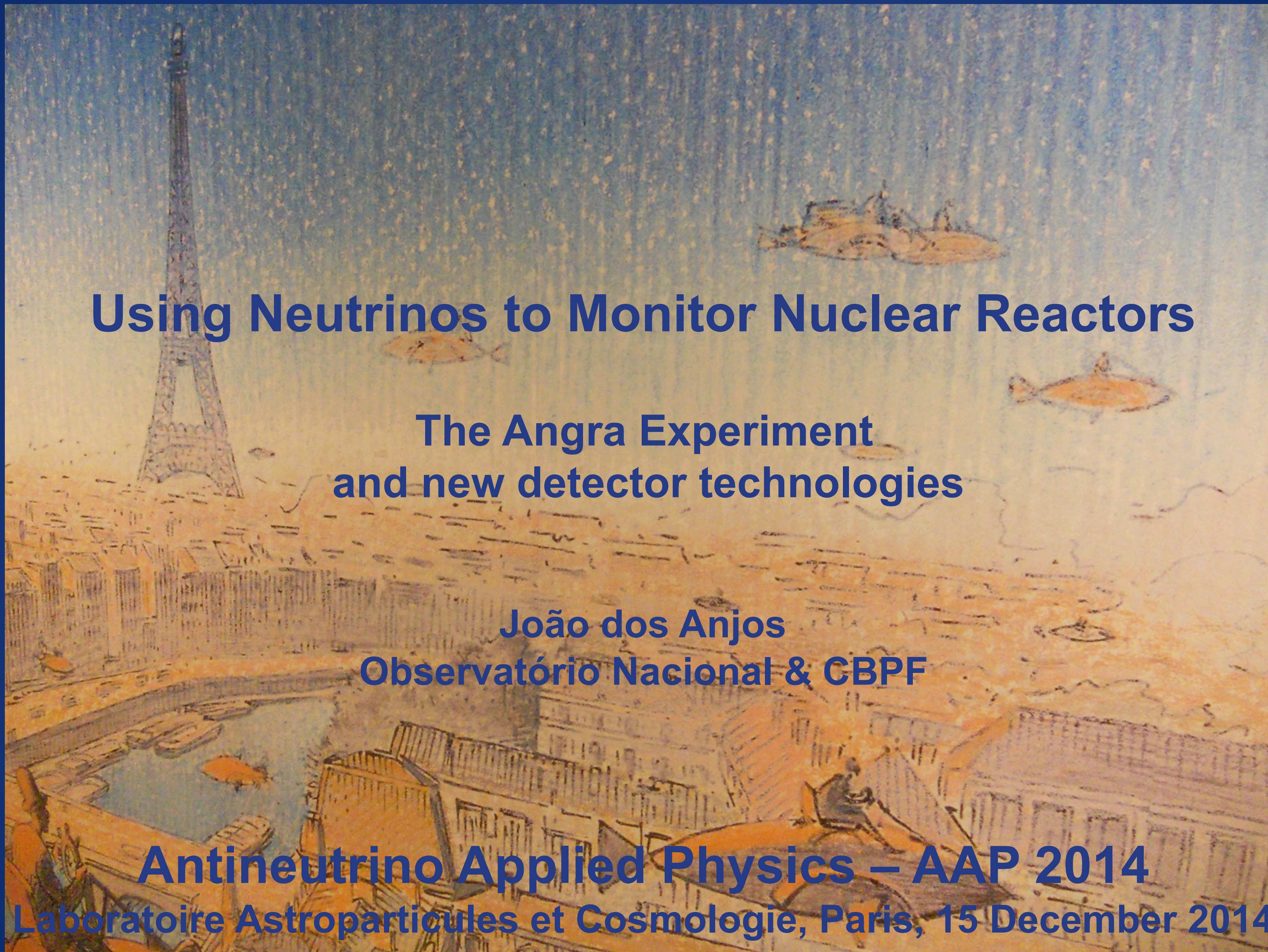


Using Neutrinos to Monitor Nuclear Reactors

The Angra Experiment
and new detector technologies

João dos Anjos
Observatório Nacional & CBPF

Antineutrino Applied Physics – AAP 2014

Laboratoire Astroparticules et Cosmologie, Paris, 15 December 2014

Neutrinos Angra Project

ANGRA Collaboration: 9 Brazilian Institutions:

CBPF
J.C. Anjos, G.L. Azzi, H. Lima Jr, M. Souza, S. Wagner

UNICAMP
E. Kemp, L. F. González,
L. M. Santos

UFABC
P. Chimenti

UFJF
Luciano M. Andrade, Rafael A. Nóbrega,
Augusto S. Cerqueira

UFBA - Iuri Pepe
Dion Ribeiro
Paulo C. Farias
Eduardo Simas

UEFS
Germano P. Guedes

PUC-RJ
Hiroshi Nunokawa

Unifal
Gustavo Valdiviesso

Motivations for ANGRA

– Possibility to start an experimental neutrino physics program in Brazil taking advantage of existing antineutrino sources (Angra-I and II nuclear reactors).

– Possibility to do neutrino applied physics:

. nuclear safeguards applications.

. new detector technologies.

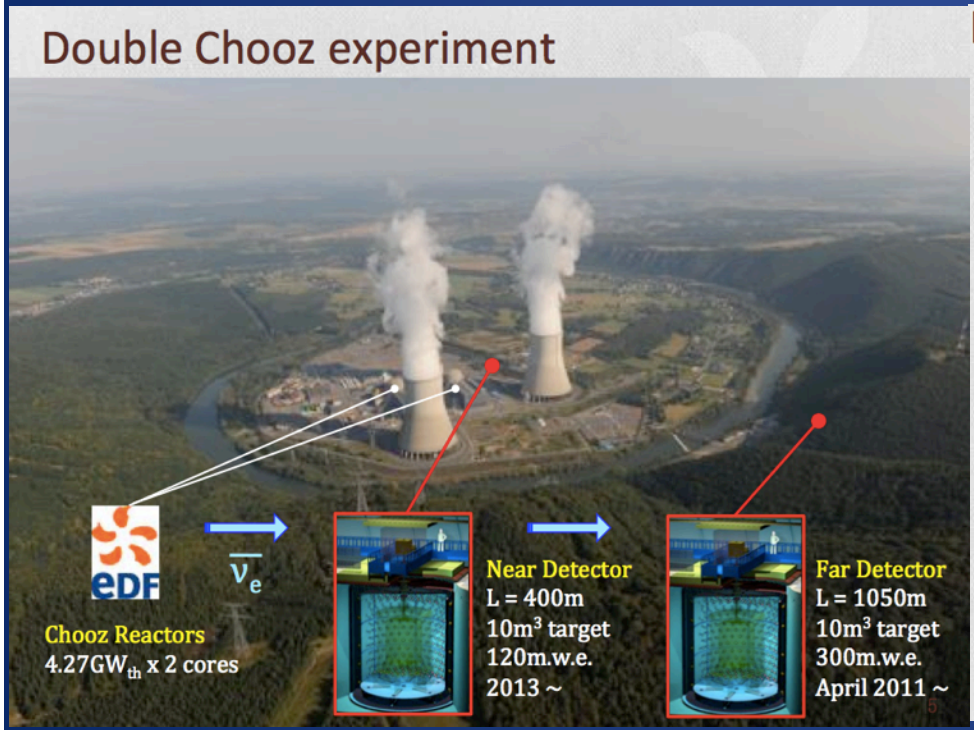
– Develop *know how* in experimental neutrino physics to be used in future projects.

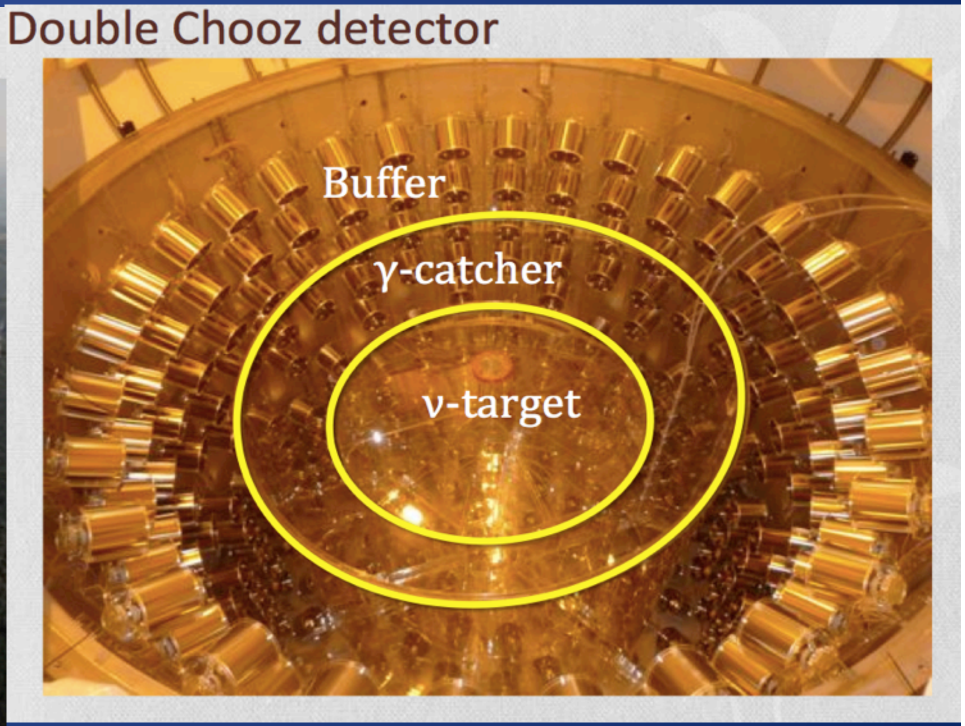
ANGRA PROJECT:

Nuclear Safeguards Applications

Monitoring of Nuclear Reactors with Antineutrinos has been Demonstrated

Double Chooz 2012



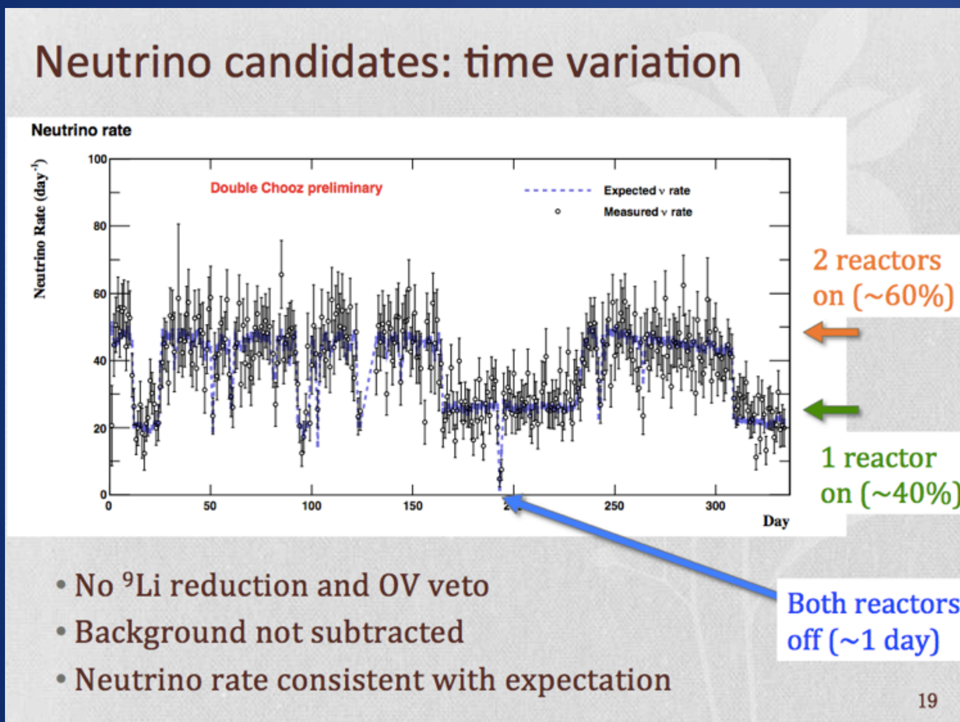


Detector site – Chooz, France

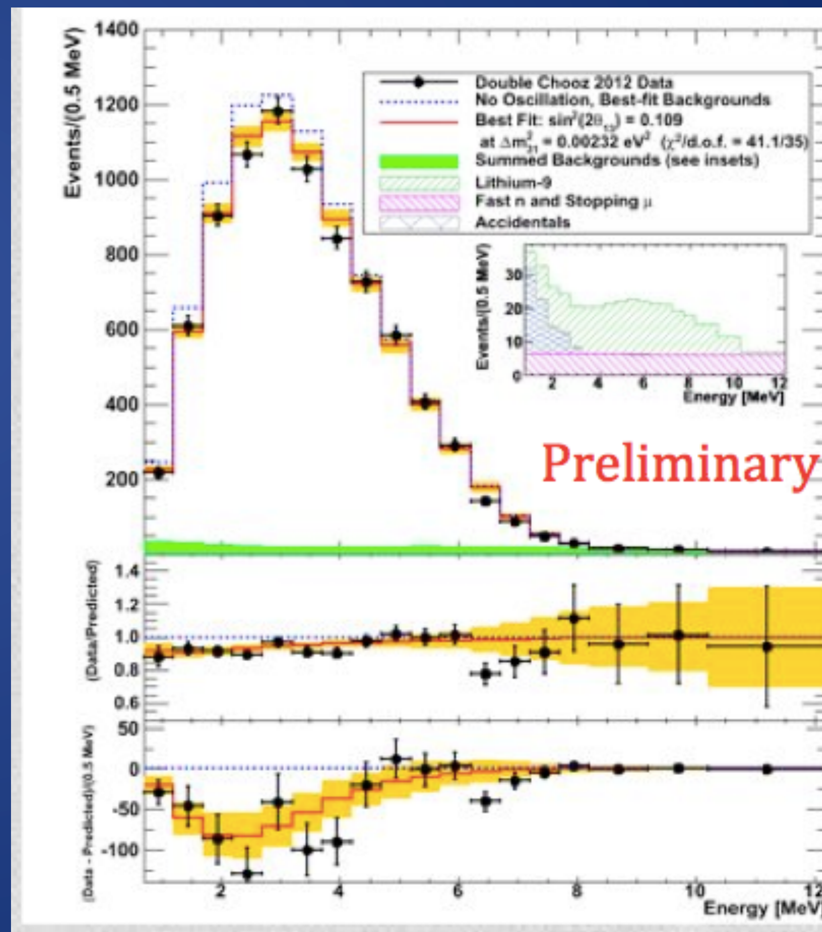
10 tons target

Monitoring of Nuclear Reactors with Antineutrinos has been Demonstrated

Double Chooz 2012



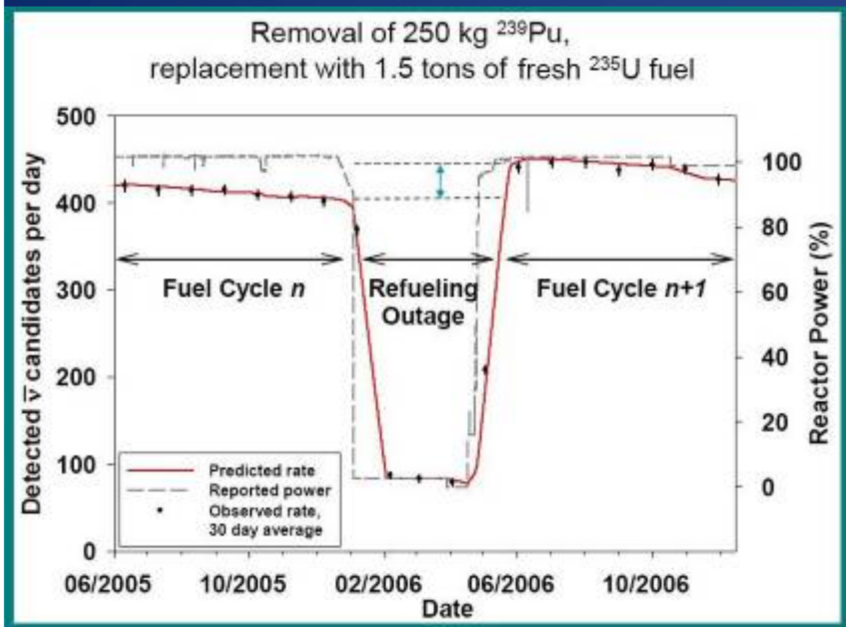
ANTINEUTRINO RATE



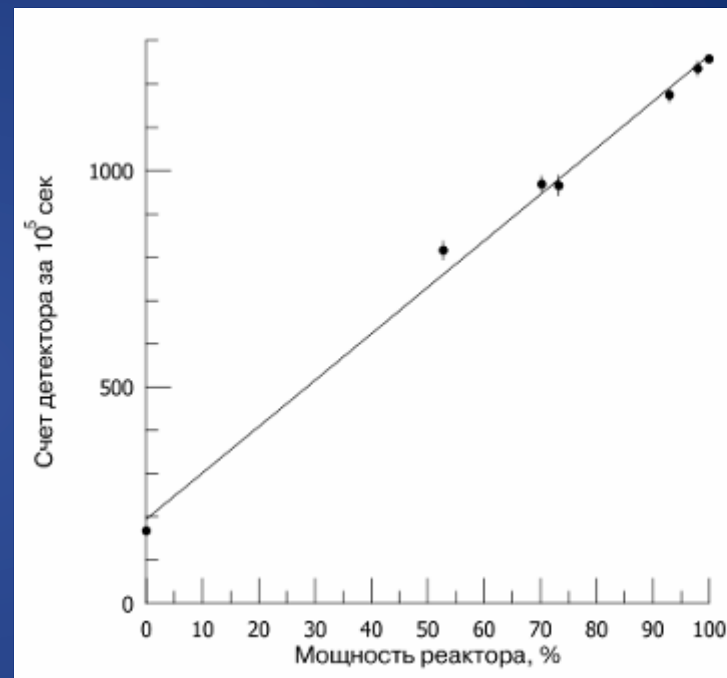
ENERGY SPECTRUM

Monitoring of Nuclear Reactors with Antineutrinos has been Demonstrated

San Onofre (USA)



Rovno/Ucraine



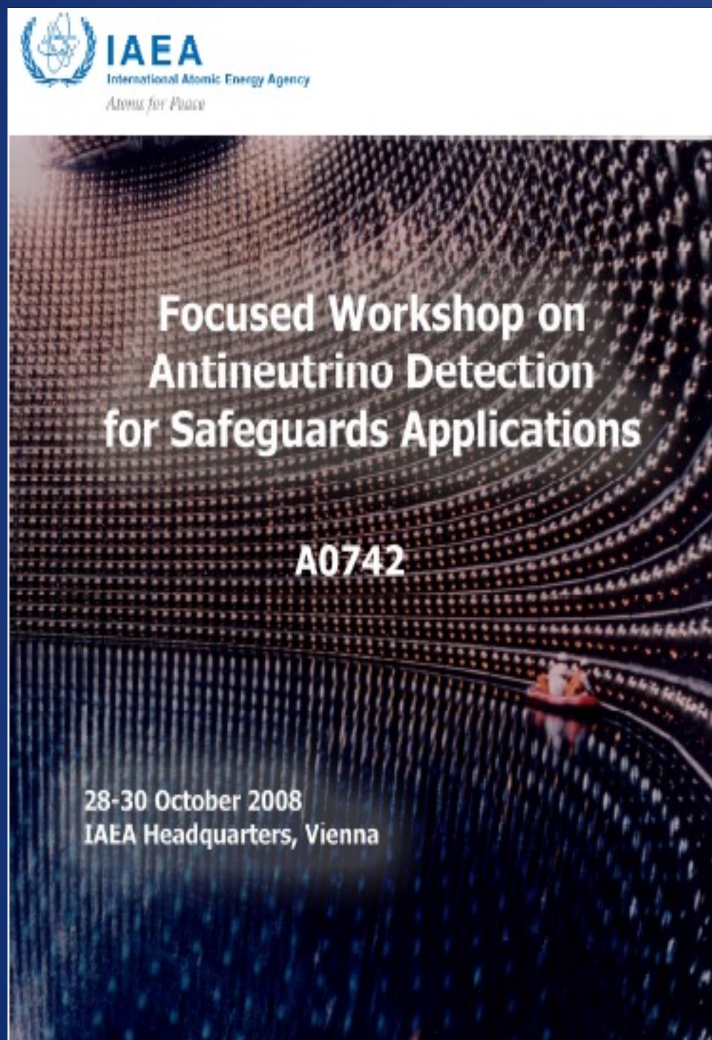
Independant Power Measurement:
Reactor Operator are also interested

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

Dependance on Detector Characteristics

Dependance on fuel composition

ANGRA PROJECT:
DESIGN GUIDELINES:



Follow recommendations of the 2008 IAEA Expert's Workshop

DESIGN GUIDELINES:

Focused Workshop on Antinu-e

Detection for SG Applications (2008)

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

New challenge: neutrino detection above ground ANGRA Neutrino Laboratory:

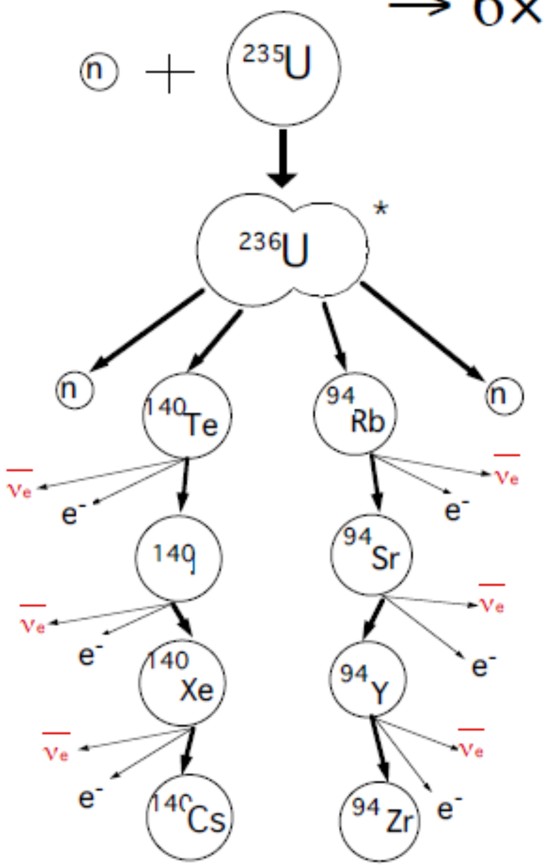
Neutrino laboratory: 40' container

Why reactors?

- ~6 ν's/fission, ~200MeV/fission

  → 6×10^{20} ν/sec for a typical commercial reactor

  (1GW power ~ 3GW thermal)



(example)

Reactors are powerful and "free" sources of low-energy (isotropic) neutrinos

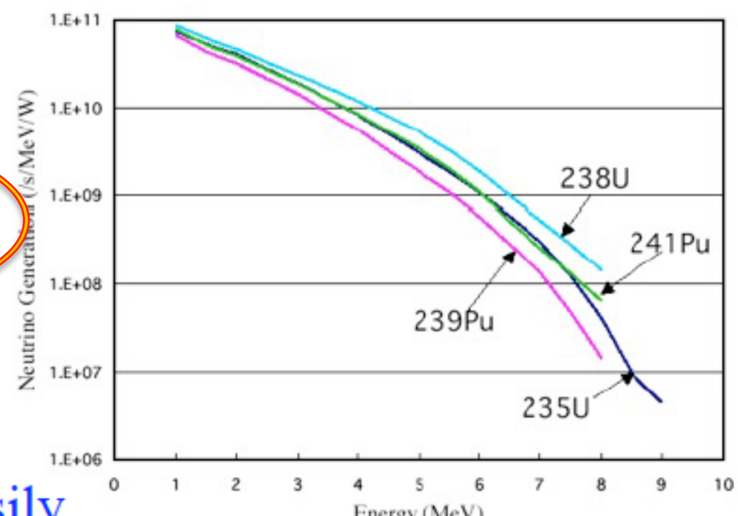
E_ν~ a few MeV

At Angra detector $7.2\text{x}10^{12}\ s^{-1}cm^{-2}$

Always full power

↕

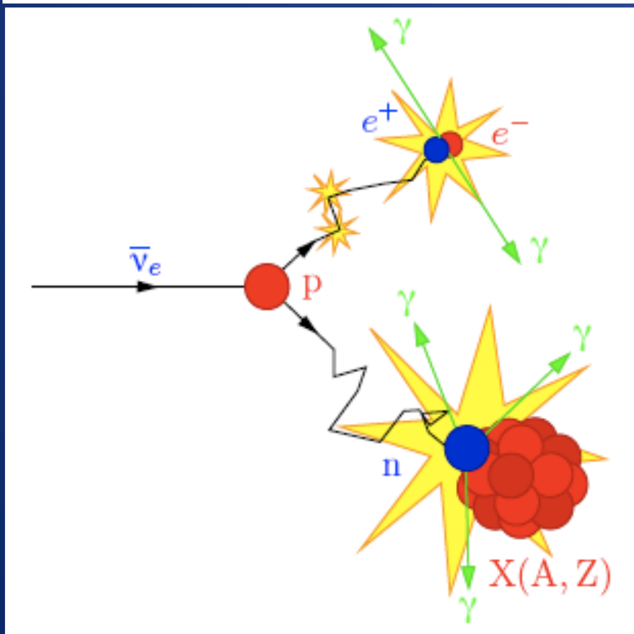
Can't switch off easily



Angra detector facts: Water Cherenkov

Reactor power: 4 GWth
Target fiducial mass: ~1 ton
Detector distance to core: ~30 meters
Inverse beta decay interactions per day: ~5,000

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

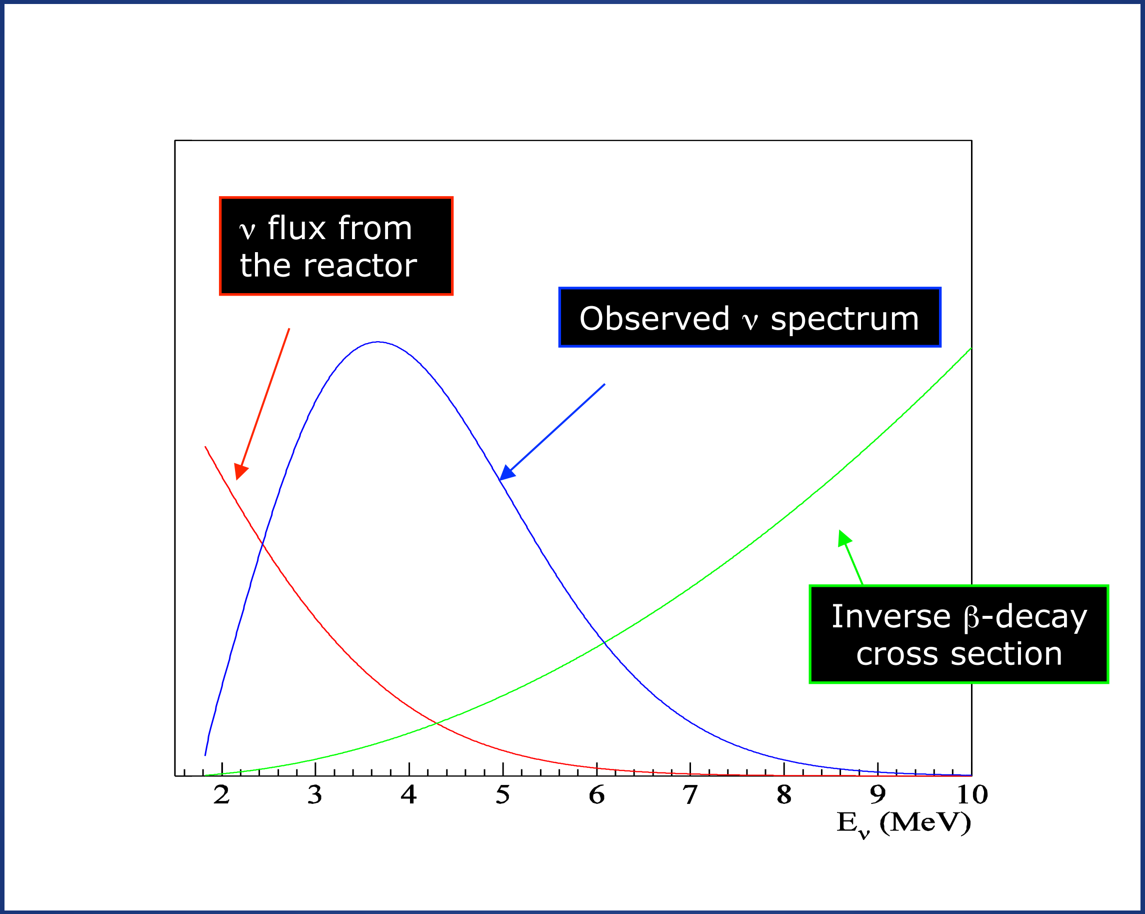


Prompt signal:
Positron
1 ~ 12MeV

Delayed signal:
γ's from neutron capture
on Gd: 8MeV

Time interval:
Δt ~ 30μsec

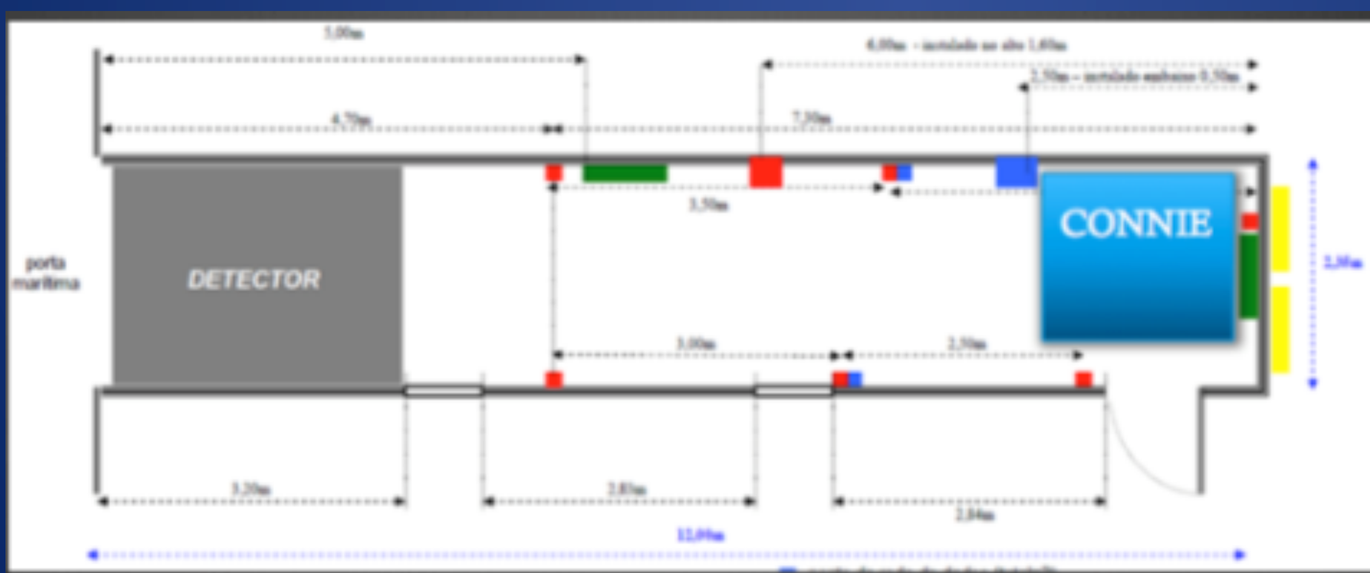
Monitoring nuclear reactors with antineutrinos



The observed energy spectrum is the result of the antineutrino flux emmited weighted by the antineutrino-proton cross section

ANGRA Status:
New Container High Cube type, 40’

New container being prepared: size 40 ‘ High Cube model, to allow better shielding

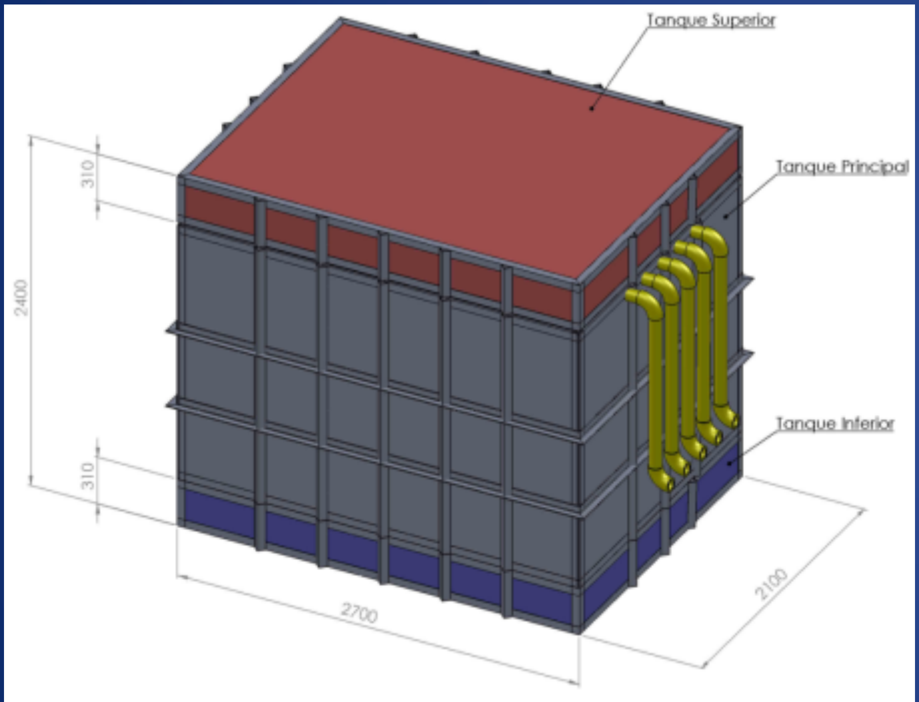


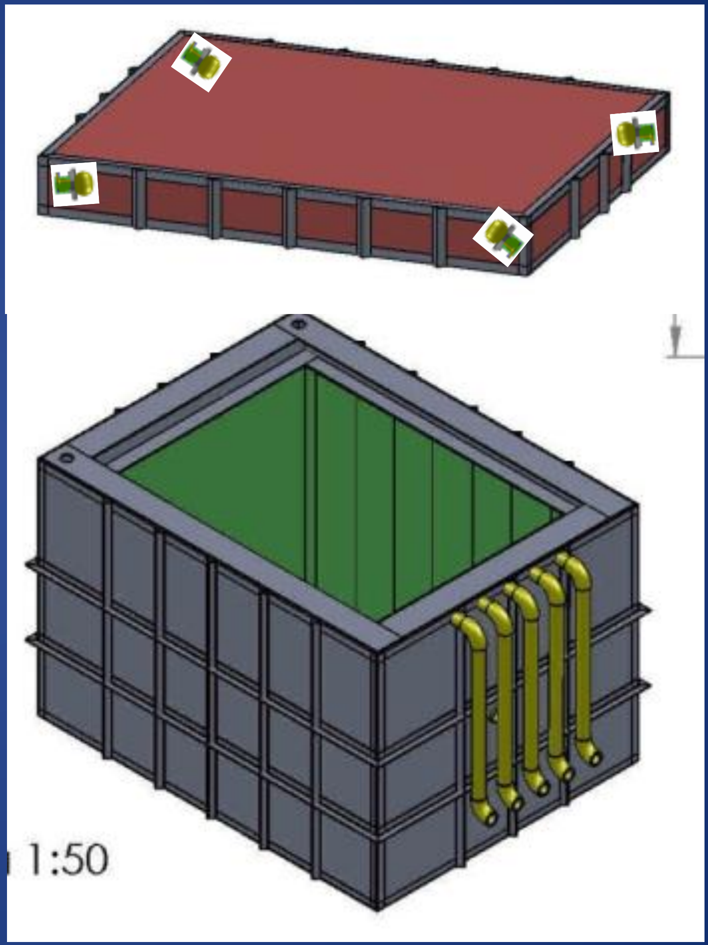
Top view of the container showing detectors position

New Container High Cube type, 40’

View of the new container for experiments ANGRA and CONNIE

Detector Design



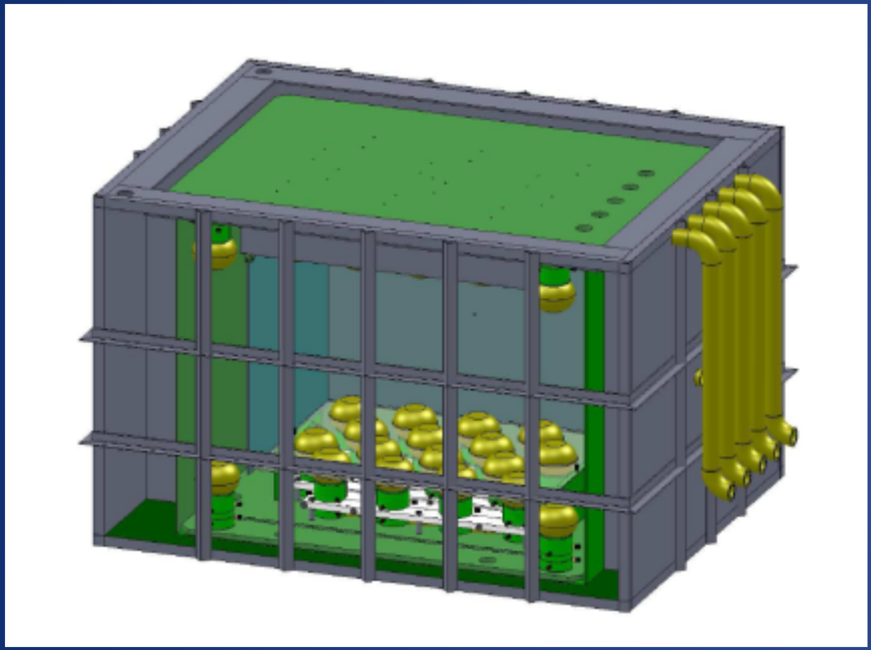


external water shield

Active Shield: 3 water tanks with 4 PMTs each: top, bottom and central tanks

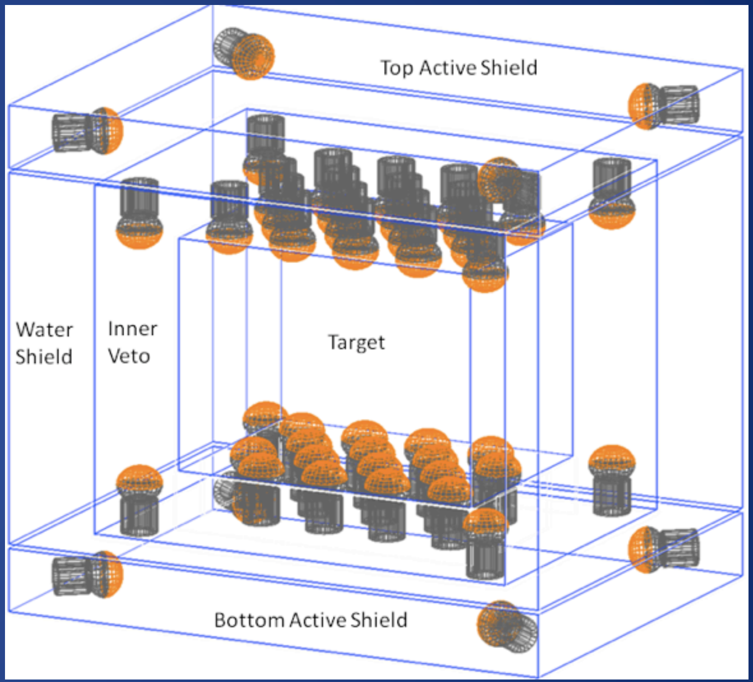
Detector Target Design

Detector design (2011)



(detector + active shielding)

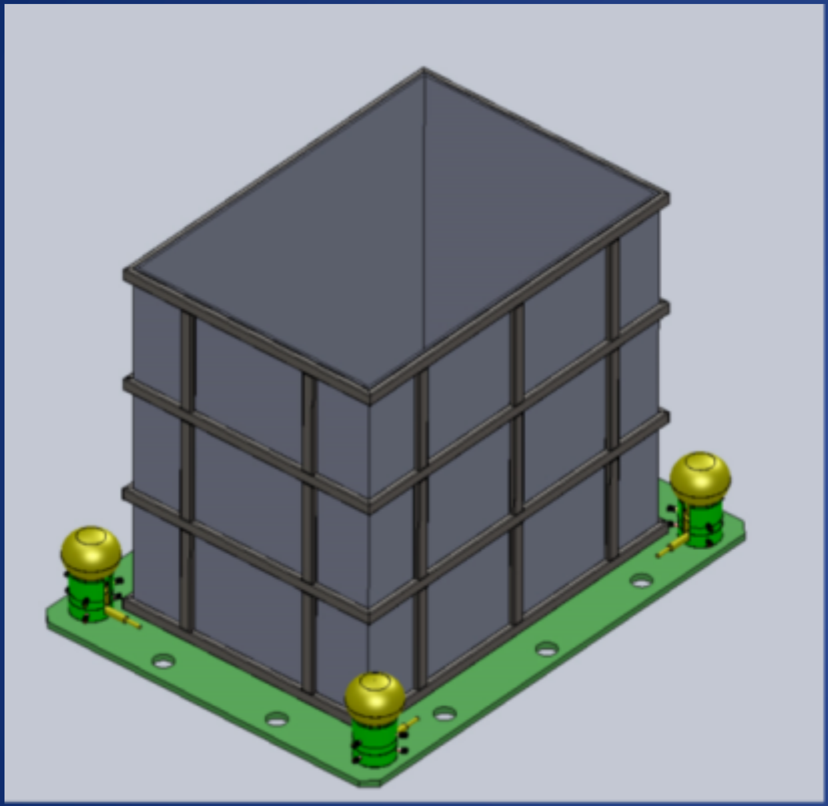
Detector Simulation 2013



Detector Simulation with GEANT4

Target tank: gadolinium loaded water and 32 PMTs (Hamamatsu 8")
(16 PMTs at top lid + 16 at bottom to detect Cherenkov radiation

New Target Design



New target tank lay-out
by Ivanoe (UFBA)

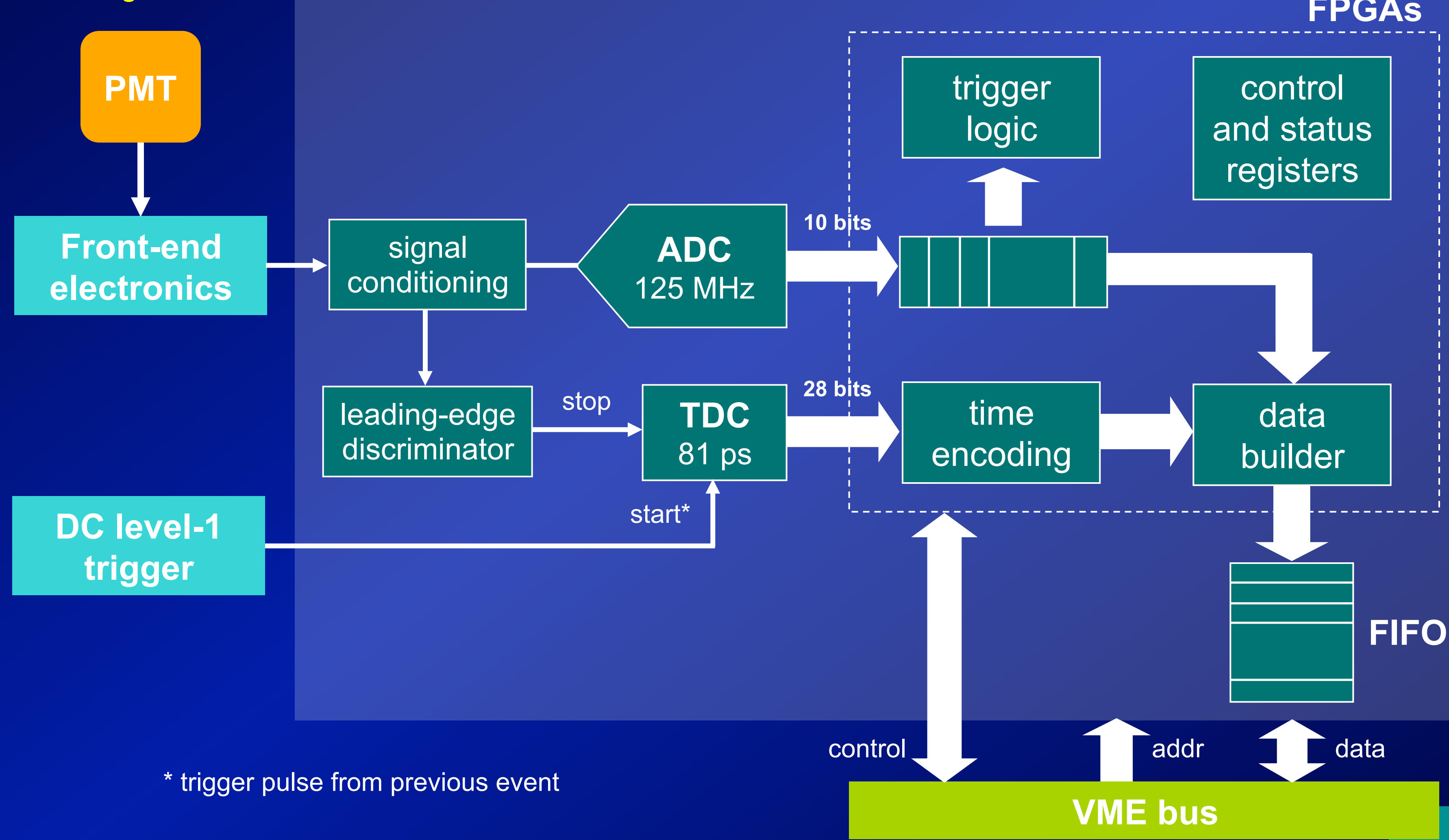
New target tank

Built by Incomplast - Rio

ELECTRONICS STATUS

Eletronics Design - (conceptual diagram 2007)

DAQ diagram



* trigger pulse from previous event

Data Acquisition module ready

VME 6U Board:
DAQ:
waveform digitizer
+ time stamp

- Lay-out of VME board developed in collaboration with Brazilian industry CADSERVICE

- Components mounted by CADSERVICE (Campinas, SP)

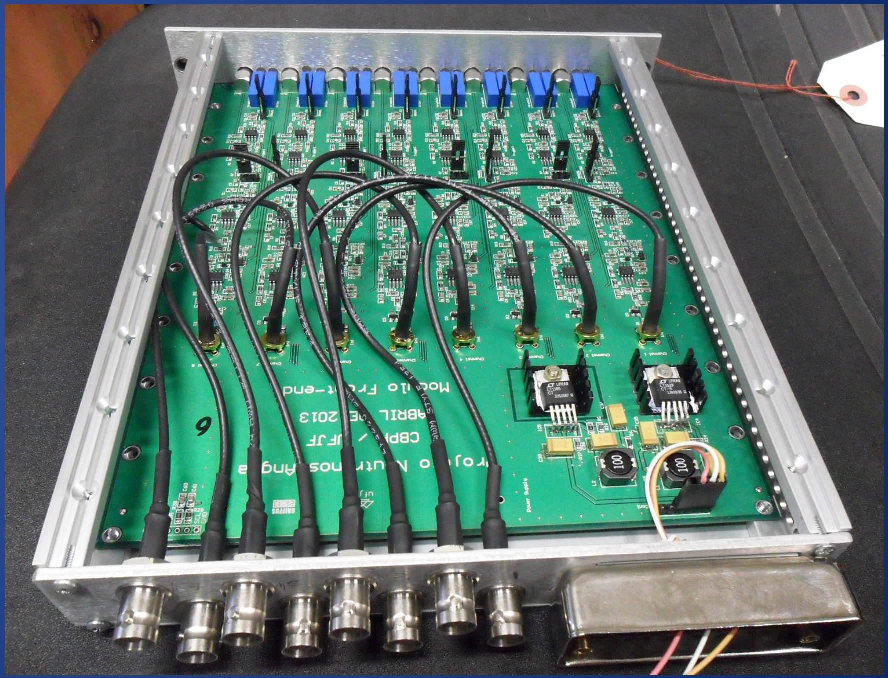
Front-end Electronics - UFJF

✓ 4 stages operational amplifier

✓ 8 channels circuit using NIM standard module.

✓ boards (PCB) built in July/2012 and are mounted.

✓ Ready



Data Acquisition Software

Data readout (*software*)

✓ Readout software code developped in C

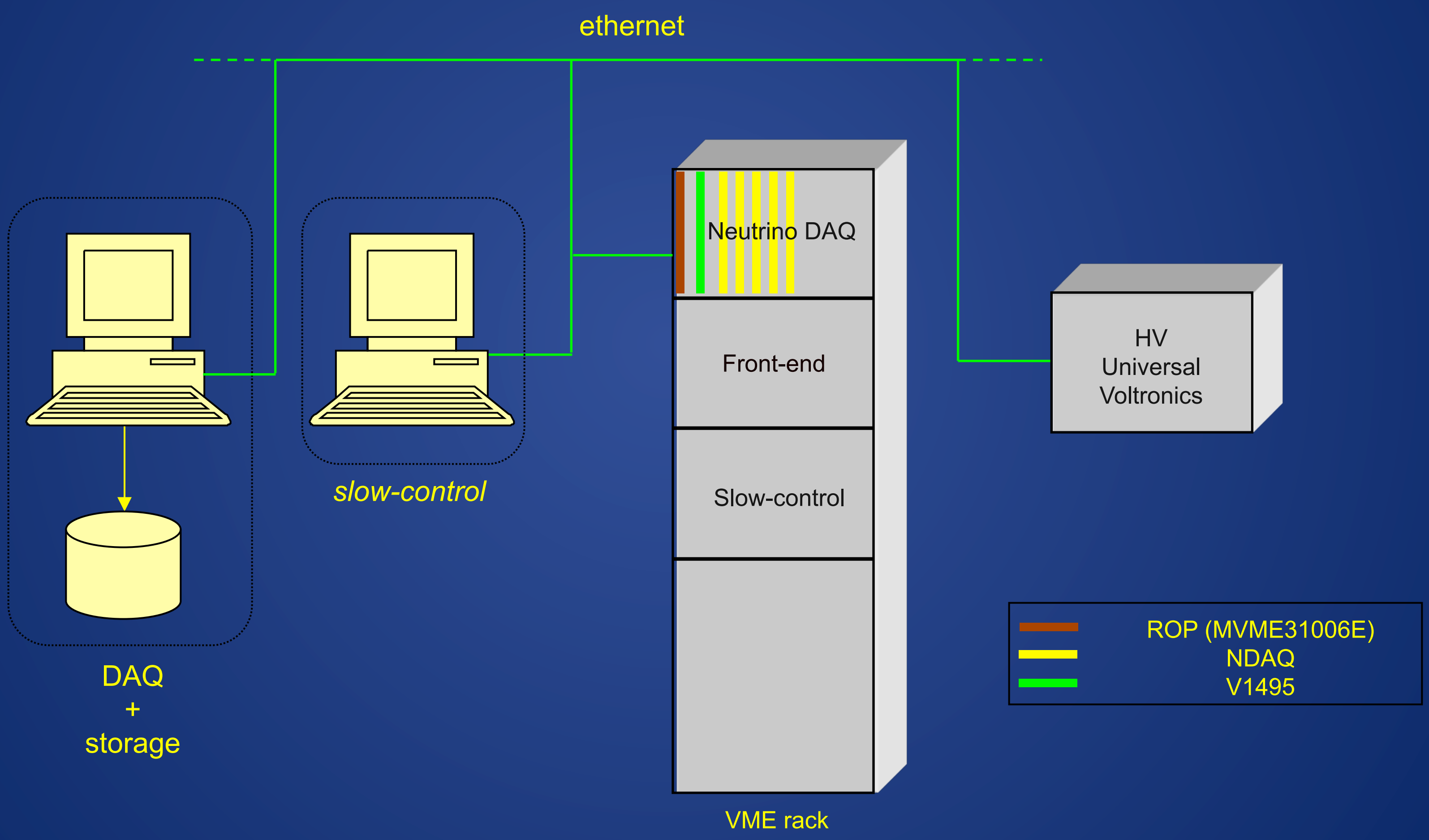
✓ 3 fully working systems, each one with one ROPs + NDAQs (2 at CBPF e 1 at Unicamp)

✓ Last firmware and DAQ software version is very stable, working without problems for few days continusly in lab tests.

✓ All software is SVN version controled.

✓ Last implemented code has a check of the serial number and firmware version at the startup in the DAQ-level.

System Integration Scheme



Detector Simulation Studies

Data Analysis: simulation of expected signal and background

Signal and background Simulation:

- Positrons (from neutrino interaction)
- Neutrons (from neutrino interaction)

- Cosmic ray induced background

Signal and cosmic background frequency

Particles	Frequency (HZ) 10-200 P.E
Positrons	0.050±0.001
Neutrons	0.050±0.001

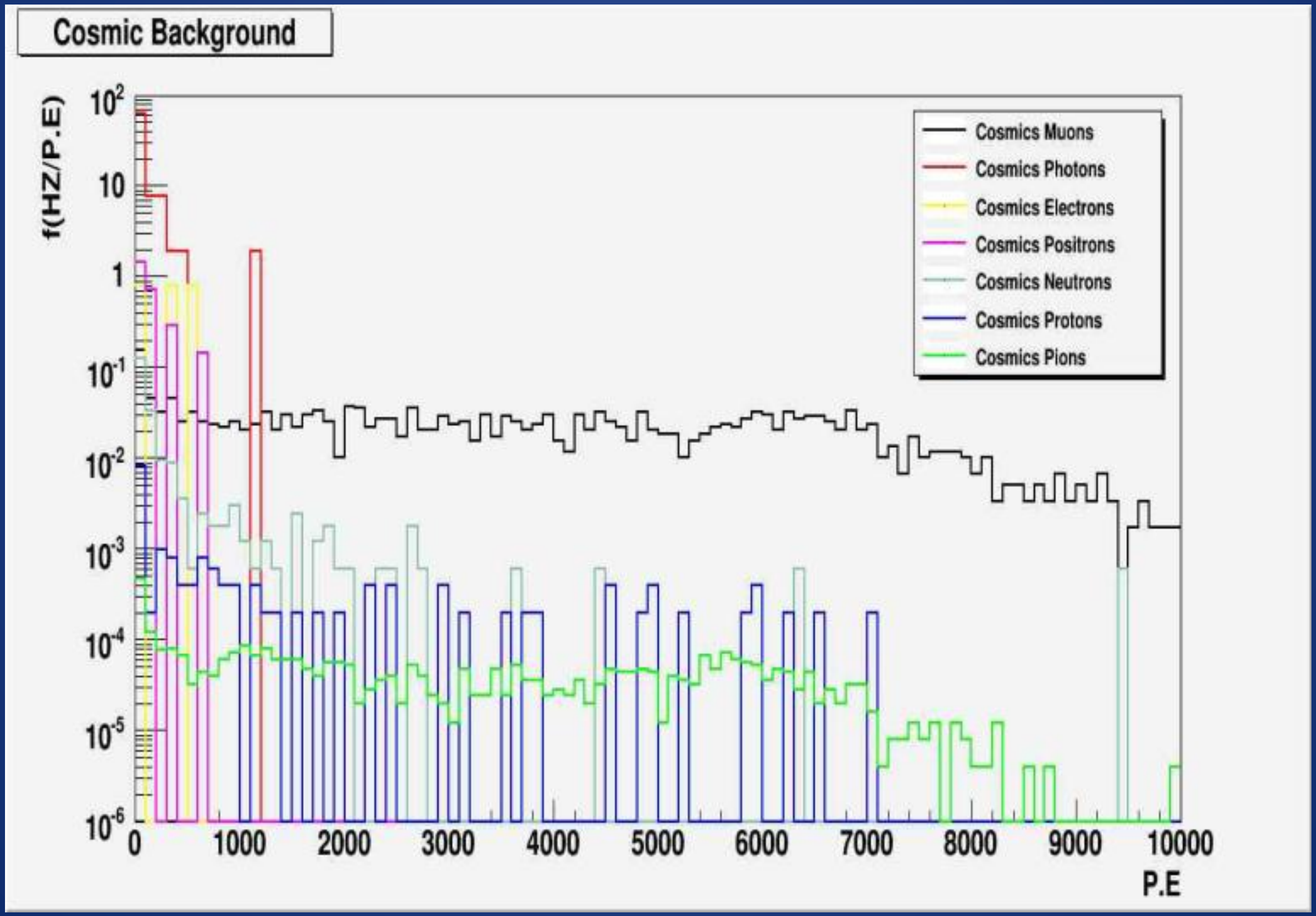
Table 1: Particle from antineurino signal

Particles	Frequency (HZ)
Muons	210±6
Neutrons	20±1
Protons	2.0±0.2
Pions	0.40±0.01
Photons	$(8 \pm 1)\times10^{3}$
Positrons	257±61
Electrons	242±140

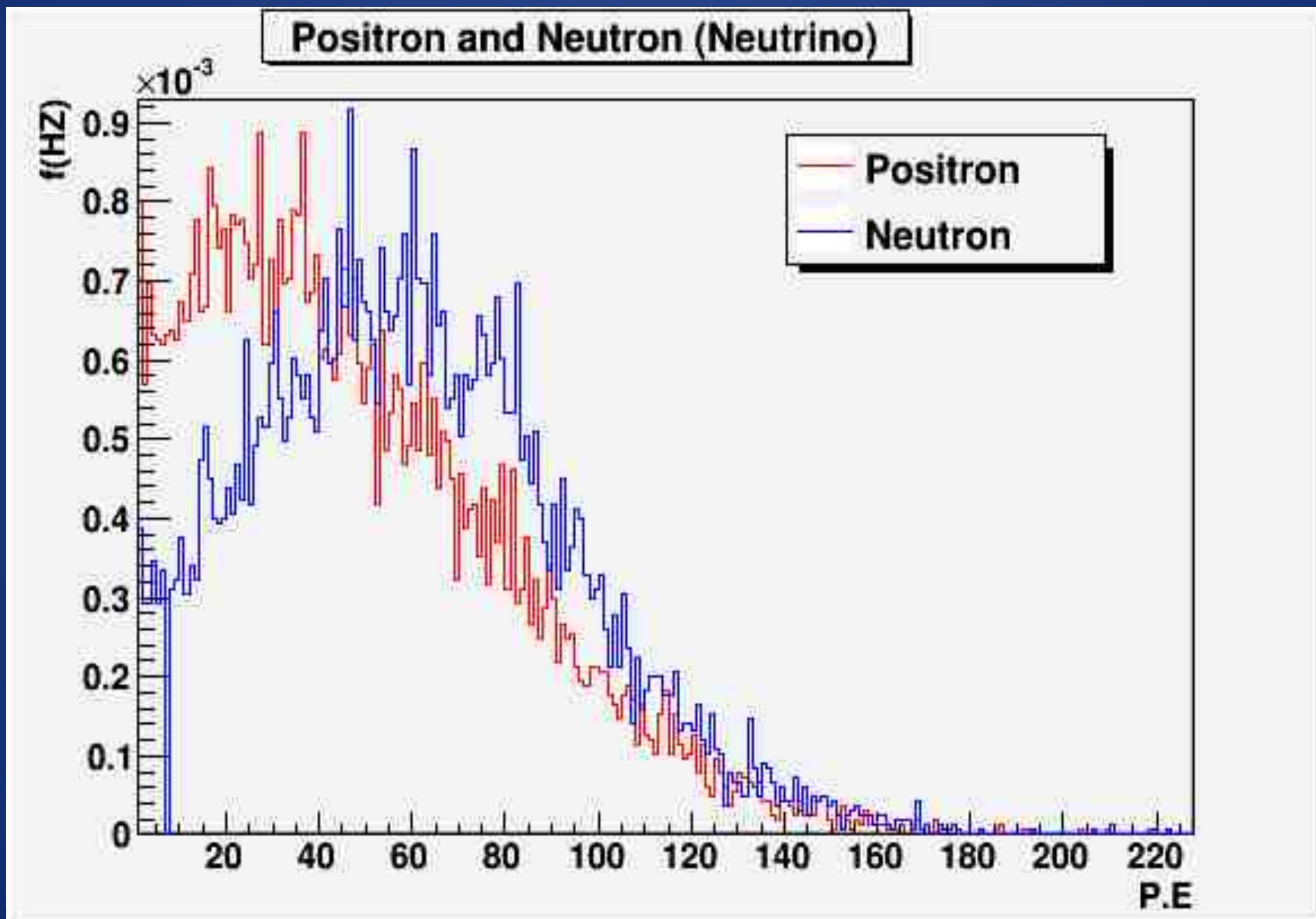
Table 2: Particles from cosmic background

Particles	Frequency (HZ) 10-200 P.E
Muons	12±1
Neutrons	13±1
Protons	0.44±0.09
Pions	0.048±0.004
Photons	$(5.7 \pm 1.1)\times10^{3}$
Positrons	158±48
Electrons	<186 (90% C.L)

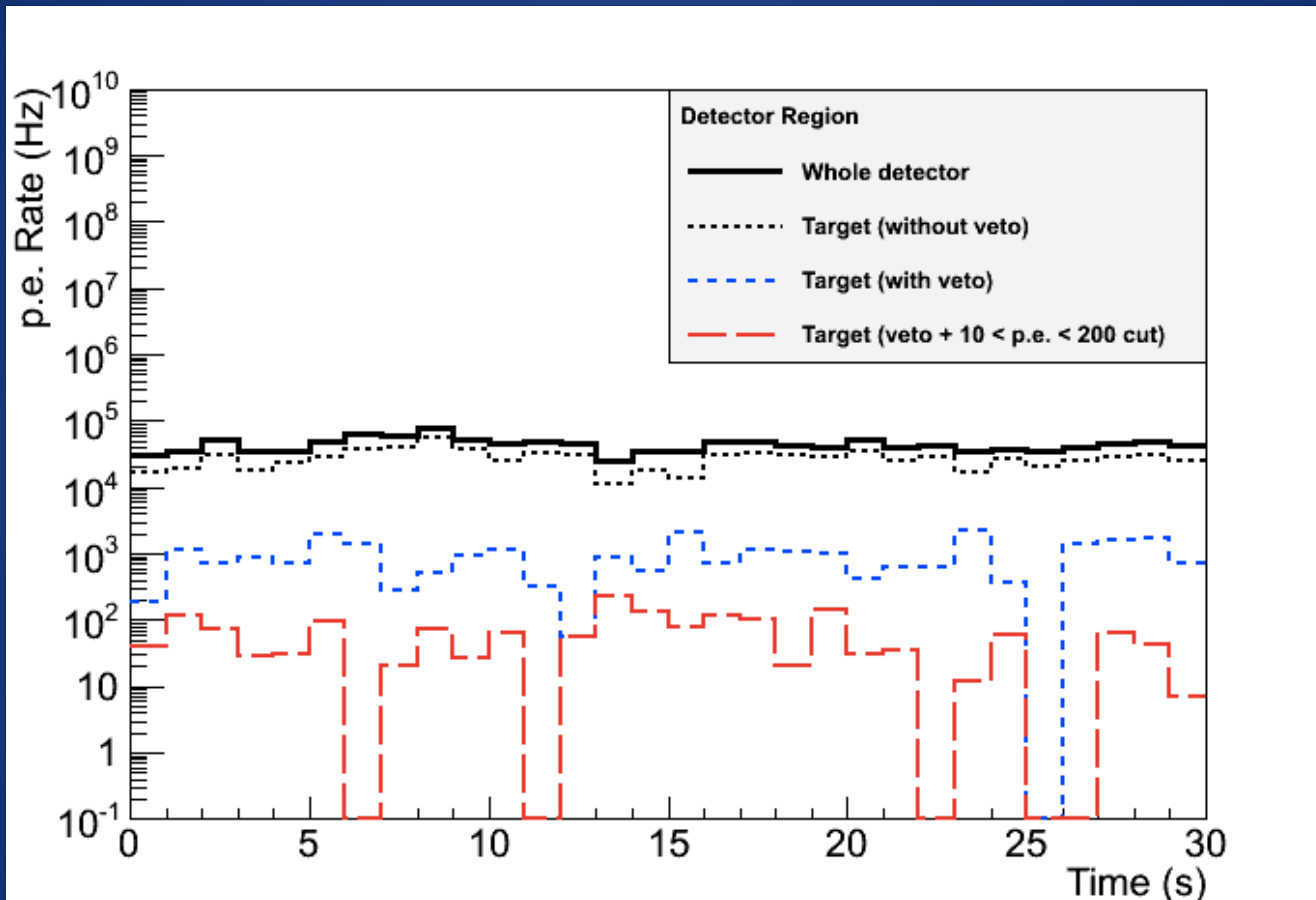
Muons, neutrons, protons, pions, photons, positrons and electrons



Particle frequency density from antineutrino signal



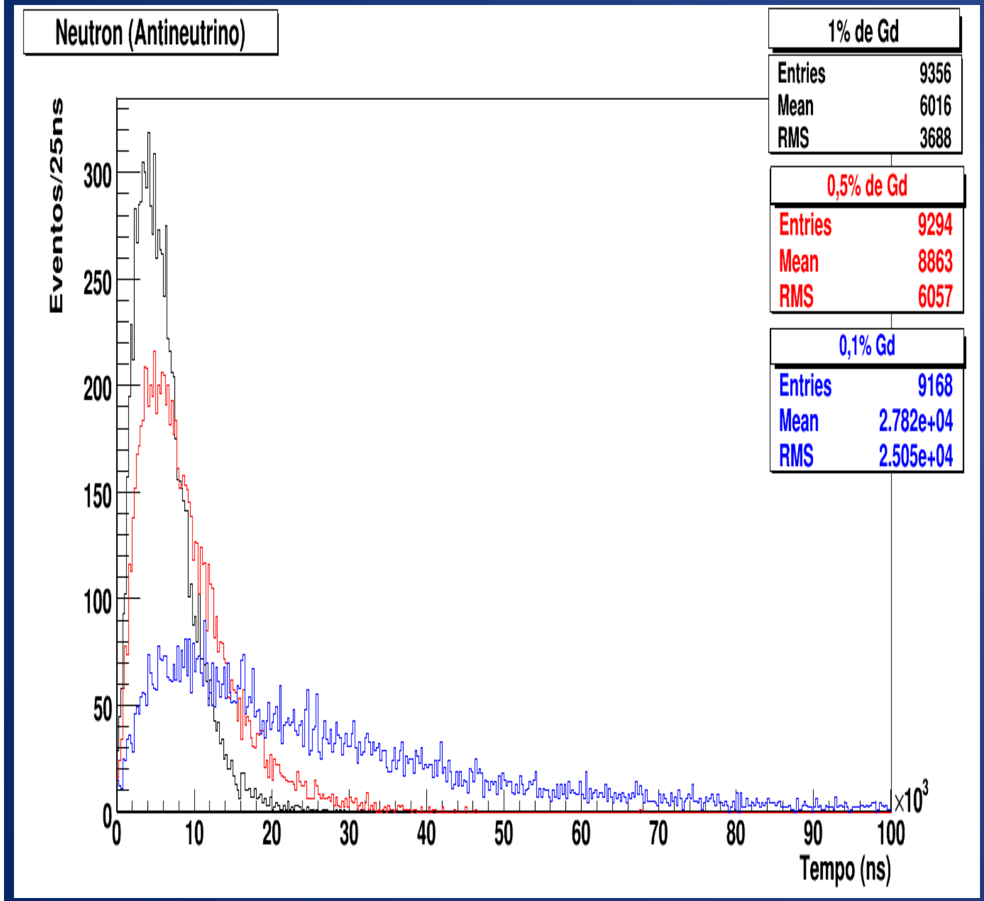
BACKGROUND SIMULATION



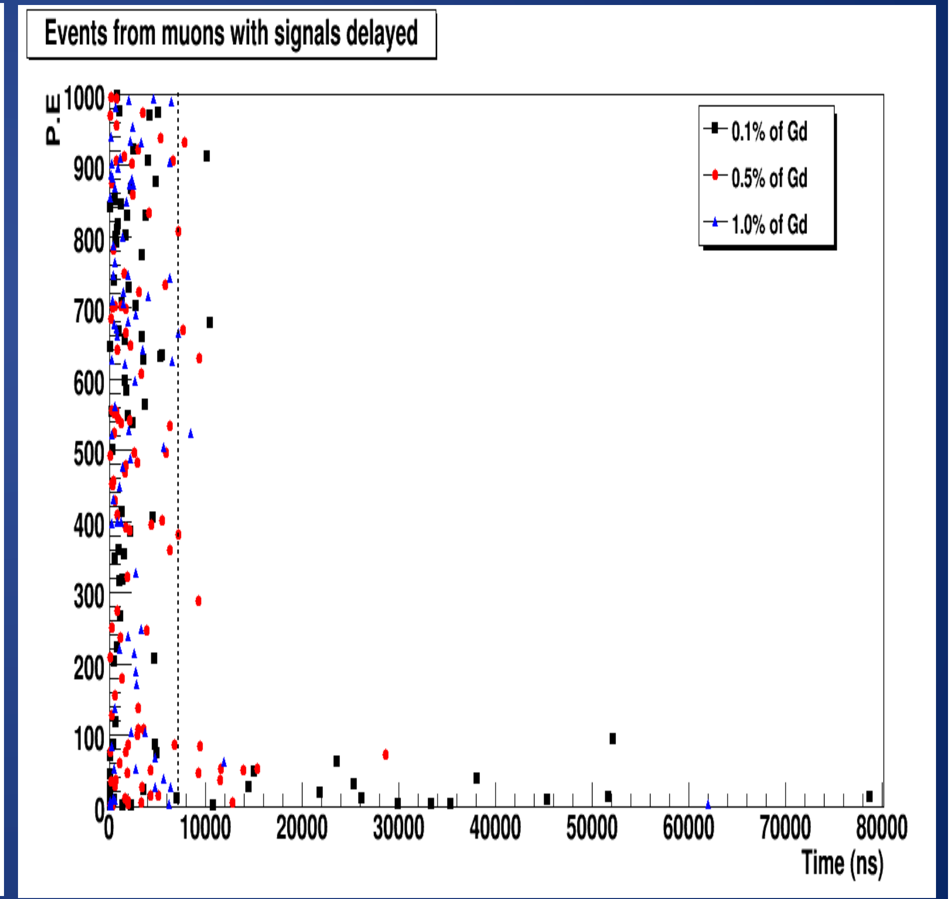
Expected trigger rates coming from all PMTs (black) and from the target: without veto or cuts (blue), with inner/top/bottom veto and with a 100 p. e. cut, resulting on a 45Hz rate.

Study of Gadolinium concentration

Delayed coincidence for
0.1, 0.5 and 1.0% Gd



Stopping muons and spallation neutrons
for 0.1, 0.5 and 1.0% Gd



Study of shielding

Table 1: Cosmic neutron events

Shielding	Neutrons simulated	Neutrons detected	Neutrons with signal delayed
Polyethylene	10.000	299	153
Water	10.000	282	98

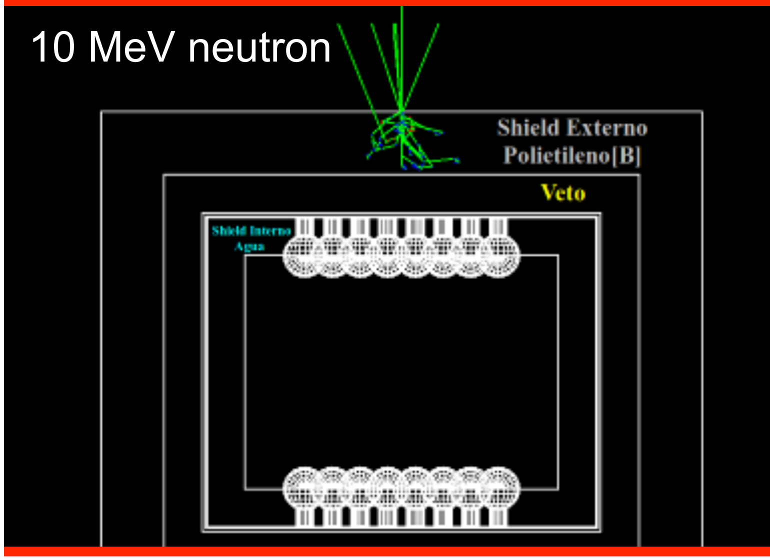
Table 2: Cosmic muons events: 10,000 generated

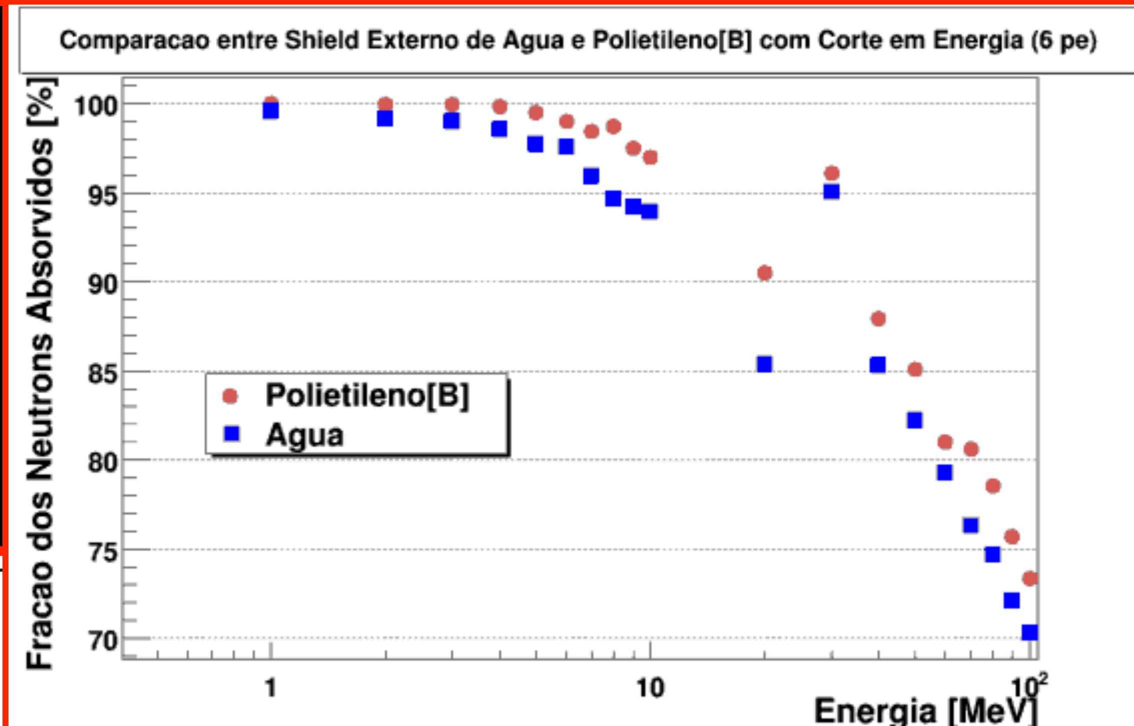
Shielding	Muons signal delayed	Spallation neutrons	Muons with multi-neutrons
Polyethylene	56	28	5
Water	59	17	1

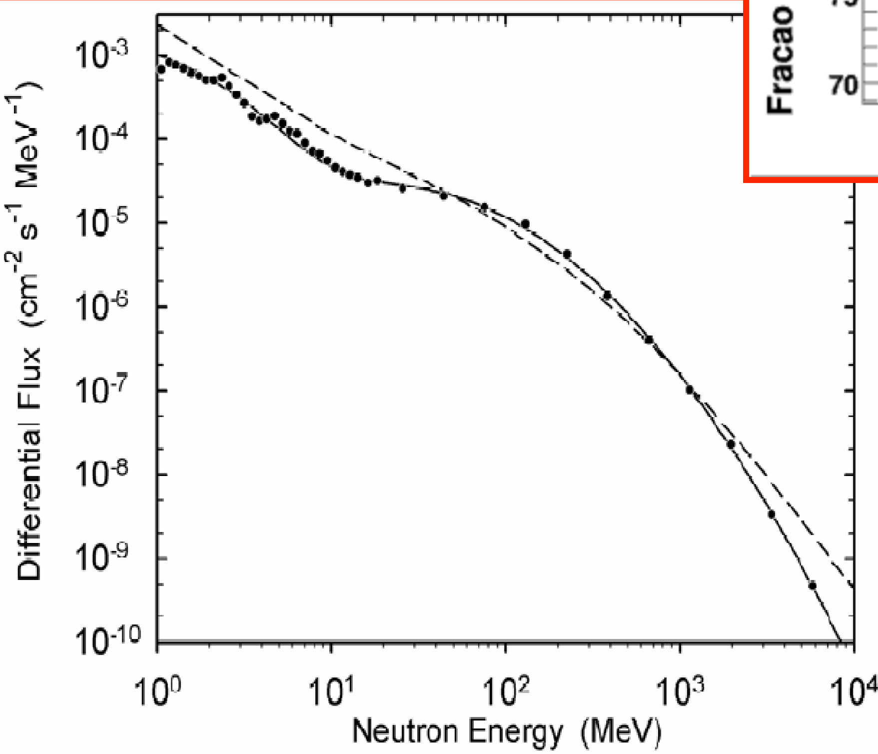
Table 3: Muons events

Shielding	Fake signals	Frequency (Hz)
Polyethylene	8	1.3±0.5
Water	6	1.0±0.4

GEANT4: study of neutron shielding







Experimental Flux measured at LNGS (1,000 m): $E_n > 10$ MeV

N_flux = 75 n/m^2.s

Angra (sea level): reduction 3x

N_flux = 25 n/m^2.s

Shielding Atenuation
(~ 85% above E=10 MeV)

N_flux = 4 n/m^2.s → ~ 5% contamination

Main Results

- Best material for neutron shield: water
- Less multiple neutrons produced by high energy muons than in polyethylene

- Best Gadolinium concentration: $0.1\% < C < 0.5\%$ $\cong 0.3\%$
- Smaller time window for delayed coincidence

- Study of best “dead time” after a muon (to avoid spallation neutrons)
- Study of best “dead time” after prompt to avoid stopping muons

DETECTOR STATUS

DETECTOR STATUS

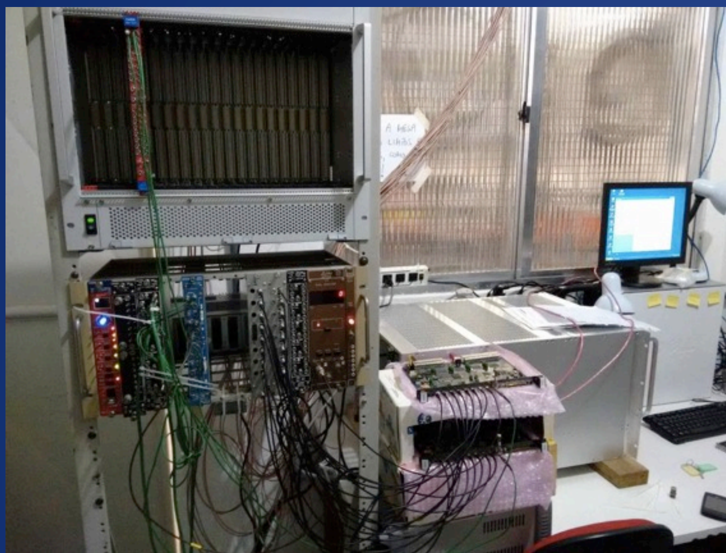
Arrival of water shielding vessels at CBPF

DETECTOR STATUS

Mounting Active shield

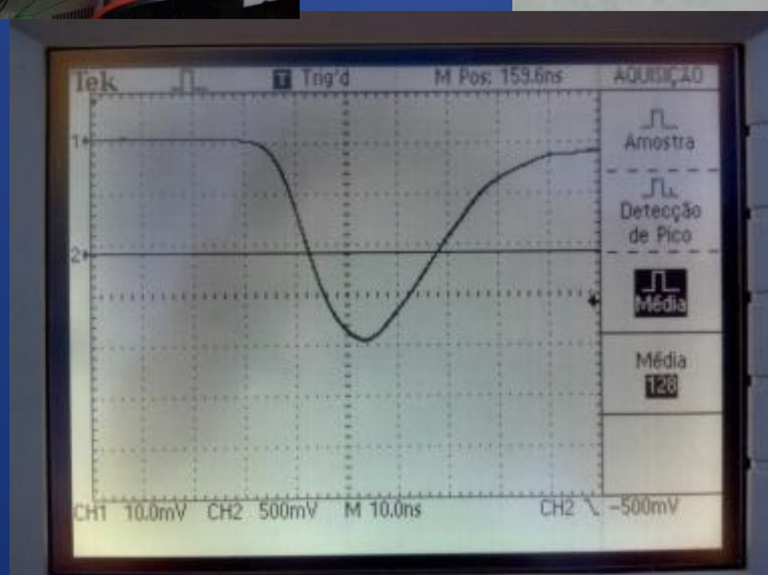
Covering internal walls with Tyvek
and installing PMTs

DETECTOR STATUS



DAQ first test System
on the real tank

LED signal
Tank without water



DETECTOR STATUS

Mechanical assembly of the target top lid PMTs

DETECTOR STATUS

Water filling system for the water tank

DETECTOR STATUS

Mounting of target tank inside active shield water tank

Interior of Target tank

Status of the Neutrinos ANGRA project

- New 40' High Cube container: **deployed** in Angra

- Geant4 simulation of detector response to signal and background events: **working**

- Neutrino signal extraction – **simulated**

- New detector design: **active water shield**

- Water shield and target vessels: **built**

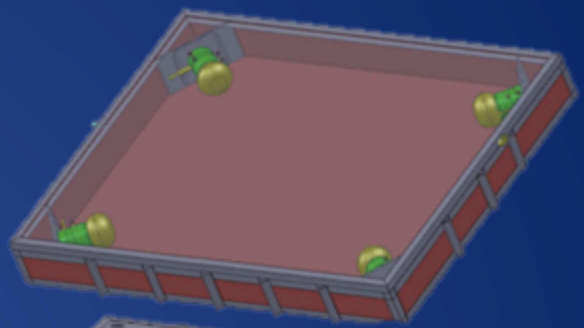
- Front-end electronics: **ready**

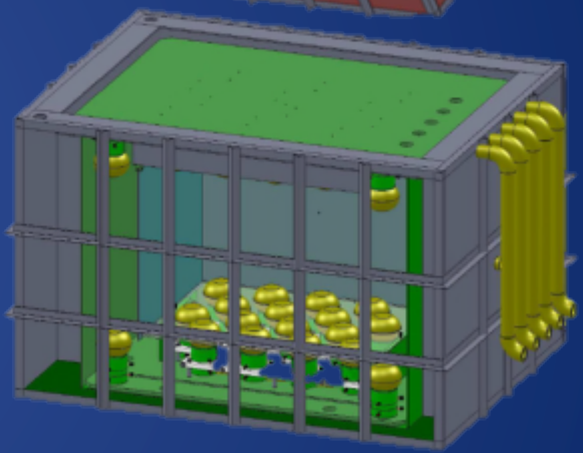
- Electronics for DAQ: **ready**

- Data acquisition software: almost **ready**

- Detector test at CBPF: **during 2014**

- Deployment in Angra: **begining 2015**





Summary

- Previous experiments demonstrated a good capability of using antineutrinos for nuclear reactor distant monitoring.
- Neutrino laboratory already installed in Angra
- Cosmogenic background estimated
- Remote data transfer (CBPF-Angra link) working.
- Simulation is running and guided final detector design.
- Electronics is ready and being tested
- Expected data taking at ANGRA by beginning 2015

New Detector Technologies

CONNIE
Neutrino coherent scattering detection at Angra

arXiv: 1405.5761v1

Coherent neutrino-nucleous interaction

$$\nu + N \rightarrow \nu + N$$

is a fundamental interaction predicted by the standard model whose X-section, for E_V < 50 MeV, is expressed by

$$\sigma_{Tot} = \frac{{G_F}^2}{4\pi}[Z(4sin^2\theta_w - 1) + N]^2$$

$$\sim 4.22 \times 10^{-45} N^2 (\frac{E_v}{1MeV})^2 cm^2$$

$N^2 \rightarrow \sigma_{tot}$ **Very High**

(for ^{28}Si, N=14)

It has never been observed !!

COherent Neutrino-Nucleous Interaction Experiment (CONNIE)

The use of CCD detectors (as in the DAMIC experiment) and the facilities of the Angra-neutrino project allows an opportunity to search for coherent neutrino - nucleous scattering.

The CONNIE collaboration was initiated in 2011and brings together researcher from several institutions

Fermilab (USA) – Juan Estrada (spokesman)
Univ. Zurich (Switzerland)
Univ. Nacional del Sur (Argentina)
Univ. Nacional Autonoma de Mexico UNAM (Mexico)
Univ. Nacional de Assunción (Paraguay)
Univ. Federal do Rio de Janeiro UFRJ (Brasil)
Centro Brasileiro de Pesquisas Fisicas CBPF (Brasil)

Hard to observe process

Detector should:
1) be able to distinguish nuclear recoil
2)present extremely low electronic noise

CCD (Charged Coupled Device)
are silicon detectors that convert photons in electrons generating a current that can be quantified by an ADC

CCD detectors present low electronic noise and can register nuclear recoil!

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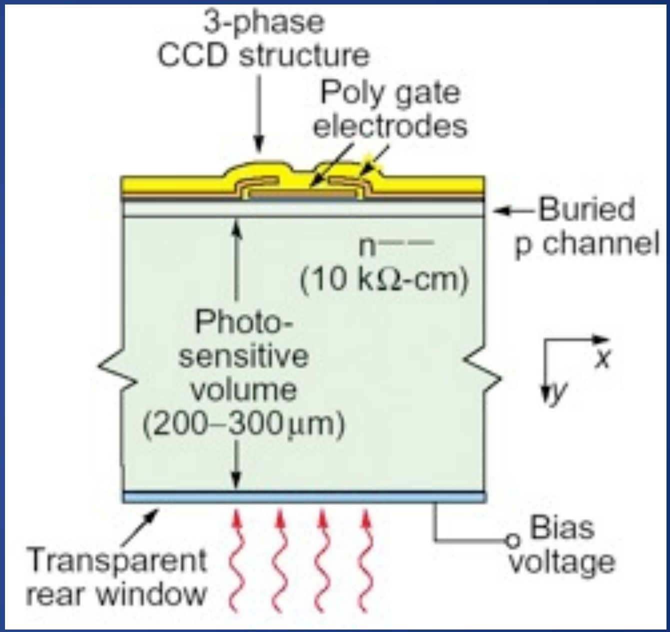
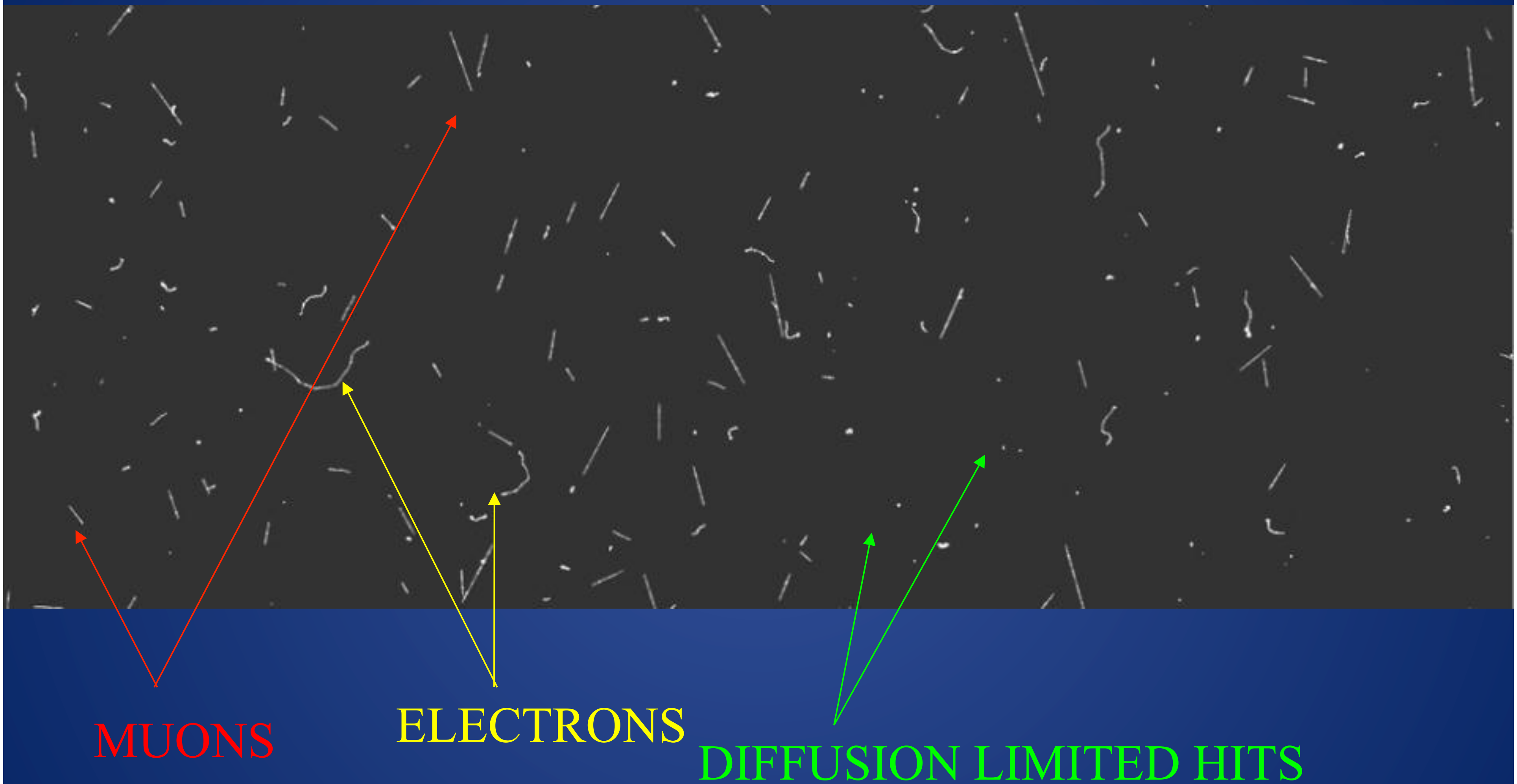
CCD detectors have been used in dark energy and dark matter experiments like DES (Dark Energy Survey) and DAMIC (Dark Matter in CCD).

DAMIC CCD:
- CCD are readout serially
(2 output for 8 million pixels)
- Very low noise level ~7.2 eV
- 1 g per CCD
- 18 cm^2
- 250 μm thick



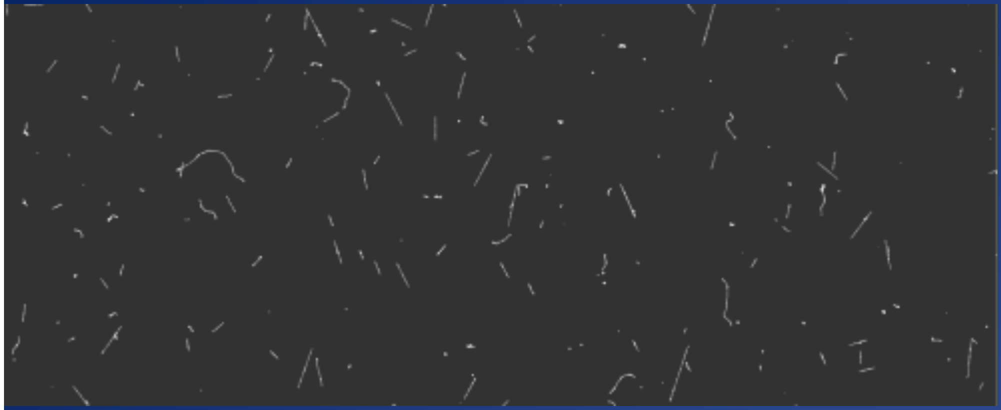
CCD detectors are potential candidates for experiments aimed at observing coherent neutrino-nucleous interactions.

How radiation shows in CCDs

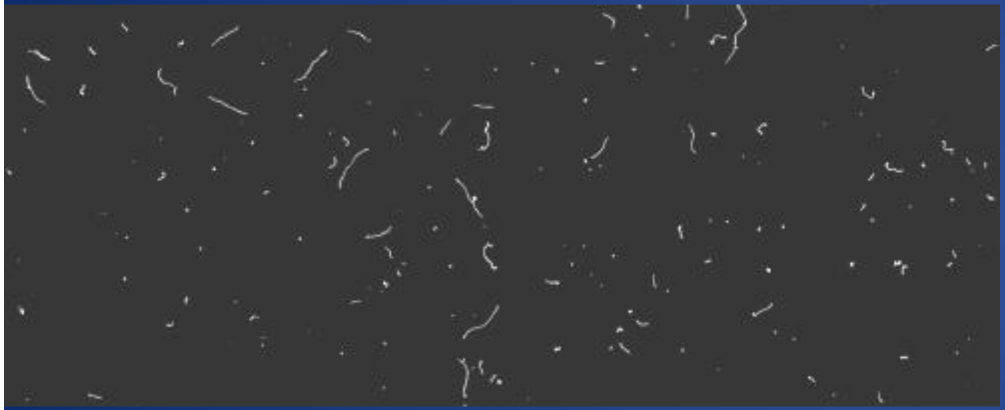


Nuclear recoils produce diffusion limited hits

50



Lab-A (Fermilab)



MINOS cave (100 m underground)

MINOS + lead shield

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But ...can we detect neutrinos with such small devices?

YES! WE CAN !

Either we have a massive detector or ...
a small detector with a very intense flux.

Typical anti-neutrino flux ($cm^{-2}\ s^{-1}$)

4GW nuclear reactor $\sim 10^{12}$ (30m from core)

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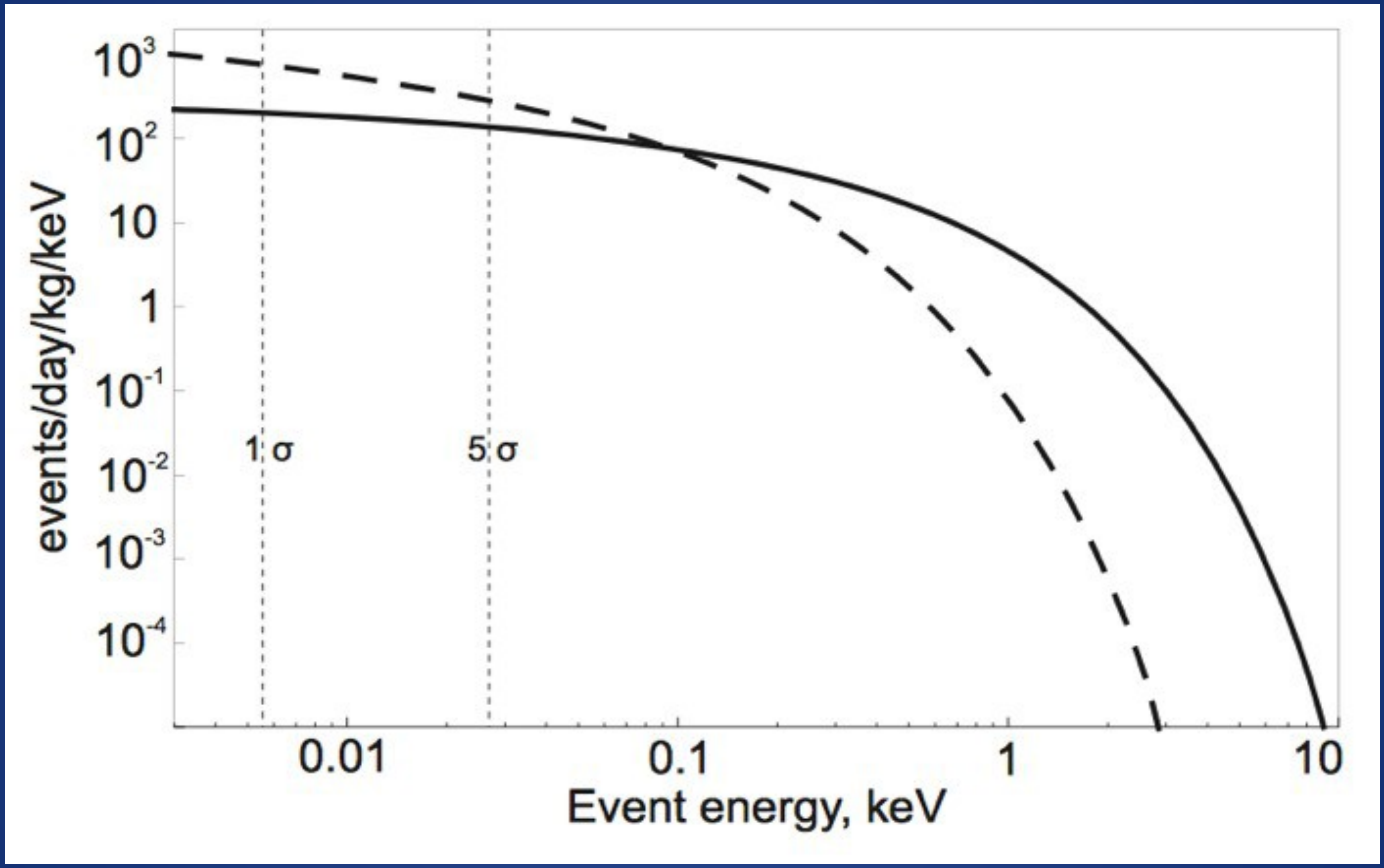
Spectrum of expected events

assuming a CCD at 30 meters from a nuclear reactor of 3.9GW



Most detectable events are below 3 KeV, therefore the CCD readout noise, the detection software, and the background control become very importatnt for this experiment

CONNIE FACTS

Number of CCD detectors: 10

Total mass: 10 g

Reactor thermal power: 4 GW

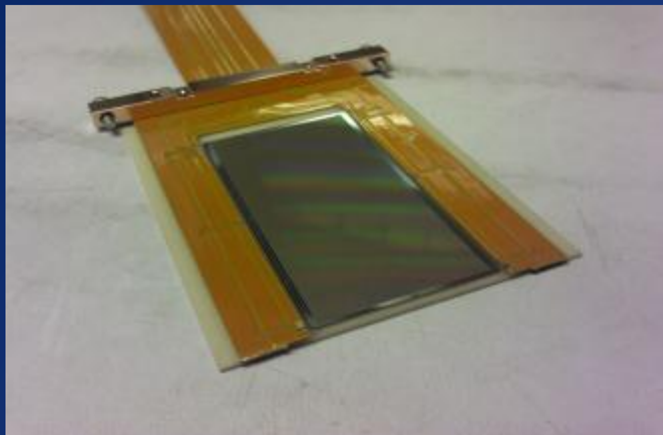
Detector distance from reactor core: 30 m

Anti-neutrino flux at the detector: $\sim 7 \times 10^{12}\ cm^{-2}\ s^{-1}$

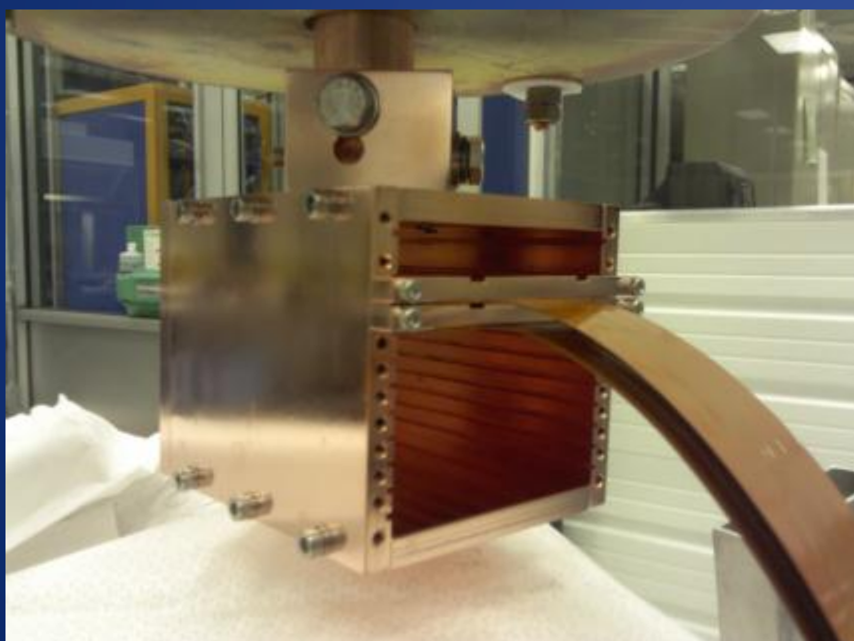
Event rate : ~1 event every 4 days

Shielding and noise reduction are the critical factors.

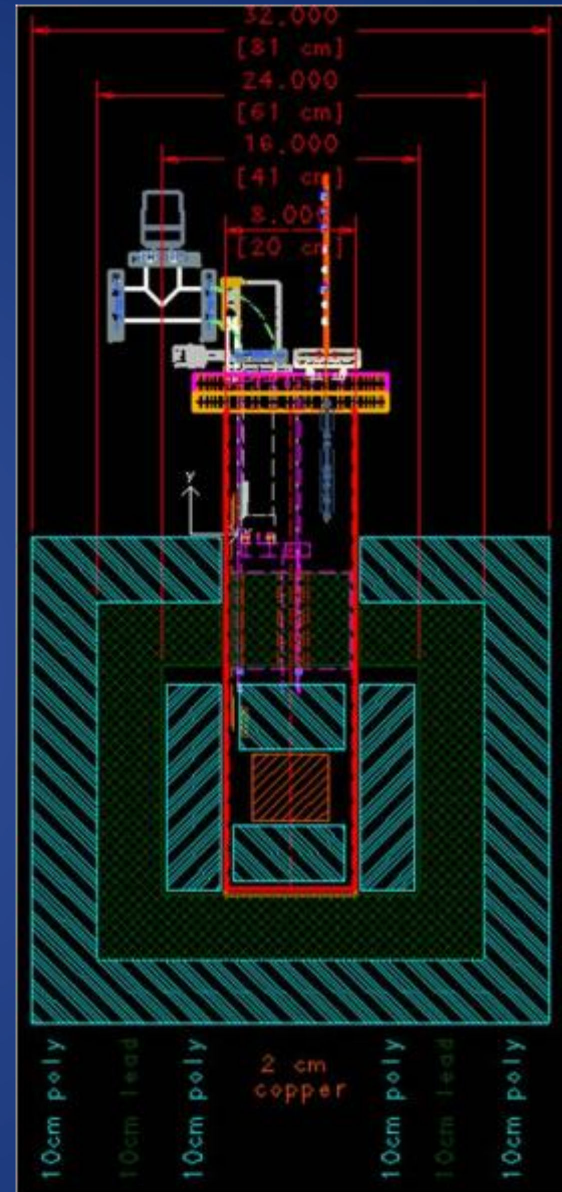
Development of noise reduction techniques in the core of the project.



CCD – Angra detector

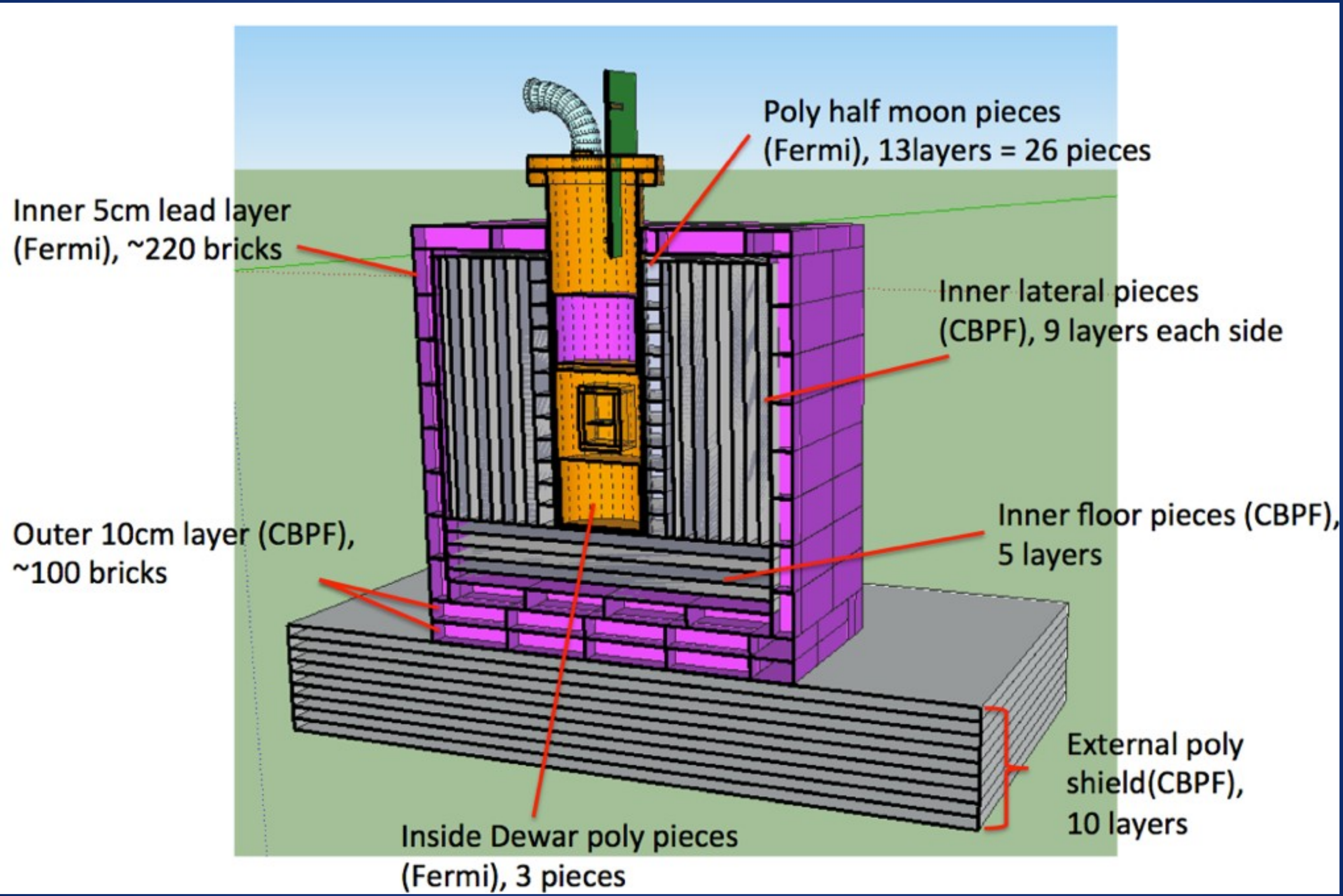


Box with 2 CCD for the
CONNIE experiment



Vessel design with shield

First stage of the shield



CONNIE

Mounting the polyethylane and lead shields at ANGRALAB

Detector instaled

CONNIE mounted at the Angra neutrino lab

First light October 16, 2014!

Summary and Final remarks

- CCDs can be used as particle detectors with good resolution and very low electronic noise

- Capability to detect nuclear recoils (DAMIC, CONNIE)

- Can be used to detect coherent neutrino nucleon interaction with reactor anti-neutrinos

- CONNIE Detector instaled at Angra.
  First light October 16, 2014

- Things to do:
  Achieve needed S/N (improve shield and/or add mass)
  Add CCDs
  Detect the neutrinos!

THANKS!

Using Neutrinos to Monitor Nuclear Reactors

The Angra Experiment
and new detector technologies

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Observatório Nacional & CBPF

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