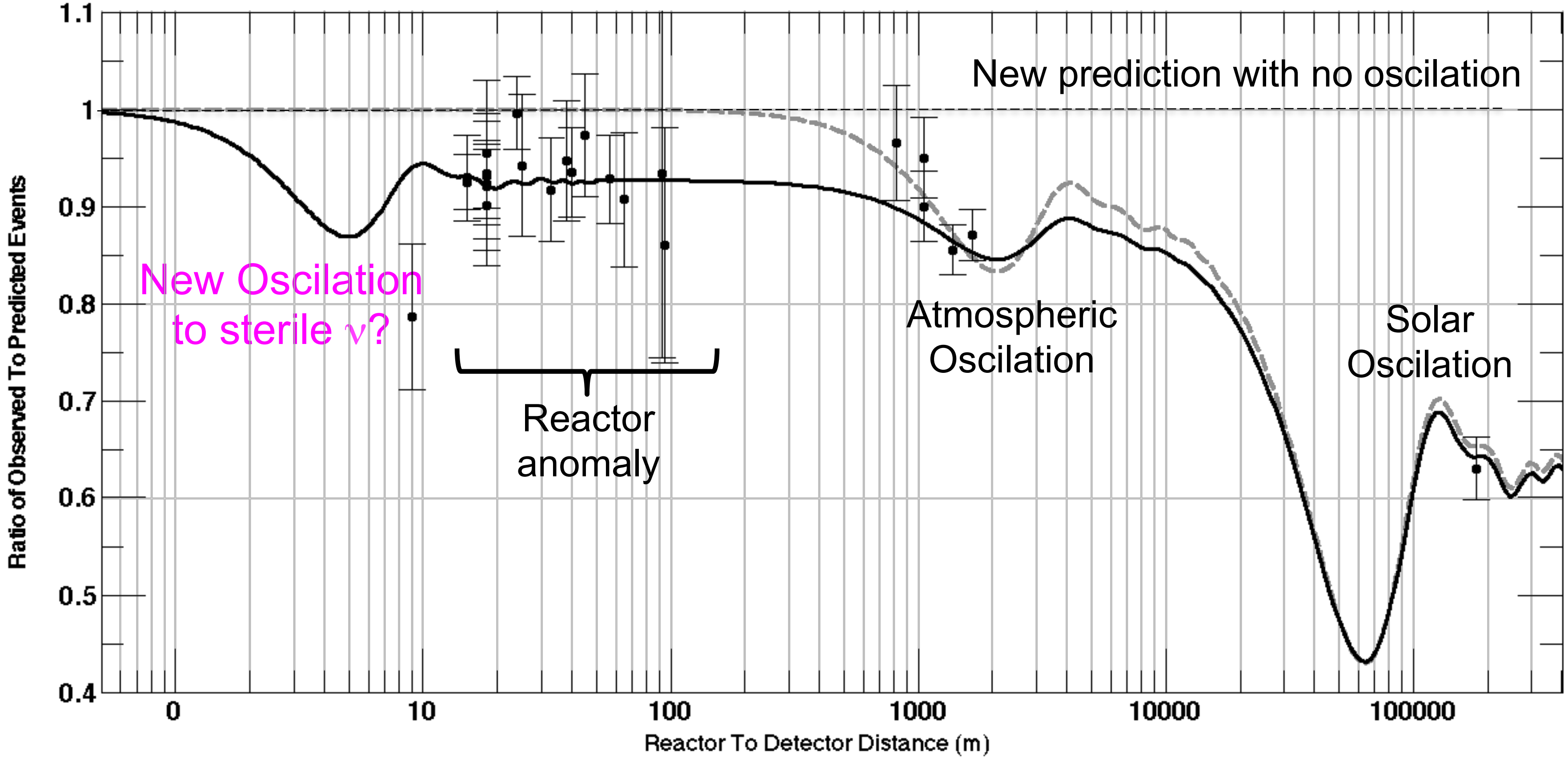
Reactor Neutrinos: a status of predicted spectra and review of sterile neutrino searches at very short baselines

David Lhuillier – CEA Saclay

The Reactor $\bar{\nu}_e$ Anomaly

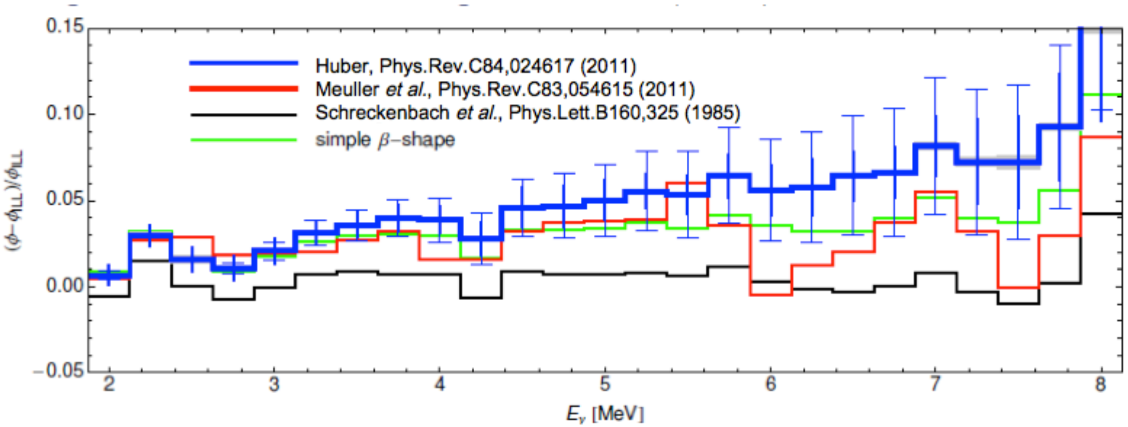
See T. Lasserre's talk



Observed/predicted averaged event ratio: R=0.936±0.024 (2.7 σ)

Increased Expected ν Rate

i) **$\nu_{emission}$: Improved reactor neutrino spectra**
→ +3.5%

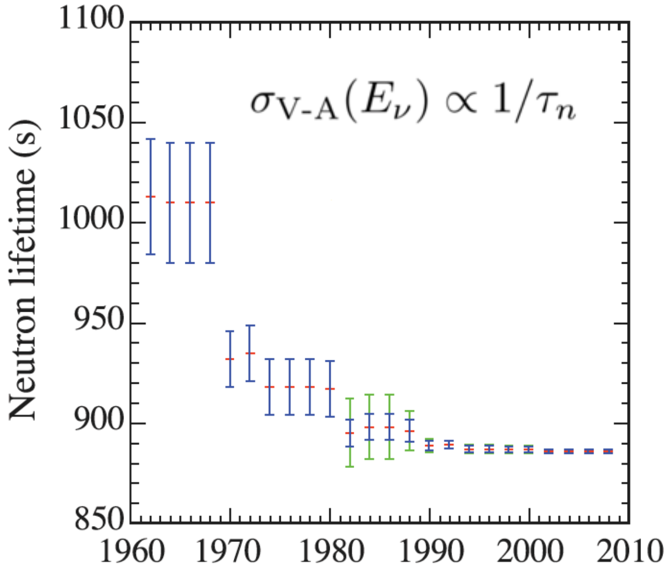


PRC83, 054615 (2011)

PRC84, 024617 (2011)

ii) **$\nu_{detection}$: Reevaluation of σ_{IBD} → +1.5%**
Evolution of the neutron life time

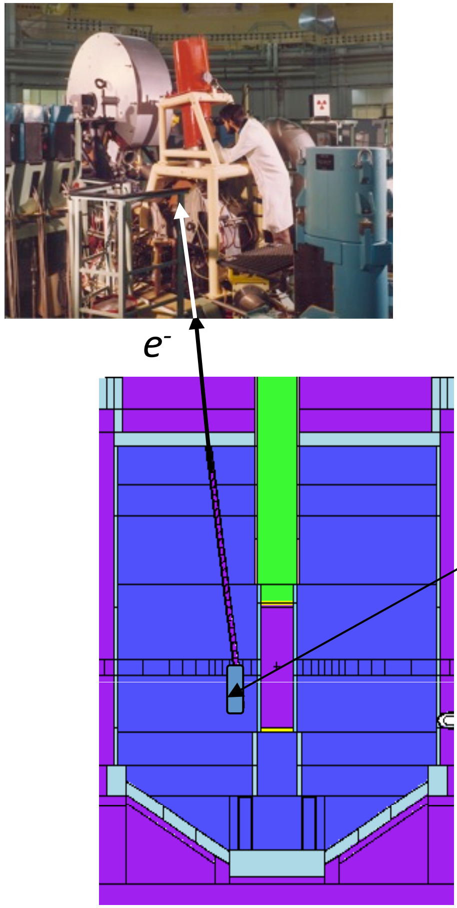
PRD 83, 073006 (2011)



iii) **$\nu_{detection}$: Accounting for long-lived isotopes in reactors → +1%**

PRD 83, 073006 (2011)

ILL data

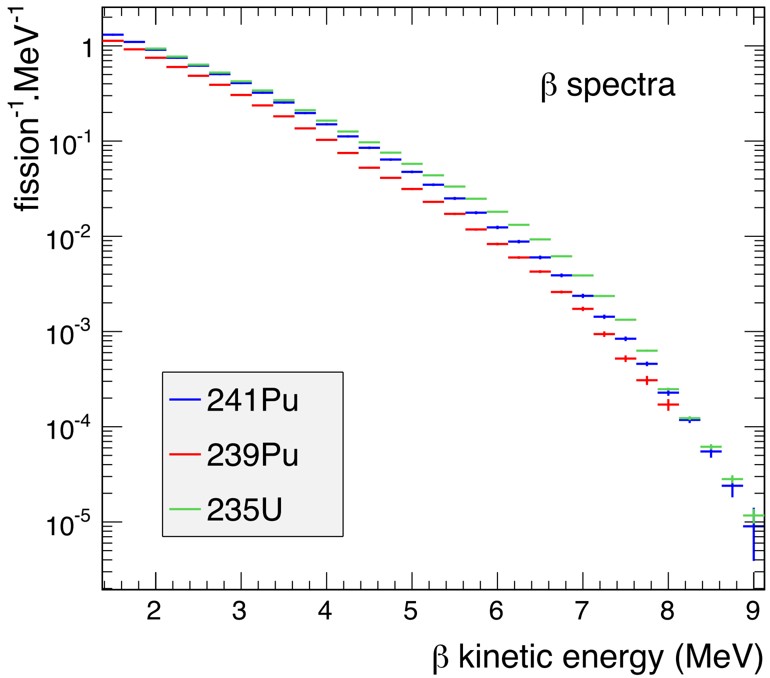


Magnetic BILL Spectrometer built in late 70's

Target foil (^{235}U, ^{239}Pu, ^{241}Pu) in thermal n flux

ILL research reactor (Grenoble, France)

Emitted β spectra per fission of each isotope



Phys. Let. B218,365 (1989)+ refs therein

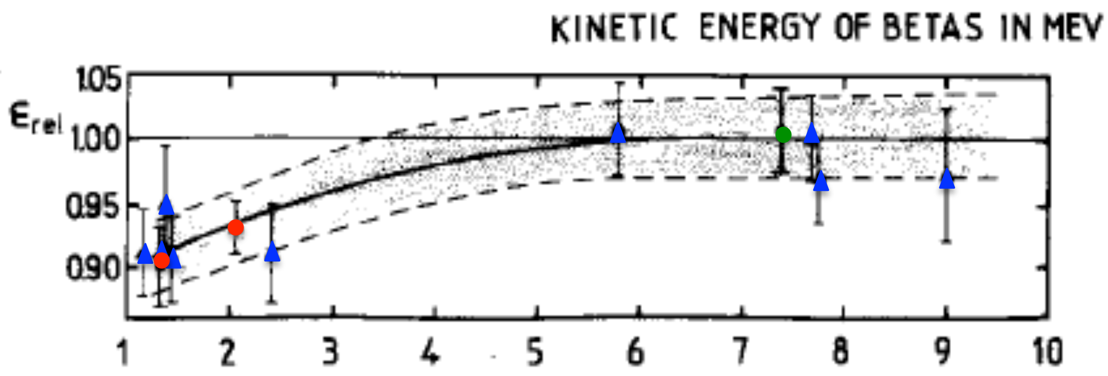
Reference electron data converted to $\bar{\nu}_e$ spectra for the prediction of all past reactor experiments

Dominant Uncertainties

- Normalization of electron data
- Shape distortions induced by the nuclear corrections to Fermi Theory in the conversion process.

Normalization of ILL data

- Absolute calibration via specific target foils emitting internal conversion electron lines of known partial cross section per neutron capture. Error = 1.8 % (1 σ).



Absolute normalization :

$^{115}In(n, \gamma)^{116m}In$ & $^{207}Pb(n, \gamma)^{208}Pb$

Relative normalization :

$^{113}Cd(n,\gamma)^{114}Cd$

- Correlated across all energy bins of all isotopes
  + directly propagates into all predicted reactor antineutrino spectra.

- But cancelling the reactor anomaly with this only syst effect would require a 4σ deviation …

Corrections to Fermi theory

Example of a single branch with Z=46, A=117, E_0=10 MeV

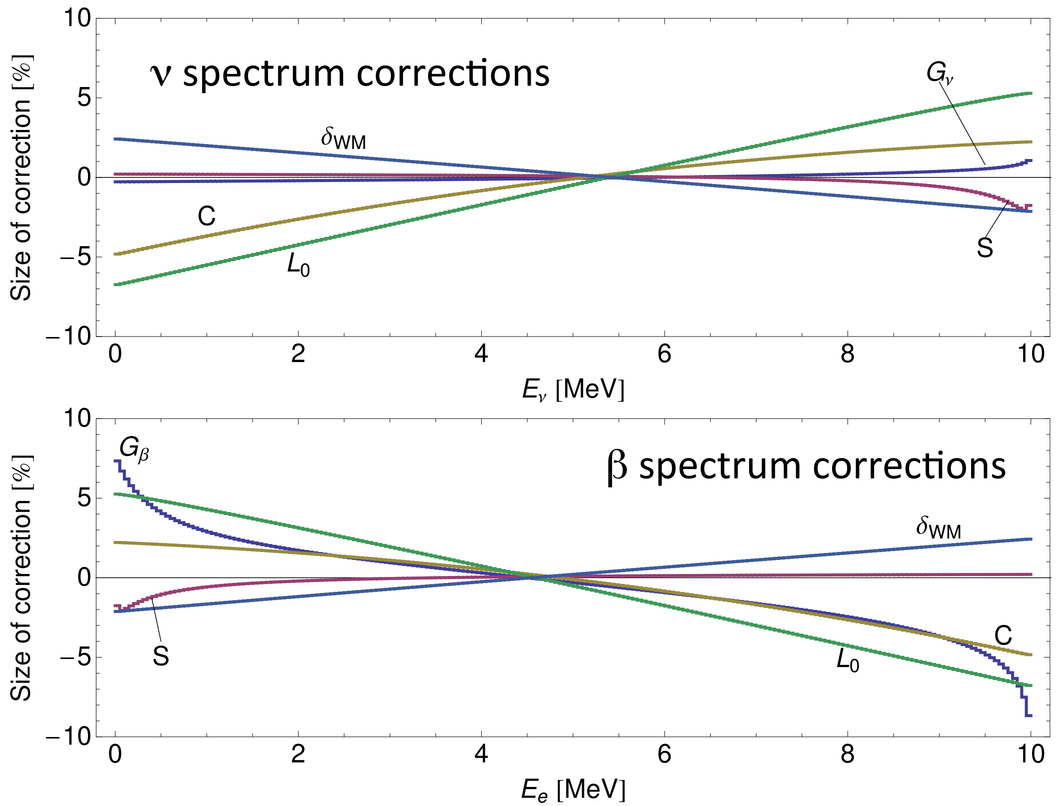
L_0: finite size of nuclear charge

G: QED radiative correction

S: screening of atomic e-

C: finite size distrib. of decaying neutron

δ_{WM}: weak magnetism

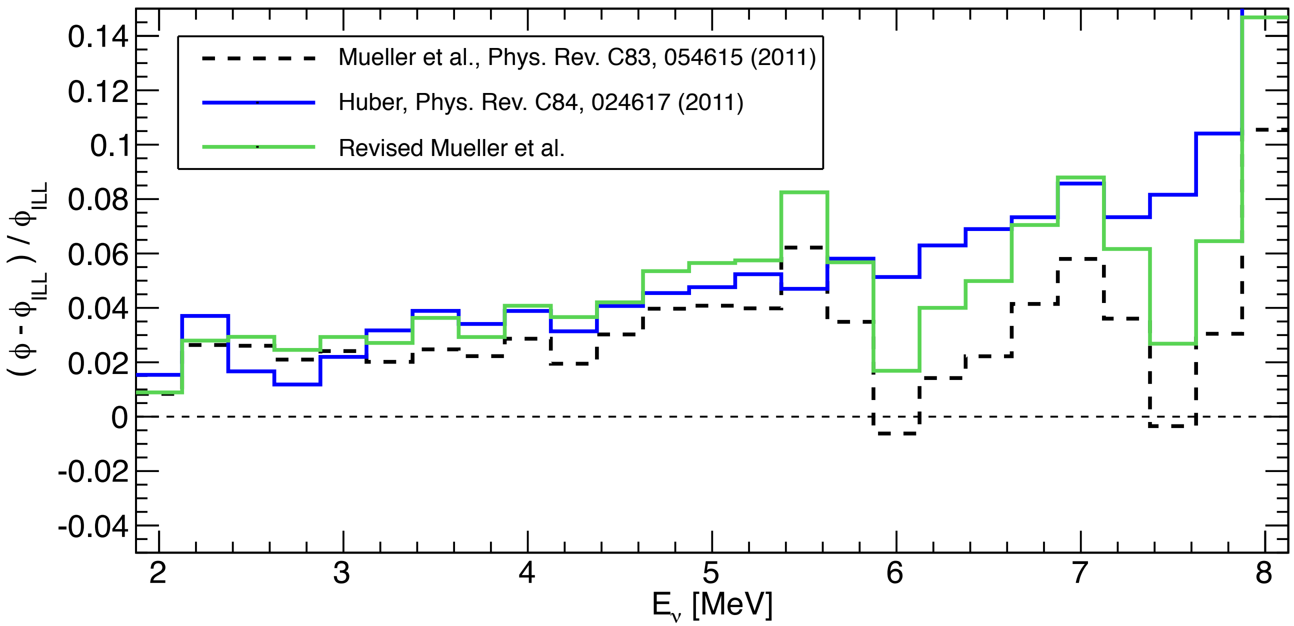


P. Huber

- Very large uncertainty on δ_{WM}, difficult to assess
- Larger than expected effect would show up as an extra global slope factor in the predicted fission spectra.

Converted antineutrino spectra

2 independent works predict an increase of the fission antineutrino spectra



The difference between the two published predictions is now understood:

- L0 correction not correctly implemented in Mueller et al. re-evaluation.
- Different expressions of C(Z,W) term.

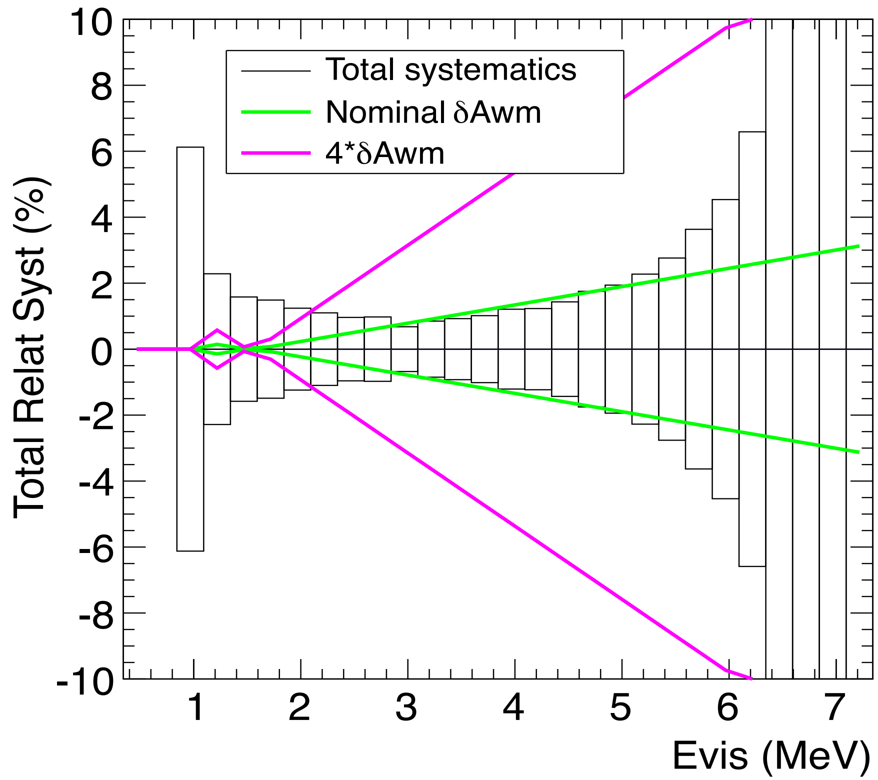
Weak Magnetism

- Some nuclei exhibit very large WM corrections (P. Huber).
  Representative of fission products?

- A factor 4 increase of δ_{WM} would compensate the +4% deviation from ILL spectra, but also induce a large negative tilt.

- **Upcoming data from DayBay, Reno and Double Chooz near detectors have the potential to confirm the current shape uncertainty!**

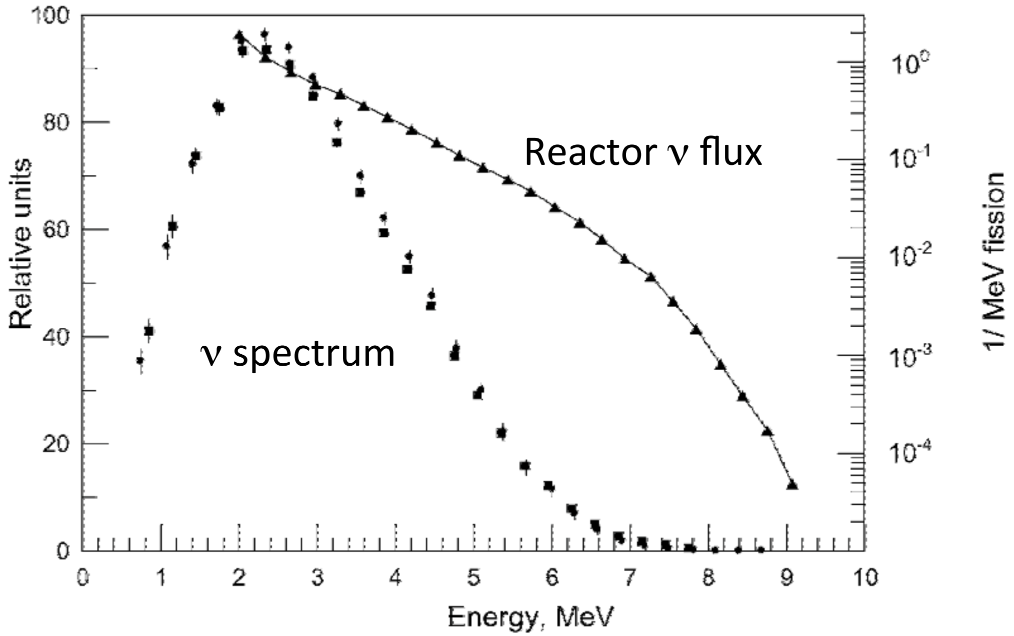
- **First constraints from Rovno, Bugey3 data.**



- Estimated **shape uncertainty** with DC near detector: ~3.5 10^5 accumulated neutrinos, δ_{Escale} = 0.5% and ~4% ^{9}Li background.

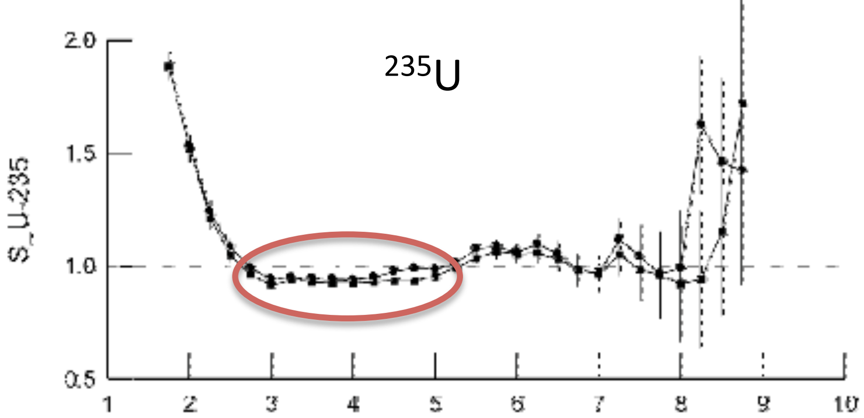
Rovno Data

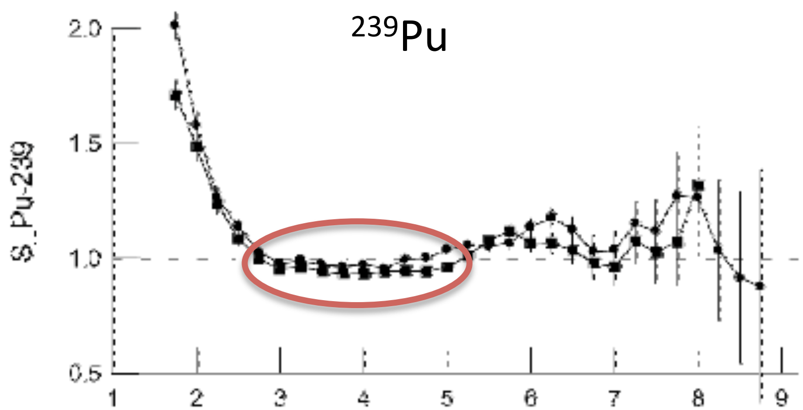
V. Sinev, arXiv:1207.6956



- Fission spectra determined from Rovno data.
- No significant linear trend although not conclusive yet given the current level of uncertainties.

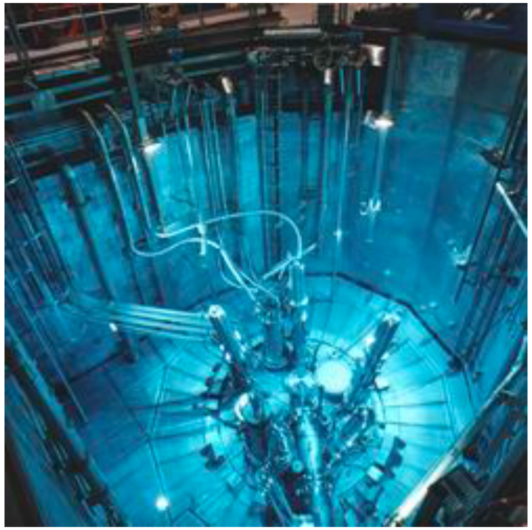
Rovno / Prediction ratios



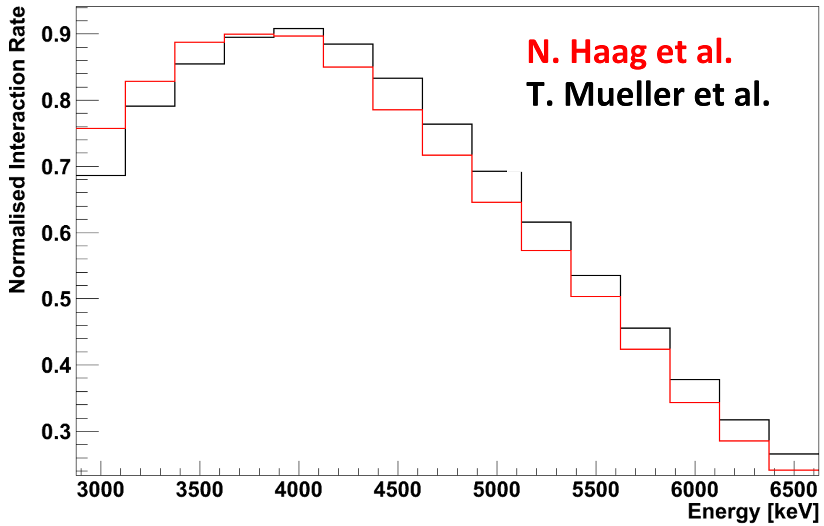


New complementary results

New ^{238}U data



- ~10% correction of spectrum shape as predicted by ab-initio calculations
- Improved error budget by more than a factor two (total error ≲6% up to 6 MeV).

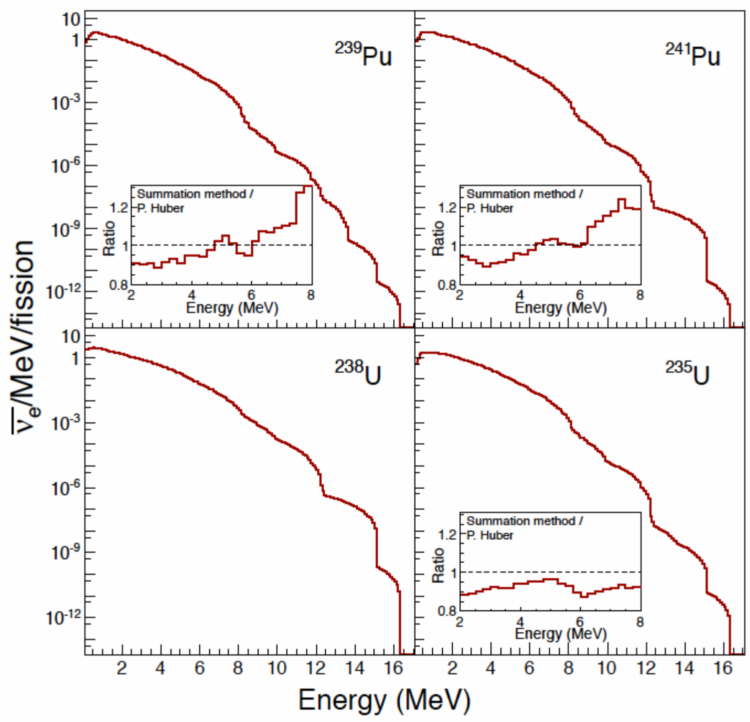


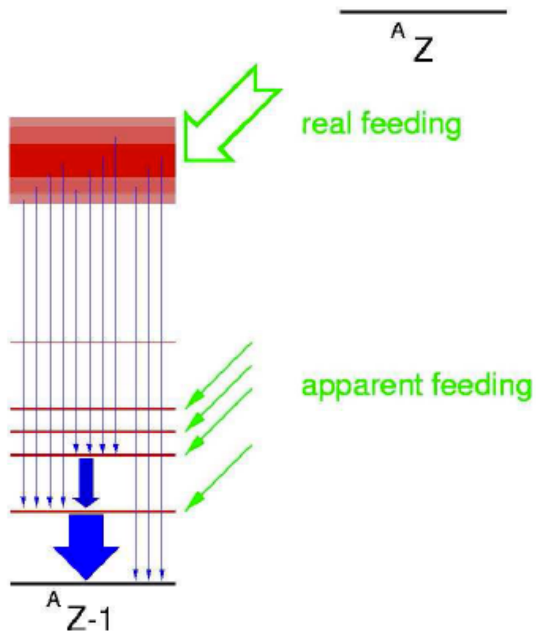
Haag PhD thesis

- New measurement performed by Nils Haag et al. with the fast-n flux of FRM II reactor (Munich).
- **Absolute normalization anchored on ILL data.**

- **Modest impact on anomaly (^{238}U fission rate 0-10% of total fission rate).**
- **Should be included for accurate shape prediction of reactor spectra.**

Ab-initio approach



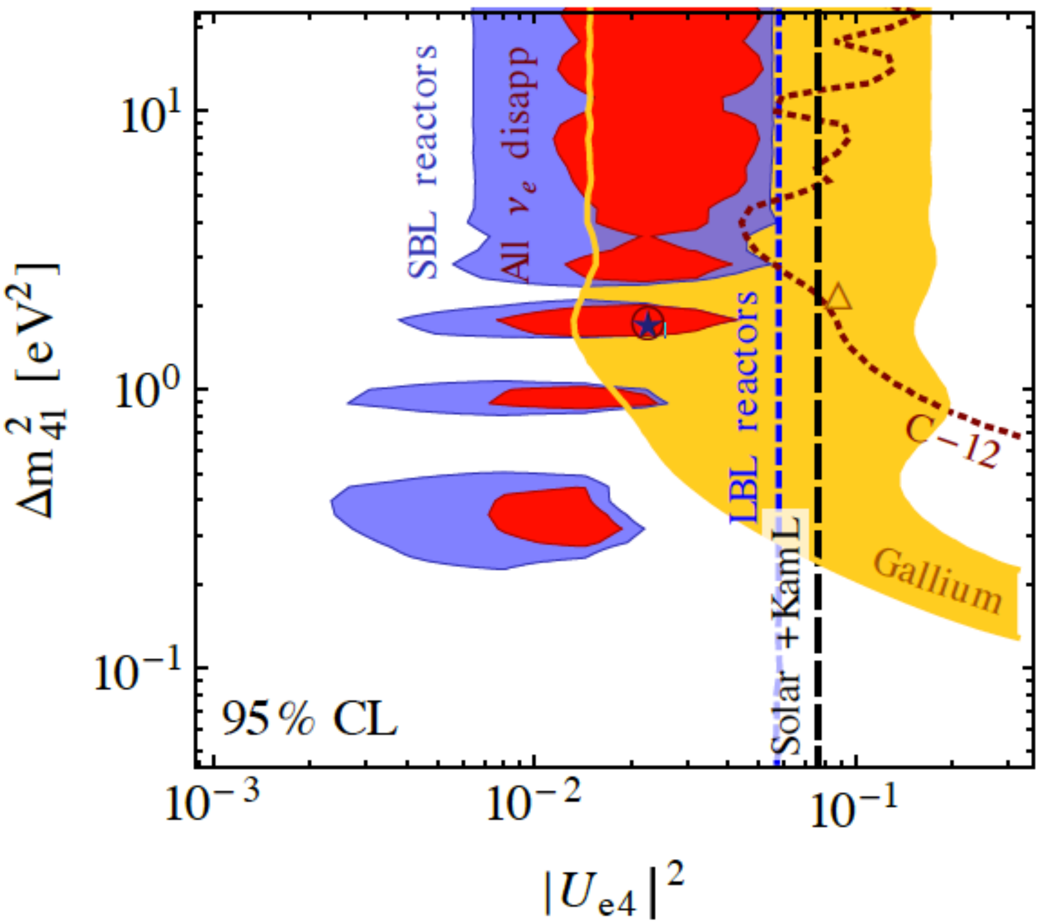


M. Fallot et al, Phys.Rev.Lett. 109 (2012) 202504

- Sizeable correction induced by the replacement of only 7 nuclei pointing to large remaining systematic effects in nuclear databases.
- Ongoing experimental program to measure a short list of remaining "pandemonium candidates".

Sterile Neutrino Search at Reactors

Sterile Neutrino Contour



J. Kopp et al., hep/ph:1303.3011

- Combined Gallium and Reactor anomalies: non-oscill hypothesis disfavored at 3.3 σ level.

Experimental Strategy

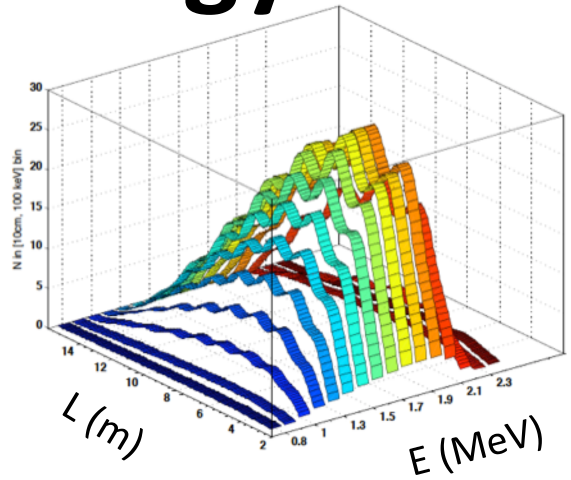
- **Goal**: **direct test**, beyond the current mean deviation from predicted rate

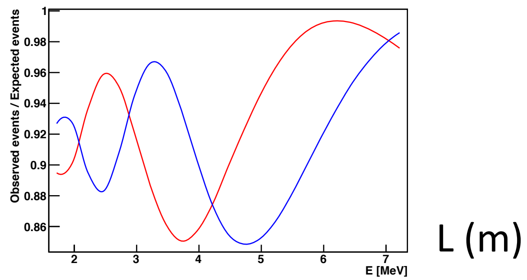
→ **Search for a new oscillation pattern in E & L**

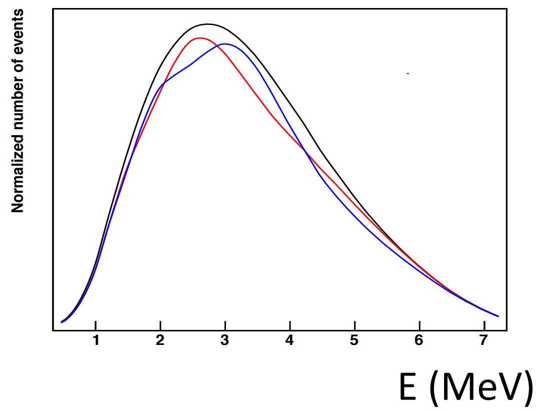
- Sensitivity to few m scale oscillations:
  - Compact source
  - Good position and energy resolutions
  - High statistics

- Few % stat + syst measurements to cover the anomaly contour

→ **Measurement of relative shape distortion**, completed by norm information.



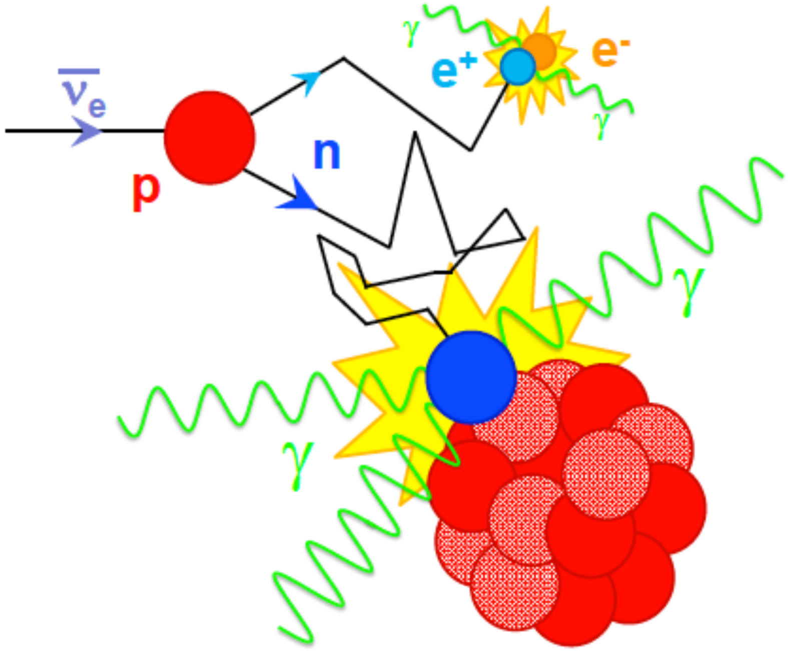




Neutrino Interaction

Inverse Beta Decay

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



Selective coinc

e^+ prompt signal & n-capture

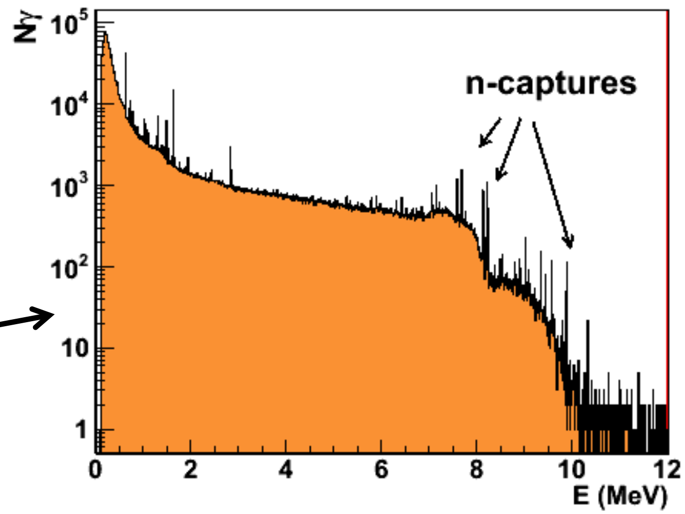
Background rejection

- Accidental γ-neutron coincidence
  - Shielding
  - Segmentation
  - Neutron discrimination
  - R&D on positron discrimination
- Fast-n correlated background
  - Rejection of recoil protons with PSD
  - Cosmic rays induced:
    Reactor OFF
    Overburden
  - Reactor induced: must be negligible.

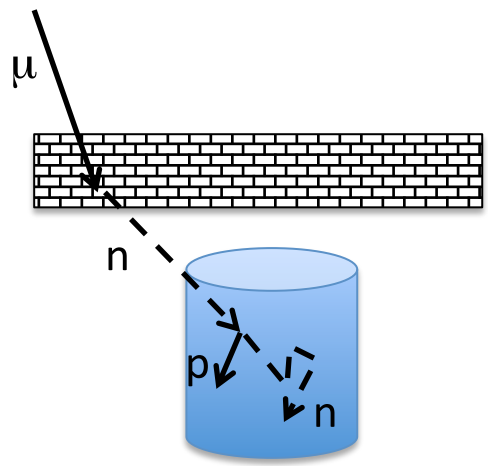
Challenging Background Subtraction

- Large reactor induced background at very short baseline. Requires massive passive shielding and discrimination technics.

- High energy γ induced by capture of reactor neutrons on metals
  → possible contamination of neutron capture signal from neutrino events.

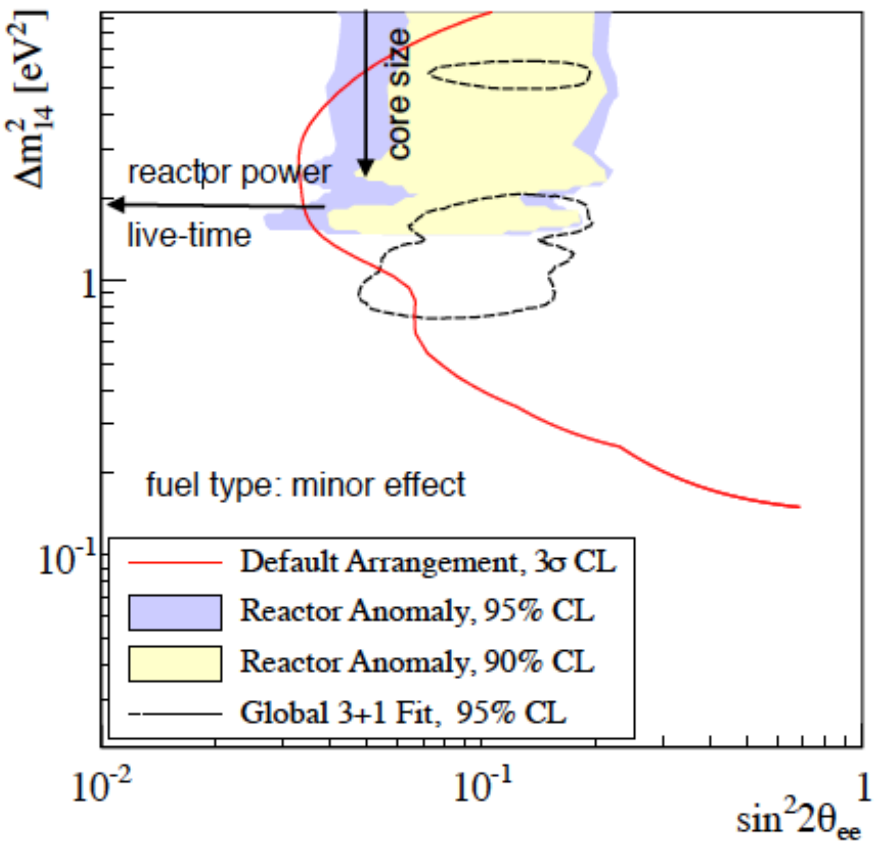


- Shallow depth experiment, exposed to significant fast neutron flux induced by cosmic rays.

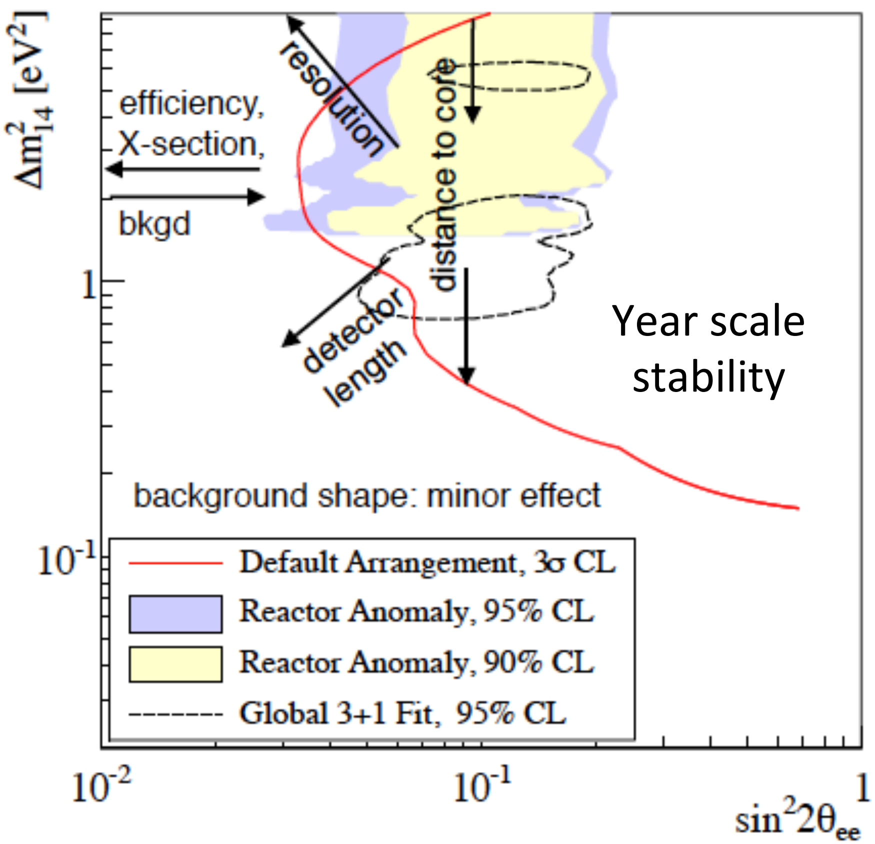


Sensitivity

Source

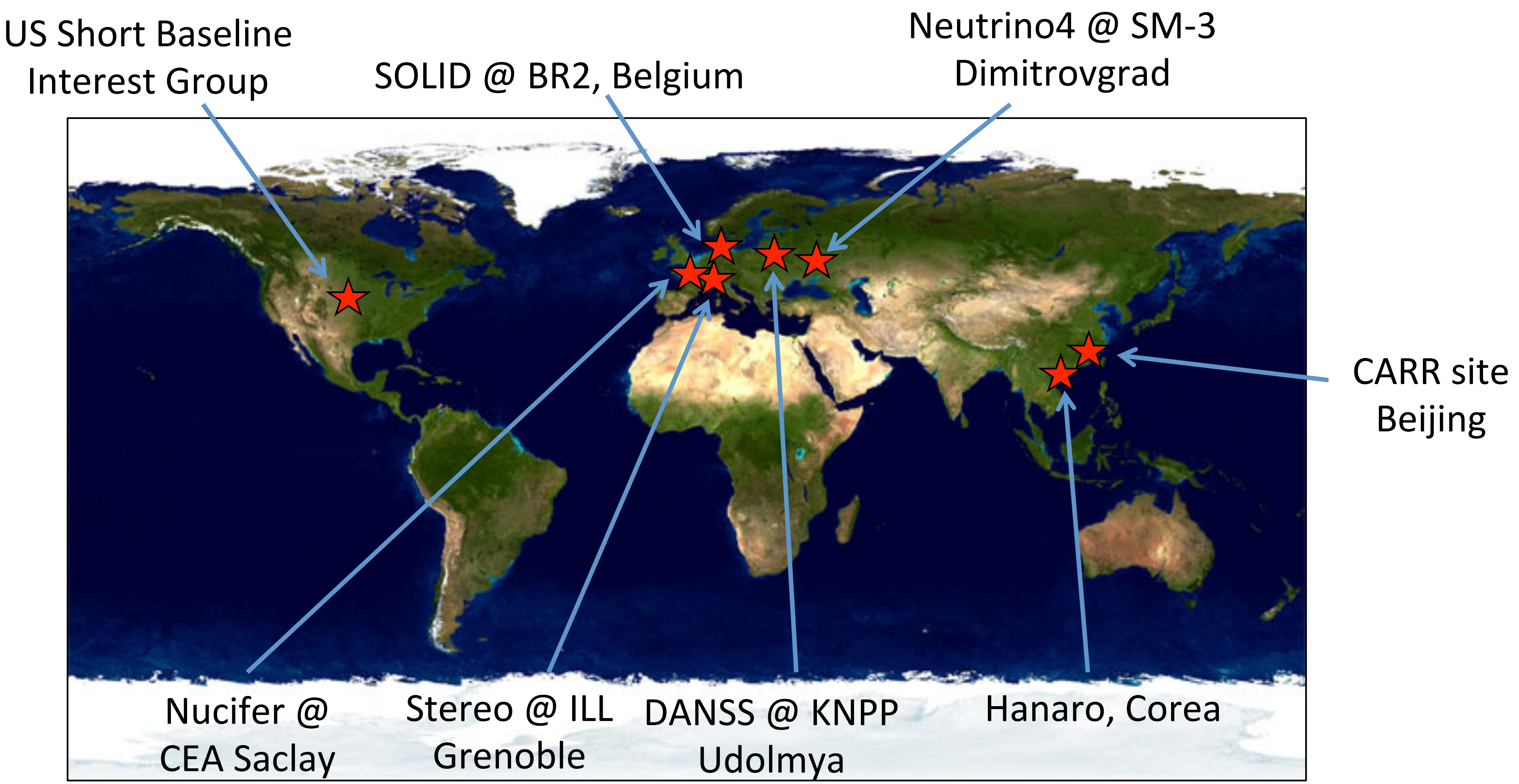


Detector



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

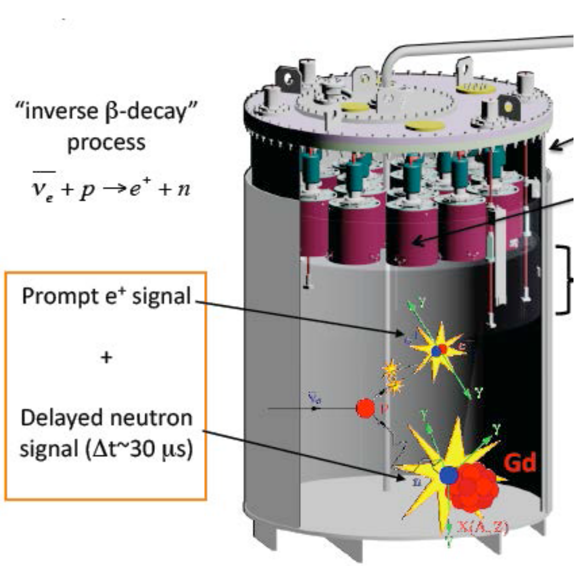
New Short Baseline Reactor Experiments

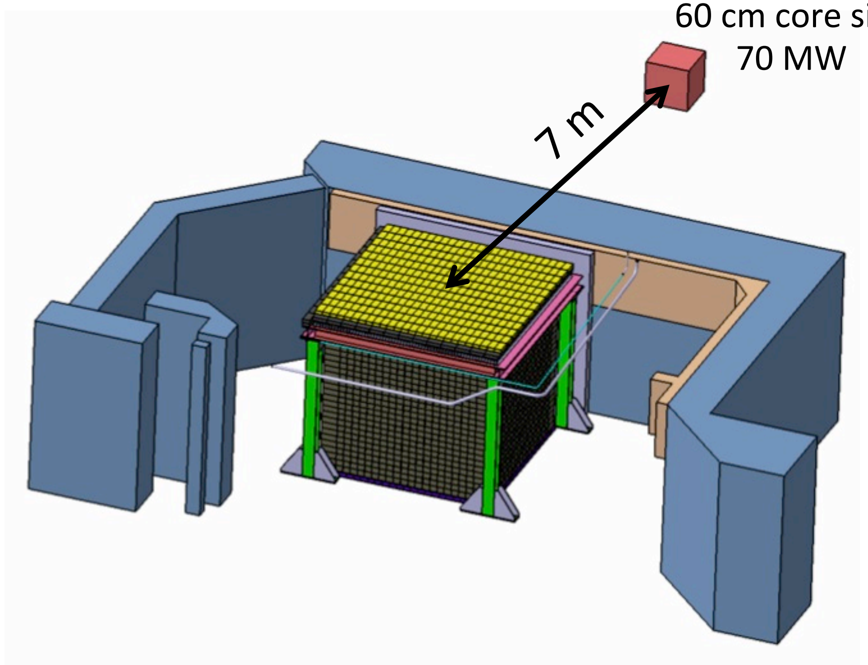


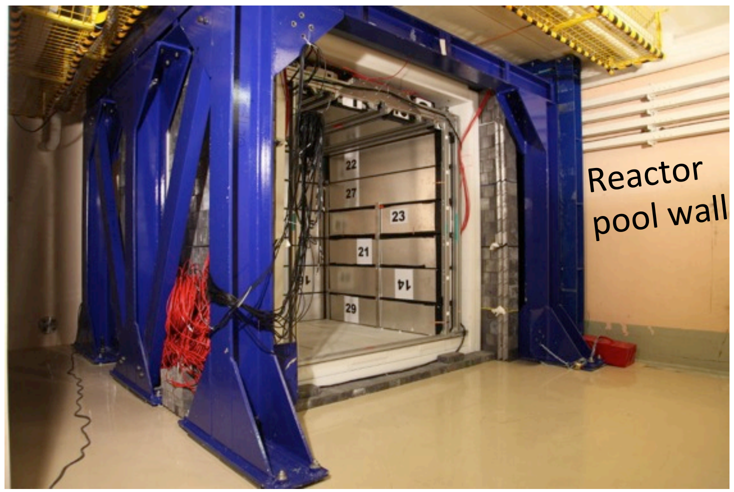
Mature technology of Gd-Doped liquid scintillators

- Validated by many experiments at reactors. Signature of n-capture by an 8 MeV γ-cascade.
- Large light yield, fast n background rejected by PSD capability
- Sensitive to high-E gammas → large passive shielding
- Projects:
  - Nucifer
  - Stereo
  - Neutrino4

Nucifer @ OSIRIS







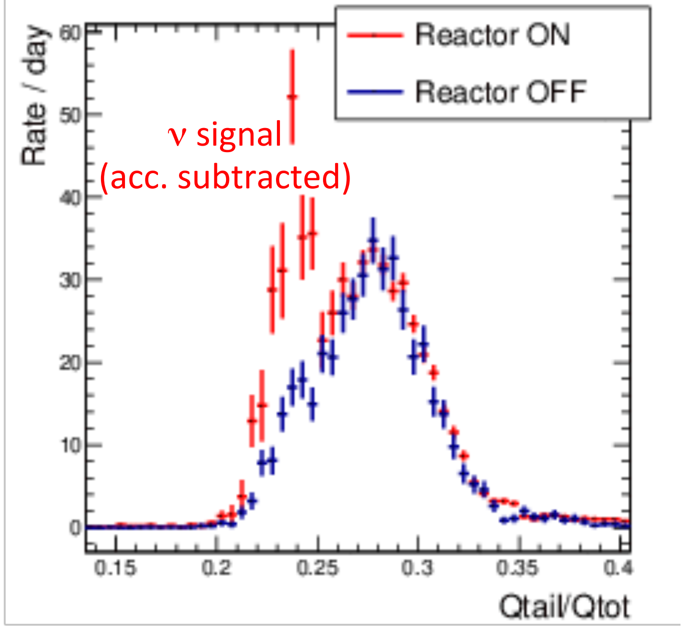
Designed for non-proliferation studies

- 7m from 70 MW compact core of OSIRIS reactor
- Very simple design based on **Gd-loaded LS** (Double Chooz R&D)
- High-E γ background (~1 MHz/m^2 above 2 MeV)
- Heavy passive shielding + active μ-veto.

Contact: T. Lasserre, CEA-Saclay

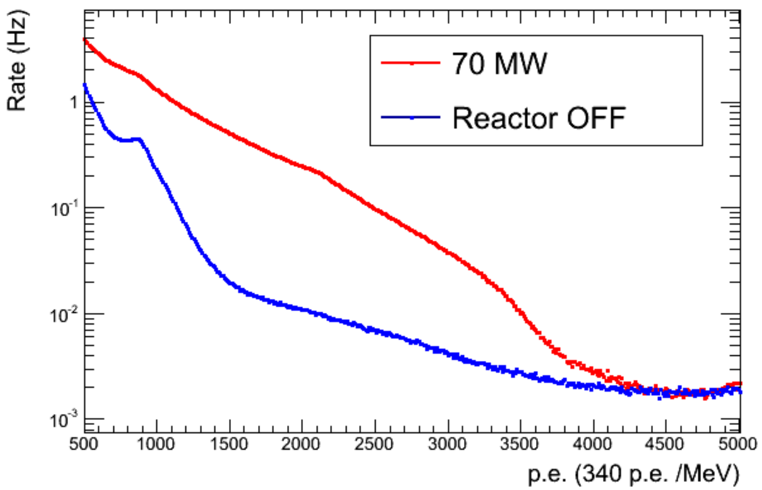
Nucifer @ OSIRIS

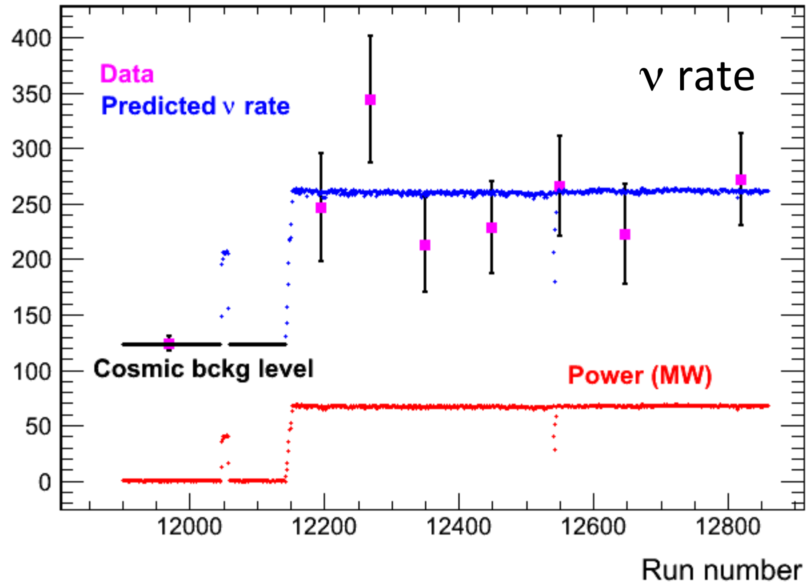
PSD



- No reactor induced fast n.
- Efficient rejection of cosmic background.
- Need further γ attenuation to reach S/B~1. Extra 3.75 cm of lead to be implemented this year.

γ spectra

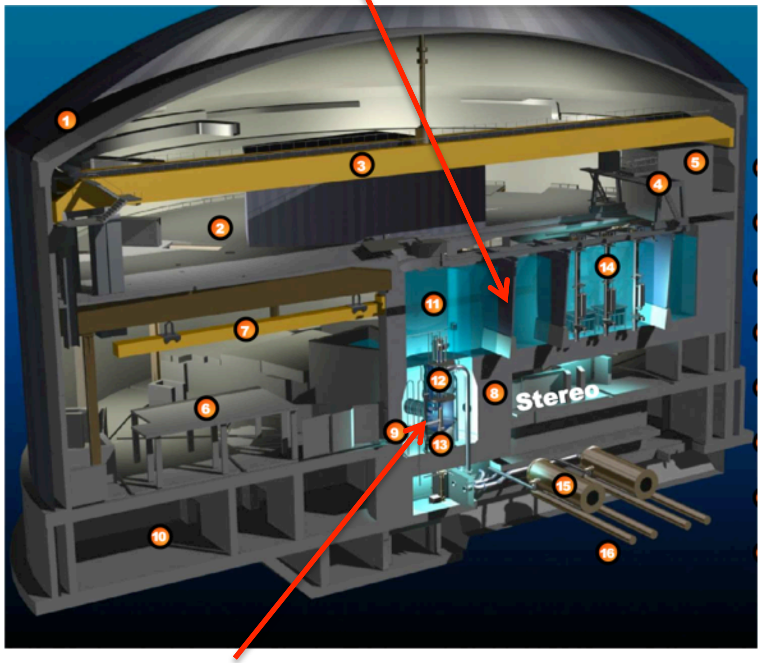




Stereo @ ILL

Contact: D. Lhuillier, CEA-Saclay

Good overburden from water channel, factor 4 attenuation of vertical flux

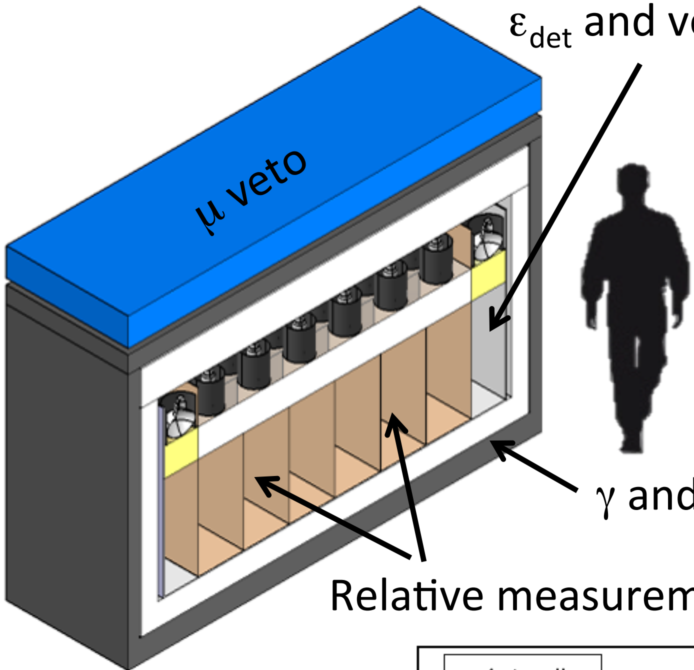


50 MW core
h=80cm, Φ=40cm

[8.5-11] m baseline range

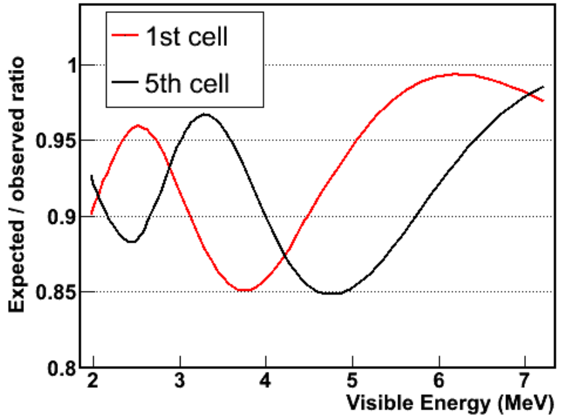
Detector based on Double Chooz and Nucifer developments.

Outer crown for improved ε_{det} and veto of external background

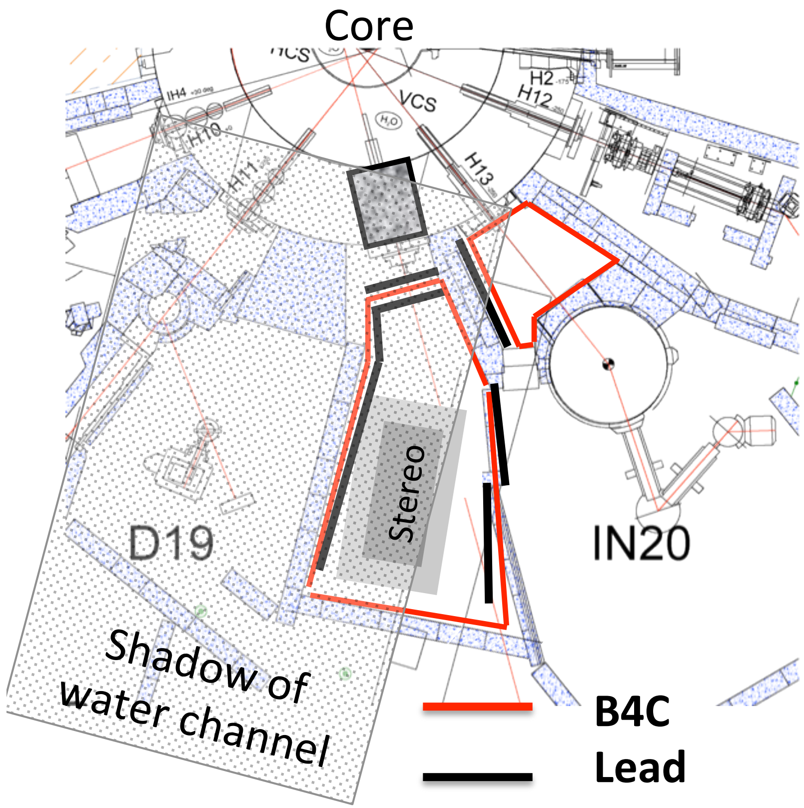


γ and n shielding

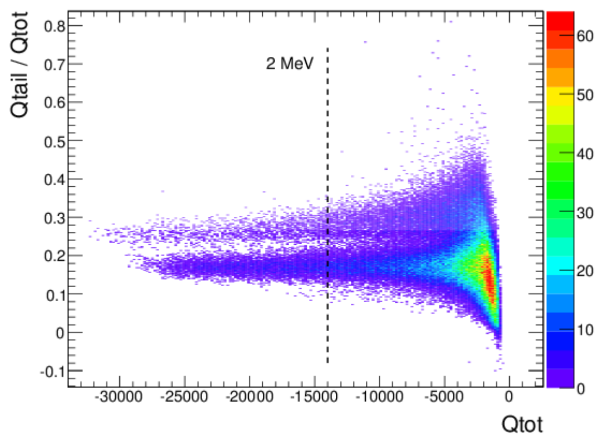
Relative measurement in 6 cells



Background Rejection

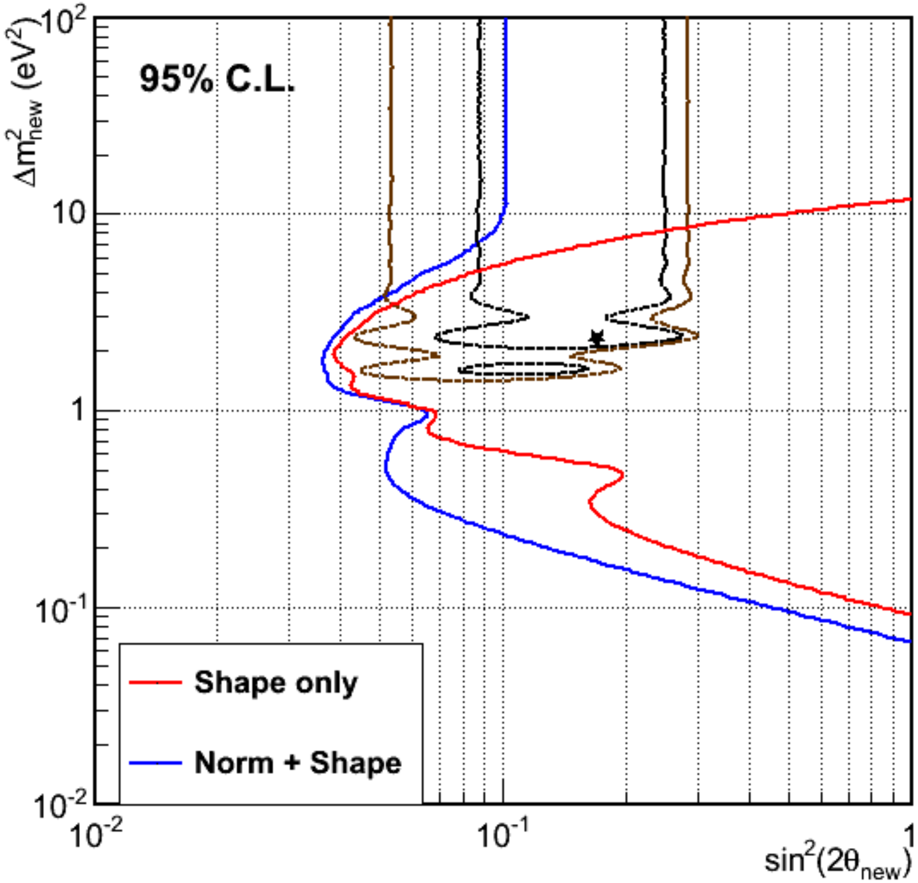


- Extensive on site measurements of muon, thermal n, fast n and γ background
- Massive deployment of shielding during the upcoming long reactor shutdown. 30 cm of lead in front hot γ spots + hermetic B4C coating.
- Dedicated plug of the neutron line already designed.



Liquid R&D for optimal light yield and PSD

Stereo Sensitivity



- 6 ILL cycles (1.5 year running)
- L_0 = 9.8 m
- S/B = 1.5
- E_{vis}>2 MeV, Neutron cut = 5 MeV
- Complete det response
- δL=20 cm, δE/E~10%@ 1MeV
- δEscale = 2%
- All syst. of ^{235}U spectrum
- 3.5% total norm error
- 480 ν/day expected

- Funded by ANR grant

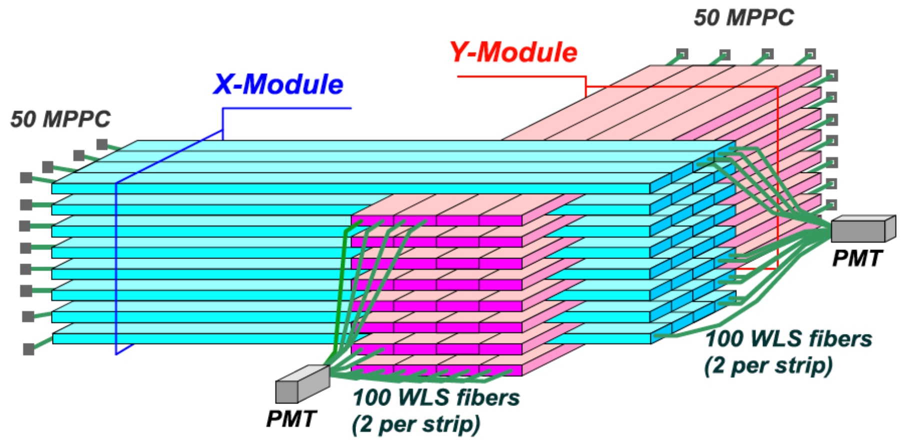
- Time schedule:
  - 2013-2014: design and construction
  - Mid-late 2014: installation
  - 2015-2016: data taking

Highly Segmented Detectors

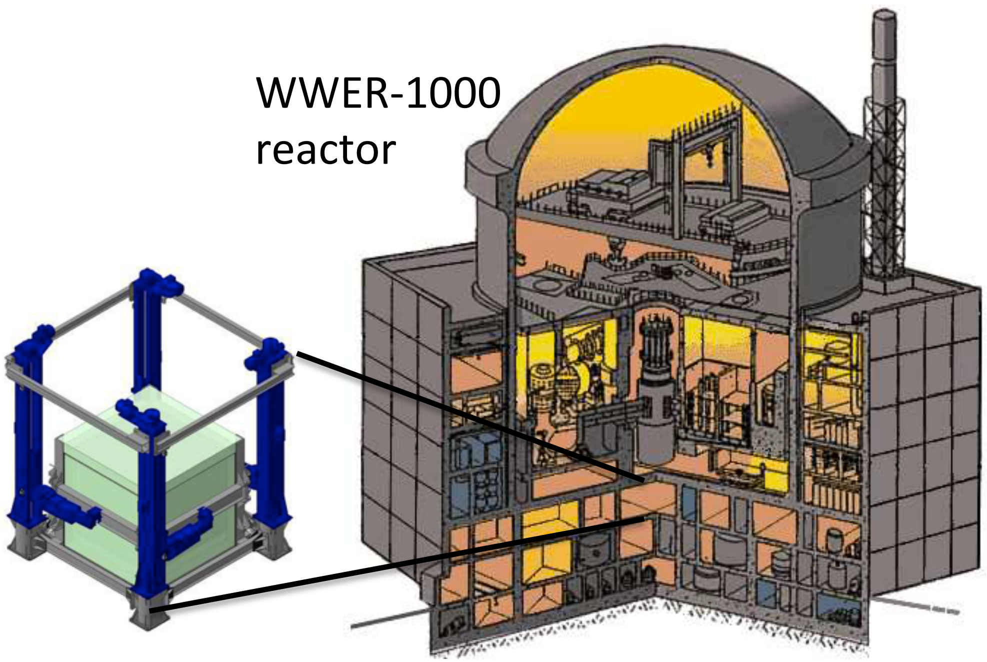
- Improved background rejection:
  - Distance between prompt and delayed E deposition
  - Topology of E depositions (compact e track versus large interaction length of γs)

- Projects:
  - DANSS
  - SoLid.

DANSS @ KNPP

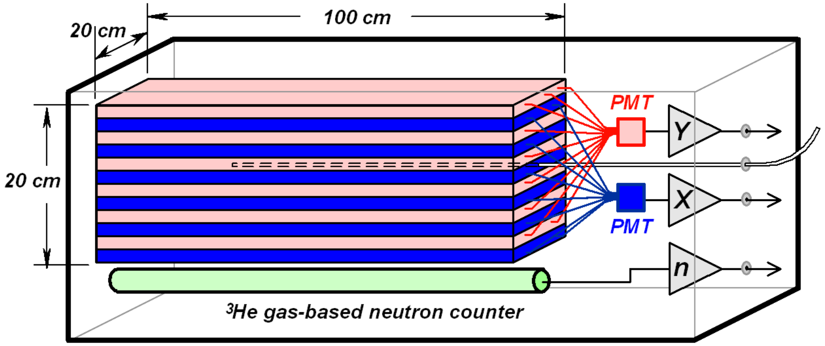


- Plastic strips with Gd-loaded interlayer, read out by WLS fibers.
- E resol ~20% at 1 MeV.
- Vertical motion of the detector from 9.7 to 12.2 m baseline.
- 10^4 evt/day expected at 11m.
- Good overburden from core structure. Extended source.



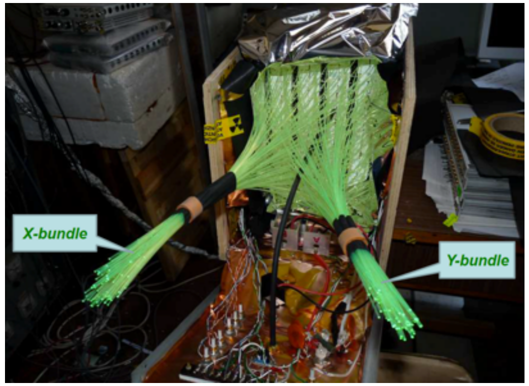
DANSSINO Prototype

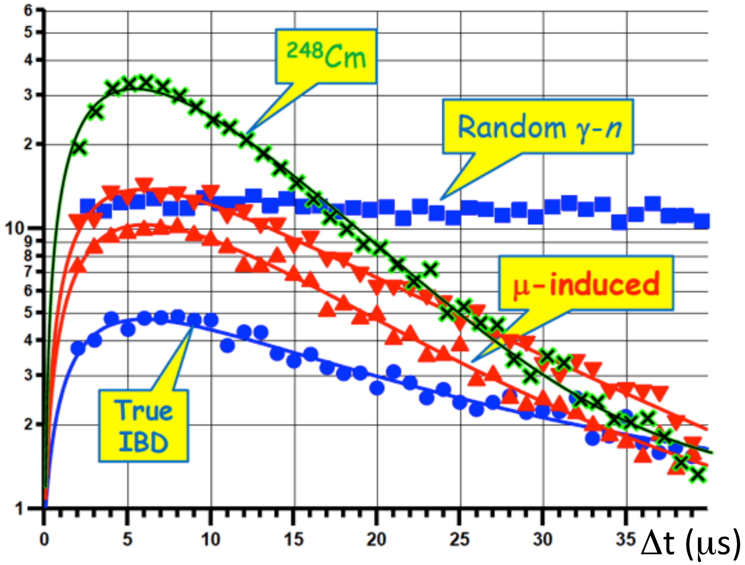
1/25th of DANSS

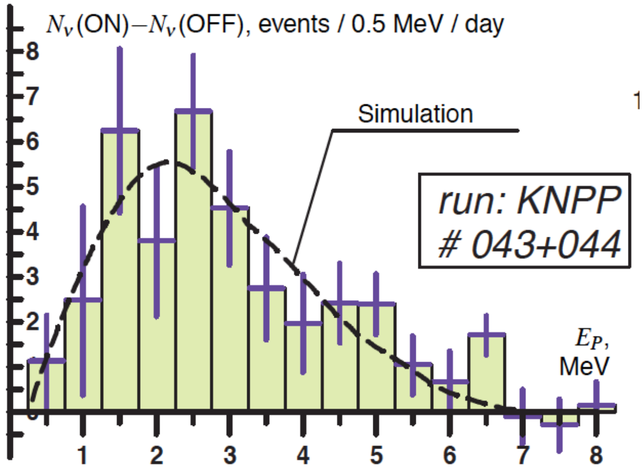


10 cm Cu-Lead + 10 cm CH_2 shelding

Tested for
~20 days
@ KNPP







- Accidentals well suppressed
- S/B~1, limited by cosmic fast neutrons.

Improved Neutron Discrimination

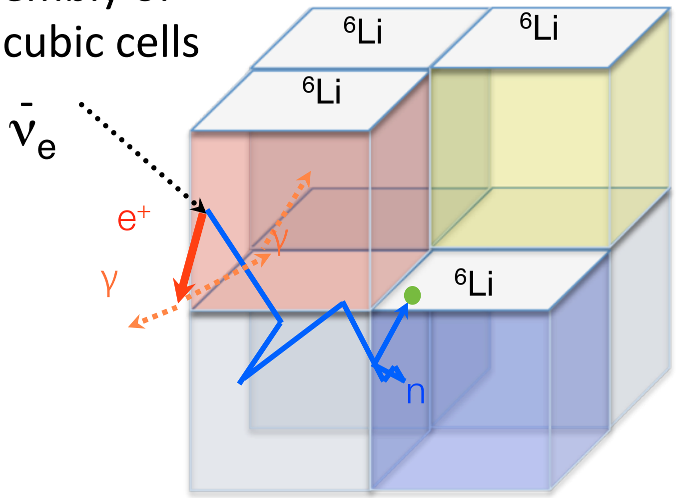
- Unique signature of neutron capture using Li-doped liquid or plastic scintillator:

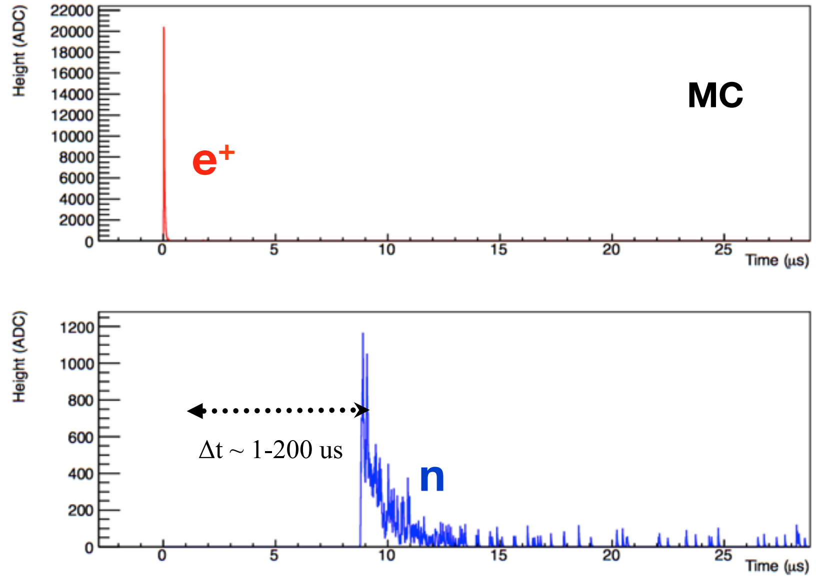
$$^{6}Li + n \rightarrow \alpha + t$$

- Projects:
  - Hanaro
  - SoLid

SoLi∂ Antineutrino detection

Assembly of 5cm cubic cells

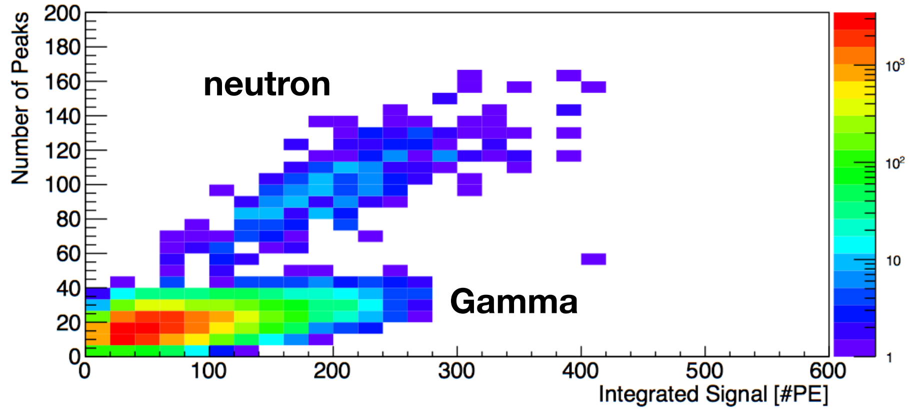




$$^{6}_{3}\mathrm{Li} + \mathrm{n} \rightarrow^{2}_{4} \mathrm{He}\ (2.05\ \mathrm{MeV}) +^{1}_{3} \mathrm{T}\ (2.75\ \mathrm{MeV})$$

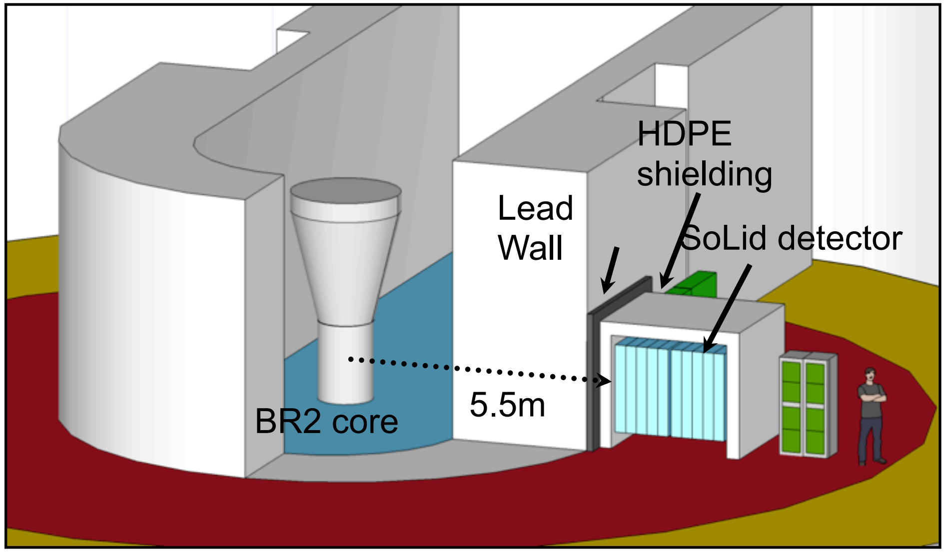
- Very **discriminant neutron signal** in ^{6}LiF:ZnS. High neutron-γ rejection factor
- 3D reconstruction close to interaction point : **high background rejection capability using topological information of IBD.**
- High light yield and good energy resolution (~17% at 1 MeV)

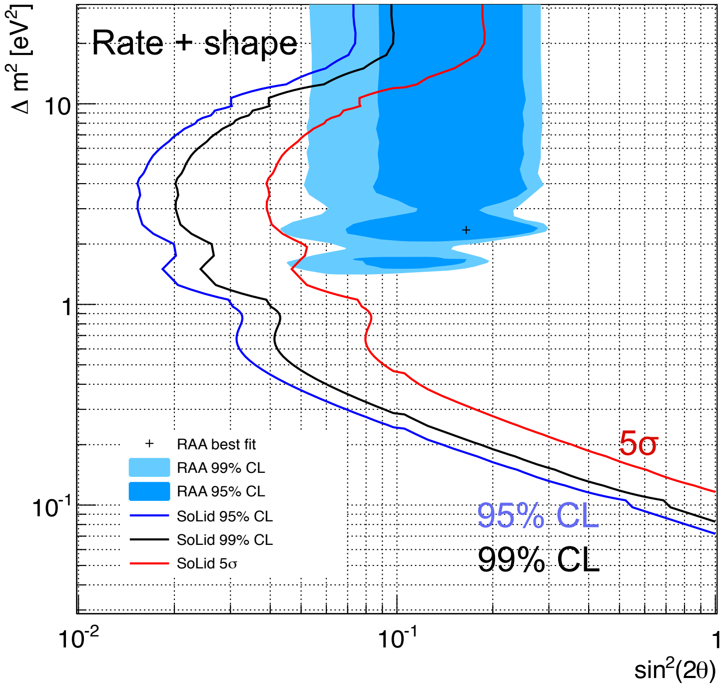
Data AmBe run



SoLiə

contact : antonin.vacheret@physics.ox.ac.uk





BR2 REACTOR, Mol, Belgium

- **Core: 45-80 MW, ~ 50cm diameter**
- **Overburden 10 m.w.e.**

DETECTOR

- **2.88t fiducial volume**
- **1920 channels read out by MPPCs**
- **Prototype testing this fall**

- 300 days (~ two years running)
- 45% IBD efficiency, 1200 n/day expected
- S/B = 6
- Normalization 4.1%, total ~5%
- Physics run scheduled for start of 2016

Extended Baseline Range

- Improved sensitivity to lower Δm^2
  Larger fiducial volume and/or longer running time

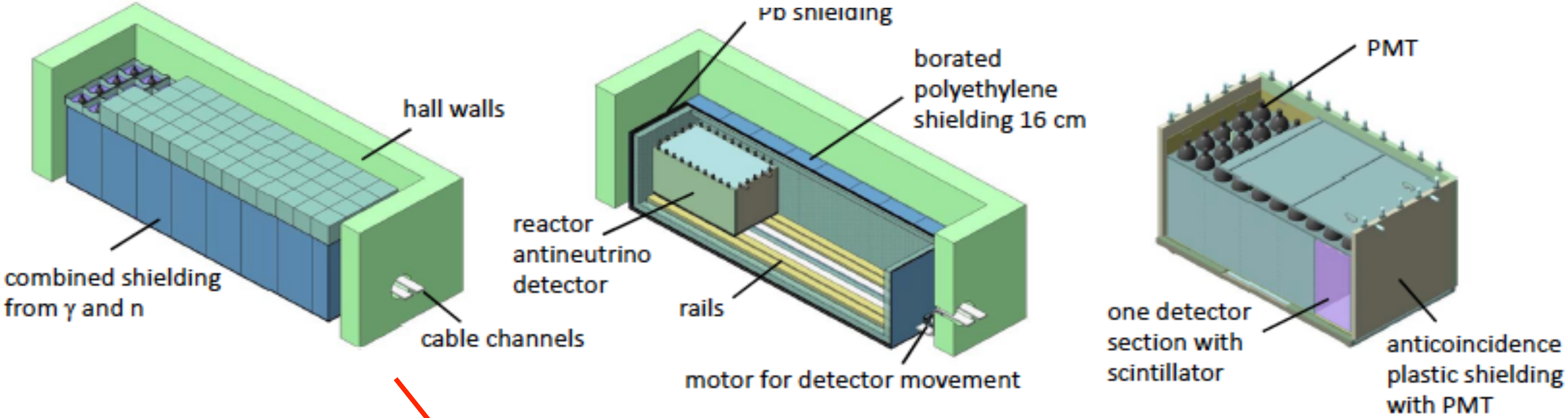
- Moving detector:
  - DANSS
  - NEUTRINO4

- Multi detector setup:
  - US project
  - China Advanced Research Reactor site

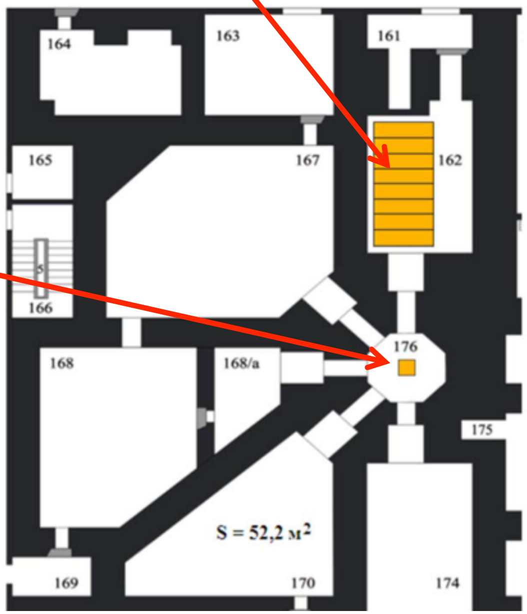
Neutrino-4 @ SM3

Contact: A. Sereborv, Gatchina

5 section movable detector [6-12] m, 2.5 m^3 target

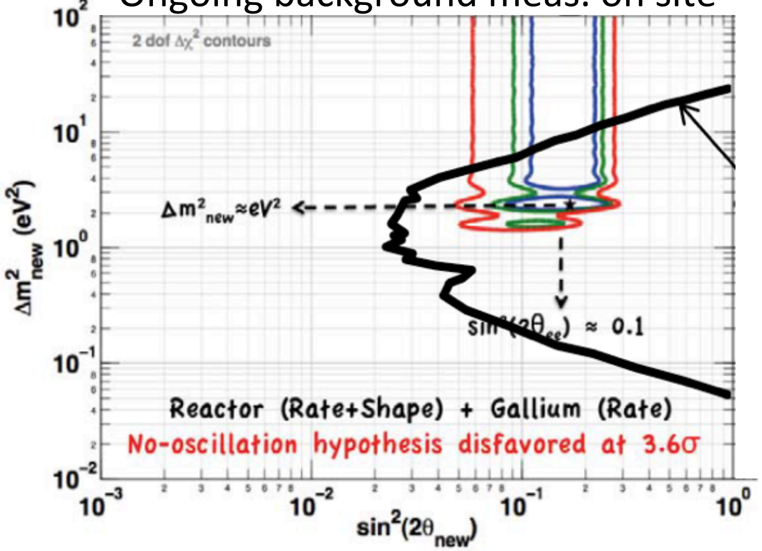


100 MW compact core ($35x42x42\ cm^3$)

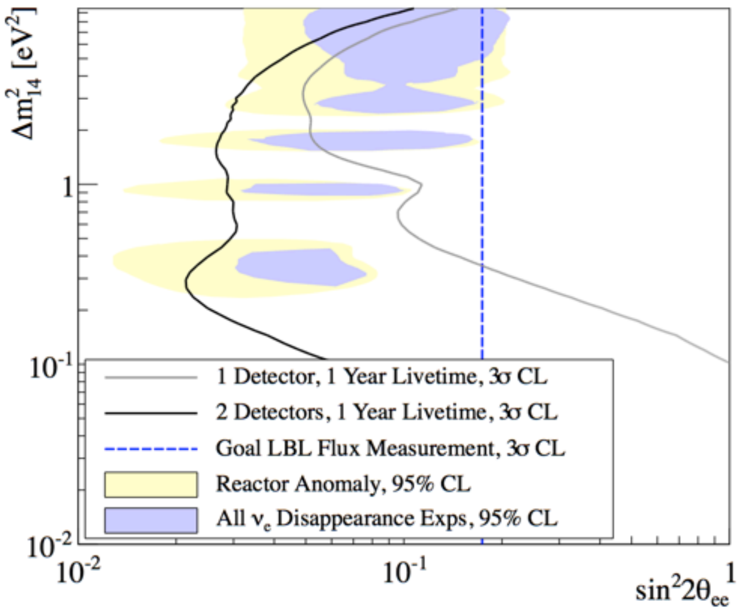


E_{prompt}>2.2 MeV, No background

Ongoing background meas. on site

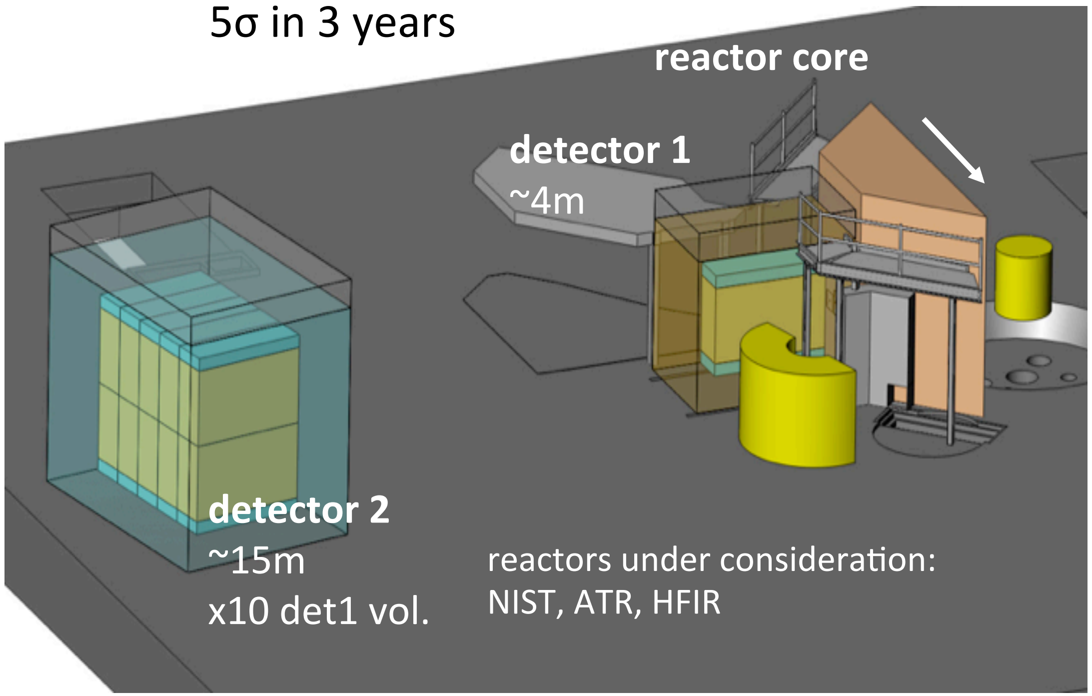


A 2-Detector Oscillation Experiment



Discovery Potential

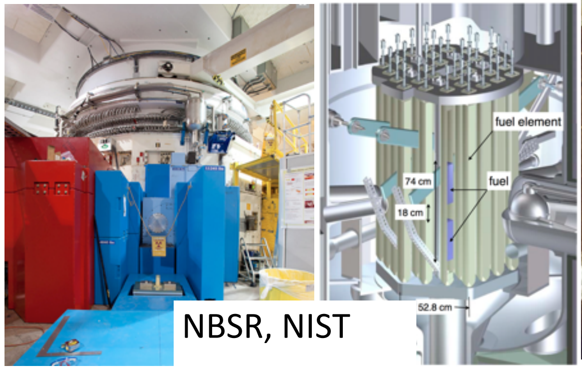
3σ in 1 year
5σ in 3 years



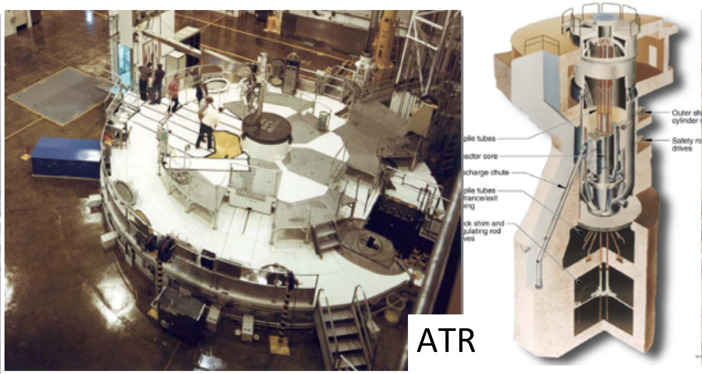
- 3 potential sites under investigation in the US: NIST, ATR, HFIR

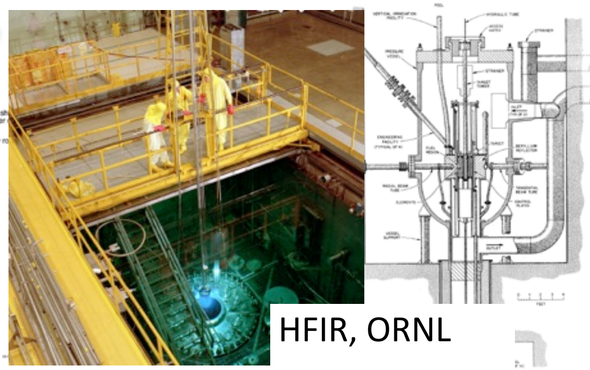
Mumm, Littlejohn, K.M.Heeger, arXiv:1307.2859 (2013)

US Research Reactors



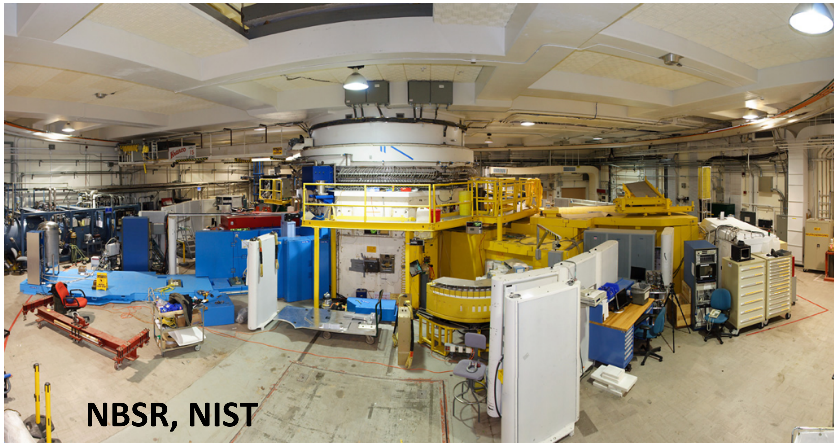
NBSR, NIST


ATR


HFIR, ORNL

Site	Power	Duty Cycle	Near Detector Baseline	Average $\bar{\nu}$ Flux (Near)	Far Detector Baseline	Average $\bar{\nu}$ Flux (Far)
NIST	20 MW_{th}	68%	3.9m	1	15.5	1
HFIR	85 MW_{th}	41%	6.7m	0.96	18	1.93
ATR	120 MW_{th}	68%	9.5m	1.31	18.5	4.30

Ongoing site characterization


NBSR, NIST

Technically Limited Schedule:

- FY13-14 - R&D
- FY14-15 - design&construction
- FY 2016 - first data?

Conclusions

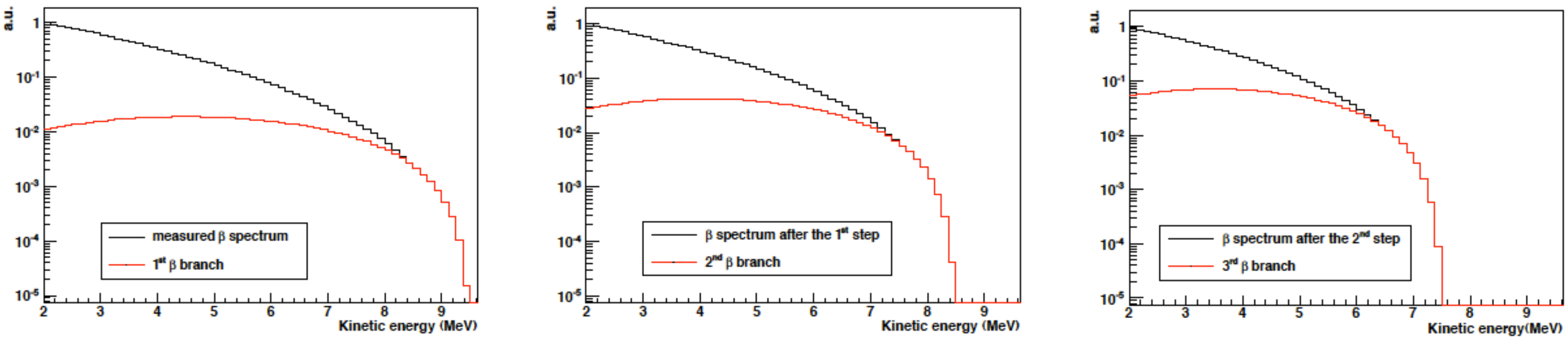
- Reactor flux calculations
  - Bias of original ILL analysis confirmed by 2 independent works.
  - Significant uncertainties remains but cancelling the anomaly requires either large deviation from expectation or conspiracy of several systematics.
  - Shape to be constrained soon by near detectors of θ_{13} reactor experiments.

- Reactor experiments
  - Offer direct tests of the 4th neutrino hypothesis with sensitivity nicely covering the anomaly contour →Discovery potential within the next 5 years.
  - Challenging background suppression. Site characterization is crucial.
  - Nice combination of mature and new technologies; Synergies with reactor monitoring efforts; Complementarity with source experiments.

Back up Slides

$\beta^- \rightarrow \nu$ Conversion

1- Need to break down the total e^- spectrum into single β-branches
$\rightarrow$ fit the data with 30 virtual branches:



2- Convert each virtual e^- branches to ν branches

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

Theory of β-decay

Fermi theory:

$$N_\beta^F(W) = K \underbrace{p^2 (W - W_0)^2}_{\text{Phase space}} \underbrace{F(Z,W)}_{\text{Fermi function}} \underbrace{C_{Shape}(W)}_{\text{Shape factor of forbidden}}$$

- W = total energy
- W_0 = end-point
- p = momentum
- Z = Nuclear charge

Corrections:

$$N_\beta(W) = N_\beta^F(W)\, L_0(Z,W)\, S(Z,W)\, C(Z,W)\, G_\beta(Z,W)\, (1 + \delta_{WM} W)$$

- $L_0(Z,W)$: Finite size of nuclear electric charge
- $S(Z,W)$: Screening of Atomic e-
- $C(Z,W)$: Finite size distrib. of decaying neutron
- $G_\beta(Z,W)$: QED radiative correction
- δ_{WM}: Weak magnetism

ν branch obtained by replacing: $W \rightarrow W_0 - W$, $G_\beta \rightarrow G_\nu$

Ab initio

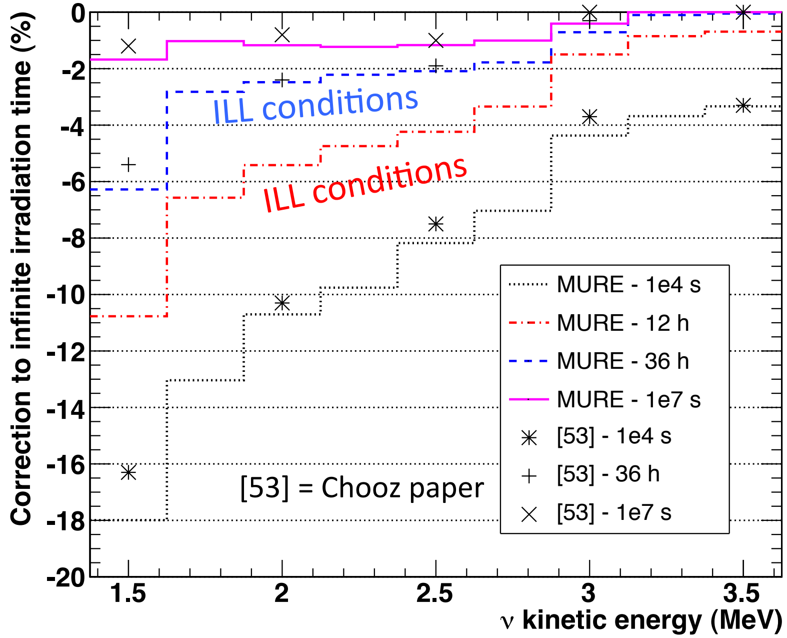
Study of relative spectrum variations to reach equilibrium

- ILL reference data are photos of β decays after 12-36h irradiation time.

- Long-lived isotopes, dominant at low energy, keep accumulating over several weeks.

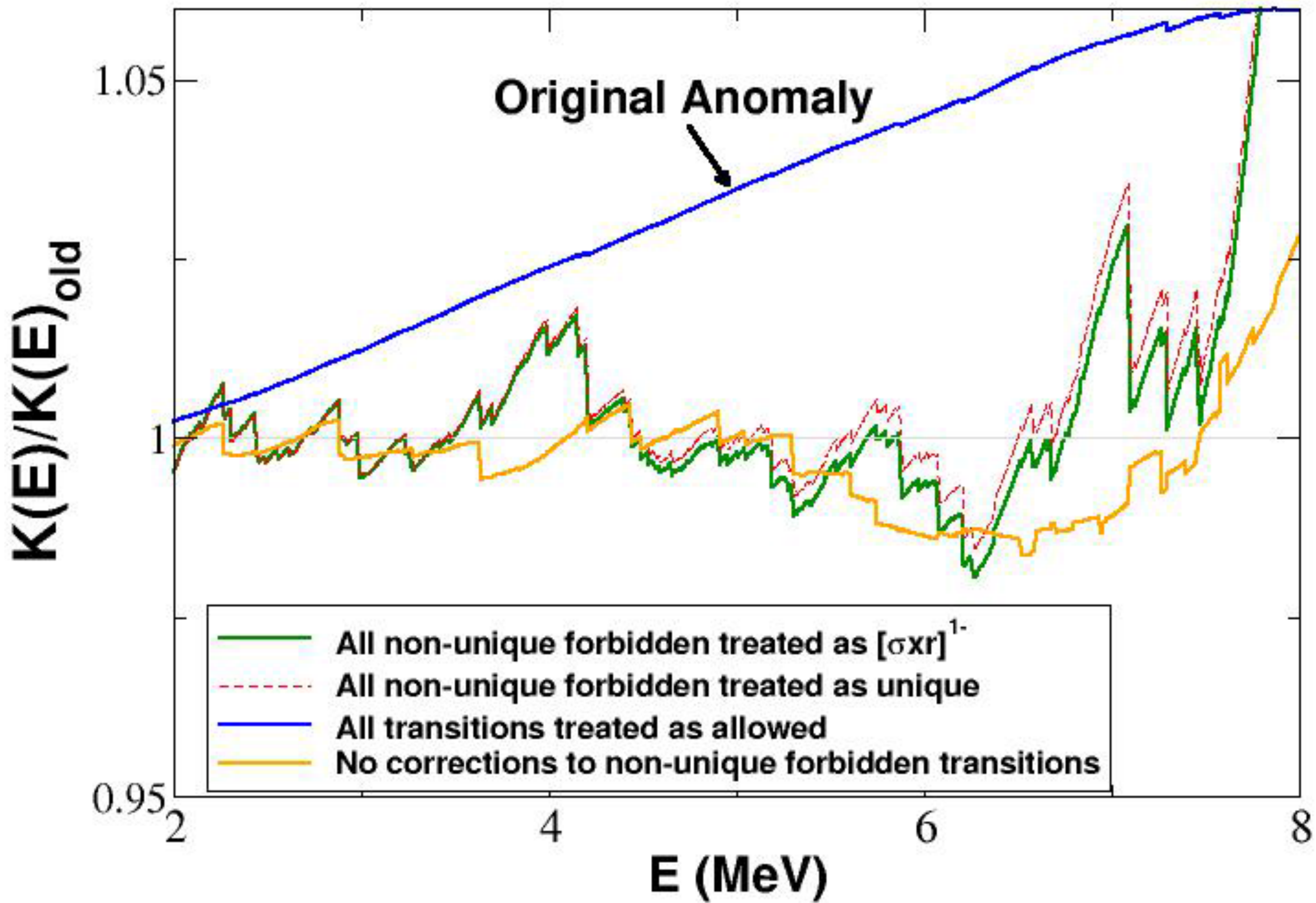
→ Sizeable correction to ILL data in below 3 MeV; +1% total detected flux

Off-eq. correction as computed by the MURE



See poster 146, A., Reactor and antineutrino spectrum calculation for the Double Chooz first phase result

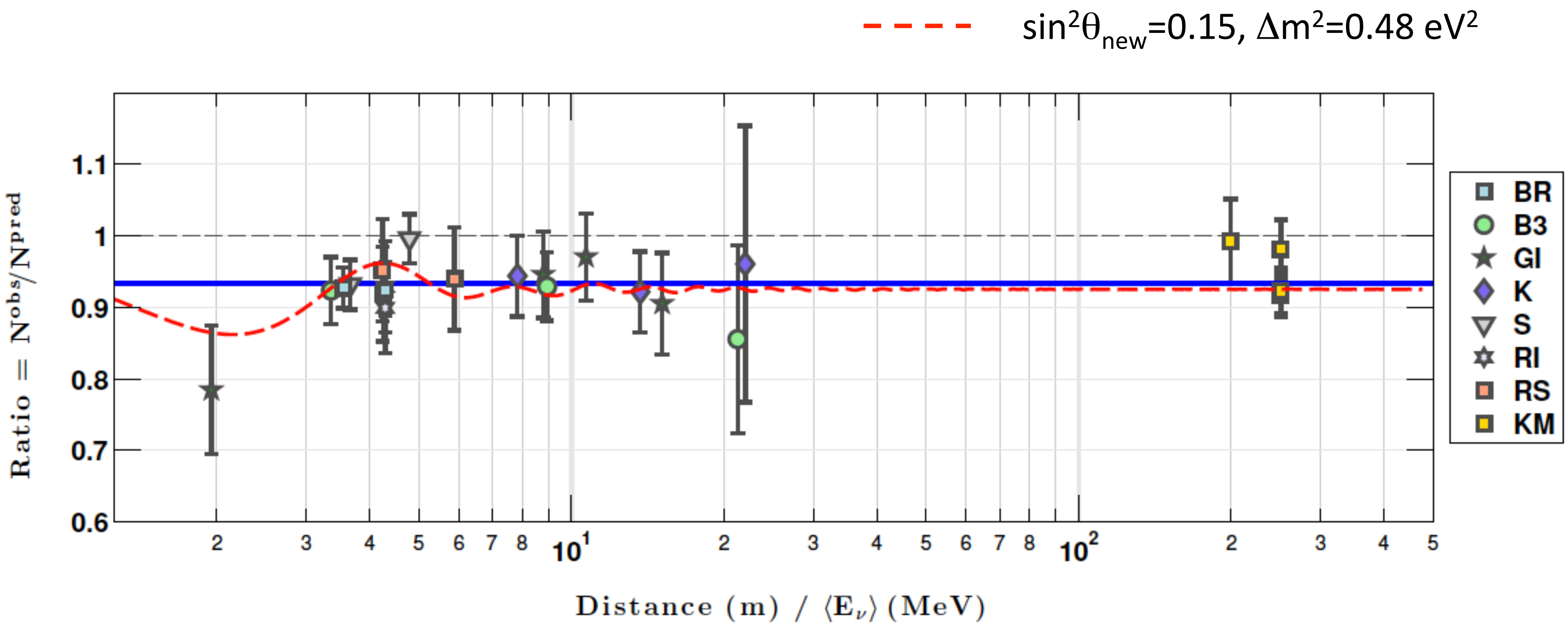
C. Jones et al. arXiv:nucl-ex/1109.5379v1



1.05
1
0.95
2
4
6
8
E (MeV)
K(E)/K(E)old
Original Anomaly
All non-unique forbidden treated as [σxr]1-
All non-unique forbidden treated as unique
All transitions treated as allowed
No corrections to non-unique forbidden transitions

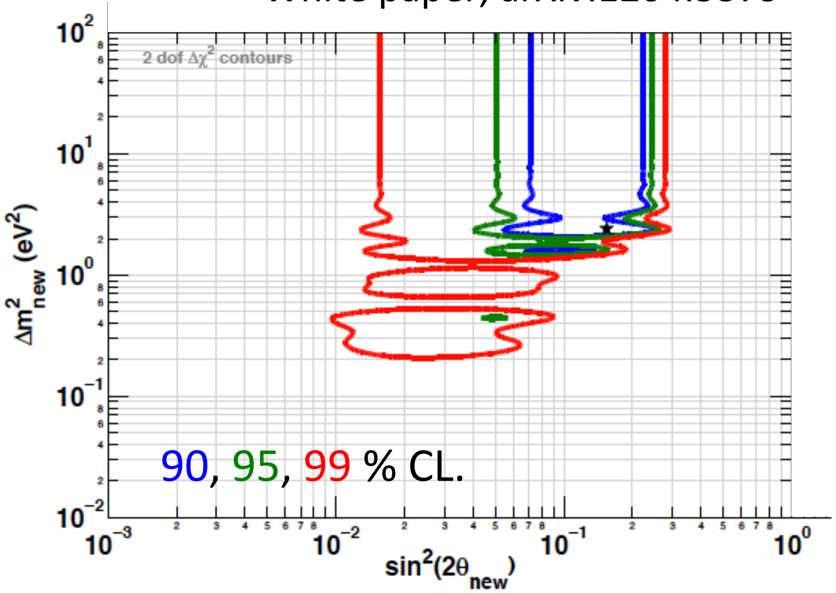
A. Hayes

Low Δm^2 Solution

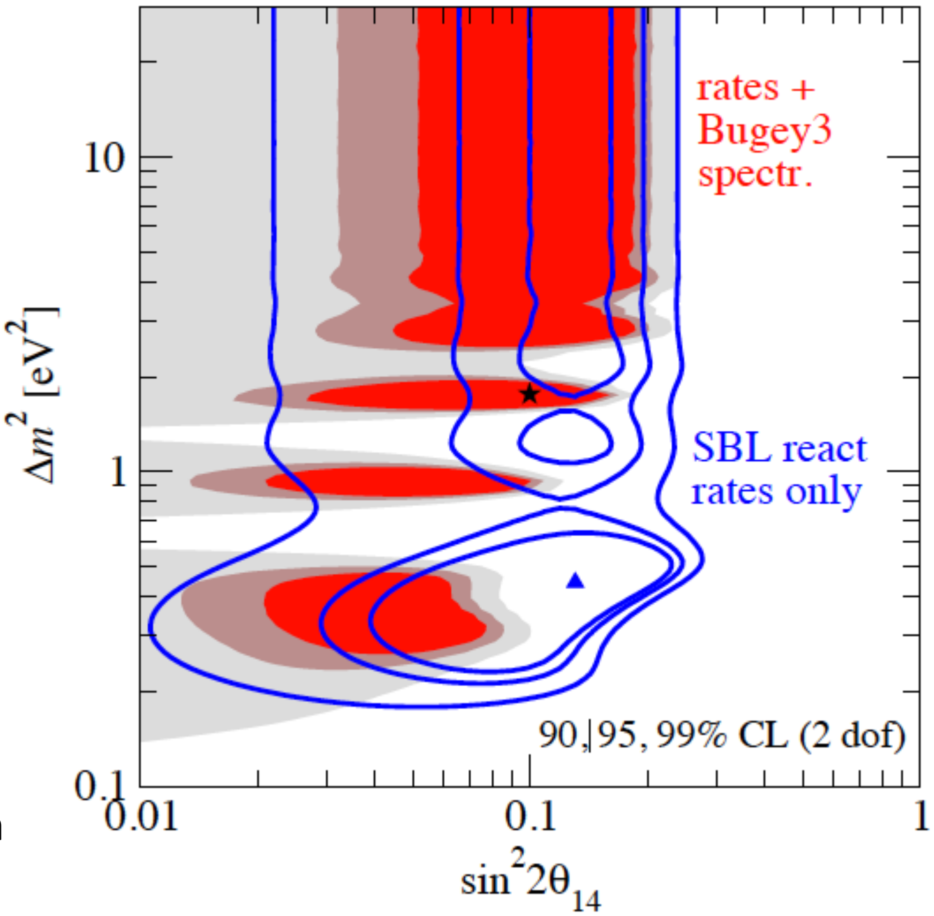


The Sterile Neutrino Hypothesis

White paper, arXiv:1204.5379

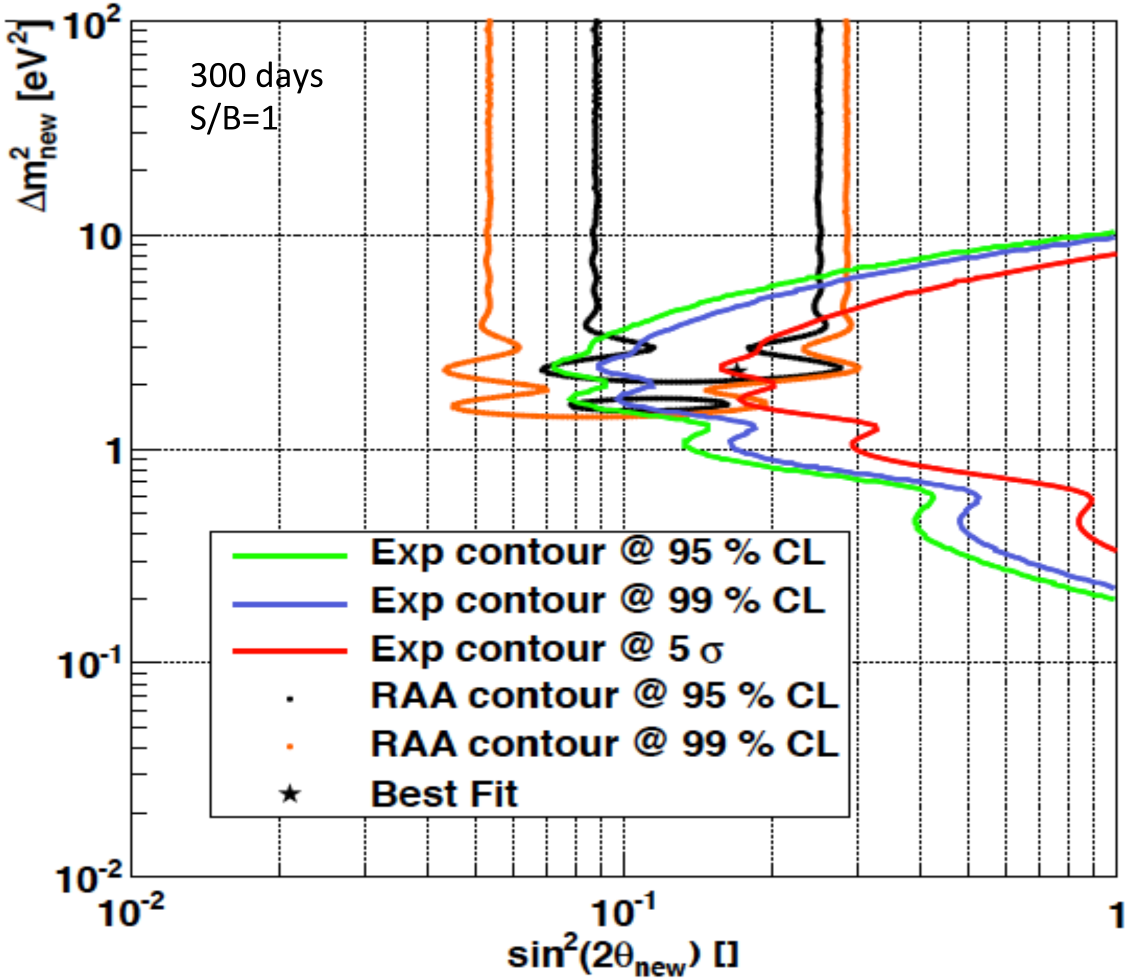


J. Kopp et al., hep/ph:1303.3011

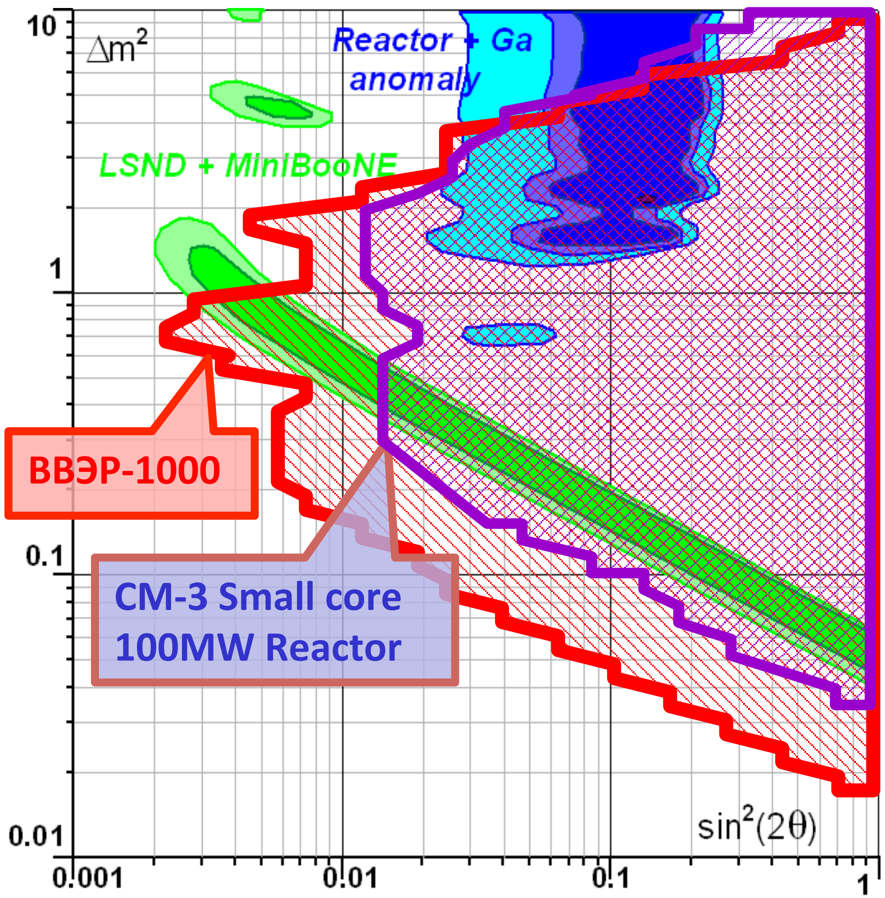


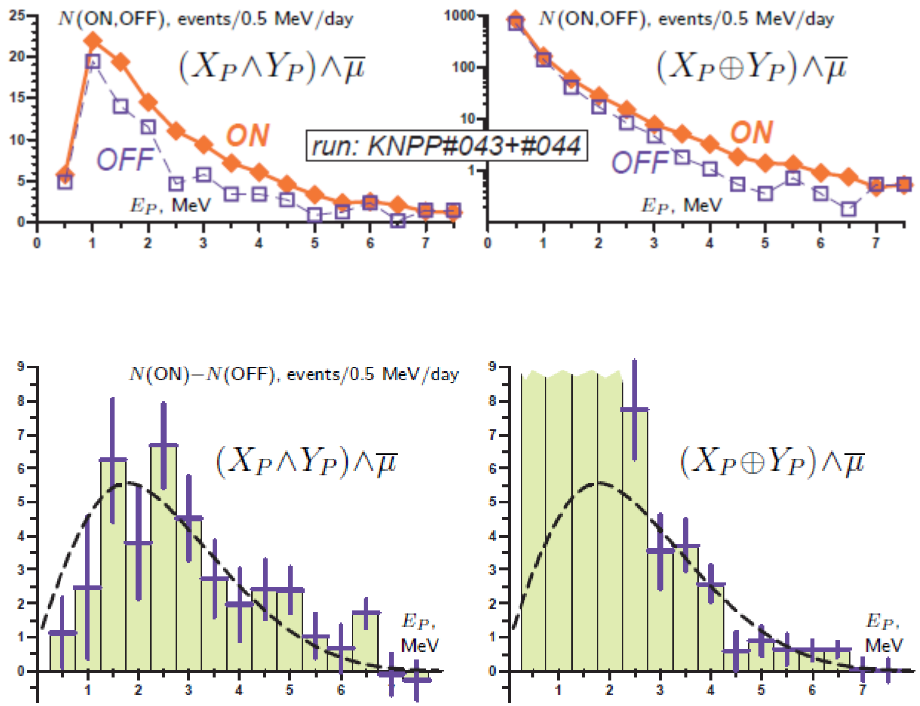
- Δm^2=0.2- 1 eV2 region very sensitive to the treatment of correlations.
- Lowest Δm^2 spot driven by the lever arm of ILL and SRP points.

Nucifer expected contour



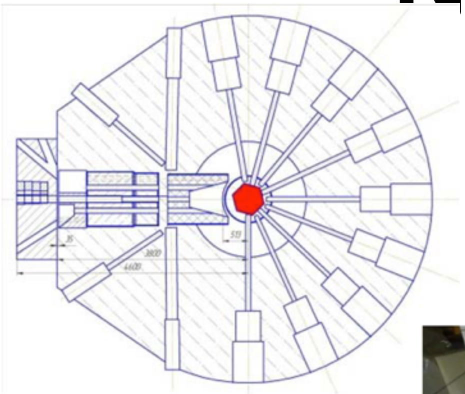
DANSS





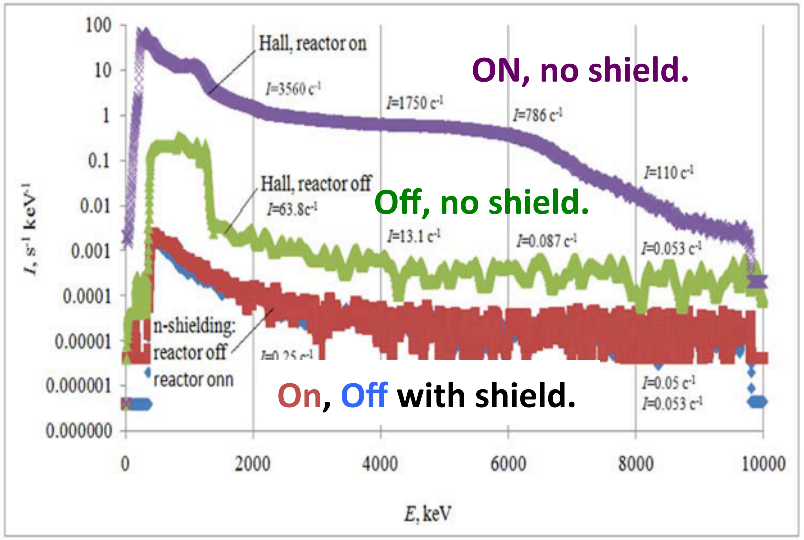
Pure Stat contours, no syst effect

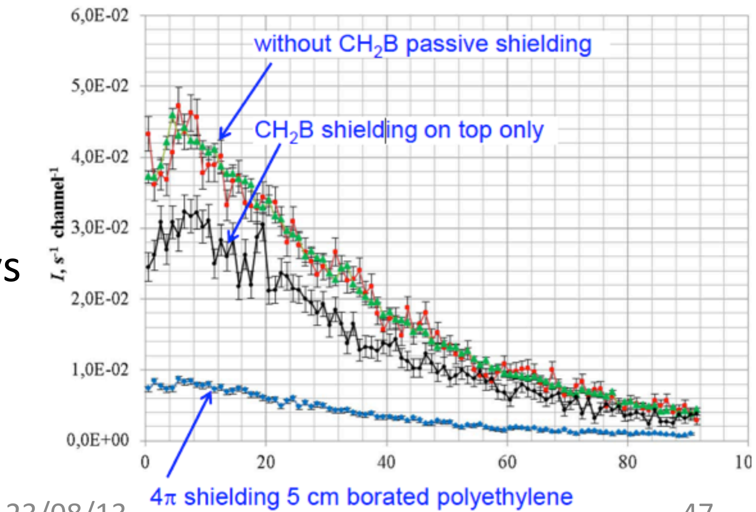
Neutrino-4 Prototype



Validation of a prototype detector at the WWR-M 17 MW reactor (Gatchina)

- Good suppression of γ background





- Neutrino detection currently limited by cosmic rays induced fast neutrons.
- Installation of shielding at the SM-3 site foreseen this fall.