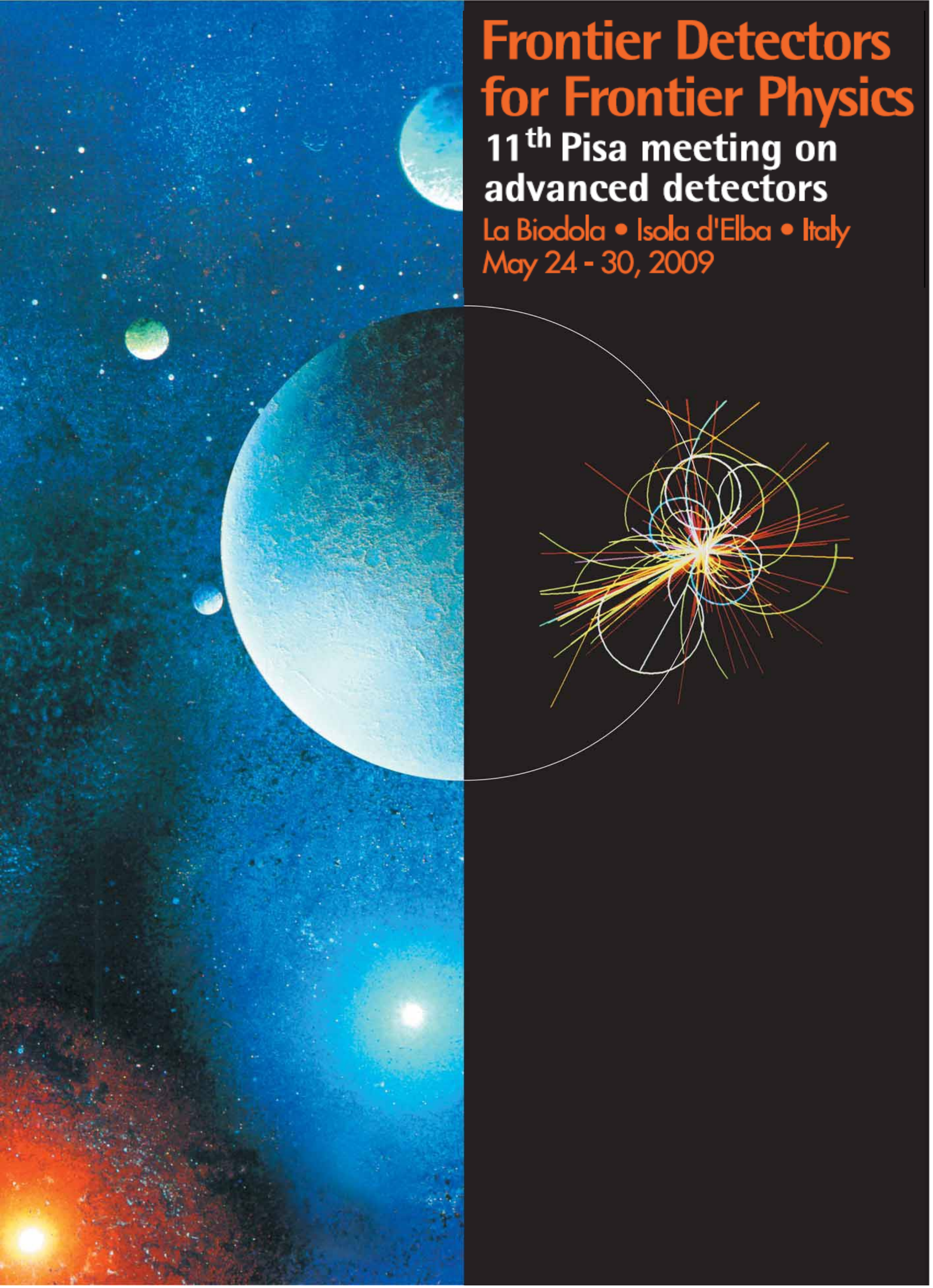


An antineutrino detector to monitor nuclear reactor’s power and fuel composition

Marco Battaglieri
Istituto Nazionale di Fisica Nucleare
Genova- Italy

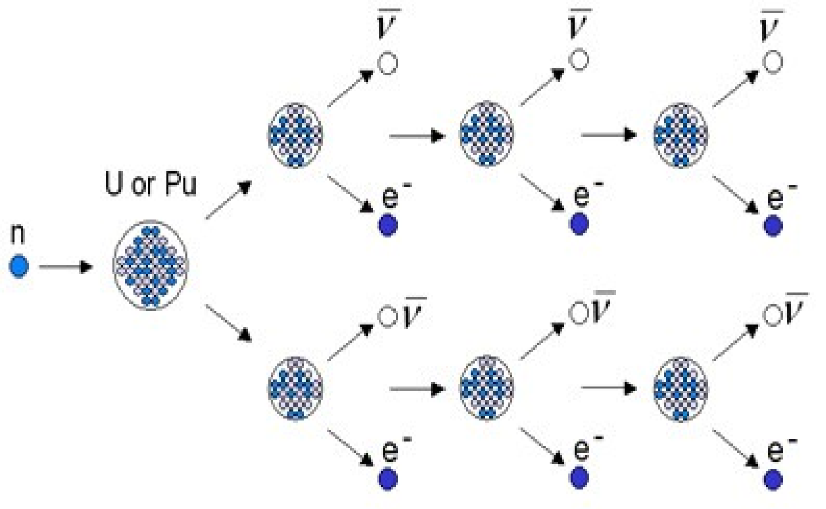
Motivations

How to detect $\bar{\nu}$

Detector set-up

R&D and prototyping

Power reactor core antineutrinos



Antineutrinos are directly produced in fission (~10^{20} $\bar{\nu}$/s)

Counts/day in organic scintillator detector (water-like)

$$10^6 \times V(m^3) \times P(GW) \;/\; D^2(m^2)$$

~ 6000 ev/d @ 1m^3 P=3GW D=20m

$\bar{\nu}$ flux proportional to power

Integrated counts allow to monitor the reactor power

$\bar{\nu}$ energy spectrum related to isotope decay

antineutrino energy spectrum reveals the reactor core isotopic composition (^{235}U and ^{239}Pu)

Why antineutrinos?

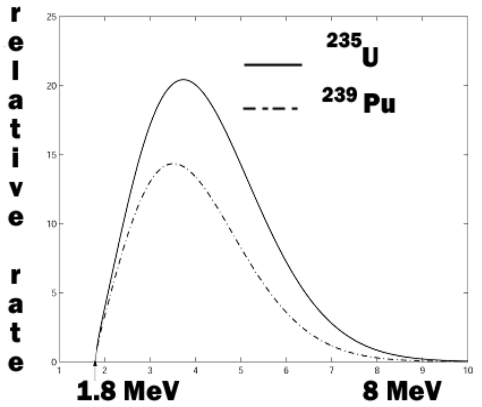
This is NOT the simplest way to monitor a reactor but ...

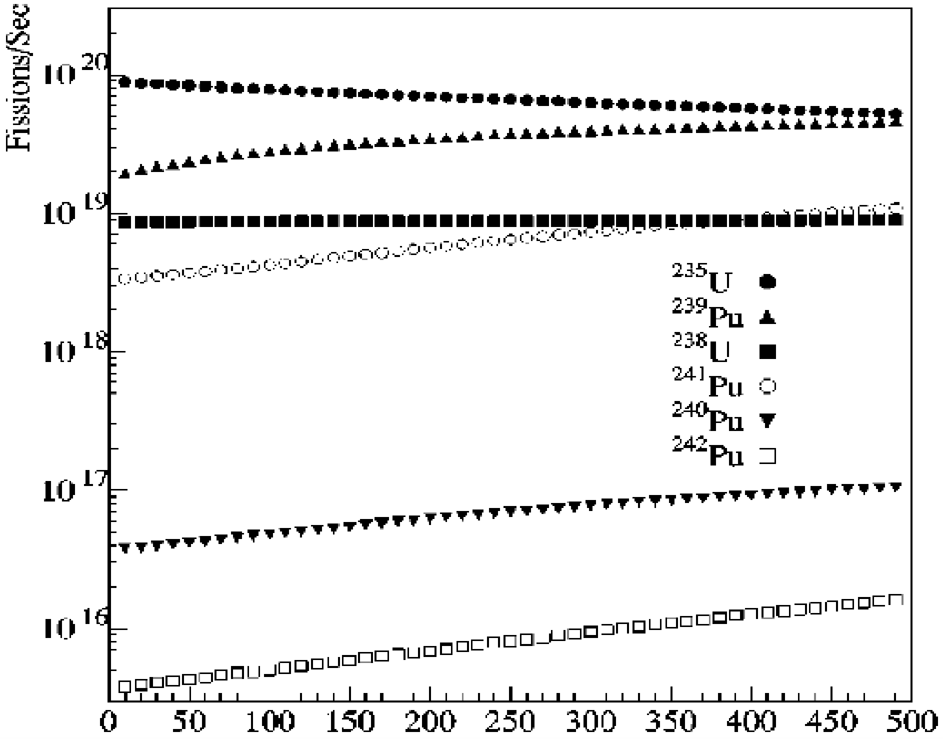
- **independent on-line monitor of the reactor power**
- **the measurement is performed outside the core (safety issues) and does not affect the normal plant operations**
- **detector installation does not need any engineering work and can be done anytime in any plant**
- **antineutrino can not be shielded and are only sensitive to fission material**
- **direct measurement of core nuclear activity and fuel burn-up**
- **early detection of unauthorized plutonium production and subtraction (sensitivity down to 10th kg)**

Core isotopic composition

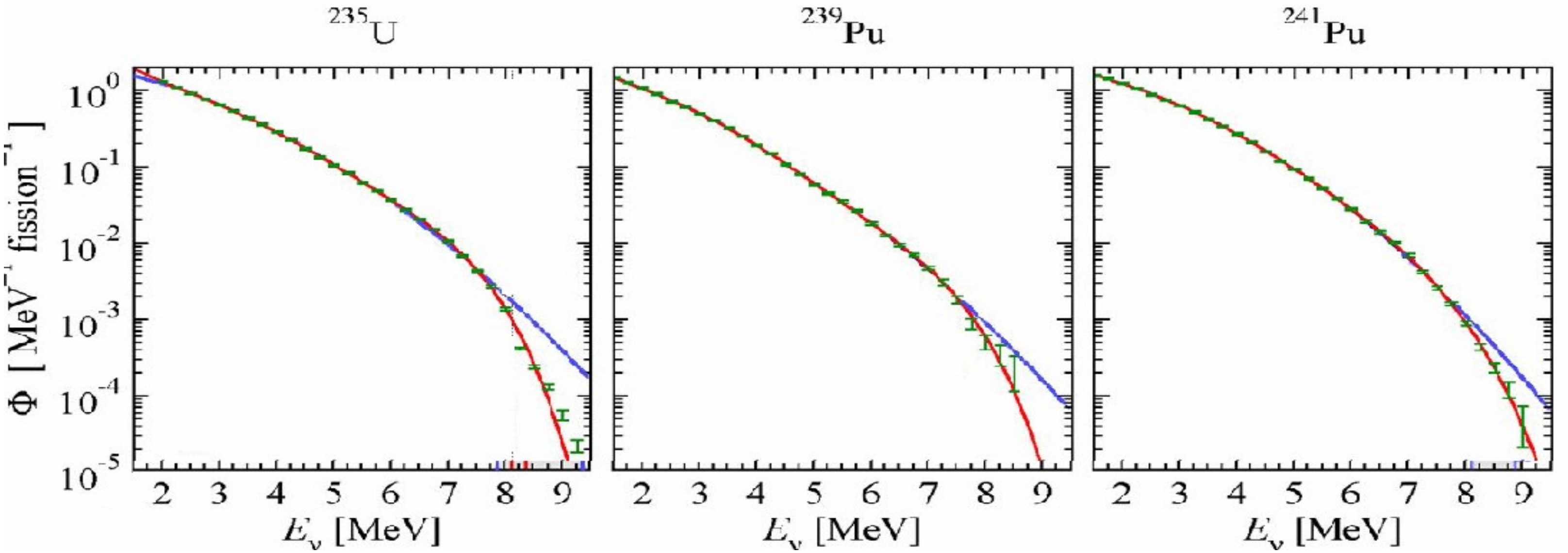
- **Antineutrino rate varies with time and isotope**
- **As reactor fuel burns the composition change**

*Bernstein, et al., J. Appl. Phys.: **91** (2002)*





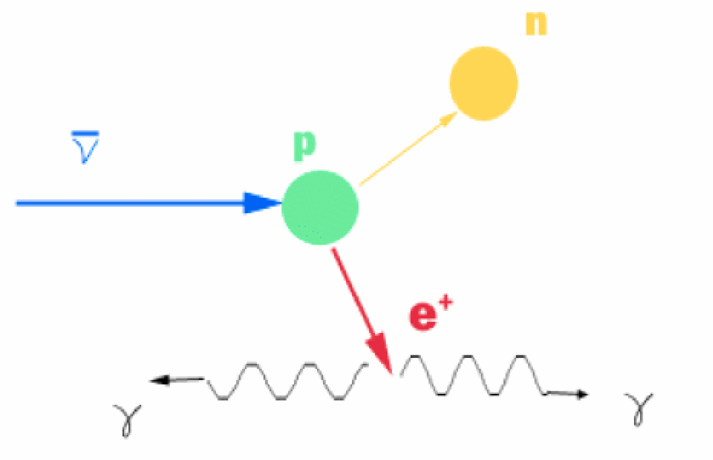
Antineutrino energy spectrum



How to detect antineutrinos?

both detected

Inverse beta decay: $\nu\, p \rightarrow \beta^+\, n$



E_ν

- Reaction threshold E_ν=1.8 MeV

  → reactor-off contribution (long-life isotopes emitting low E_n) is negligible!
- E_ν (1.8 - 7 MeV)

β+

- $E_\nu \sim E_{e+}$
- few MeV positron: ionization
- $e^+ e^- \rightarrow \gamma\gamma$ (2 x 0.511 MeV)
- prompt signal (t<1μs)

n

- thermalization ($np \rightarrow np$)
- capture on nucleus A
- γ cascade (E_{tot} = 2-8 MeV)
- delayed signal ($\tau \sim$ 5-100 μs)

Measured:

- energy deposition
- time interval

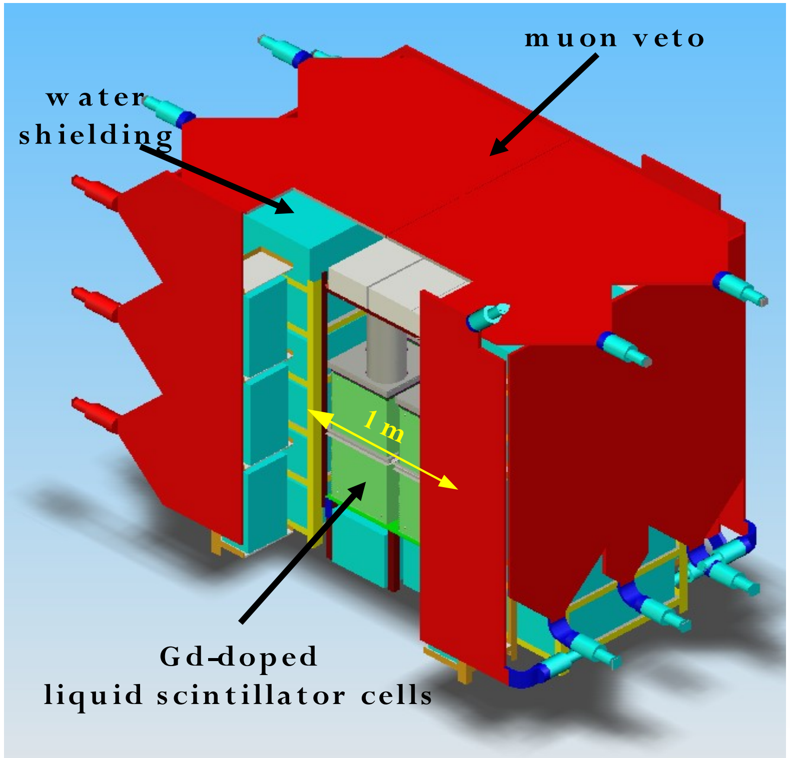
Detector requirements

Inverse beta decay: $\nu\ p \rightarrow \beta^+\ n$

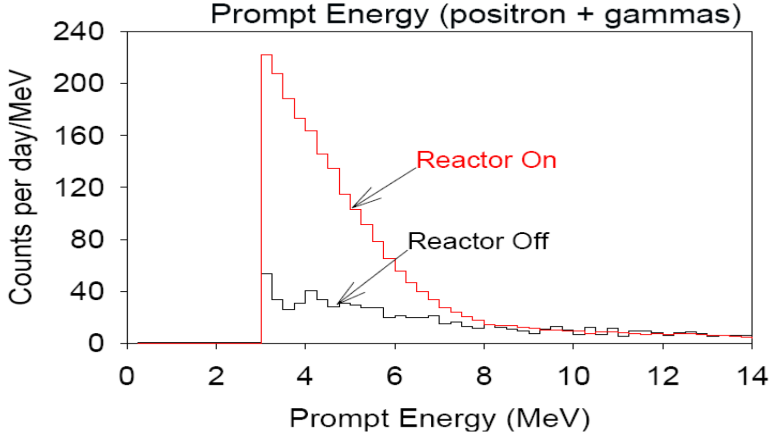
- proton rich target
- active target to detect e+ ionization
- ~1 m^3 target volume (low $\sigma_{\nu\ p \rightarrow \beta+\ n}$~$10^{-43}cm^{-2}$ @ E_ν~MeV)
- high segmentation for background rejection
- homogeneous target to have good e+ energy resolution
- clear signature for neutron capture
- small n-capture time (τ_{cap}) to reduce e+/n time coincidence window
- good cosmic rays background rejection

Does it work?

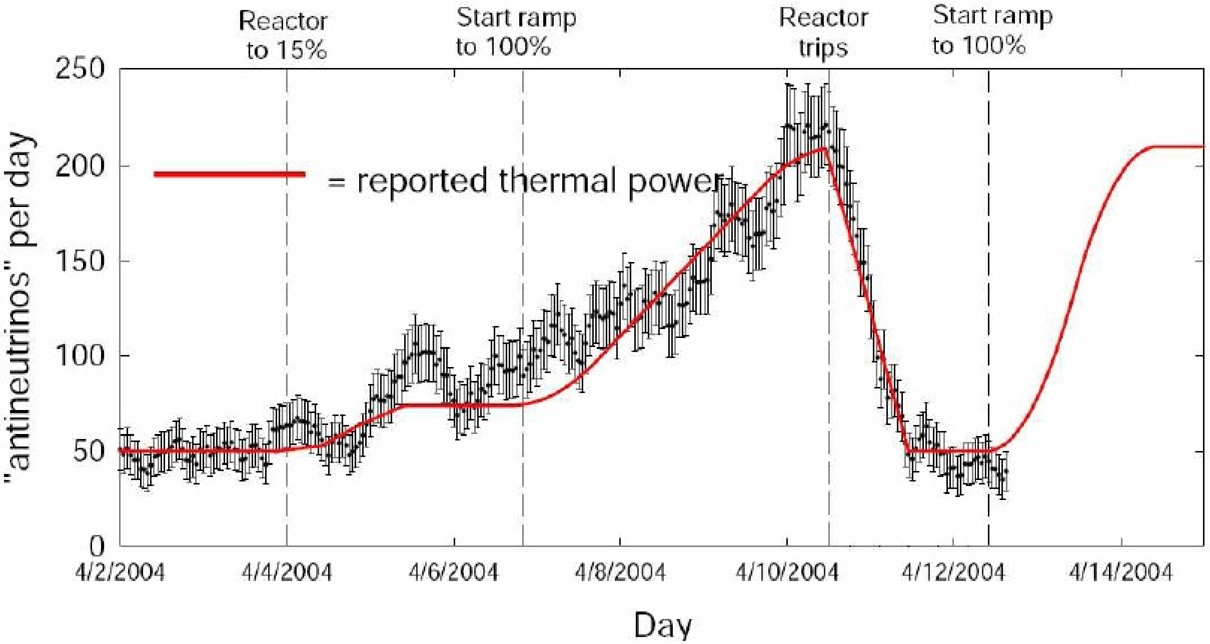
Sandia National Laboratory antineutrino detector (SONGS1)
S.Onofre (Ca) 3.5 GW commercial power plant

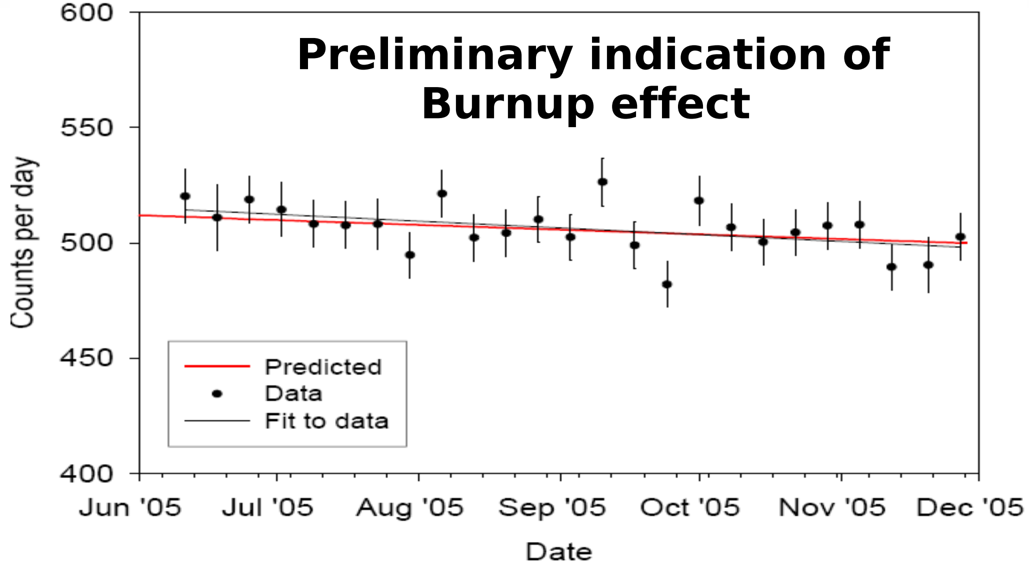


Detection efficiency (10.7±1.5) %



★ **Daily power monitoring using only antineutrinos**

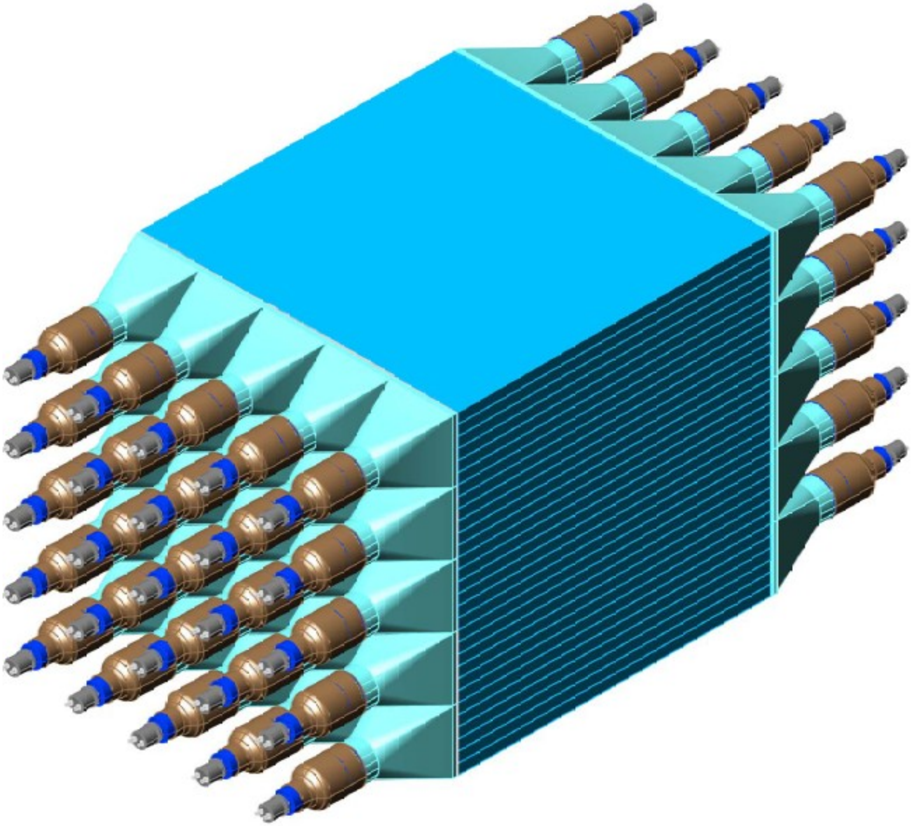



Preliminary indication of Burnup effect

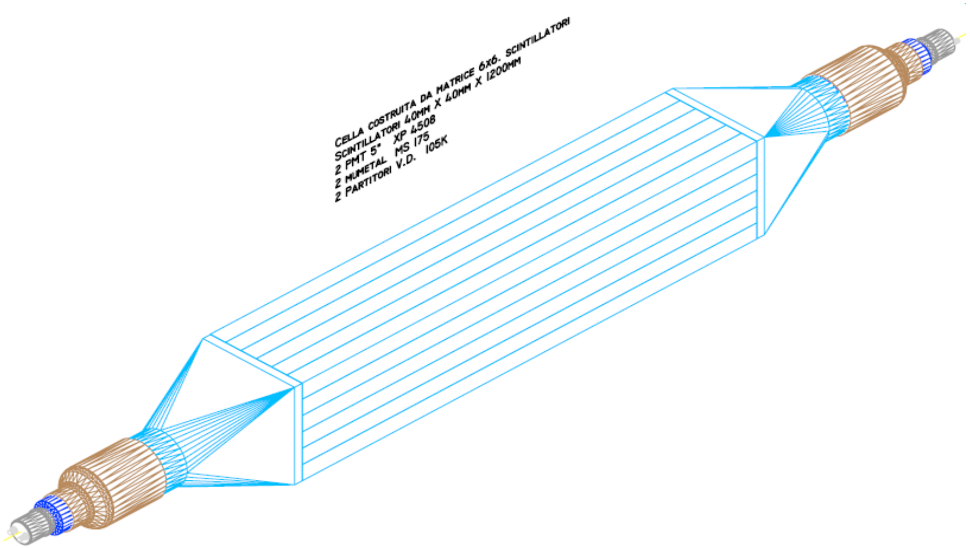
CORMORAD

CORe MOnitoRing by Antineutrino Detection

- **Project part of the INFN-E strategic plan and in the INFN-Ansaldo agreement**



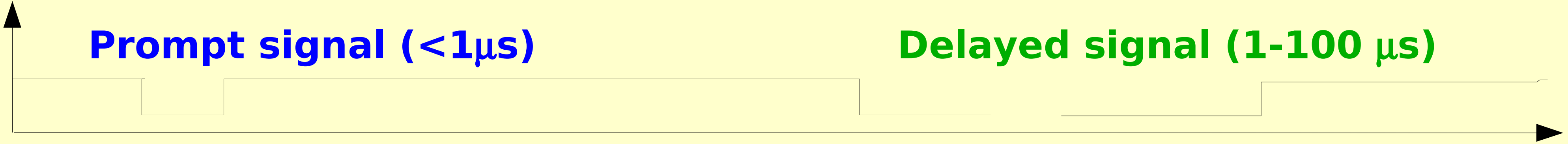
- **3'' PMT on Each side**
- **10-15% of produced light collected**
- **minimum light attenuation**
  a.l. of plastic scintillator ~300cm@425nm
- **A total of 36+36 PMTs**
- **ADC and TDC read-out**



- **Active volume: 0.6 x 0.6 x 0.6 m^3**
- **(3 x 3) x 4 x 4 = 144 plastic scintillator bars wrapped in 12.5μm Mylar-Gd foils**
- **Bar sizes: 5 x 5 x 60 cm^3**

Reaction selection and bg rejection

Signal $\nu\, p \rightarrow \beta^+ n$



Prompt signal (<1μs)

Delayed signal (1-100 μs)

- antineutrino interact with H in plastic
- positron releases energy within a cell
- Then annihilates
- two gammas mainly interact via Compton scattering
- $E_\nu \propto E_{Prompt} = E_{ion} + 2 \times 0.511$ MeV
- $N_{hit} > 2$

- n thermalizes ($np \rightarrow np$)
- tenth of cm (> cell size)
- capture on A
- delayed signal ($\tau \propto 5\text{-}100$ μs)
- $E_{Delayed} = E_{elastic} + 7\text{-}8$ MeV
- High hit multiplicity

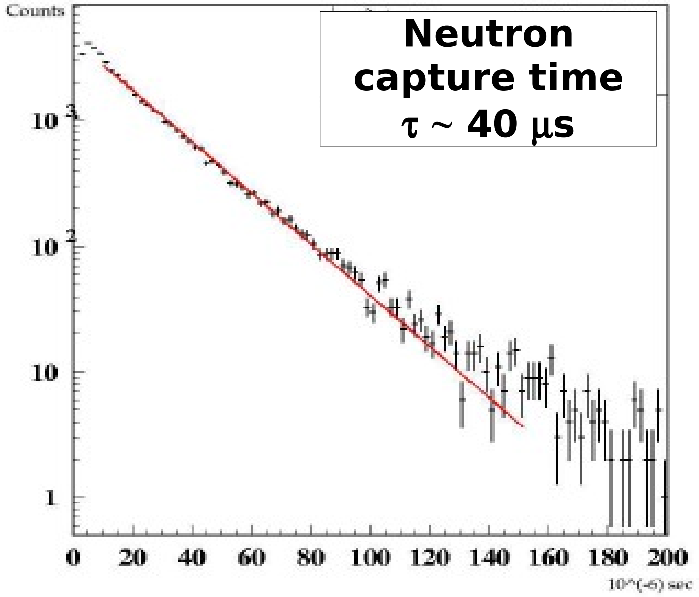
Background

- Atmospheric and solar → negligible
- Cosmic muons
  random coincidence in a wide time-window → tracked and rejected
- Residual radioactivity in PMTs and surrounding material in off-line analysis
- Spallation neutron
  slowed down by elastic np scattering
  p fast signal (similar to e+)
  n delayed signal (as in inverse β decay) → the real issue!

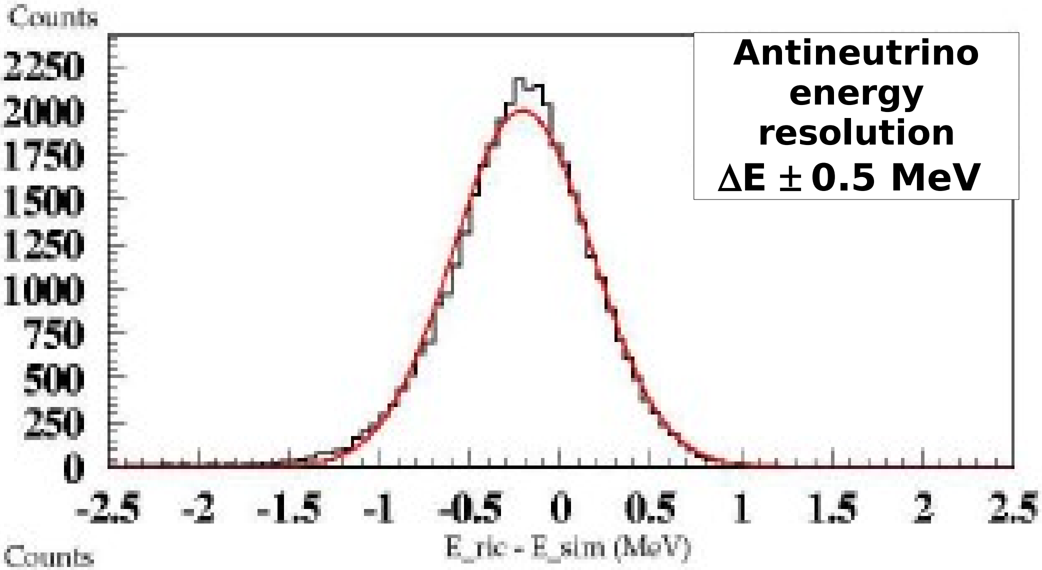
same time-coincidence signature
rejected by using hit multiplicity
need segmented detector !

Expected performance and results (GEANT4)

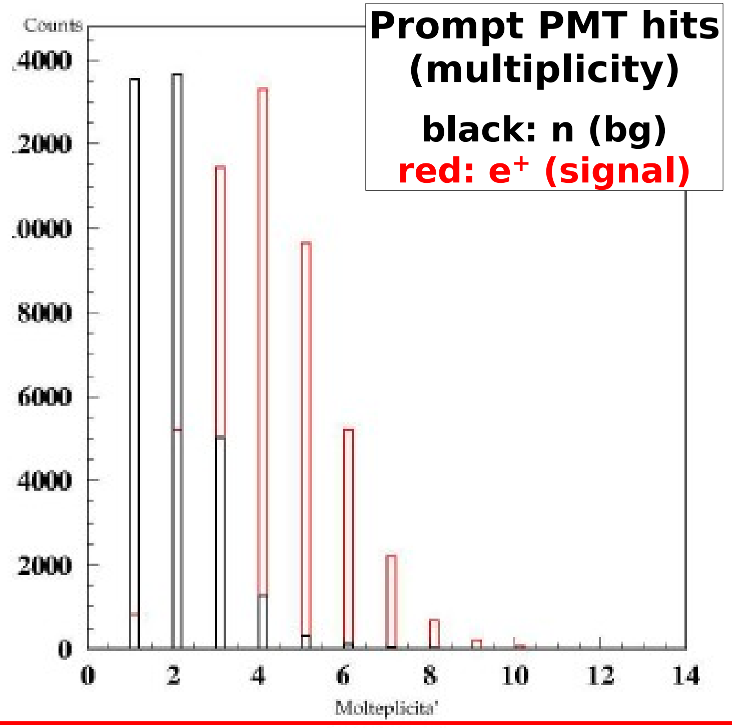
R. De Vita



Neutron capture time
τ ~ 40 μs

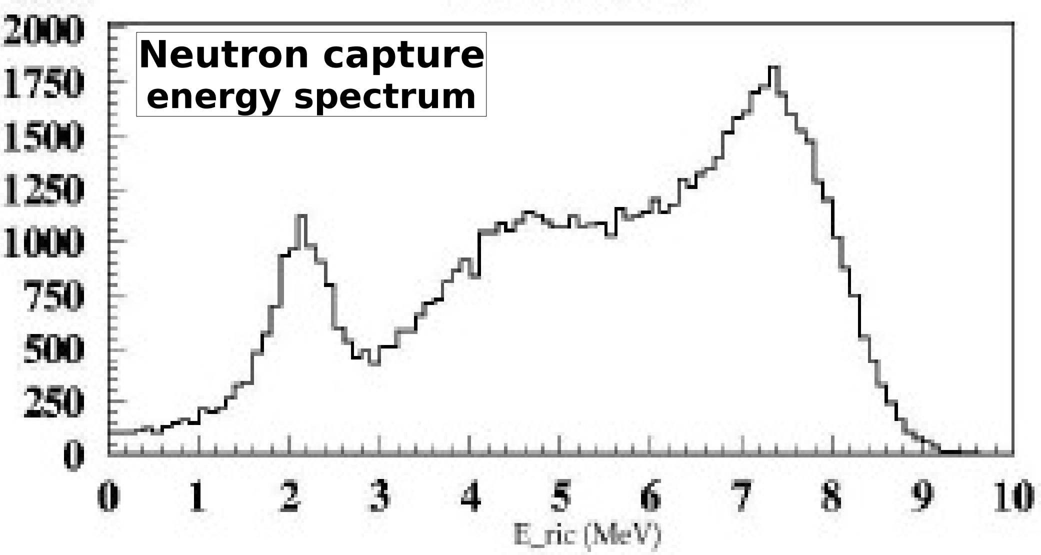


Antineutrino energy resolution
ΔE ± 0.5 MeV



Prompt PMT hits (multiplicity)

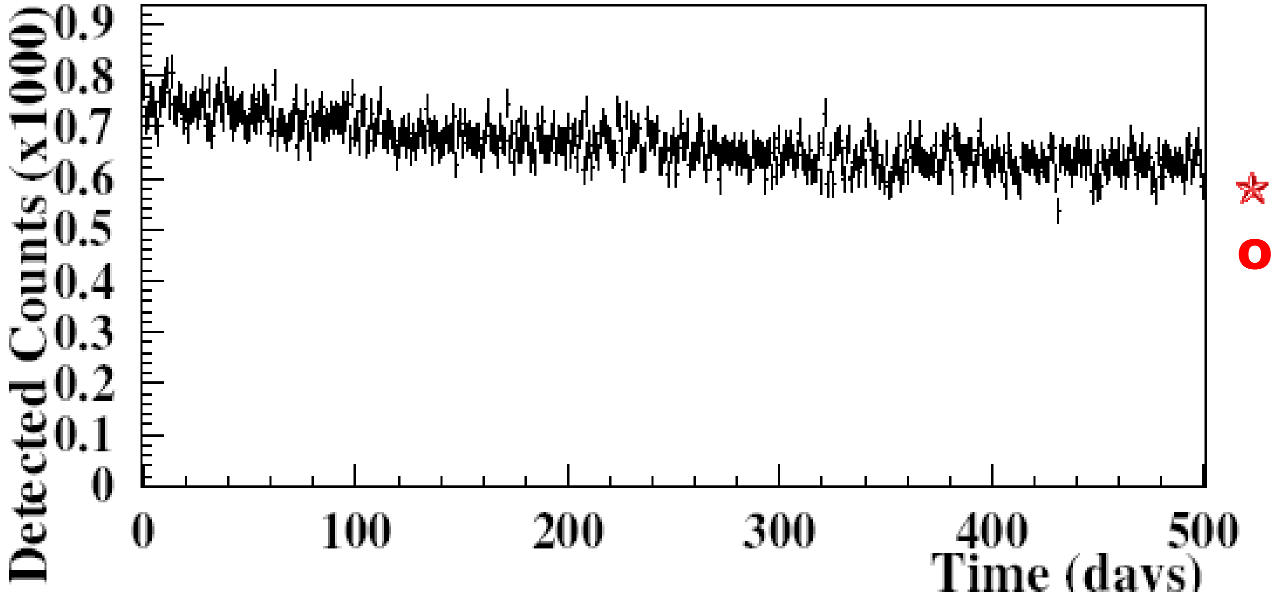
black: n (bg)
red: e^+ (signal)



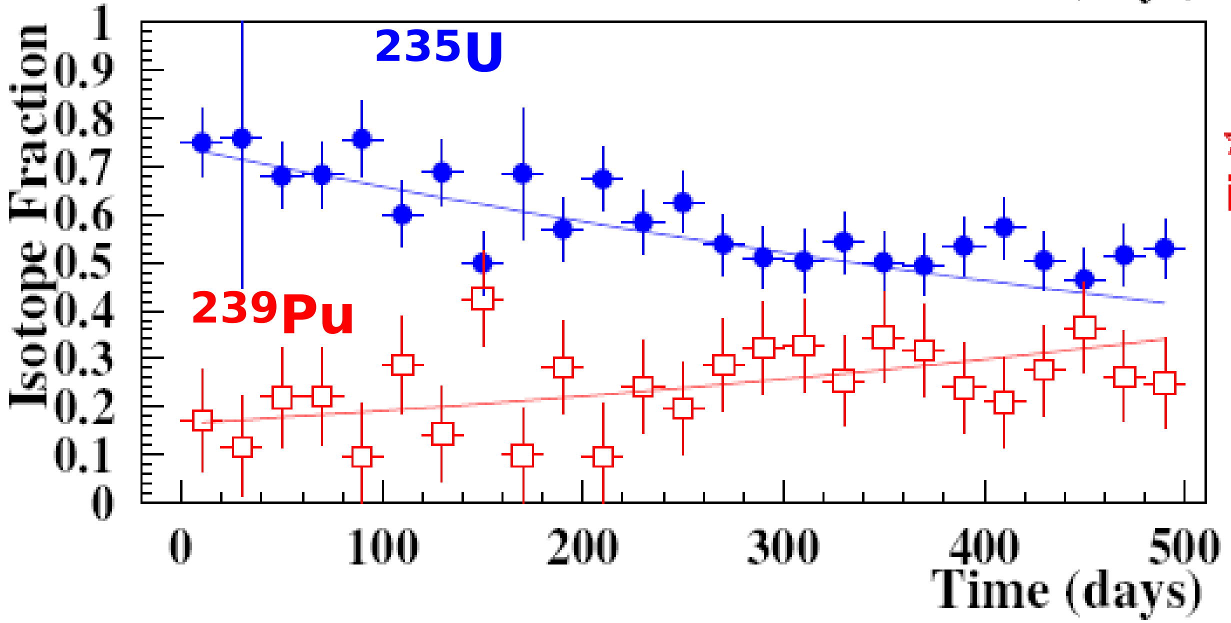
Neutron capture energy spectrum

Detection Efficiency ~ 40%

Expected performance and results (GEANT4)



- **Power plant monitor on daily base**

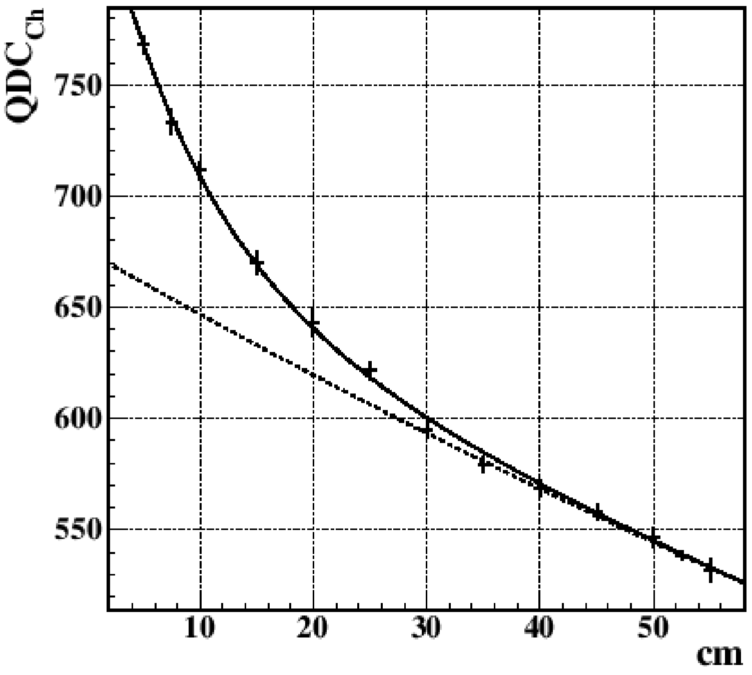


- **Fuel burn-up integrating over 10 days**

R&D and prototyping

G. Firpo

- Attenuation length (cm)



BC525: 26.3±0.7 (HiFi)

32.1±1.3 (3M)

Liquid

BC408: 294±93 (Mylar)

EJ200: 286±45 (3M)

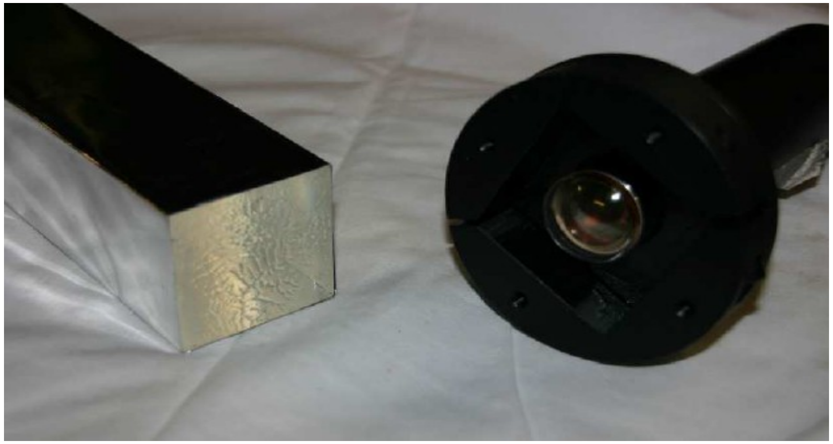
243±45 (HiFi)

232±39 (Mylar)

Plastic

NE110: 106±12 (Mylar)

JINR: 86±14 (Mylar)

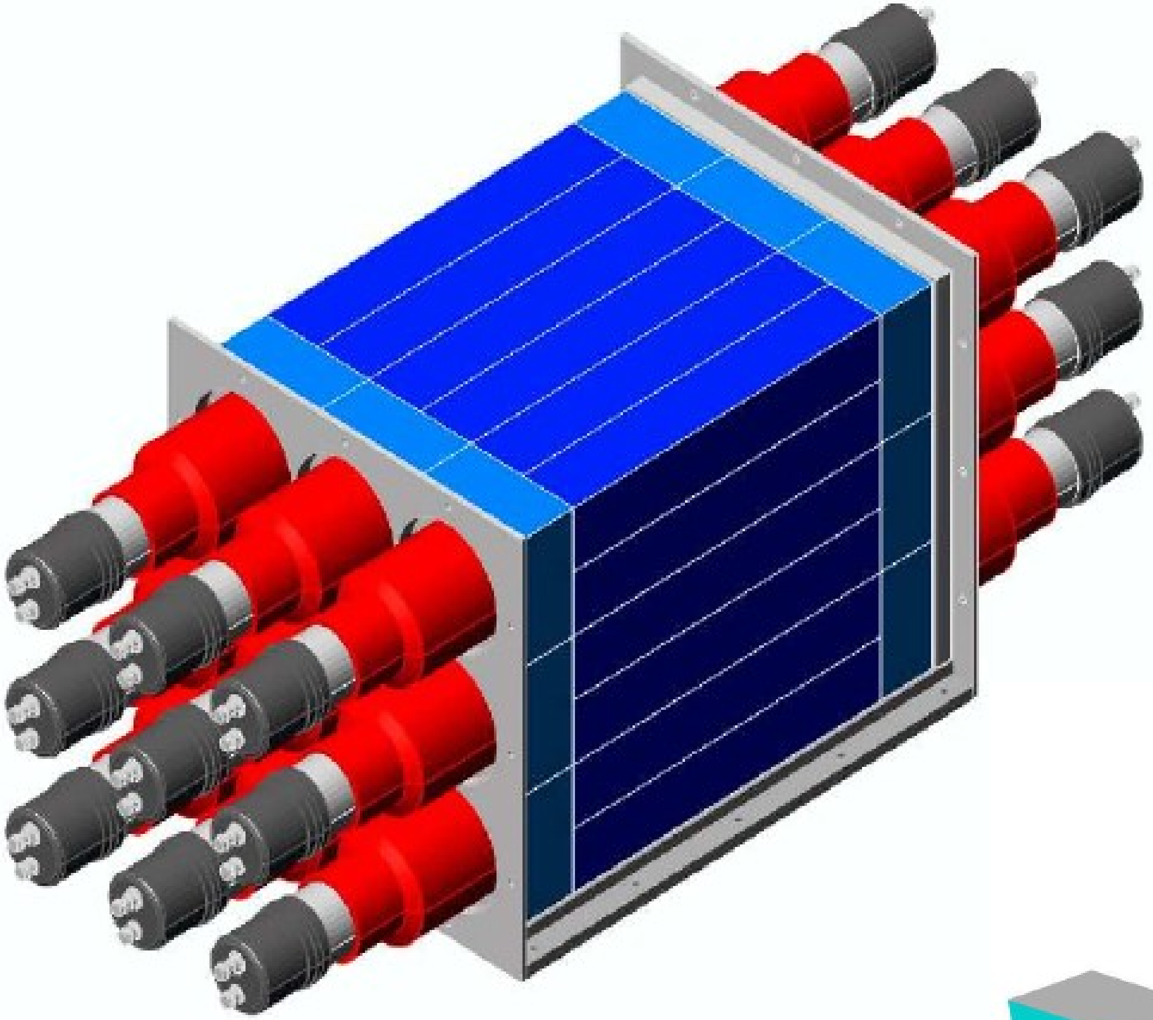


- Energy resolution (e- @ 478 keV)

BC525	BC408	NE110	EJ200
30%	14%	18%	16%

- Time resolution: σ_t~170 ps
- Space resolution: σ_x~8 cm

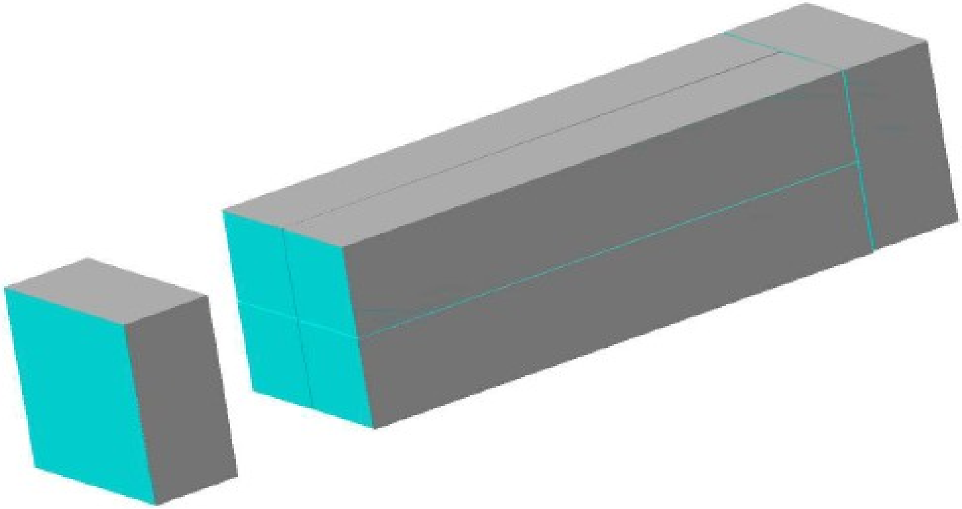
Scale 1:3 prototype

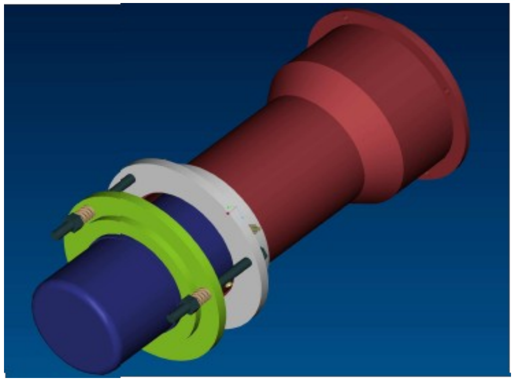


- Size: 40 x 30 x 30 cm^3

Prototype cell

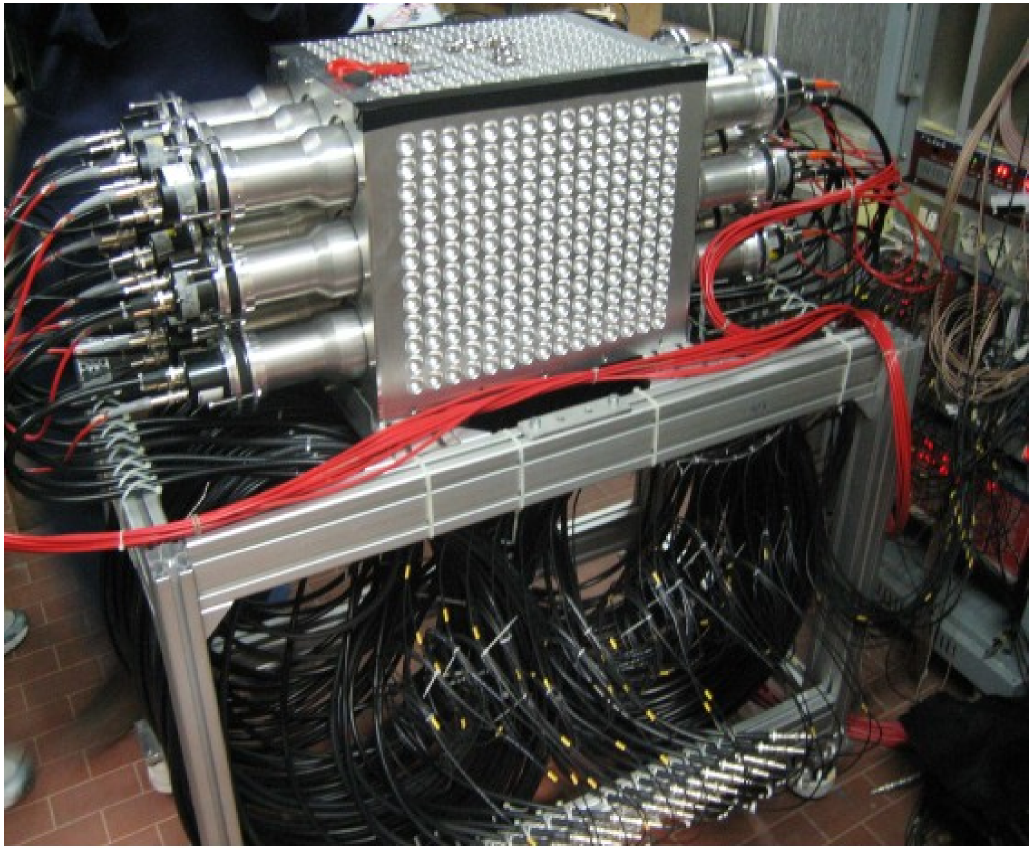
- 4 30x5x5 cm^3 NE110 bars
- 1 5x10x10 cm^3 NE110 block
- 12.5 μm Gd foils wrapping





- Light read-out: 18 Photonis XP2312 3” PMTs

R&D and prototyping

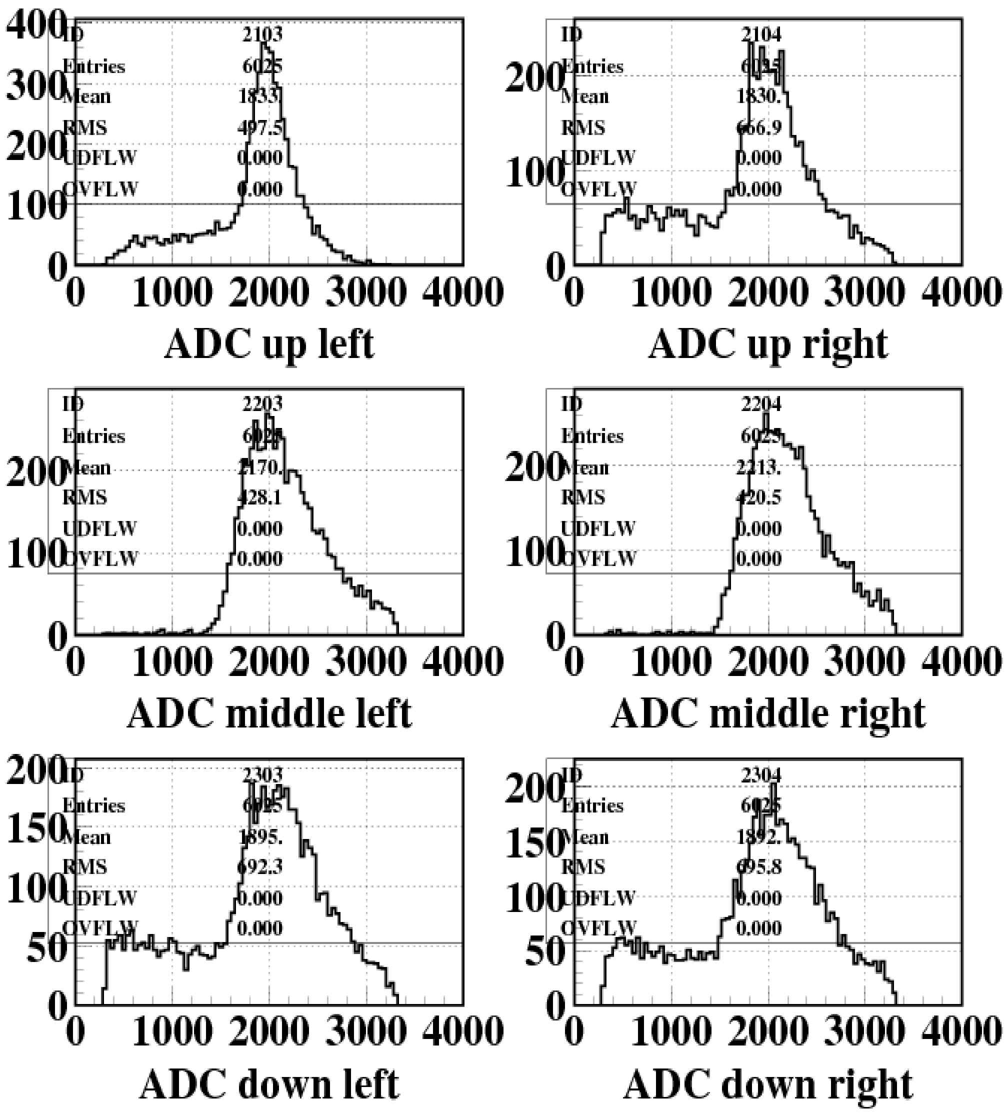


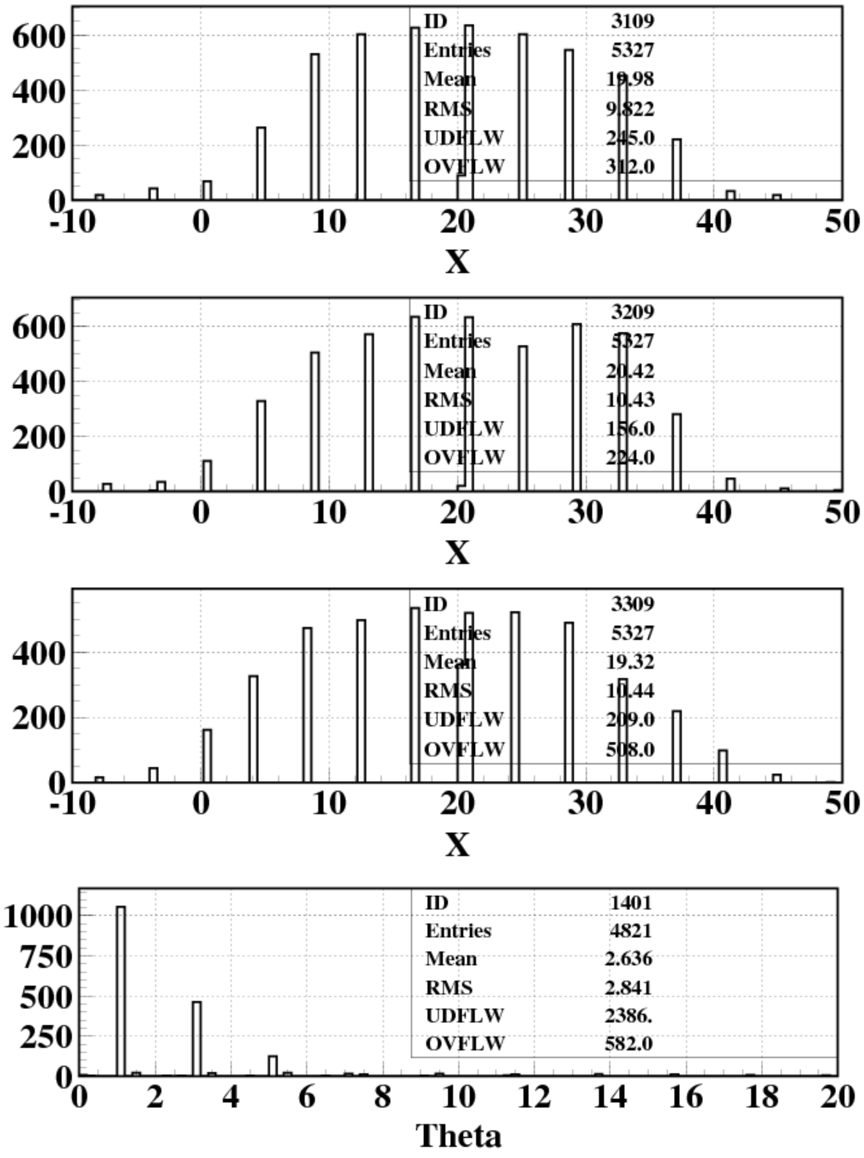
Energy and time calibration using cosmic rays

R. De Vita

- Self calibration (Up/Middle/Down crossing)
- 12dB attenuation (x0.25) to avoid saturation
- All peaks at ADC_{ch}=2000 (1.35 10^{-3} MeV/ch)

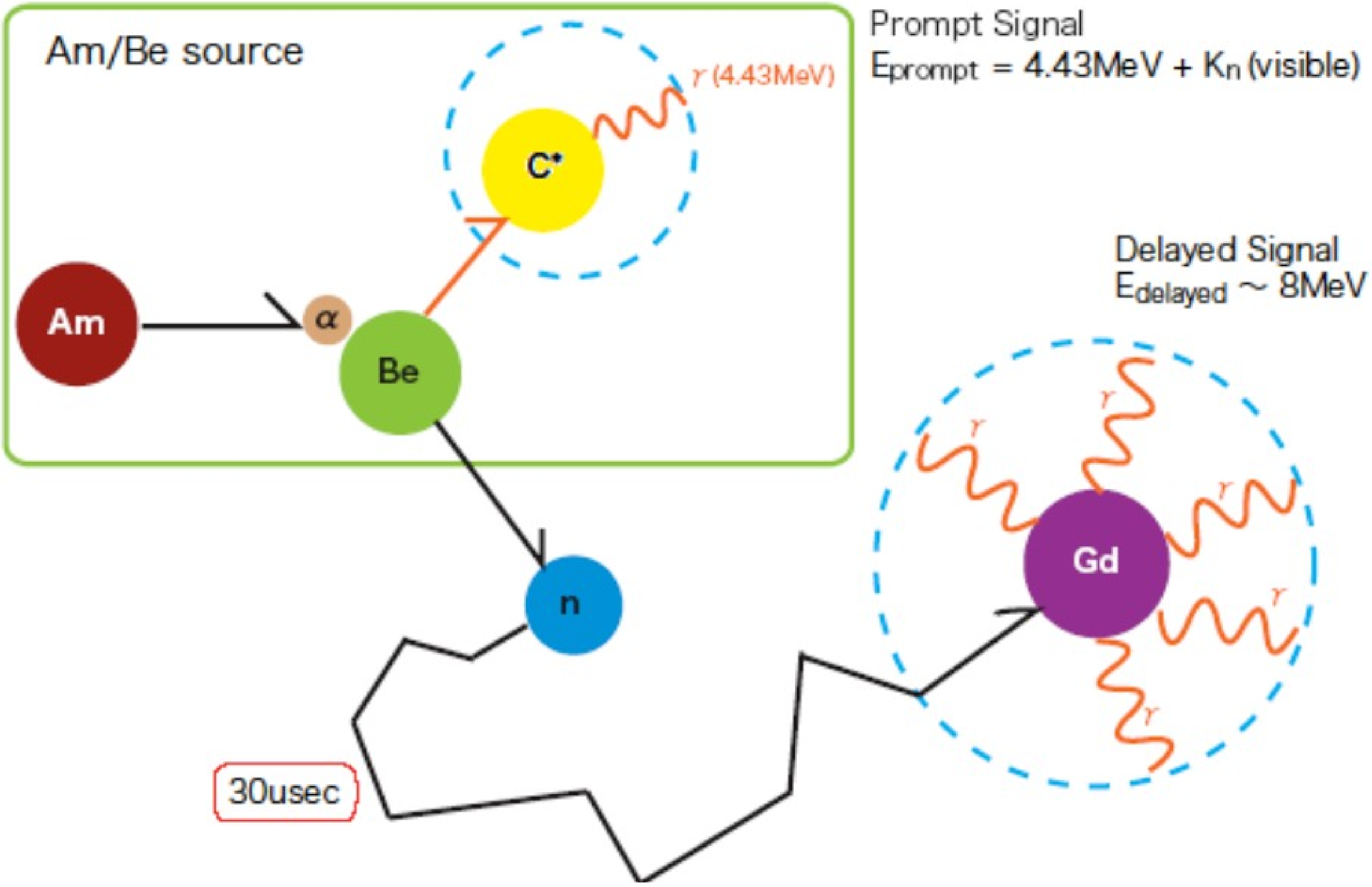
- Position = (V x ΔT_{LR}+40)/2 V=13 cm/ns
- TDC res = 625ps → $\Delta x \sim 5$cm





Calibrations: AmBe source

The prompt (gamma) and delayed n capture mimics the anti-neutrino signal



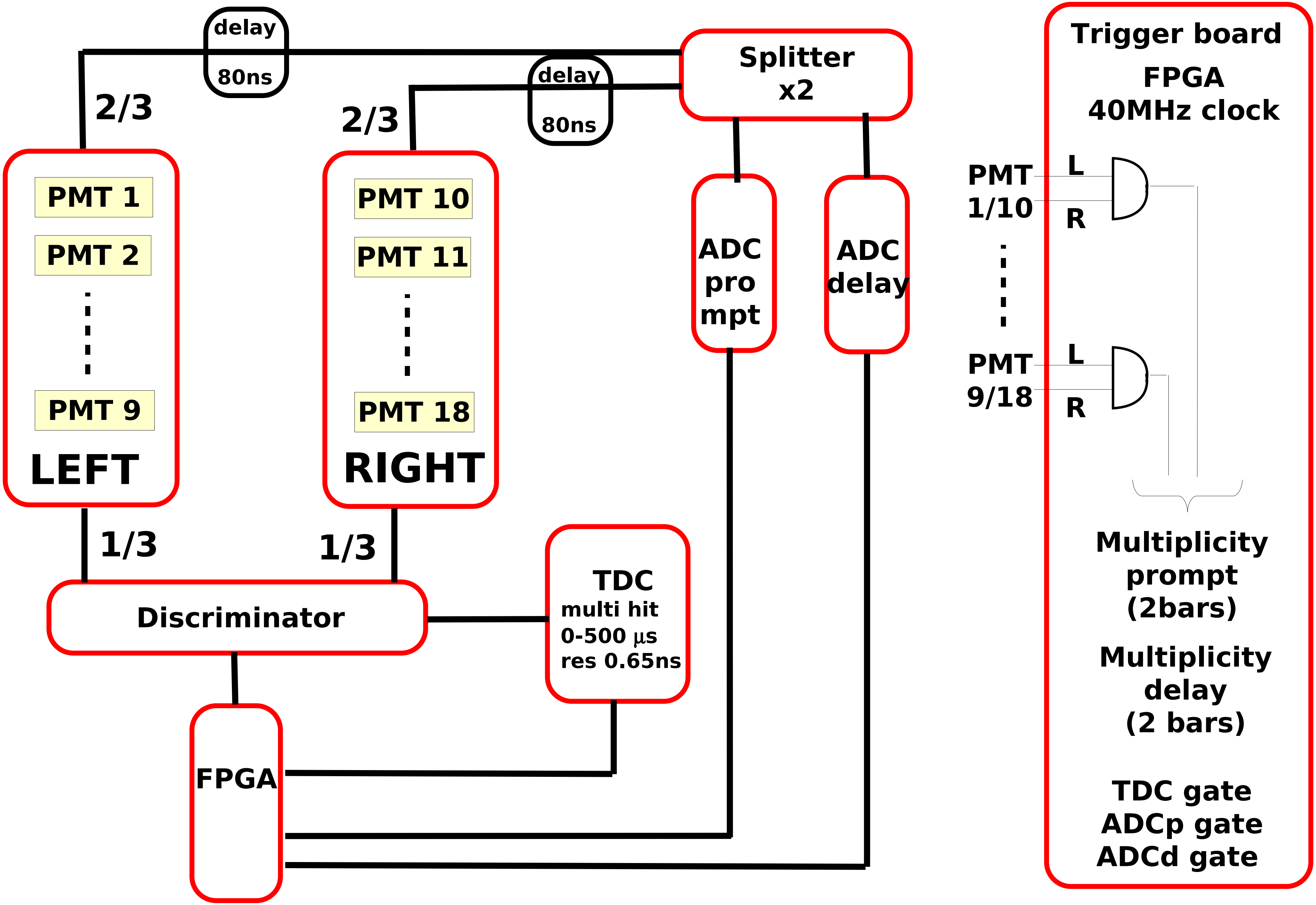
Prompt Signal
$E_{prompt} = 4.43\text{MeV} + K_n$ (visible)

Delayed Signal
$E_{delayed} \sim 8\text{MeV}$

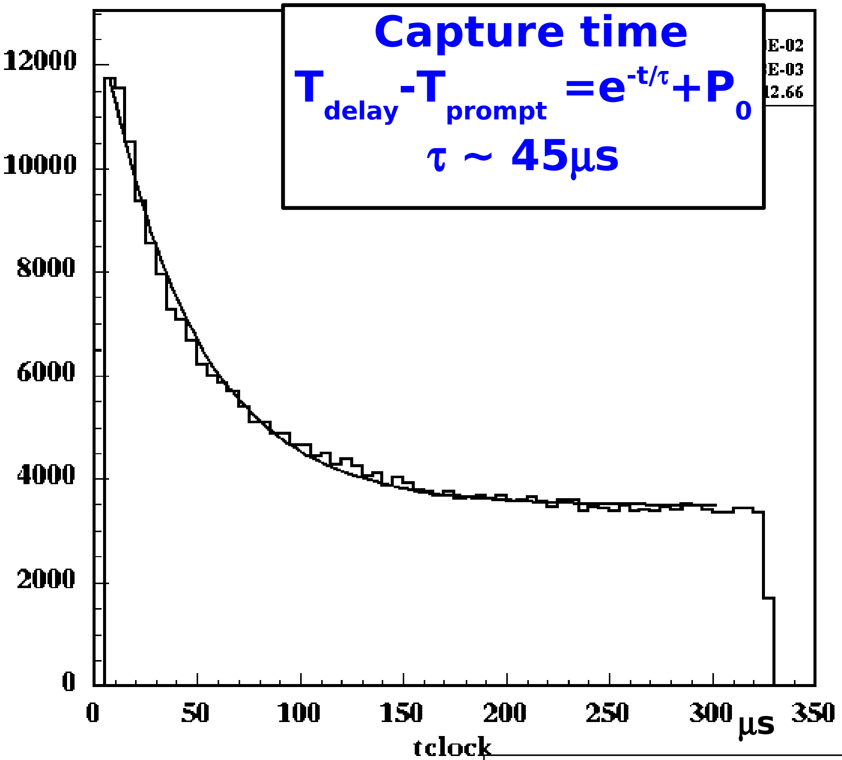
The real double-hit trigger is needed!

DAQ scheme (VME based)

D. Piombo



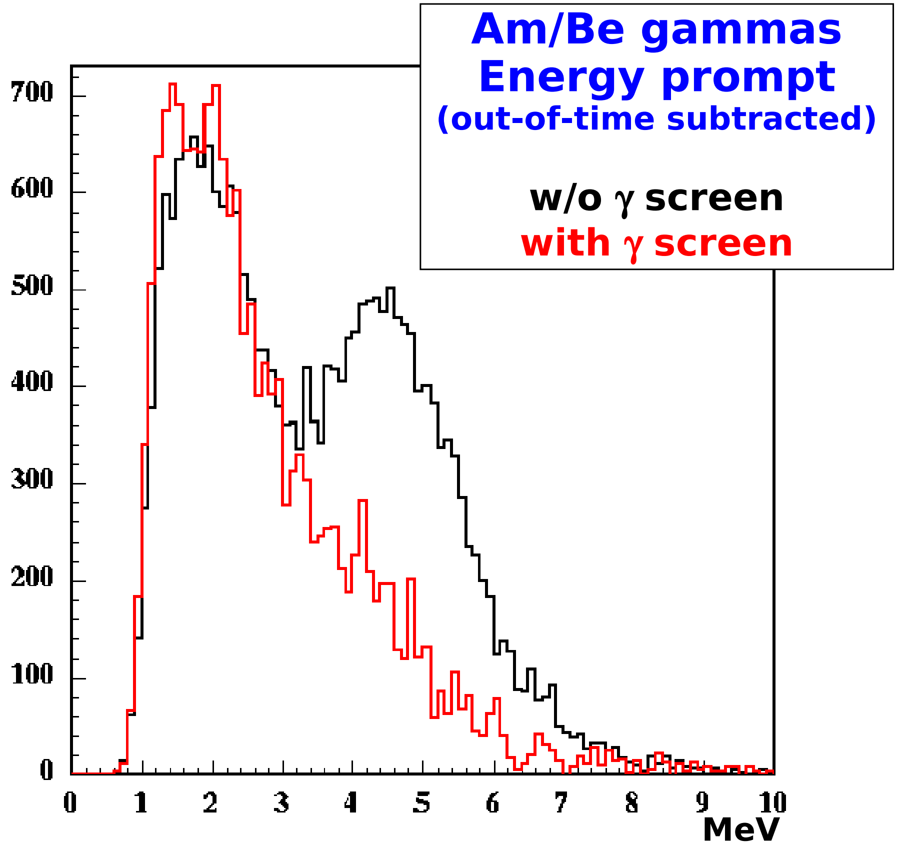
AmBe source



Capture time

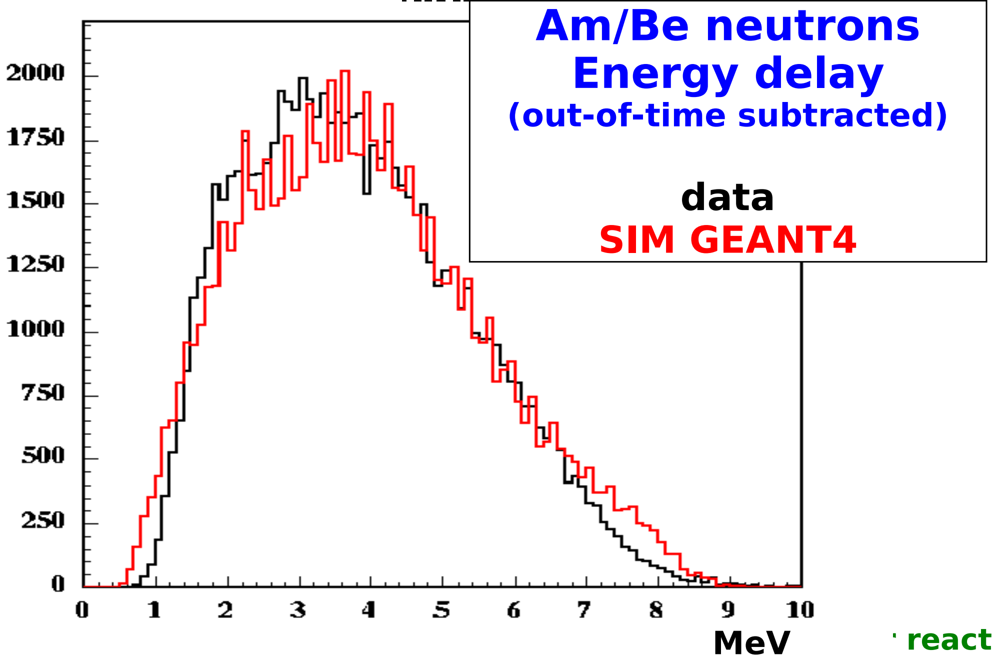
$T_{delay}-T_{prompt}=e^{-t/\tau}+P_0$

$\tau \sim 45\mu s$



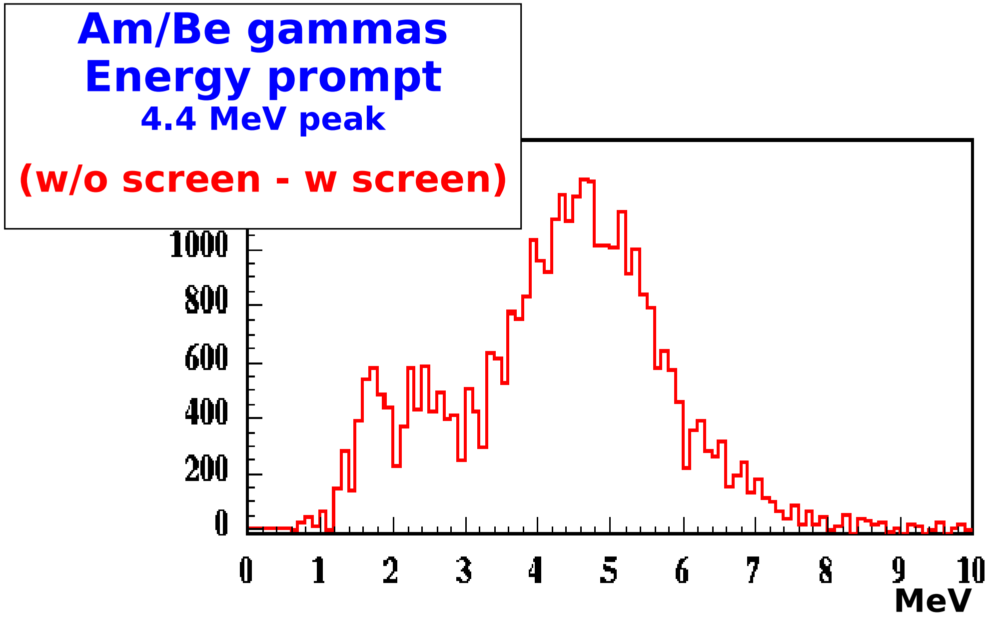
Am/Be gammas
Energy prompt
(out-of-time subtracted)

w/o γ screen
with γ screen



Am/Be neutrons
Energy delay
(out-of-time subtracted)

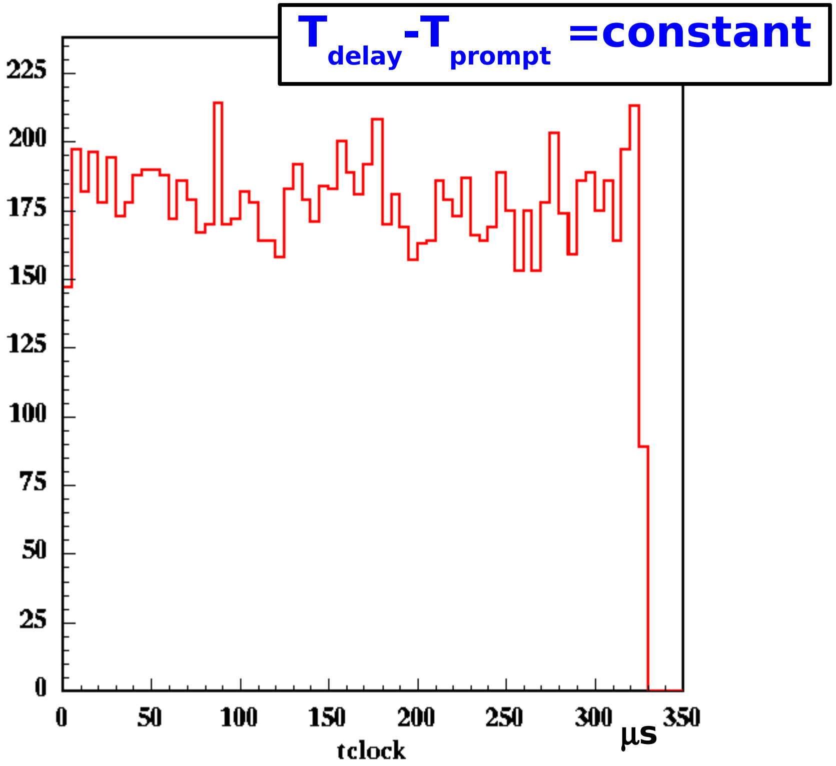
data
SIM GEANT4

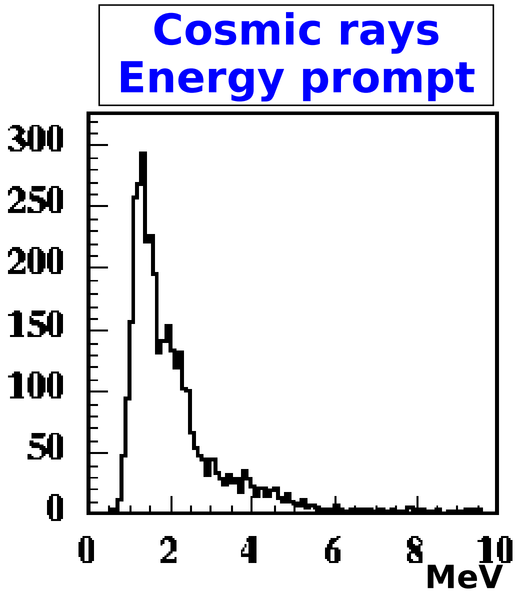


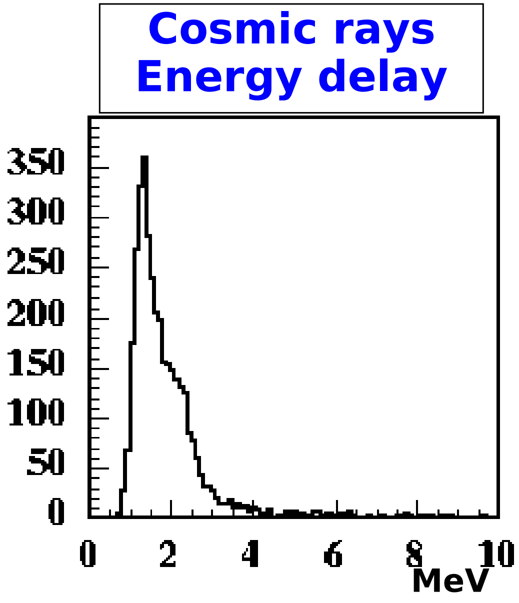
Am/Be gammas
Energy prompt
4.4 MeV peak

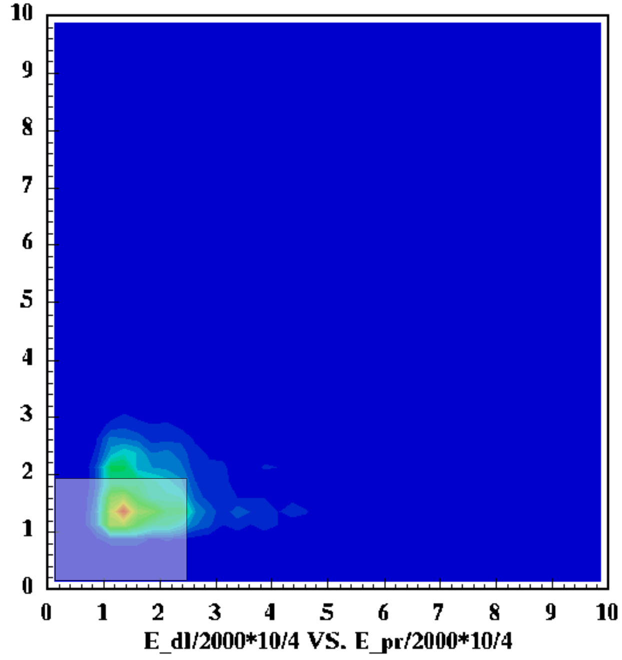
(w/o screen - w screen)

Background: cosmic rays









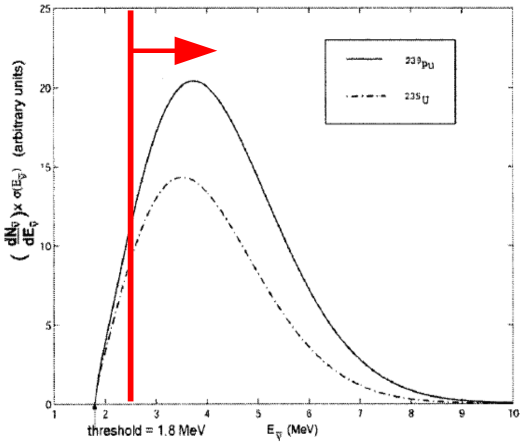
Cuts

- ☆ T< 100 μs
- ☆ Ep>2.5MeV
- ☆ Ed>2.0 MeV
- ☆ Multiplicity P ≥2
- ☆ Multiplicity D>2

Bg	anti-ν
0.2%	20%

Rejection factor:

~500



Need more detailed simulations to reduce bg (work in progress)

Measurement@ Cernavoda (Ro)

Test run in Cernavoda (Ro) SNN nuclear power plant during outage/restart in May 09

2 GW reactor off/on for maintenance
~20m from the reactor core
In-truck movable detector

Test Goals

- In-situ measurement
- Experimental set-up optimization
- Background rates
- Reactor On/Off change
- MC validation
- Data analysis optimization

Expected rates/yields

antineutrino

2000 ev/d/mq/GW

2GW
0.036mq
Detection eff~20%

30 ev/d x 25d = 750 ev

cosmic

100 ev/d

based on home measurement
off-line analysis
rejection ~ 500

x 25d = 2500 ev

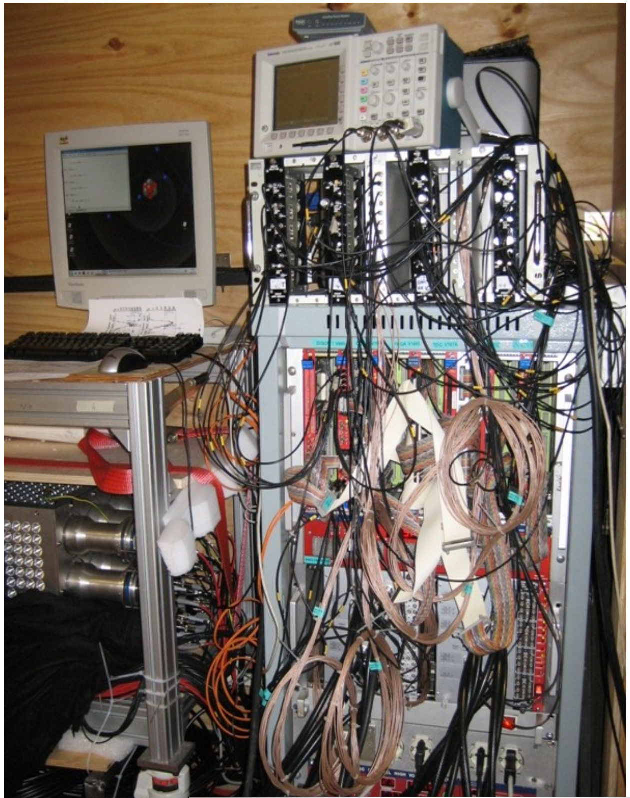
other

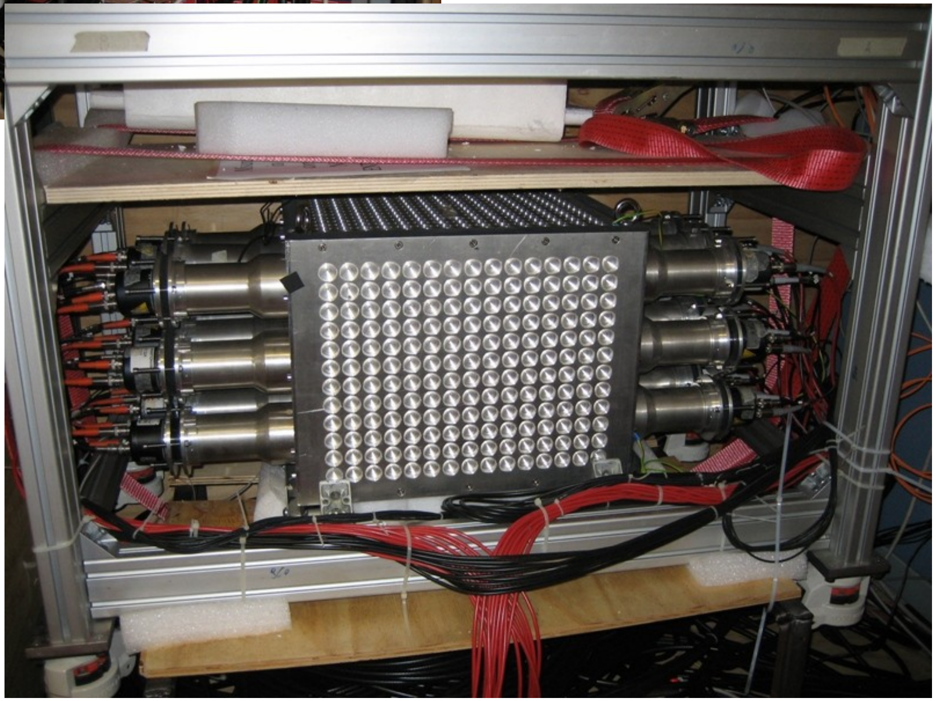
?? ev/d

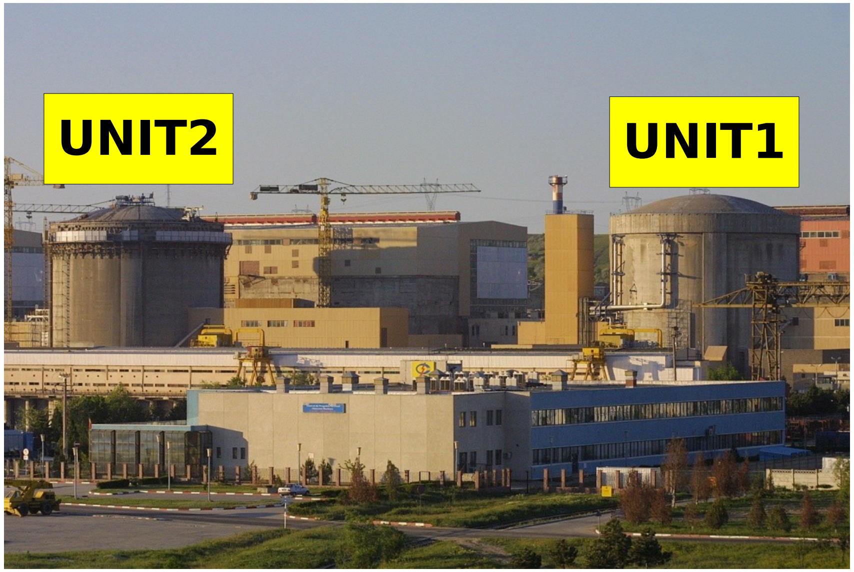
spallation n
residual n flux
residual γ flux

x 25d = ??? ev


DANGER
Radiation risk
Misure in corso NON ENTRARE







- **Detector and electronics mounted in a van and moved to Cernavoda (Ro)**

- **The van has been parked in front of Unit2 where will remain up to June 25th**

- **After 2 days of commissioning it is now taking data with the reactor off**

- **The reactor will be resumed on June 5th**

- **We expect to collect data**
  - **10 days reactor off**
  - **20 days reactor on**

Conclusions

- Antineutrinos can be used to monitor power and isotopic composition of a power nuclear reactor

- Antineutrino are detected via inverse-beta decay measuring the (fast) positron and the (delayed) neutron

- The 1 mq detector we proposed is made by plastic scintillator bars wrapped in thin gadolinium foils

- Segmentation (individual bar read-out) helps in reducing the background

- Extensive GEANT4 simulations shows we expect a 40% efficiency (power monitoring on day base and isotopic composition integrating 15 days of data)

- A prototype, scale 1:3, has been built in Genova and after lab tests, it has been installed in the Cernavoda (Ro) NPP where is taking data up to the end of June

Back-up slides

Data analysis

DATA

SIMULATIONS (GEANT4)

DATA FORMAT

Trigger bits
FPGA ΔT (prompt-delay)
TDC hits (prompt and delay)
ADC prompt
ADC delay

CALIBRATION CONSTANT

ADC/TDC conversion
ADC pedestals
time constants

ANALYSIS PROGRAM

Time cluster recognition
TDC independent analysis
ADC independent analysis

Event builder
ADC/TDC correlated analysis

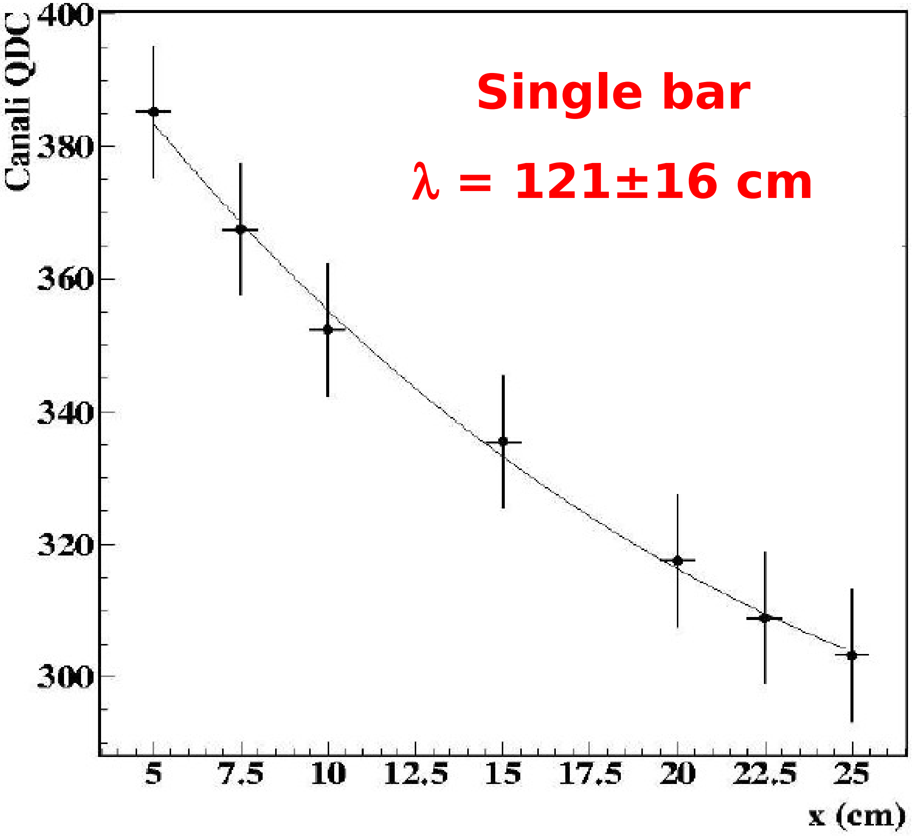
OUTPUT

Raw data
Detector calibration oriented
Prompt/Delay

Attenuation length

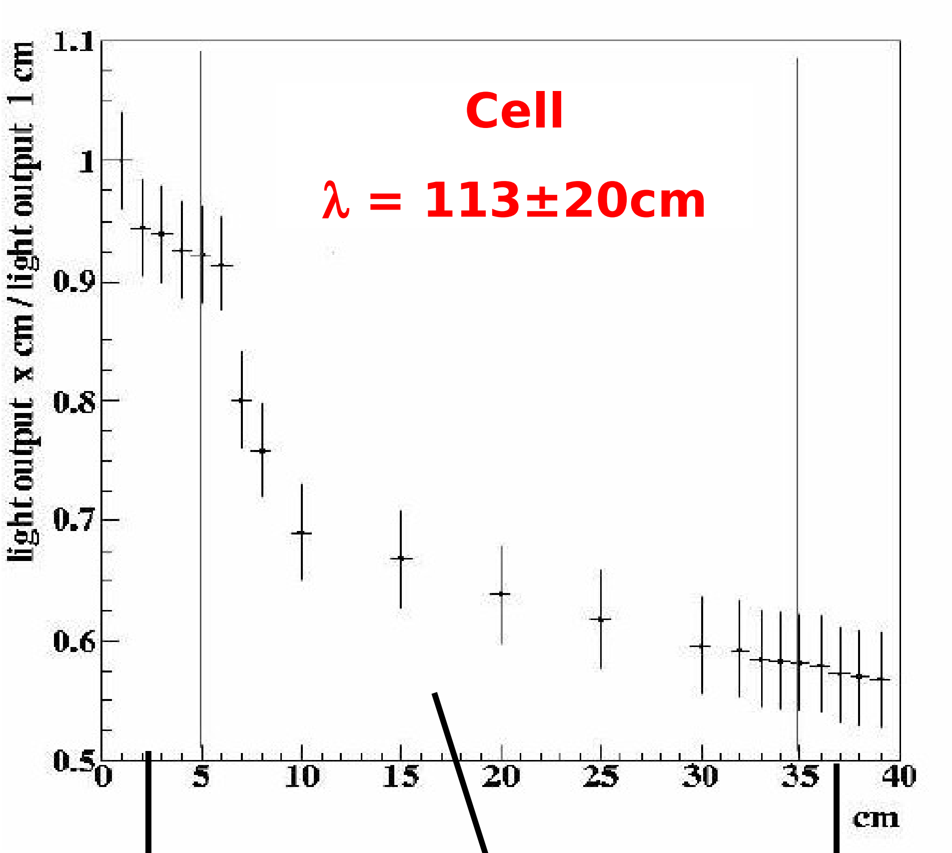
G. Firpo

10% loss at the interface



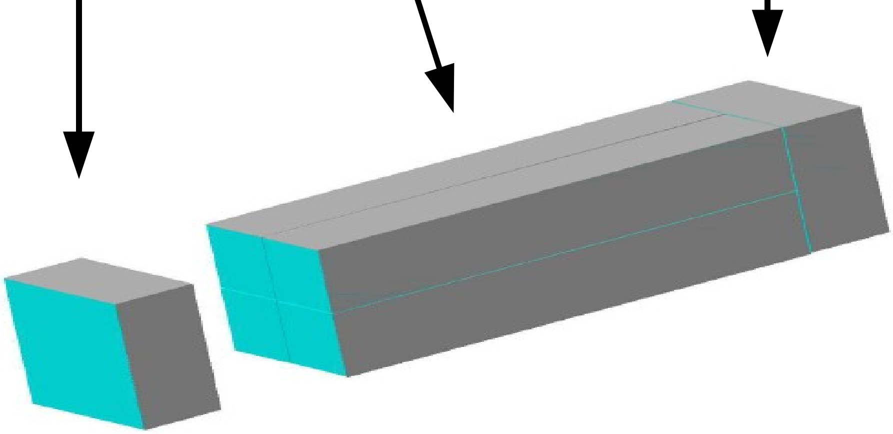
Single bar

λ = 121±16 cm



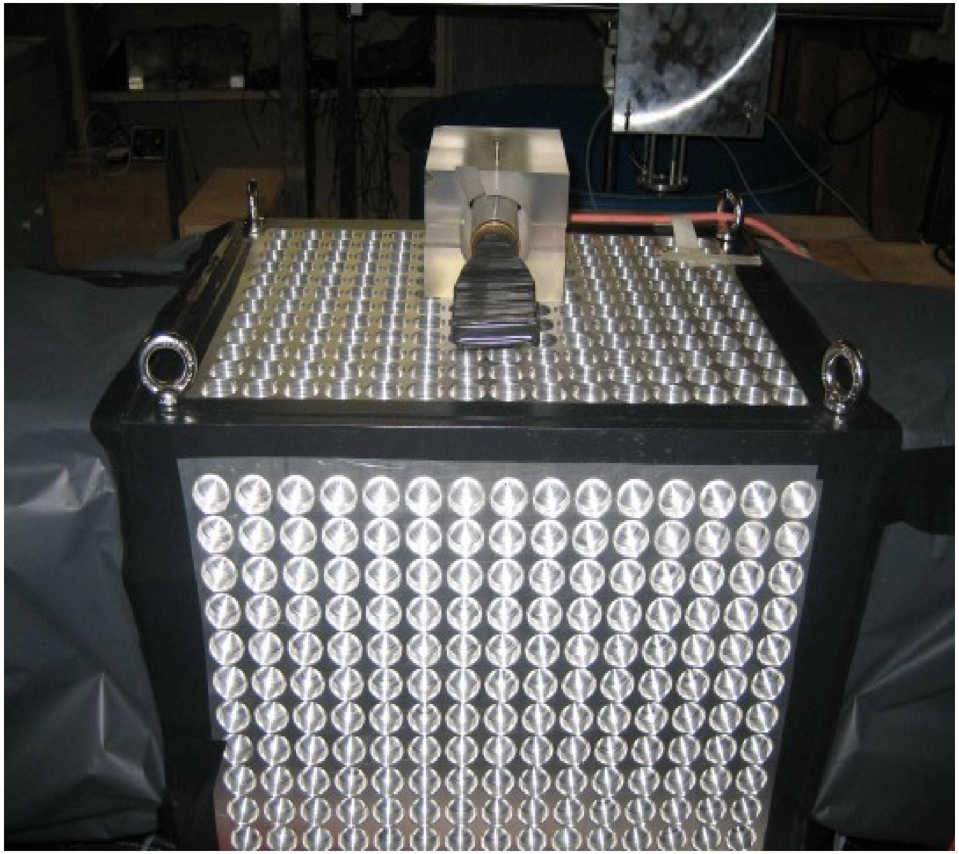
Cell

λ = 113±20cm

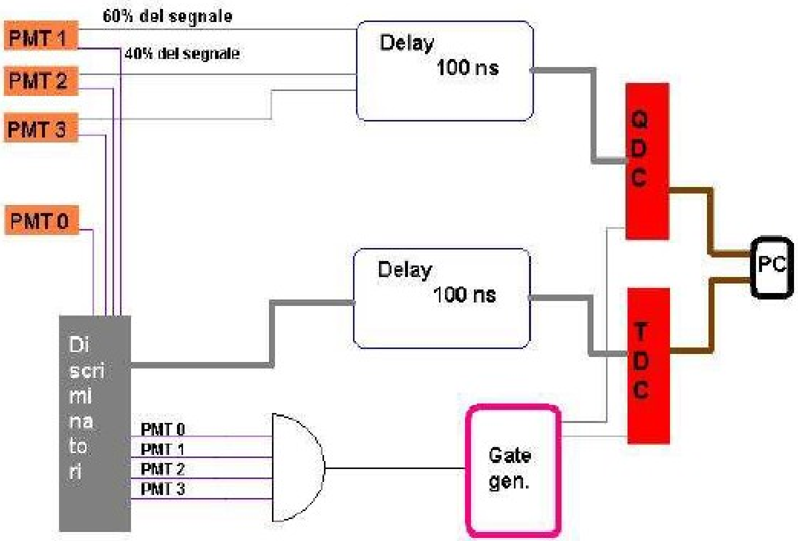


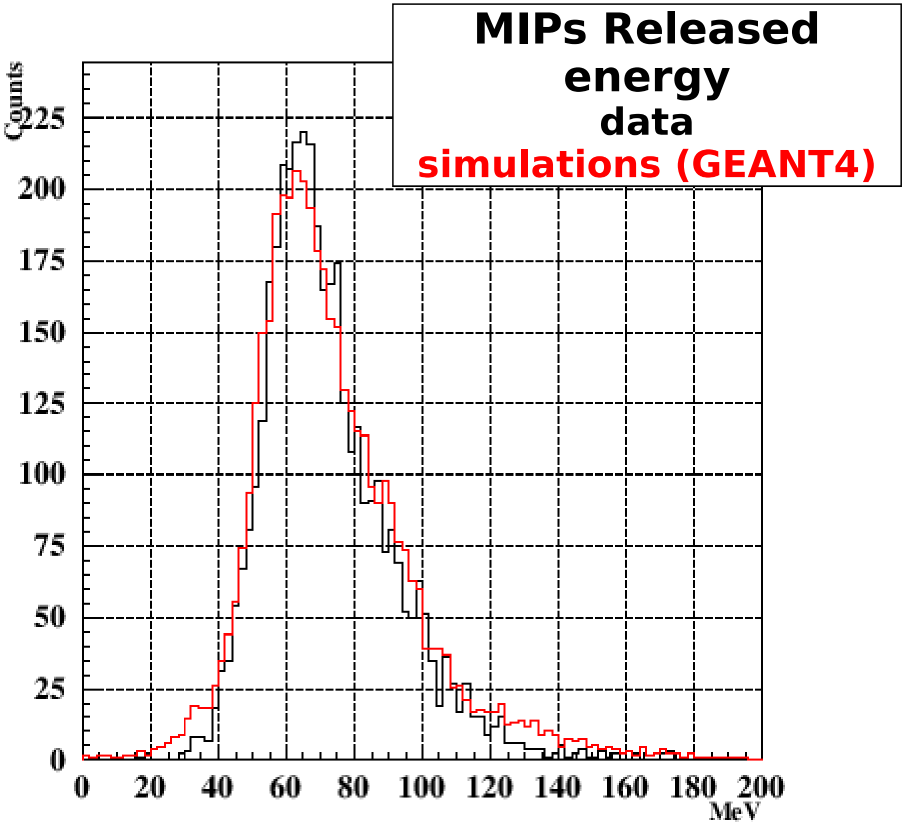
Calibrations: Cosmic rays

G. Firpo



Single hit trigger





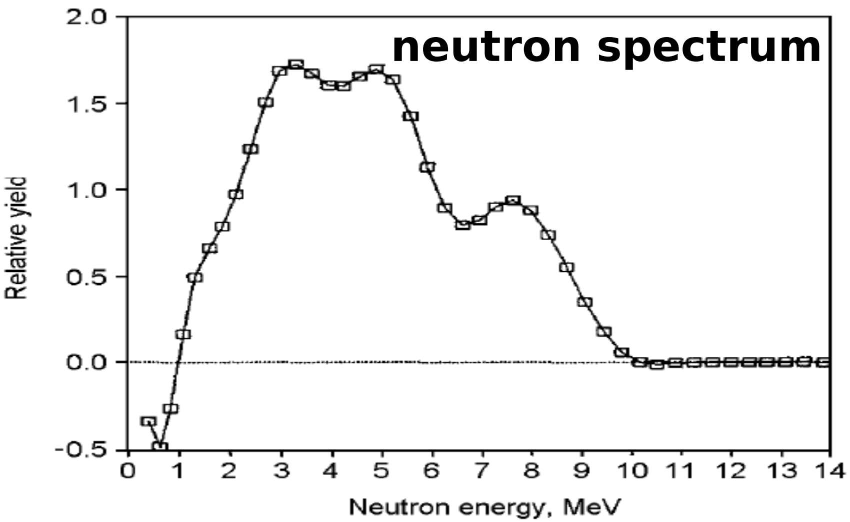
MIPs Released energy

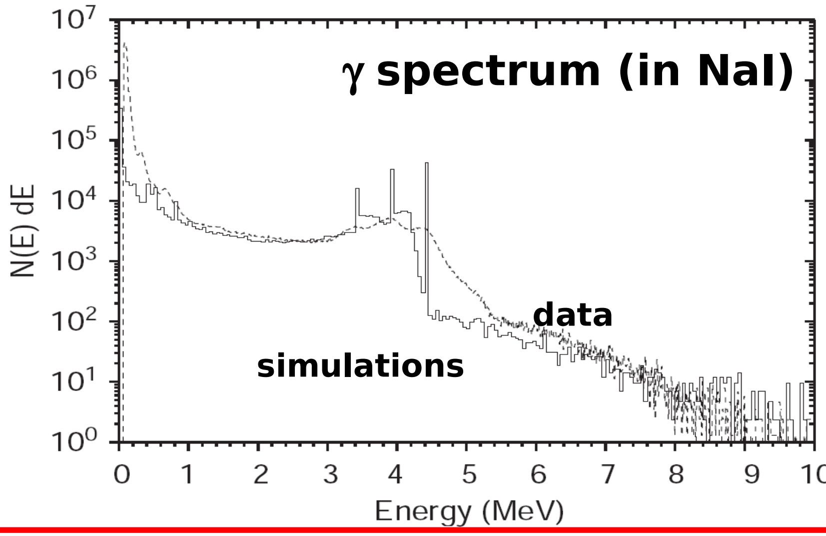
data

simulations (GEANT4)

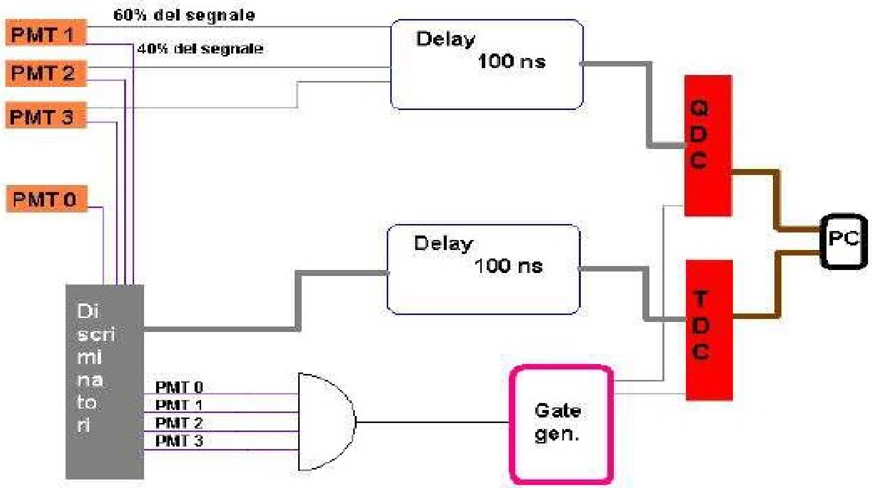
Calibrations: AmBe source

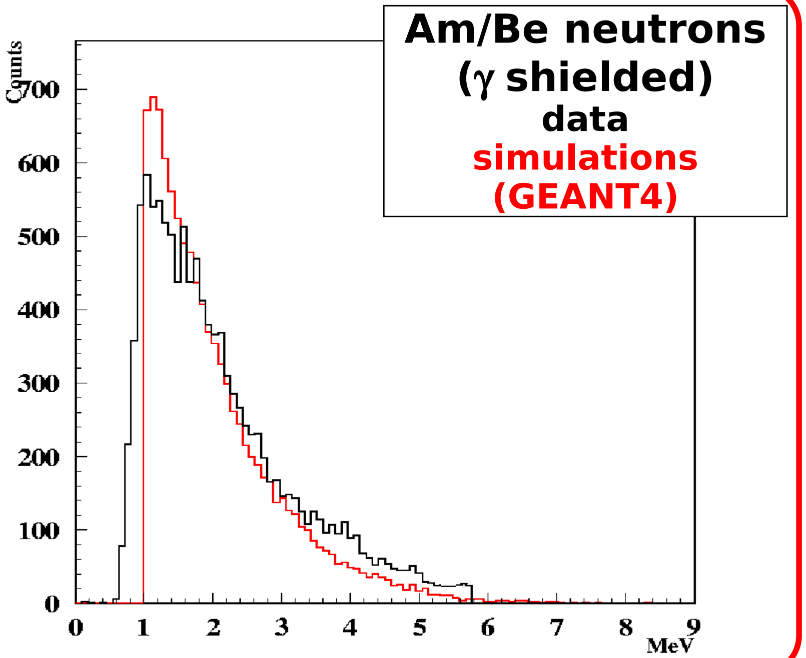
^{241}Am is an intense α emitter → ^{9}Be (α,n) ^{12}C
60% of n are emitted with a 4.4 MeV γ (first excited 2+ state of ^{12}C)
Encapsulated source has a more complex spectrum
Neutron rate: 5 10^3 n/s



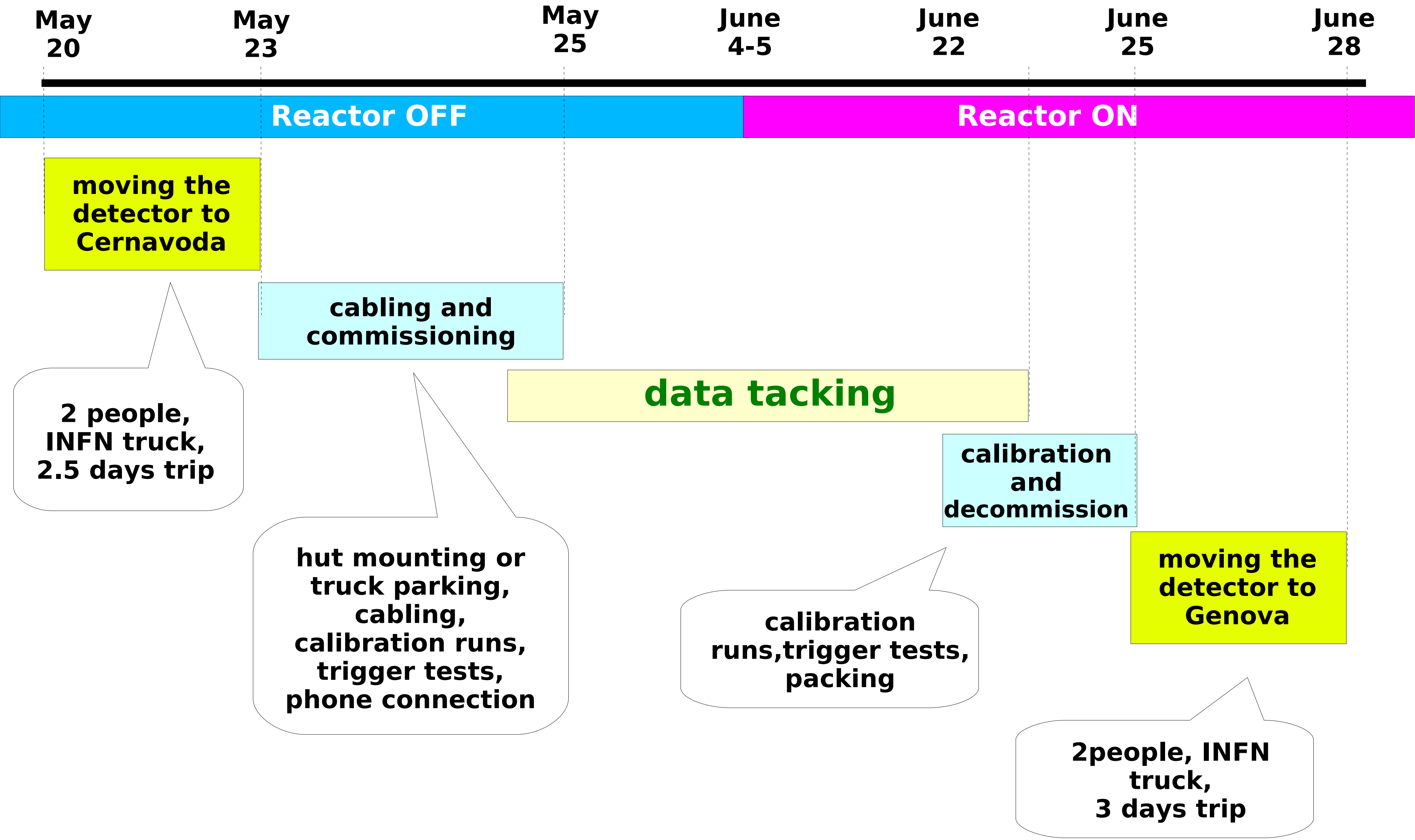


Single hit trigger: neutron detection





Tests in Cernavoda (Ro) Workplan



May 20

May 23

May 25

June 4-5

June 22

June 25

June 28

Reactor OFF

Reactor ON

moving the detector to Cernavoda

2 people, INFN truck, 2.5 days trip

cabling and commissioning

hut mounting or truck parking, cabling, calibration runs, trigger tests, phone connection

data tacking

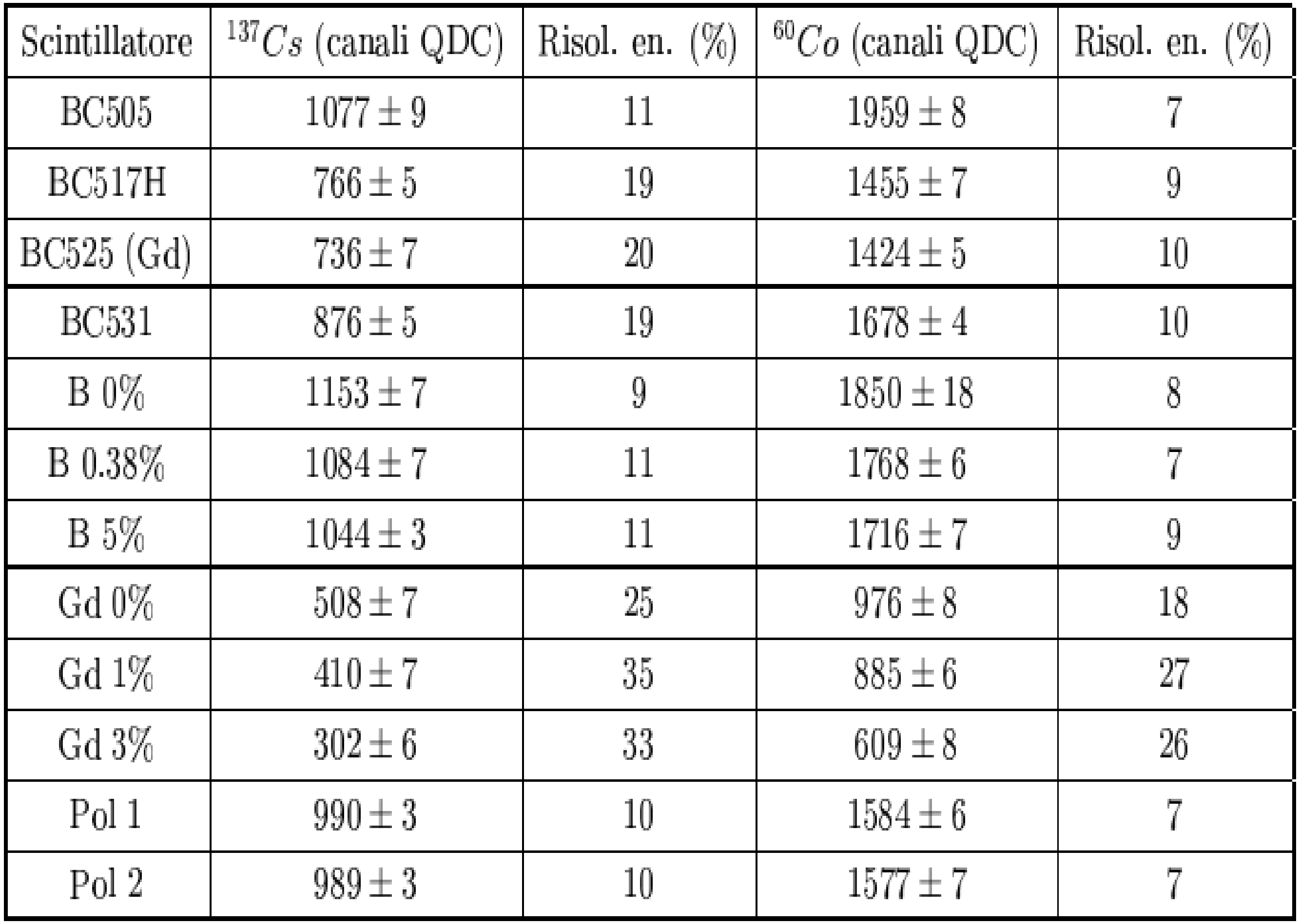
calibration and decommission

calibration runs,trigger tests, packing

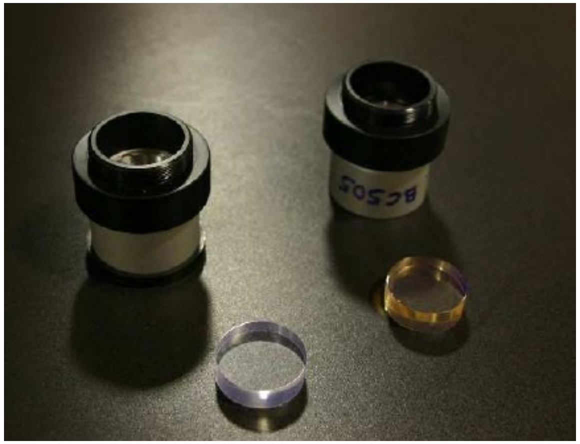
moving the detector to Genova

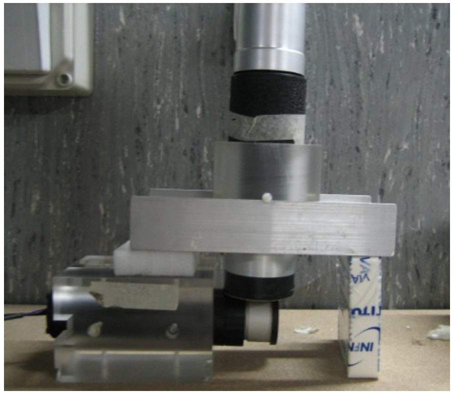
2people, INFN truck, 3 days trip

Gd-and B-doped plastic scintillators



Scintillatore	^{137}Cs (canali QDC)	Risol. en. (%)	^{60}Co (canali QDC)	Risol. en. (%)
BC505	1077 ± 9	11	1959 ± 8	7
BC517H	766 ± 5	19	1455 ± 7	9
BC525 (Gd)	736 ± 7	20	1424 ± 5	10
BC531	876 ± 5	19	1678 ± 4	10
B 0%	1153 ± 7	9	1850 ± 18	8
B 0.38%	1084 ± 7	11	1768 ± 6	7
B 5%	1044 ± 3	11	1716 ± 7	9
Gd 0%	508 ± 7	25	976 ± 8	18
Gd 1%	410 ± 7	35	885 ± 6	27
Gd 3%	302 ± 6	33	609 ± 8	26
Pol 1	990 ± 3	10	1584 ± 6	7
Pol 2	989 ± 3	10	1577 ± 7	7





Can we do it better?

Previous doped liquid scintillator showed aging problems
Need testing commercial available samples (BC-525)

Plastic scintillator advantages:

- chemical stability longer in time
- easier assembling
- null chemical hazard

Different possible solutions:

1) standard plastic scintillator + Cd foils or Gd /foils-paint
   Explored, G4 simulations done, reasonable results, easy mechanic assembly but a high segmentation is required to not degrade energy resolution and light collection (higher costs?)

2) doped plastic
   Commercial available: B-loaded plastic scintillator Saint-Gobain BC-454 (5%) but 10 x 10 x 100cm = 200k euro

   Research group: Laboratori Nazionali di Legnaro (Italy)
   Research group: Oak Ridge National Lab (USA)
   Research group: Dubna (Russia)

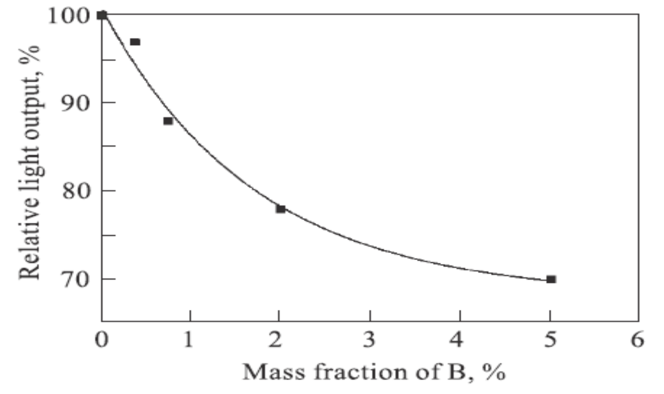
JINR-Dubna Group neutron detectors

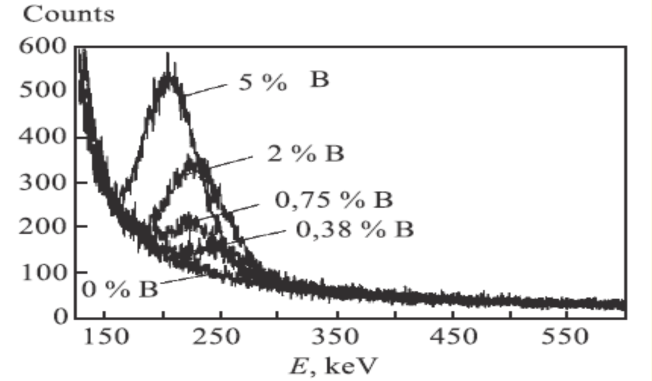
1) B-loaded plastic scintillator (0,5% - 5%)

$$n + {}^{10}\mathrm{B} \longrightarrow {}^{7}\mathrm{Li}^{*} + \alpha + 2.31\ \mathrm{MeV}$$

$$\longrightarrow {}^{7}\ \mathrm{Li}^{*} + \gamma\ (480\ \mathrm{keV}).$$

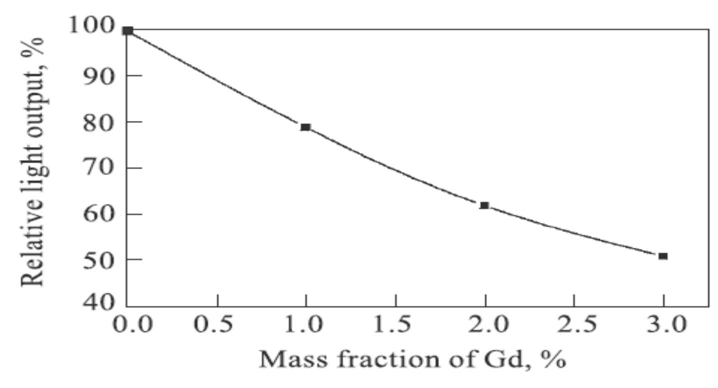
Polistyrene + p-Terphenil +POPOP
high light output (70% of unloaded with 5% B)
small sample 3 x 1 cm (reduced light emission of 1.5 MeV α particle)

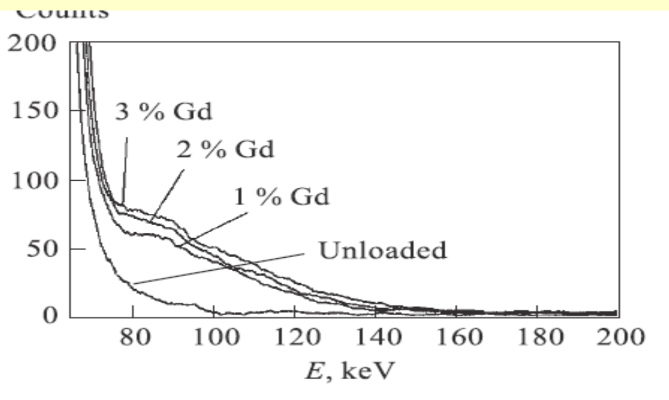




2) Gd-loaded plastic scintillator (0,5% - 3%)

PMMA Naphtalene +PPO +POPOP
high light output (60% of unloaded with 2% Gd)
small sample (3 x 1 cm) does not absorb the whole gamma cascade
claimed to be able to produce long bars (10 x 10 x 100 cm)





Oak Ridge neutron detectors

Two newtron sensors:

1) Silicone rubber Gd-loaded (1%)
   - good radiation hardness
   - hight T operation (up to 200°C)
   - small samples (~1cm)
   - not cheap (1$/g ?)
   - small attenuation length (10-20 cm ?)
   - need a container

2) Doped plastic (PS and PVT +PPO + Gd 1-1,5%)
   - small samples
   - good light transmission
   - long stability (up to 6 years)

B. Zane from ORNL was contacted:
'Cheaper plastic can be home-made
manufactured but needs more R&D'