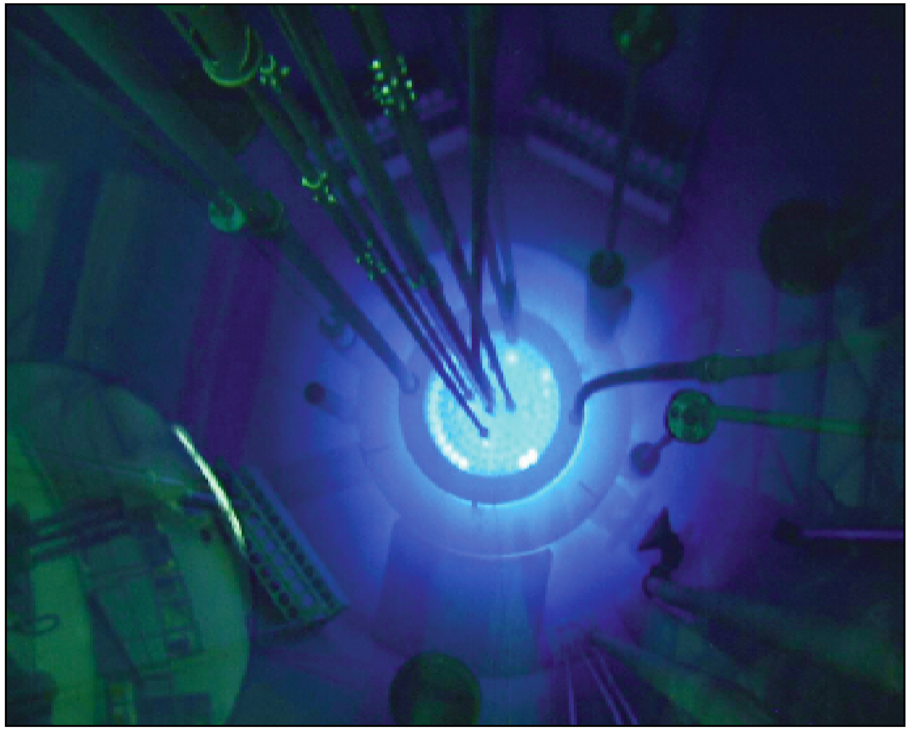
Reactor Neutrinos

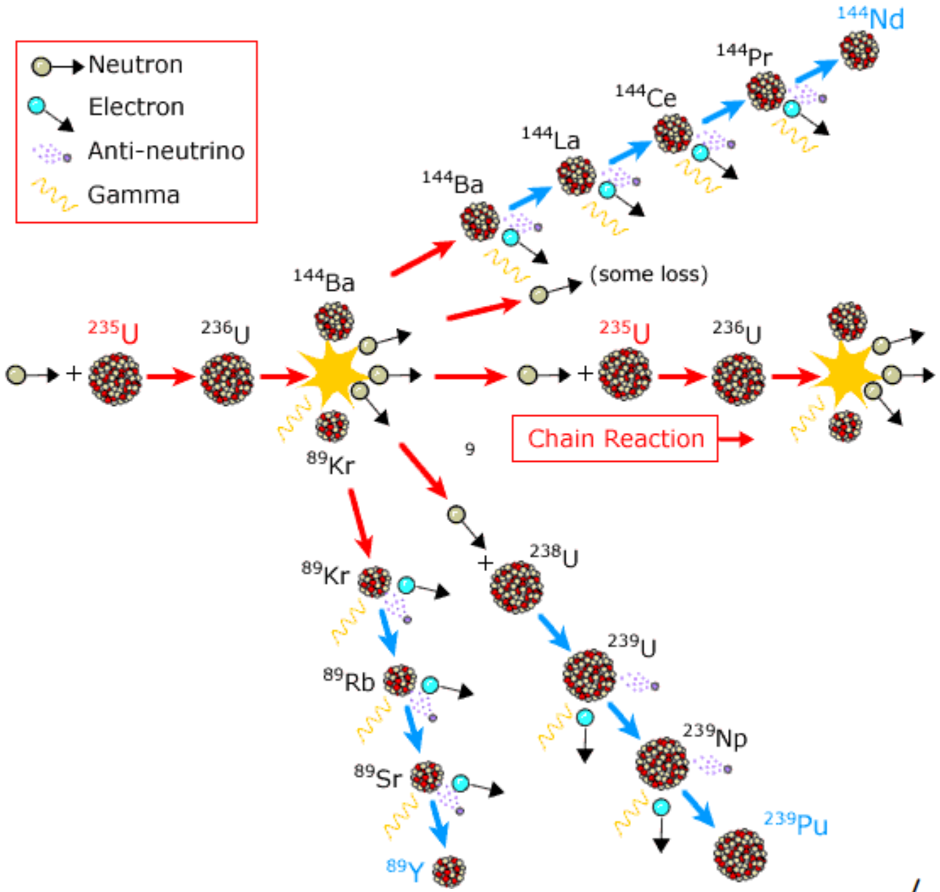


Launch Workshop

Sept 2017, Heidelberg

D. Lhuillier, CEA Saclay

Reactor Neutrinos



- Pure $\bar{\nu}_e$ source
- Intense: ~10^{20} ν/GW/s
- Few MeV Energy

Detected neutrino rate

$$N_\nu^{exp}(s^{-1}) \;=\; \frac{1}{4\pi L^2} N_p\, \epsilon\, \frac{P_{th}}{\langle E_f \rangle}\, \langle \sigma_f \rangle$$

Mean cross section per fission

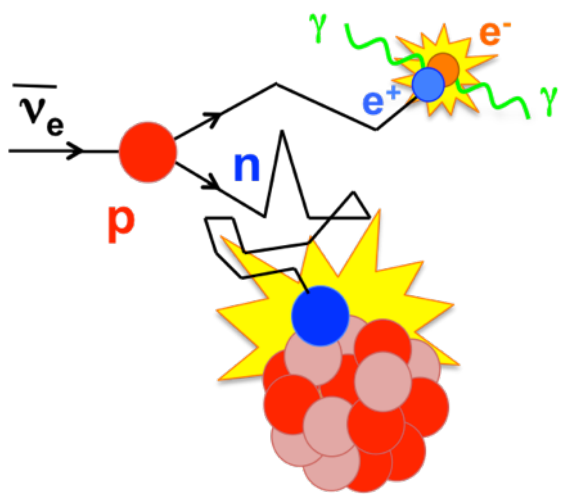
$$\langle \sigma_f \rangle = \sum_k \alpha_k \int_0^\infty dE\, S_k(E)\, \sigma_{IBD}(E)$$

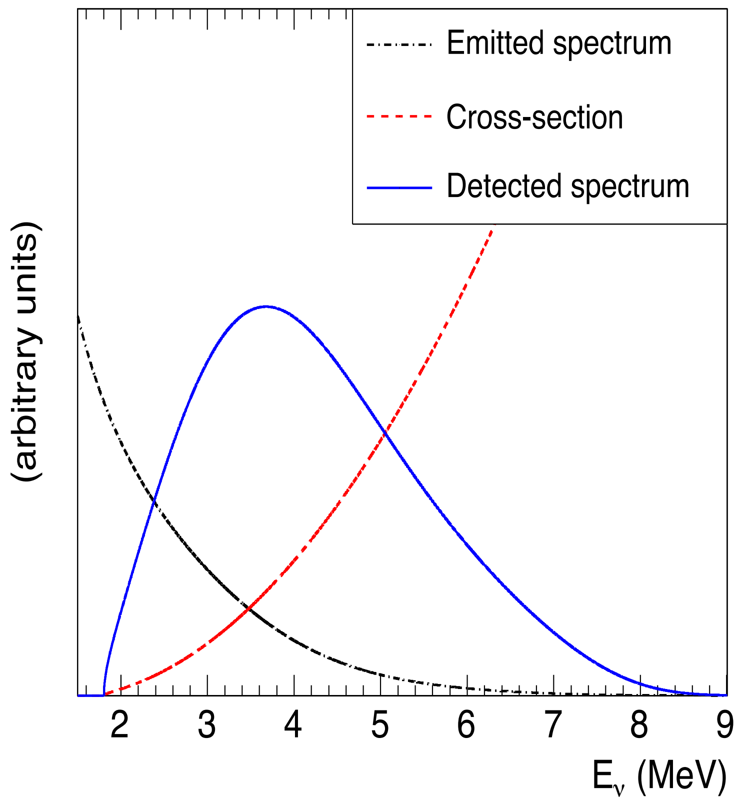
$$(k = {}^{235}U, {}^{239}Pu, {}^{238}U, {}^{241}Pu)$$

Detection Process

Inverse Beta Decay

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



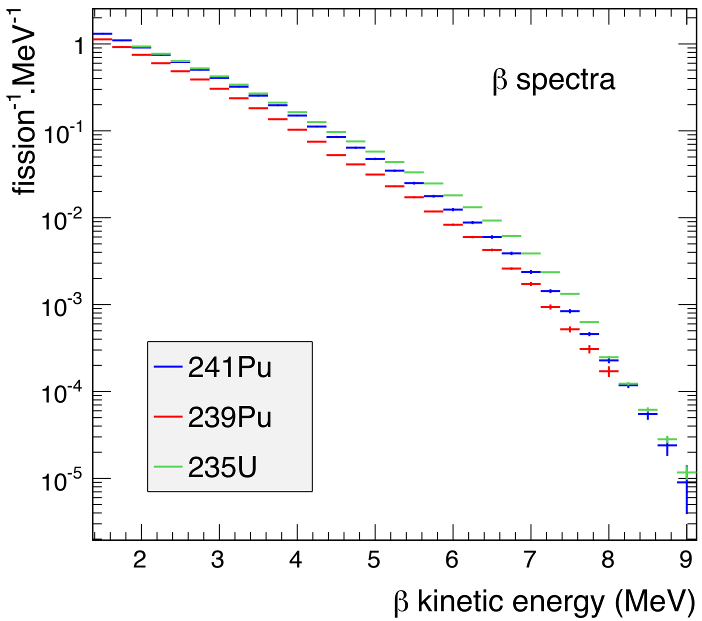


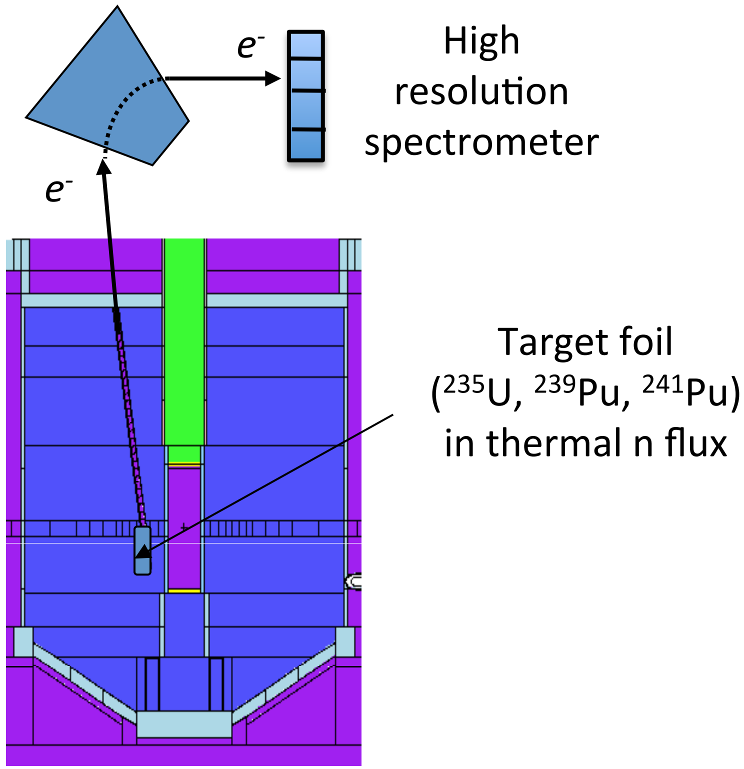
- Selective prompt-delayed signal sequence
- Discriminant n-capture on H, Gd (high E γ's) or Li (α+t)

$E_{vis} = E_{\nu} - 0.8$ MeV

The ILL electron Data “Anchor point”

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



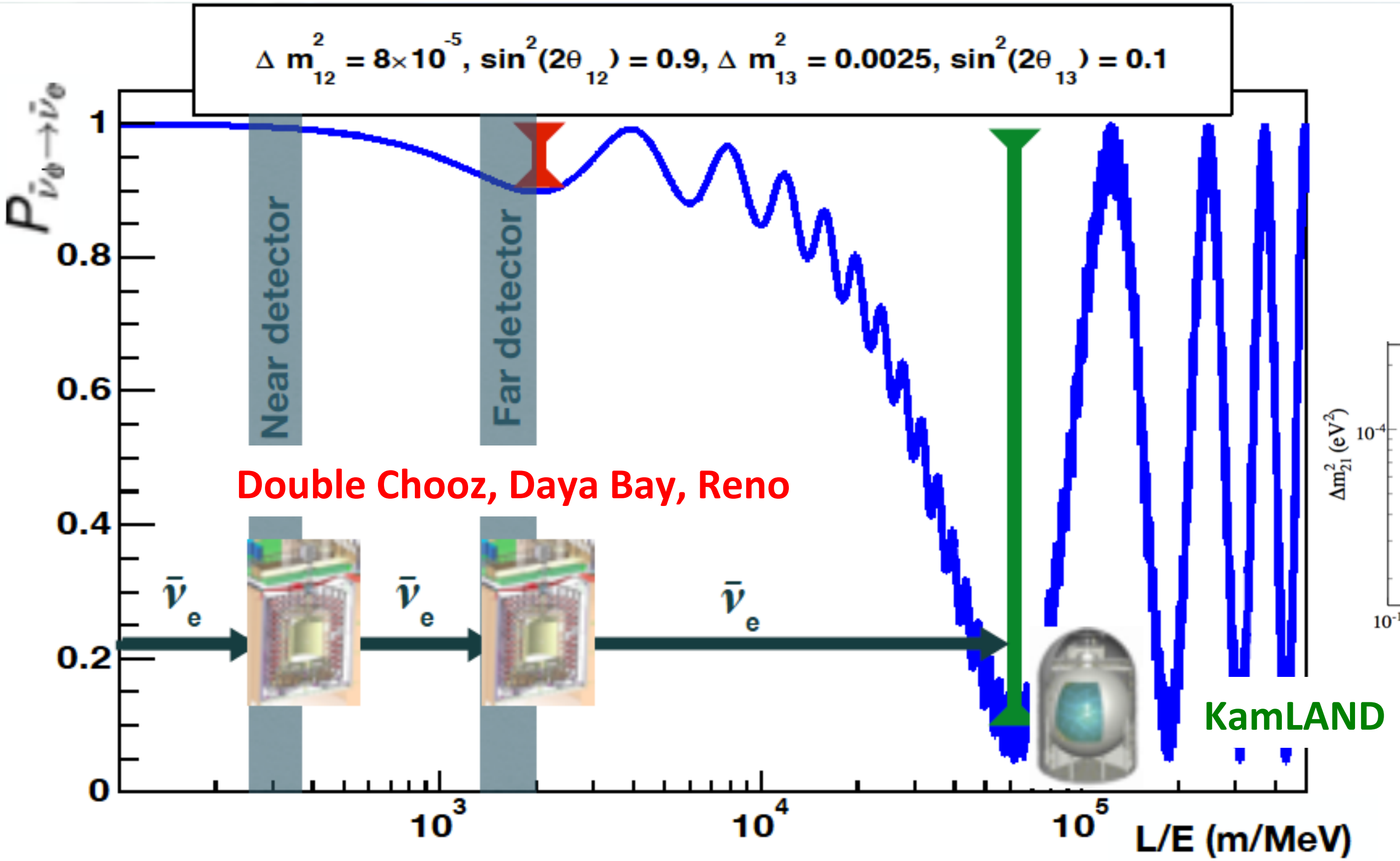


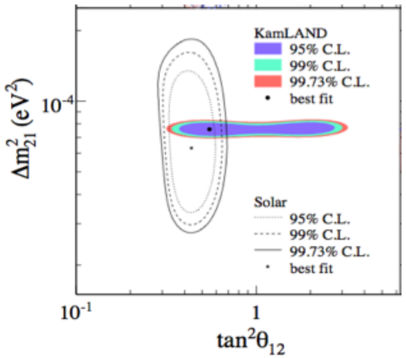
ILL research reactor (Grenoble, France)

- **Accurate fission b-spectra measured in the 80’s converted into ν-spectra.**
- **Key improvement in the quest for oscillations**

Oscillations of Reactor Antineutrinos

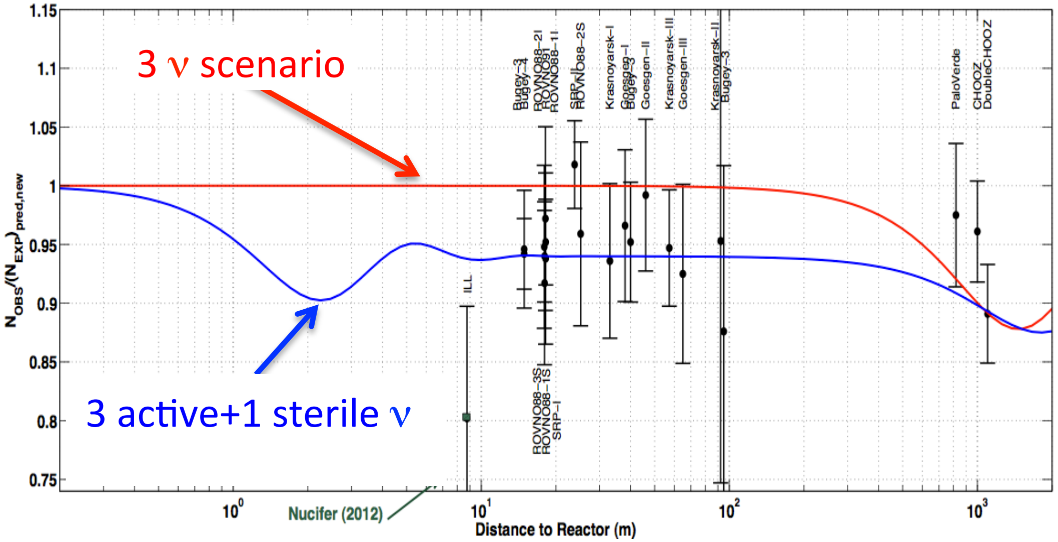
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{23} L/4E) - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta m^2_{12} L/4E)$$

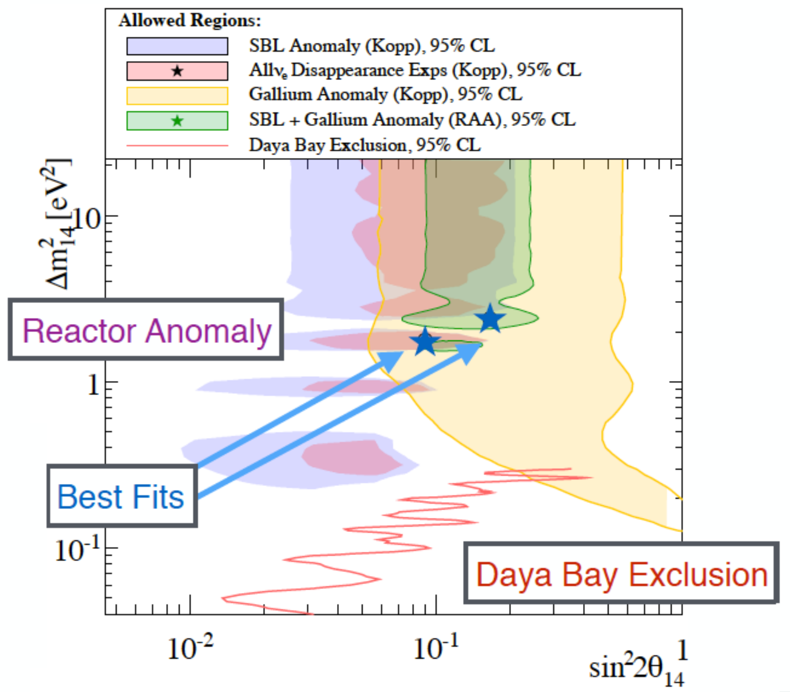




Reactor Antineutrino Anomaly

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2(2\theta_{ee})\sin^2(\Delta m^2_{14} L / 4E)$$



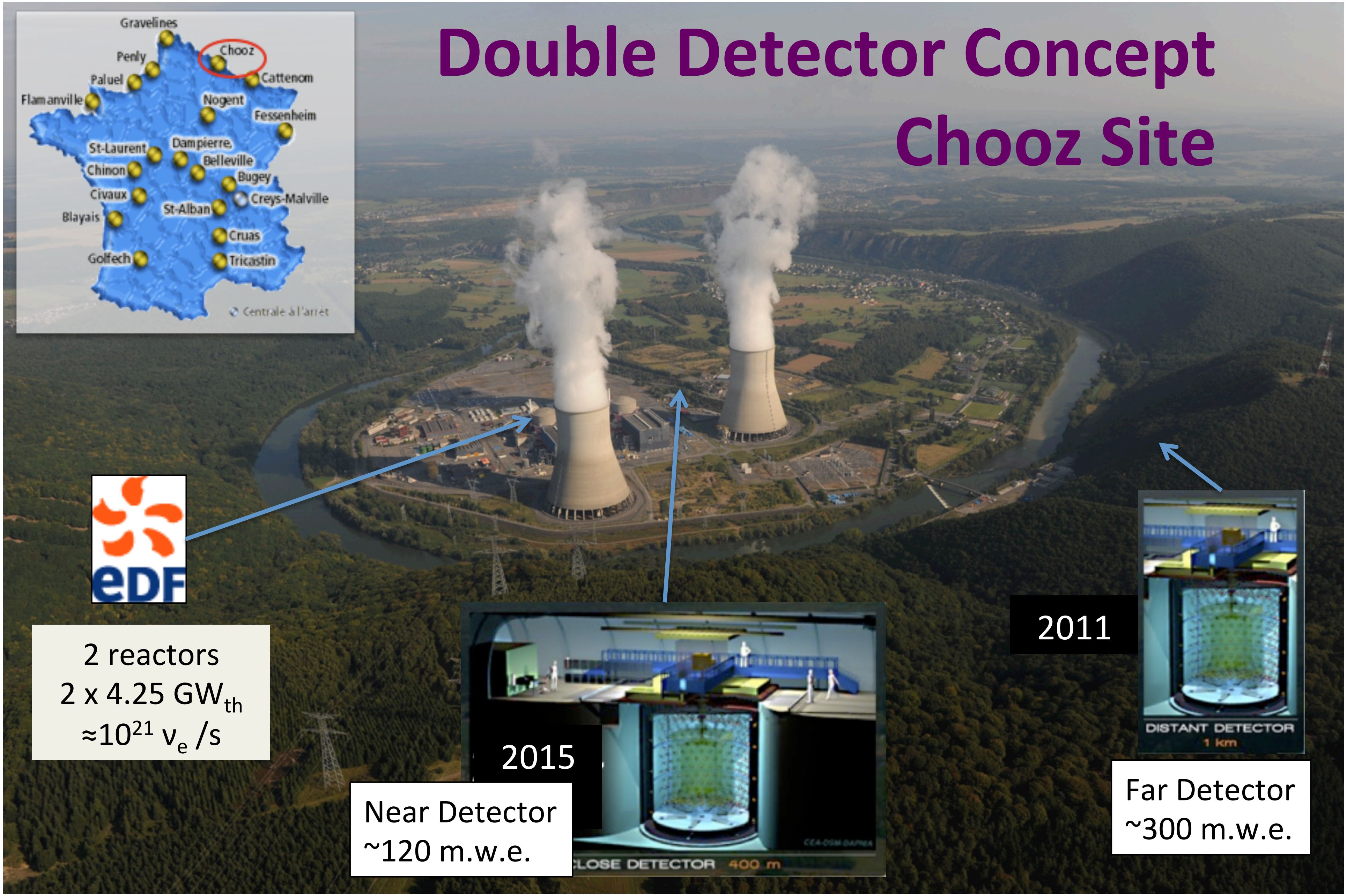


Best Fit :

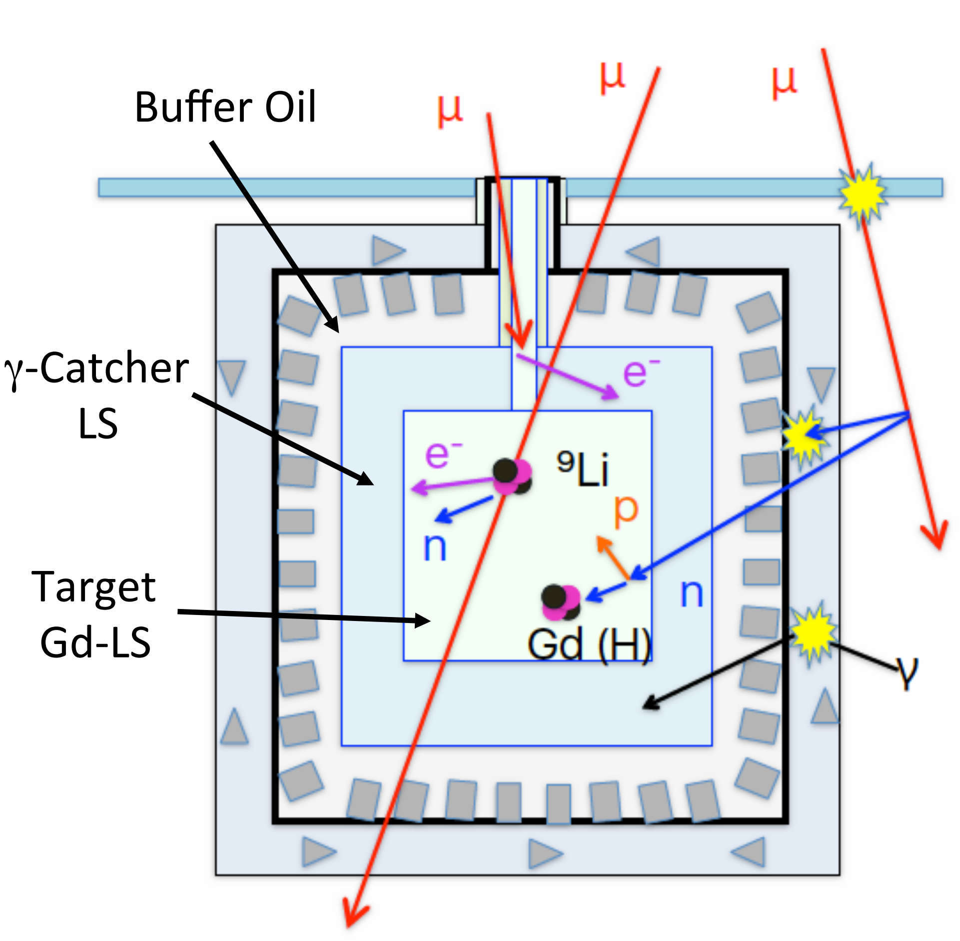
- $\Delta m^2 \sim 1\ eV^2$
- Mixing ~ 10%

θ_{13} Measurements

Double Detector Concept
Chooz Site



Backgrounds



- **Correlated BG, induced by muons**

  Cosmogenic isotopes
  ^{9}Li → β^- + α's + n

  Fast neutron
  Recoil p + n capture

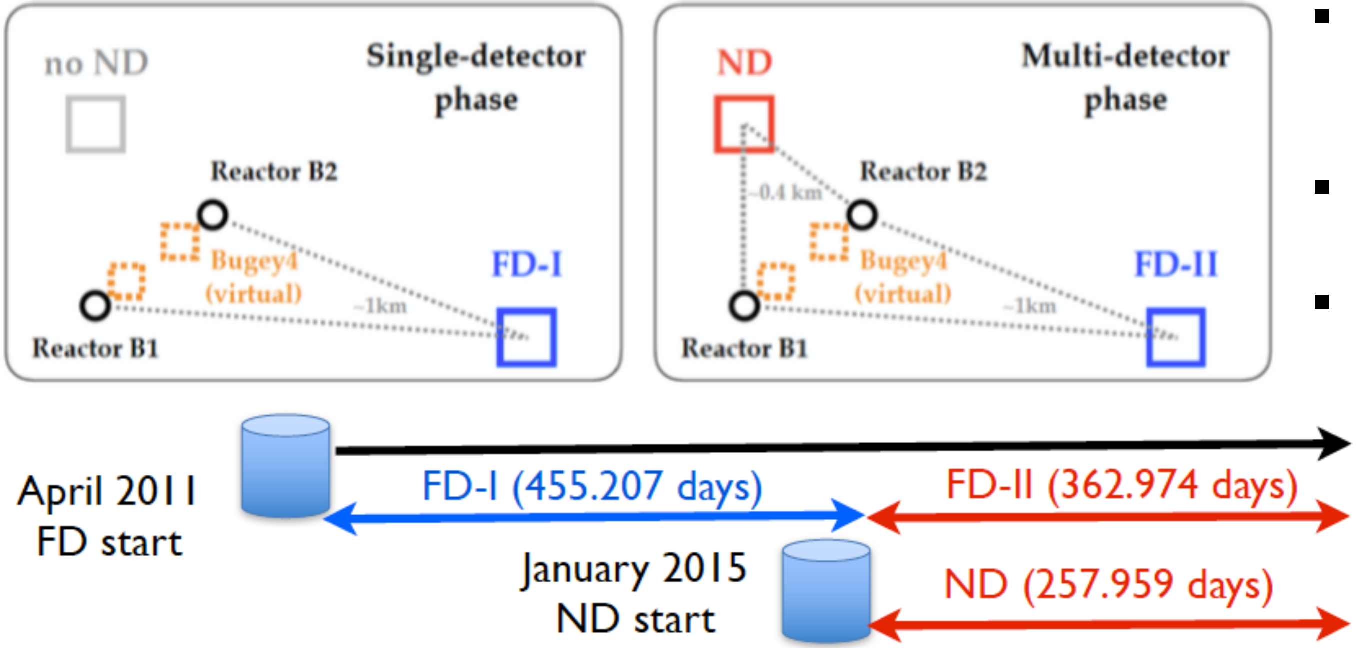
  Stopping μ
  μ → Michel e^- + ν's

- **Accidental coincidence**

  γ + γ or γ + n-capture


INETICS

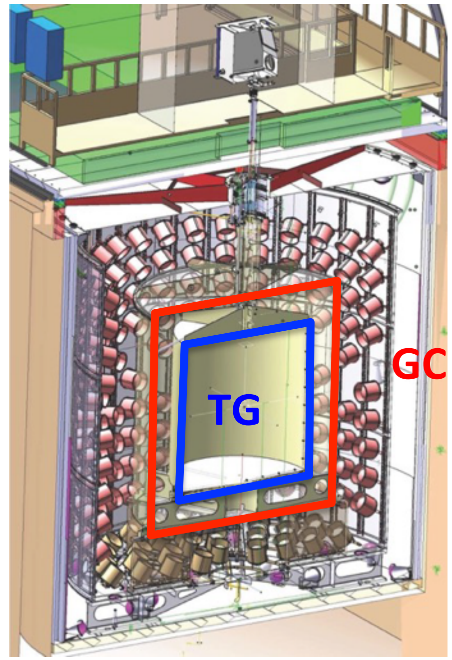
Data Sets and Analysis



- Simple config: 2 cores, 2 det. close to isoflux curve.
- Anchor point of Bugey4 rate.
- 7.5 Days with both reactors OFF.

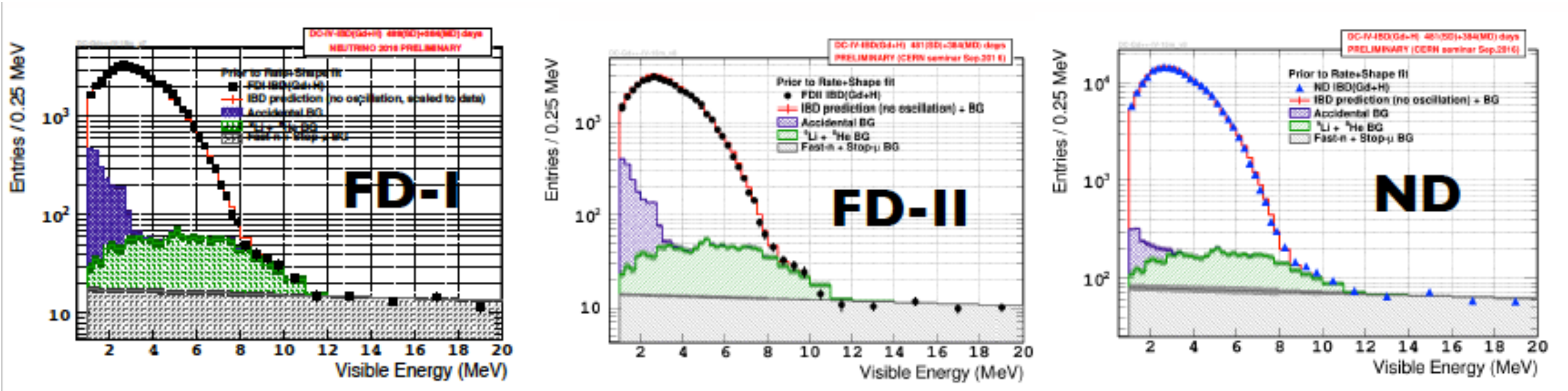
Gd+H analysis:

- use delayed n-capture on both Gd and H atoms in TG+GC volume
- ~3 x more events
- Dominant systematic from GC proton number
- Increase in accidental BG (rejected by neural-network)



θ_{13} Measurement

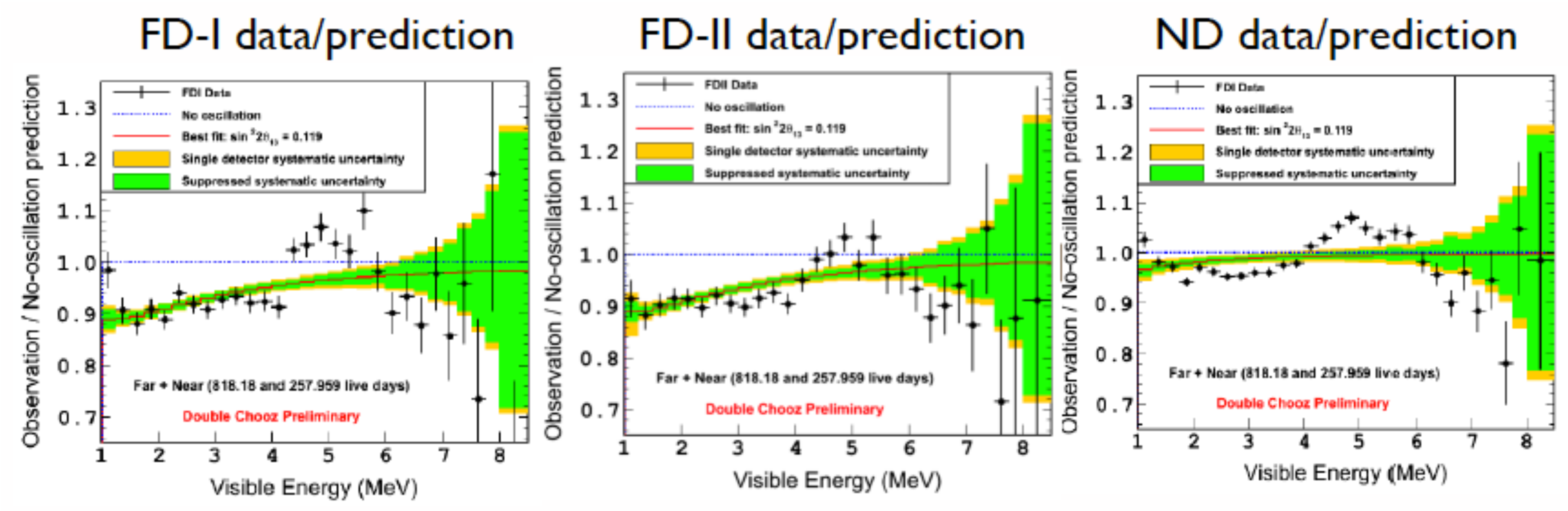
- Compare FD and ND data simultaneously to predictions



- All correlation of systematic uncertainties are taken into account (common n flux uncertainty between FD-II and ND).

- Background rate and shape are estimated from specific data selection; simulation of β-n emitters.

θ_{13} Measurement

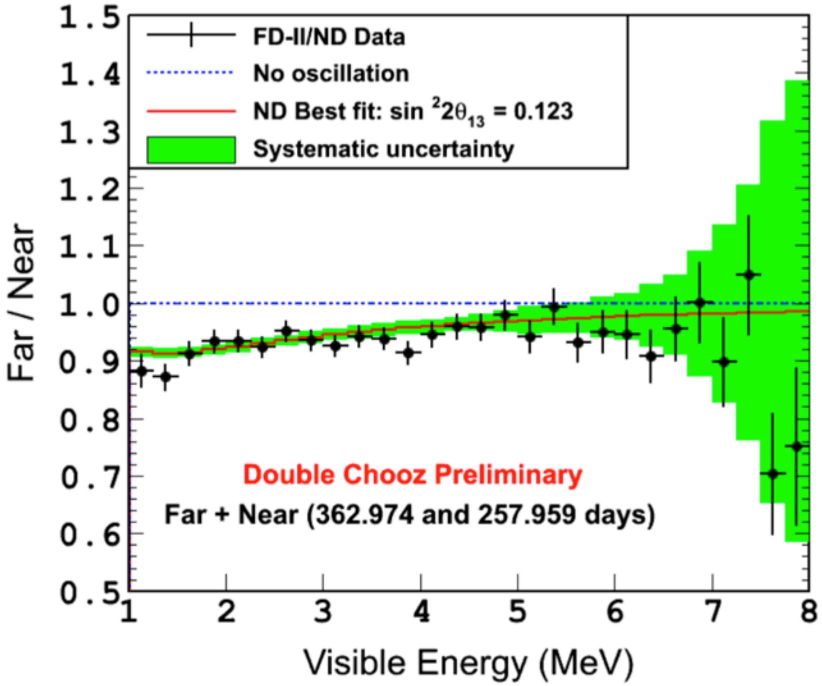


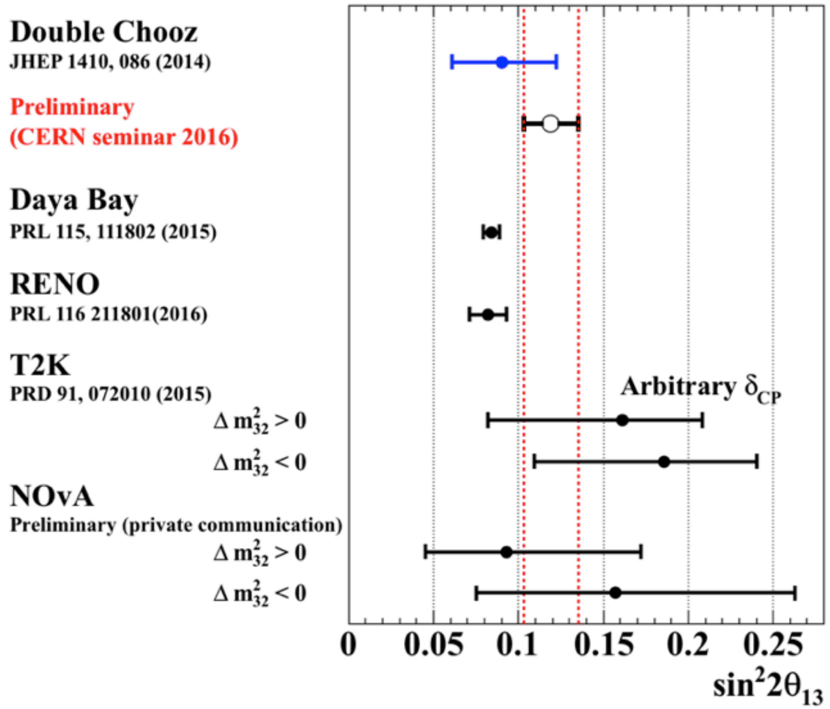
$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$

$\chi 2$/ndf: 236.2/114

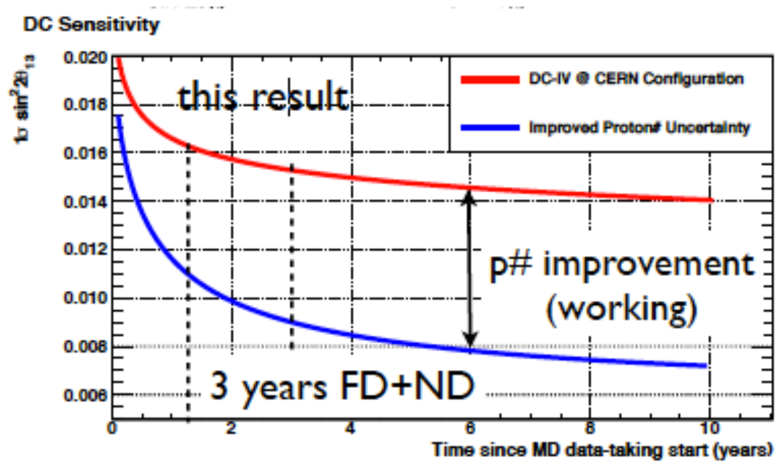
Large χ^2 due to a common difference of spectral model to data

Θ_{13}

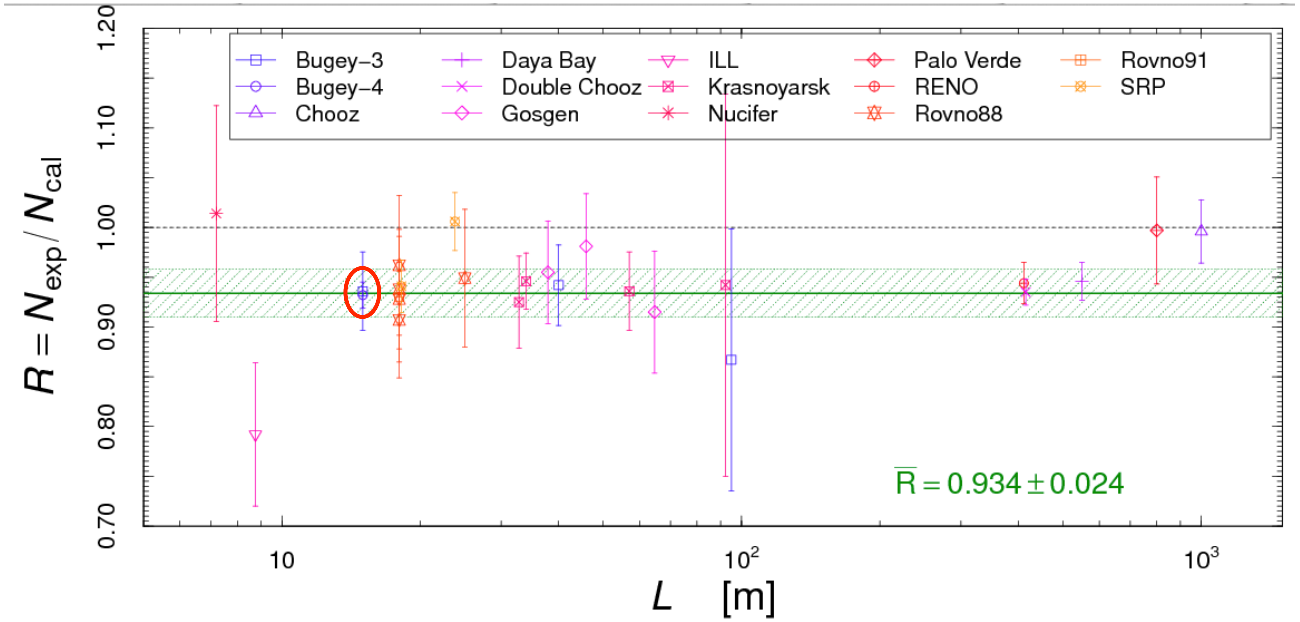




- Spectral distortion w.r.t. prediction nicely cancel in the F/N detector ratio.
- **World average θ_{13} reaches the 5% accuracy.**
- Key input for future δ_{CP} and mass hierarchy measurements.



Reactor Antineutrino Anomaly

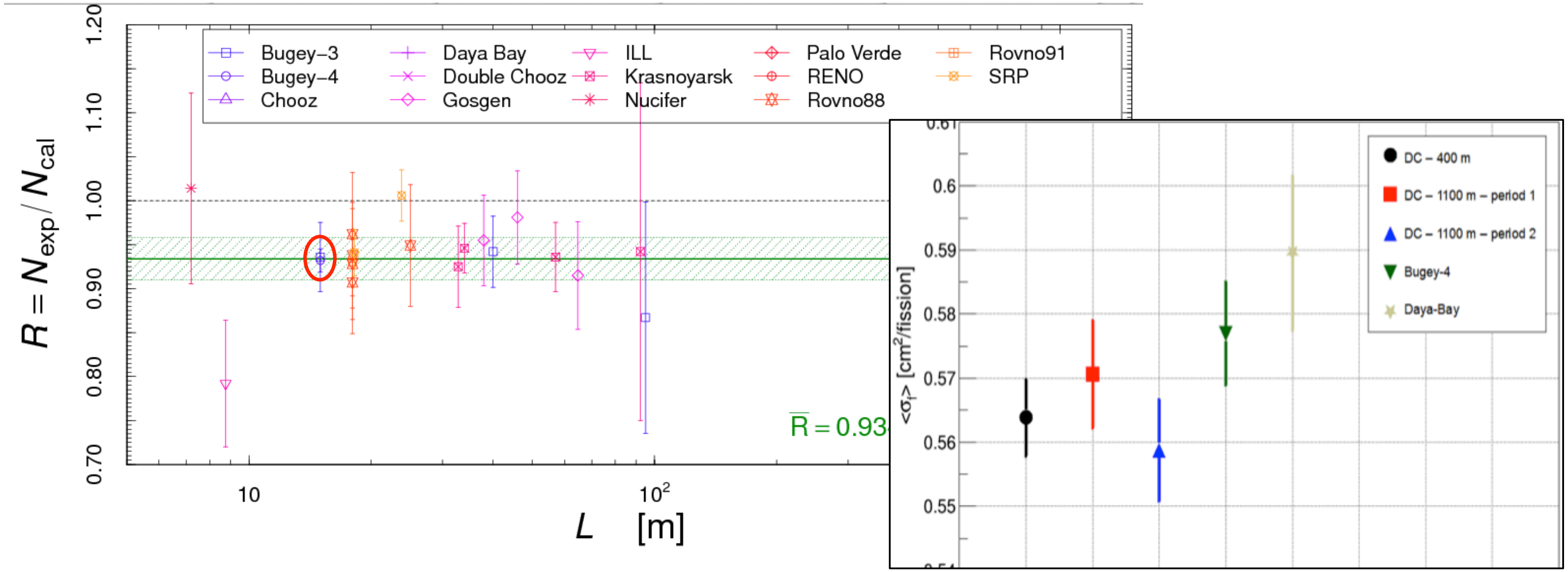


- All experiments measure the same mean neutrino flux to high precision
  DC record for fission cross section: **$<\sigma_f>_{ND}$= 0.564x10^{-42}cm^2/fission ±1.1%**

- 5 MeV bump questions the validity of the predictions

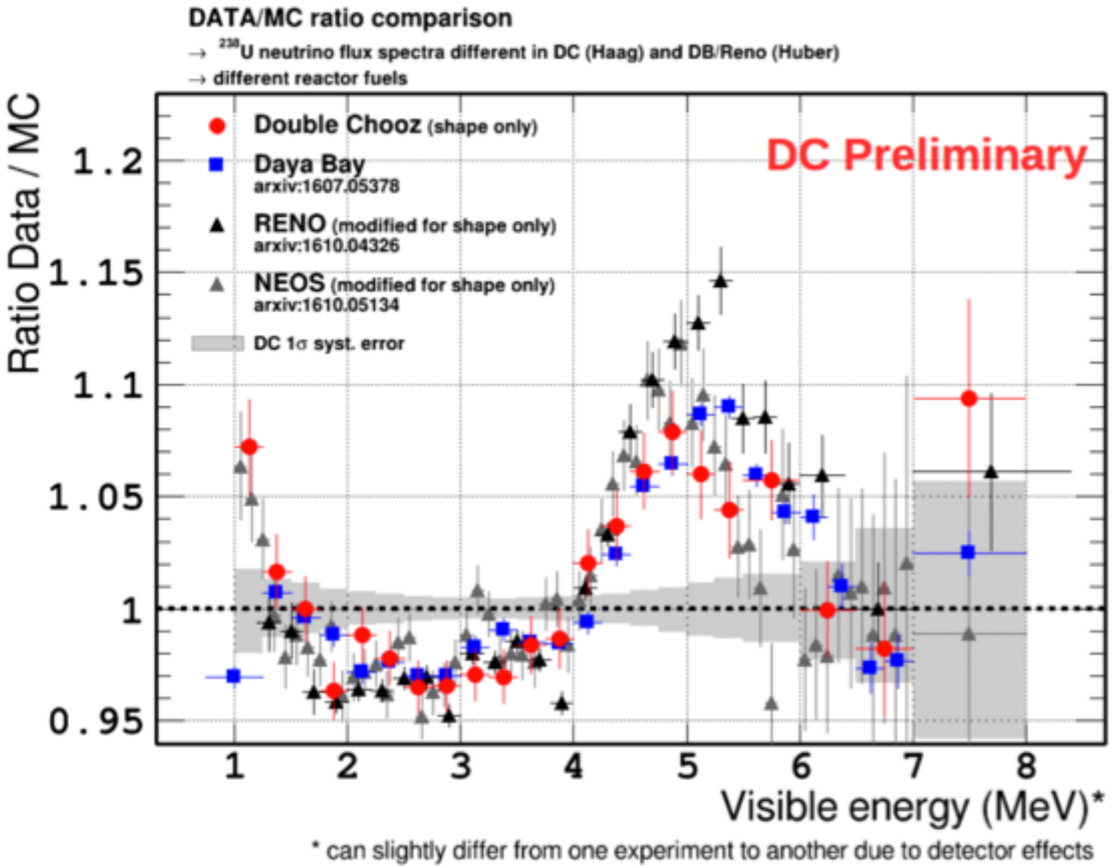
- Recent DB separation of ^{235}U and ^{239}Pu spectra kills the sterile neutrino hypothesis?

Reactor Antineutrino Anomaly



- All experiments measure the same mean neutrino flux to high precision
  DC record for fission cross section: **$<\sigma_f>_{ND}$= 0.564x10^{-42}cm^2/fission ±1.1%**
- 5 MeV bump questions the validity of the predictions
- Recent DB separation of ^{235}U and ^{239}Pu spectra kills the sterile neutrino hypothesis?

5 MeV Bump



- Similar structure seen by several experiments.
- Triggered lot of activities about possible biases in the predicted spectra.

Biases in Predictions

A. Hayes and P. Vogel, arXiv:1605.02047

1) Forbidden transitions

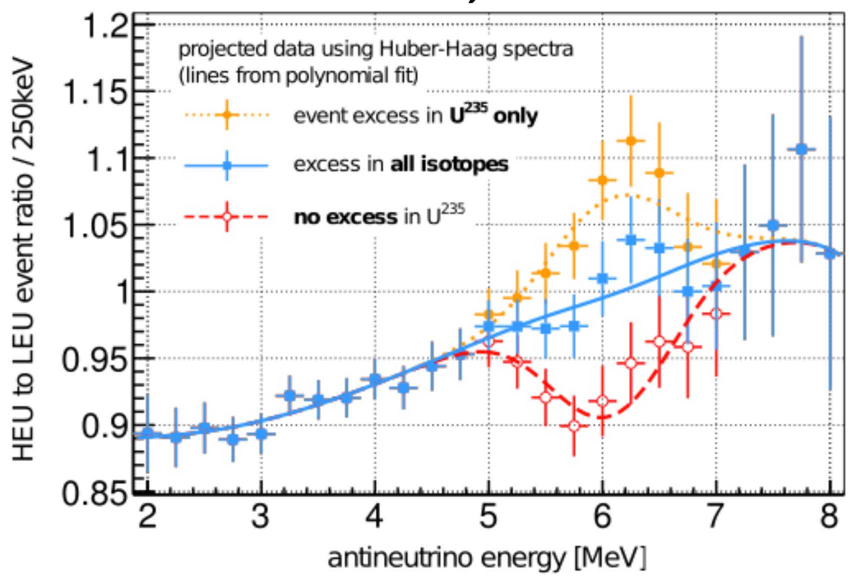
2) Corrections to Fermi theory

- Not likely to explain the bump
- Extra systematics in the predictions, to be quantified

3) ^{238}U spectrum:
   - excess appears in latest ab initio calculation using the JEFF library
   - Enhanced contribution of ^{238}U in the 5 MeV range.

4) Reference beta spectra measured at ILL with a highly thermalized neutron spectrum

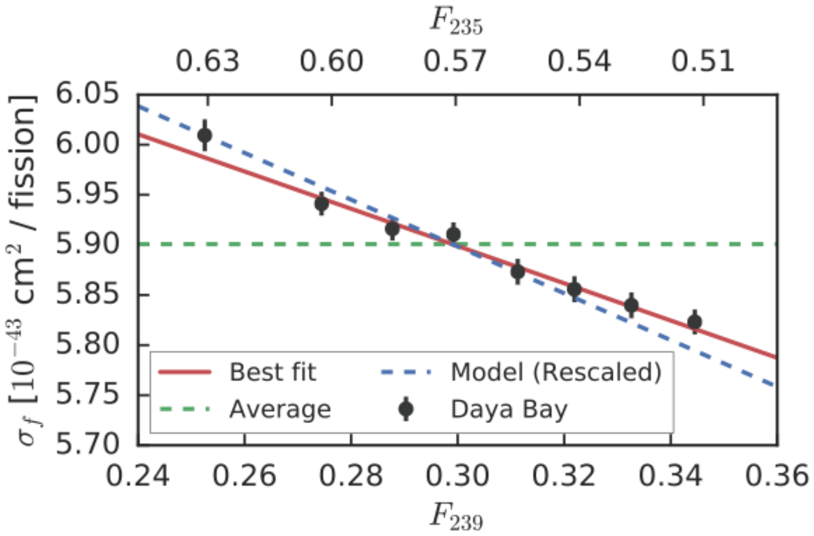
C. Buck et al, arXiv:1512.06656

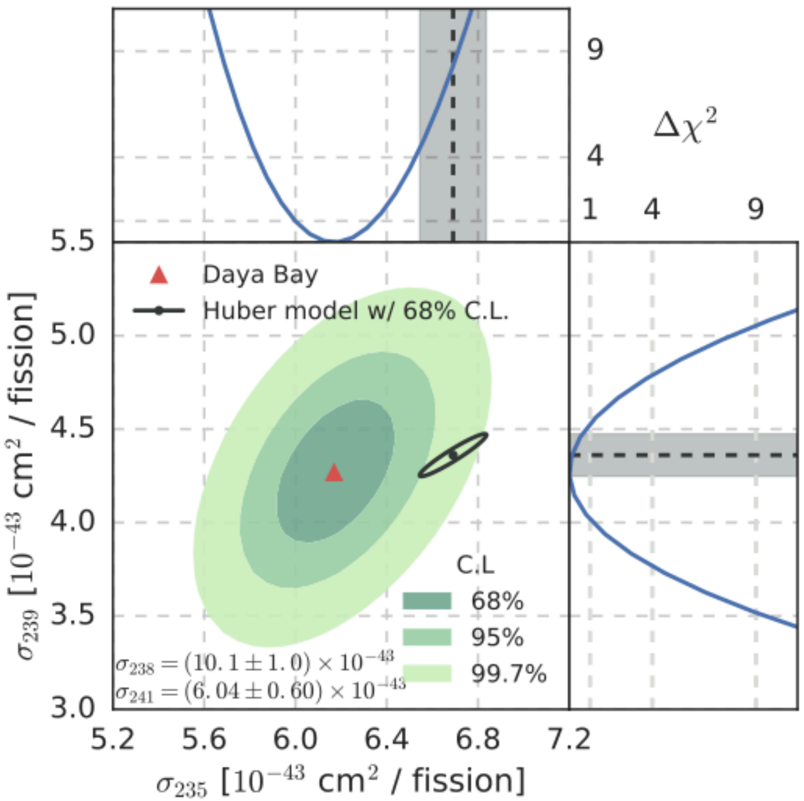


To be tested by Research reactor experiments

Spectrum Evolution vs Burnup

Daya Bay, PRL118, 251801 (2017)





- Evolution of the antineutrino flux vs the fisison fraction of ^{239}Pu allows for a combined fit for ^{235}U and ^{239}Pu.

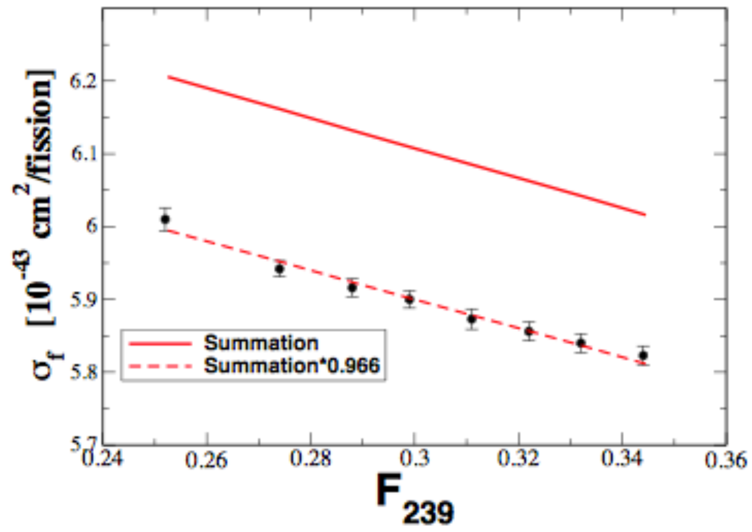
- Global measured deficit seems to be carried by the ^{235}U only (8% lower rate) while ^{239}Pu is consistent with prediction.

- Equal deficit hypothesis, from oscillation toward a sterile ν, is disfavored at 2.8 σ

Sterile ν Hypothesis Still Alive

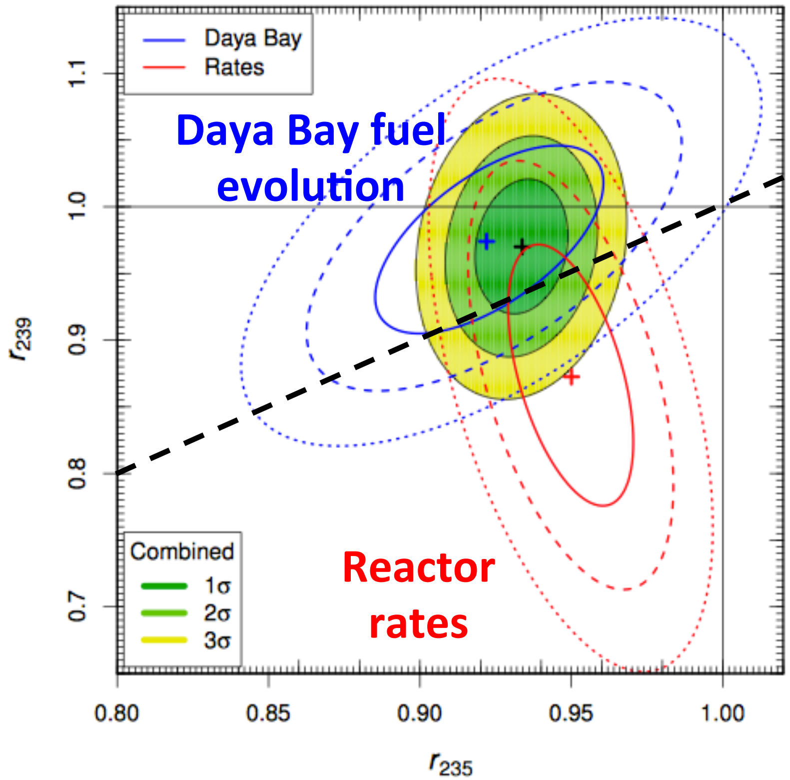
Hayes et al., arXiv 1707.07728

- Summation (ab initio) calculation compatible with DB result and still showing shared deficit



Giunti et al., arXiv 1708.01133

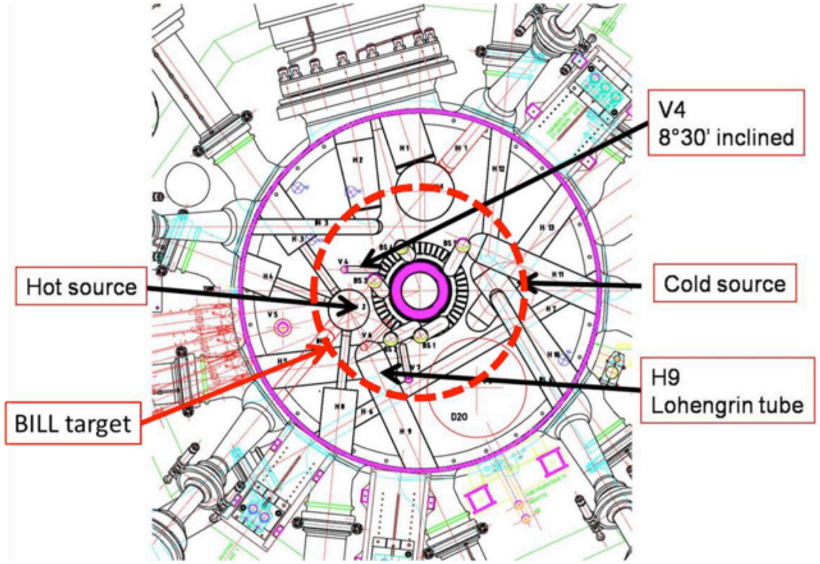
- Combined analysis of DB and short baseline data favors the oscillation scenario ($\Delta m^2 = 0.48$ eV^2, $\sin^2(2\theta) = 0.15$)
- Best fit obtain with a slight increase of ^{239}Pu normalization.

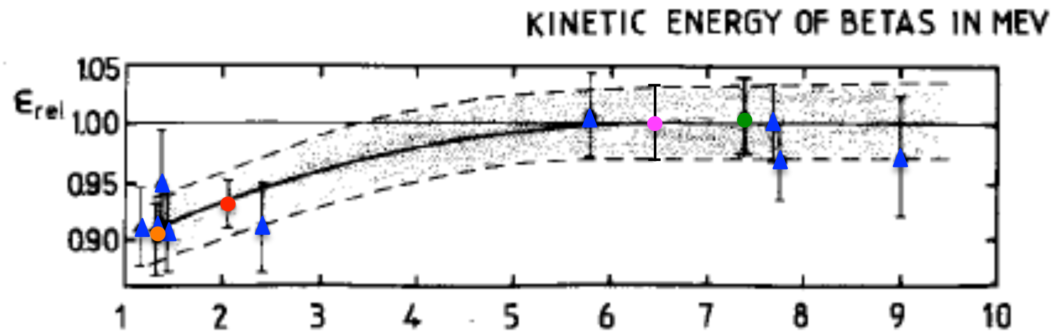


Normalization of ILL spectra

- **Fission cross section** of U and Pu isotopes:
  - Computation with updated nuclear data recovers the ^{235}U cros-section but leads to a 1.8% increase of the ^{239}Pu prediction.

- **Neutron flux and detection efficiency:**
  - Reference electron conversion lines with know n-capture cross sections.
  - Different lines were used for the energy part of the electron spect





$^{115}In(n,\gamma)^{116m}In$ $^{113}Cd(n,\gamma)^{114}Cd$ $^{207}Pb(n,\gamma)^{208}Pb$

$^{115}In(n,\gamma)^{116}In$ $^{197}Au(n,e-)^{198}Au$

Courtesy of A. Letourneau

Normalization of ILL spectra

^{235}U

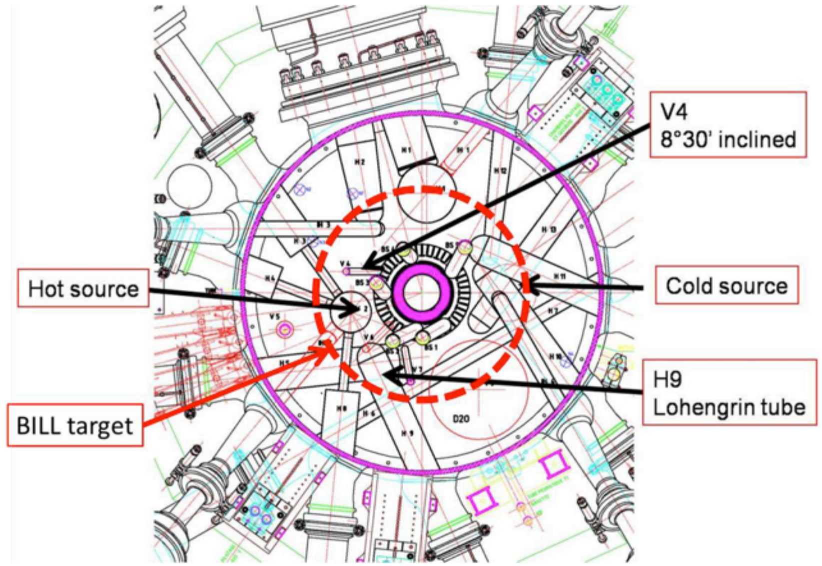
1) K. Schreckenbach et al., PLB99 (1981) 251
   Normalized on: $^{197}Au(n,e-)^{198}Au$
2) K. Schreckenbach et al., PLB160 (1985) 325
   Normalized on: $^{207}Pb(n,e-)^{208}Pb$ and $^{115}In(n,e-)^{116m}In$ reactions

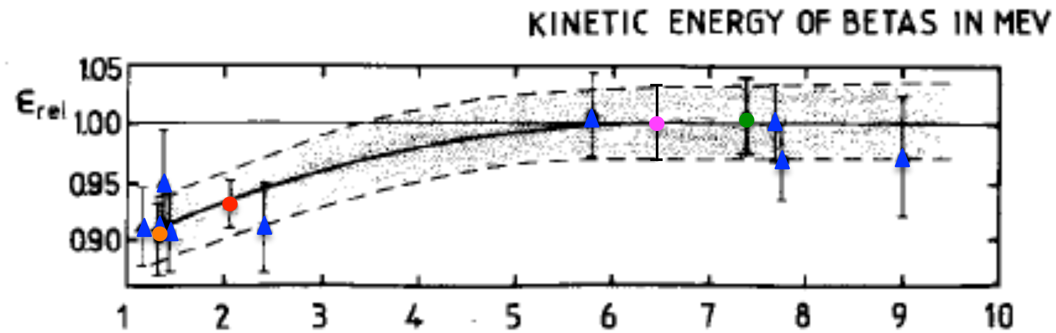
^{239}Pu

3) F. Feilitzch et al., PLB118 (1982) 162
   Normalized as 1) on: $^{197}Au(n,e-)^{198}Au$ and $^{115}In(n,\gamma)^{116}In$ electron spectra

^{241}Pu

4) A.A Hahn et al., PLB218 (1989) 365
   Normalized as 2)





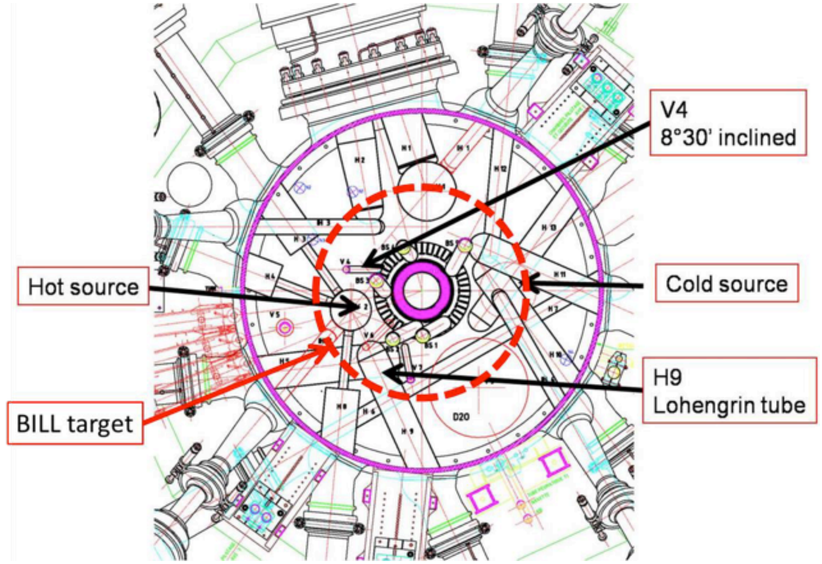
$^{115}In(n,\gamma)^{116m}In$ $^{113}Cd(n,\gamma)^{114}Cd$ $^{207}Pb(n,\gamma)^{208}Pb$

$^{115}In(n,\gamma)^{116}In$ $^{197}Au(n,e-)^{198}Au$

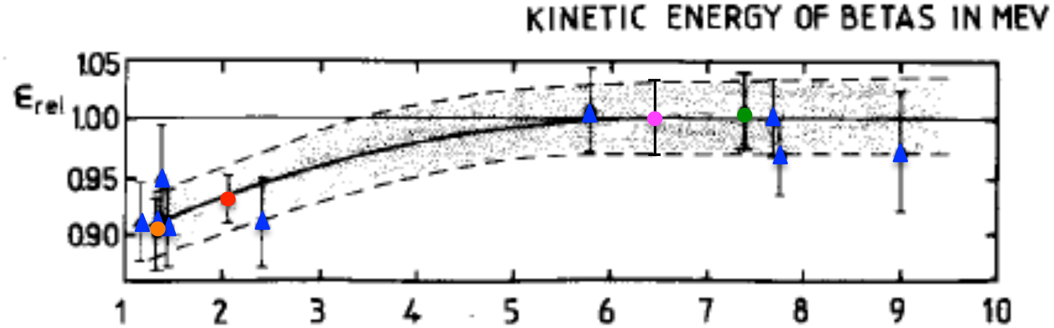
Courtesy of A. Letourneau

Normalization of ILL spectra

- **Fission cross section** of U and Pu isotopes:
  - 1.8% of ^{239}Pu prediction
- **Neutron flux and detection efficiency:**
  - Reference electron conversion lines with know n-capture cross sections.
  - Different lines were used for the high energy part of the electron spectrum



The normalization of the ILL beta spectra include uncorrelated inputs that could allow independent variations of ^{235}U and ^{239}Pu.

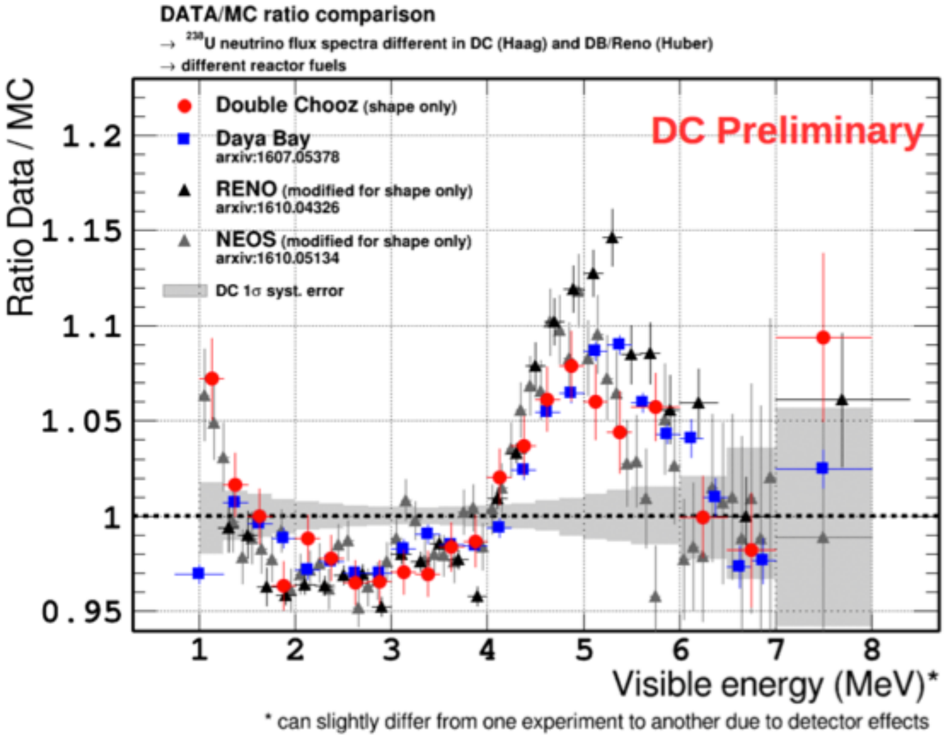


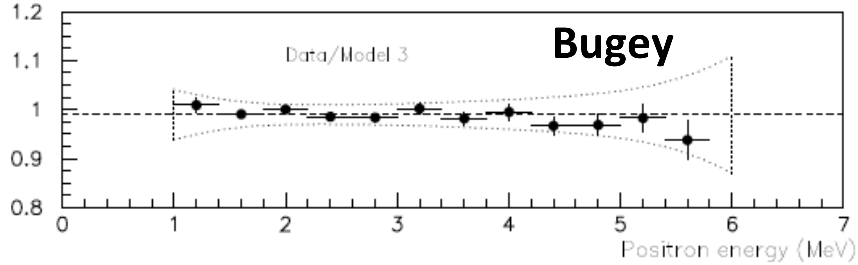
$^{115}In(n,\gamma)^{116m}In$ $^{113}Cd(n,\gamma)^{114}Cd$ $^{207}Pb(n,\gamma)^{208}Pb$

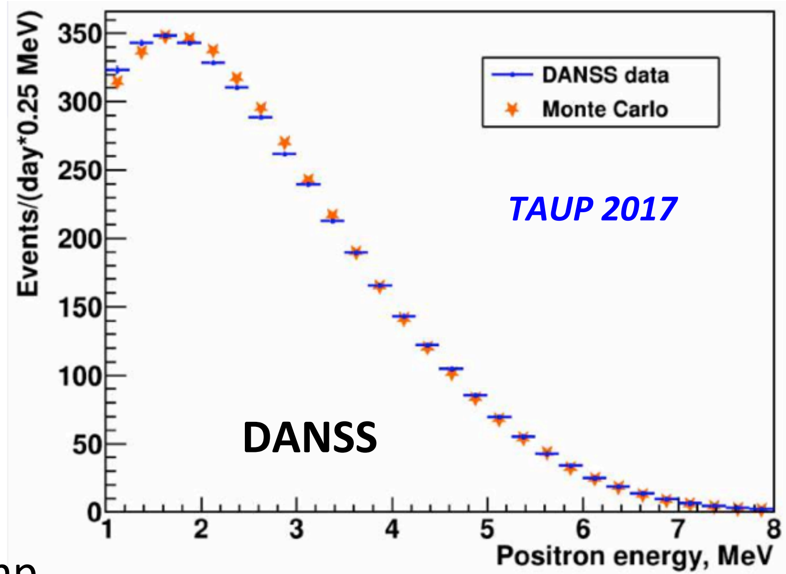
$^{115}In(n,\gamma)^{116}In$ $^{197}Au(n,e-)^{198}Au$

Courtesy of A. Letourneau

5 MeV Bump





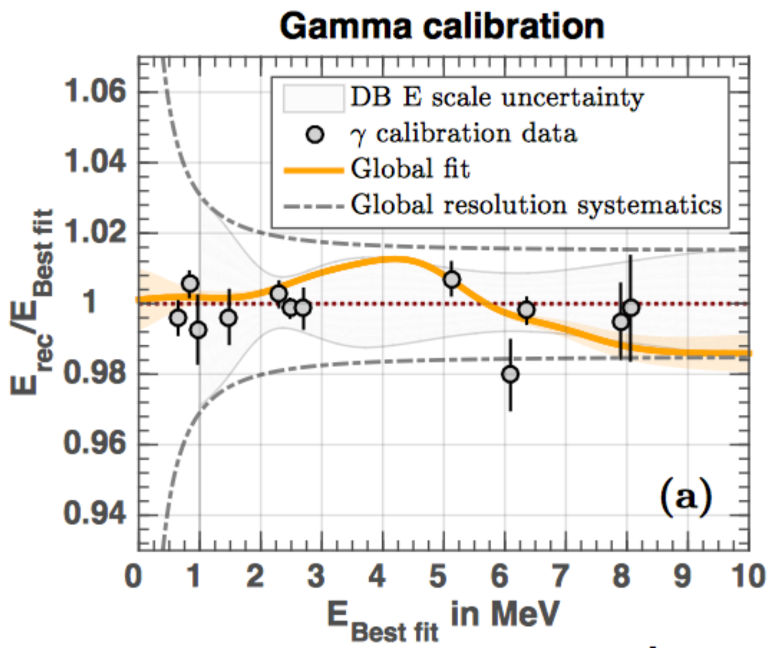


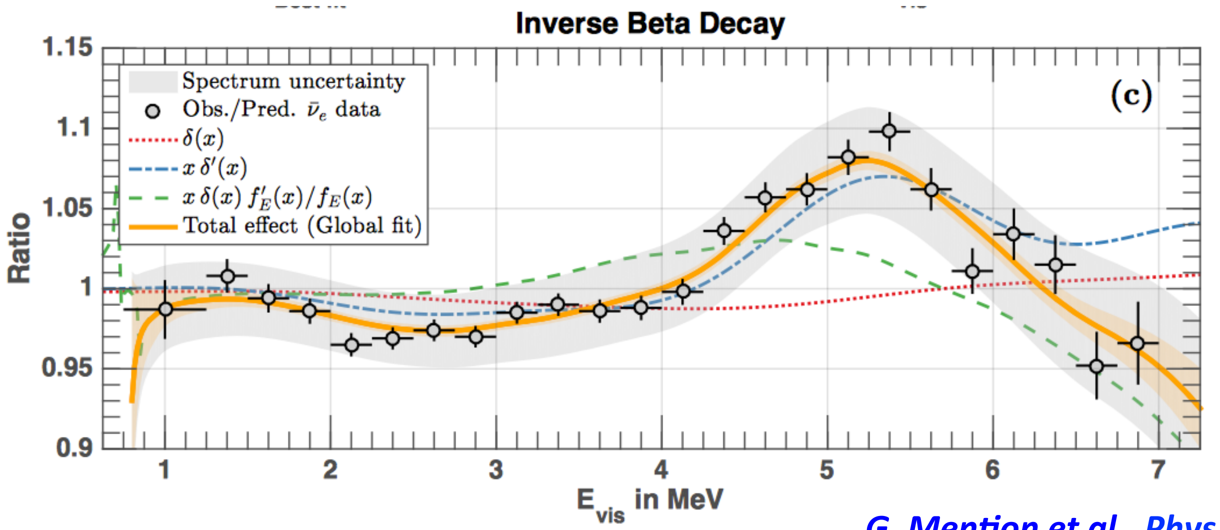
- Still some experiments don't see any bump
- Compatibility p-value between DB and Reno is below 7.10^{-4} (with free norm)

5 MeV Bump

Alternative explanation:

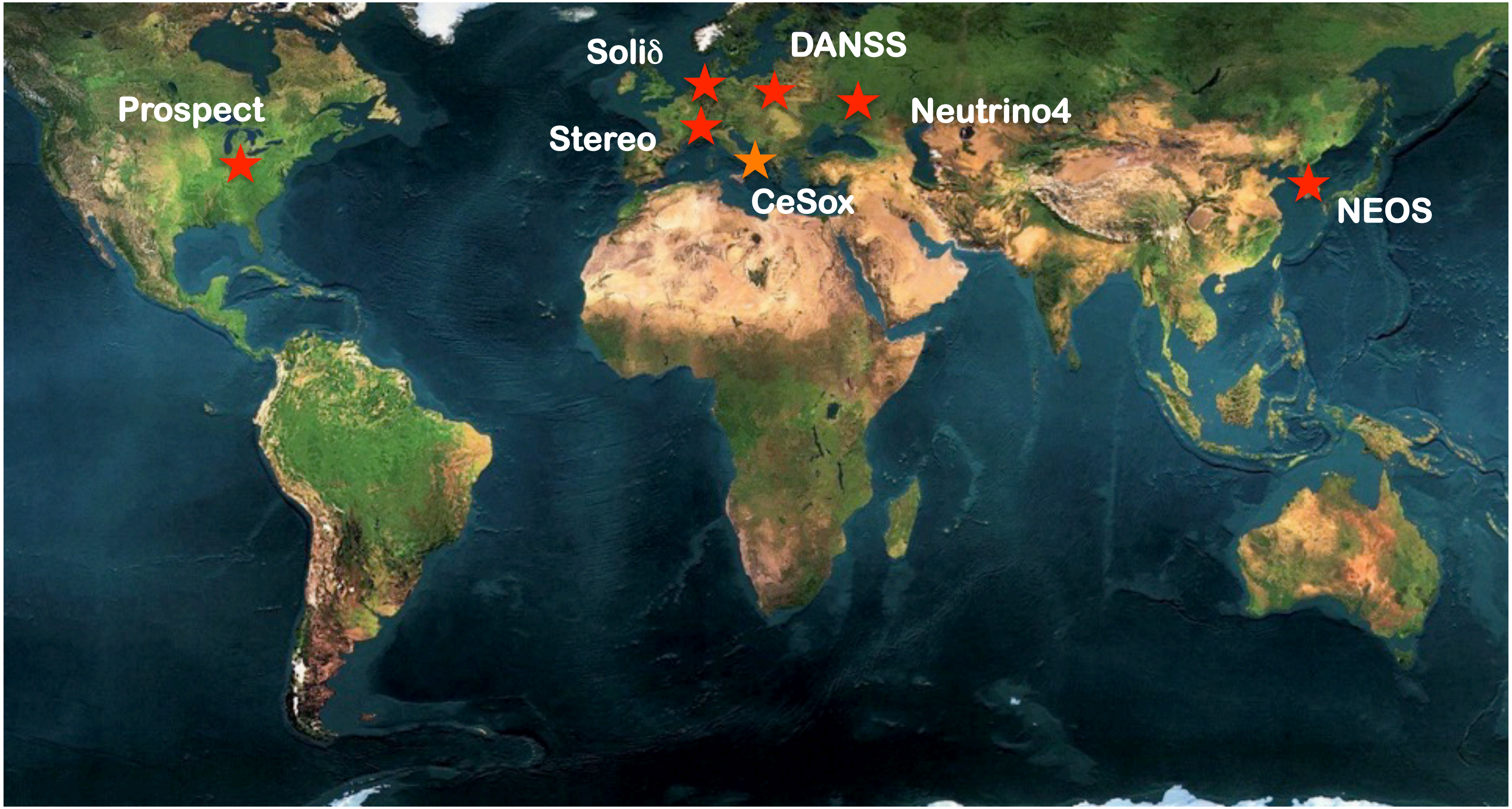
- Observed distortions correspond to quite small (%) artifacts of detector calibration.
- 5 MeV bump and anomaly might be decoupled
- Calls for <u>relative</u> measurements among identical detectors, as modern experiments do.





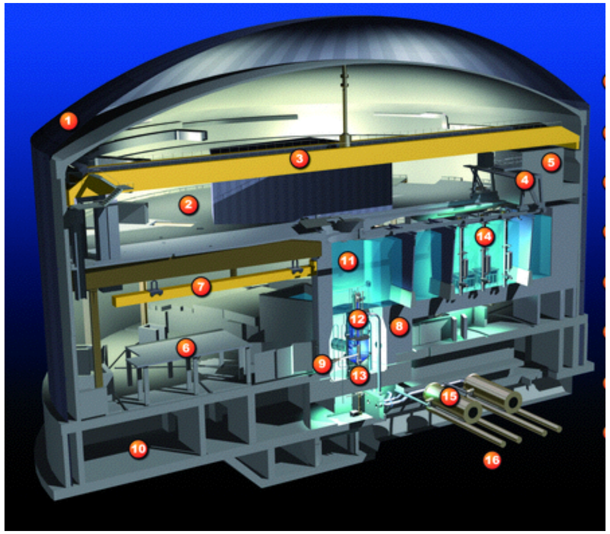
G. Mention et al., Phys.Lett. B773 (2017) 307-312

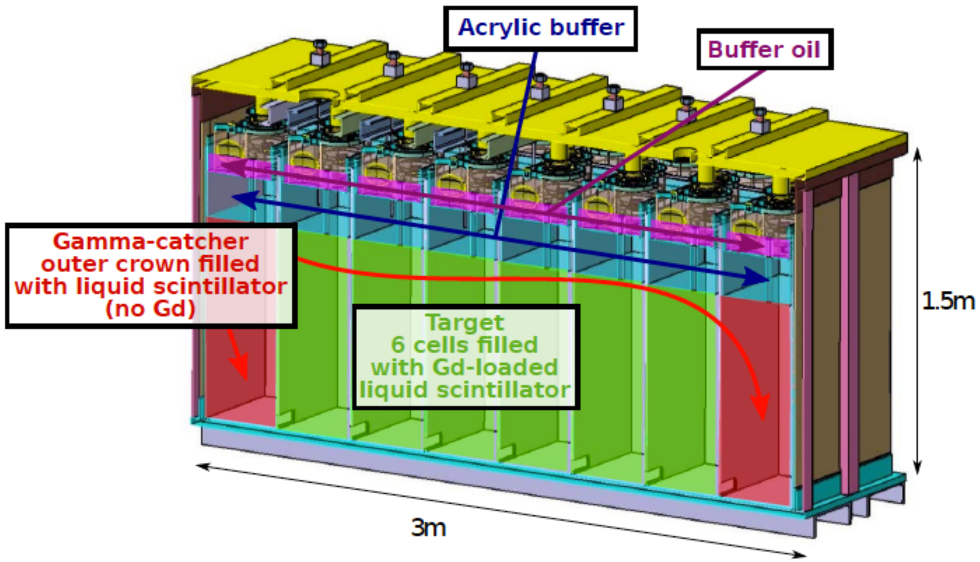
Quest for Sterile Neutrinos

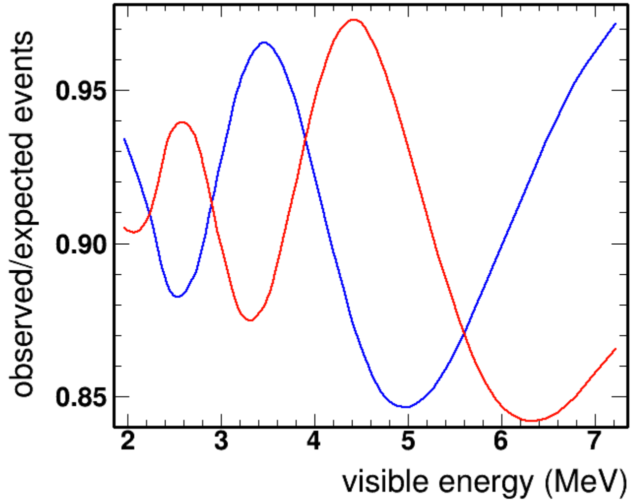


STEREO Detector

- **[8.9–11.1] m** from the ILL reactor core (France).
- Compact **(⌀ = 37 cm)**, with a **93% ^{235}U fuel**, and **58.3 MW_{th}** nominal power
- Under a water channel (~**15 mwe overburden** from cosmics)
- Look for spectra distortion in 6 identical target cells filed with Gd-doped LS.

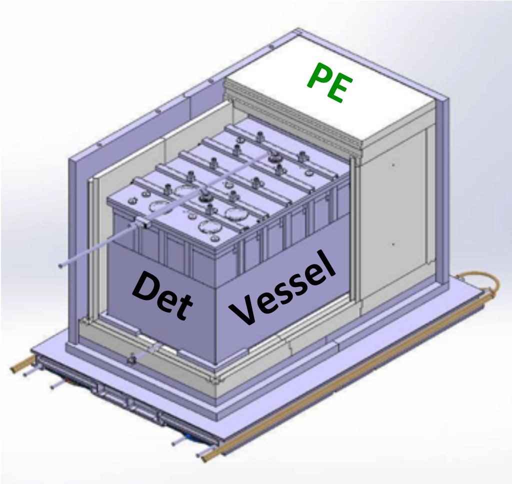


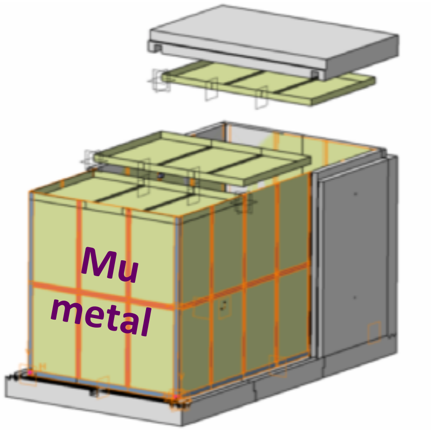


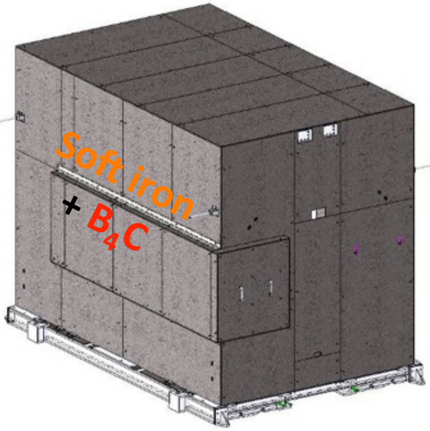


STEREO

Extensive shielding

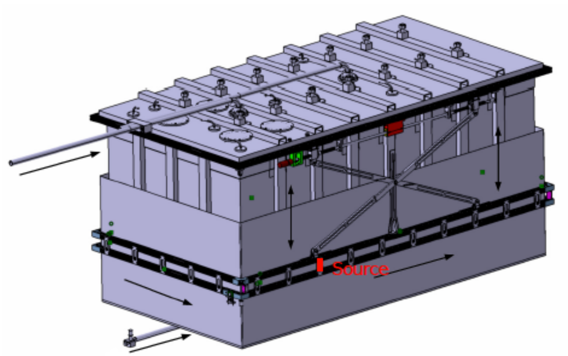




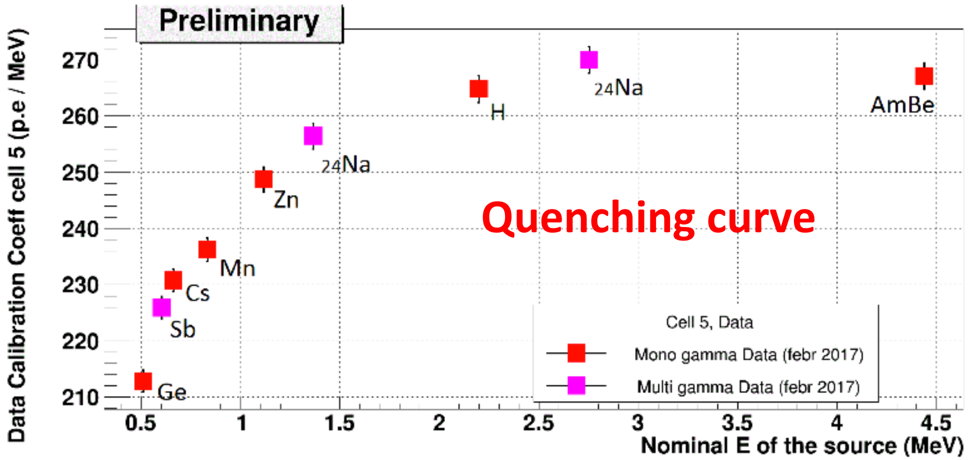


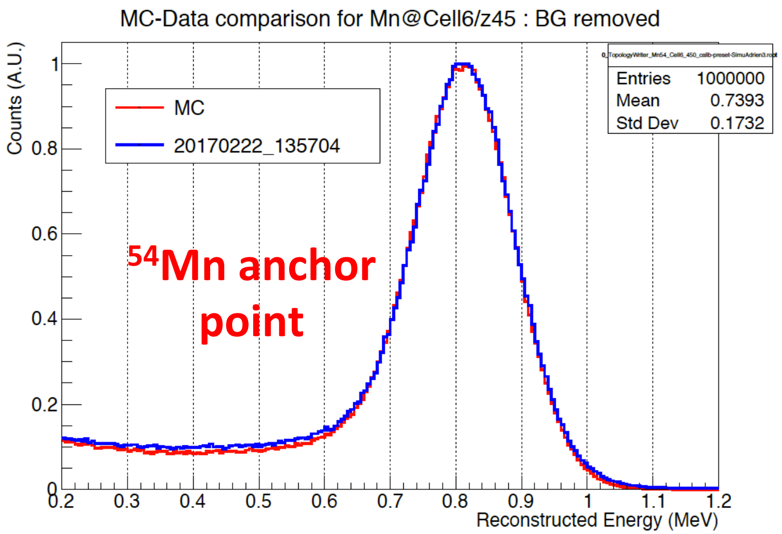
Filing and data taking in Nov. 2016

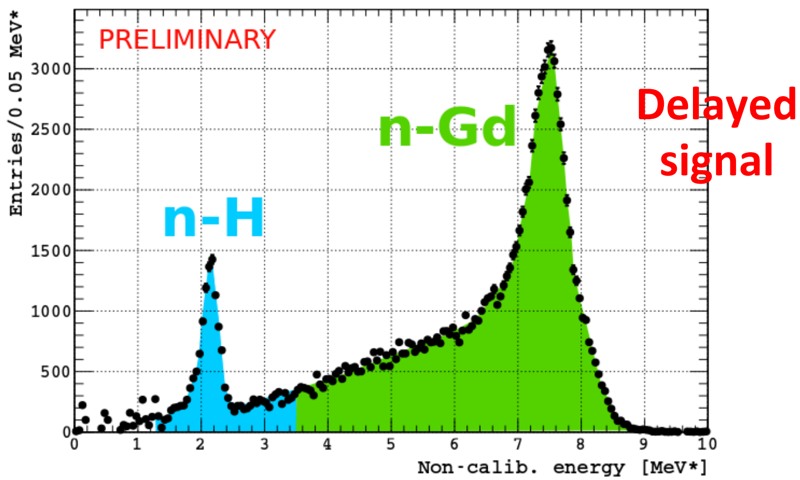
STEREO



Accurate monitoring of the detector response via regular calibration runs

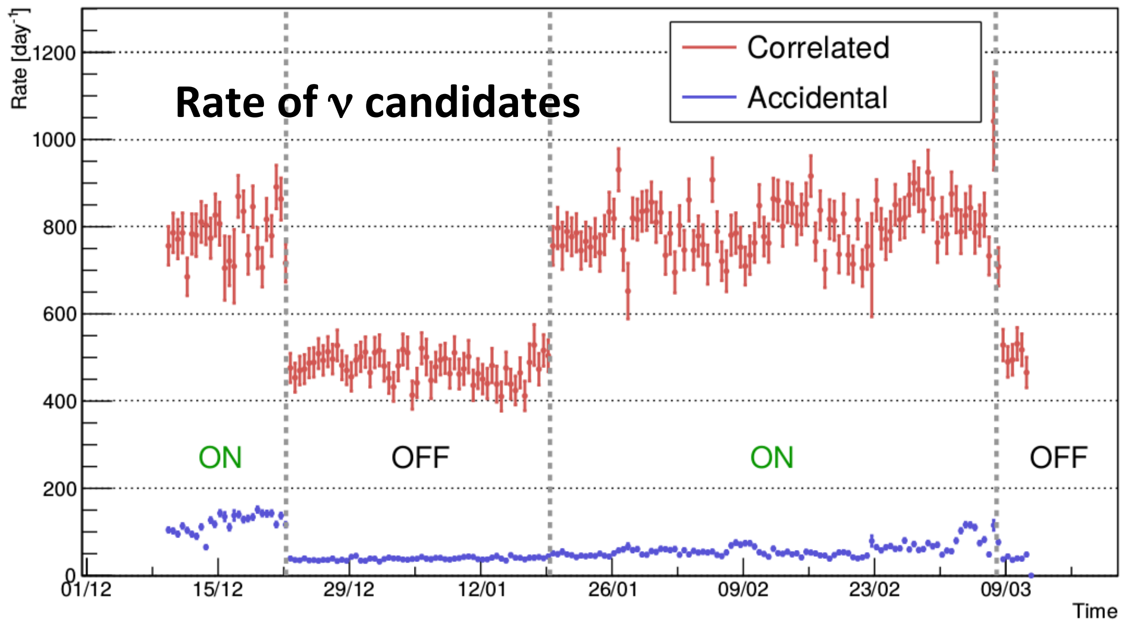


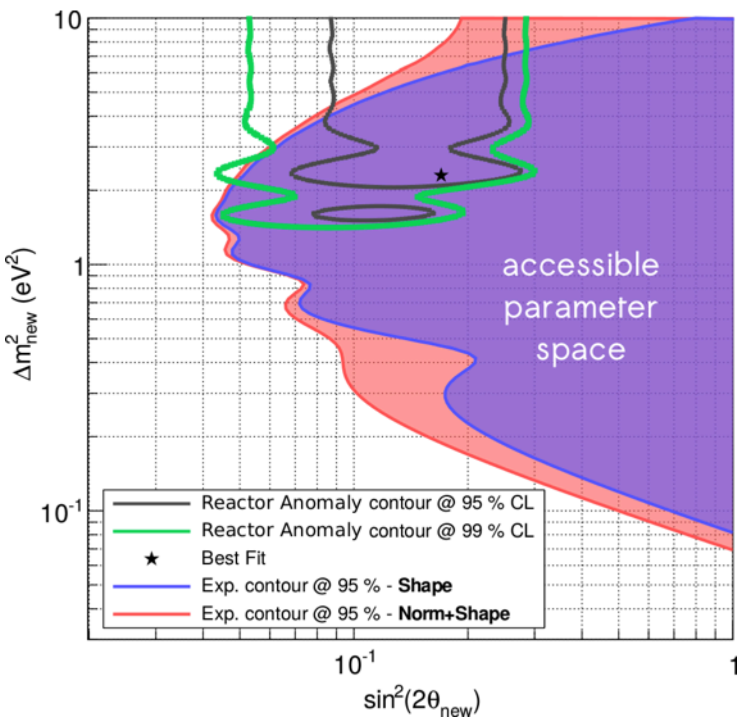




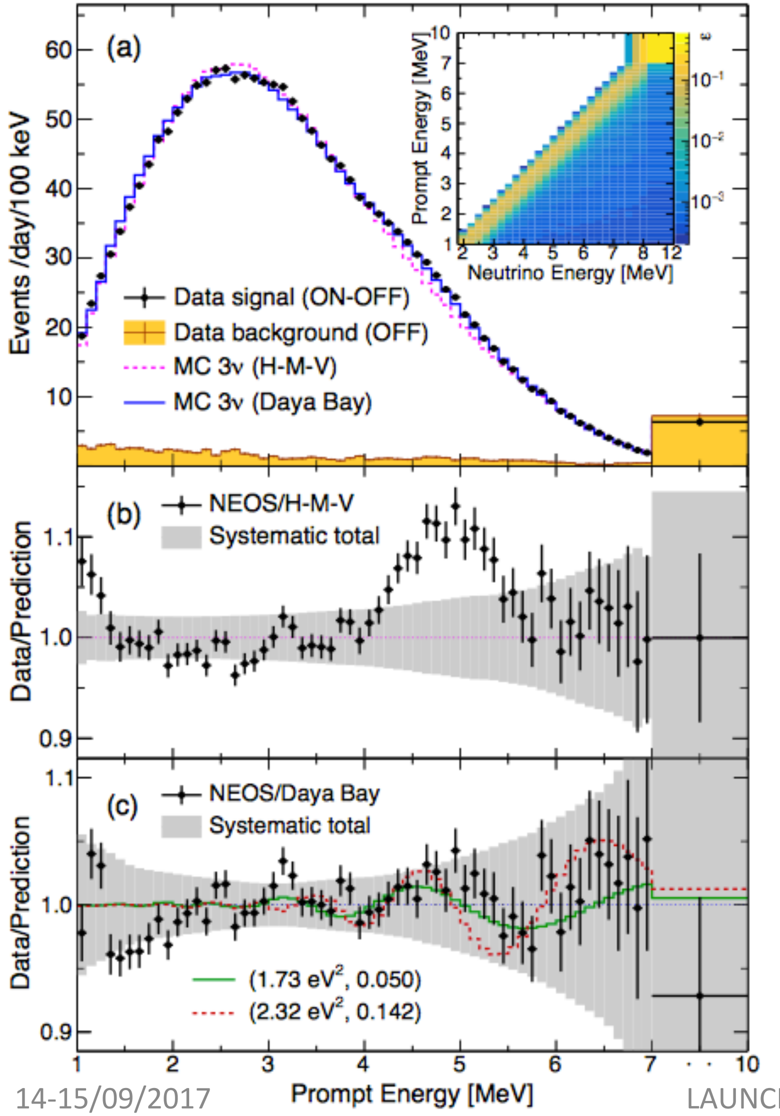
STEREO

- 75 of reactor ON acquired so far + ~25 days OFF
- About 20 000 ν on disk
- Long reactor shutdown this year + detector maintenance
- Resuming data taking next month, more reactor OFF data to come
- Completion of the 300 days reactor ON expected in 2018-2019

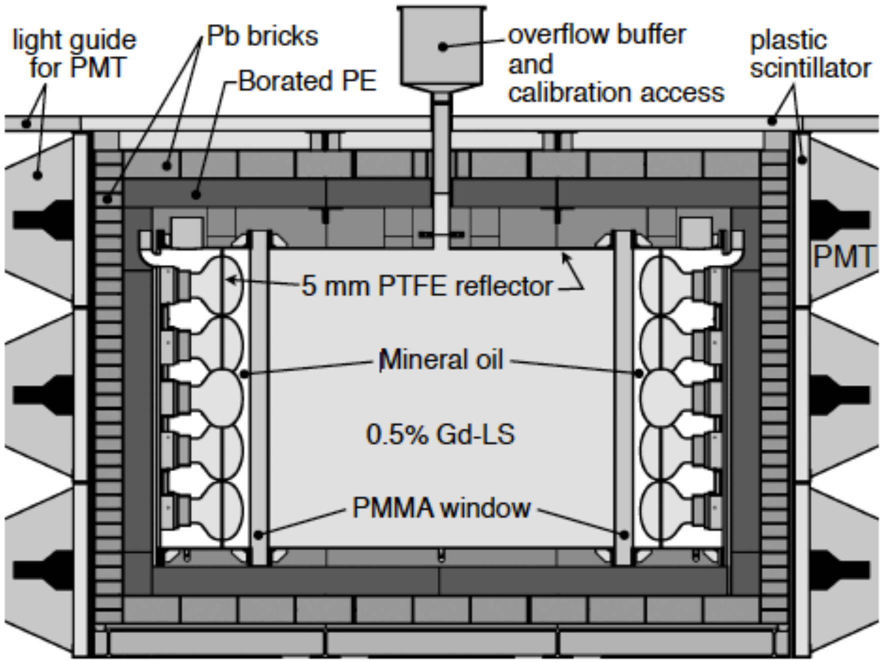




NEOS



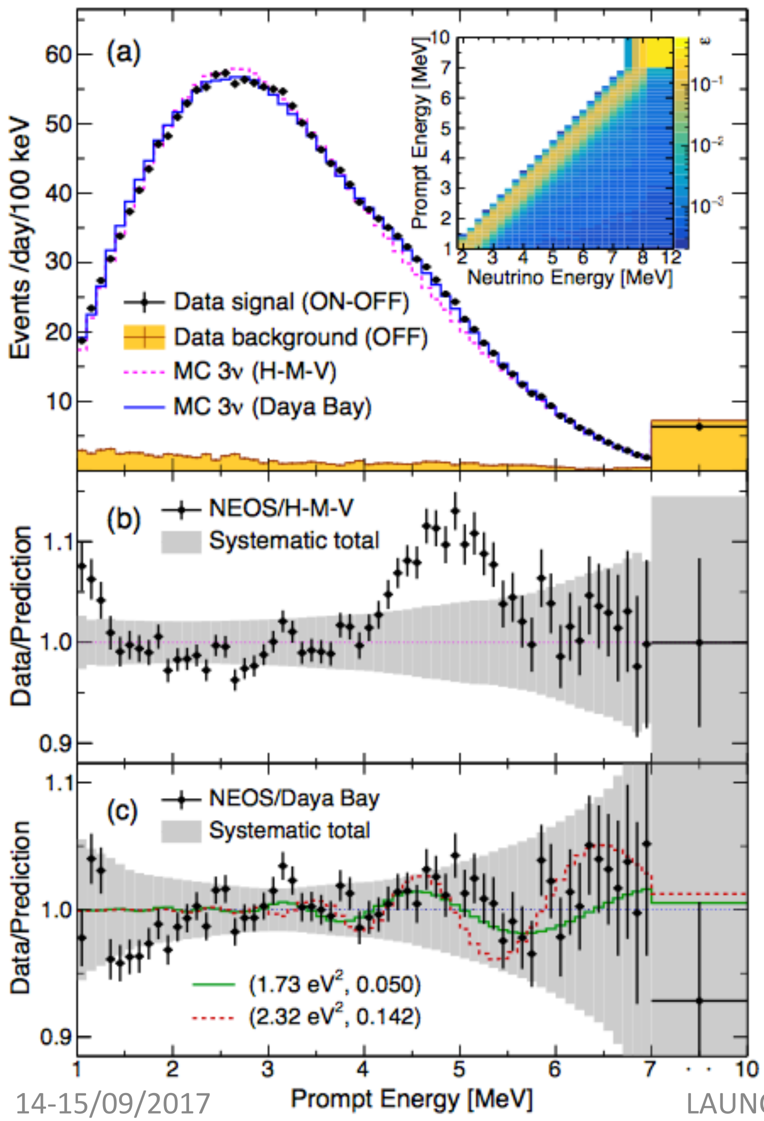
- 25 m from a 2.8 GW core, Hanbit-Korea
- 350 kν, confirms the bump at 5 MeV
- **Comparison between one spectrum and one prediction in a narrow E band.**
- **0.5% syst on E scale**

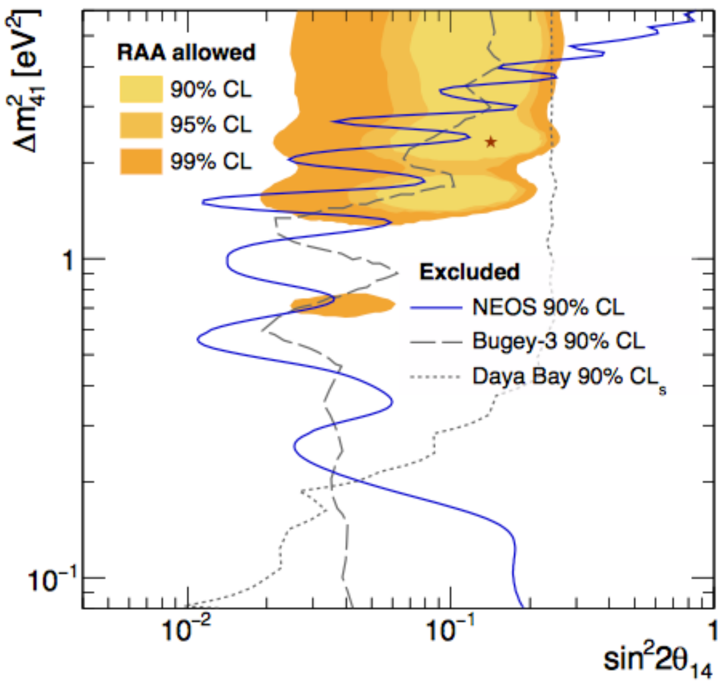


Phys.Rev.Lett. 118 (2017) no.12, 121802

NEOS

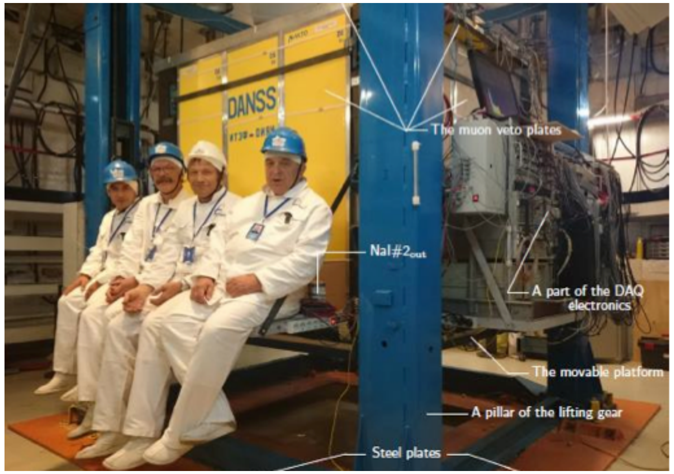
- 25 m from a 2.8 GW core, Hanbit-Korea
- 350 kν, confirms the bump at 5 MeV
- **Comparison between one spectrum and one prediction in a narrow E band.**
- **0.5% syst on E scale**



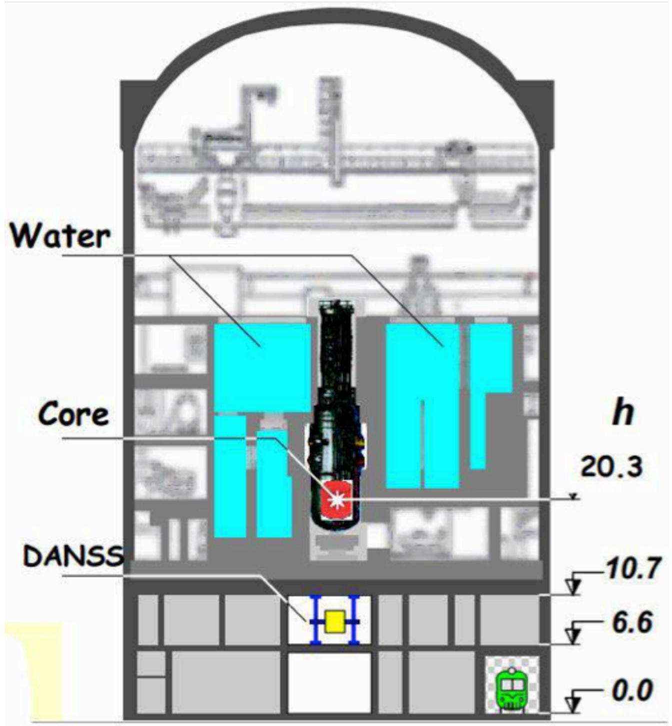


Phys.Rev.Lett. 118 (2017) no.12, 121802

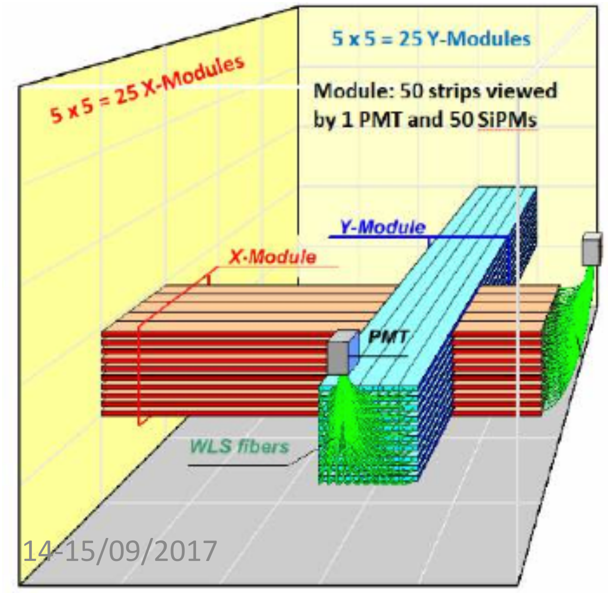
DANSS



Movable detector platform with 10.5-13 m baseline

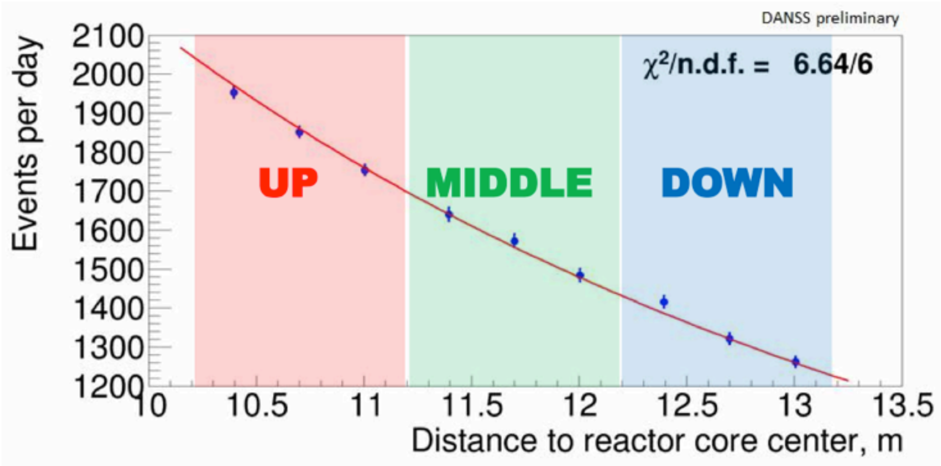


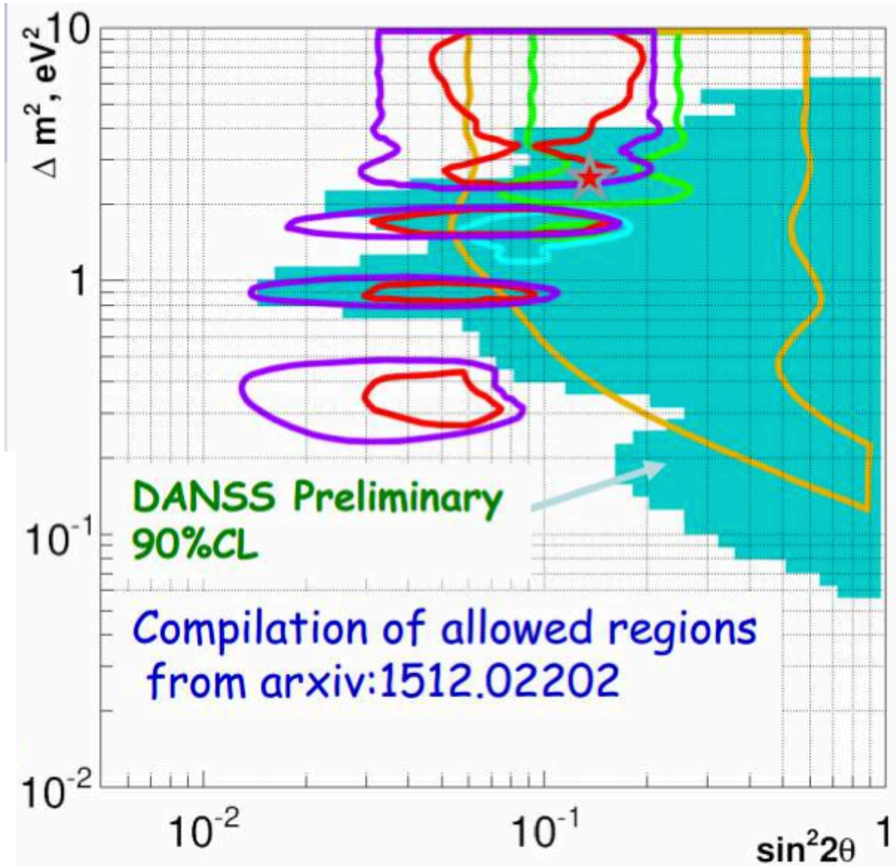
Underneath the Kalinin 3GW WWER core



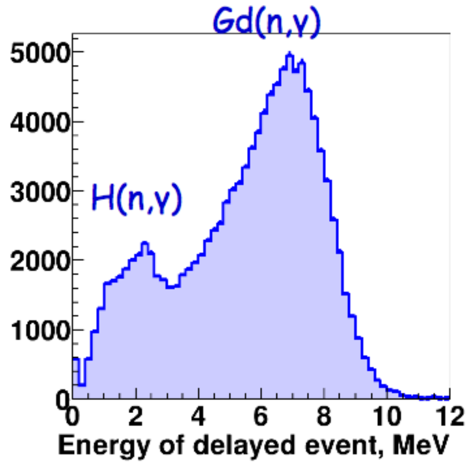
- Highly segmented PS detector
- Ratio of spectra at ≠ positions mitigating detector systematics and being prediction free.
- Huge statistics (~5000/day) compensate for damped ν signal at low E

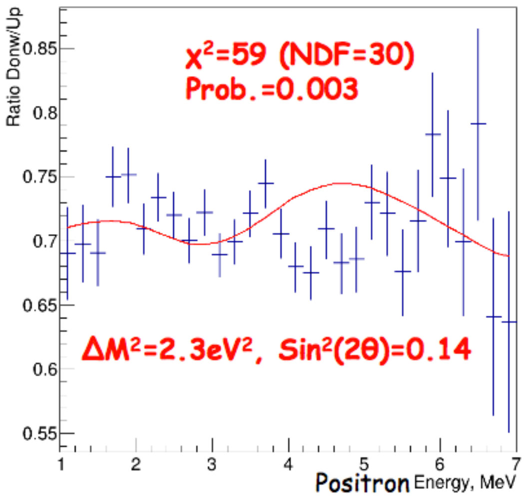
DANSS





Accurately follows the $1/r^2$ expected behavior



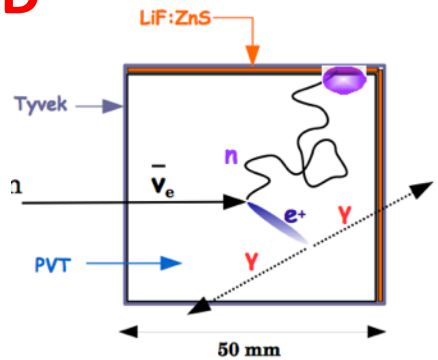


n-capture on Li

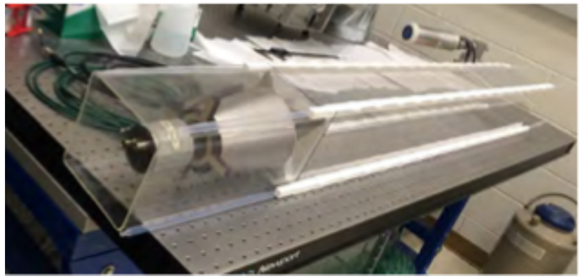
Highly segmented detectors
Very discriminant n-capture: n + Li → α +t

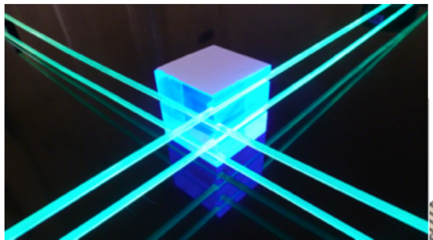
PROSPECT

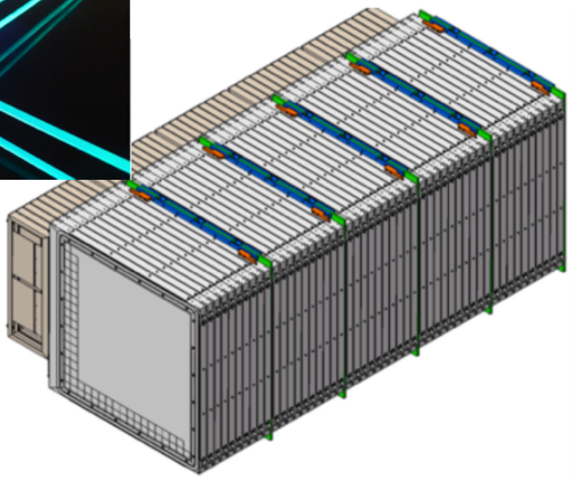
SOLID

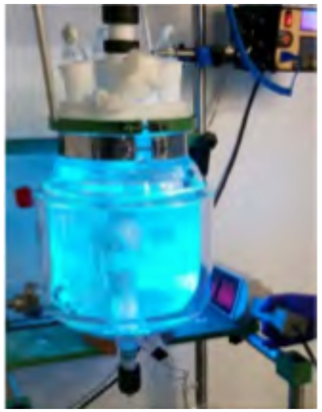


Data taking expected by the end of the year

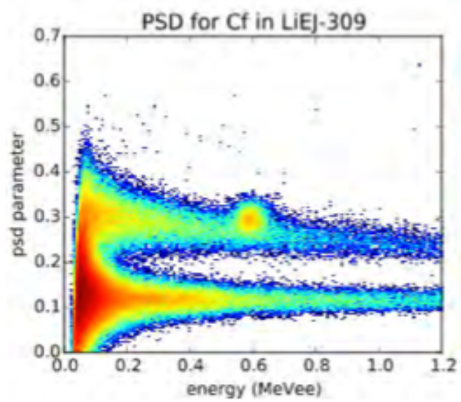








^{6}Li-loaded LS

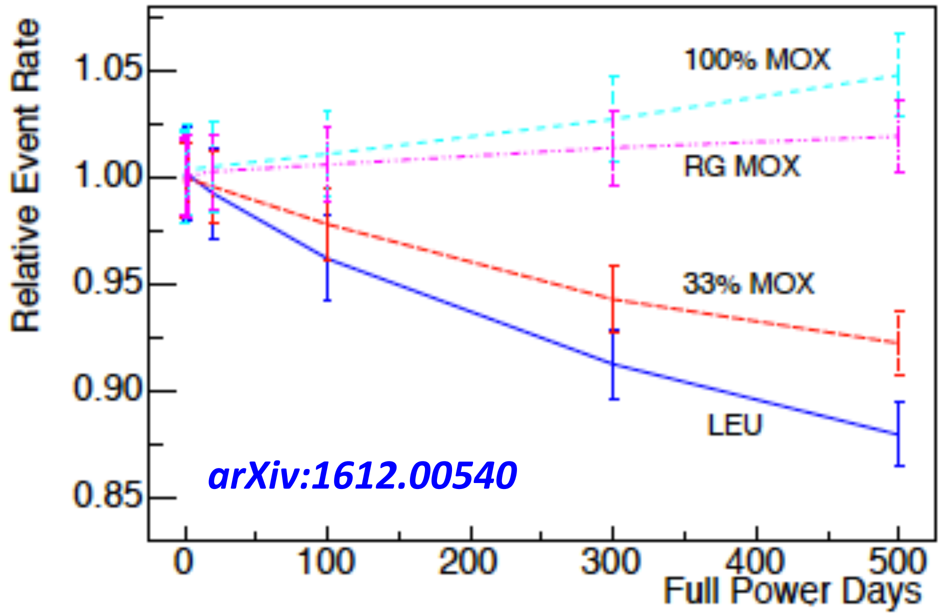


Non proliferation

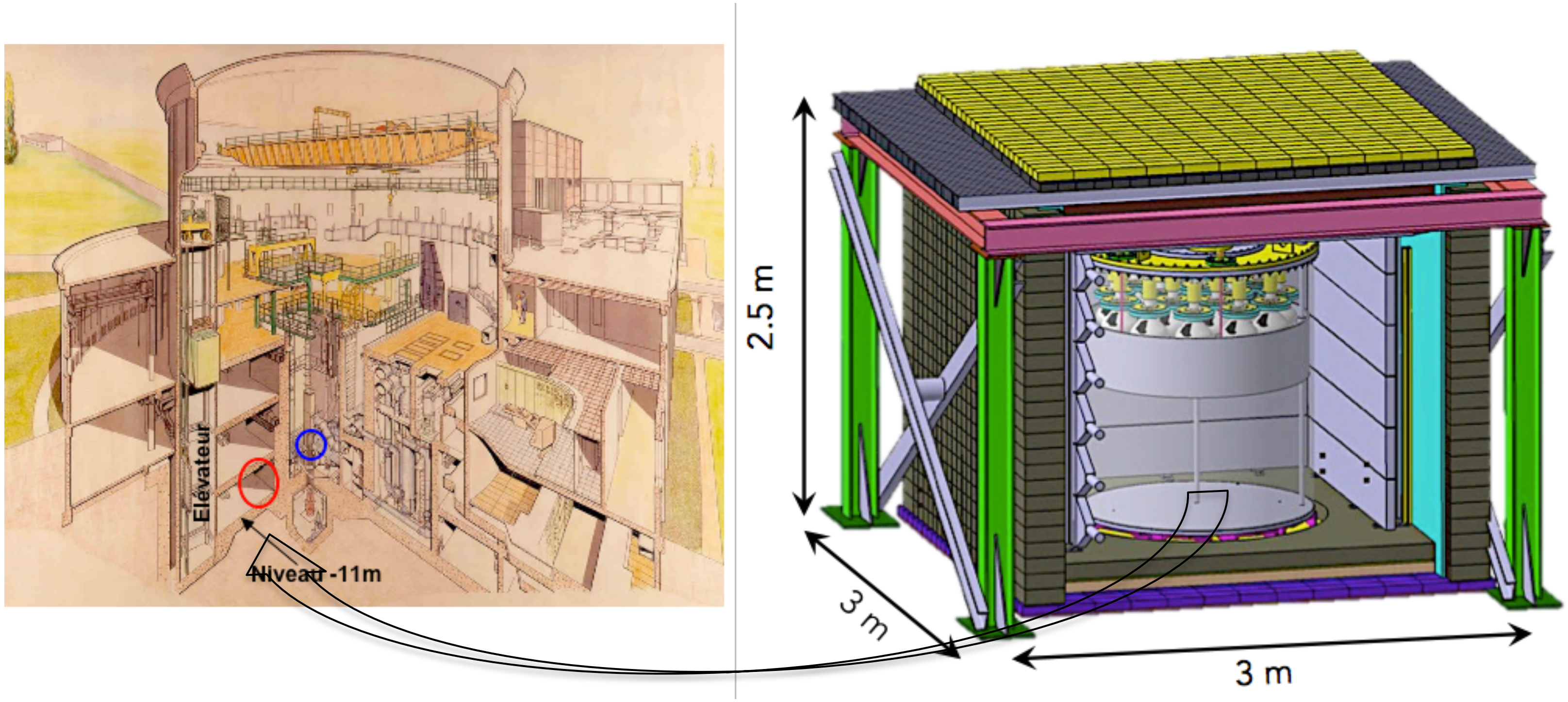
- Synergy with the sterile search for the development of detection technics close to surface.

- Rate and shape evolution of the detected neutrino spectrum nicely confirmed by recent Daya Bay results.

- Niche application: verification of the disposition of military plutonium surplus in nuclear reactors by looking at the relative evolution of detected rates.

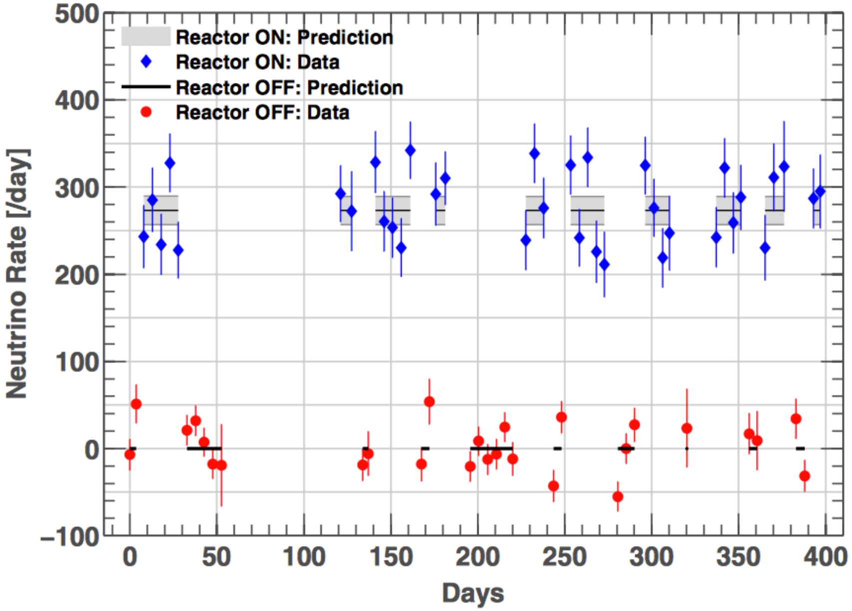


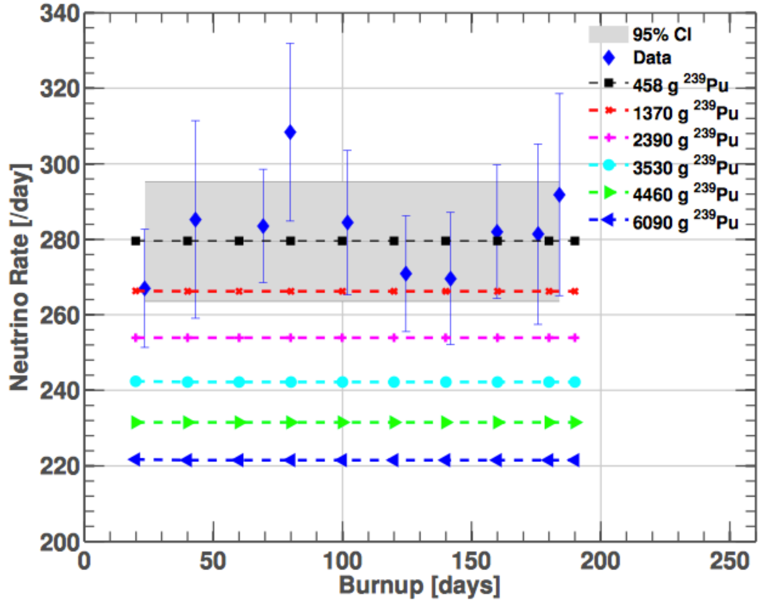
Nucifer



- Experimental nuclear reactor: Pth ≈ 70 MW, enriched 235U fuel (20%)
- 12 m.w.e. overburden against cosmic rays, 7m from core
- Large comic-rays and reactor induced backgrounds$
- 1m^3 of Gd-loaded LS from MPIK

Nucifer





- S/B = 1/20 (total)
- S/B = 1/12 (accidentals)
- S/B = 1/4 (cosmic-rays induced)

- Use this quasi-pure ^{235}U run as an anchor point
- Simulate the operation of a MOx fuel
- Nucifer would detect the presence of 1.5 kg of Pu with 95% C.L.

Conclusion

- θ_{13} as big as it could be, most precisely measured mixing angle.
- Paves the way for δ_{CP} and mass hierarchy measurements
- High precision physics of reactor neutrinos is challenging nuclear databases!
- Alive sterile ν hypothesis is still alive in the context of the observed rate deficit and spectral distortions.
- Running/Upcoming experiments should be able to settle the important topic of eV sterile neutrino.