From Safeguards Application to Fundamental Physics: Advancements in Reactor Neutrino Detection with the ν-Angra Experiment

III LASF4RI for HECAP Symposium

28/08/2024

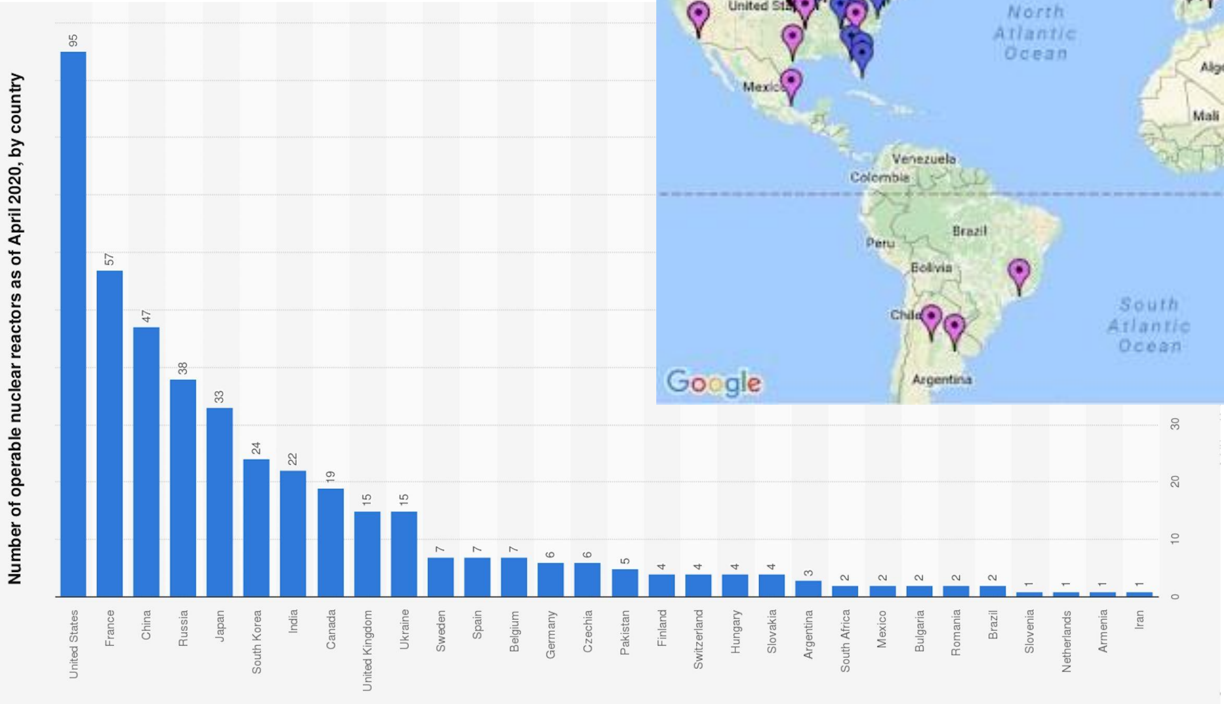
ICTP-SAIFR, São Paulo, BR

Ernesto Kemp (kemp@unicamp.br)

on behalf of the Neutrinos Angra Collaboration.

Reactor Neutrinos as Safeguards Tool

440 nuclear reactors in operation in ~ 30 countries around the world.



A 1000 MWe light water reactor gives rise to about 25 tonnes of used fuel a year, containing up to 290 kilograms of plutonium.

It takes about 10 kilograms of nearly pure Pu-239 to make a bomb

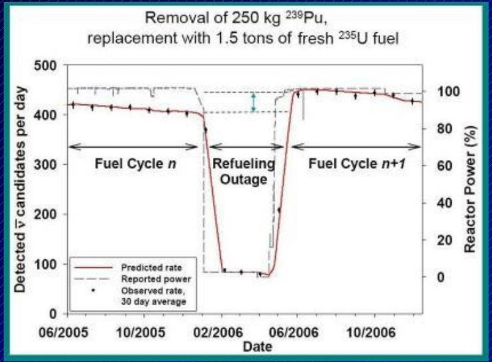
Reactor Neutrinos as Safeguards Tool

Why the interest in antineutrino detectors?

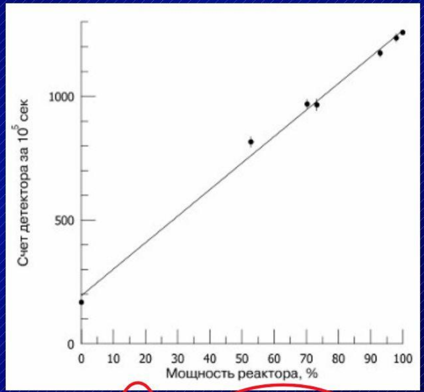
- Antineutrinos can not be shielded and are produced in very large amounts in nuclear reactors
  (~ 10^{20} antineutrinos/s)
- Antineutrinos produced in reactors can reveal fissile composition of nuclear fuel
- Non-intrusive monitoring in real-time the reactor state:
  - thermal power & fissile material
- Search for new methods on safeguards verification

Monitoring nuclear reactors with antineutrinos:
It is feasible

San Onofre (USA)



Rovno/Ucraine



Thermal power control:
Interesting topic for Eletronuclear

$$N_\nu = \gamma \cdot (1 + k) \cdot P_{th}$$

Factor carrying detector features

Factor carrying fuel composition features

The Neutrinos Angra Experiment

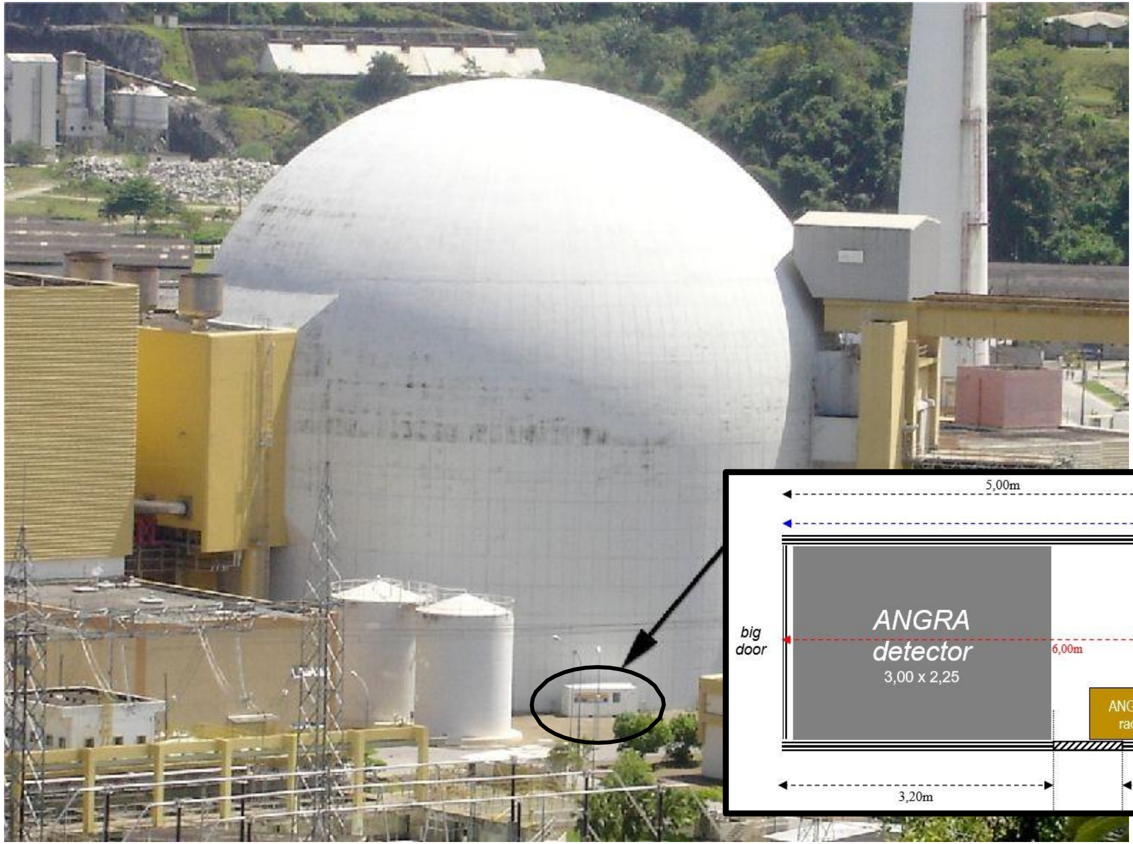
The Angra Collaboration

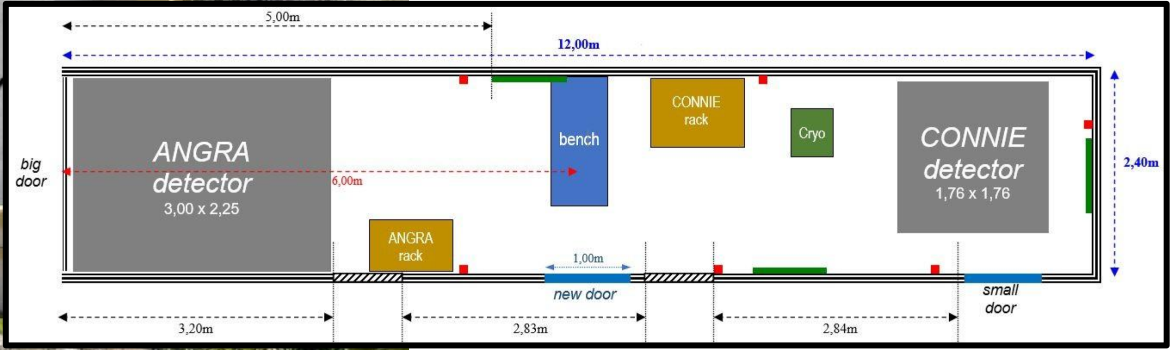
6 Brazilian Institutes:

- CBPF (Rio de Janeiro - RJ)
- UEFS (Feira de Santana - BA)
- UEL (Londrina - PR)
- UFBA (Salvador - BA)
- UFJF (Juiz de Fora - MG)
- Unicamp (Campinas - SP)

8 Researchers
3 Students

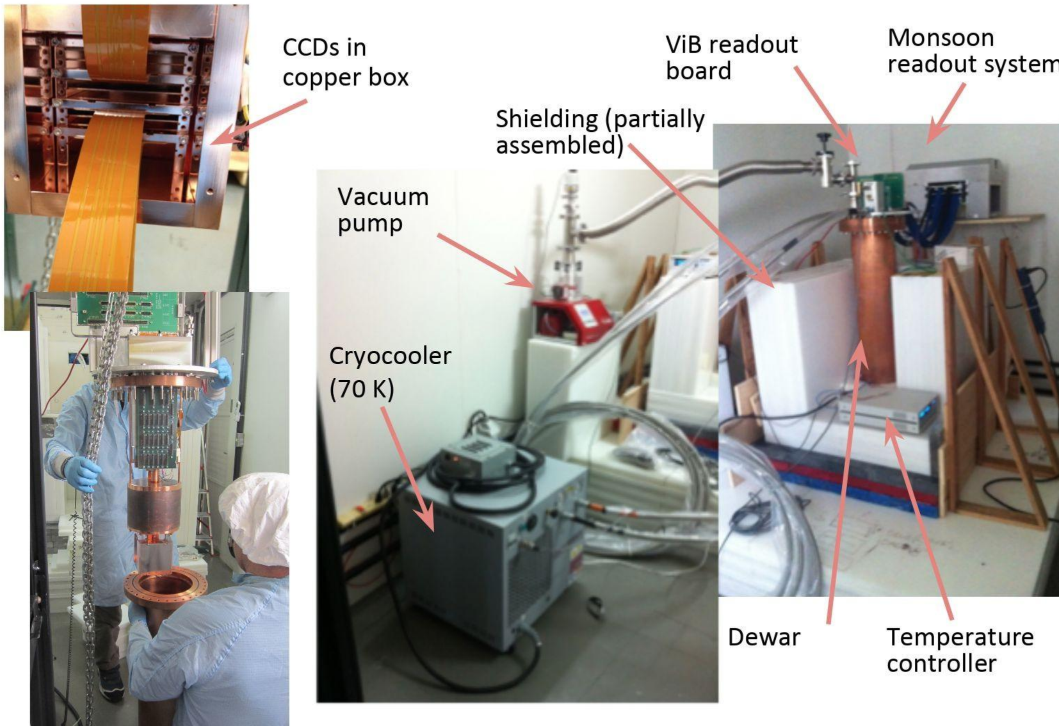
The experimental Lab





The experimental Lab

CONNIE detector installed in 2014



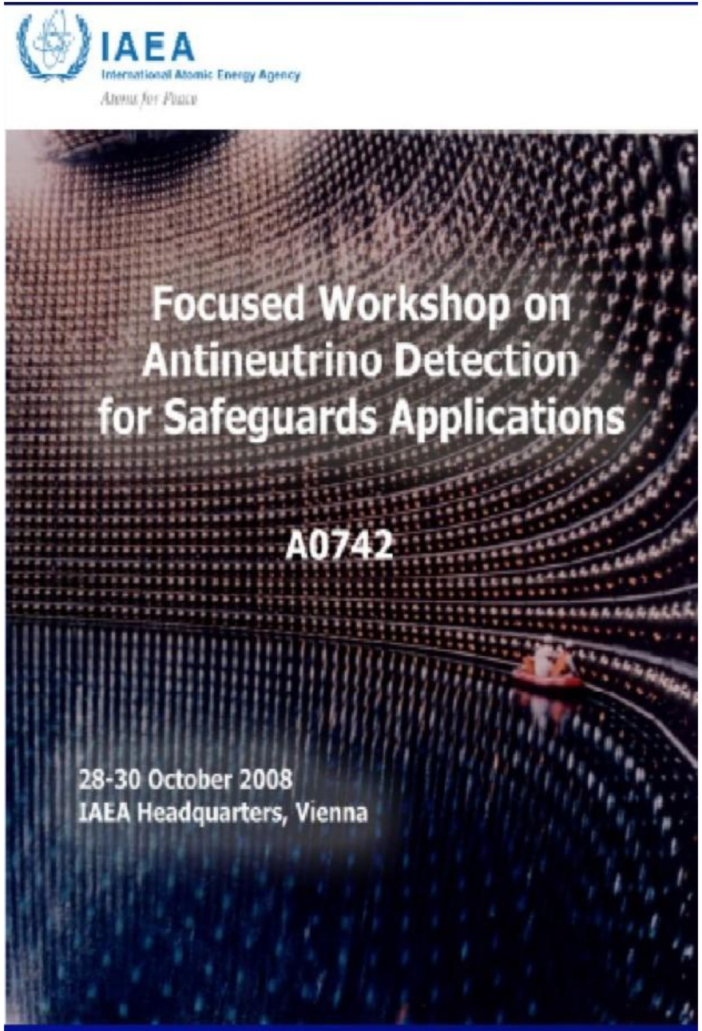
C. Boniazi talk:

Session X: White Paper Presentation - Neutrinos
14:00-14:20 - Coherent Neutrino-Nucleus Scattering Experiment (CONNIE) - Carla Bonifazi
14:20-14:40 - Latin American Contributions to the NOvA Experiment - Ricardo Gomes
14:40-15:00 - Neutrino Astronomy in the Peruvian Andes with TAMBO - Carlos Argüeles
15:00-15:20 - DUNE in the context of LASF4RI - the Colombian case - an update - Deywis Moreno
15:20-15:40 - From Safeguards Application to Fundamental Physics: Advancements in Reactor Neutrino Detection with the Brazilian ν-Angra Experiment - Ernesto Kemp
15:40-16:00 - GRAND: Giant Radio Array for Neutrino Detection - Rafael Batista

The ν-ANGRA Experiment

Major objectives:

- Non-invasive monitoring of reactor activity.
- Estimation of the thermal power produced in the reactor core.
- Development of new antineutrino detection techniques.
- Contribution to the International Atomic Energy Agency (IAEA) safeguards and non-proliferation efforts.
- Integration of Latin American scientists and engineers into global scientific collaborations.



DESIGN GUIDELINES:

Focused Workshop on Antinu-e

Detection for SG Applications (2008)

IAEA.org
International Atomic Energy Agency

7.2 Medium Term:

If the above near-term goals are met, it is the opinion of the workshop conferees that antineutrino detectors will have demonstrated utility in response to the stated inspector needs in some specific areas of reactor safeguards. To further expand the utility of antineutrino detectors, several useful medium term (5-8 year timeframe) R&D and safeguards analysis goals are proposed.

1. Above ground deployment. Above ground deployment will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied;

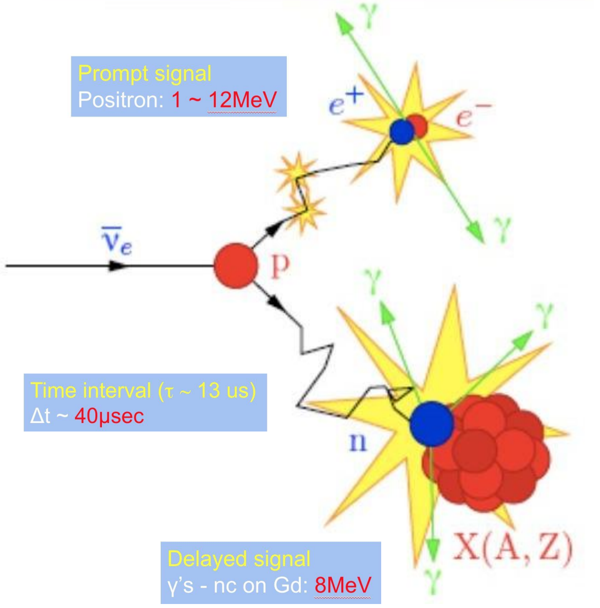
2. Provide fully independent measurements of fissile content, through the use of spectral information. This will allow the IAEA to fully confirm declarations with little or no input from reactor operators, purely by analysis of the antineutrino signal;

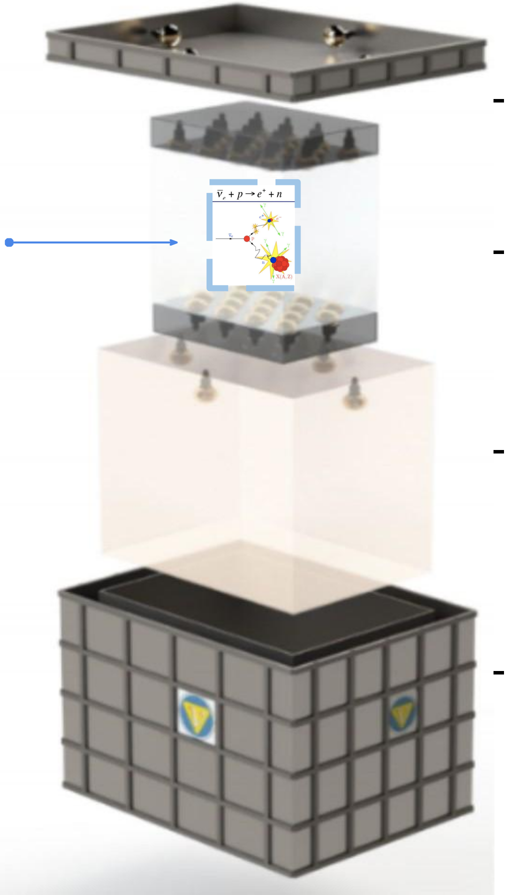
3. Develop improved shielding and reduced detector footprint designs, to allow for more convenient deployment. Current footprints are of order 2-3 meters on each side; modest reductions in footprint would expand the general utility of antineutrino detectors. .In this regard, a possible deployment scenario is envisaged where the component parts of the detector, shielding and all associated electronics are contained within a standard 12 metre ISO container, facilitating ease of movement and providing physical protection to the instrument. It should be noted that due to size and weight restrictions of ISO containers (approximately 25,000 kg net load) the

ν-ANGRA: a Water Cherenkov Detector

MADE IN BRAZIL

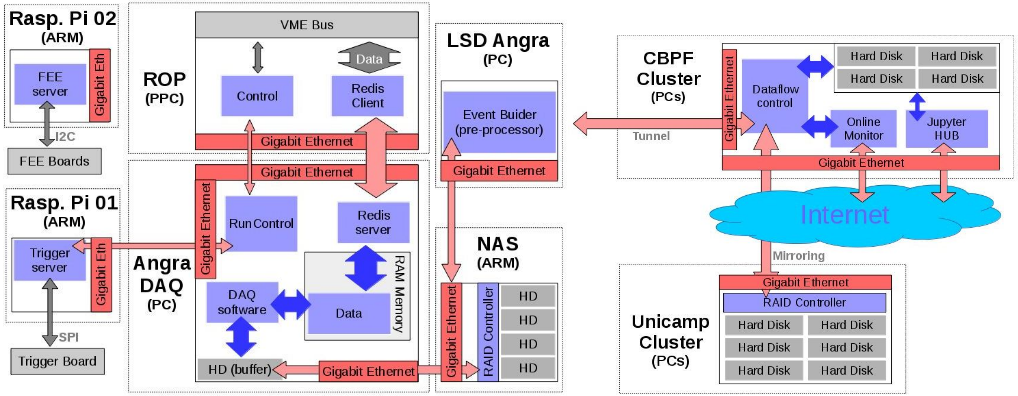
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

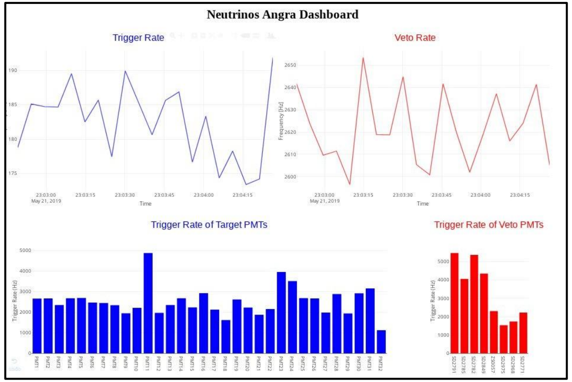




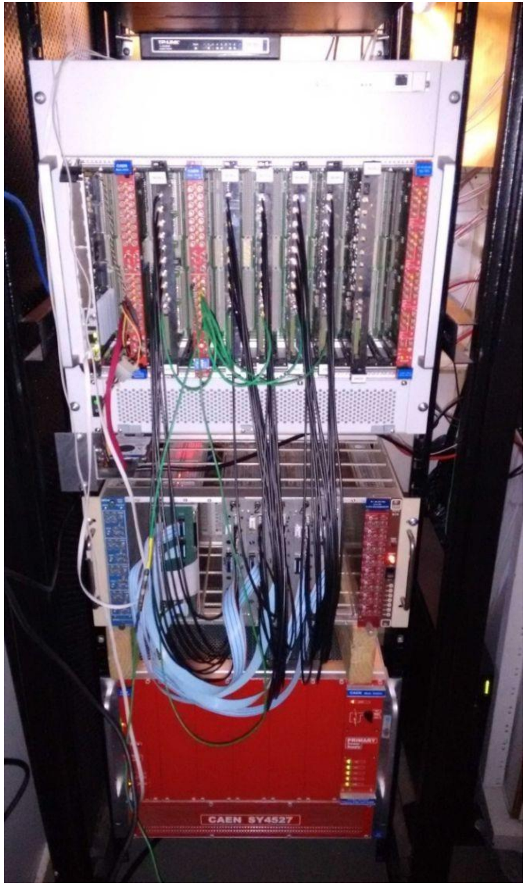
- Top veto (active): 4 PMTs
  25 cm height - pure water
- Neutrino Target (active): 32 PMTS
  ~ 1 ton GdCl3 doped water (0,2%)
- Inner Veto (active): 4 PMTs
  25 cm thick - pure water
- Shield (passive):
  25 cm thick- pure water

The Data Acquisition System (DAQ)

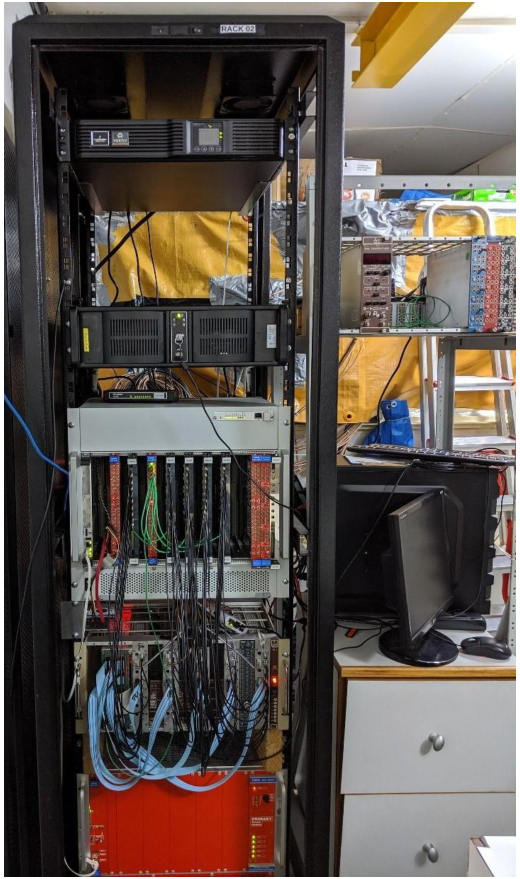




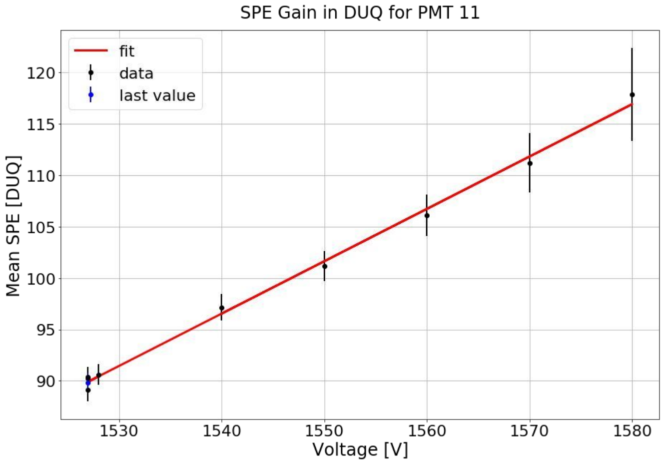
MADE IN BRAZIL

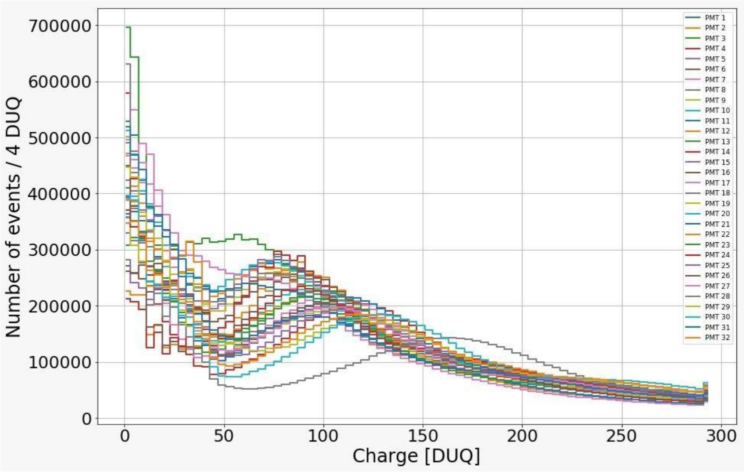


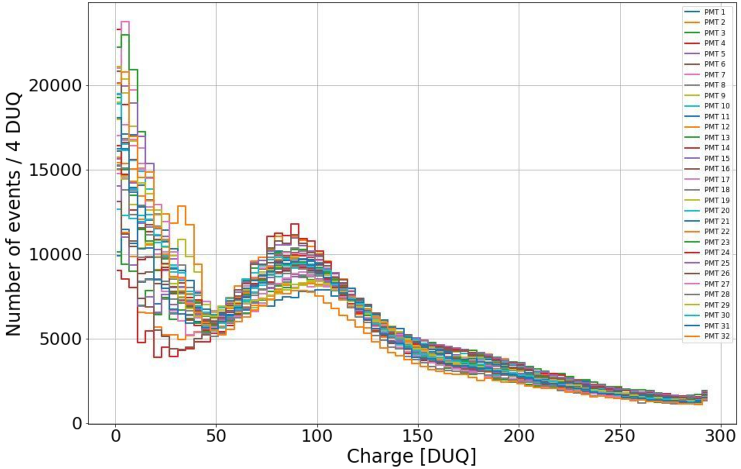
Commissioning



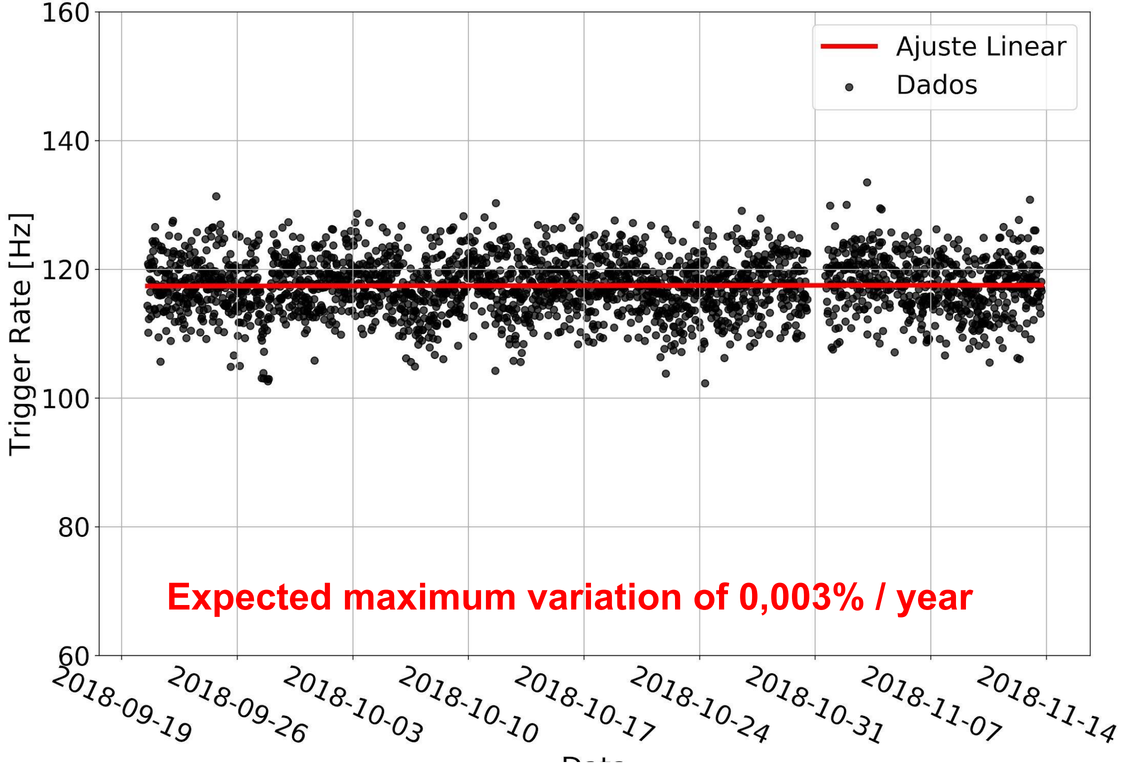
Full DAQ Control: Down to photoelectron level



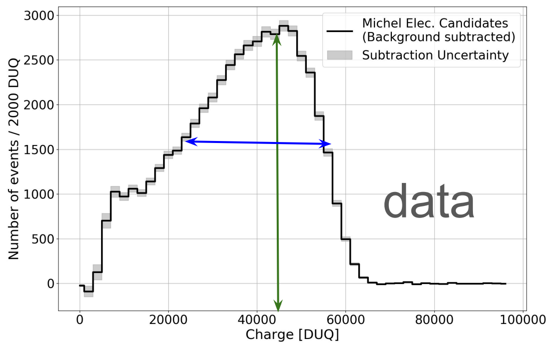


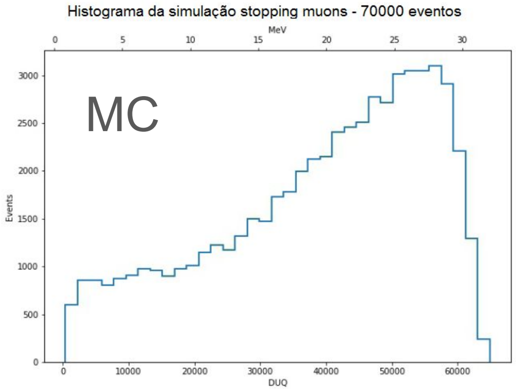


Stability


Trigger Rate [Hz]
160
140
120
100
80
60
Ajuste Linear
Dados
Expected maximum variation of 0,003% / year
2018-09-19
2018-09-26
2018-10-03
2018-10-10
2018-10-17
2018-10-24
2018-10-31
2018-11-07
2018-11-14

Stability check: Michel Electrons





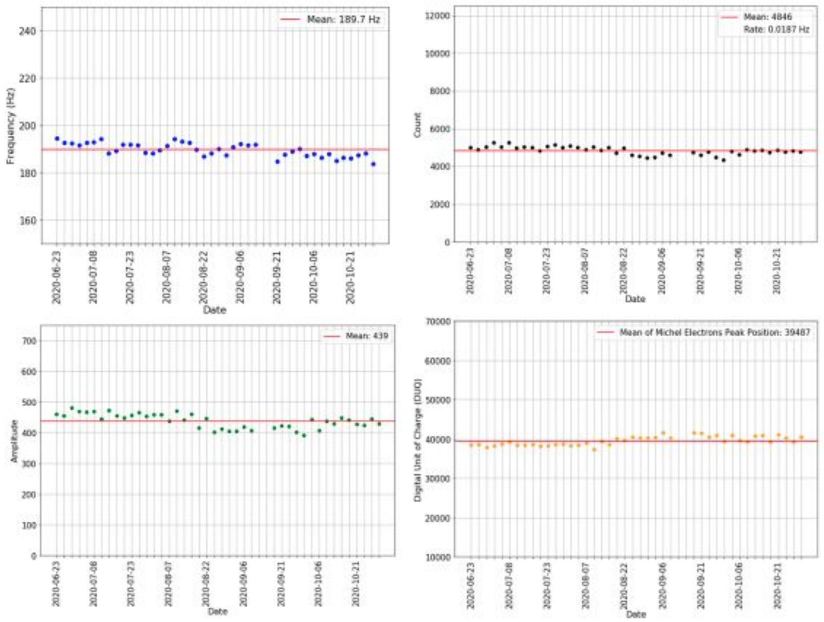


Figure 9: Upper left: Trigger rate of the ν-Angra detector for the analyzed dataset; Upper right: Time evolution of Michel electrons (ME) counting; Lower left: Time evolution of ME spectrum amplitude; Lower right: Time evolution of ME spectrum peak position.

Data analysis & Results

Data analysis & Results

Results from ON-OFF analysis of the Neutrinos-Angra detector

E. Kemp[1,*], W. V. Santos [1], J. C. Anjos[2], P. Chimenti[3], L. F. G. Gonzalez[4], G. P. Guedes[5], H. P. Lima Jr.[2,6], R. A. Nóbrega[7], I. M. Pepe[8], and D. B. S. Ribeiro[8]

[1]Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, Campinas, 13083-859, SP, Brazil
[2]Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, 22290-180, RJ, Brazil
[3]Departamento de Física, Universidade Estadual de Londrina, Londrina, 86057-970, PR, Brazil
[4]Instituto de Computação, Universidade Estadual de Campinas, Campinas, 13083-852, SP, Brazil
[5]Universidade Estadual de Feira de Santana, Feira de Santana, 44036-900, BA, Brazil
[7]Astroparticle Physics Division, Gran Sasso Science Institute, L'Aquila, 67100, Italy
[7]Departamento de Circuitos Elétricos, Universidade Federal de Juiz de Fora, Juiz de Fora, 36036-900, MG, Brazil
[8]Instituto de Física, Universidade Federal da Bahia, Salvador, 40170-115, BA, Brazil
[*]**Corresponding author:** kemp@unicamp.br

June 26, 2024

Abstract

The Neutrinos Angra Experiment, a water-based Cherenkov detector, is located at the Angra dos Reis nuclear power plant in Brazil. Designed to detect electron antineutrinos produced in the nuclear reactor, the primary objective of the experiment is to demonstrate the feasibility of monitoring reactor activity using an antineutrino detector. This effort aligns with the International Atomic Energy Agency (IAEA) program to identify potential and novel technologies applicable to nonproliferation safeguards.

Operating on the surface presents challenges such as high noise rates, necessitating the development of very sensitive, yet small-scale detectors. These conditions make the Angra experiment an excellent platform for both developing the application and gaining expertise in new technologies and analysis methods. The detector employs a water-based target doped with gadolinium to enhance its sensitivity to antineutrinos.

In this work, we describe the main features of the detector and the electronics chain, including front-end and data acquisition components. We detail the data acquisition strategies and the methodologies applied for signal processing and event selection. Preliminary physics results suggest that the detector can reliably monitor reactor operations by detecting the inverse beta decay induced by electron antineutrinos from the reactor.

arXiv:2407.20397v2 [hep-ex] 7 Aug 2024

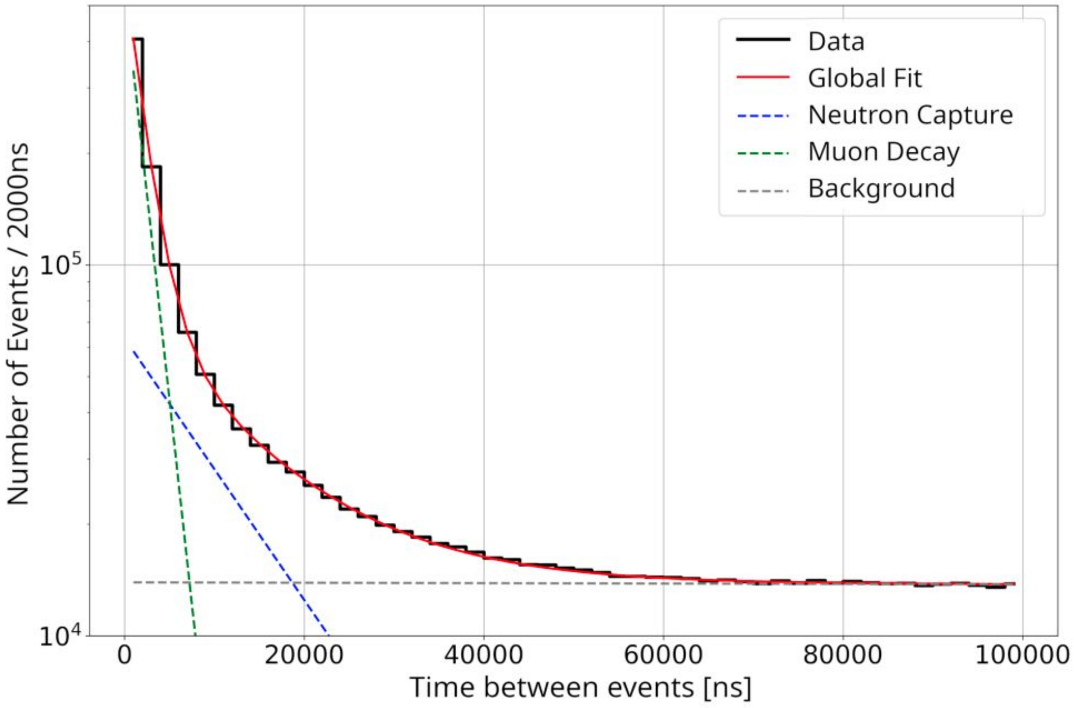
Event Selection:

Strategy: searching for pairs (e^+,n) from IBD

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

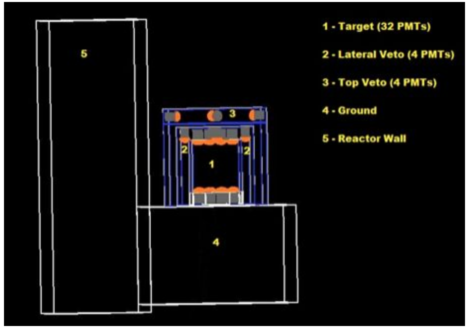
- Time between 2 consecutive events: from n-capture data
- e^+ (prompt): known and well-defined energy
- n (delay): known and well-defined energy (Gd de-excitation line)

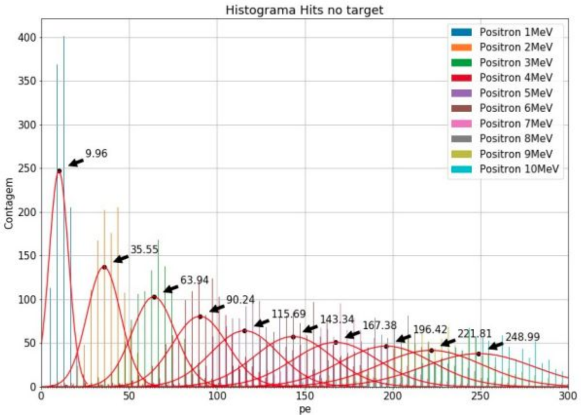
Time analysis

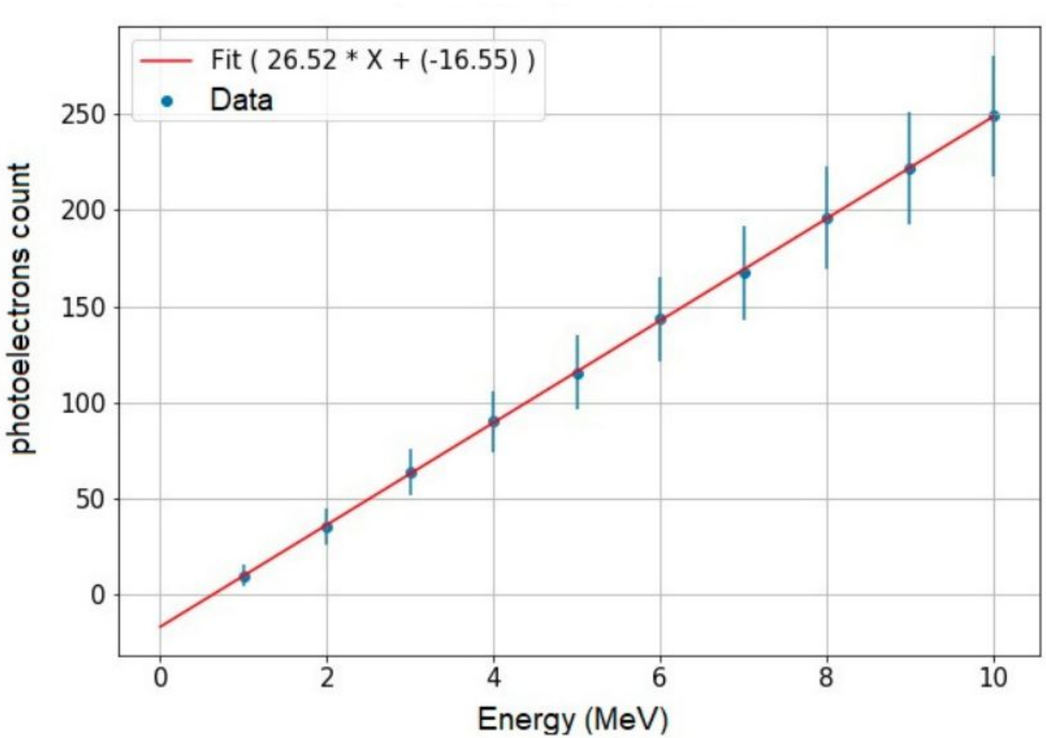


Component	λ
Muon Decay	$(1.9 \pm 3)\ \mu s$
Neutron Capture	$(12.32 \pm 0.05)\ \mu s$
Background Noise	(7.92 ± 0.01) ms

e^+ (prompt) cuts: energy scale from GEANT4 simulations







e^+ (prompt) cuts: energy scale from GEANT4 simulations

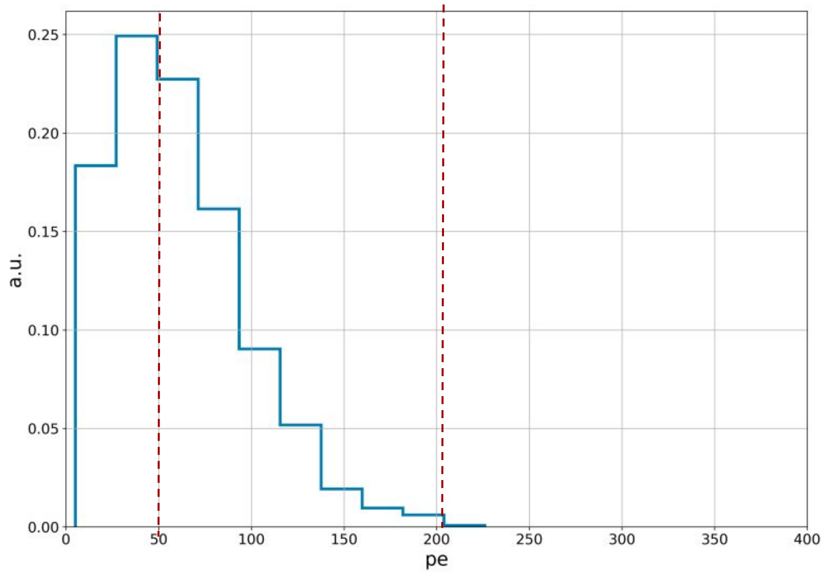


Figure 14: Detector response for IBD positrons generated from reactor antineutrino spectrum (prompt signal PDF).

arXiv:2407.20397v2 [hep-ex] 7 Aug 2024

n (delay) cuts: energy scale from GEANT4 simulations (Gd de-excitation line)

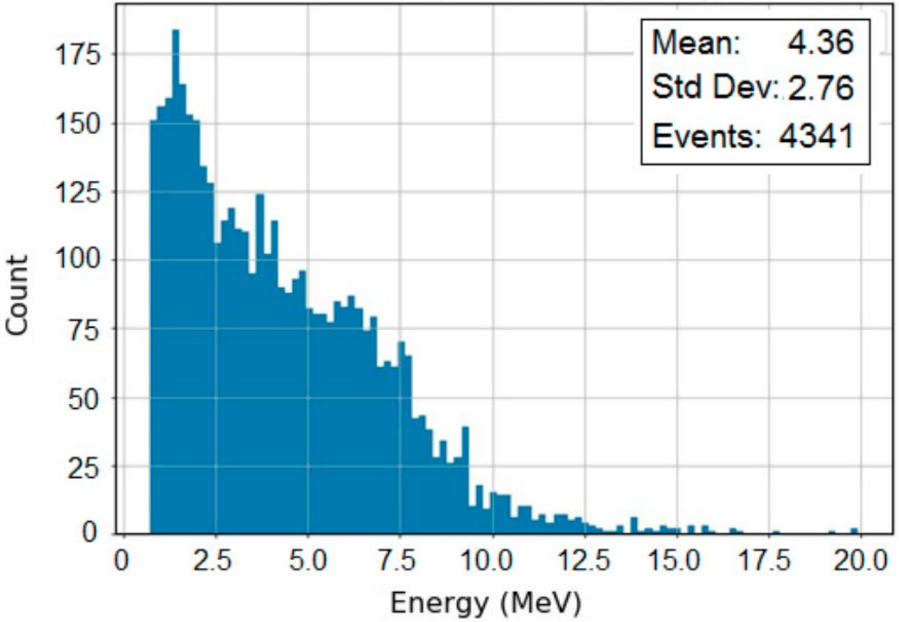


Figure 15: Expected spectrum of the delay signals, produced by gammas from the de-excitatio
of Gd after neutron capture [23].

arXiv:2407.20397v2 [hep-ex] 7 Aug 2024

n (delay) cuts: energy scale from GEANT4 simulations (Gd de-excitation line)

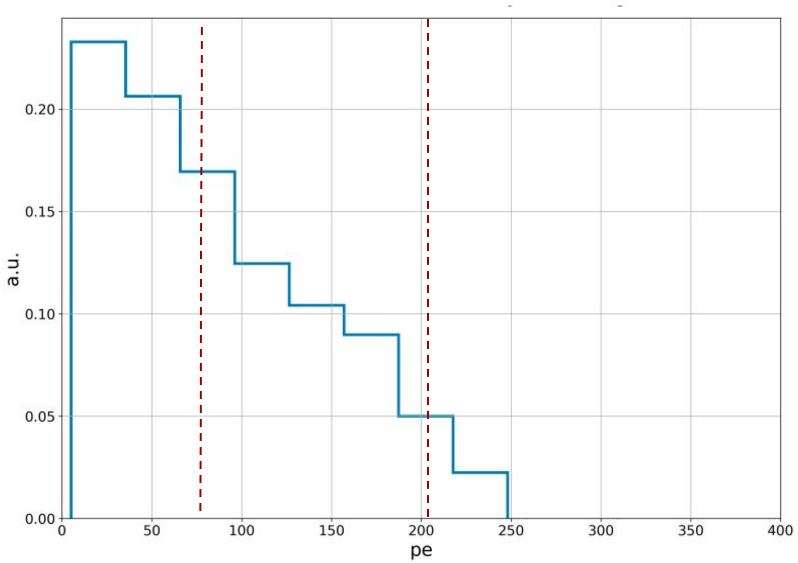


Figure 16: Detector response for the gammas from de-excitation of Gd atoms in the target after neutron capture (delay signal PDF).

arXiv:2407.20397v2 [hep-ex] 7 Aug 2024

ON-OFF analysis: Results

ON-OFF: reactor neutrino IBD events are identified by comparing 2 datasets

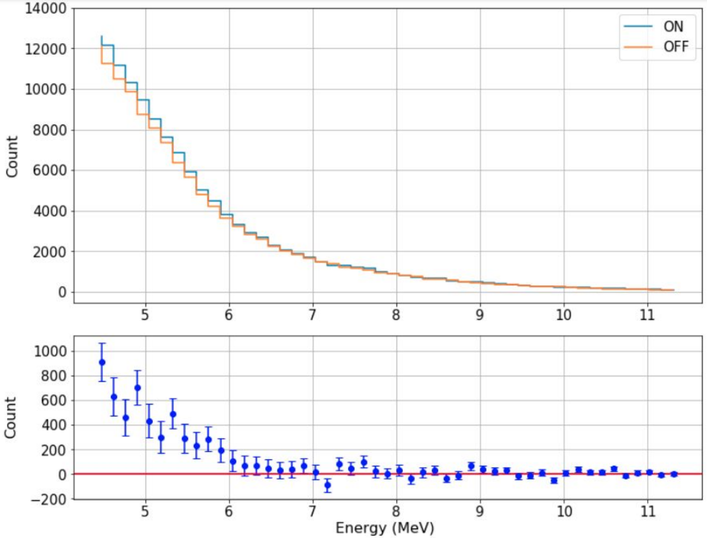
ON: reactor is fully operational

OFF: reactor shutdown for maintenance and refueling.

ON-OFF analysis: Results

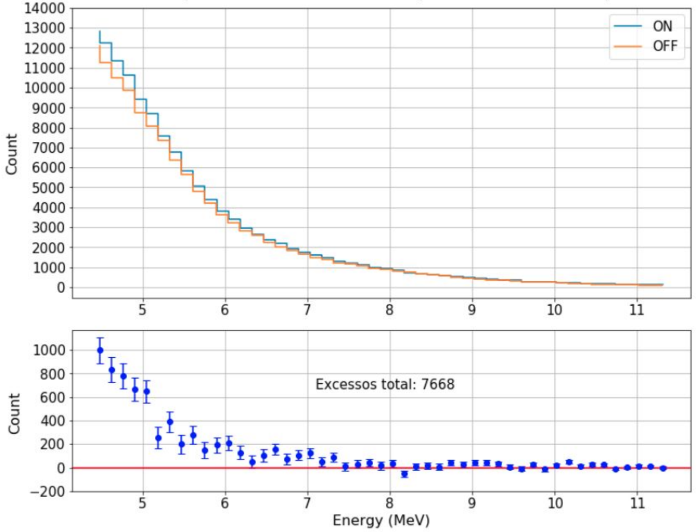
OFF: jul/2020;
ON1: aug-sep/2020;
ON2: sep-oct/2020.

ON1-OFF



$$\chi^2/dof \sim 13.4$$

ON2-OFF



$$\chi^2/dof \sim 17.3$$

H_0: Excess are bkg fluctuations → ***Rejected*** (p-value < 10^{-9})

Upgrades

Possible upgrades:

- Segmented scintillators on top and bottom of the tank
  - Better background rejection (PID)
  - Another calibration tool (muon tracks)

- Enhanced calibration methods
  - More sophisticated simulation models
  - Portable calibration sources (in compliance with safety regulations)
  - In-situ calibration techniques:
    - remote-controlled LEDs with different wavelengths → enhancements in the accuracy of the energy scale calibration.

- Improved DAQ: hardware trigger based on AI (FPGAs)
  - Trigger does not depend on fixed thresholds (more efficient data handling)

- Water replacement with WBLS
  - better energy resolution → possible fuel content evolution measurements

ν-Angra 2.0: The cryogenic detector

Low-temperature Calorimeters

- Low-temperature detectors operated at mK temperature is a proven technology for rare event searches.
- Principle of operation:
  - When a particle interacts with a crystal at mK temperature, the majority of the energy deposition goes through the phonon production channel (thermal, thermal, acoustic, ballistic)
- By operating at 15 mK, the thermal noise is reduced significantly.
- High precision and efficient detectors

More on this in P. Guillaumon talk

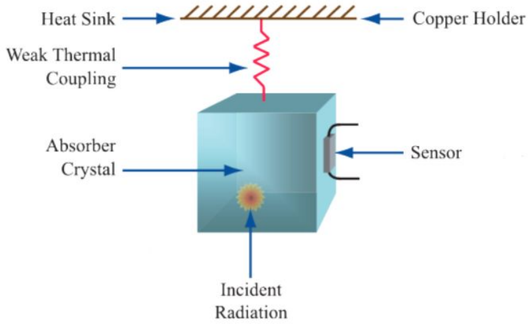
Thursday August 29
Session XII: White Paper Presentation - High Energy Astrophysics
9:00-9:20 - The Cherenkov Telescope Array Observatory (CTAO): Construction of the SSTs and LSTs - Diego Falceta-Gonçalves
9:20-9:40 - The ASTRI MINI-ARRAY: a Precursor for the Cherenkov Telescope Array Observatory (CTAO) - Elisabete de Gouveia Dal Pino
9:40-10:00 - Southern Wide-field-of-view Gamma-ray Observatory (SWGO) - Ulisses Barres de Almeida
10:00-10:20 - The Latin American Giant Observatory - Luis A. Nunez

Session XIII: White Paper Presentation - Quantum materials and sensors
11:00-11:20 - LAMBDA: A World-Class Particle Physics Lab in South America - Dario Rodrigues
11:20-11:40 - Future Rare Events Searches with Low-Temperature Detectors and Quantum Sensors in Latin America - Pedro V Guillaumon
11:40-12:00 - Quantum Materials at the Interface between Condensed Matter and High Energy Physics - Alfredo Raya

Low-temperature Calorimeters

- Release energy converted into increase of temperature: $\Delta T \propto \Delta E / C$
- Low detector working temperature: $C \propto T^3$

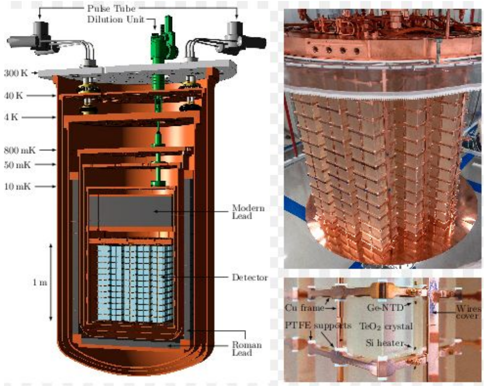
At 15mK a particle of keV produces an increase of temperature of ueV!



Low-temperature Calorimeters

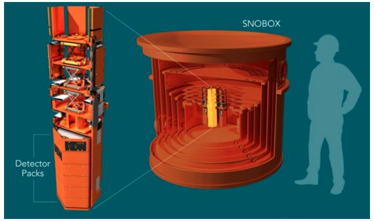
Main experiments with calorimeters for neutrinos and dark matter physics:

- neutrinoless double beta decay: CUORE/CUPID
- dark matter: CRESST, superCDMS
- CEvNS: RICOCHET, NU-CLEUS

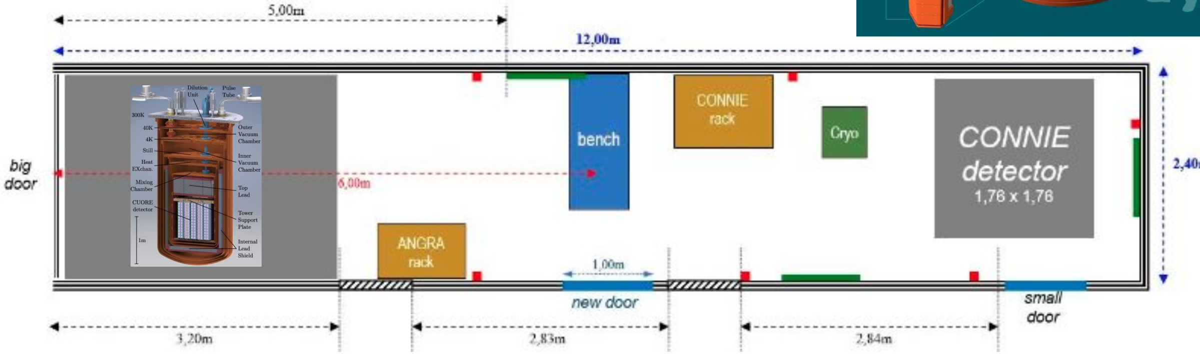


Current typical dimensions

- In order to have a 100 kg detector, you just need a small cryostat:
  - The cryostat, electronics etc can be put inside a room of 5x5x3 m^3



Chalenging but feasible:
Fit the detector inside the container lab



Low-temperature Calorimeters

ν-ANGRA 2.0 : Cherenkov → CEvNS

- Different technique from CONNIE: explore complementarity

- To measure CEvNS you need sensors with high resolution in the biggest crystal possible
  - Transition Edge Sensors have already been proved to have threshold of a few eV
  - Kinect Inductance Sensors could in principle achieve similar sensitive

↓

Quantum sensors

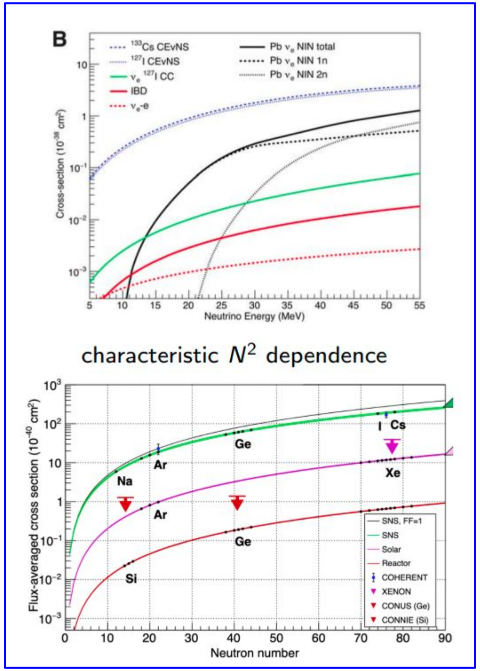
Low-temperature Calorimeters

ν-ANGRA 2.0 : Cherenkov → CEνNS

- Antineutrino Applied Physics:
  we should keep looking at the reactor activity,

  AND

- Fundamental physics:
  CEνNS phenomenology and characterization
  - X-section depends on TARGET MATERIAL
  - Calorimetry with different crystals in the detector



Timeline and costs

5.1 Year 1-5: Operation and Upgrades of Cherenkov Detector

- **Operation and Data Collection (Years 1-5):**
  - Continue operation of the current water-based Cherenkov detector for reactor monitoring and data collection.
  - Perform regular maintenance and calibration to ensure optimal performance.
- **System Enhancements (Years 2-5):**
  - Implement system upgrades to improve sensitivity and data quality.
  - Introduce software and hardware improvements to improve data acquisition and processing.

5.2 Year 1-3: Planning and Initial Development of Cryogenic Calorimeter

- **Feasibility Study and Proposal Development (Year 1):**
  - Conduct a detailed feasibility study to assess the potential and requirements for replacing the Cherenkov detector with a cryogenic calorimeter.
  - Develop a comprehensive project proposal and secure funding.
- **Design and Specification (Years 2-3):**
  - Develop detailed designs for the cryogenic calorimeter system.
  - Specify the requirements for the cryostat, detectors, DAQ system, and veto system.

5.3 Year 3-5: Development and Testing of Cryogenic Calorimeter

- **Component Procurement and Prototype Development (Years 3-4):**
  - Procure necessary components and begin the development of prototype systems.
  - Conduct initial testing and optimization of the prototypes.
- **System Integration and Preliminary Testing (Year 5):**
  - Integrate all components into a working prototype system.
  - Perform preliminary testing to ensure system functionality and performance.

5.4 Post Year 5: Assembly and Commissioning of Cryogenic Calorimeter

- **Site Preparation and Installation (Post Year 5):**
  - Prepare the installation site at the Angra dos Reis reactor.
  - Install the cryogenic calorimeter system and perform initial setup checks.
- **Calibration and Full Commissioning (Post Year 5):**
  - Calibrate the system using known sources and Monte Carlo simulations.
  - Complete full commissioning and transition to regular data collection.

Timeline and costs

- **Cherenkov Detector Upgrades and Running Costs:**
  - System Upgrades: $180,000
  - Maintenance and Calibration: $60,000
  - Operational Costs: $30,000
  - **Subtotal Cherenkov Detector:** $270,000
- **Cryogenic Calorimeter System:**
  - Cryostat: $450,000
  - Detectors and DAQ System: $55,000
  - Veto System: $110,000
  - Infrastructure: $55,000
  - **Subtotal Cryogenic Calorimeter System:** $670,000

Total Estimated Costs: $940,000

Conclusions

Final Remarks

- The Neutrinos Angra Experiment was totally made by Brazilian scientists and engineers.
  - We have designed, prototyped, built, tested, and commissioned the detector, the FE electronics, and the DAQ boards.
  - The whole R&D was made in Brazilian labs also in cooperation with local commercial partners, demonstrating the maturity of Brazilian experimental groups to conduct high-level research with autonomy.

- We have results showing that the data has been taken with high quality,
  - We demonstrated the ability of the detector to count antineutrino events in correlation with the delivered thermal power of the reactor.
  - The future physics program might include measurements of the fractions of nuclear isotopes in the nuclear fuel.

Final Remarks

- Different technologies can be explored in a second run.
  - water based liquid scintillator (WBLS).

→ total compliance with the safety rules + enhanced energy resolution

→ additional physics topics ?

- Towards new technologies
  - Cryogenic calorimeters

- New technologies require knowledge and expertise of local research groups
  - Partnership with USP - Prof. Pedro Guillaumon

Final Remarks

- The Angra nuclear reactors have shown to be an excellent tool for the development of particle detectors technology and also to perform particle physics research.

- The experiments ν-Angra and CONNIE are sharing space and running in the neutrino lab.
  - We have successfully created a Latin American research facility with the cooperation of the power plant operator.
    - Any scientific group, in principle, can carry experimental programs using the reactor as a particle source.

- The facility has a large potential to boost Latin American science using nuclear reactors
  - Easier, when compared to overseas labs.

- The facility can be very attractive for international researchers
  - healthy exchanging of knowledge and technology.

Take-away message

- The future of the scientific facility (the neutrino lab) at the Angra dos Reis power plant is very promising.

- The two collaborations running neutrinos experiments, ν-Angra and CONNIE, have successfully demonstrated the feasibility to conduct high-level and rather complex experiments in cooperation with the power plant operator.

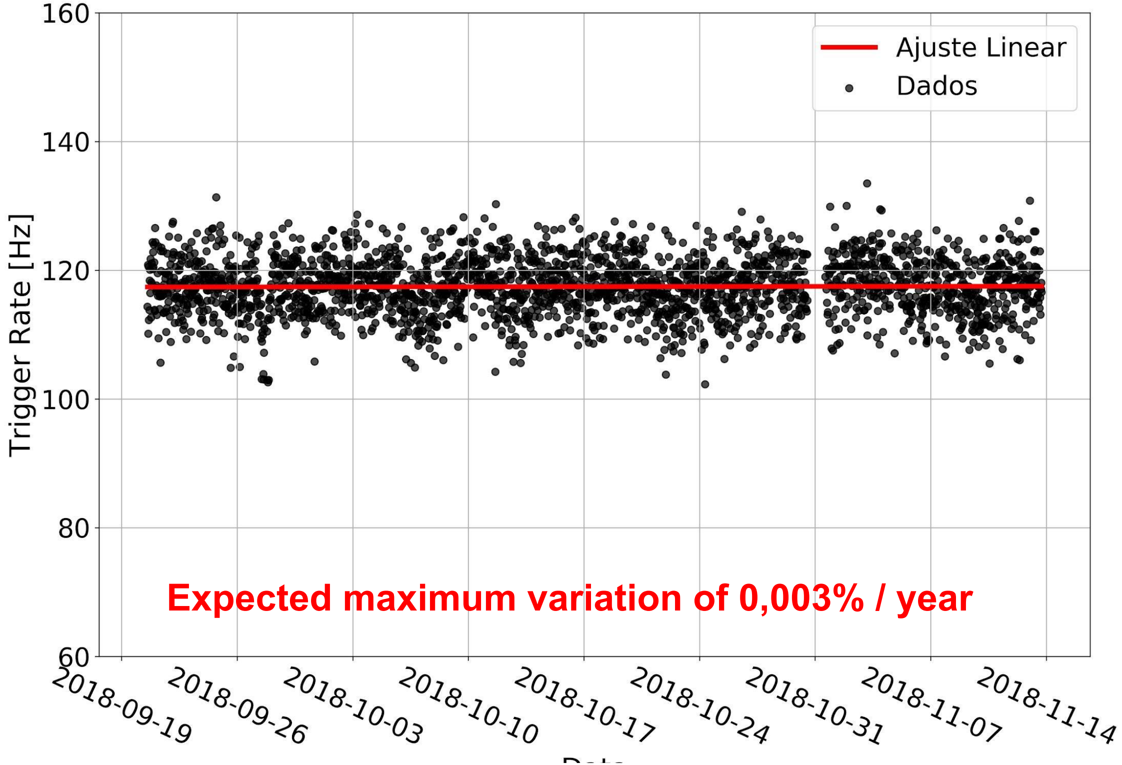
We DO hope that
the neutrino lab in Angra dos Reis can insert
Latin America in the world map of research facilities
in particle physics.

Thanks!

CAPES CNPq Finep INOVAÇÃO E PESQUISA FAPESP

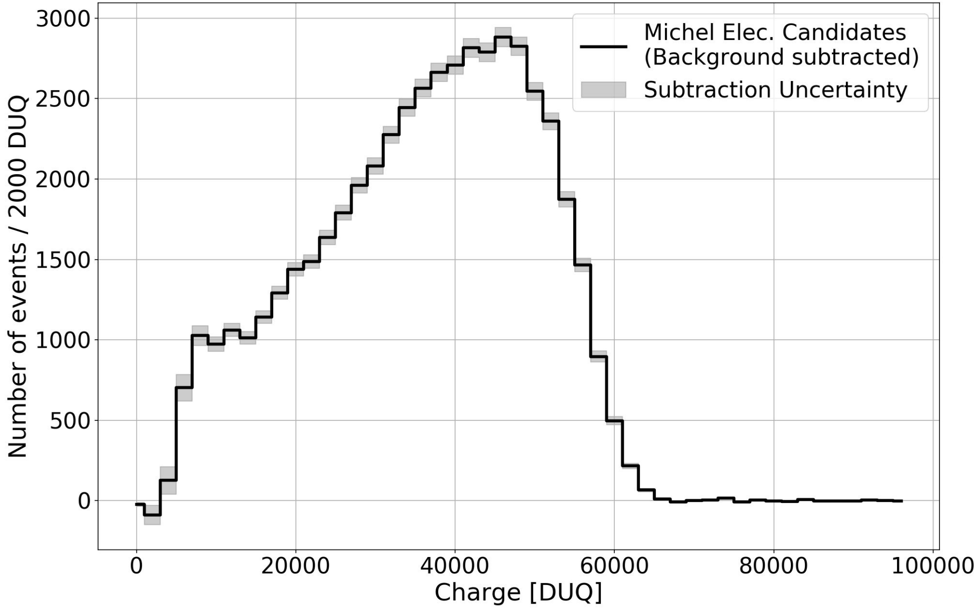
Backup

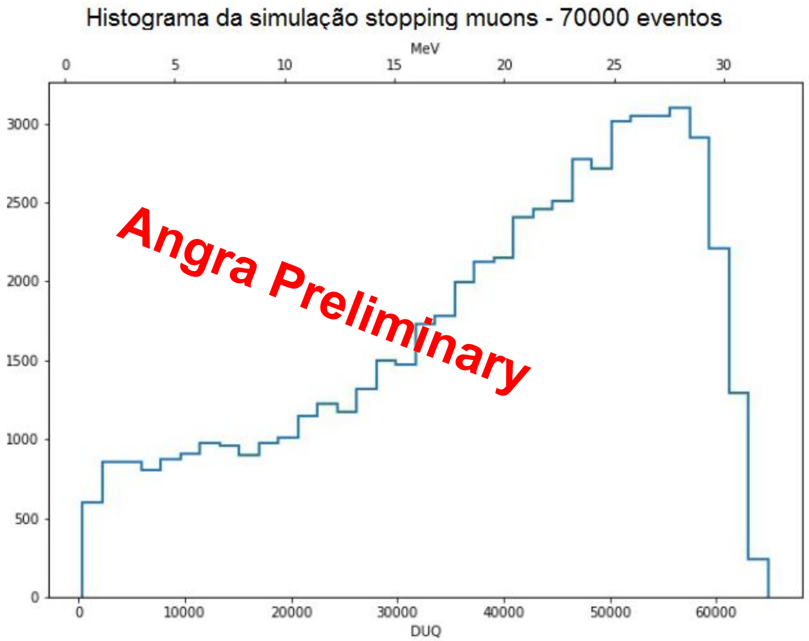
Stability



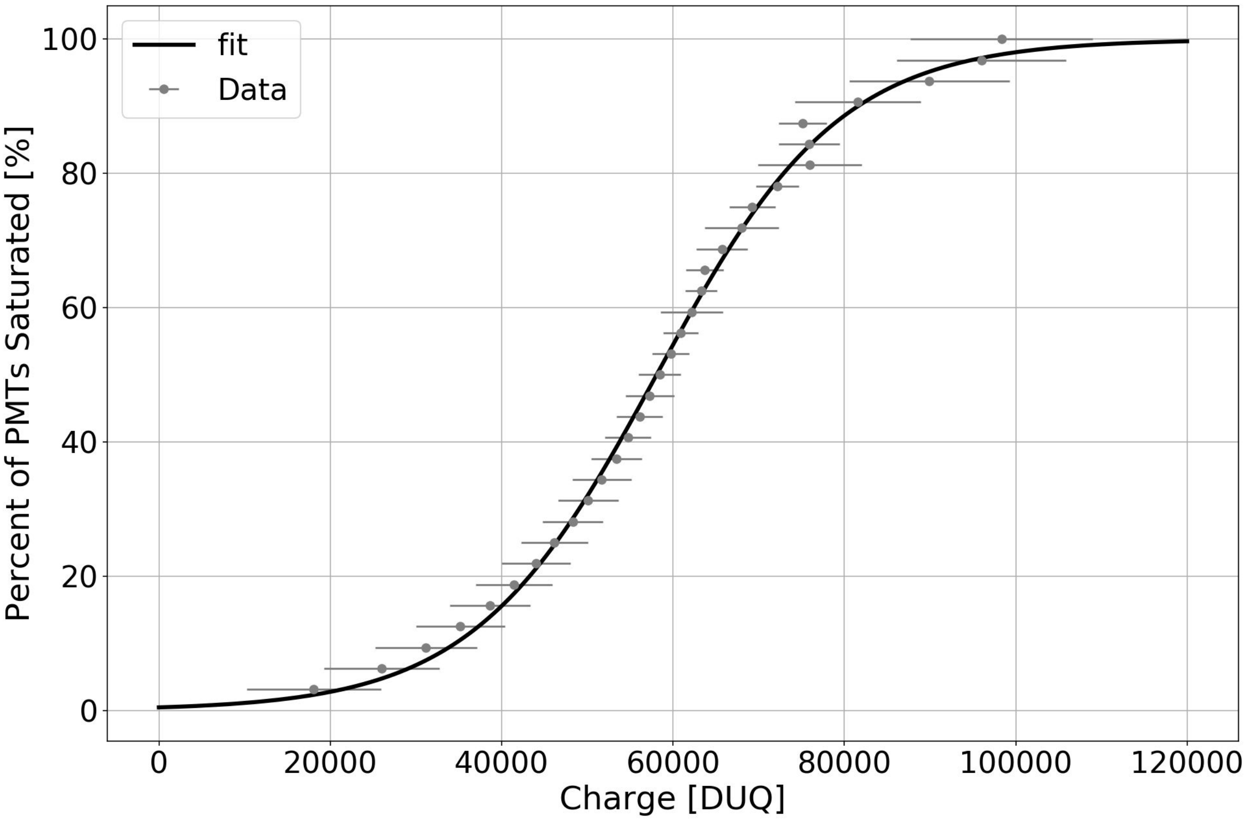
Ajuste Linear
Dados
Trigger Rate [Hz]
160
140
120
100
80
60
Expected maximum variation of 0,003% / year
2018-09-19
2018-09-26
2018-10-03
2018-10-10
2018-10-17
2018-10-24
2018-10-31
2018-11-07
2018-11-14

Michel Electron Candidates

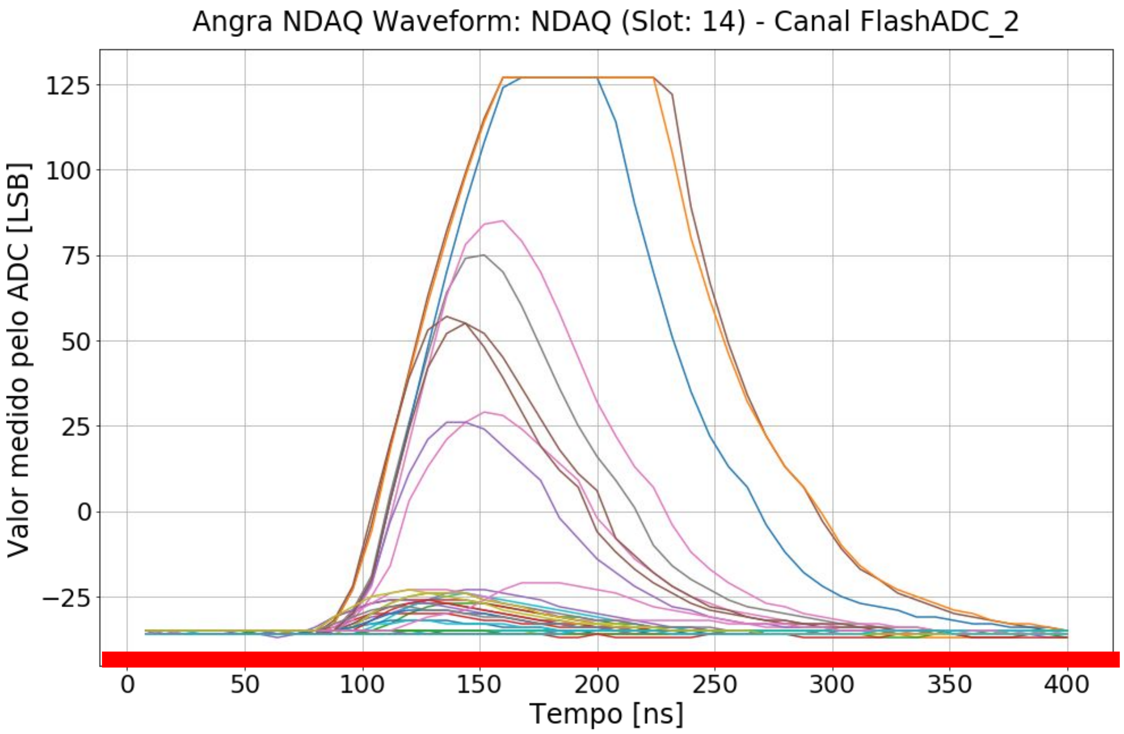




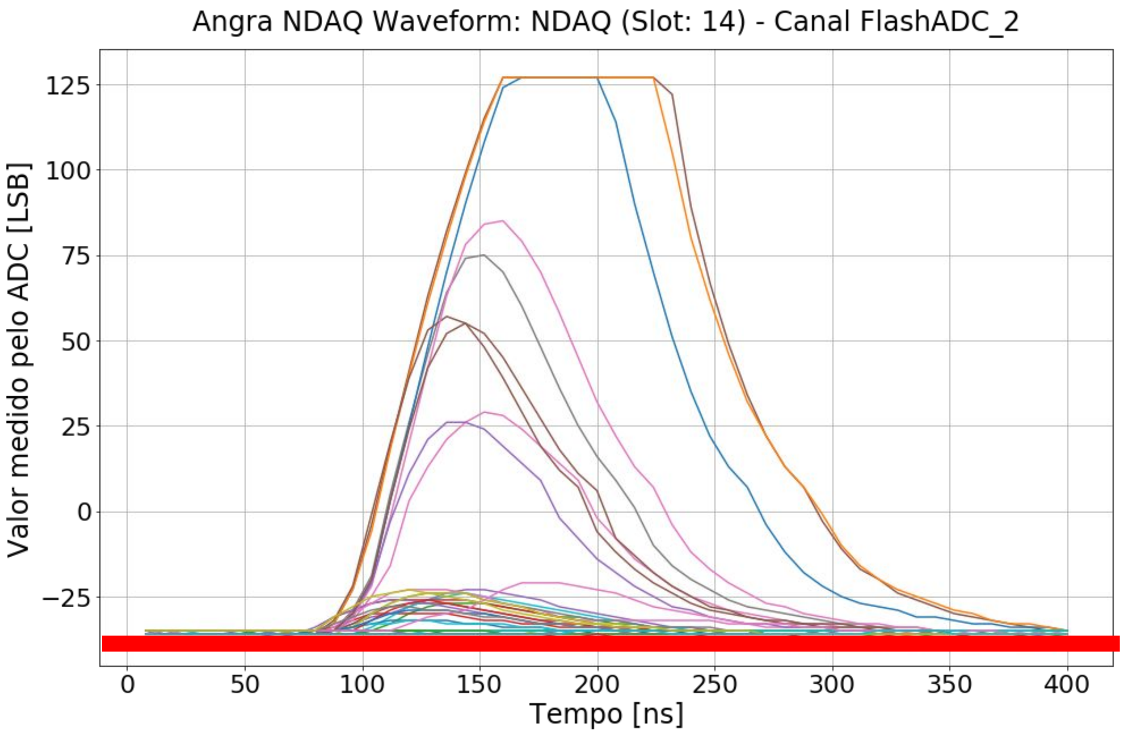
Saturation vs Charge



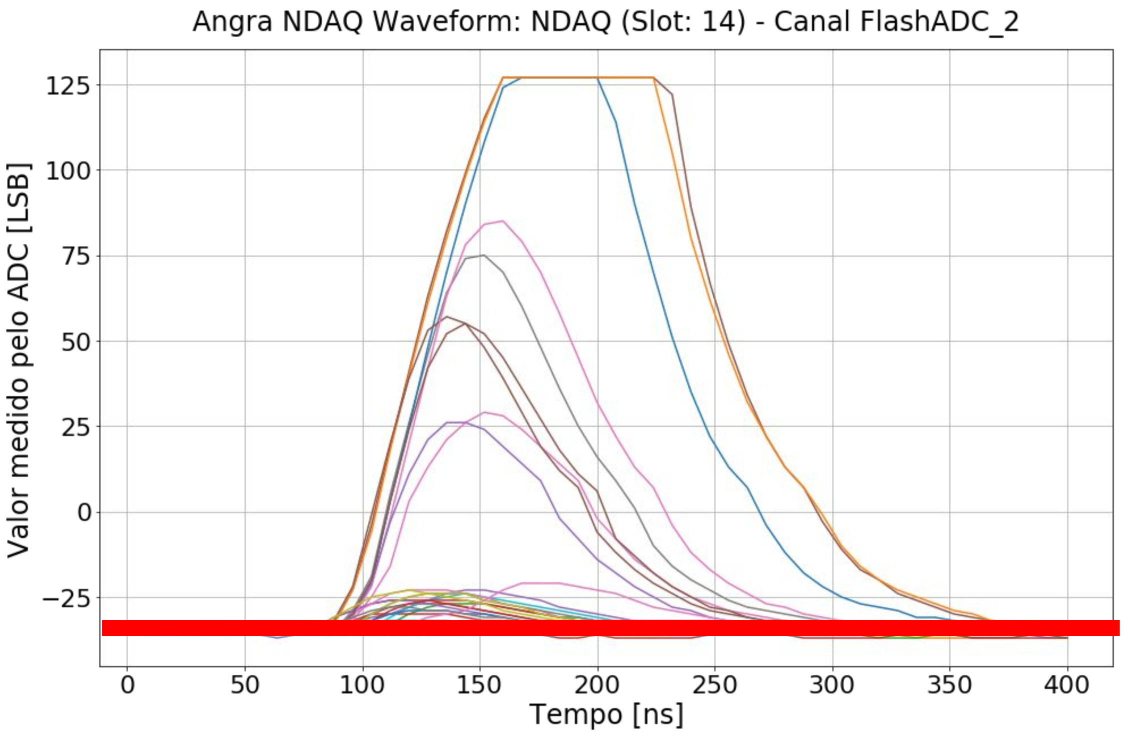
Trigger Calibration: The threshold scan



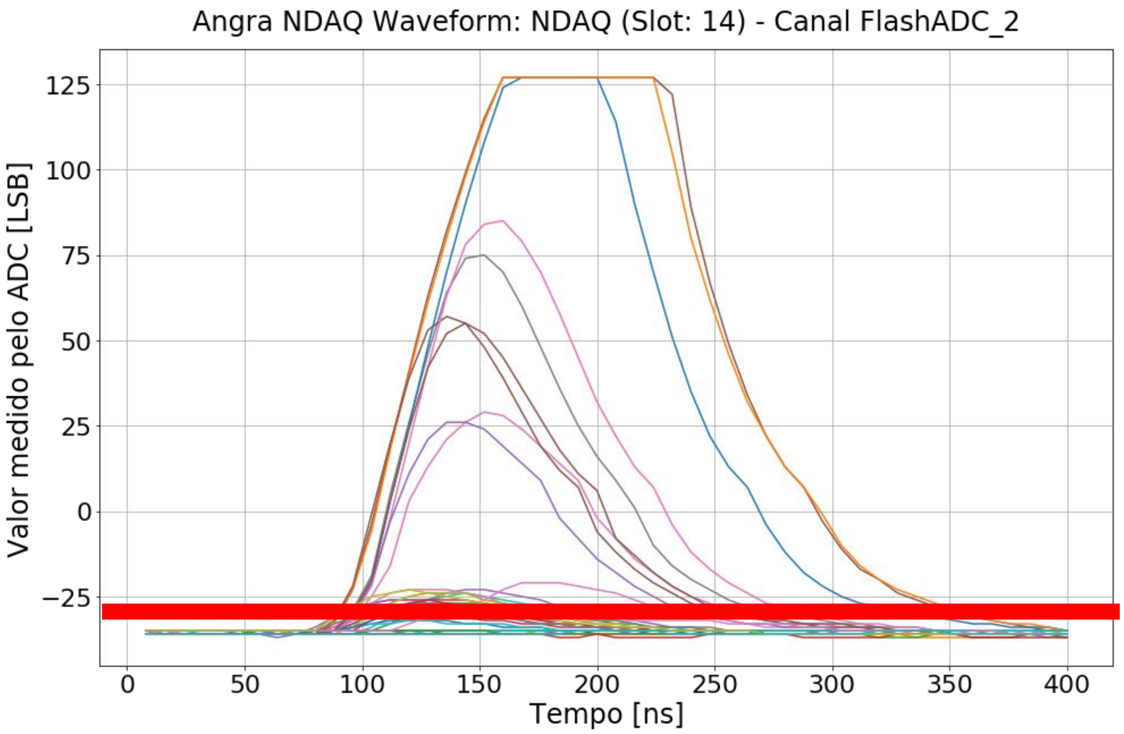
Trigger Calibration: The threshold scan



Trigger Calibration: The threshold scan



Trigger Calibration: The threshold scan



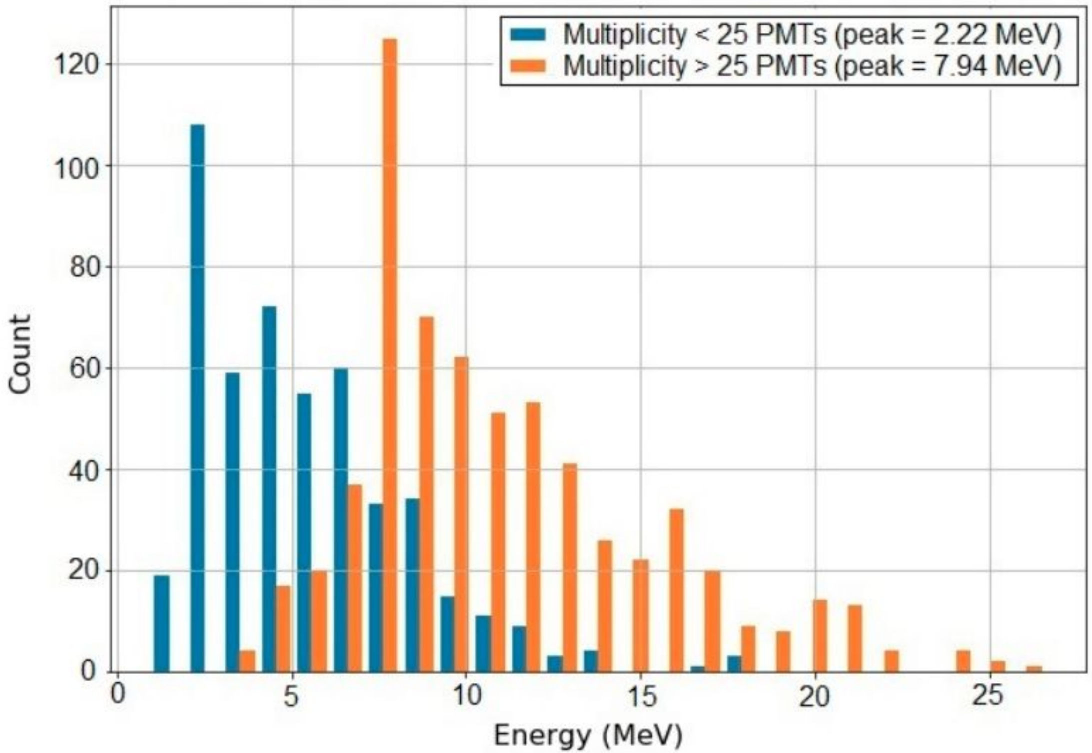


Figure 17: Simulated spectra of gammas from neutron capture filtered by the multiplicity M of PMTs activated in the events. M$\geq$25 selects efficiently gammas Gd de-excitation from those of deuteron formation.