Neutrino Detectors for Reactor Monitoring: the Angra Project

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On Behalf of the Angra Collaboration

XII WORKSHOP ON PARTICLES AND FIELDS
Sociedad Mexicana de Fisica

Mazatlan, Mexico, Nov 9-14, 2009

The ANGRA Neutrino Project

- Now: Safeguards Tool Development
- Eventually: Nu Oscillation Measurement

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T. Lasserre (informal support)

Angra dos Reis
RJ – Brazil

Angra-III

Main Goal:

- Monitor reactor with antineutrinos:
  - Gain insight on the technique
  - Improve it

Possible Future Goal:

- Neutrino Oscillations:

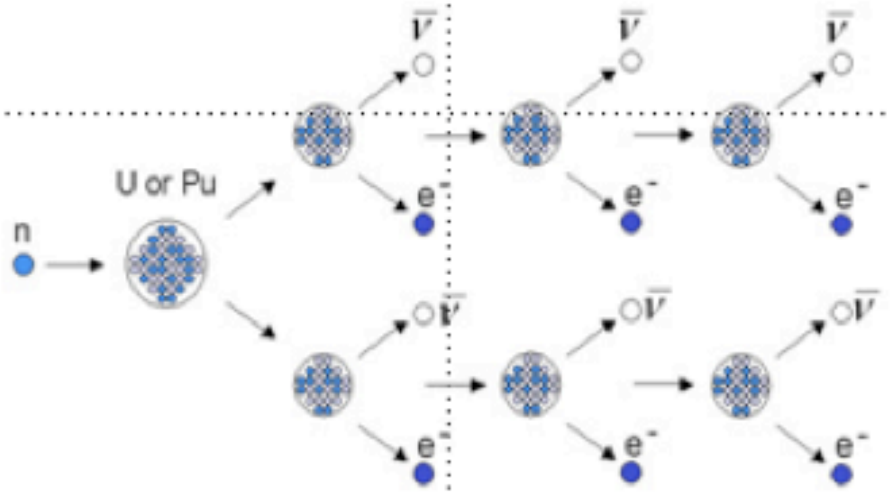
  Measure the mixing angle θ_{13}

Neutrinos from Reactors

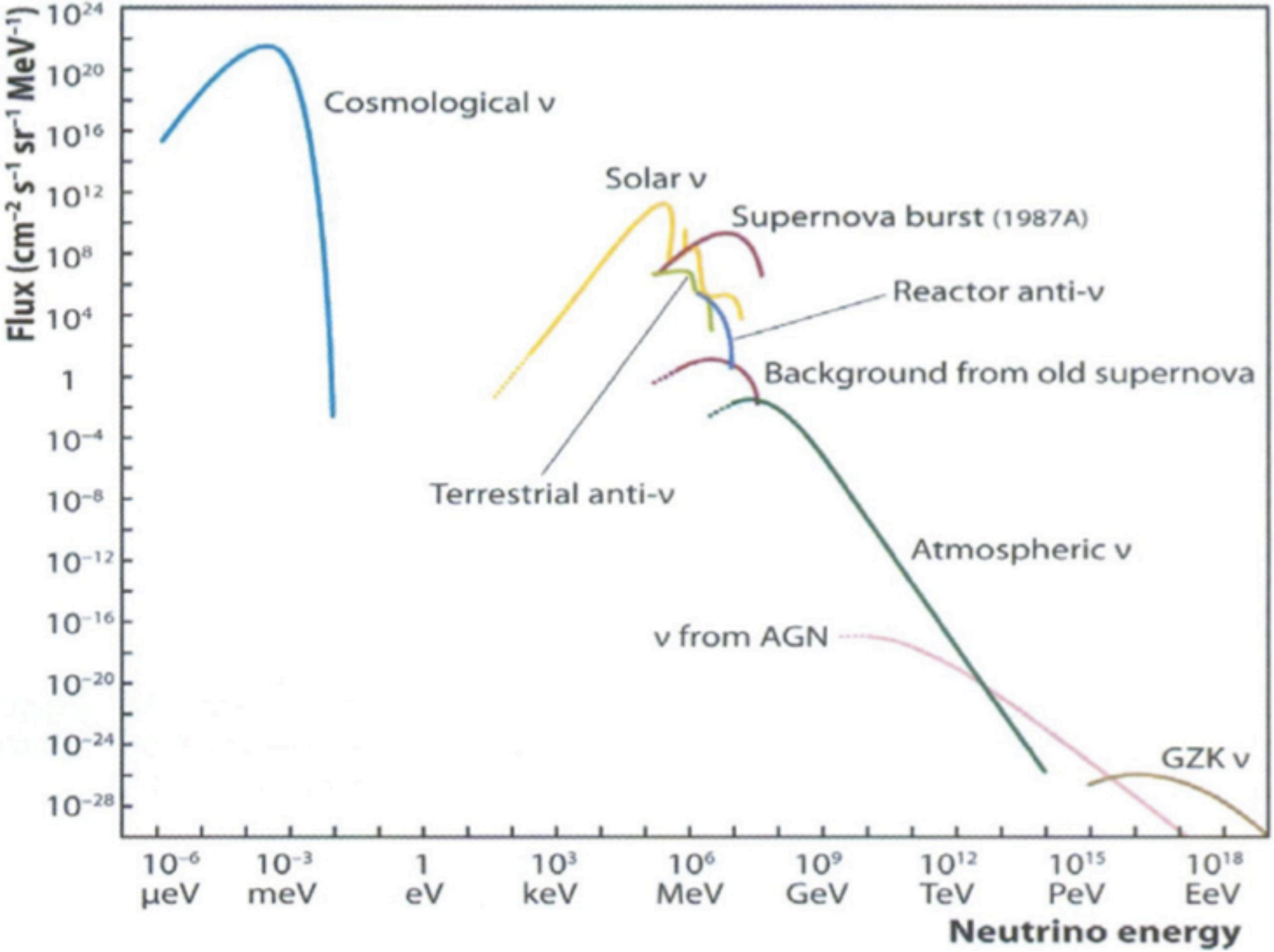
- Nuclear reactors produce lots of (electron) antineutrinos
- Typical fluxes: 10^{20} s^{-1}
- Typical energy: a few MeVs

Reactor Neutrinos: main features

- Source: copious β-decays from fission process



$\langle N_\nu \rangle = 6{,}7$ antineutrinos / fission


Flux ($\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}}$)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

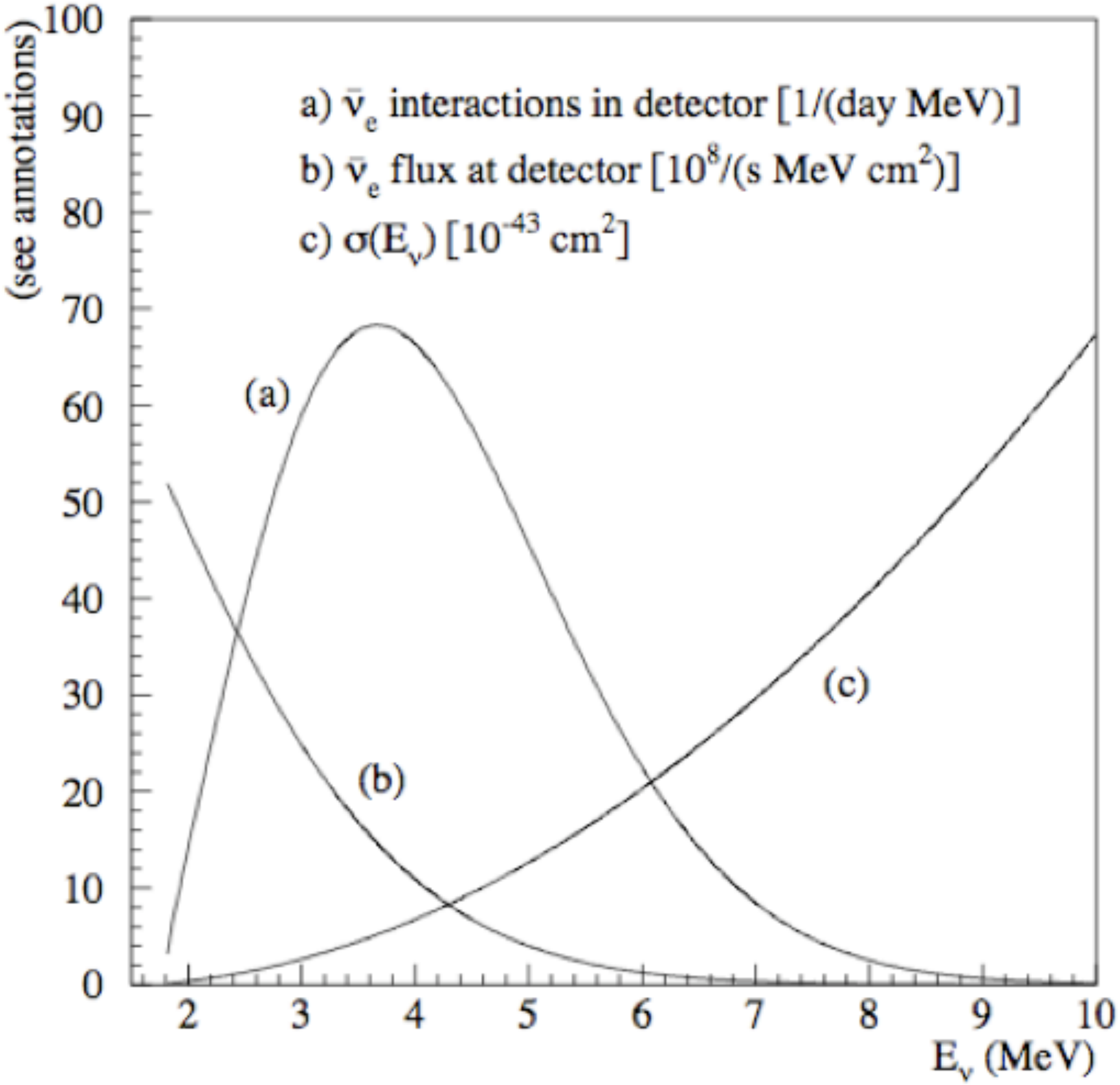
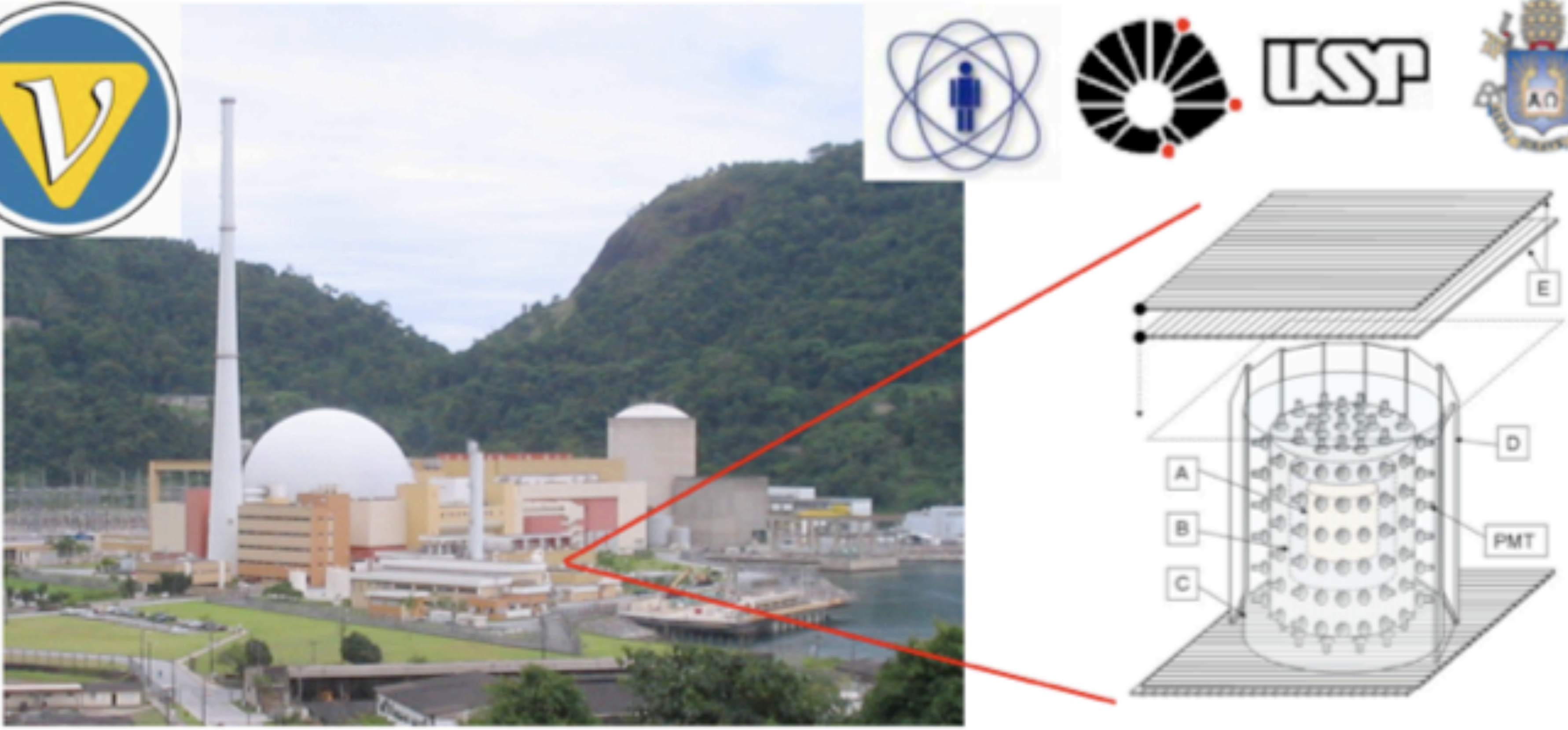


FIG. 2. Reactor $\bar{\nu}_e$ flux, inverse beta decay cross section, and $\bar{\nu}_e$ interaction spectrum at a detector based on such reaction.

Applicação de Física dos Neutrinos

monitoramento de reactores nucleares



salvagurada e não-proliferação de armas nucleares

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Neutrino Detection Principle

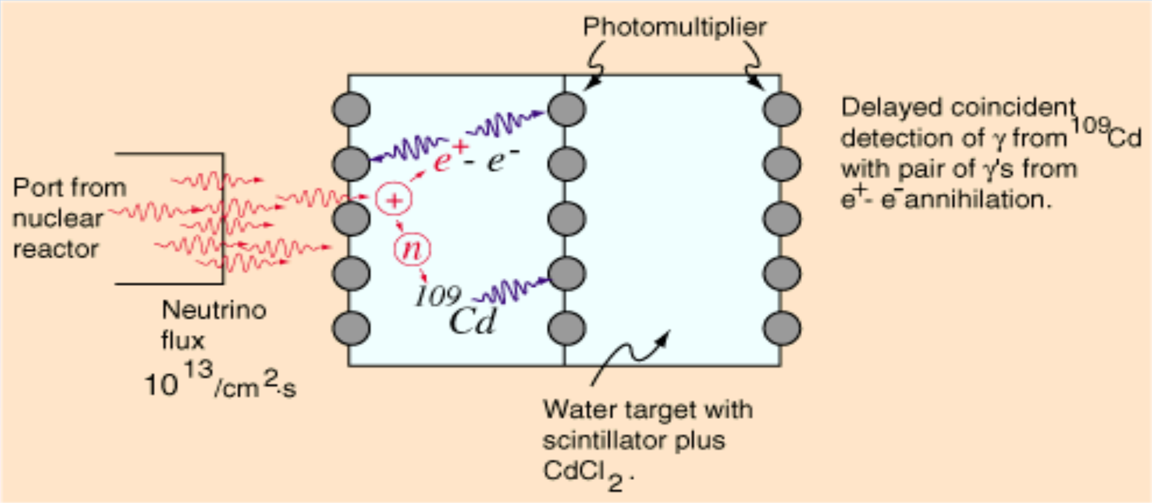
The $\bar{\nu}_e$ interacts with a proton (from the target) via the **inverse β-decay**:

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

The e+ quickly annihilates

Later the neutron gets captured producing a *coincident* signal

Reines and Cowan used Cd to enhance the n capture



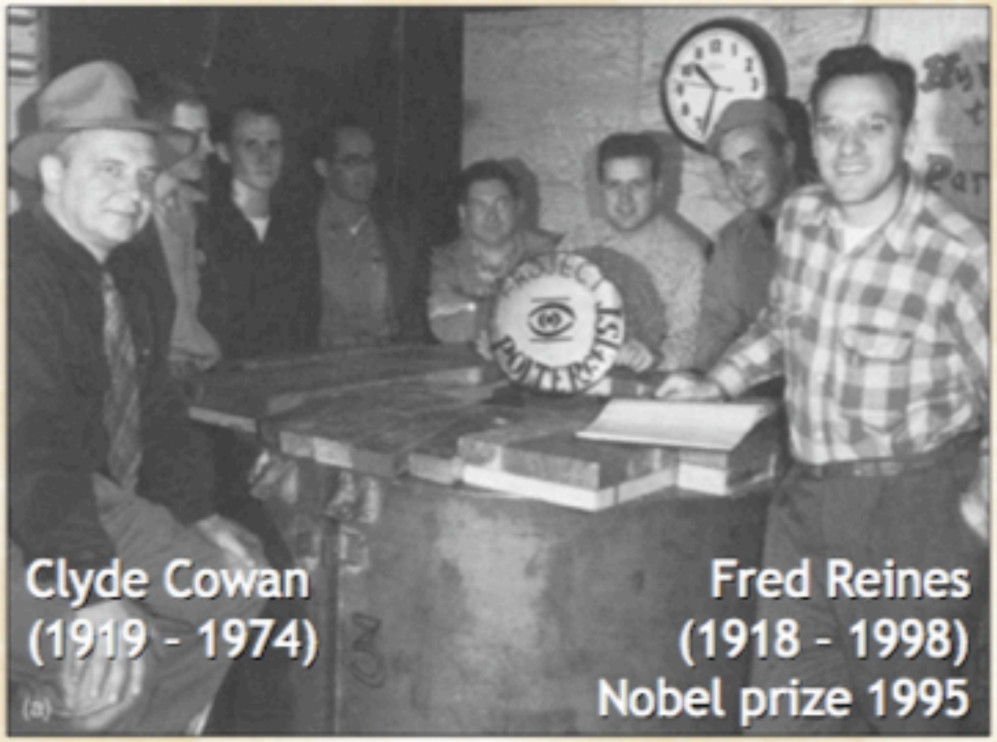
1953-1956

The Reines-Cowan Experiments

Detecting the Poltergeist

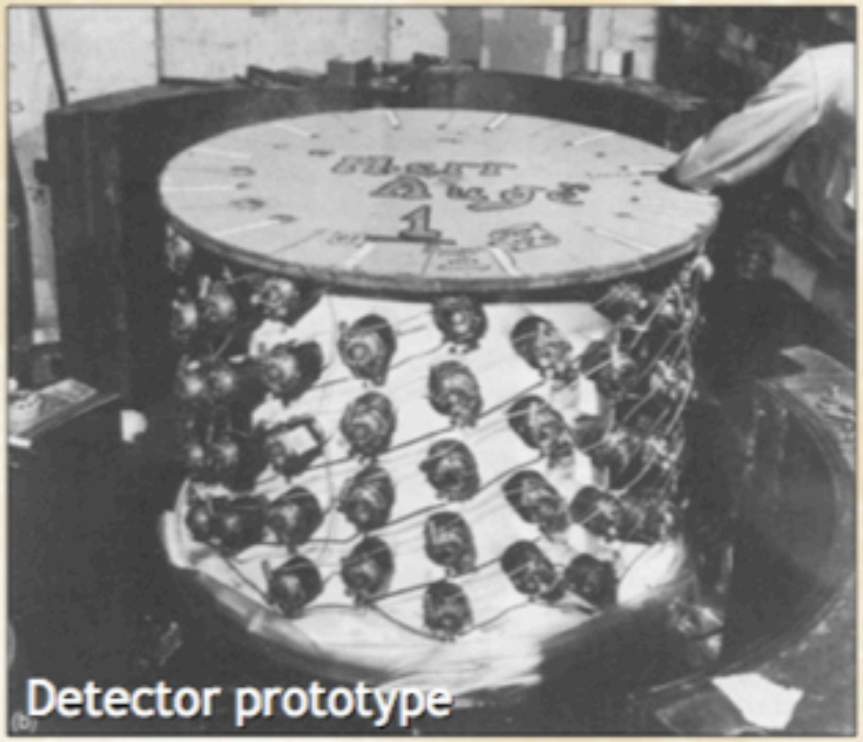
Hanford Team 1953

First Detection (1954 - 1956)

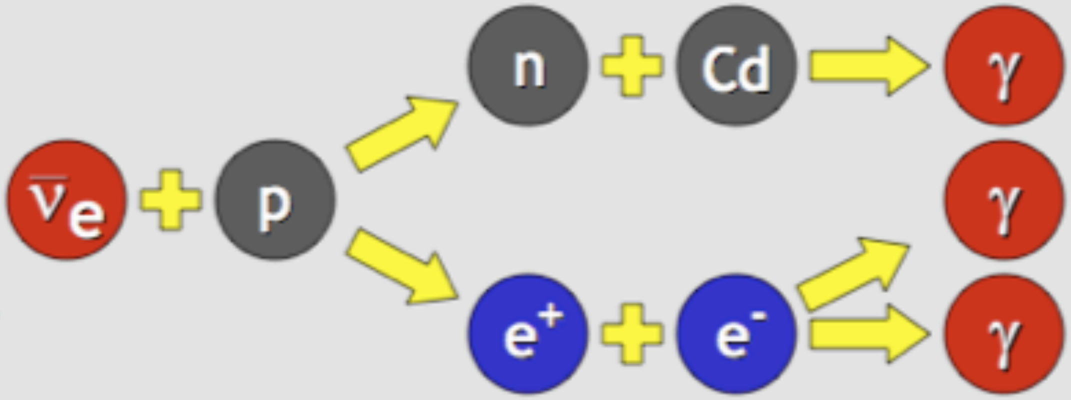


Clyde Cowan
(1919 - 1974)

Fred Reines
(1918 - 1998)
Nobel prize 1995



Detector prototype



Anti-Electron
Neutrinos
from
Hanford
Nuclear Reactor

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

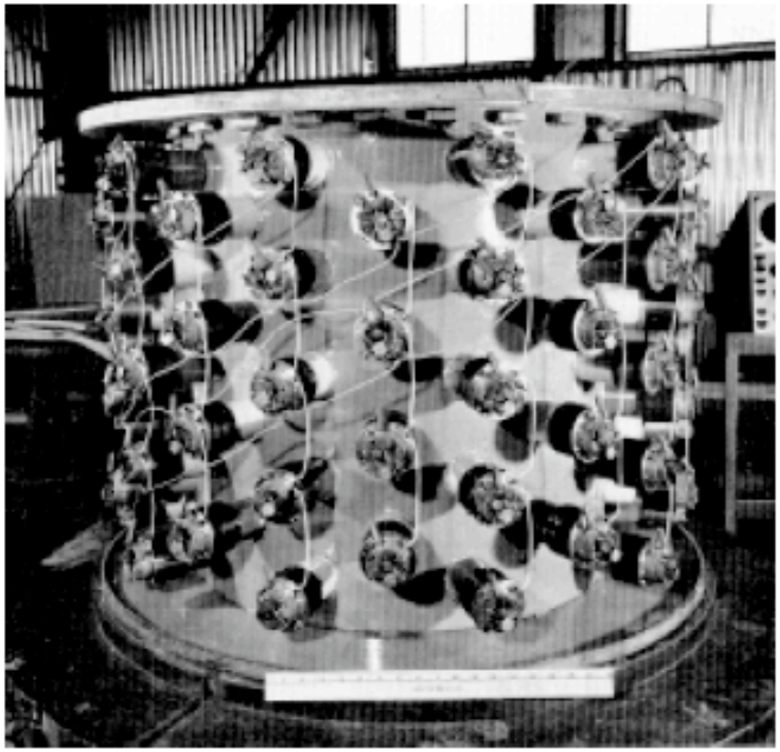
$n + \mathrm{Cd} \rightarrow \gamma$

$e^+ + e^- \rightarrow \gamma\ \gamma$

3 Gammas
in coincidence

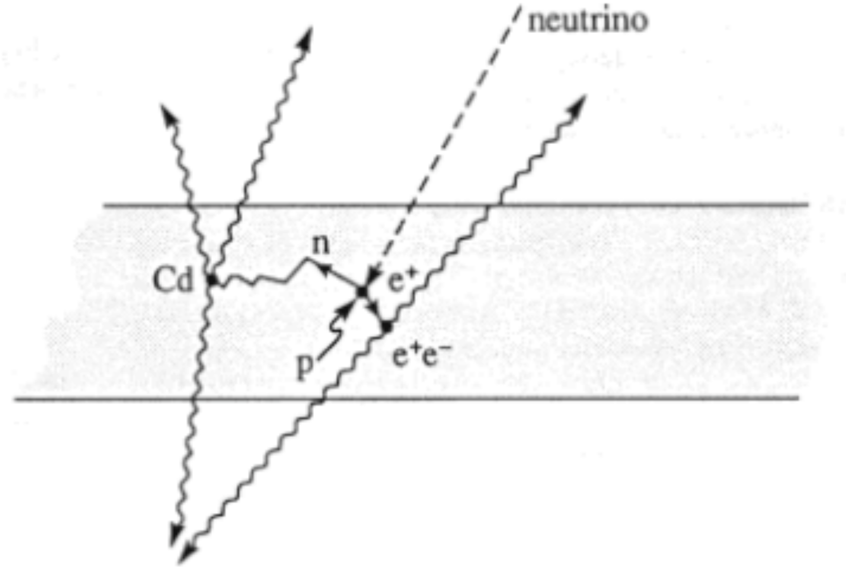
Reines-Cowan first Detector

Hanford experiment (1953)



"Herr Auge"

300 lt target, 90 2" PMT's

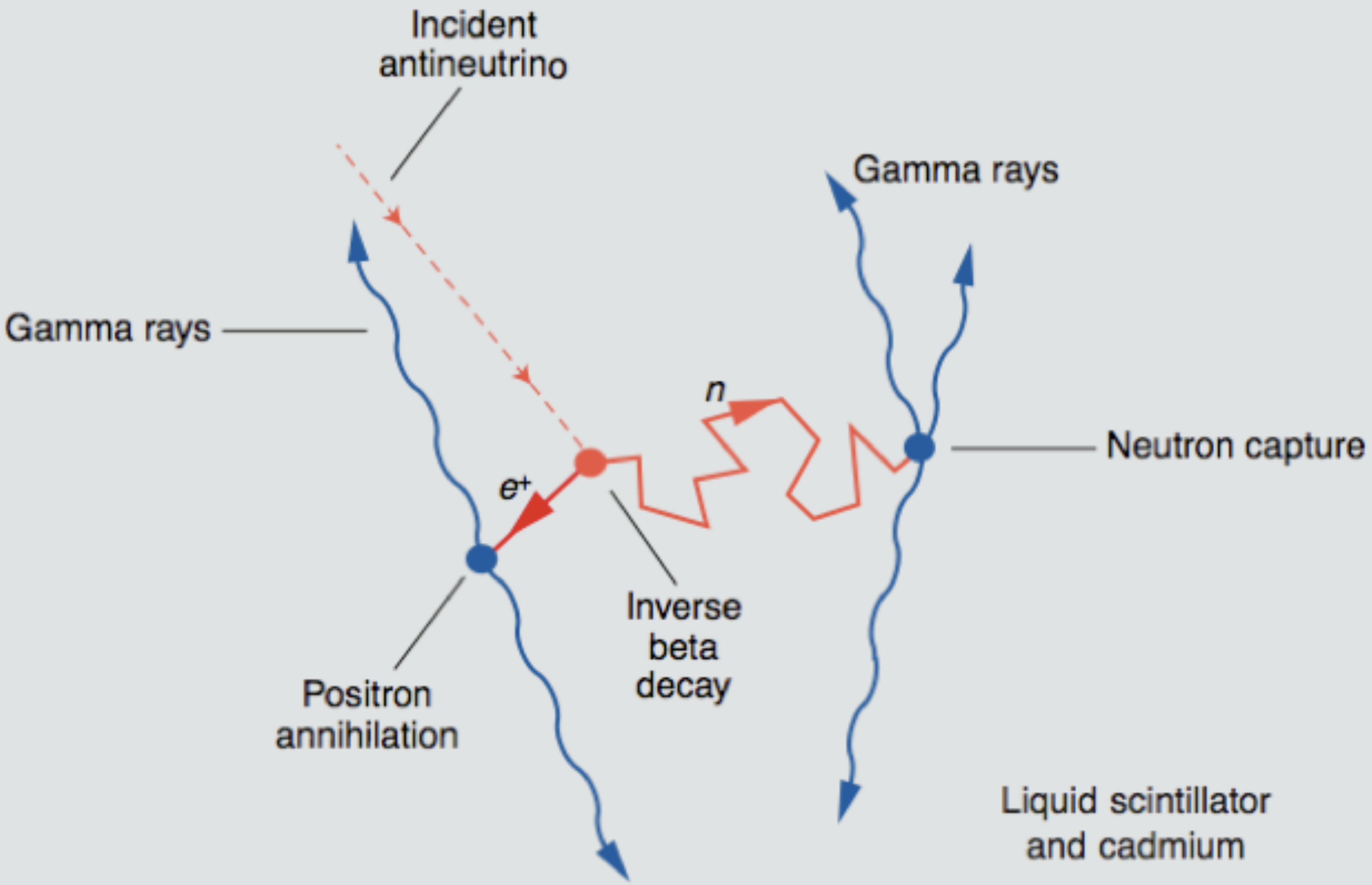


$$p + \bar{\nu}_e \rightarrow n + e^+$$

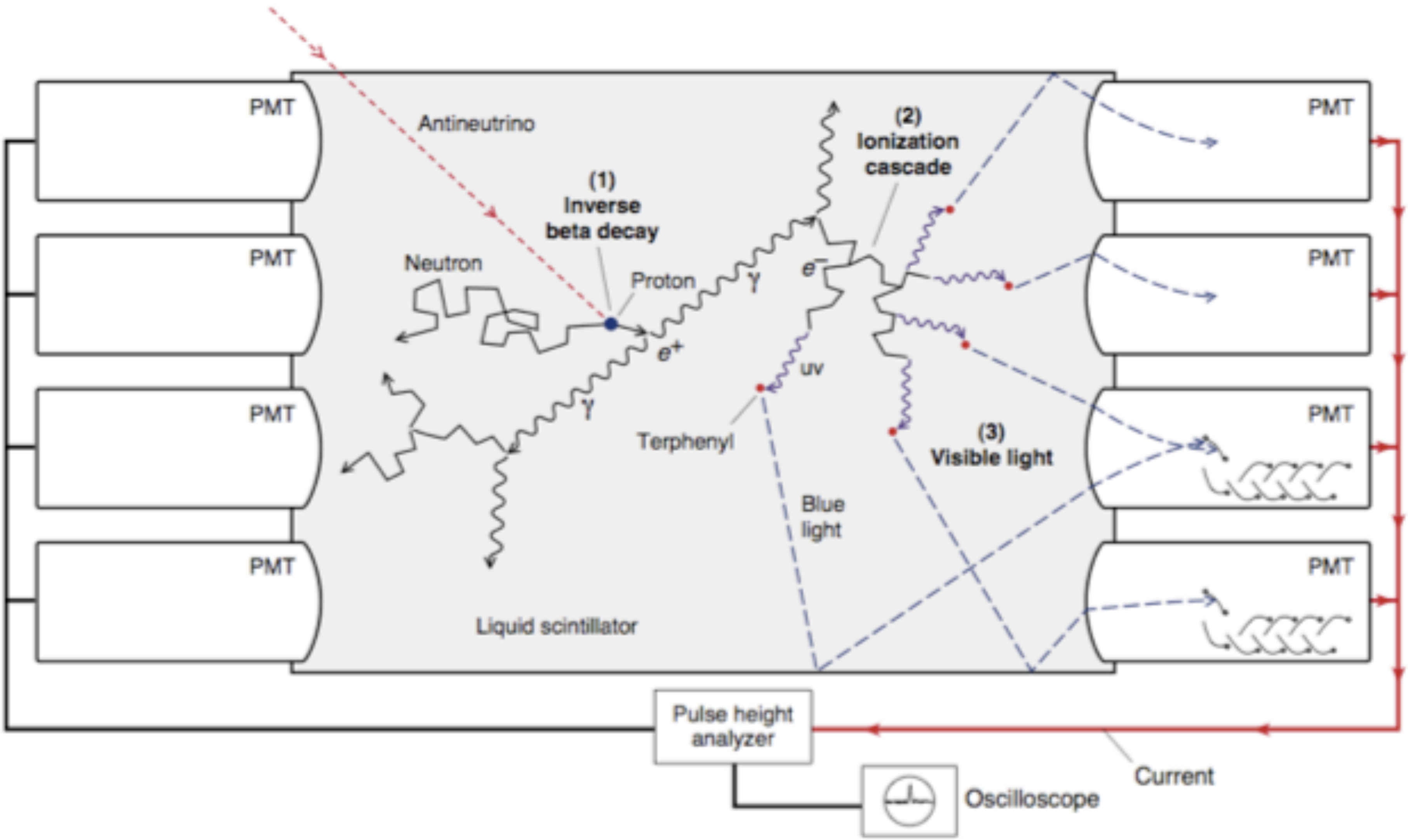
Captured by Cadmium

Annihilation with electron

H. Nunokawa


Incident antineutrino
Gamma rays
Gamma rays
n
Neutron capture
e+
Inverse beta decay
Positron annihilation
Liquid scintillator and cadmium

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



Neutrino Event Signature:

- Two-component coincidence signal (→ bckgd reduction)
- Scintillator doped with Gd to enhance n capture

Reactor (anti)Neutrinos

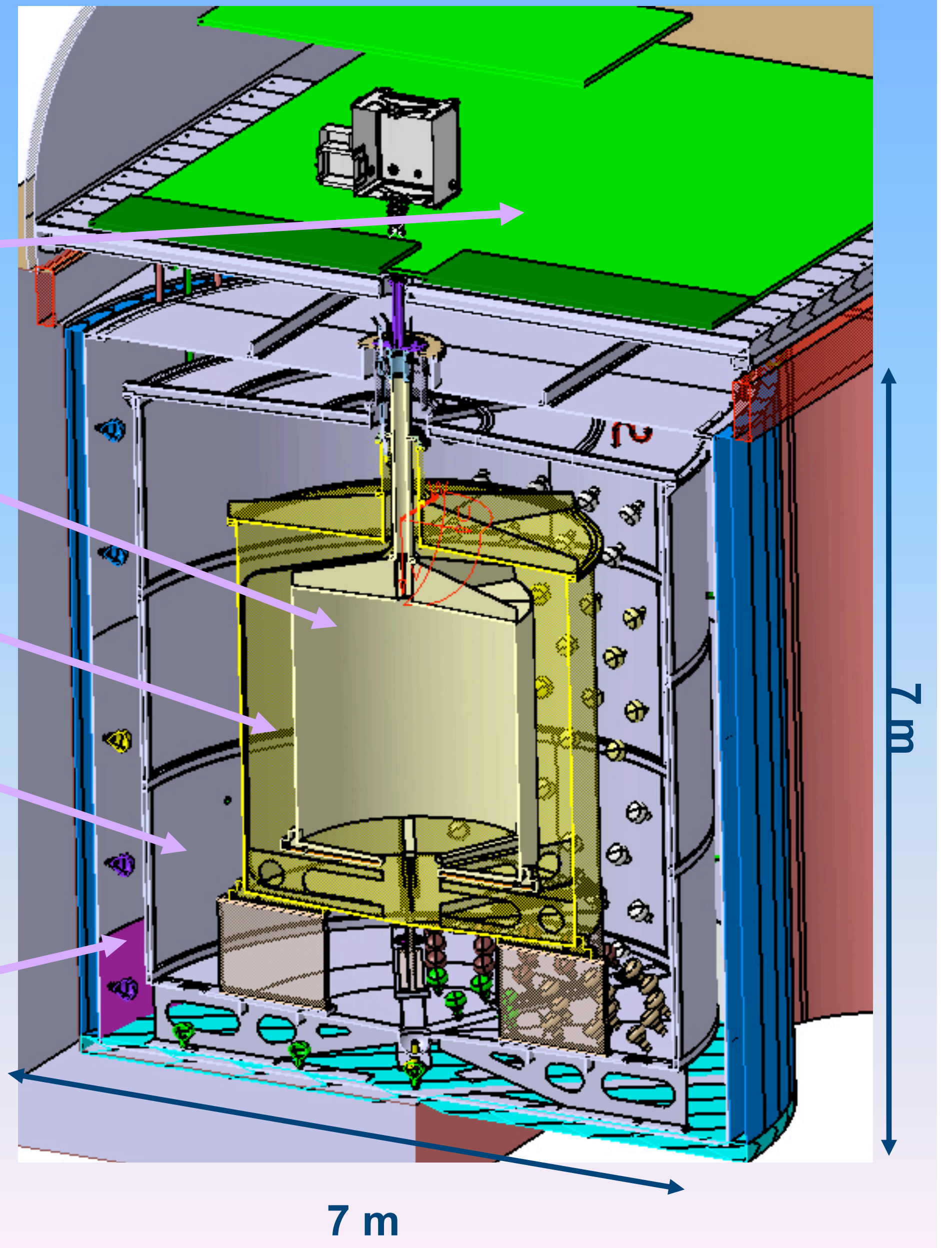
Flux:

$$\Phi_\nu = \frac{< N_\nu >}{4\pi D^2}\left(6.241\times 10^{21}\cdot\frac{P_{th}[GW]}{W[MeV]}\right)\ s^{-1}cm^{-2}$$

D : distance from reactor core	[~ 50 m]
Pth : delivered thermal power	[~ 4 GW]
W : energy release per fission	[203.87 MeV]
$< N_\nu >$	~ 6.7/fission

$$\boxed{\Phi_\nu = 2.6\times 10^{12}\, s^{-1}cm^{-2}}$$

Double Chooz Detector



Outer Veto :
Scintillator panels

Target ν : 10,3 m^3
80% $C_{12}H_{26}$+ 20% PXE +0,1% Gd
+ PPO + Bis-MSB

γ Catcher : 22,6 m^3
80% $C_{12}H_{26}$ + 20% PXE + PPO + Bis-MSB

Non-scintillating Buffer : 114 m^3
mineral oil

Buffer vessel & 390 10" PMTs :
Stainless steel 3 mm

Inner Muon Veto : 90 m^3
mineral oil + 70 8" PMTs

Steel Shielding :
17 cm steel, All around

Motivations for ANGRA

- *Neutrino Applied Physics in Latin America*

Motivations for ANGRA

- Possibility to do frontier experimental Physics by using existing infrastructure: Angra-I and Angra-II reactors
- --> **Low-cost**

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International Atomic Energy Agency

Neutrinos & Non-Proliferation

- ~ 450 nuclear power reactors worldwide
- ~ 200 Kg Pu produced per reactor cycle (~1.5 y)
- ~ 90 tons Pu produced every year worldwide
- A few Kg of Pu suffice to make a nuclear weapon

IAEA.org
International Atomic Energy Agency

Neutrinos & Non-Proliferation

- **IAEA - verification authority**

The International Atomic Energy Agency inspects nuclear facilities under safeguards agreements: keep track of all Pu produced; verify that fissile materials are used for civil appliances

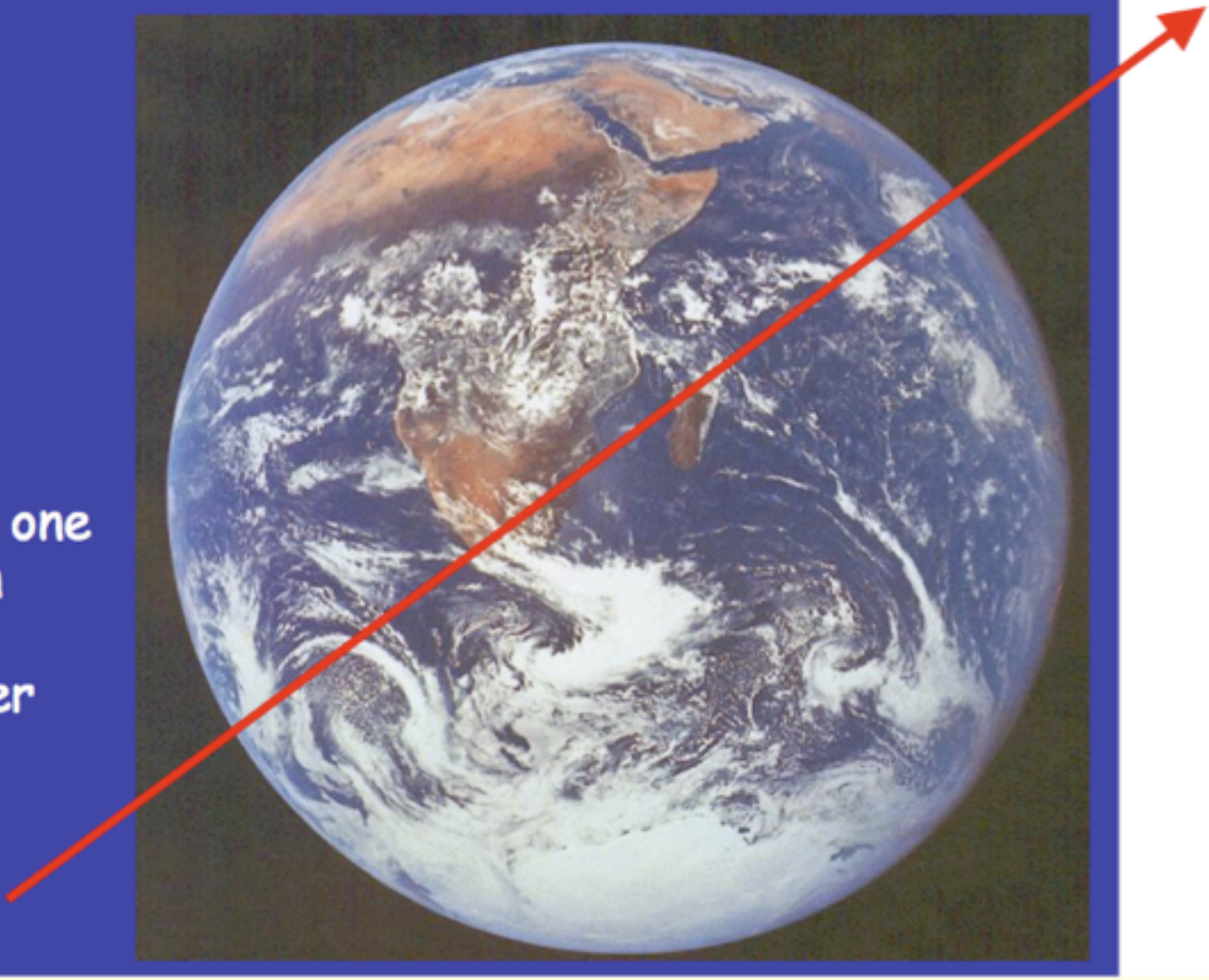
Why Neutrino Detectors?

- Explore new methods for nuclear safeguards
- Antineutrinos can not be shielded
- Reactor Antineutrinos can reveal fissile composition of nuclear fuel
- Reliable, Non-intrusive, Remote, Real-Time monitoring
- Can provide Thermal Power info as well as

Neutrino
energy
E = 1 MeV

Neutrino
cross-section
$\sigma = 10^{-44}\ \mathrm{cm}^2$

Probability of one
interaction in
crossing the
Earth diameter
$P \sim 10^{-11}$

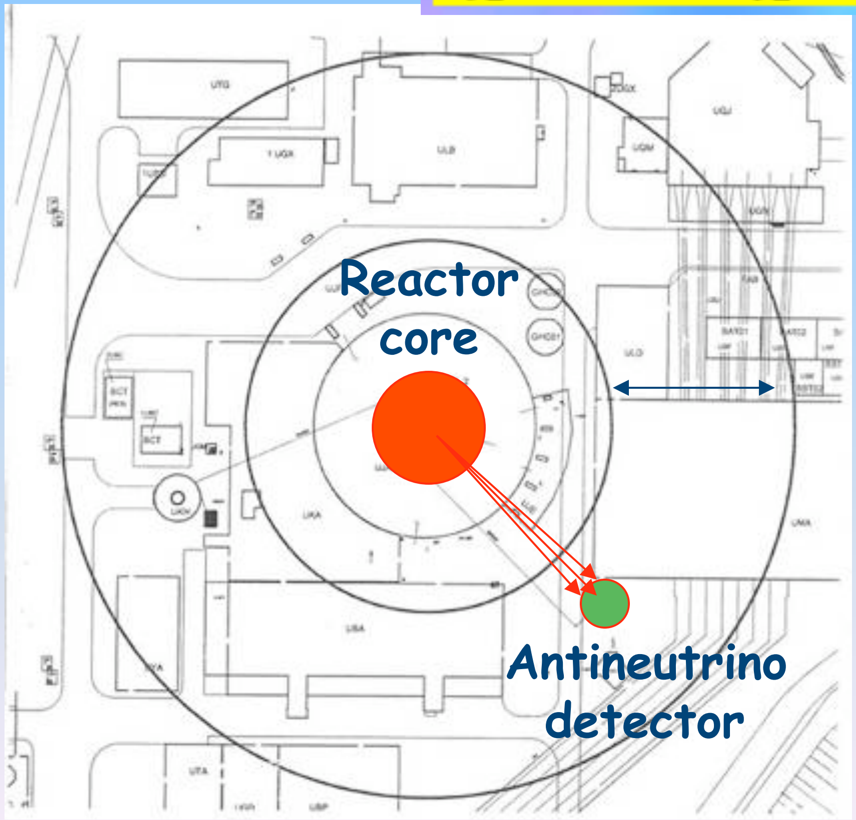


The Angra Project

a **non-intrusive** method to check reactor activity

$$^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \xrightarrow{23\ \mathrm{min}} {}^{239}_{93}\mathrm{Np} \xrightarrow{2.3\ \mathrm{d}} {}^{239}_{94}\mathrm{Pu}$$

Pu production chain

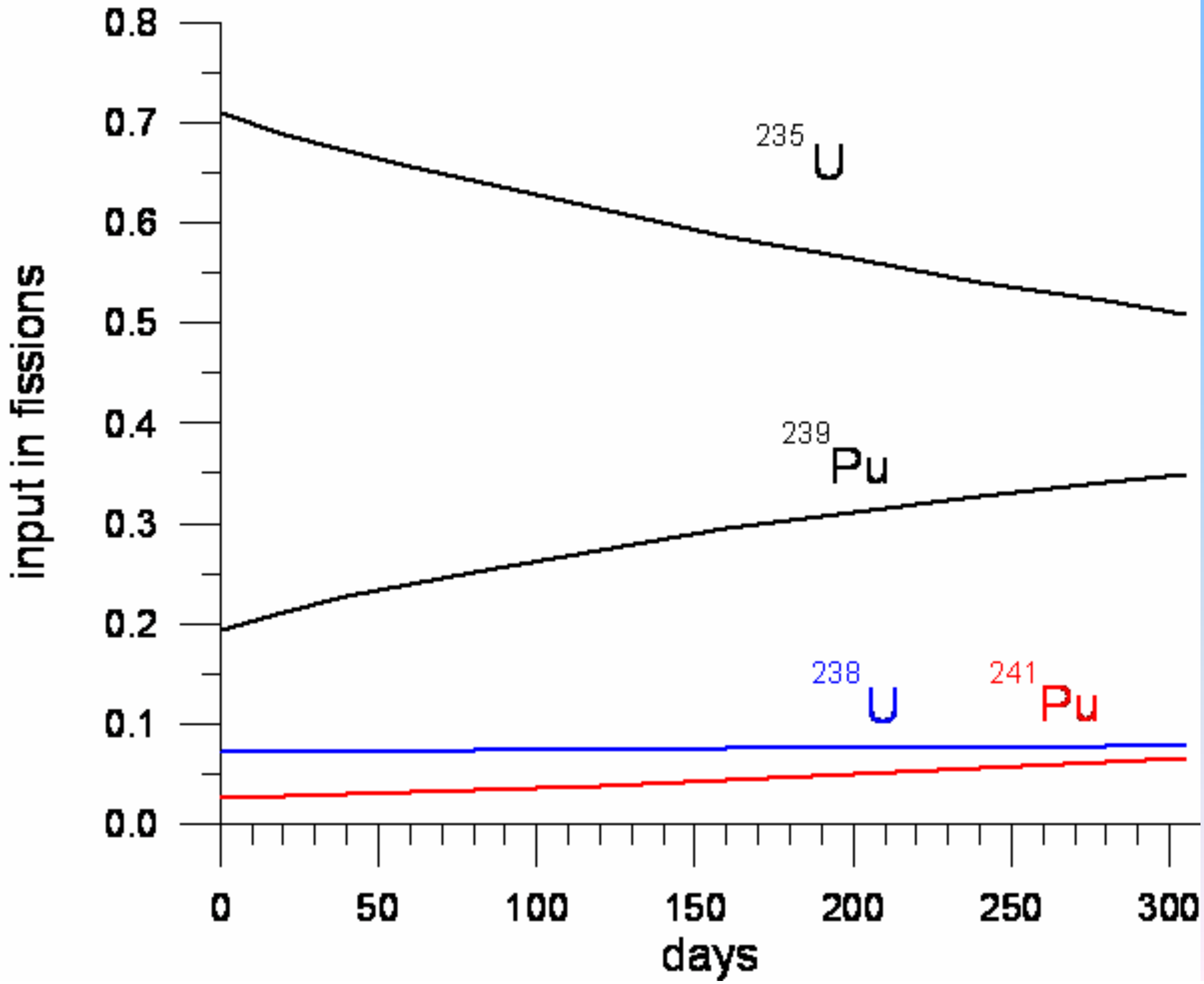


$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

Reactor Fuel Monitoring: (anti)**Neutrino rates**

- As the reactor goes through its irradiation cycle, the amount of U decreases and the amount of Pu increases
- The number of antineutrinos emitted by U-235 and by Pu-239 differs sensibly
- As Pu-239 builds up in the reactor over time, the antineutrino rates measured in a detector will drop (by about 5-10% over the reactor fuel cycle)

Fuel Composition Burn-up Effect



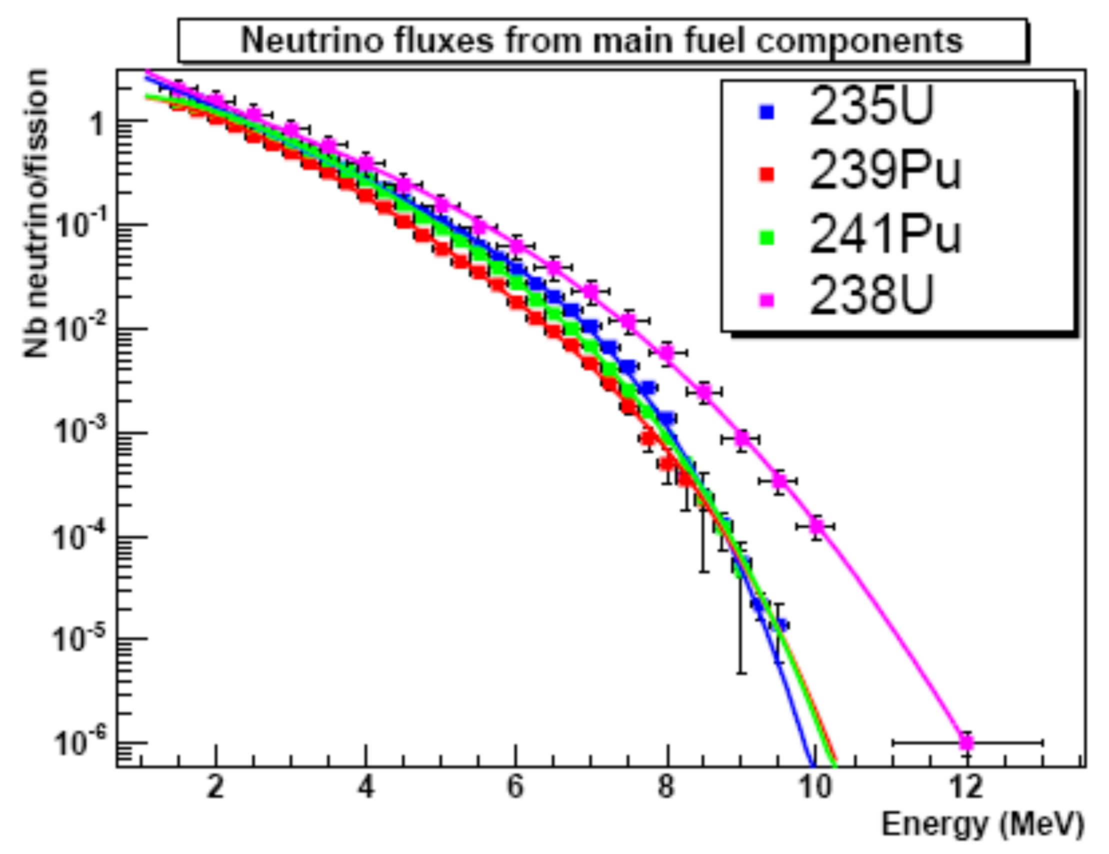
Reactor Fuel Monitoring:
Antineutrino Rates

- Removing Pu along the way or altering operation parameters to increase Pu production will show up in the antineutrino count rates
- Method works better with independent reactor power measurement

Reactor Fuel Monitoring:
Energy Spectra Comparison

- The energy spectra of antineutrinos emitted by Pu-239 and U-235 are different
- Can determine the relative amounts of Pu and U by measuring ratios between spectra taken at different times
- No need for independent power measurement

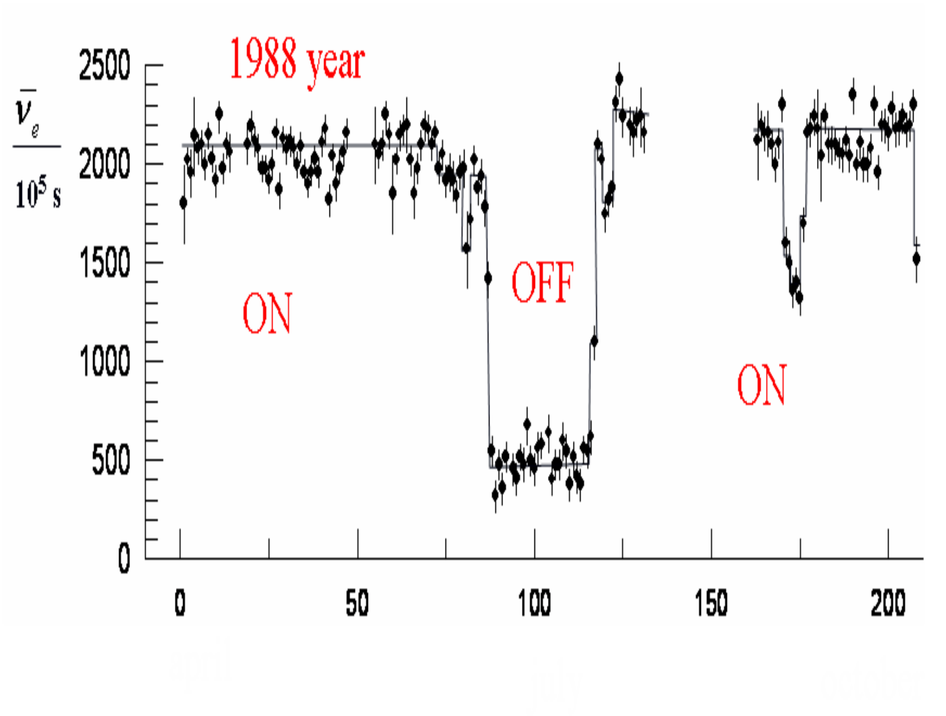
Reactor Fuel Antineutrino Spectra



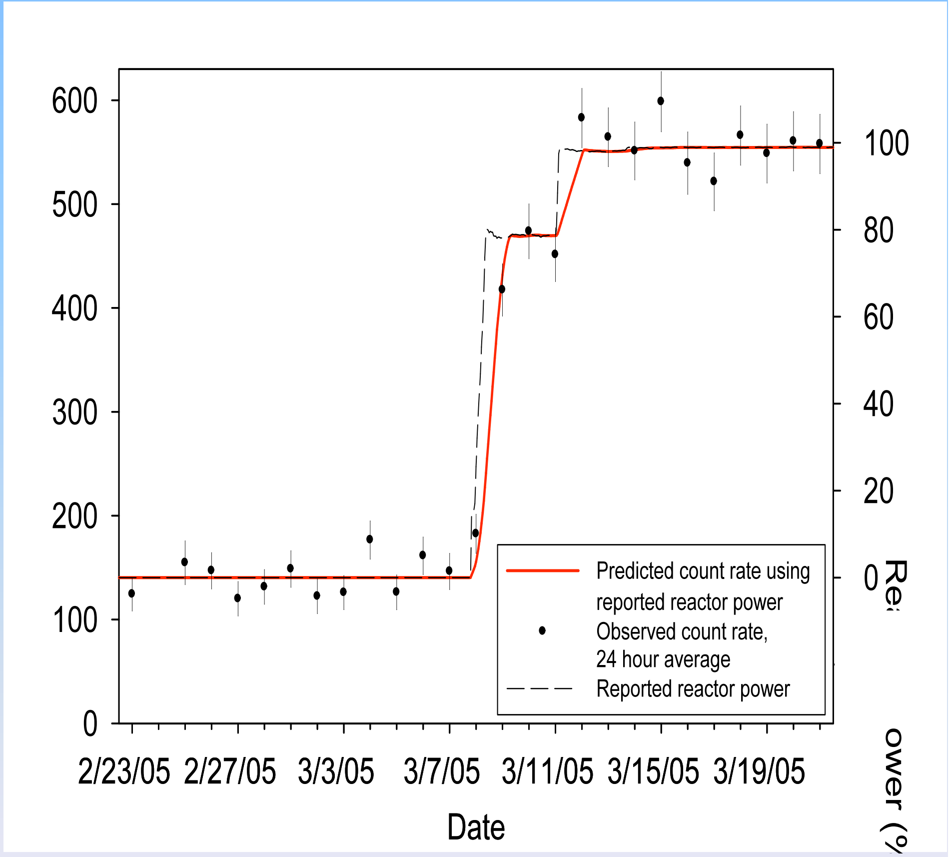
Antineutrino spectra measured 1983-1989

	Mean energy per fission (MeV)	Start of Cycle	End of Cycle
^{235}U	201.7 ± 0.6	60.5%	45.0%
^{238}U	205.0 ± 0.9	7.7%	8.3%
^{239}Pu	210.0 ± 0.9	27.2%	38.8%
^{241}Pu	212.4 ± 1.0	4.6%	7.9%

San Onofre: reactor activity:



Rovno (Ukraine)



San Onofre (USA)

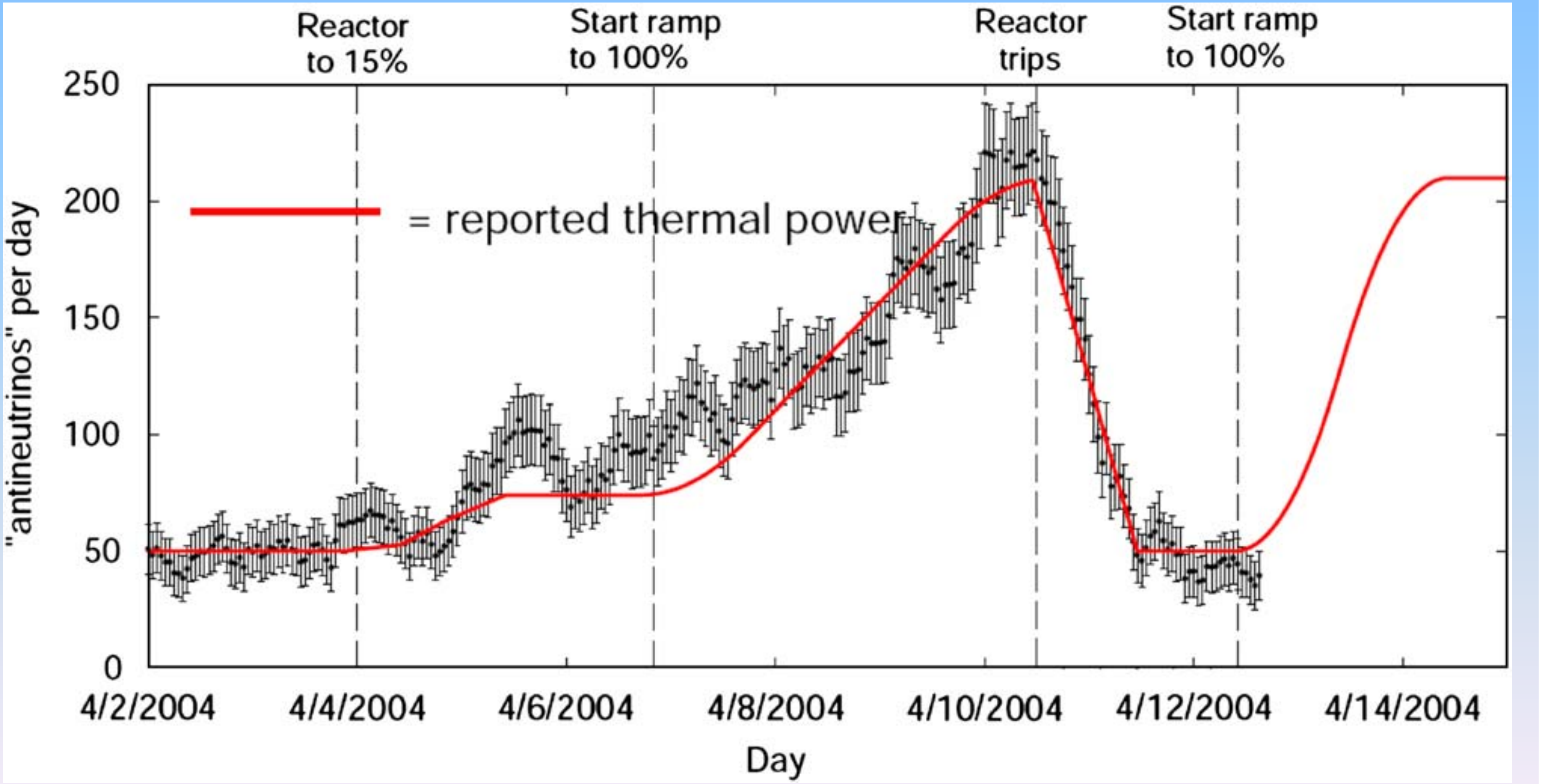
Reactor Thermal Power and Antineutrino flux

Delivered thermal power and antineutrino rates

$$N_\nu = \underbrace{\gamma}_{\text{Dependence on detector features}} \cdot \underbrace{(1 + k)}_{\text{Dependence on fuel composition}} \cdot P_{th}$$

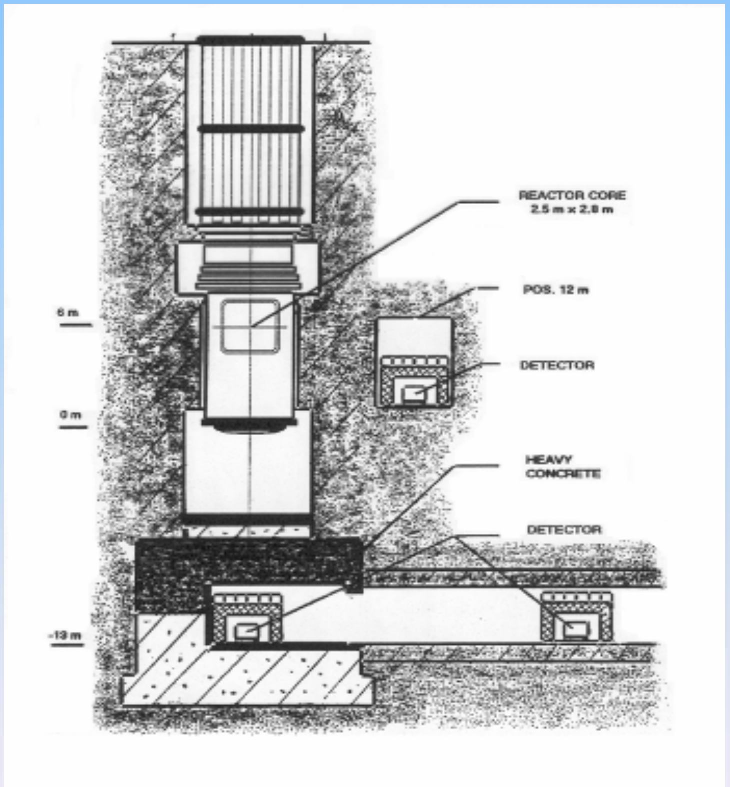
(Topic of interest for Eletronuclear, CFE, etc.)

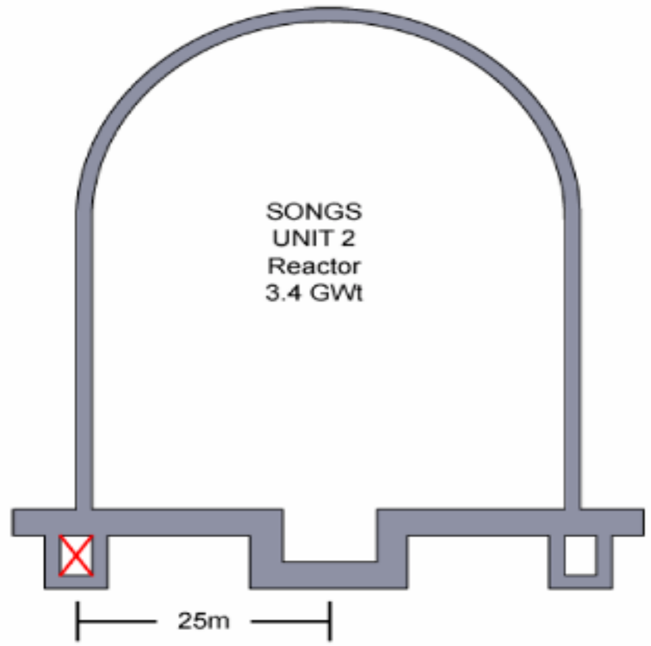
San Onofre: Thermal Power Measurement



Previous and On-going Experiments:

Rovno (Ukraine, 88-90) **San Onofre** (USA, 2004)



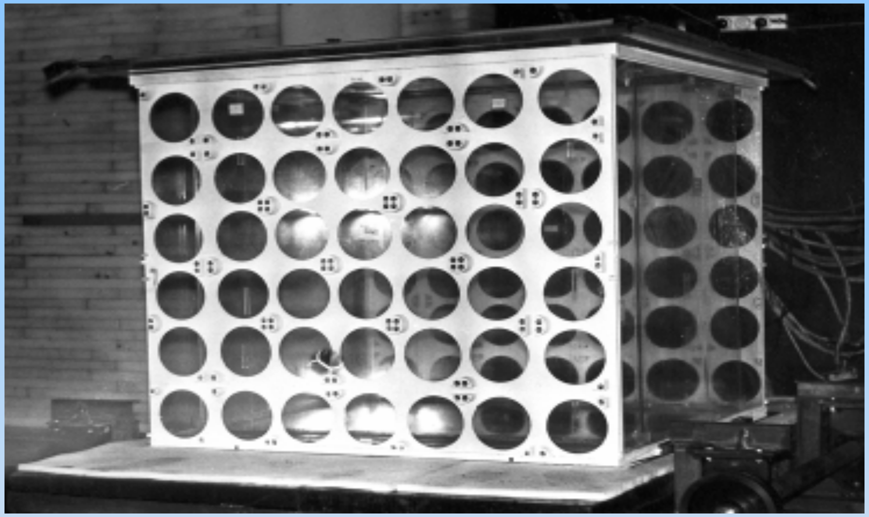


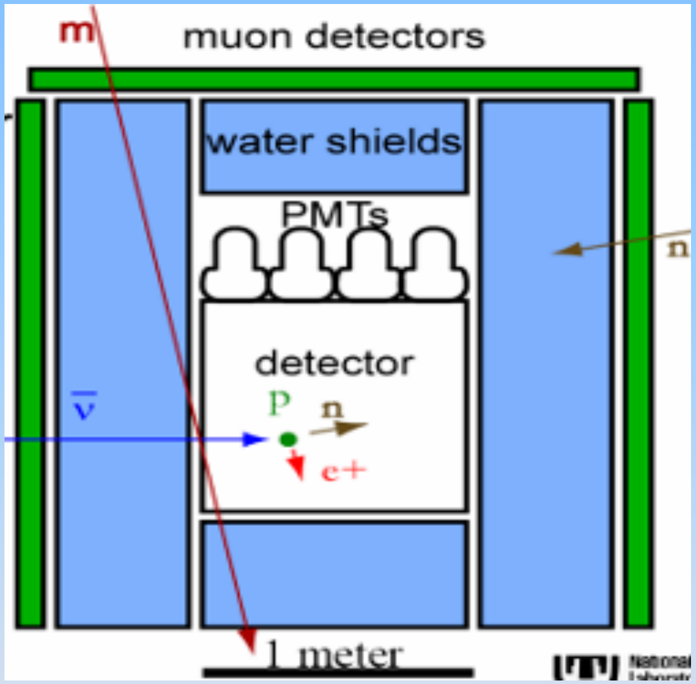
Bugey (France, 1994)

Previous and On-going Experiments:

Rovno

San Onofre

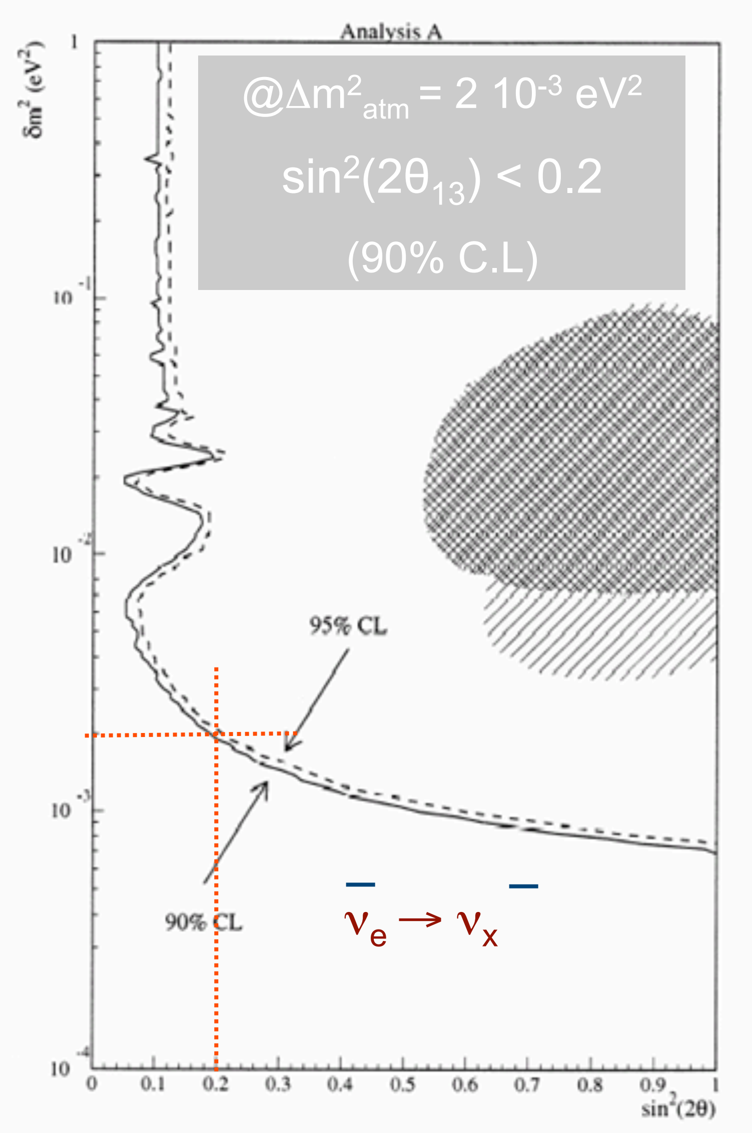




- 1,050 lt liquid scintillator
- central volume: 510 lt
- 0.5 g/lt Gd
- 84 PMTs

- 1 m^3 liquid scint central detector
- Gd loaded
- 8 PMTs on top
- Passive water shield
- Active muon shield

Best Current Limit: CHOOZ



$@\Delta m^2_{atm} = 2\ 10^{-3}\ eV^2$

$\sin^2(2\theta_{13}) < 0.2$

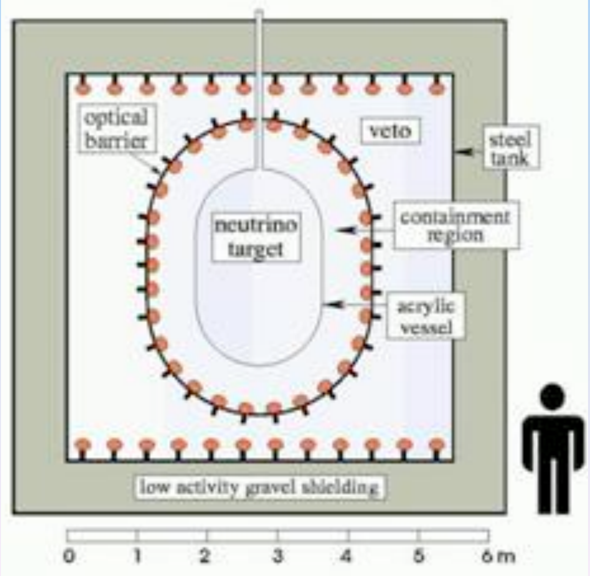
(90% C.L)

$\bar{\nu}_e \rightarrow \bar{\nu}_x$

M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374

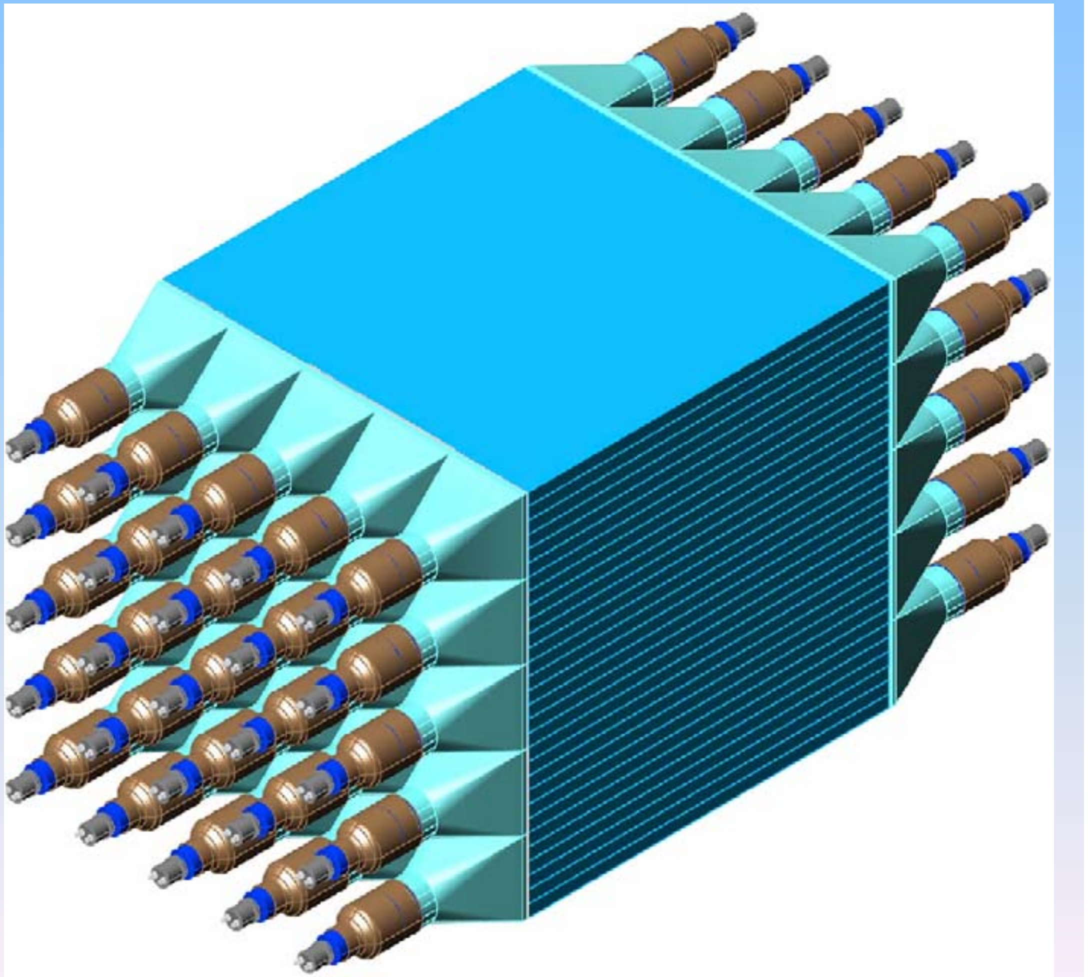
$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment)

P_{th}= 8.4 GW_{th}, L = 1.050 km, M = 5 t
Overburden: 300 mwe



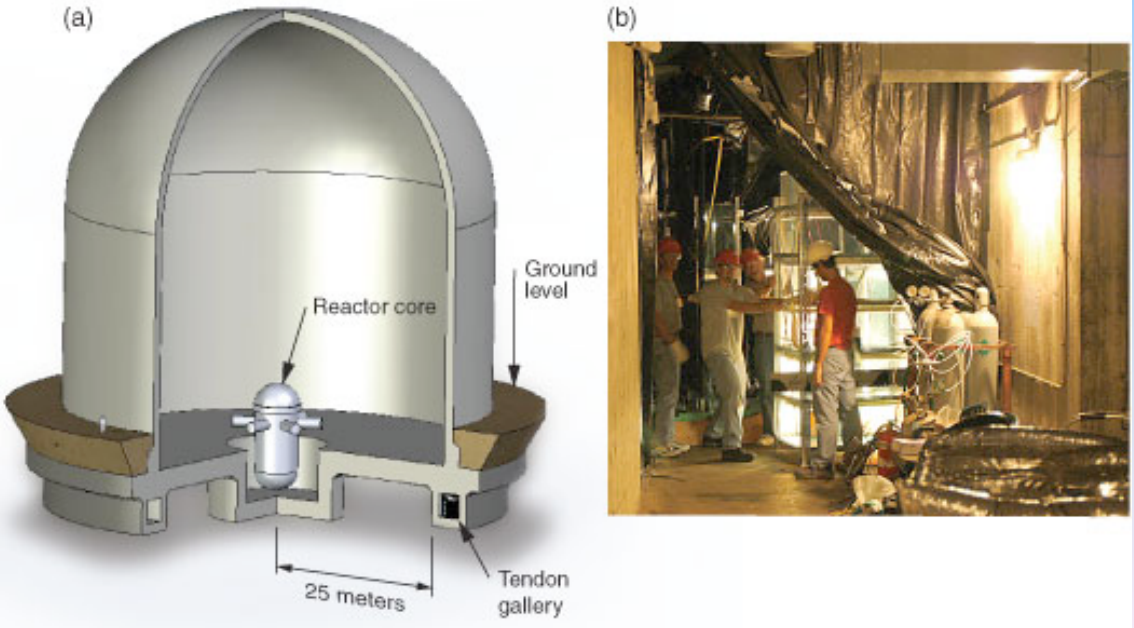
Italian (INFN-Genova) Prototype

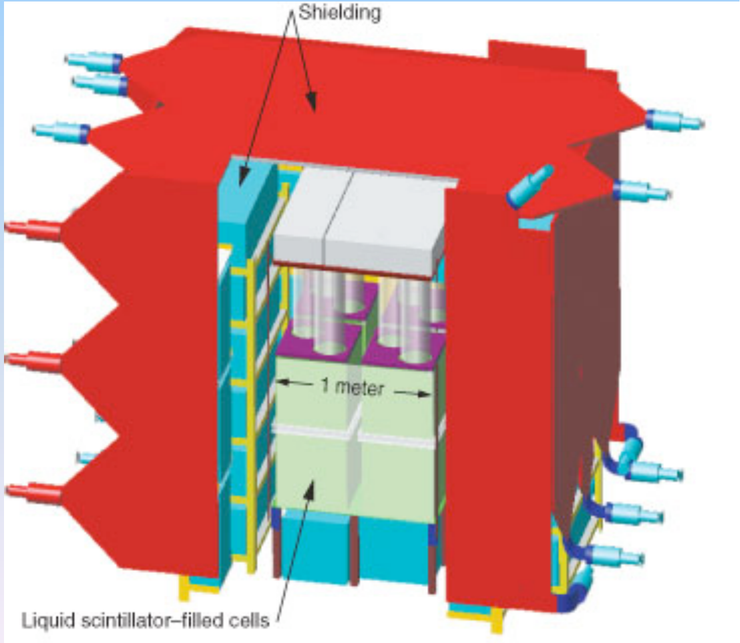
- Plastic Scintillator
- Gd foils



San Onofre Detector

- San Clemente, California, 2004-2009
- Livermore Lab + SANDIA Teams
- Size: 3m x 3m x 3m
- 25 m from reactor, 10m underground

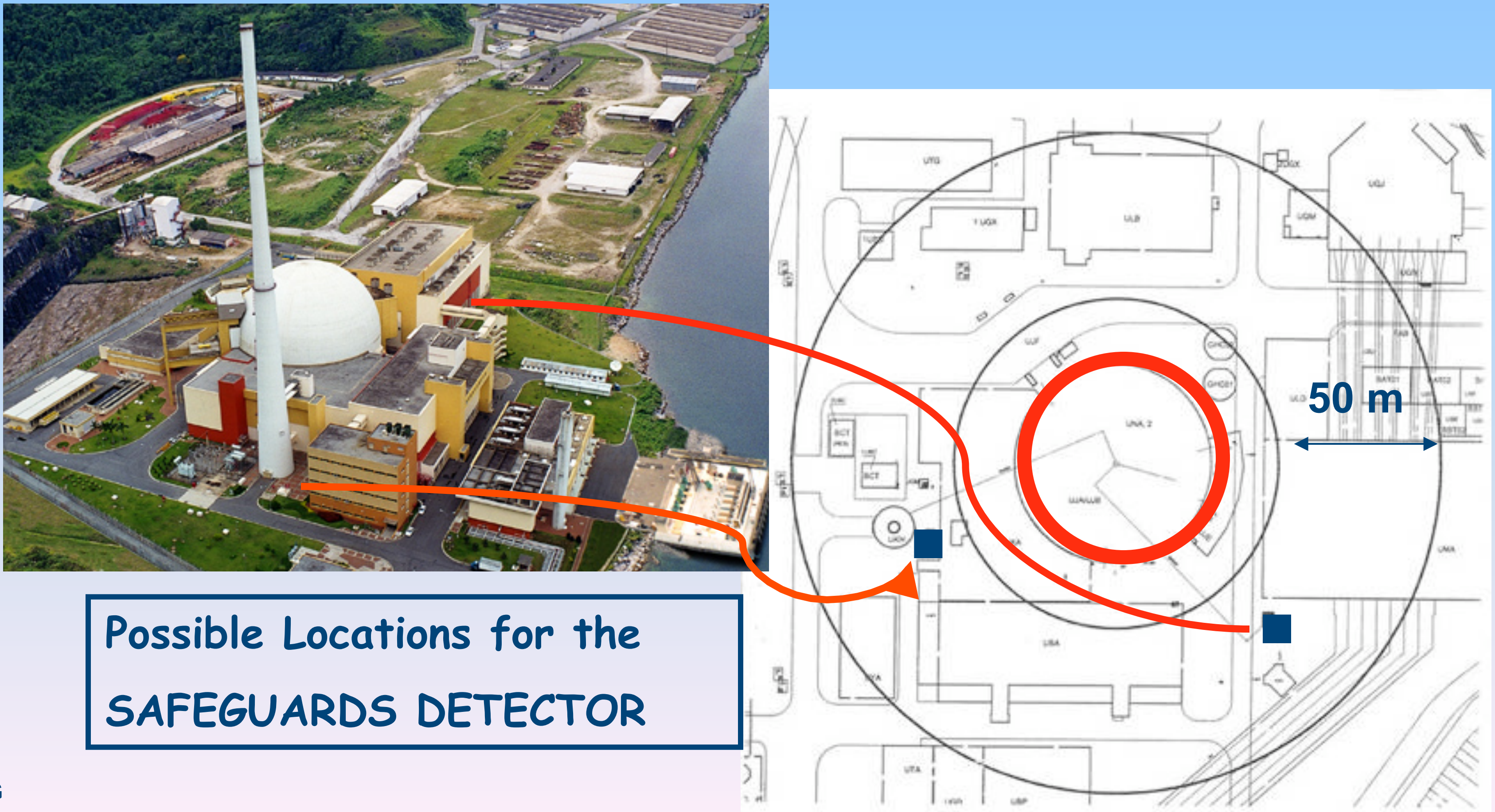




Workshop on the ANGRA Detector Design

CBPF - May 16-19, 2006, Rio de Janeiro

Safeguards Detector site:



Possible Locations for the

SAFEGUARDS DETECTOR

Safeguards Detector: Initial Design: 3-volume

A) Target (R_1=0.5m; h_1=1.3m)

- **Acrylic vessel + lqd scintillator(+Gd)**

B) Gamma-Catcher (R_2=0.8m h_2=1.9m)

- **Acrylic vessel + lqd scintillator**

C) Buffer (R_3=1.4m; h_3=3.10m)

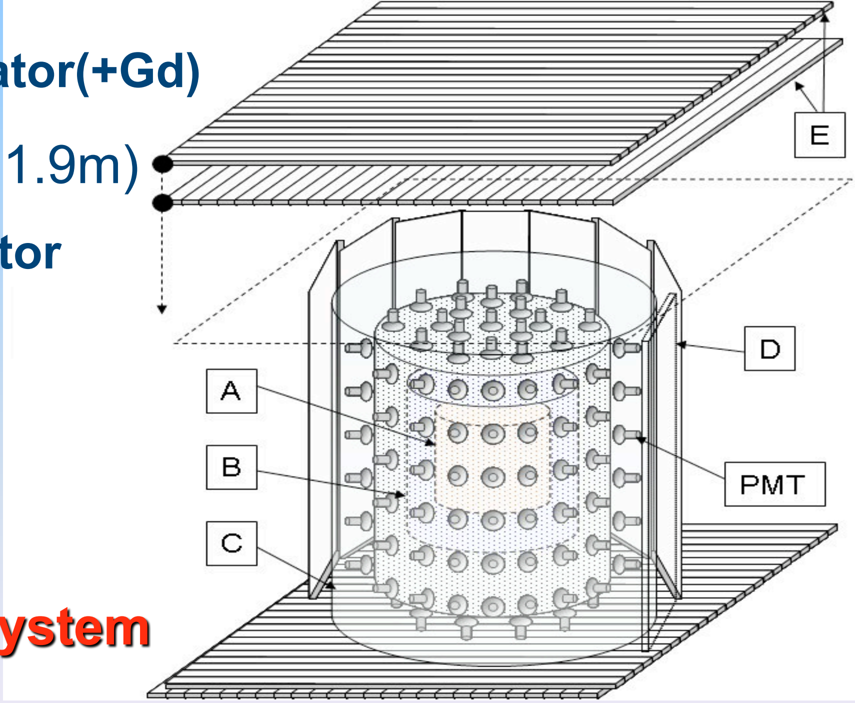
- **Steel vessel + mineral oil**

D) Vertical Tiles of Veto System

E) X-Y Horizontal Tiles of Veto System

- **Plastic scintillator padles**

above and under the external steel cylinder: muon tracking through the detector



Important Dates:

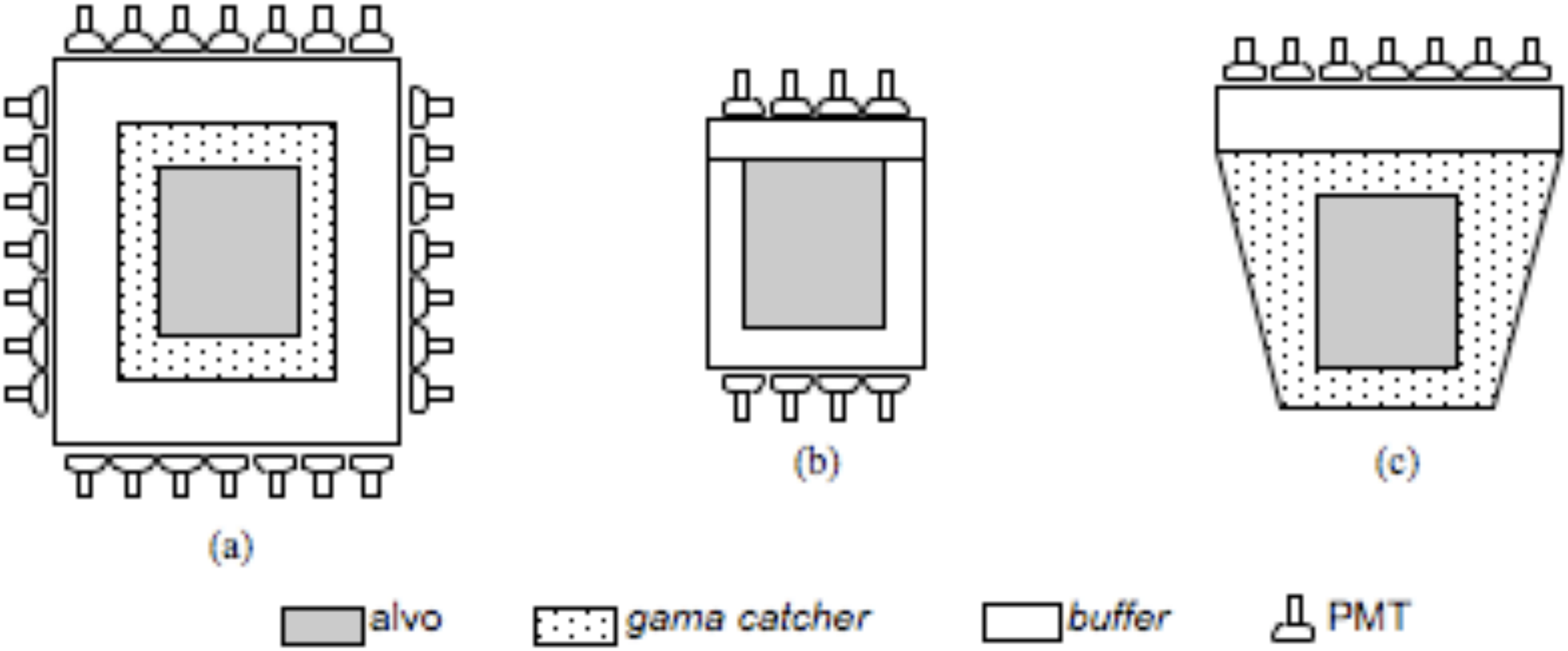
- Sep 2006: Meeting with Eletronuclear representatives
- Dec 2006: Proposal presented to the Brazilian Minister of Science and Technology
- March 2007: Project Neutrinos Angra approved by FINEP ~ 0.6 MUSD

Projeto NEUTRINOS ANGRA

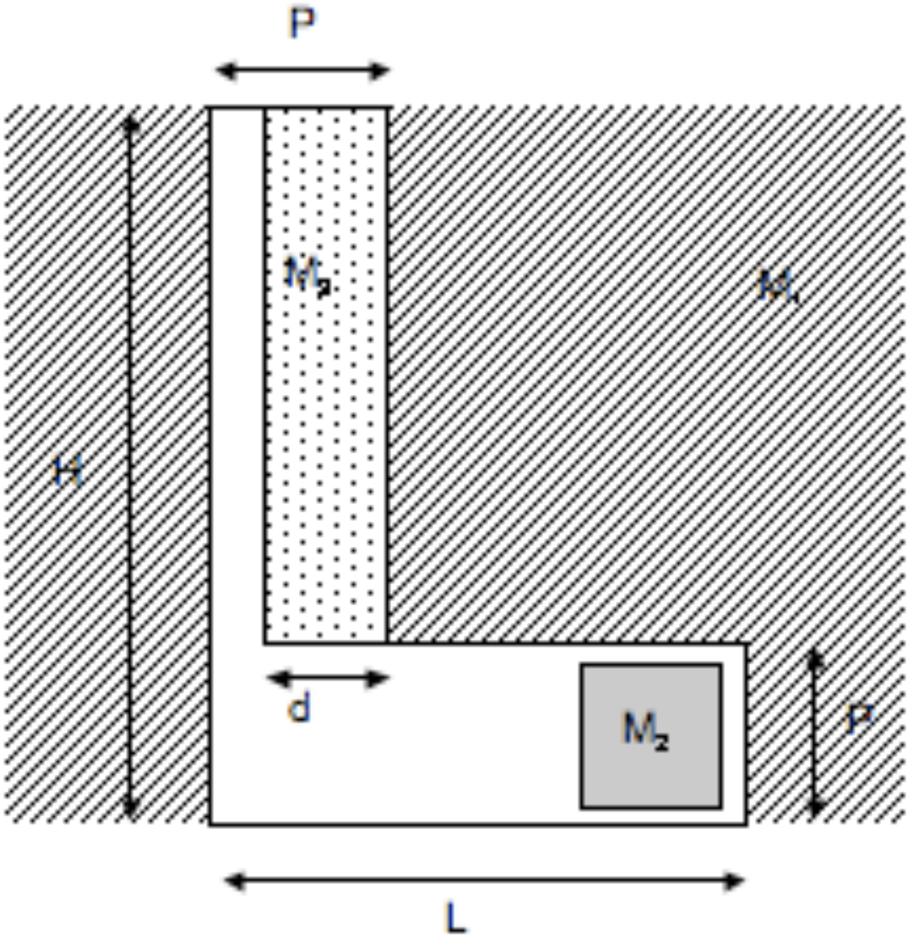
23/09/2008

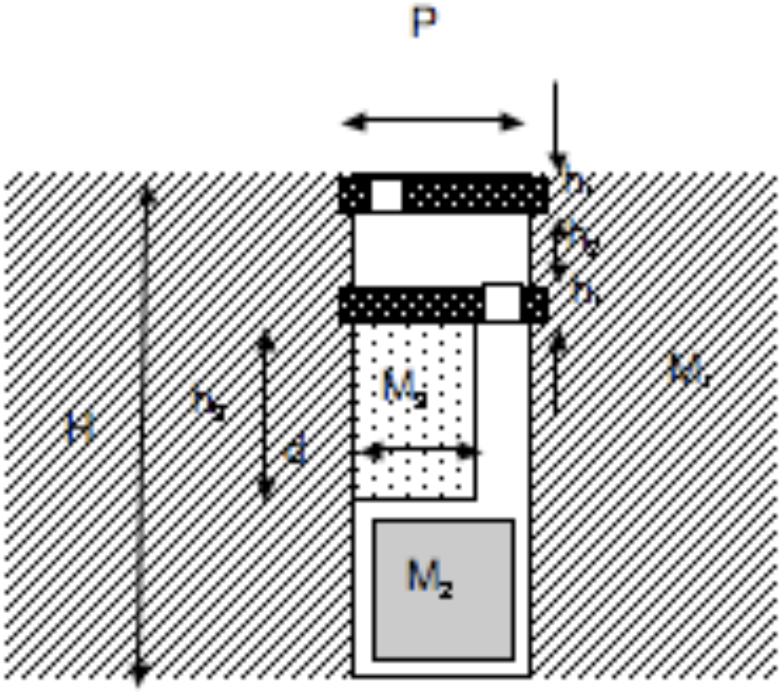
contêiner: 1º laboratório em Angra

Some possible detector geometries



Some Shaft Options





Expected Neutrino Signals & Muon Background

Cylindrical Detector

R: 1.40m; H: 3.10m; Target Mass: 1ton

Distance (m)	Signal (d^{-1})
60	1270
70	933
80	714
90	564
100	457

Depth (mwe)	Muons (Hz)
20	755
30	450
40	350
50	245
80	110

Number of Photomultiplier Tubes

Cylinder R= 1.10m; H=2.50m,
A_{Top} = 3.80132; A_{Side} = 17.2787; A_{Total} = 24.8814

Photocathode Coverage (%)	Number of PMTs	PMT Density (PMTs / m^2)
6	40	1.58
8	53	2.11
10	66	2.63
12	79	3.16
14	92	3.68
16	105	4.21

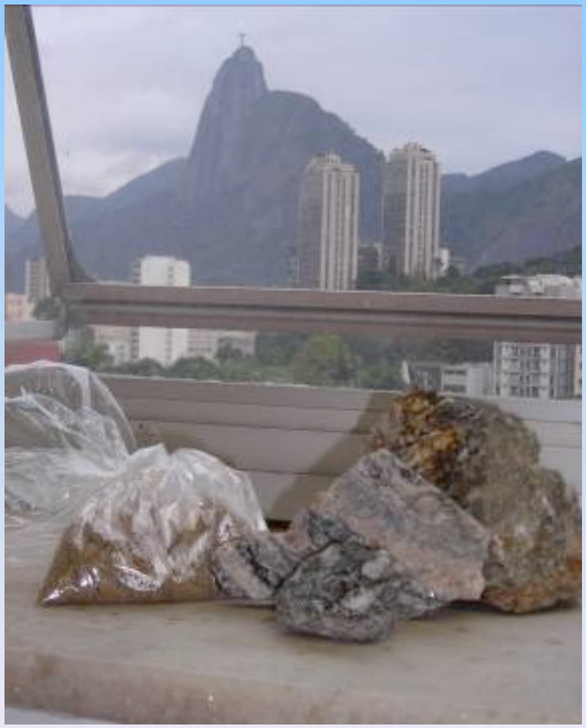
Phase I:

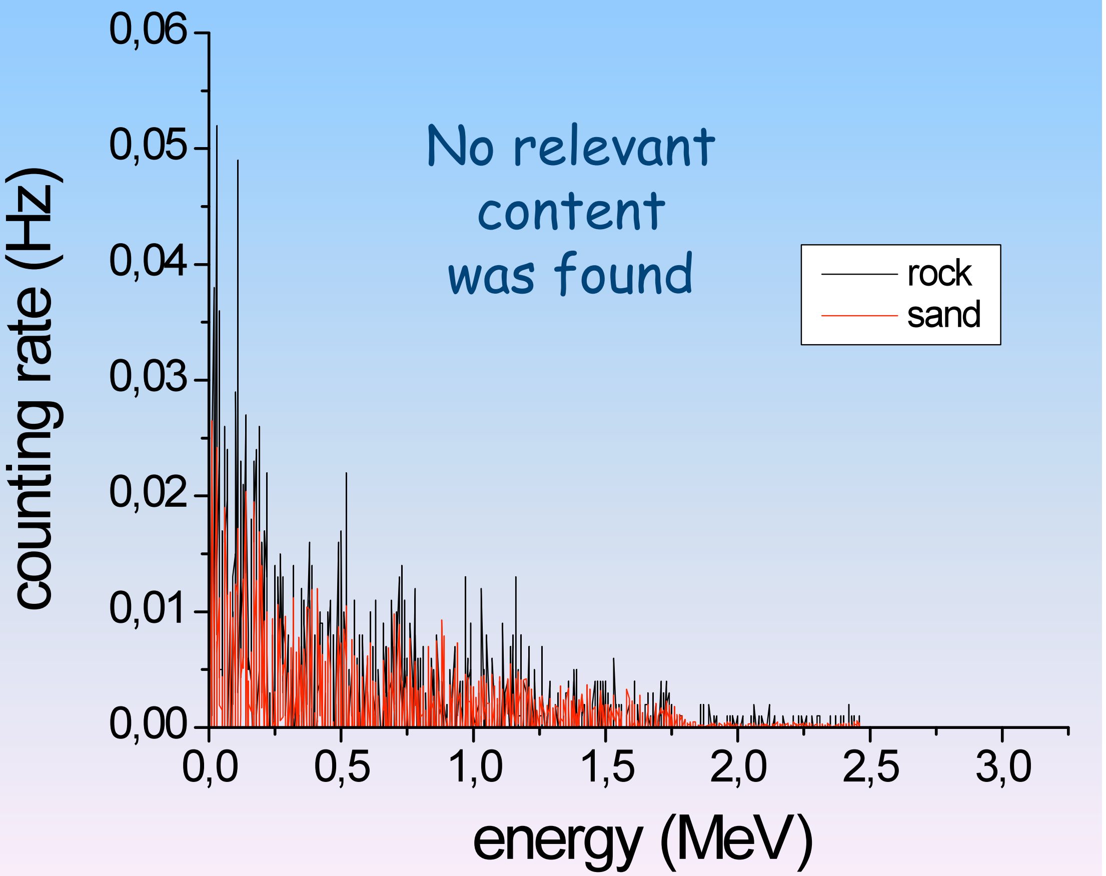
Setup infrastructure at CBPF & UNICAMP:

Start tests of components at CBPF and UNICAMP:

- **Central detector**: test 8″ PMTs
- **Muon veto**: test 64 channels PMTs
- **DAQ**: design VME electronics
- **High Voltage**: design power supply
- **Radioactivity Background**: survey local material
- **Network communication**: build Infrastructure

Radioactivity Site Background Measurement (rocks and sand)



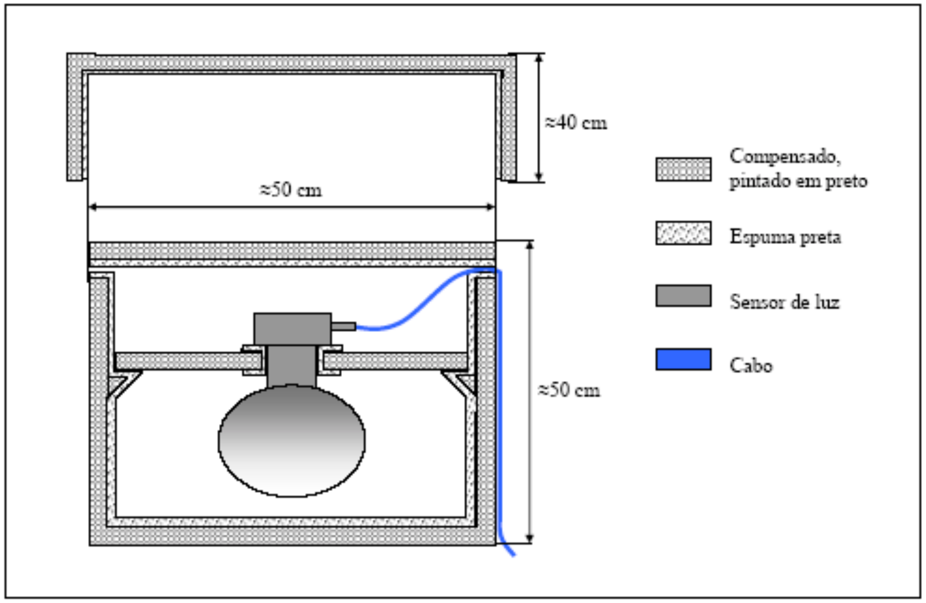


No relevant content was found

R&D at CBPF: Test of components

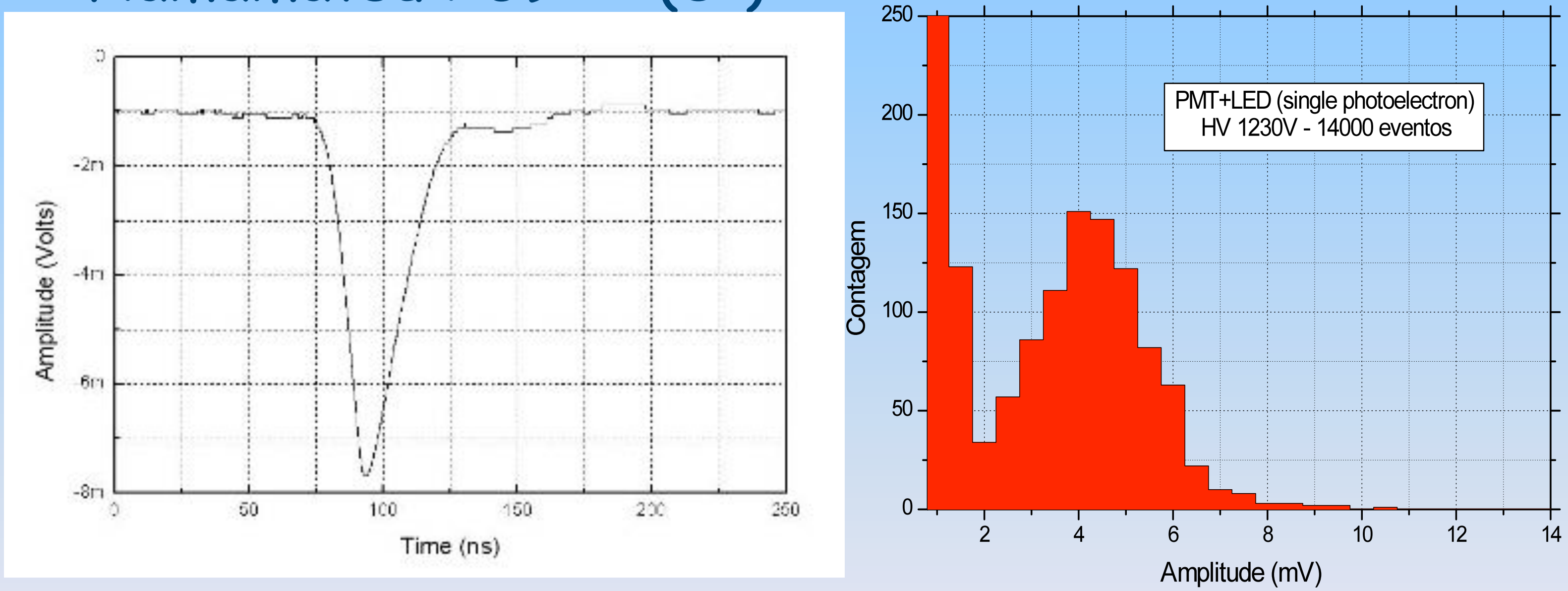
- Hamamatsu 8" PMT characterization

CÂMERA ESCURA



R&D at CBPF:
PMT characterization

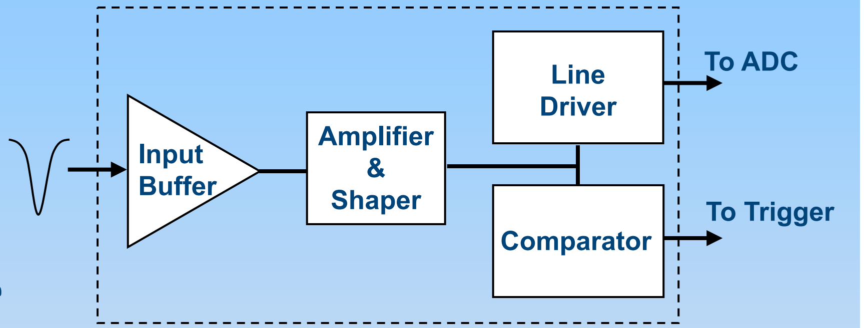
- Hamamatsu R5912 (8")



Tipical Signal, *100MHz* digital osciloscope
Rise time ≈*20ns*, duration ≈*50ns* (FWHM)

Electronics & DAQ

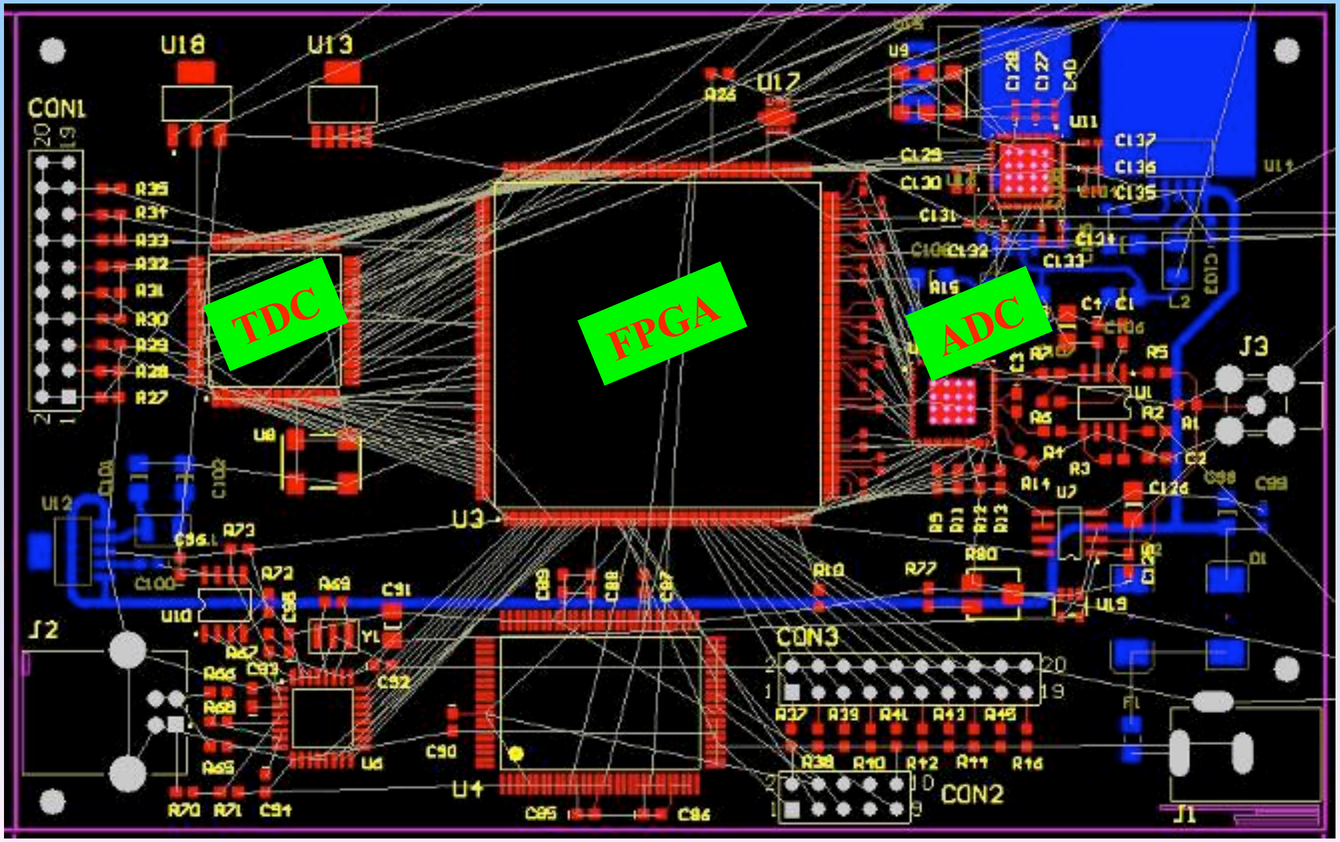
- Front-end electronics
  - ✓ input buffer + amplifier/shaper
  - ✓ To ADC: + line driver
  - ✓ To Trigger system: + comparator



- Data Acquisition (DAQ)
  - ✓ VME-based
  - ✓ off-the-shelf high-performance devices (ADCs, FPGAs, FIFOs)
  - ✓ two sub-systems: neutrino signal / VETO
  - ✓ Neutrino: ~ 120 input channels sampled at 250Msps / 10-bit resolution
  - ✓ VETO: ~ 110 LVDS signals to a large/fast FPGA (Stratix II)

R&D at CBPF: DAQ electronics prototype

Layout design - top layer (red), bottom layer (blue)



digital inputs

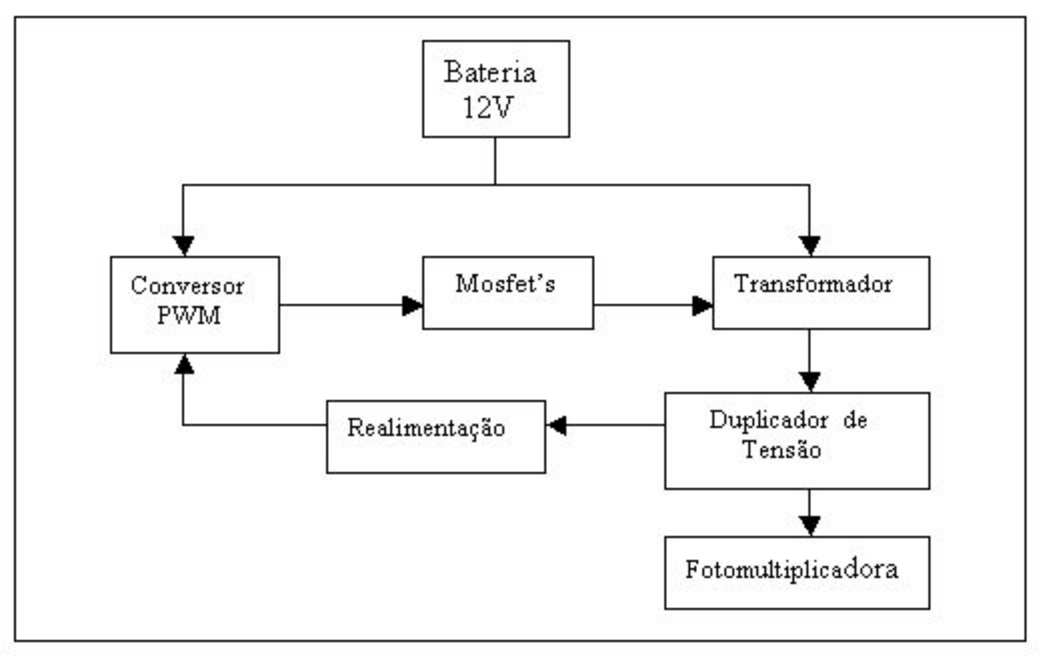
analog input

USB connector

power connector

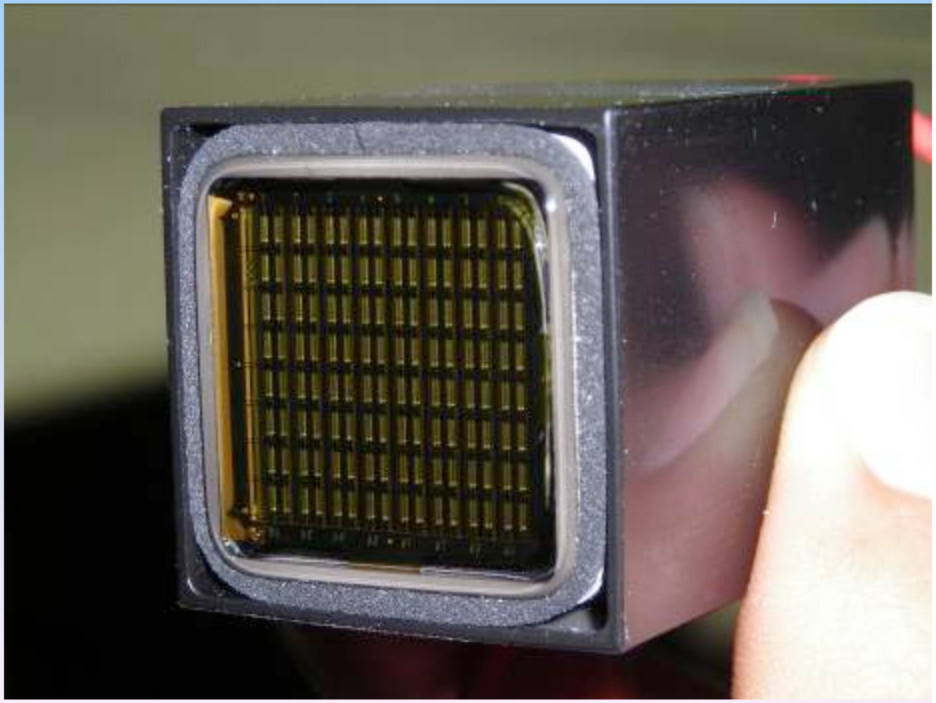
R&D at CBPF: test of components

CBPF HVPS - High Voltage Switching Power Supply



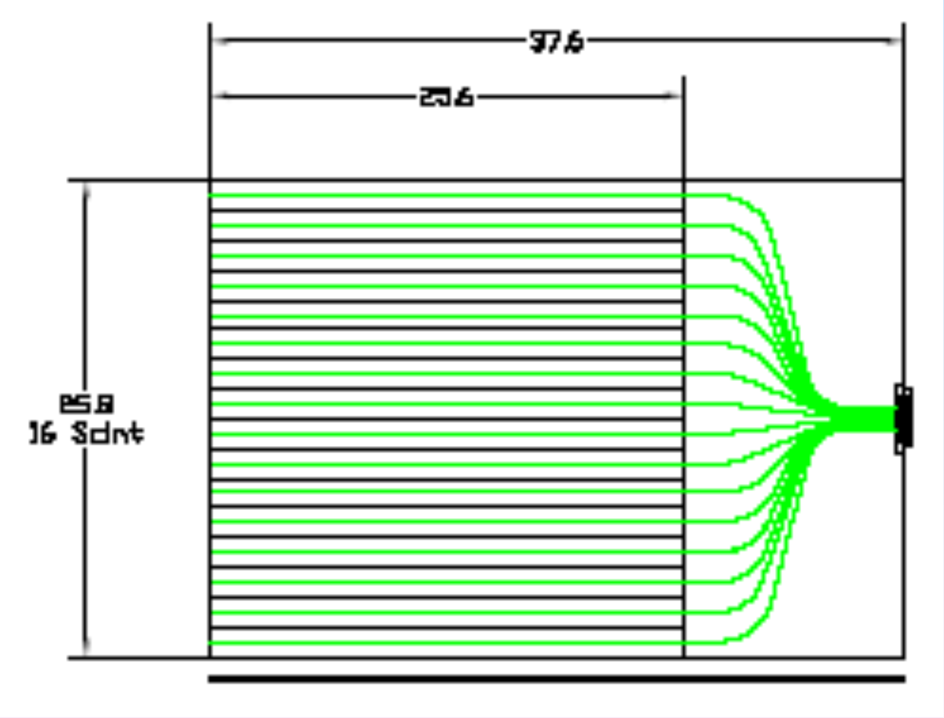
R&D at CBPF: Outer Muon Veto Test

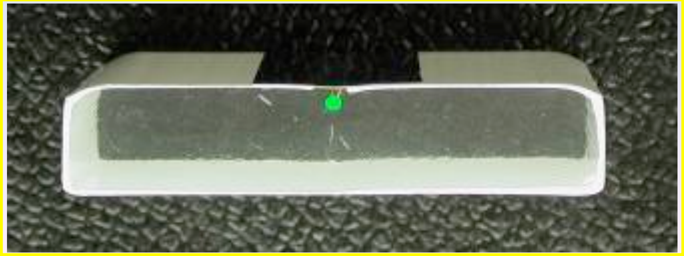
- 64-channel PMTs **Hamamatsu R8520**



R&D at CBPF: Outer Muon Veto Tests

- Muon telescope: 4 planes (MINOS type scintillator)





Setup infrastructure at the Angra site:

- 20' container

near reactor building

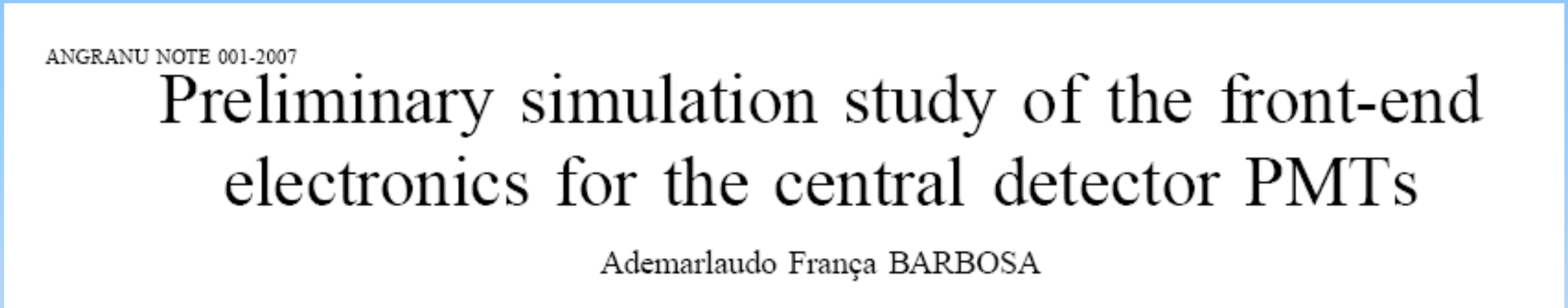
- Measurement of local muon flux: Cerenkov detector

(Auger test tank)

- Muon telescope deployment

(4 Minos scintillator planes)

R&D: ANGRA NOTES



ANGRANU NOTE 001-2007

Preliminary simulation study of the front-end electronics for the central detector PMTs

Ademarlaudo França BARBOSA

Front-end electronics integration for the Angra Project central detector

P. C. M. A. Farias, G. P. Guedes
Universidade Estadual de Feira de Santana - UEFES
V. L. Filardi, I. M. Pepe[+]
Universidade Federal da Bahia - UFBA

Current Angra Detector Design

Central Detector: 1-ton water (liq scint: flammable, toxic, and carcinogenic!!) with Gd salts

Size: 1,90m (l) x 1,60m (w) x 1,60m (h)

Muon active Veto, Neutron shielding

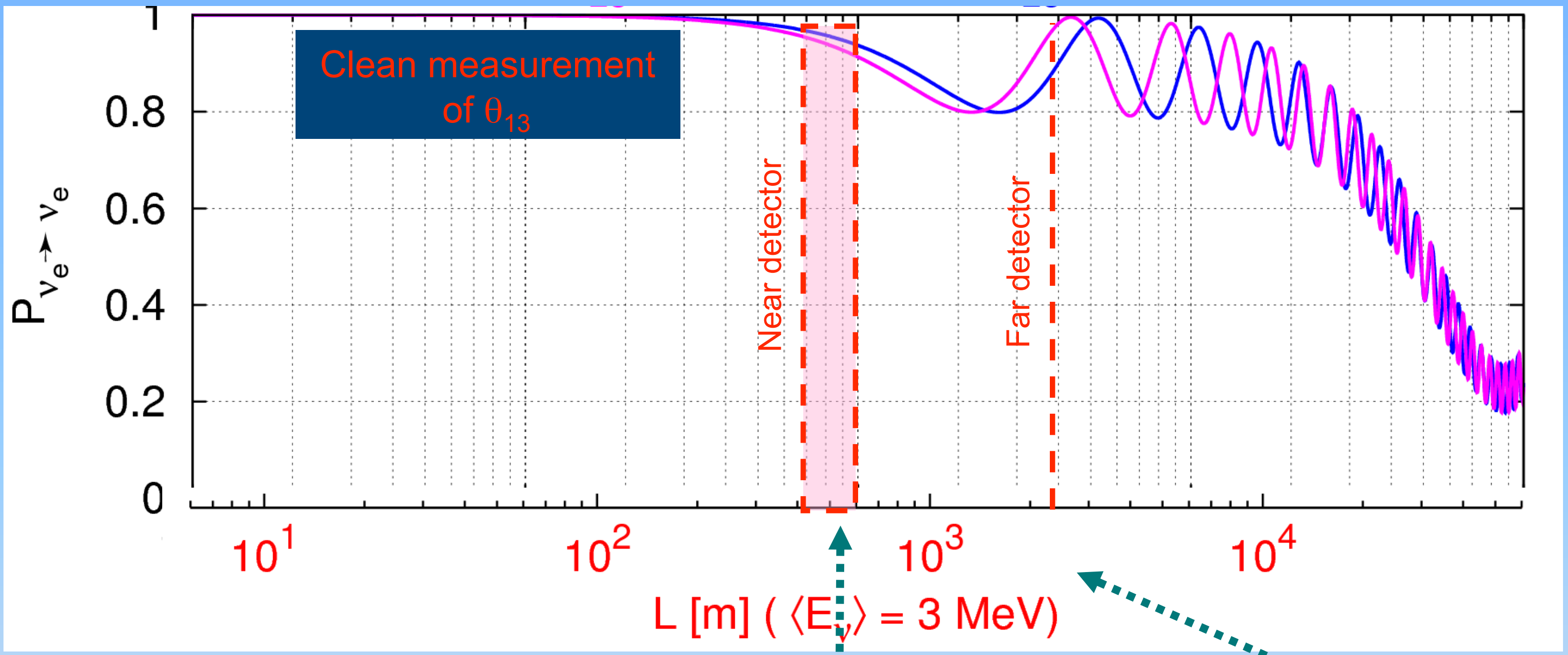
75 9-in head-on PMTs

θ_{13}

The Chooz site in French Ardennes

Experimental Approach

$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31} L/4E)$

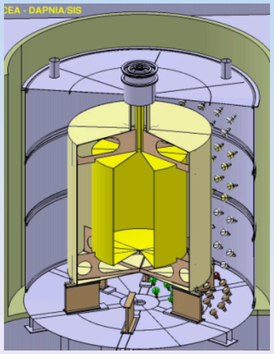


Nuclear power station
2 cores: 4.27 GW_{th}

Électron antineutrinos
flux : 10^{21} $\bar{\nu}_e$/s

$\bar{\nu}_e$

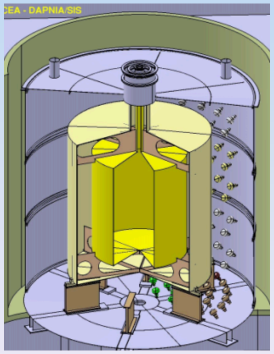
Near detector



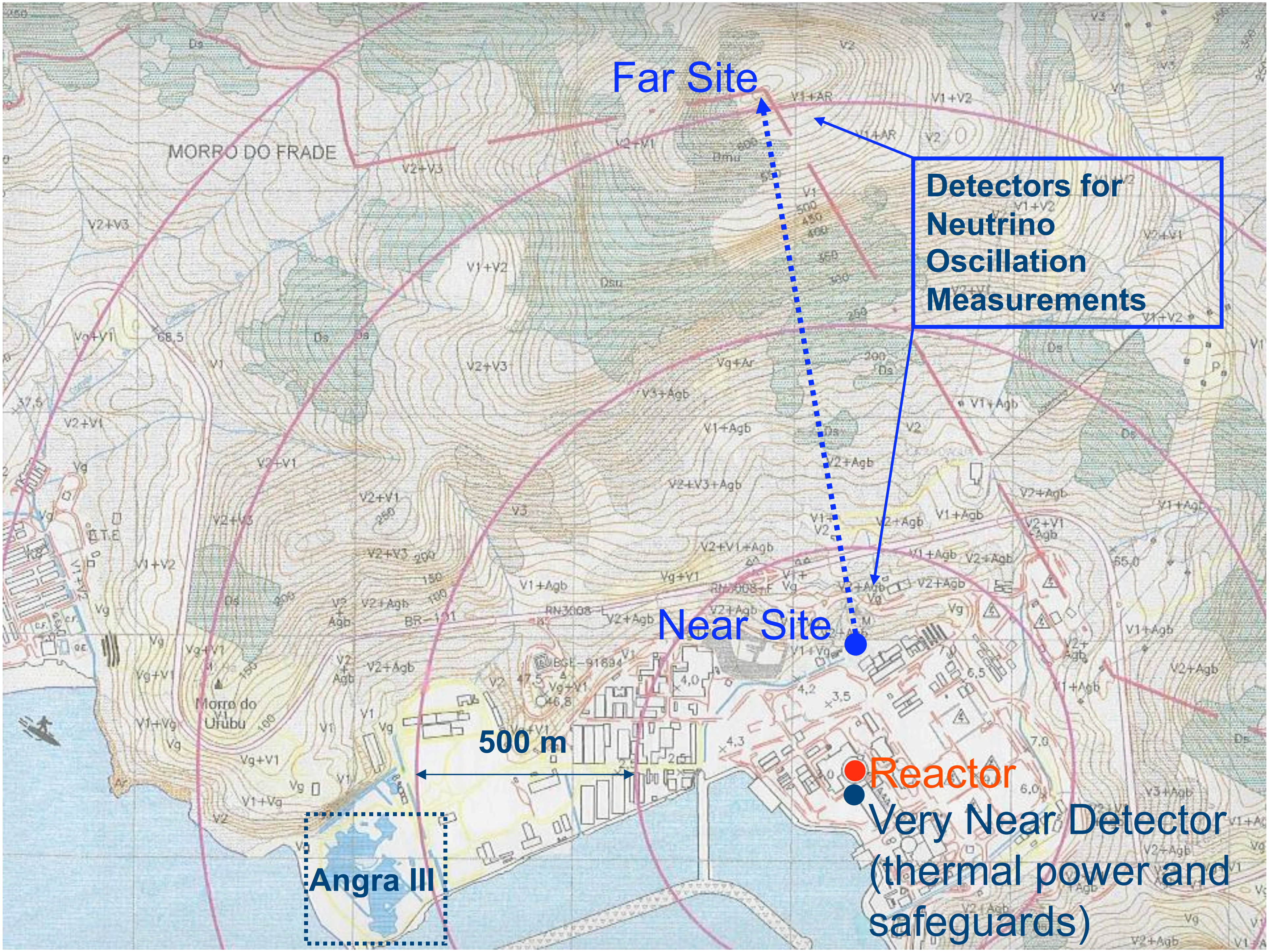
~250 m

$\bar{\nu}_{e,\mu,\tau}$

Far detector



1050 m



Far Site

Detectors for Neutrino Oscillation Measurements

Near Site

500 m

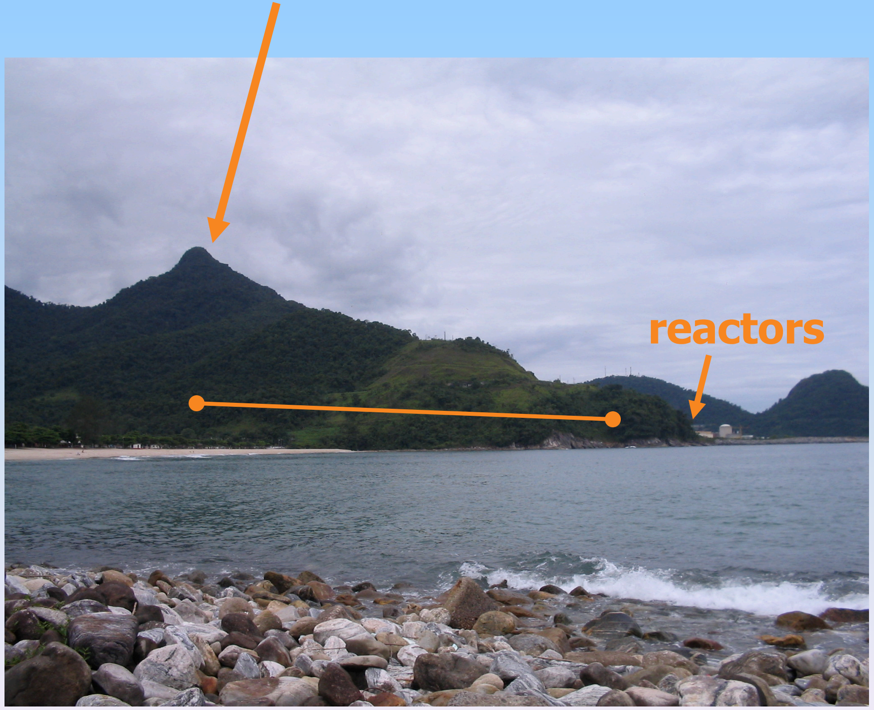
Reactor

Very Near Detector (thermal power and safeguards)

Angra III

2015, perhaps:
high precision measurement of θ_{13}

“Morro do Frade”



- Near (reference) detector:
  - 50 ton detector (7.2 m dia)
  - 300 m from core
  - 250 m.w.e.
- Far (oscillation) detector:
  - 500 tons (12.5 m dia)
  - 1500 m from core
  - 2000 m.w.e.
    (under “Frade” peak)
- Very Near detector:
  - 1 ton prototype project
  - < 50m of reactor core
- Detector Construction
  - Standard 3 volume design

ECL
DCI-UG

Conclusions

- Previous experiments indicate feasibility of using nu detectors for nuclear reactor distant monitoring
- Thermal power and fuel composition measurement can be achieved
- Better accuracy and general improvement of technique is needed
- Good opportunity to develop experimental nu physics in LA and to contribute to develop new safeguards techniques
- Neutrino Oscillations: collaboration with Double Chooz. Way towards high precision experiment in LA by 2015.

Thanks

elinares@fisica.ugto.mx

Pu production chain

$^{238}U_{92} + {}^{1}n_{0} \Rightarrow {}^{239}U_{92} + \gamma$

$^{239}U_{92} \underset{23\ \text{min}}{\Rightarrow} {}^{239}Np_{93} + e^{-}$

$^{239}Np_{93} \underset{2.3\text{d}}{\Rightarrow} {}^{239}Pu_{94} + e^{-}$

Pu production chain (cont…)

$^{239}Pu_{94} + {}^{1}n_{0} \Rightarrow {}^{240}Pu_{94} + \gamma$

$^{240}Pu_{94} + {}^{1}n_{0} \Rightarrow {}^{241}Pu_{94} + \gamma$

$^{241}Pu_{94} + {}^{1}n_{0} \Rightarrow {}^{242}Pu_{94} + \gamma$

Ar- and Ge-based nu detectors

Detect antineutrinos through coherent neutrino–nucleus scattering.

In this process, an antineutrino collides with a nucleus of argon or germanium,
which results in nuclear recoil.

As the recoiling nucleus collides with its neighbors, it shakes loose a few electrons.

Then a sensitive transistor can extract and amplify the electrons.

Ar- and Ge-based nu detectors (cont…)

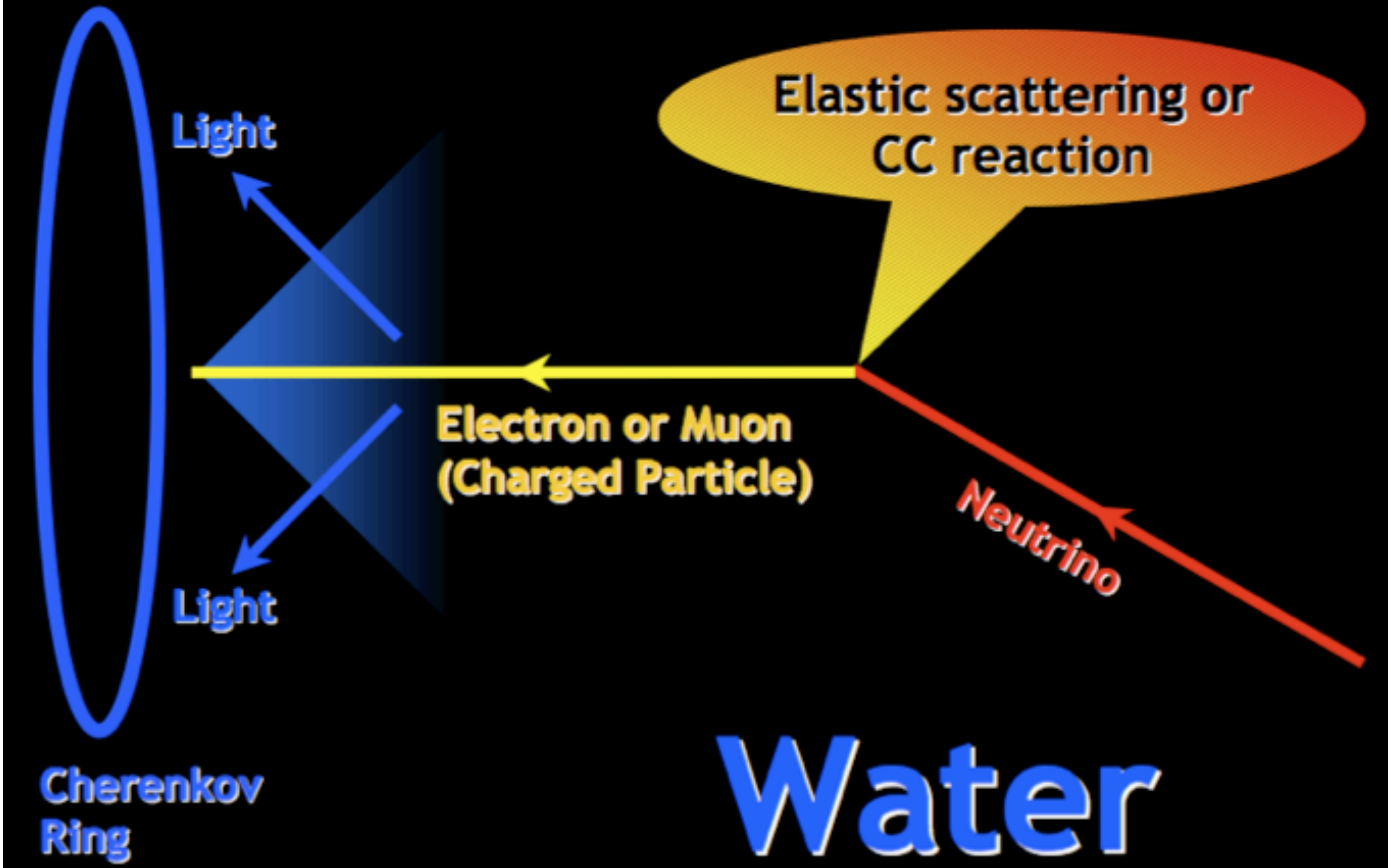
The Ar detector uses a dual-phase detection process.

In the first phase, the electron signal is produced in liquid Ar. In the second phase, the signal is amplified in an Ar gas blanket above the liquid to generate copious scintillator light, which is detected by PMTs.

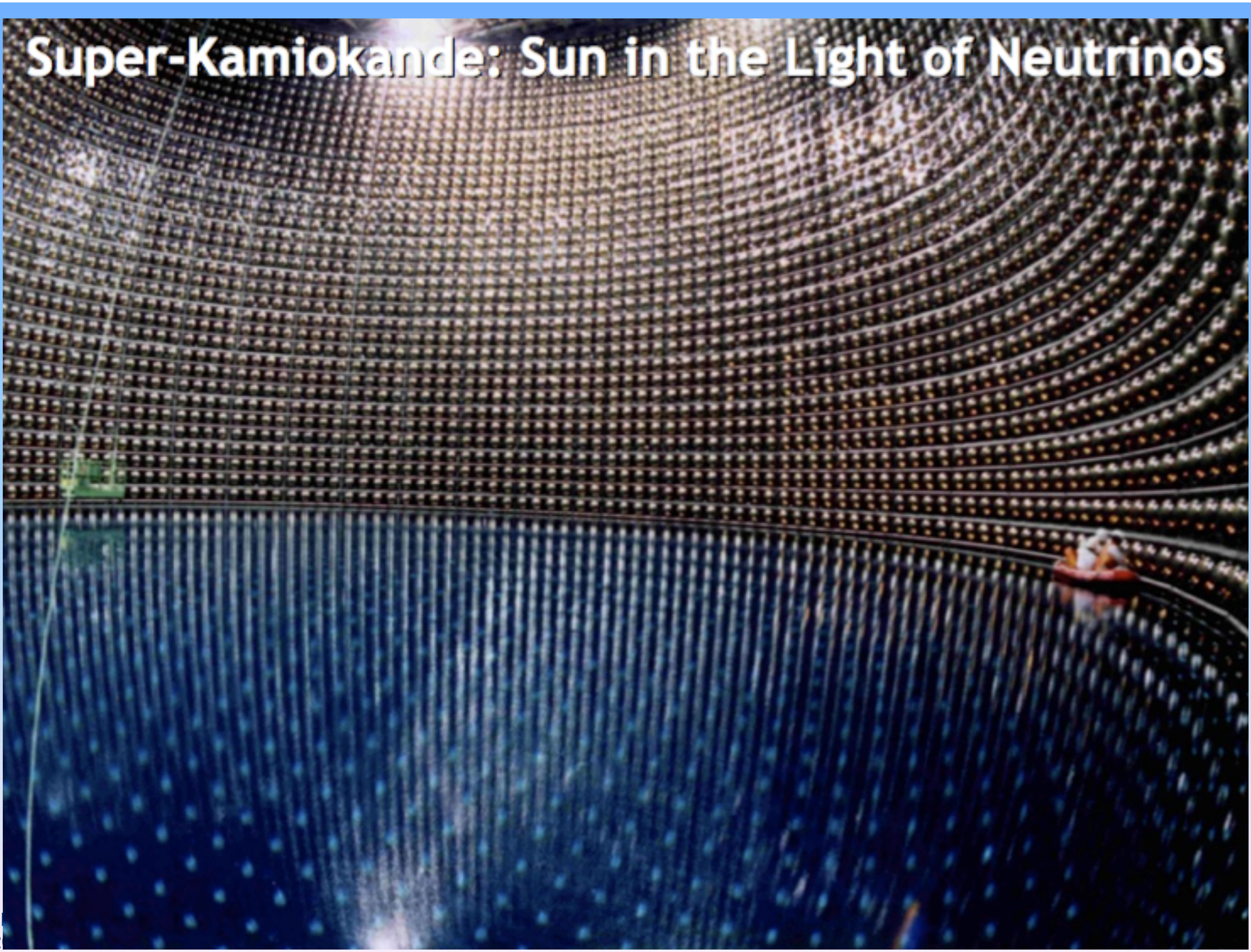
The coherent scatter process has a much higher antineutrino interaction rate per volume of detection medium compared with detectors that rely on inverse beta decay. This process has long been predicted but never observed. Detecting the coherent scatter signal with either approach would signify a major breakthrough.

Because detectors that use coherent scatter have a high probability of interaction per unit mass, they can also have a much smaller footprint, possibly as small as 1 cubic meter with the necessary shielding.

Cherenkov Effect



Super-Kamiokande: Sun in the Light of Neutrinos



Prospects for a Reactor Measurement of $\sin^2 2\theta_{13}$

Angra, Brazil $\sin^2 2\theta_{13} < 0.005$

- R&D on reactor monitoring. Proposal for θ_{13} measurement after Double Chooz.

Daya Bay, China $\sin^2 2\theta_{13} < 0.01$

- Approved by the Chinese Academy of Science for 50M RMB.
- Other Chinese agencies are expected to contribute ~100M RMB.
- US DOE has provided 0.8M$ for R&D for FY06. Working towards US project start in FY08.
- Plan to start near-mid data taking in 2009, and begin full operation in 2010.

Double-CHOOZ, France $\sin^2 2\theta_{13} < 0.03$

- Funding committment in France and Germany.
- Begin running far detector in 2008.
- Complete near detector in 2009.

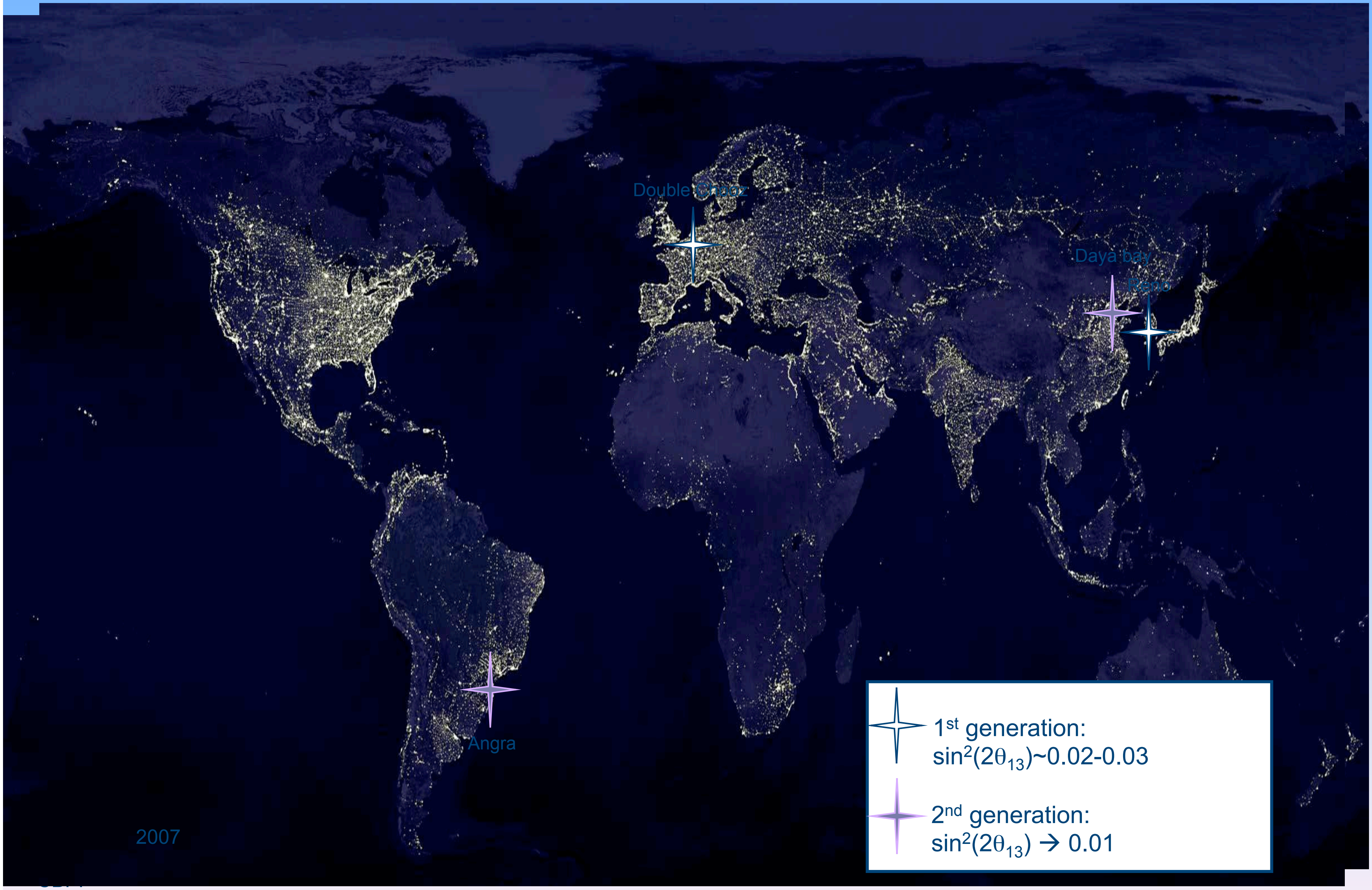
RENO, Korea $\sin^2 2\theta_{13} < 0.02$

- Approved by Ministry of Science and Technology for US $9M. R&D program starting.
- Plan to begin data taking in 2009/2010.

KASKA, Japan $\sin^2 2\theta_{13} < 0.025$

- R&D program in progress. If funded, plan to begin data taking in 2009/2010.

Remaining (alive) proposals… .



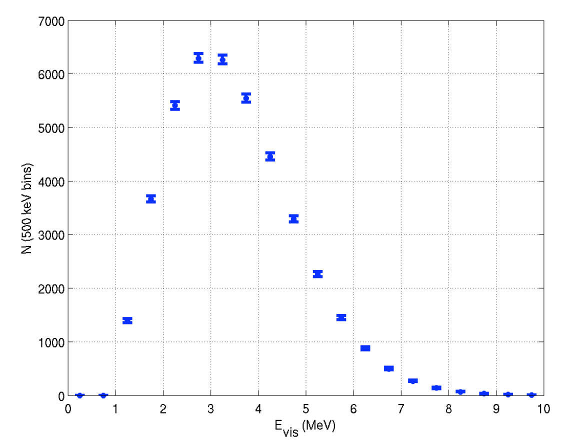
✦ 1st generation:
$\sin^2(2\theta_{13})$~0.02-0.03

✦ 2nd generation:
$\sin^2(2\theta_{13}) \rightarrow 0.01$

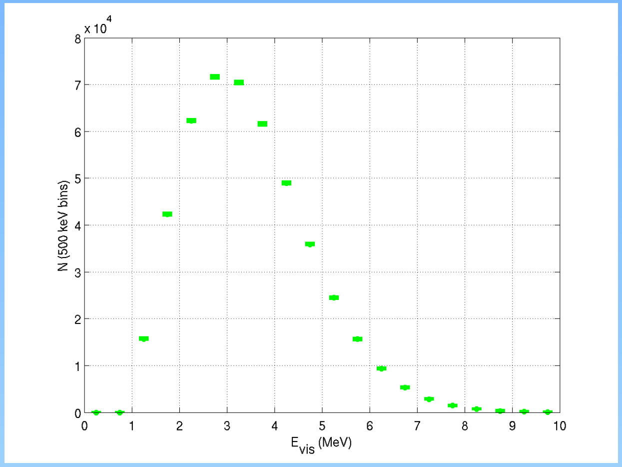
Double Chooz Collaboration

Research groups from: France, Germany, USA, Spain, Japan, UK, Russia, Brazil, Italy
> 120 physicists & engineers

Expected Oscillation Signal



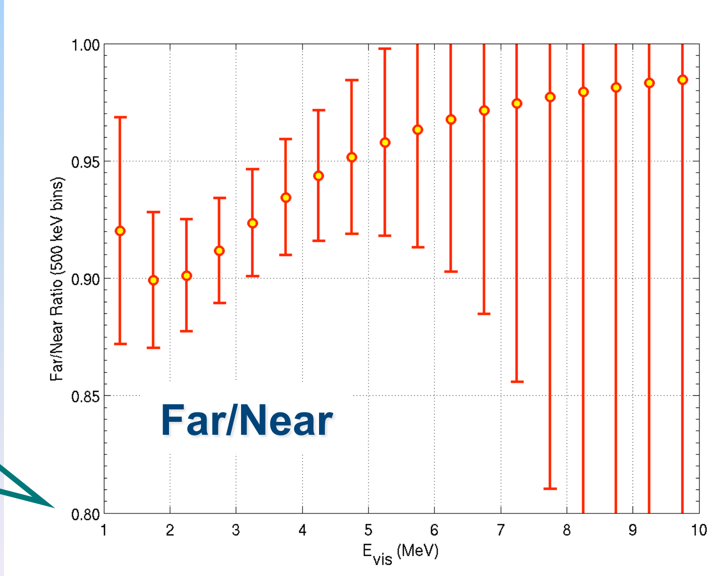
Far Spectrum



Near Spectrum

Δm^2_{atm}= 3.0 10^{-3} eV^2

$\sin^2(2\theta_{13})$=0.12

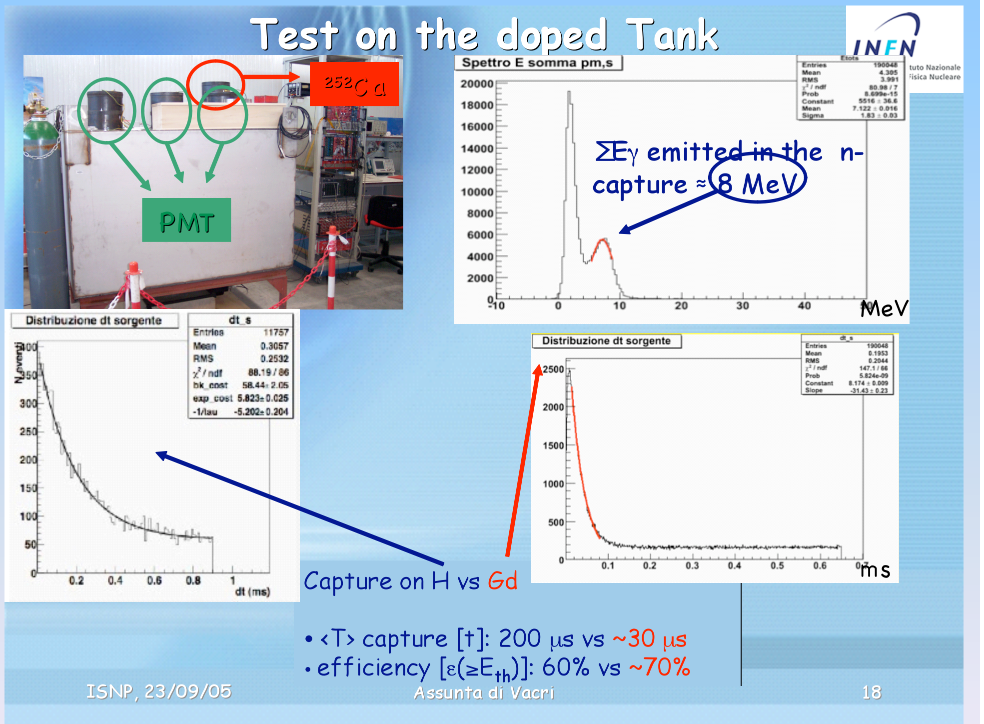


Far/Near

@1,05 km

Deploy LVD tank

- 1 ton Gd doped
  liquid scintillator tank
- Test signal+background
- Tests with Californium
  source
- Final site selection for
  underground laboratory



Test on the doped Tank

ΣEγ emitted in the n-capture ≈ 8 MeV

Capture on H vs Gd

- <T> capture [t]: 200 μs vs ~30 μs
- efficiency [$\varepsilon(\geq E_{th})$]: 60% vs ~70%

ISNP, 23/09/05 Assunta di Vacri 18

SOURCES OF NEUTRINOS

- *Neutrinos from mankind's activity*

  - *Nuclear reactors* produce $\bar{\nu}_e$, typical energy few MeV, flux 10^{20} per second

  - *Particle accelerators (CERN, Fermilab)* produce *beams* of $\nu_\mu, \bar{\nu}_\mu (\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\tau)$
  Energies up to 500 GeV, typical flux 10^{11} per second

- *Neutrinos from the Earth*

  - *Natural radioactivity* provides the Earth with 20 TW of power.
  Generates $\bar{\nu}_e$ of a few MeV, typical flux 10^7 per cm^2 per second

- *Neutrinos from Space*

  - *The Sun* is a prolific source of ν_e (10^{38} per second). Flux on Earth 10^{11} per cm^2 per second
  Typical energy < 1 MeV, but spectrum extends up to 15 MeV

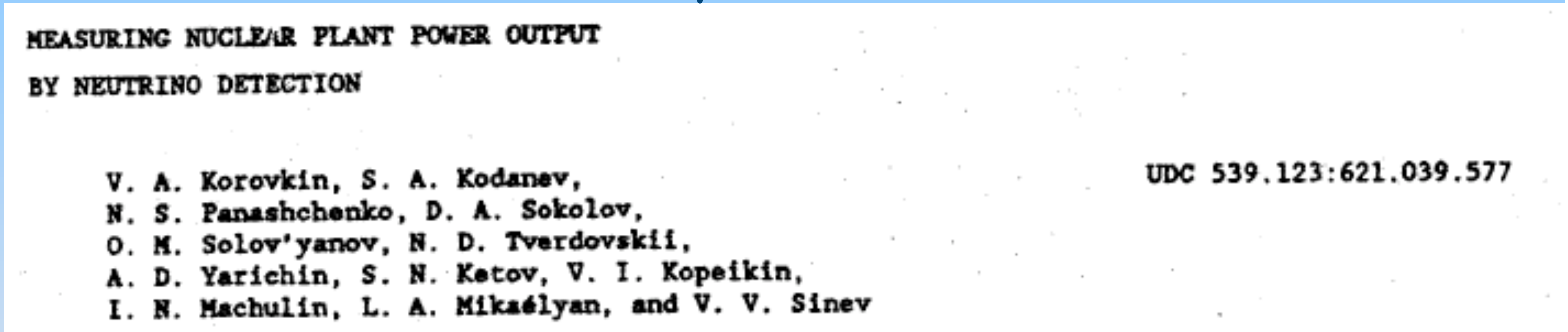
  - *Supernova* explosions produce 10^{57} ν_e in 10 seconds. Flux on Earth depends on distance.

  - *Cosmic rays* (mainly protons) interacting in the atmosphere generate $\nu_\mu, \bar{\nu}_\mu$ $(+\nu_e, \bar{\nu}_e)$
  produced in pion (muon) decay. Typical energy 1 GeV, typical flux 10^3 per m^2 per second

  - *The Big Bang* generated 10^{87} neutrinos of all types. Typical energy today 0.0004 eV
  Average density in Universe 660 per cm^3

The idea is quite old...

- Kurchatov Institute, 1988

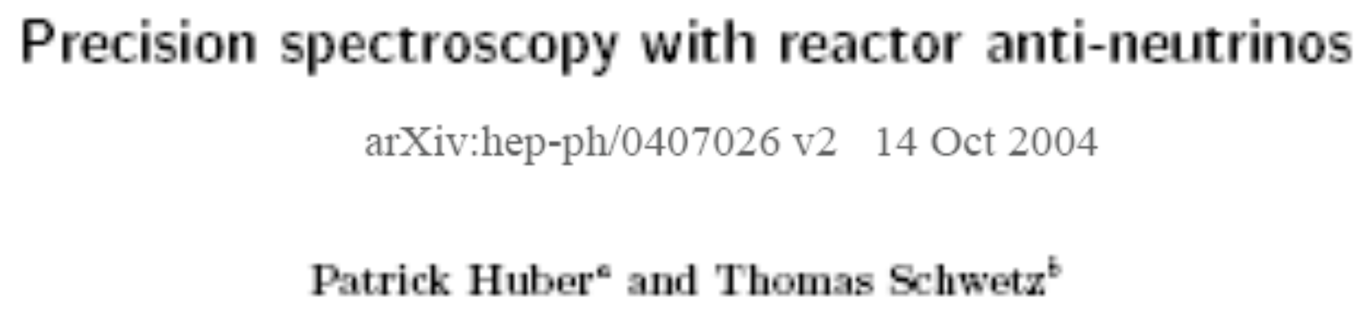


MEASURING NUCLEAR PLANT POWER OUTPUT
BY NEUTRINO DETECTION

V. A. Korovkin, S. A. Kodanev,
N. S. Panashchenko, D. A. Sokolov,
O. M. Solov'yanov, N. D. Tverdovskii,
A. D. Yarichin, S. N. Ketov, V. I. Kopeikin,
I. N. Machulin, L. A. Mikaélyan, and V. V. Sinev

UDC 539.123:621.039.577

Revisited recently



Precision spectroscopy with reactor anti-neutrinos

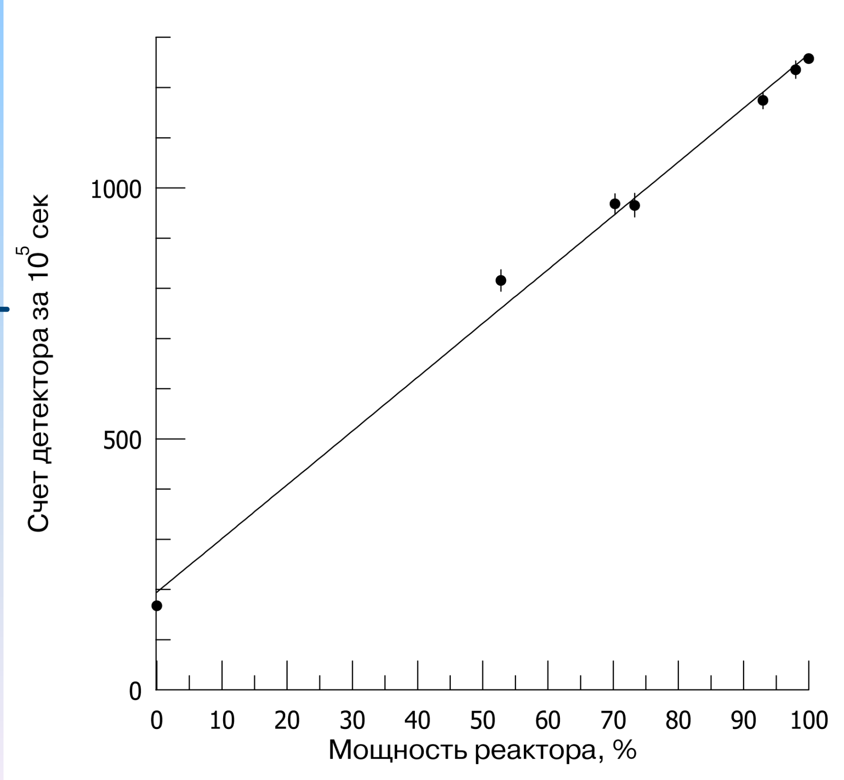
arXiv:hep-ph/0407026 v2 14 Oct 2004

Patrick Huber[a] and Thomas Schwetz[b]

Reactor power x neutrino flux

Measuring of power production by neutrino method

Neutrino Rate per 10^5 sec



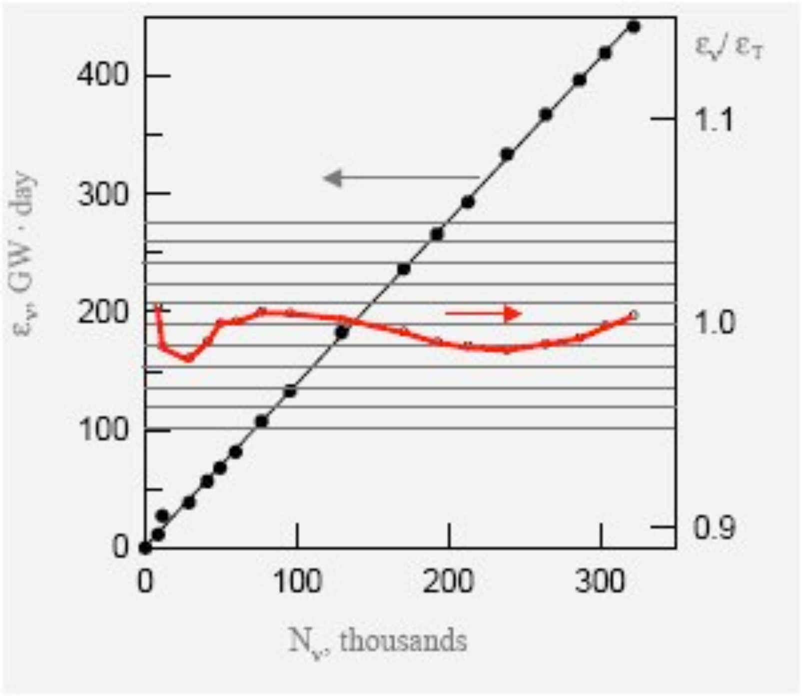
Reactor power in % from nominal value (1375 MW)

CBPF
2007

25/10/07

Reactor power x neutrino flux

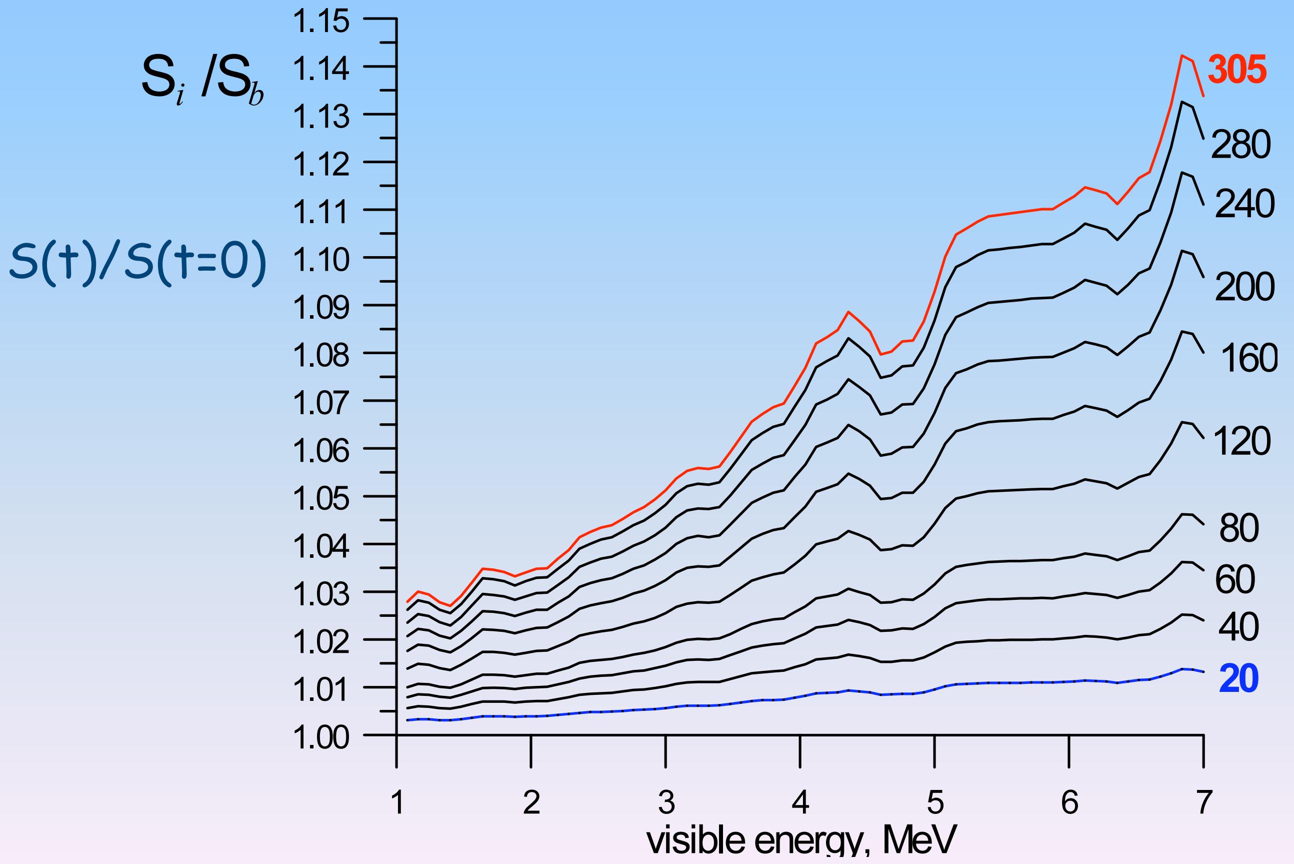
Power generation



Power ν / Power Th

Number of antineutrinos

Ratio of spectra: time evolution



time (days)

after reactor

starts

International
Committee for
Future Accelerators

Reactor ν experiment physics

Reactor	Optimistic start date	GW-t-yr (yr)	90% CL $\sin^2 2\theta_{13}$ sensitivity	for Δm^2 (10^{-3}eV^2)	efficiencies	Far event rate
ANGRA	2013(full)	3900(1) 9000(3) 15000(5)	0.0070 0.0060 0.0055	2.5	0.8×0.9	350,000/yr
Braidwood	2010	845(1) 2535(3) 7605(9)	0.007 0.005 0.0035	2.5	0.75	41,000/yr
Daya Bay	08(fast) 09(full)	3700(3)	0.008	2.5	0.75×0.83	70,000/yr 110,000/yr (before/after 2010)
Double Chooz	Oct 07(far) Oct 08(near)	29(1) 29(1+1) 80(1+3)	0.08 0.04 0.025	2.5	0.8 ×0.9	15,000/yr
KASKA	Mar 09	493(3)	0.015	2.5	0.8×0.88	24,000/yr
RENO	Late 09	340(1)	0.03	2.0	0.8	18,000/yr

Expected Signal & Background

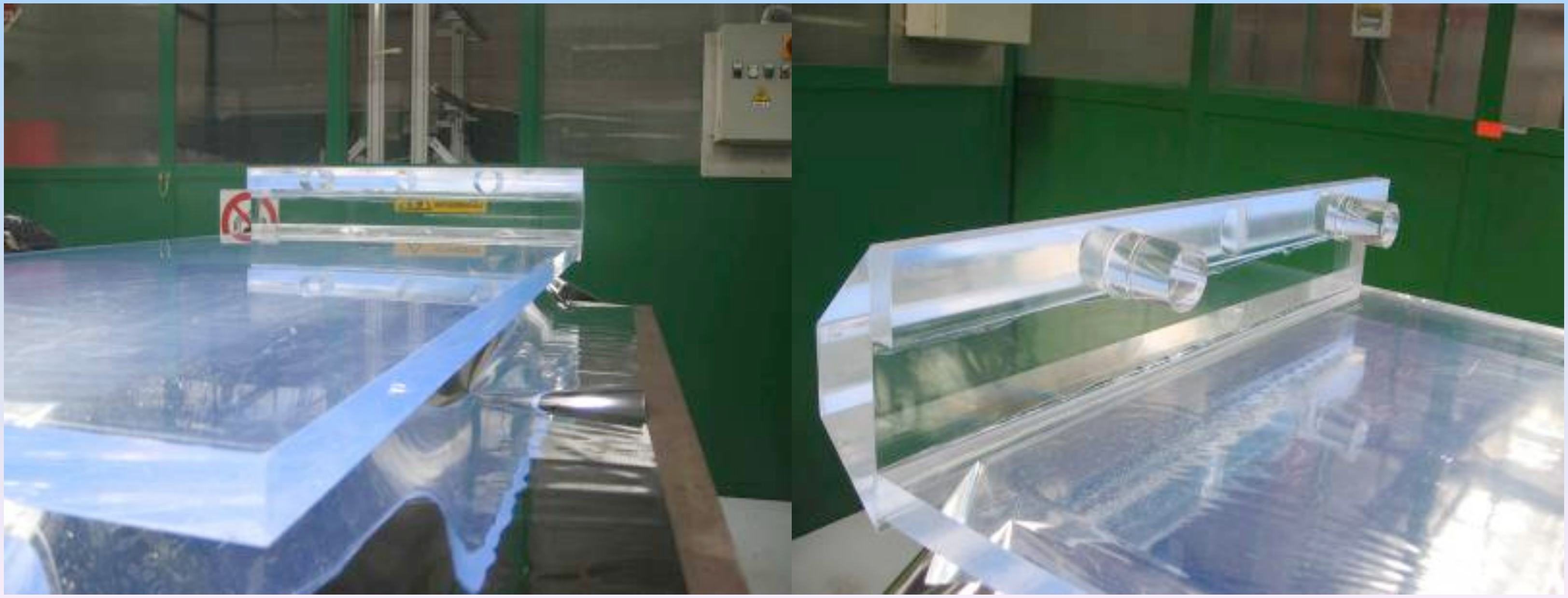
Rates presented at ICRC 2007

Cylindrical Detector - R_3= 1.40m; H=3.10m

Depth (mSR)	Muons (Hz)
10	365
20	150
30	063
40	043
50	019

Phase II: Deploy LVD tank

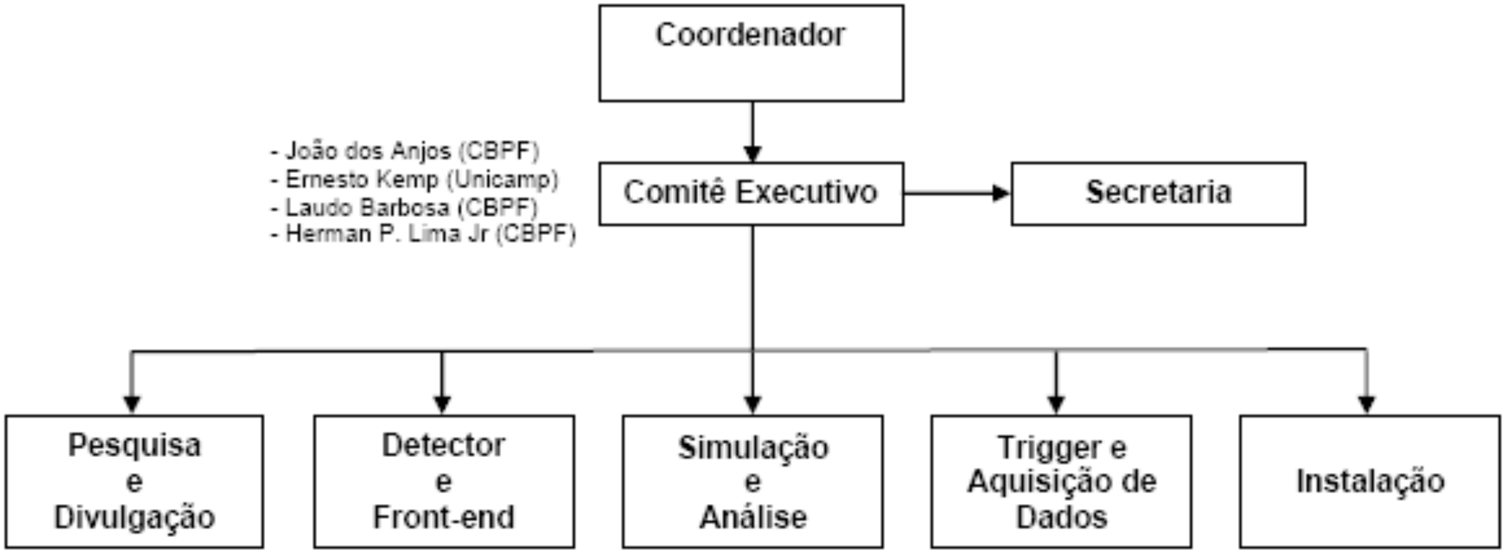
Muon veto construction at LNGS



Projeto Neutrinos Angra

Estrutura Funcional

20/03/2007



Coordenador

Comitê Executivo

- João dos Anjos (CBPF)
- Ernesto Kemp (Unicamp)
- Laudo Barbosa (CBPF)
- Herman P. Lima Jr (CBPF)

Secretaria

Pesquisa e Divulgação

Líder: Marcelo Guzzo
Equipe:
- Hiroshi Nunokawa
- Orlando Peres
- Pedro Holanda

Detector e Front-end

Líder: Laudo Barbosa
Equipe:
- Paulo Marinho

Simulação e Análise

Líder: Javier Magnin
Equipe:
- Anderson Schilithz
- André P. de Almeida

Trigger e Aquisição de Dados

Líder: Herman Lima Jr
Equipe:
- Artur Vilar
- Luciano Manhães
- Márcio Portes

Instalação

Líder: Ernesto Kemp
Equipe:
- Ilson Soares
- Luis Gonzalez
- Rogério Machado

Physics Motivations:

- The discovery of neutrino oscillations implies that neutrinos are massive and that the SM is incomplete.
- These observations may have profound astrophysical consequences. CP violation in the lepton sector may hold the key of matter-antimatter asymmetry in the universe.
- **The minimal extension of the SM requires 3 mass eigenstates, ν_1, ν_2, ν_3 and a unitary mixing matrix U which relates the neutrino mass basis to the flavor basis.**

Standard Model Extension:

- Minimal extension of the SM requires **7** parameters:
  3 neutrino masses $\mathbf{m_1}$, $\mathbf{m_2}$ and $\mathbf{m_3}$
  3 mixing angles θ_{12} , θ_{23} , and θ_{13}
  a CP violating phase parameter δ
- The oscillation probabilities depend on the mass-squared differences $\Delta m^2_{12} = m_2^2 - m_1^2$ and $\Delta m^2_{23} = m_3^2 - m_2^2$
- **Challenges of neutrino experimental community include to measure** as precisely as possible
  θ_{12}, θ_{23} , θ_{13} , Δm^2_{12} , Δm^2_{23}

Neutrino Mixing Matrix Experimental status:

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\boxed{\text{Atmospheric}}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\boxed{\text{Reactor and LBL}}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\boxed{\text{Solar}}}$$

- The parameters θ_{23} and Δm^2_{23} determined using atmospheric neutrino data from Super-Kamiokande and K2K. (10% level)
- Data from SNO, KamLAND and Super-Kamiokande used to determine θ_{12} and Δm^2_{12} with 10 – 20% precision.
- **For θ_{13} there exists only a limit by the reactor experiment CHOOZ $\sin^2(2\,\theta_{13}) < 0.2$**

Motivations for reactor experiments:

- **Physics considerations:**
  - Measurement of θ_{13} is important for it is a fundamental parameter
  - It is crucial for investigation of leptonic CP violation
  - CP violation phase δ can be measured only if $\theta_{13} \neq 0$
  - Its value will determine the tactics to best address other questions in neutrino physics

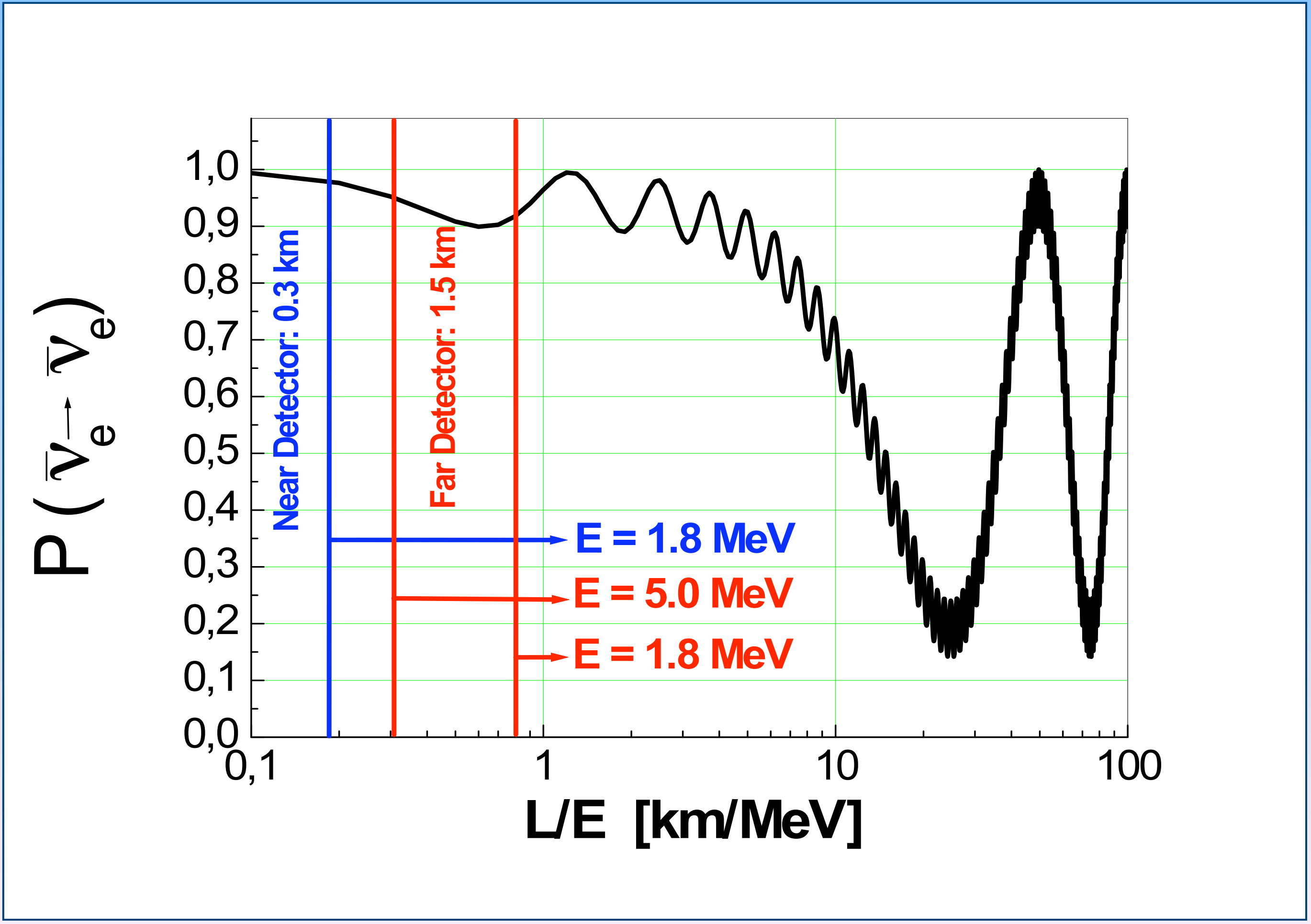
Motivations for reactor experiments:

- **Reactor Experiment ADVANTAGES**
  - **Clean measurement** of θ_{13} : L ~ 1-4Km : too short for matter effects to be important → **No matter-effects** and parameter degeneracy
  - **High luminosity**: 4 GW thermal power (Angra II)
    ~ 10^{20} antineutrinos/s
  - 50 - 500 tons detectors – high number of target protons
  - Precise shape measurement of energy spectrum
  - Can have Low Background: large overburden

ANGRA II:

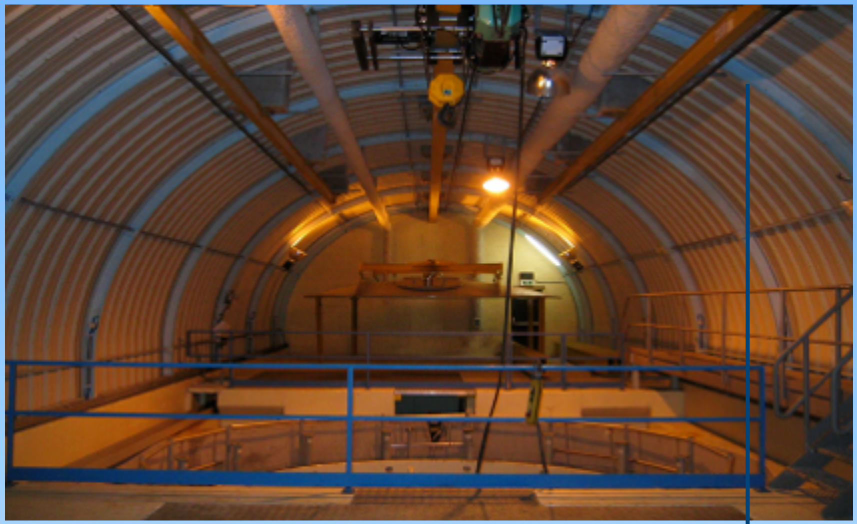
ν Survival Probability

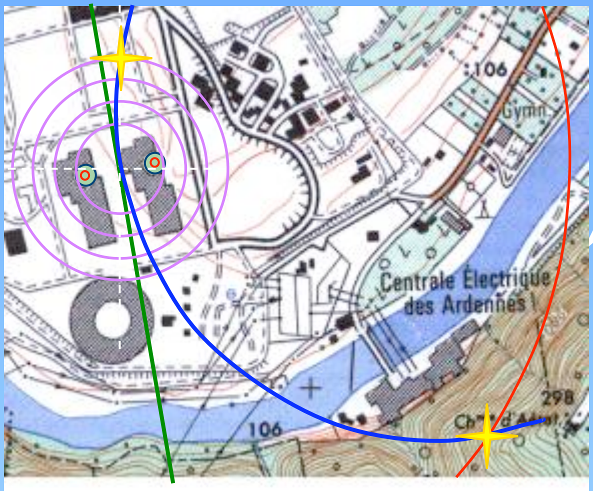
$E_{mín}$ = 1.8 MeV; 95%@5MeV (far detector)



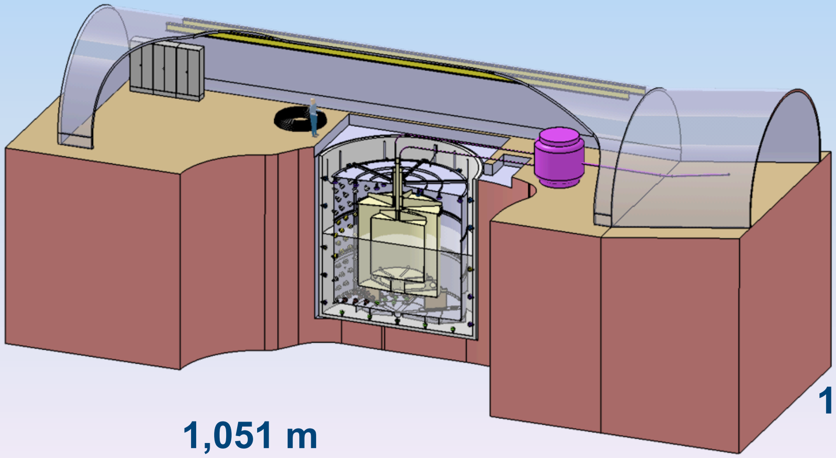
1 km site

274 m site



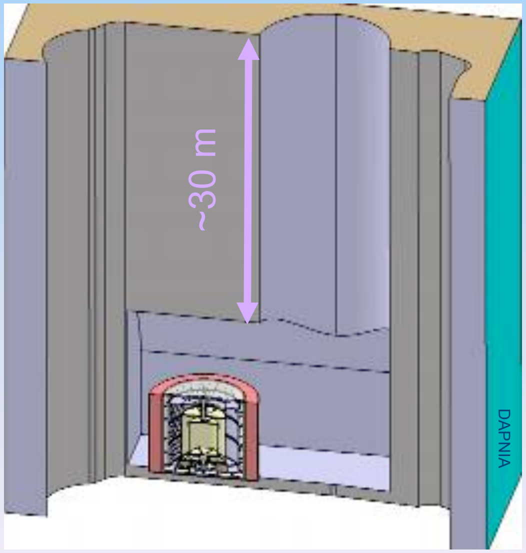


Integration start mid-2007



1,051 m
300 mwe
15,200 events/y

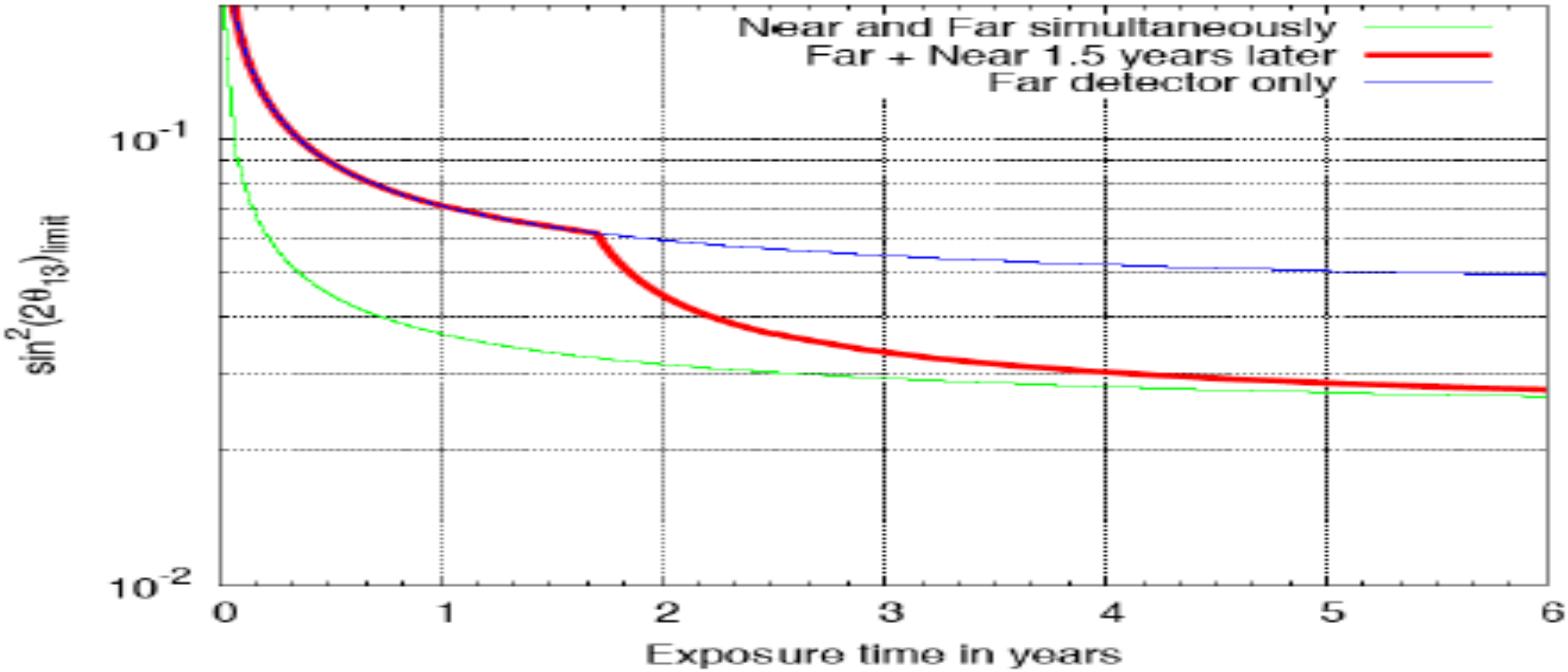
274 m
80 mwe
162,260 events/y



Integration end of 2009

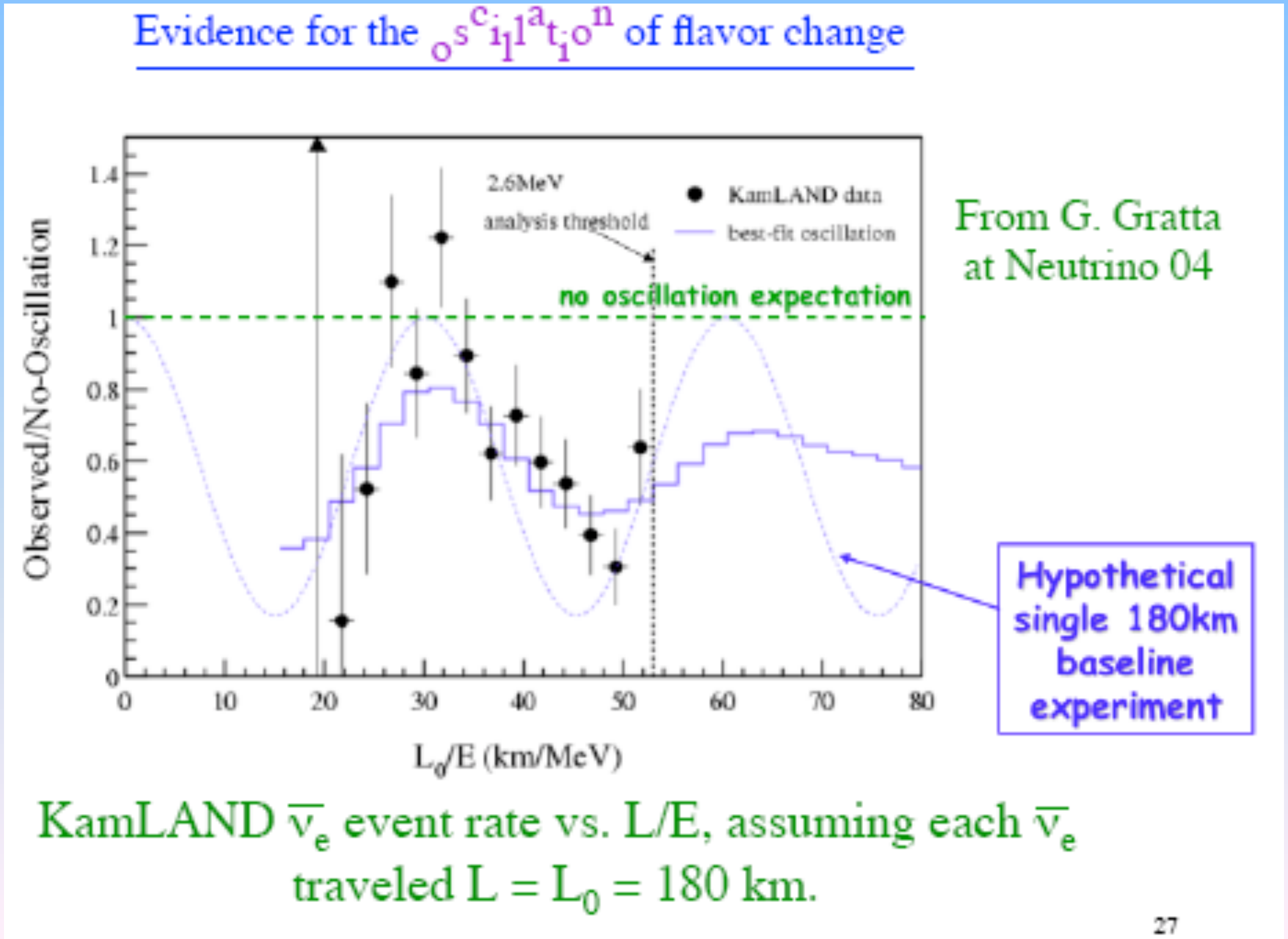
EXPECTED SENSITIVITY

Sensitivity Goal




Far Site
MORRO DO FRADE
Near Site
Morro do Urubu
BR-101
RN3008-L
RN3008-F
IBGE-91894
E.T.E
Very Near Detector

KamLAND results



Evidence for the oscillation of flavor change

From G. Gratta at Neutrino 04

Hypothetical single 180km baseline experiment

KamLAND $\overline{\nu}_e$ event rate vs. L/E, assuming each $\overline{\nu}_e$ traveled $L = L_0 = 180$ km.

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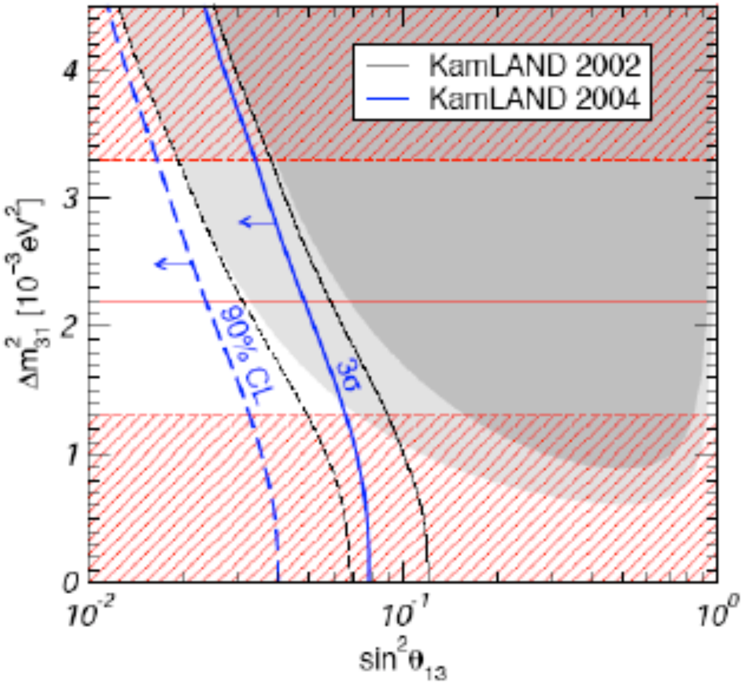
Neutrino Mixing

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$\theta_{23} = \sim 45°$

$\theta_{13} = ?$

$\theta_{12} \sim 32°$

Radiochemical experiments

$$\boxed{\nu_e + N \rightarrow N' + e^-}$$

Proposed by Pontecorvo in 1946.

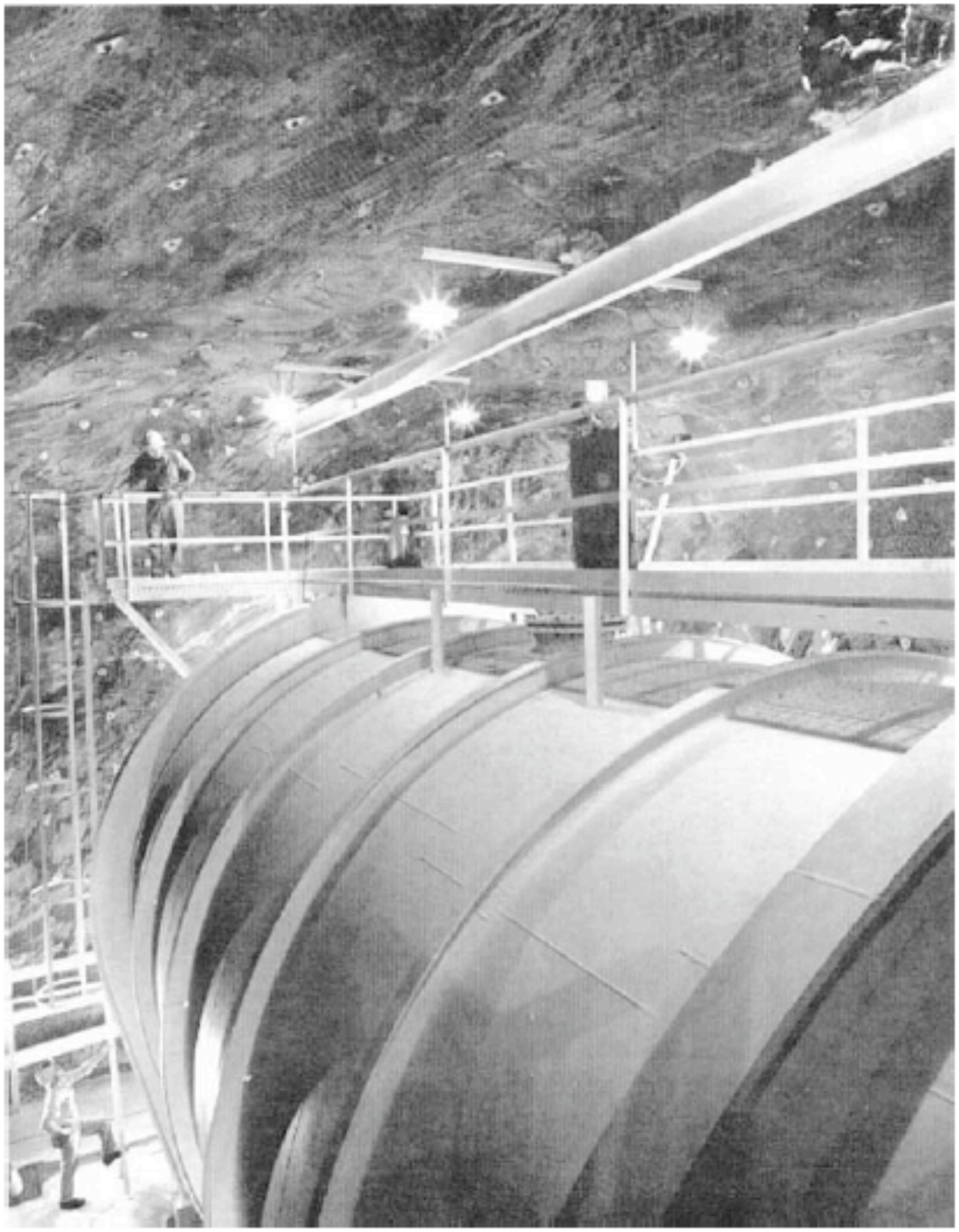
N' (unstable) is separated from the target with physical-chemical techniques and quantitatively measured by observing its decay back in N.

$$Interaction\ Rate\ (R) = N_{\text{target}} \cdot \sum_{\mathrm{i}} \int \sigma_i(E) \cdot \frac{d\Phi_i(E)}{dE} dE$$

$$\sigma_{\mathrm{i}} \sim 10^{-46}\ cm^2;\ \Phi_{\mathrm{i}} \sim 6 \times 10^{10}\ [s\ cm^2]^{-1}$$

J.J. Gómez-Cadenas

Experiment Homestake (1967-2002)



Raymond Davis Jr.

$$^{37}\mathrm{Cl} + \nu_e \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

615 ton de C_2Cl_4

2.2×10^{33} atmos de ^{37}Cl

H. Nunokawa

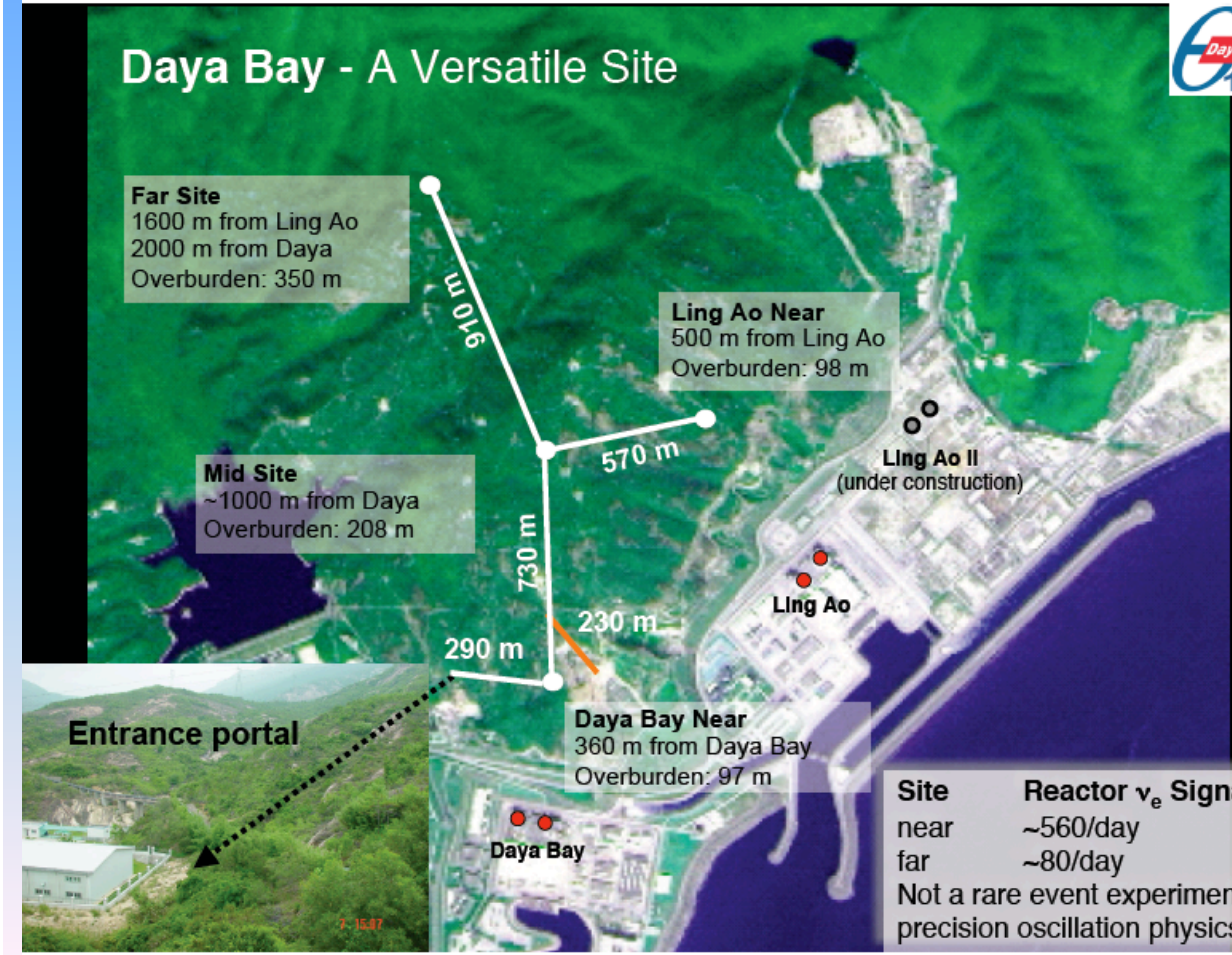
KamLAND results

KamLAND actually does see —

$$\frac{\phi_{\overline{\nu}_e}}{\phi_{\overline{\nu}_e}\Big|_{\substack{\text{No}\\ \text{Disappearance}}}} = 0.658 \pm 0.044(\text{stat}) \pm 0.047(\text{syst})\ .$$

Reactor $\overline{\nu}_e$ do disappear.

Daya Bay - A Versatile Site



Far Site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Mid Site
~1000 m from Daya
Overburden: 208 m

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

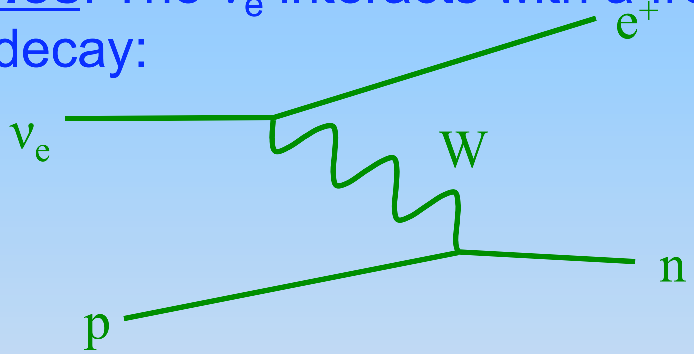
Site	Reactor ν_e Signal
near	~560/day
far	~80/day

Not a rare event experiment, precision oscillation physics.

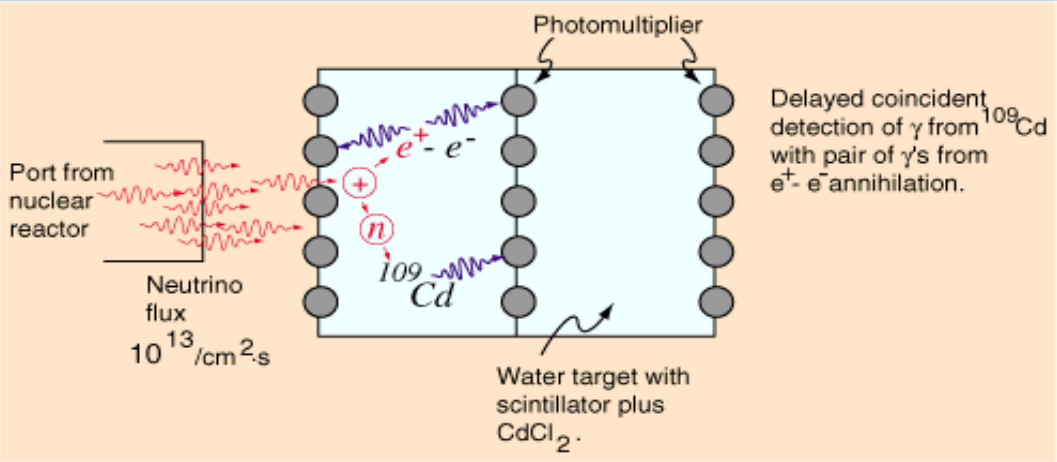
Reactor Neutrinos: detection principles

…actually we detect ***anti-neutrinos***. The $\bar{\nu}_e$ interacts with a free proton (hydrogen) via inverse β-decay:

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



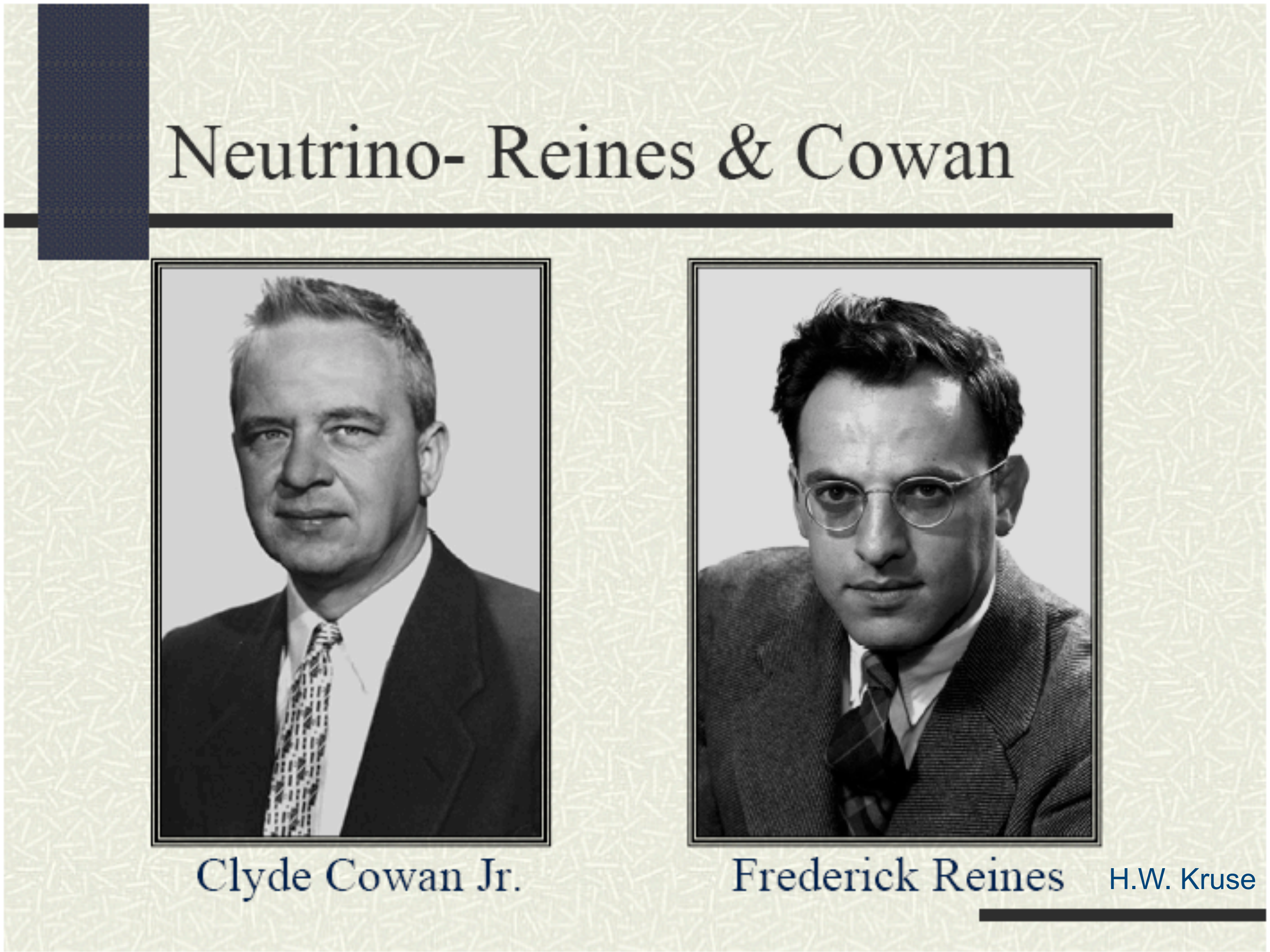
Later the neutron captures giving a coincidence signal. Reines and Cowan used cadmium to enhance the neutron capture



Non-proliferation in Latin-America: ABACC

- The **Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC)** is a binational agency created by the governments of Brazil and Argentina (1991), responsible for verifying the pacific use of nuclear materials that could be used, either directly or indirectly, for the manufacture of weapons of mass destruction.

Neutrino discoverers



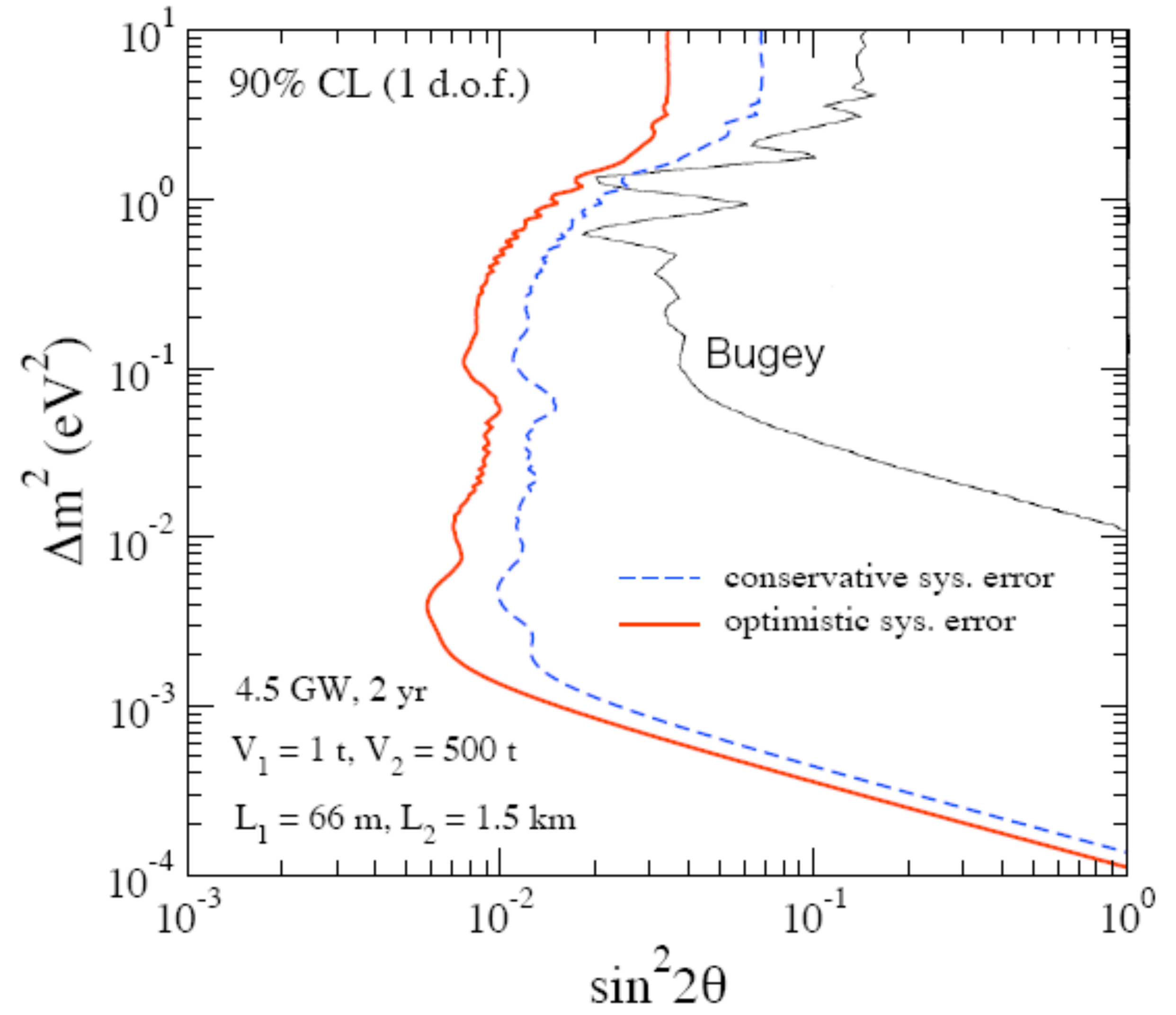
Neutrino- Reines & Cowan

Clyde Cowan Jr.

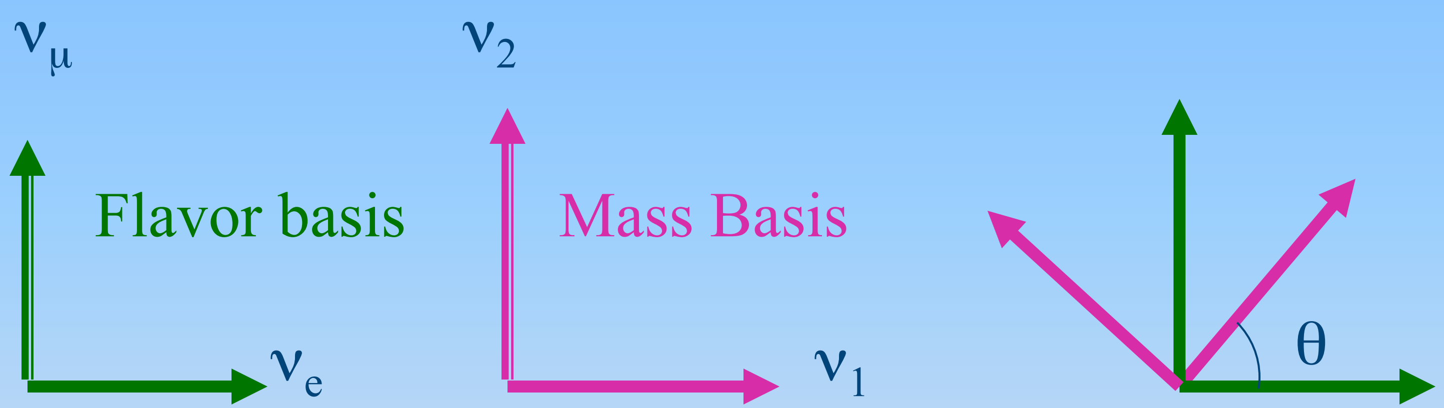
Frederick Reines

H.W. Kruse

Sensitivity to Sterile Neutrinos



Physics:
Flavor Oscillation basics



$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

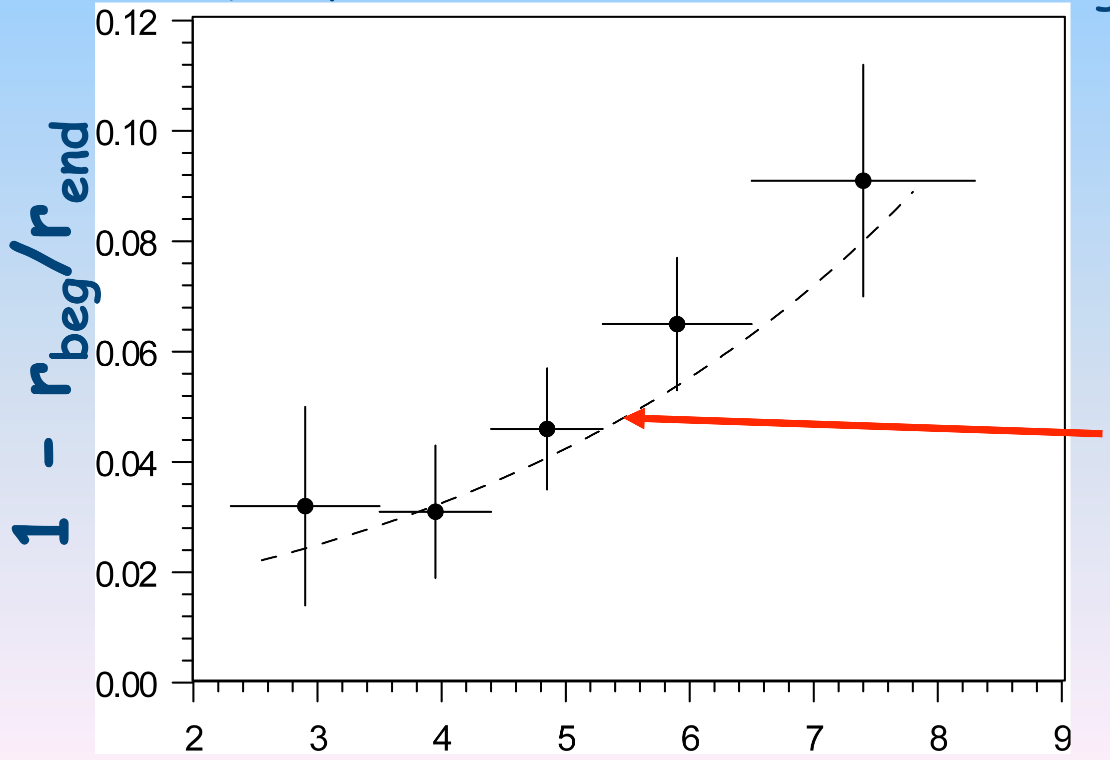
$$\nu(t)=e^{-\iota E t}\nu(0)$$

$$P(\nu_e \rightarrow \nu_\mu) = <\nu_\mu (t)|\nu_e (0)> = \sin^2\theta\cos^2\theta|e^{-\iota E_2 t}-e^{-\iota E_1 t}|^2$$

$$= \sin^2(2\theta)\ \sin^2(1.27\ \Delta m^2 L/E)$$

Composition of the Fuel

- The effect of the composition of the fuel is more strongly manifested in the antineutrino energy spectrum



Rovno 1988-1990

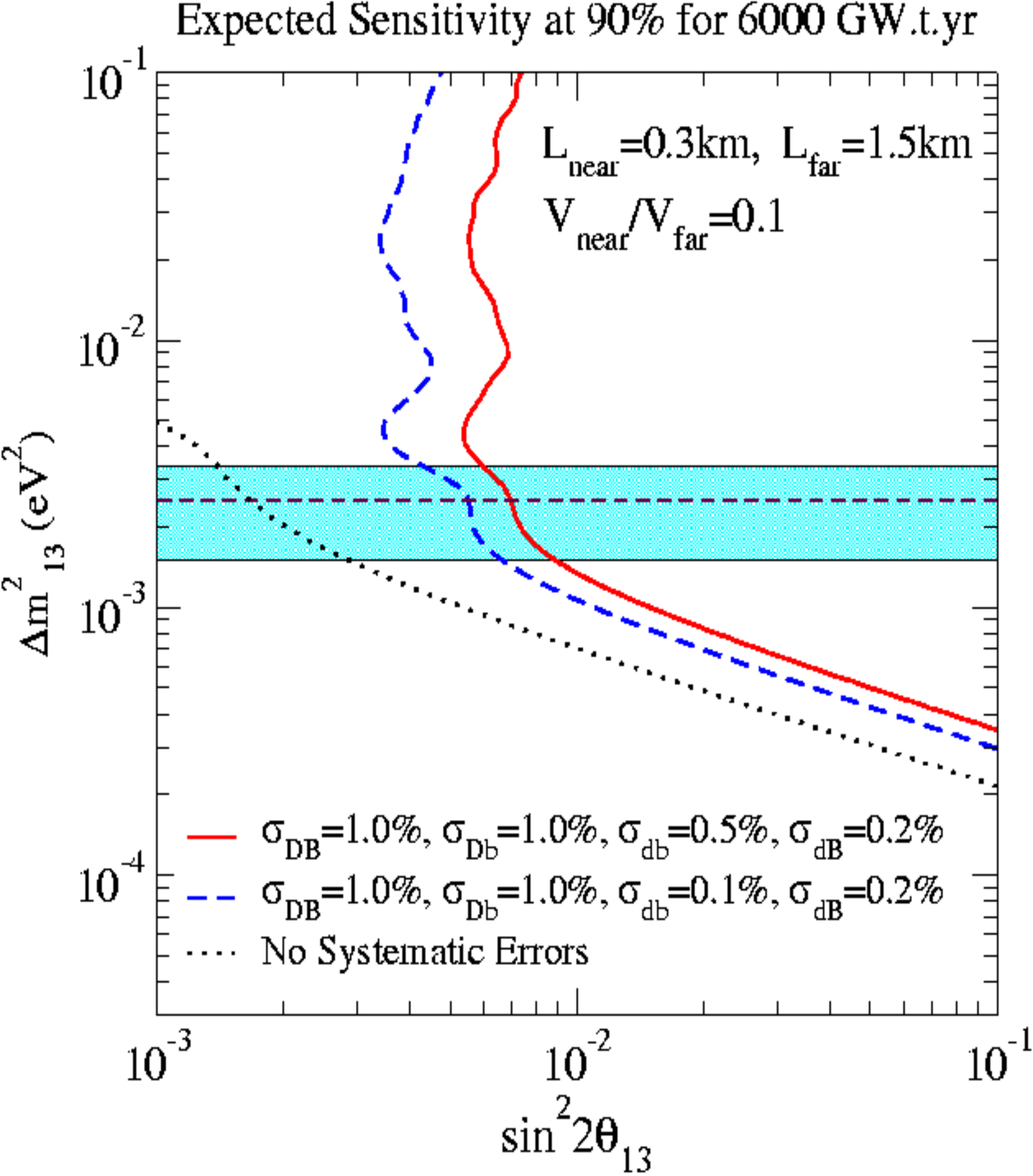
Main ABACC interest

Expected from ILL spectra

Sensitivity studies

conventions

- d/D: detectors
- b/B: bin (energy)
- capital: correlated
- small: uncorrelated



Outline

- The Angra dos Reis nuclear power plant
- The ANGRA Neutrino Project
- The Angra Detector
- Conclusions

Double Chooz Status

- **Funding has been established in Europe**
  → Request in Japan and US

- **First goal: measurement of θ_{13}**

  Double Chooz moving towards the construction phase !

  - ***2007-08*** ***→ Detector construction & integration***
  - ***2008*** ***→ Start of phase I : Far 1 km detector alone***
    $\sin^2(2\theta_{13}) < 0.06$ in 1,5 year (90% C.L.)
  - ***2009*** ***→ Start of phase II : Both near and far detectors***
    $\sin^2(2\theta_{13}) < 0.025$ in 3 years (90% C.L.)
    Complementarity with Superbeam experiments: T2K, Nova

- **Feasability study on non proliferation**

  Reactor ν's track the Pu isotopic content of reactors

  - **2009-10** **→ Near detector at 280 m = prototyping a future IAEA monitor?**