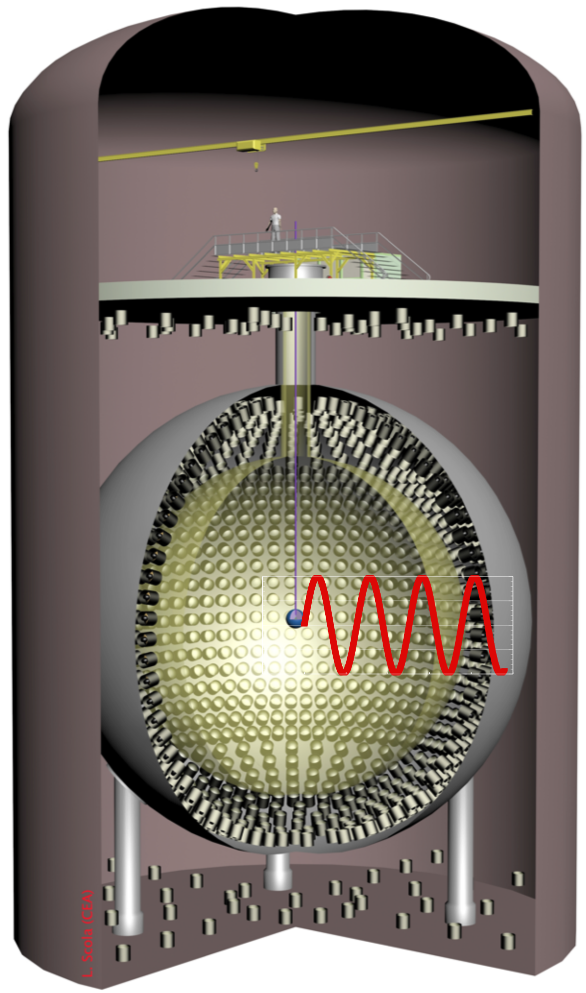
XV International Workshop
On Neutrino Telescope
March 12, 2013

XV International Workshop on Neutrino Telescope, Venezia, March 12, 2013

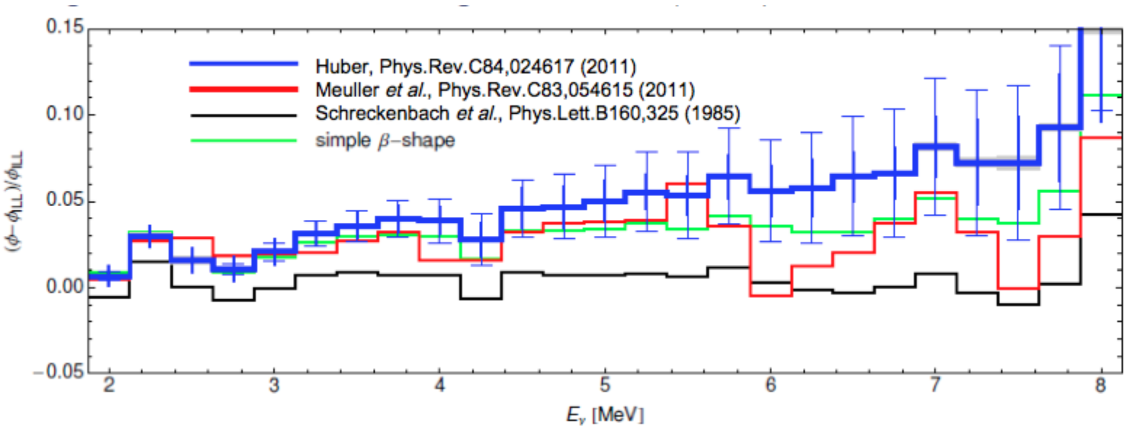
Reactors antineutrino anomalies and searches for sterile neutrinos in Europe



Michel Cribier
CEA/DSM Irfu/SPP & APC-Paris

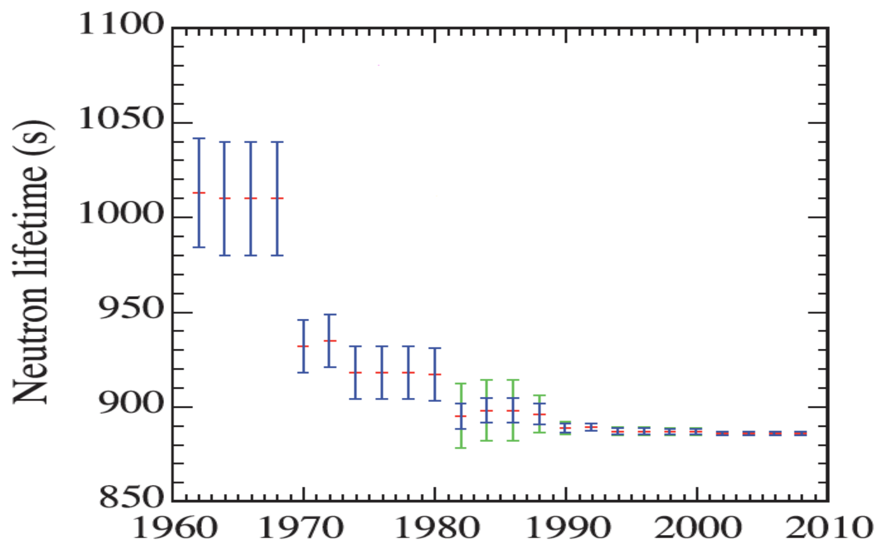
Need
a
fourth neutrino ?

Reevaluation of antineutrino spectrum emitted by reactors



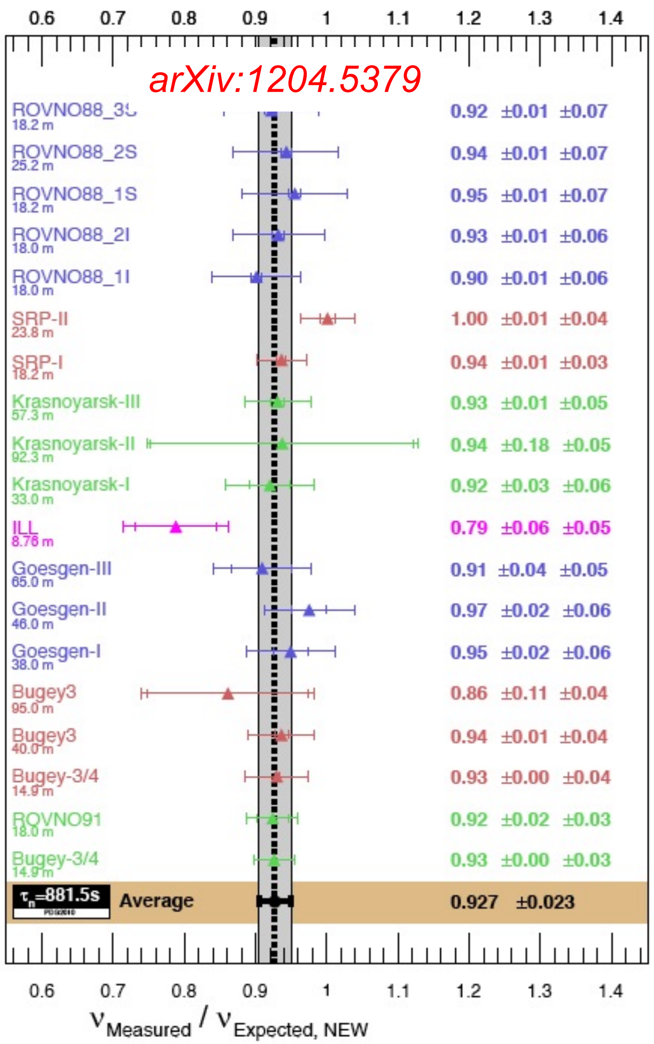
- ❖ Based on same ß spectrum measured by Schreckenbach et al.
  - at ILL in 1985
- ❖ Input of recent nuclear data bases
  - Improved reactor ν spectrum
  - + 3.5 %

- ❖ Higher IBD X-section
  - decreasing n lifetime
  - + 1%
- ❖ Long life isotopes
  - + 1%



Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)

The Reactor Antineutrino Anomaly



- Reanalysis of the 19 previous experiments at reactors < 100 m
  - G. Mention et al.

    Phys. Rev. D83, 073006 (2011), arXiv:1101.2755

    - *R = 0.943 ± 0.023*
  - Light sterile neutrinos : A White Paper

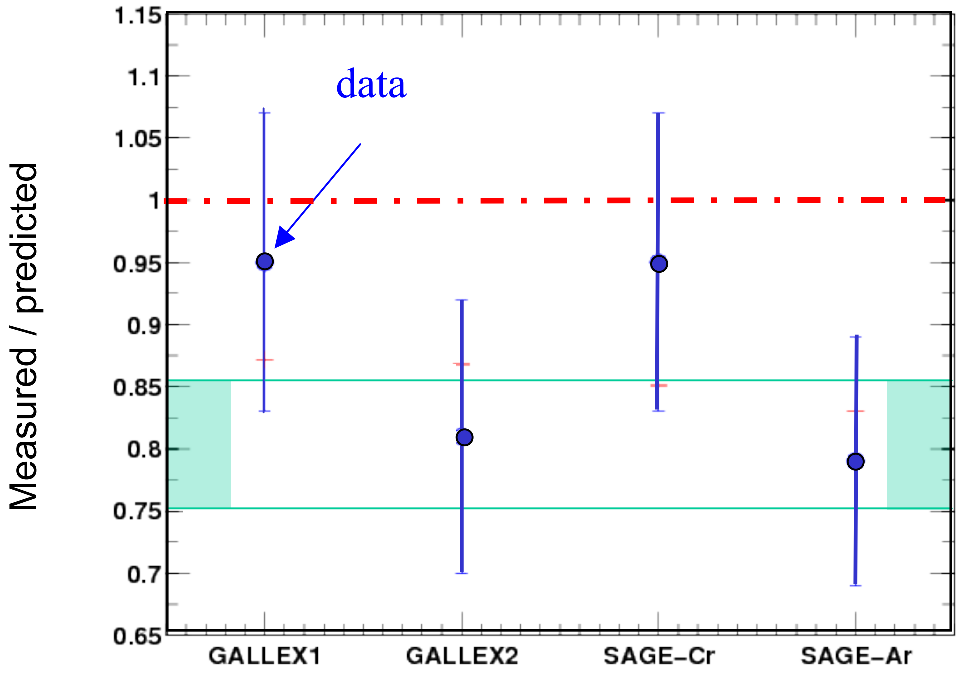
    arXiv:1204.5379
- Treatment of correlations between experiments
  - similar techniques/detectors
  - same reactors
  - same ILL ν spectrum
- An overall deficit : $R^{(meas/pred)}=0.927 \pm 0.023$

The Gallium Anomaly

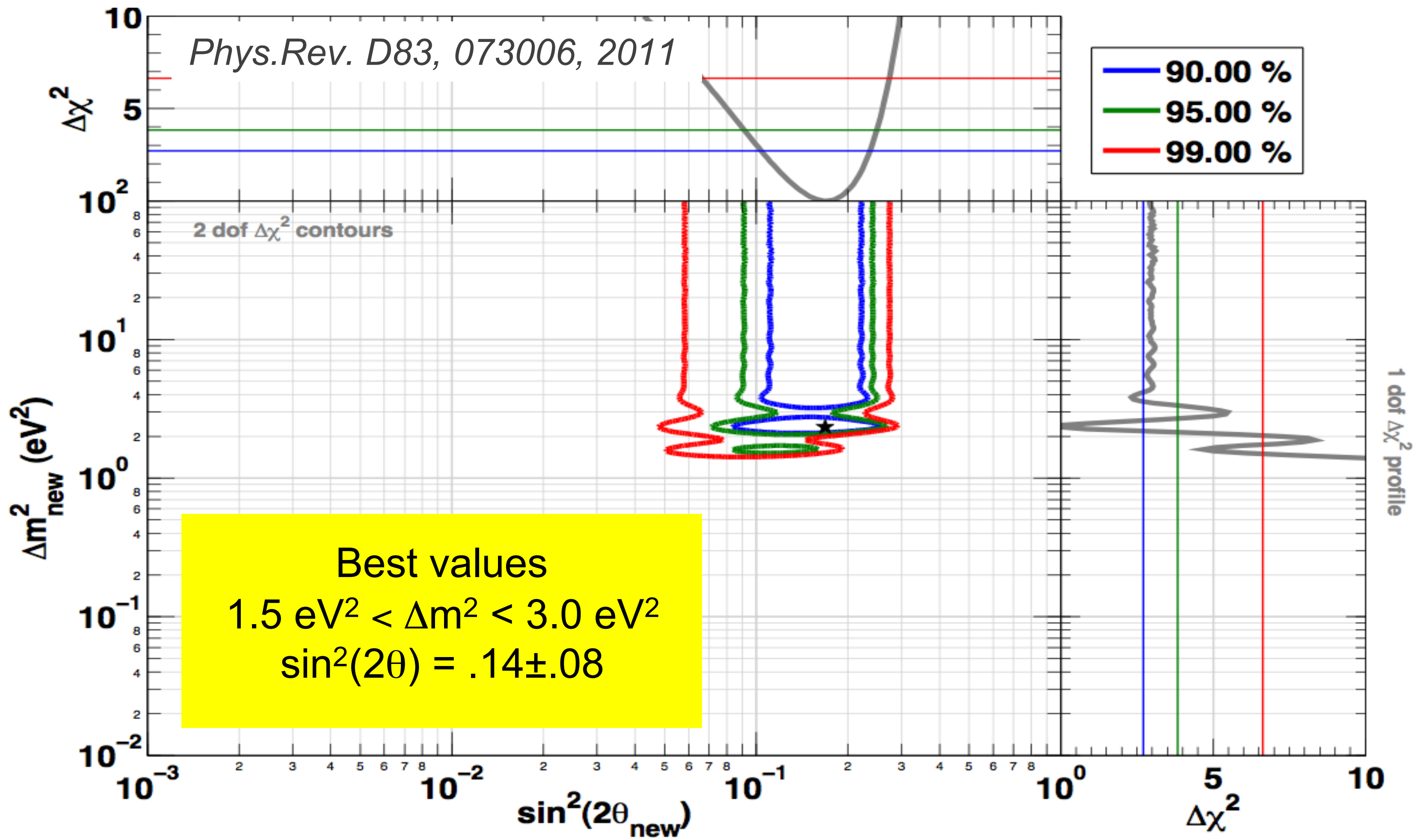
- C. Giunti & M. Laveder
  Phys. Rev C 83, 065504 (2011)
  arXiv 1210.5715
- Calibration of solar neutrino experiments
  - distance <≈ 1 m
  - with low energy neutrinos
- Gallex
  - 2 ^{51}Cr ν sources <L> = 1.9 m
- Sage
  - 1 ^{51}Cr ν source
  - 1 ^{37}Ar ν source <L> = 0.6 m
- Overall deficit : R = 0.75 - 0.86

	G1	G2	S1	S2	<R>
$R_{\rm B}$	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
$R_{\rm HK}$	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
$R_{\rm FF}$	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
$R_{\rm HF}$	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$

<R> with different σ for $\nu_e(^{71}Ga,^{71}Ge)e$



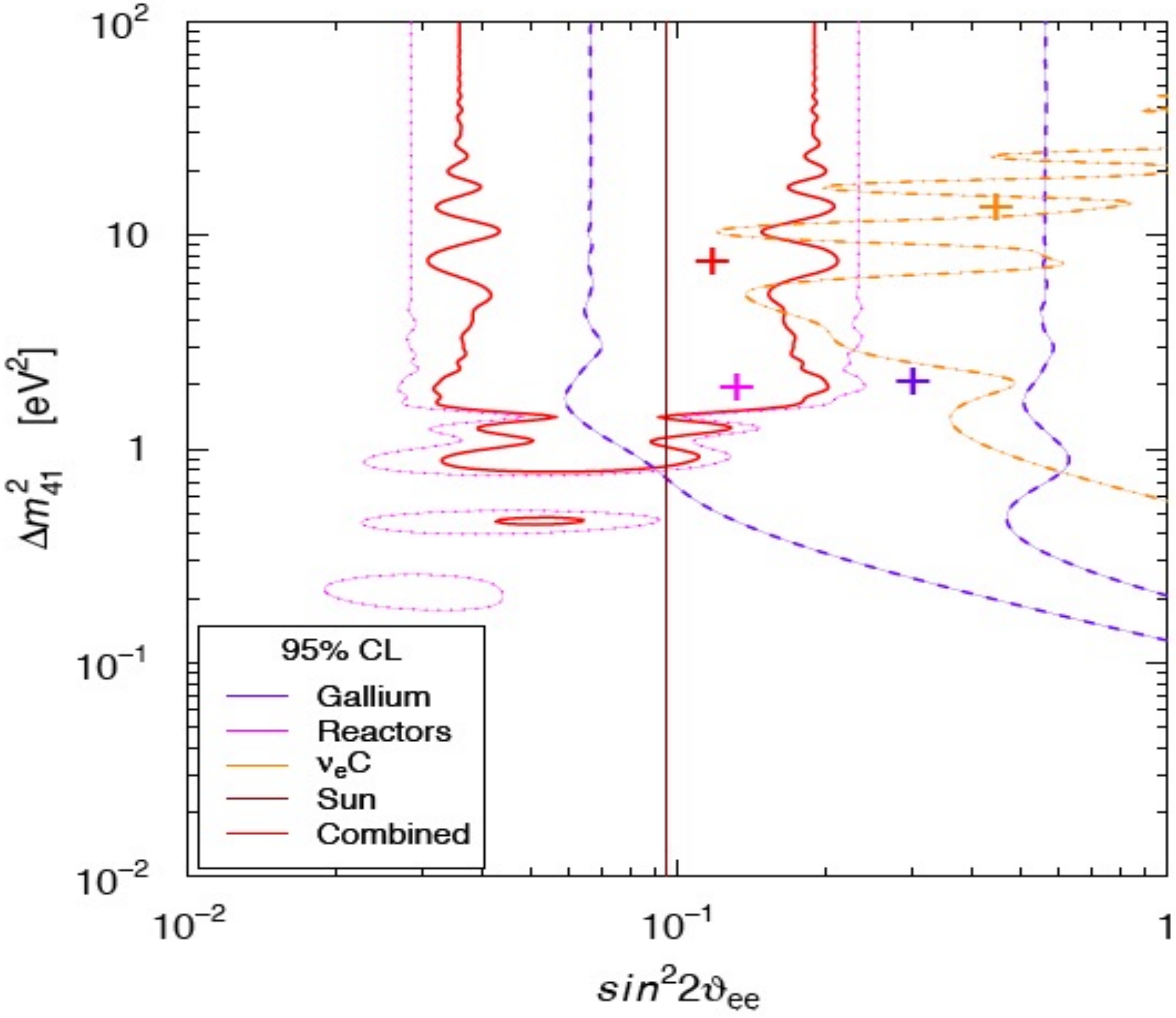
Reactors and Gallium



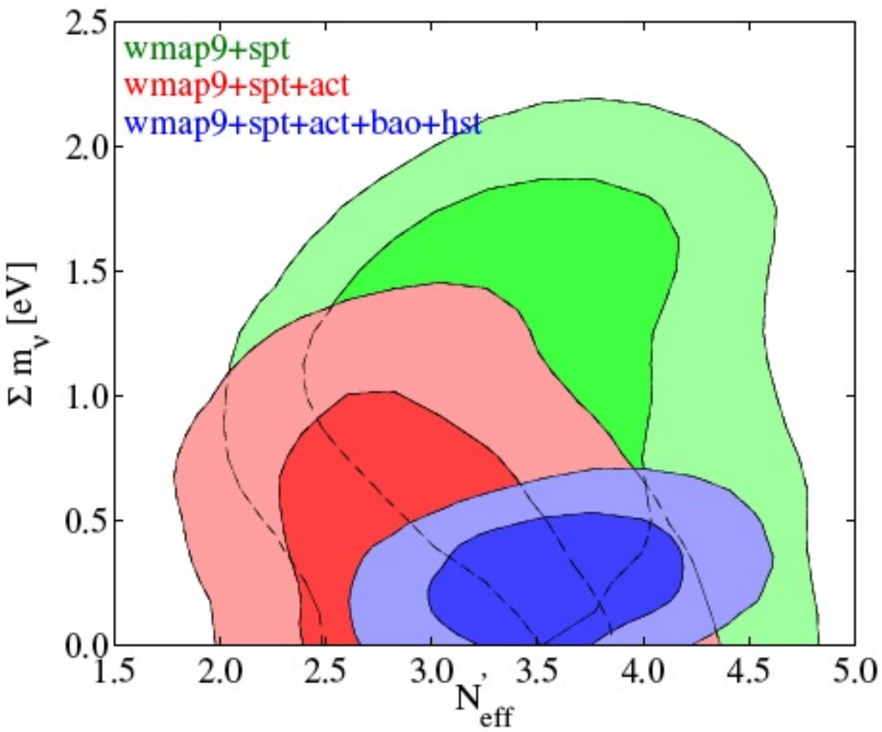
The no-oscillation hypothesis is disfavored at 99.8% CL

Low energies anomalies

C. Giunti, M. Laveder, Y.F. Li, D.Y. Liu, H.W. Long, arXiv 1210.5715



Waiting for Planck's result…

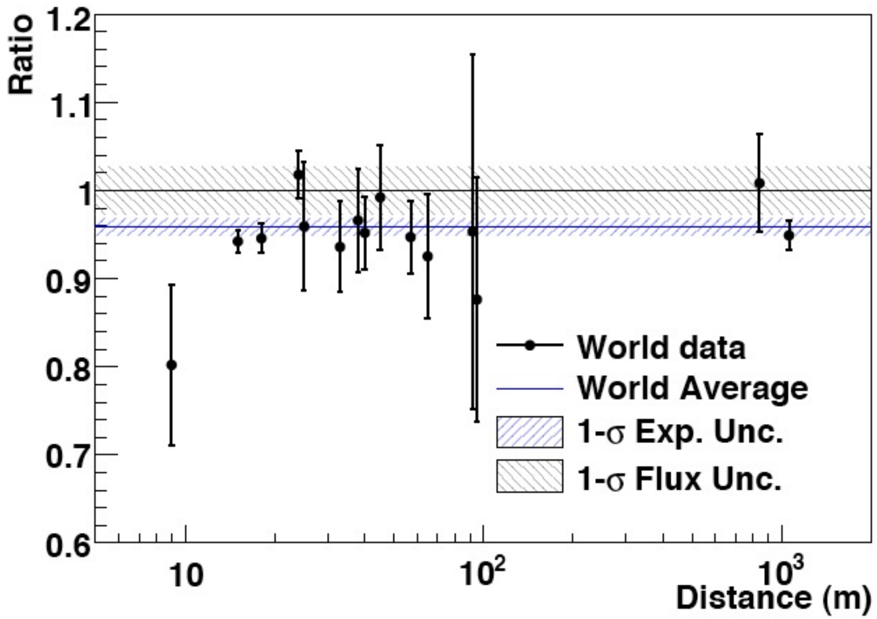


From M. Archidiacono et al.
arXiv 1302.6720

- So far Cosmology prefers :
  - ≈ one extra ν (3+1)
  - with a sub eV mass
- Tension between exper. datas included with WMAP9 in analysis
  - ACT vs SPT
- Correlations with other cosmological parameters
- Very soon Planck…

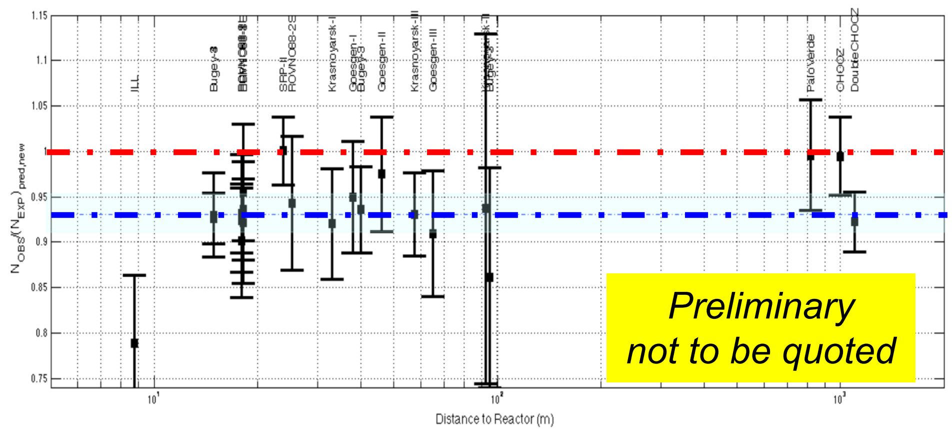
on P. Vogel's et al. new reanalysis

C.Zhang, X.Qian & P.Vogel ; arXiv:1303.0900v1



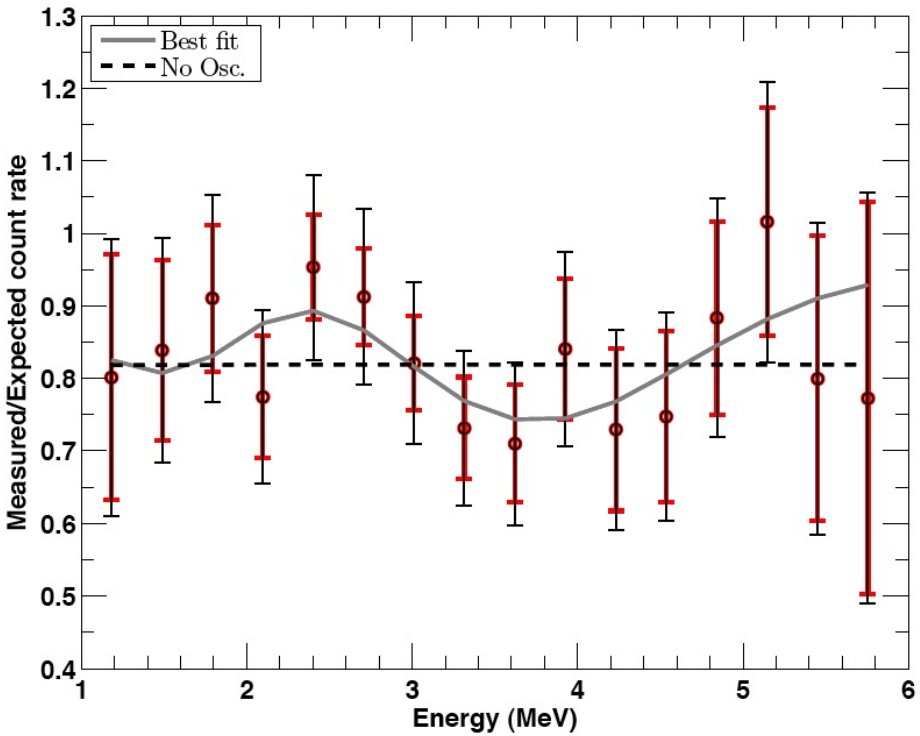
- ❖ New reanalysis of old 19 reactors antineutrinos experiments adding :
  - *$sin^2(2\theta_{13})$* = 0.089±0.011
  - allow to use Chooz, Palo Verde, Double Chooz (Gd & Hyd. datas)
  - *=> R = 0.959±0.009(stat.) ±0.027(react.flux) : 1.4 σ effect*

- ❖ First quick comments from Saclay's group
  - which IBD cross-section used ?
  - which neutrino flux ? with P. Huber's improvments ?
  - wrong error used by authors in RAA
    - 0.027 instead of 0.023
    - taken wrongly as fully correlated : only ILL electron data is fully correlated
  - Saclay <u>preliminary</u> similar reanalysis : ≈ 0.93 ± 0.022 *: > 3 σ effect*
  - short written answer in preparation



An intriguing result
1st ILL experiment

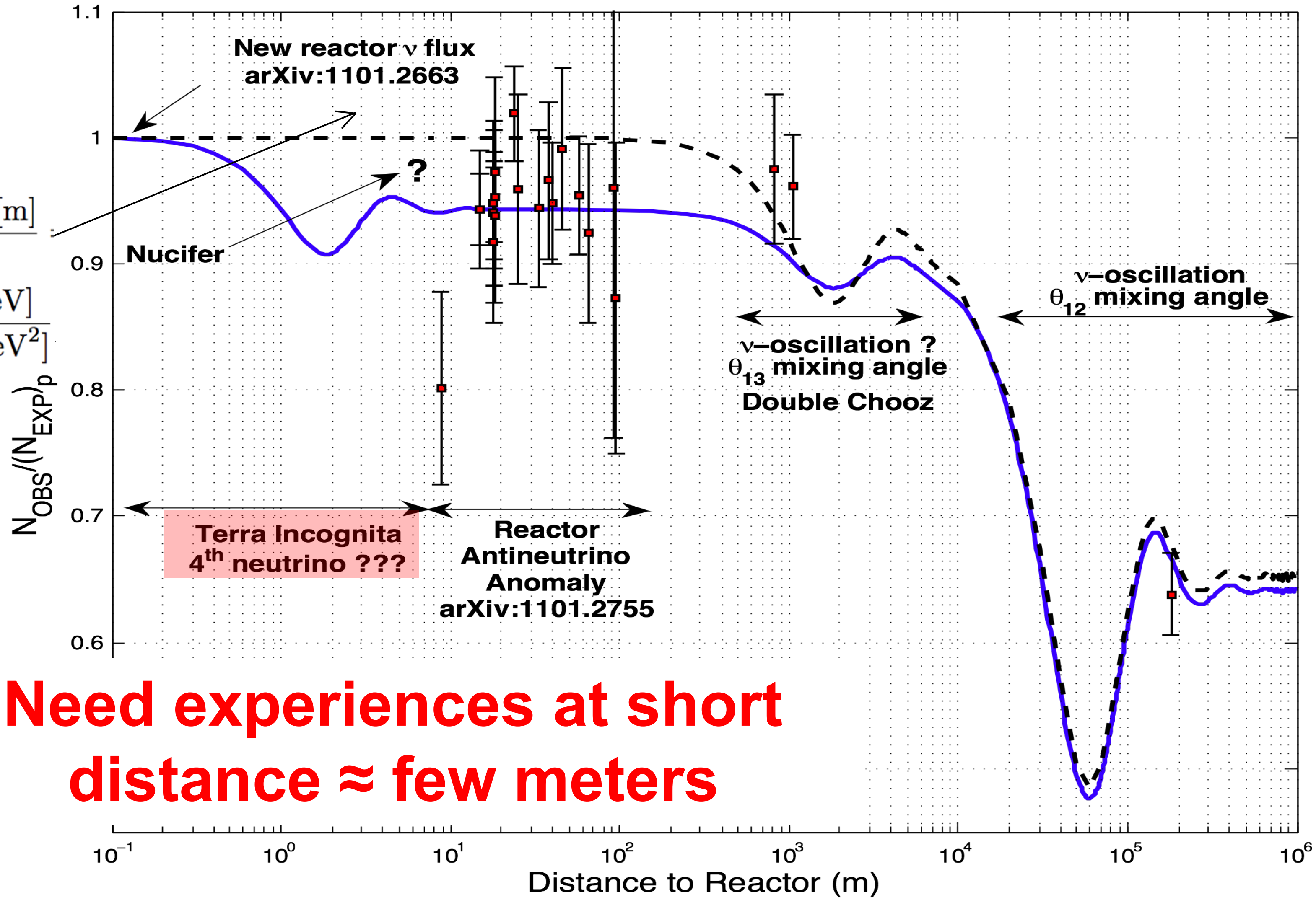
- ❖ Performed in 1980 at ILL reactor in Grenoble @ < 9 m
- ❖ Reevaluation in 1990 by 9.5 % of the reactor power
  - really a « blind analysis »
- ❖ Reanalysed in 1995 : A. Hoummada et al., Appl. Radiat. Isot. 46 (1995) 449



Fit with
$\Delta m^2 = 2.3\ eV^2$
$\sin^2(2\theta) = .24$

We need new experimental input !

$$L_{optim} = \frac{L_{osc}[\mathrm{m}]}{2} = 1.24\frac{E_{\overline{\nu}_e}[\mathrm{MeV}]}{\Delta m^2_{\mathrm{new}}[\mathrm{eV}^2]}$$



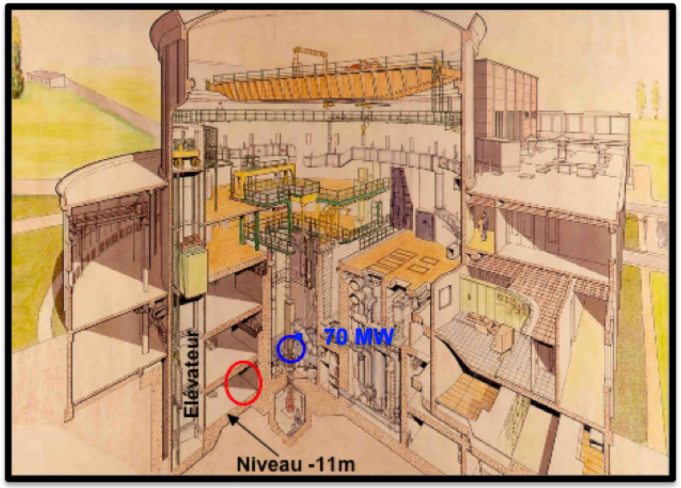
Need experiences at short distance ≈ few meters

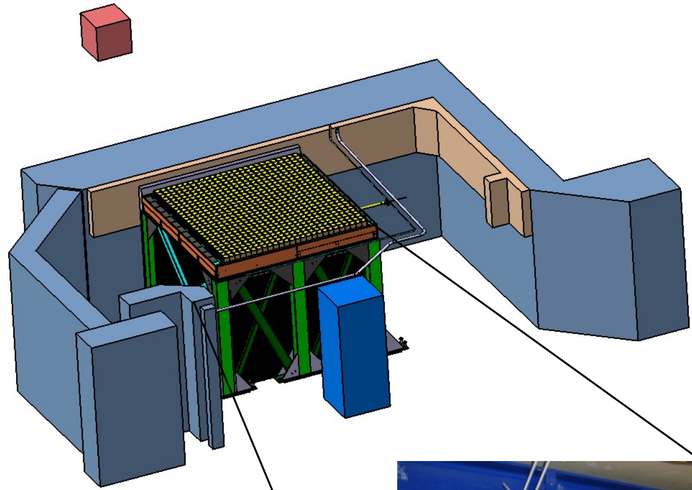
Many experimental projects

Sources	Reactors	Beams
CeLAND ^{144}Ce 75 kCi@ KamLAND funded	Nucifer 7 m from Osiris reactor Data taking	IsoDAR Cycloton to produce ^{8}Li arXiv:1205.4419
SoX in Borexino ^{51}Cr > 5 MCi & ^{144}Ce funded	Stereo 8m @ ILL	OscSNS New « Karmen type » exp. arXiv:0810.3175
Baksan ^{51}Cr 3 MCi unlikely funded	Solid 8m @ ILL	MicroBoone Clarification of LSND/MiniBoone anomalies ?
SNO+ / LENS ^{51}Cr 10 MCi R & D	Scraam, Neutrino-4, DANNS, Poseidon	Icarus/Nessie 2 liq. Ar detec @ CERN
Katrin ^{3}He in construction	…	…

Some of the proposed experiments

Nucifer



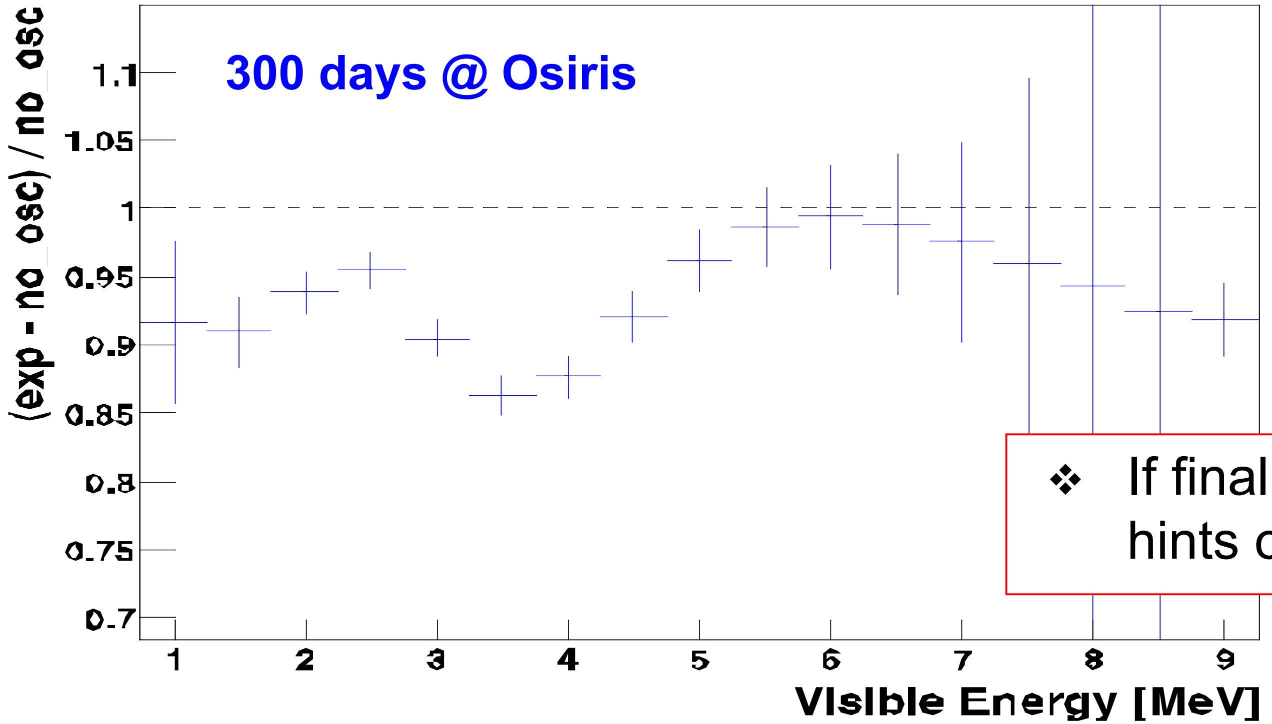


- Osiris research reactor @ Saclay
  70 MW, 20% ^{235}U and compact core
- Very short base line : 7m
- Detector optimized for monitoring of reactor
  - 850 kg Gd-LS : ≈ 350 interactions/day

Nucifer and sterile neutrinos

Many difficulties so far :

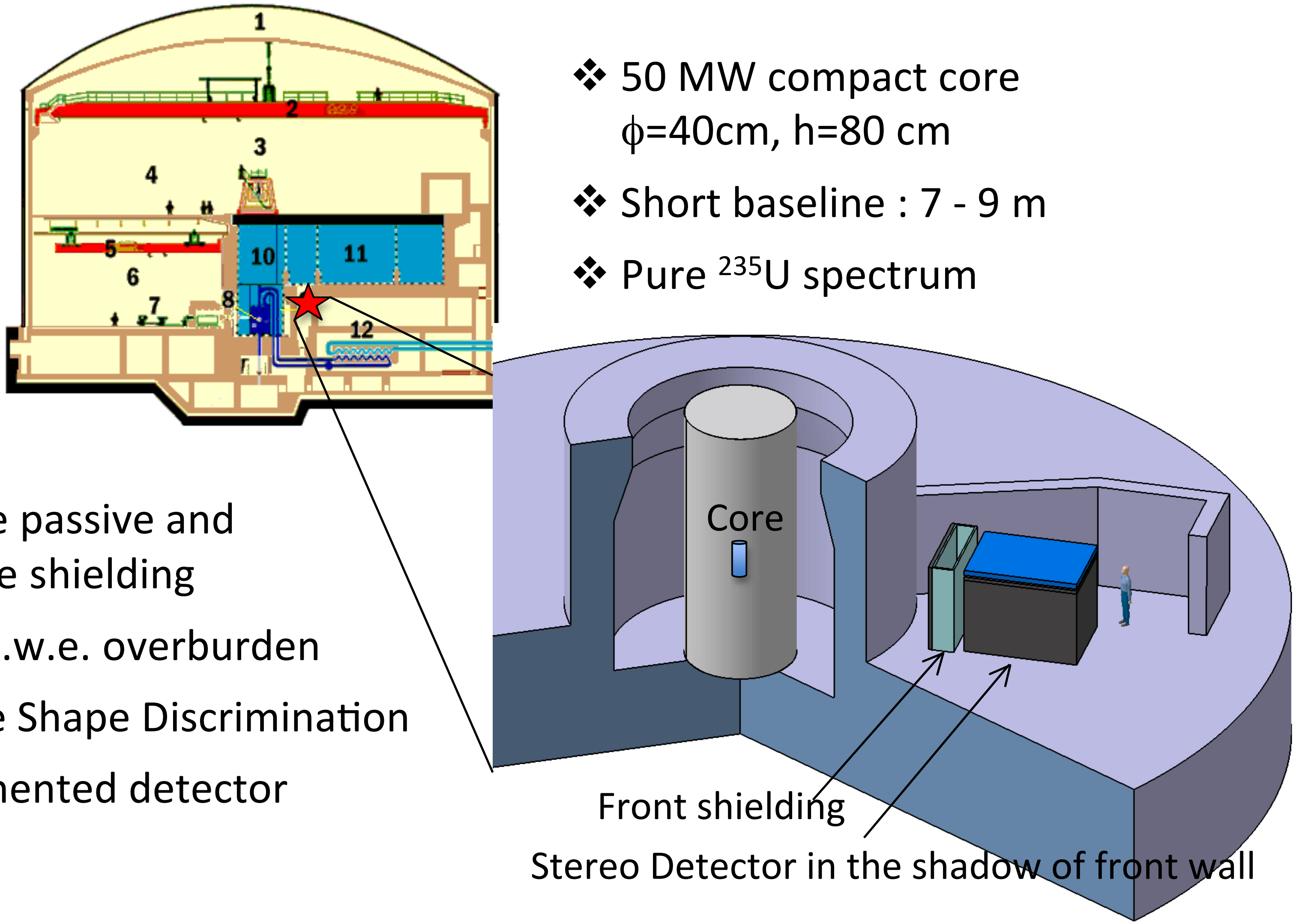
- Bad liquid scintillator
  - Replace by Double Chooz LS
- Unexpected high γ bkgds
  - 6-7 MeV from $^{16}O(n,p)^{16}N$
  - New lead wall installed
- Osiris maintenance
  - At least 6 months stop



- If finally lucky : possible hints of sterile neutrinos

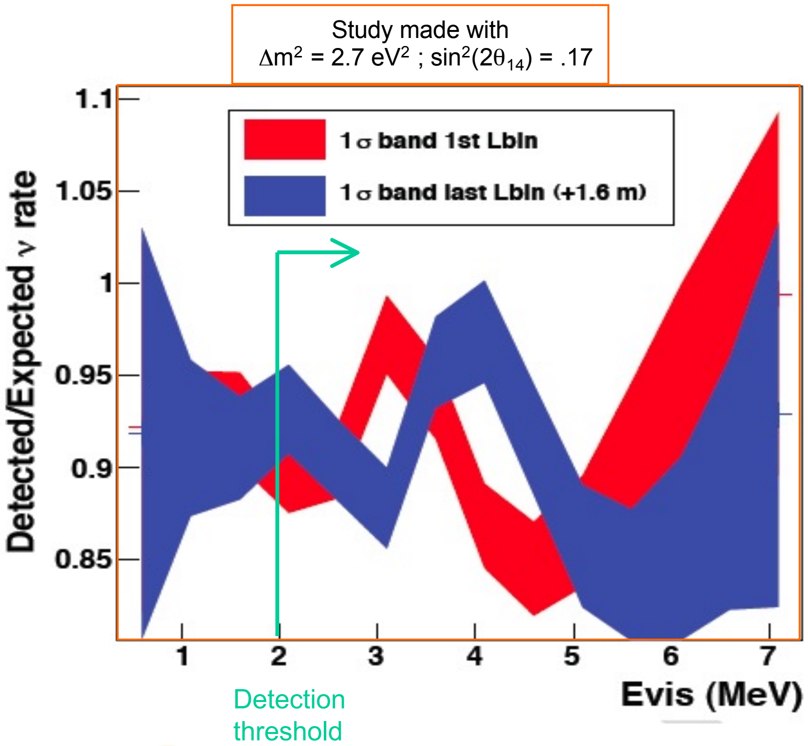
Stereo @ ILL Grenoble

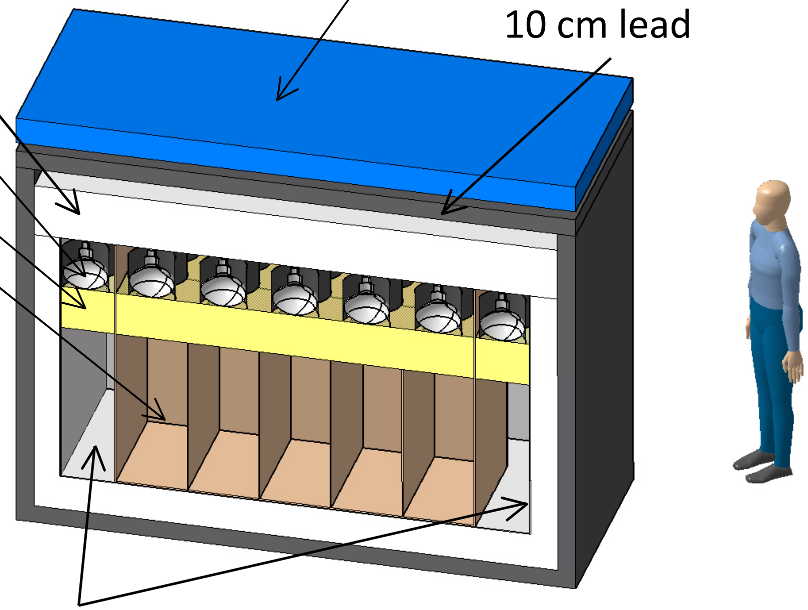
- 50 MW compact core
  ϕ=40cm, h=80 cm
- Short baseline : 7 - 9 m
- Pure ^{235}U spectrum



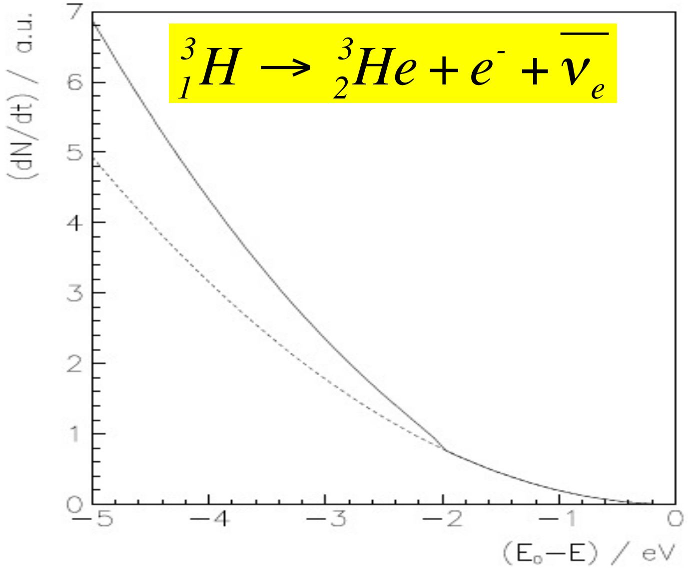
- Large passive and active shielding
- 15 m.w.e. overburden
- Pulse Shape Discrimination
- Segmented detector

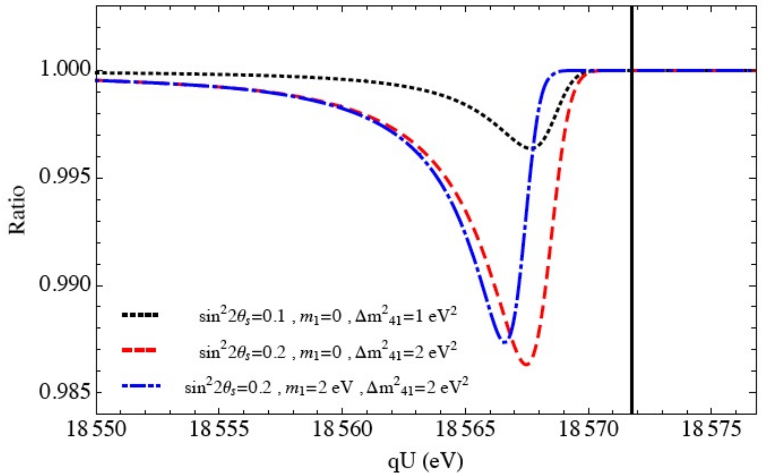
Stereo detector and signal



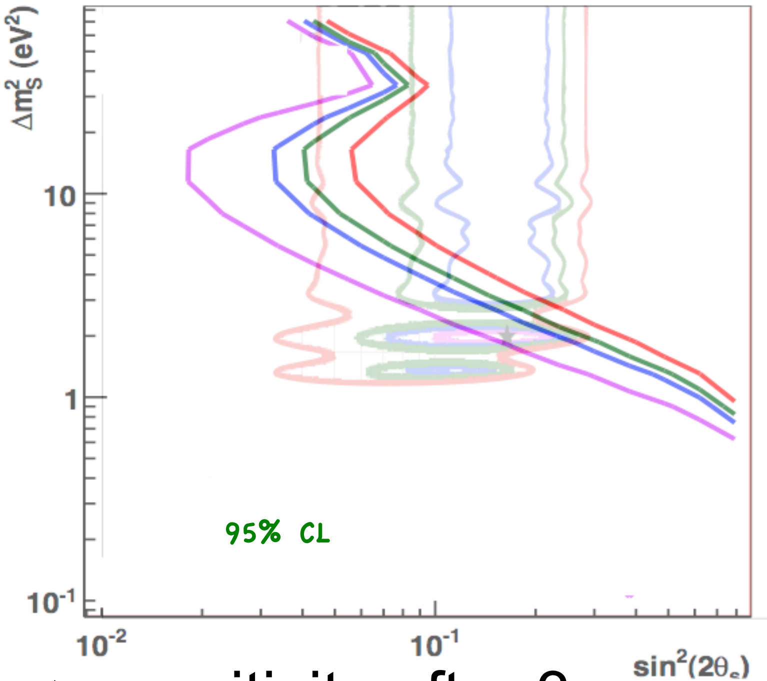


Katrin



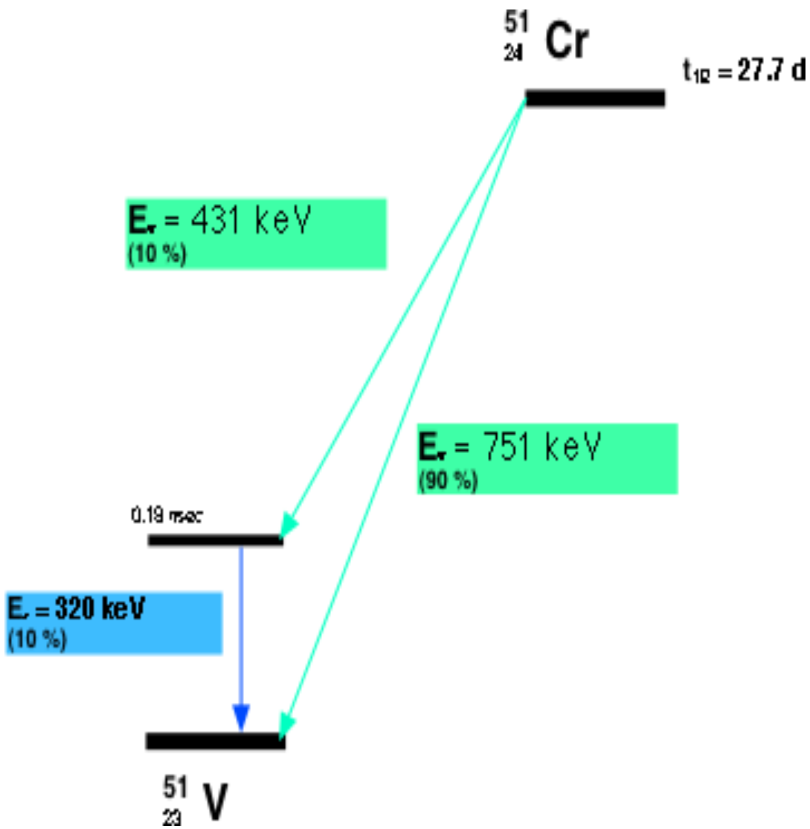


- a 4th neutrino :
  - displacement of end point



- sensitivity after 3 years

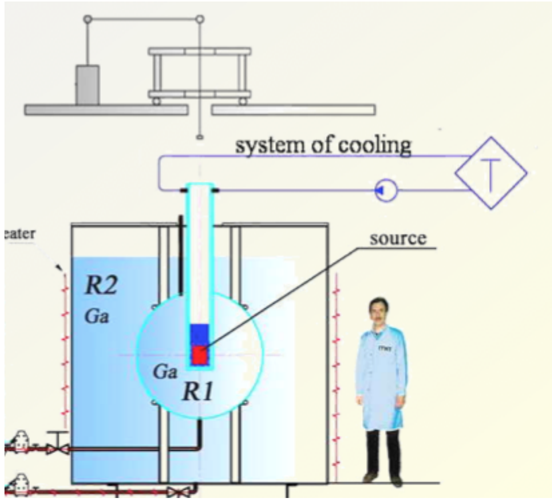
^{51}Cr

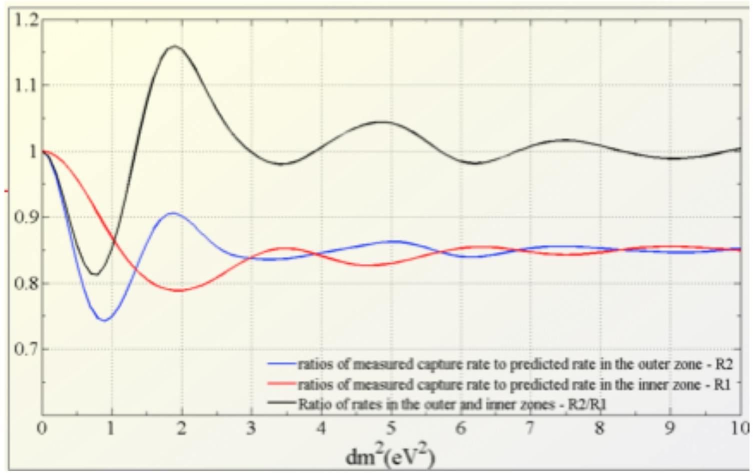


- Used in Gallex & Sage
  - Calibration solar ν experiments
  - Need enriched Cr in ^{50}Cr
- Irradiation in intense thermal neutron flux
  - In Russia, Oak-Ridge ?
- Mean-life : 40 days
- In liquid scintillator detector
  - Elastic scattering
  - ^{7}Be solar ν as bkgd

The Baksan proposal

- V. Gavrin et al.
  - arXiv:1006.2103
- New Gallium experiment
  - well known technology
  - zone 1 : 8 t
  - zone 2 : 42 t
- Source
  - ^{51}Cr - 3 Mci
  - 50 days irradiation in research reactor SM3
- Well known background
  - Solar neutrinos
- Partial sensitivity to the reactor anomaly



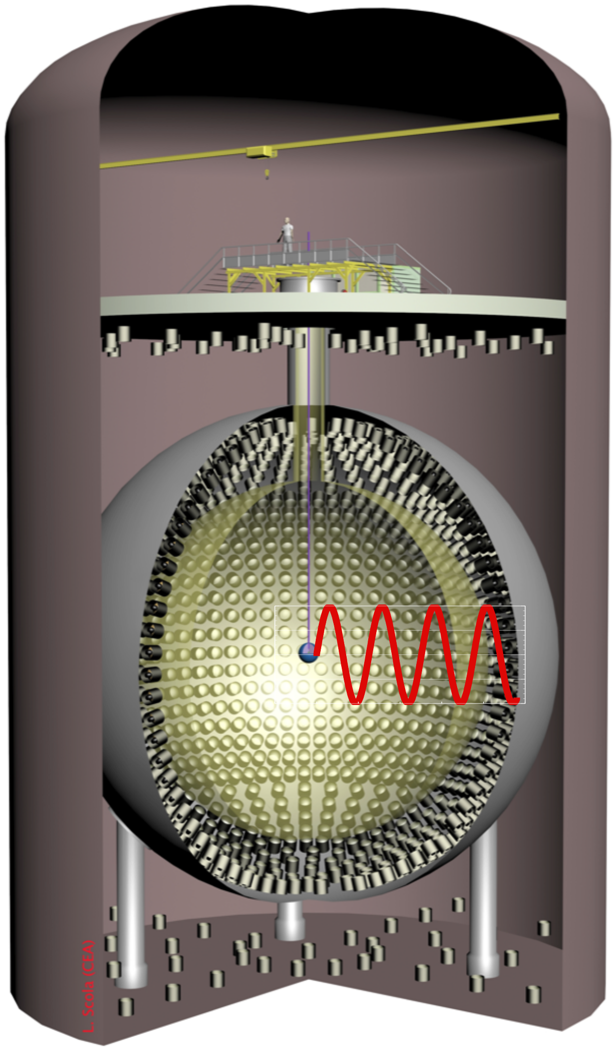


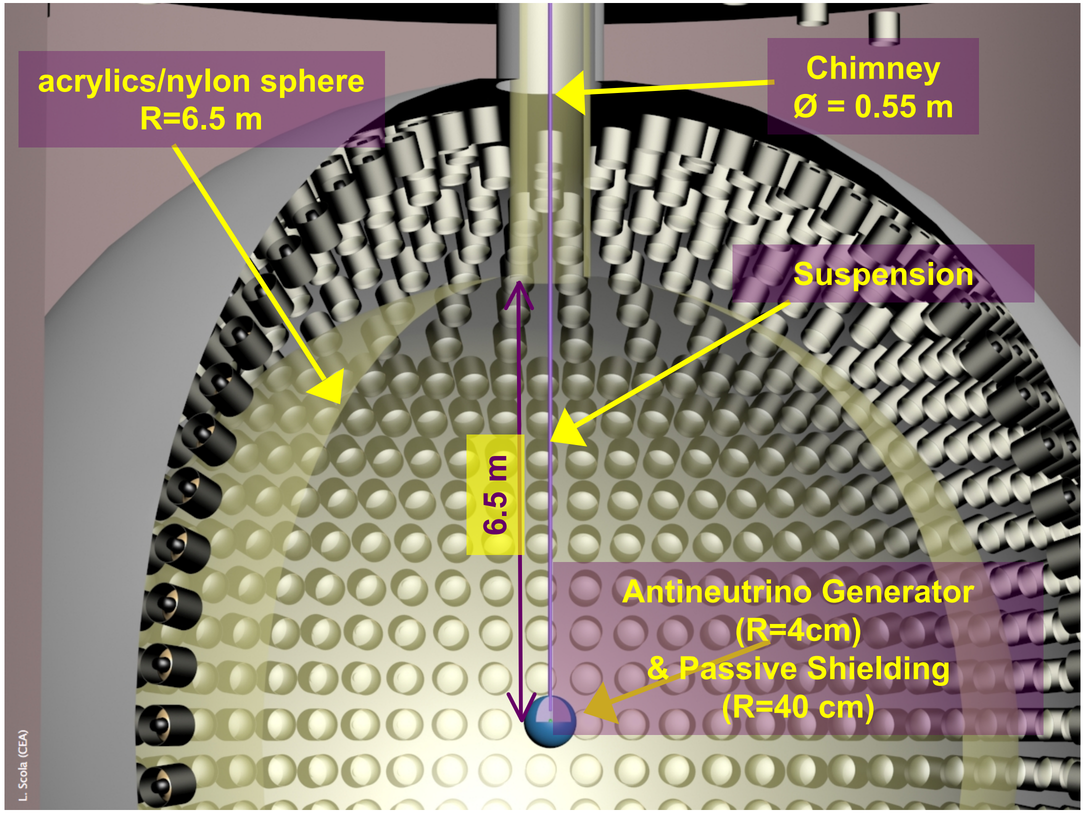
A proposed search for a fourth neutrino with a PBq anti-neutrino source

M. Cribier, M. Fechner, T. Lasserre, D. Lhuillier, A. Letourneau, G. Mention, D. Franco, S. Schoenert, V. Kornoukhov

Phys. Rev. Lett. 107, 201801 (2011)

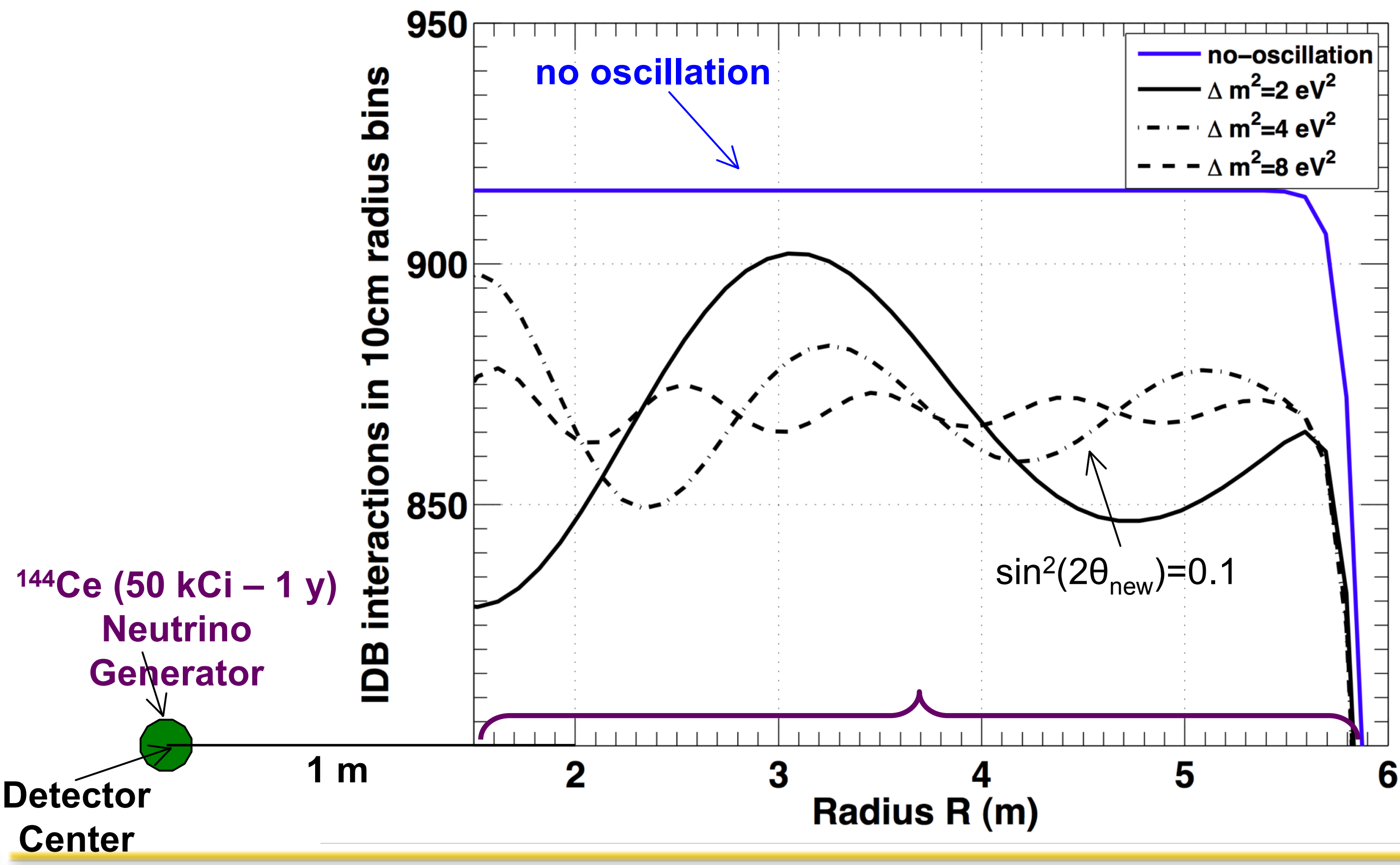
Concept : Oscillometry





An Unambiguous Proof

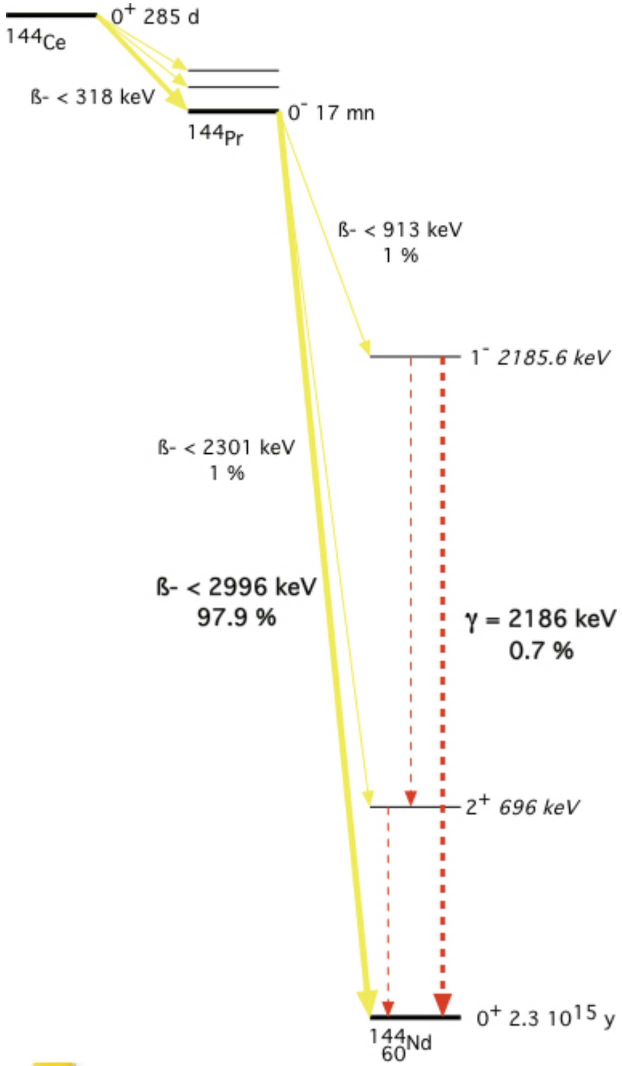
$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{\cancel{4\pi R^2}} \times \langle\sigma\rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E\rangle}\right)$$



Advantages of antineutrinos

- Antineutrino detection via inverse beta-decay
  - high cross section ($\approx 10^{-43}$ cm^2) : from **MCi to kCi** !
  - antineutrino must have **E_ν>1.8 MeV**
  - long Lifetime : more easy production, transport and measurement
  - e^+-n delayed coincidence : **background free experiment**
- Antineutrino source must involve
  - a long-lived low-Q nucleus…
  - … that decays into a short-lived high-Q nucleus
  - possible candidates
    - ^{90}Sr-^{90}Y , **^{144}Ce-^{144}Pr** , ^{106}Ru-^{106}Rb , ^{42}Ar-^{42}K
  - have been already produced

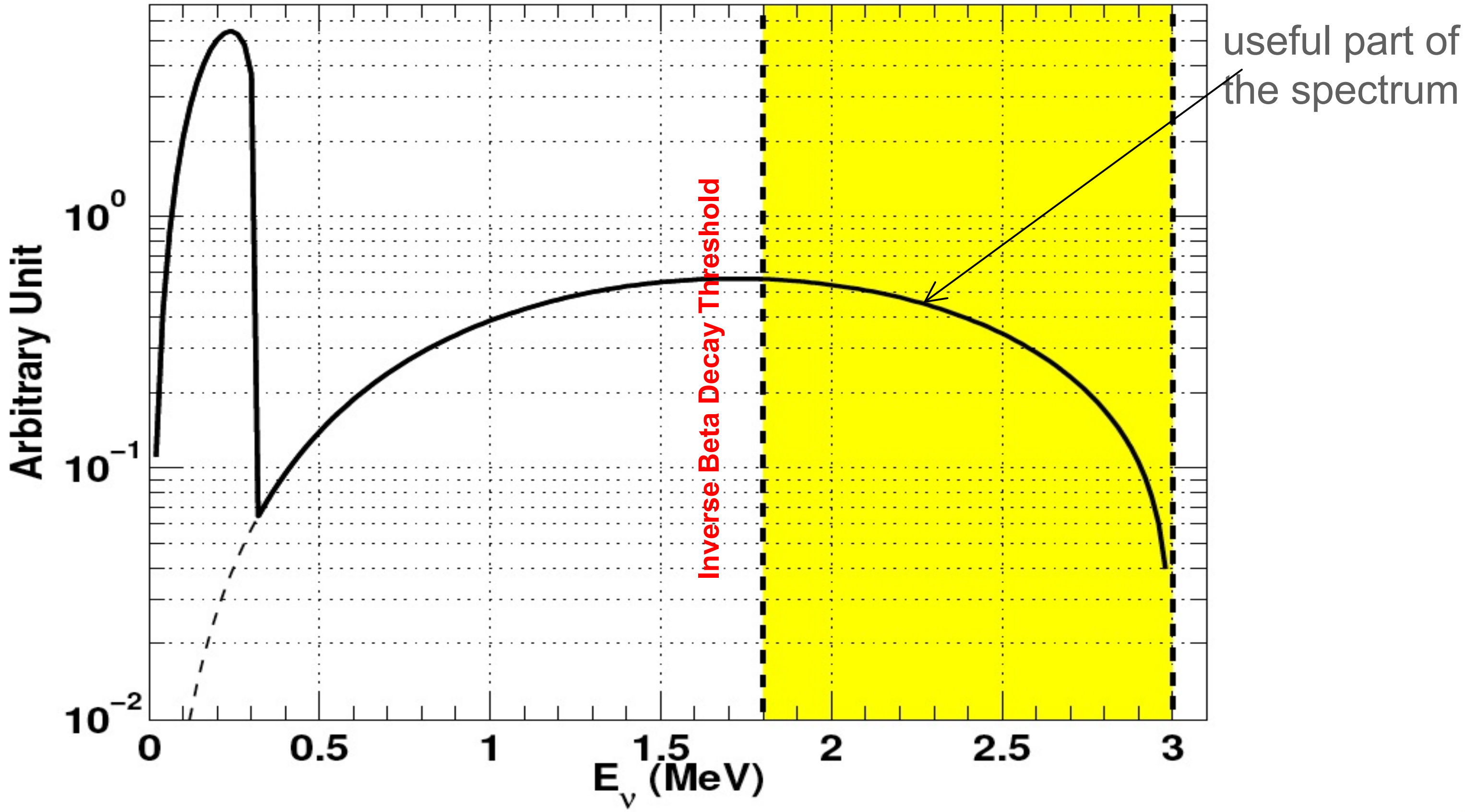
^{144}Ce-^{144}Pr



- Cerium, Praseodymium, Neodymium
- Mean life : 411.01 d ; -5% in 3 weeks
  - 1st forbidden, non unique decay
  - ^{144}Nd : 60 protons, 84 neutrons
  - nearest magic number : 82 neutrons
- 75 kCi (2.77 PBq)
  - 23.55 g ^{144}Ce
  - ≈ 9.0 kg of CeO_2
- 75 kCi => 599 W
  - <power>1y = 352 W
  - 7.90 W/kCi
- A well identified background
  - γ @ 2.186 MeV ; BR: 7 ‰
  - need a 10^{-12} reduction

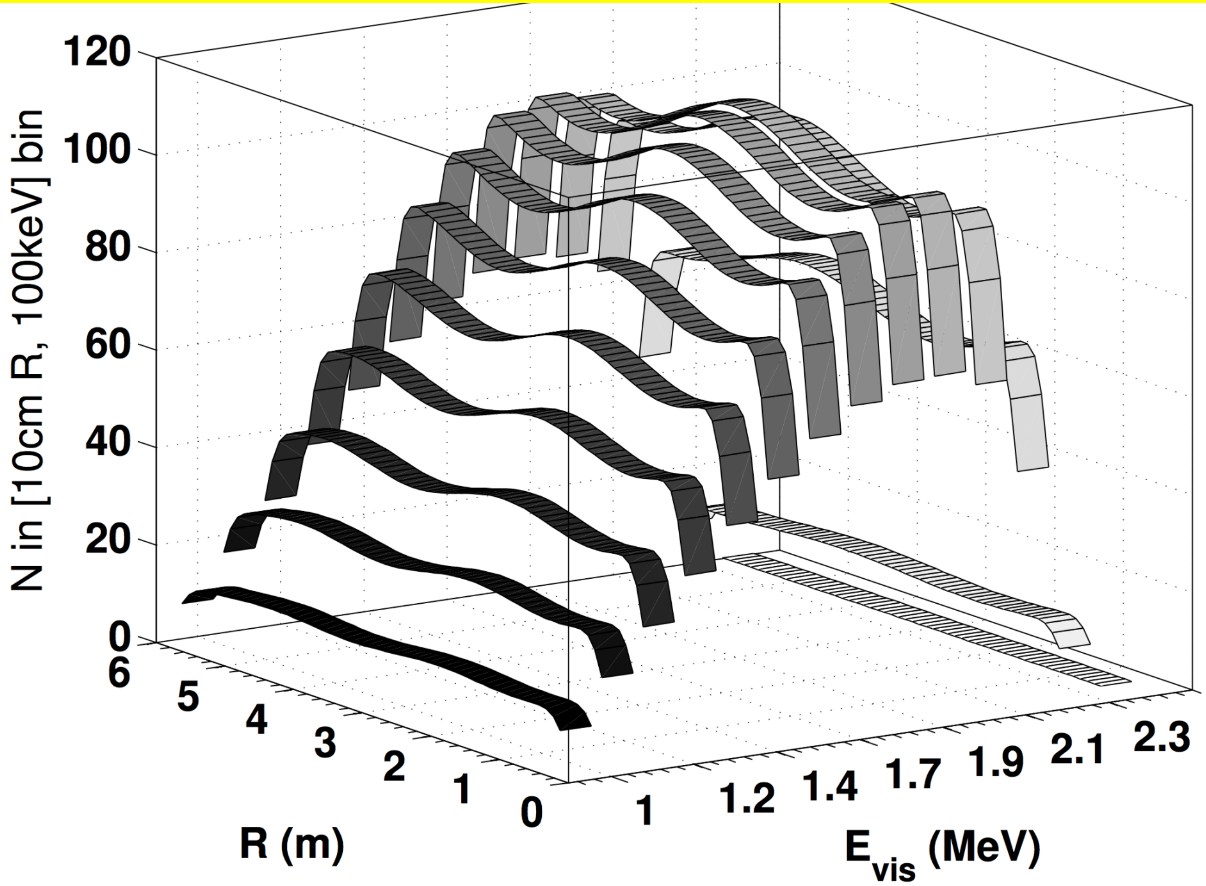
Spectrum of ^{144}Pr antineutrinos

- 48.75 % of antineutrinos emitted above IBD threshold
- Forbidden decay => uncertainties on end of ν spectrum
- Measure ß spectrum of pure ^{144}Pr sample after separation from ^{144}Ce



2-D imprint in E_ν, R space

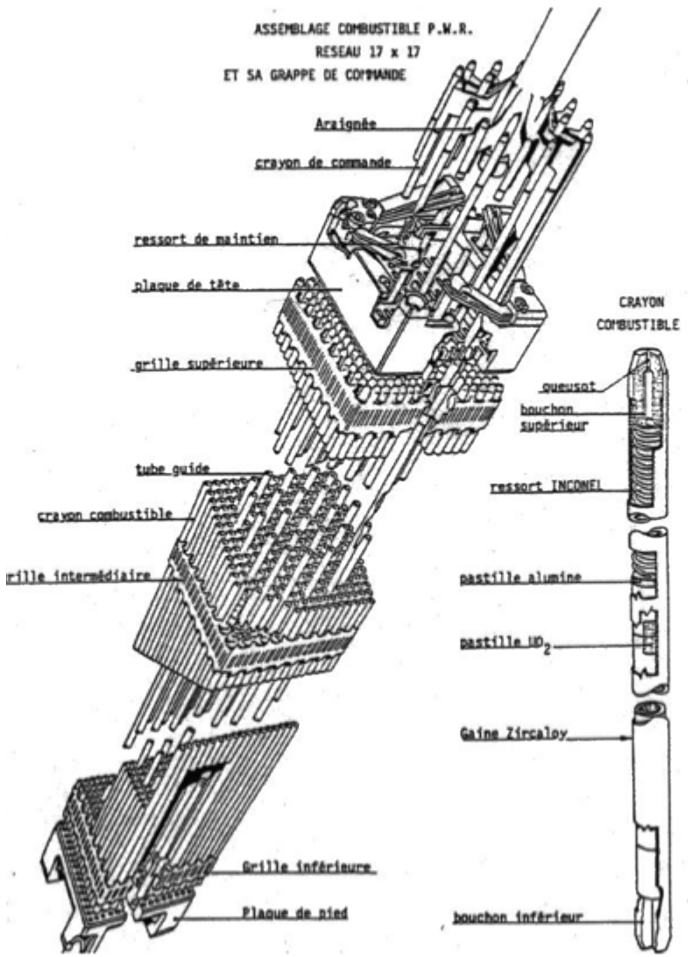
$$\frac{d^3N(R,E_\nu,t)}{dRdE_\nu dt} = A_0 \times n \times \sigma(E_\nu) \times S(E_\nu) \times P(R,E_\nu) \times e^{-t/\tau_{Ce}}$$



Making an antineutrino generator

Scheme of production

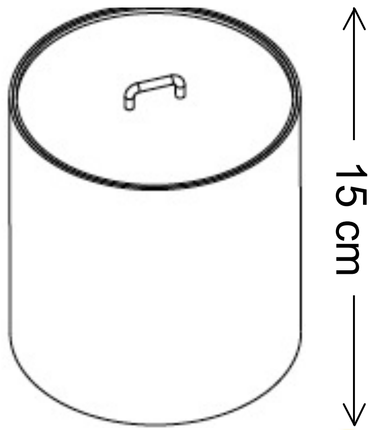
Cerium
an abundant fission product



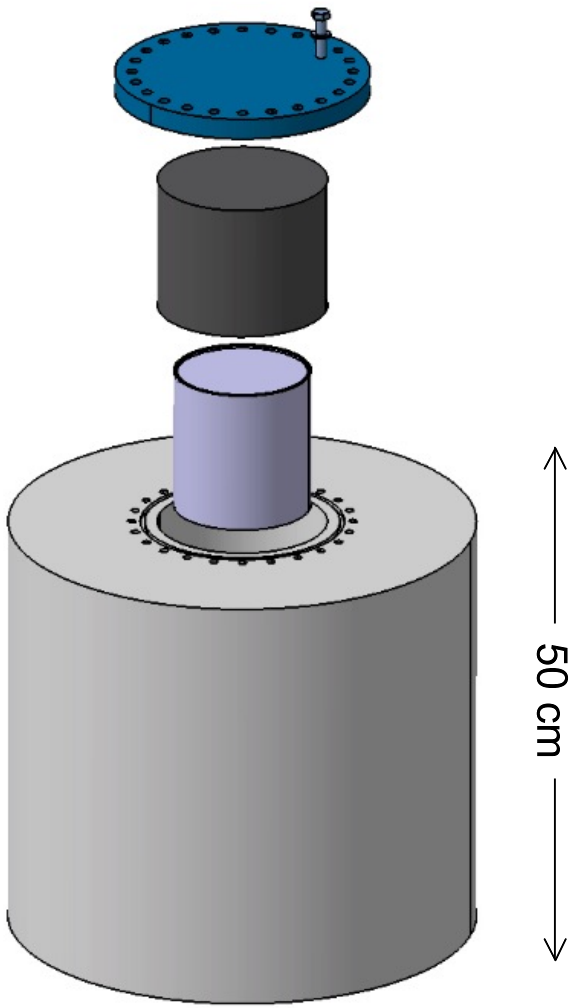
- 1 ton of spent fuel
  - Fission products : 44 kg
  - Rare earth : 15 kg
  - Cerium : 4 kg
  - ^{144}Ce : 22 g ie 80 kCi
- Extraction process
  - Displacement chromatography
  - French experts tested at lab scale
- Need the required industrial capability
  - La Hague type
  - **PA Mayak in Russia** : the only place in the world
- Constraint on radioactive impurities

Caracteristics of the antineutrino generator

- Cerium is in the chemical form of CeO_2
  - ^{144}Ce remain mixed with stable Cerium isotope
- A powder of apparent density ≈ 4-5 g/cm^3
- Operations
  - Mixing of the ≈ 9 kg of powder
  - Cold or hot pressing to reach ≈ 4.5 g/cm^3
  - In hot cell with remote handling
- The ^{144}Ce-^{144}Pr antineutrino generator (AνG)
  - a cylindrical object of ≈ 15 cm in diameter a
  - Cerium powder enclosed in a steel enveloppe
  - Compact : R « L_{osc}



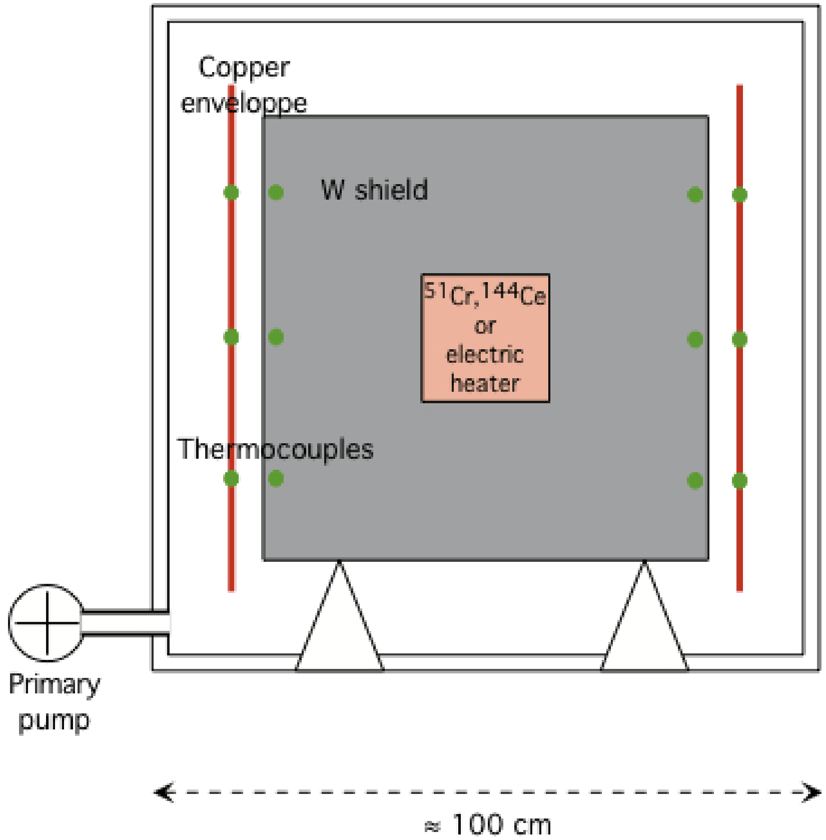
Characteristics of the source



- 75 kCi = 2.77 PBq
  - ≈ 9 kg of CeO_2 (ρ= 4 g/cm^3)
  - 2.0 liters
- Inner double sealed stainless steel cylinders
- Cylindrical tungsten shield
  - Densimet® 185
    - 18.5 g/cm^3 ; 97%W +Fe,Ni
  - water tight upper cork
  - 47 cm x 47 cm
  - 15 cm width minimum
  - 1.4 ton and ext. surface ≈ 1 m^2
- Dose rate (scaled estim. by SPR)
  - 1.5 mSv/h at contact
  - 50 µSv/h at 1m from shielding
- Estimated temperature at surface
  - 599 W ; external temp. 38 °C
  - ≈ 125 °C

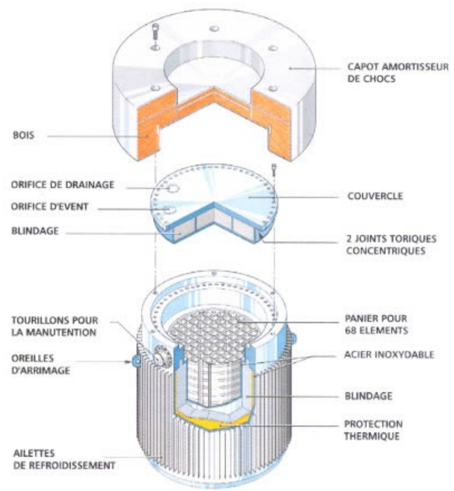
Activity measurements

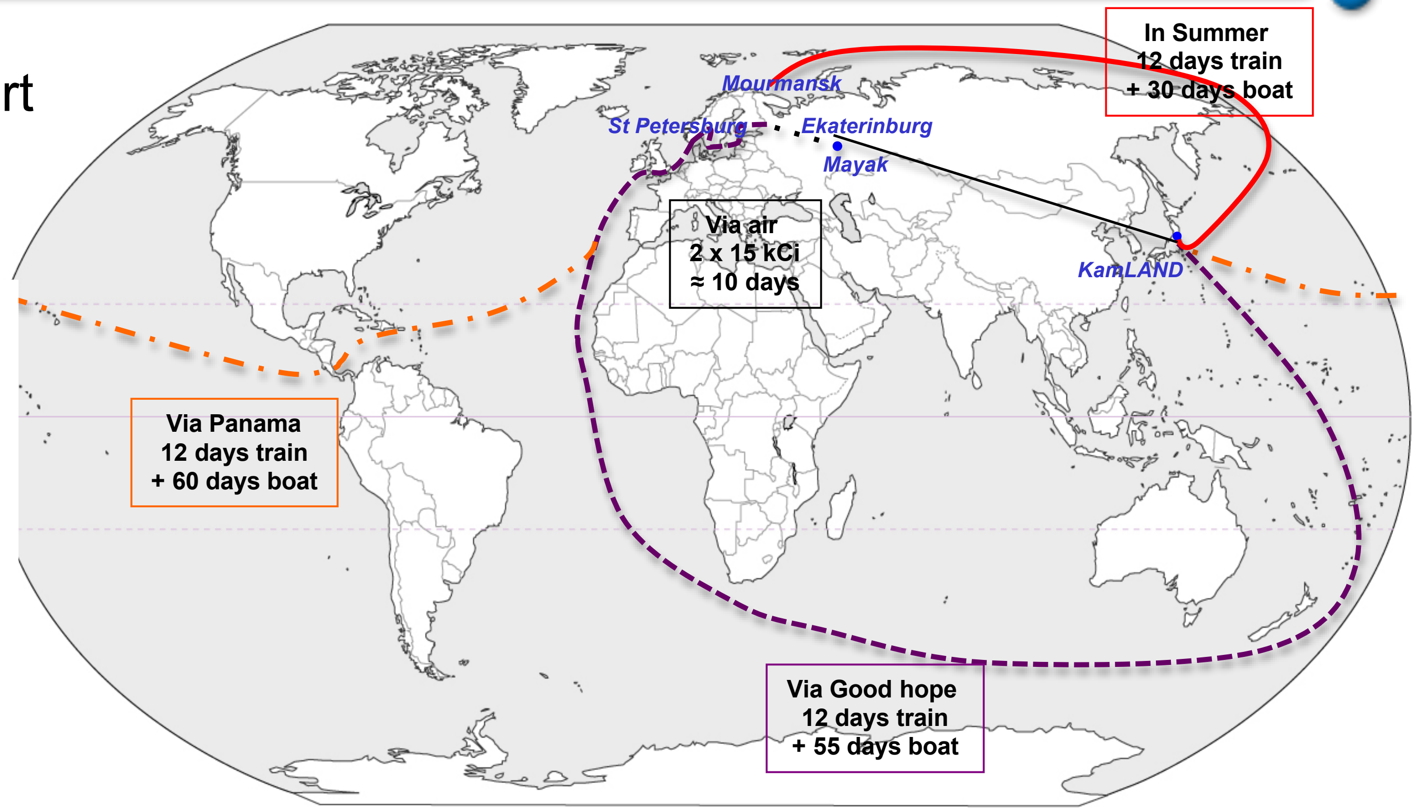
- Several ideas studied with specialists
  - Differential calorimetry in hot cells
    - 1.5 % accuracy ; need sampling ?
    - Needs 3-4 days for thermalization and counting
    - Technique used in Sage
  - Large calorimeter as used in Gallex
    - measurement prior and after the experiment
  - Common equipment with SoX ?
- Sampling and counting @ Saclay
  - Sampling, dissolution, large dilution
  - Shipment to external labs
  - Counting in Ge-counter
  - <u>needs << 1/% mass measurements</u>
- Not a limiting factor for the experiment



Transportation issues

- Certified transport container
  - 23 tons !



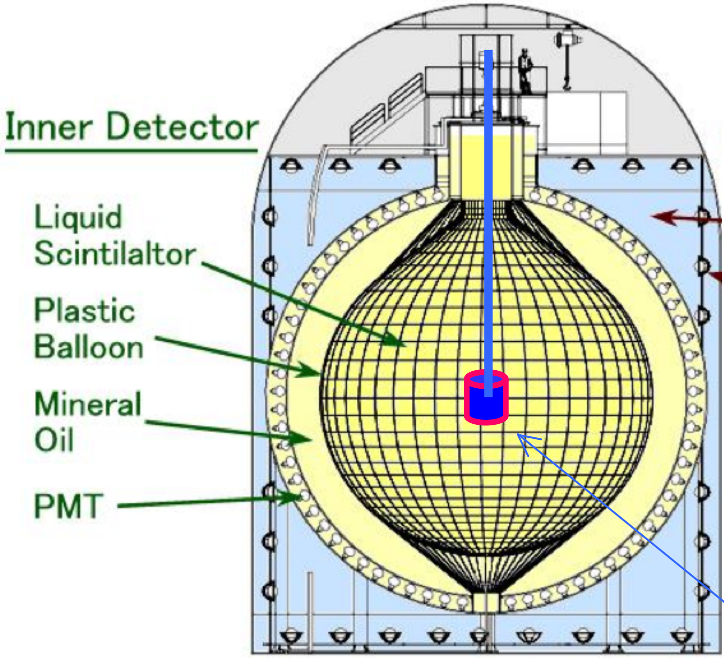


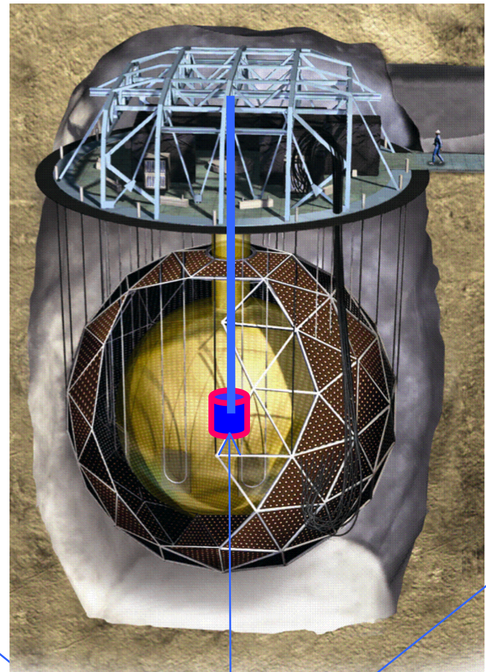
- Severe constraints based on regulation issued by IAEA
  - nothing impossible, but long, bureaucratic and costly
  - by air limit for each radioisotope : 16.2 kCi for ^{144}Ce, 2.4 MCi for ^{51}Cr
  - by boat : only limited number of harbours agreed for radioactive materials

Solving experimental constraints

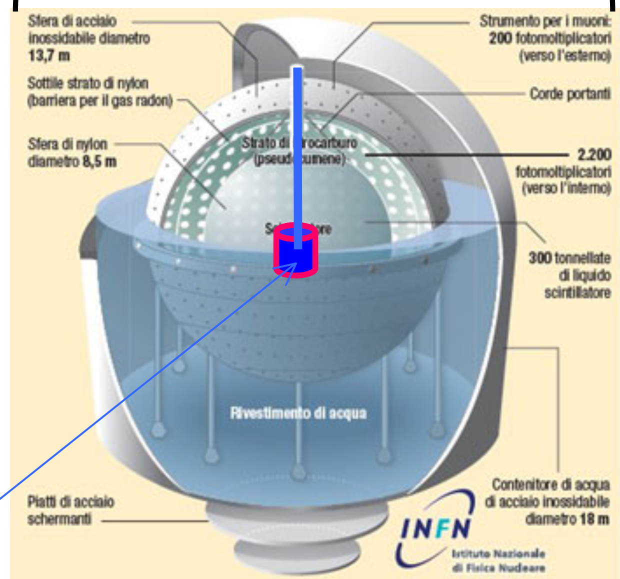
Large liquid scintillator detectors ?

- 3 possible candidates : Borexino, KamLAND, SNO+
  - Interferences with the present experimental programs
  - Technical issues : size of chimney, liquid purity, electronics…
  - Good energy resolution : 5 %
  - Good position resolution : ≈ 15 cm << L_{osc}



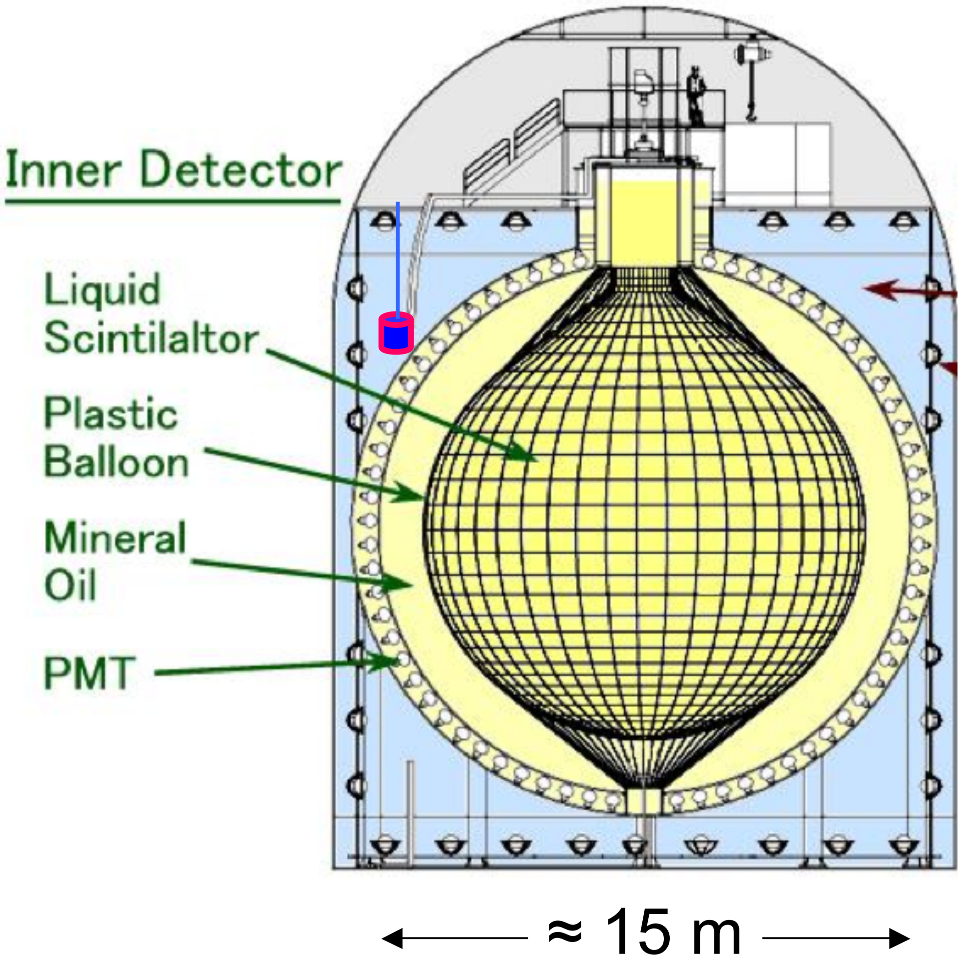


+ internal initiative
by Borexino Collaboration

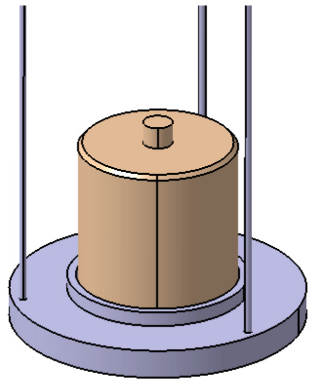


50 kCi ^{144}Ce-^{144}Pr source

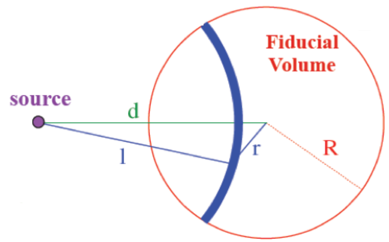
CeLAND at KamLAND : 1st phase



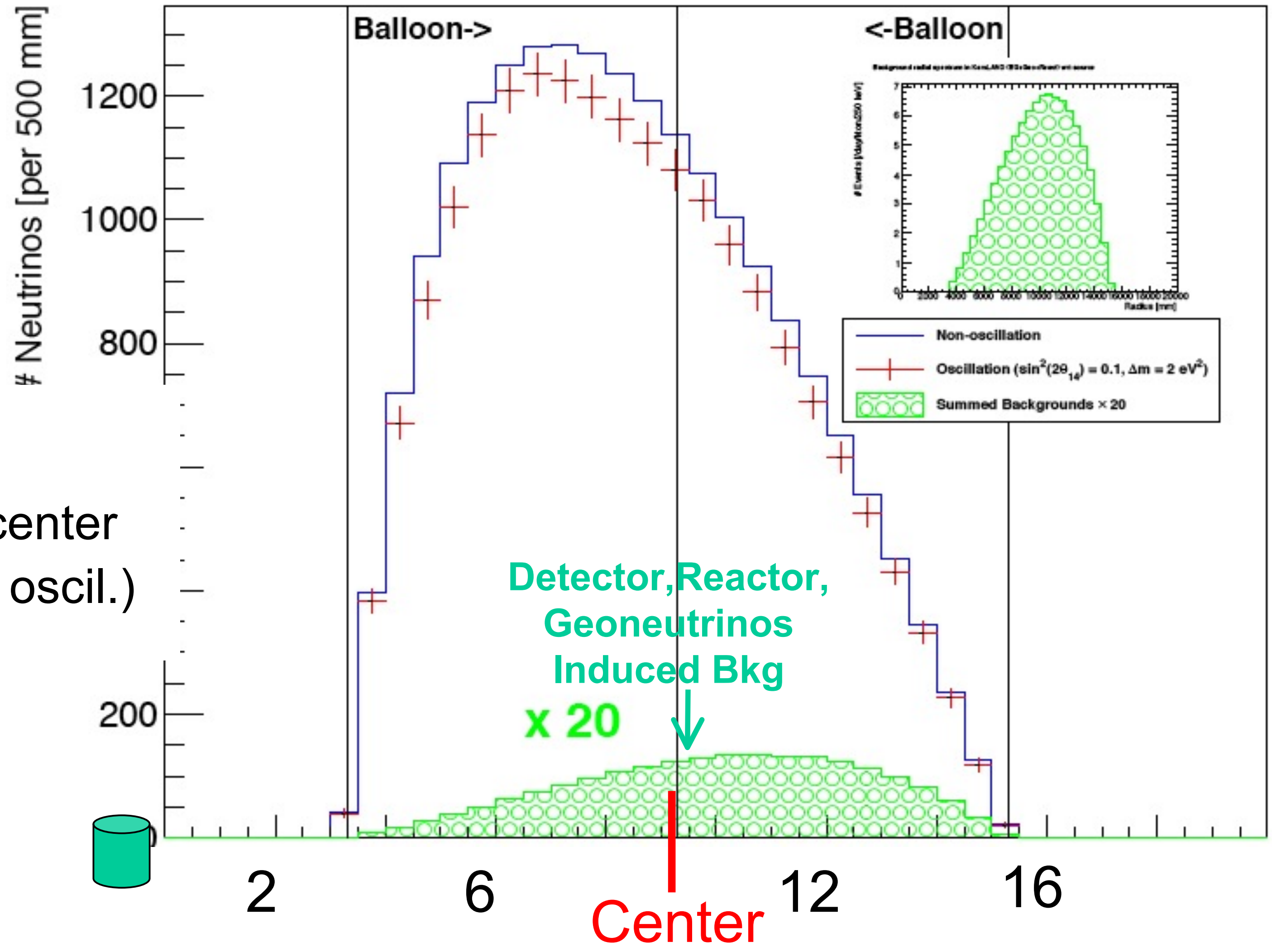
- ❖ Detector mostly studied so far
  - easily applied to Borexino
- ❖ Ranked #1 for future projects
  - a 75 kCi ^{144}Ce source in spring/summer 2015
- ❖ In the outer water veto
  - 2.5 m from liquid scint.
  - much more easy to handle
- ❖ 6-18 months data taking



Signal & Backgrounds : 1st phase

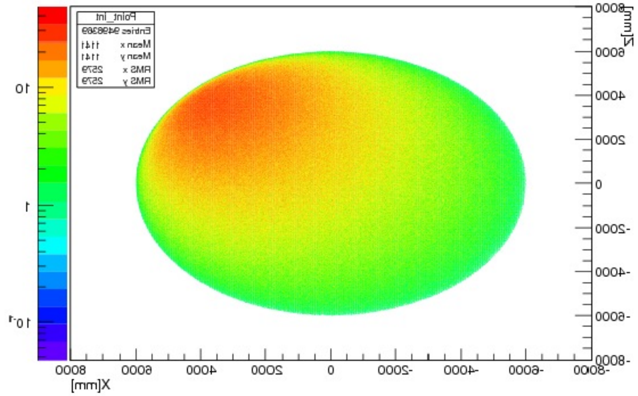


- 75 kCi ; 1 year outside @ 9.5 m from center
- 20000 evts (no oscil.)



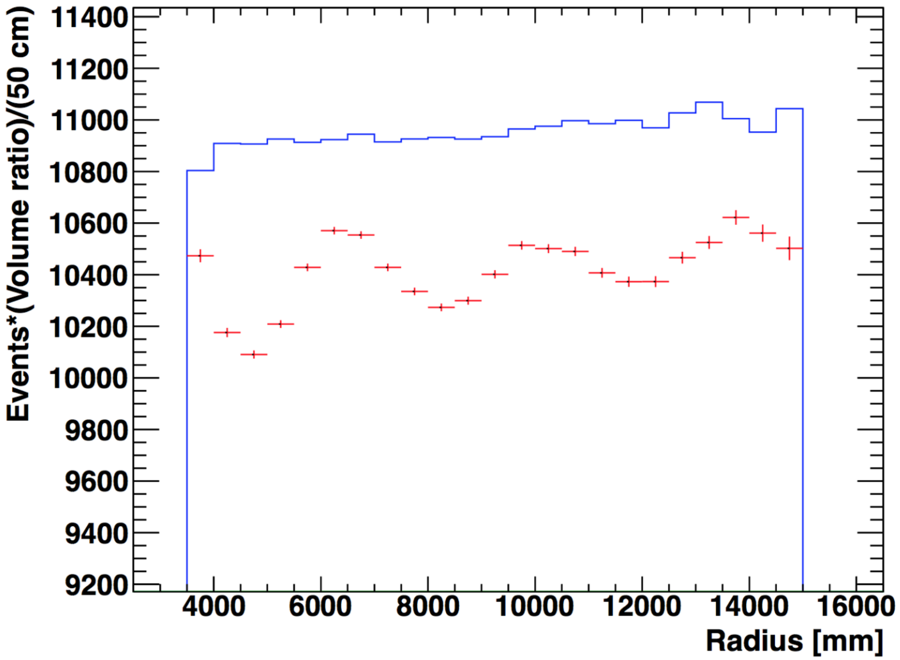
Michel Cribier
CEA/DSM Irfu/SPP & APC-Paris

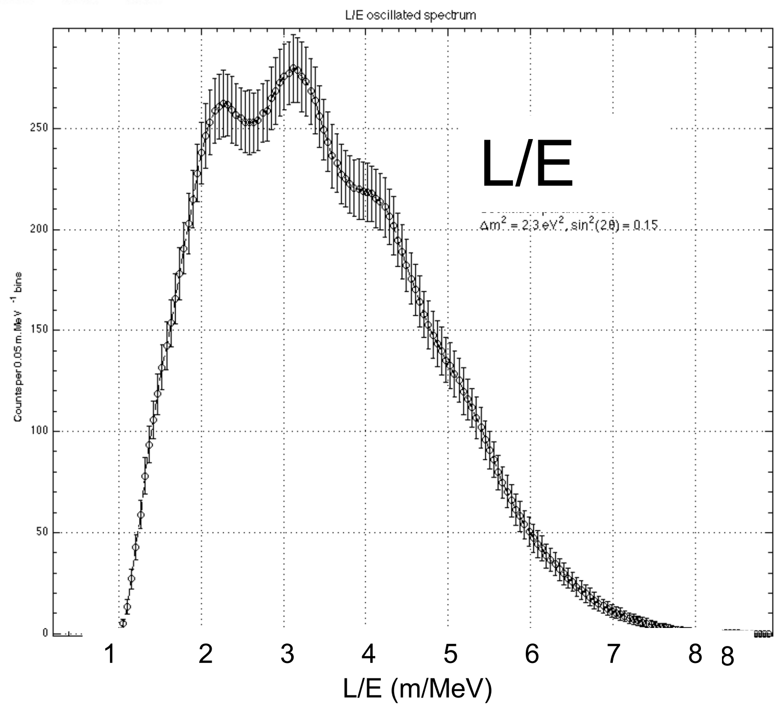
Clear signal : 1^{st} phase



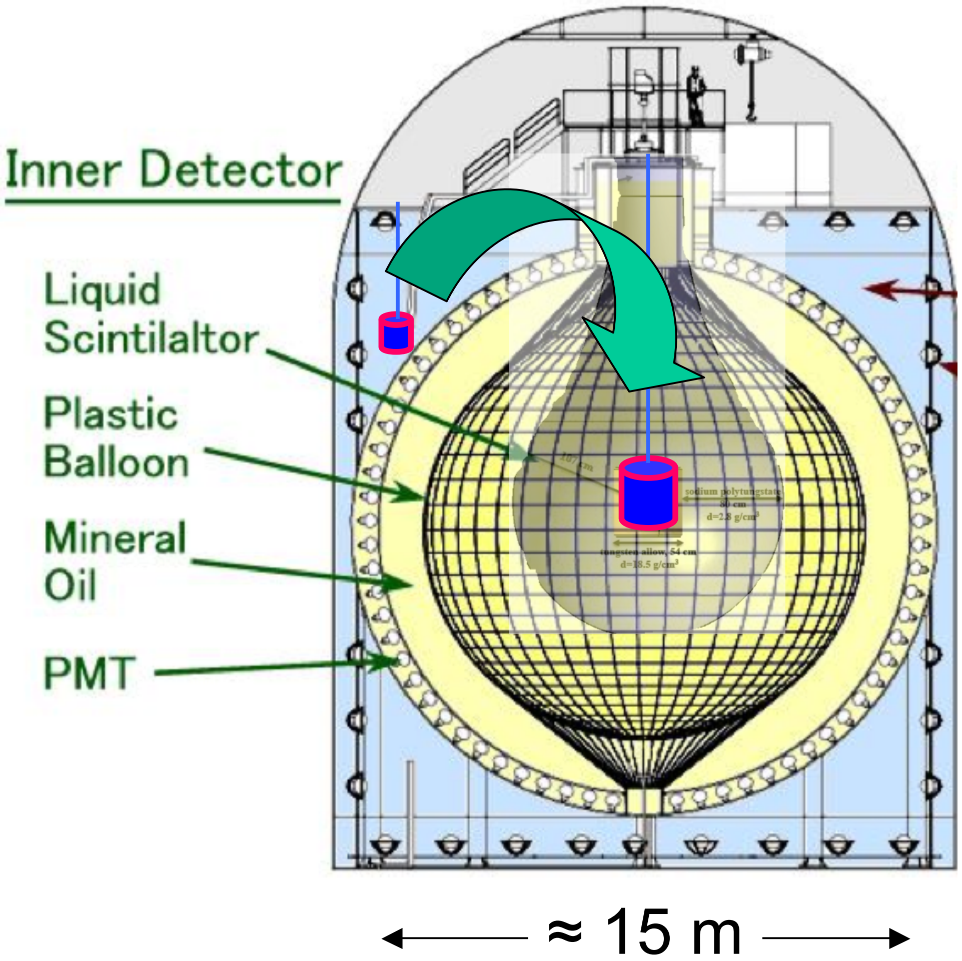
- $\Delta m^2 = 2.3\ eV^2$
  $\sin^2(2\theta_{14}) = 0.15$

- 75 kCi ; 12 months outside @ 9.5 m from center



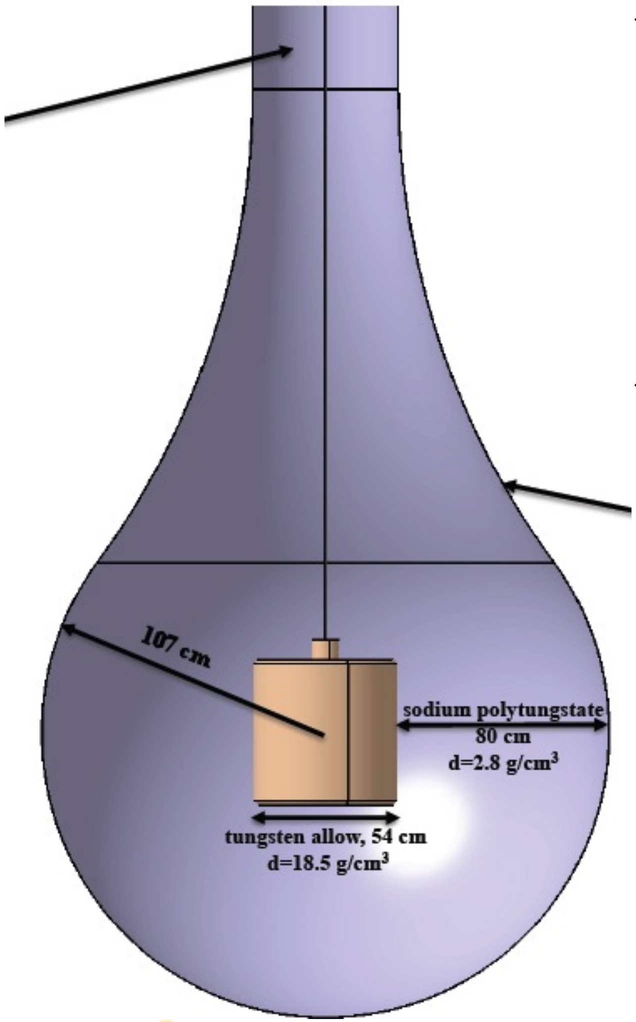


CeLAND : 2nd phase



- Several constraints
  - an existing underground detector
  - full of an extra pure mineral oil
    - Avoid contaminations
- The entrance hole
  - 50 cm in diameter
  - delicate operations to insert the source in center
- Planned operations
  - if hints of oscillation signal
  - move the same ^{144}Ce source in the center with an extra shielding
  - 18 more months : ≈ 56 000 evts

Shielding : 2nd solution



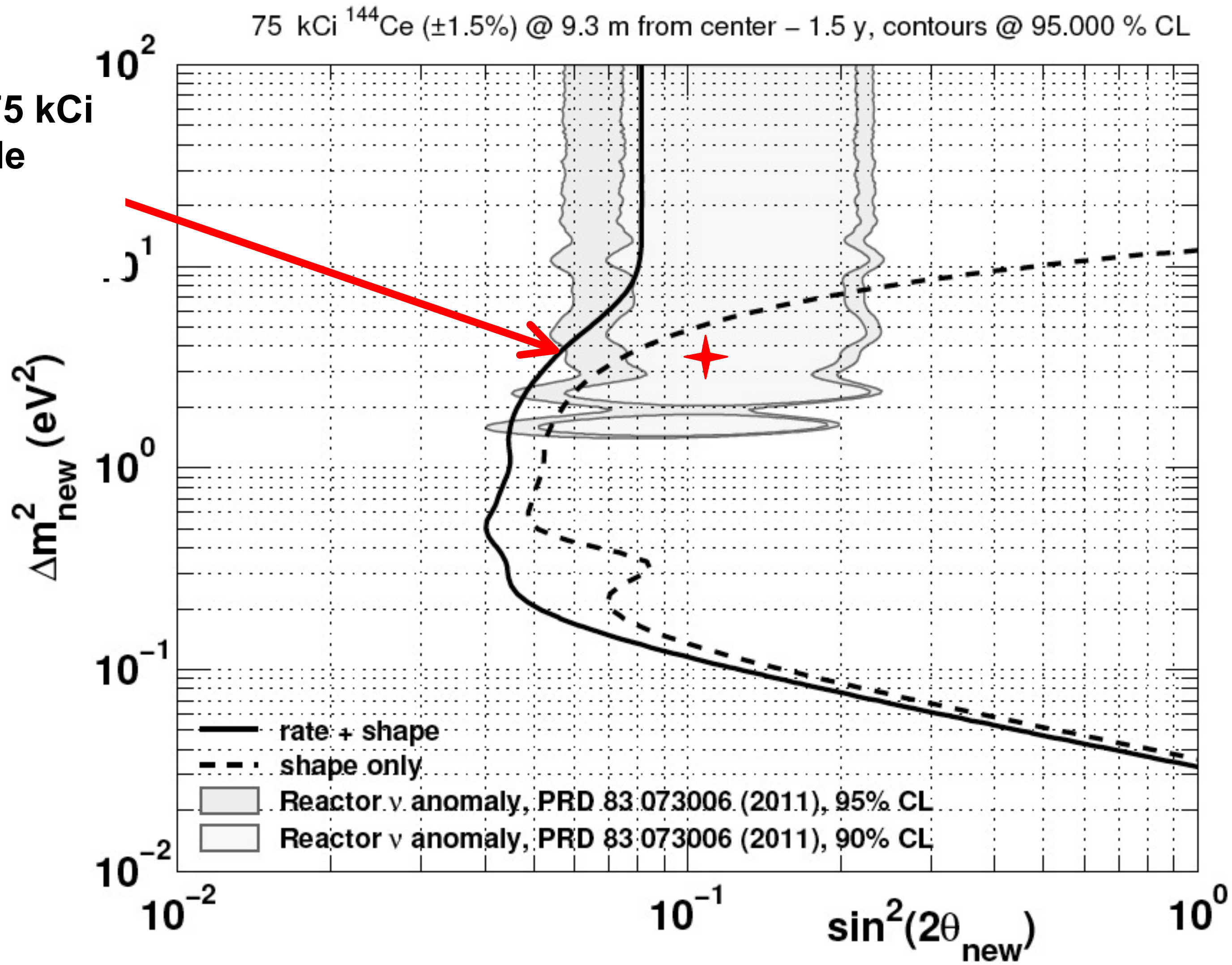
- Central part in Densimet
  - diameter 54 cm to fit through chimney
  - central cavity to host ^{144}Ce Ø ≈ 8 cm
  - weight : 2.3 tons
  - more than enough for biological protection
- A balloon in nylon containing heavy liquid : *Sodium paraTungstate*
  - density : 2.82 g/cm^3
  - viscosity better than olive oil
  - interaction length @ 2.2 MeV : 8.1 cm
  - external radius : 107 cm
  - weight : 14.2 tons (10.5 t. with buoyancy)

Fourth neutrino
the decisive test

Full range of parameters : 1st phase

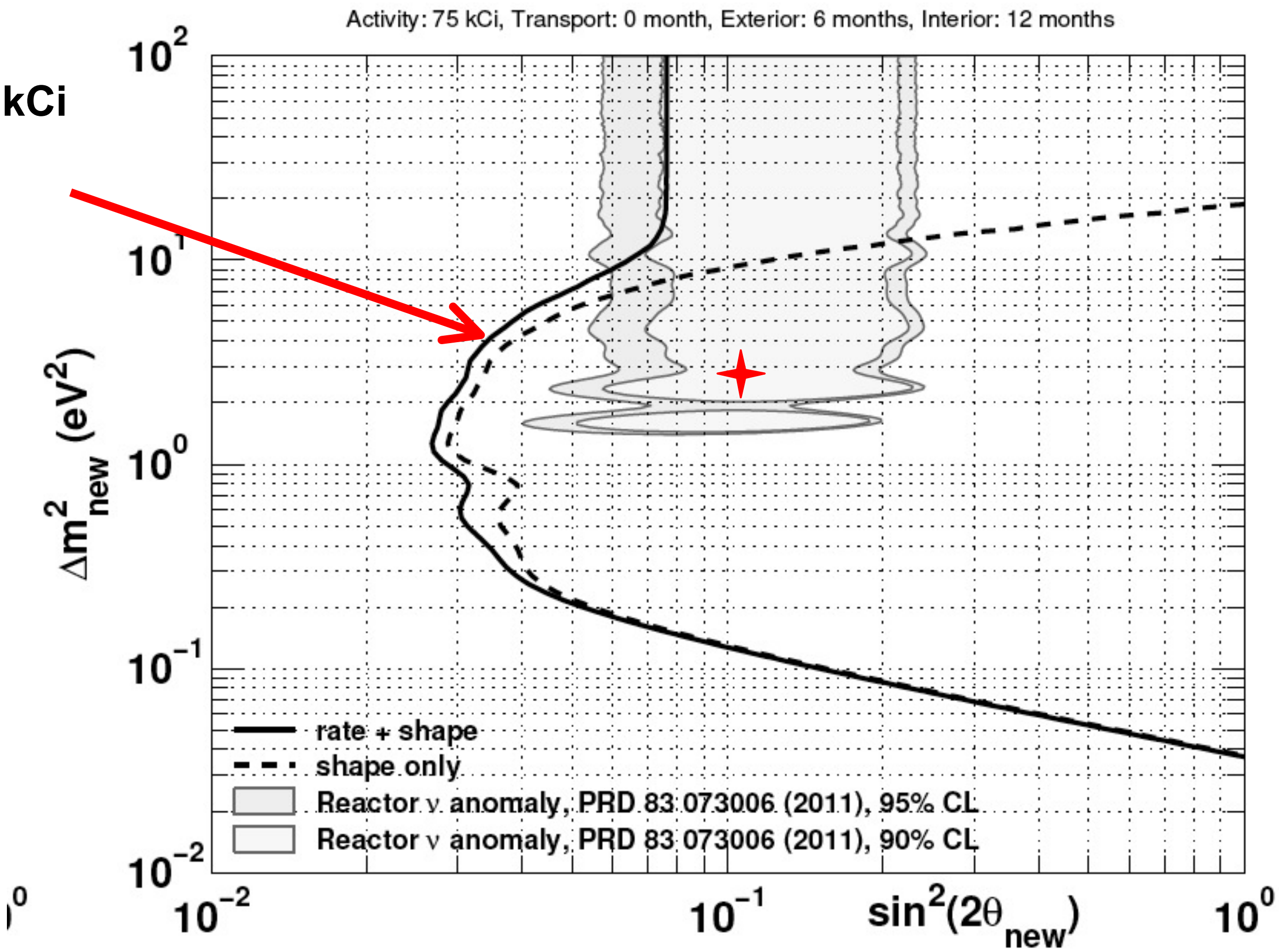
^{144}Ce-^{144}Pr : 75 kCi
1.5 y outside

95%CL



Full range of parameters : 2nd phase

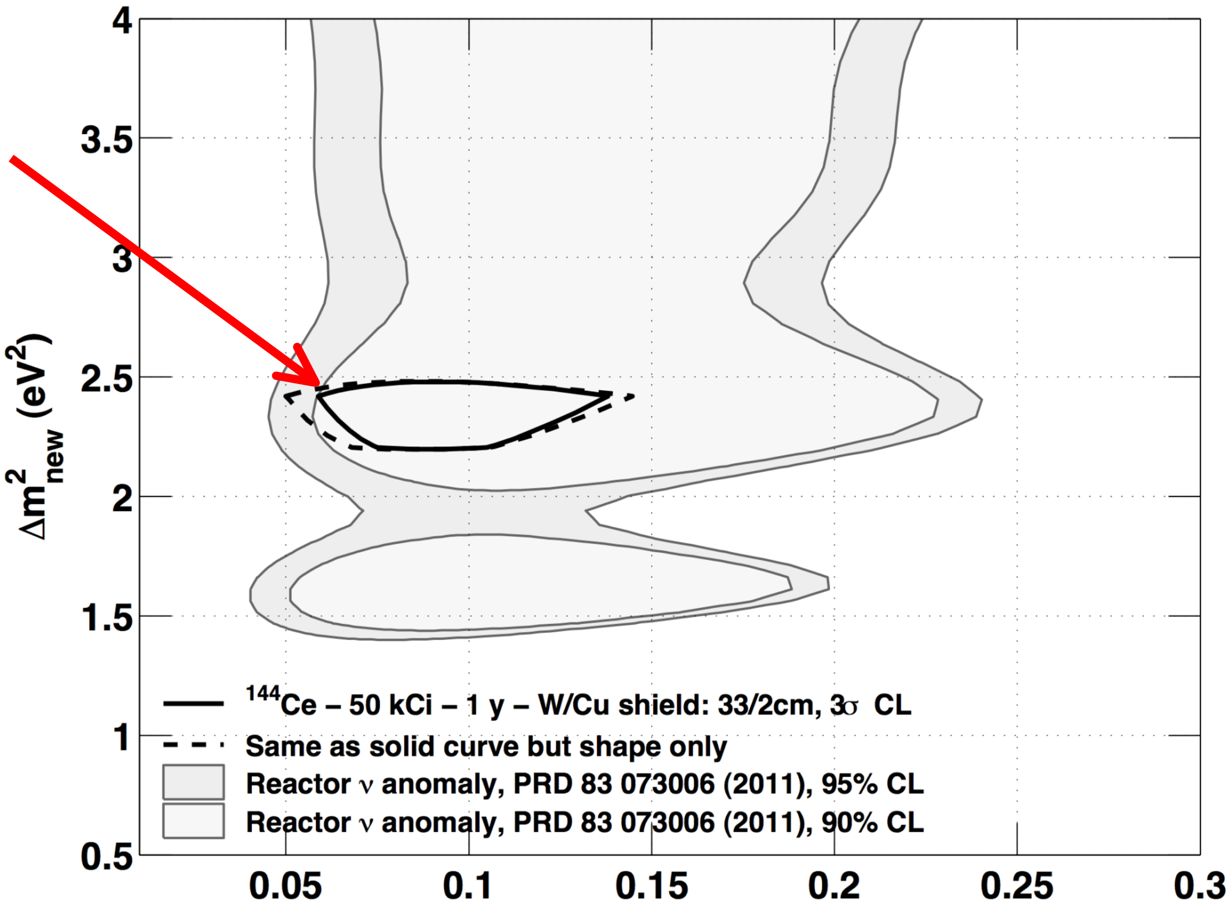
^{144}Ce-^{144}Pr : 75 kCi
0.5 y outside
1 y inside
95%CL



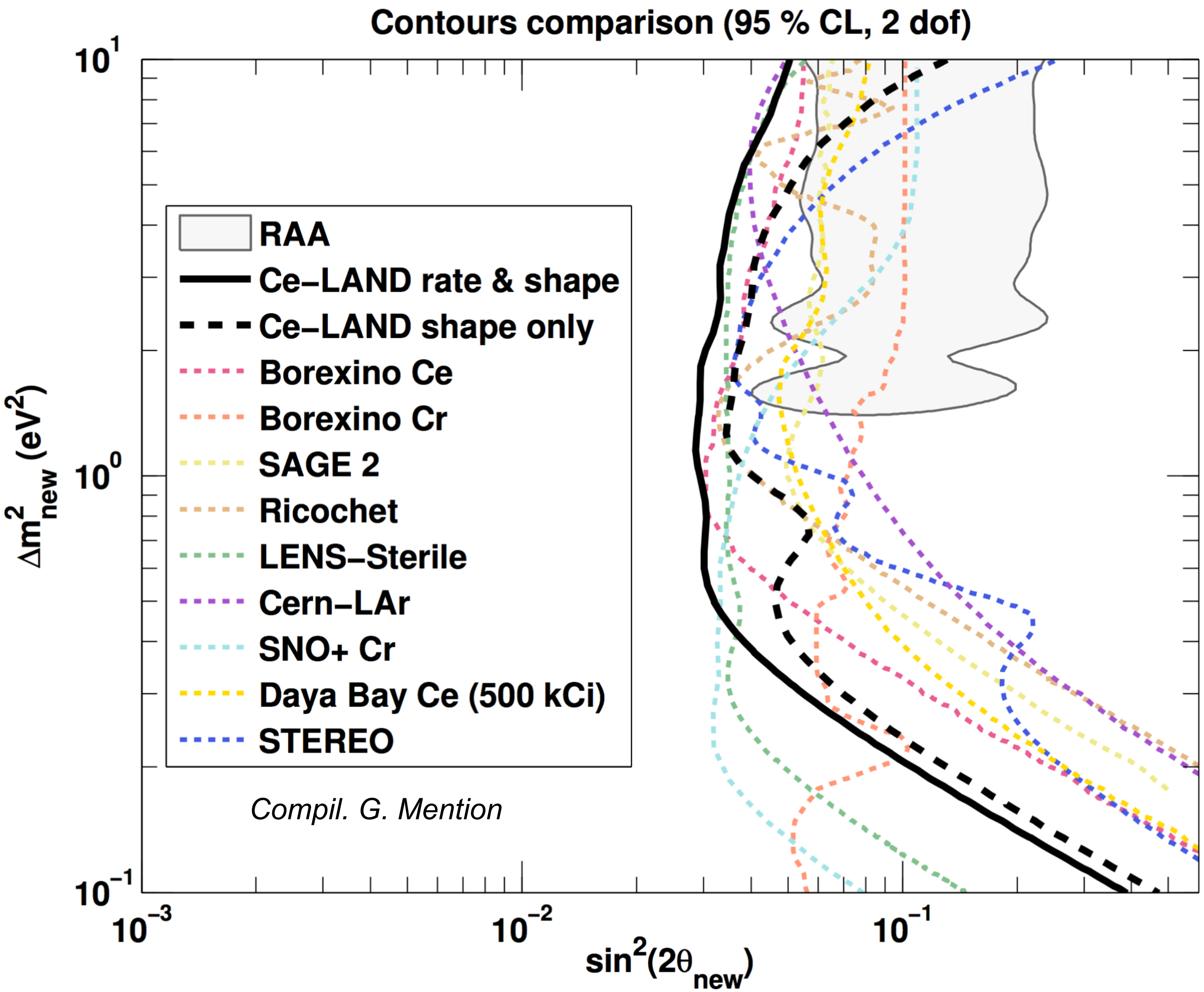
Discovery potential

$\sin^2 2\theta = 0.1$ & $\Delta m^2 = 2.2$ eV^2 tagged at 3σ

1 y – 50 kCi
^{144}Ce-^{144}Pr
3σ contour



Proposal sensitivities



Conclusions

- Do we need a fourth neutrino ?
  - Intriguing anomalies in reactors experiments, Gallium,…
  - A possible revolution in physics
  - A hot topic : ERC put 5 M€ in this subject
  - Is cosmology input decisive for neutrino physic ?
    - an incredible example of multidiscipplinary approach
- We need reliable experimental answers soon
  - Sources of neutrinos and antineutrinos
    - CeLAND and SoX ; KamLAND or Borexino
    - Final option dictated by easiest solutions
  - Use of antineutrinos from reactors
    - Stéreo or Solid @ ILL
  - Direct observation with Katrin
  - …
- A clear answer in a few years

Just do it.

Backup slides

Conclusions

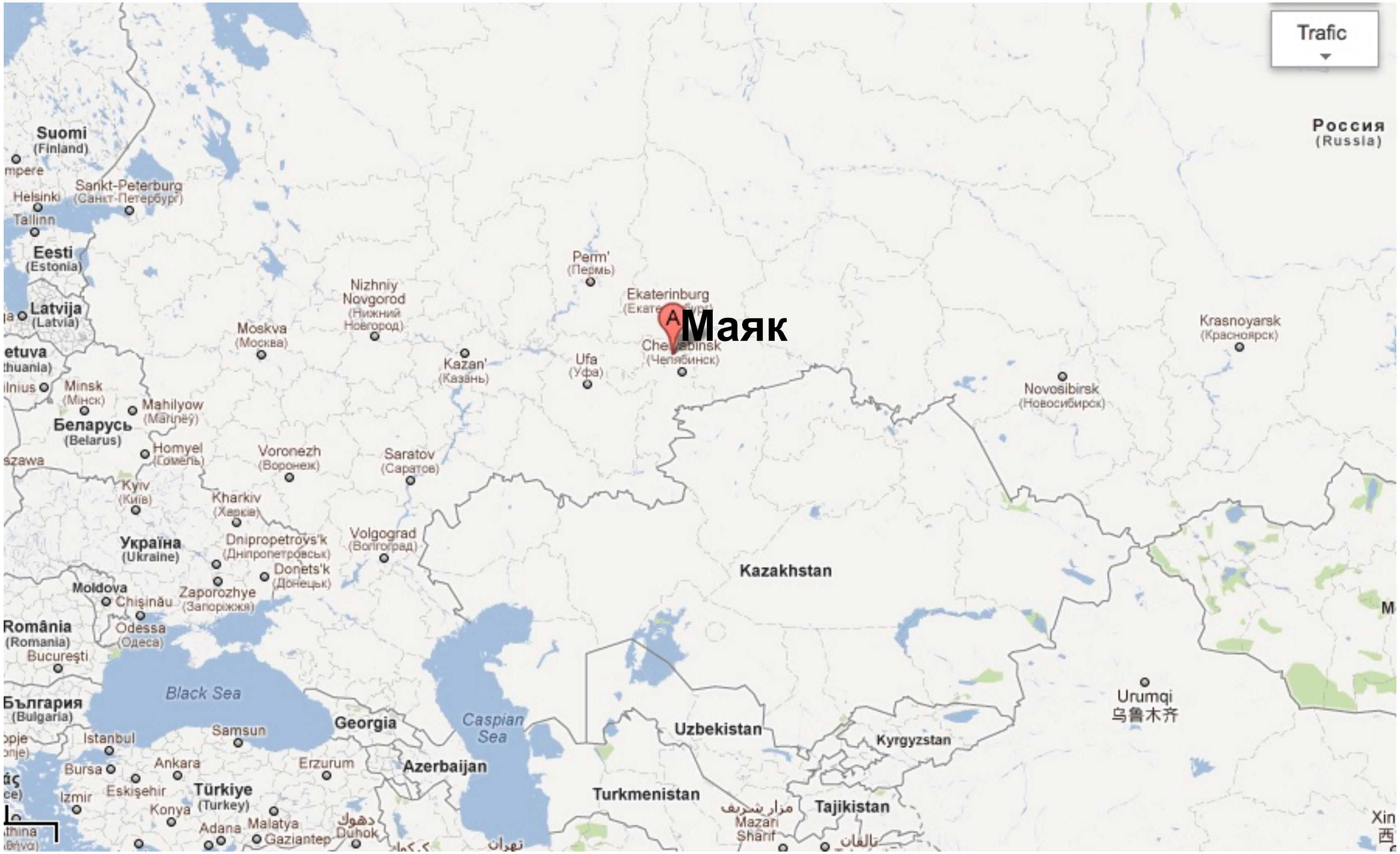
- Do we need a fourth neutrino ?
  - Intriguing anomalies in reactors experiments, Gallium,…
  - A possible revolution in physics
- An elegant experimental answer : ^{144}Ce-^{144}Pr
  - Able to cover the full range of expected parameters
  - Difficult, but not unrealistic to achieve
    - Advance contacts with russian nuclear industry
    - Contacts for tungsten shielding encouraging
    - Preliminary studies for transport
    - Discussions with Borexino and KamLAND
  - Could be made in the 3-4 years to come
    - Few technical uncertainties
    - Mainly regulation issues to solve

- **Five years funding from European Research Council granted to Thierry Lasserre**

Mayak Маяк

- Production association « Mayak »
  - State corporation of atomic energy « Rosatom »
  - Main russian center for nuclear fuel reprocessing
  - Host also « Ludmila », a 1000 MW heavy water reactor
  - Restricted access on main site, but also « clean » parts accessible
- Former important military sites
  - Several severe nuclear accidents

In the Oural mountains



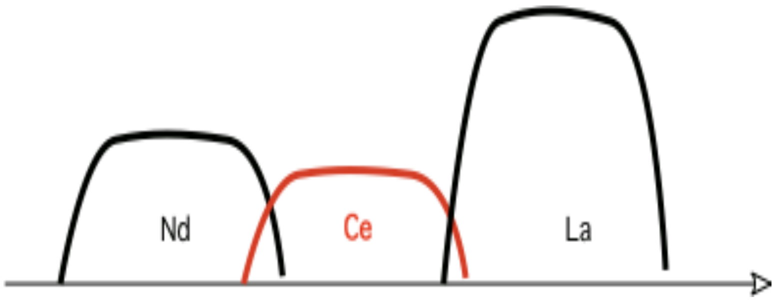
Production at Mayak

- Facility to produce kCi ^{144}Ce already existing
  - Dedicated mainly to ^{60}Co
    - main world producer : 8 MCi/y
  - ^{147}Pm production :1 prod. per ≈ 5 years
    - Used for antistatic purpose and emergency lights
  - Reprocess fuel elements from VVER-440
    - After 3-5 years of cooling : favorable for ^{147}Pm
    - For ^{144}Ce : better to have less than 3 y cooling with the maximal burn-up possible => increase ^{144}Ce content in final Ce product.

^{144}Ce production technology

- Produced already 30 kCi of ^{144}Ce in 1965
  - Line is « still almost ready » but needs « slight » upgrades
- « Standard » unit to feed the reprocessing line : 1 ton of spent nuclear fuel (SNF) ie 8 elements
  - Usual operations : cutting, dissolution in HNO_3 acid, Purex, evaporation, stripping ^{137}Cs
  - 13 kg of REE (rare earth) and trans-uranium (250 g Am, 10g Cu) : total ≈ 3 m^3

- Separation of REE by displacement chromatography in facility used for ^{147}Pm
  - 7 columns (5 m high) in series called « *Canyon* »
  - Ce is one of the last element, between Nd and La.
  - Moreover Ce only REE with a valence 4



1 ton of SNF => 2.8 kg of Ce with 22 g of ^{144}Ce (> 60 kCi)

Transport to Japan

- Mayak send ^{60}Co worldwide
  - By plane, normal or dedicated flight
- Present ideas under consideration
  - Ship the W shielding to « clean » Mayak
  - Fit on site the AνG inside the shielding
  - Fit in the certified transport container (rented)
  - Dedicated flight to an airport close to Kamioka
  - Transport by truck to detector
- Think to the return from Japan to Russia

Signal and Backgrounds

- 75 kCi ^{144}Ce-^{144}Pr
- 15 600 evts in 1st 6 months
- 56 000 evts in 1.5 year
  - 1 mHz
- Inverse ß-decay coinc.
  - $E_{prompt} > 0.9$ MeV
  - $E_{delayed} > 2.0$ MeV
  - $\Delta t < 750$ µs
  - $\Delta V < 10$ m^3

- Background from ^{144}Pr
  - After 1m in liquid. scint.
  - R_{promt} = 2.5 Hz
  - $R_{delayed}$ = 0.6 Hz
  - $R_{accident}$ = 1 mHz

  S/B ≈ 1

  - After 1.5 m : S/B = 100
- 3 cm of tungsten
  bkgd rate divided by 10
- W induced bkgd
  - From measures by Gerda
  - Bkgd << γ from ^{144}Pr
  - to be rechecked with actual W

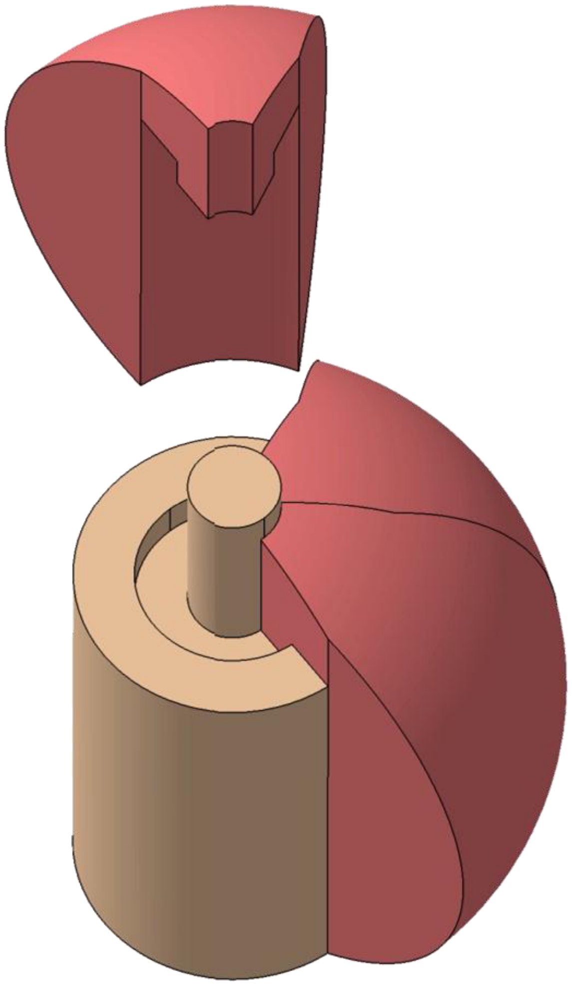
Shielding

- Pure tungsten impossible to manufacture
  - Must use alloys (Ni, Fe)
- Densimet® from Plansee company
  - Densimet 185, the highest density
    - 18.5 g/cm3 *(pure W : 19.3 g/cm^3)*
    - 97 % W + Ni, Fe
  - Used already for the ^{51}Cr neutrino source in Gallex
  - Used in nuclear medecine
- Radioactive impurities content ?
- Meeting next Friday @ Saclay with Plansee engineers

Shielding - 2

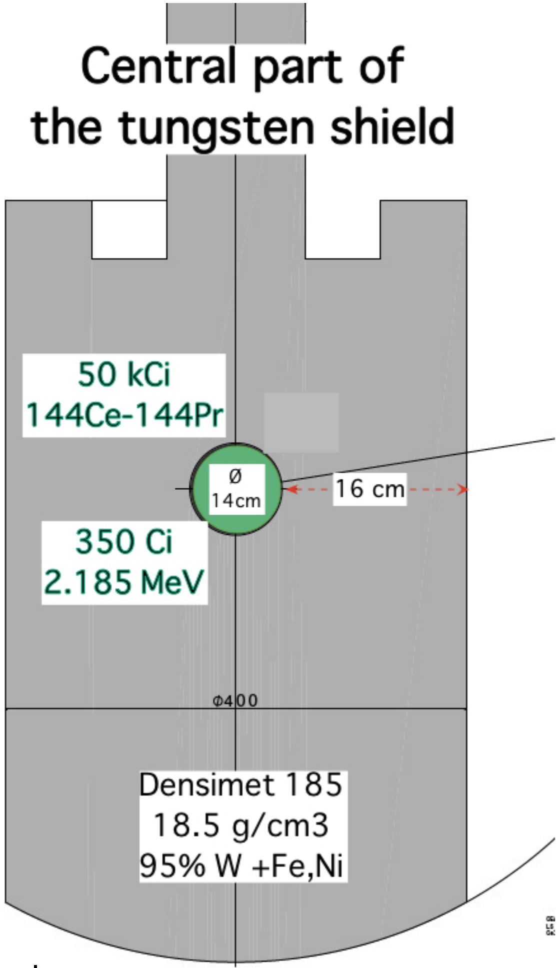
- Radiation length in Densimet
  - ≈ 1.2 cm for 2.2 MeV
- We need a reduction of 10^{-12}
  - To reach 13 γ/s entering the liquid scintillator
  - ≈ 80 cm from the center, Signal/Bkg > 10
- Total width of the W shielding : 33 cm
  - Inner radius : 8 cm ; outer radius : 41 cm
  - Weight : 5300 kg

Shielding : the first idea



- Two separate goals
  - usual biological protection
    - Could be achieved with ≈ 15 cm of W
  - minimisation of accidental background during the experiment
    - need an extra 20 cm of W or equivalent attenuation for 10^{-12} reduction
  - experimental requirements well above legal safety constraints
- 7 pieces to insert and assemble through chimney
  - Like a boat in a bottle…
- Impurities in tungsten ?
  - Test @ Saclay
  - Previous tests for Gerda
- Discussion with industry (Plansee)
  - Looks possible

Radioprotection



Not to scale

- At least 16 cm of W
- Dose rate
  - Basic formula for a γ point source

$$D = A \frac{E}{4\pi L^2} \times \frac{\mu_{en}}{\rho}$$

  - In water (μ_{en}/ρ = .025 cm^2/g)
  - Attenuation in W
    - exp(-16/1.2) = 1.6 10^{-6}
    - => 50 kCi (^{144}Ce) -> 350 Ci (2.2 MeV)

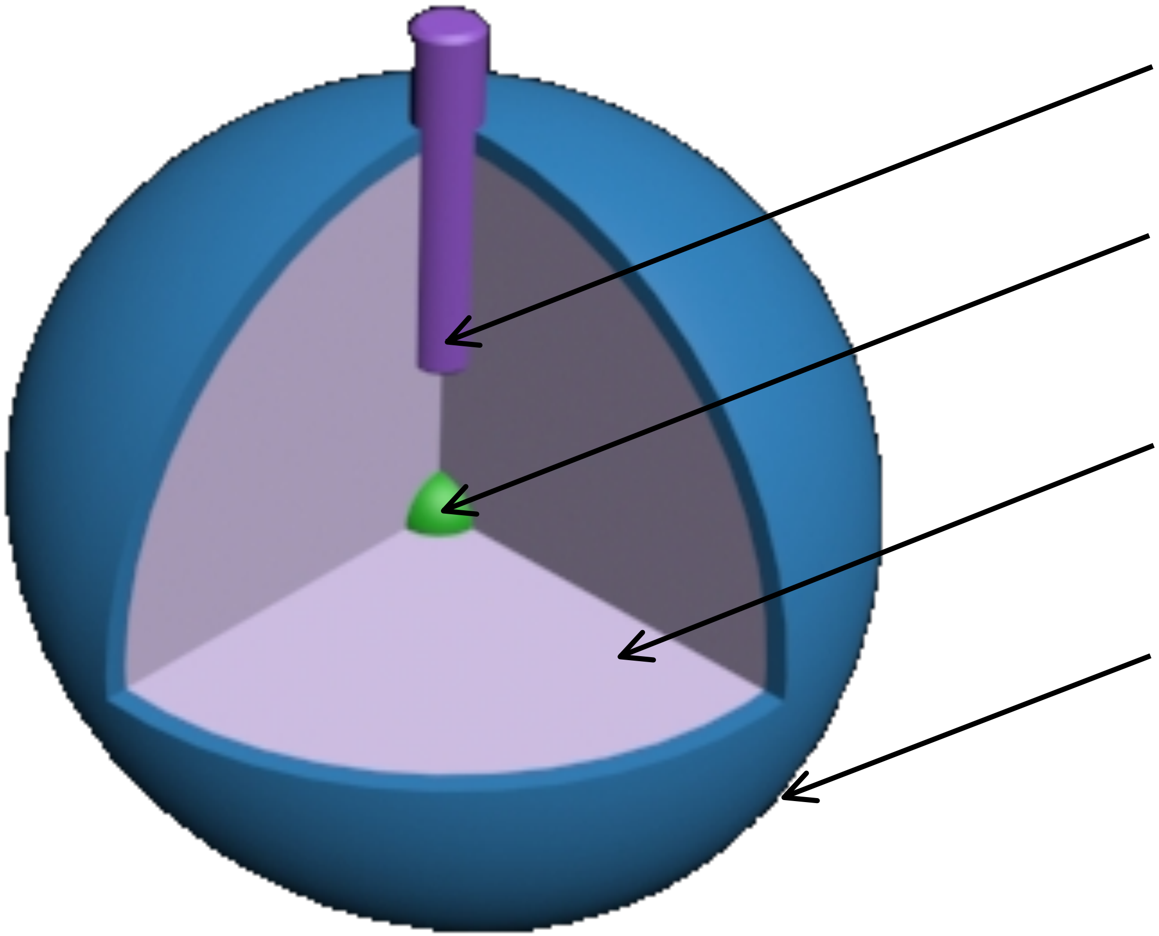
$$D(mSv/h) = 4.25 \times A(Ci) \times E(MeV) \frac{1}{L^2(m)}$$

- Result : 5.2 *μSv/h*

Samples

- Physicist's concern : high energy gamma emitters
- We ask to receive samples at Saclay
  - Use the next production of ^{147}Pm
    - Early 2013
  - Russian propose to make measurement @ « clean » Mayak with us
    - Usually mainly concern with ß lines
    - Interesting to met local people involved in the project
  - We insist to have samples (also) checked @ Saclay
- Required activity of the sample
  - ≈ 100 kBq total ie 1 kBq for the 2.2 MeV line
  - Modest, makes shipment easier

The Antineutrino generator



mass ≈ 5.5 tons
Total diameter ≈ 82 cm

Thermal problems

- ^{144}Ce-^{144}Pr, mainly a ß emitters
  - Heat deposition localised only (99%) in the CeO_2 or in the 1st few mm of shielding.
- 50 kCi ^{144}Ce-^{144}Pr produce 382 W
  - Decrease as lifetime of 144Ce
    - 157 W after one year
- Densimet
  - Density : 18.5 g/cm^3
  - Heat capacity : 130 J/kg.K
  - Thermal conductivity : 82 W/m.K (much smaller than pure W)
  - Linear expansion : 5.2 10^{-6} m/m
  - Young modulus : 380 GPa

Thermal problems - 2

- Time to heat the shielding

$$\frac{dT}{dt} = \frac{P}{c_p^W M} = \frac{382}{82 \times 5387} = 3.1^\circ per \quad hour$$

- Surface temperature at equilibrium in air
  - h_{air} : heat exchange coefficient with air

$$P = h_{air} \times 4\pi R_2^2 (T_W - T_{air})$$

$$h_{air} \approx 4 \quad W/m^2K \Rightarrow T_W - T_{air} \approx 45 \quad ^\circ C$$

- Exchange with liquid scintillator
  - h_{LS} : heat exchange with liquid scintillator (convection)

$$P = h_{LS} \times 4\pi R_2^2 (T_W - T_{LS})$$

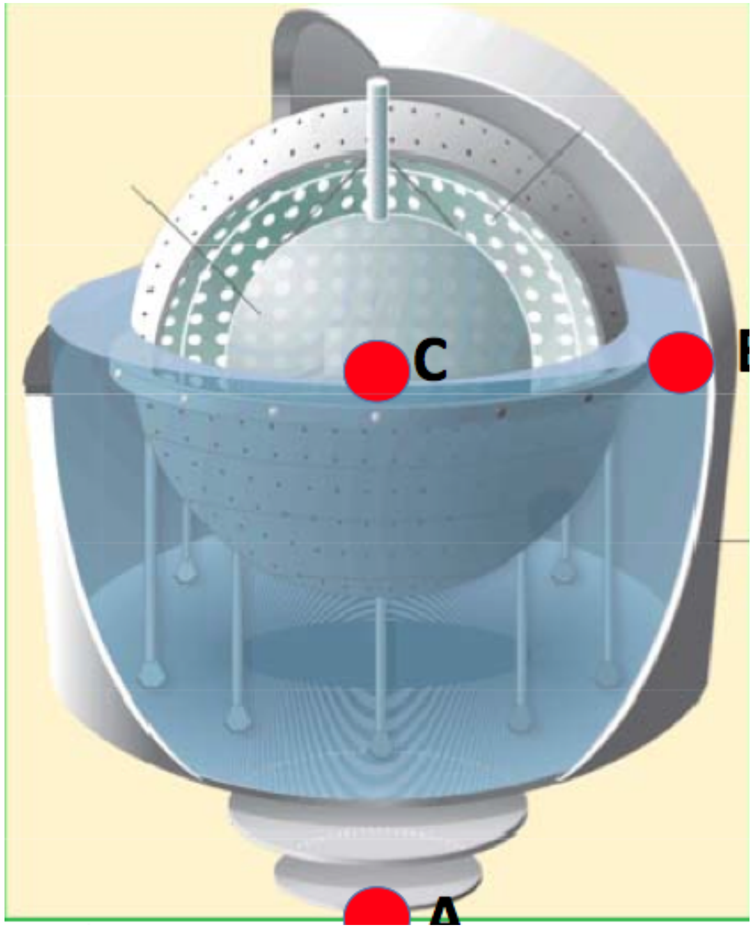
$$h_{LS} \approx 200 \quad W/m^2K \Rightarrow T_W - T_{LS} \approx 1 \quad ^\circ C$$

Thermal problems - 3

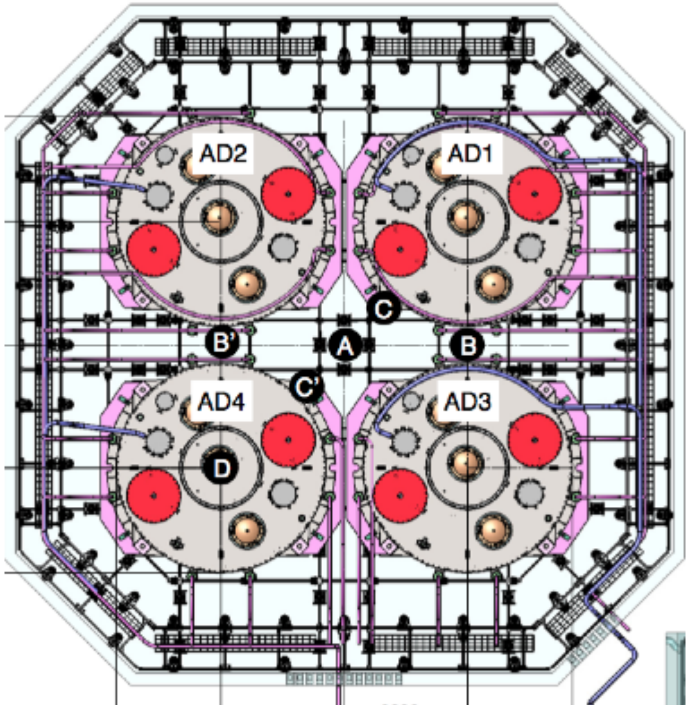
- Try to avoid active cooling
  - Very modest water flow needed ≈ 60 lit./hour
  - Huge complication in the shielding, operations
- Comparison with the PMT's in KamLAND
  - 1325 PMT's in the inner detector
  - 500 W ?
- Impact on the liquid scintillator
  - 914 tons
  - w/o thermal leaks => increase of 4 °C in a year
  - Possible slight convection

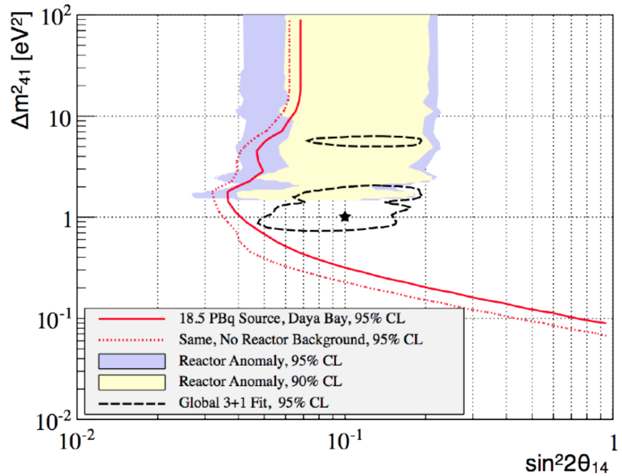
The Borexino proposal

- **Significant Effort**
- **Planned experiments**
  - **1st ^{51}Cr > 5 MCi in pit A**
    - **Gallex enriched Cr still available in Saclay**
    - **Compatible with existing program**
  - **2nd ^{144}Ce in center C**
    - **need major work on detector**
    - **After end of solar ν program**
- **ERC funding : 3.5 M€**



The Daya Bay proposal





- **D. Dwyer et al. arXiv:1109.6036**
- **Based on our PRL paper**
- **500 kCi ^{144}Ce-^{144}Pr source in the Daya Bay FD pool**
- **Realisation ?**
  - **no fuel reprocessing in the US**
  - **activity impossible to reach in Russia**