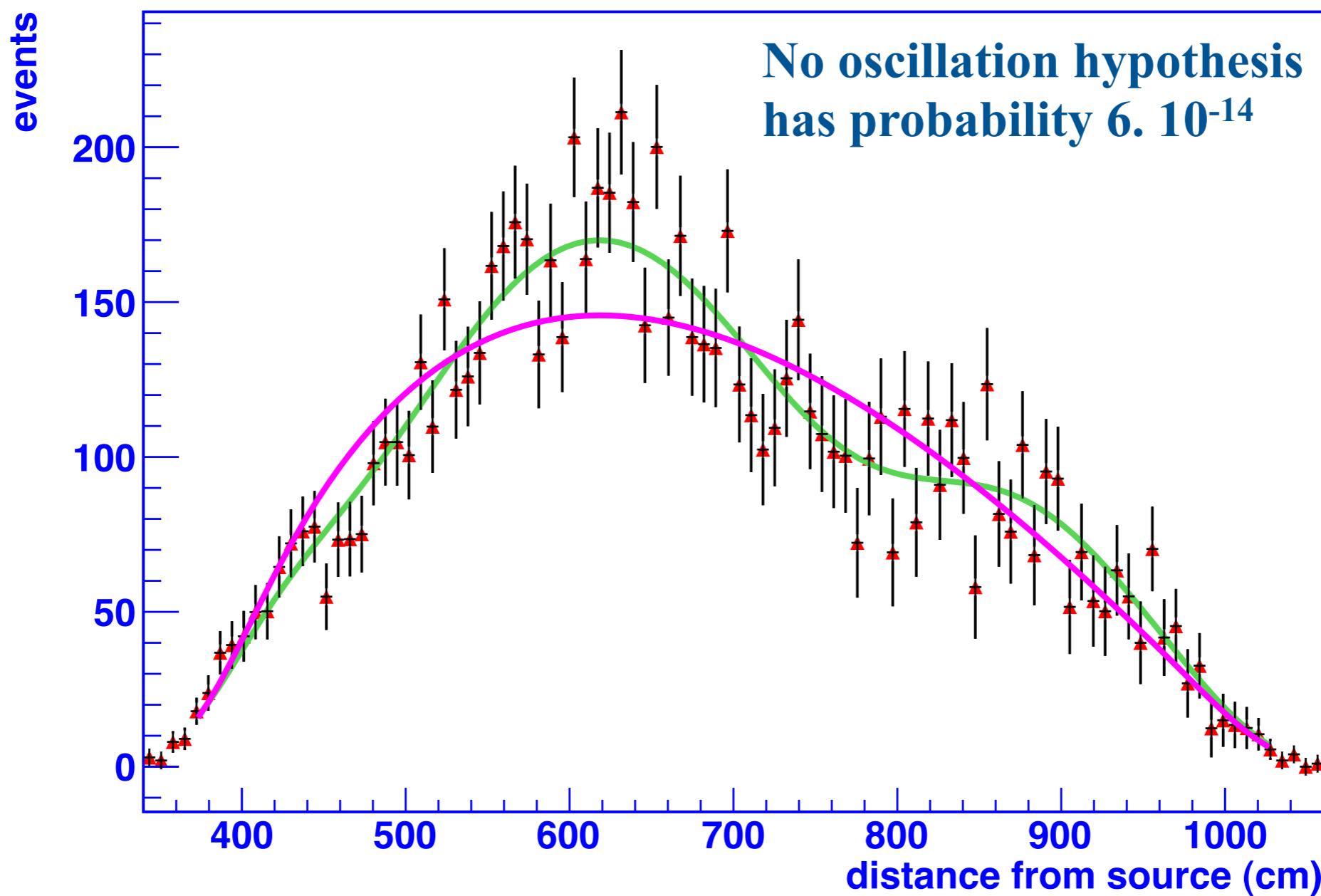


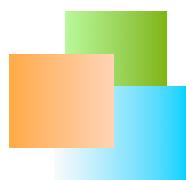


Example: waves with ^{51}Cr source in WT



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

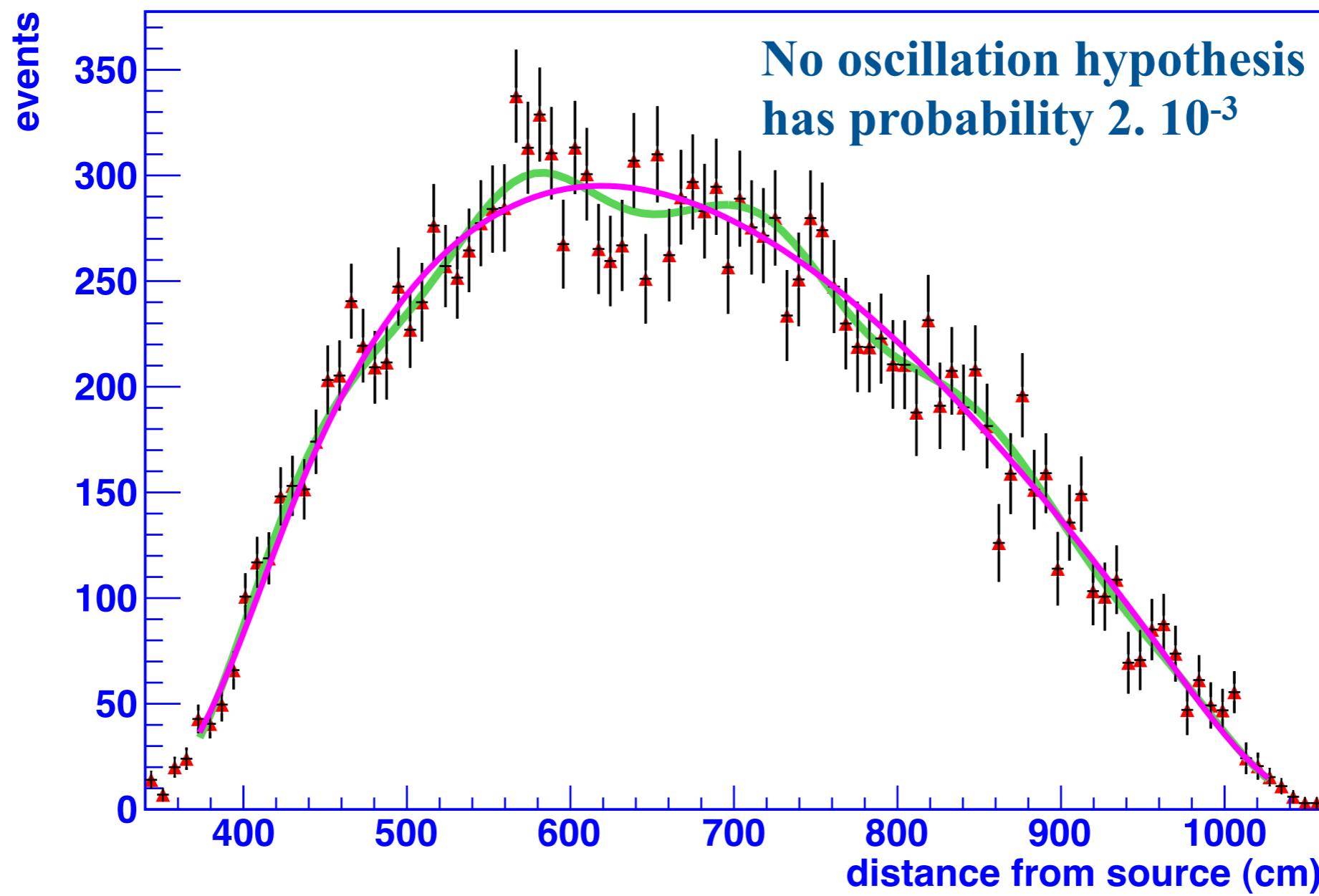


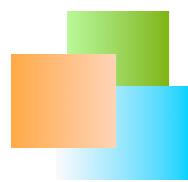


Example: waves with ^{51}Cr source in WT



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

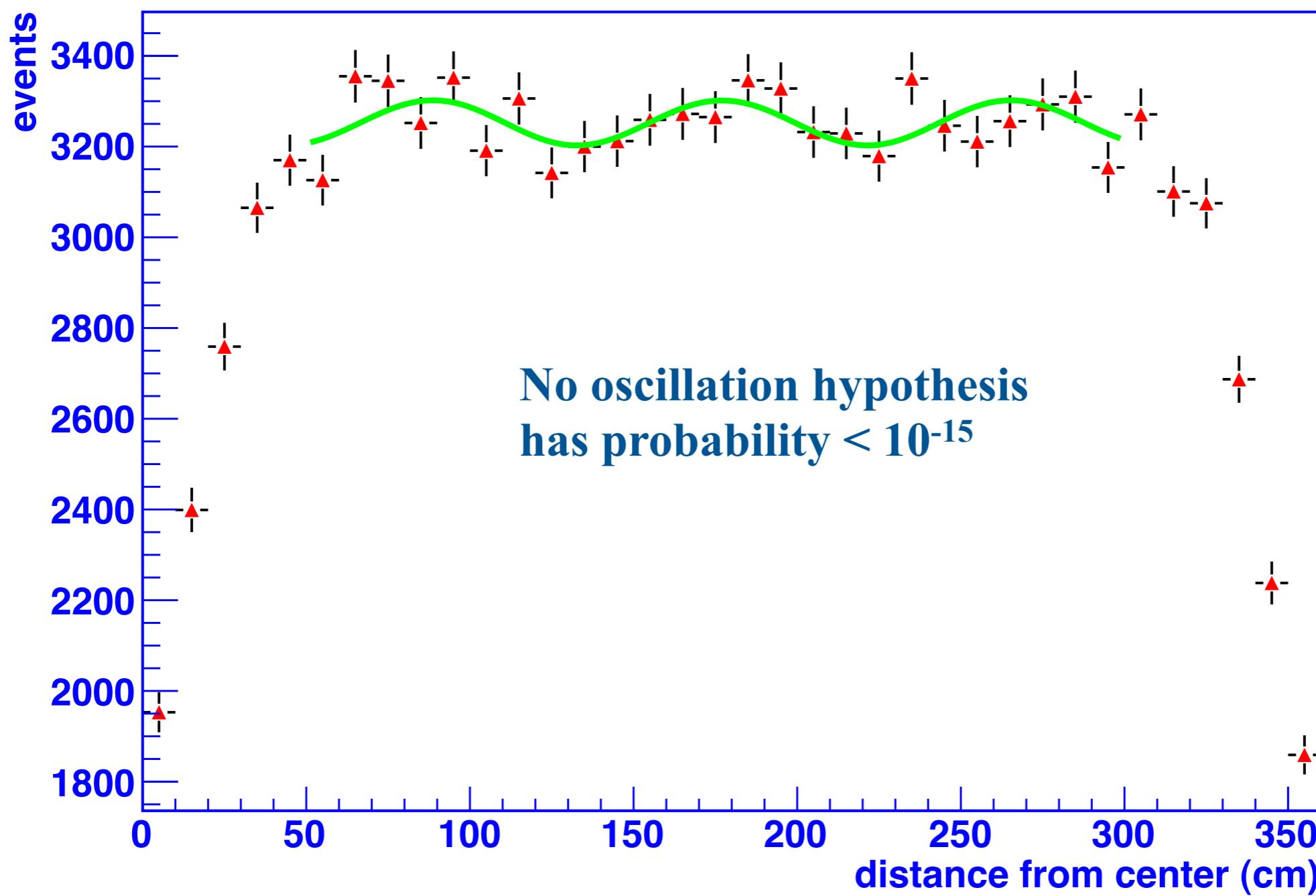


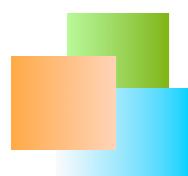


Example: waves with ^{51}Cr in the center

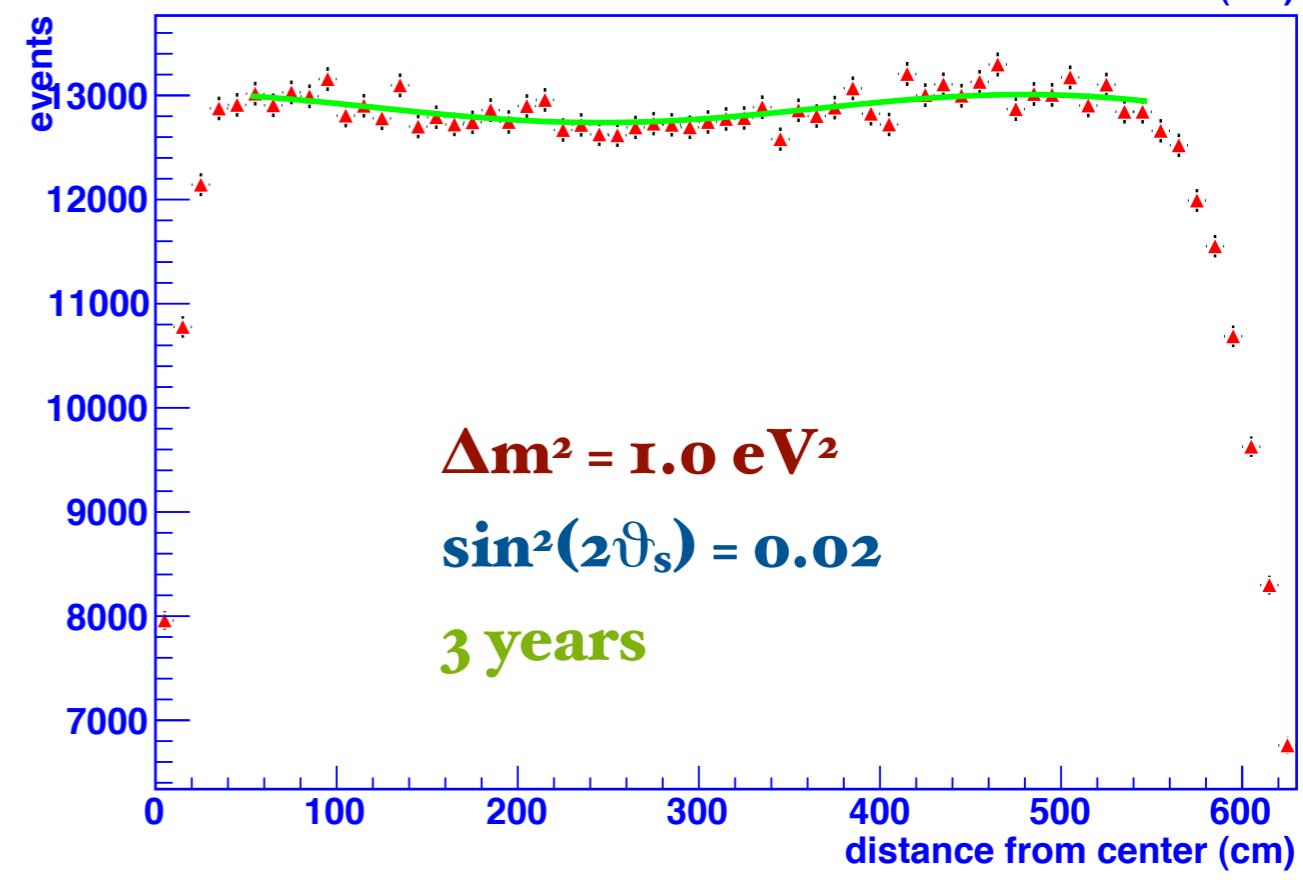
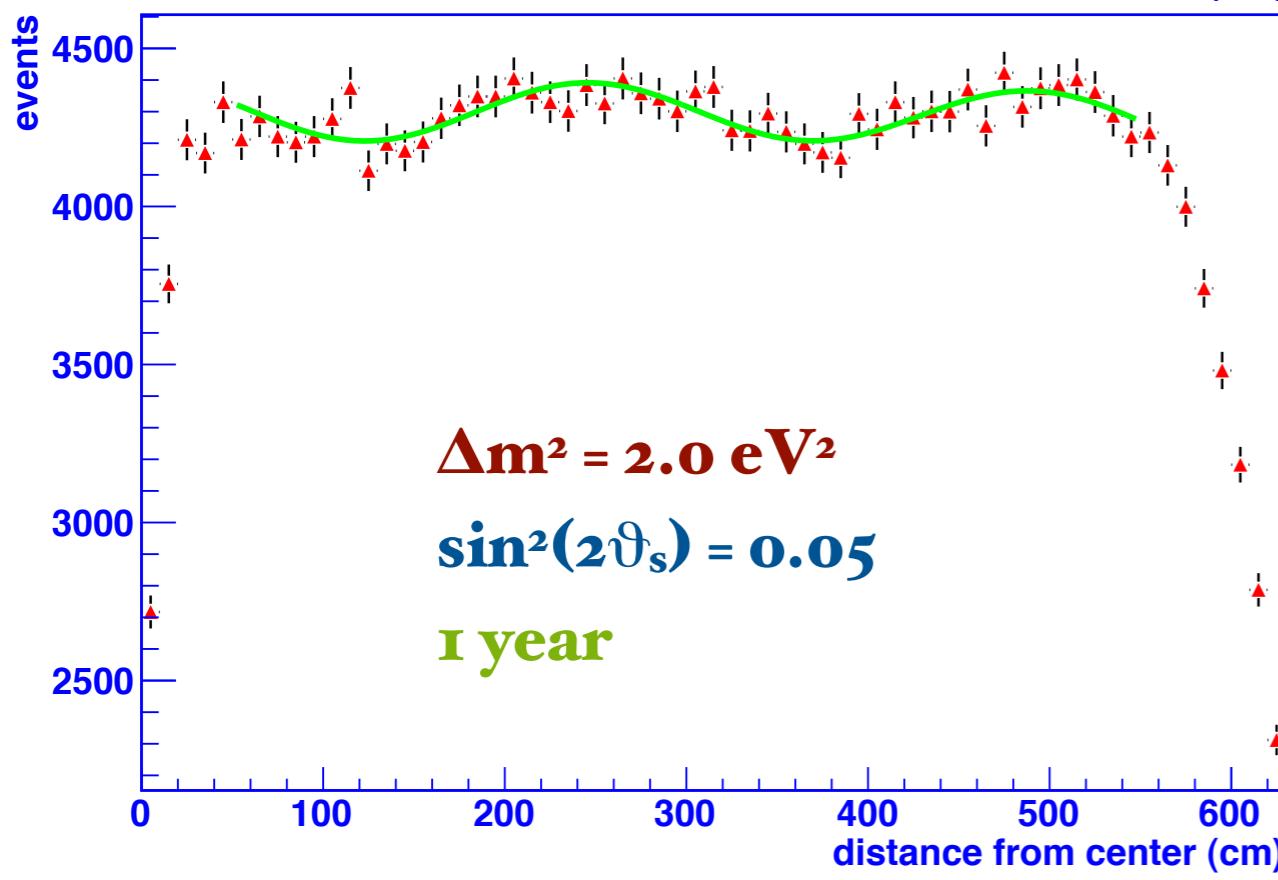
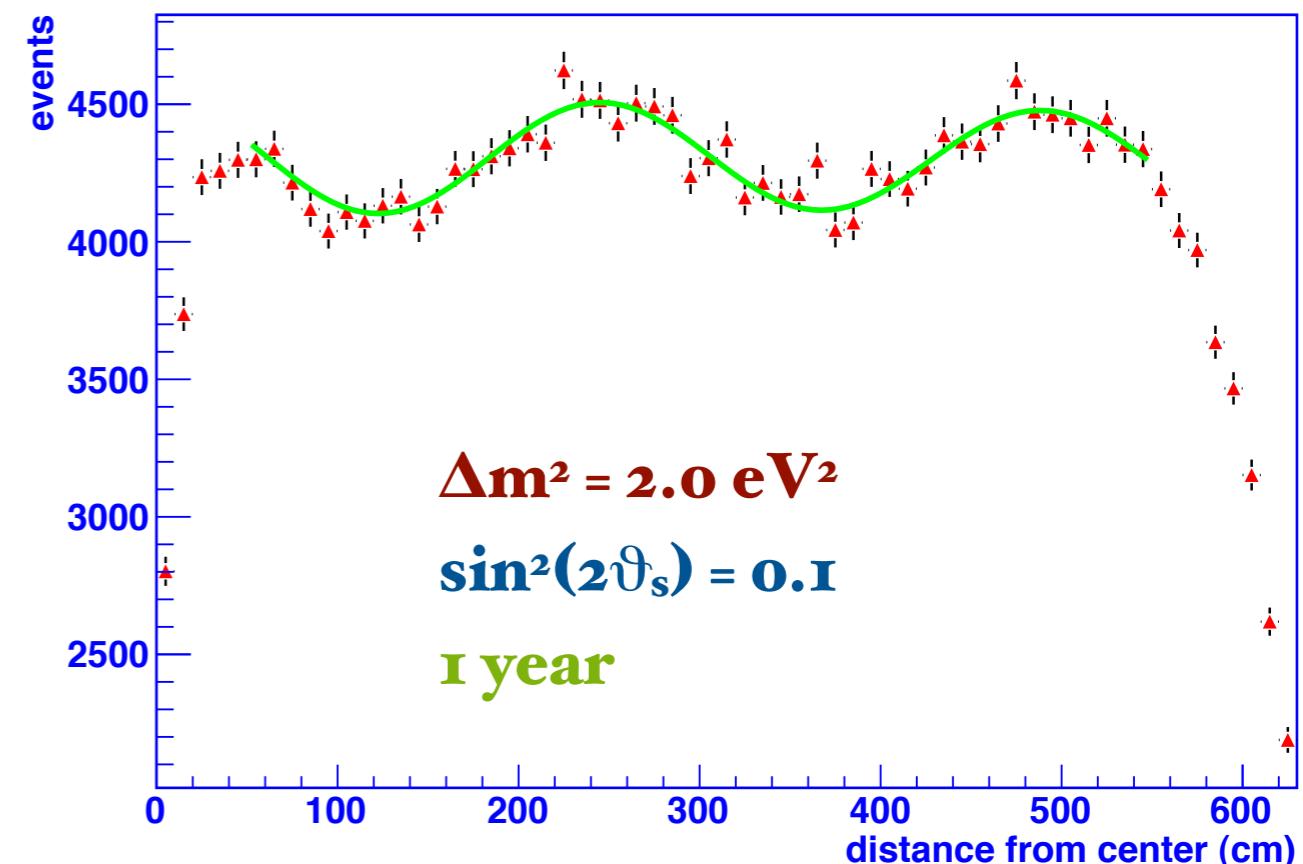
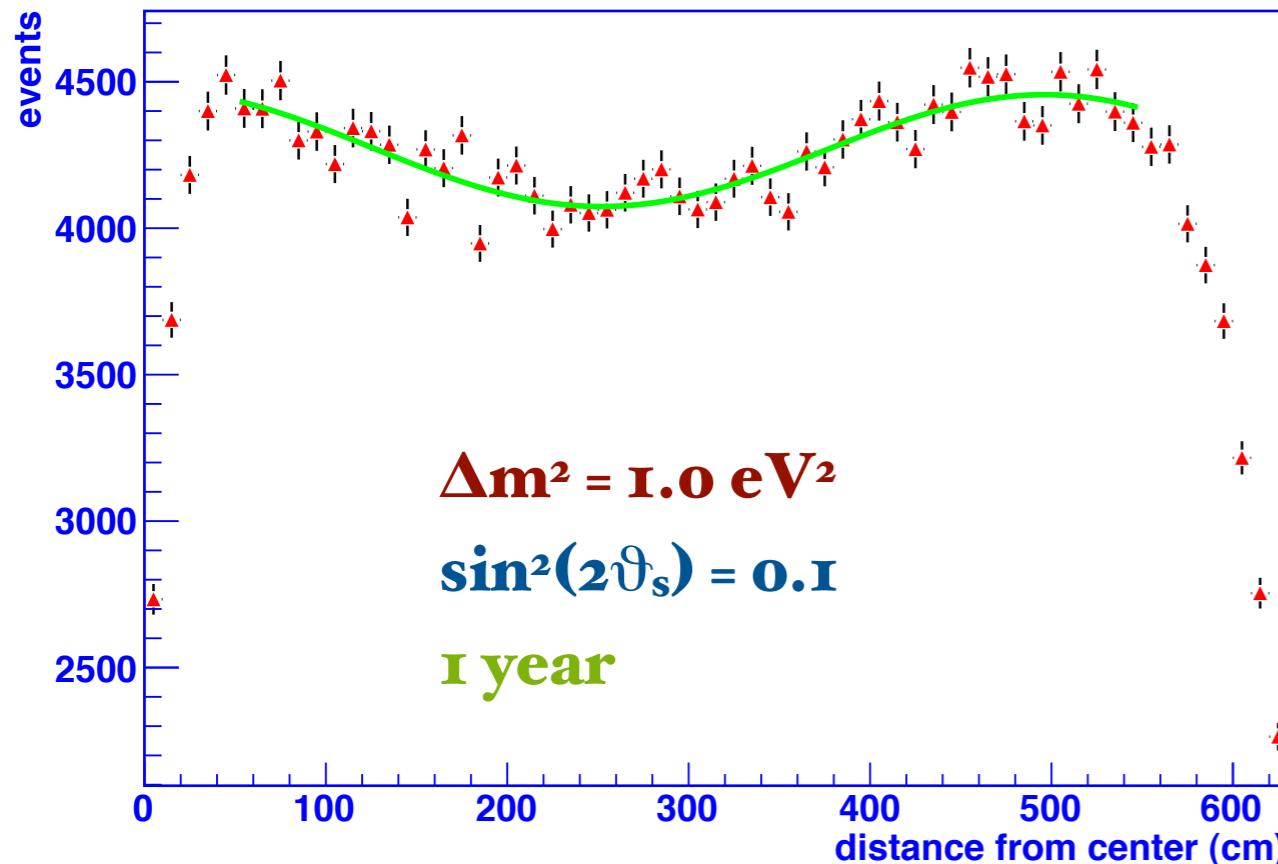


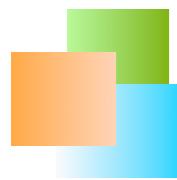
- 5 MCi ^{51}Cr source in the **center** of Borexino
- 3.3 m F.V. radius
- $\Delta m^2 = 2 \text{ eV}^2$ $\sin^2(2\vartheta_s) = 0.10$





Examples with ^{90}Sr in the center

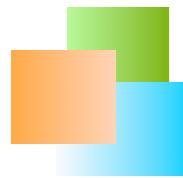




Sensitivity



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

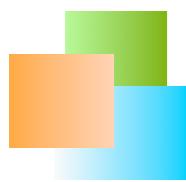


Expected number of signal events



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



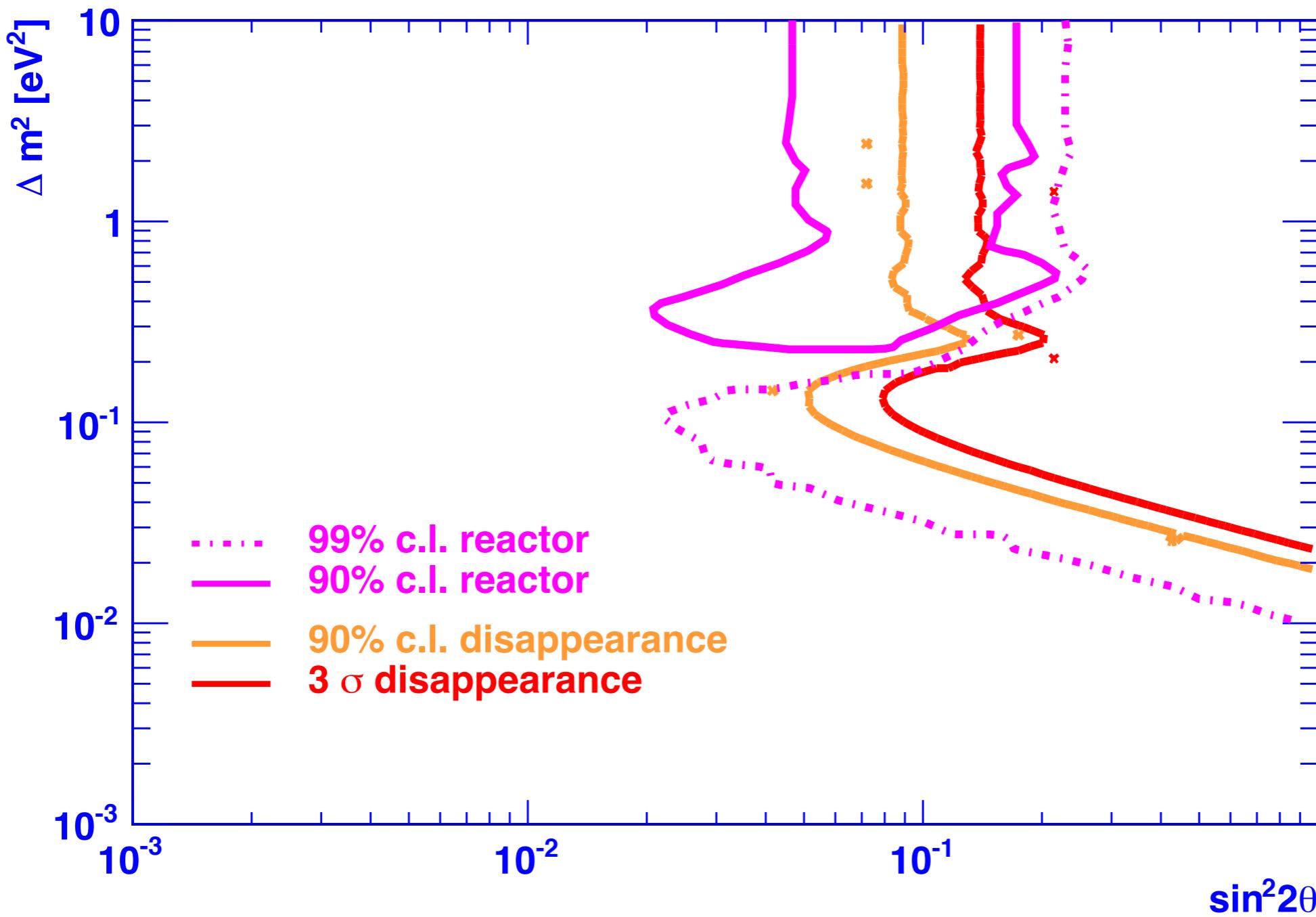


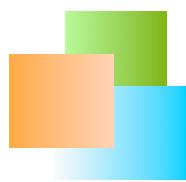
^{51}Cr – TOTAL COUNTS



- **10 MCi ^{51}Cr source in the WT**

- 3.3 m F.V. radius

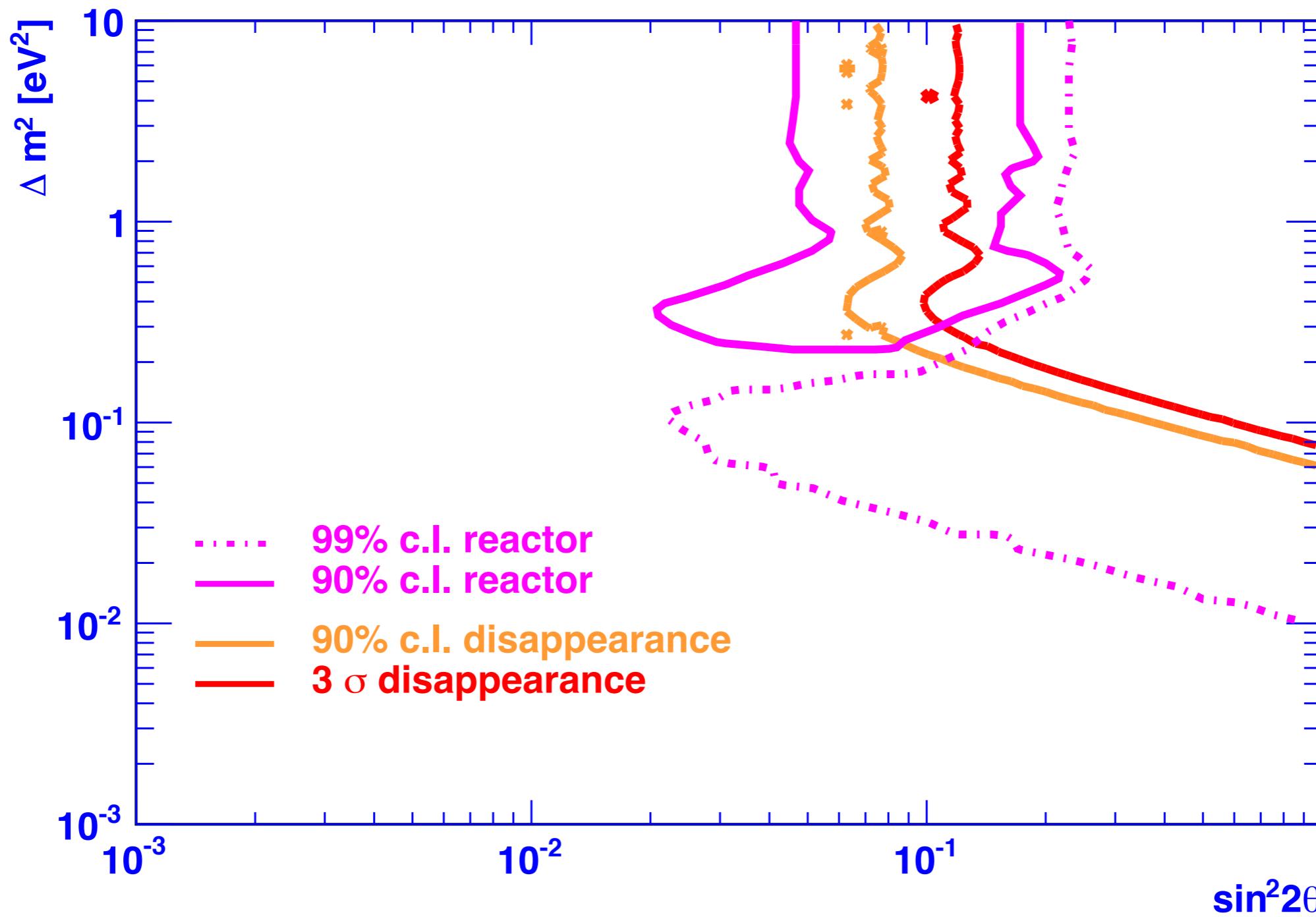


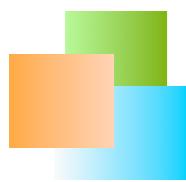


^{51}Cr – TOTAL COUNTS



- 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.

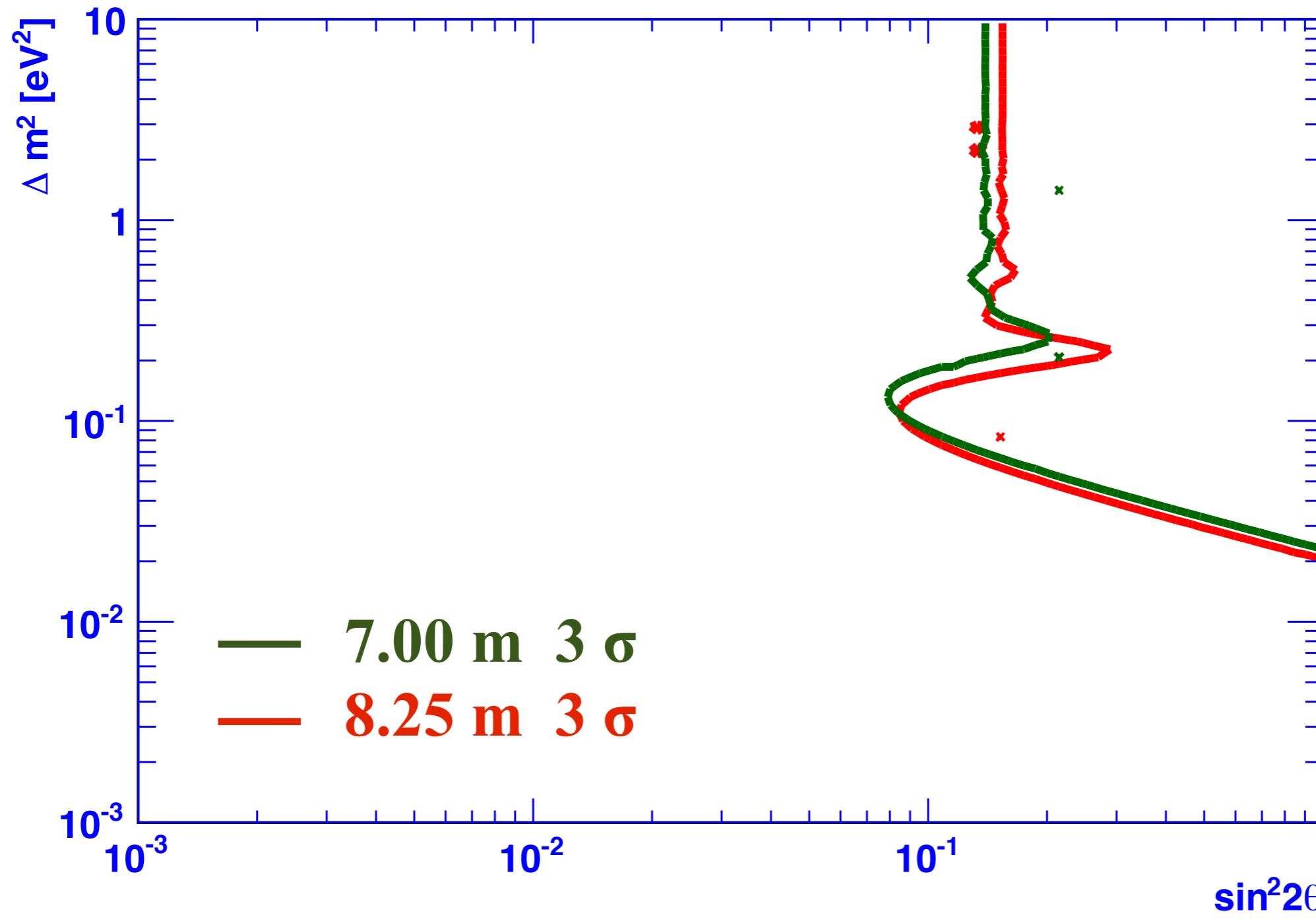


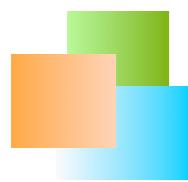


Small difference between IP and WT

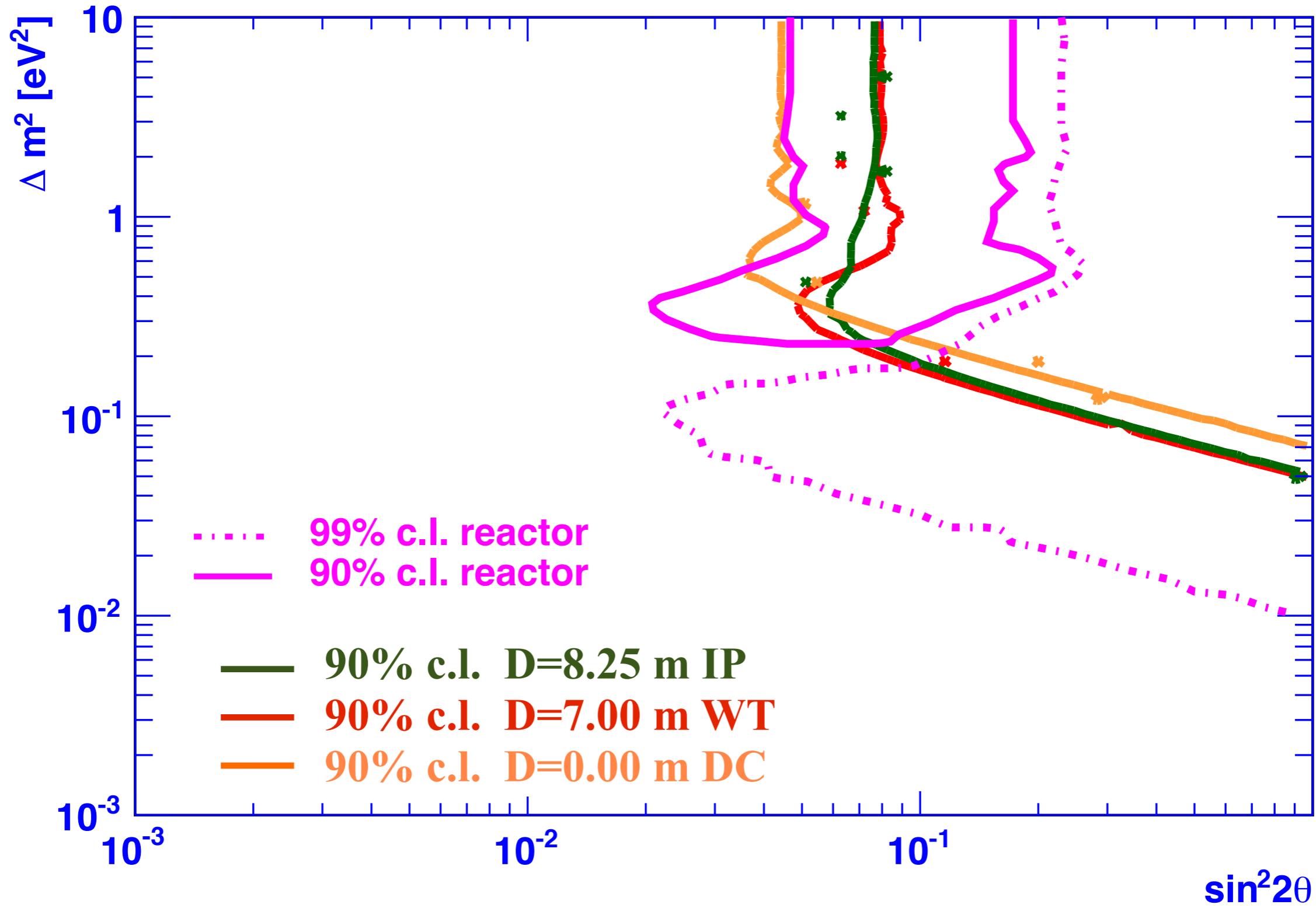


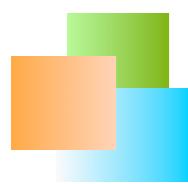
- Comparison between ^{51}Cr source (10 MCi)



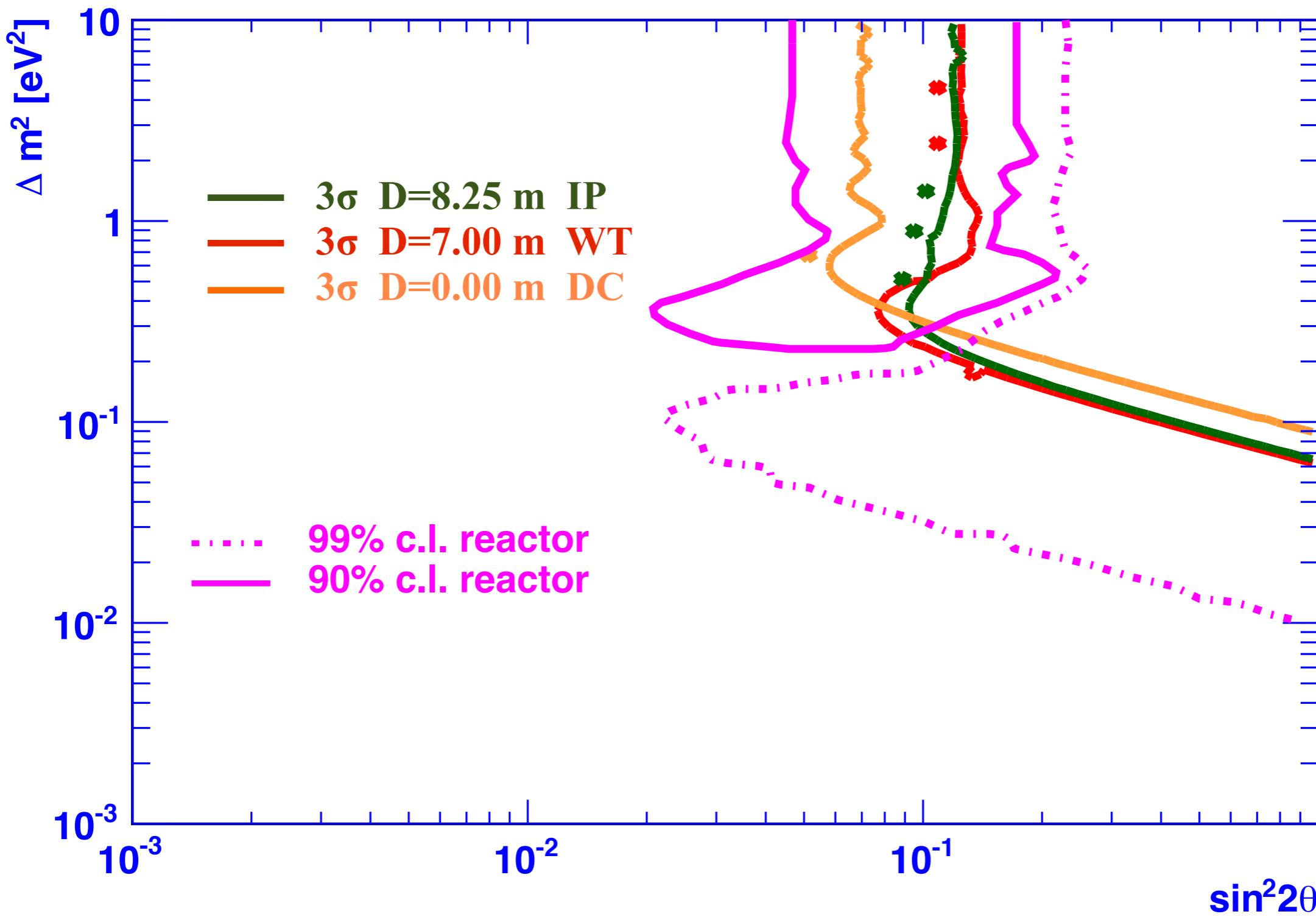


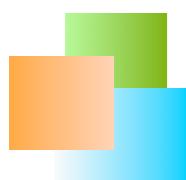
^{90}Sr – 90% c.l. sensitivity



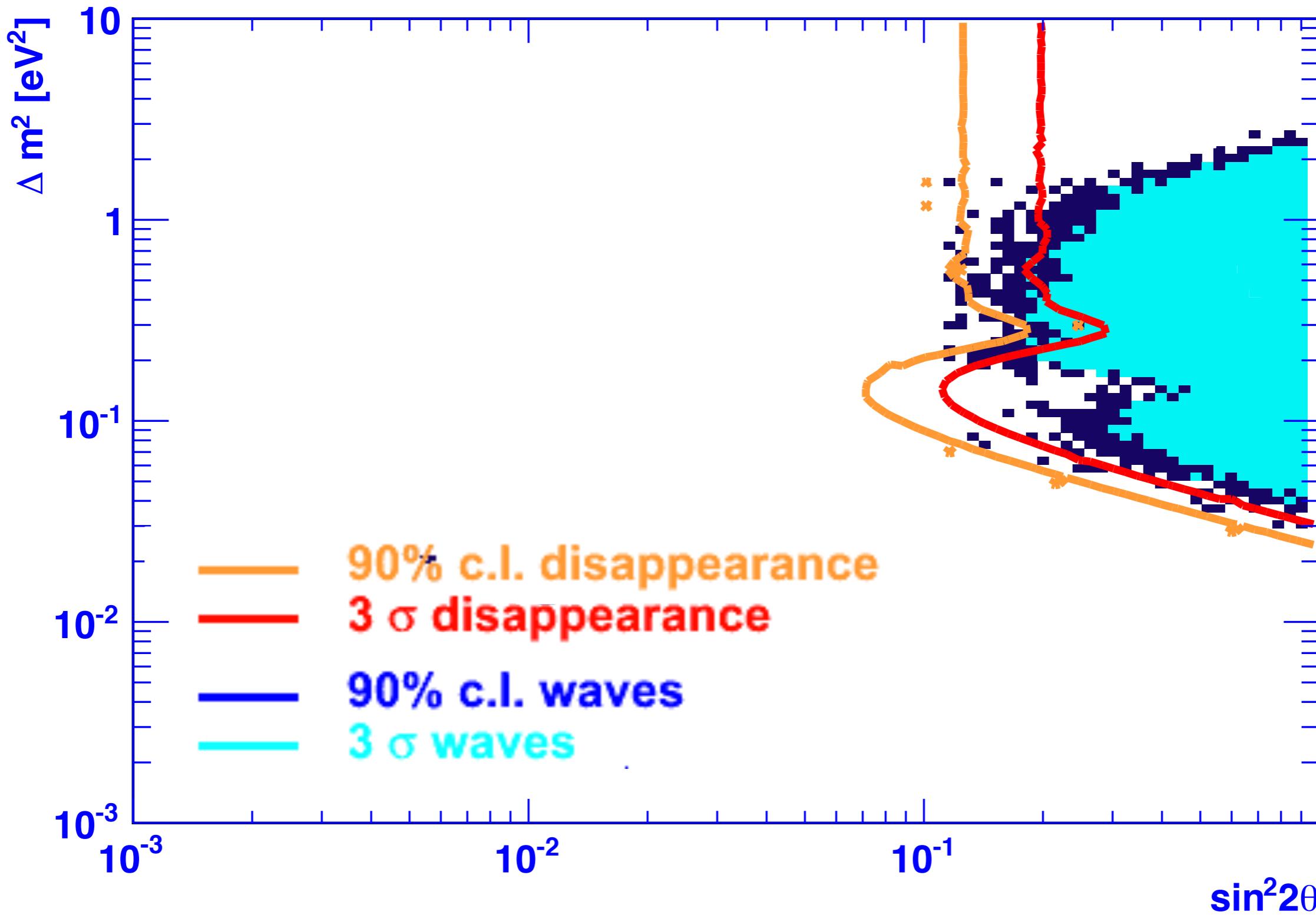


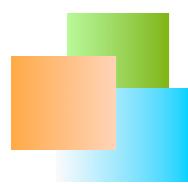
^{90}Sr – 3σ exclusion – 1 MCi



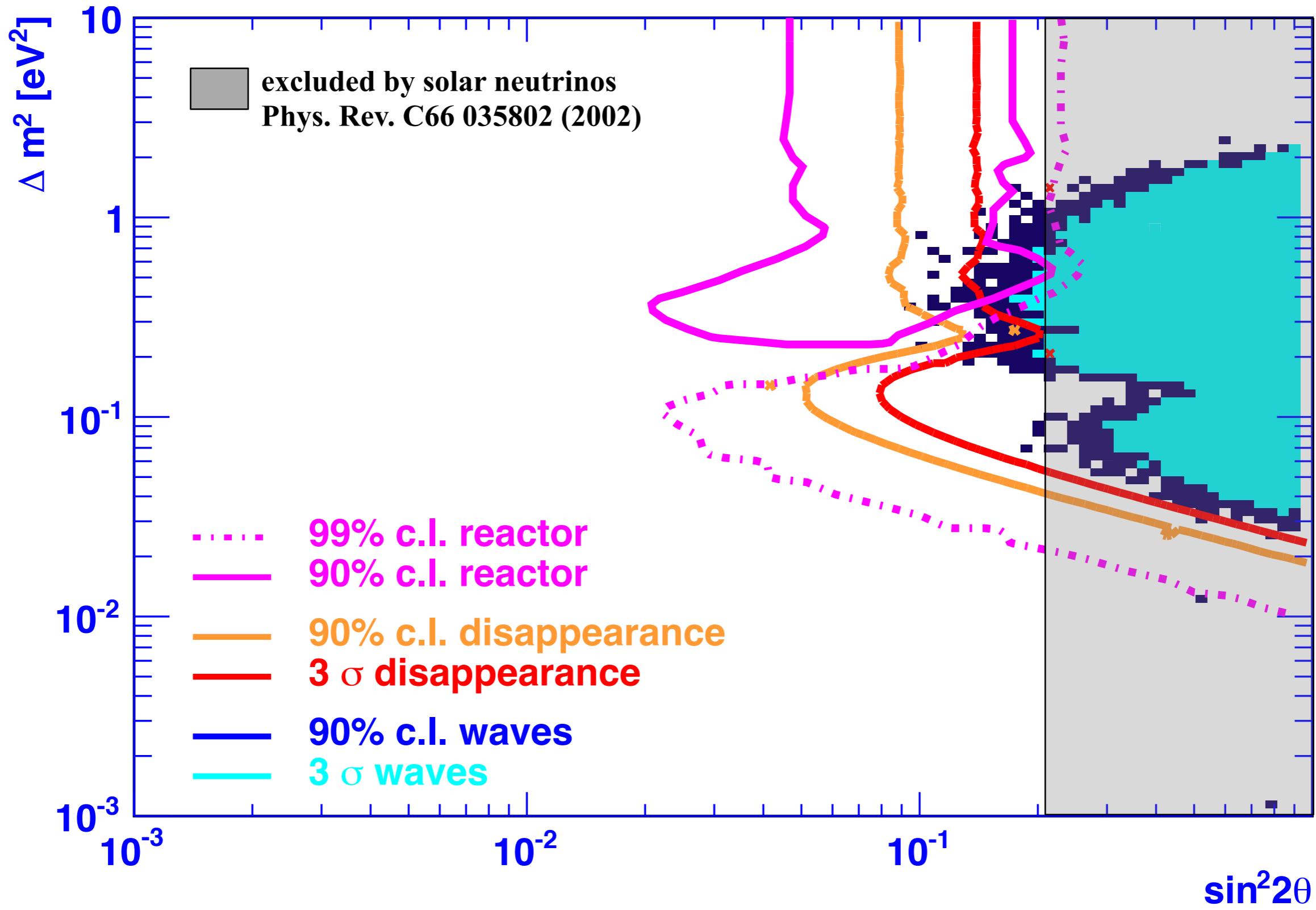


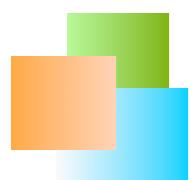
37Ar – 2.5 MCi – External



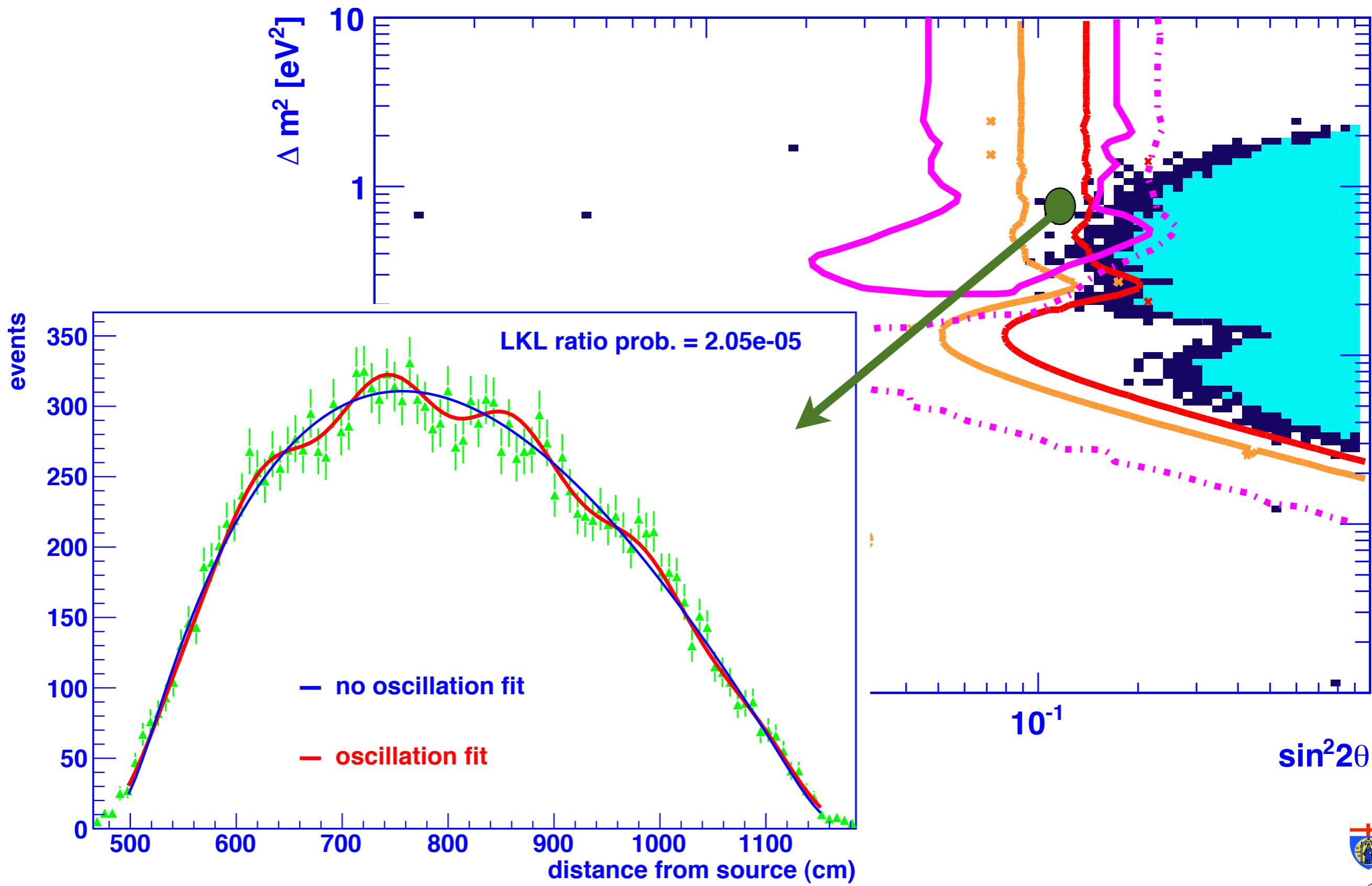


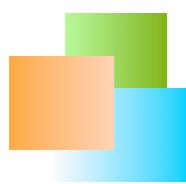
^{51}Cr – 10 MCi – External



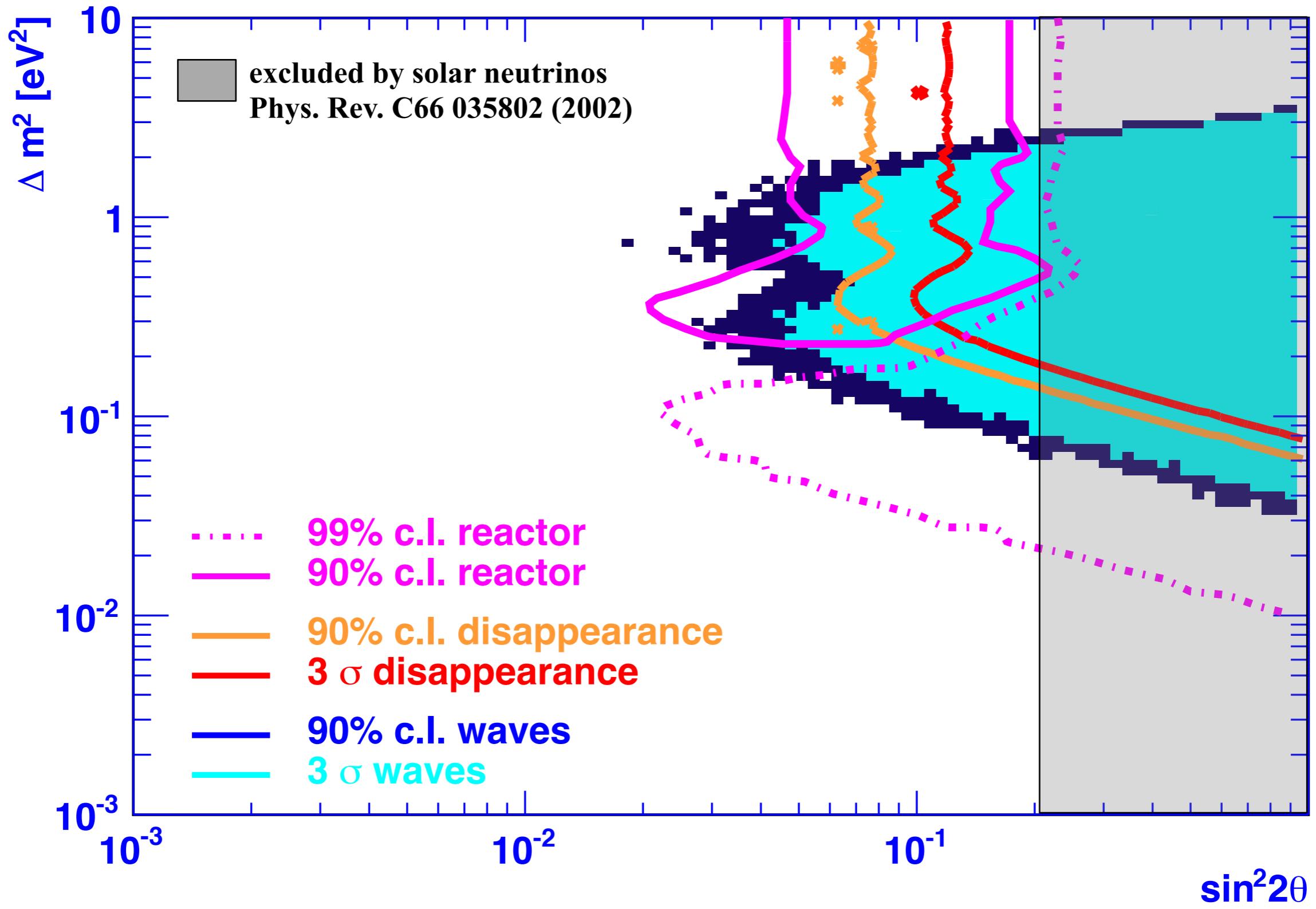


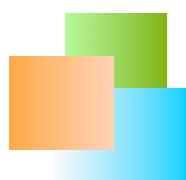
^{51}Cr – 10 MCi – External





^{51}Cr – 5 MCi source – center

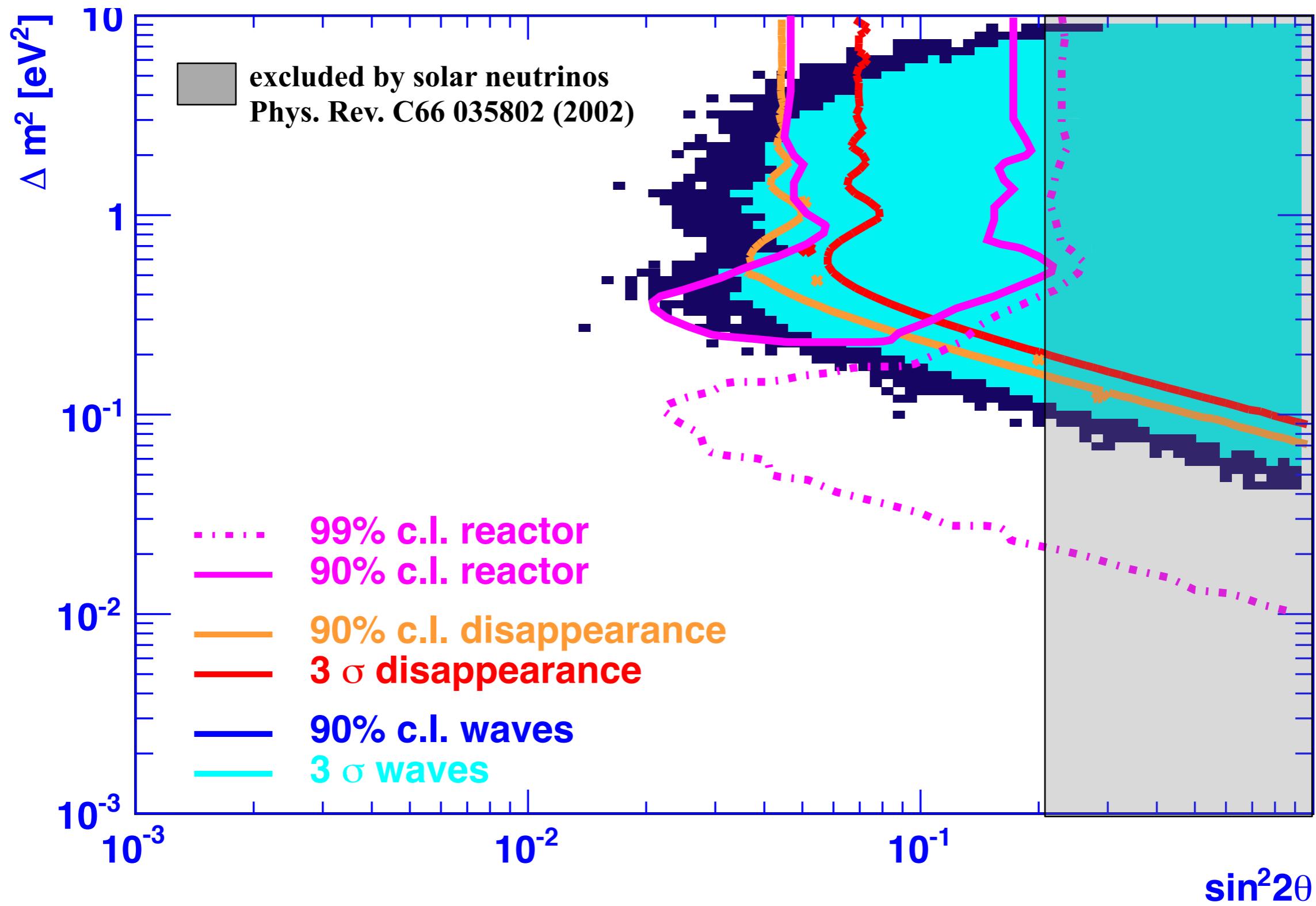


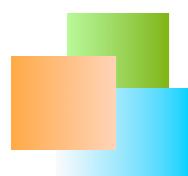


^{90}Sr – Total rate and waves – center – 1 year

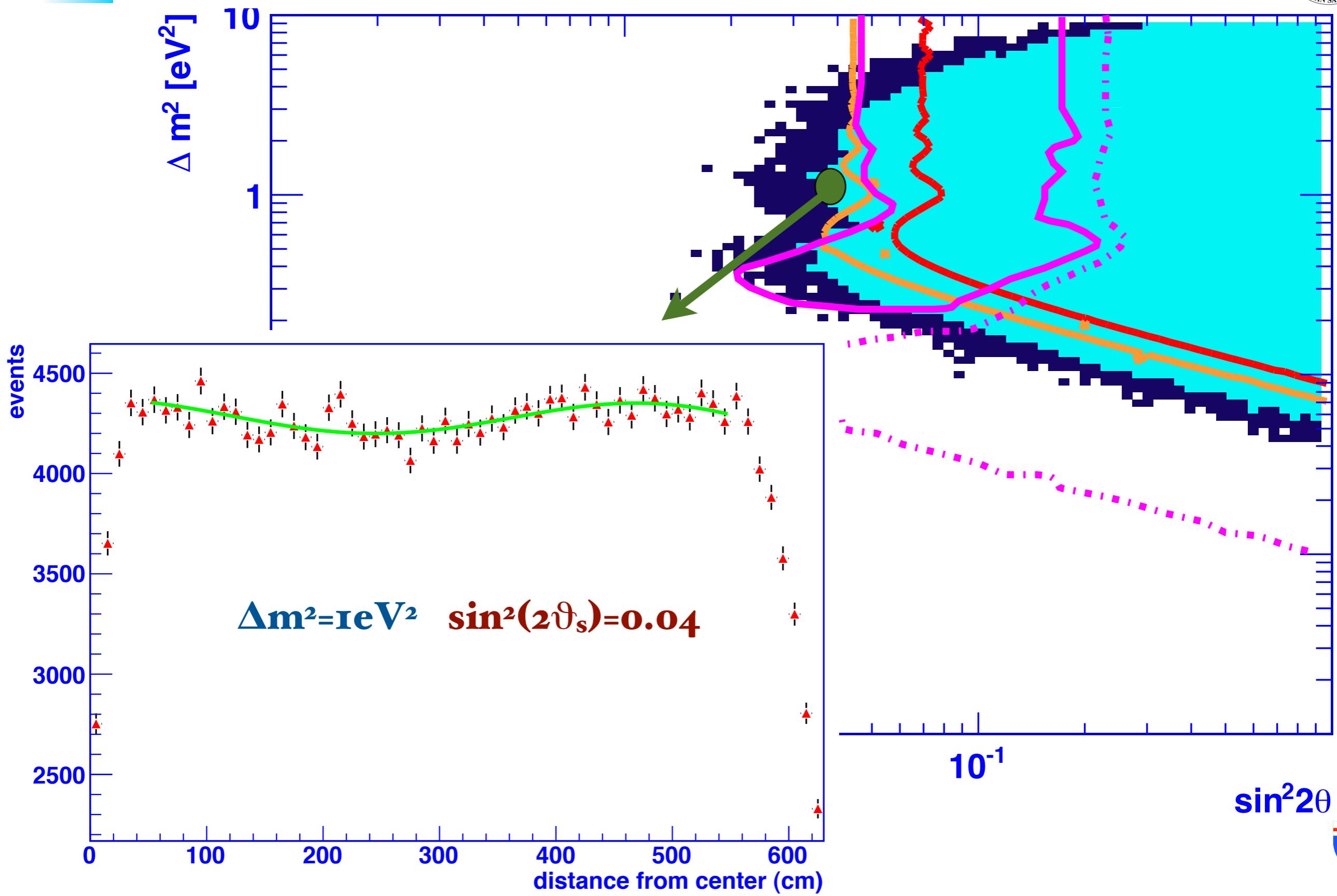


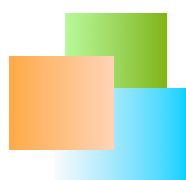
- 1 year, 1 MCi, $R = 6 \text{ m}$, source in the center



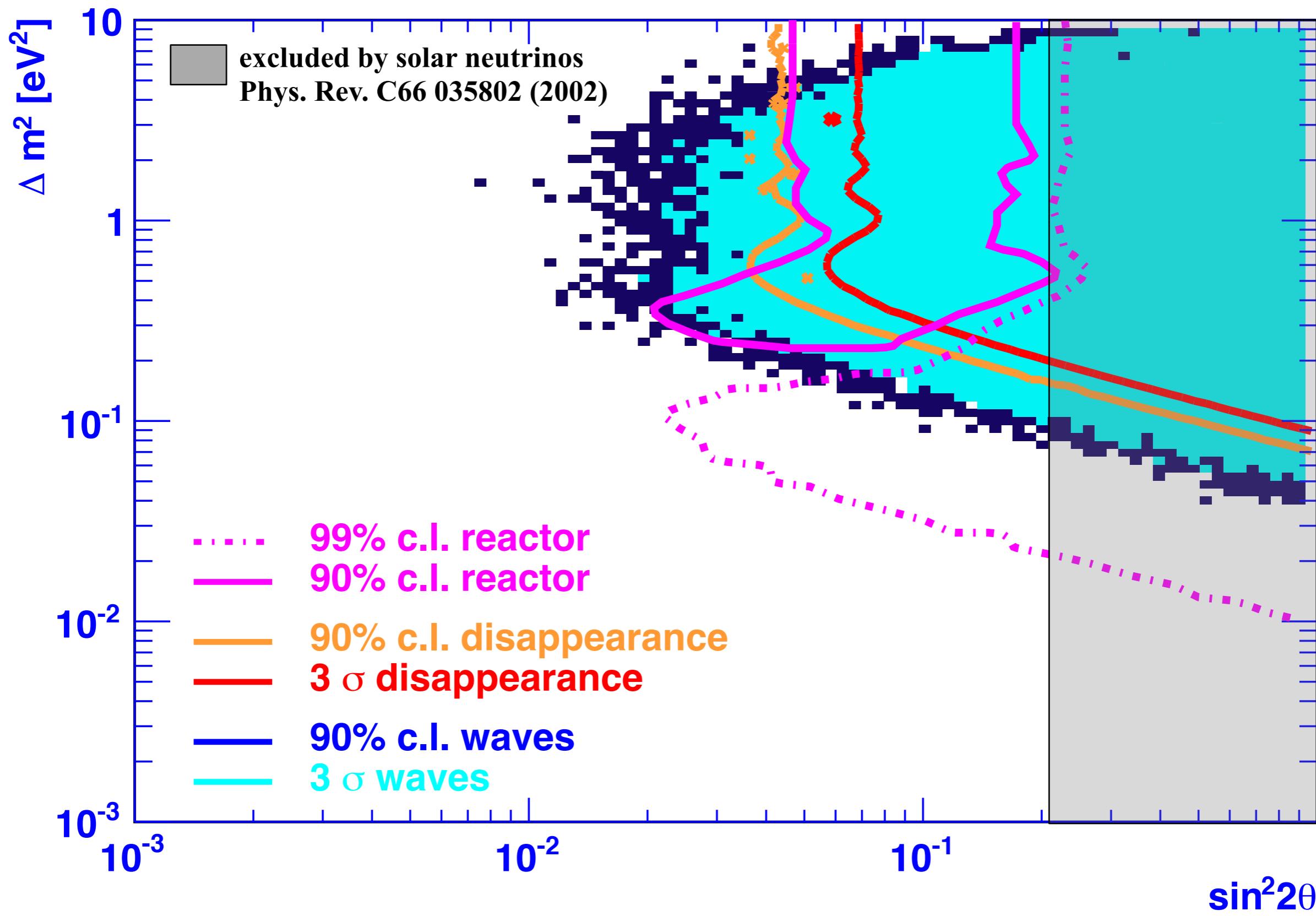


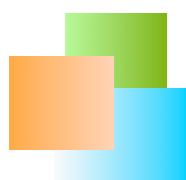
^{90}Sr – Total rate and waves – center – 1 year



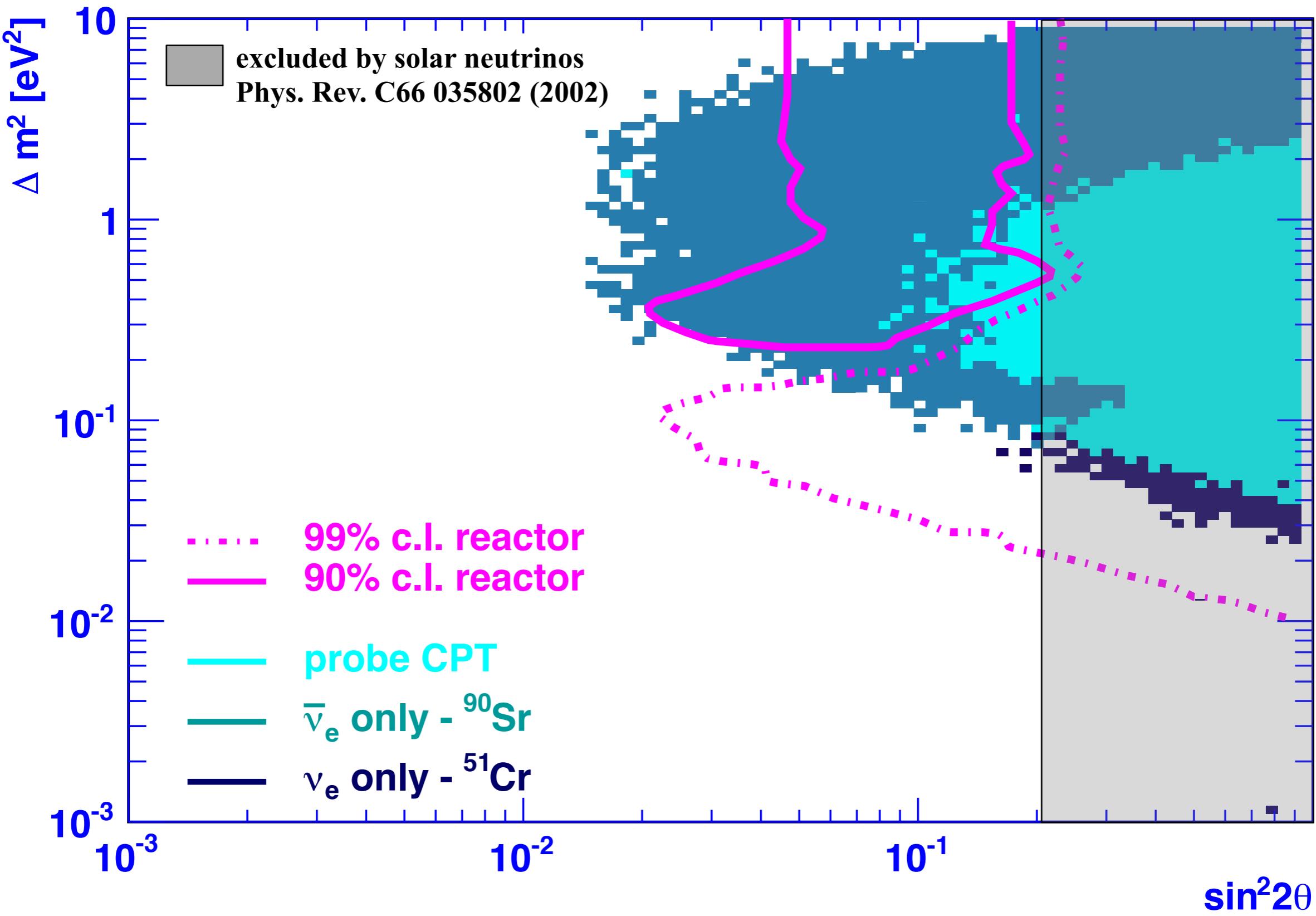


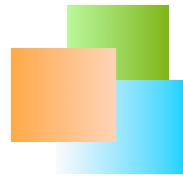
^{90}Sr – 3 years – source in the center





Probing CPT



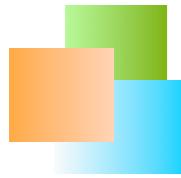


Comments on sensitivity



- 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** or, as LNGS Director might like to see, **margin to reduce source intensity** keeping the sensitivity good enough
- **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 $\bar{\nu}$

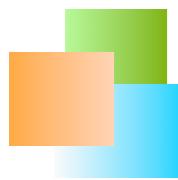
- ~ 1 year of work to prepare this

- 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**
- **INFN seems to have in hand the two key technologies to address this exciting physics case**

Thank you

