The Abdus Salam
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2047-26

Workshop Towards Neutrino Technologies

13 - 17 July 2009

A proposal for a high segmented power reactor antineutrino detctor

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ICTP The Abdus Salam International Centre for Theoretical Physics

IAEA

The Abdus Salam International Centre for Theoretical Physics (ICTP), in collaboration with the International School for Advanced Studies (SISSA) and the Italian Institute for Nuclear Physics (INFN), will hold a

Workshop

TOWARDS NEUTRINO TECHNOLOGIES

13 - 17 July 2009

Miramare, Trieste, Italy

The achieved knowledge of neutrino properties opens up new possibilities to use them as a tool for the study of other objects and eventually for practical applications. The goal of this workshop is to review the existing achievements and efforts and to consider areas of neutrino physics which can potentially lead to the development of neutrino technologies.

TOPICS INCLUDE

* Neutrino properties: masses, mixing and interactions
* Coherent neutrino scattering
* Neutrino Moessbauer effect and other exotic effects
* New neutrino sources and detection techniques
* Geo-neutrinos
* Neutrino tomography of the Earth and stars
* Neutrino communication systems
* Reactor neutrinos and control of nuclear reactors

ORGANIZERS

Gianni FIORENTINI (University of Ferrara)

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A proposal for a high segmented power reactor antineutrino detector

Marco Battaglieri
Istituto Nazionale di Fisica Nucleare
Genova- Italy

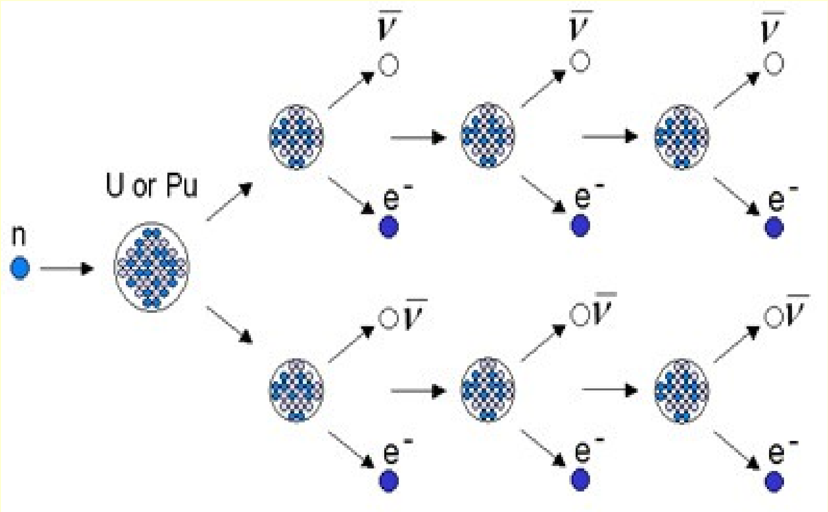
Motivations

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?

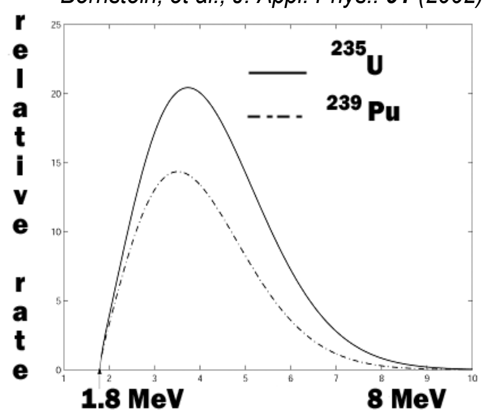
This is NOT the simplest way to monitor a reactor but ...

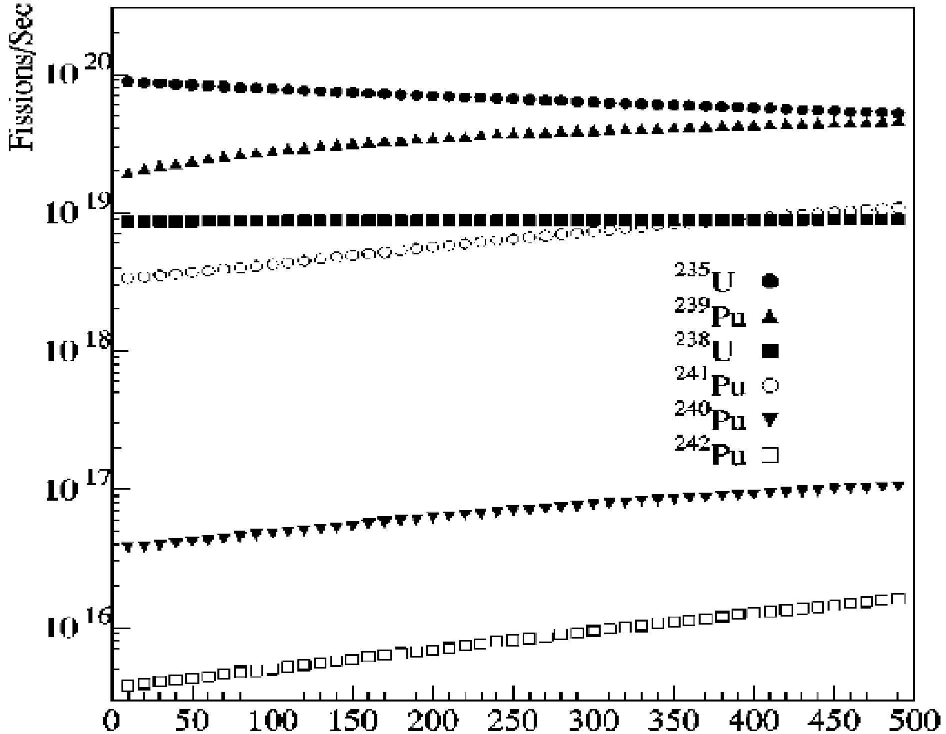
- independent on-line monitor of the reactor power
- the measurement is performed outside the core (safety issues) and does not affect the normal plant operations
- detector installation does not need any engineering work and can be done anytime in any plant
- antineutrino can not be shielded and are 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

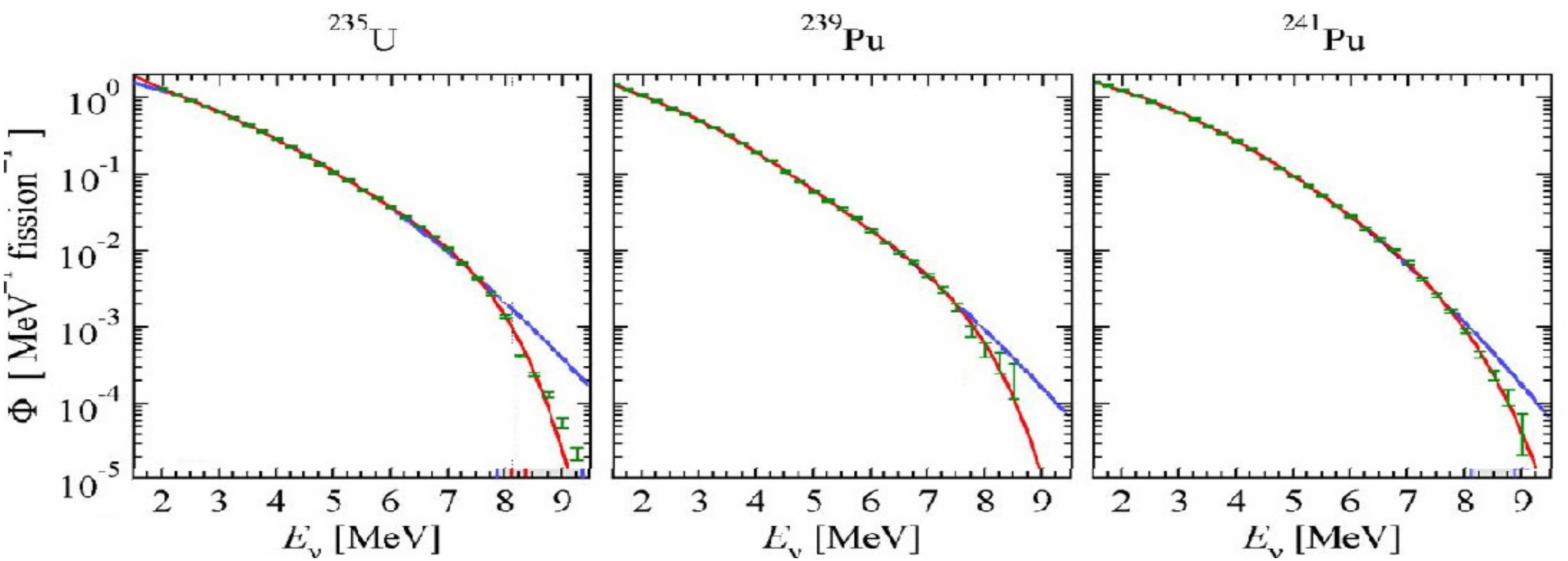
- Antineutrino rate varies with time and isotope
- As reactor fuel burns the composition change

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





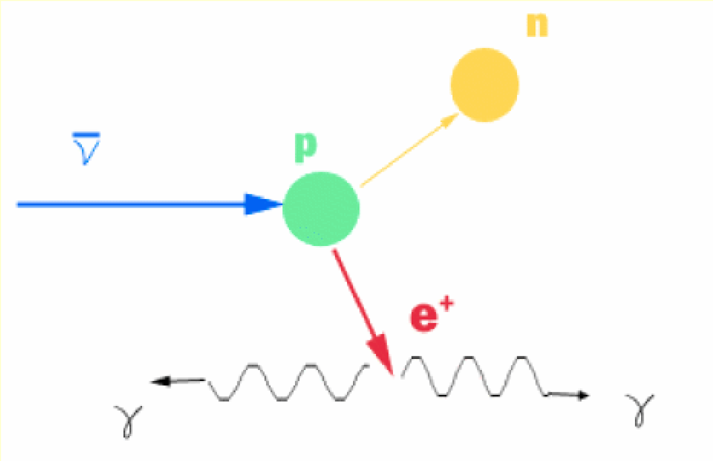
Antineutrino energy spectrum



How to detect antineutrinos?

both detected

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



E_ν

- **Reaction threshold E_ν=1.8 MeV**

  $\rightarrow$ 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**

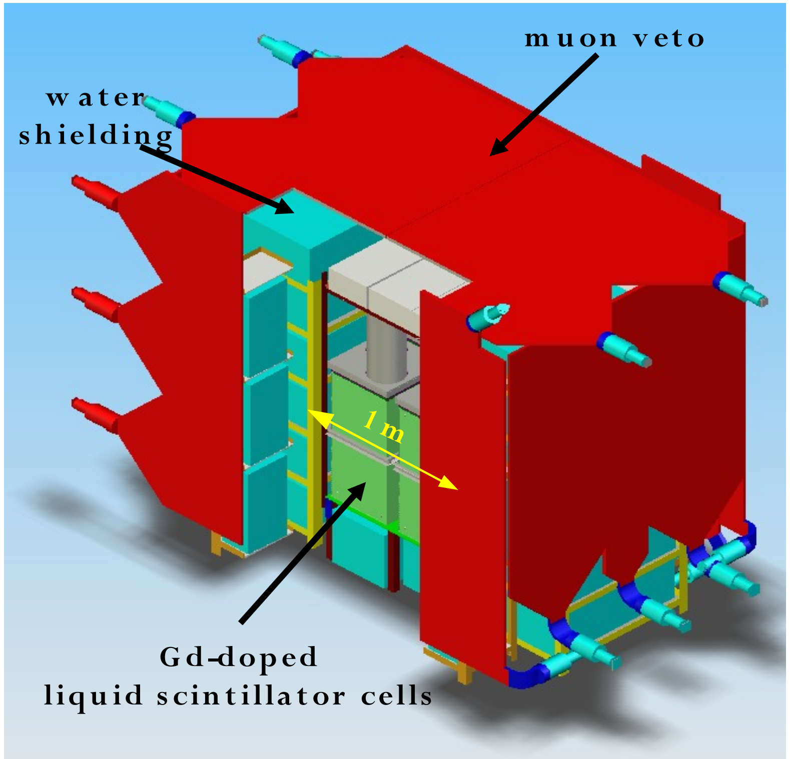
Detector requirements

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

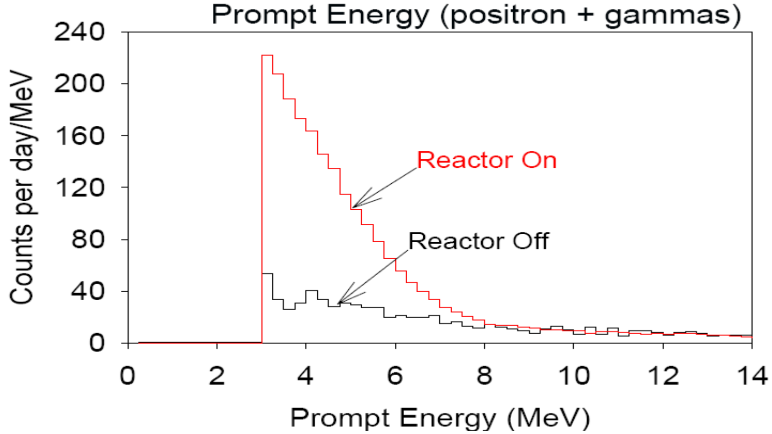
- proton rich target
- active target to detect e+ ionization
- ~1 m^3 target volume (low $\sigma_{\nu\, p \rightarrow \beta+\, n}$~$10^{-43}cm^{-2}$ @ E_ν~MeV)
- high segmentation for background rejection
- homogeneous target to have good e+ energy resolution
- clear signature for neutron capture
- small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

Does it work?

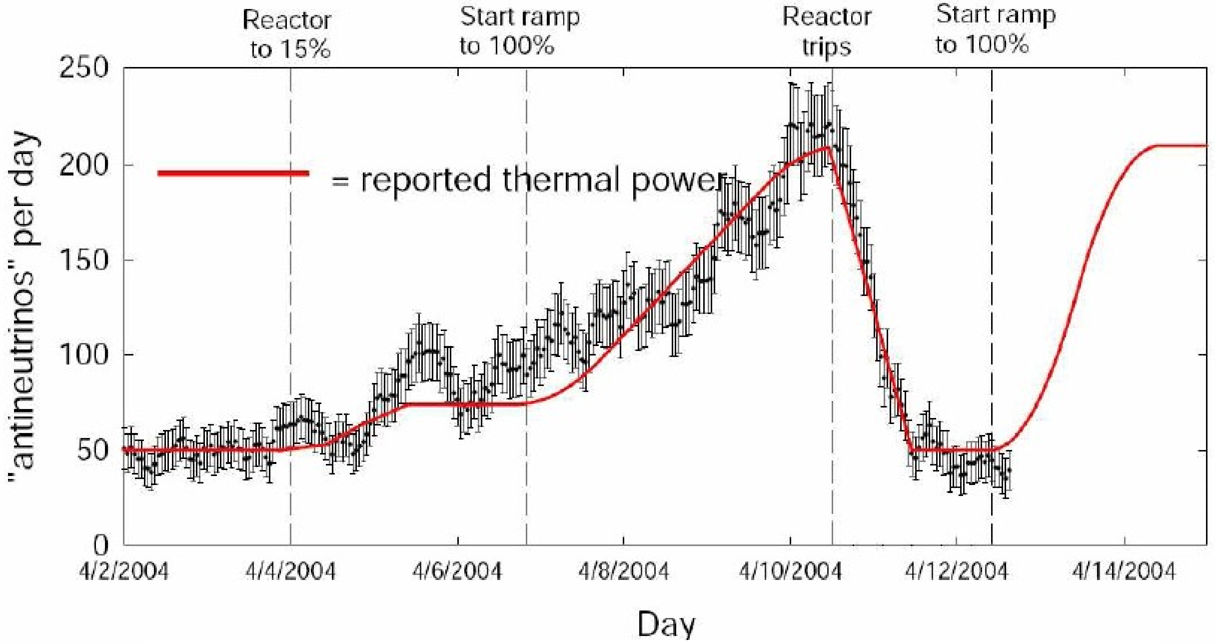
Sandia National Laboratory antineutrino detector (SONGS1)
S.Onofre (Ca) 3.5 GW commercial power plant

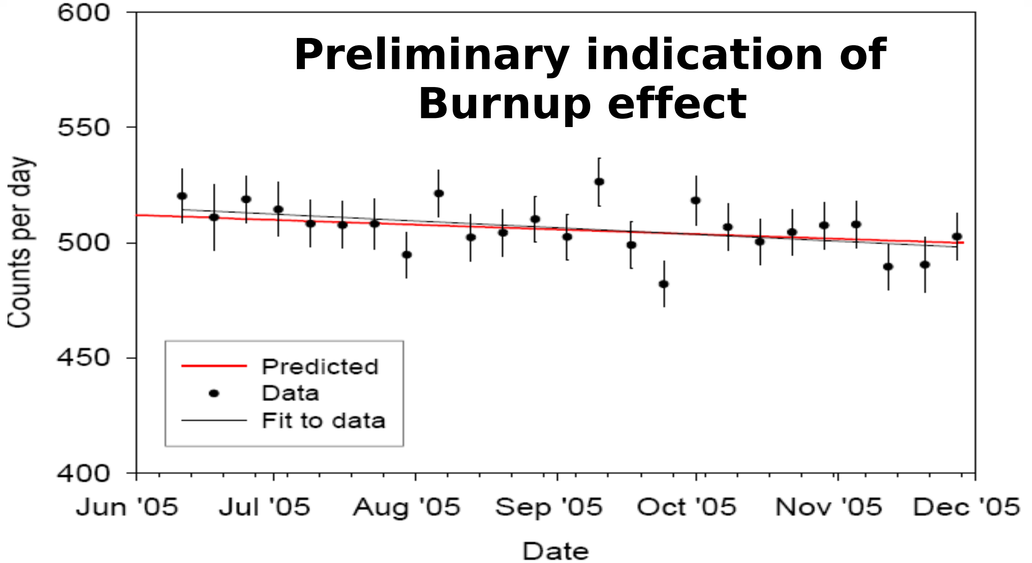


Detection efficiency (10.7±1.5) %



Daily power monitoring using only antineutrinos





Is liquid scintillator the only possible solution?

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

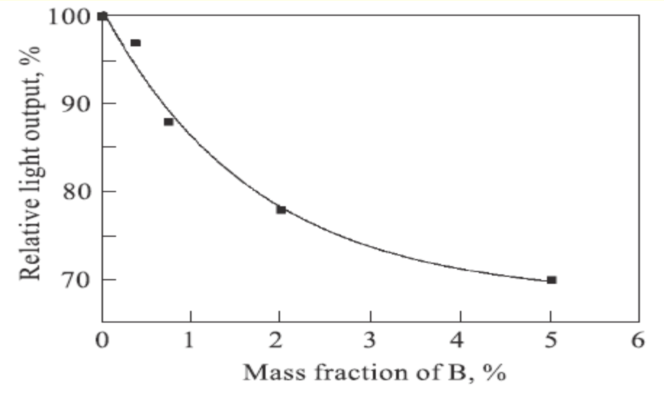
Research group: Laboratori Nazionali di Legnaro (Italy)
Research group: Oak Ridge National Lab (USA)
Research group: Dubna (Russia)

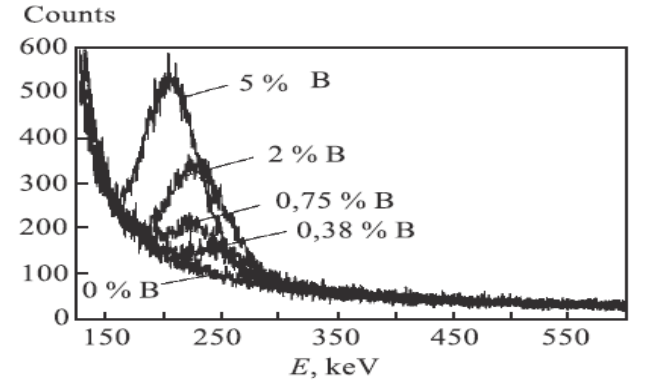
JINR-Dubna Group neutron detectors

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

$$n + {}^{10}\mathrm{B} \longrightarrow {}^{7}\mathrm{Li}^{*} + \alpha + 2.31\ \mathrm{MeV}$$
$$\longrightarrow {}^{7}\mathrm{Li}^{*} + \gamma\ (480\ \mathrm{keV}).$$

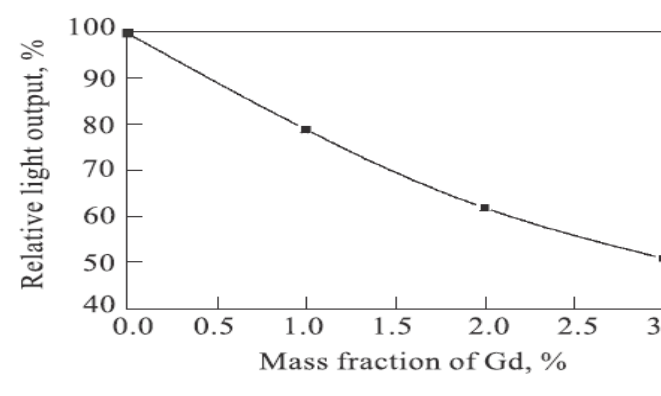
- Polistyrene + p-Terphenil +POPOP
- high light output (70% of unloaded with 5% B)
- small sample 3 x 1 cm (reduced light emission of 1.5 MeV α particle)

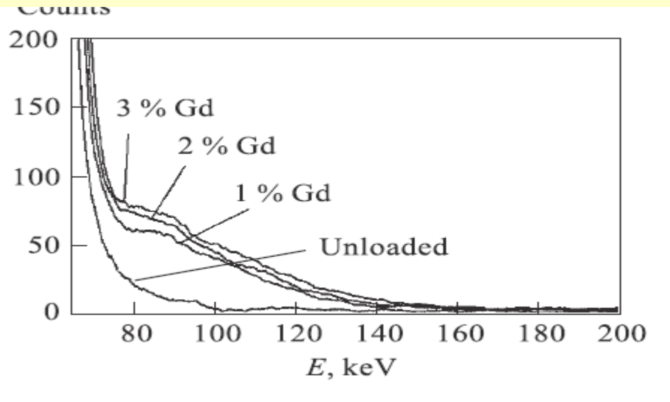




2) Gd-loaded plastic scintillator (0,5% - 3%)

- 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)

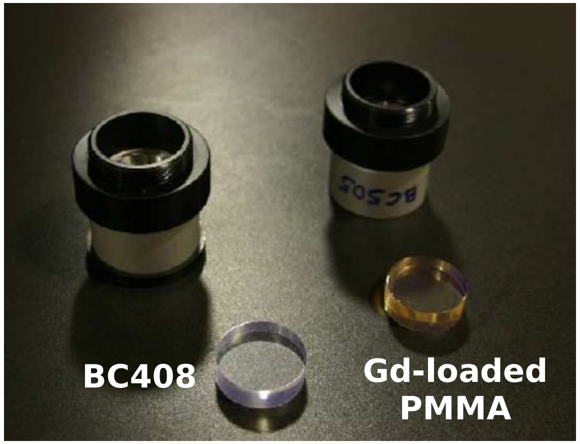


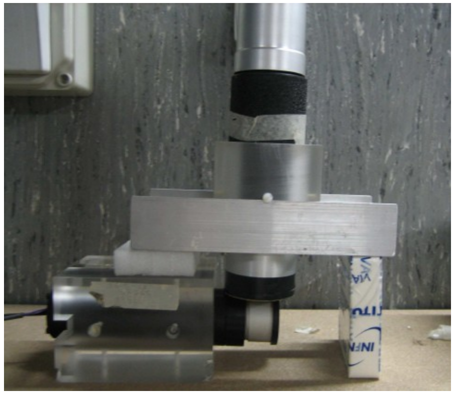


Gd- and B-doped plastic scintillators

Energy resolution for JINR and commercial samples

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



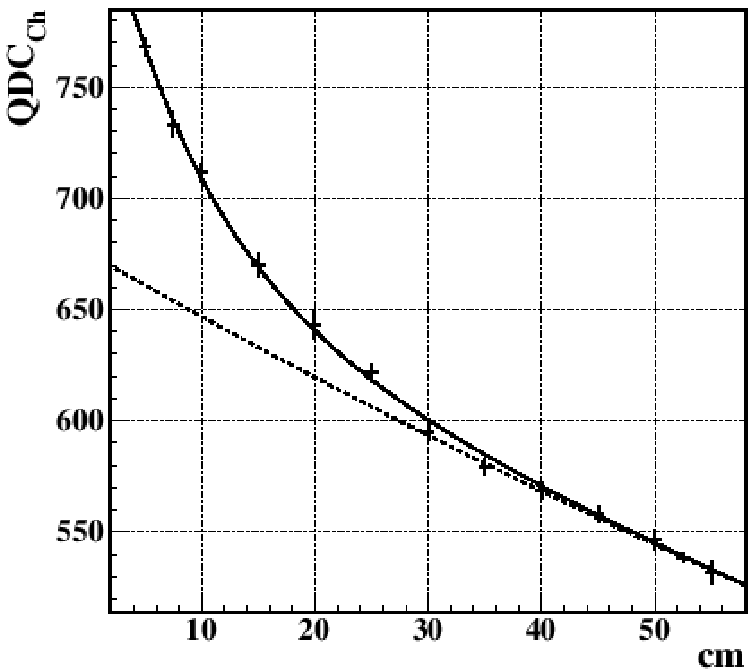


Technology for Gd-doped plastic scintillator is not good enough!

Plastic scintillator wrapped in Gd-coated mylar foils

Testing commercial scintillators

- Attenuation length (cm)

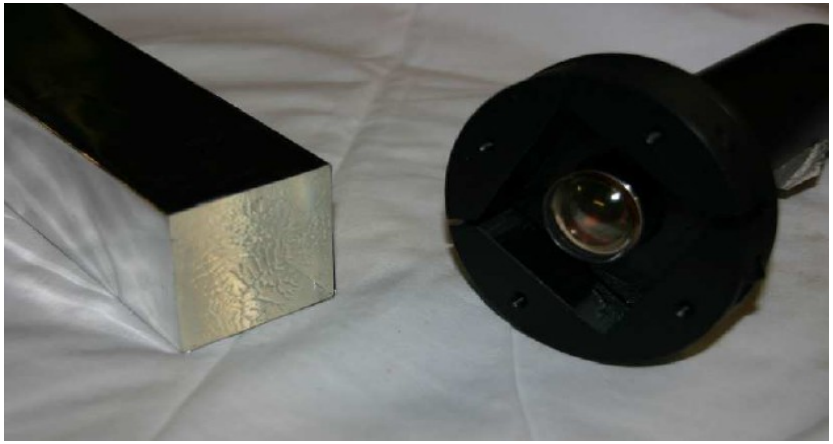


BC525: 26.3±0.7 (HiFi)
32.1±1.3 (3M)

Liquid

BC408: 294±93 (Mylar)
EJ200: 286±45 (3M)
243±45 (HiFi)
232±39 (Mylar)
NE110: 106±12 (Mylar)
JINR: 86±14 (Mylar)

Plastic



- Energy resolution (e- @ 478 keV)

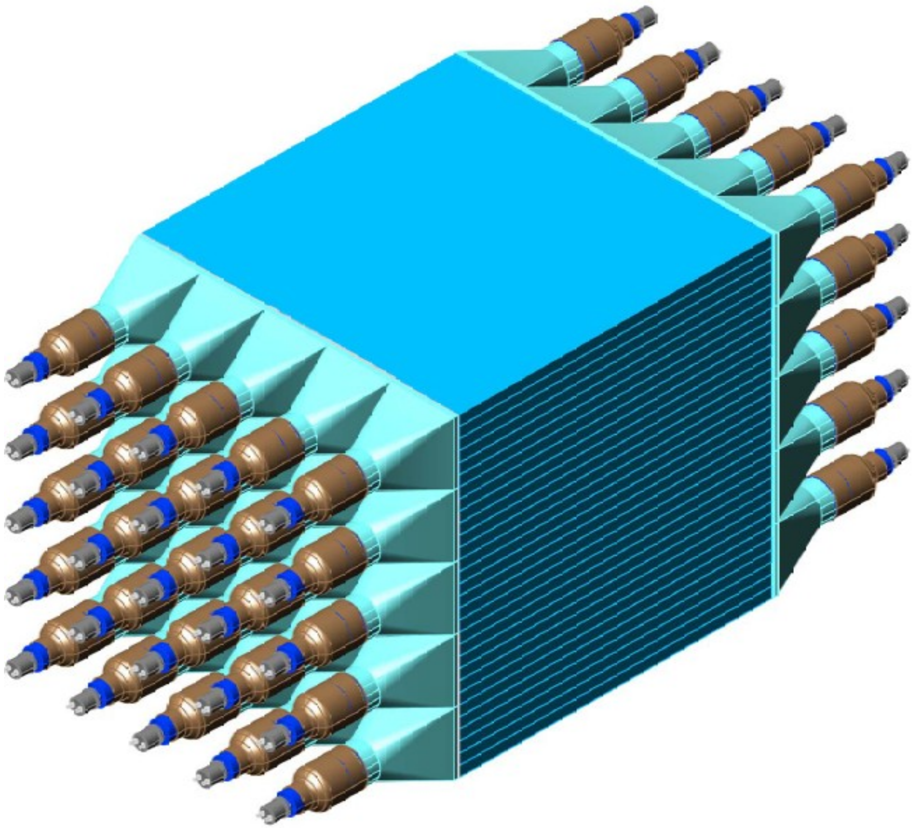
BC525	BC408	NE110	EJ200
30%	14%	18%	16%

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

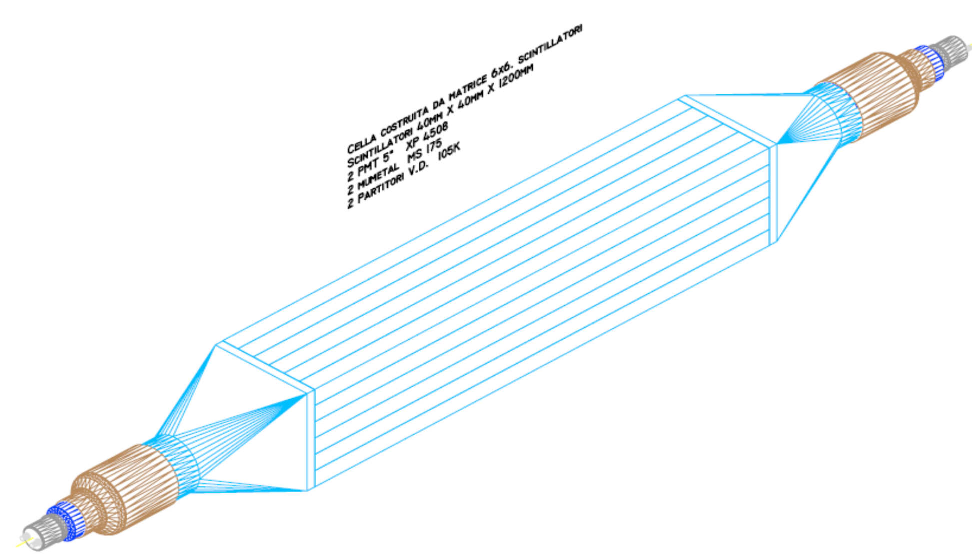
CORMORAD

CORe MOnitoRing by Antineutrino Detection

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



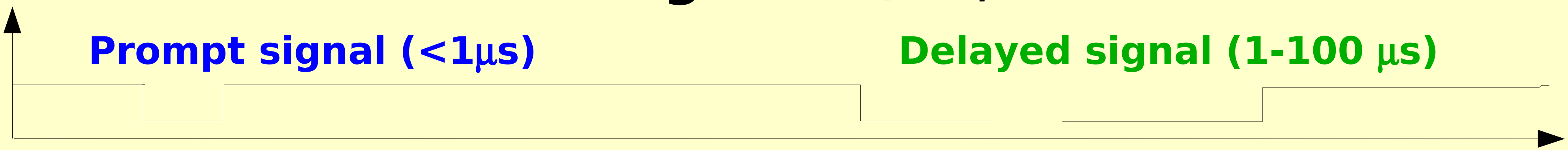
- **3'' PMT on Each side**
- **10-15% of produced light collected**
- **minimum light attenuation**
  a.l. of plastic scintillator ~300cm@425nm
- **A total of 16+16 PMTs**
- **ADC and TDC read-out**



- **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 $\nu\, p \rightarrow \beta^+\, n$



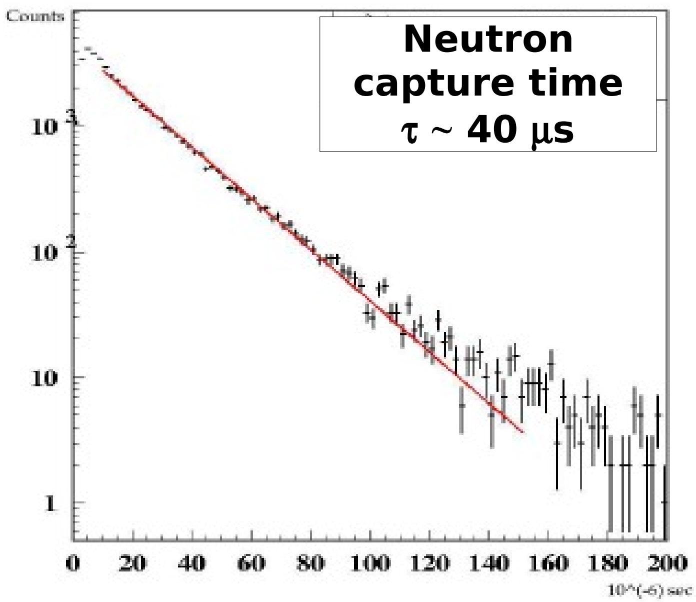
- **antineutrino interact with H in plastic**
- **positron releases energy within a cell**
- **Then annihilates**
- **two gammas mainly interact via Compton scattering**
- $E_\nu \propto E_{Prompt} = E_{ion} + 2 \times 0.511$ **MeV**
- $N_{hit} > 2$

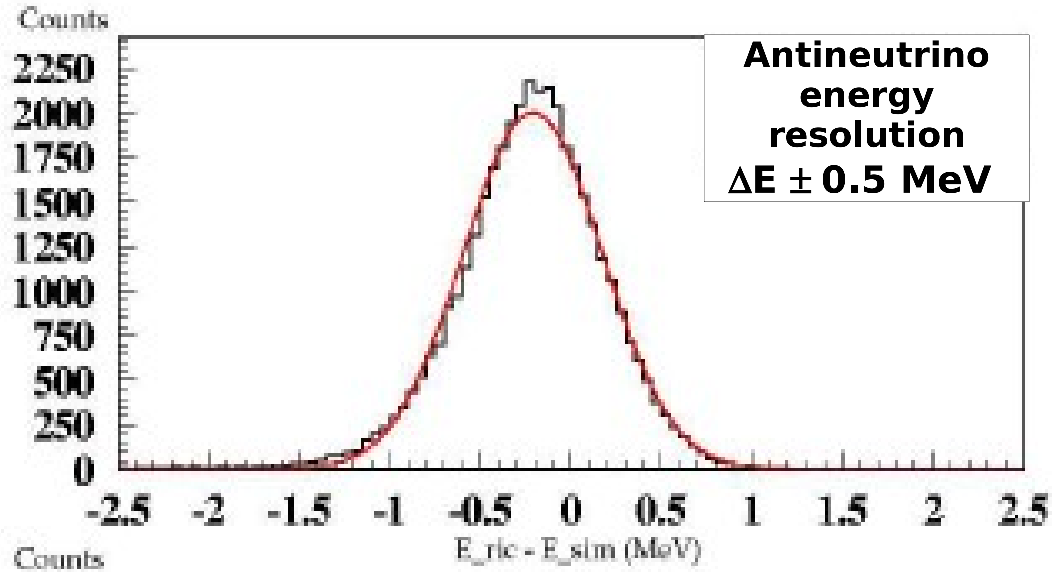
- **n thermalizes (np→np)**
- **tenth of cm (> cell size)**
- **capture on A**
- **delayed signal (τ∝5-100 μs)**
- $E_{Delayed} = E_{elastic} + 7\text{-}8$ **MeV**
- **High hit multiplicity**

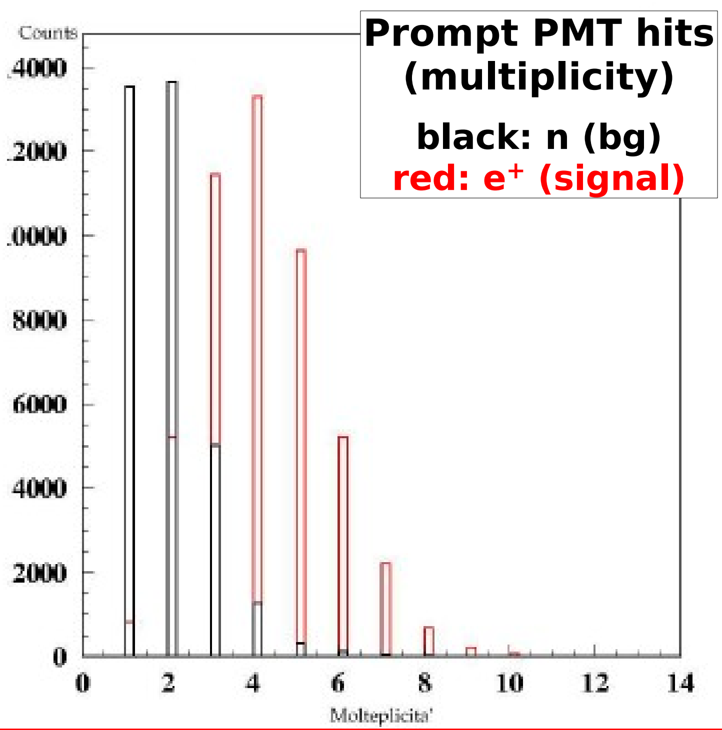
Background

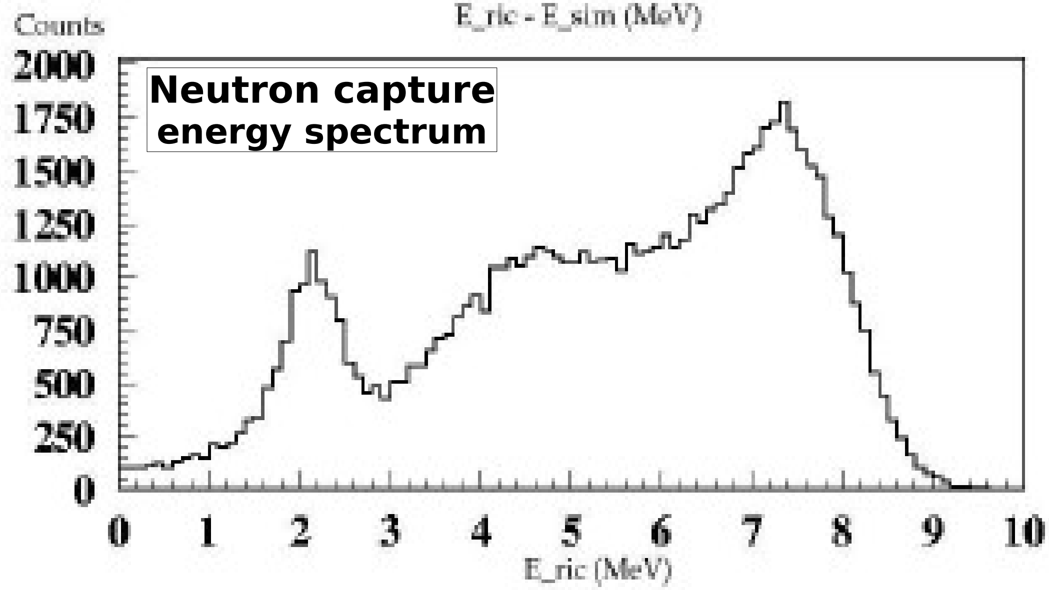
- **Atmospheric and solar** → **negligible**
- **Cosmic muons**
  random coincidence in a wide time-window → **tracked and rejected in off-line analysis**
- **Residual radioactivity in PMTs and surrounding material** → **trigger optimization**
- **Spallation neutron**
  slowed down by elastic np scattering
  p fast signal (similar to e+)
  n delayed signal (as in inverse β decay)
  →
  - **same time-coincidence signature**
  - **rejected by using hit multiplicity**
  need segmented detector !
- **Reactor background**
  thermal neutrons
  few MeV gammas from n activation
  → **random coincidences depending on the single hit rates**
  need shielding

Expected performance and results (GEANT4)



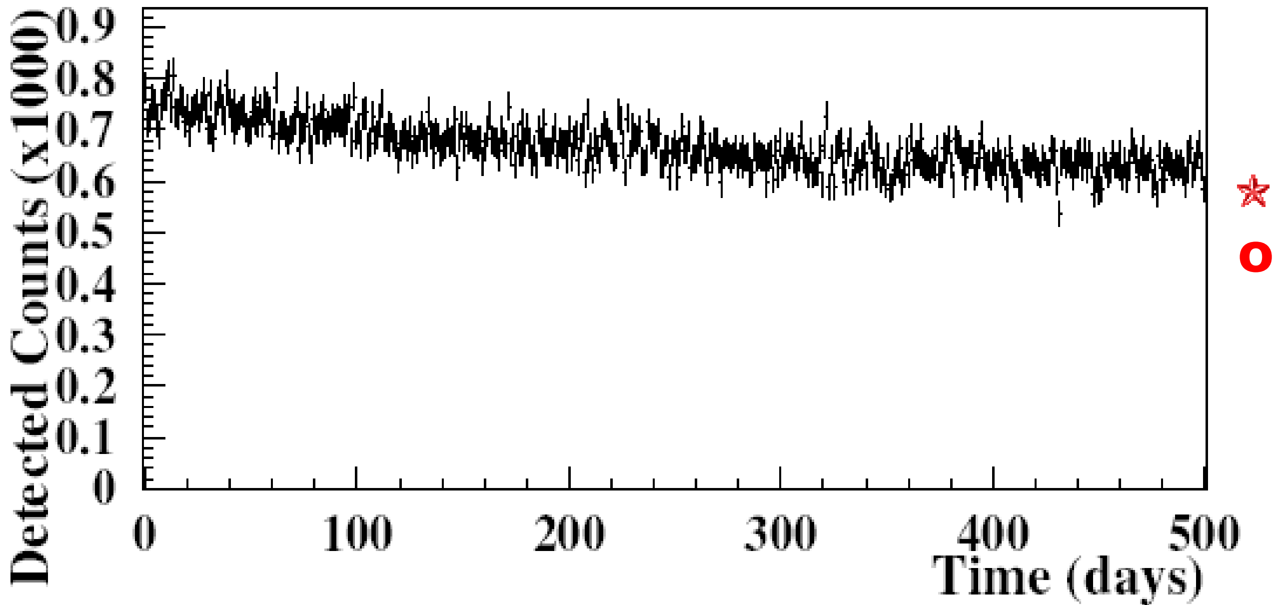




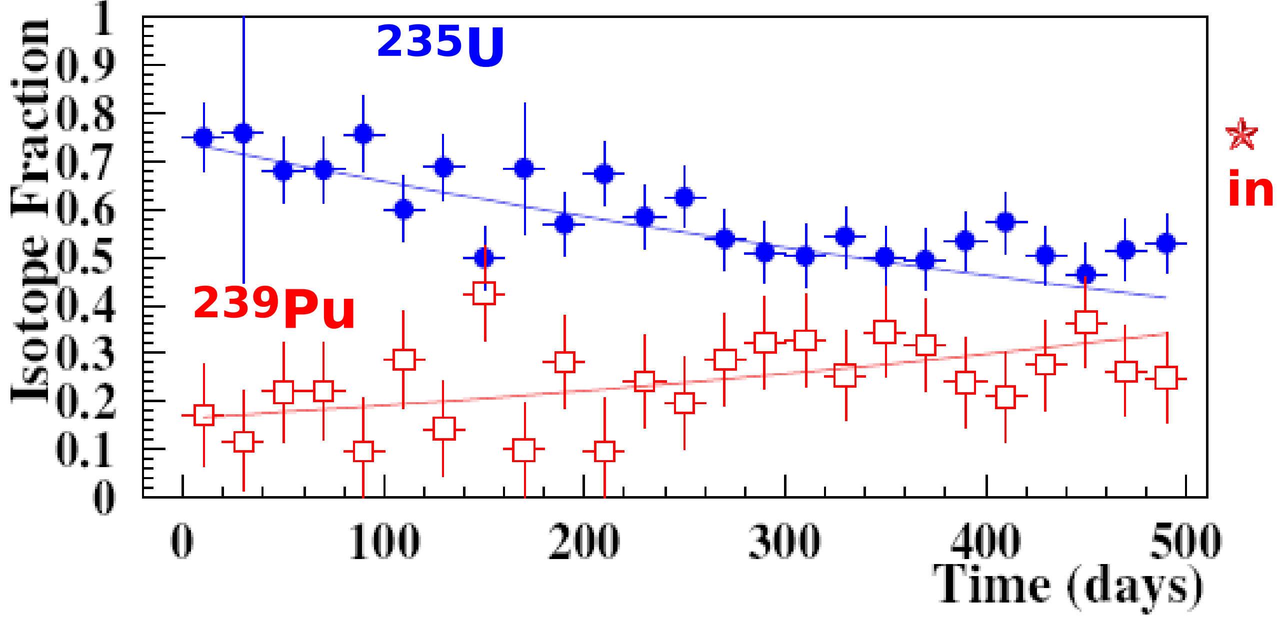


Detection Efficiency ~ 40%

Expected performance and results (GEANT4)

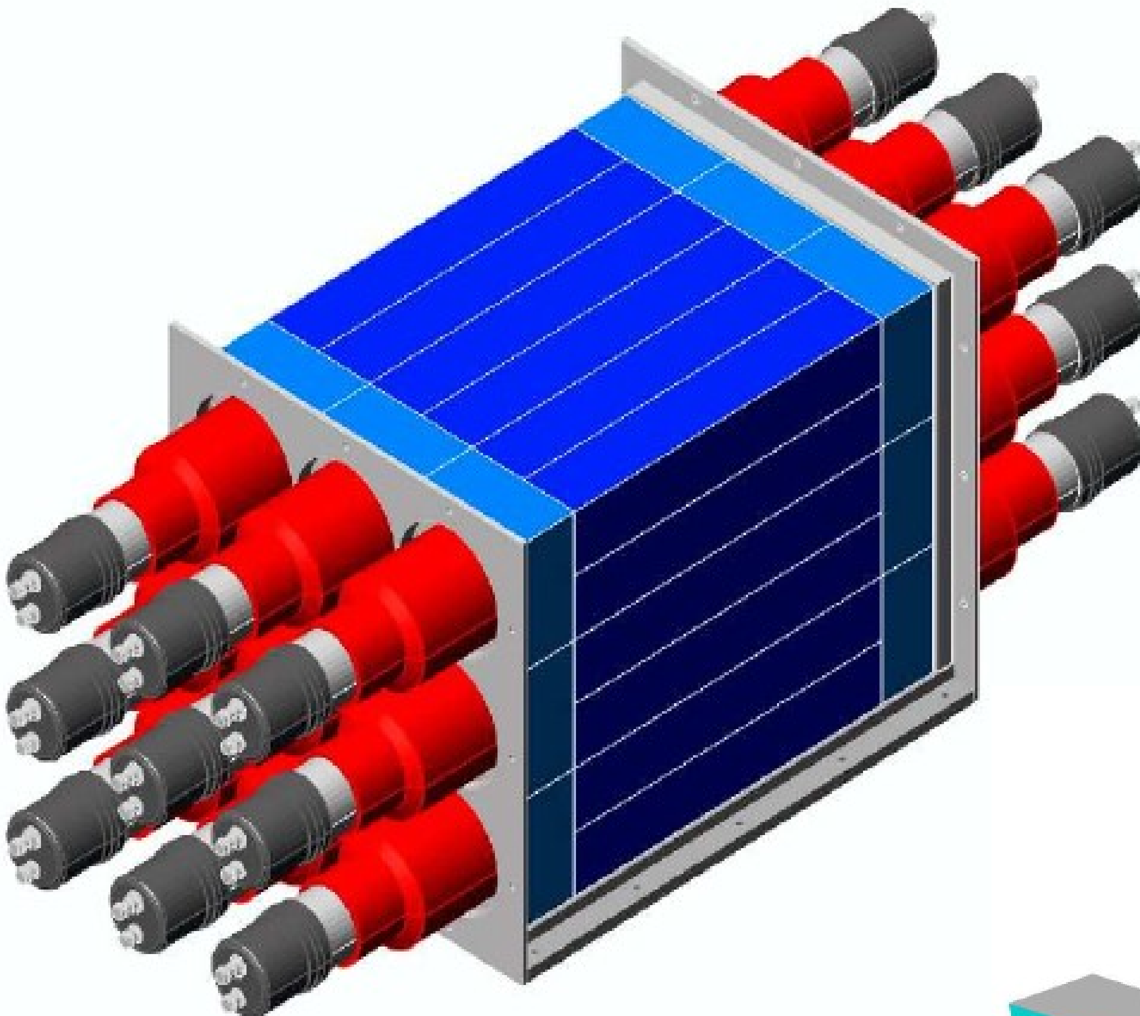


☆ **Power plant monitor on daily base**



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

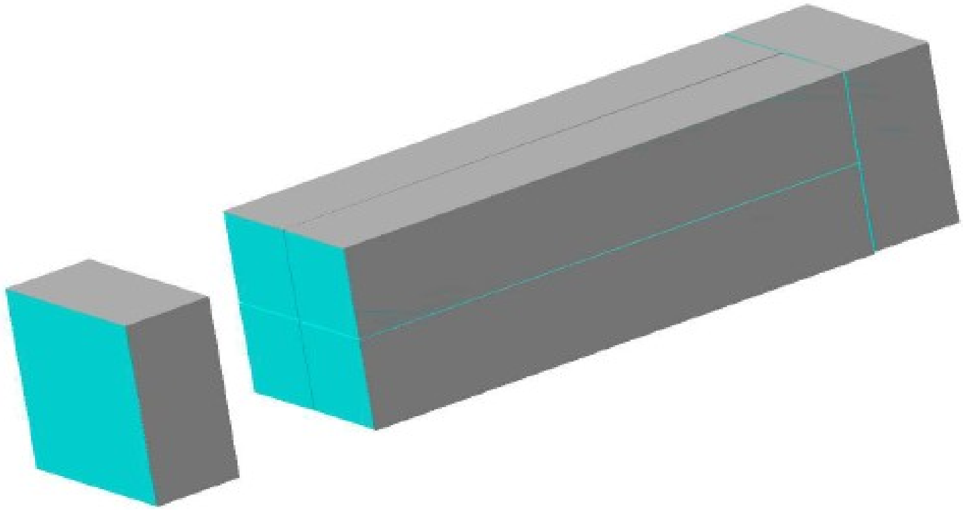
Scale (1:3)^3 prototype

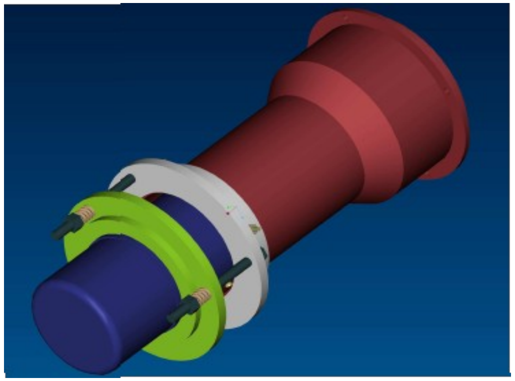


- Size: 40 x 30 x 30 cm^3

Prototype cell

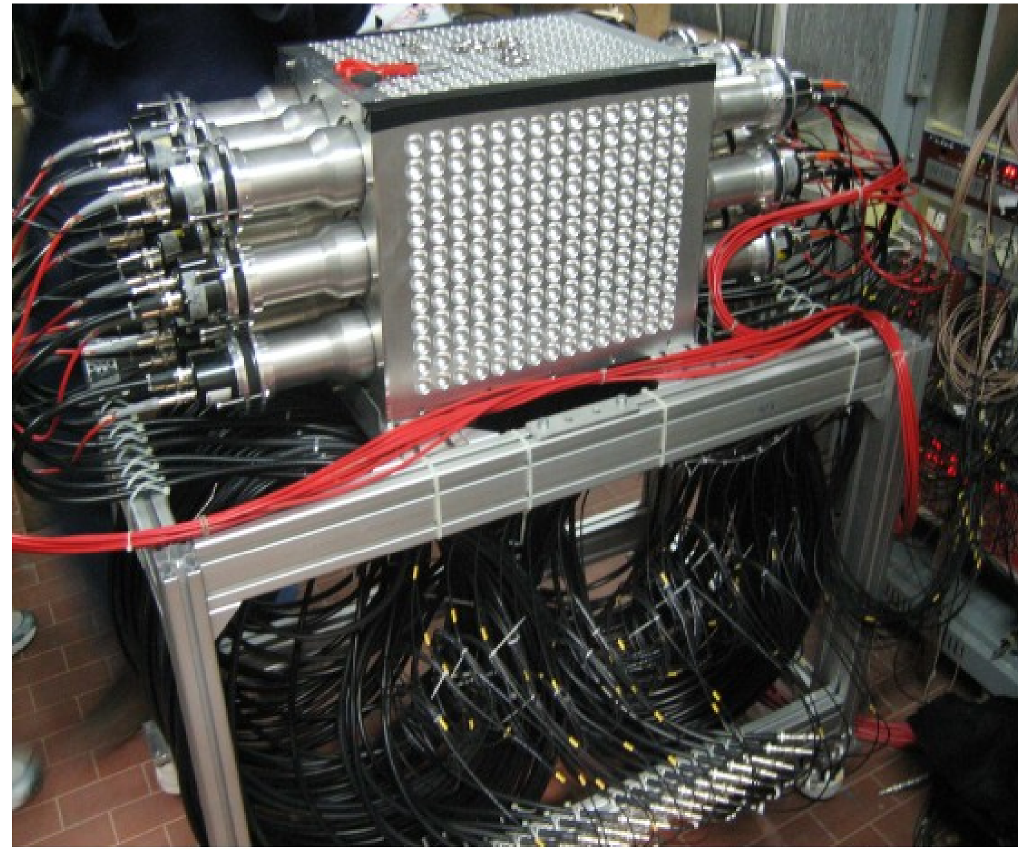
- 4 30x5x5 cm^3 NE110 bars
- 1 5x10x10 cm^3 NE110 block
- 12.5 μm Gd foils wrapping



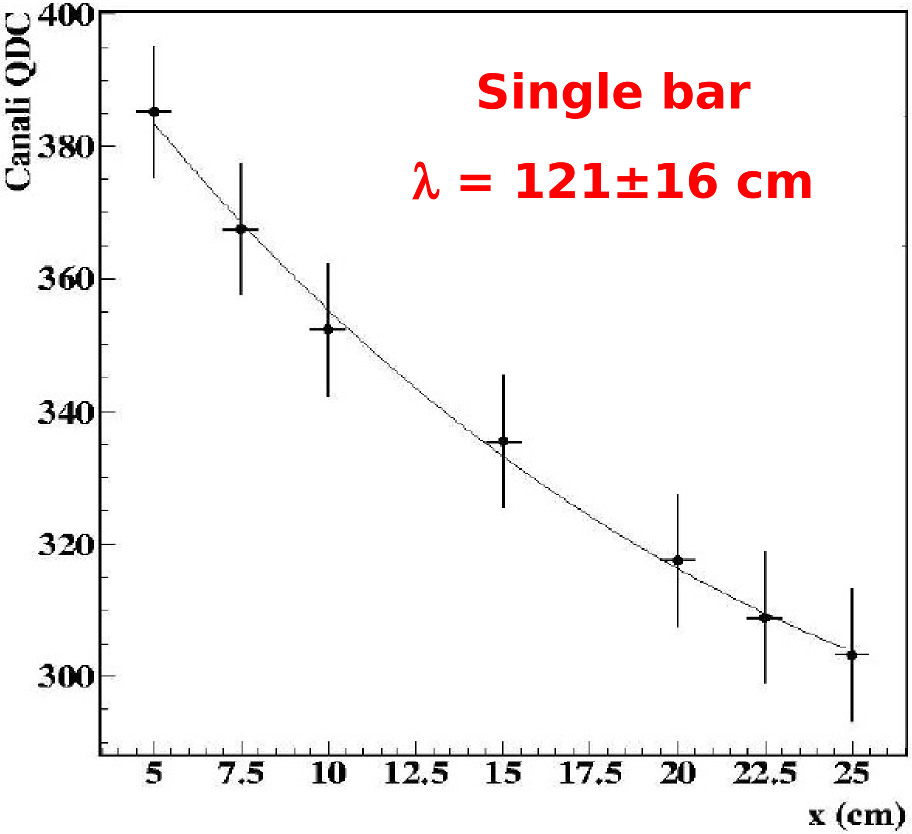


- Light read-out: 18 Photonis XP2312 3” PMTs

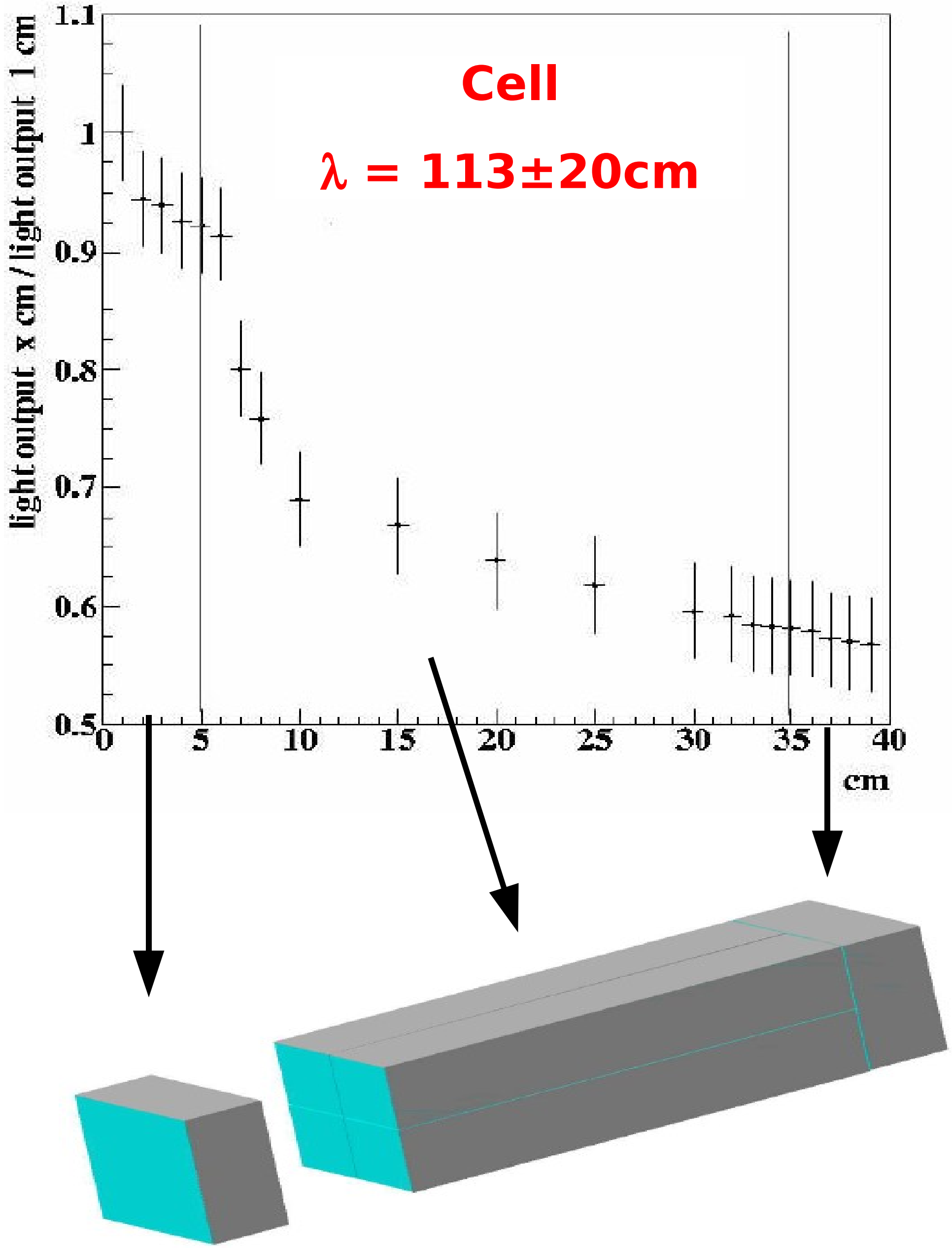
R&D and prototyping



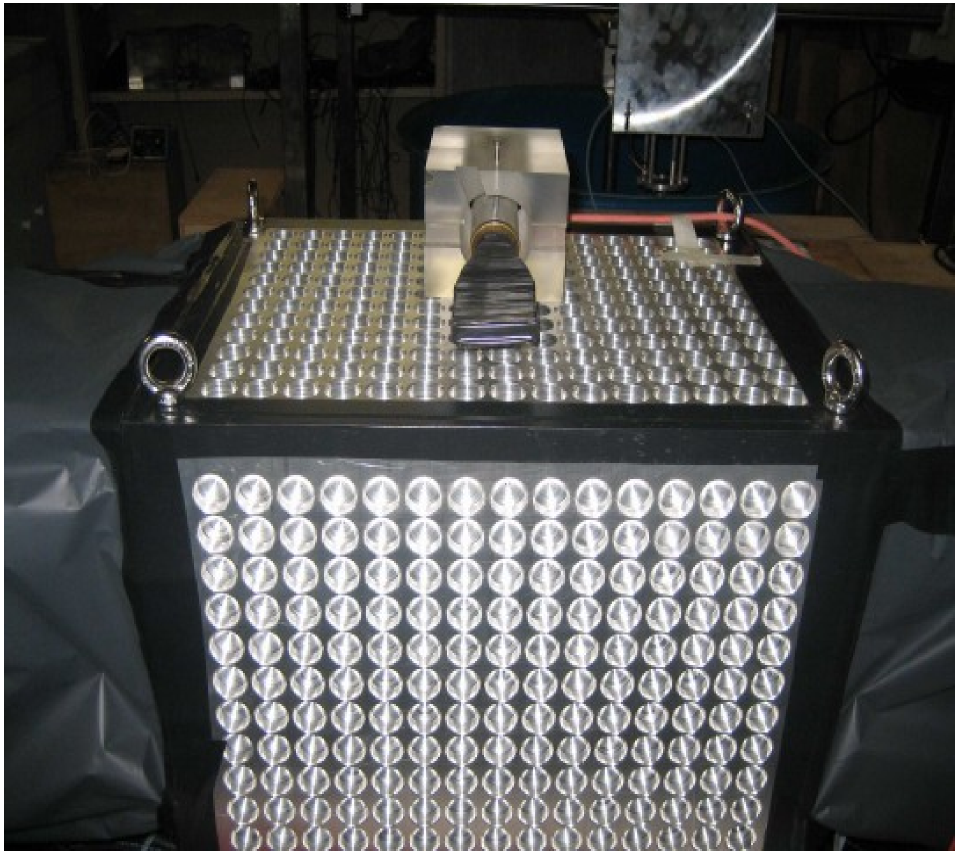
Attenuation length



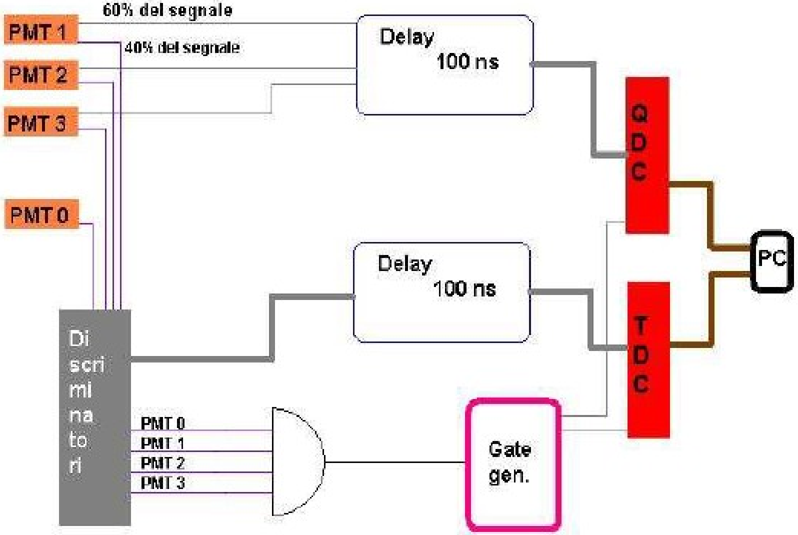
★ 10% loss at the interface

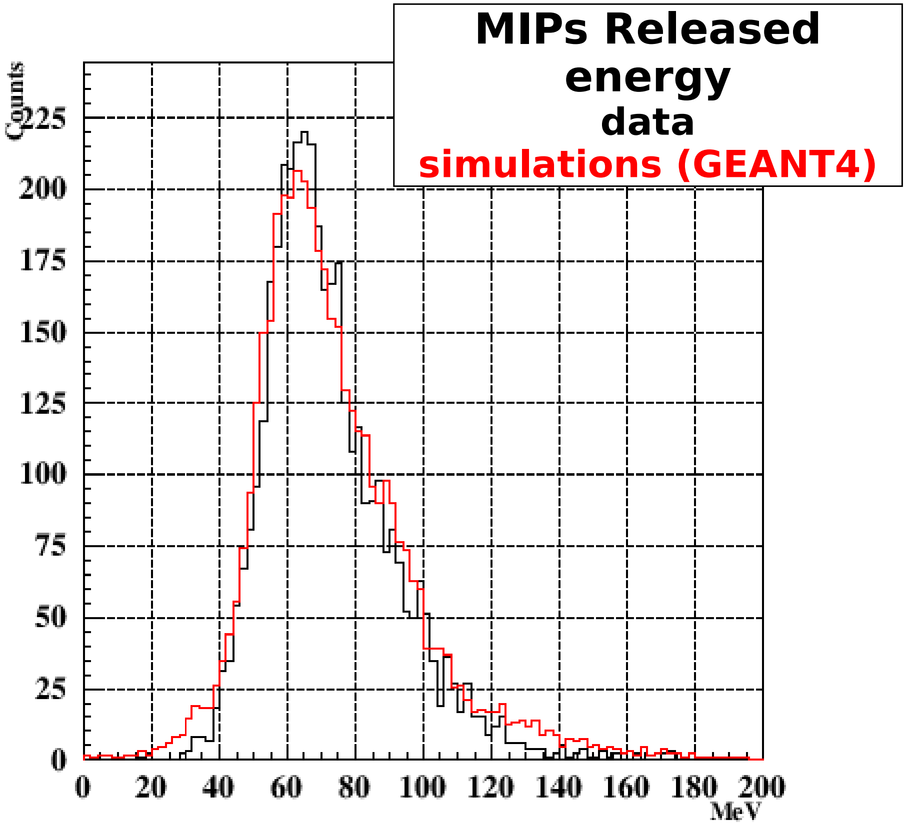


Calibrations: Cosmic rays



Single hit trigger

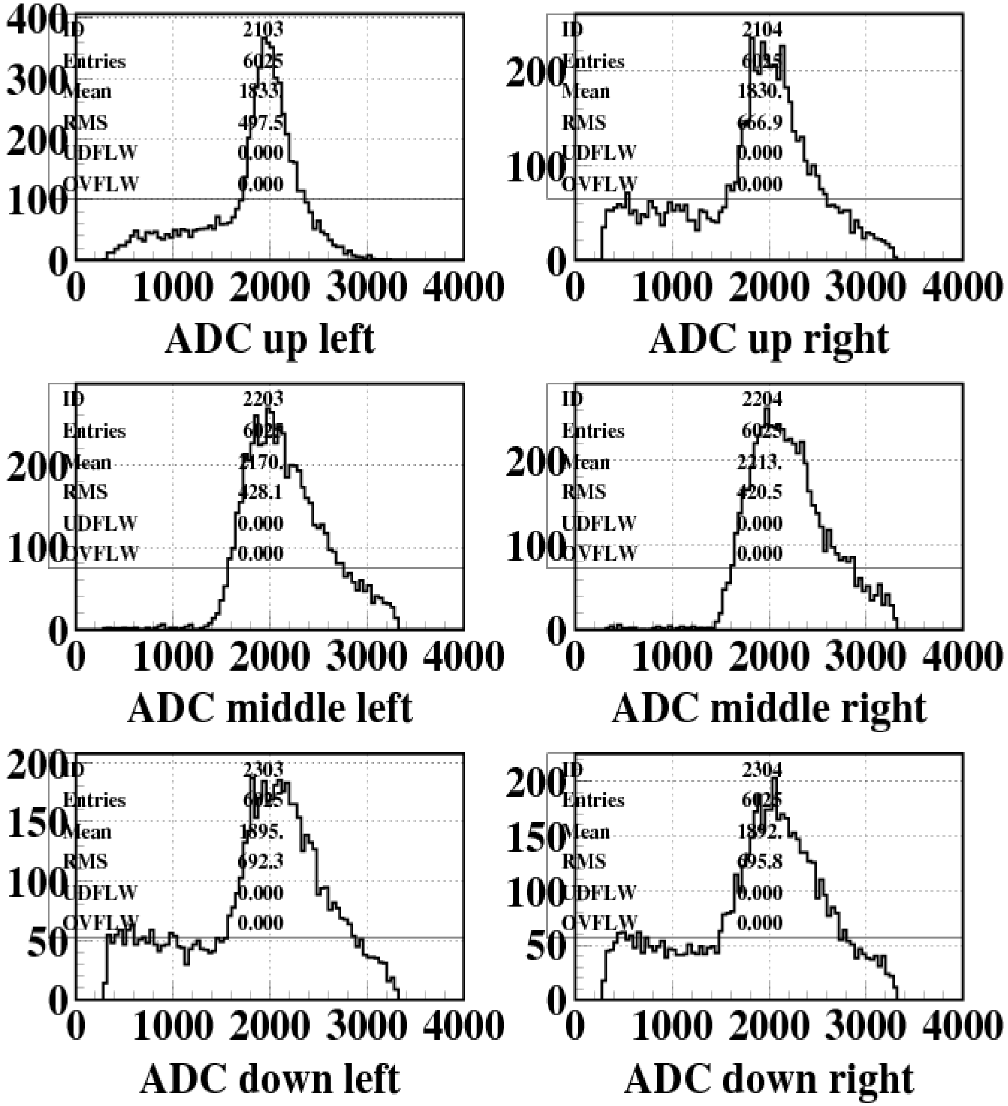


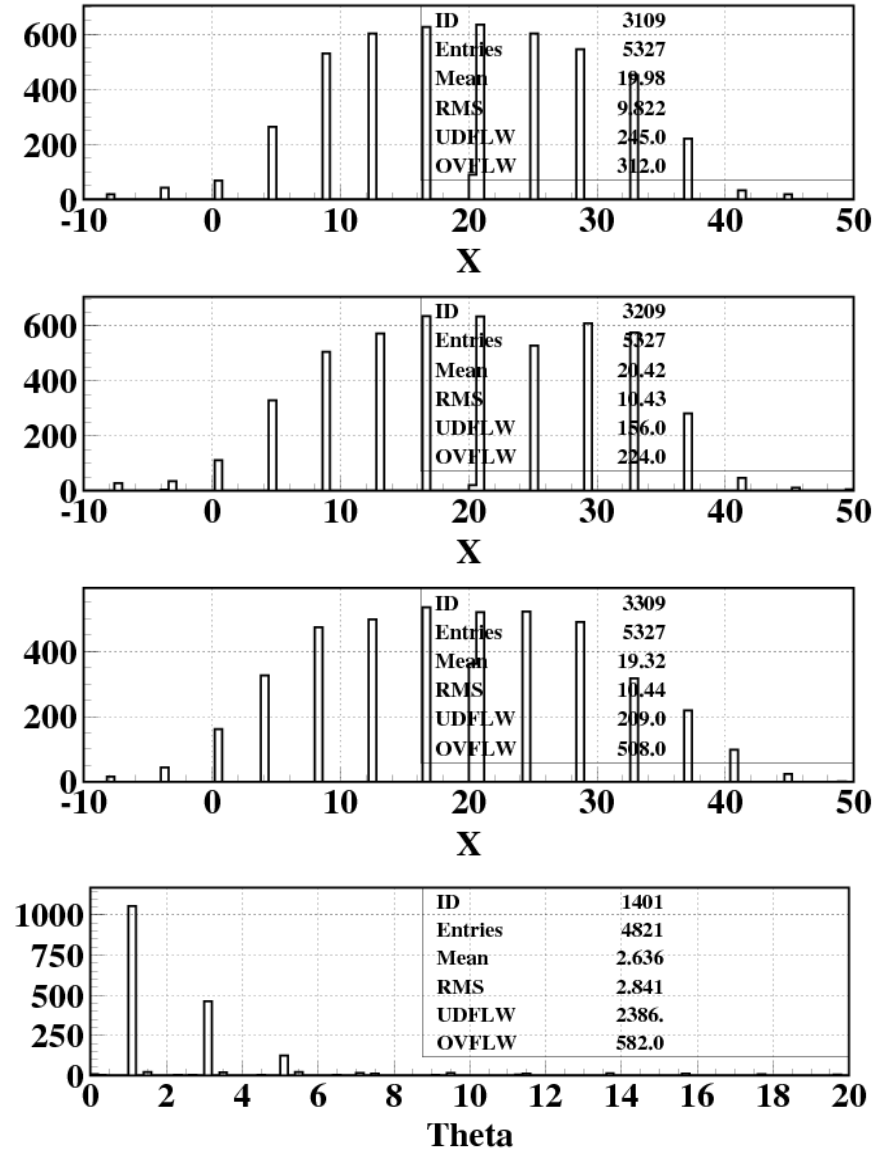


Energy and time calibration using cosmic rays (self-triggering)

- 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)

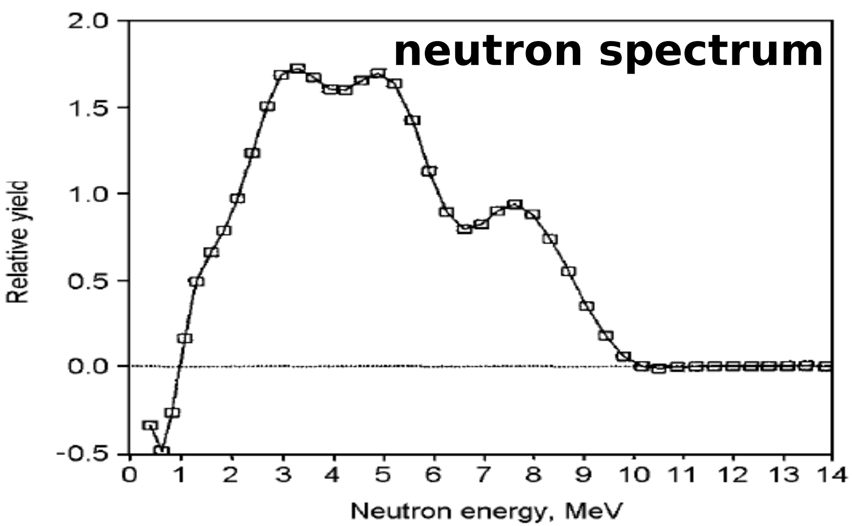
- Position = (V x ΔT_{LR}+40)/2 V=13 cm/ns
- TDC res = 625ps $\rightarrow$ $\Delta x \sim 5$cm

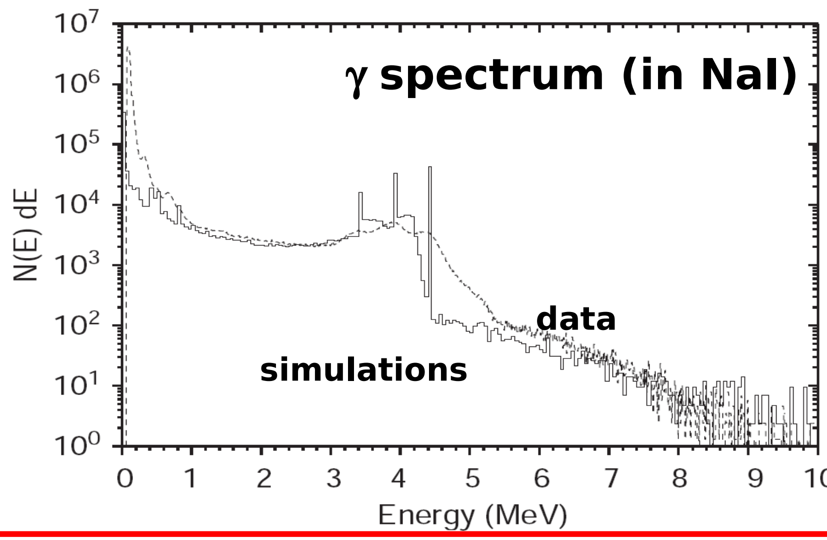




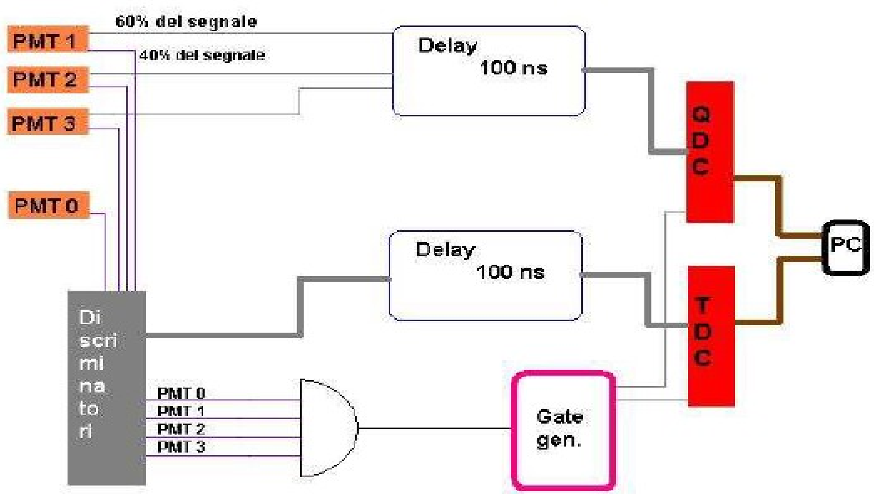
Calibrations: AmBe source

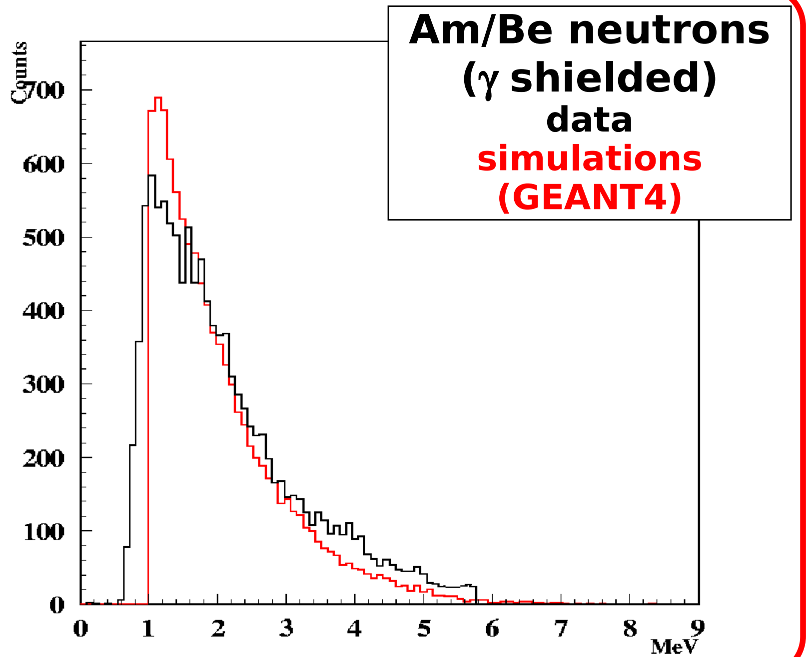
- ^{241}Am is an intense α emitter $\rightarrow$ ^{9}Be (α,n) ^{12}C
- 60% of n are emitted with a 4.4 MeV γ (first excited 2+ state of ^{12}C)
- Encapsulated source has a more complex spectrum
- Neutron rate: 5 10^{3} n/s





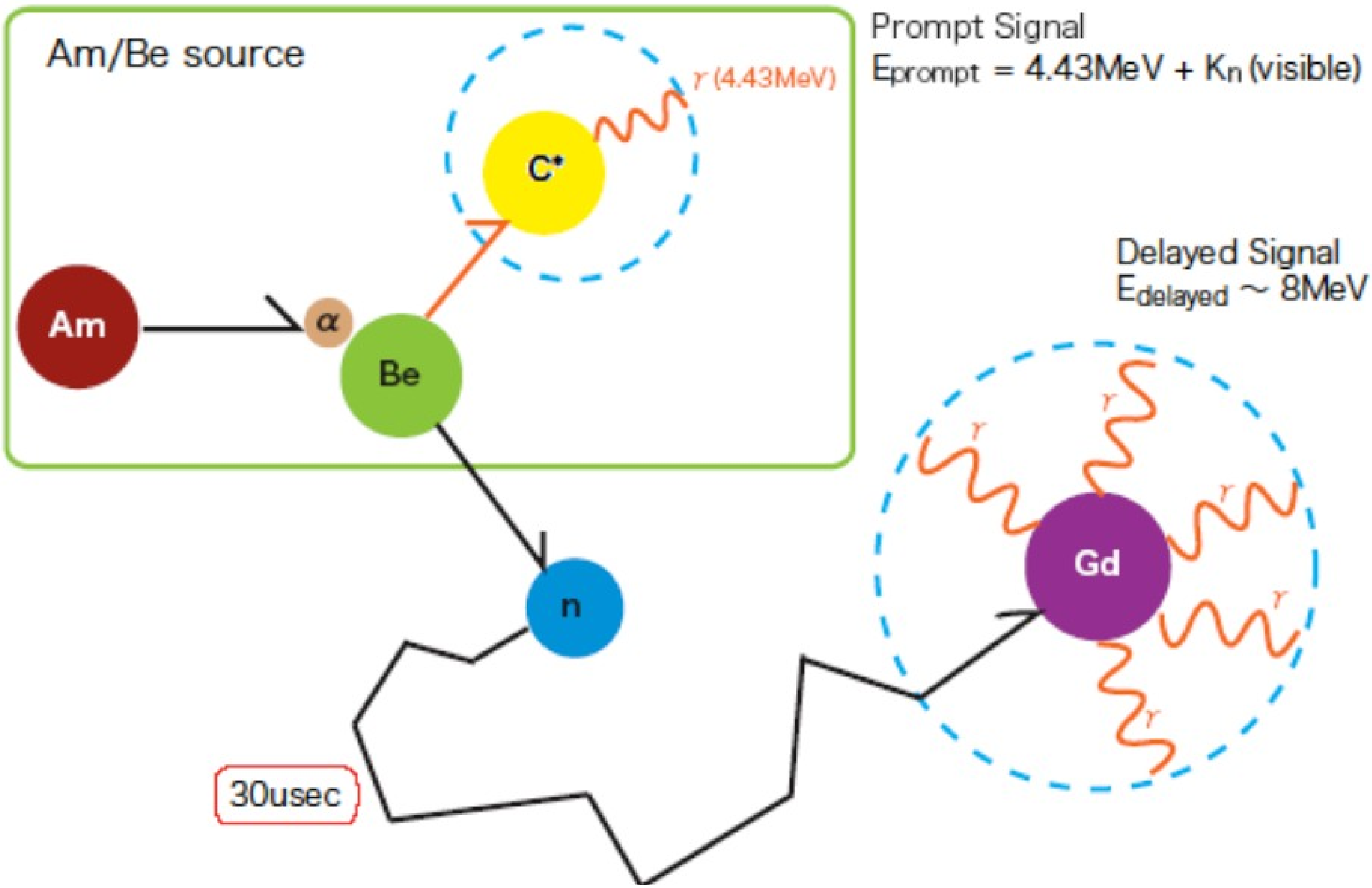
Single hit trigger: neutron detection





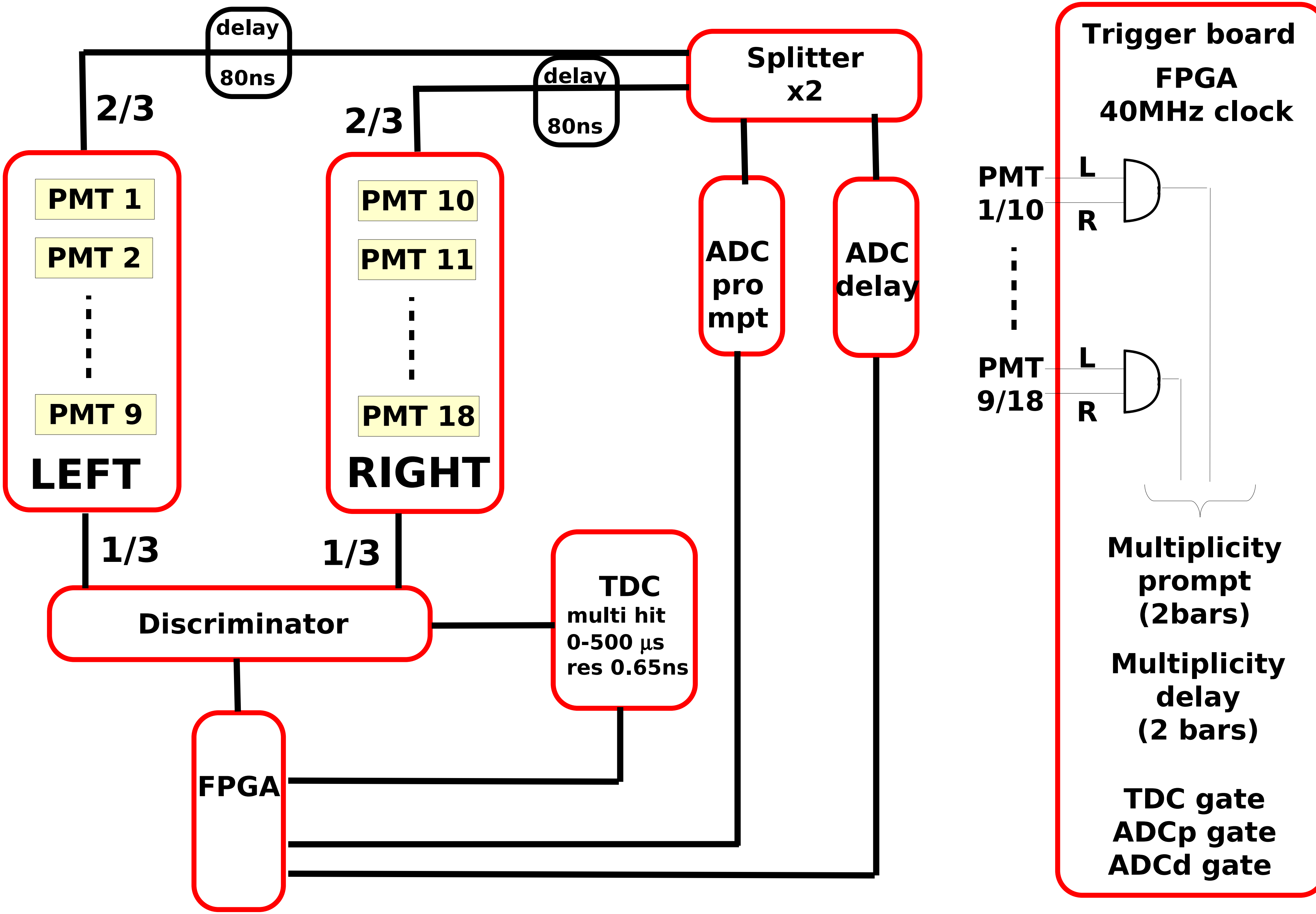
Calibrations: AmBe source

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



The real double-hit trigger is needed!

DAQ scheme (VME based)



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

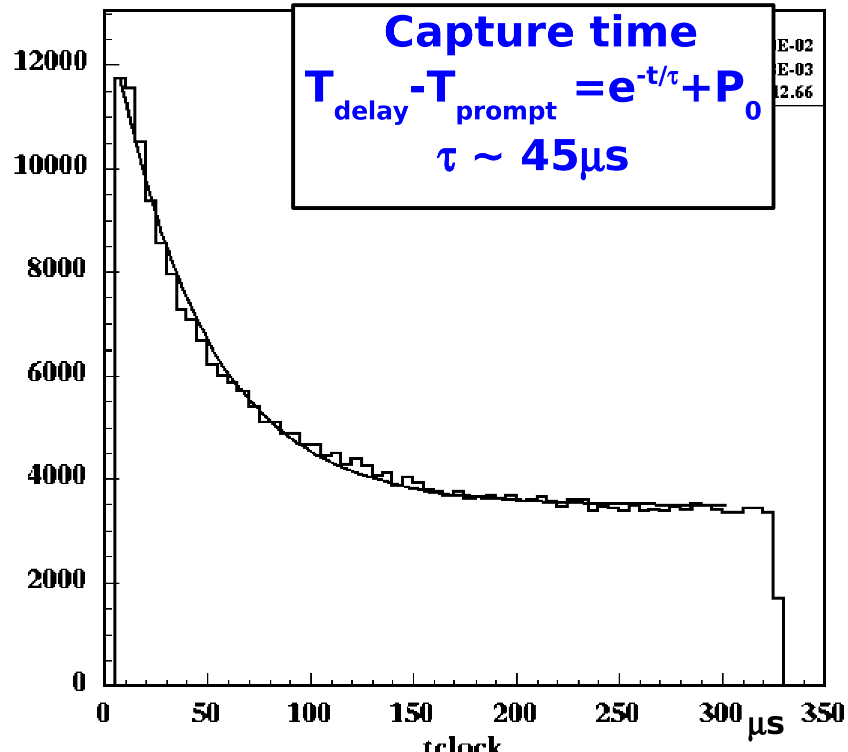
Time cluster recognition
TDC independent analysis
ADC independent analysis

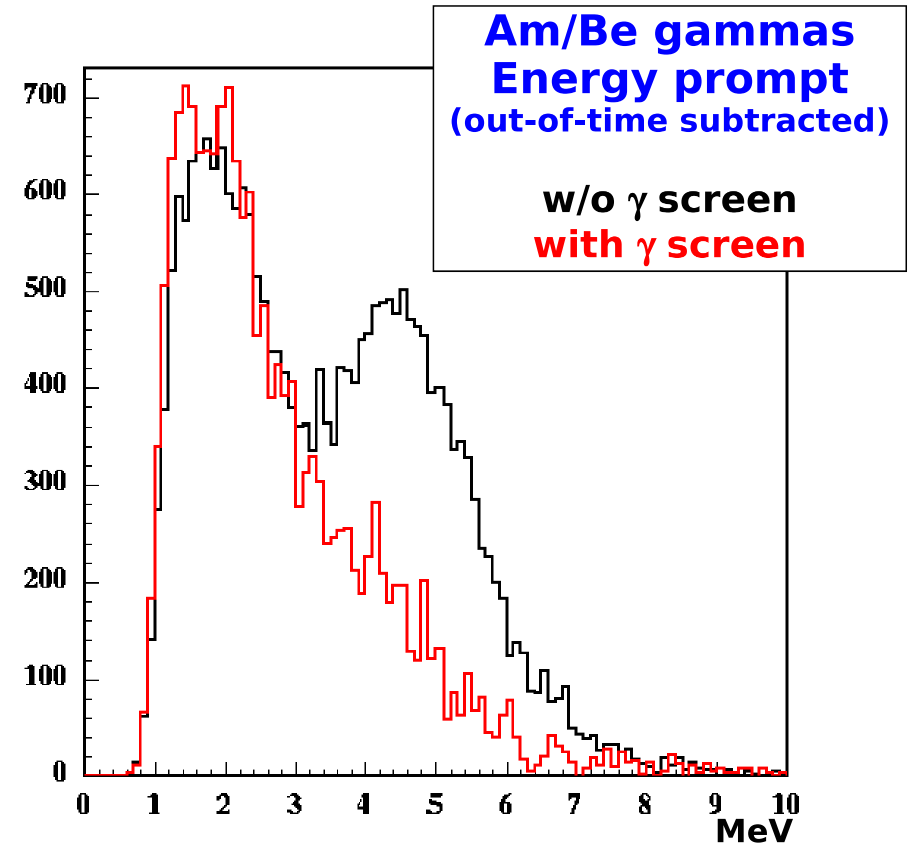
Event builder
ADC/TDC correlated analysis

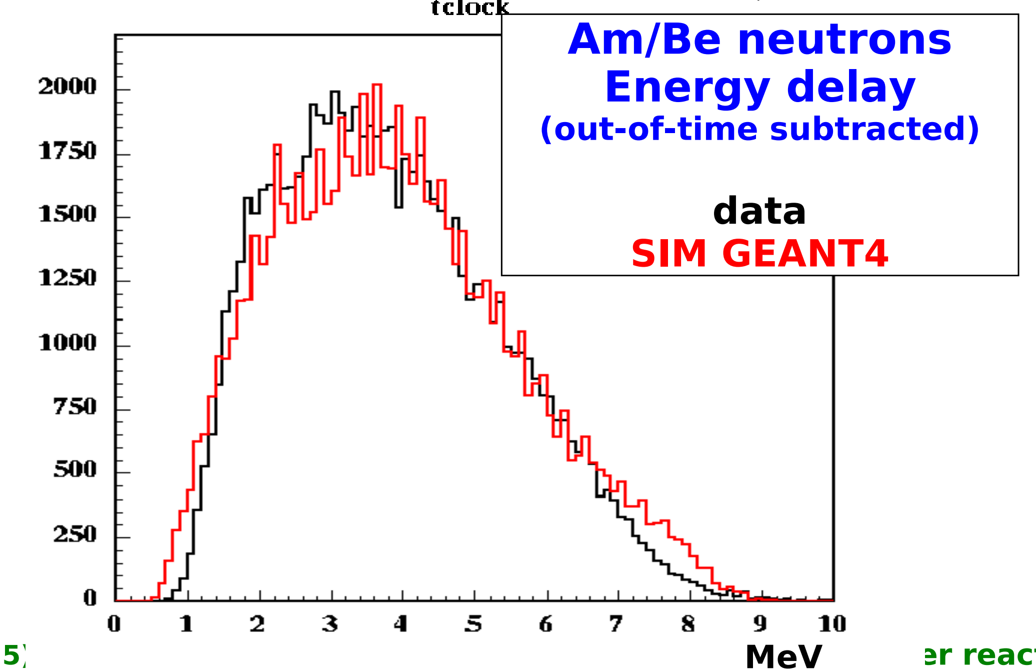
OUTPUT

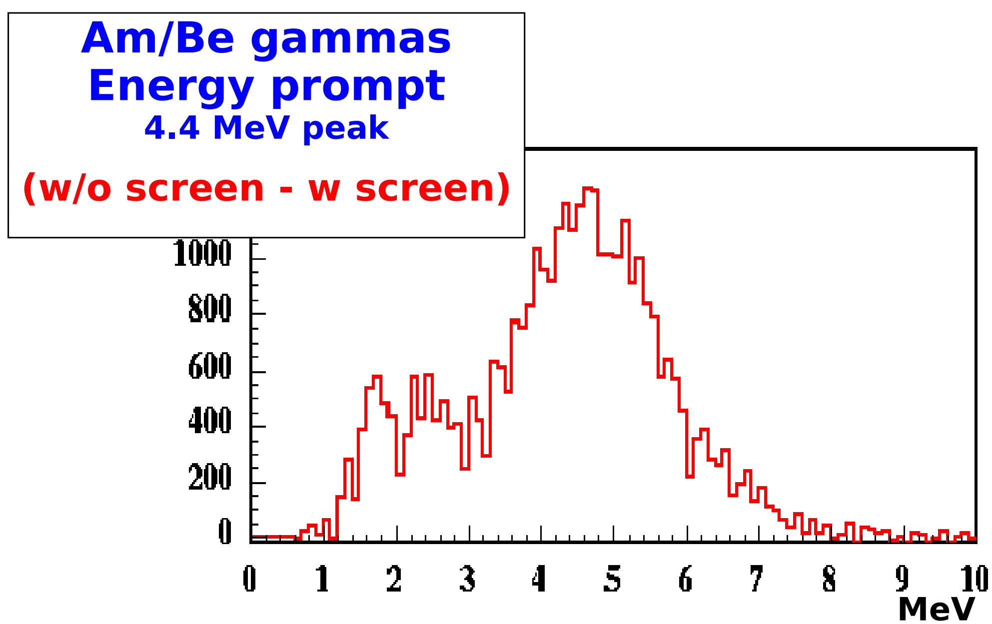
Raw data
Detector calibration oriented
Prompt/Delay

AmBe source measuretments

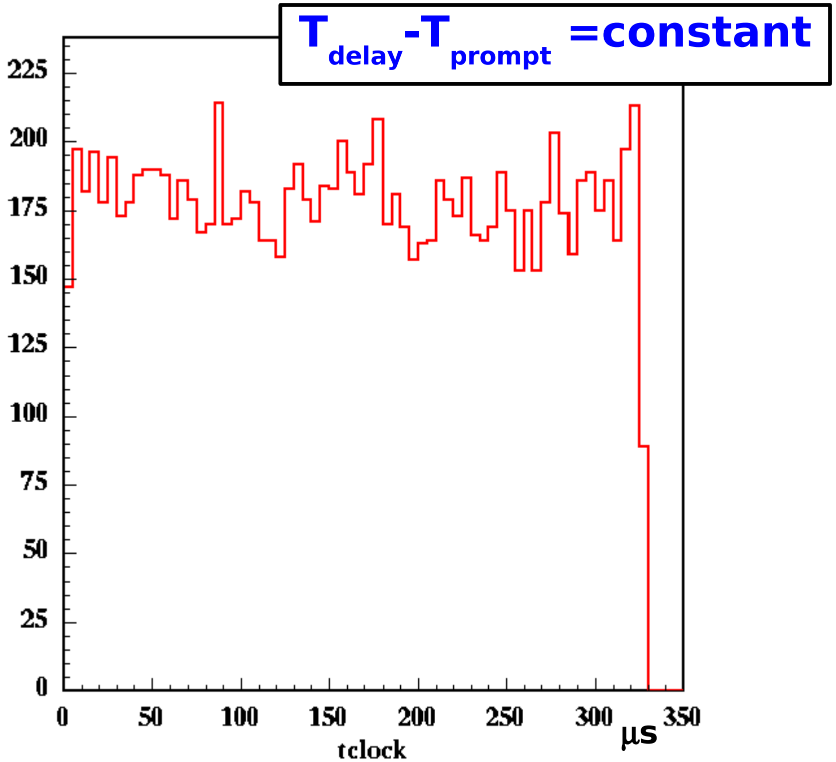


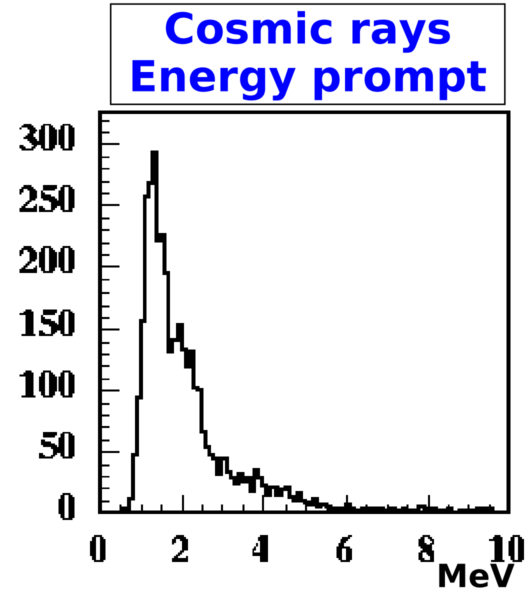


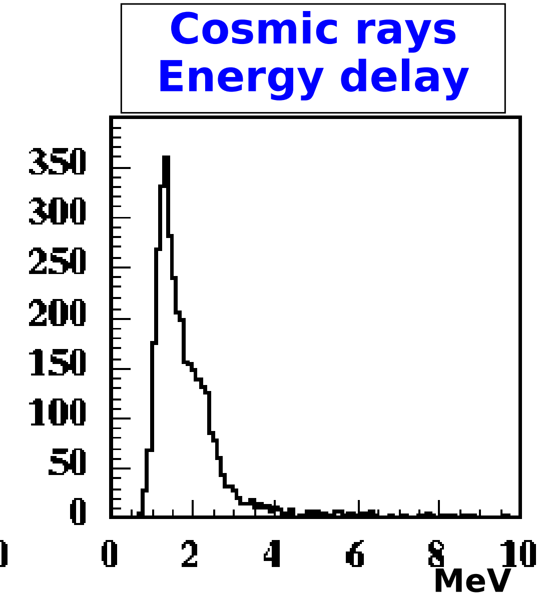


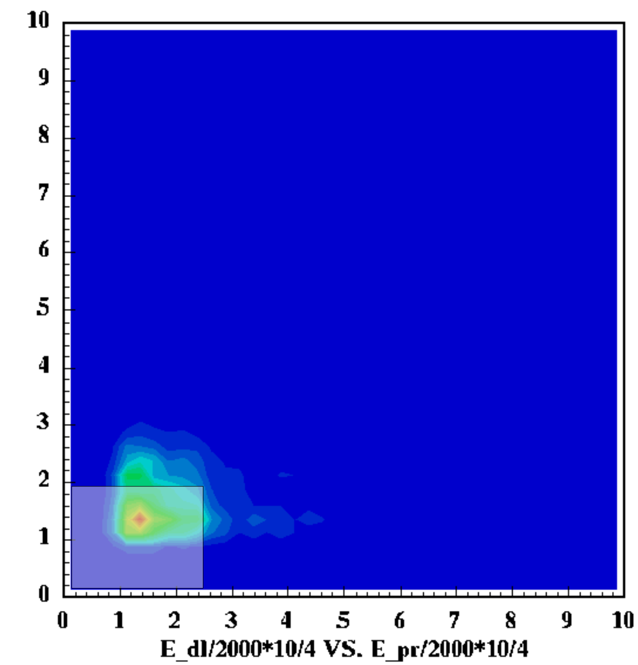


Background:
cosmic rays + intrinsic activity





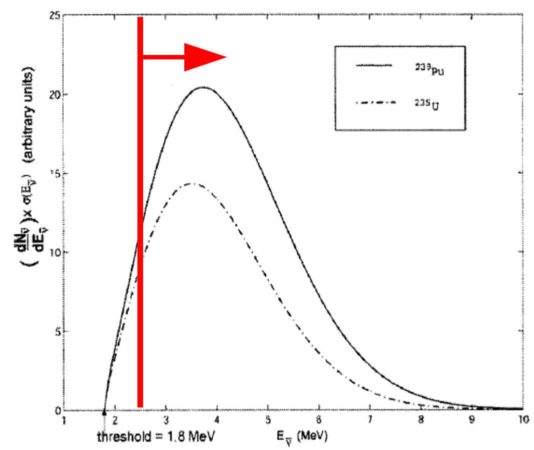




Cuts

- 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 (CANDU) during outage/restart in May-Jun 09

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

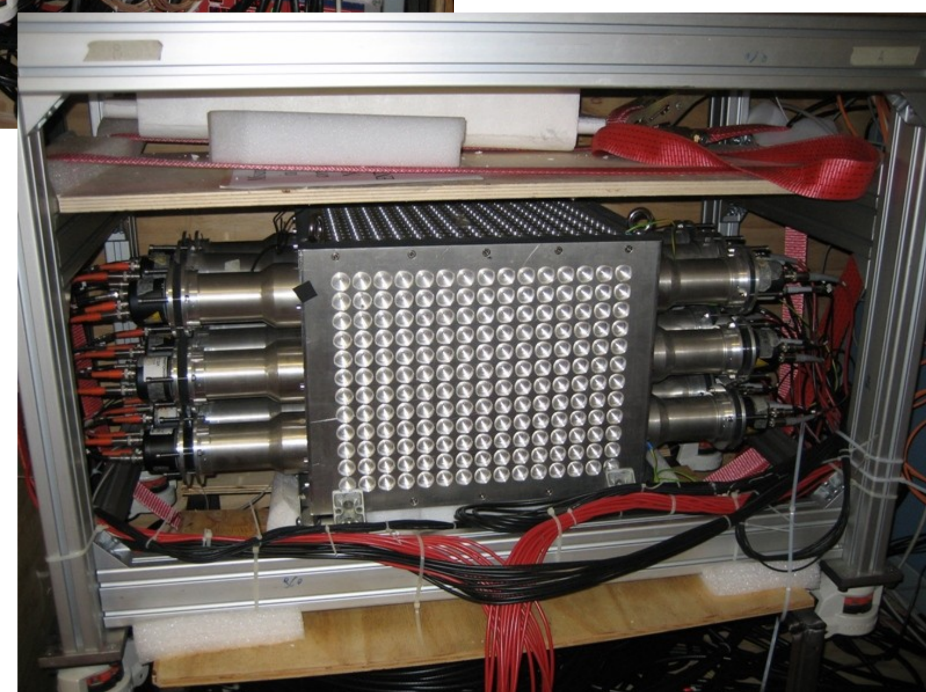
Test Goals

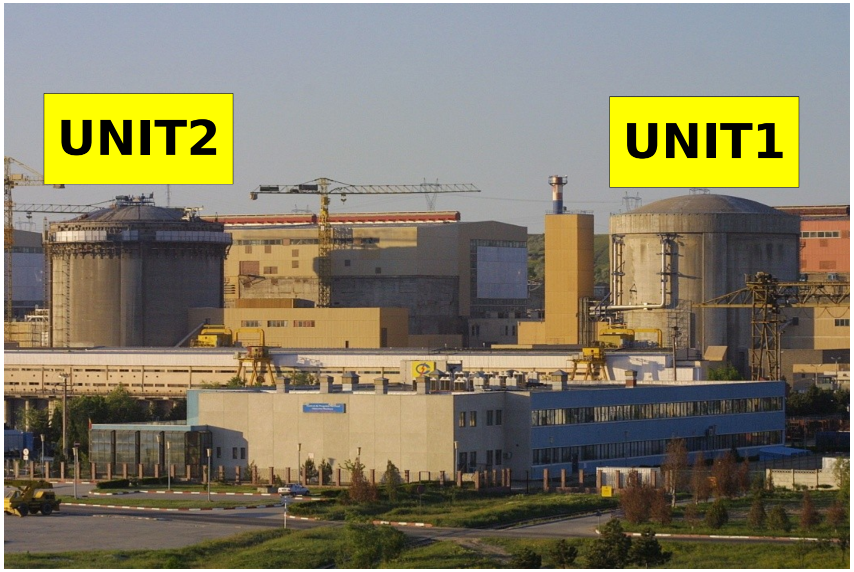
- In-situ measurement
- Experimental set-up optimization
- Background rates
- Reactor On/Off change
- MC validation
- Data analysis optimization

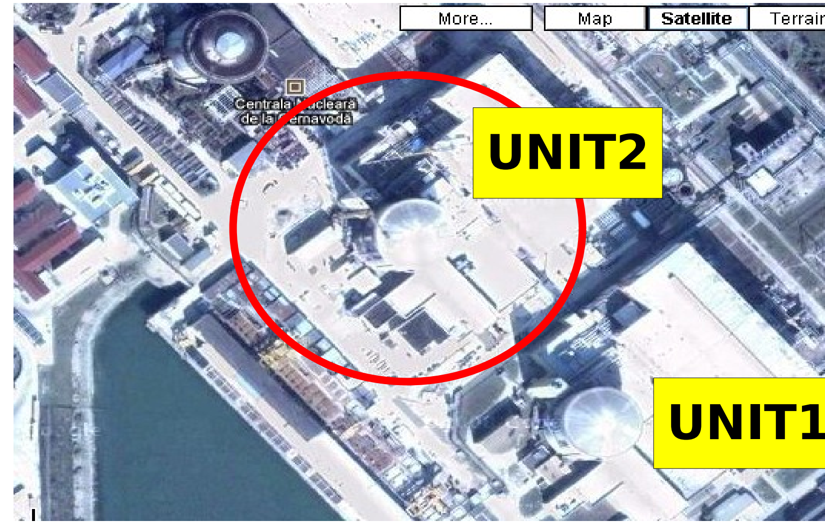
Expected rates/yields

antineutrino	cosmic	other
2000 ev/d/mq/GW	100 ev/d	?? ev/d
2GW 0.036mq Detection eff~20%	based on home measurement off-line analysis rejection ~ 500	spallation n residual n flux residual γ flux
30 ev/d x 25d = 750 ev	x 25d = 2500 ev	x 25d = ??? ev


DANGER
Radiation risk
Misure in corso NON ENTRARE







- Detector and electronics mounted in a van and moved to Cernavoda (Ro) on May 25th
- The van has been parked in front of Unit2 (~30m far) where remained up to June 30th
- Unit2 was resumed on June 1st (while Unit1, 2GW, 130m far was always on)

We collected data
- 7 days reactor off
- 30 days reactor on

Data Taking

- The detector was remotely controlled using a simple modem/phone connection (VME and HV)
- Smooth running for the whole month
- Cosmic ray runs for calibration at the beginning and at the end

Trigger Rates

Single hit:
>1hit
Threshold 15mV (Etot>1 MeV

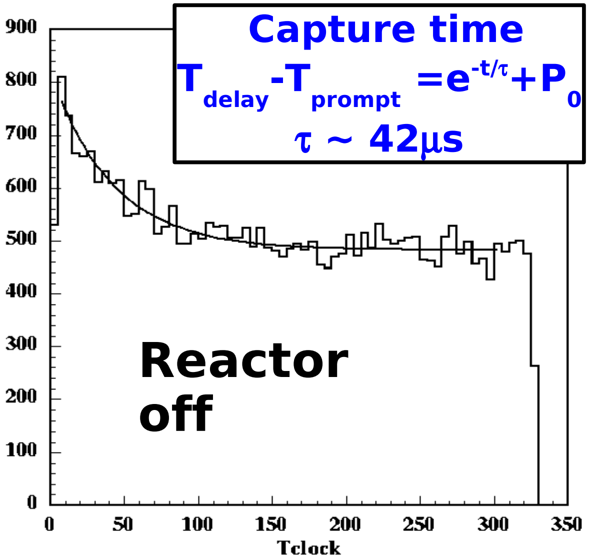
Production
>1hit Prompt
>1hit Delayed
Threshold 15mV (Etot>1 MeV)

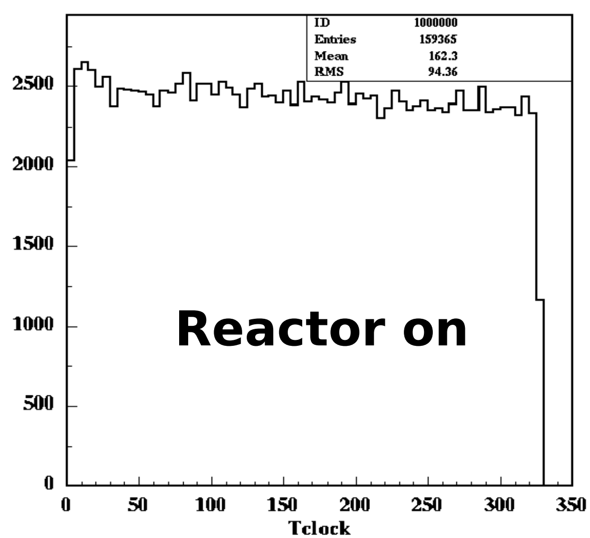
Reactor off:	R~ 50 Hz	**Reactor off:**	R~ 1.7 Hz
Reactor on (max pwr):	R~120 Hz	**Reactor on (max pwr):**	R~ 9 Hz

Capture time

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

$\tau \sim 42\mu s$





Production rate is dominated by random coincidences

$R \sim 2\, R_{prompt}\, R_{delayes}\, \tau$

$\sim 2\, R_{single\ hit}\, R_{single\ hit}\ 330\mu s$

Data analysis in under way

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 m^3 detector we proposed is made by plastic scintillator bars wrapped in thin gadolinium foils

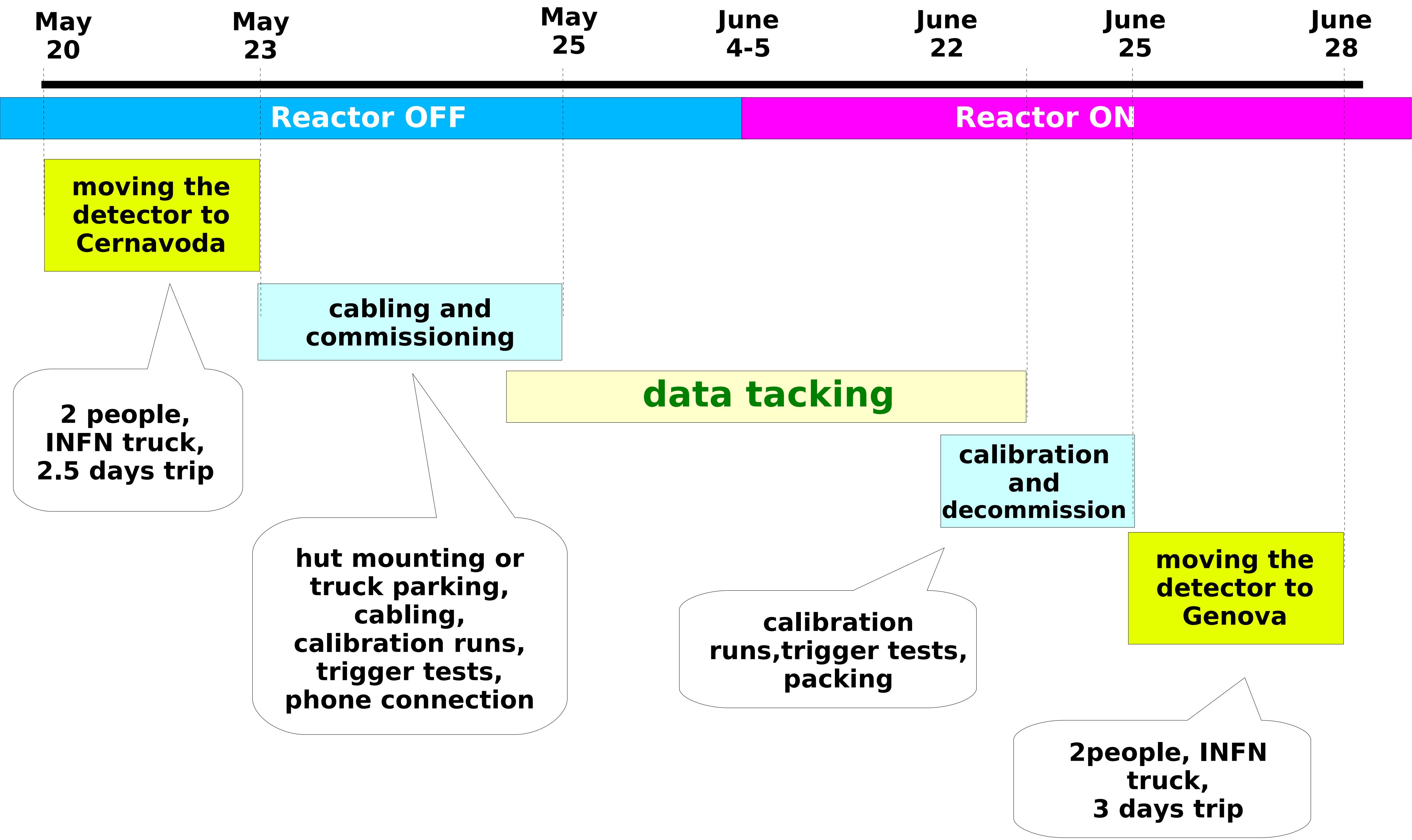
- Segmentation (individual bar read-out) helps in reducing the background

- 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 $(1:3)^3$, has been built in Genova and after lab tests, it has been installed in the Cernavoda (Ro) NPP. Data analysis in under-way.

Back-up slides

Tests in Cernavoda (Ro) Workplan



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'