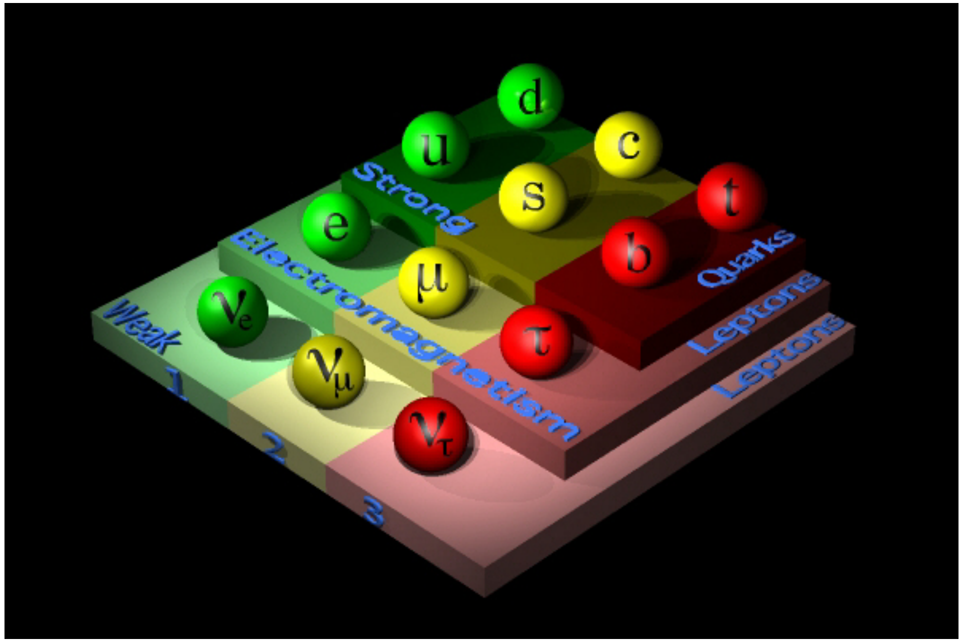
Use of neutrinos while still learning about them

David Lhuillier
CEA-Saclay

Fundamental properties of ν's



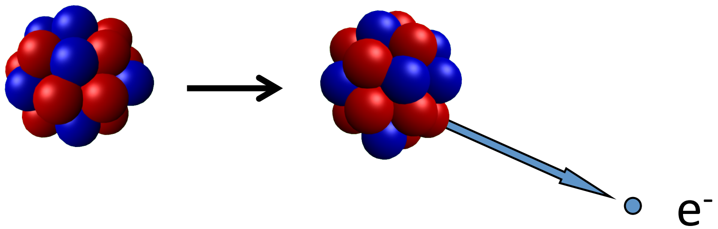
- 3 flavors of neutrinos
- Interact only via the weak force and gravitation
- $\sigma_{int} \sim 10^{-43}\ cm^2$ @ 1 MeV

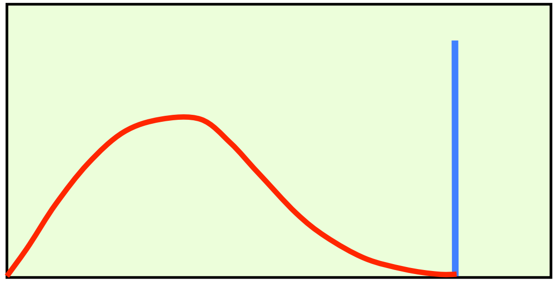
→ Very penetrating particles

- Challenging detection technics
- Remote observation of intense sources (possibly inaccessible otherwise)

Neutrino footprints

Missing energy in β decays

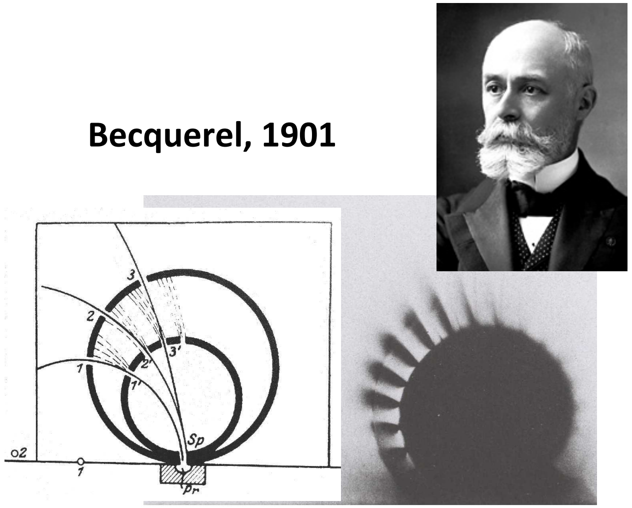




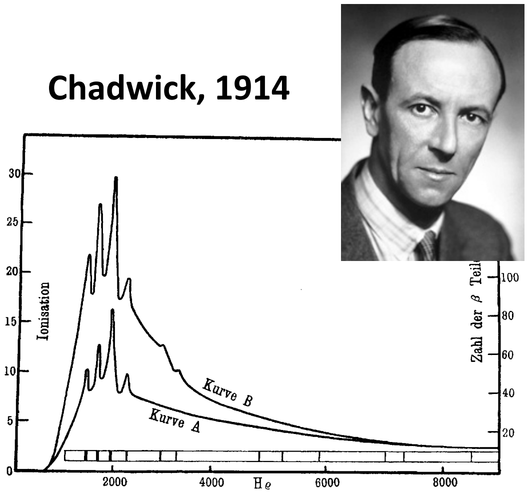
Electron energy

Measurements:

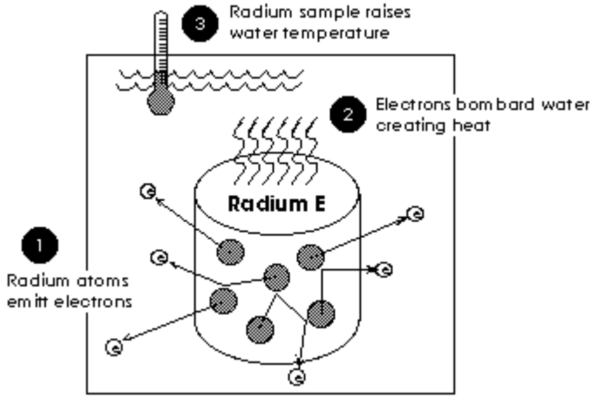
Becquerel, 1901



Chadwick, 1914



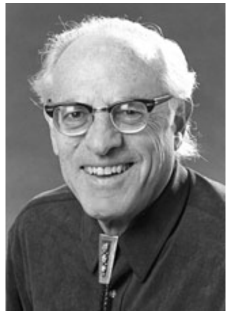
Ellis & Wooster, 1927



Neutrino footprints

Discovery at nuclear reactors

Cowan



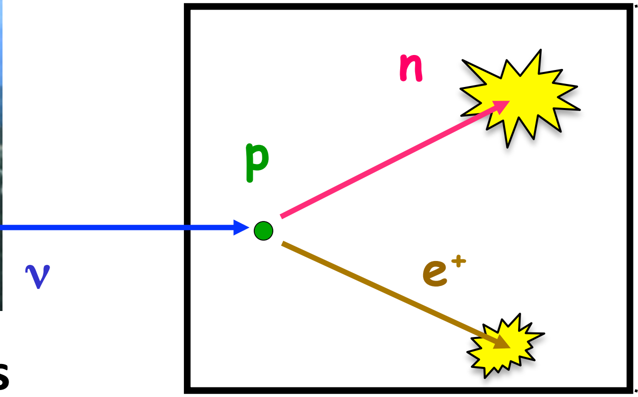
Reines

- Discovery in 1956
- Nobel prize 1995

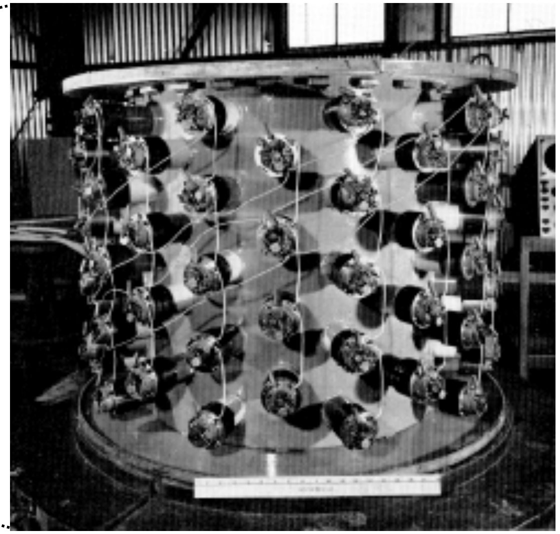
Savannah River
Nuclear Reactor

1 GW, ~10^{20} ν/s

25 m



Inverse β decay process

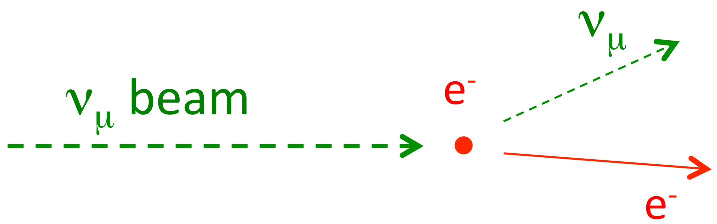


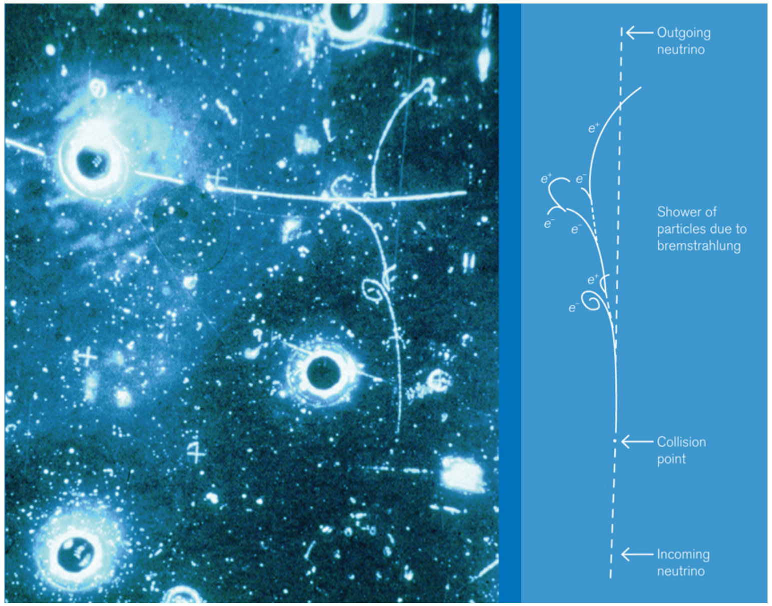
1 m³ liquid scintillator

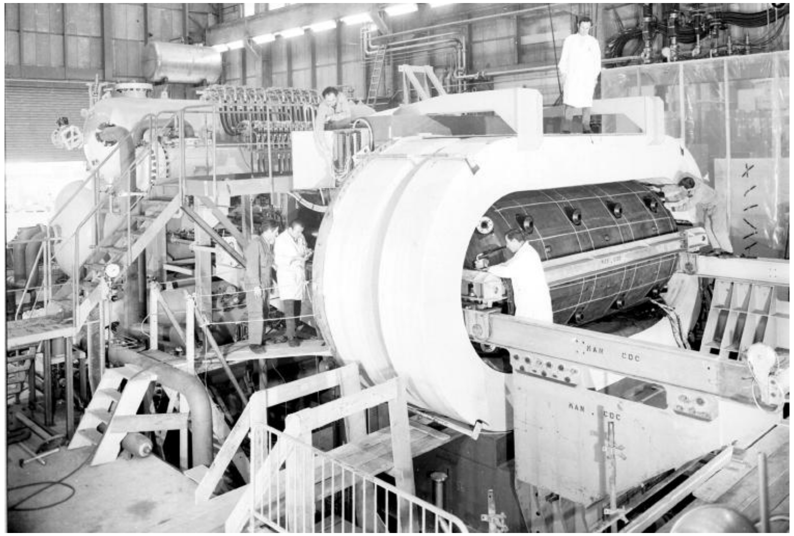
~3 ν/hour correlated to reactor operation

Neutrino footprints

Observation of a neutrino weak neutral current

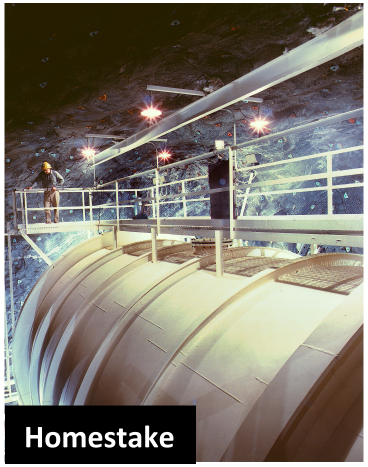


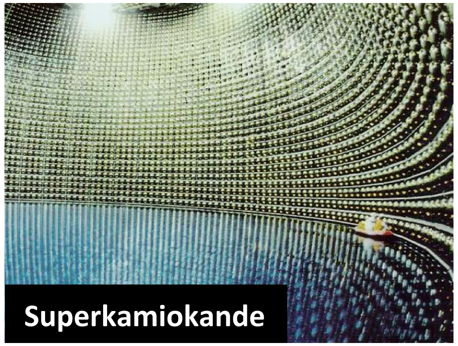




- Evidence of the weak neutral current in the Gargamelle bubble chamber at CERN – 1972

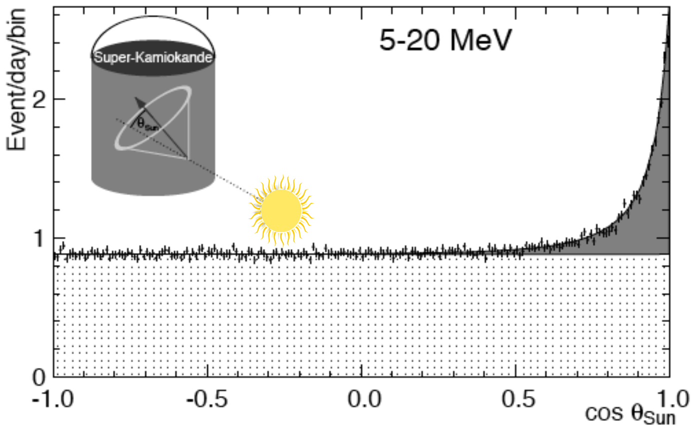
Neutrino footprints

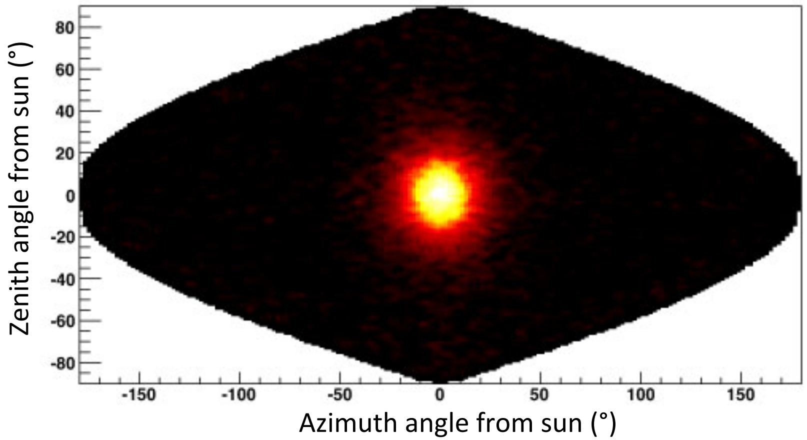




Solar neutrinos

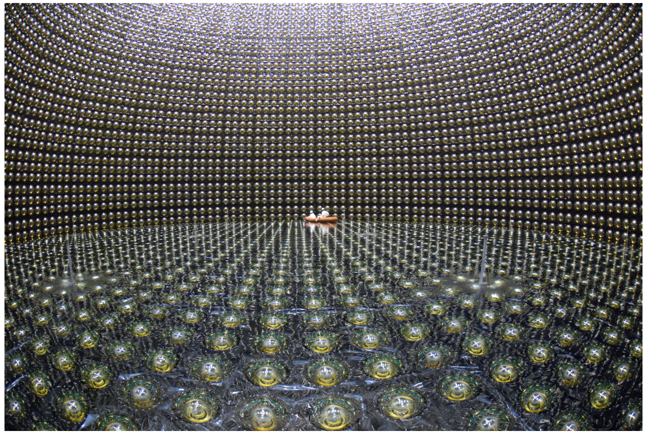
- Kamiokande can detect the Cerenkov light emitted by recoiling electrons struck by the most energetic solar neutrinos (^{8}B).
- The reconstructed direction of incoming neutrinos builds up the first neutrino photo of the sun, from deep underground (SK data)

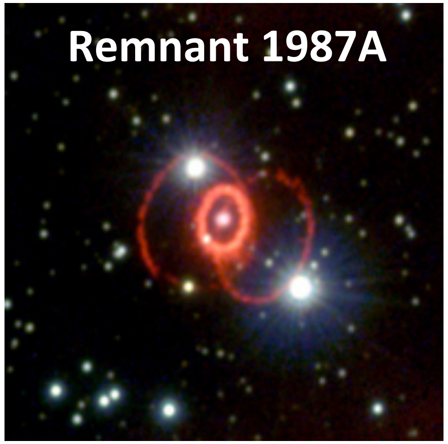




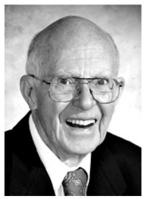
Neutrino footprints

Supernova neutrinos





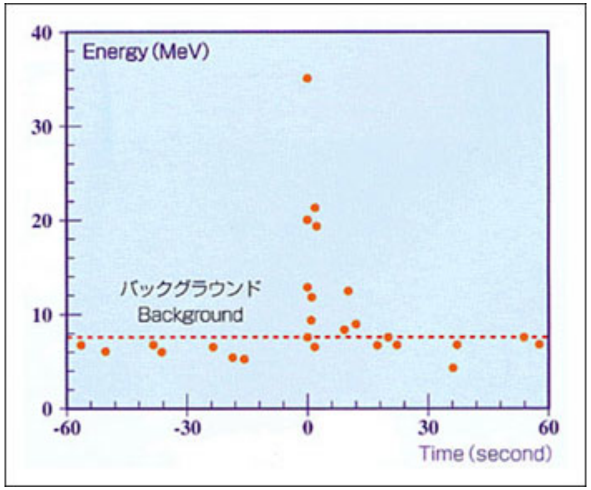
- The neutrino flux of SN1987A was detected by the large neutrino detectors



R. Davis

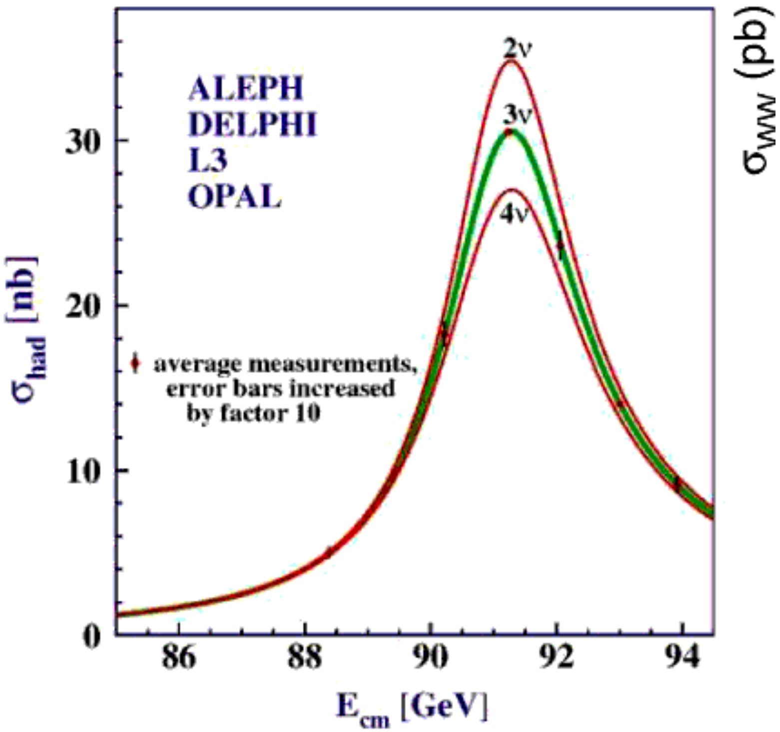
Nobel 2002
Cosmic ν

M. Koshiba



Neutrino footprints

Width of the Z boson decay

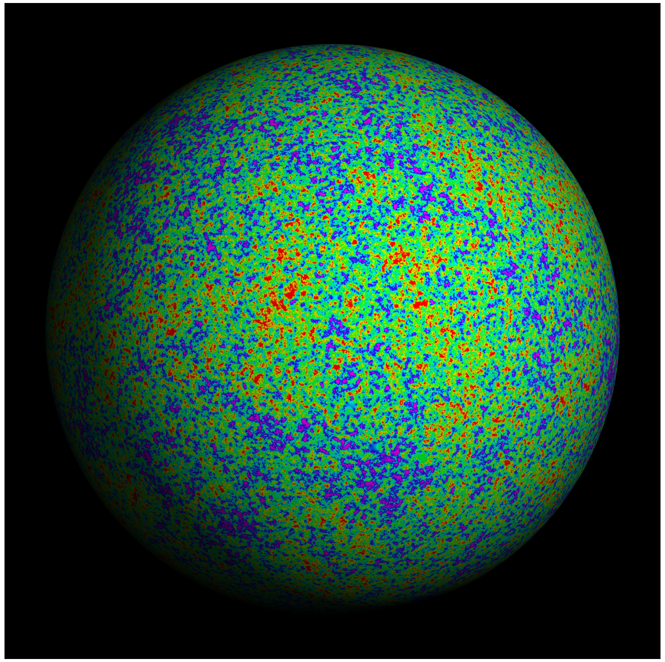


- $Z \rightarrow \nu \bar{\nu}$ decays contribute to the observed total width of the Z boson
- $N_\nu = 2.9840 \pm 0.0082$

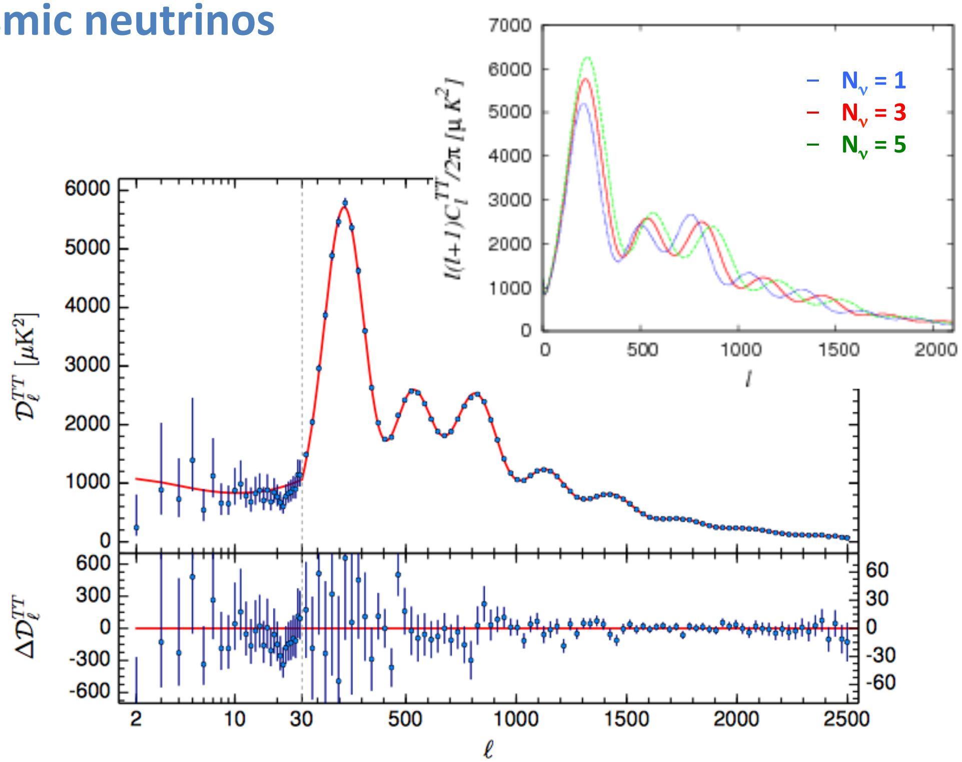
→ 3 neutrino flavors couple to the Z^0 boson

Neutrino footprints

Cosmic neutrinos



Map of the Cosmic Microwave Background
from the Planck satellite



http://arxiv.org/abs/1502.01589

N_ eff = 3.15 +/- 0.23

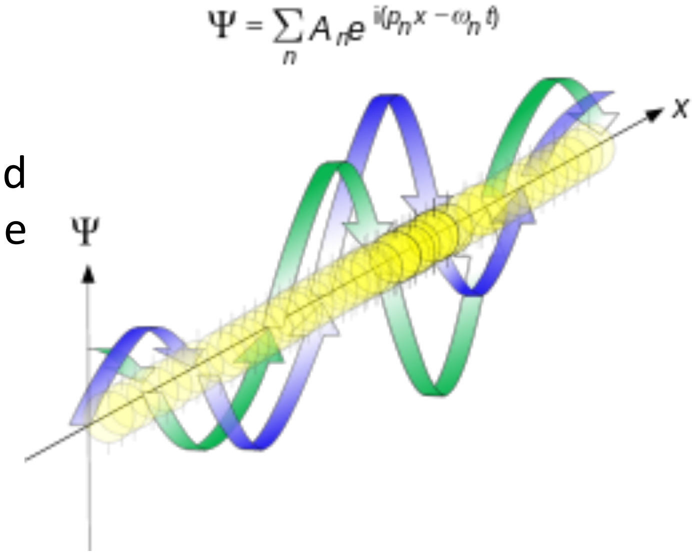
Neutrinos are the most abundant matter particles in the universe

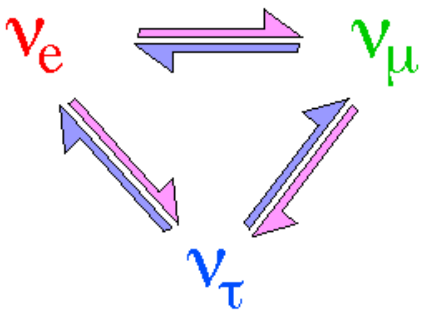
Neutrino oscillations

Propagation of coherent states

- 3 neutrino states carrying the same conserved quantum numbers

→ Coherent superposition of the 3 eigen states could lead to an oscillation phenomenon along the propagation of the neutrinos.

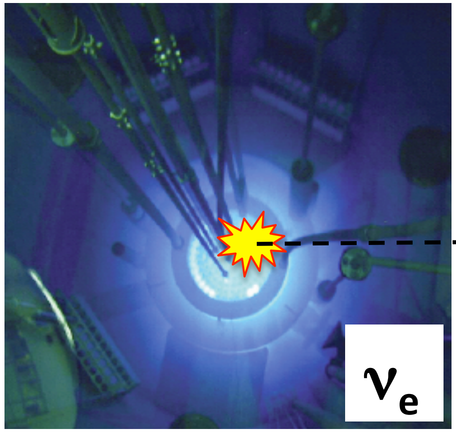




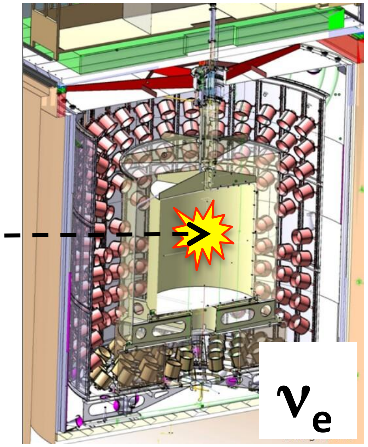
B. Pontecorvo

- Requires different masses hence at least two non zero.
- The coherence of the wave packets over macroscopic length scales requires Small mass splitting (prevents the oscillations of charged leptons)

Formalism



ν_1, ν_2, ν_3



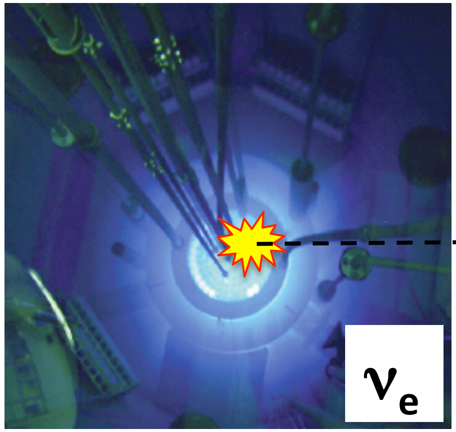
Interaction / Flavor — Propagation / Mass — Interaction / Flavor

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix} \theta \end{bmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \quad \cdots\cdot \quad \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \begin{bmatrix} \theta \end{bmatrix}^{-1} = \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

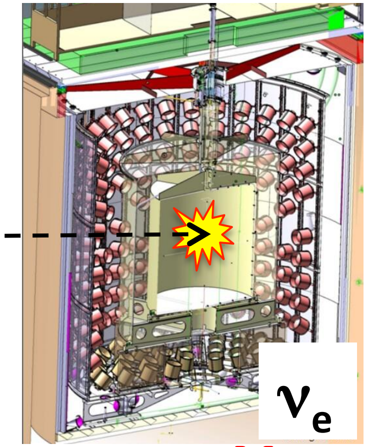
$$\Delta m^2$$

3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$ — 2 non-zero square mass splitting : Δm^2_{21} , Δm^2_{31}

Mixing parameters



ν_1, ν_2, ν_3



Flavor

Mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Large mixing angles

$\theta_{12} = 33.5 \pm 1.5°$

$\theta_{23} = 40.4 \pm 5°$

$\theta_{13} = 8.42 \pm 0.26°$

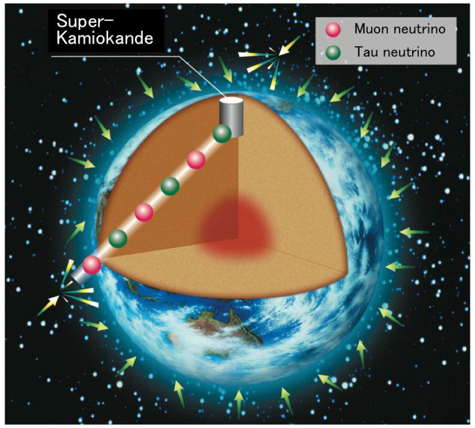
2 mass sectors

$\Delta m^2_{21} = 7.6 \pm 0.2\ 10^{-5}\ eV^2$

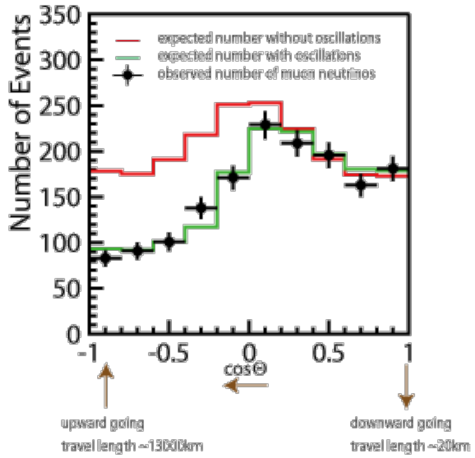
$|\Delta m^2_{31}| = 2.5 \pm 0.1\ 10^{-3}\ eV^2$

Oscillations

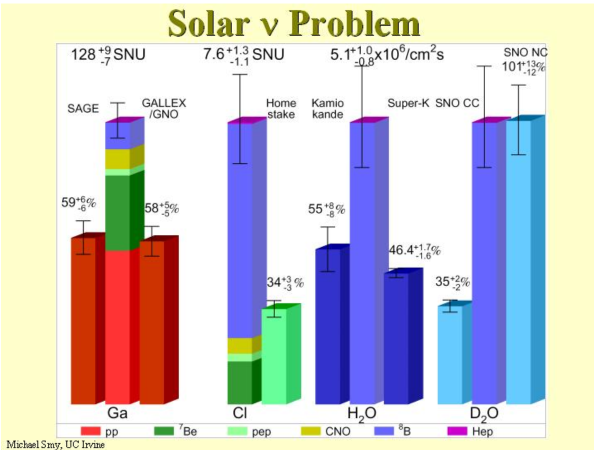
Awarded the Nobel prize 2015



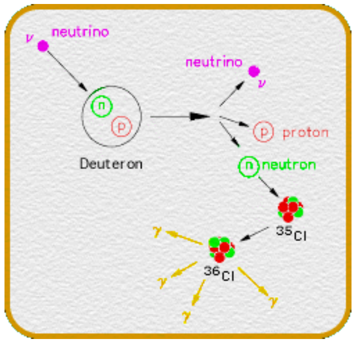
Super K observes the oscillation of atmospheric ν

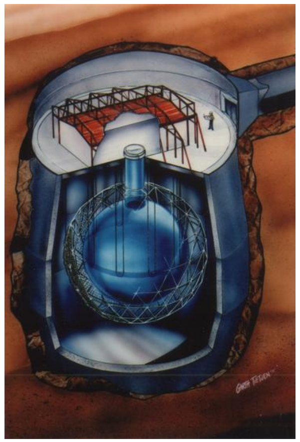


T. Kajita



SNO solves the solar ν problem





A.B. McDonald

Reactor neutrinos

Neutrinos from fission

Per fission:

- 200 MeV
- 6 neutrinos

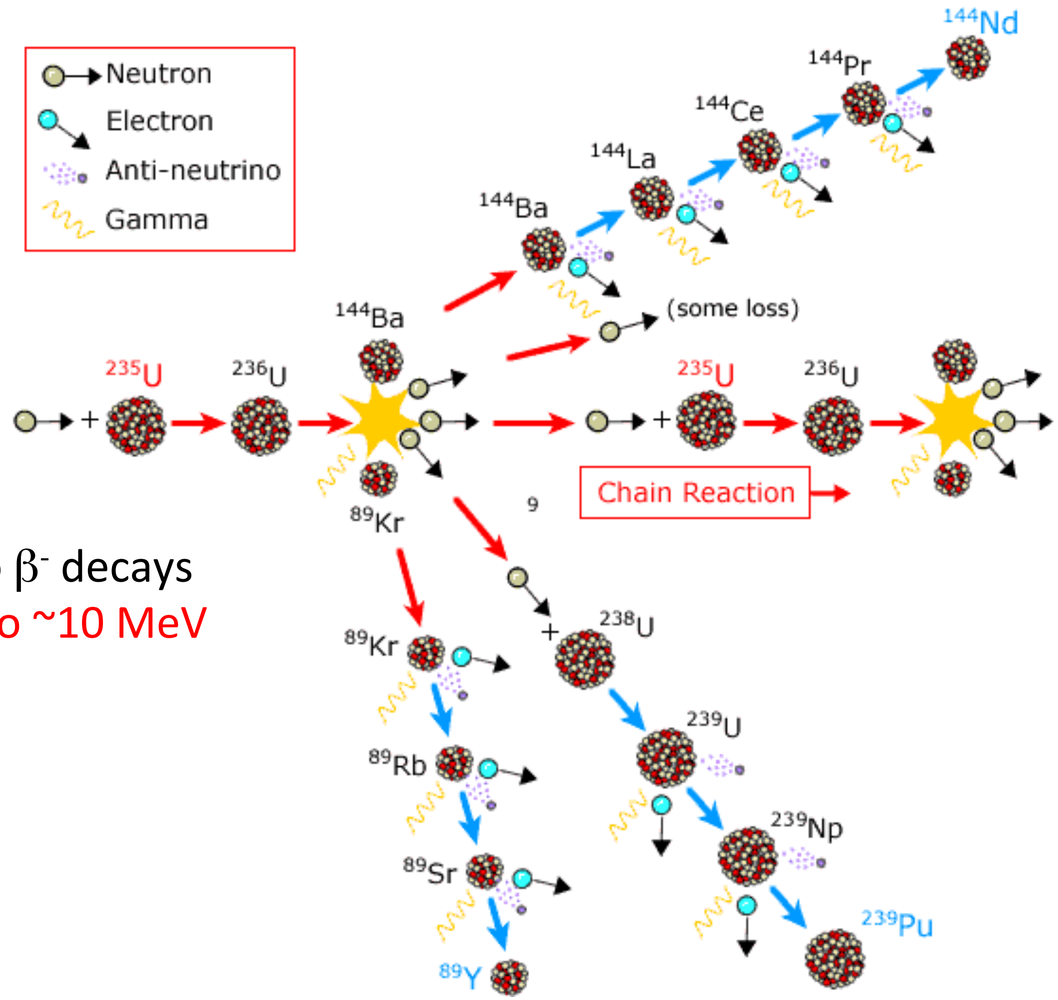
→ Intense source
$2\ 10^{20}\ \nu/s/GW_{th}$

Neutron rich FPs undergo β^- decays
→ Pure source of $\bar{\nu}_e$, up to ~10 MeV

Complex total spectrum

$$S_k(E) = \Sigma \text{ all FPs}$$

~ 800 nuclei
~ 10 000 β-branches



The guts of $S_k(E)$

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branches of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR_{fp}^b \times S_{fp}^b(Z_{fp}, A_{fp}, E_{0fp}^b, E)$$

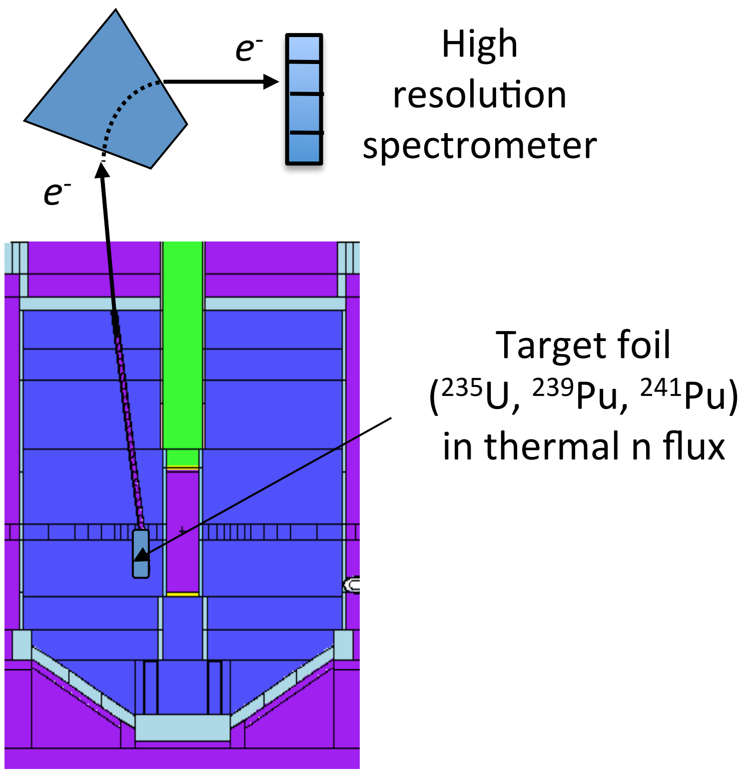
Theory of β-decay

$$S_{fp}^b = \underbrace{K_{fp}^b}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E_{0fp}^b)^2}_{\text{Phase space}} \times \underbrace{C_{fp}^b(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta_{fp}^b(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

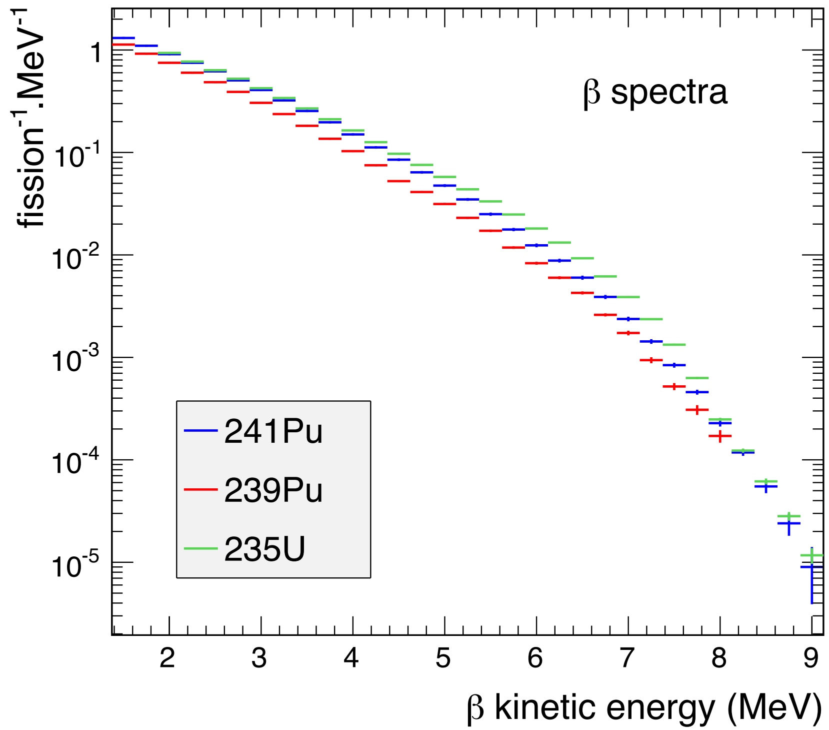
$$\delta_{fp}^b = G_{\nu(QED)} + L_{0(coulomb\ size)} + C_{(weak\ size)} + S_{(screening)} + \delta_{WM\ (weak\ magnetism)}$$

The ILL electron data

Total electron spectra from the β-decays of ^{235}U, ^{239}Pu and ^{241}Pu fission products.



ILL research reactor
(Grenoble, France)



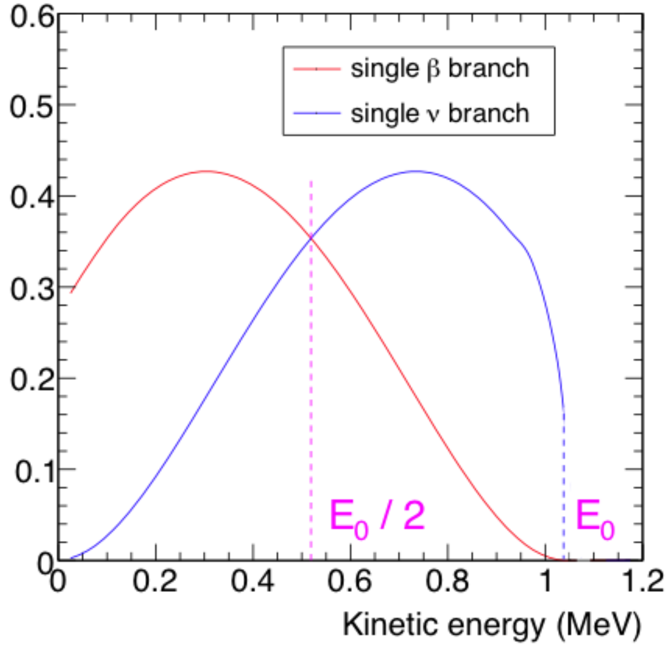
Unique reference of β fission spectra

K. Schreckenbach et al., Phys. Let. B218,365 (1989)+ refs therein

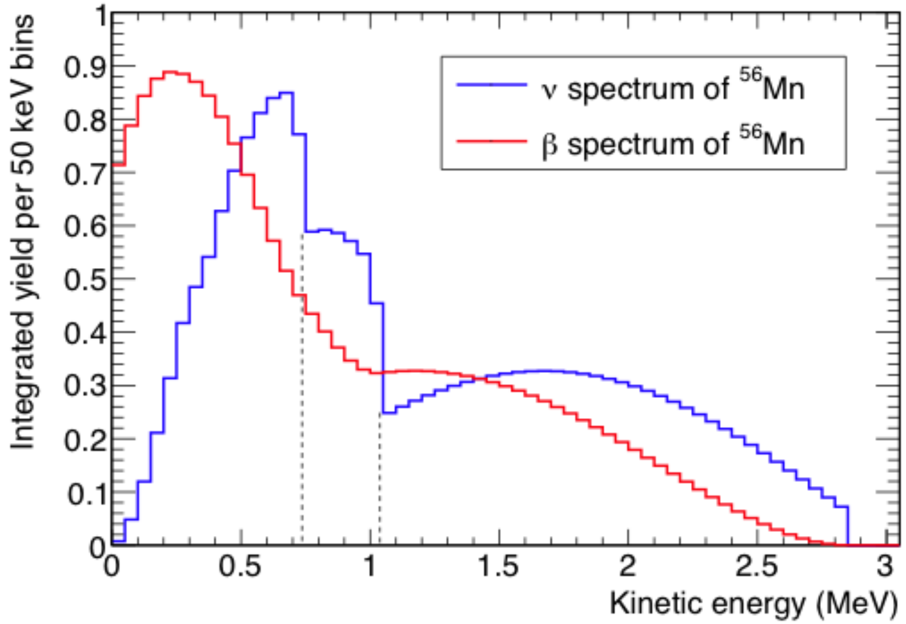
$e^- \rightarrow \nu$ conversion

• Exact conversion requires complete knowledge of all contributing β-transitions

β-branch level



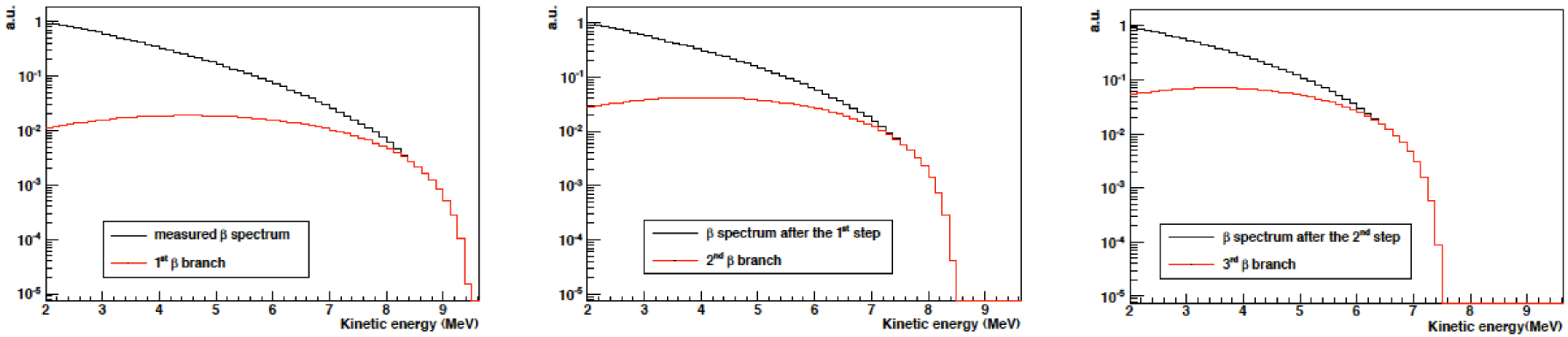
Fission product level



• **Lot of relevant quantities**: Z, A, End-points, J^{π}, nuclear matrix elements, branching ratios, fission yields, life time… **but scarce data as E_0 increases**

Conversion of reference e$^-$ spectra

1- Fit total e$^-$ spectrum with a sum of 30 effective β branches determined by iterative method (instead of ~10,000+ real branches)

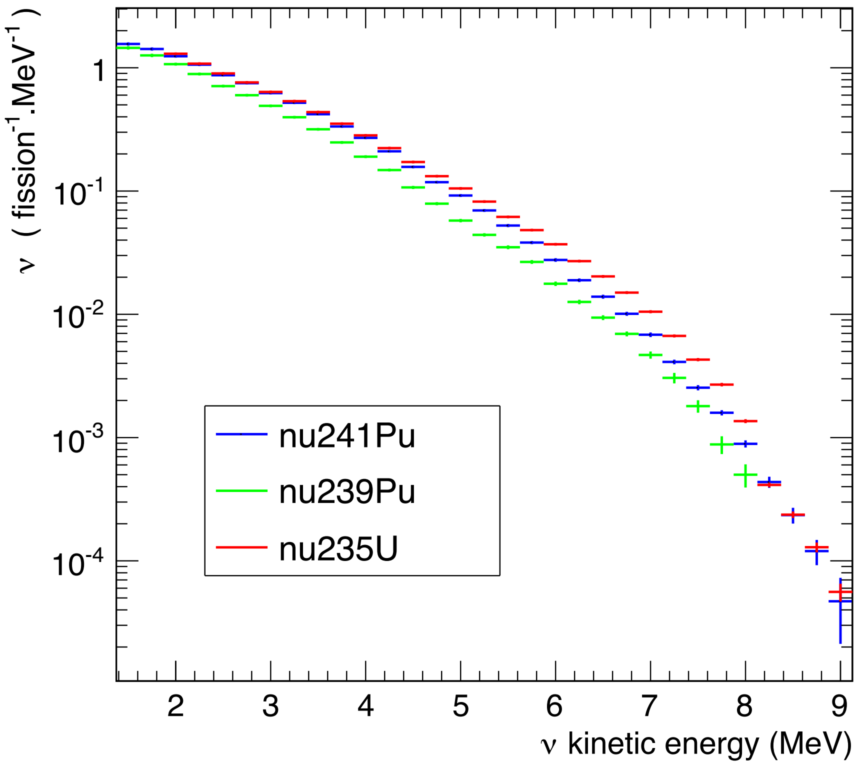


2- Convert each effective e$^-$ branches to ν branches

3- Sum all converted ν branches to get total ν spectrum

K. Schreckenbach et al., Phys. Lett. 99B, 251 (1981).

Reference fission ν spectra

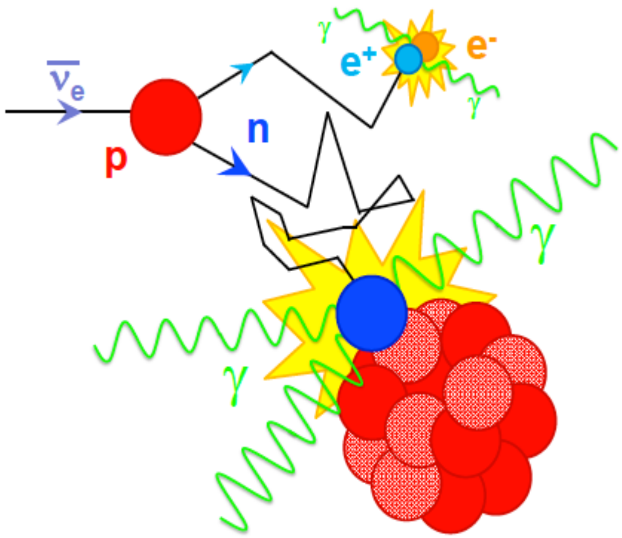


- Antineutrino spectra converted from the β spectra measured at ILL
- Reference spectra over the last 25 years

Detection

Inverse Beta Decay

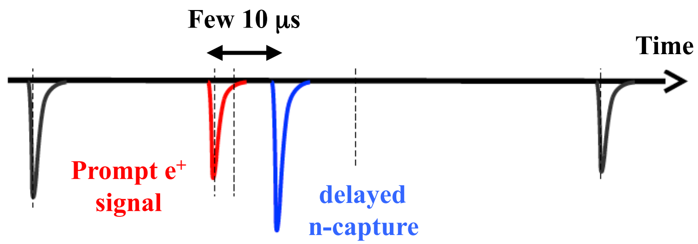
$$\overline{\nu}_e + p \rightarrow e^+ + n$$



1.8 MeV reaction threshold

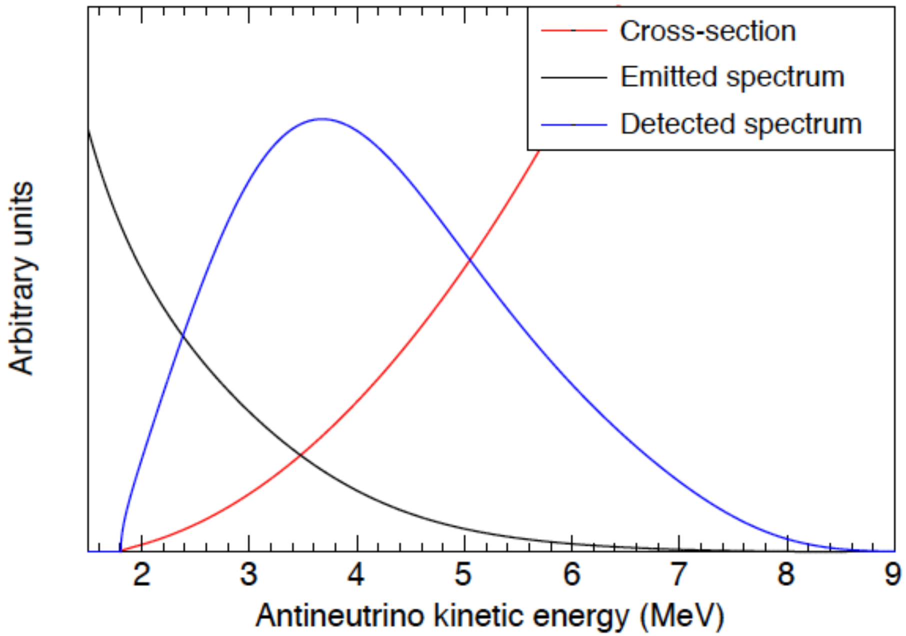
- A neutral current process would have to compete with any single e- recoil induced by natural radioactivity

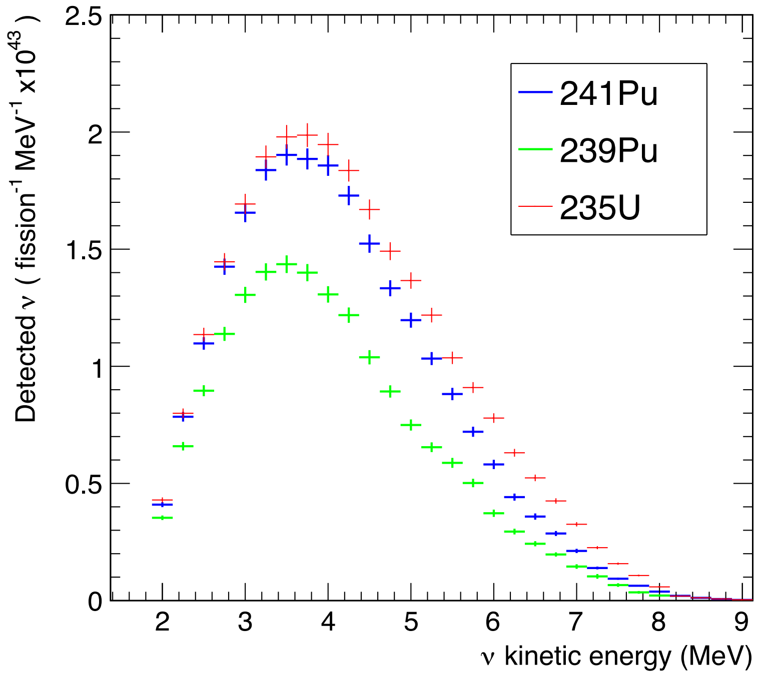
- IBD process provides a selective signal sequence



- An organic scintillator doped with a neutron absorber efficiently combines a proton target with the detection of prompt and delayed signals

Prediction of detected reactor neutrino spectra



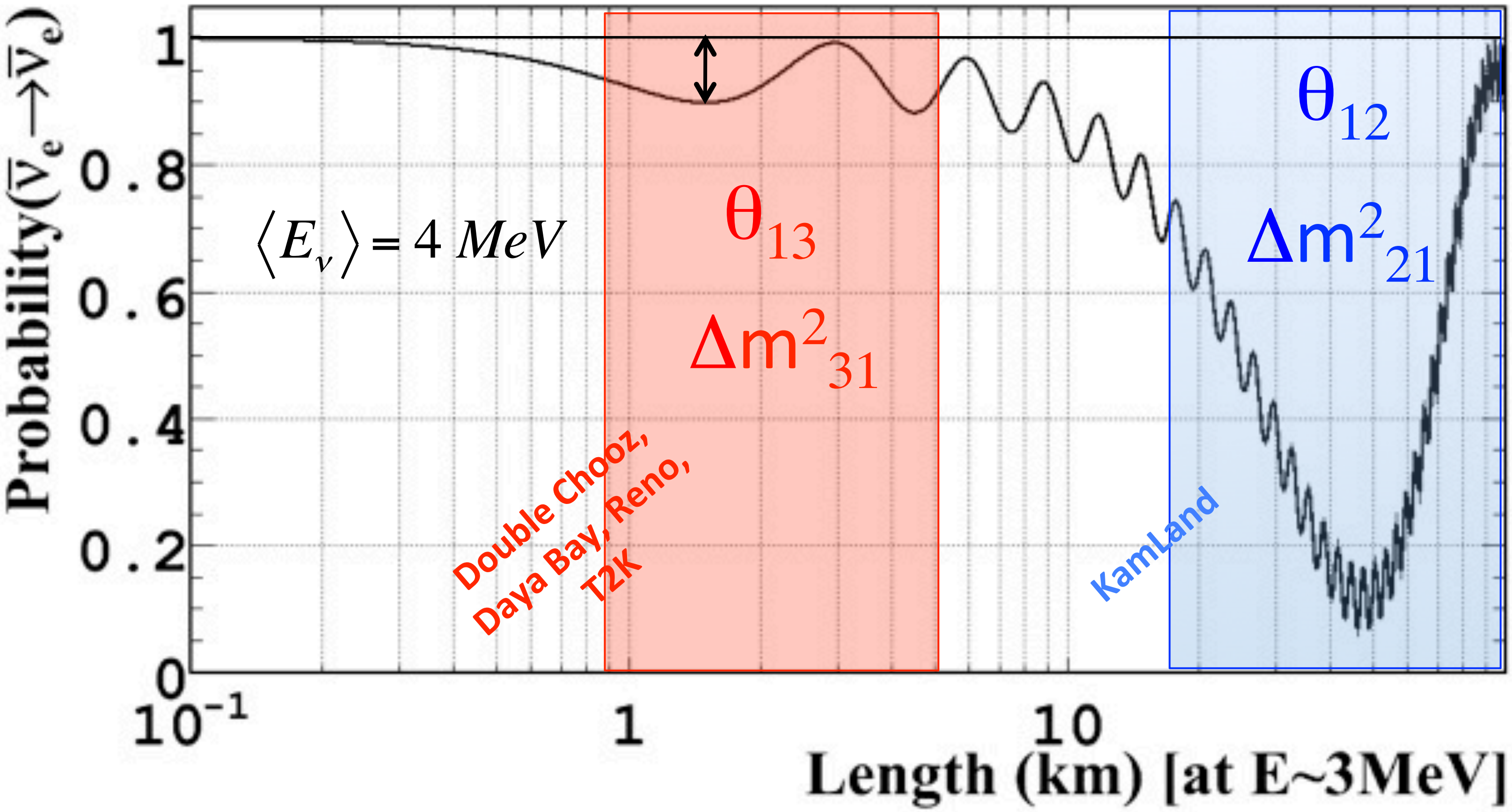


- Error matrix determined from uncertainties of ILL measurements and conversion procedure.
- 239Pu fissions lead to less detected neutrinos than 235U fissions?

ν oscillations at reactors

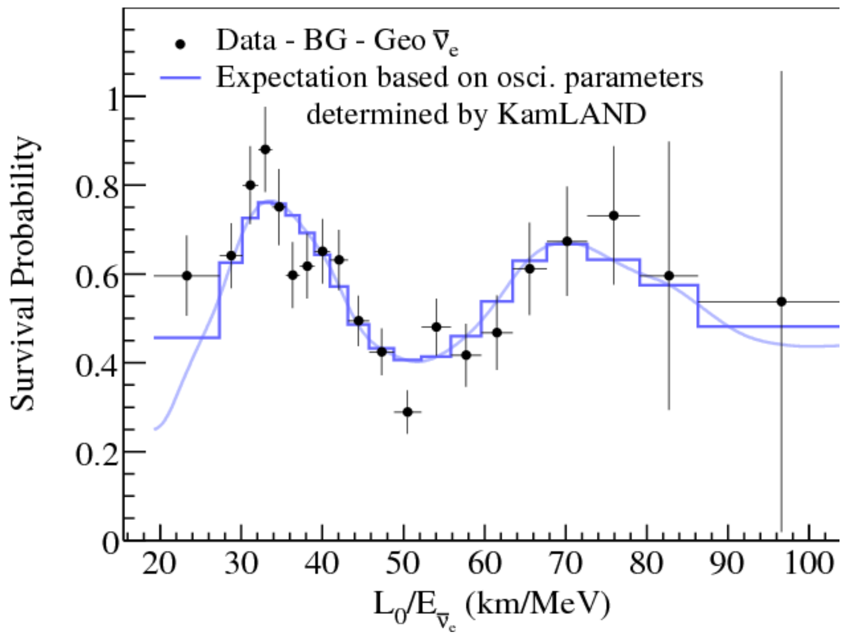
Below μ^+,τ^+ production threshold → look for $\bar{\nu}_e$ disappearance

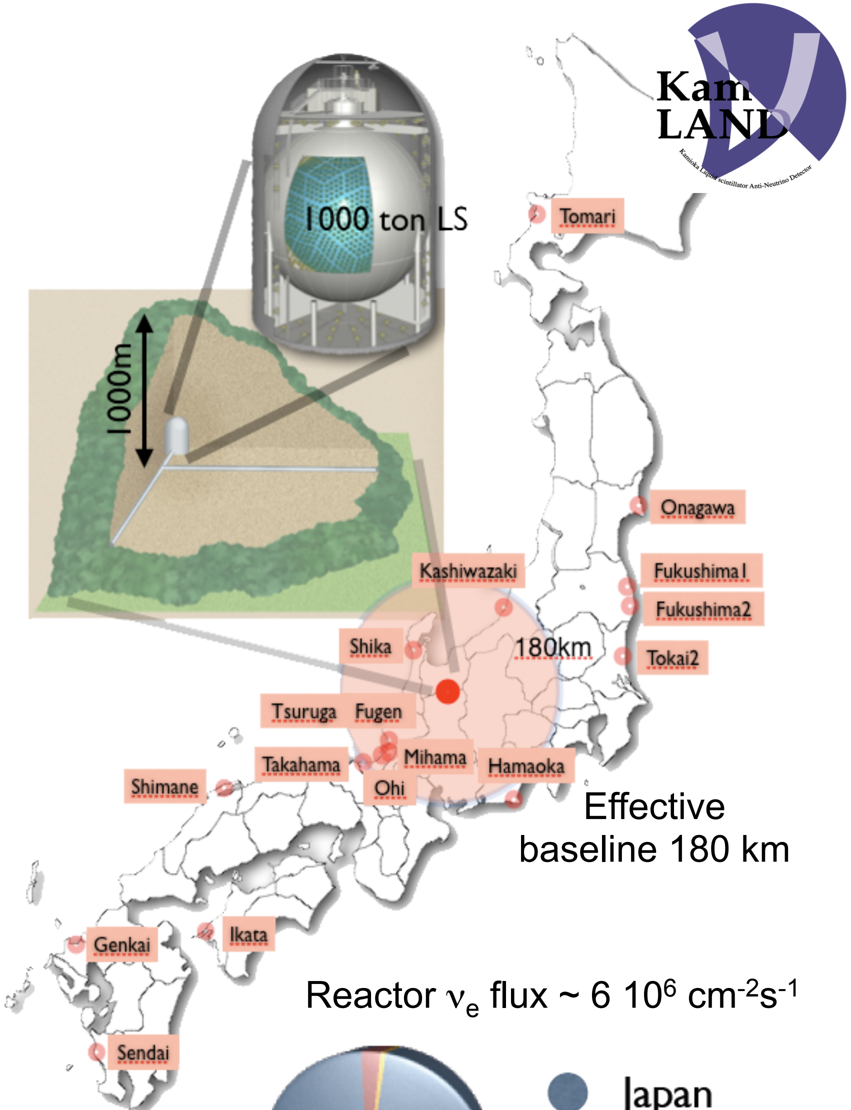
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\,\sin^2(\Delta m^2 L/4E)$$



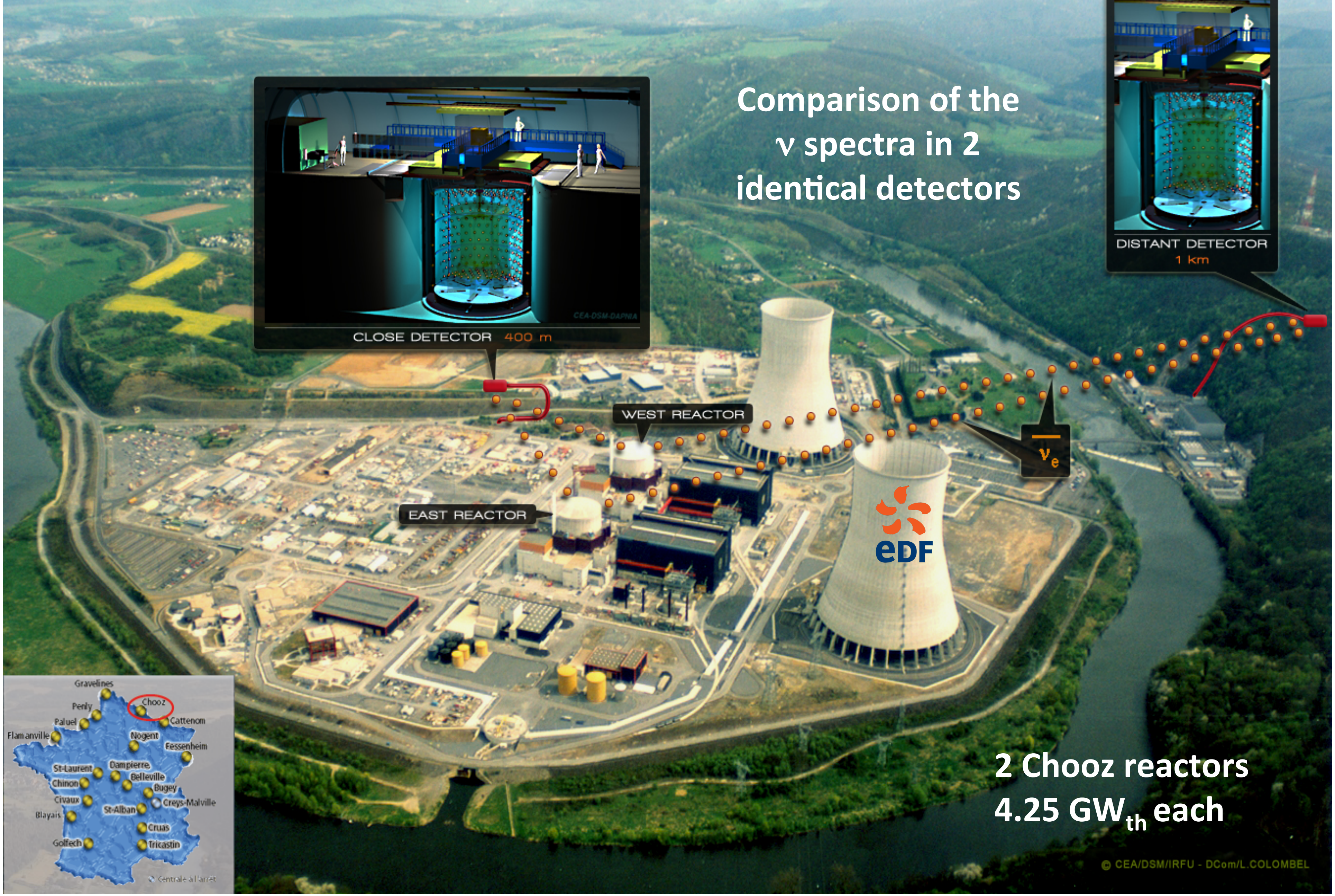
KamLAND

- Large liquid scintillator detector at ~180 km of many Japanese reactors
- Confirmation of the solar oscillation and accurate measurement of Δm^2_{12}





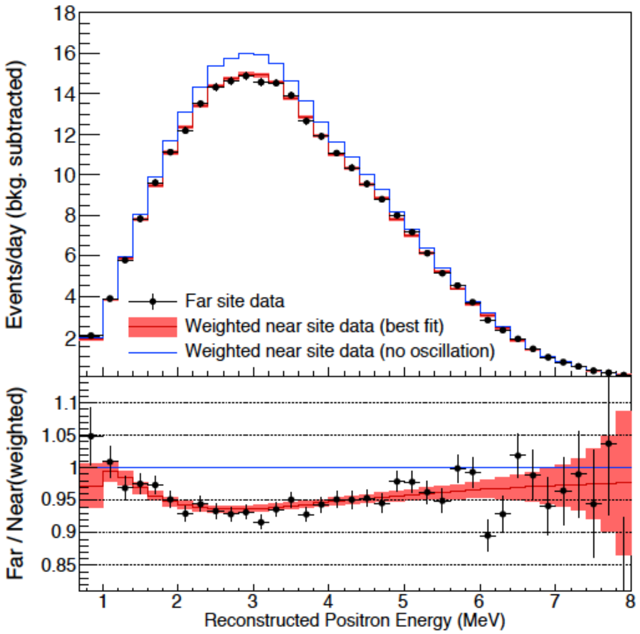
Double Detector concept @ the Chooz Site

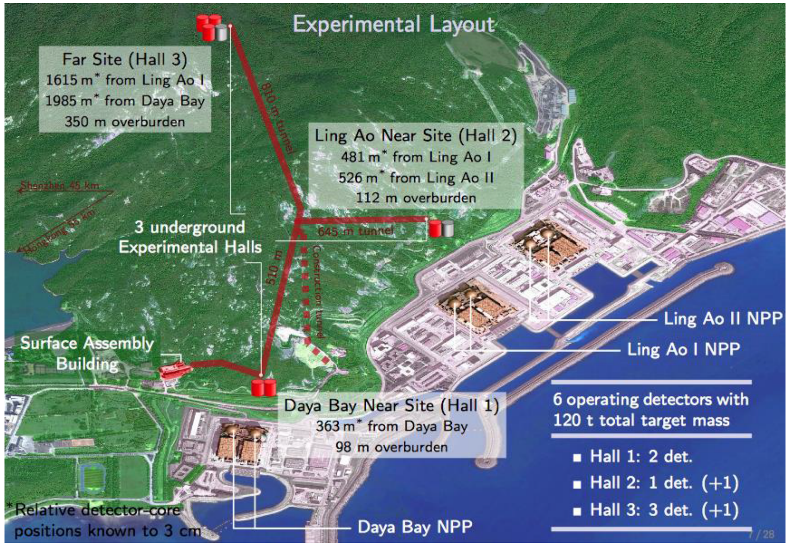


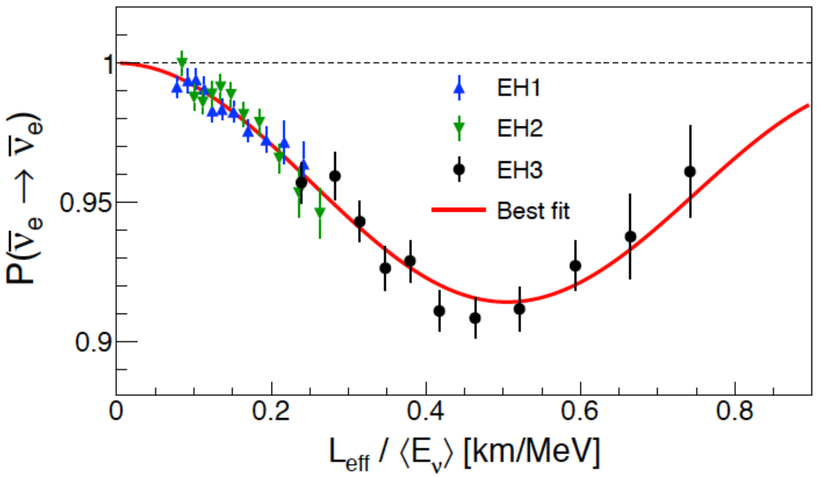
Last mixing angle measured: θ_{13}

$\sin^2 2\theta_{13} = 0.084 \pm 0.005$

→ Era of neutrino precision measurements



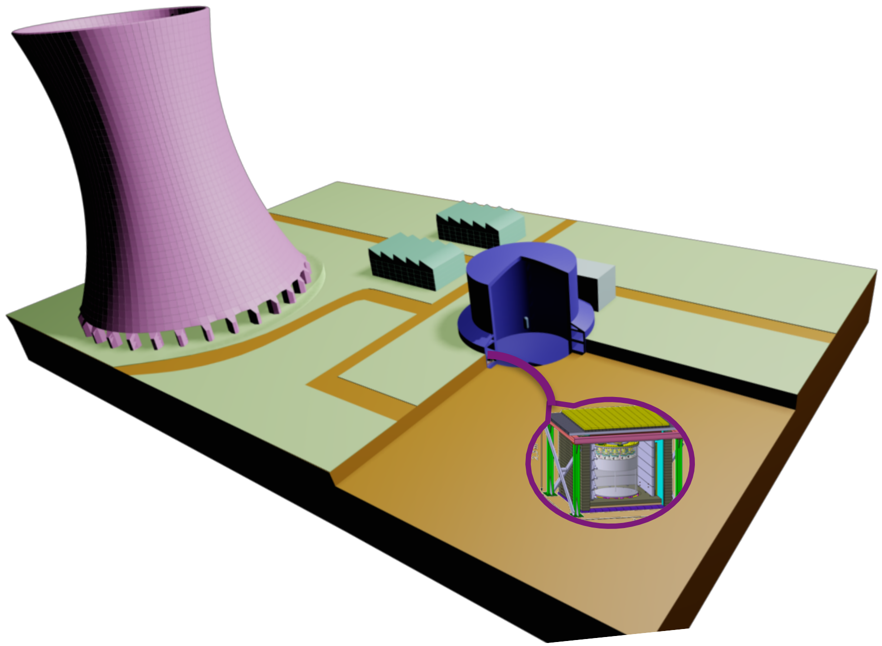


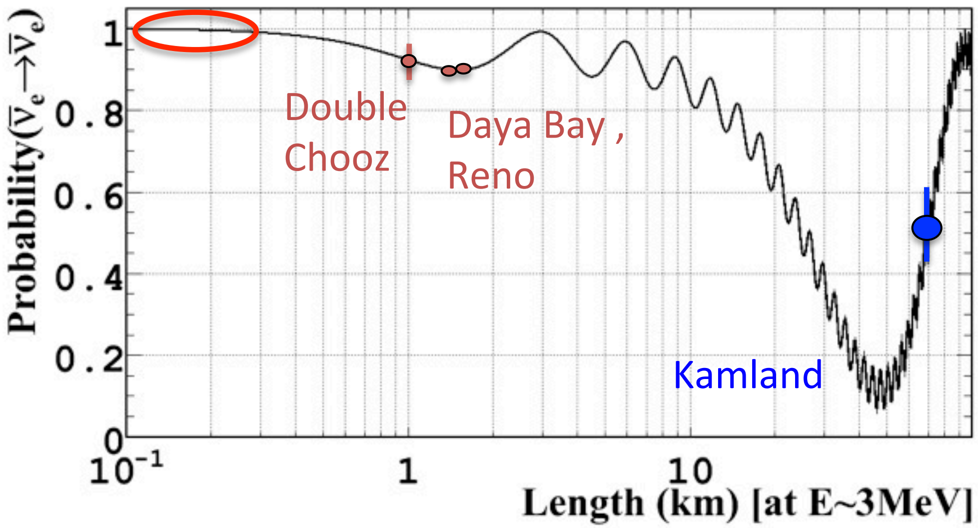


arXiv:1505.03456

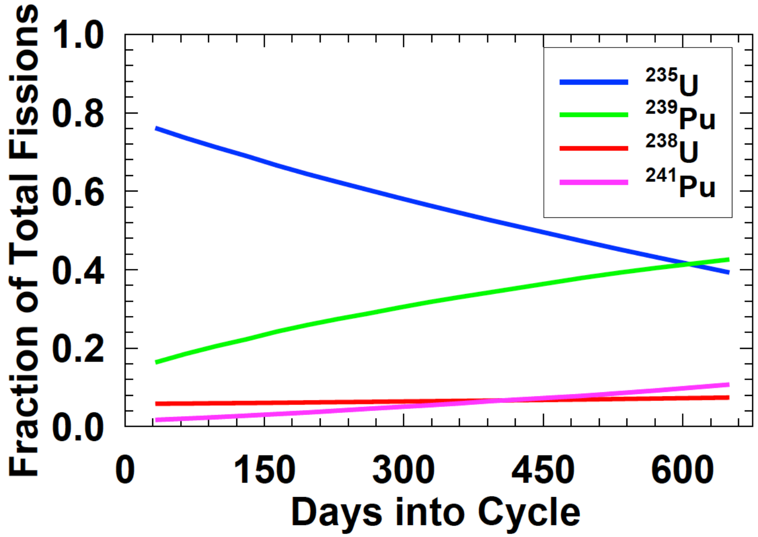
Application of neutrinos to the surveillance of nuclear reactor

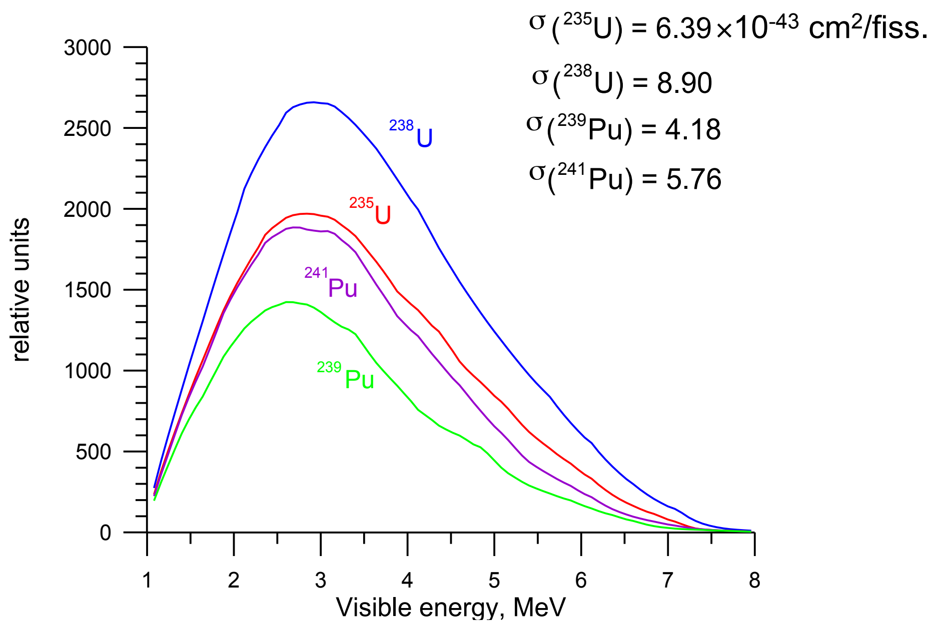
- Monitor the operation of a reactor using a small (1m3 scale) neutrino detector at short distance (few 10 m) from the core





Nuclear Fuel Evolution





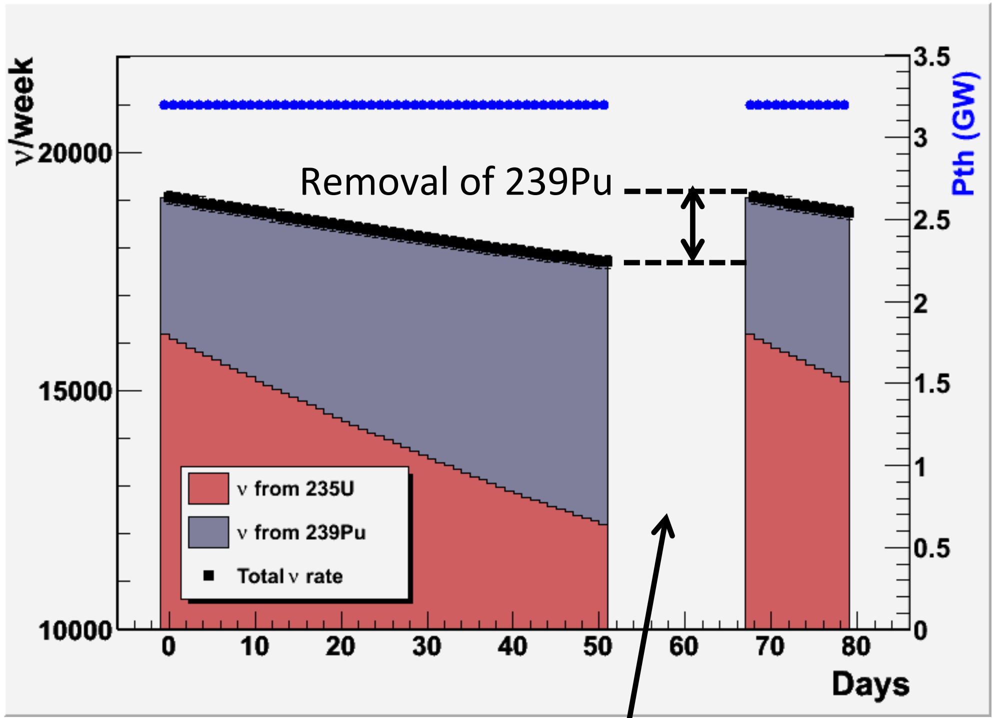
- Antineutrinos encode information about fissile production and consumption in reactors through the burnup effect

Sensitivity to Pu content

1m^3 LS target, ε_{det}=50%
25 m from a 3 GW$_{th}$ core

	^{235}U	^{239}Pu
E / fission	201.7 MeV	210.0 MeV
$< E_\nu >$ (E_ν>1.8 MeV)	2.94 MeV	2.84 MeV
# ν / fission (E_ν>1.8 MeV)	1.92	1.45
$< \sigma_{\nu\ int} >$	≈ 3.2 10^{-43} cm^2	≈ 2.76 10^{-43} cm^2

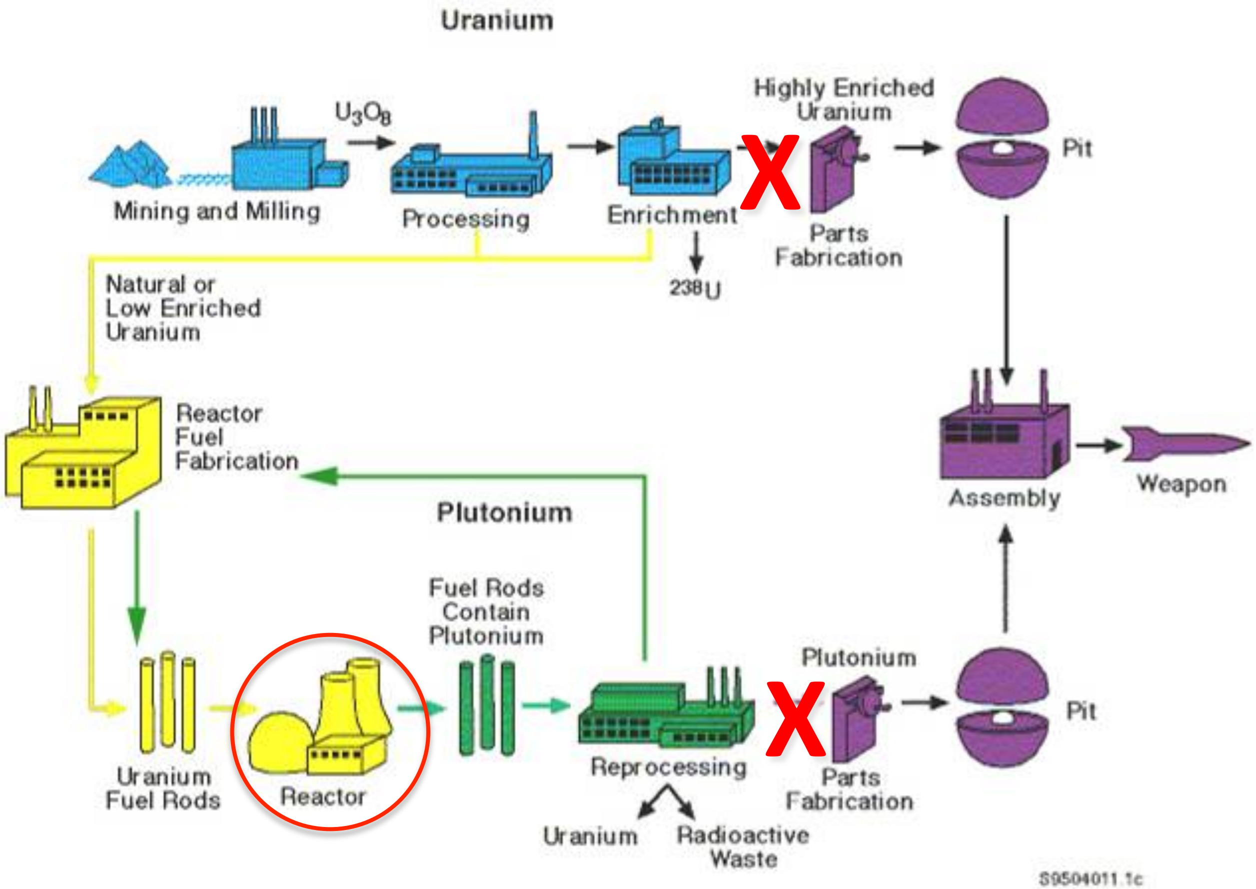
$$\frac{\#\nu\ \mathrm{int}\left(^{235}U\right)}{\#\nu\ \mathrm{int}\left(^{239}Pu\right)} = \frac{210.0}{201.7} \times \frac{1.92}{1.45} \times \frac{3.2}{2.76} = 1.60$$



Replace 1/3 of spent fuel

Control of Fissile Material

IAEA goal: detect diversion of fissile material from peaceful to military programs



$\bar{\nu}_e$ measurements could monitor the fissile inventories in operating reactors

Specifications of a neutrino monitor

- Compact, portable *(easy installation, operate close to surface)*

- Safe *(no connection with the core or the primary circuit, no impact on reactor operation and safety)*

- Simple *(operated by non-experts)*

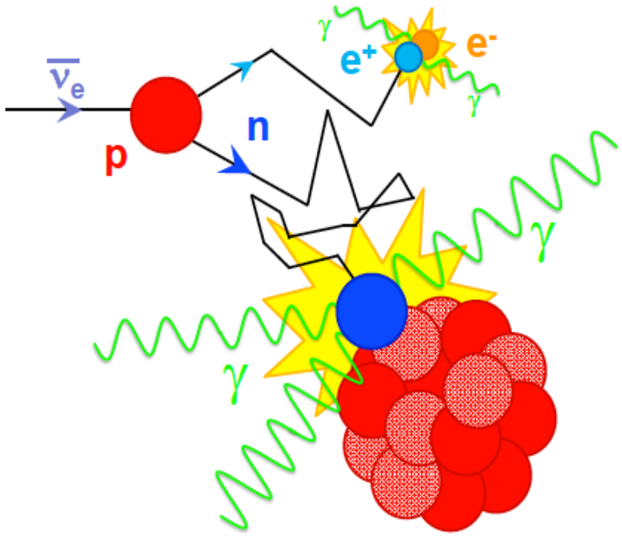
- Remotely controlled *(no on site inspection, little maintenance)*

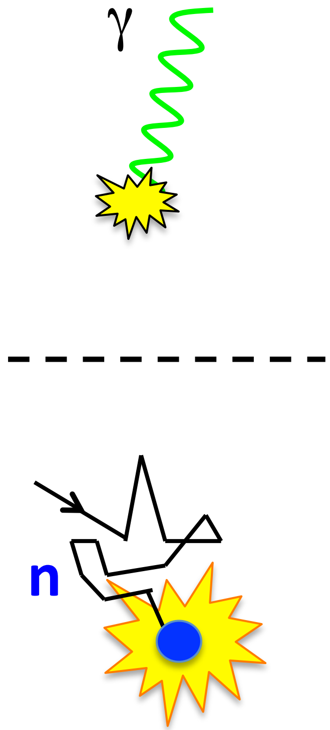
- Challenging simplification w.r.t state of the art neutrino detectors
- Challenging mitigation of external background

Background

Inverse Beta Decay

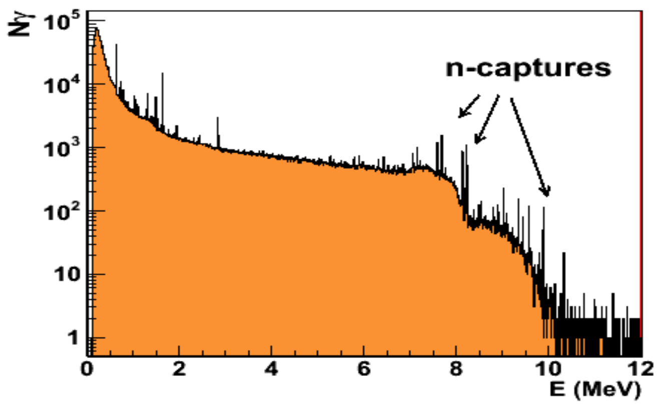
$$\overline{\nu}_e + p \rightarrow e^+ + n$$





Accidental [γ-n_{th}] coinc

- Natural radioactivity + reactor leakage
- High E γ's from n-capture on metals, ^{16}N production in primary circuit, …

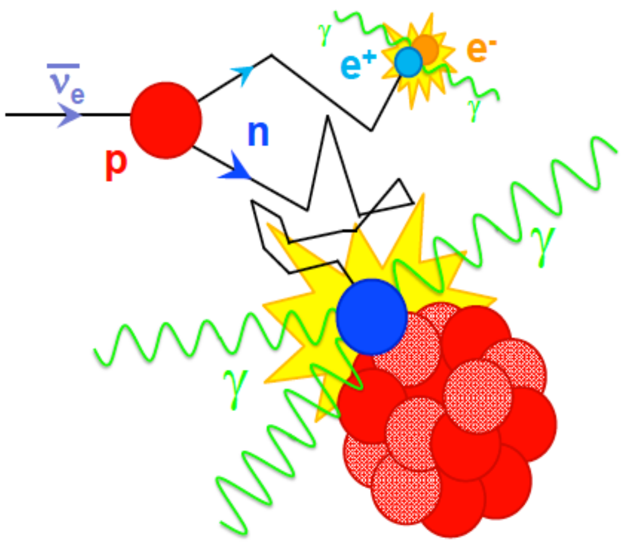


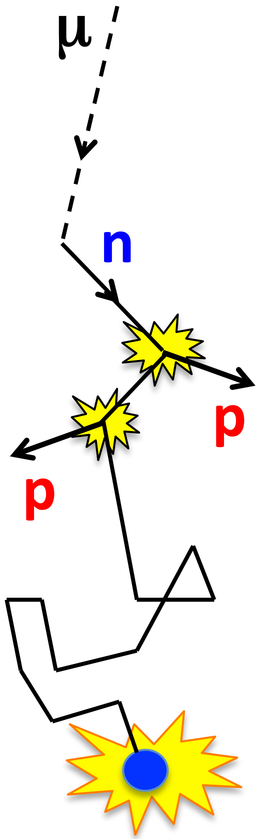
- On site measurements + heavy shielding design
- Online measurement and subtraction

Background

Inverse Beta Decay

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

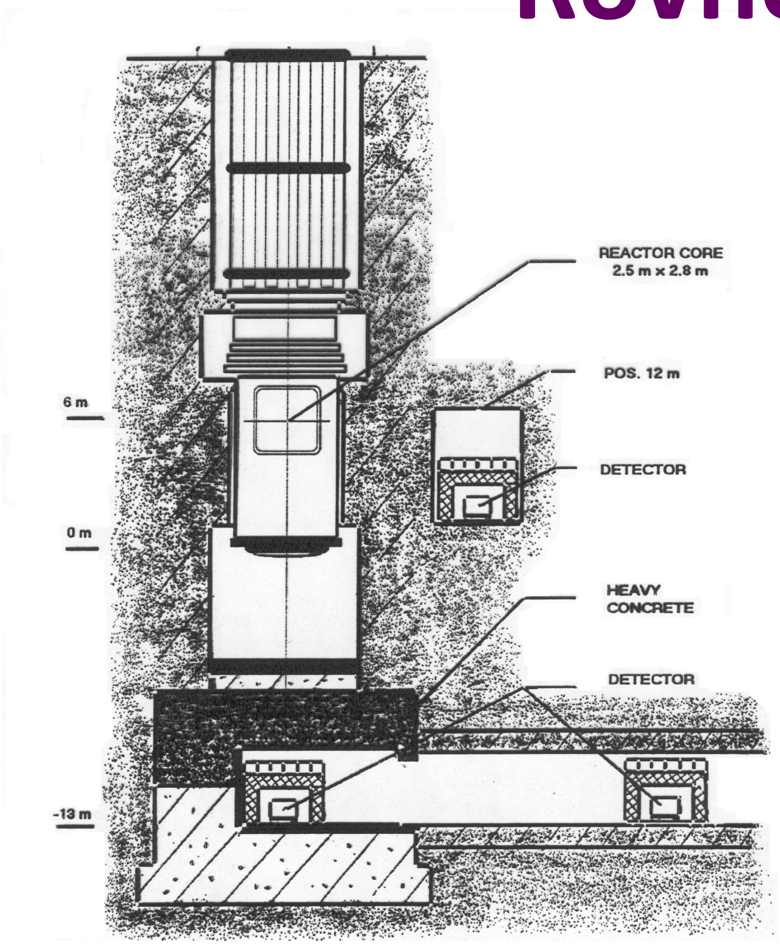




Correlated background from fast n

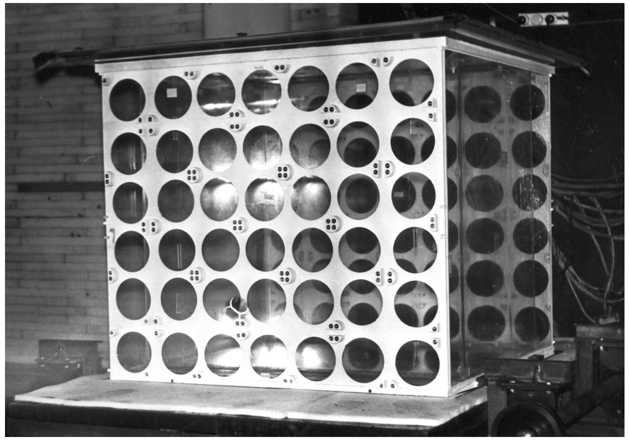
- Cosmic rays - induced
- **Online rejection:**
  - Minimal overburden
  - Active μ veto around target
  - PSD
- **Offline**:
  - Subtraction of reactor OFF data
- Must suppress all fast n from reactor

Rovno experiment



3GW Rovno NPP – Ukraine

Detector vessel

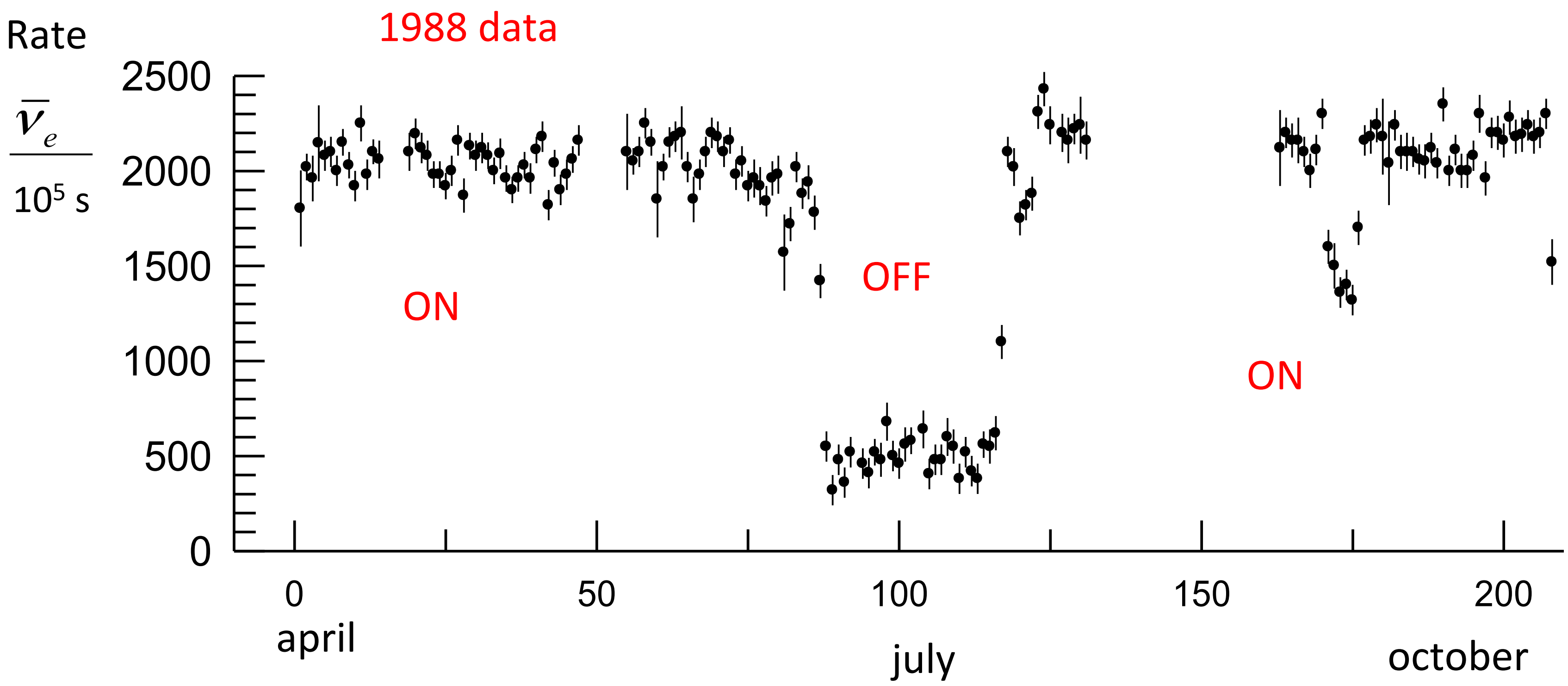


$1m^3$ of liquid scintillator + 0.5 g/l Gd
84 PMT
ε_{det} ~50%

Favorable signal/noise configuration:

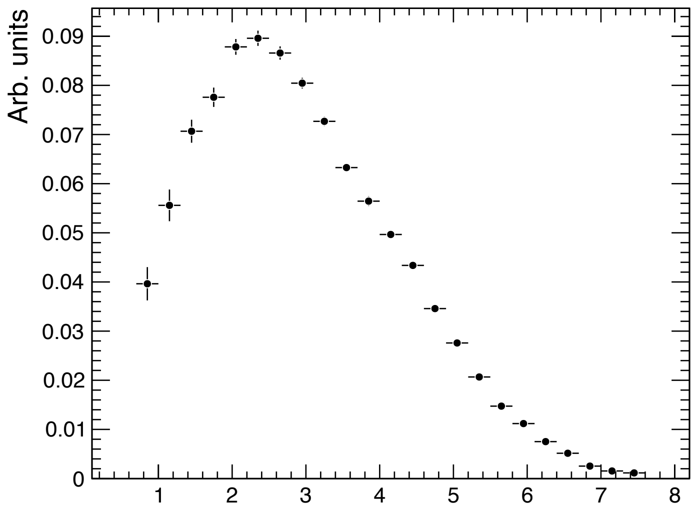
- 18 m from the core
- 30 m.w.e. oberburden

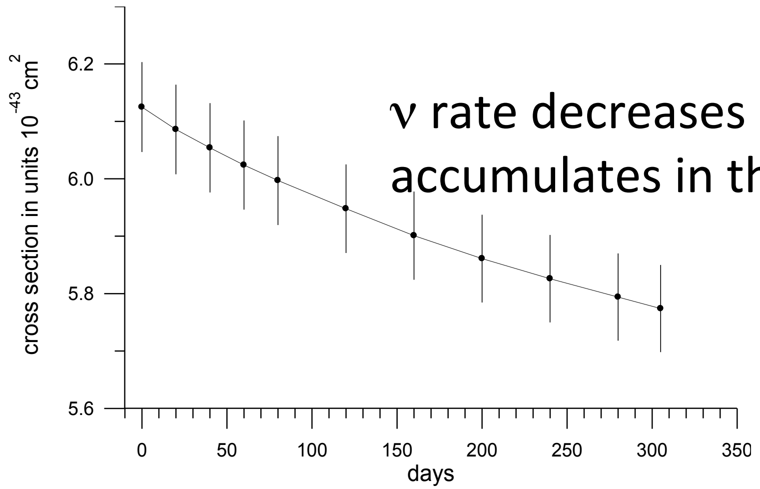
Rovno experiment



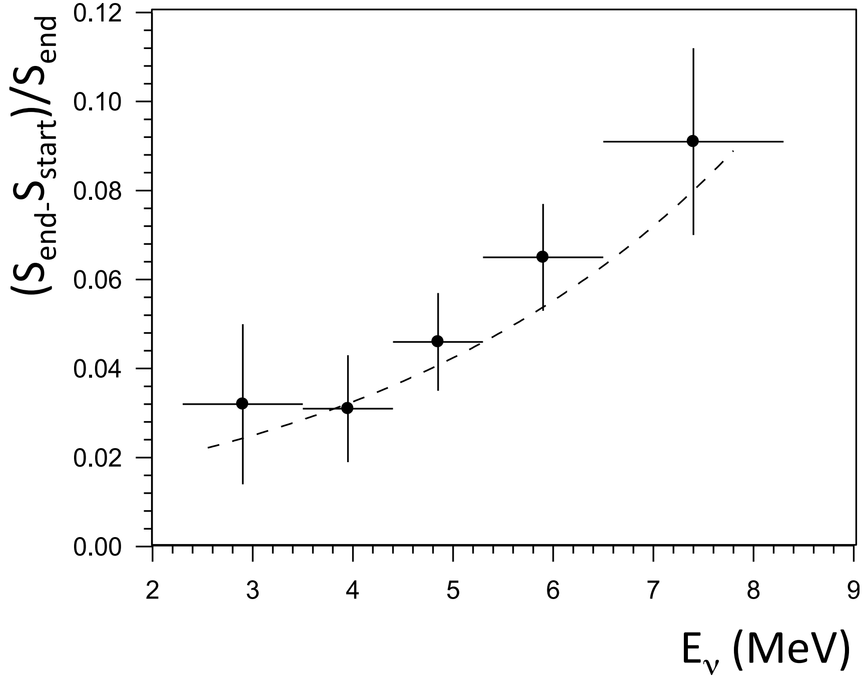
Rovno experiment

174000 ν events



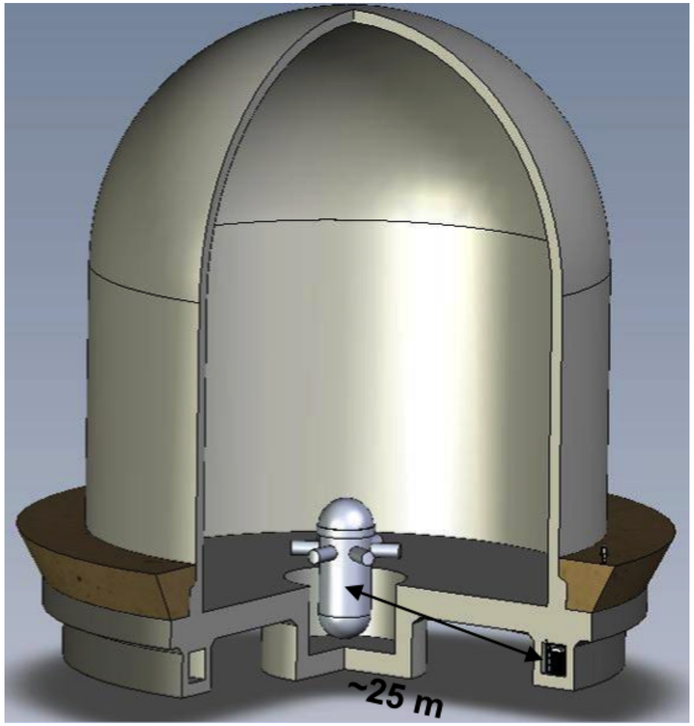


ν rate decreases as Pu accumulates in the core



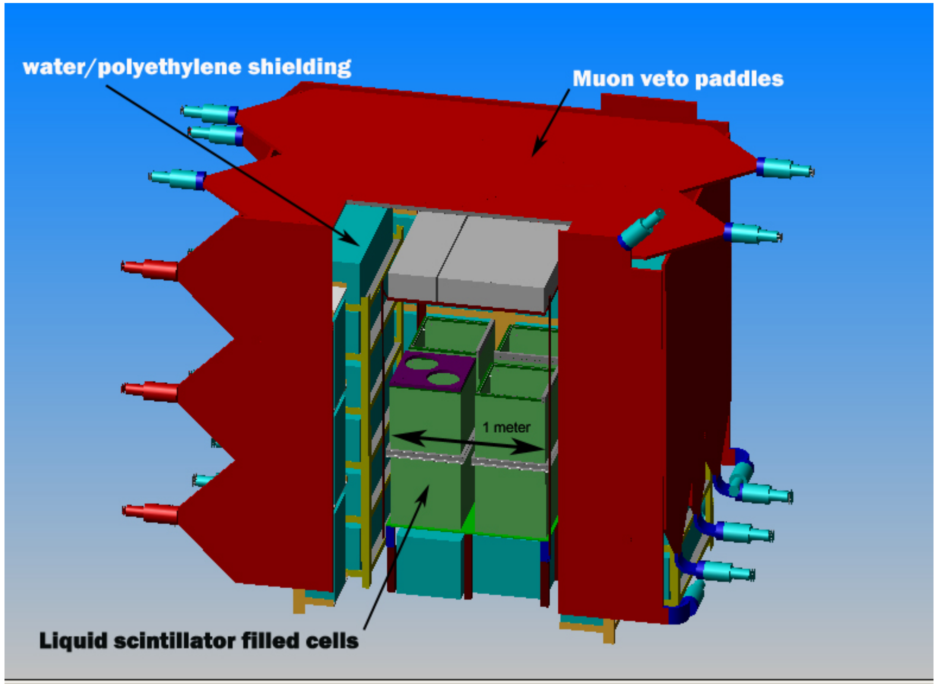
ν spectrum gets harder

SONGS



- 3.4 GW_{th} ➡ ~10^{21} ν/s
- 3800 int. expected per day in $1m^3$ liq. scint. target

SONGS detector deployed at the San Onofre Nuclear Generating Station

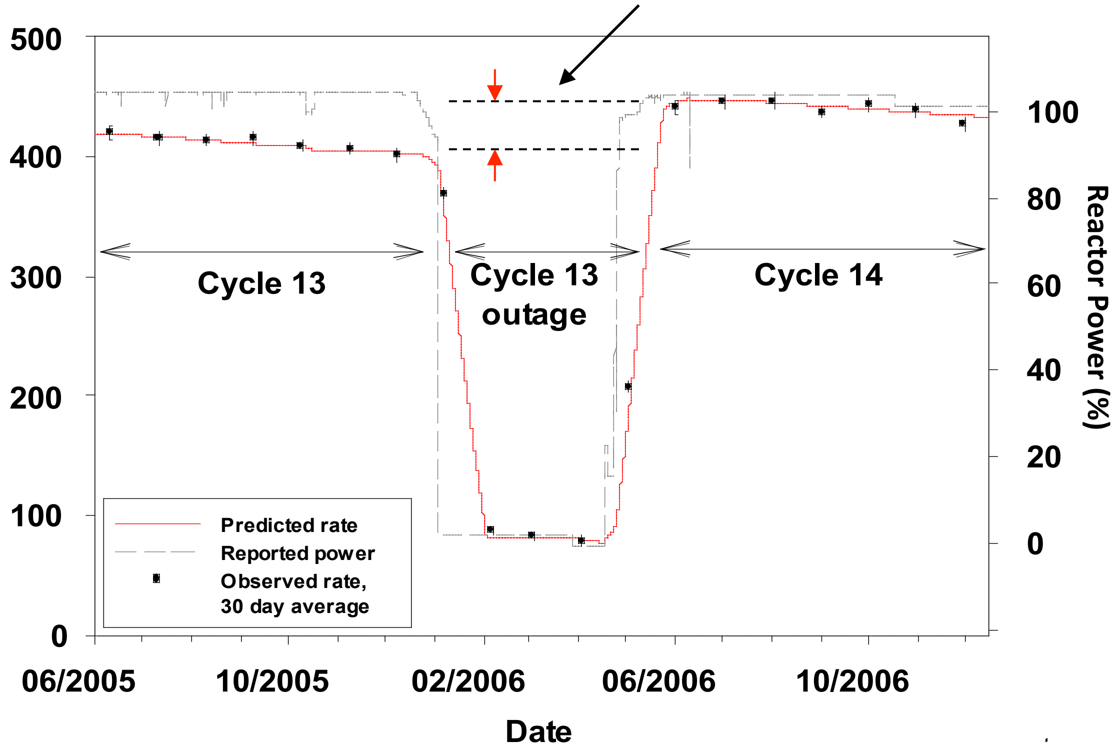


- **Low cost and robust detector**
- **Very simple design and light shielding**
- **Automated, non intrusive measurement**

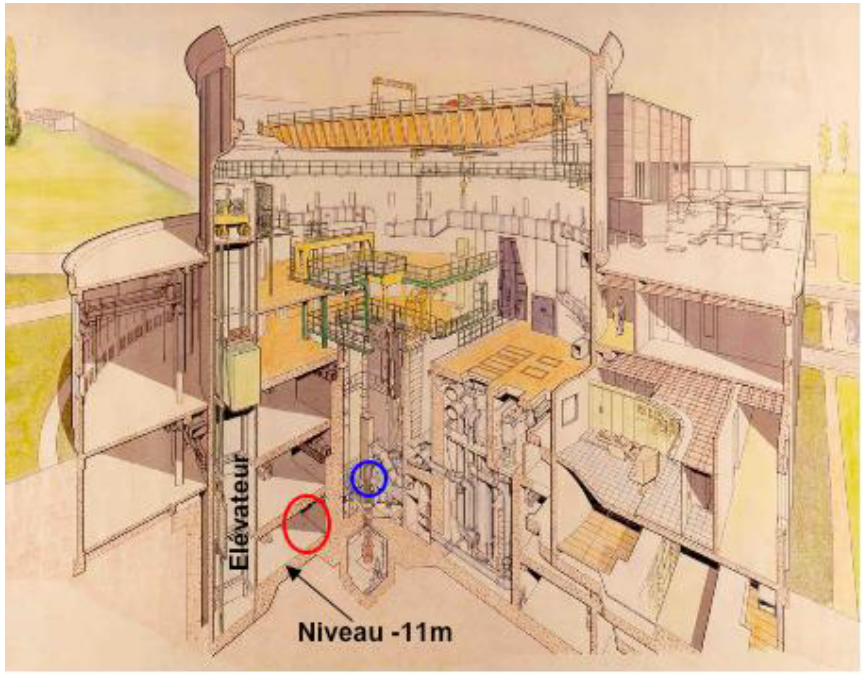
SONGS

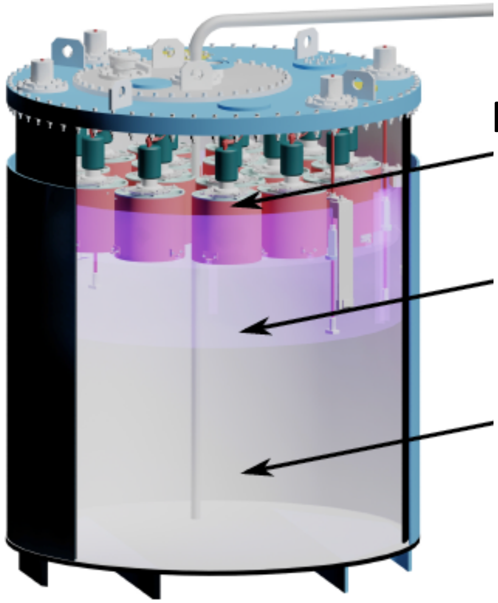
- Remarkable monitoring of the reactor operation
- Good signal/noise ratio
- Sensitivity limited by the low detection efficiency

Removal of 250 kg ^{239}Pu, replacement with 1.5 tons of fresh ^{235}U fuel



NUCIFER

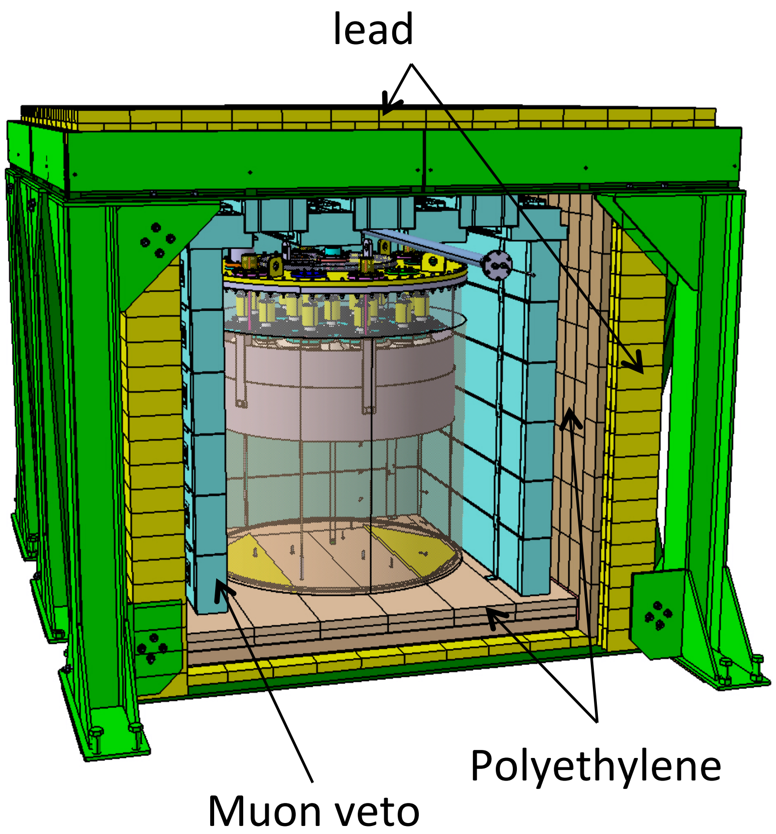


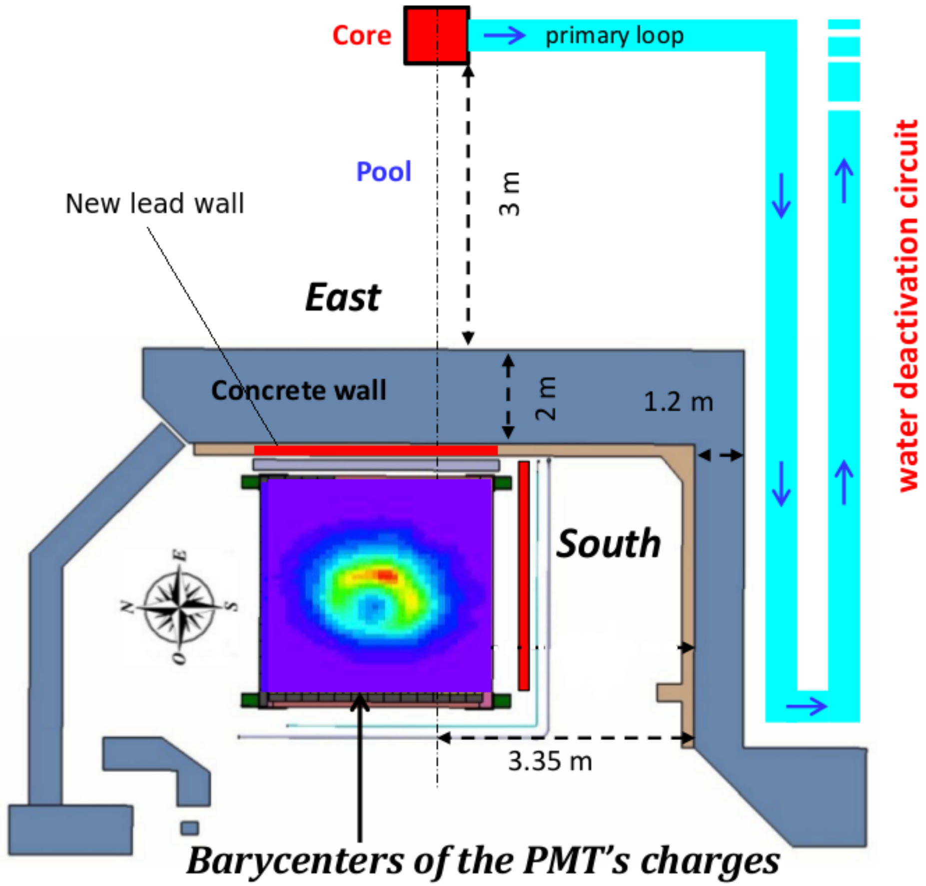


- OSIRIS: 70 MW research reactor at CEA-Saclay, France
- Nucifer is only 7.2 m away from the core!
- Aiming at demonstrating the concept of “neutrinometry" at the pre-industrialized stage.

Nucifer shielding

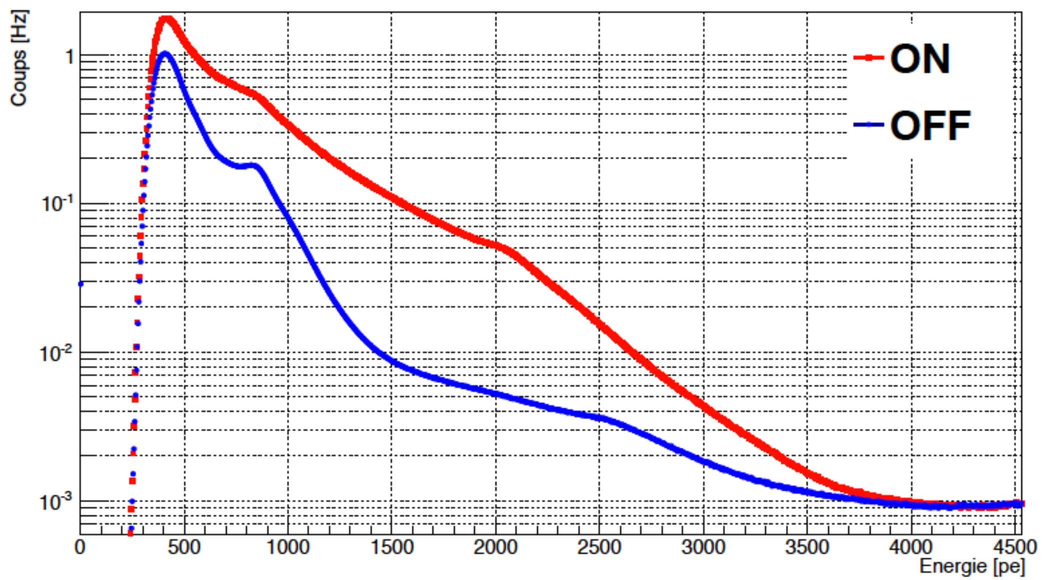
Very challenging background induced by the reactor and the cosmic rays

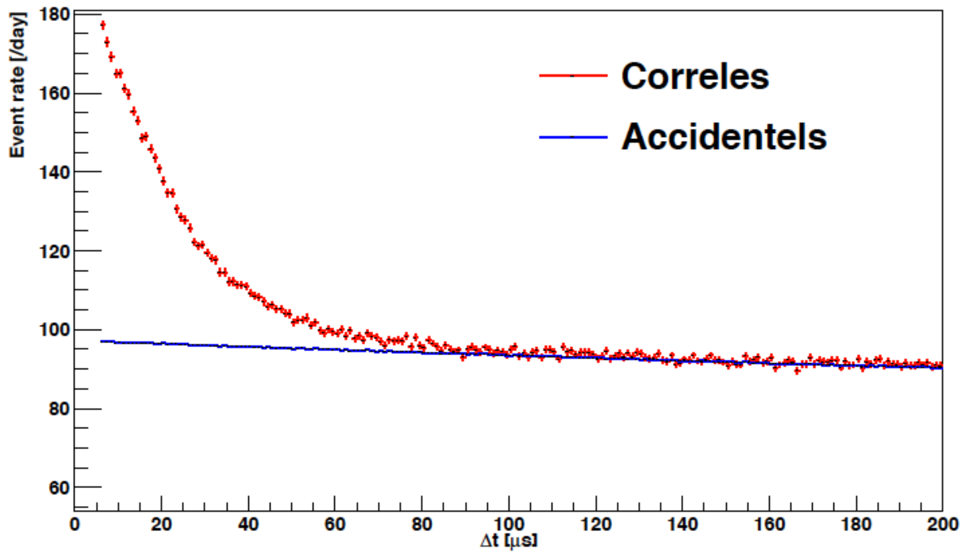




Background

- Contamination of high gammas from the reactor in the prompt and delayed energy window
- Large accidental background scaling with $(P_{reactor})^2$
- 4733±6 candidate pairs /day 3332.8±0.5 accidentals/days, accurately measured online

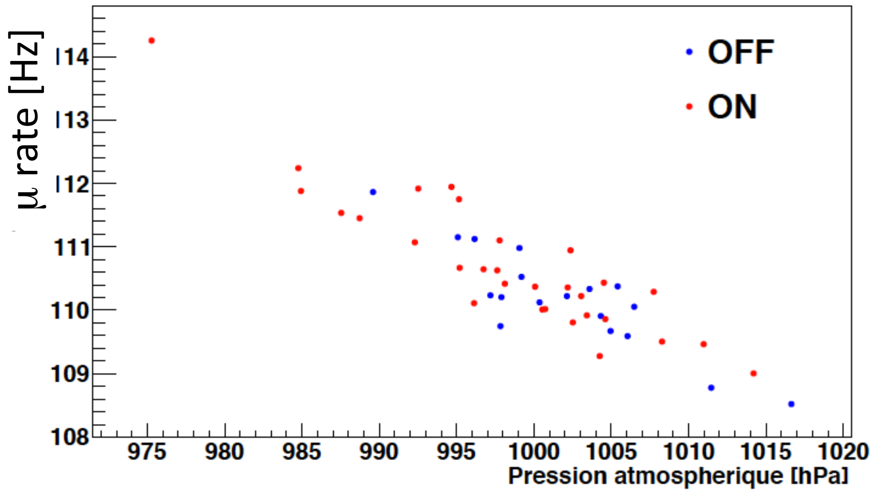


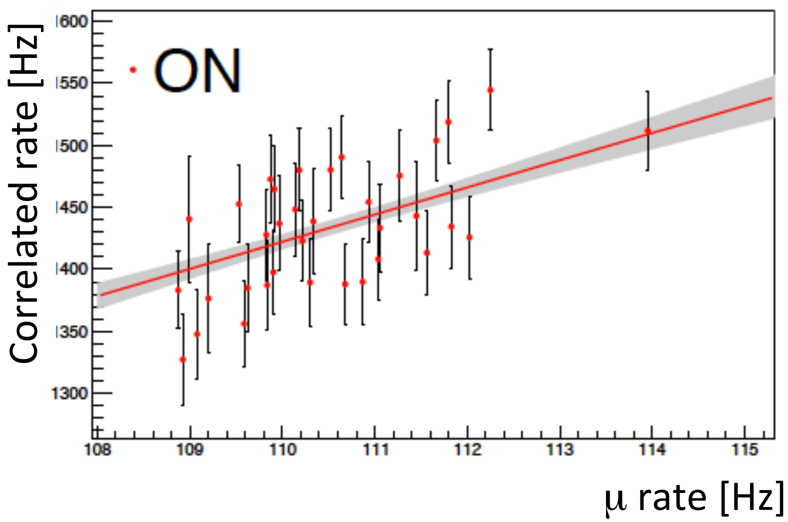


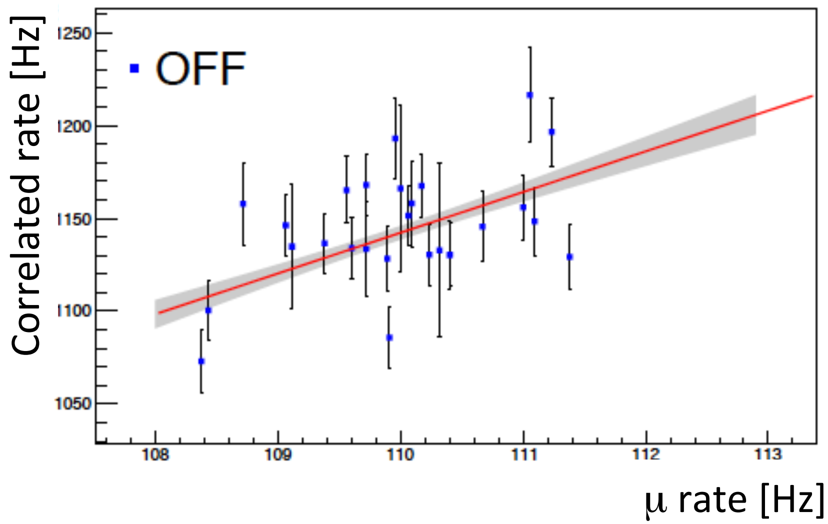
Cosmic rays induced background

A clear correlation between P_{atmos} and the μ rate in Nucifer is observed

→ The subtraction of reactor OFF background has to be corrected for the ≠ of μ rate between ON and OFF periods.

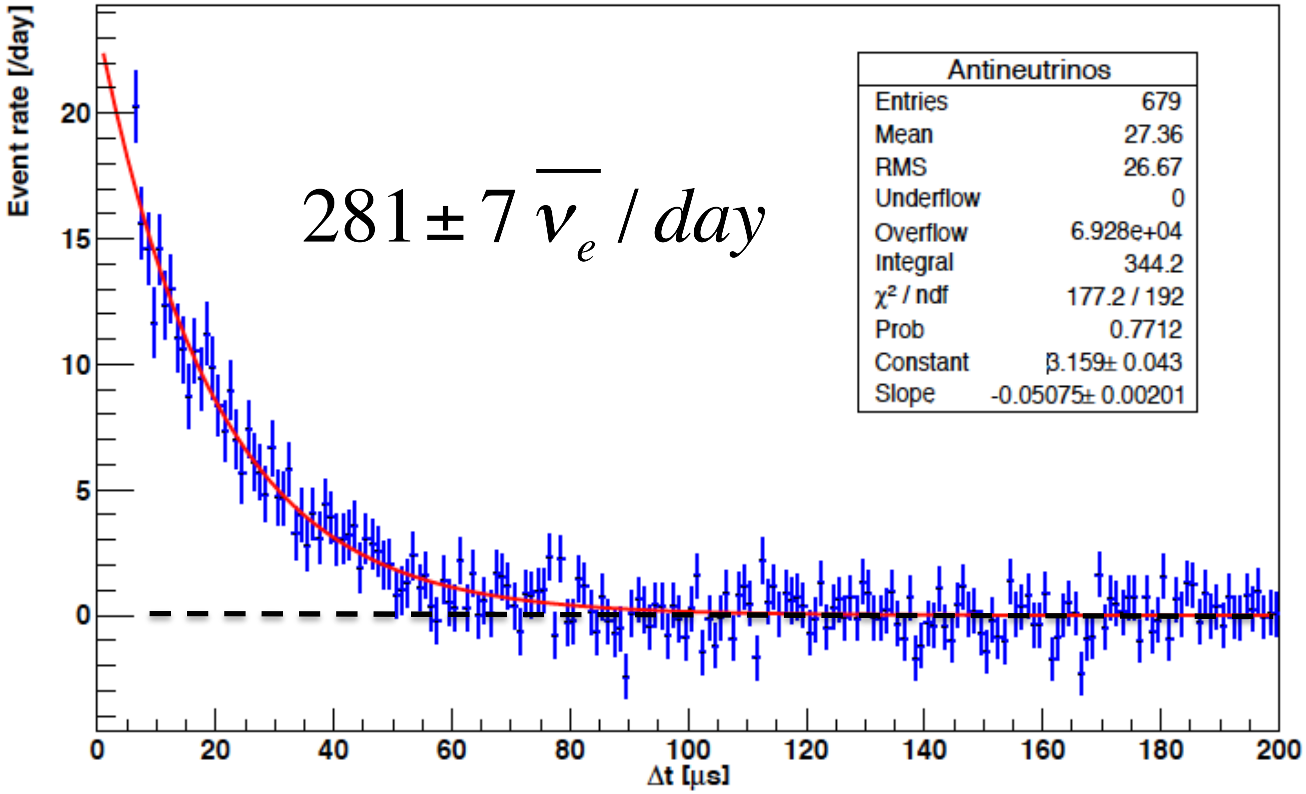




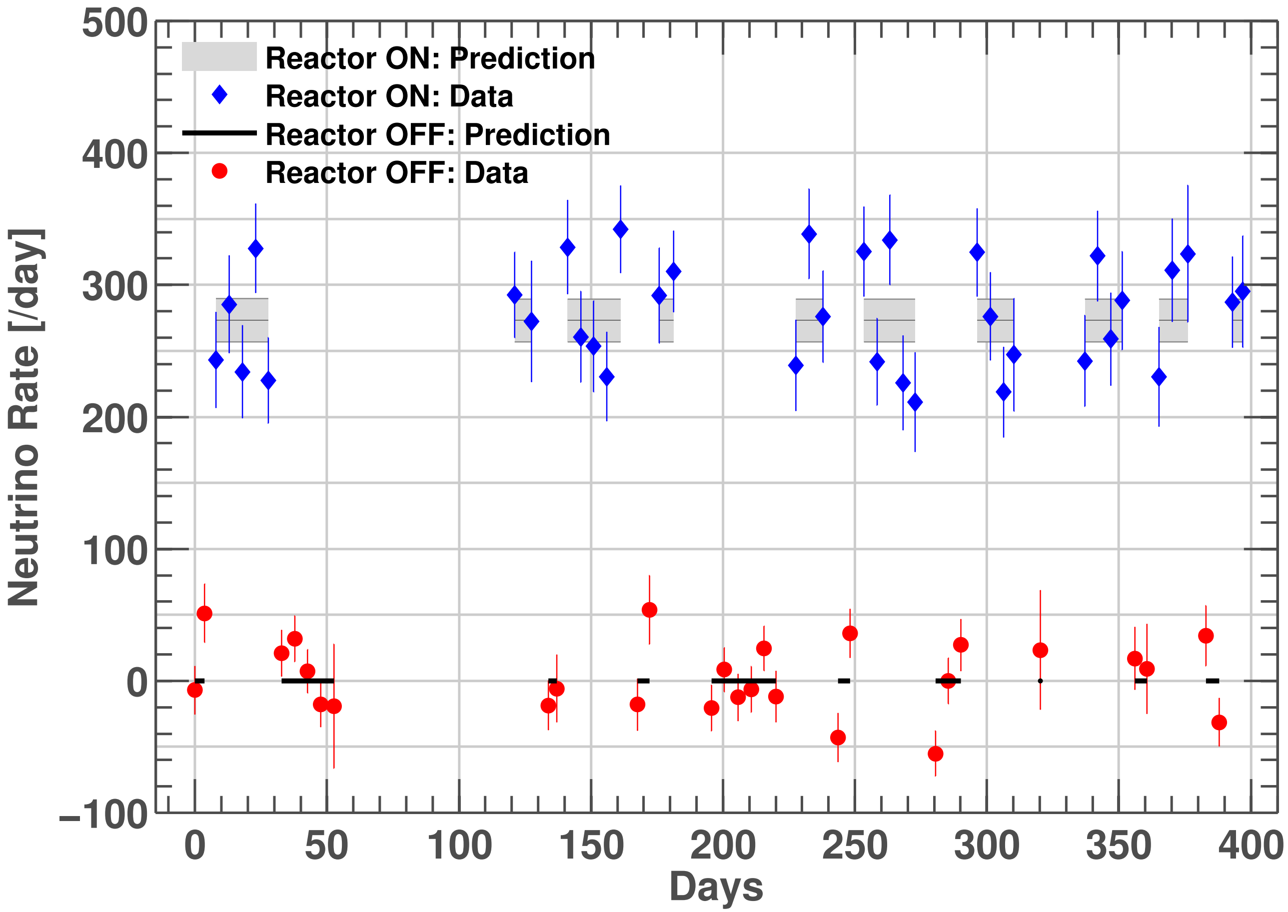


Nucifer results

$$R^{ON}_{\overline{\nu}_e}(R_\mu) = R^{ON}_{paires} - R^{ON}_{acc} - R^{OFF}_{corr}(R^{ON}_\mu)$$



Nucifer results

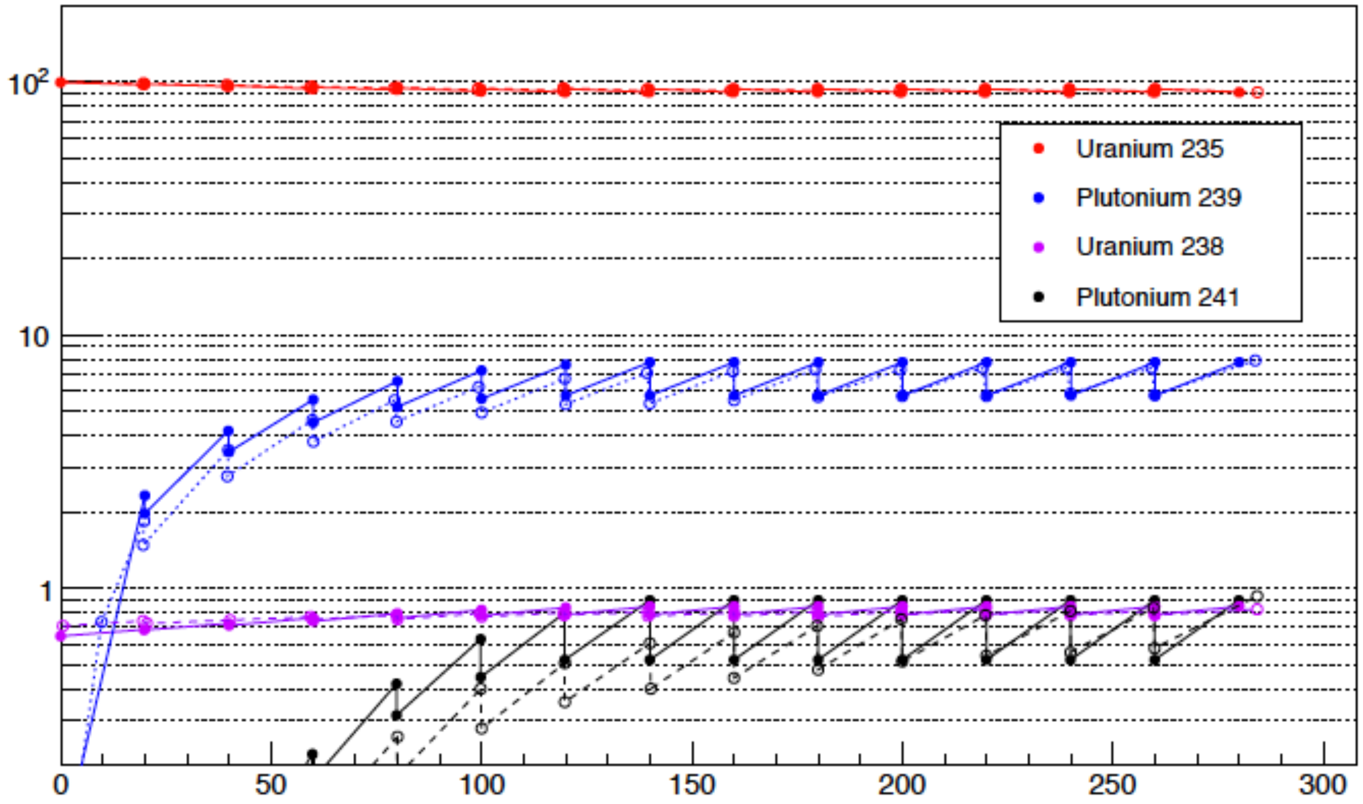


arXiv:1509.05610

Sensitivity study

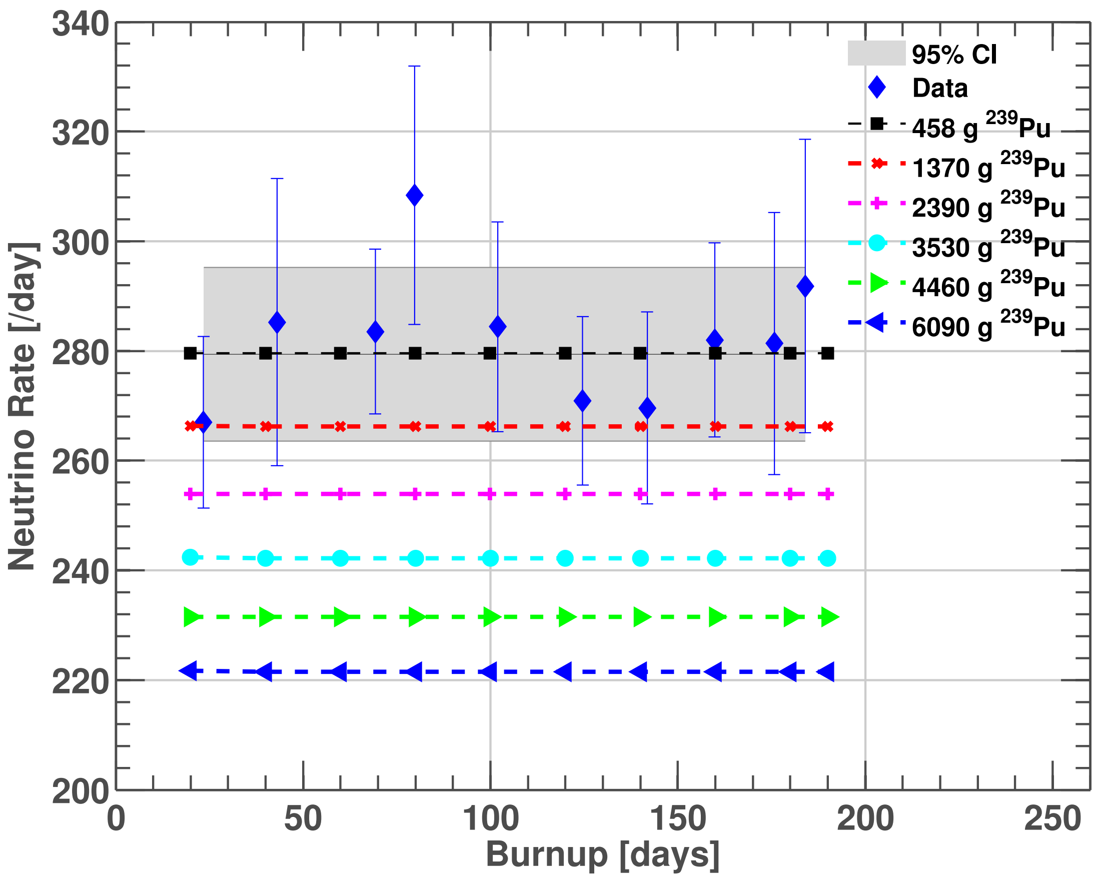
Osiris uses highly enriched 235U fuel with short cycles

→ The evolution of the fuel composition is undetectable (<1% change in the neutrino rate)



Sensitivity study

- Various levels of Pu were simulated in the core
- Within the current background conditions Nucifer would have seen the effect of ~1.5 kg of Pu in Osiris at 95% C.L., that is ~10% of the total fissile mass.

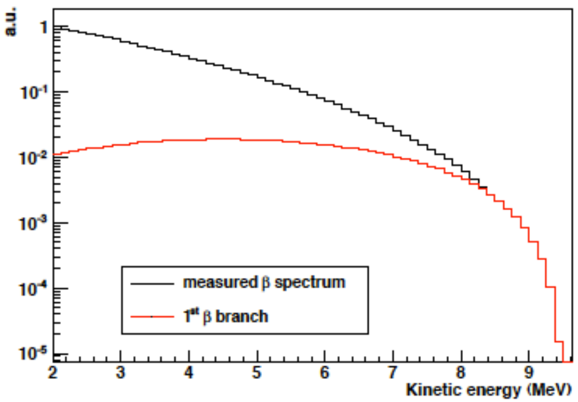


Reactor surveillance with neutrinos

- Antineutrino monitoring can assess the plutonium content in water-cooled nuclear reactors for nonproliferation applications.
- Need to demonstrate further sensitivity and deployment capacities before competing with the current tools of reactor surveillance.
- Direct information on the fission processes in the core is an asset for the surveillance of online refueling/reprocessing reactors. But the lever arm on the neutrino signal is small.
- Disposal of weapon-grade plutonium by irradiation in fast reactors (Plutonium Management and Disposition Agreement) could be monitored by neutrinos with simple observables like total burnup and $<N_\nu>$/GW
- New detection technics are being developed in synergy with fundamental research activities.

Accurate prediction of neutrino fission spectra

Conversion of the ILL spectra with virtual β-Branches



Fitted on ILL β-spectrum

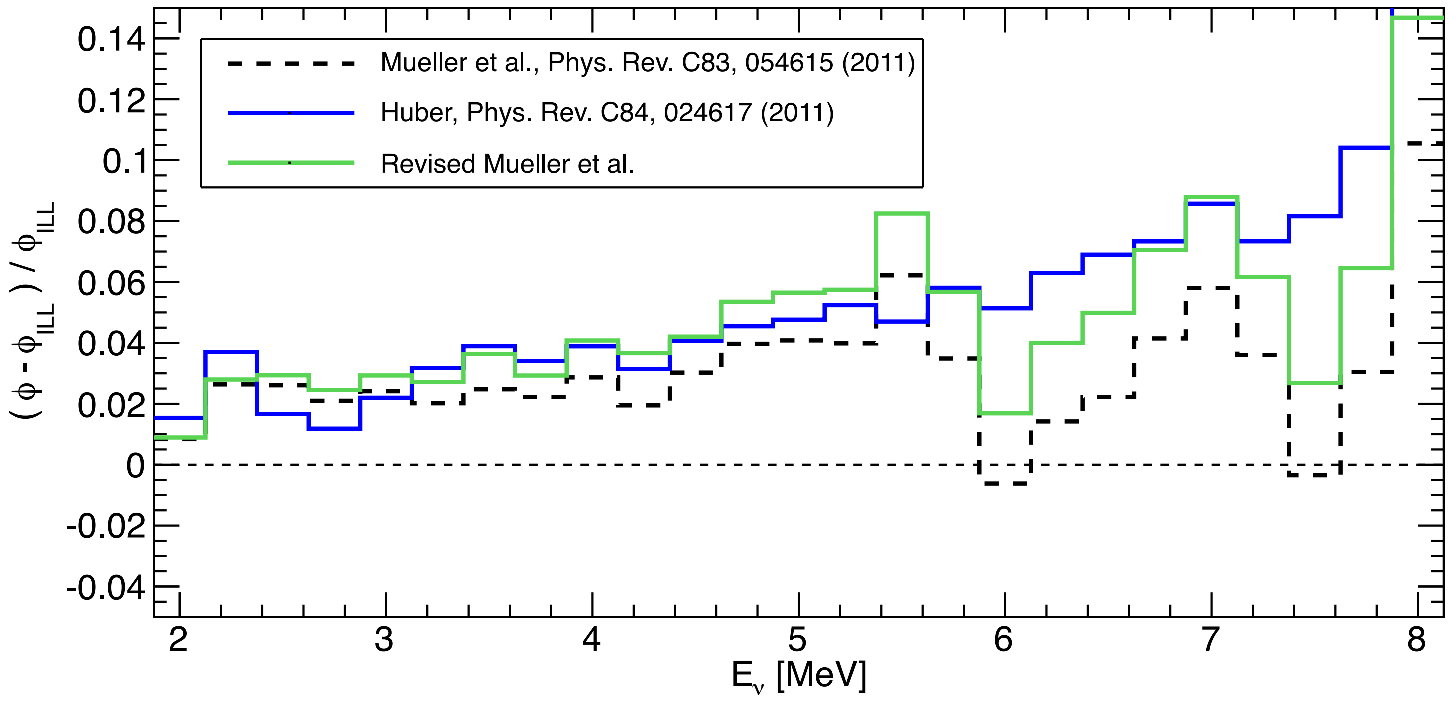
$$S^b_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}} \times \underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

The mean Z(E0) from nuclear databases

Set to 1

Effective δ_{WM} and δ_{CW} corrections applied after the conversion process

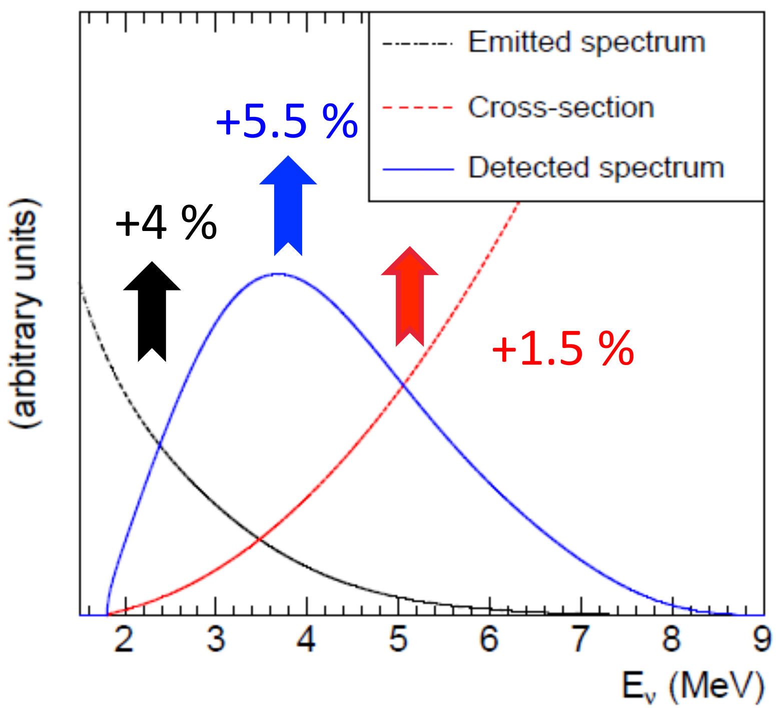
Conversion of ILL Spectra Revisited



- Confirms global increase of predicted spectrum
- Fixes remaining oscillations of mixed-approach prediction
- Extra deviation at high energy from more complete correction to Fermi theory (weak interaction in the finite volume of the parent nucleus).

New Prediction

Improved converted spectra

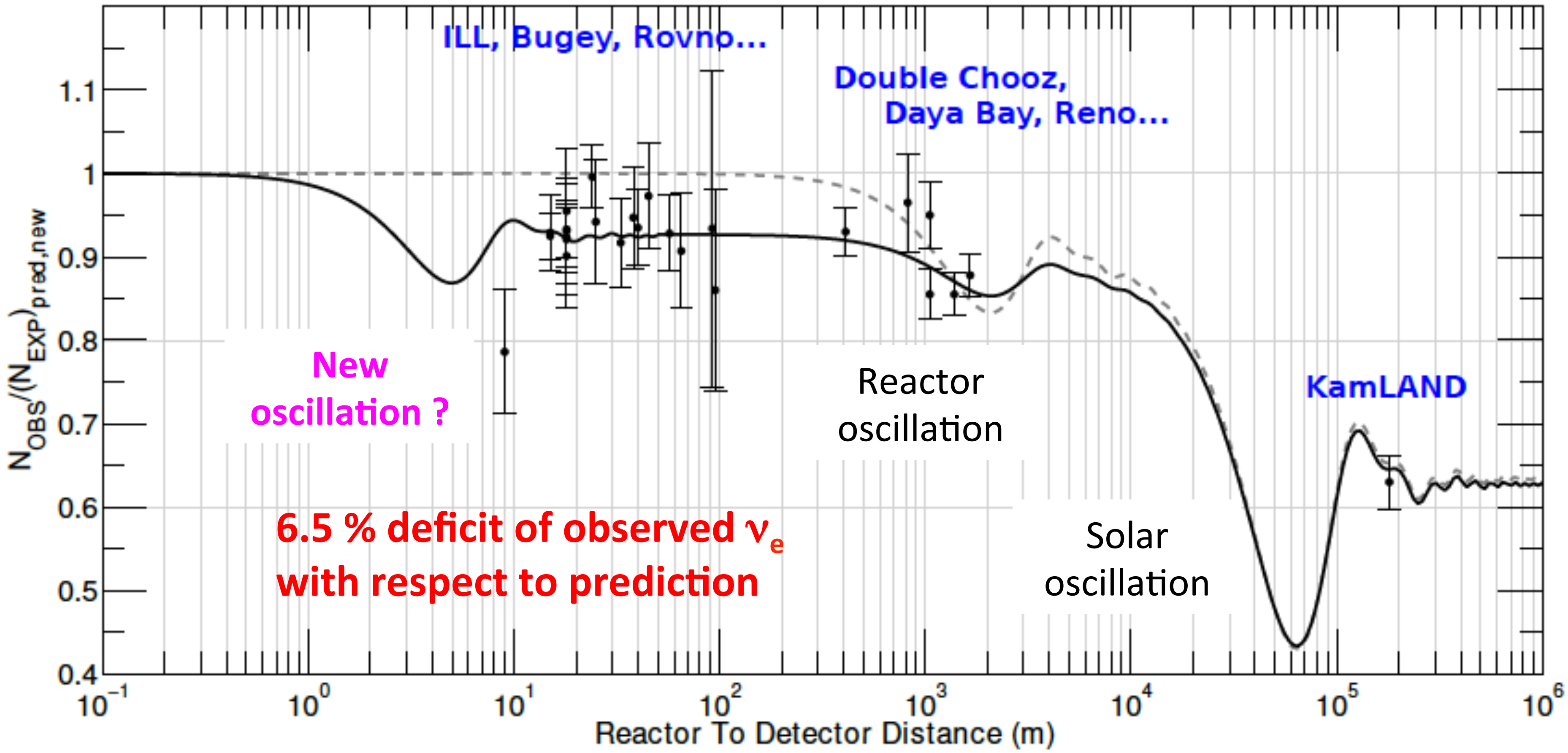


Measured value of neutron lifetime has evolved in time and $\sigma_{int} \propto 1/\tau_n$

G. Mention et al, Phys. Rev. D83, 073006, 2011

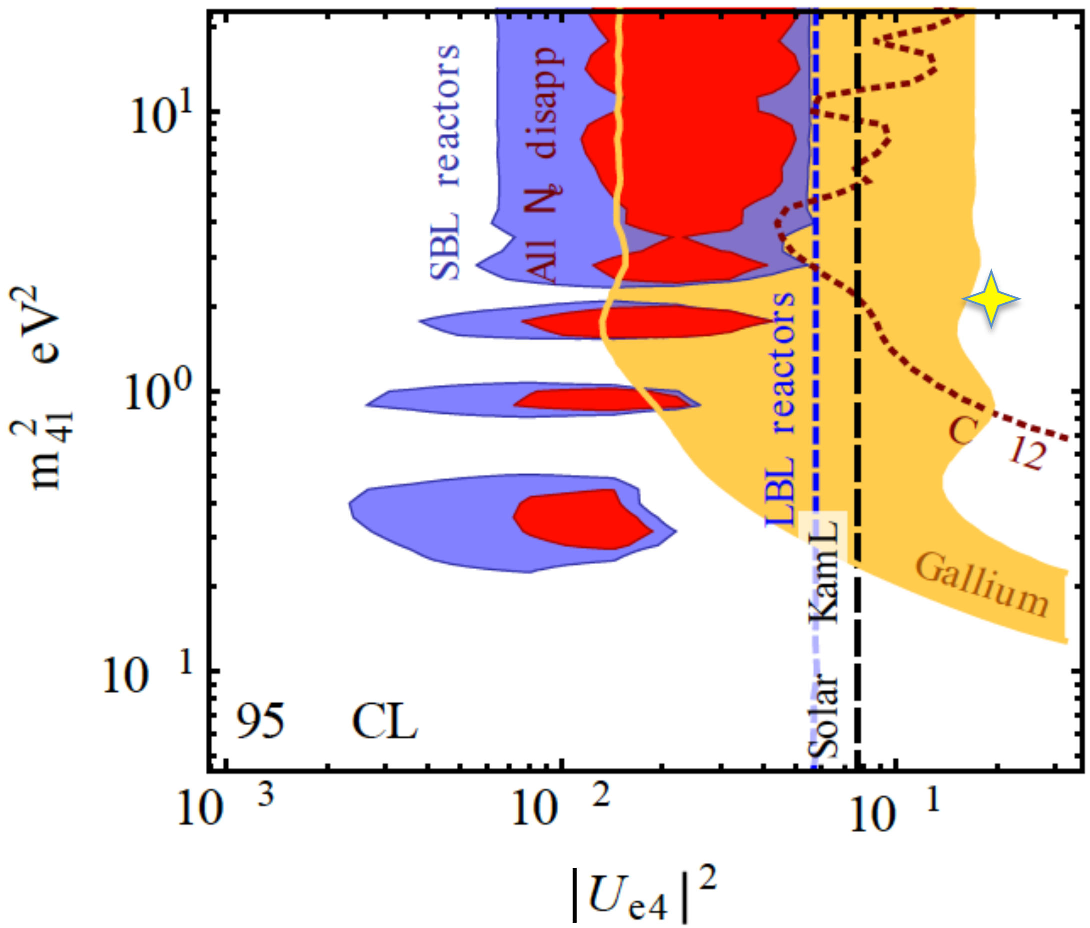
→Predicted flux increases by ~5.5 %

Reactor Antineutrino Anomaly



Sterile Neutrino ?

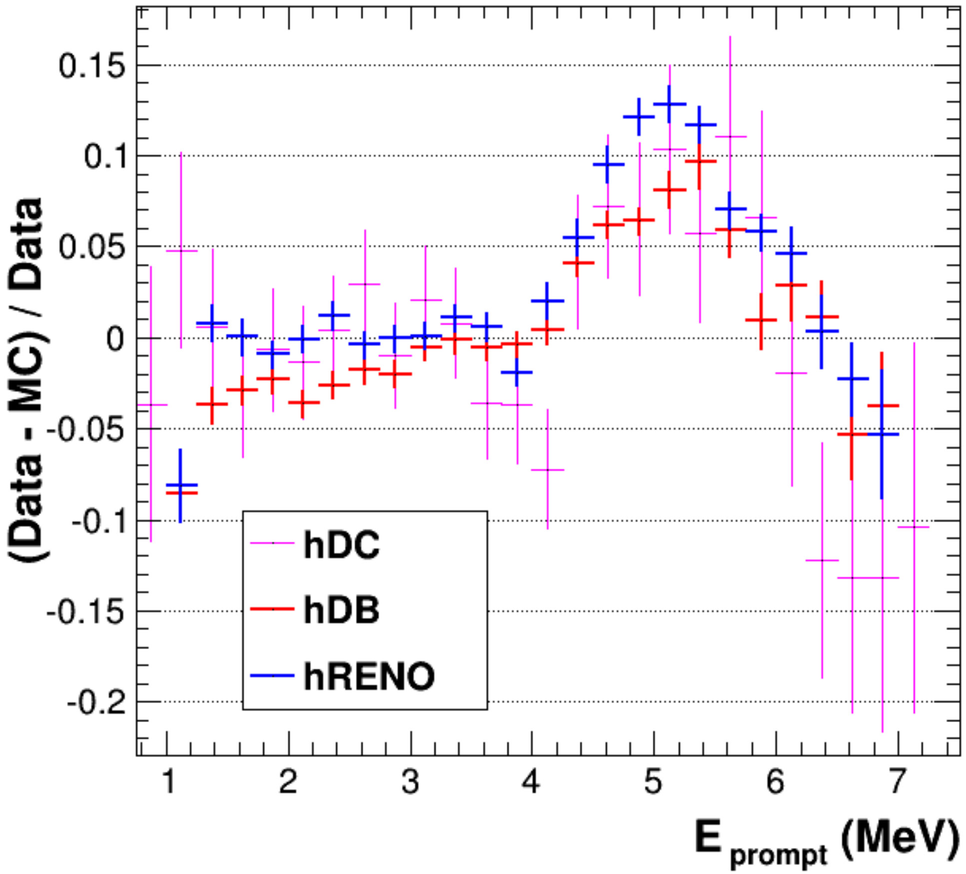
J. Kopp et al, JHEP 1305 (2013) 050



- Puzzling convergence of several ν_e disappearances toward the same oscillation parameters.
- Tension with nm disappearance data and cosmology fits
- Triggered a worldwide experimental program for a direct search of a new oscillation pattern.

… or bias in the converted spectra?

Double Chooz, Daya Bay, Reno



3 experiments point to the same deviation

→ Biased prediction?

→ Biased reactor anomaly?

Potential Biases

A.C. Hayes et al, Phys. Rev. D92 (2015) 3, 033015

- Differences between ILL and commercial reactors:
  - neutron energy spectrum and fission yields
  - Off-equilibrium effects (under control, impact at low energy only, <3 MeV)
  - non-fission sources of antineutrinos (not likely)

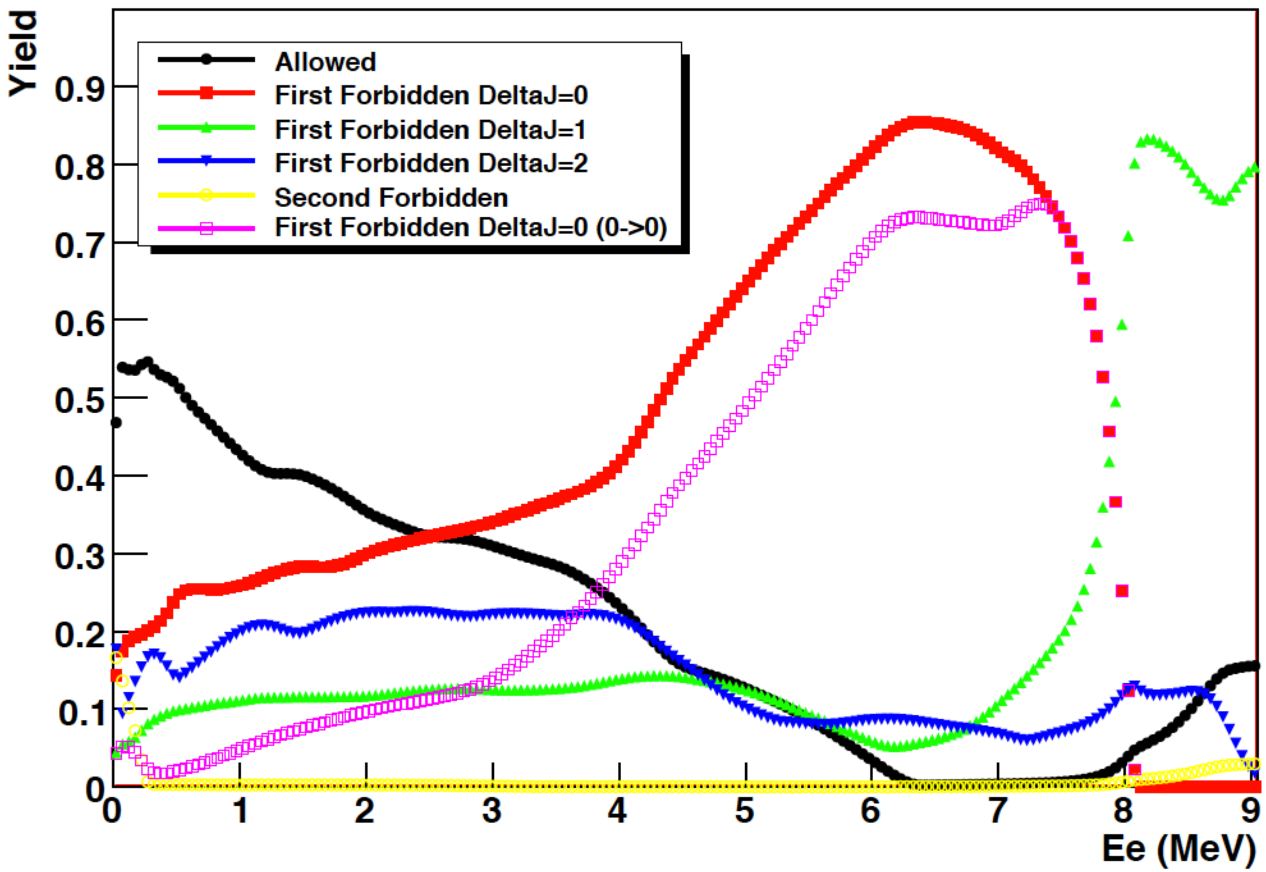
- Error in the ILL electron spectra (?)
  - Would need a complementary experiment with similar accuracy

- Forbidden transitions

- Corrections to Fermi theory

Contribution of Forbidden Decays

- Relative contribution of different transition types in each energy bins of the total fission spectrum
- Only well known decays computed, quite few after 6 MeV.

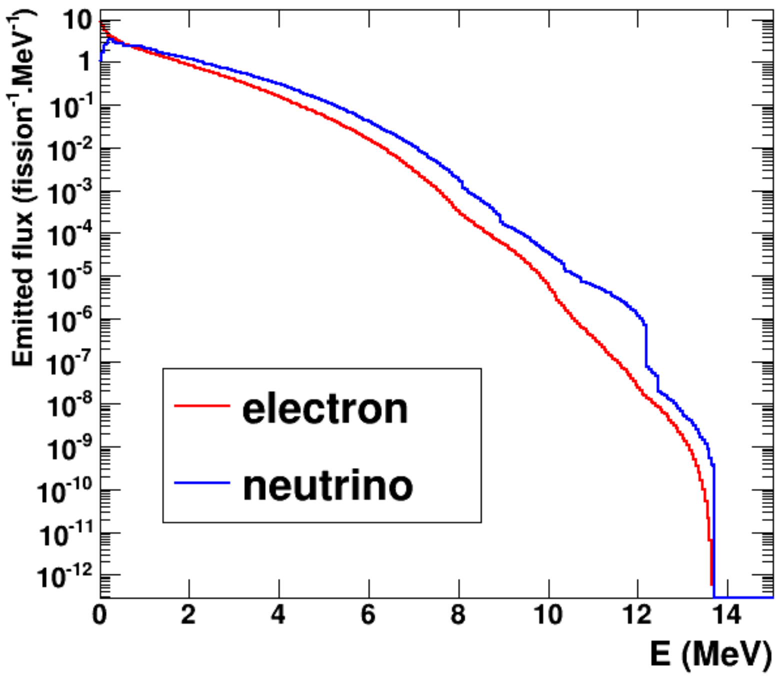


A. Letourneau

Tool for numerical studies of the conversion process

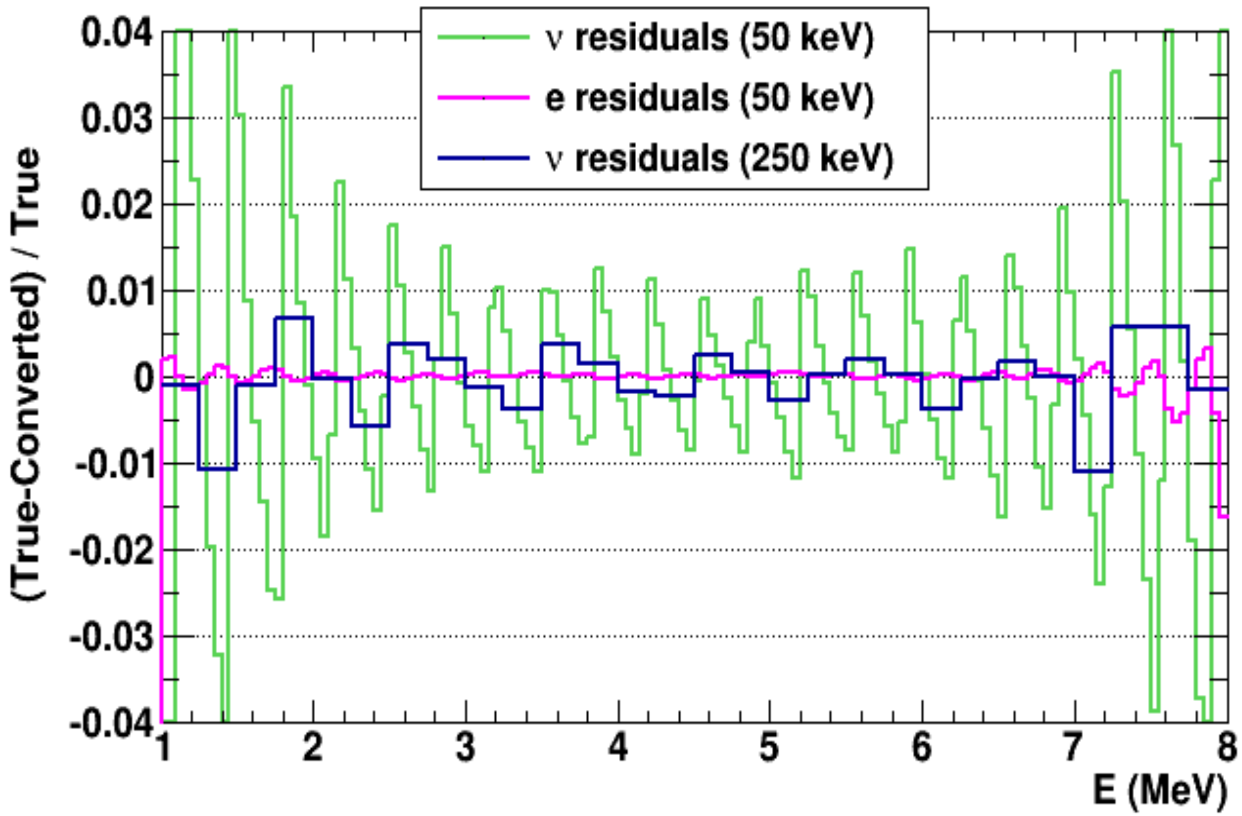
- Numerical studies of the impact of forbidden decays using calculated fission spectra based on all **decays indexed in the ENSDF nuclear database**.
- Each decay shape is determined from spin-parity data.
- Despite all systematics of such calculation, **electron and neutrino spectra are true images of each other**.
- Although they do not match perfectly the ILL spectra they contain a **good approximation of the physical distribution of β-decays with full control of the forbidden shapes we put in**.

ENSDF based ^{235}U fission spectra



Validation with allowed β-branches

- Consistency cross-check: when all ENSDF branches are forced to be of allowed type and the effective branches are allowed as well, both electron and neutrino residuals are zeroed.



Forbidden Decays

Nuclear operators

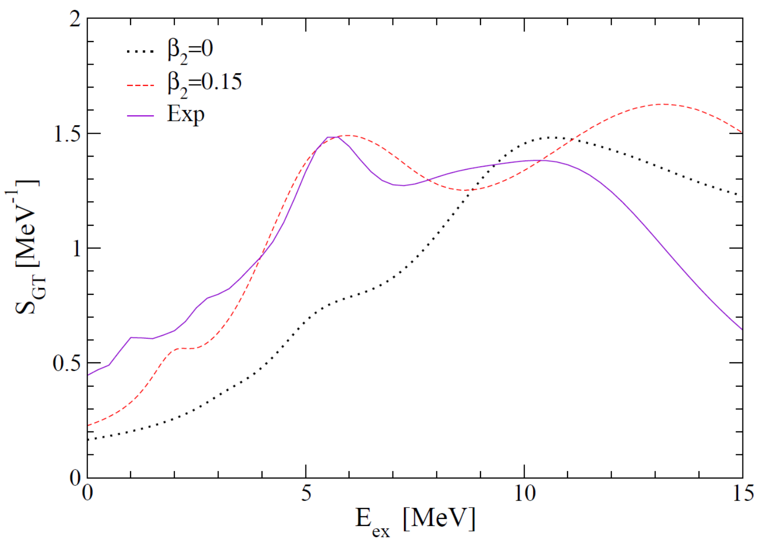
		Allowed	First Forbidden			Second Forbidden	
Polar V.	Matrix	$\int 1$	$\int \mathbf{r}$, $\int \boldsymbol{\alpha}$			R_{ij}, A_{ij}	$\int \boldsymbol{\alpha} \times \mathbf{r}$
	ΔJ	0	0, ± 1 (no $0 \to 0$)			± 1, ± 2 (no $1 \leftrightarrow 0$)	± 1
	Parity Change	no	yes			no	no
Axial V.	Matrix	$\int \boldsymbol{\sigma}$	$\int \boldsymbol{\sigma} \cdot \mathbf{r}$, $\int \gamma_5$	$\int \boldsymbol{\sigma} \times \mathbf{r}$	B_{ij}	T_{ij}	S_{ijk}
	ΔJ	0, ± 1 (no $0 \to 0$)	0	0, ± 1 (no $0 \to 0$)	0, ± 1, ± 2 (no $0 \to 0$, $\frac{1}{2} \to \frac{1}{2}$, $1 \leftrightarrow 0$)	± 2	± 2, ± 3 (no $2 \leftrightarrow 0$)
	Parity Change	no	yes	yes	yes	no	no

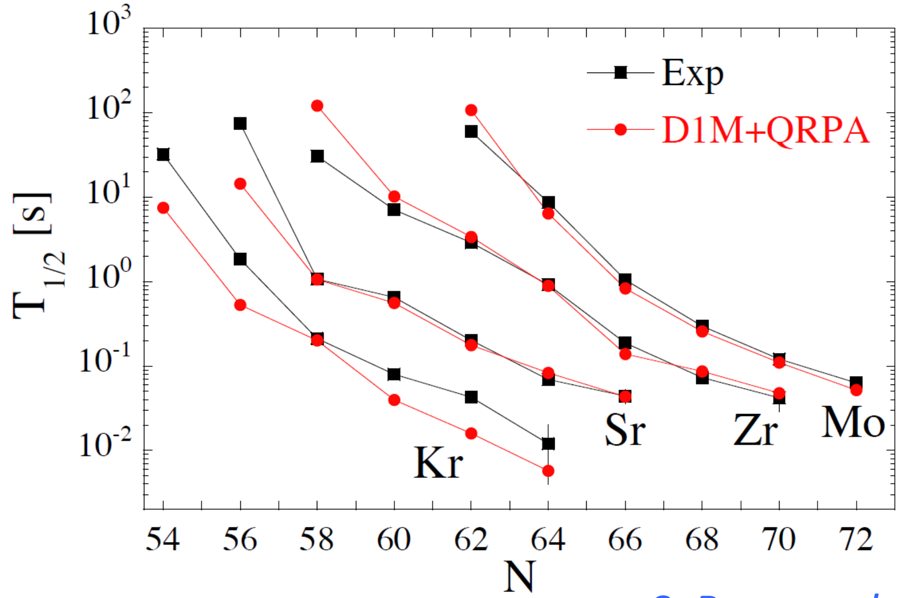
- One single nuclear operator.
- No E dependence.

- Several nuclear operators with basically unknown relative contributions.
- Complex E dependence.

pnQRPA Strength Distributions with Gogny (D1M and D1S) force

- Calculation of all pair-pair nuclei available
- Deformation of the nuclei included in the prediction of β-strengths
- Current effort to extend it to all fission products
- Should bring valuable new inputs to study the shape of 1st forbidden decays and the weak magnetism corrections

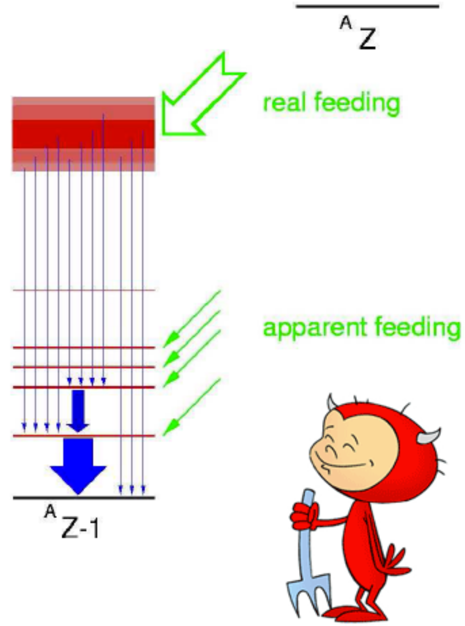




S. Peru et al.

Summation Method

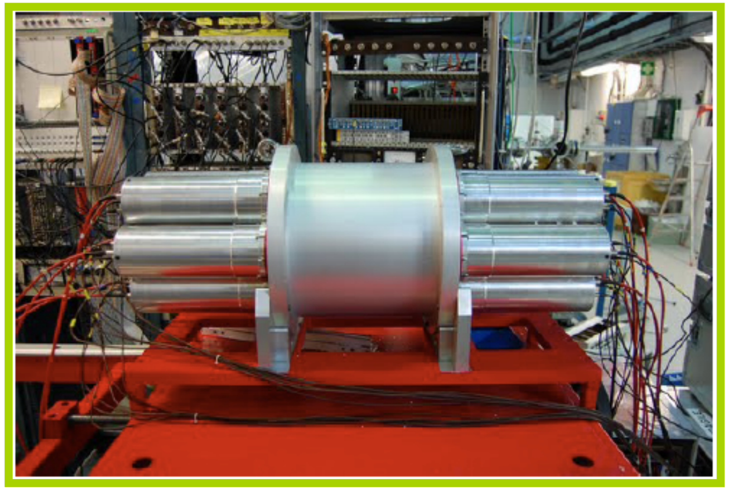
TAGS measurements



- Pandemonium effect: experimental bias giving too much weigth to high energy transitions →Total Absorption γ-ray Spectrometry.

- Short list of main contributor fission products

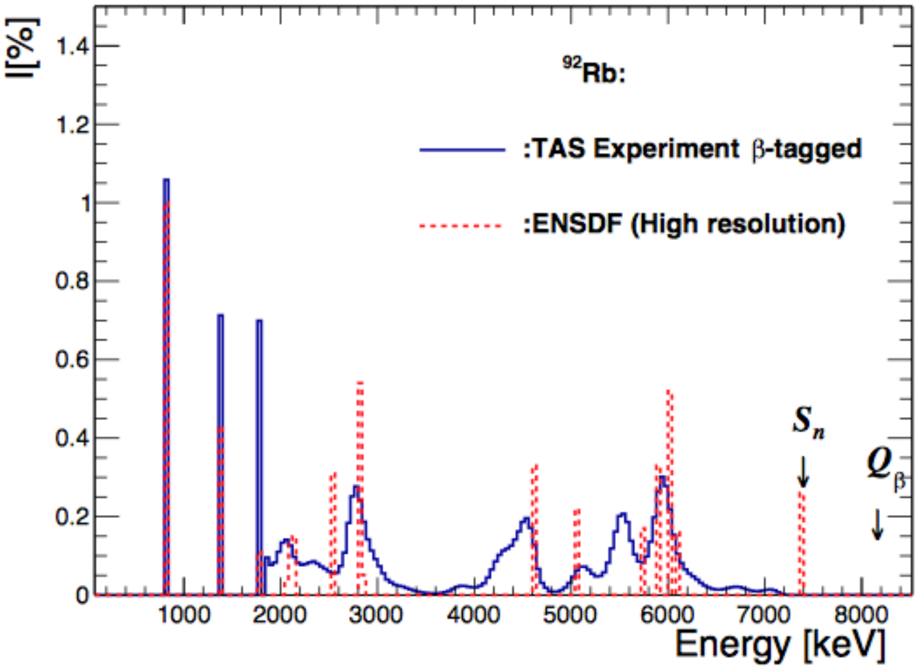
	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

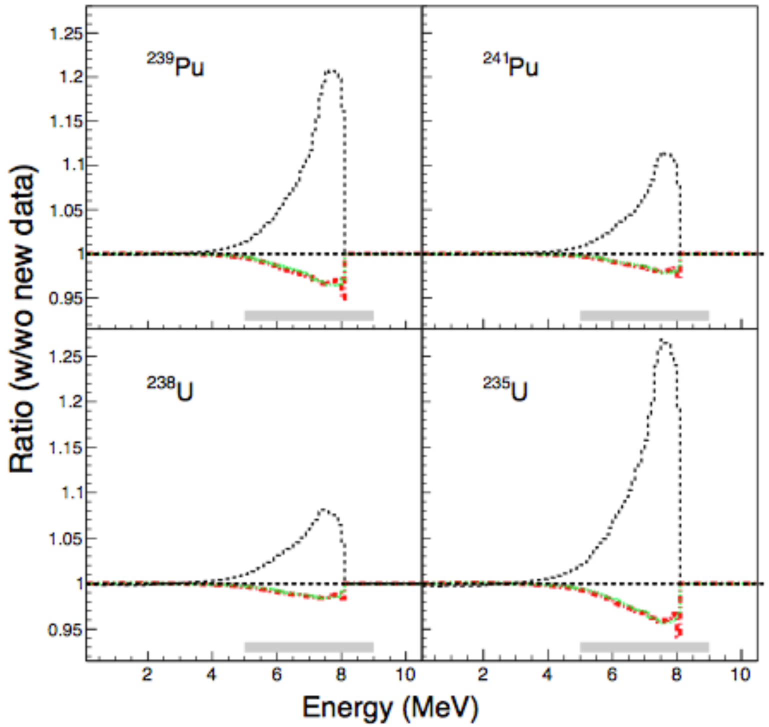


A. Algora et al., Phys. Rev. Lett. 105, 202501 (2010)

TAGS MEASUREMENTS

arXiv:1504.05812

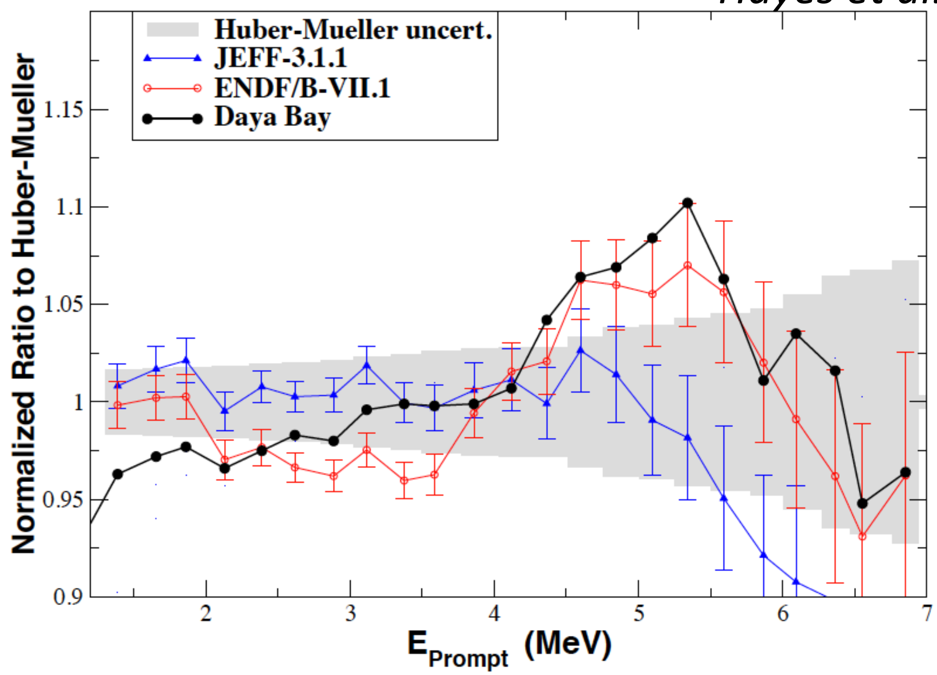




- More and more complete data set reducing the impact of pandemonium
- Improvement of the shape uncertainty and impact of unknown nuclei
- Estimation of the final uncertainty at the few % level remains difficult

Sensitivity to Evaluated Fission Yield

Hayes et al.

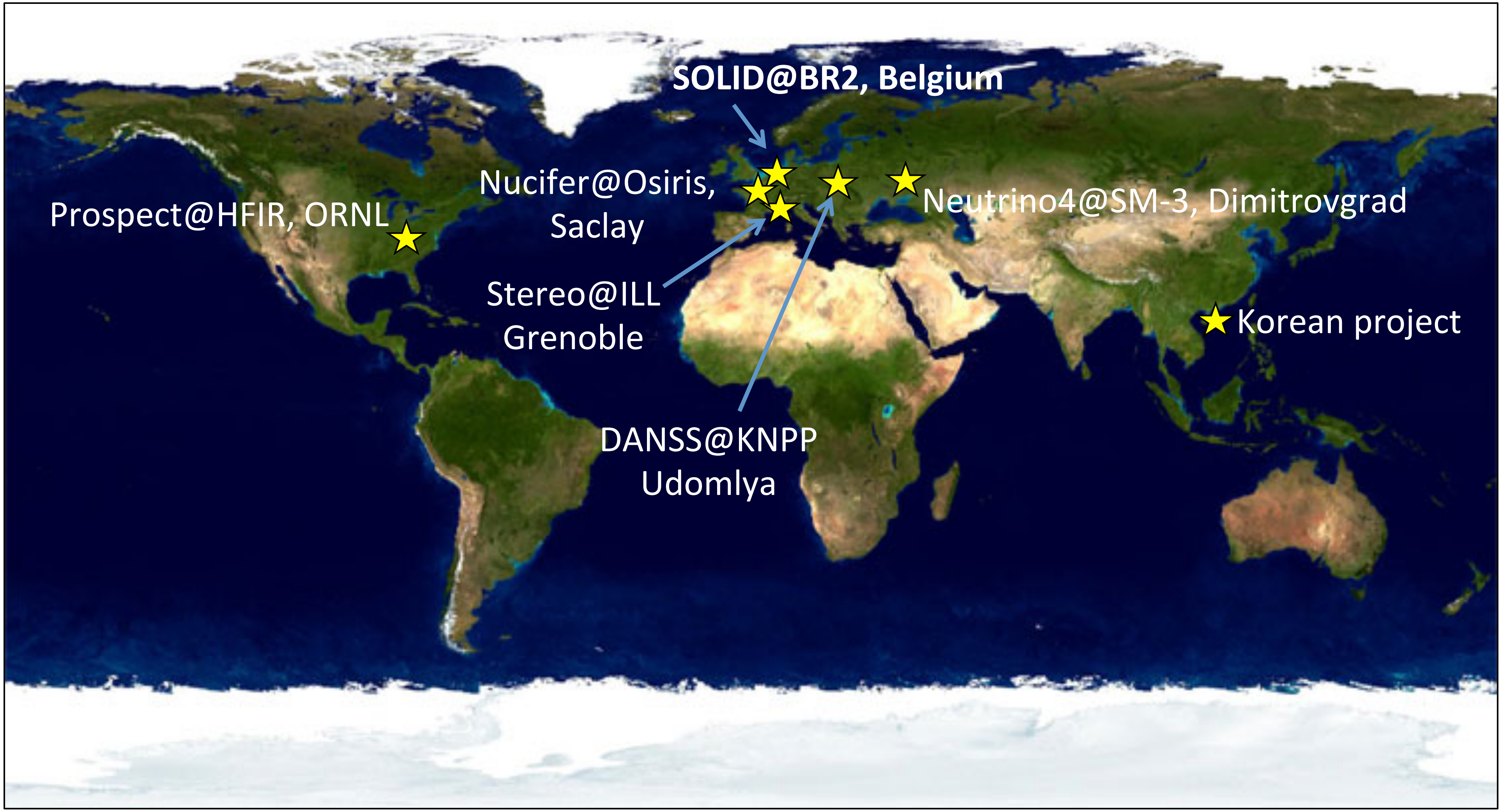


- The predicted neutrino spectrum is quite sensitive to the choice of the nuclear database of evaluated fission yields.
- TAGS data don't provide information on the shape of forbidden decays

→ synergy with the ongoing studies on the conversion method

Search for a sterile neutrino

Worldwide Overview

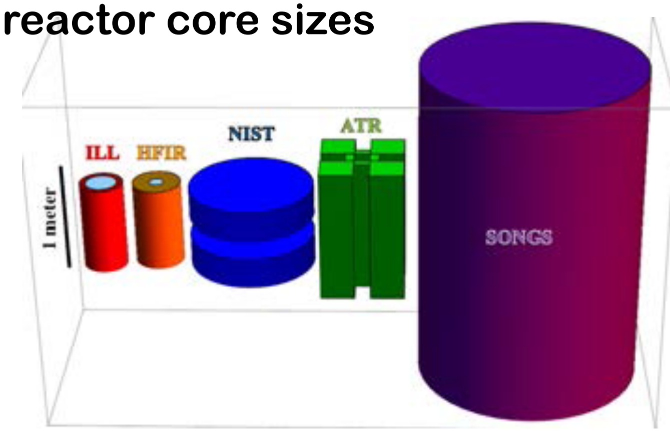


Research Reactors

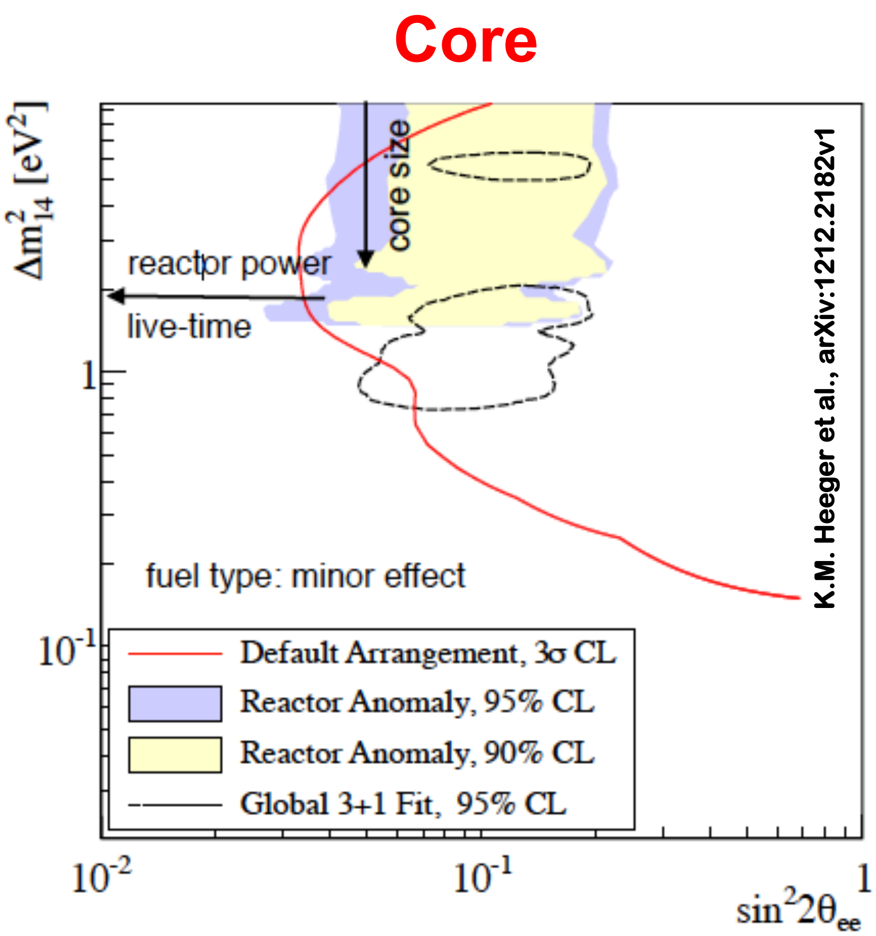
- **Compact sources**
  - No oscill. smearing.
- **High statistics, typically few 100 evts/day/t**
  - Intense source
  - Very short baselines available (5-50 m)
- **Alternation of reactor ON/OFF periods**
  - moderate overburden compensated by accurate measurement of the cosmogenic component.
- **Highly enriched fuel**
  - Well known ^{235}U fisison spectrum.
- **But challenging reactor-induced backgrounds (γ and n)**

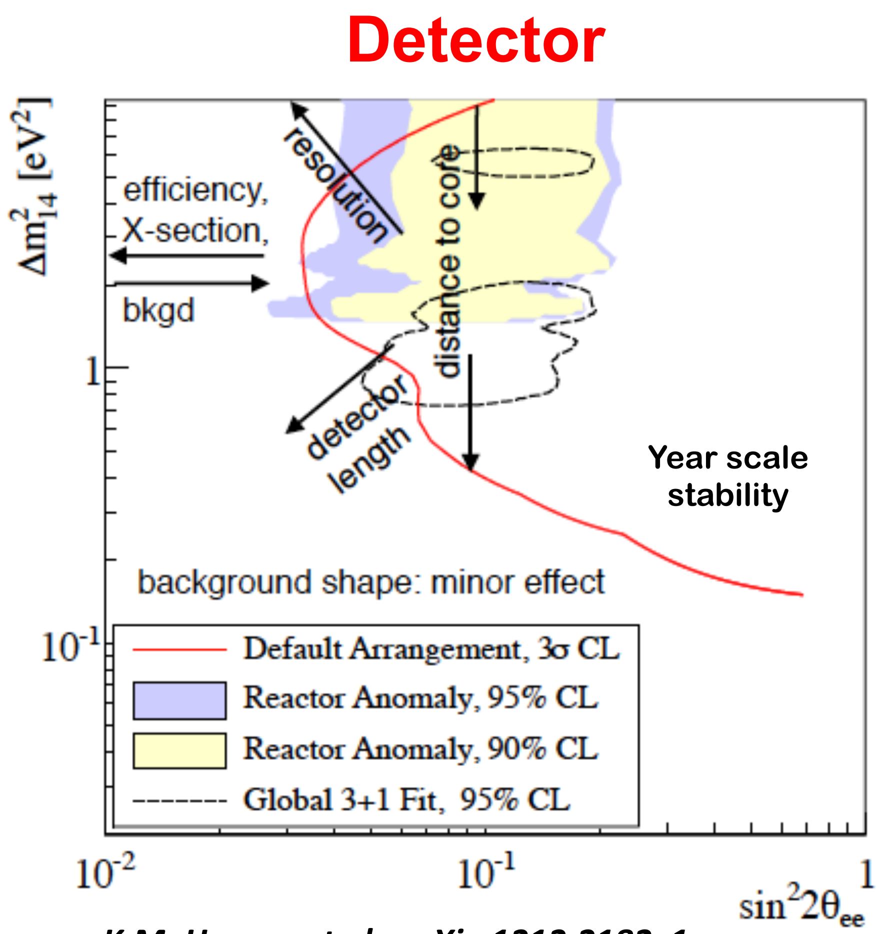
→ Requires comprehensive site characterization.

Typical reactor core sizes



Key experimental parameters



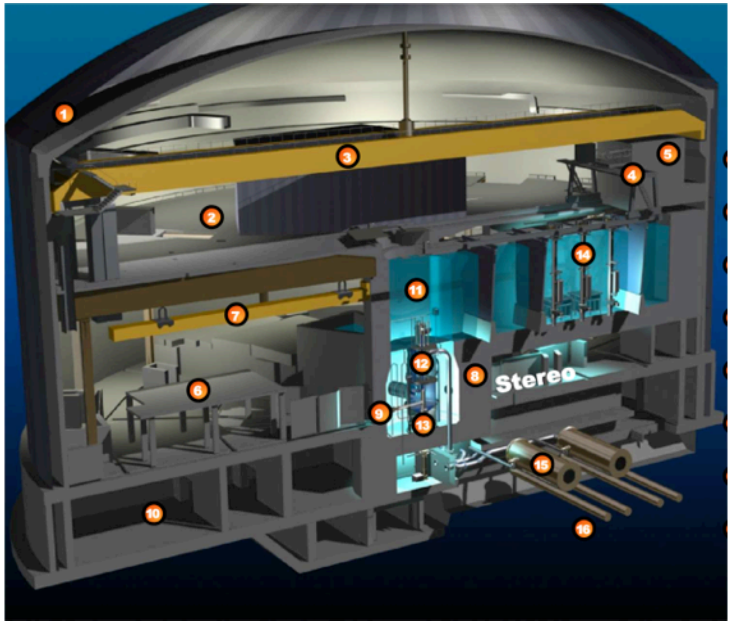


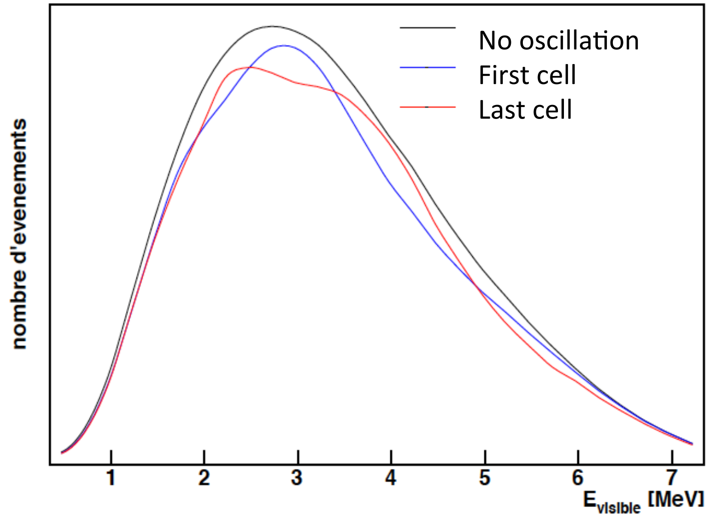
K.M. Heeger et al., arXiv:1212.2182v1

Reactor Proposals

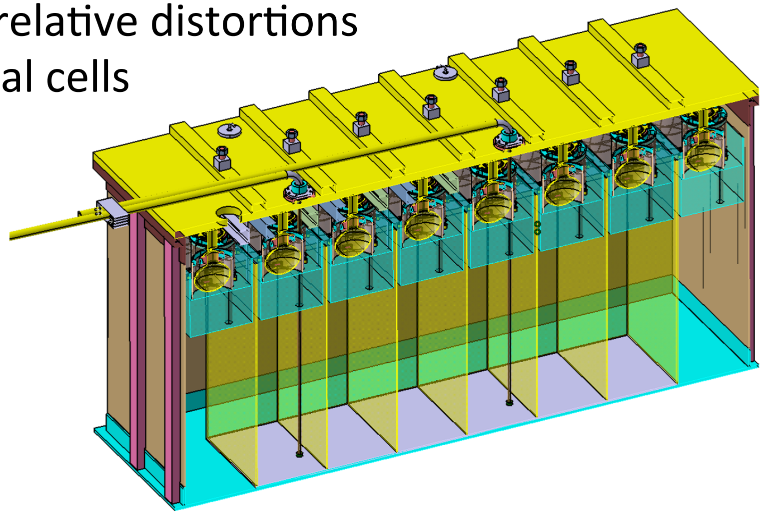
	Gd	^{6}Li	Highly Segmented	Moving detector	2 det.
Nucifer (FRA)	■				
Poseidon (RU)	■				
Stéréo (FRA)	■			■	
Neutrino 4 (RU)	■			■	
Hanaro (KO)	◣	◥	■	■	
DANSS (RU)	■		■		
Prospect (USA)	◣	◥	■	■	■
SoLid (UK)		■	■		

STEREO @ ILL





Look for relative distortions in identical cells

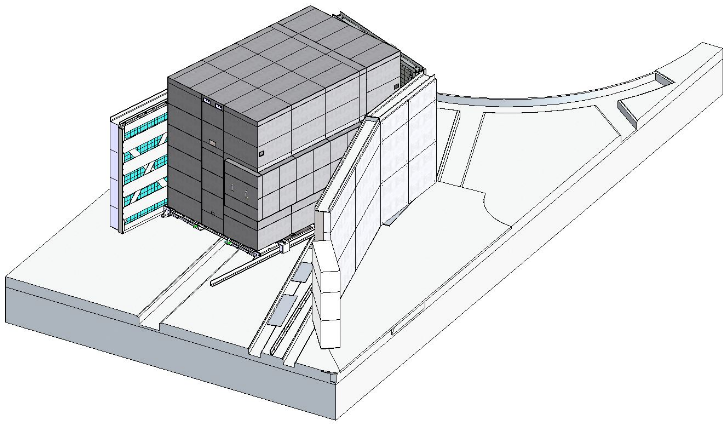


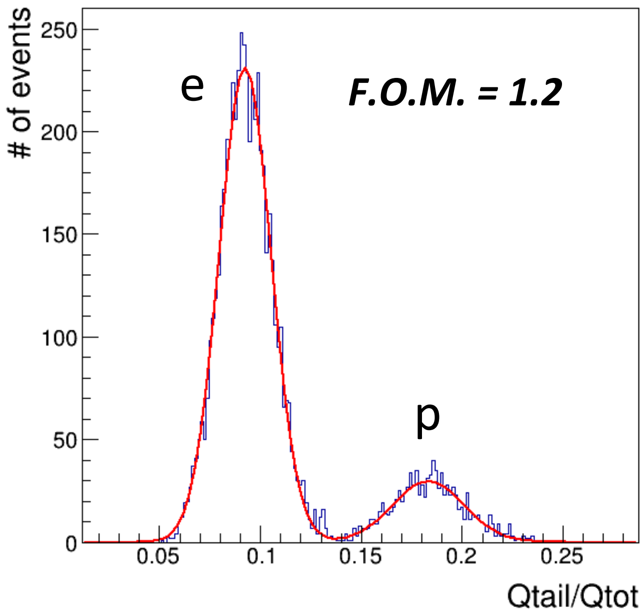
ILL site:

- 57 MW, compact core < 1m
- [8.9–11.1] m from core,
  possible extension to 12.3 m.
- 15 mwe overburden
- High level of reactor background

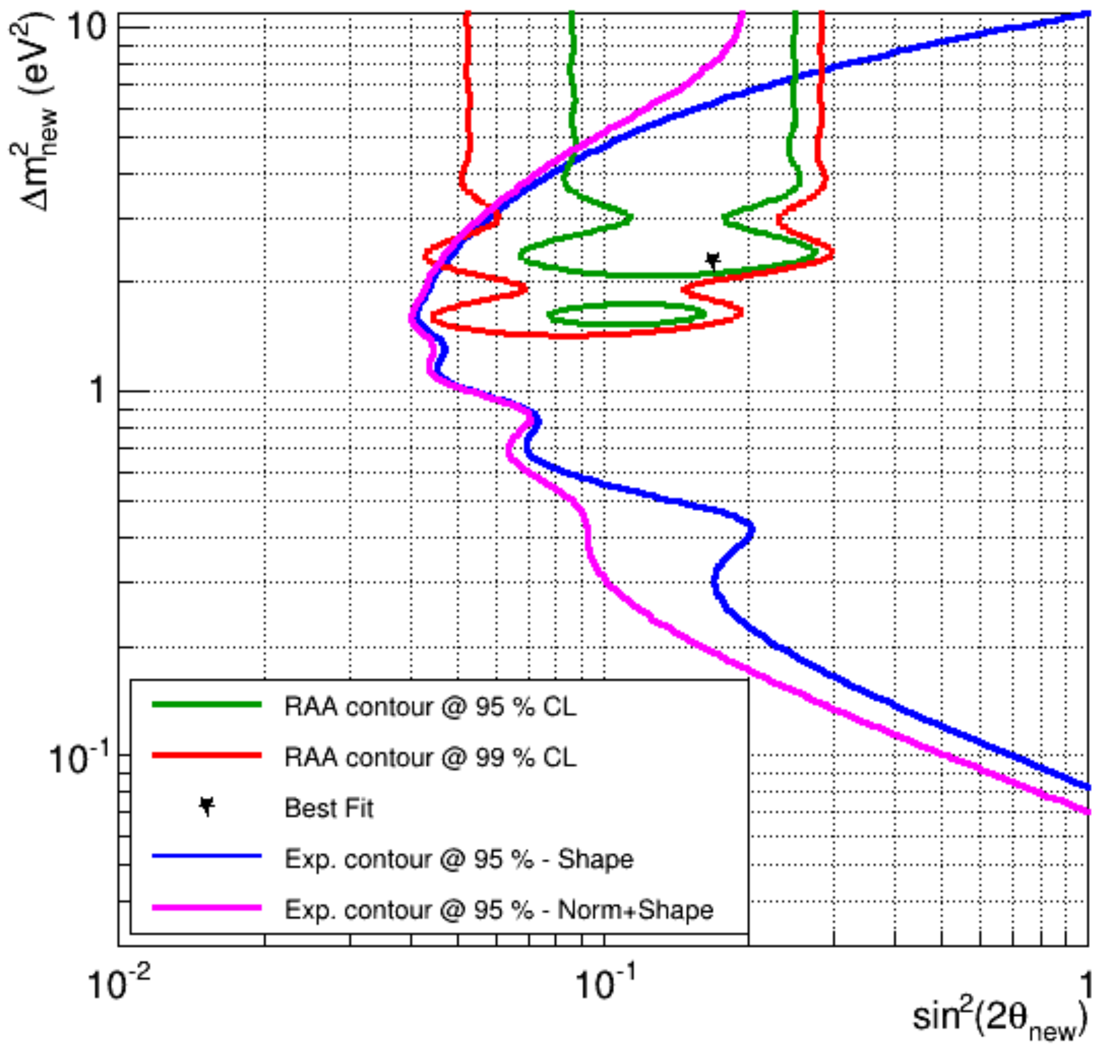
Background rejection

- Comprehensive on site measurements performed last year: μ, n and γ backgrounds.
- Sequential installation/validation of external shielding before detector installation early 2015.
- Muon induced:
  - Overburden
  - Active outer-crown and μ-veto
  - Liquid scintilator optimized for PSD capability and light yield



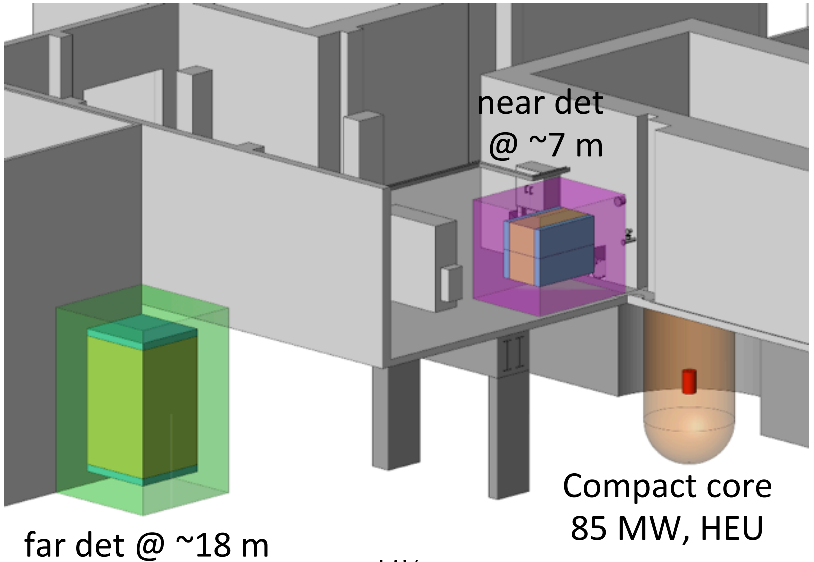


STEREO Sensitivity



- 300 days, L_0 = 10 m
- E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
- ~410ν_e/day
- δE_{scale} = 2%
- All syst. of predicted spectra
- S/B = 1.5, 1/E+flat model
- Norm 4%
- Start data taking mid-2016

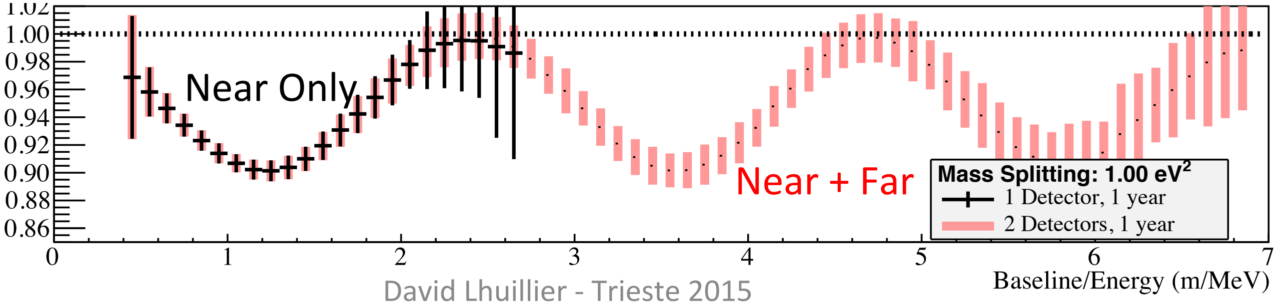
PROSPECT Experiment



Physics Goals

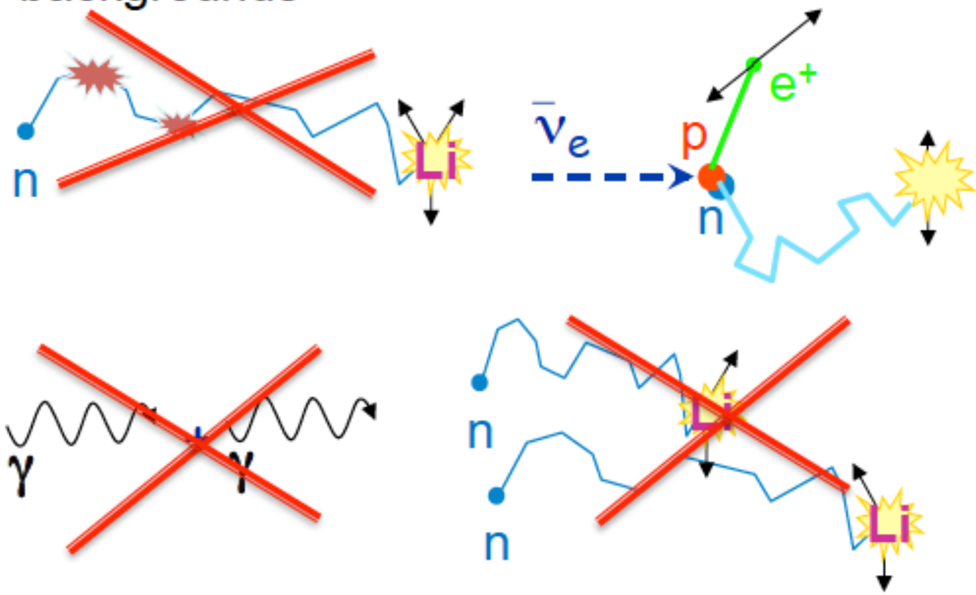
- Search for sterile ν_e oscillations at short-baseline.
- Probe and resolve "reactor anomaly".
- Precision measurement of reactor ν_e spectrum for physics and safeguards.

Map out L/E Oscillations

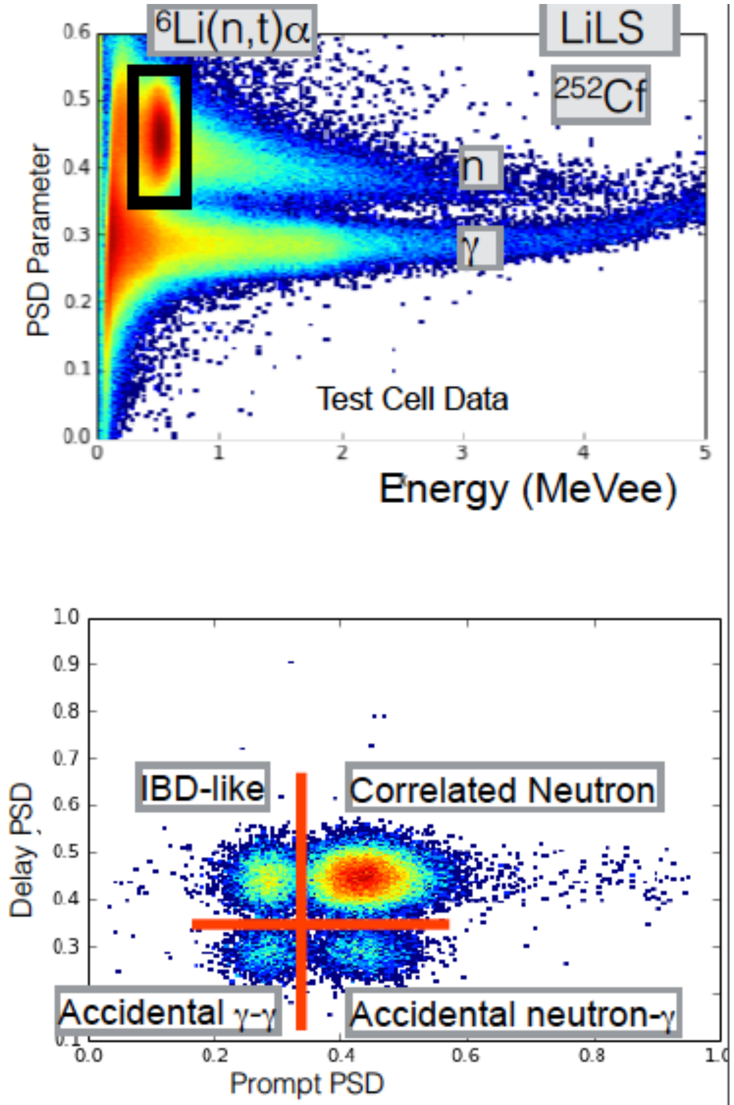


6Li-doped liquid scintillator

- ^{6}Li-capture, Pulse Shape Discrimination, and topology from segmentation
- Strong rejection of accidental and correlated backgrounds



- Using simulation/deployment data to understand and mitigate electromagnetic-neutron capture correlated backgrounds



Courtesy N. Bowden

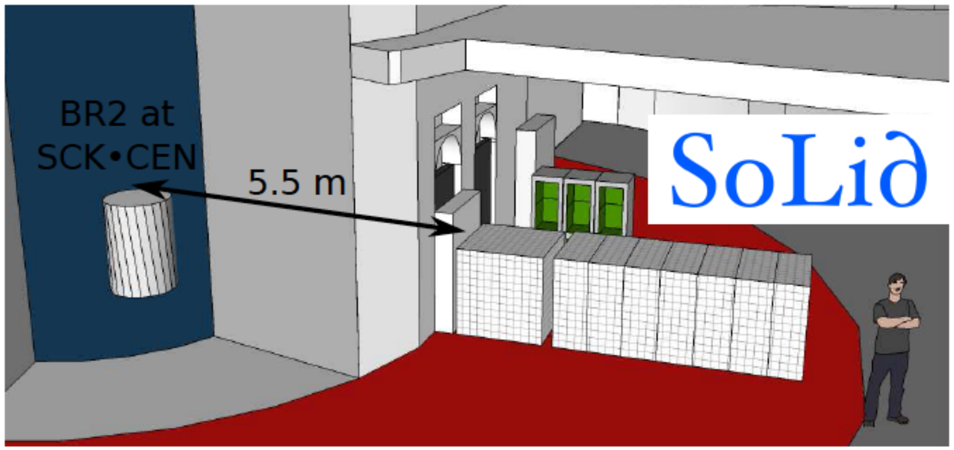
SoLi∂ Experiment

BR2 REACTOR, Mol, Belgium

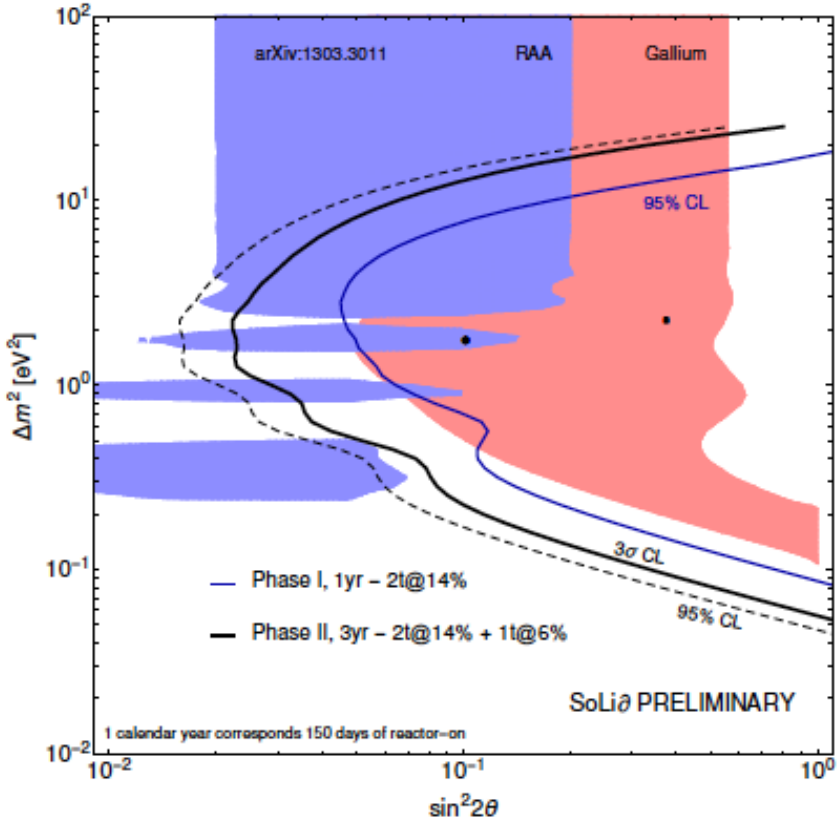
- Core: 45-80 MW, HEU fuel
- Favorable reactor background level

DETECTOR

- **Novel type of composite solid scintillator detector** (PVT + ^{6}LiF:ZnS)
- 2.88 t fiducial volume, highly segmented.
- 288 kg prototype under test



Expected sensitivity

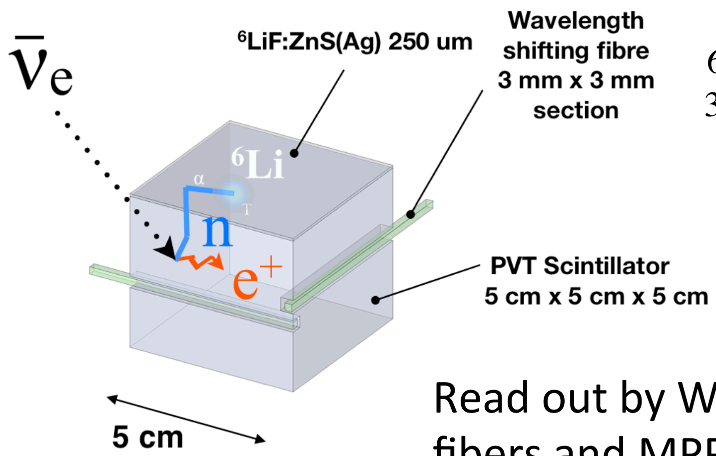


http://arxiv.org/abs/1510.07835

SoLi∂ dectection

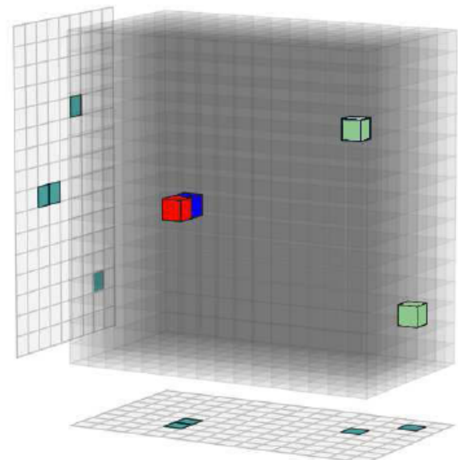
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

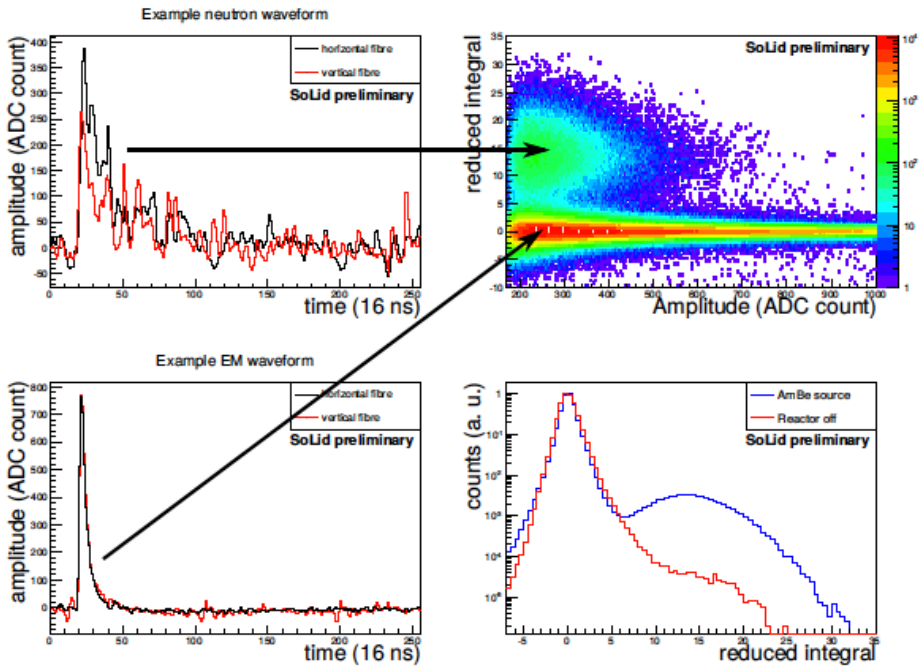
$$^6_3Li + n \rightarrow \alpha + t$$



Read out by WLS fibers and MPPC

IBD candidate: positron + neutron
(+ accidental gammas)





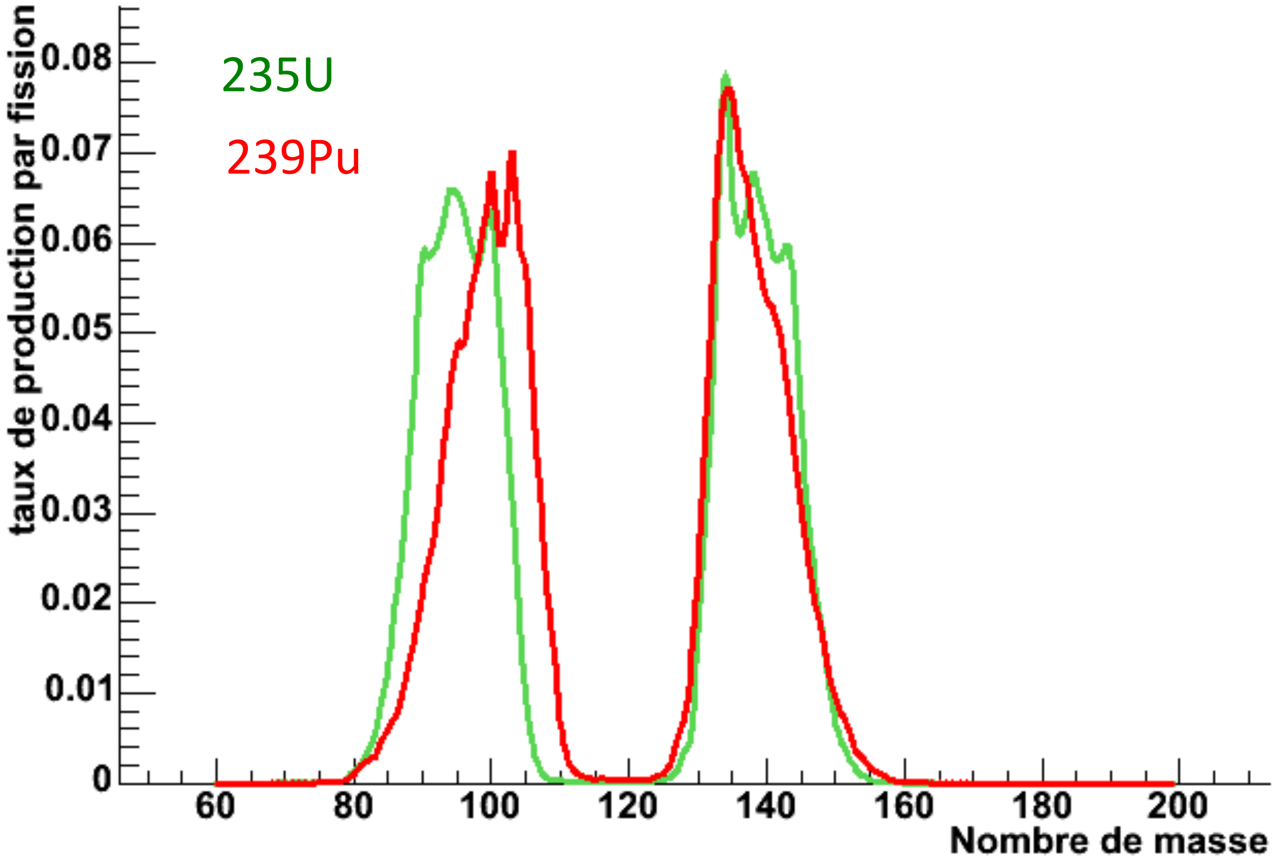
- Very **discriminant neutron signal** in ^{6}LiF:ZnS. High neutron-γ rejection factor
- 3D reconstruction close to interaction point : **high background rejection capability using topological information of IBD.**
- Limited resolution due to light collection

Conclusion

- Neutrinos connect a wide range of physics, from nuclear decays to cosmology.
- Modern experiments at reactors perform precision measurements, becoming sensitive to few percent effects on the neutrino flux and spectrum shape. The last mixing angle θ_{13} has been measured and a new "anomaly" has been revealed, pointing to a possible new sterile neutrino state.
- A mature detection technology allows the development of the first application of neutrino to non-proliferation. Common effort of all short baseline experiment is ongoing to improve the background rejection in small detectors. Lithium doped scintillator should allow an efficient online rejection of the cosmic-rays induced background, which is the ultimate limitation of the sensitivity of neutrino measurements close to surface.
- Reactor neutrino benefit from the huge information available in nuclear databases. The comparison of measurements and absolute predictions is now reaching a highlevel of accuracy providing a sensitive probe of the quality of the nuclear data.

Backup Slides

Mass distributiond



Forbidden Decays

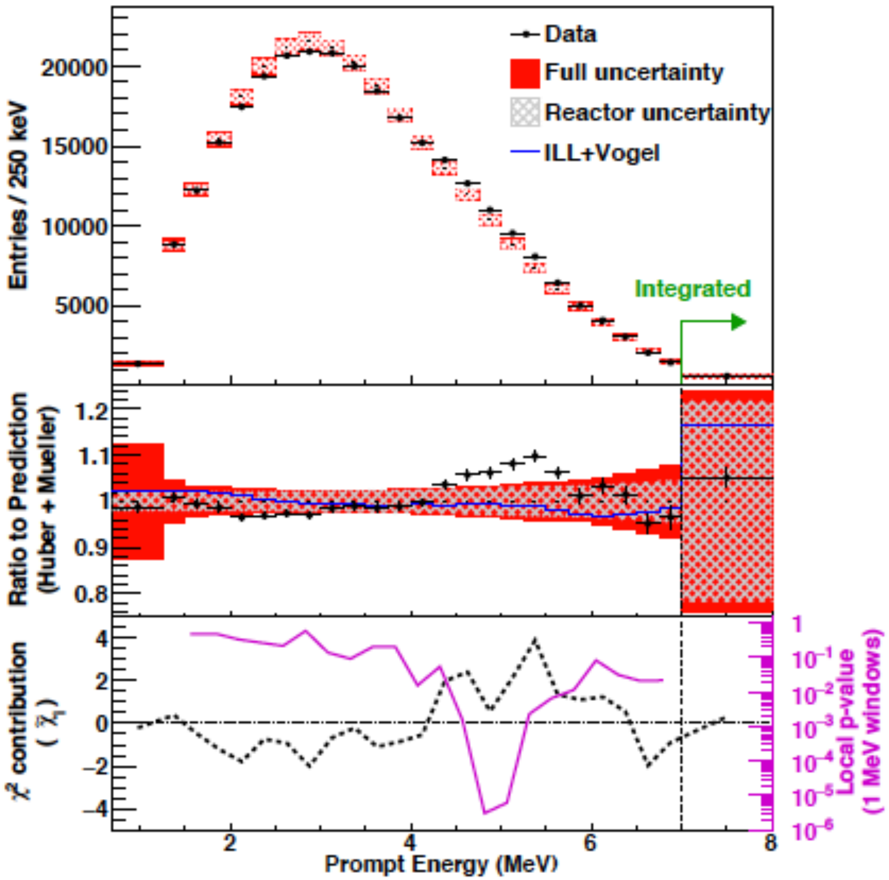
Konopinsky and Ulenbeck *Phys. Rev. vol. 60, June 1941.*

Shape factor C(E) = Nuclear matrix element x Lepton matrix element

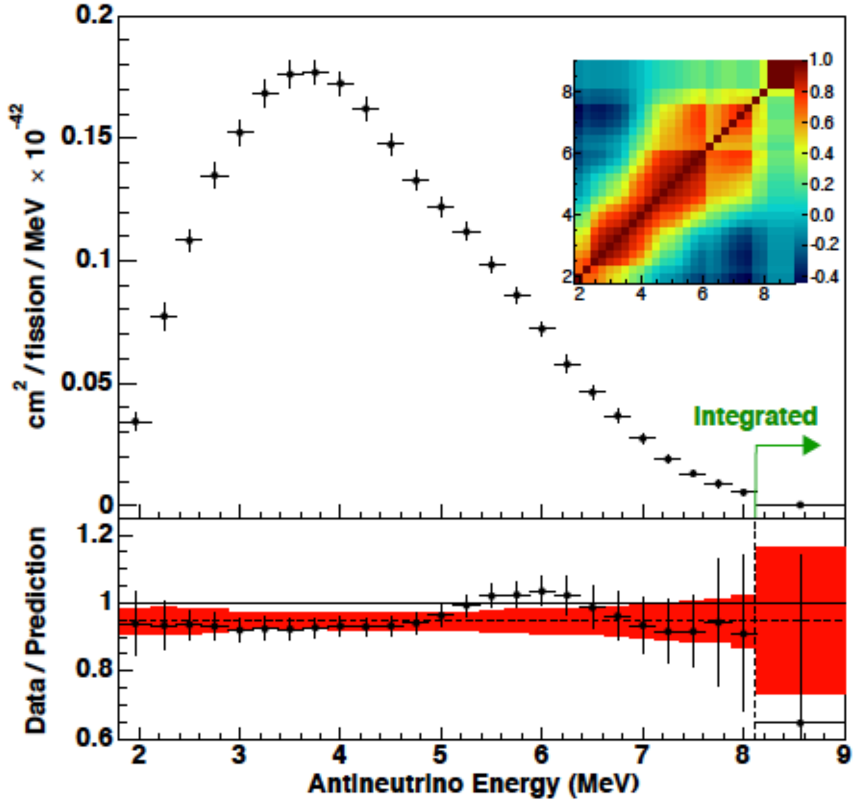
ΔJ^π	Nuclear matrix	Lepton matrix
	Vector	
$0^-, 1^-$	$\left\| \int \mathbf{r} \right\|^2$	$\frac{1}{3}q^2 L_0 + 2L_1 + M_0 - \frac{2}{3}qN_0$
$0^-, 1^-$	$\left\| \int \boldsymbol{\alpha} \right\|^2$	L_0
$0^-, 1^-$	$(\int \boldsymbol{\alpha}).(\int \boldsymbol{r})$	$\frac{1}{3}qL_0 - N_0$
	Axial	
0^-	$\left\| \int \boldsymbol{\sigma}.\mathbf{r} \right\|^2$	$\frac{1}{9}q^2 L_0 + M_0 - \frac{2}{3}qN_0$
0^-	$\left\| \int \gamma_5 \right\|^2$	L_0
0^-	$(\int \boldsymbol{\sigma}.\boldsymbol{r}).(\int \gamma_5)$	$\frac{1}{3}qL_0 - N_0$
$0^-, 1^-$	$\left\| \int \boldsymbol{\sigma}. \times \boldsymbol{r} \right\|^2$	$\frac{1}{6}q^2 L_0 + \frac{1}{2}L_1 + M_0 + \frac{2}{3}qN_0$
$0^-, 1^-, 2^-$	$\|B_{ij}\|^2$	$\frac{1}{12}q^2 L_0 + \frac{3}{4}L_1$

Adds dependence on lepton momenta →

Daya Bay



Data
Full uncertainty
Reactor uncertainty
ILL+Vogel
Integrated
Entries / 250 keV
Ratio to Prediction (Huber + Mueller)
χ^2 contribution ($\tilde{\chi}_i$)
Local p-value (1 MeV windows)
Prompt Energy (MeV)



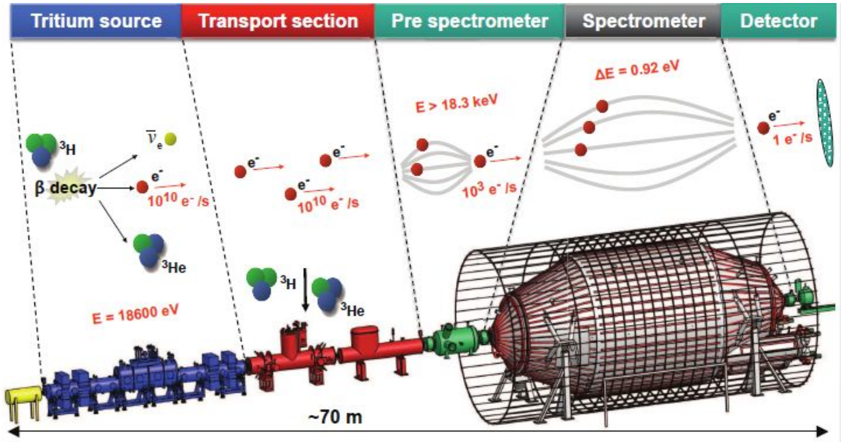
cm^2 / fission / MeV × 10^{-42}
Integrated
Data / Prediction
Antineutrino Energy (MeV)

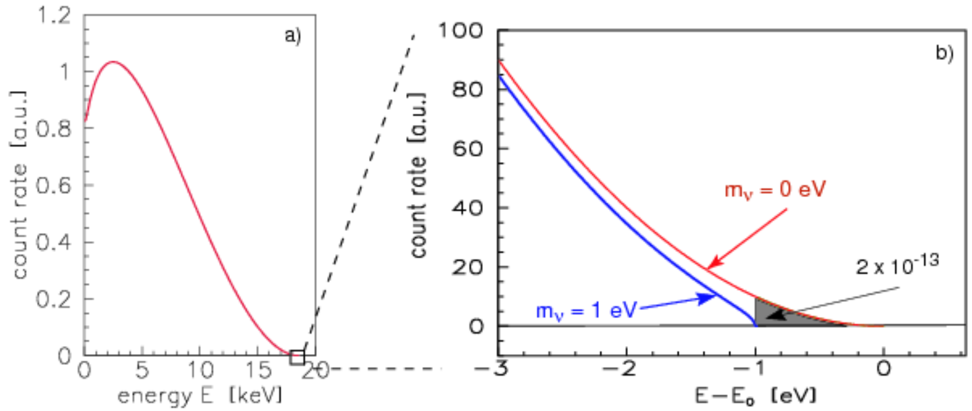
Open questions

Absolute Mass

Katrin experiment

- Direct measurement
- Looking at the end of the tritium β-spectrum



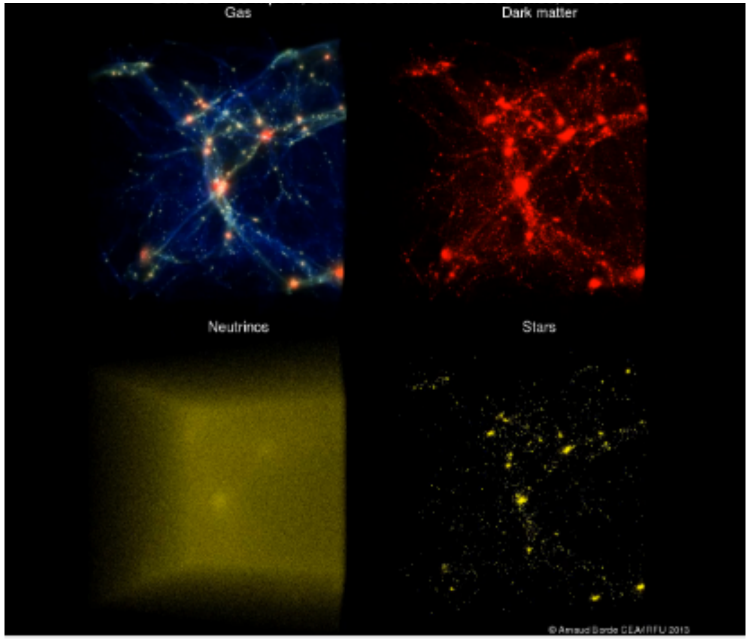


Open questions

Absolute Mass

All combined cosmology data

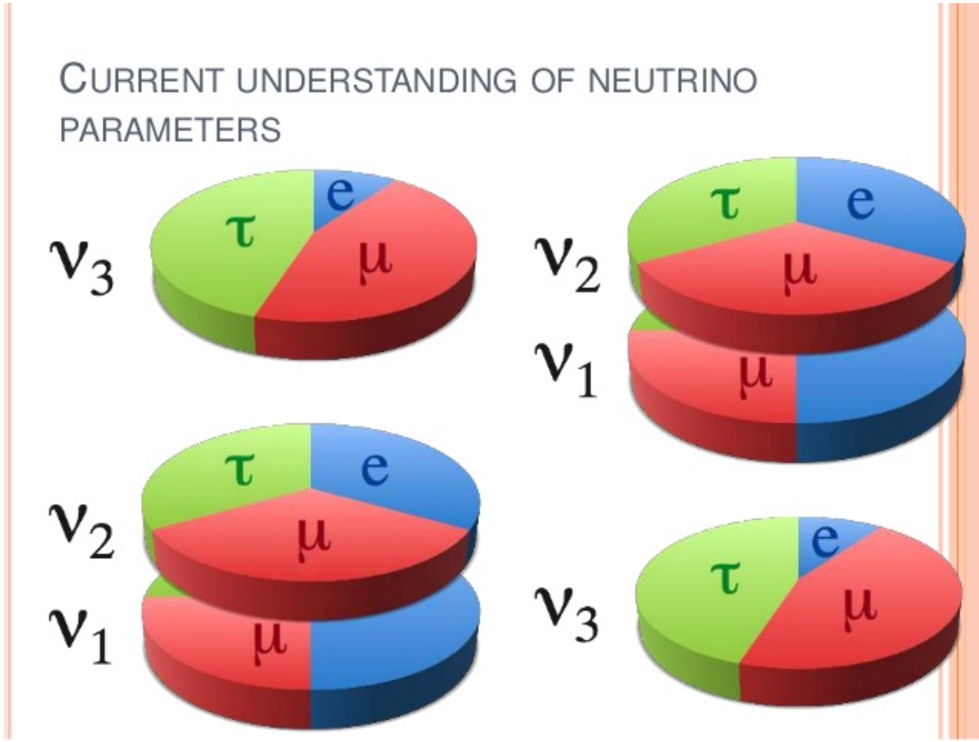
$\Sigma M_\nu < 0.12$ eV (95% C.L.)



http://arxiv.org/abs/1506.05976

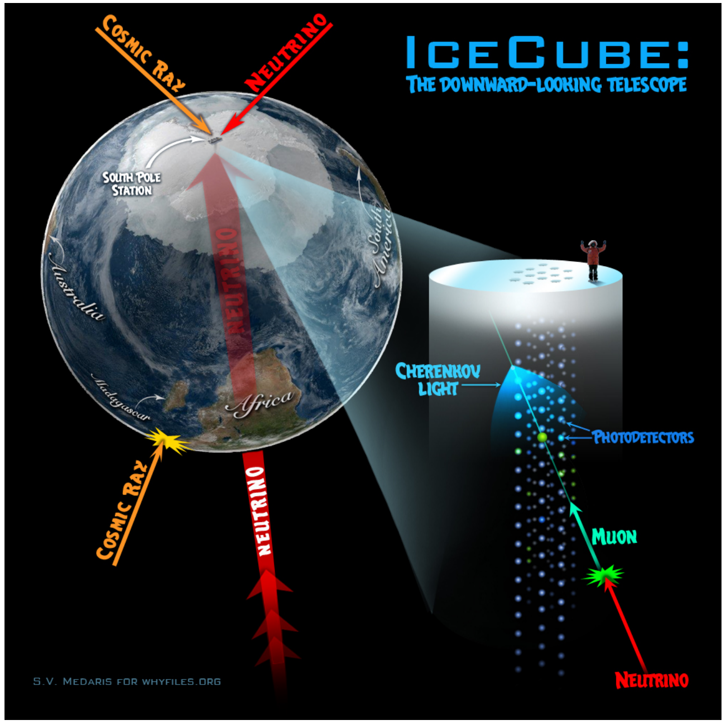
Open questions

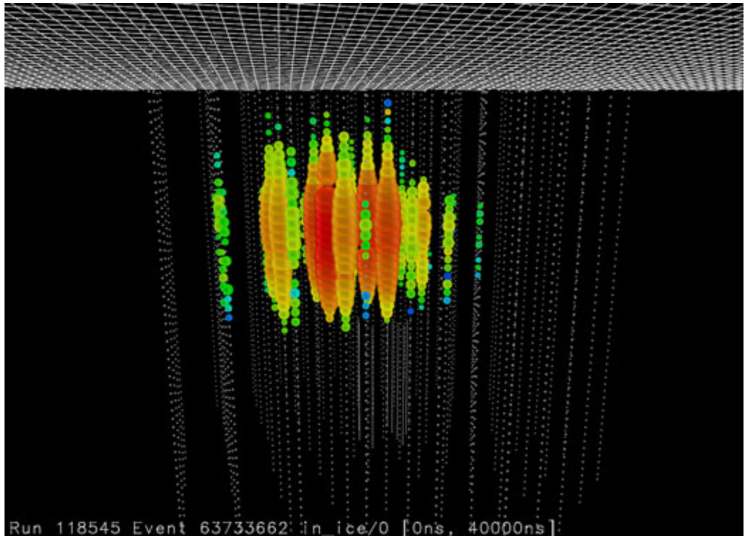
Mass hierarchy



S. K. Verma

Neutrino Astronomy





PeV neutrino event

Geo-Neutrinos