On the origin of the Reactor Antineutrino Anomalies

A particle to nuclear physics journey

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Particle Physics Seminar – University of Bonn -13 July 2023

A 10 years-long journey

PHYSICAL REVIEW D **83**, 073006 (2011)

Reactor antineutrino anomaly

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uary 2011; published 29 April 2011)

Article

STEREO neutrino spectrum of ^{235}U fission rejects sterile neutrino hypothesis

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Check for updates

The STEREO Collaboration*

Anomalies in past neutrino measurements have led to the discovery that these particles have non-zero mass and oscillate between their three flavours when they propagate. In the 2010s, similar anomalies observed in the antineutrino spectra emitted by nuclear reactors have triggered the hypothesis of the existence of a supplementary neutrino state that would be sterile, that is, not interacting by means of the weak interaction[1]. The STEREO experiment[2–6] was designed to investigate this conjecture, which would potentially extend the standard model of particle physics. Here we present an analysis of the full set of data generated by STEREO, confirming observed anomalies while rejecting the hypothesis of a light sterile neutrino. Installed at the Institut Laue–Langevin (ILL) research reactor, STEREO accurately measures the antineutrino energy spectrum associated to the fission of ^{235}U. The segmentation of the detector and its very short distance to the compact core are crucial properties of STEREO for our analysis. The measured antineutrino energy spectrum suggests that anomalies originate from biases in the nuclear experimental data used for the predictions[7,8]. Our result supports the neutrino content of the standard model and establishes a new reference for the ^{235}U antineutrino energy spectrum. We anticipate that this result will allow progress towards finer tests of the fundamental properties of neutrinos but also to benchmark models and nuclear data of interest for reactor physics[9,10] and for observations of astrophysical or geoneutrinos[11,12].

Physics — SYNOPSIS

Explaining Anomalies in Reactor Antineutrinos

A new analysis finds that discrepancies between reactor neutrino experiments and theory may be the result of errors in the analysis of elect

By Mic

PHYSICAL REVIEW LETTERS **130**, 021801 (2023)

Featured in Physics

Origin of the Reactor Antineutrino Anomalies in Light of a New Summation Model with Parametrized β^- Transitions

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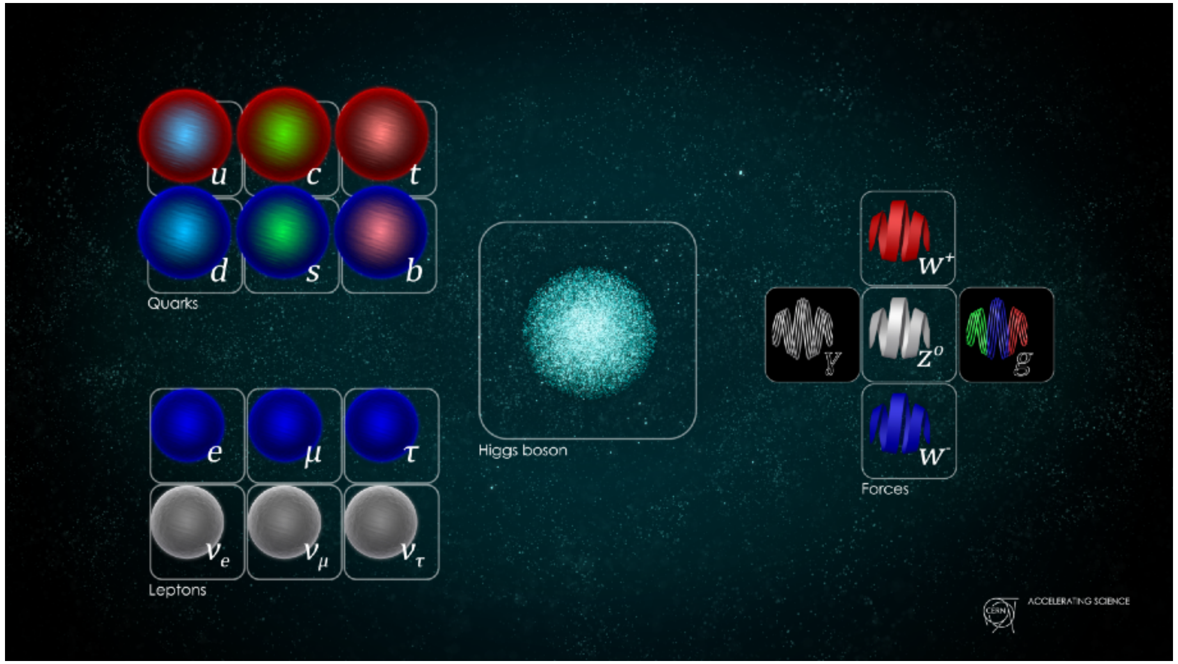
We investigate the possible origins of the reactor antineutrino anomalies in norm and shape within the framework of a summation model where β^- transitions are simulated by a phenomenological model of Gamow-Teller decay strength. The general trends of divergence from the Huber-Mueller model on the antineutrino side can be reproduced in both norm and shape. From the exact electron-antineutrino correspondence of the summation model, we predict similar distortions in the electron spectra, suggesting that biases on the reference spectra of fission electrons could be the cause of the anomalies.

DOI: 10.1103/PhysRevLett.130.021801

2011 — **2023**

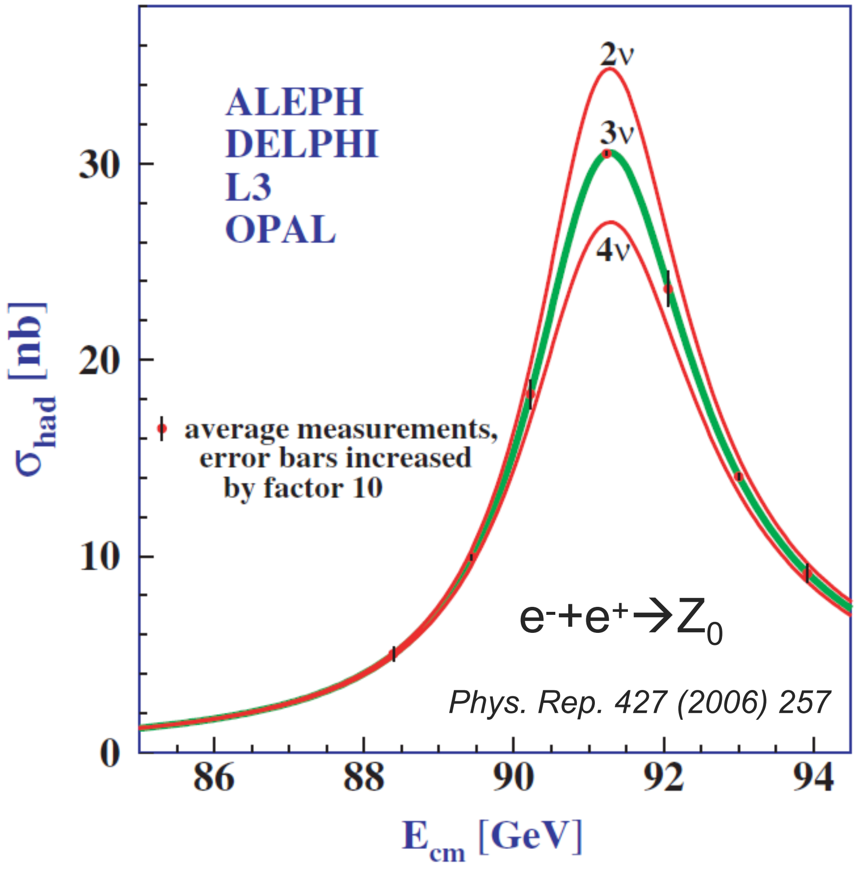
Few things about Neutrinos



What is known:

- Discovered in 1956
- Letpon particles with only 3 flavors

Few things about Neutrinos



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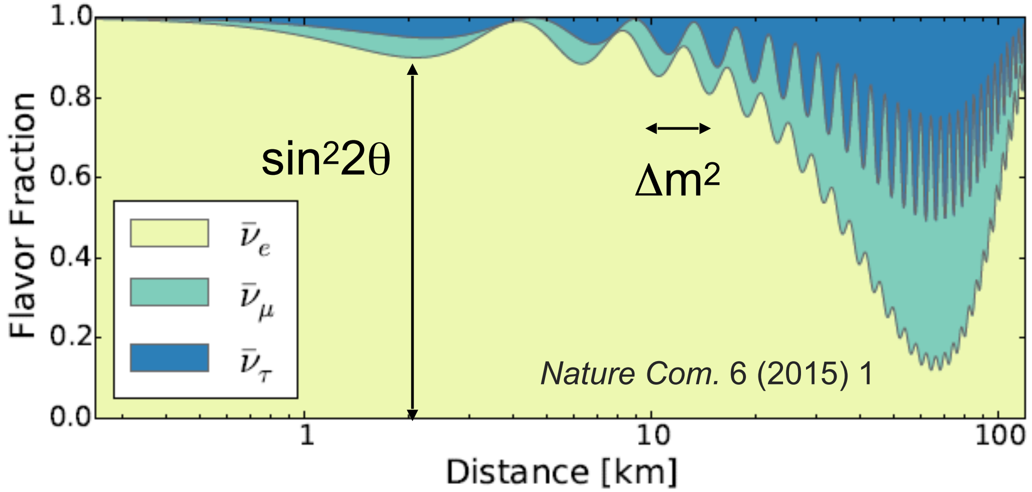
Few things about Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left(U_{PMNS}\right) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



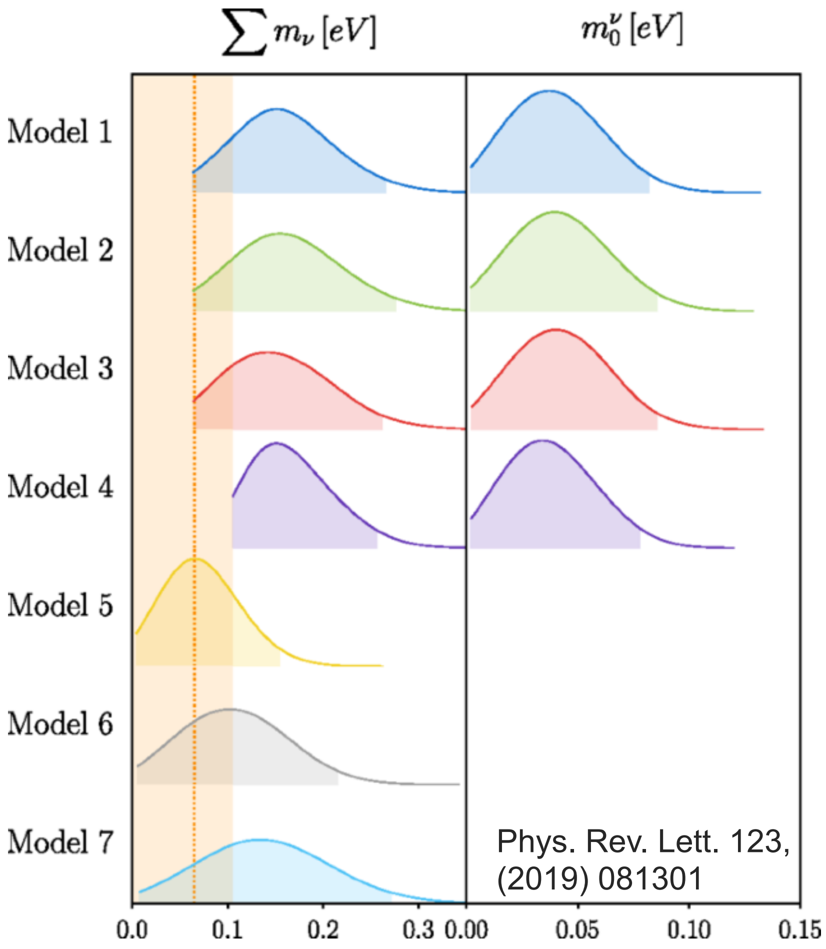
What is known:

- Discovered in 1956
- Letpon particles with only 3 flavors
- Mass and flavour eigenstates are not aligned
  - Mixing angles known better than 10%
  - Δm^2 ~2 %

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \left| < \bar{\nu}_e(t) \,|\, \bar{\nu}_e(0) > \right|^2 = f(\sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} L\right))$$

Few things about Neutrinos

Combined Cosmological Observations and Particle Physics Experiments

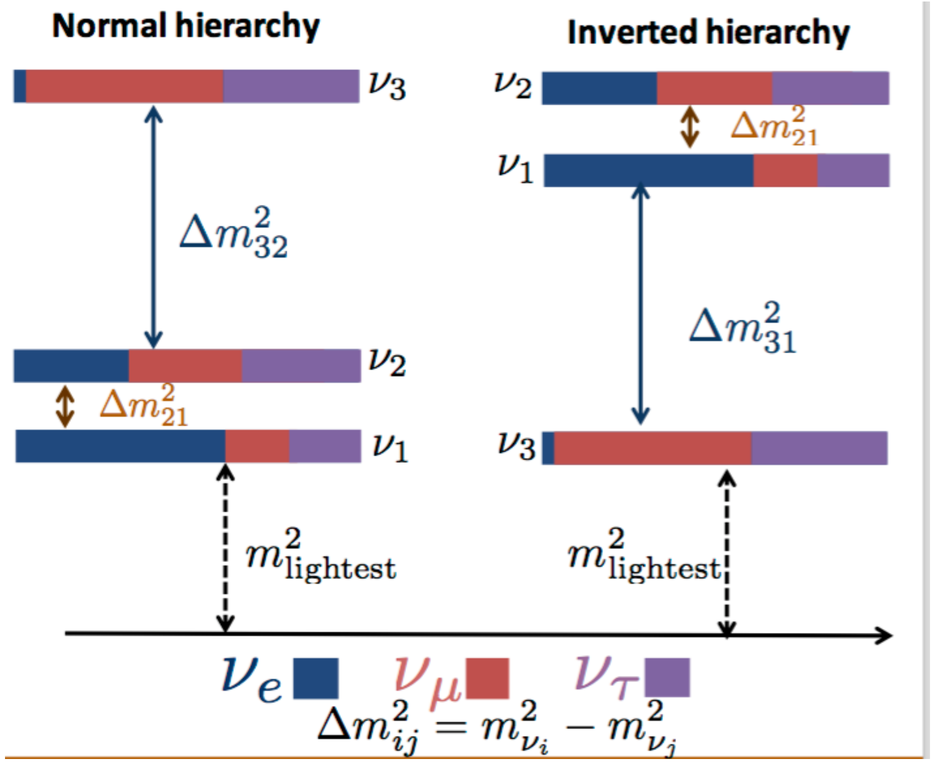


Phys. Rev. Lett. 123, (2019) 081301

What is known:

- Discovered in 1956
- Letpon particles with only 3 flavors
- Mass and flavour eigenstates are not aligned
- Masses are tiny: $\sum m_\nu$< 0.25 eV, m_0 < 0.086 eV

Few things about Neutrinos



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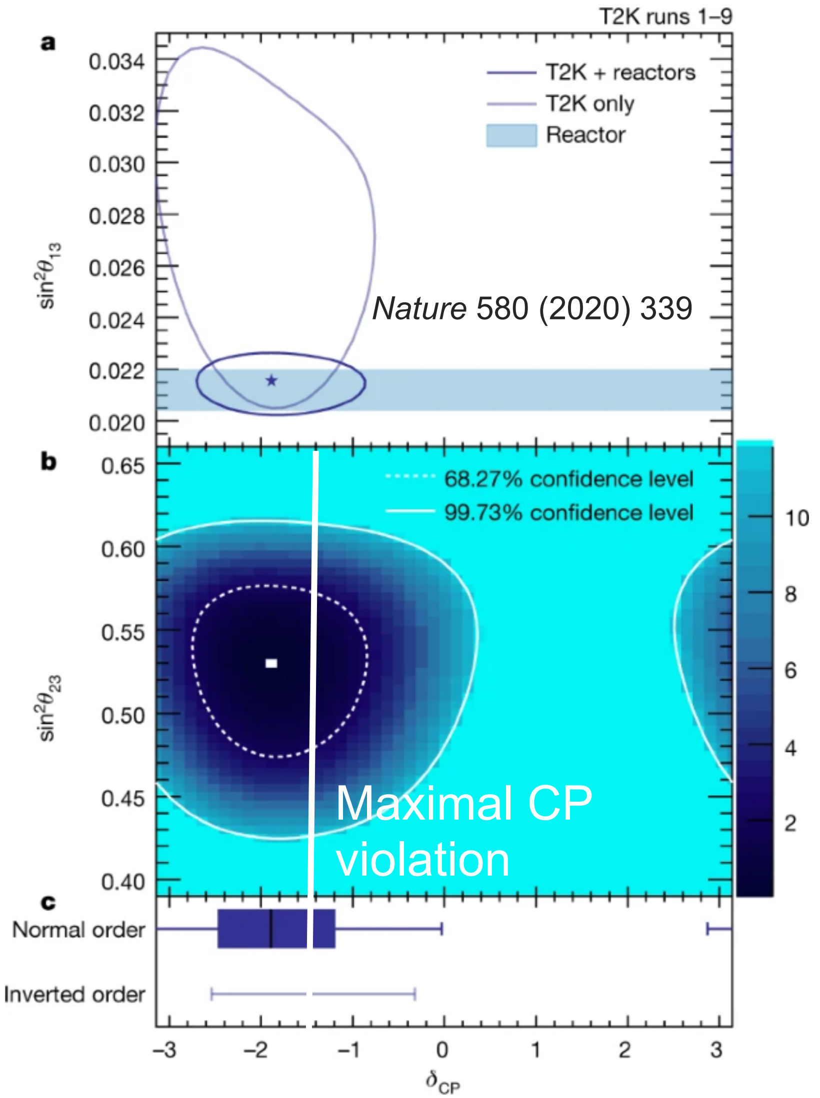
Burning questions:

- The mass values, hierarchy and nature (Majorana or Dirac) ?

Few things about Neutrinos



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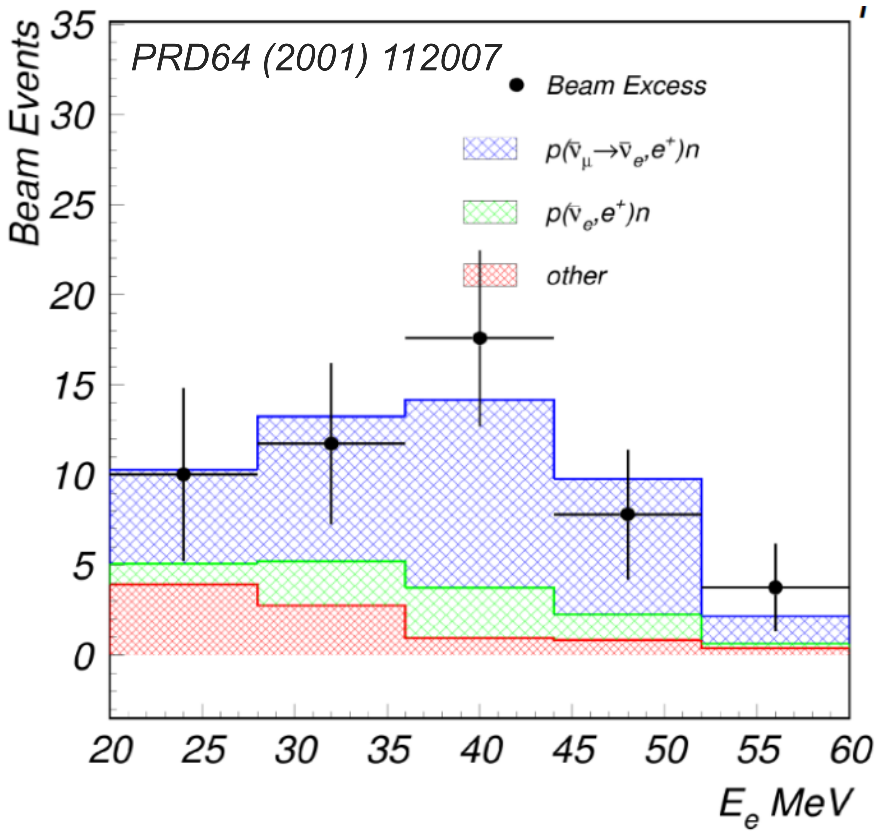
Burning questions:

- The mass values, hierarchy and nature (Majorana or Dirac) ?
- The CP symmetry violation phase ?

Few things about Neutrinos

- Excess of $\bar{\nu}_e$ in LSND $\bar{\nu}_\mu$ beams: 87.9±22.4±6.0 events (3.8σ)



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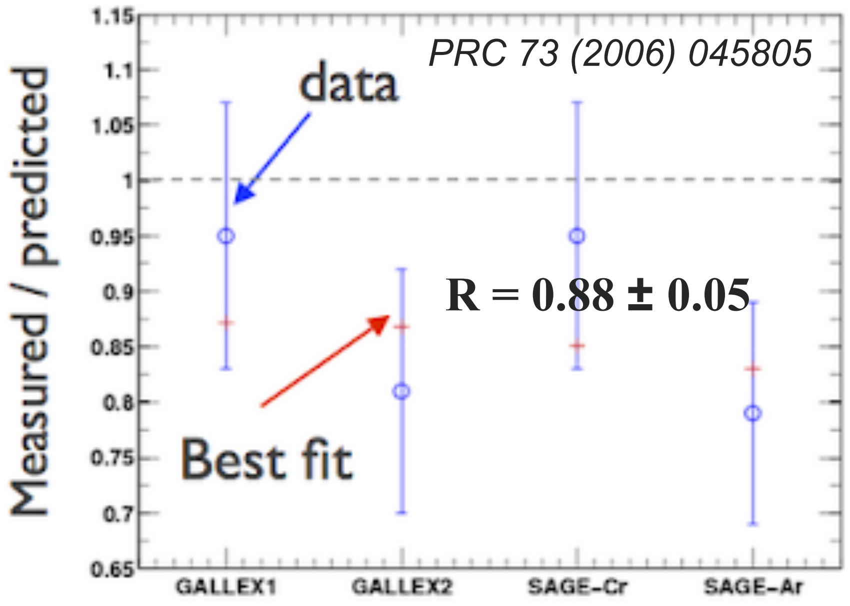
Burning questions:

- The mass values, hierarchy and nature (Majorana or Dirac) ?
- The CP symmetry violation phase ?
- Origin of some anomalies ?

- Not confirmed by MiniBooNe experiment but an excess at lower energy

Few things about Neutrinos

- Deficit of ν_e produced by ^{51}Cr and ^{37}Ar sources in Gallium solar neutrino detectors



- Confirm by the BEST experiment (R= 0.78±0.05)

What is known:

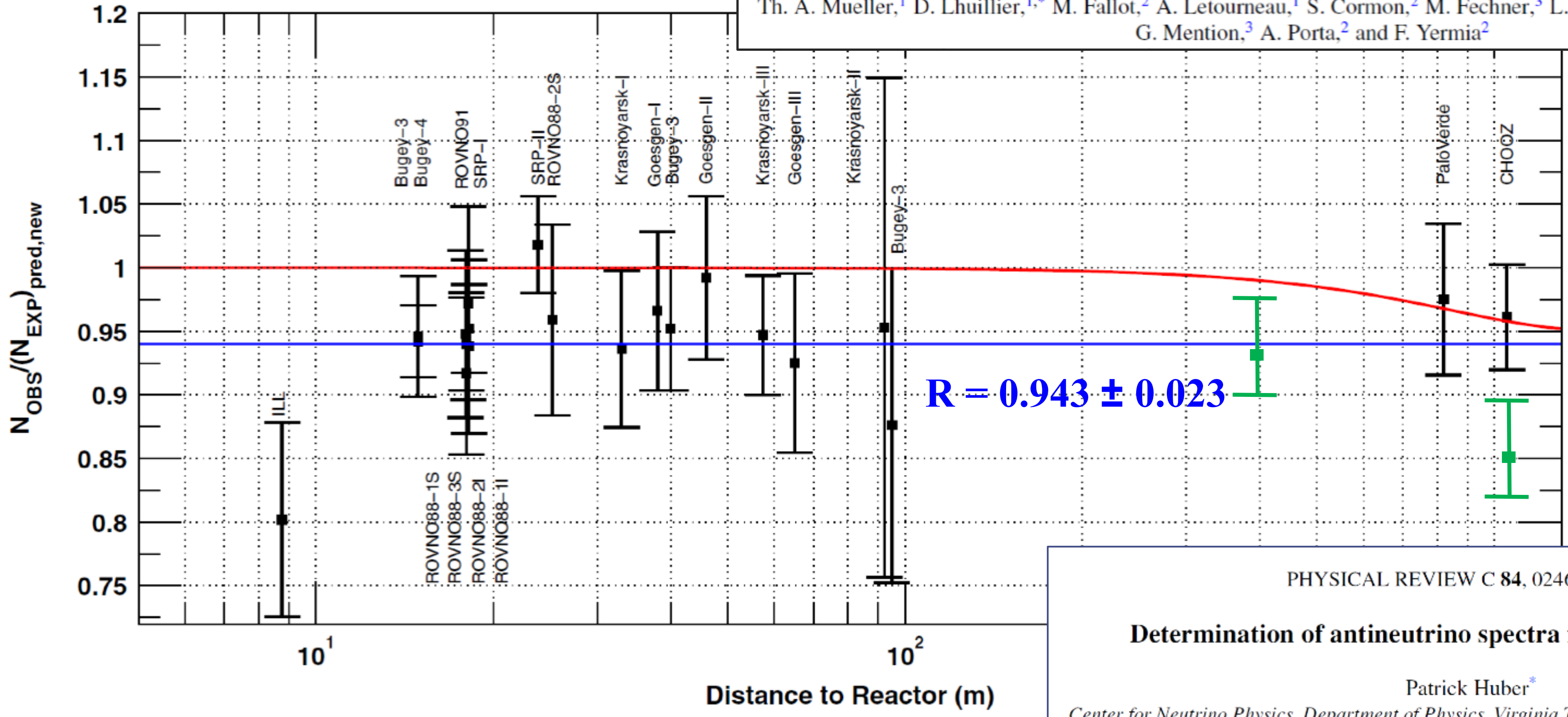
- Discovered in 1956
- Letpon particles with only 3 flavors
- Mass and flavour eigenstates are not aligned
- Masses are tiny: $\sum m_\nu < 0.25$ eV, $m_0 < 0.086$ eV

Burning questions:

- The mass values, hierarchy and nature (Majorana or Dirac) ?
- The CP symmetry violation phase ?
- Origin of some anomalies ?

The Reactor Antineutrino Anomaly (RAA)

- Deficit of $\bar{\nu}_e$ produced by nuclear reactors



PHYSICAL REVIEW C **83**, 054615 (2011)

Improved predictions of reactor antineutrino spectra

Th. A. Mueller,[1] D. Lhuillier,[1,*] M. Fallot,[2] A. Letourneau,[1] S. Cormon,[2] M. Fechner,[3] L. Giot,[2] T. Lasserre,[3] J. Martino,[2] G. Mention,[3] A. Porta,[2] and F. Yermia[2]

PHYSICAL REVIEW C **84**, 024617 (2011)

Determination of antineutrino spectra from nuclear reactors

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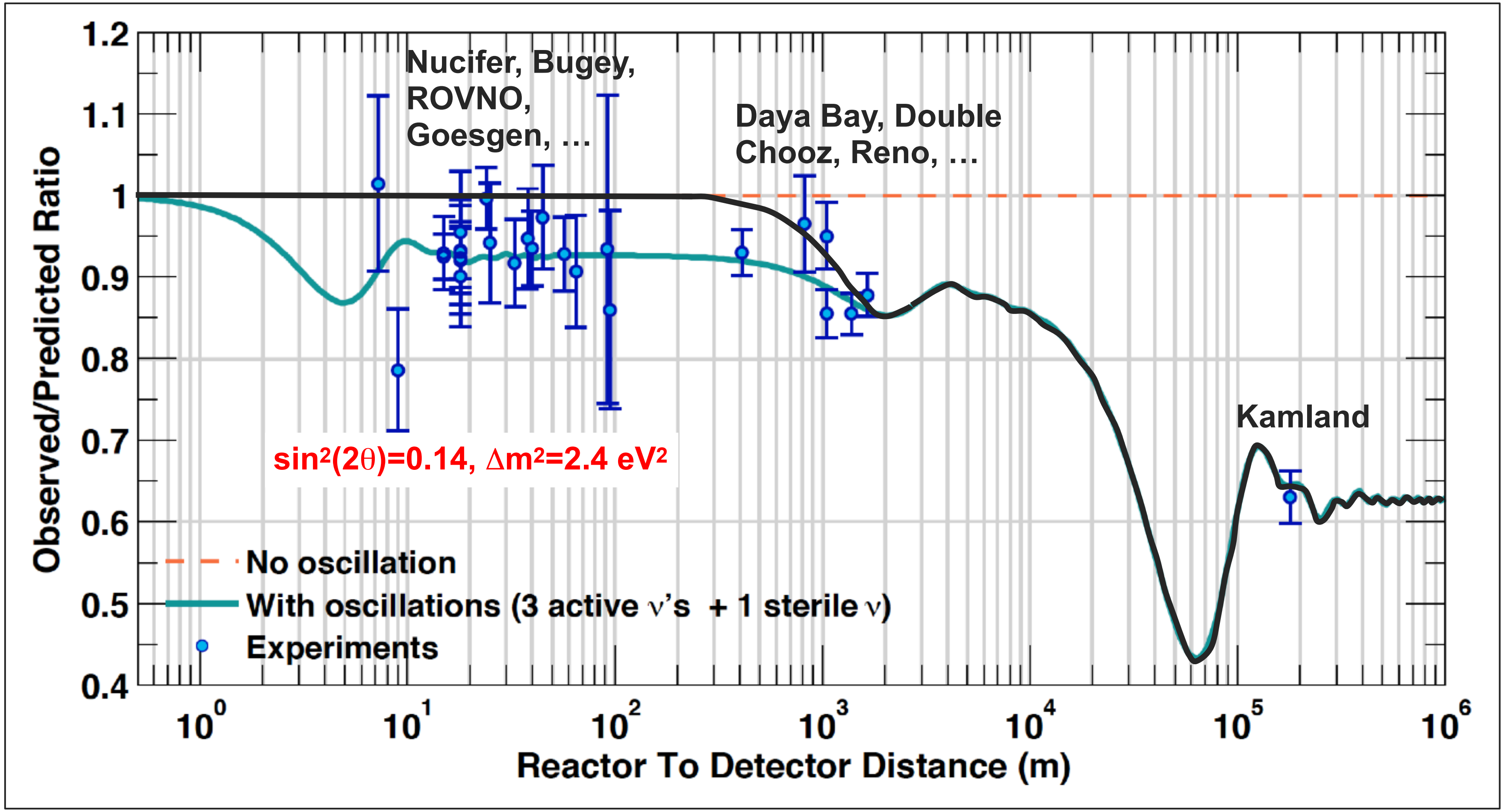
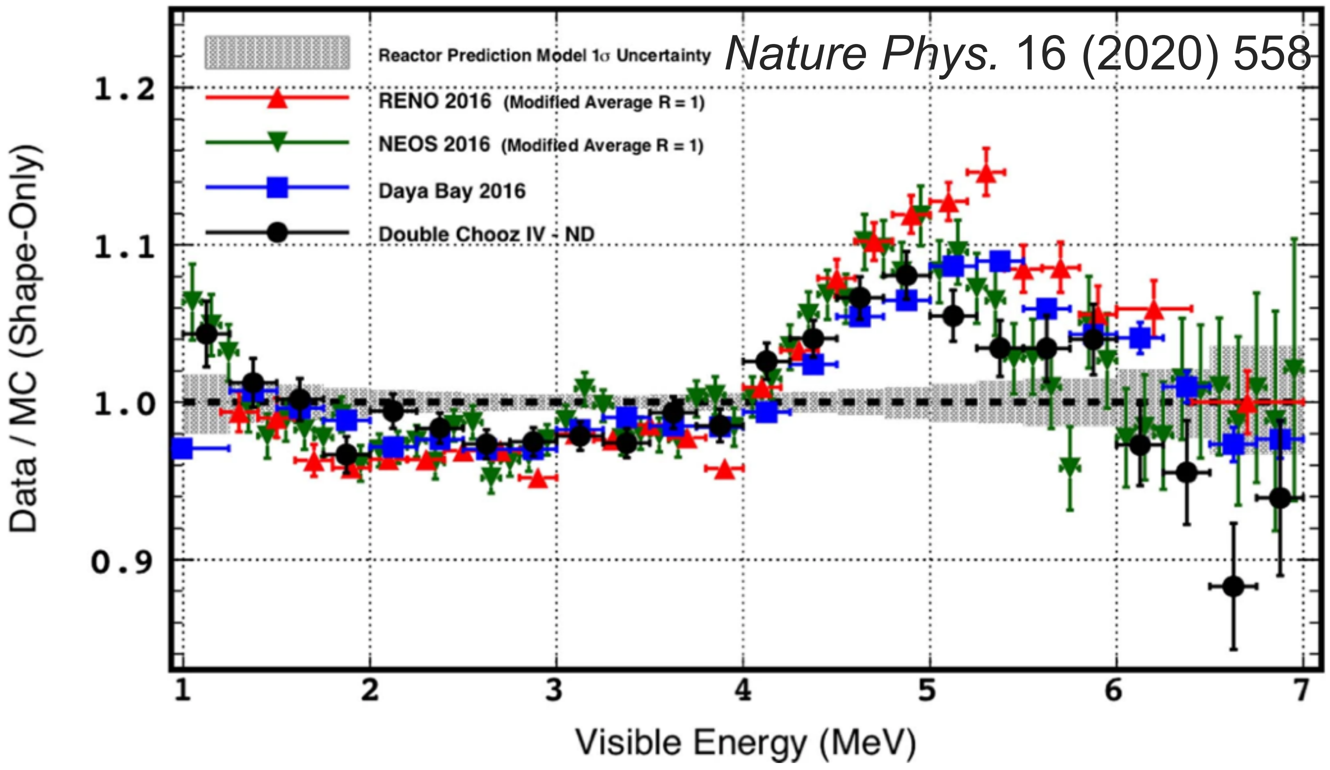
Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA
(Received 16 June 2011; published 29 August 2011)

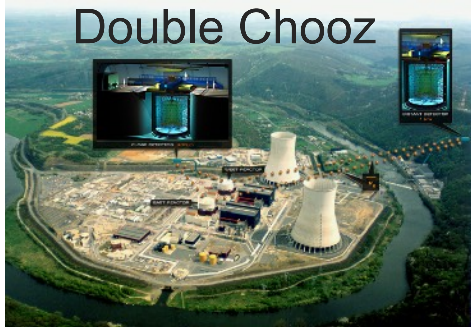
Existence of ligth sterile neutrinos ?



The « 5 MeV bump » anomaly



Nature Phys. 16 (2020) 558

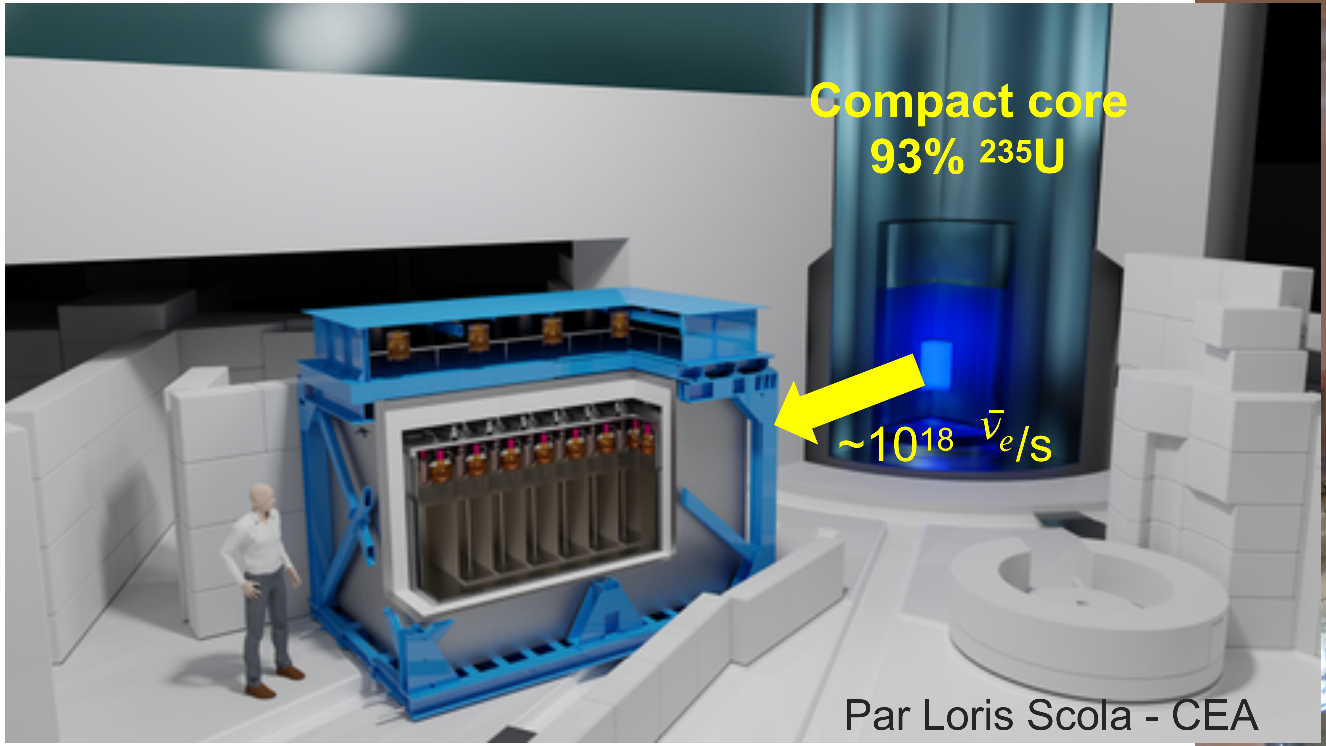


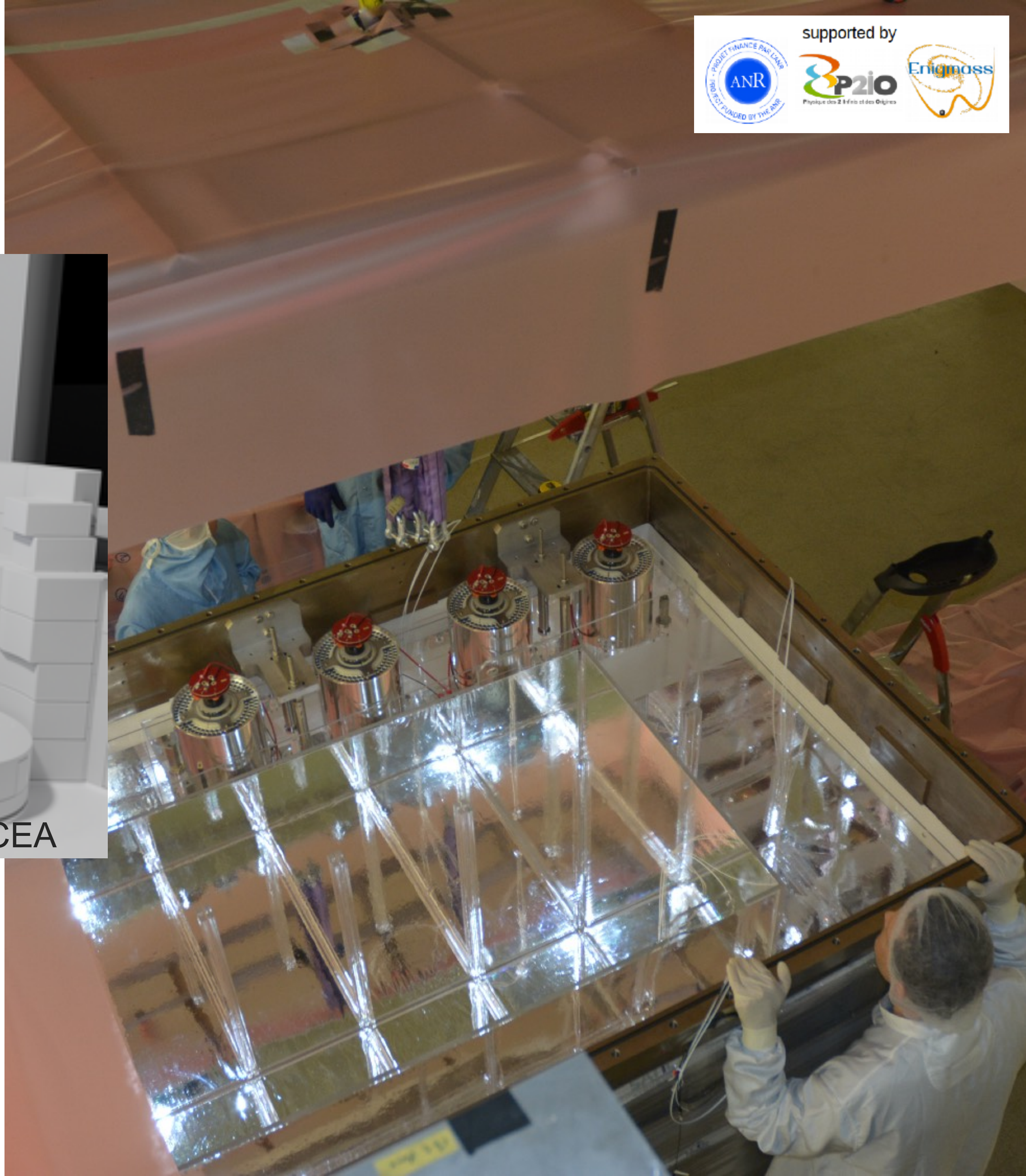
Reactor Antineutrino Experiments in the world

- Short Baselines (400-1000 m)
- Very short Baselines (10-100 m)

The Sterile Neutrino hypothesis

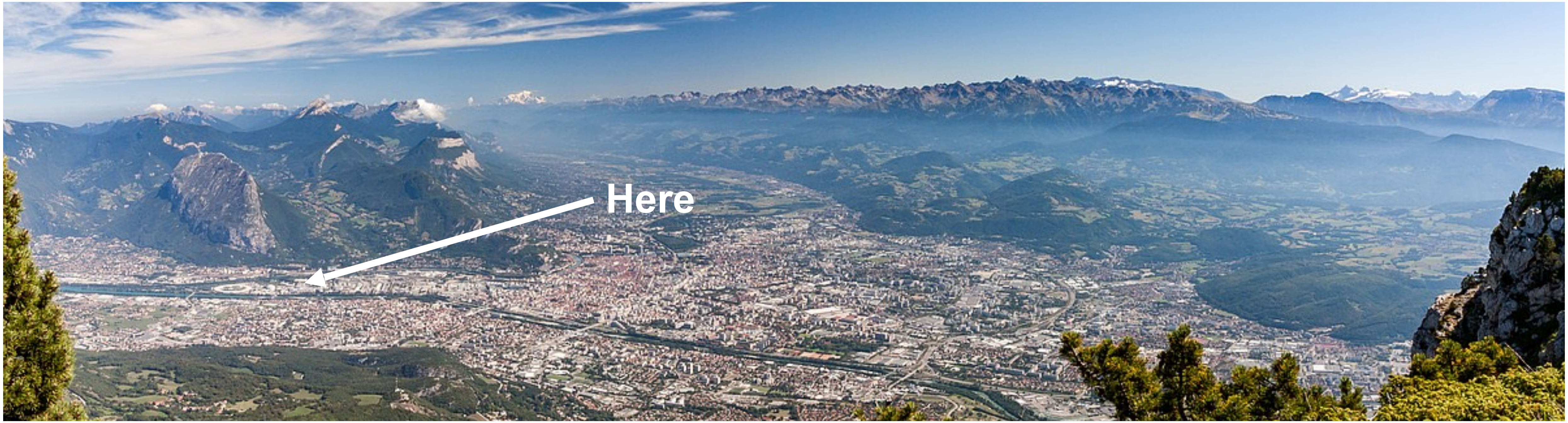
STEREO experiment



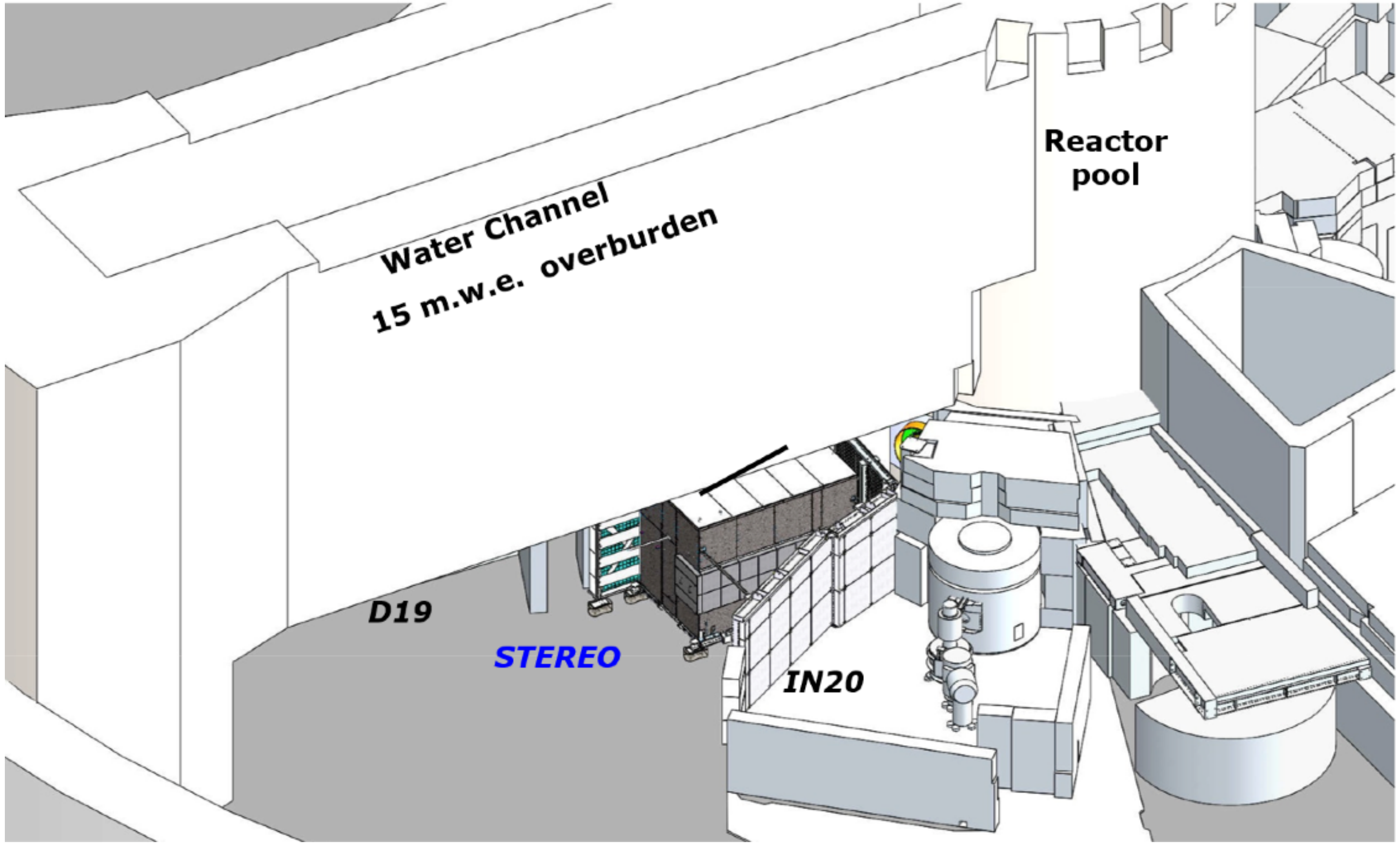


supported by

High Flux Reactor @ Institut Laue Langevin

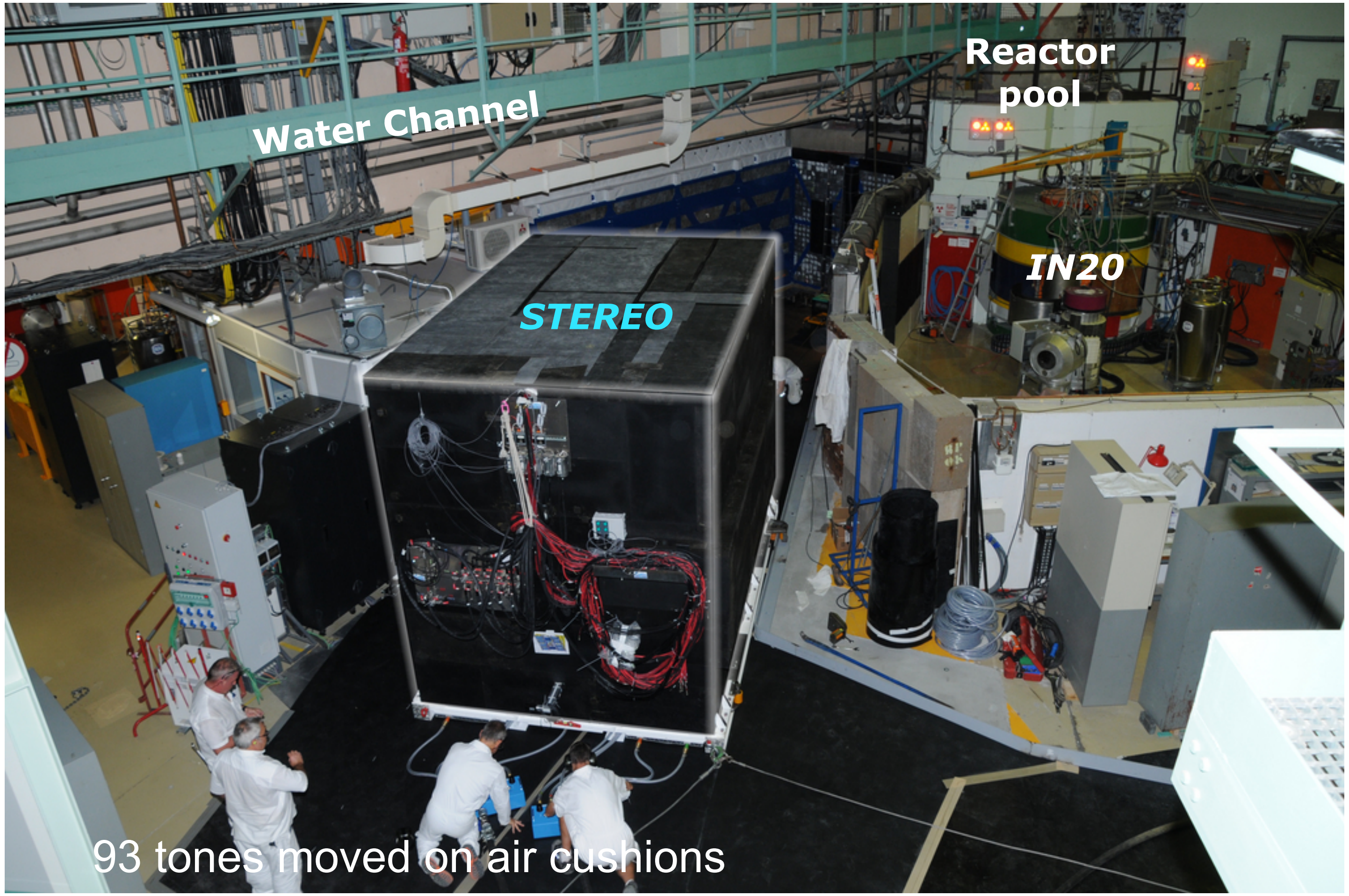


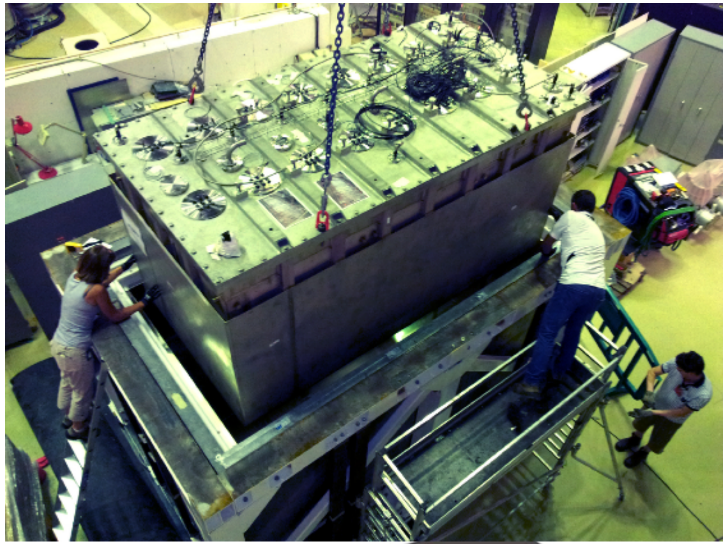
HFR@ILL site

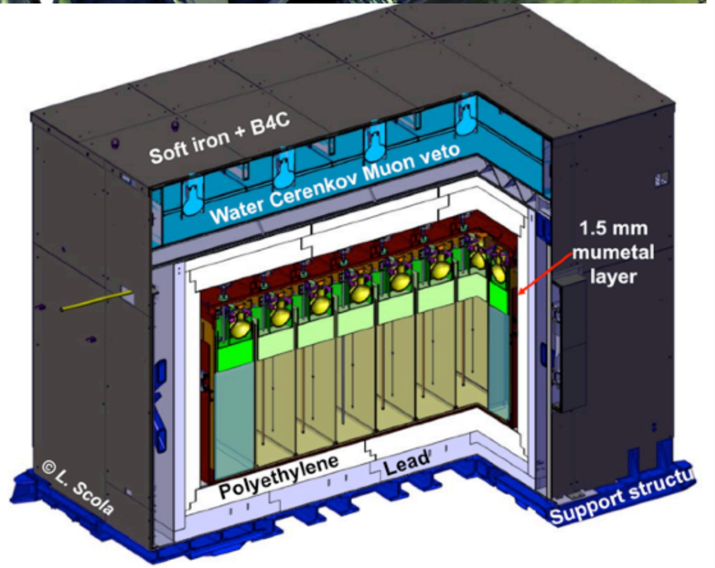


- Challenging mitigation of the background :
  - reactor
  - neighboring experiments
  - cosmic-rays.

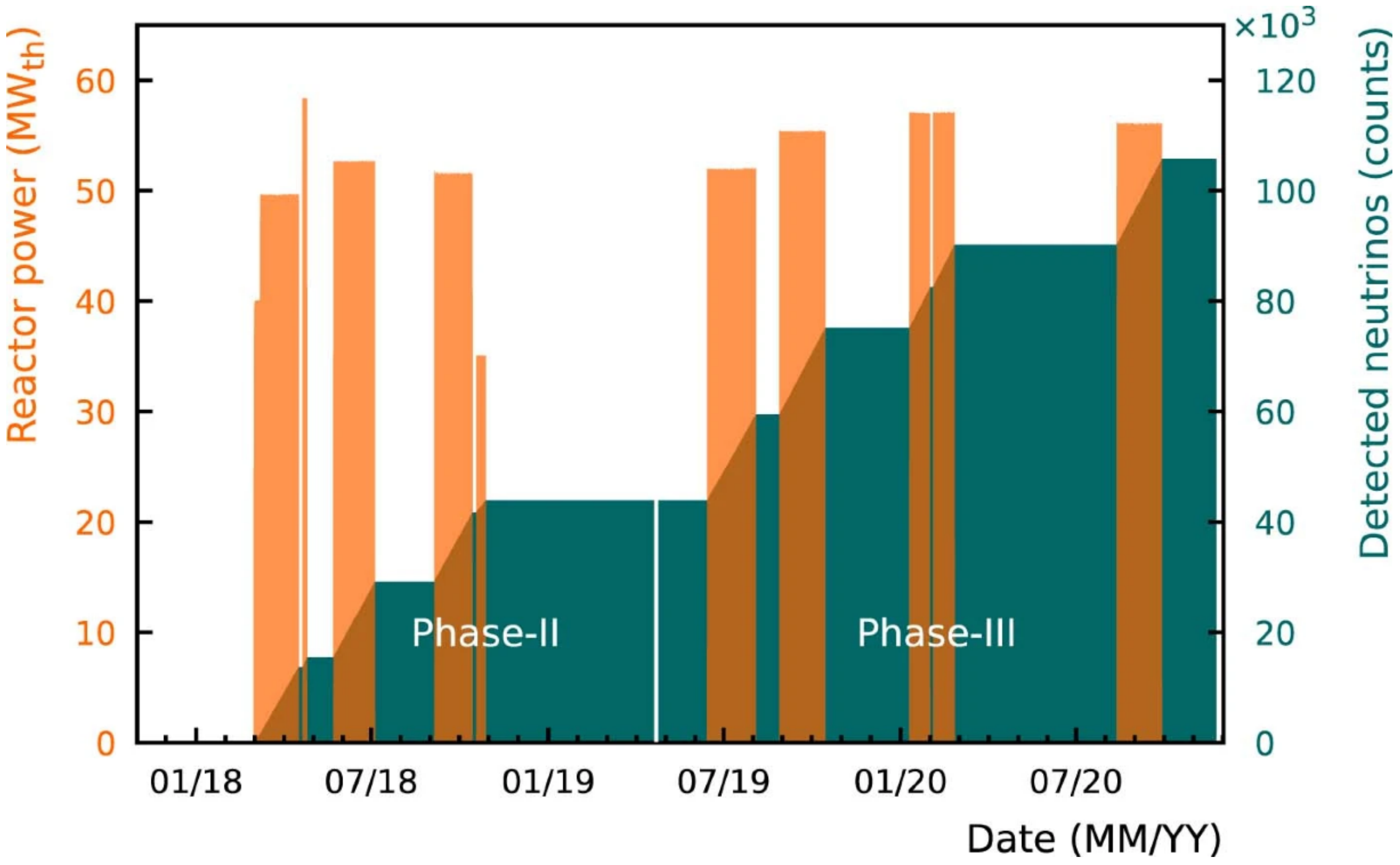
HFR@ILL site


Water Channel
Reactor pool
IN20
STEREO
93 tones moved on air cushions




Soft iron + B4C
Water Cerenkov Muon veto
1.5 mm mumetal layer
Polyethylene
Lead
© L. Scola
Support structu

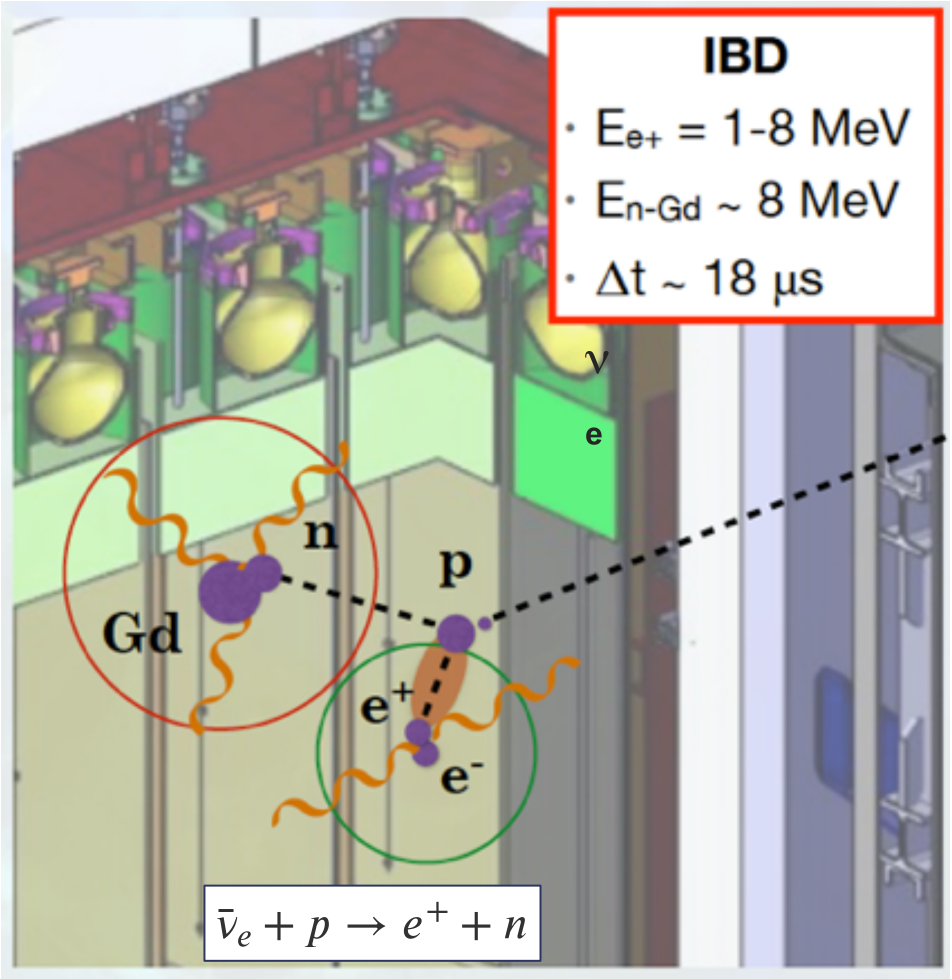
Stereo data taking



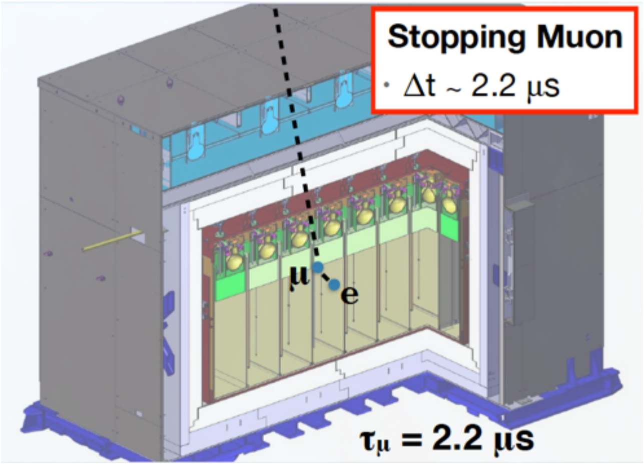
- From Nov 2016 to Nov 2020
- ~ 273 days of reactor ON

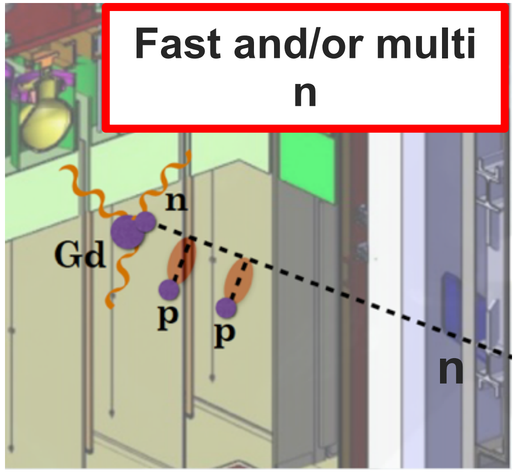
  → ~100'000 IBD events
- 520 days of reactor OFF
- Deficient optical during Phase I

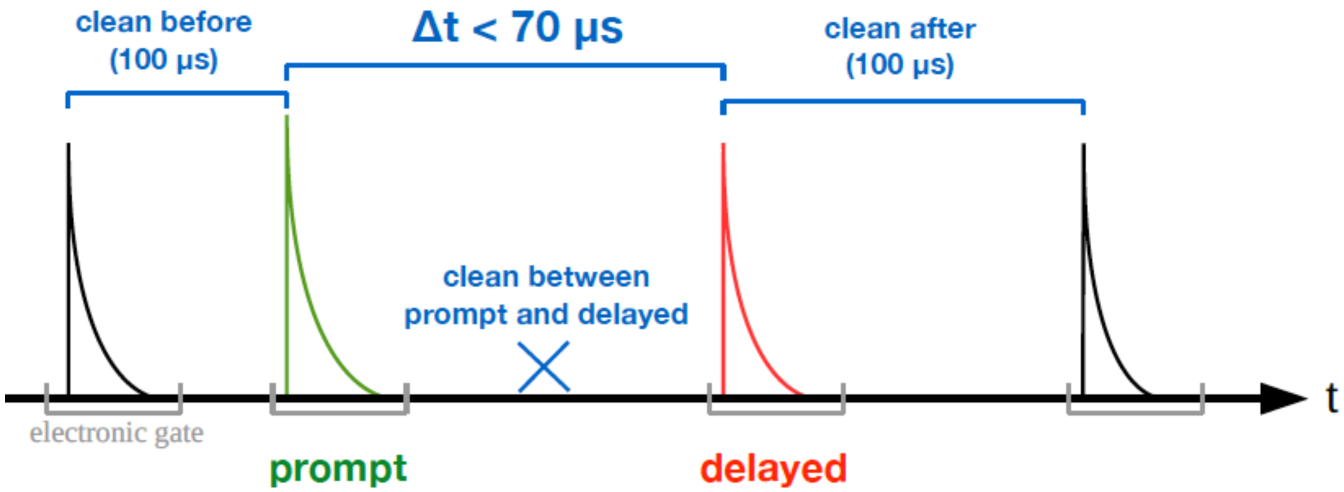
Inverse Beta Decay event selection



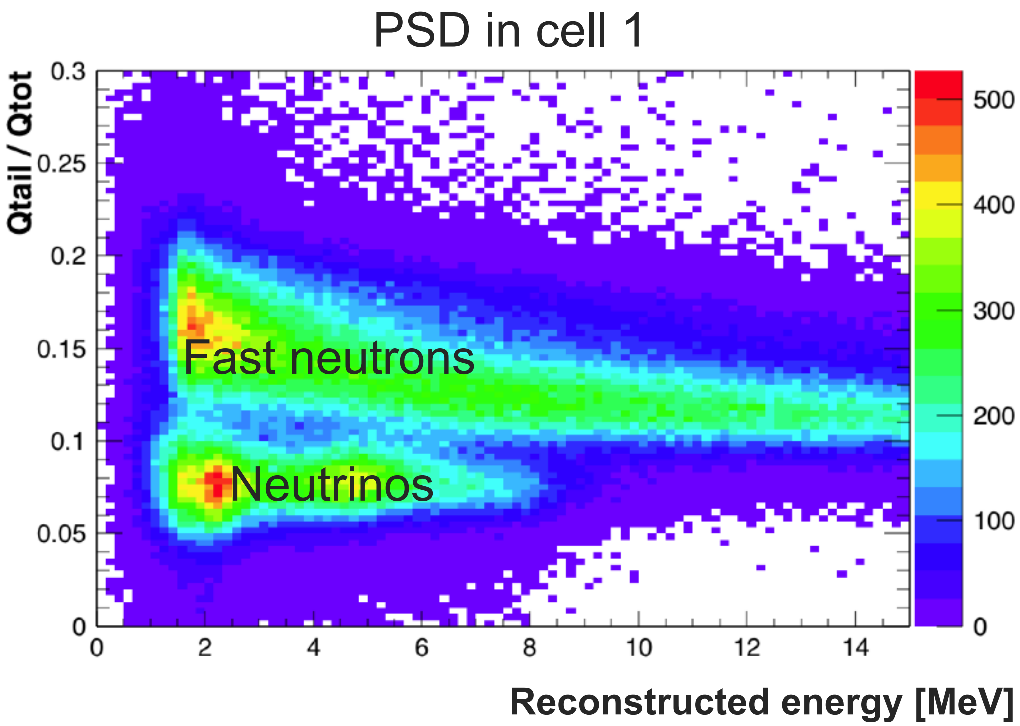
Background rejection (cosmic rays)

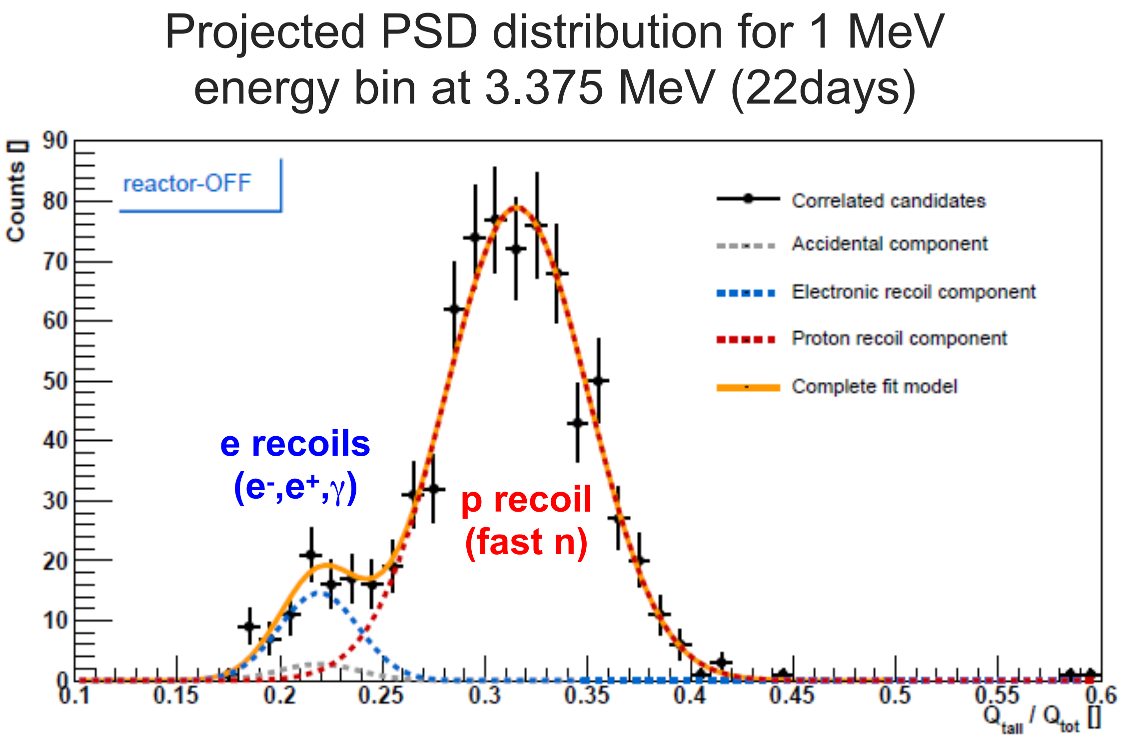






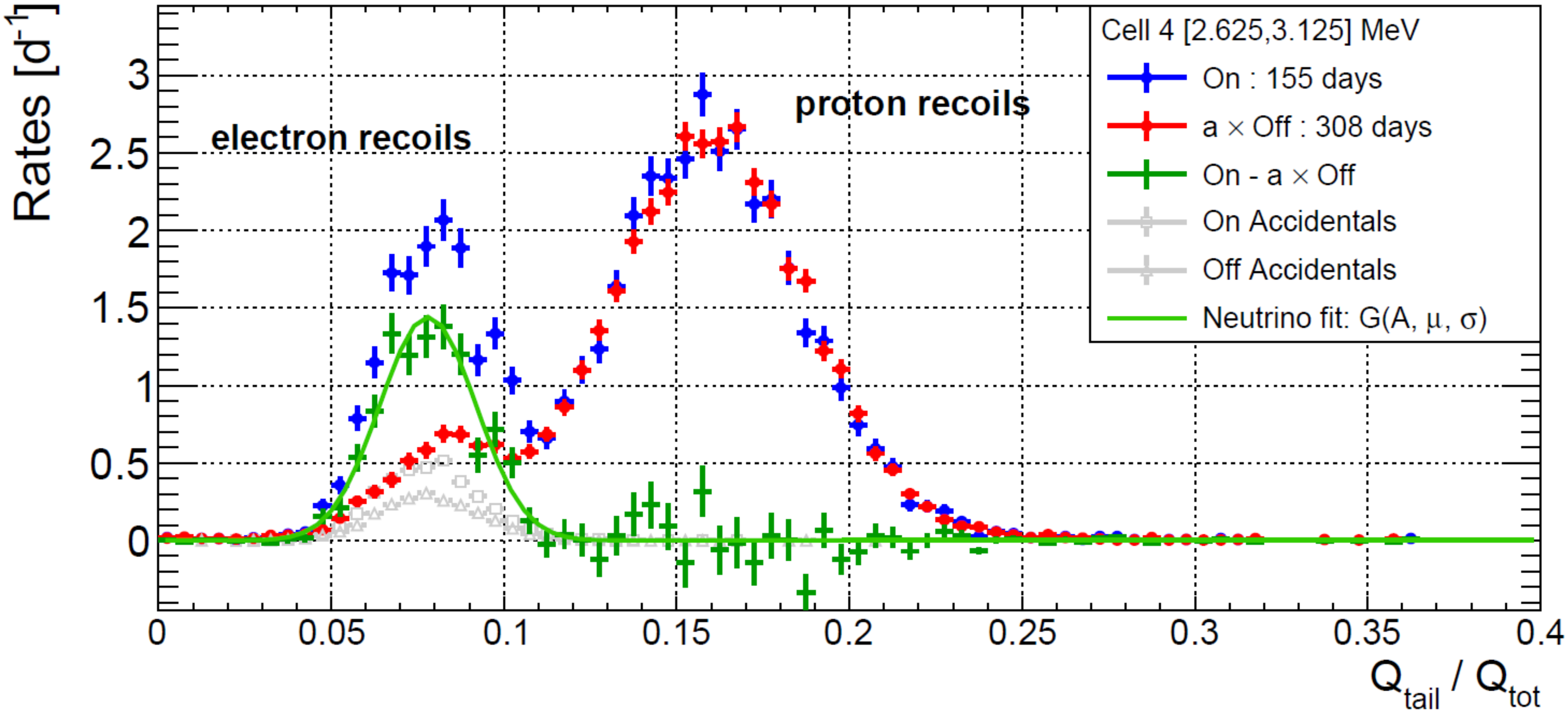
Pulse Shape Discrimination for background rejection



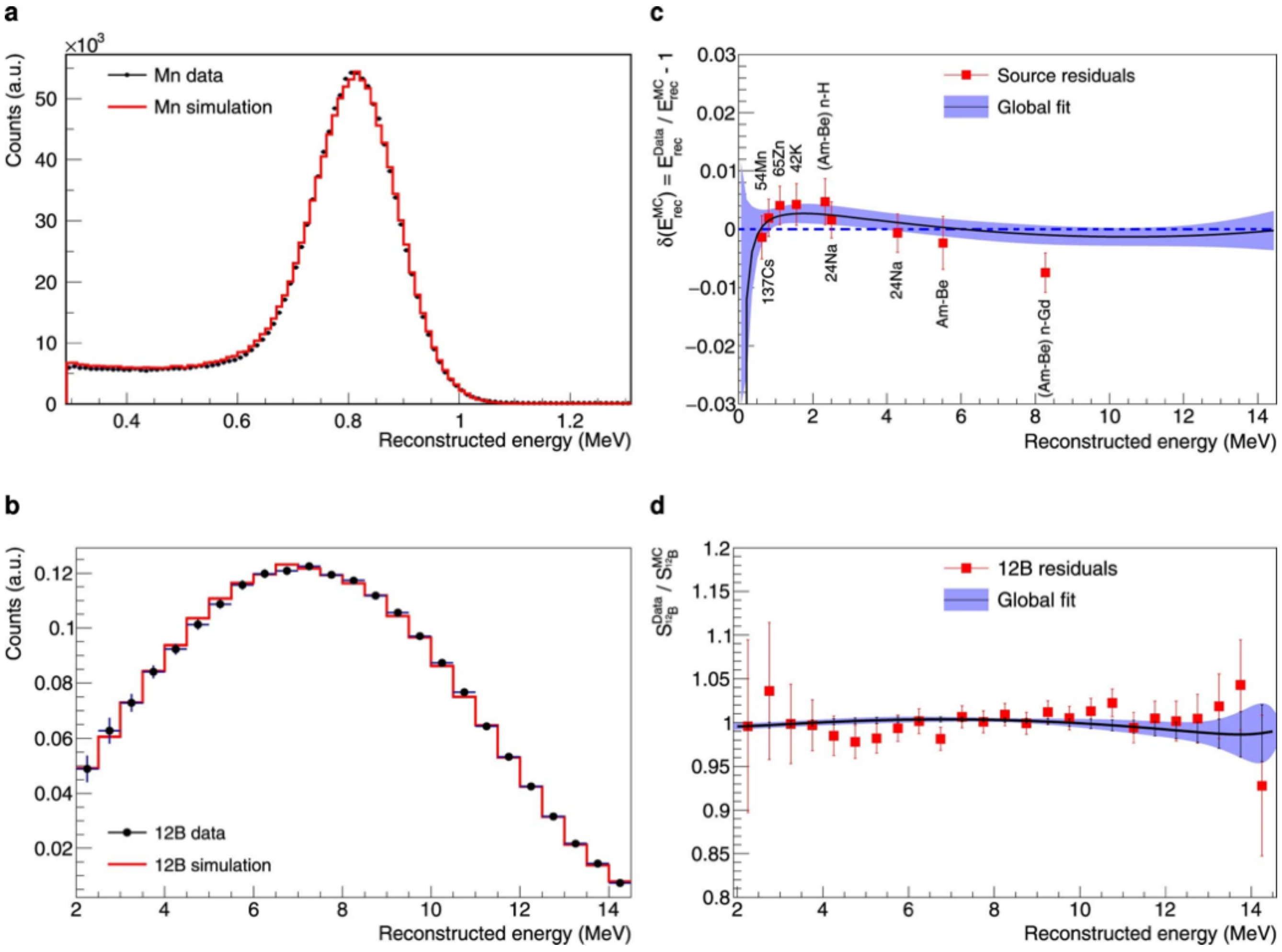


PSD allows to reject fast neutrons

Neutrino rate extraction



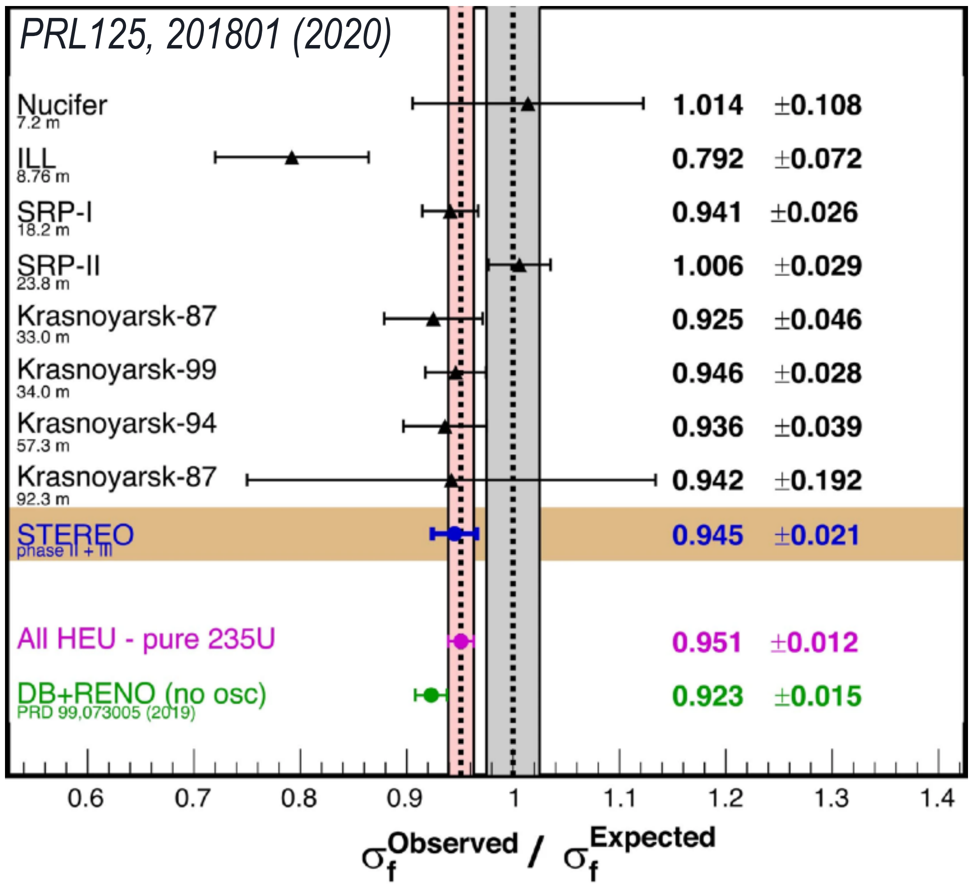
Accurate control of detector response

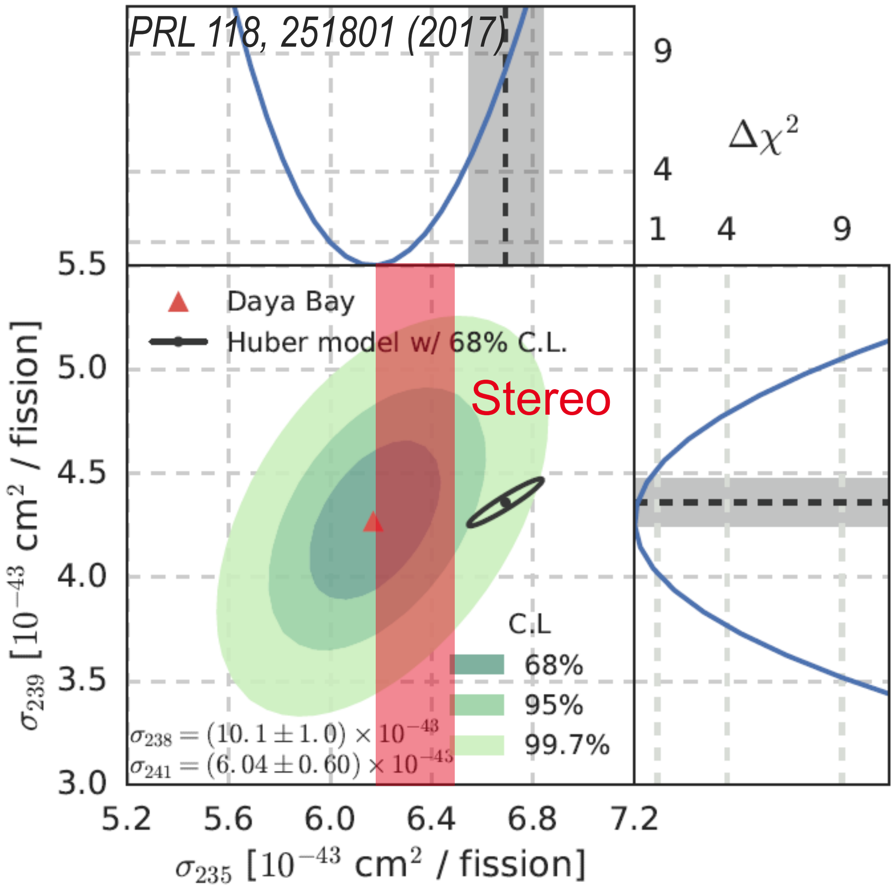


- Tuned MC of the detector
- Weekly calibration with ^{54}Mn source
- Every few month, full calibrations with ^{137}Cs, ^{54}Mn, ^{65}Zn, ^{42}K, ^{60}Co, ^{24}Na, ^{241}Am^{9}Be sources
- Stability of the detector response monitor with LED and n-H reaction, better than 0,5%

Energy resolution 9% at 1 MeV, 5% at 8 MeV
A control of the systematic uncertainties at the 1% level

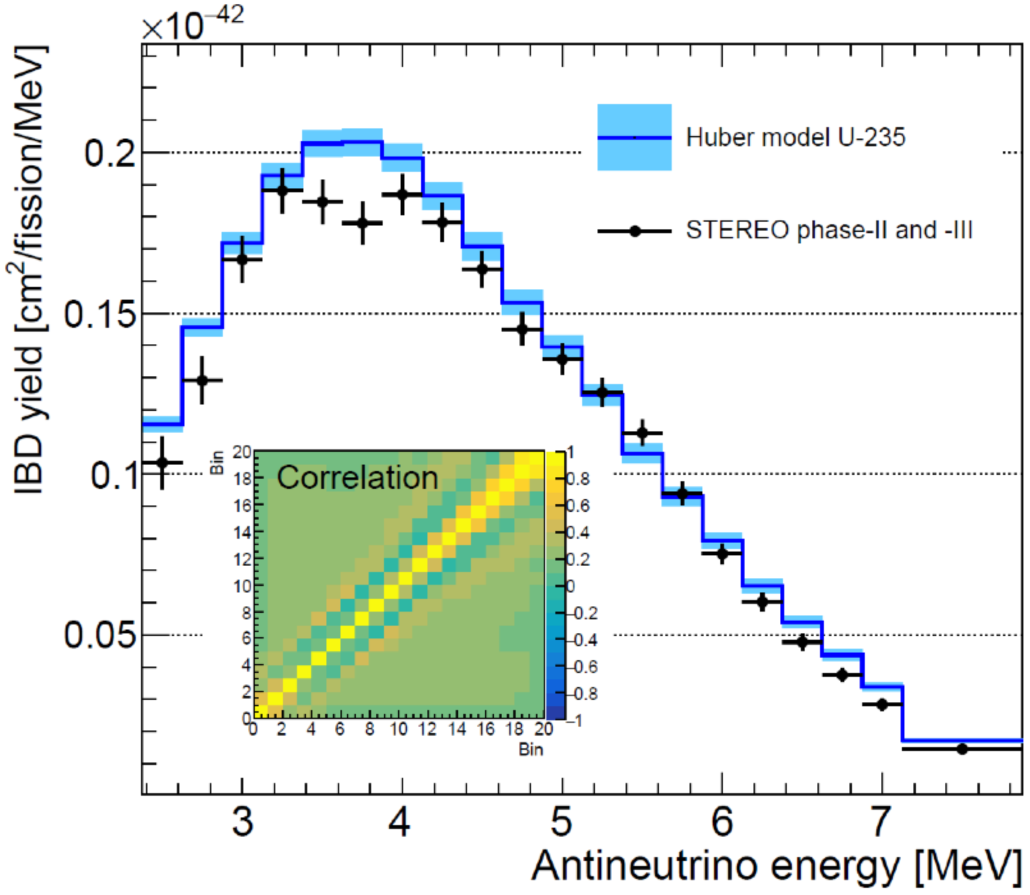
STEREO results (1/3)

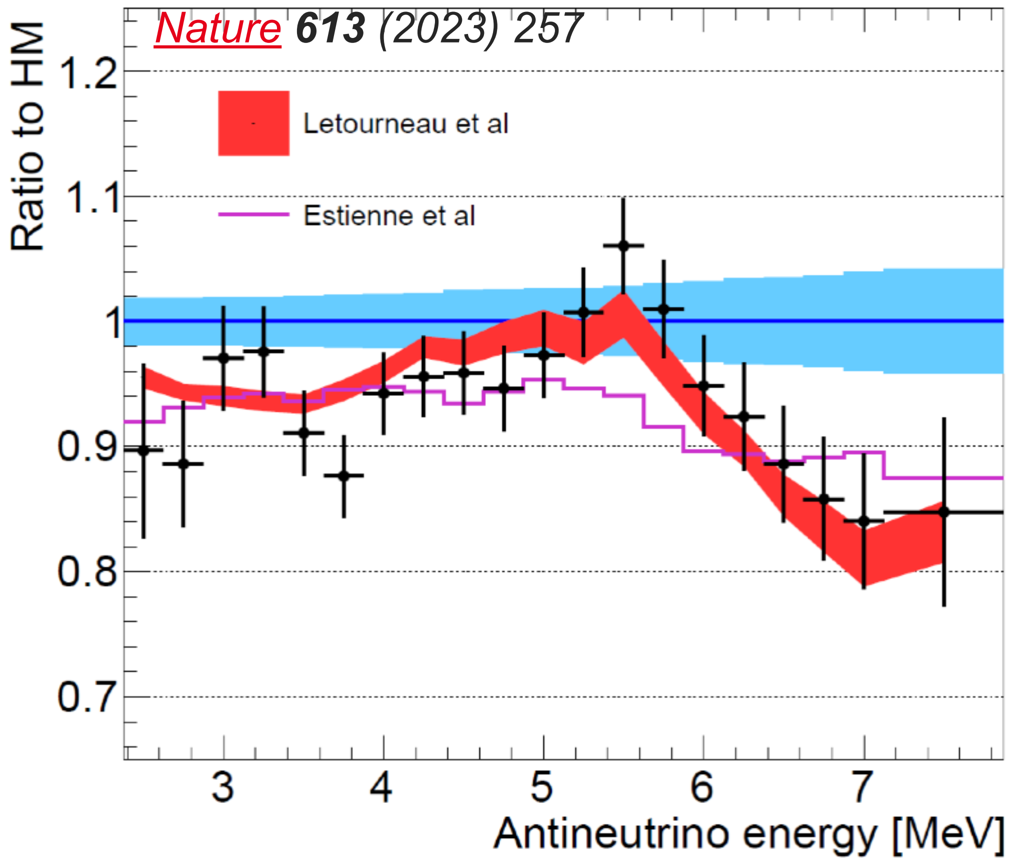




Confirms the RAA in ^{235}U and possibly ^{235}U as the primary source of the RAA

STEREO results (2/3)

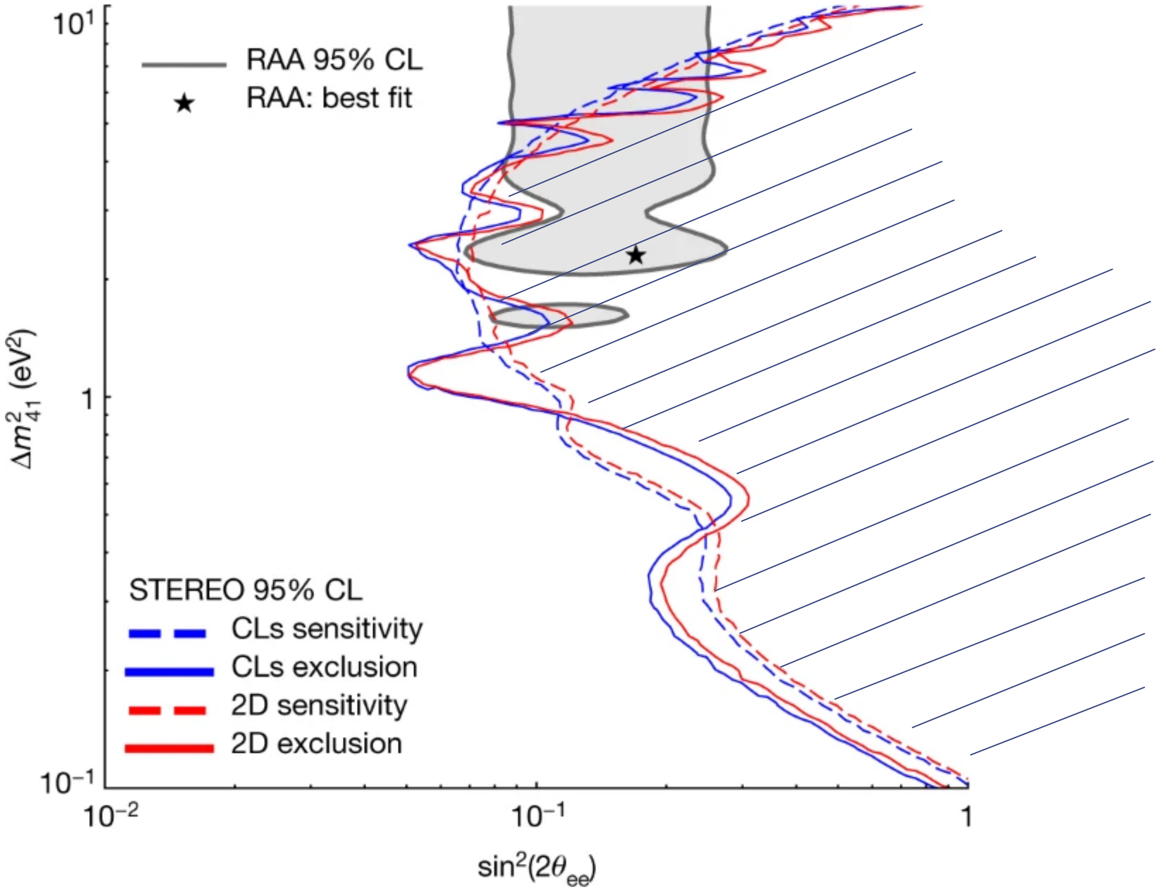




Confirms the « 5 MeV bump » in ^{235}U and provides a new energy spectrum reference

STEREO results (3/3)

Nature ***613*** *(2023) 257*

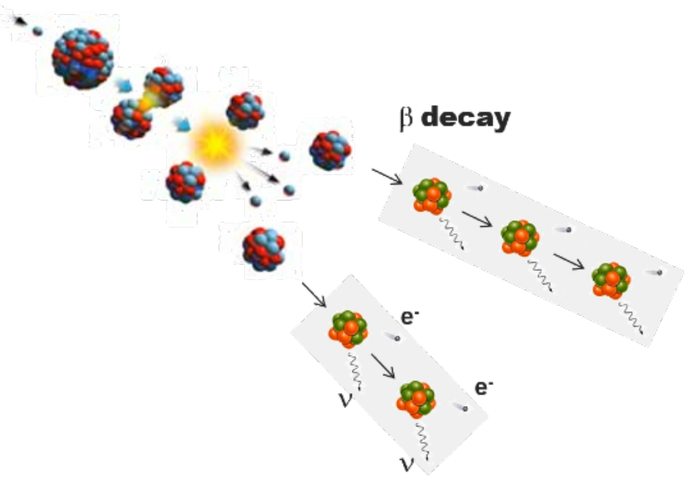


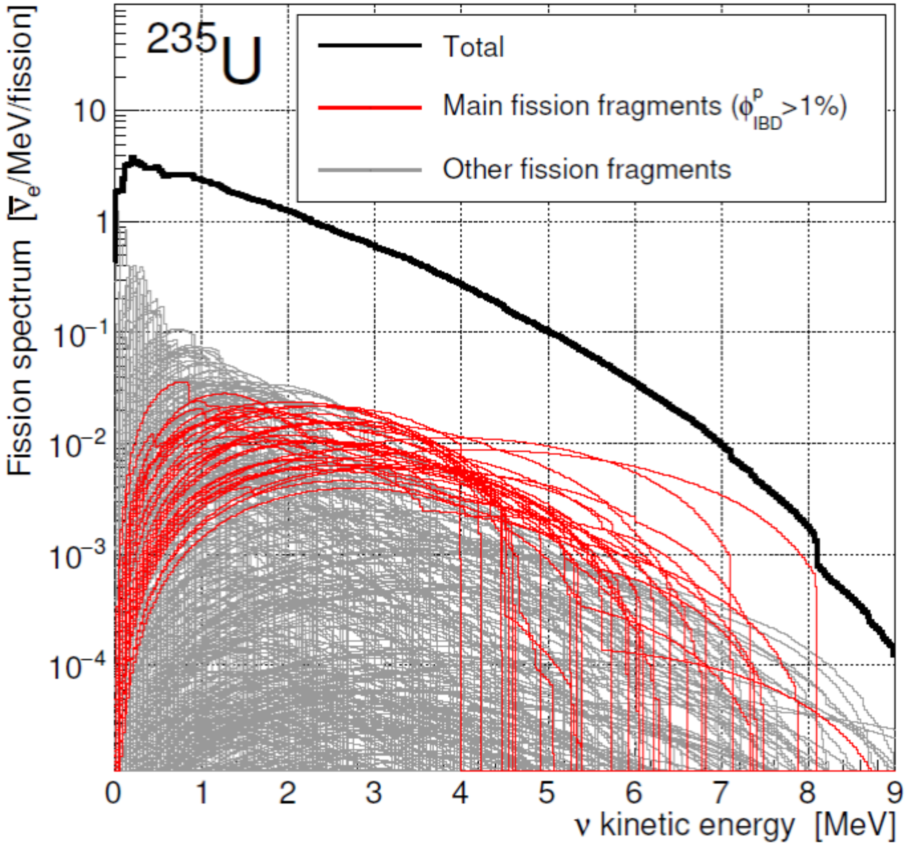
Rejects the hypothesis of a light Sterile neutrino to explain the RAA

Reactor Antineutrino Modeling

Summation method for fission β spectra modeling

$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$



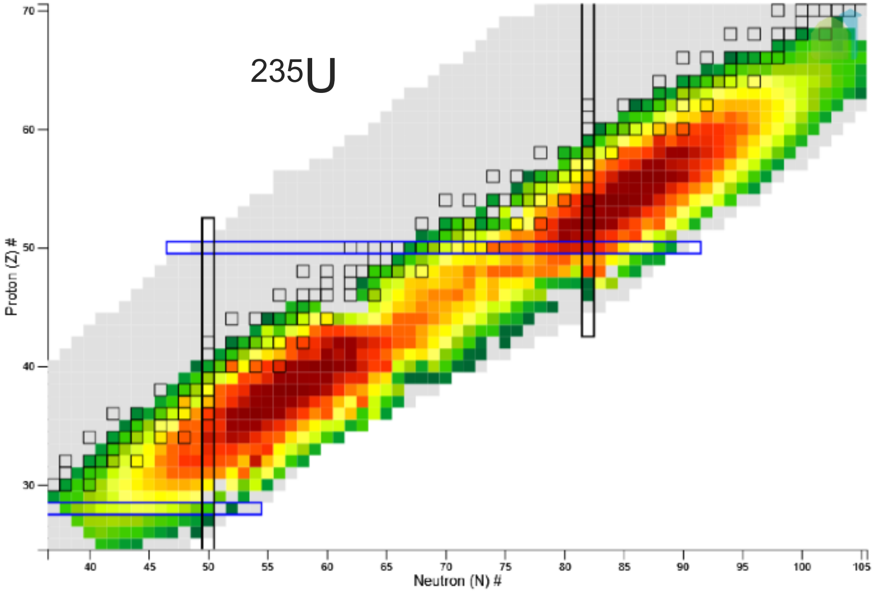


More than 800 fission fragments, more than 10000 β-decay branches

Summation method for fission β spectra modeling

$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$

- Fission fragment activities

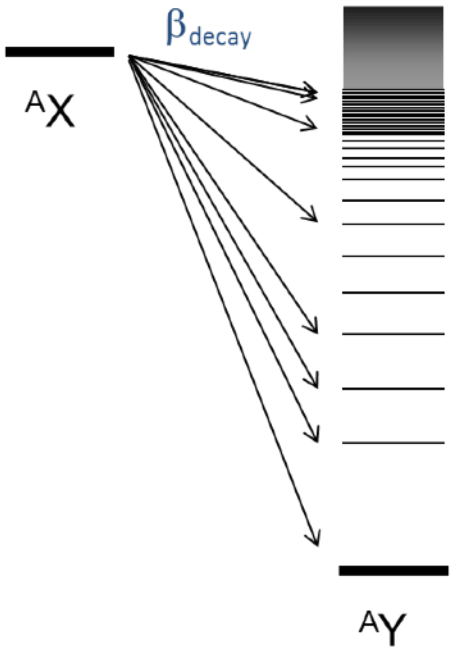


- Fission yields from nuclear data bases (JEFF, ENDF, JENDL) or fission models (GEF)
- Evolution code (FISPACT) or cumulative yields

Summation method for fission β spectra modeling

$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$

- Beta branch intensities



- Intensities from evaluated nuclear structure data base (ENSDF)

Summation method for fission β spectra modeling

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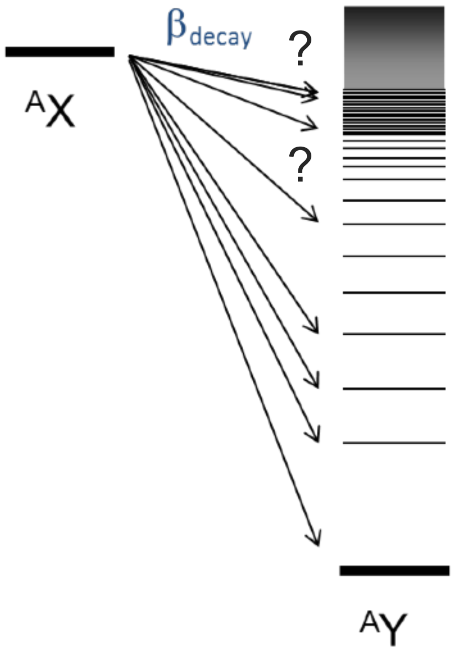
- Beta branch intensities

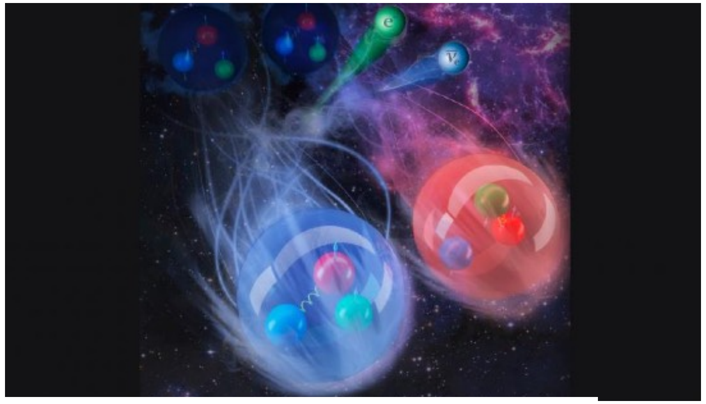


- Intensities from evaluated nuclear structure data base (ENSDF)
- But incomplete and Pandemonium effect

Summation method for fission β spectra modeling

- Electron/Antineutrino energy spectrum

$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$



Fermi Golden rule: $S(E_e)dE_e = (G_F^2/2\pi^3)\,|H|^2 p_e E_e (E_0 - E_e)^2 dE_e$

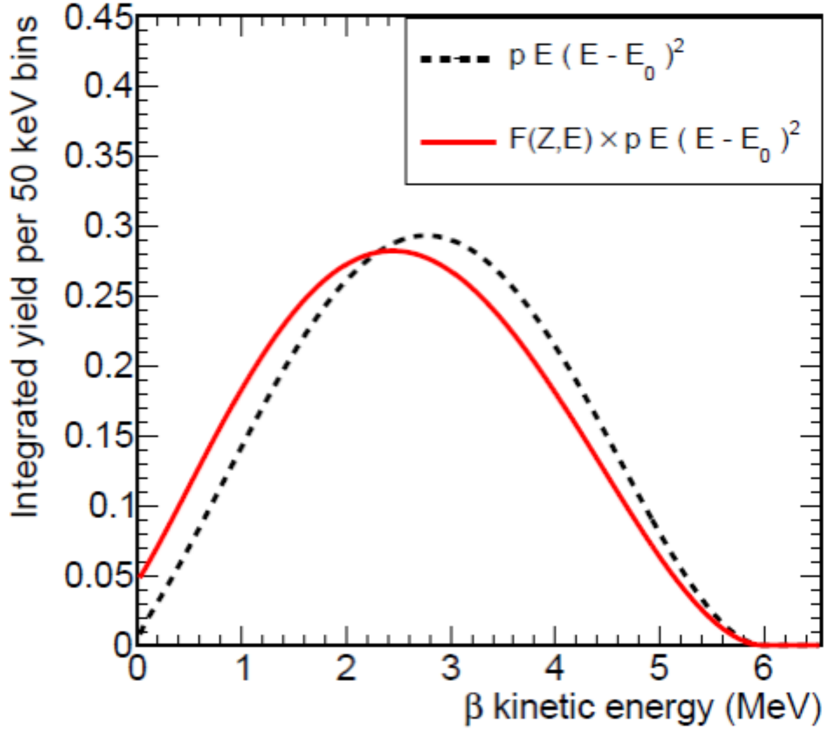
$$H = \frac{G_F}{\sqrt{2}} \sum_k \sum_\mu \int \underbrace{\left[\psi_f^* Q_k^- (\gamma_\mu - \lambda\gamma_\mu\gamma_5)\psi_i\right]}_{\text{Nuclear current}} \underbrace{\left[\psi_e^* \gamma^\mu (1+\gamma_5)\psi_\nu\right]}_{\text{Lepton current}}$$

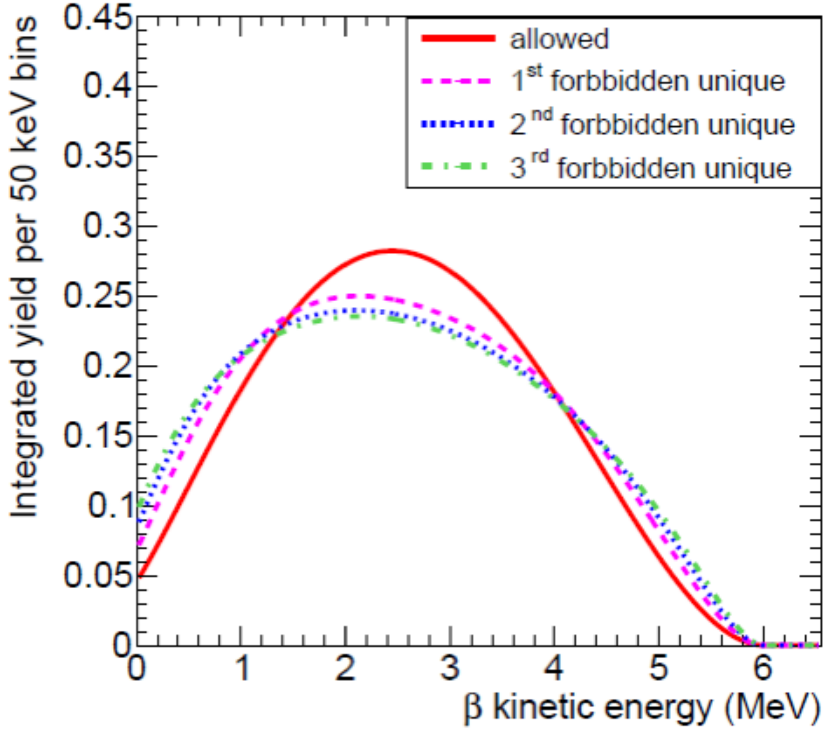
Nuclear current

Lepton current

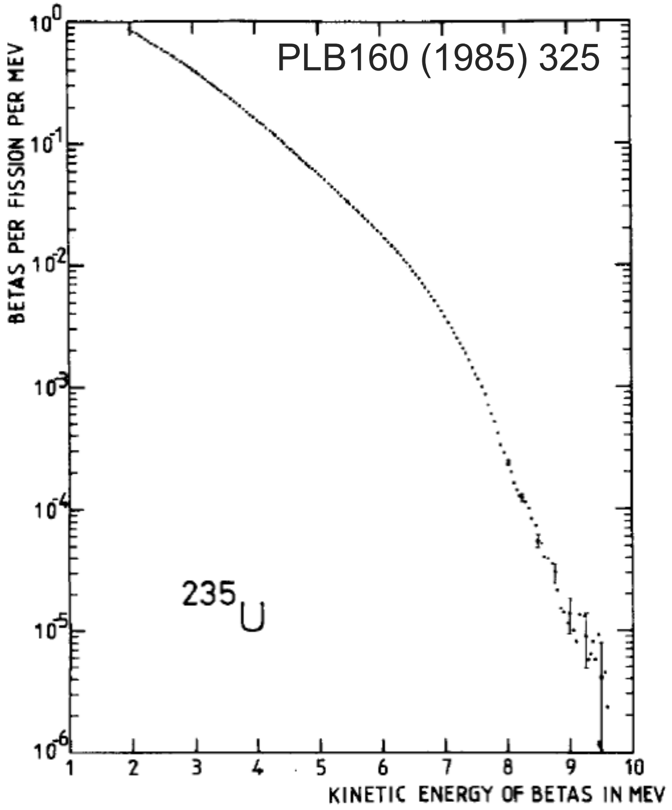
β spectrum modeling

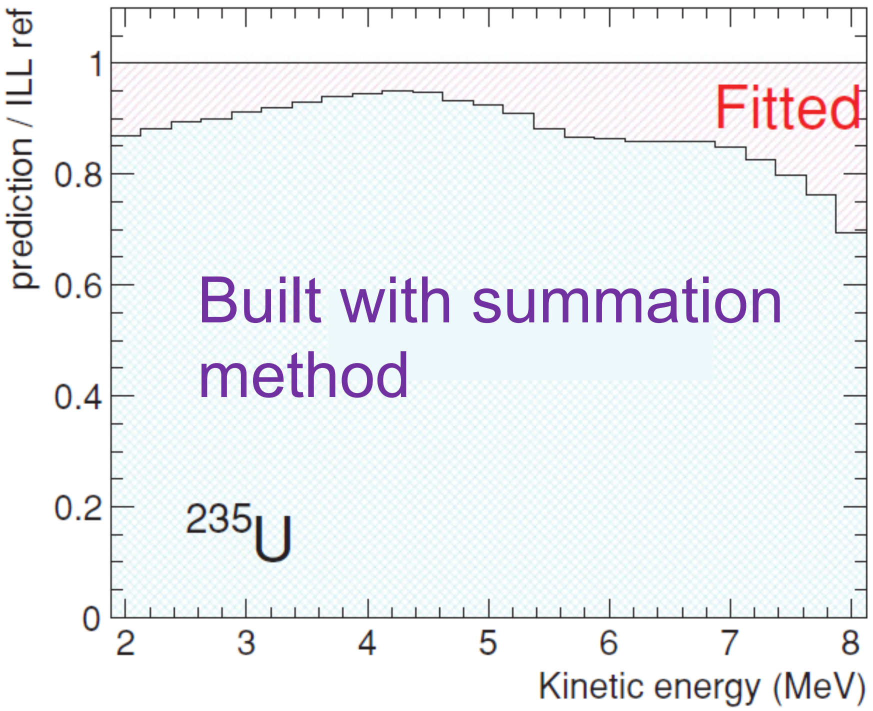
$$S_f^b(E) = K_f^b \times \mathcal{F}(Z_f, E) \times pE(E - E_{0f}^b)^2 \times C_f^b(E) \times \left(1 + \delta_f^b(Z_f, A_f, E)\right)$$

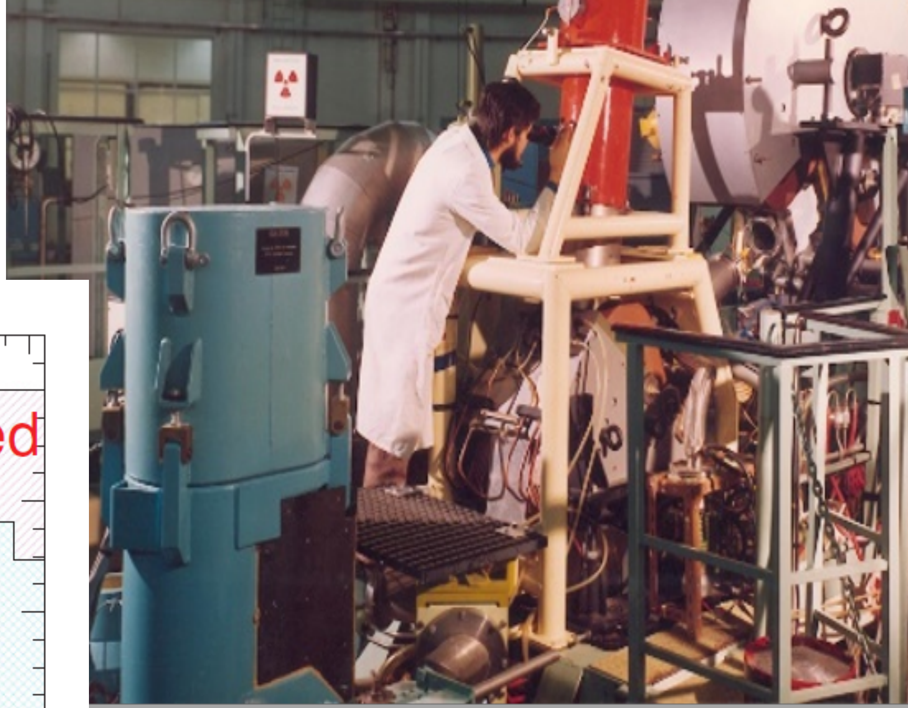




Comparison to ILL fission electrons





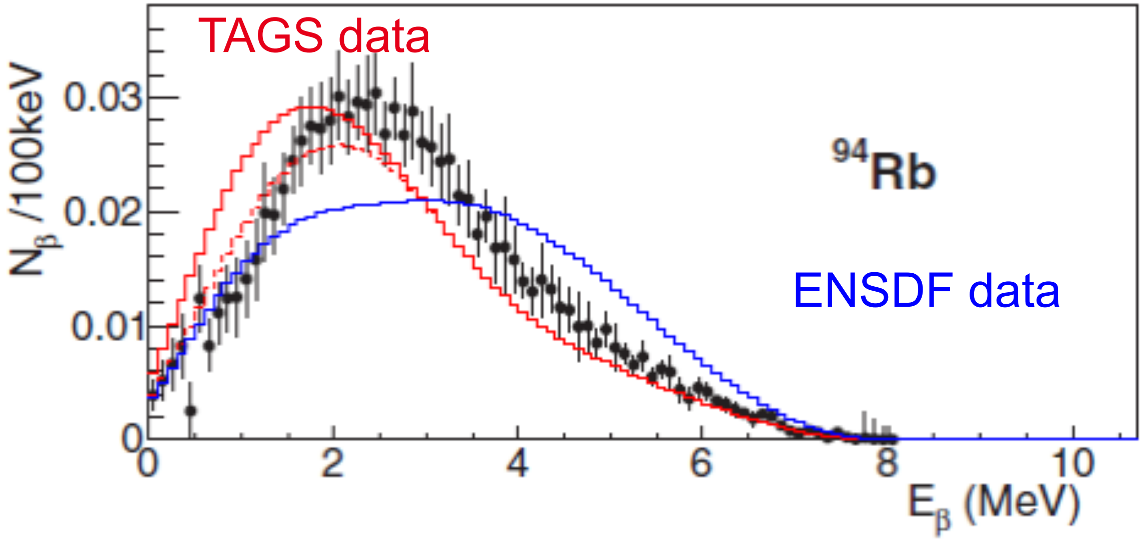


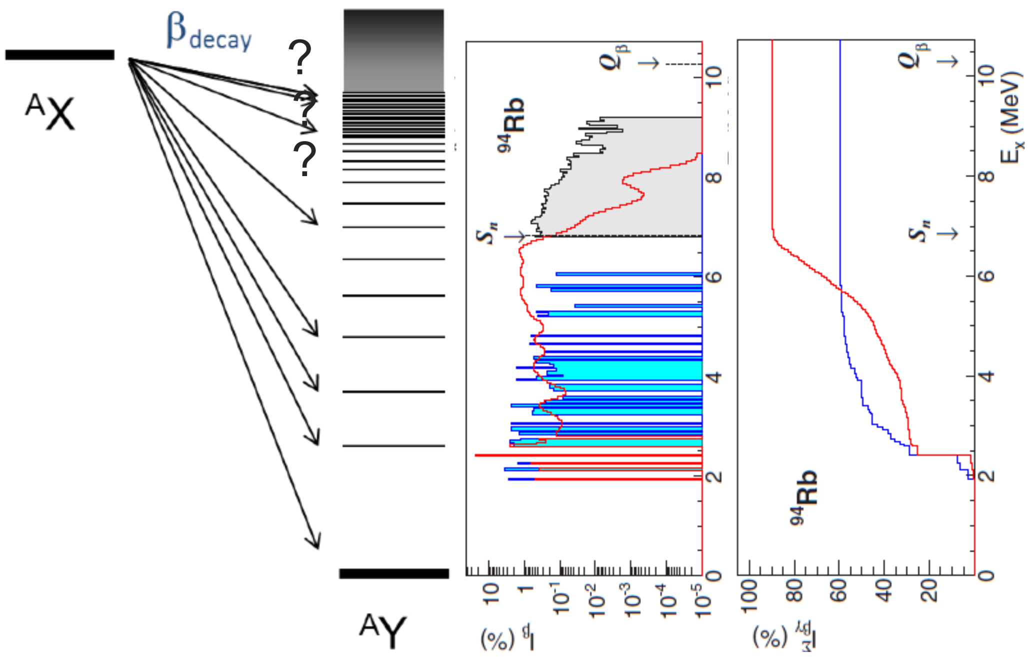
Muller-Huber model converts the ILL fission electron spectra

How to improve the summation method ?

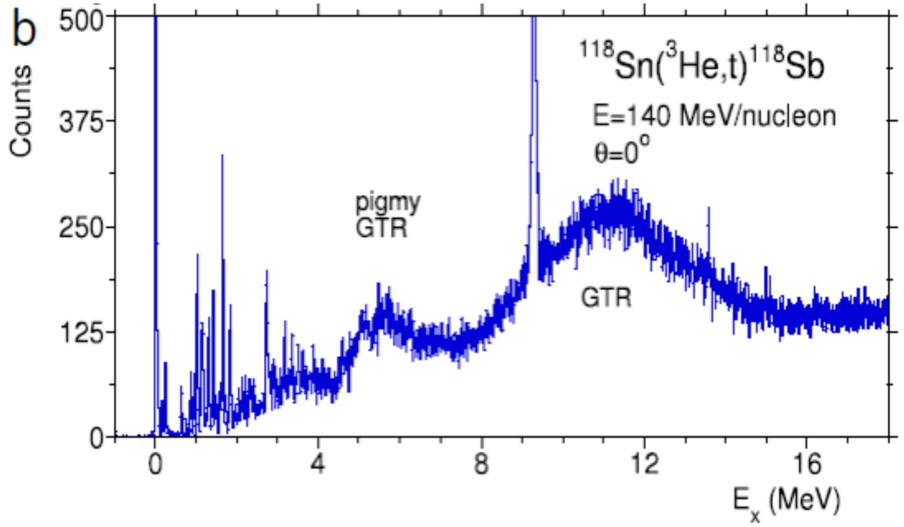
$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$

- Pandemonium and missing data

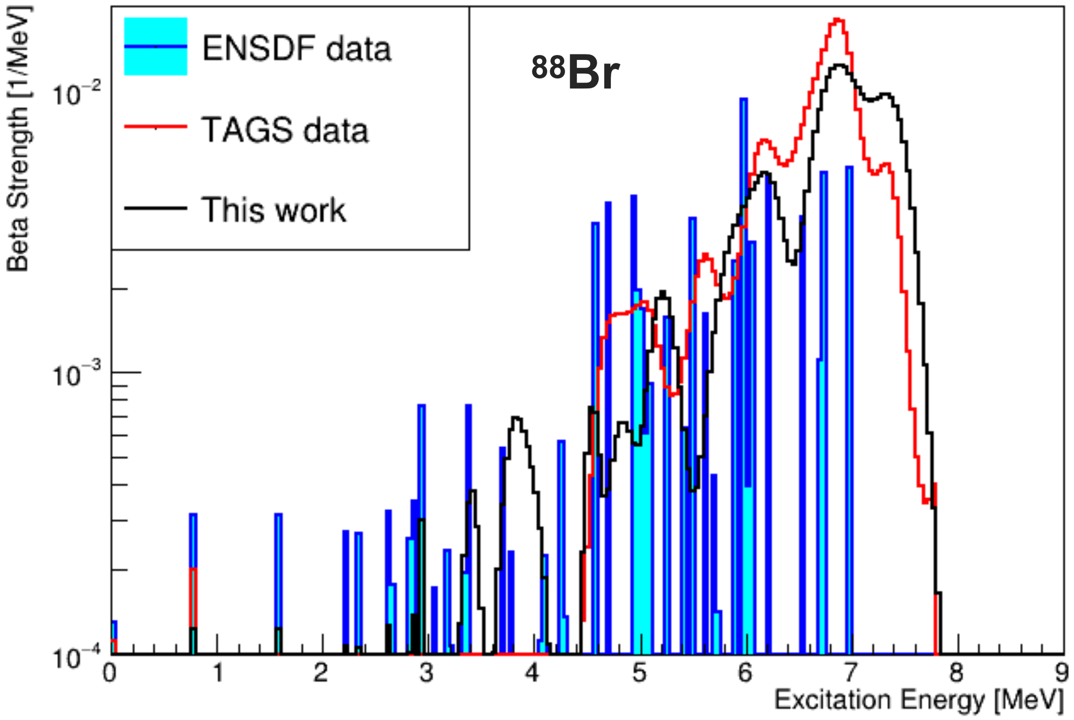




Phenomenological Gamow-Teller strength model



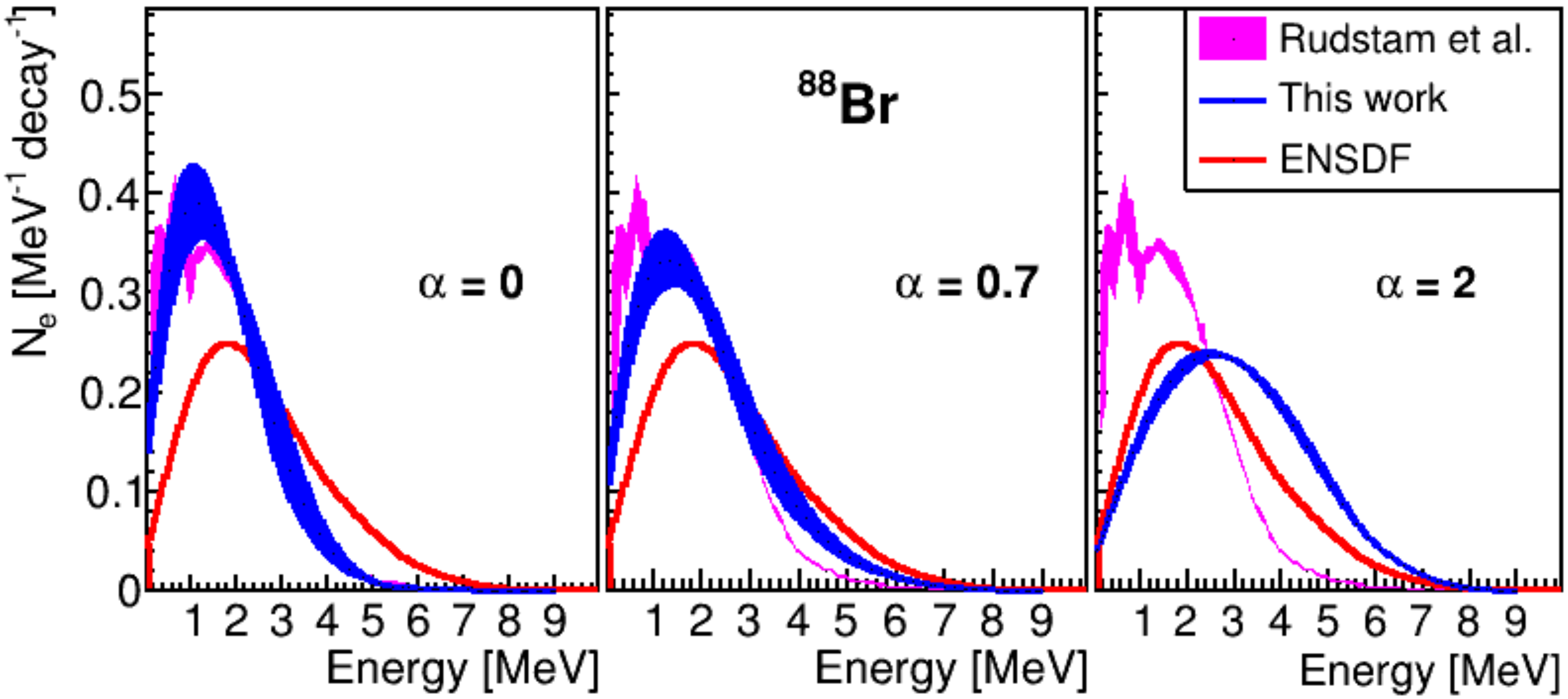
- Based on the observation that in charge exchange reactions, resonance structures appear in the strength of the reaction due to collective effects with universal features.



- Below 2-3 MeV, ENSDF data are used or random discrete transitions are generated
- Above, random resonances are generated using the resonance parameter distributions from TAGS data.
- The strength is supposed to be proportional to the nuclear level densities :

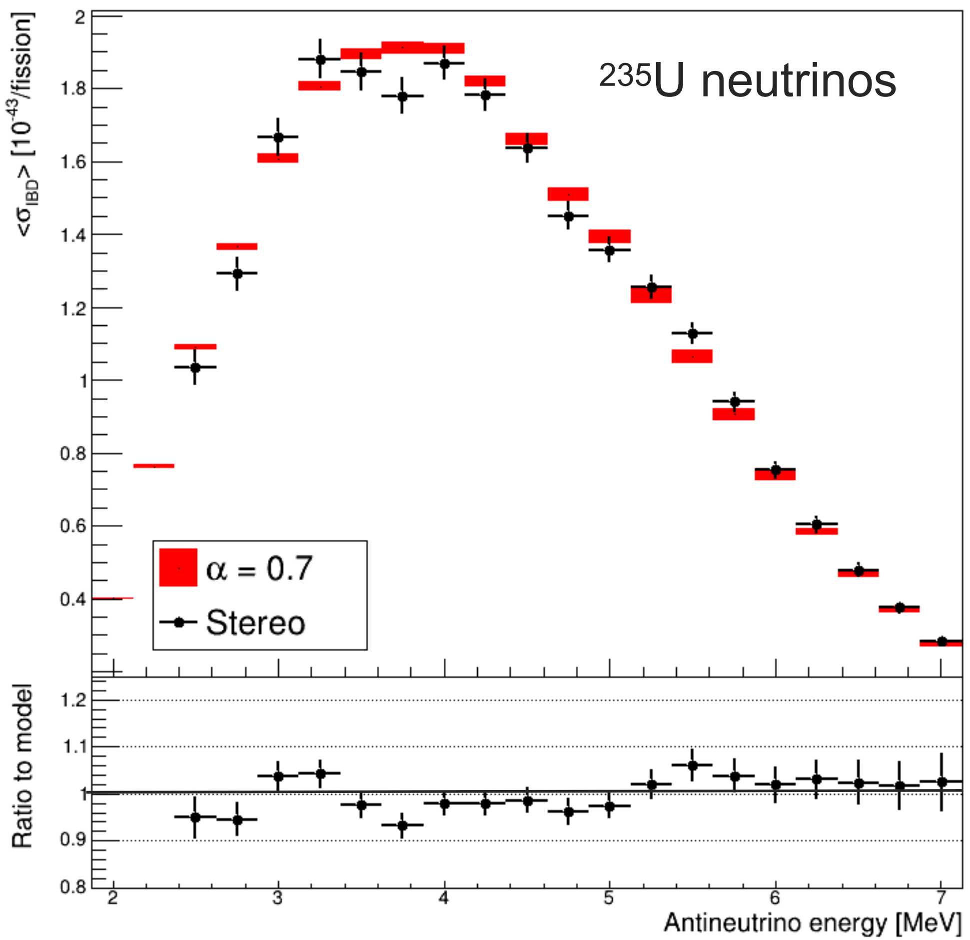
$$\rho(E^*) = e^{\alpha\sqrt{E^*}}\rho_{HFB}(E^*)$$

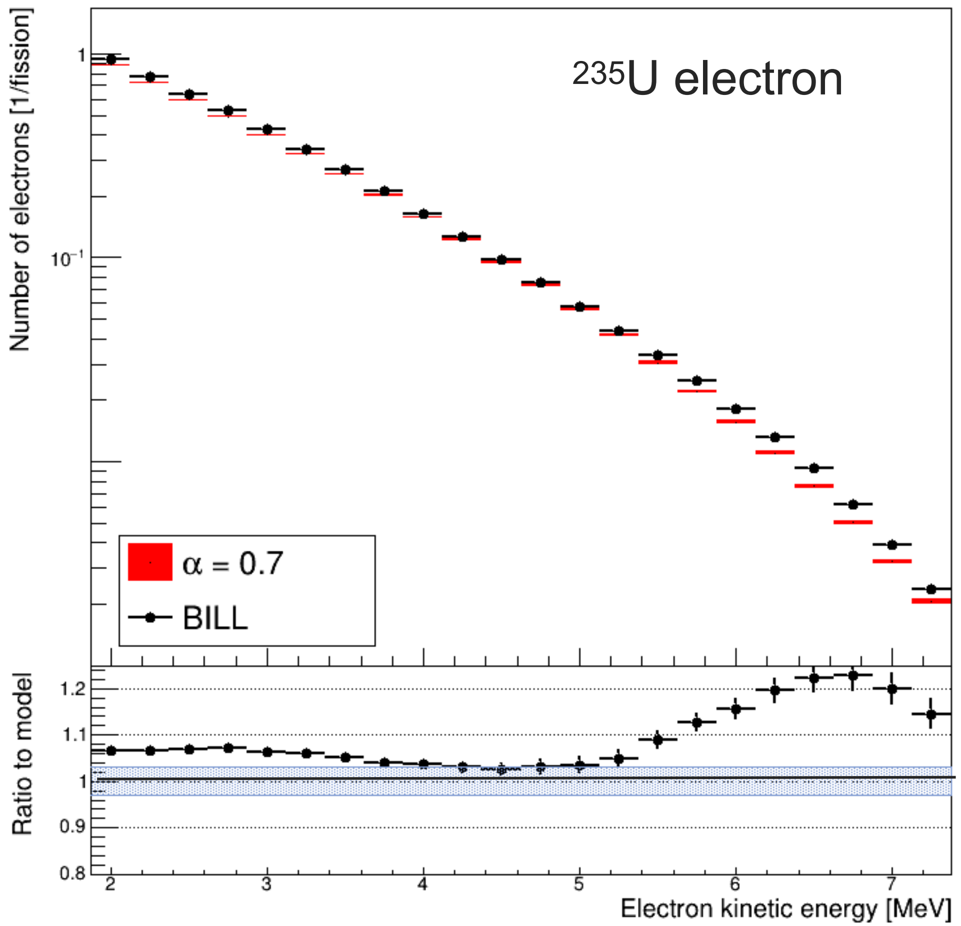
Effect of α parameter



Overall in good agreement for α ~ 0,7

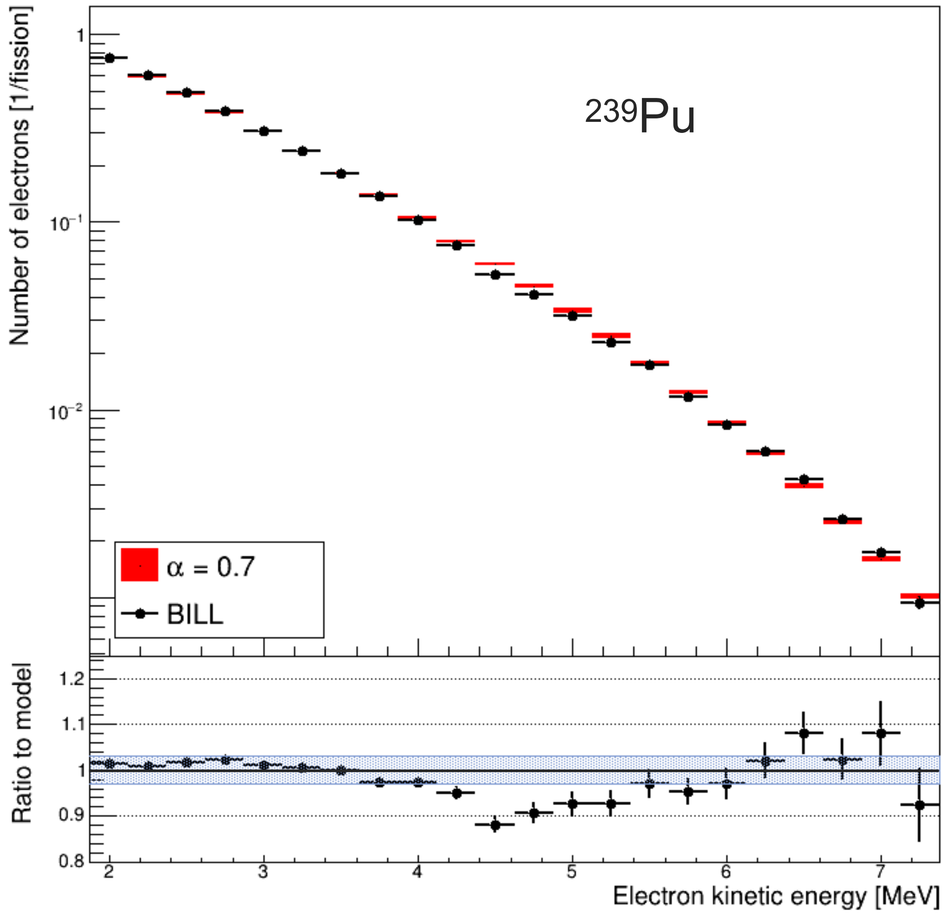
Antineutrino and electron spectra for ^{235}U

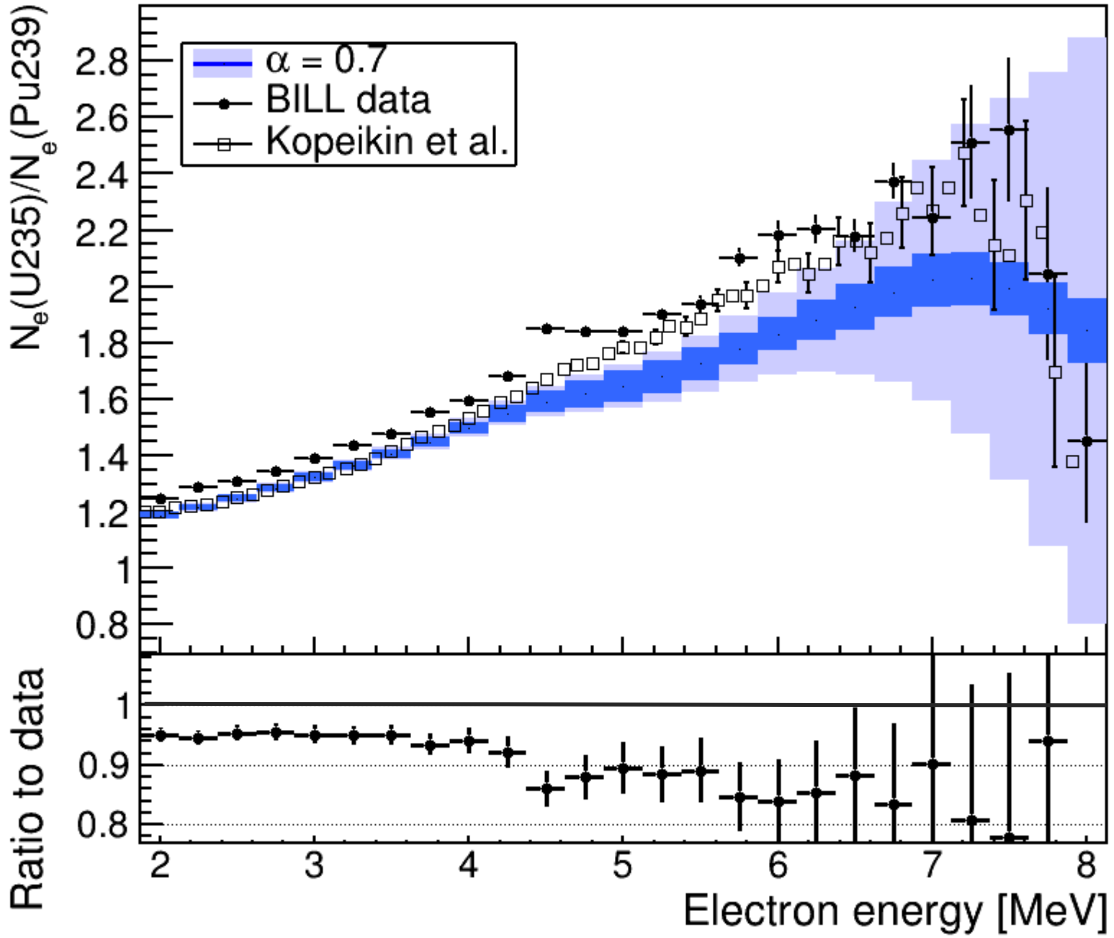




Shape and Norm incompatibility between STEREO antineutrino and BILL electron spectra for ^{235}U

Electron spectra





The norm anomaly is carried by ^{235}U but the shape anomaly seems to be carried by both

Conclusions and perspectives

- The **Norm** and **Shape** reactor antineutrino anomalies are 10 years long exciting scientific adventure opening the possibility for the existence of a light sterile neutrino.

- This hypothesis is now **rejected** by the results of the STEREO experiment.

- Recent theoretical works points to **biases** in the ILL fission electron energy spectra used to anchor the prediction as the origin of the anomalies.

- Progresses in the **antineutrino energy spectra modeling** and **new measurements** of the fission electron energy spectra are needed for confirmation

- Neutrino physics is now in the **precision area** allowing testing **non standard interactions**. **Most systematic uncertainties are now on nuclear physics models**.

Thank you for your attention