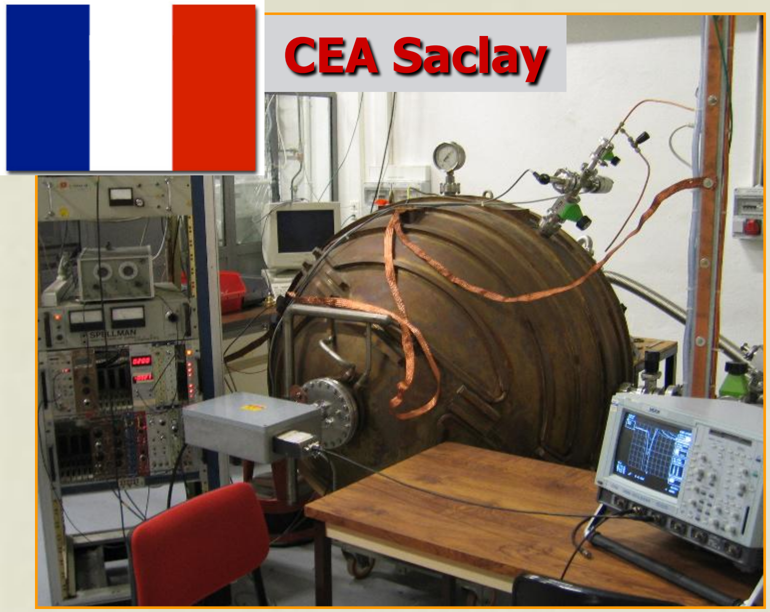
Large Volume Spherical Proportional Counter: Development and Applications

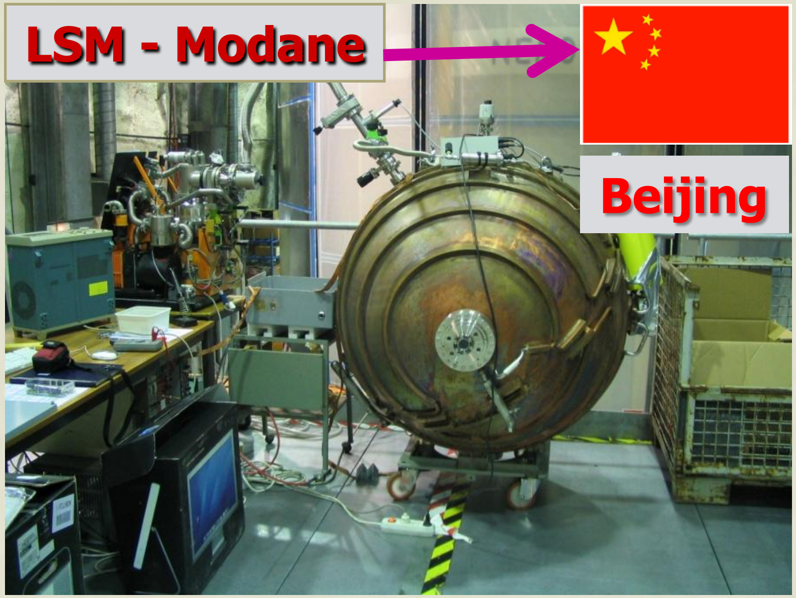
Savvidis Ilias
Aristotle University of Thessaloniki

OUTLINE

- The design of the detector
- Low flux neutron detection
- Uranium, plutonium detection
- Relativistic atmospheric neutron detection
- Supernova neutrino and reactor neutrino detection
- conclusions

The three detectors

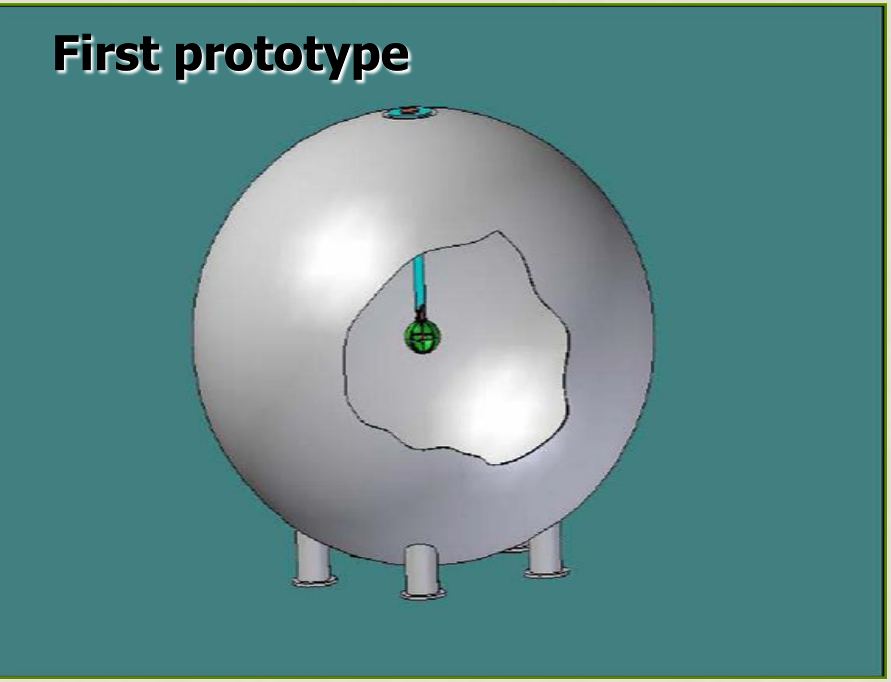

CEA Saclay

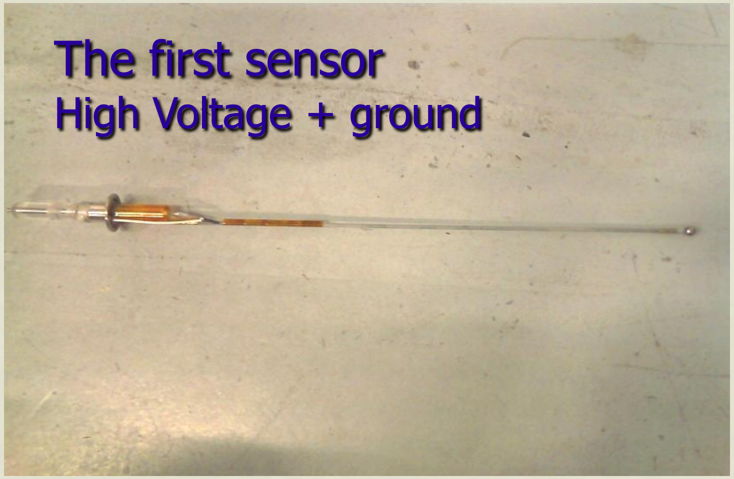

LSM - Modane

Beijing


Thessaloniki

The detector


First prototype


The first sensor
High Voltage + ground

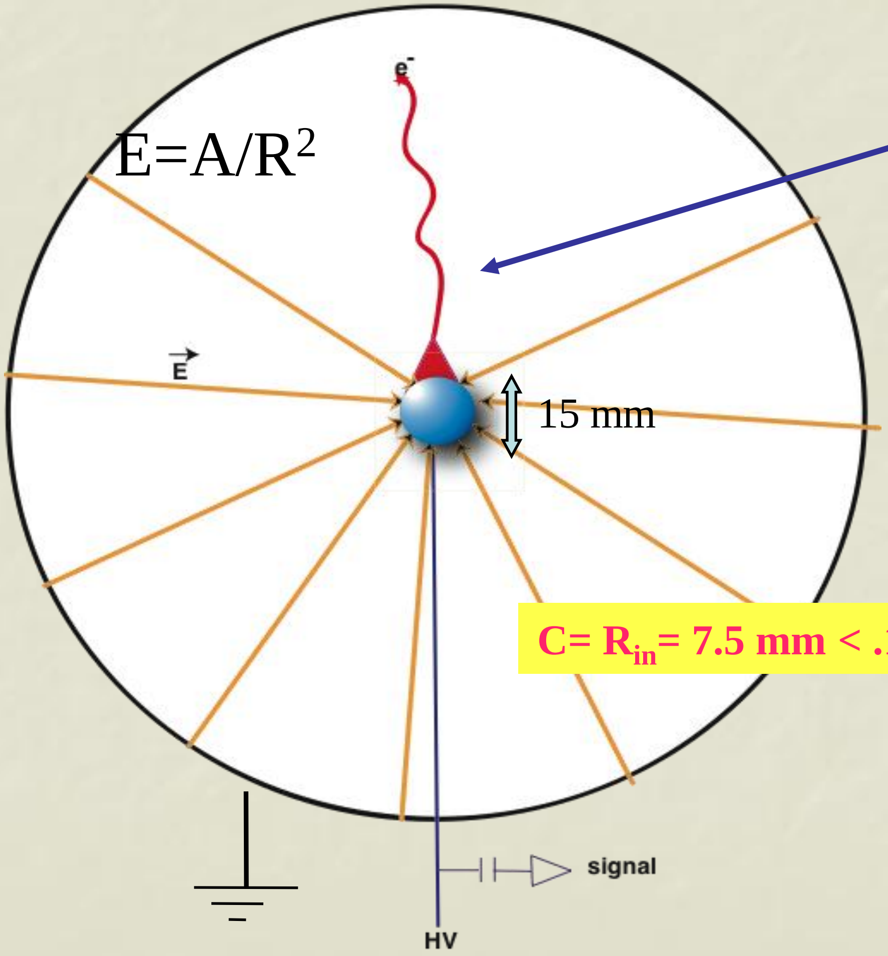

The new sensor
Two high Voltage + ground

Volume = 1 m3, Cu 6 mm
Gas leak < 5x10-9mbar/s.
Gas mixture Argon + 2%CH4
.Pressure up to 5 bar
Internal electrode at high voltage.
Read-out of the internal electrode 15 mm

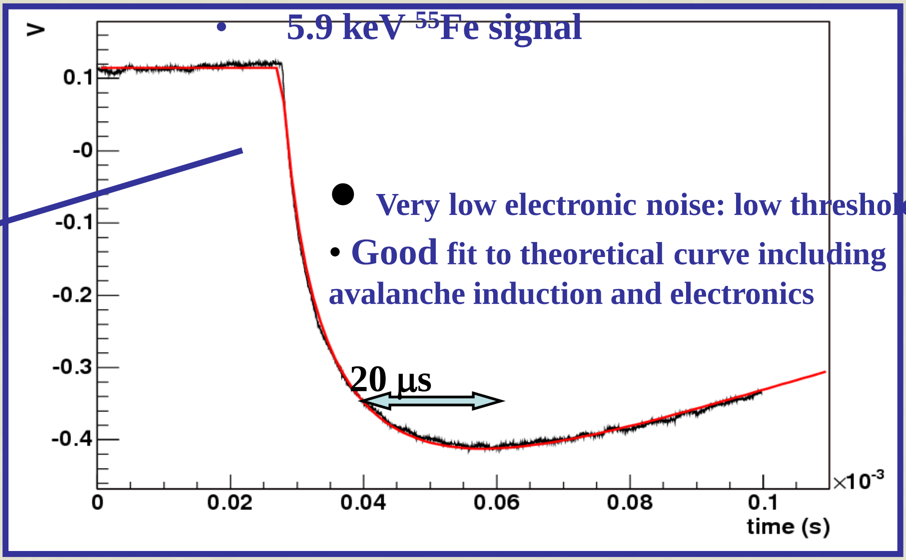
Radial TPC with spherical proportional counter read-out

A Novel large-volume Spherical Detector with Proportional Amplification read-out, I. Giomataris *et al.*, JINST 3:P09007,2008

Saclay-Thessaloniki-Saragoza



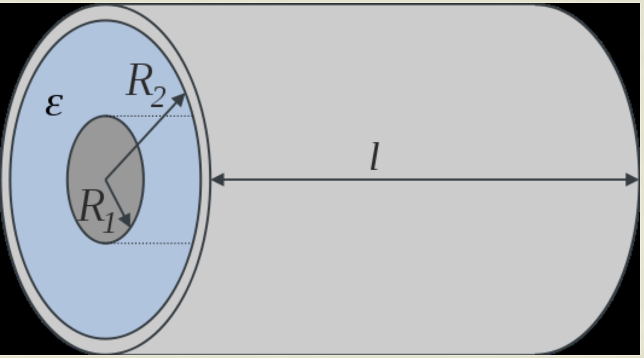
$C= R_{in}= 7.5\text{ mm} < .1\text{pF}$



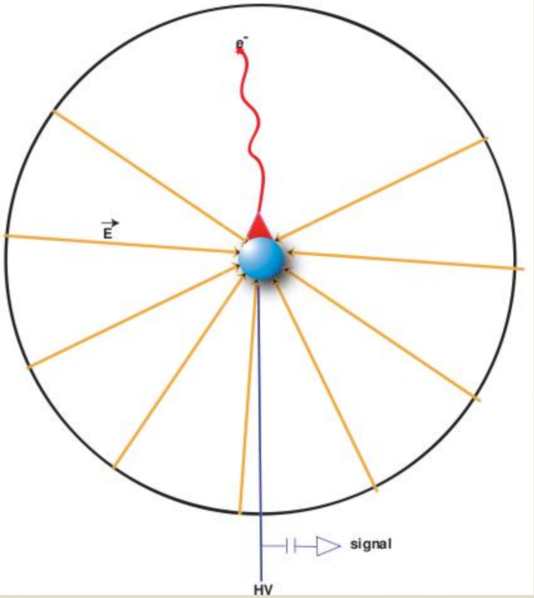
- 5.9 keV ^{55}Fe signal
- Very low electronic noise: low threshol
- Good fit to theoretical curve including avalanche induction and electronics

- Simple and cheap
- single read-out
- Robustness
- Good energy resolution
- Low energy threshold
- Efficient fiducial cut

Low C and low electronic noise



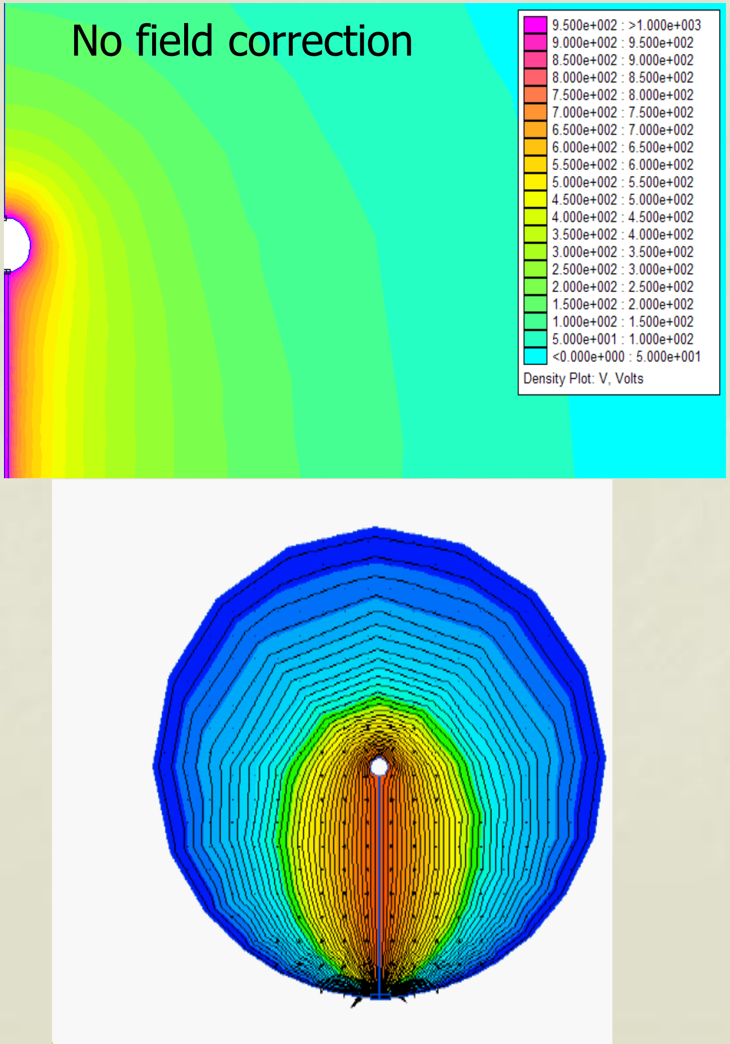
Cylindrical Proportional Counter
$C = \varepsilon_0 L \log(R_1/R_2)$
For large detectors: $C > 100\mathrm{pF}$

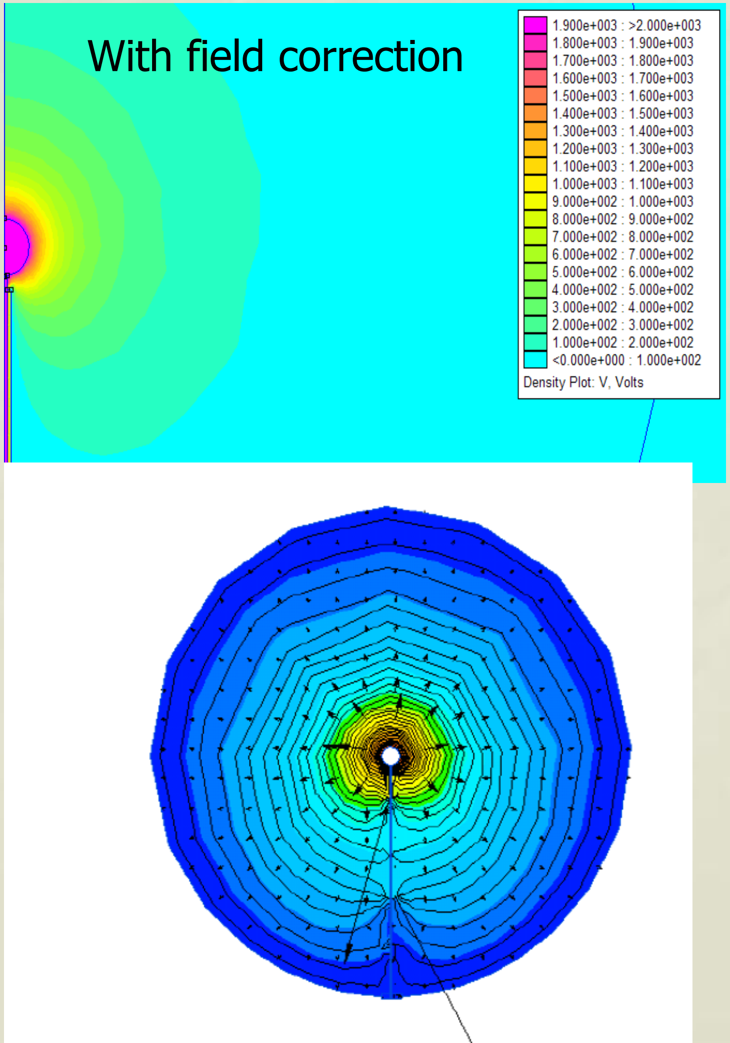


Spherical Proportional Counter
$C = 4\pi\varepsilon_0 R_{\mathrm{ball}}$
For large detectors: $C > 0.05\mathrm{pF}$

Electrostatic field (simulation results)

LEFT: 15 mm sphere, 1mm Cu cable covered with 3mm PE
RIGHT: 15 mm sphere, 1mm Cu cable covered with 3mm PE + graphite (ground).
Distance sphere to graphite 4mm





Alpha particle spectroscopy and thermal neutrons

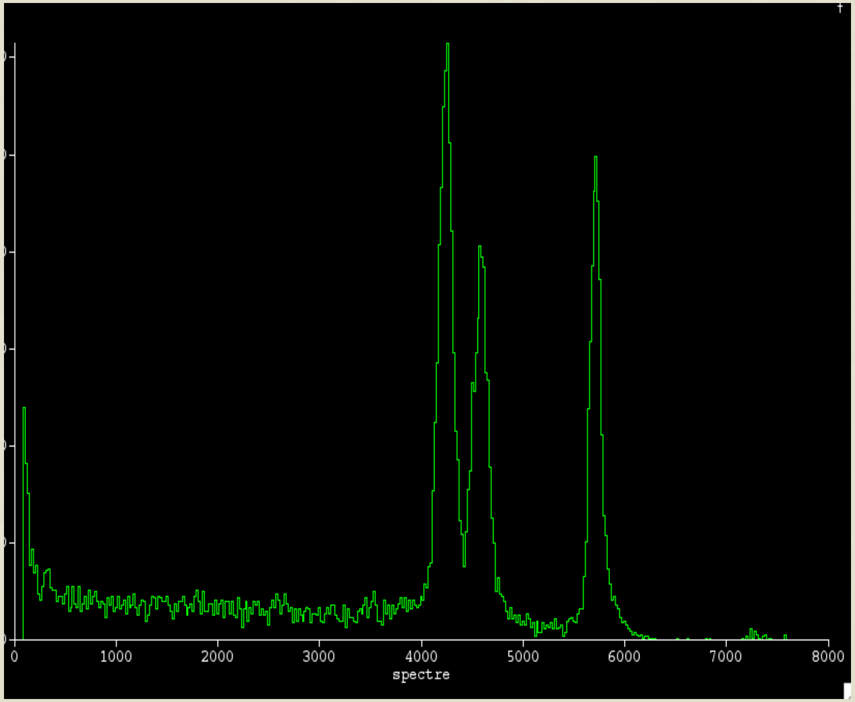
Rn-222: 5.49 MeV alpha
Po-218: 6.00 MeV alpha
Po-214: 7.68 MeV alpha
Resolution: σ=1.5%
Gas: 98% Ar + 2% CH4,P=200 mbar

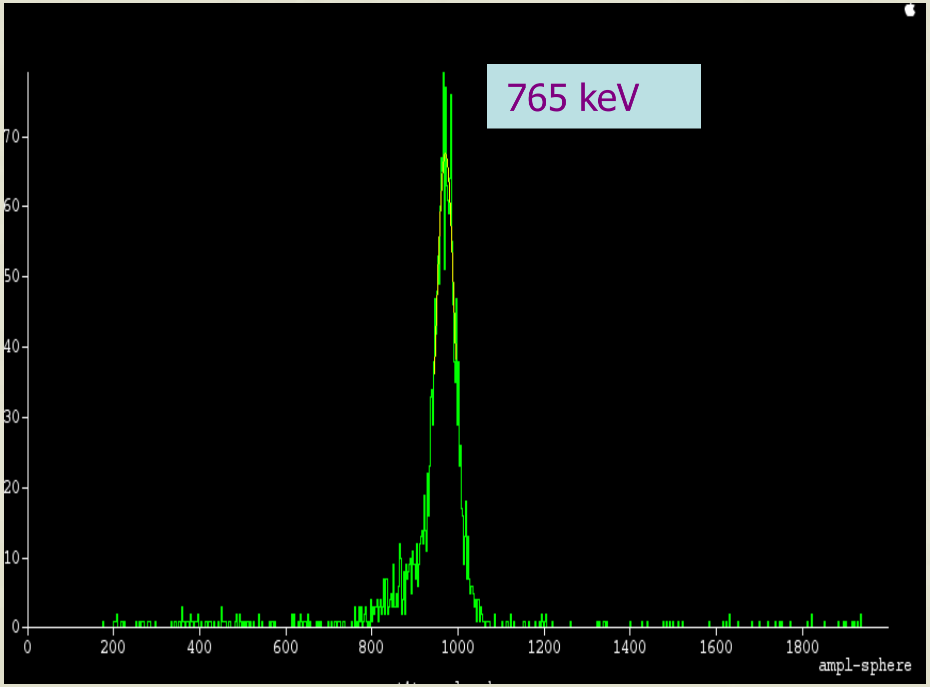
Underground thermal neutrons peak in LSM, after rise time cut.

3gr He-3 in the sphere

R=417 evts/d, Φth.neutron = 1.9 10-6 n/cm2/s

n + He-3 → p + H-3 + 765 keV





Uranium-Plutonium detection

The problem

- Building an atomic bomb of highly enriched uranium (HEU) or plutonium since the knowhow to build a gun-type HEU-based bomb has been in the public domain for several decades.
- Improvised nuclear weapons (dirty bombs, based on either HEU or Plutonium) are easier to build than military grade weapons, and they can be delivered to populated areas by modes of civilian transport such as road or sea which militaries are not equipped to defend, including cars, containers, trucks, boats, trains, helicopters, planes, or ships.
- For HEU with shielding, such as lead, concrete, or steel, passive detection is impossible beyond the range of 1 meter using gamma and neutron detection equipment.

Neutron emission from uranium and plutonium isotopes

Nuclide	**Half-life**	**Spontaneous Fission prob. (%) per decay**	**Neutrons per fission**	**Neutrons per (g.s)**
^{235}U	7.04x10^{8} years	7.0x10-9 %	1.86	1.0x10^{-5}
^{238}U	4.47x10^{9} years	5.4x10-5 %	2.07	0.0136
^{239}Pu	2.41x10^{4} years	4.4x10-10 %	2.16	2.2x10^{-2}
^{240}Pu	6569 years	5.0x10-6 %	2.21	920
^{252}Cf	2.638 years	3.09 %	3.73	2.3x10^{12}

Minimum detectable neutron flux for the spherical proportional counter

- Neutron detection:

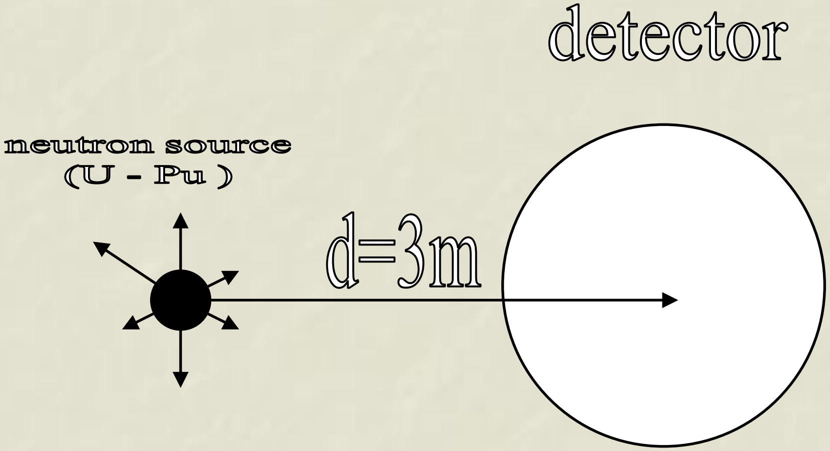
  n+3-He→p+3-H+765 keV (present system)
  En=E(H-3)+E(p)+765 keV

- For thermal neutrons: **Φmin=1.4x10-6 n/cm2.sec**
- Count rate with 3gr of He-3: **R=4.2x10-3 c/sec**

- Estimated count rate from 10 gr of He-3:**R=1.26x10-2 c/sec**

(Jacques Derre calculations from the LSM Modane first data)

Neutron flux decrease with the distance



Neutron flux decrease

$\Phi = A/4\pi d^2$

For d=3m: $1/4\pi d^2$= 2.65x10^{-6} 1/cm^2

Uranium detection

- **U-235** spontaneous fission neutron emission: **1x10-5 n/gr.sec**
  For **m=10** kgr, Distance **d= 3m**
  The neutron flux in the detector is: **Φ= 2.65x10-7 n/cm2.sec**
  (Very low to be measured even if we can thermalise all the neutrons using PE).

- **U-238** spontaneous fission neutron emission: **0.0136 n/gr.sec**
  For **m=1 kgr,** Distance **d= 3m**
  Φ= 3.6x10-5 n/cm2.sec
  If all of them are thermal neutrons then the count rate of the detector is:
  R=21 cnts /min

Plutonium detection

- The neutron emission depends on the isotope composition and the isotope composition depends on the type of the reactor.

	Weapons grade	**Reactor grade**	**MOX grade**
Pu-239 (%)	93.8	60.3	40.4
Pu-240 (%)	5.8	24.3	32.1
Pu-241 (%)	0.35	9.1	17.8
Pu-242 (%)	0.022	5	7.8

- **MOXgrade Pu** (Mixed Oxide fuel, mixture of uranium and plutonium oxide)
  4.8x10 5 n/kgr.sec

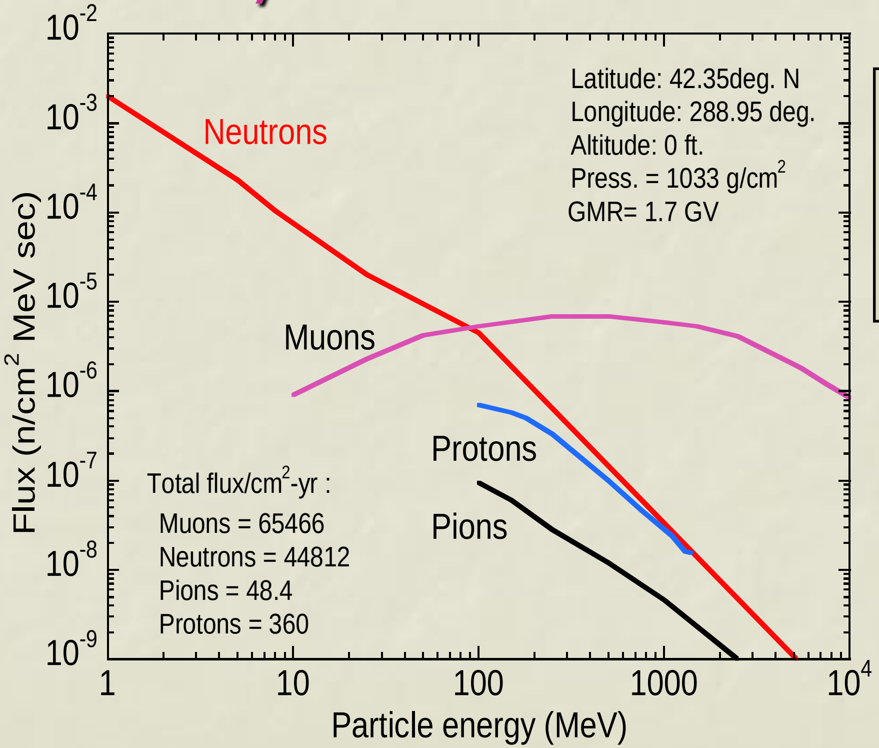
- **Weapons grade Pu**: **5.4 x10 4 n/kgr.sec**

- At a distance **d=3m** the neutron flux is:
- **Φ1= 1.27 n/cm2.sec (MOX grade)**
- **Φ2= 0.14 n/cm2.sec (weapons grade)**

- **Both the above neutron fluxes are well detecting using PE moderator, also in the case of the shielding material.**

The possibility to measure the very fast atmospheric neutrons (En > 100 MeV) at the ground level, using Bi-209 fission

Cosmic-ray environment on the earth



Thermal Neutron flux = 120 n/cm^2 d

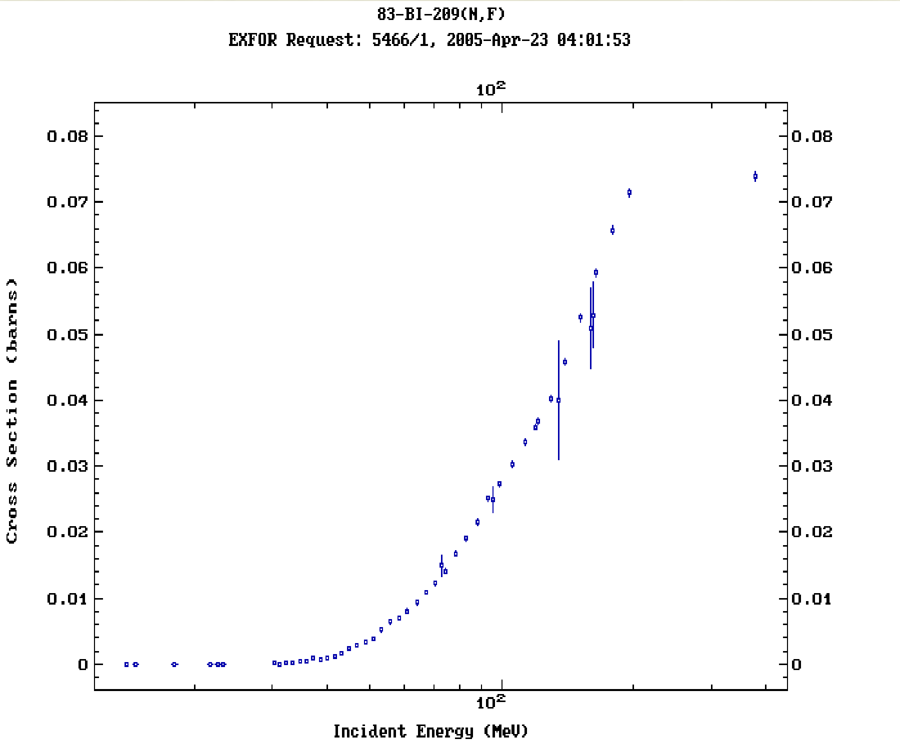
1 MeV< En <10 MeV = 432n/cm2 d

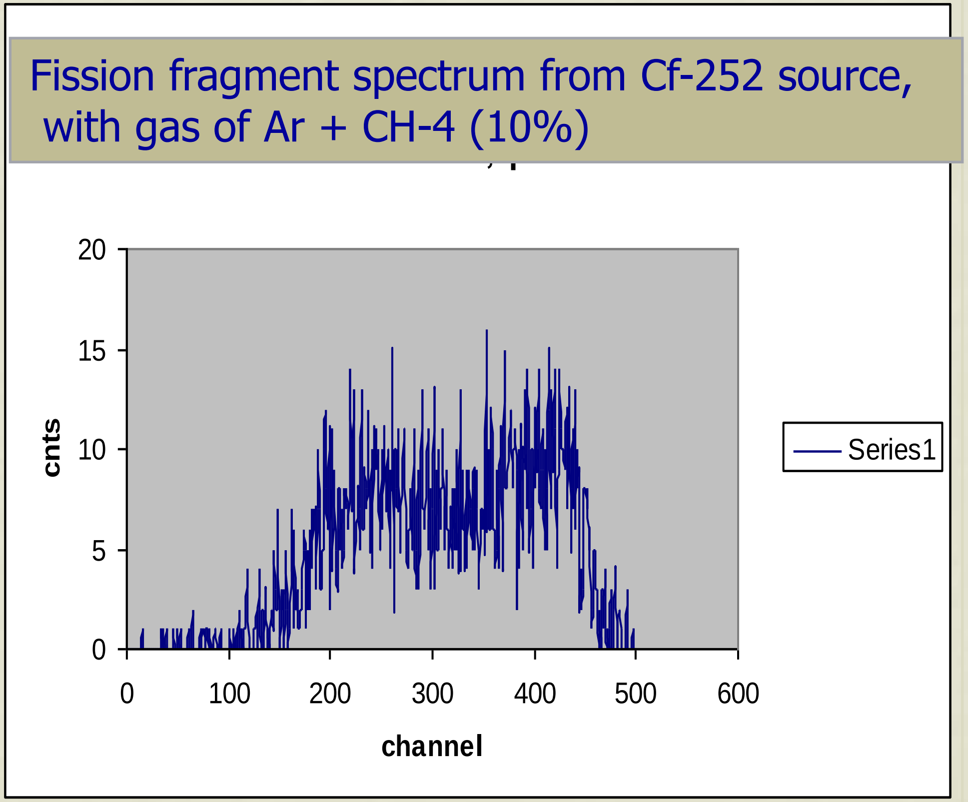
100 MeV<En< 1000 MeV = 43n/cm2 d

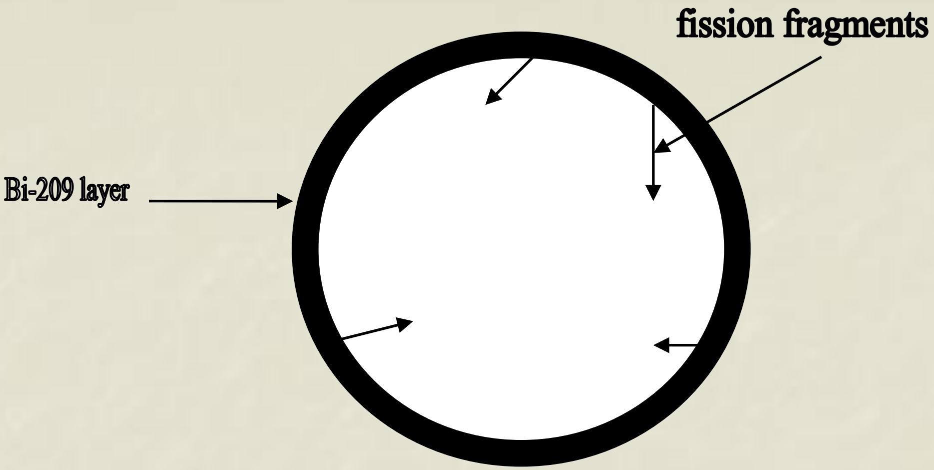
Sea level @ New York

Ref.) J.F. Ziegler, “Terrestrial cosmic rays”, IBM J. Res. Develop. Vol. 40, No. 1 (1996), p. 19

For relativistic neutrons (En>100MeV) directly measurements (without any moderation), the use of Bi-209(n,fission) reactions in the sphere, could give detectable results.




Fission fragment spectrum from Cf-252 source, with gas of Ar + CH-4 (10%)



Mean rang of Bi-209 fission fragments in Bi-209: **ro=10 µm**

Surface of the detector: **S= 4.23 m^2 = 4.23 x 10^{4} cm^2**

Total Bi-209 layer mass m = 413 gr

Total number of Bi-209 atoms **N(Bi-209) = 1.2 x 10^{24} atoms**

For **En > 200 MeV, σ = 0.075 barn**

If **Φ = 5 x 10^{-4} n/cm^2**

The number of reaction in Bi-209 layer = 4 /day

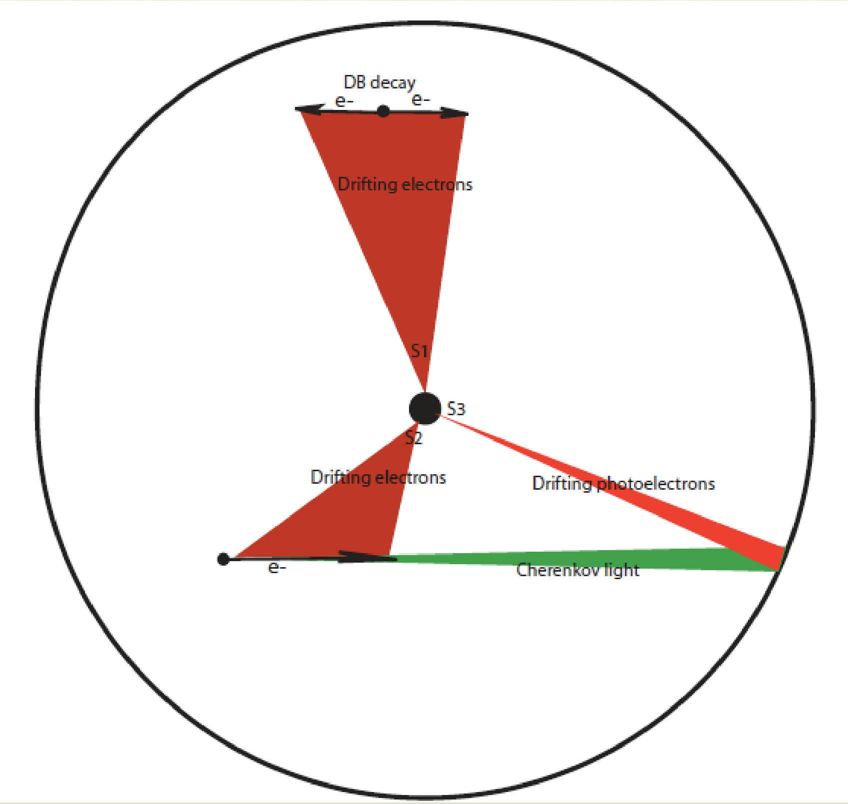
The number of counts in the detector = 2 cnts/day

Neutrino less double beta decay, ββ(0ν)

A well-designed Time Projection Chamber (TPC) filled with 136Xe is a good candidate. A competitive double beta decay candidate is the **136-Xe** gas whose natural abundance is rather high (9 %).

Xenon gas can be easily enriched by centrifugation methods to high concentrations of 136Xe: for example, an enrichment of 80% is being used by the EXO-200 experiment.

In order to separate the tail of the ββ(2ν)distribution from the ββ(0ν) peak, which constitute an irreducible background for the latter, the energy resolution of an experiment would be kept as low as possible of the order of 1%.



- Two electrons from ββ(0ν) with an energy of about 1.24 MeV are ionizing
- the Xenon gas. Secondary electrons (in red) are drifting to the central ball where they
- are amplified giving rise to a signal (S1). A background electron of 2.46 MeV (above
- Cherenkov threshold will generate a signal (S2) by ionization process and a second
- signal (S3) by the Cherenkov radiation (in green) interacting with the CsI
- photocathode.

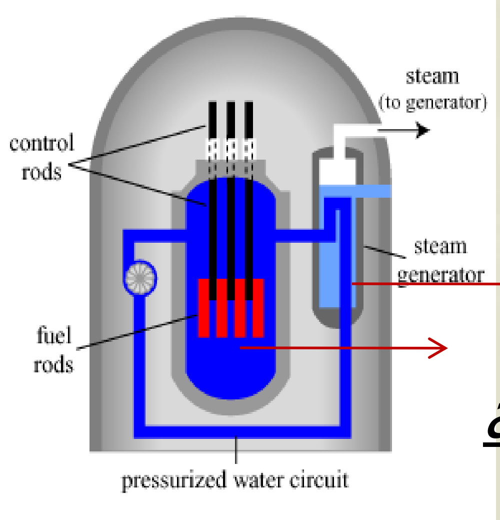
Can we detect the neutrinos?

super nova explosion

neutrinos

antineutrinos

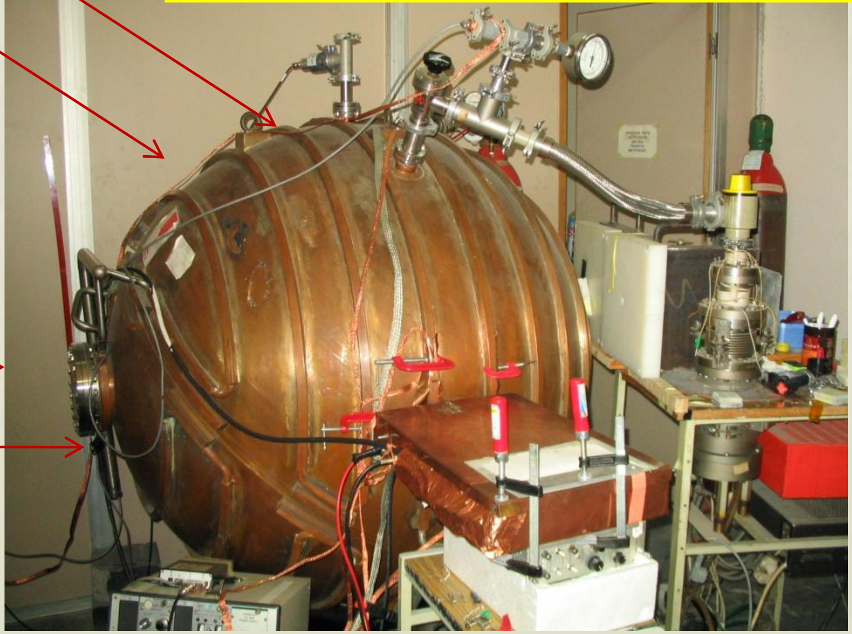
nuclear reactor core



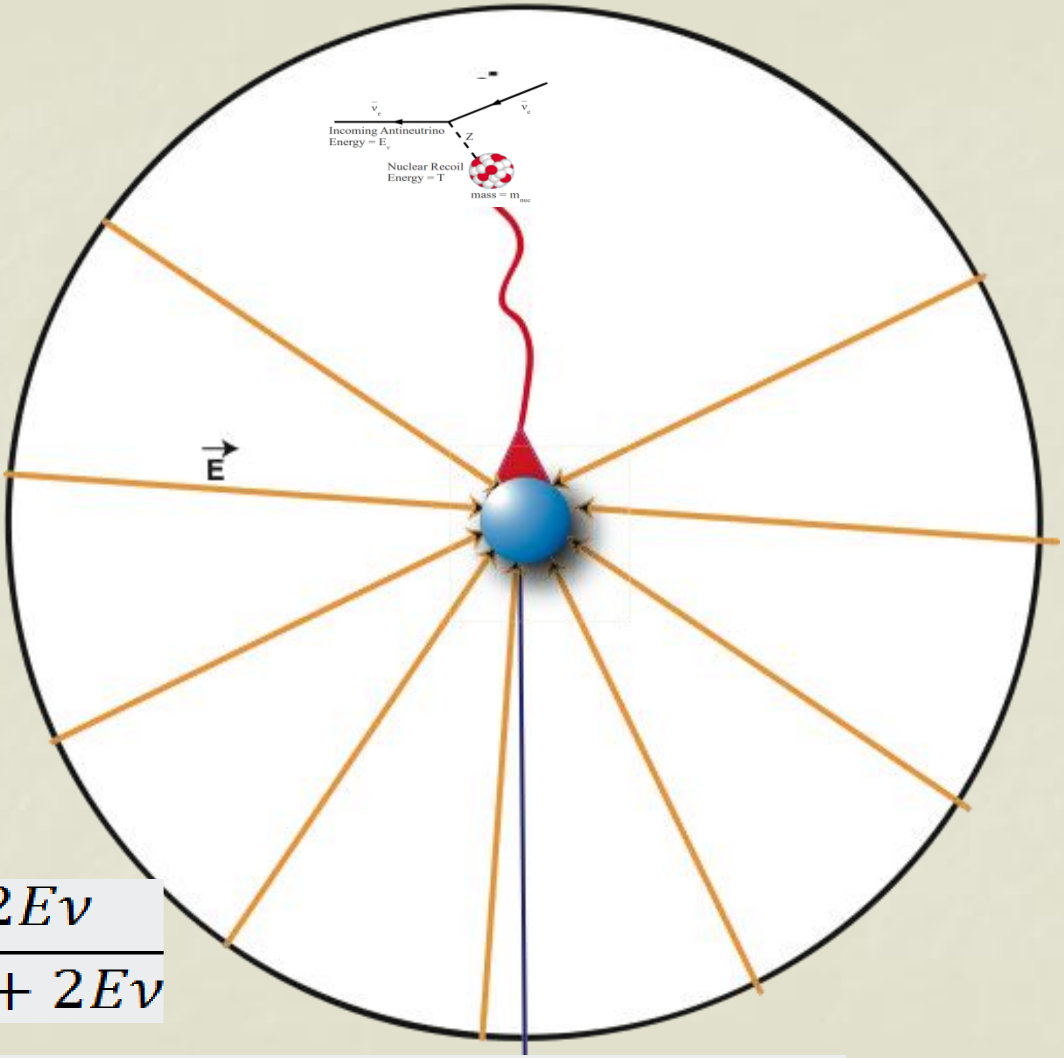
neutrinos

antineutrinos

Spherical Proportional Counter



Neutrino detection via coherent elastic scattering



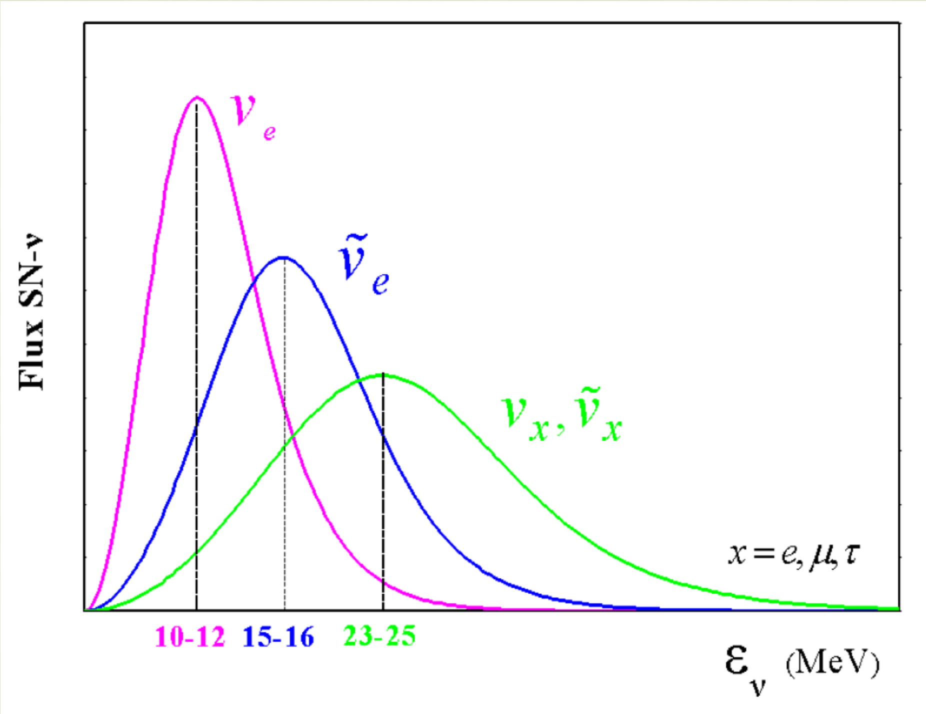
n + N --> n +N

$$Tmax = \frac{2E\nu}{M + 2E\nu}$$

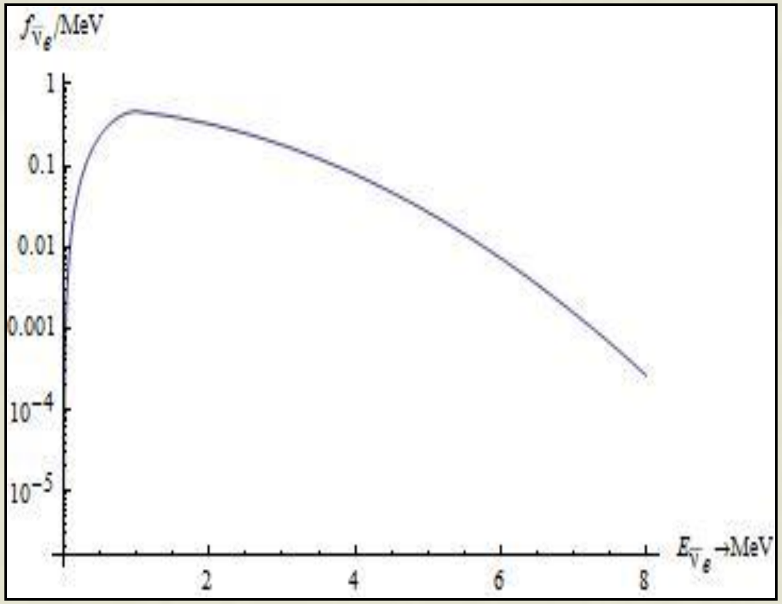
$$\sigma_{coh} = \frac{1}{16}\sigma_0\left(\frac{E_\nu}{m_e c^2}\right)^2 A^2\left[1 - \frac{Z}{A} + (4sin^2\theta_\omega - 1)\frac{Z}{A}\right]^2$$

Neutrino Sources

- Neutrino energy-spectra emitted in Core-collapse Supernova



Typical Reactor Antineutrino Spectrum



Other neutrino sources:

Geoneutrinos, Solar neutrinos

Response of the detector to the reactor and supernova neutrinos

Nuclear reactor neutrinos:

With present prototype at 10 m from the reactor, after 1 year run ($2x10^7$s), assuming full detector efficiency:

- Xe ($\sigma \approx$ $2.16x10^{-40}$ cm^2), $2.2x10^6$ neutrinos detected, T_{max}=146 eV
- Ar ($\sigma \approx$ $1.7x10^{-41}$ cm^2), $9x10^4$ neutrinos detected, T_{max}=480 eV
- Ne ($\sigma \approx$ $7.8x10^{-42}$ cm^2), $1.87x10^4$ neutrinos detected, T_{max}=960 eV

Supernova neutrinos:

- For a detector of radius 4 m with a gas under 10 Atm and a typical supernova in our galaxy, i.e. 10 kpc away, one finds 1, 30, 150, 600 and 1900 events for He, Ne, Ar, Kr and Xe respectively (*Y. Giomataris, J. D. Vergados, Phys.Lett.B634:23-29,2006)*

Sensitivity for reactor neutrinos detection

The number of events in one day for the present spherical TPC detector:
P=5 Atm, R=.65 m, T=300^0K, anti-neutrino flux= $10^{13}/cm^2/s$

target	**anti ν_e (QF, no Thr)**	**anti ν_e (QF) Thr = 1 electron**	**anti ν_e (QF) Thr = 2 electron**
Xe	2325	**825**	**275**
Ar	430	**292**	**210**

This a considerable signal

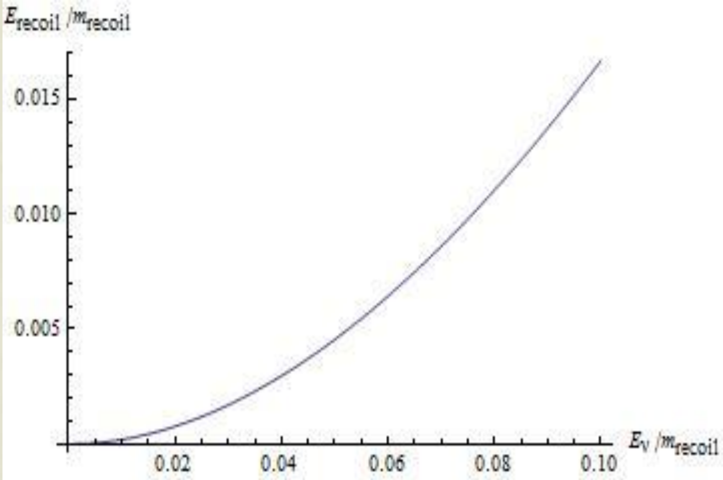
Argon is a good candidate

But we need to build a new detector with appropriate shield

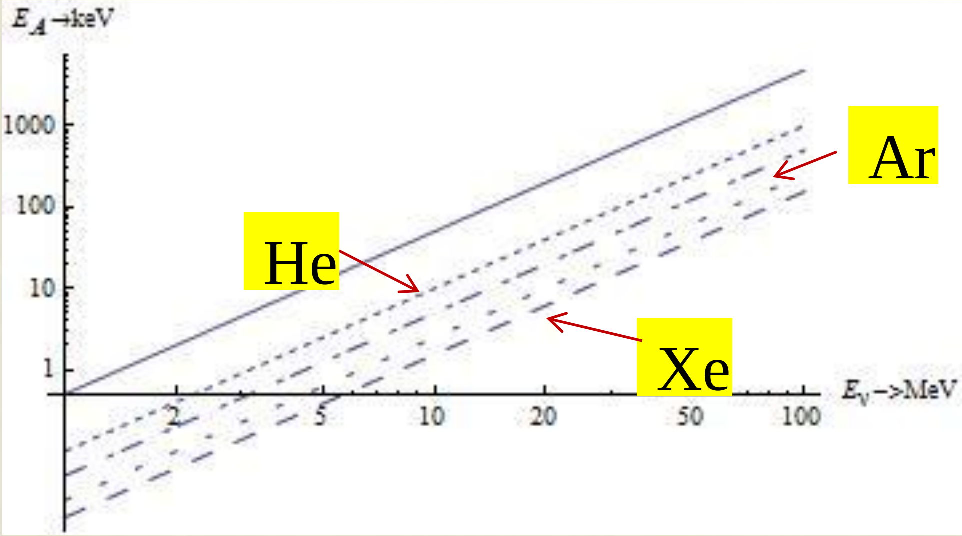
Background at 1 electron level?

The energy of the recoil nucleus

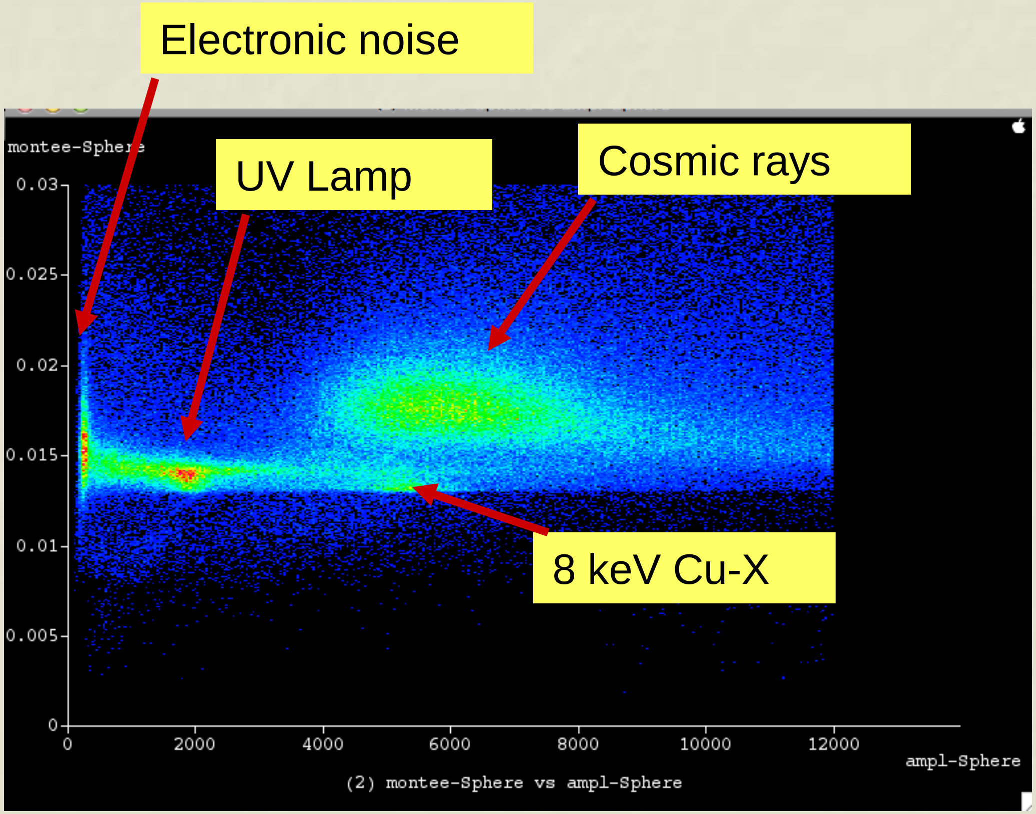
The maximum recoiling energy versus the neutrino energy (both in units of the recoiling mass).



The nuclear recoil energy versus the neutrino energy. From top to bottom nuclear targets with A=4, 20, 40, 84, 131 for the elements He, Ne, Ar, Kr and Xe respectively.



The calibration and the 8 keV Cu –X
Ne + 5% CH4, P=500 mbar

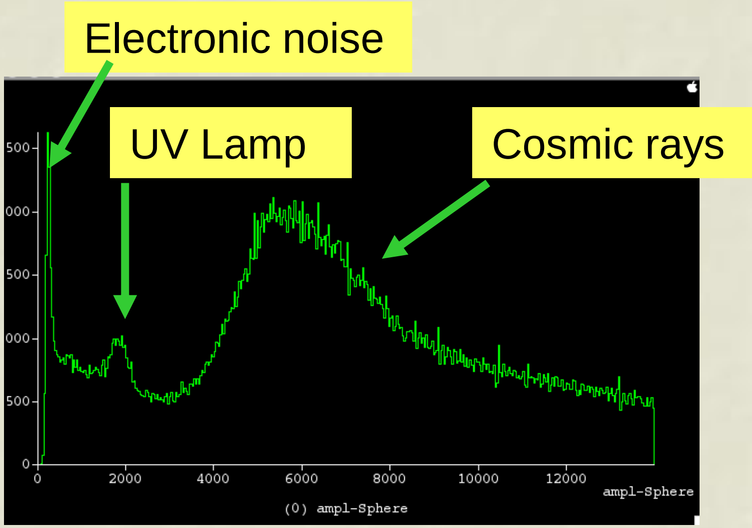


Electronic noise

UV Lamp

Cosmic rays

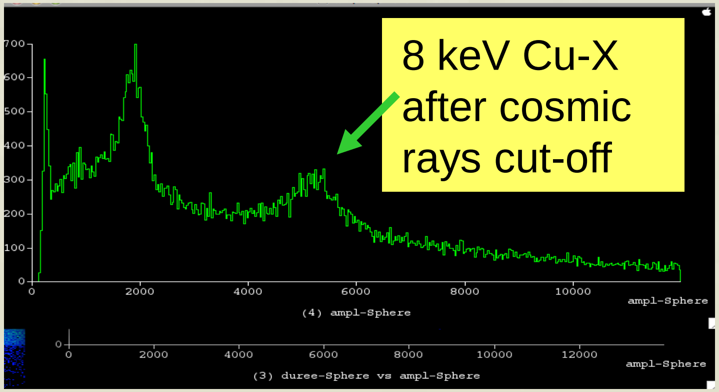
8 keV Cu-X



Electronic noise

UV Lamp

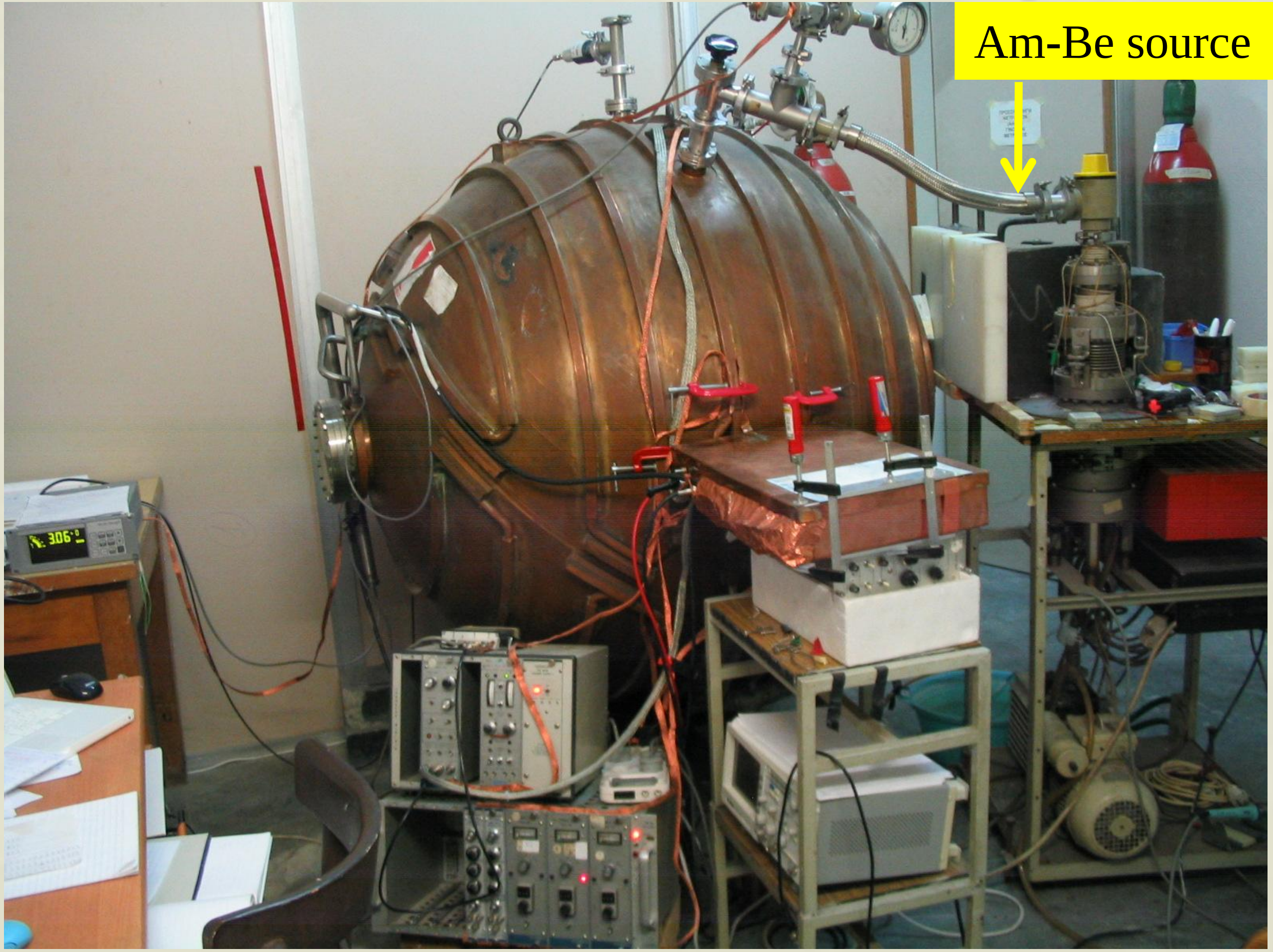
Cosmic rays



8 keV Cu-X after cosmic rays cut-off

Low energy Ar recoils detection using Am-Be neutron source

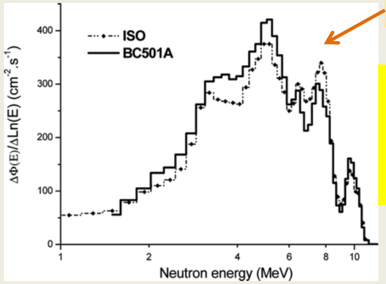
(Thessaloniki, Nuclear Physics Laboratory)



Am-Be source

Am-Be neutron source

(Nuclear Physics Laboratory)

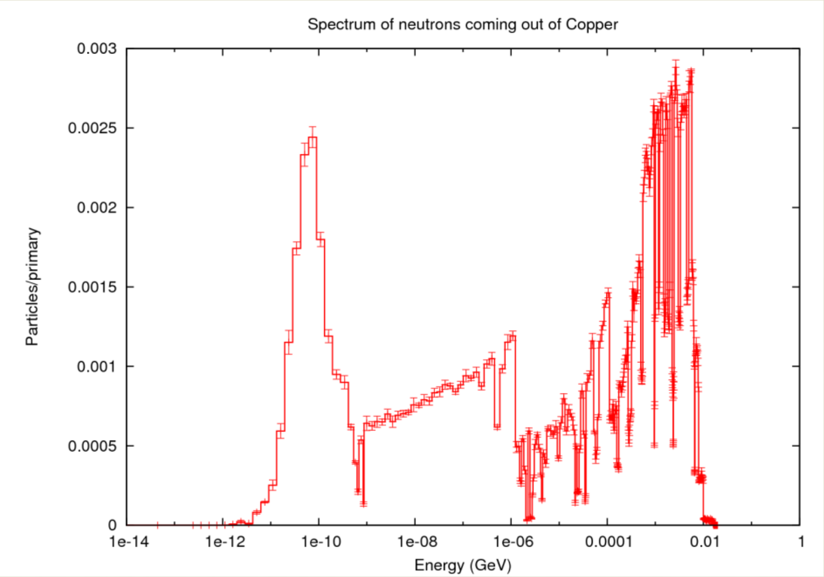


Am 241**: 30 mCi**
Total neutron flux: **6.6X10^4 neutrons/sec**

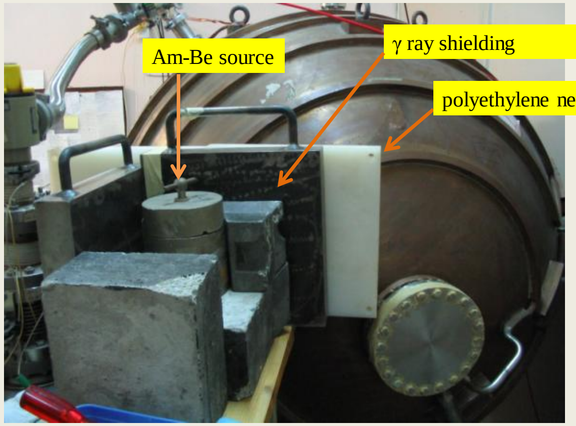
γ ray activity of theAm-Be sources

α + 9Be (target) → 12C + neutron + 5.71 MeV

~4.4 MeV gamma ray resulting
from the deexcitation of 12C



Am-Be source shielding



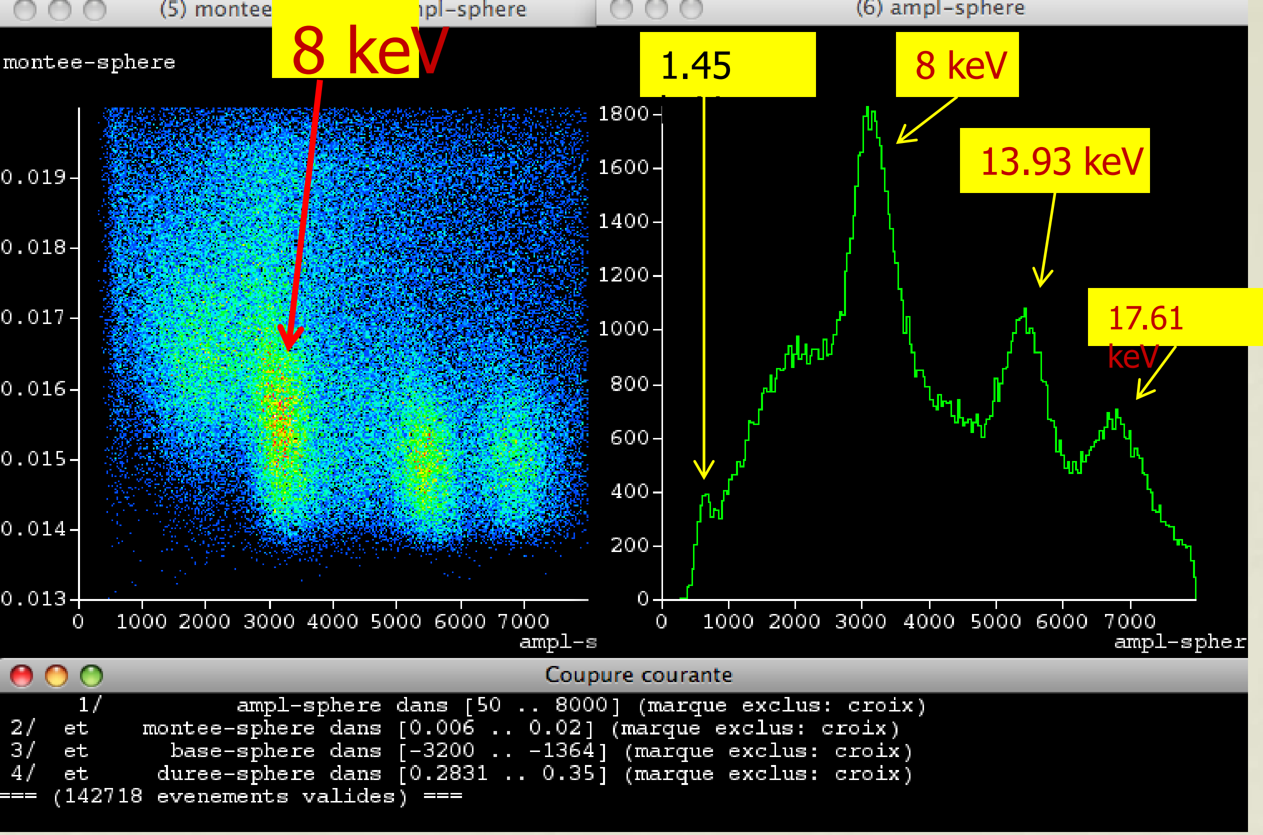
Am-Be source

γ ray shielding

polyethylene neutron moderato

Shielding
Pb= 9cm
Fe= 5cm
PE= 2cm

Low energy spectroscopy
X-ray peaks

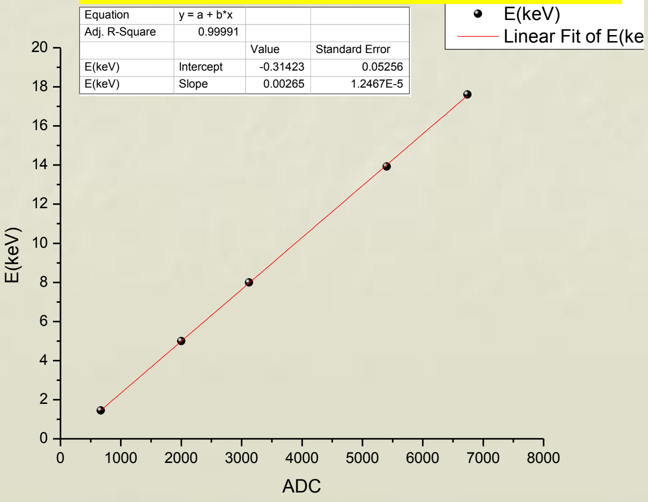


```
     1/          ampl-sphere dans [50 .. 8000] (marque exclus: croix)
2/  et     montee-sphere dans [0.006 .. 0.02] (marque exclus: croix)
3/  et       base-sphere dans [-3200 .. -1364] (marque exclus: croix)
4/  et      duree-sphere dans [0.2831 .. 0.35] (marque exclus: croix)
=== (142718 evenements valides) ===
```

13mm sensor, 50mbar
Ar+2%CH4

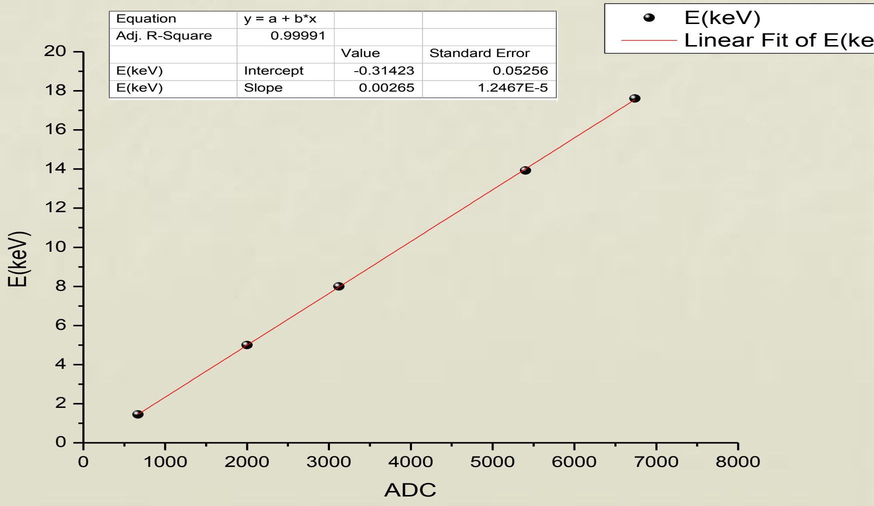
Aluminium (1.45 keV)
Copper (8 keV)
Neptunium(Lα) (13.93 keV)
Neptunium(Lβ) (17.61 keV)

High gain X-ray linearity



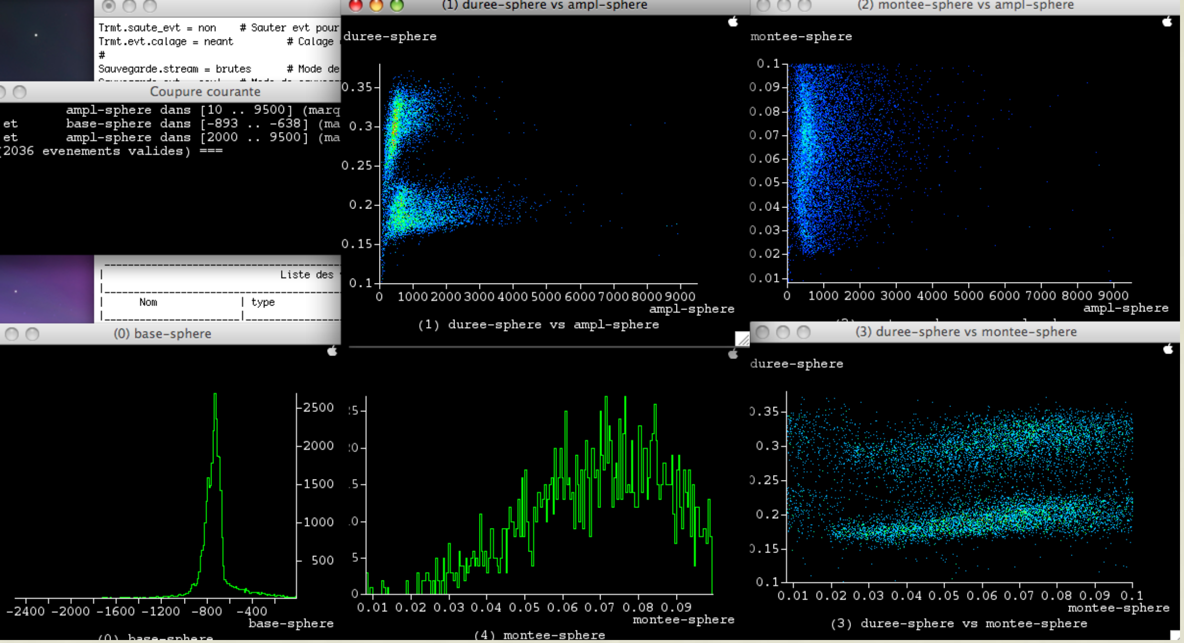
Equation	y = a + b*x		
Adj. R-Square	0.99991		
		Value	Standard Error
E(keV)	Intercept	-0.31423	0.05256
E(keV)	Slope	0.00265	1.2467E-5

Low gain X-ray linearity



Equation	y = a + b*x		
Adj. R-Square	0.99991		
		Value	Standard Error
E(keV)	Intercept	-0.31423	0.05256
E(keV)	Slope	0.00265	1.2467E-5

P=175 mbar, 5%CH4+4%N2
Left: No source

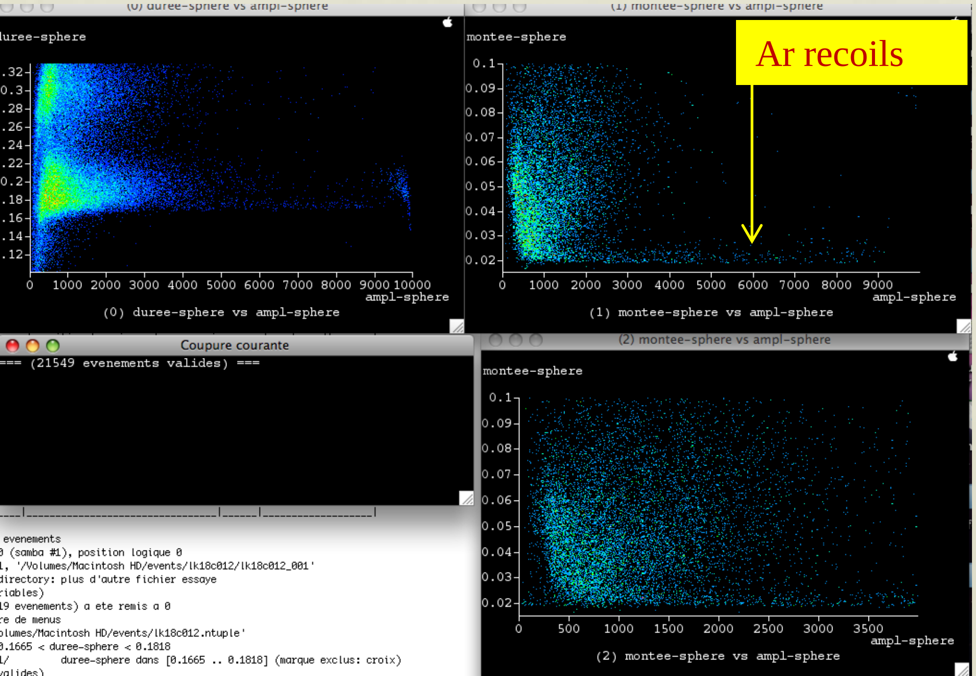


```
Trmt.saute_evt = non    # Sauter evt pour
Trmt.evt.calage = neant          # Calage
#
Sauvegarde.stream = brutes       # Mode de
```

```
           ampl-sphere dans [10 .. 9500] (marq
 et        base-sphere dans [-893 .. -638] (ma
 et        ampl-sphere dans [2000 .. 9500] (ma
(2036 evenements valides) ===
```

```
 -----------------------------------------
|                           Liste des
|_________________________________________
|      Nom                   | type
|____________________________|____________
```

Am-Be + Cs-137 (γ 661keV)



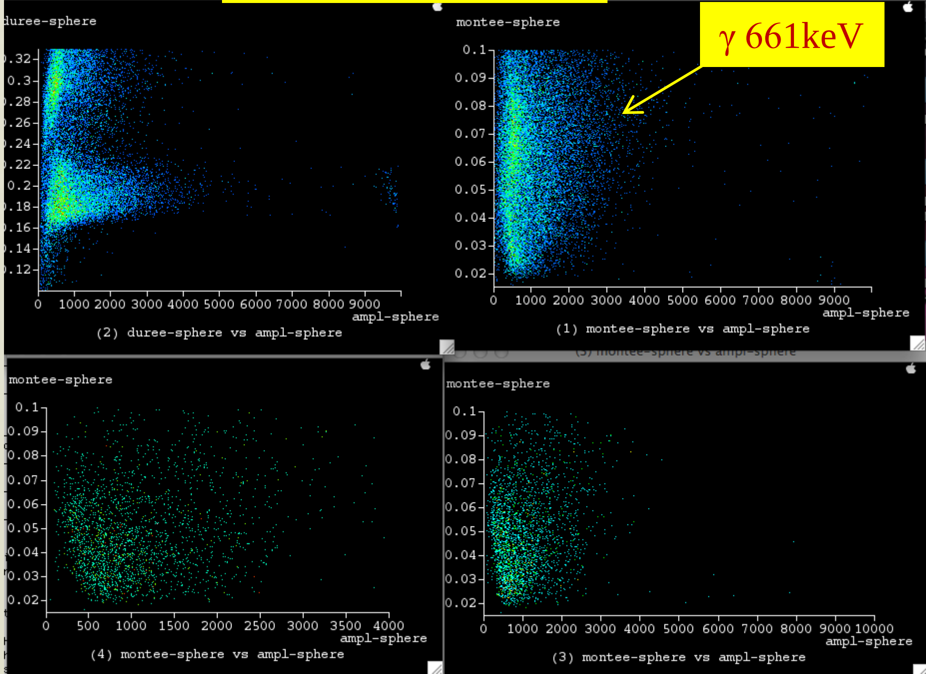
Ar recoils

```
=== (21549 evenements valides) ===
```

```
___|______________________________|_____|__________________|

 evenements
0 (samba #1), position logique 0
1, '/Volumes/Macintosh HD/events/lk18c012/lk18c012_001'
directory: plus d'autre fichier essaye
riables)
19 evenements) a ete remis a 0
re de menus
olumes/Macintosh HD/events/lk18c012.ntuple'
0.1665 < duree-sphere < 0.1818
1/         duree-sphere dans [0.1665 .. 0.1818] (marque exclus: croix)
valides)
```

Cs-137 (γ 661keV)



γ 661keV

Improvements

- Better calibration, lower than the 8keV Cu-X
- New sensor with lower capacitance
- Decrease of the electronic noise
- Decrease of the low energy background

The next step

- Next experiment in the underground laboratory in Modane (LSM), were the cosmic ray background is very low.
- Reactor measurements for neutrino detection (CEA-Saclay experiment)
- Since the detector is sensitive to low energy recoils, it is possible to measure the fast neutron recoils (Thessaloniki experiment)

The new collaboration

People

- Initiator : **I Giomataris + IRFU/Saclay** collaborators :
  G Gerbier, J Derre, A Dastgheibi Fard, P Magnier, XF Navick,
  M Gros, B Paul, D Jourde, E Bougamont, *G Tsiledakis*
- F Piquemal, P Loaiza, **LSM**
- I Savvidis , **Aristotle University of Tessaloniki**
- JD Vergados**, University of Ioannina**
- G Fanourakis **, NCSR DemoKritos**
- S Tzamaria **Hellenic Open University,**
- C Tao et al. **University of Tsinghua, Beijing**
- K Ni et al. **, Shanghai Jiao Tong University**
- C Yang, R Wang, Z Wang, **IHEP-Beijing**
- I Irastorza, **University of Saragoza**
- Jaime Ruz Armendariz, **Livermore**