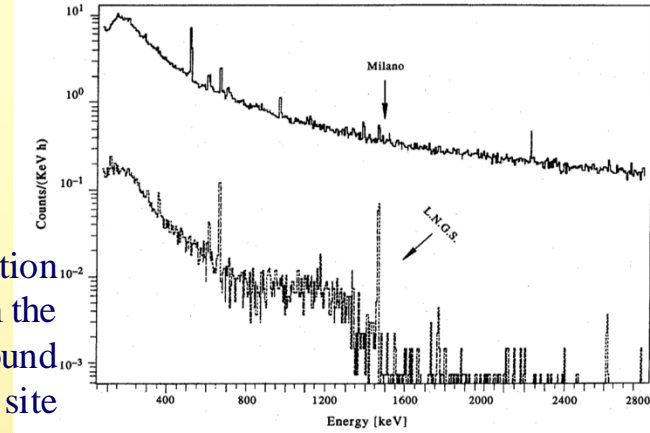
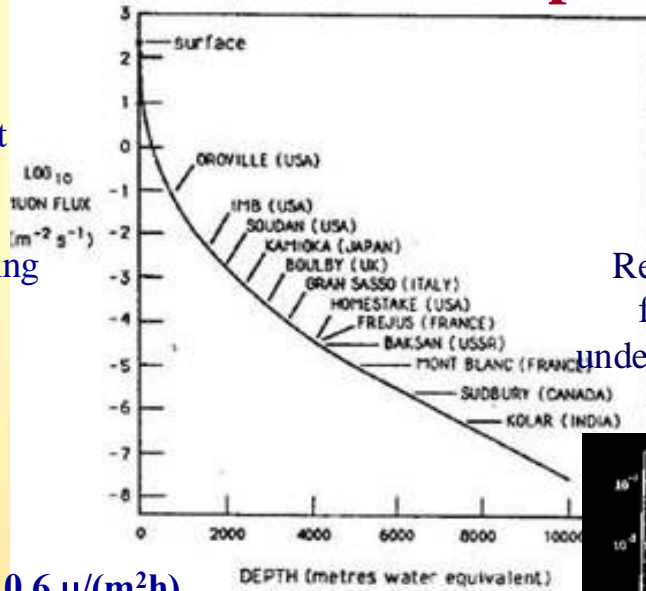


# Experimental technique of Underground Physics

# Main recipes for the Dark Matter particle direct detection

- Underground site
- Low bckg hard shields against  $\gamma$ 's, neutrons
- Lowering bckg: selection of materials, purifications, growing techniques, ...
- Rn removal systems



Reduction from the underground site

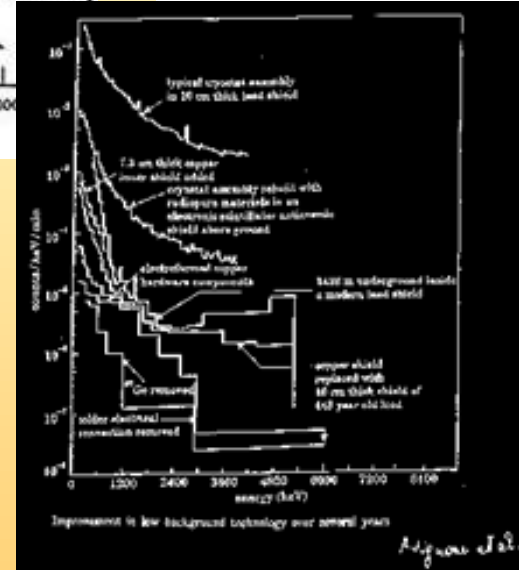
## Background sources

### - Background at LNGS:

- muons**  $\rightarrow 0.6 \mu/(\text{m}^2 \text{h})$
- neutrons**  $\rightarrow 1.08 \cdot 10^{-6} \text{ n}/(\text{cm}^2 \text{s})$  thermal  
 $1.98 \cdot 10^{-6} \text{ n}/(\text{cm}^2 \text{s})$  epithermal  
 $0.09 \cdot 10^{-6} \text{ n}/(\text{cm}^2 \text{s})$  fast ( $>2.5 \text{ MeV}$ )
- Radon in the hall**  $\rightarrow \approx 30 \text{ Bq}/\text{m}^3$

### - Internal Background:

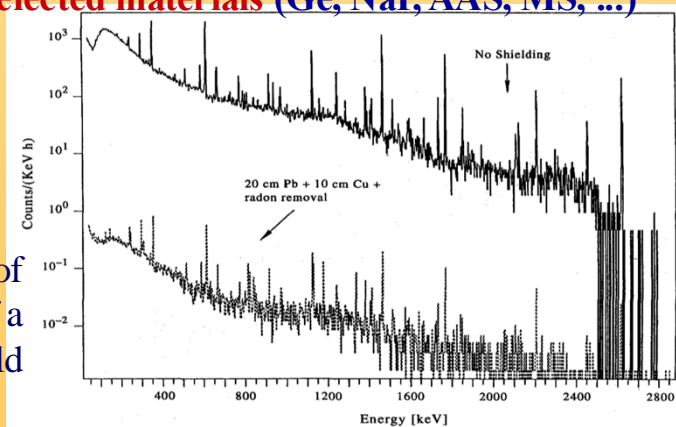
selected materials (Ge, NaI, AAS, MS, ...)



Example of background reduction during many years of work

## Shielding

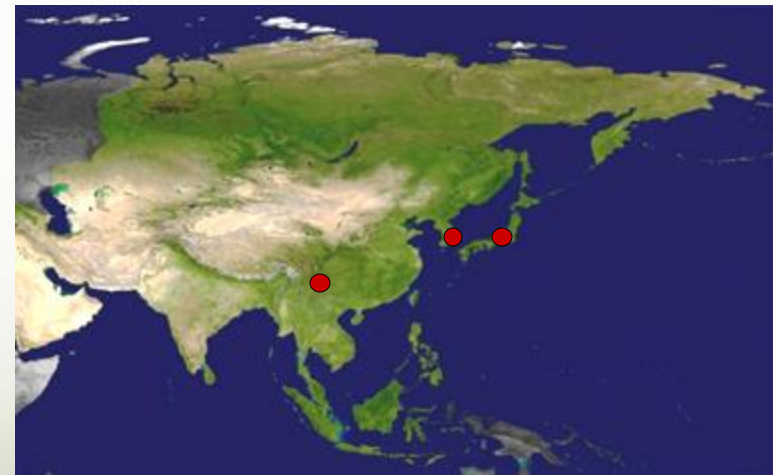
- Passive shield:** Lead (Boliden [ $< 30 \text{ Bq}/\text{kg}$  from  $^{210}\text{Pb}$ ], LC2 [ $< 0.3 \text{ Bq}/\text{kg}$  from  $^{210}\text{Pb}$ ], lead from old roman galena), OFHC Copper, Neutron shield (low A materials, n-absorber foils)
- Active shield:** Low radio-activity NaI(Tl) surrounding the detectors



Example of the effect of a passive shield

# Dark Matter direct detection activities in underground labs

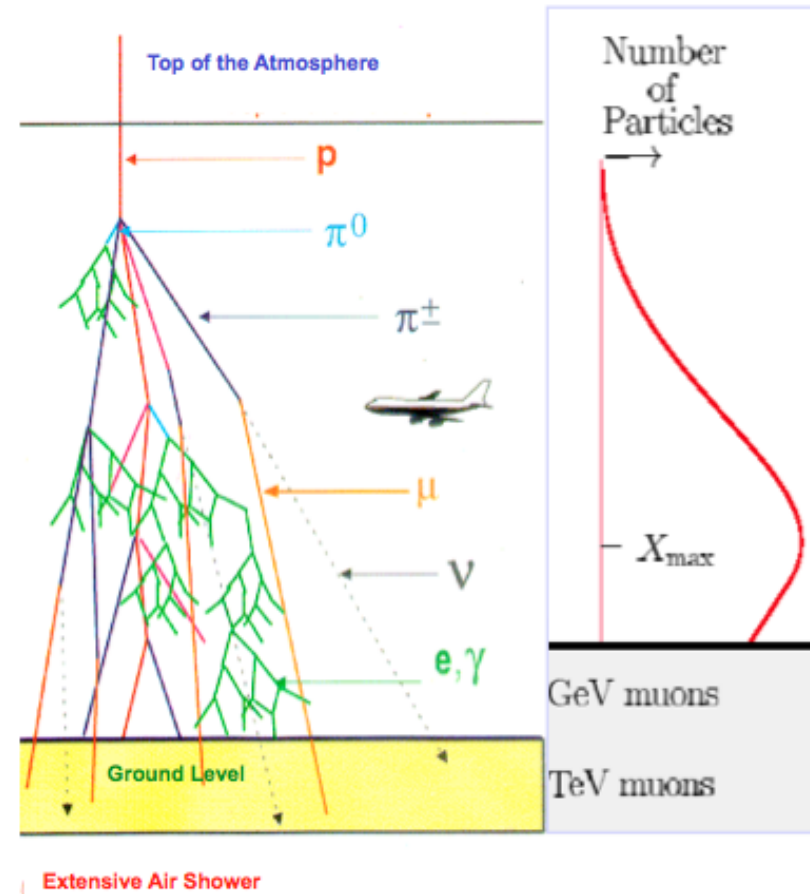
- Various approaches and techniques
  - Various different target materials
  - Various different experimental site depths
  - Different radiopurity levels, etc.
- Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, CUORE, XENON, DarkSide, SABRE, Cosinus, NEWSdm, CYGNO
  - Boulby (depth ~ 3000 m.w.e.): DRIFT, Zeplin, NAIAD
  - Modane (depth ~ 4800 m.w.e.): Edelweiss, DAMIC-M
  - Canfranc (depth ~ 2500 m.w.e.): ANAIS, Rosebud, ArDM
  - SNOlab (~ 6000 m.w.e.): Picasso, Coupp, PICO, DEAP, CLEAN, SuperCDMS, DAMIC, NEWS-G
  - Stanford (~10 m): CDMS I
  - Soudan (~ 2000 m.w.e.): CDMS II, SuperCDMS, CoGeNT
  - SURF (~4400 m.w.e.): LUX-Zeplin, MALBEK
  - WIPP (~1600 m.w.e.): DMTPC
  - South Pole: DM-ICE



- Y2L (depth ~ 700 m): COSINE-100/KIMS
- KAMIOKA: PICO-LON, NEWAGE, XMASS
- CJPL (depth ~6700 m.w.e.): Texono, CDEX, PANDAX

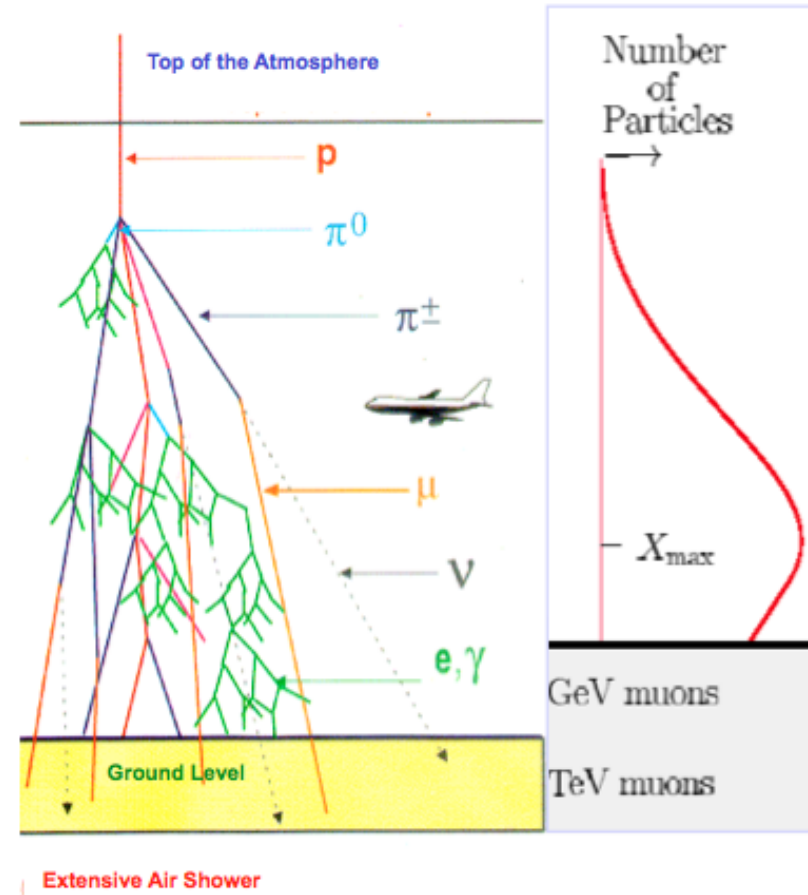
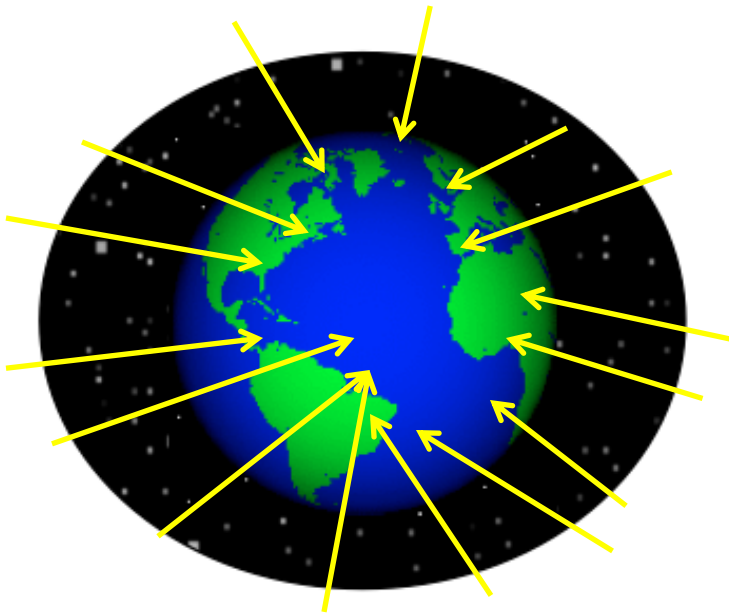
# I raggi cosmici in superficie

- A livello del mare siamo continuamente investiti da circa 200 particelle per  $\text{m}^2$  e per s, i cosiddetti “**raggi cosmici**”
  - Sono il prodotto dell'interazione di protoni di alta energia provenienti dallo spazio
  - Sono stati il primo acceleratore naturale per lo studio delle particelle elementari

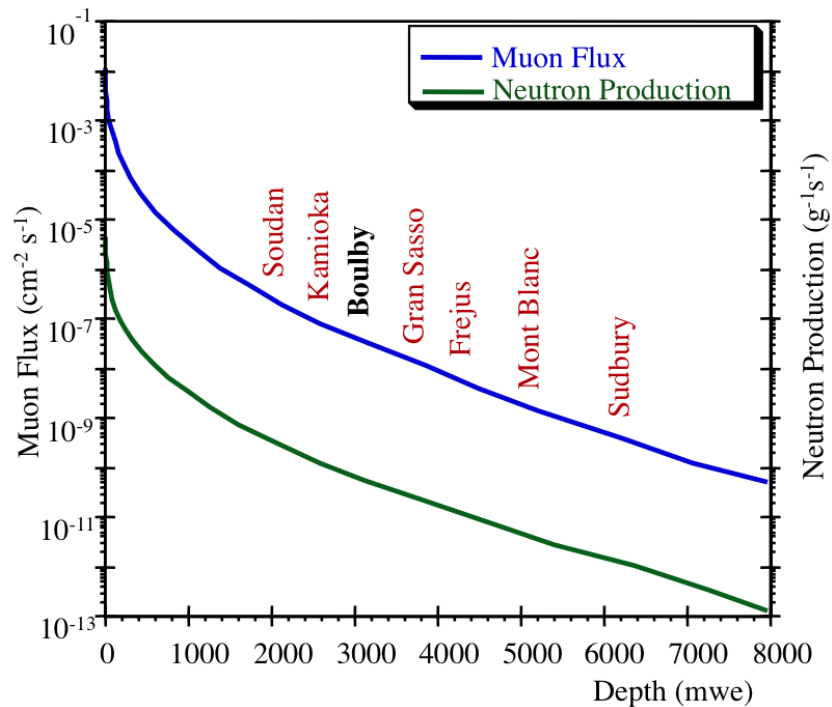
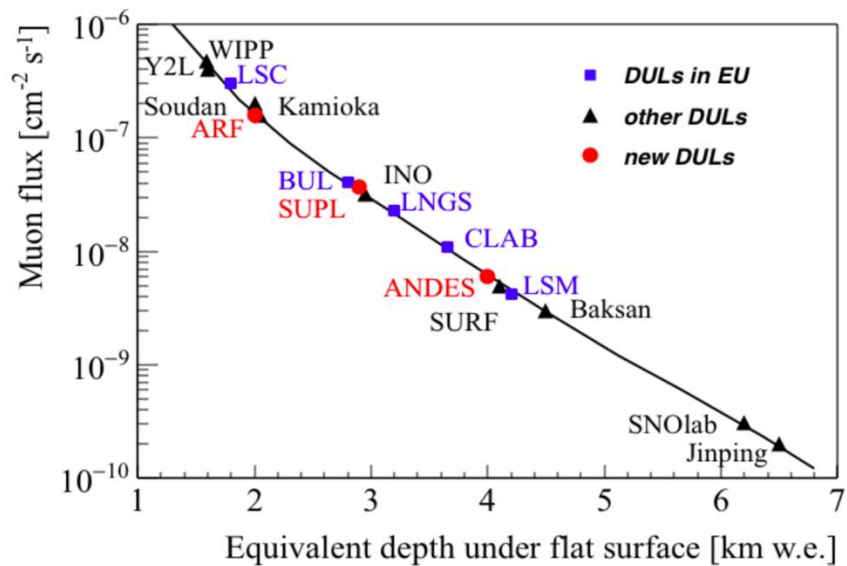
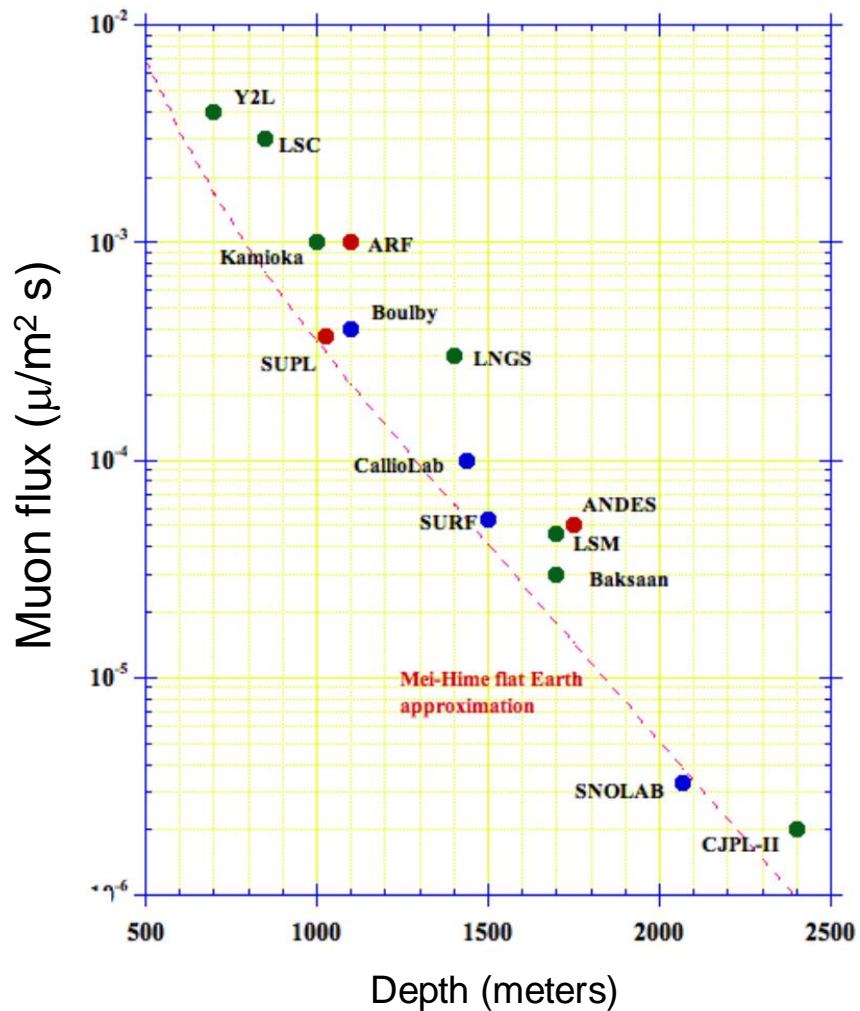


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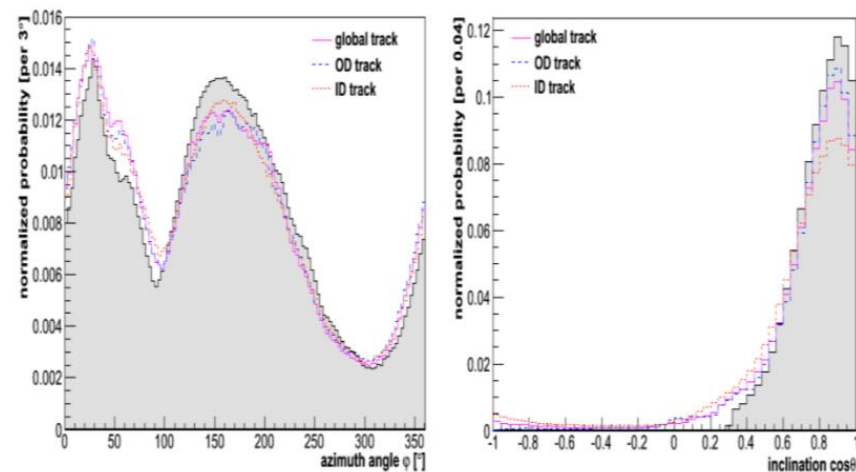
# Muon flux underground



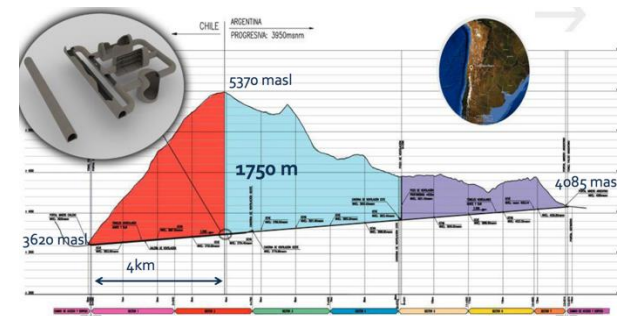
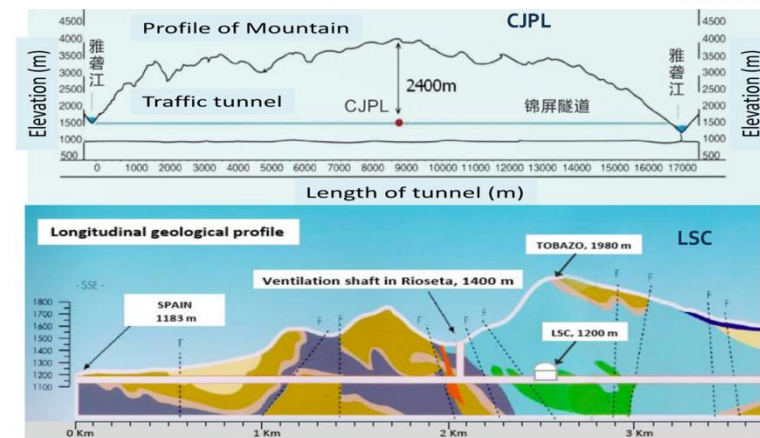
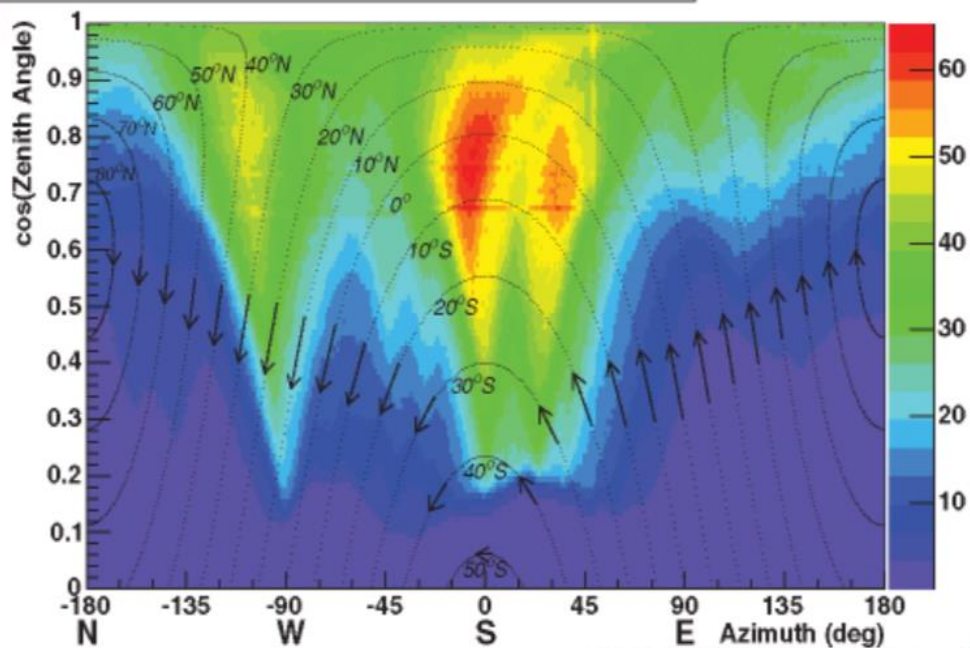
# Muon flux underground

- Under a flat surface (SNOLab, CallioLab, SURF)
- Under a mountain (Baksan, LNGS, LSC, LSM, CJPL)
- Underground cosmic-ray muons angular dependence can be important

## Muon data for LNGS: MACRO and Borexino



Cosmic ray muon rate in Super-Kamiokande-I ( $\text{day}^{-1} \text{m}^2 \text{sr}^{-1}$ )



# Cleanliness

## + Mine environment or small volume underground area

- + Specific protocol to enter lab area (SNOLab, Boulby, SURF, SUPL)
- + With some basic protocol it is possible to achieve good conditions
  - + SNOLab class 2000 or better throughout the whole volume with a more demanding protocol
  - + SURF class ~3000
  - + BOULBY main area ISO7
  - + All: dedicated personnel for regularly cleaning activity

## + Large volume, not mine environment (LNGS, CJPG)

- + Specific protocol in sectors (clean rooms)

## + Medium size volume, not mine environment (LSC, LSM)

- + Specific protocol (cleaning shoes, regular floor cleaning ...)
- + Example: at the LSC particulate counting in different areas ~ ISO7



# Main supporting facilities

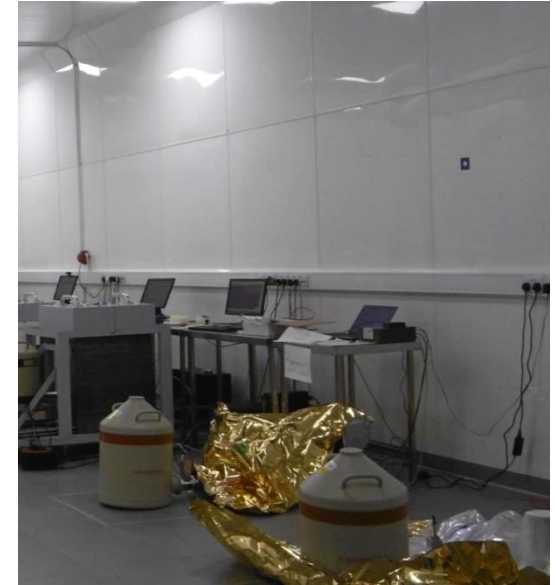
- + **HPGe screening facilities** (in all labs) + alpha counting + ICP-MS
- + **Cu electro-forming production** (SURF, LSC, CJPL, SNOLab, ARF)
- + **Clean rooms** (ISO5, ISO6)
- + **Radon abatement systems** (1000x Rn reduction)
  - + In operation at LNGS, LSC, Y2L, LSM (100 – 300 m<sup>3</sup>/h)
  - + To be installed at SURF, SNOLab, CJPL, SUPL, ARF
- + **Radon-free clean rooms**
  - + Present at LNGS
  - + To be installed at SURF, SNOLab ...
- + Sensitive **radon detectors** (<mBq/m<sup>3</sup>) for emanation and monitoring
  - + Monitoring blanket N<sub>2</sub> gas in the Borexino-CTF, Xenon1t water tanks ...
- + **Crystal growing facility** (ARF, CJPL)



# Main supporting facilities: HPGe screening facilities

	SNOLab	LNGS	LSC	SURF	LSM	Boulby	Baksan	Kamioka	CJPL
Number of HPGe detectors	5	12(+1)	7	4+1	18+6	4+3	2+2	6	10

- ✓ Sensitivities
  - Commercial detectors 0.5 – 1 mBq/kg in U, Th
  - Custom 10-50  $\mu$ Bq/kg
- ✓ Overall DULs have collected some 81 HPGe which corresponds to about 8 M€
- ✓ These detectors used to support screening for experiments and environmental research and other requests from Research Institutions not directly related to DULs



# DULs as multidisciplinary Research Infrastructures

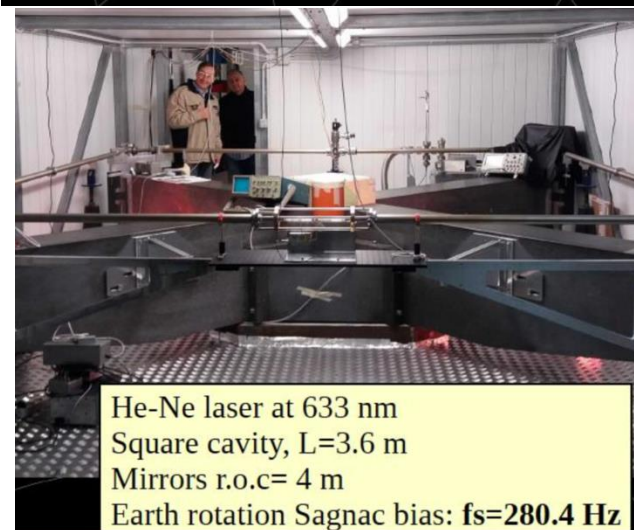
## + Geophysics

- Underground environment enhance the sensitivity to local and global phenomena using data from strain meters and seismometers
  - Local: slow earthquakes, hydrogeologically-induced deformations, seasonal charge and discharge of aquifers, ocean loading tides
  - Global: free oscillations of the Earth induced by large quakes, background free oscillations due to atmospheric environment, free core nutation ...
- Ring laser in underground for Lense-Thirring effect measurement
- DULs could provide data from different locations worldwide
- Muon tomography for deep geological mapping applications

## + Biology

### GINGERino: deep underground ring laser

GINGER-ino (INFN-LNGS)+ Seismometers (INGV)



Strain meters coupled with seismometers

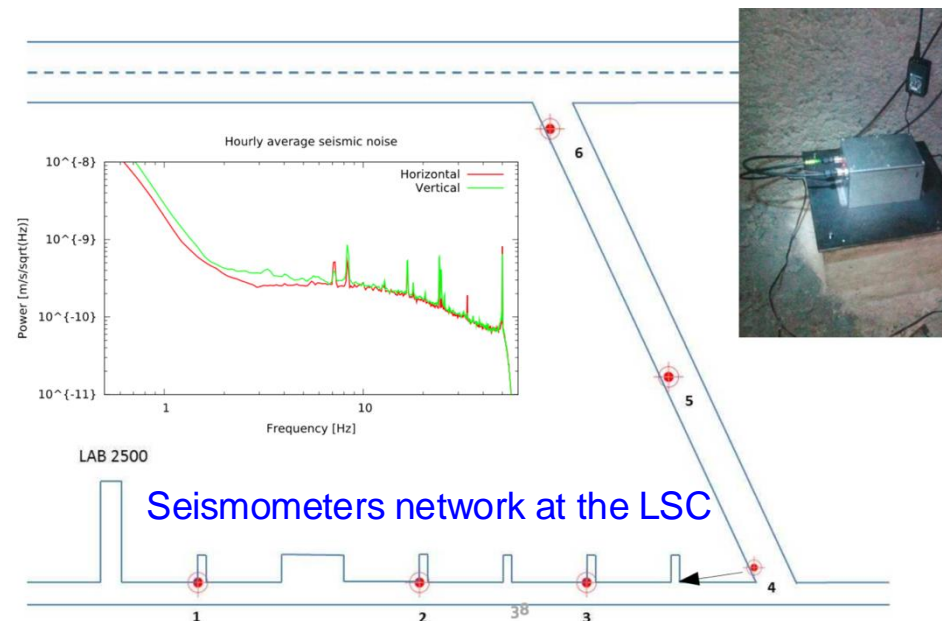
Gran Sasso interferometers  
(LNGS, Italy, 1994-2013)

Baseline length: 90 m

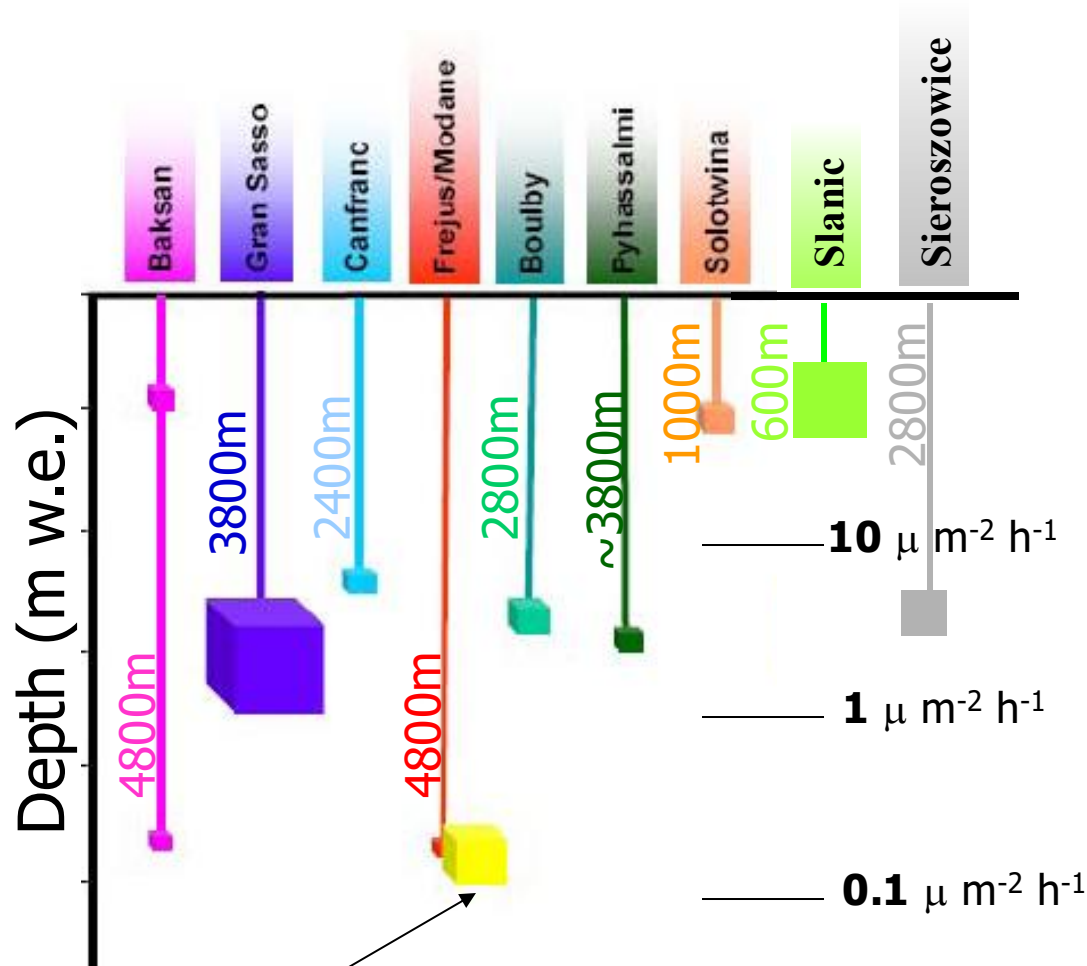
Canfranc interferometers  
(LSC, Spain, 2011-present)

Baseline length: 70 m

Nominal resolution  $\Delta l/l < 10^{-12}$   
 Maximum  $\Delta l/l$  nominally unlimited  
 Nominal bandwidth  $\approx 200$  Hz to 0 Hz  
 Maximum strain rate few  $10^{-7} \text{ s}^{-1}$   
 $1 \text{ ne} \Leftrightarrow \Delta l/l = 10^{-9}$



# The European underground facilities



Baksan, RU  
Gran Sasso, IT  
Modane, FR  
Canfranc, ES  
Boulby, UK  
Pyhäsalmi, FIN  
Sieroszowice, PL  
Slanic, RO  
Soltwina, UKR

# The origin of radiation

- Our galaxy's stock of **heavy elements** was mostly produced in **supernovae explosions** that eject stable and unstable nuclei into the interstellar medium.
- The **interstellar clouds** containing these elements may later condense to form **stellar systems**. By the time this happens, most of the short-lived nuclei would have decayed, so planets contain, at their birth, only nuclei with life-times greater than, say,  $10^6$  yr.
- On Earth,  $\sim 4.5 \times 10^9$  yr after its formation, most of the original unstable nuclei have decayed leaving only those **with  $T_{1/2} > 10^8$  yr**.
- There is also continuous **production of unstable nuclei by cosmic-rays** entering the Earth's atmosphere.
- The  $\alpha$  and  $\beta$  decays of these nuclei constitute the **natural radioactivity** that was discovered by Becquerel at the end of the nineteenth century.
- All **living species** have evolved in this bath of radiation.
- What is new on Earth is the existence of an **artificial radioactivity** due to the development of nuclear technologies, most importantly energy production by nuclear reactors.
- There are now also numerous uses of radioactive nuclei, most notably in **medical treatment** and **dating**.

## Fossil radioactivity (2)

- Most radioactive nuclei were produced in supernovae that generate a mix of neutron-rich nuclei in a period of time of order a few seconds. When, some millions of years later, the cloud condensed to form the solar system, a few radioactive nuclear species were still present.
- At the present epoch, only nuclei with **mean lives greater than**, say,  $10^8$  yr, are still present in significant numbers.
- These long-lived nuclei involve either highly forbidden  $\beta$  decays (large spin changes) or are  $\alpha$ -decays that happen to have Q-values that place the half-lives in this range.

### Nuclei with $10^8$ yr $< T_{1/2} < 10^{12}$ yr.

The “isotopic abundance” is for the terrestrial mix and the activity for the purified element corresponds to the terrestrial isotopic mix. For the activity in the Earth’s crust, the uranium and thorium activities include the activities of the daughters. Note that three nuclides,  $^{40}\text{K}$ ,  $^{146}\text{Sm}$  and  $^{235}\text{U}$  have lifetimes much less than the age of the Earth ( $\sim 4.5 \times 10^9$  yr) and therefore have very small isotopic abundances.

decay	half-life (years)	isotopic abundance (percent)	activity (Bq kg <sup>-1</sup> ) (element)	activity (Bq kg <sup>-1</sup> ) (crust)
$^{40}\text{K} \rightarrow ^{40}\text{Ca} e^- \bar{\nu}_e$ 89% $\rightarrow ^{40}\text{Ar} \nu_e$ 11%	$1.28 \times 10^9$	0.0117	$3.0 \times 10^4$	$6.3 \times 10^2$
$^{87}\text{Rb} \rightarrow ^{87}\text{Sr} e^- \bar{\nu}_e$	$4.75 \times 10^{10}$	27.83	$8.8 \times 10^5$	$8.0 \times 10^1$
$^{146}\text{Sm} \rightarrow ^{142}\text{Nd} \alpha$	$1.03 \times 10^8$	$< 10^{-7}$	$< 1$	$< 10^{-4}$
$^{147}\text{Sm} \rightarrow ^{143}\text{Nd} \alpha$	$1.06 \times 10^{11}$	15.1	$1.3 \times 10^5$	$9 \times 10^{-1}$
$^{176}\text{Lu} \rightarrow ^{176}\text{Hf} e^-$	$3.78 \times 10^{10}$	2.61	$5.5 \times 10^4$	$4 \times 10^{-2}$
$^{187}\text{Re} \rightarrow ^{187}\text{Os} e^- \bar{\nu}_e$	$4.15 \times 10^{10}$	62.6	$1.1 \times 10^6$	$8 \times 10^{-4}$
$^{232}\text{Th} \rightarrow ^{228}\text{Ra} \alpha$	$1.405 \times 10^{10}$	100	$4.05 \times 10^6$	$3.5 \times 10^2$
$^{235}\text{U} \rightarrow ^{231}\text{Th} \alpha$	$7.038 \times 10^8$	0.72	$5.7 \times 10^5$	$1.7 \times 10^1$
$^{238}\text{U} \rightarrow ^{234}\text{Th} \alpha$	$4.468 \times 10^9$	99.275	$1.2 \times 10^7$	$4.7 \times 10^2$

# L'origine della radiazione

## **Radiazione cosmica:**

Raggi cosmici primari

Raggi cosmici secondari

## **Radioattività naturale:**

Radionuclidi isolati

Famiglie radioattive naturali

## **Radioattività artificiale.**

La **radioattività naturale** può essere divisa in:

- radioattività “**fossile**” dovuta ad elementi presenti alla formazione della Terra
- radioattività “**cosmogenica**” dovuta ad elementi continuamente prodotti nell'atmosfera dai raggi cosmici.

Le tecniche per produrre **radioattività artificiale** possono essere divise in quelle che usano **neutroni** (attivazione da neutroni) e quelle che usano fasci di **particelle cariche**.

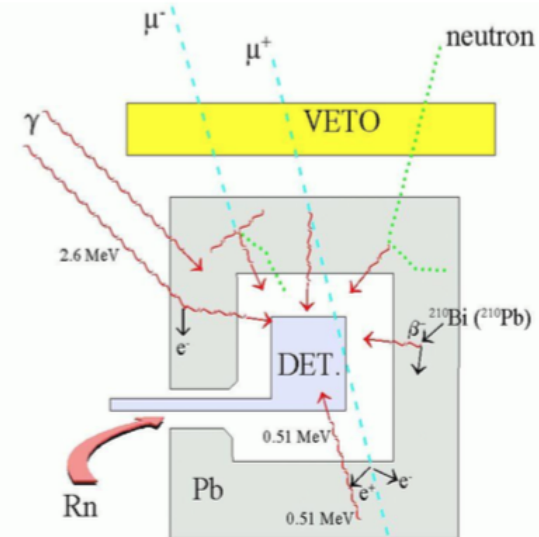
# Sources of background

- a) environmental radioactivity
- b) radioactive impurities in detector and shield material
- c) Rn and its progenies
- d) cosmic rays
- e) neutrons from natural fission and ( $\alpha$ , n) reactions

Examples:

## Background components in Ge spectrometry

- external gamma radiation (2.6 MeV  $^{208}\text{Tl}$ , {up to 3.2 MeV  $^{214}\text{Bi}$ })
- radio-impurities close to crystal (primordial, anthropogenic)
- Rn and its progenies
- cosmic rays (neutrons, muon and activation)
- neutrons from fission and ( $\alpha$ ,n) reactions



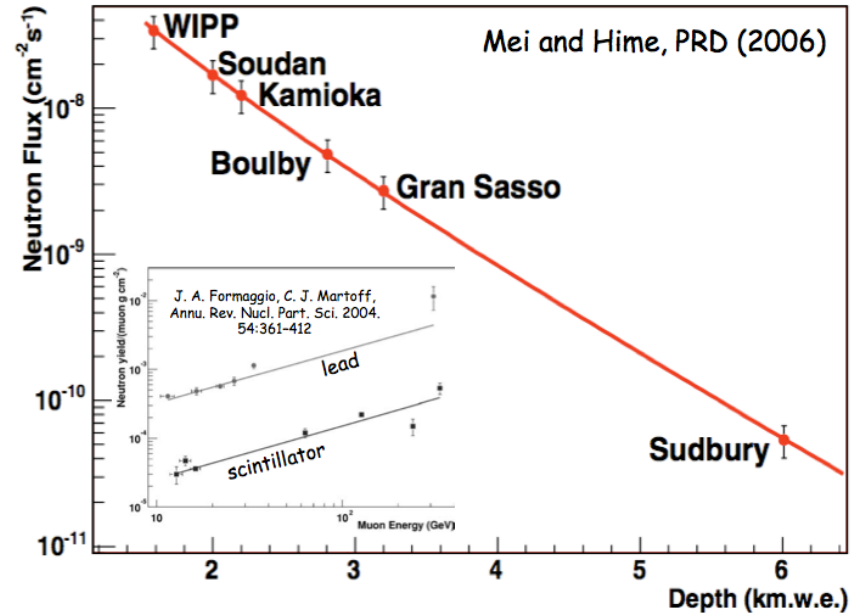
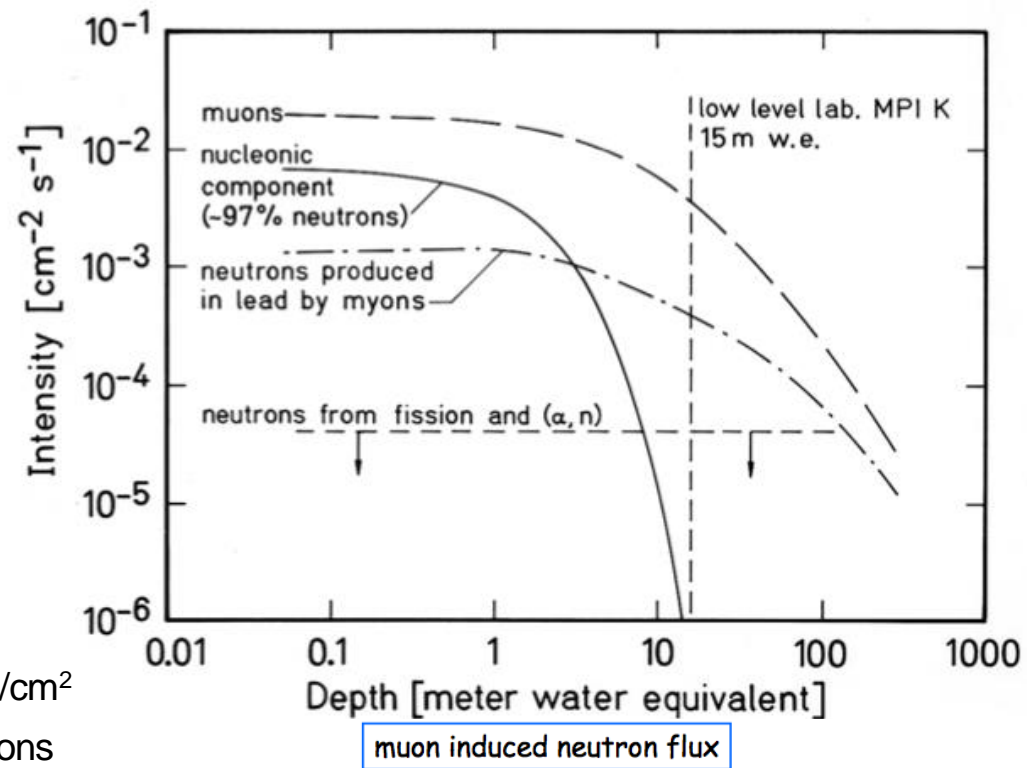
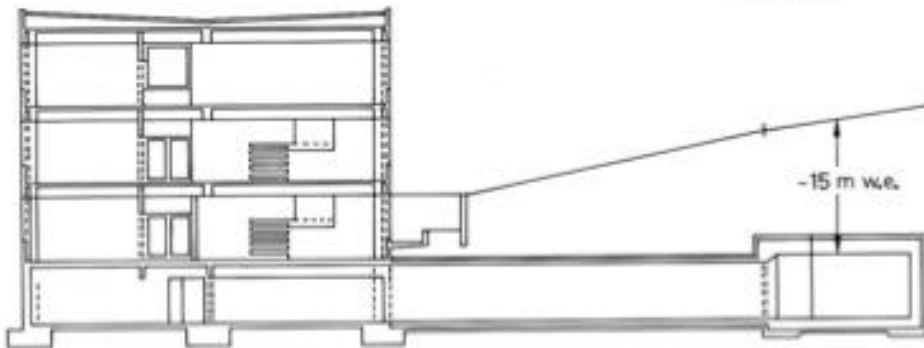
**most important: material screening**

U/Th chains and K dominant from Bq/kg down to  $\mu\text{Bq/kg}$  only reliably radiopure material - Cu - but mBq/kg cosmogenics besides Si, Ge, Au, Ag, Hg, (Pb - except Pb-210)

# The neutrons induced by muons

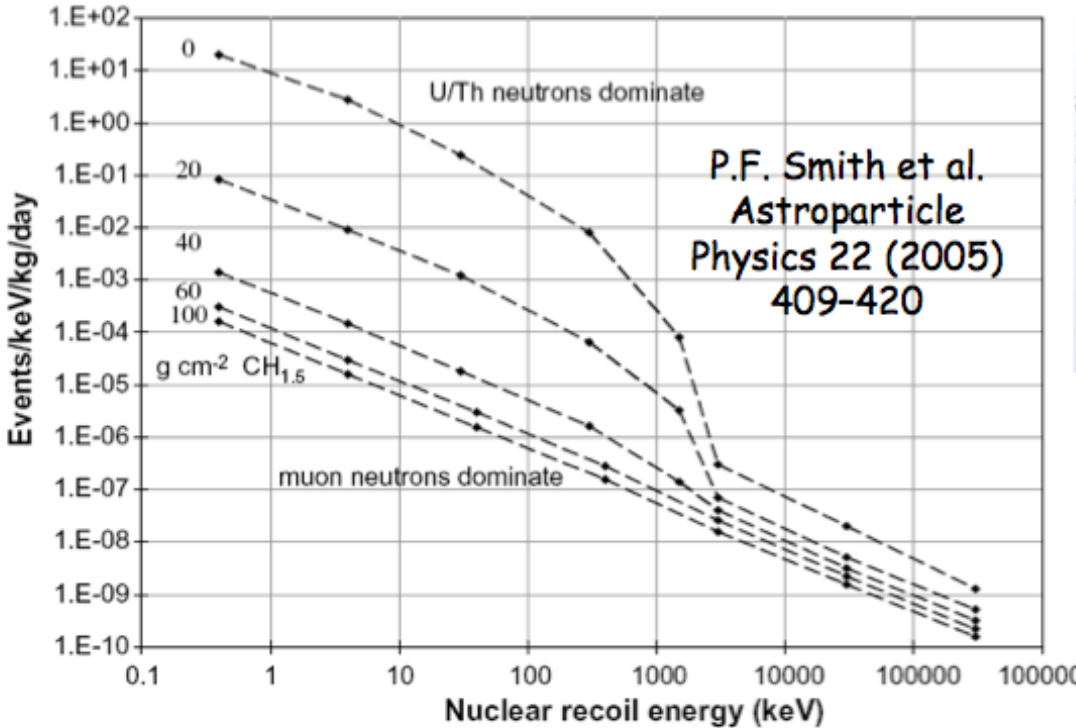
induce depth dependence of background inducing muons and neutrons

- the integral **neutron yield** critically depends on the chemical composition and on the density of the medium through which the muons interact
- the dependence on atomic weight is well described by a power law:  $Y = 4.54 \times 10^{-5} A^{0.81}$  neutrons per muon per  $\text{g}/\text{cm}^2$
- alternatively, it can also be expressed as:  $Y = 1.27 \times 10^{-4} (Z^2/A)^{0.92}$  neutrons per muon per  $\text{g}/\text{cm}^2$
- thus, the integral yield of neutrons produced by muons deep underground at LNGS is:
  - $Y \simeq (1-7) \times 10^{-4}$  neutrons per muon per  $\text{g}/\text{cm}^2$  for relatively light nuclei
  - and  $Y \simeq 4.5 \times 10^{-3}$  neutrons per muon per  $\text{g}/\text{cm}^2$  for lead

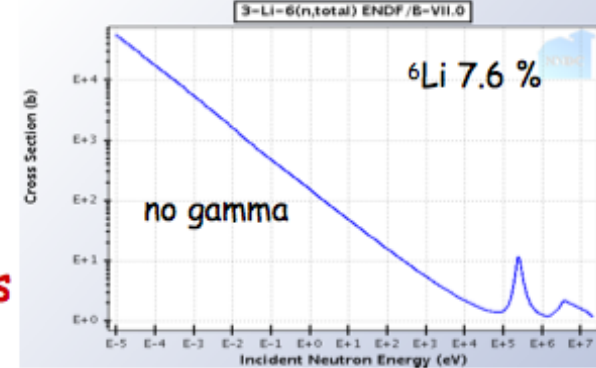
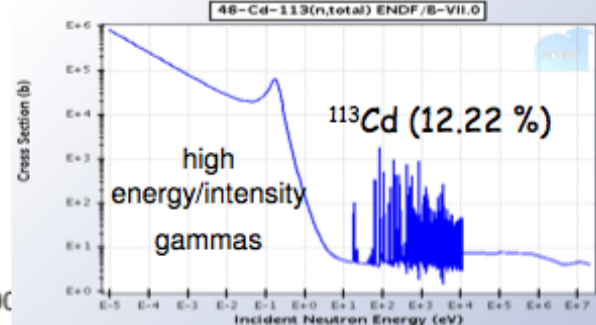
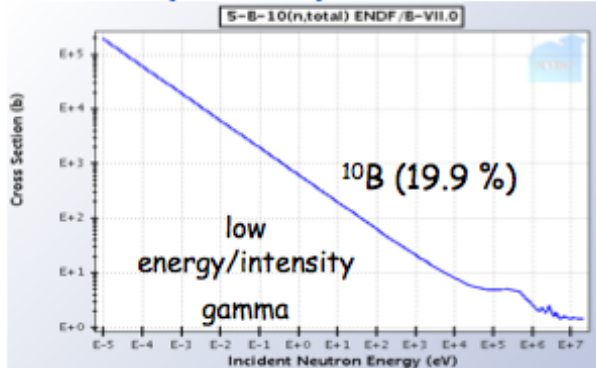


# neutron attenuation

moderate !!!  
plus capture ??



neutron background rate from U/Th and muons in NaCl rock at depth 3000 m.w.e. versus hydrocarbon shielding thickness



difficult to find radiopure n-capture compounds with little mass substitution of the moderator

Neutron shields: low-A materials (paraffin, polyethylene, plastic, ...) for moderation + foils/materials (B, Cd, Li, ...) for n-capture

# Cosmogenic radioactivity

- When cosmic-rays enter the Earth's atmosphere, they lose energy through ionization and nuclear reactions.
- The Earth's atmosphere is **sufficiently thick** that most of the primary cosmic-radiation stops in the atmosphere.
- Most cosmic radiation that reaches the Earth's surface consists of **muons and neutrinos** from the decays of pions produced in these collisions.
- A small nuclear component consisting mostly of **neutrons** reaches the surface but is quickly absorbed in the first few meters of the Earth's crust.
- **Cosmic-rays produce radioactive nuclei** via their interactions with nuclei in the atmosphere and in the Earth's crust.

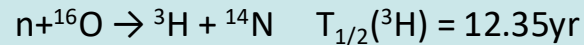
- In **atmosphere**, the most common radioactivity produced is that of  $^{14}\text{C}$  (and tritium).
- This nucleus is a secondary product of neutrons who are themselves produced by high-energy cosmic-ray protons that breakup nuclei in the atmosphere.
- The neutrons then either decay or are absorbed. The most common absorption process is the exothermic (n,p) reaction on abundant atmospheric nitrogen:  
$$n + ^{14}\text{N} \rightarrow p + ^{14}\text{C} \quad T_{1/2}(^{14}\text{C}) = 5730\text{yr}$$
- The produced  $^{14}\text{C}$  is mixed throughout the atmosphere and enters the food chain through  $\text{CO}_2$  ingesting plants. This results in a  $^{14}\text{C}$  abundance in live organic material of about  $10^{-12}$  relative to non-radioactive carbon. The resulting activity is about 250 Bq/kg.
- This allows the estimation of ages of dead organic material.

- High energy cosmic rays also produce radioactive nuclei through "**spallation**" reactions where one or more nucleons are removed from a nucleus.
- For example, a neutron with kinetic energy greater than  $\sim 20$  MeV can remove two nucleons from a germanium nucleus, e.g.  
$$n + ^{70}\text{Ge} \rightarrow 3n + ^{68}\text{Ge} \quad T_{1/2}(^{68}\text{Ge}) = 270.7\text{day}$$
- This reaction results in a radioactivity of 0.3 mBq/kg in germanium crystals produced at the Earth's surface.
- In high-purity germanium crystals used for detection of low-level radioactivity, it is the most important source of intrinsic radioactivity.
- If the crystals are placed underground, the production of  $^{68}\text{Ge}$  ceases and the activity decays away.

Another example in Iodine:

$$n + ^{127}\text{I} \rightarrow 3n + ^{125}\text{I} \quad T_{1/2}(^{125}\text{I}) = 59.4\text{d}$$
  
(for NaI(Tl) it corresponds to 2.3 mBq/kg at surface)

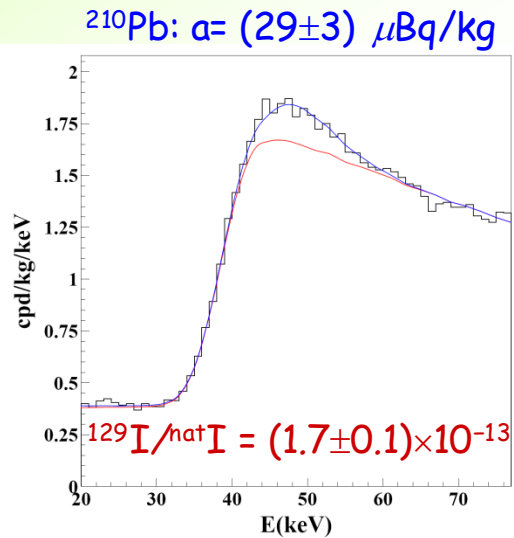
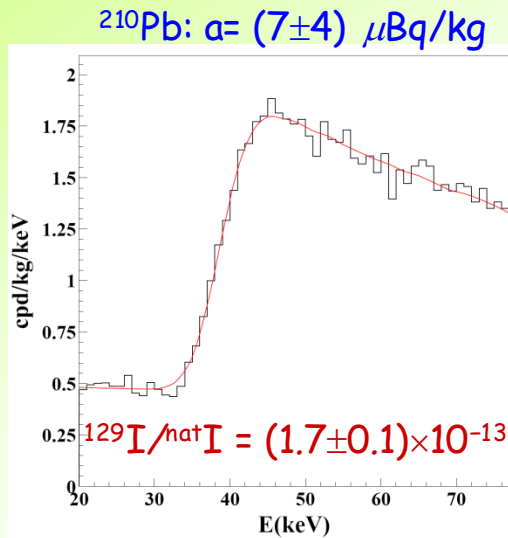
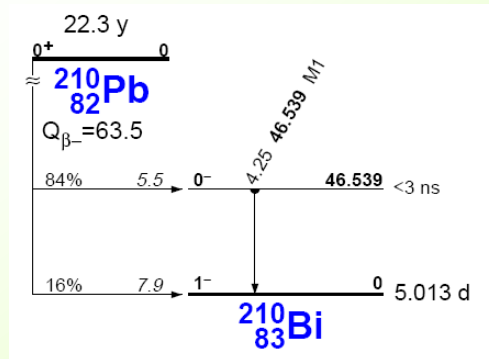
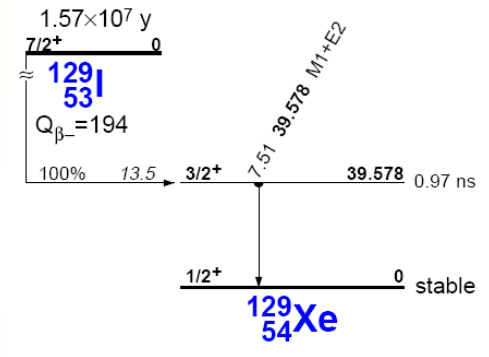
- In rare circumstances, nucleons removed in spallation reactions can combine to form nuclei.
- For example, the radioactive tritium isotope of hydrogen can be produced by cosmic rays by (for example) the reaction



- The atmospheric tritium combines with oxygen to form water that rains down on the Earth.
- Prior to the atmospheric testing of nuclear weapons and the Chernobyl reactor accident, this was the primary source of naturally occurring tritium.
- Because of its short half-life, tritium is absent in water from deep water reserves and also in crude oil.

# $^{129}\text{I}$ and $^{210}\text{Pb}$

- $^{129}\text{I}$  ( $T_{1/2} = 1.57 \times 10^7$  yr) can be present in the natural Iodine with a percentage of the order of  $1.5 \times 10^{-12}$
- $^{210}\text{Pb}$  long-lived isotope from  $^{238}\text{U}$  chain



Energy distributions of two new DAMA/LIBRA detectors (histogram)  
 + model of background for cosmogenic  $^{129}\text{I}$  contribution (red lines)  
 + contribution of internal  $^{210}\text{Pb}$  (visible only in the second detector)

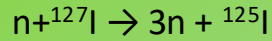
The amount of cosmogenic  $^{129}\text{I}$  is at the same level ( $\approx 1.7 \times 10^{-13}$ ) for all the new detectors (if used for dating the NaI powders  $\Rightarrow$  extracted from ore with an age of order of 50 Myr)

$^{210}\text{Pb}$  in the new DAMA/LIBRA detectors typically ranges: (5 - 30)  $\mu\text{Bq/kg}$ .

No sizeable surface pollution by Radon daughters, thanks to the new handling protocols

# Example of cosmogenic activation in some detectors

For NaI(Tl) detectors the cosmogenic activation corresponds to 2.3 mBq/kg at the Earth's surface:

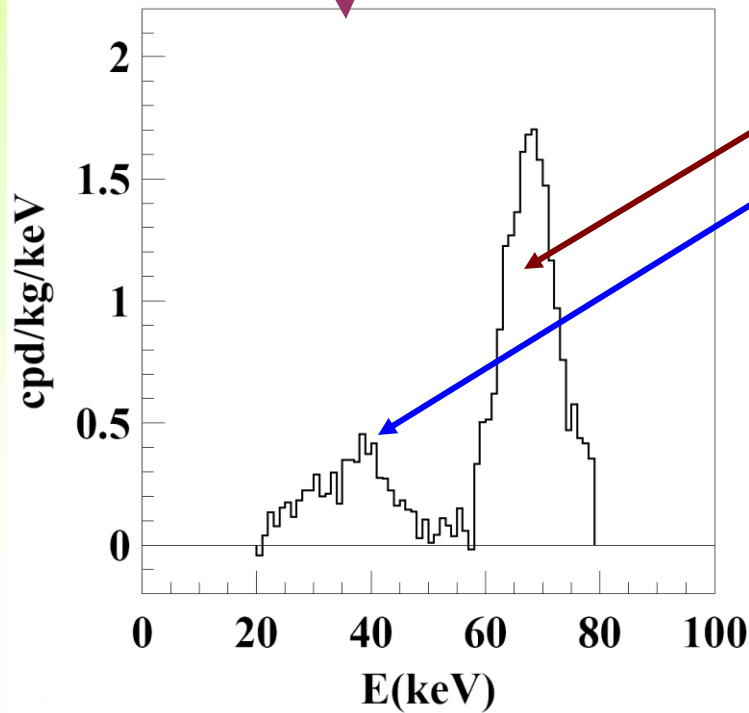
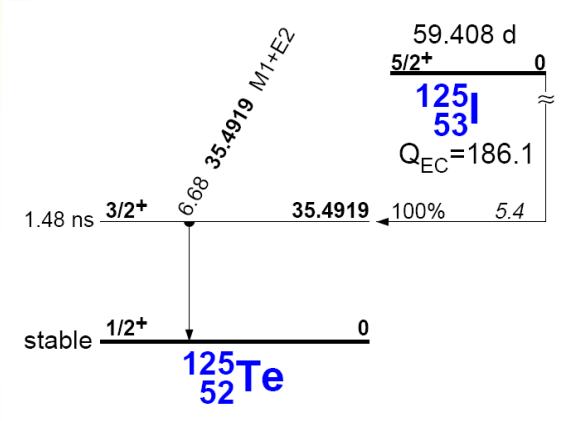
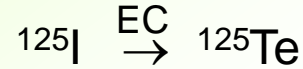


Detector just brought underground

April 03 minus July 04:

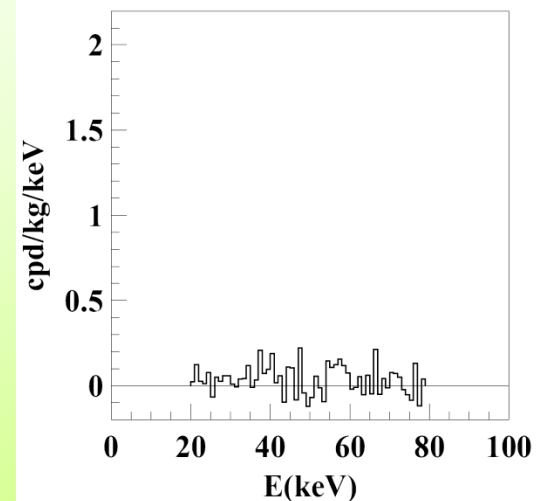
$\Delta T = 445 \text{ d}$  vs  $T_{1/2} \approx 60 \text{ days}$

${}^{125}\text{I}$  ( $T_{1/2} = 59.4 \text{ d}$ )



K shell (80.1%):  $E_{\text{det}} = 35.5 + 31.8 \text{ keV} = 67.3 \text{ keV}$   
 L shell (15.6%):  $E_{\text{det}} = 35.5 + \approx 4.6 \text{ keV} \approx 40 \text{ keV}$   
 M shell ( $\approx 4\%$ ):  $E_{\text{det}} = 35.5 + \approx 0.8 \text{ keV} \approx 36 \text{ keV}$

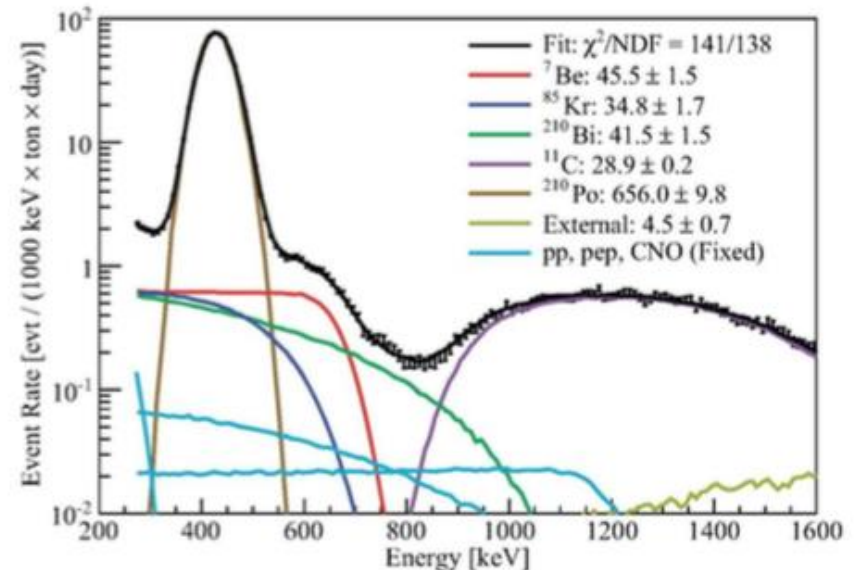
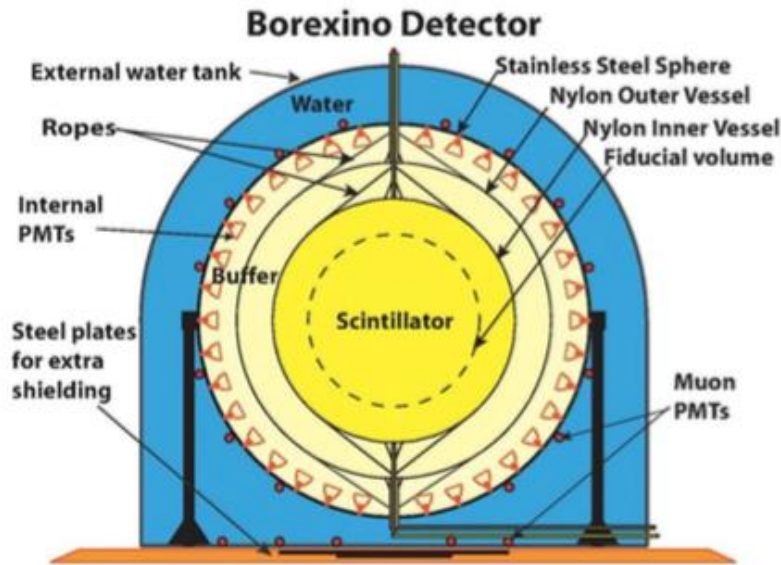
Example of detector stored underground for longer time





# Cosmogenic activation in situ

## Liquid scintillators (Borexino)



Cosmogenic Isotope	Lifetime	Q-Value [MeV]	Decay Type	Cosmogenic Isotope	Lifetime	Q-Value [MeV]	Decay Type
${}^{12}\text{N}$	15.9 ms	17.3	$\beta^-$	${}^6\text{He}$	1.16 s	3.51	$\beta^-$
${}^{12}\text{B}$	29.1 ms	13.4	$\beta^+$	${}^8\text{Li}$	1.21 s	16.0	$\beta^-$
${}^8\text{He}$	171.7 ms	10.7	$\beta^-$	${}^{11}\text{Be}$	19.9 s	11.5	$\beta^-$
${}^9\text{C}$	182.5 ms	16.5	$\beta^+$	${}^{10}\text{C}$	27.8 s	3.65	$\beta^+$
${}^9\text{Li}$	257.2 ms	13.6	$\beta^-$	${}^{11}\text{C}$	29.4 min	1.98	$\beta^+$
${}^8\text{B}$	1.11 s	18.0	$\beta^+$				

# La radioattività artificiale

Radionuclidi prodotti dall'attività umana, in seguito agli **esperimenti nucleari** negli anni cinquanta e sessanta, e per gli incidenti avvenuti alle centrali nucleari essenzialmente quelli di **Three Mile Island** e di **Tchernobyl**.

## Principali radionuclidi di origine artificiale

Nucl	$\tau$	Disintegrazione	$\gamma$ (keV)	Nucl	$\tau$	Disintegrazione	$\gamma$ (keV)
<sup>90</sup> Sr	28.6 a.	< $\beta^+$ > = 196 keV	202.5 479.5	<sup>137</sup> Cs	30.1 a.	< $\beta^+$ > = 188 keV	661.6
<sup>131</sup> I	8.02 j.	< $\beta^+$ > = 182 keV	284.3 364.5 637.1	<sup>134</sup> Cs	2.06 a.	< $\beta$ > = 157 keV	563.2 569.3 604.7 795.8
<sup>95</sup> Nb	34.9 j.	< $\beta^+$ > = 43 keV	765.8	<sup>106</sup> Ru	372 j.	< $\beta^+$ > = 10 keV	511.9
<sup>140</sup> Ba	12.7 j.	< $\beta^+$ > = 251 keV	29.9 162.7 537.3	<sup>133</sup> Ba	10.5 a.	C.E.	276.4 302.9 359.1 383.9
<sup>125</sup> Sb	2.73 a.		427.9 600.6	<sup>95</sup> Zr	64 j.	< $\beta^+$ > = 117 keV	724.2 756.7
<sup>85</sup> Kr	10.7 a.	< $\beta^+$ > = 183 keV	514.1	<sup>144</sup> Ce	285 j.	< $\beta^+$ > = 82 keV	133.5
<sup>88</sup> Kr	2.84 h.	< $\beta^+$ > = 359 keV	196.3 834.8 1529.8 2195.8 2392.1	<sup>136</sup> Cs	13.2 j.	< $\beta^+$ > = 100 keV	176.6 273.6 340.6 818.5 1048.1 1235.3

# Anthropogenic radioactivity

(appeared as result of human activity)

$^{60}\text{Co}$ <sup>1)</sup>	$\gamma$	5.3 y
$^{90}\text{Sr} - ^{90}\text{Y}$ <sup>2)</sup>	$\beta$	29 y
$^{137}\text{Cs}, ^{134}\text{Cs}$ <sup>2)</sup>	$\gamma$	30 y, 2.1 y
$^{238}, ^{239}, ^{240}, ^{242}\text{Pu}$ <sup>3)</sup>	$\alpha$	89 y, $24 \times 10^3$ y, $6.5 \times 10^3$ y, $3.7 \times 10^3$ y
$^{241}, ^{243}\text{Am}$ <sup>3)</sup>	$\alpha$	432 y, 7370 y
$^{244}\text{Cm}$ <sup>3)</sup>	$\alpha$	18 y

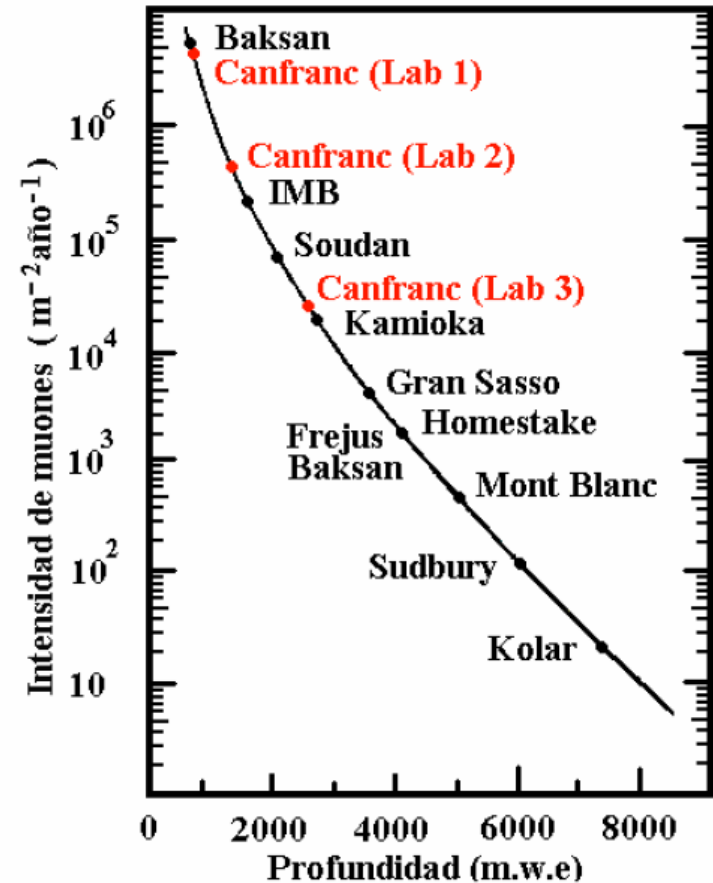
<sup>1)</sup> production of steel

<sup>2)</sup> nuclear bomb tests; Chernobyl, Fukushima

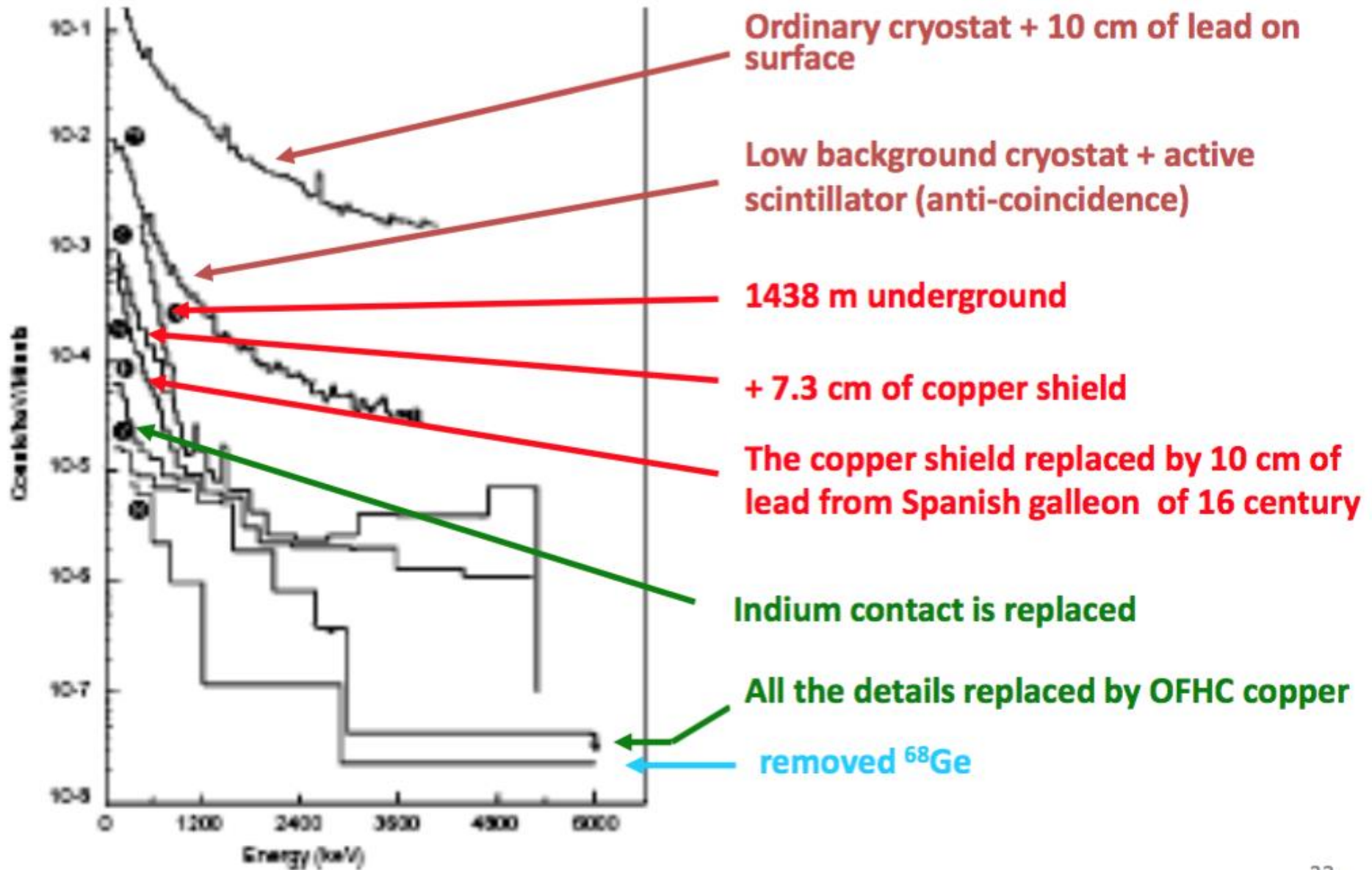
<sup>3)</sup> Nuclear power stations; handling of nuclear materials; Chernobyl, Fukushima

# Suppression of background

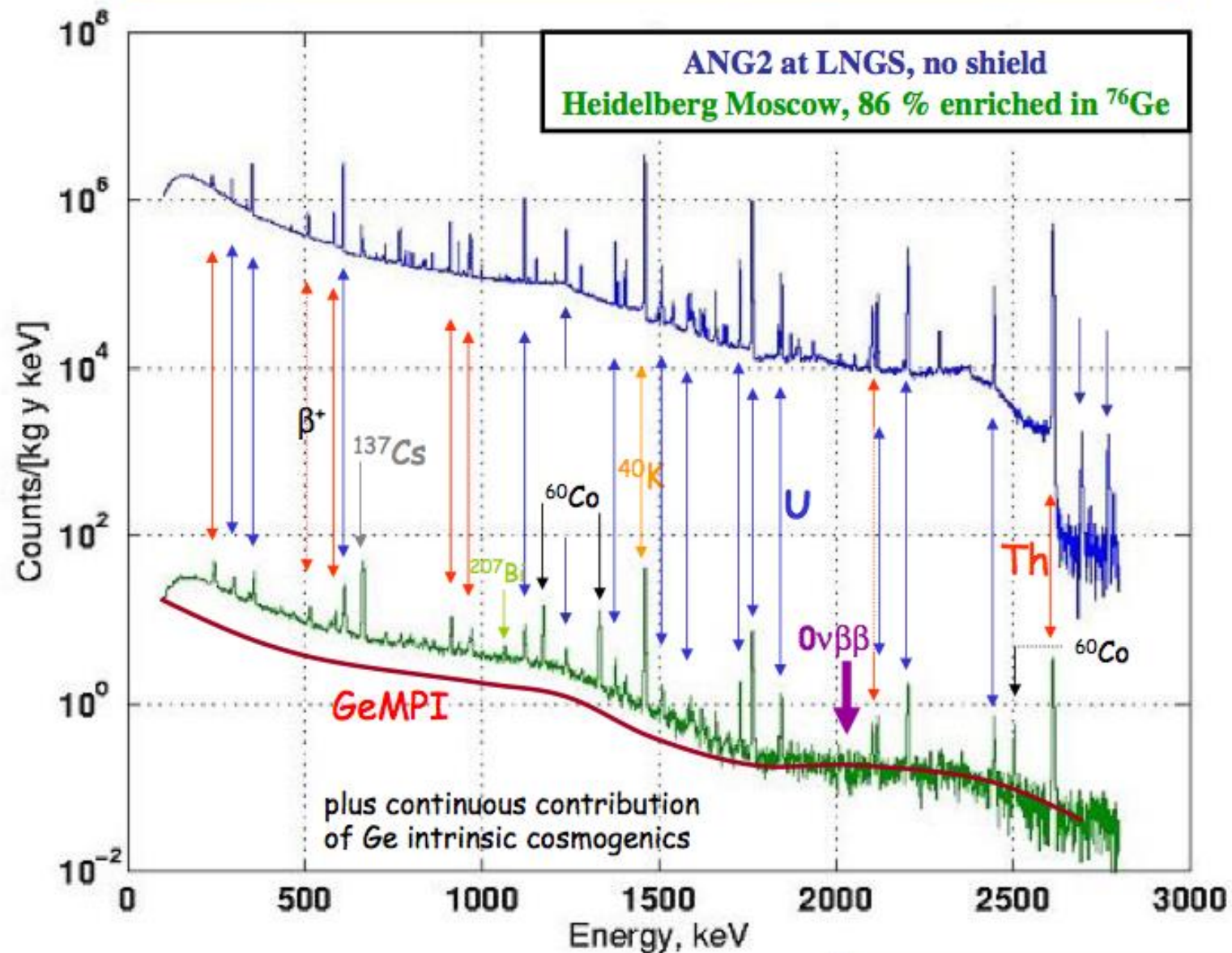
- 1) Underground laboratories
- 2) Shielding against Radon, its progenies and other airborne nuclides
- 3) External shielding
- 4) Material selection for detector construction
- 5) Limitation to the cosmic ray's exposure
- 6) Active determination of background (PSD, other bckg identification techniques, id. of a Fiducial Volume ...)
- 7) Coincidence techniques
- 8) Montecarlo simulations



# radioactive impurities in detector and shield material



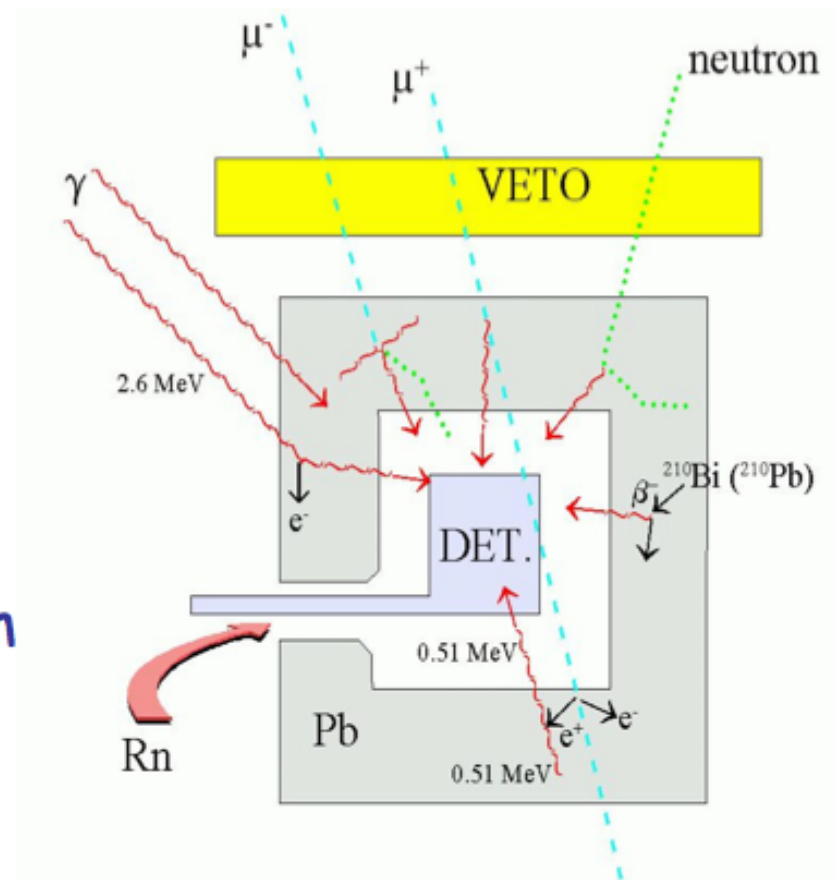
# background reduction by going underground



## origin of background in Ge spectrometry

- environmental gamma field
- radio-impurities (primordial, anthropogenic, cosmogenic) in detector/shield material, and their surface
- Rn and its progenies
- interaction with cosmic rays
- interaction with neutrons from fission and  $(\alpha, n)$  reactions

choice and thickness of shielding material correlates with d) and e)



**most important: material selection by screening**

# 238U decay chain

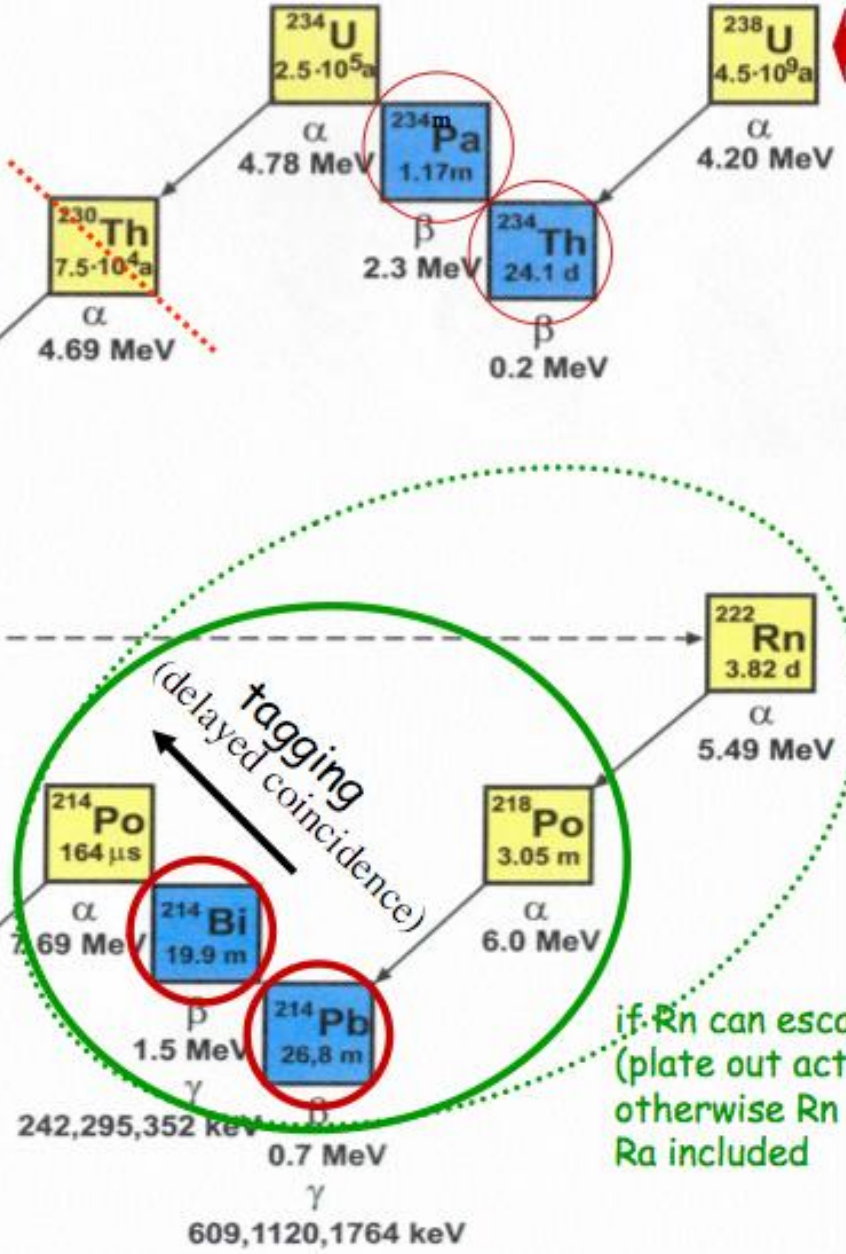
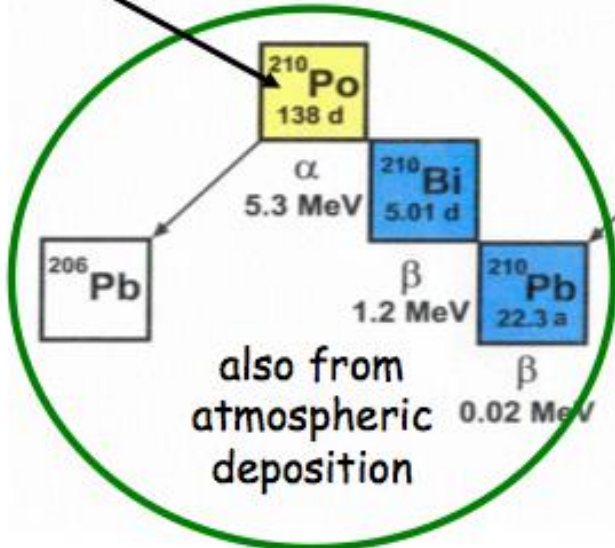
mass spectro-metry

○ ▶ gamma active nuclides

○ ▶ sub chains


equilibr. breaking


highly volatile

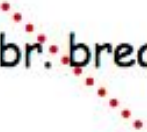


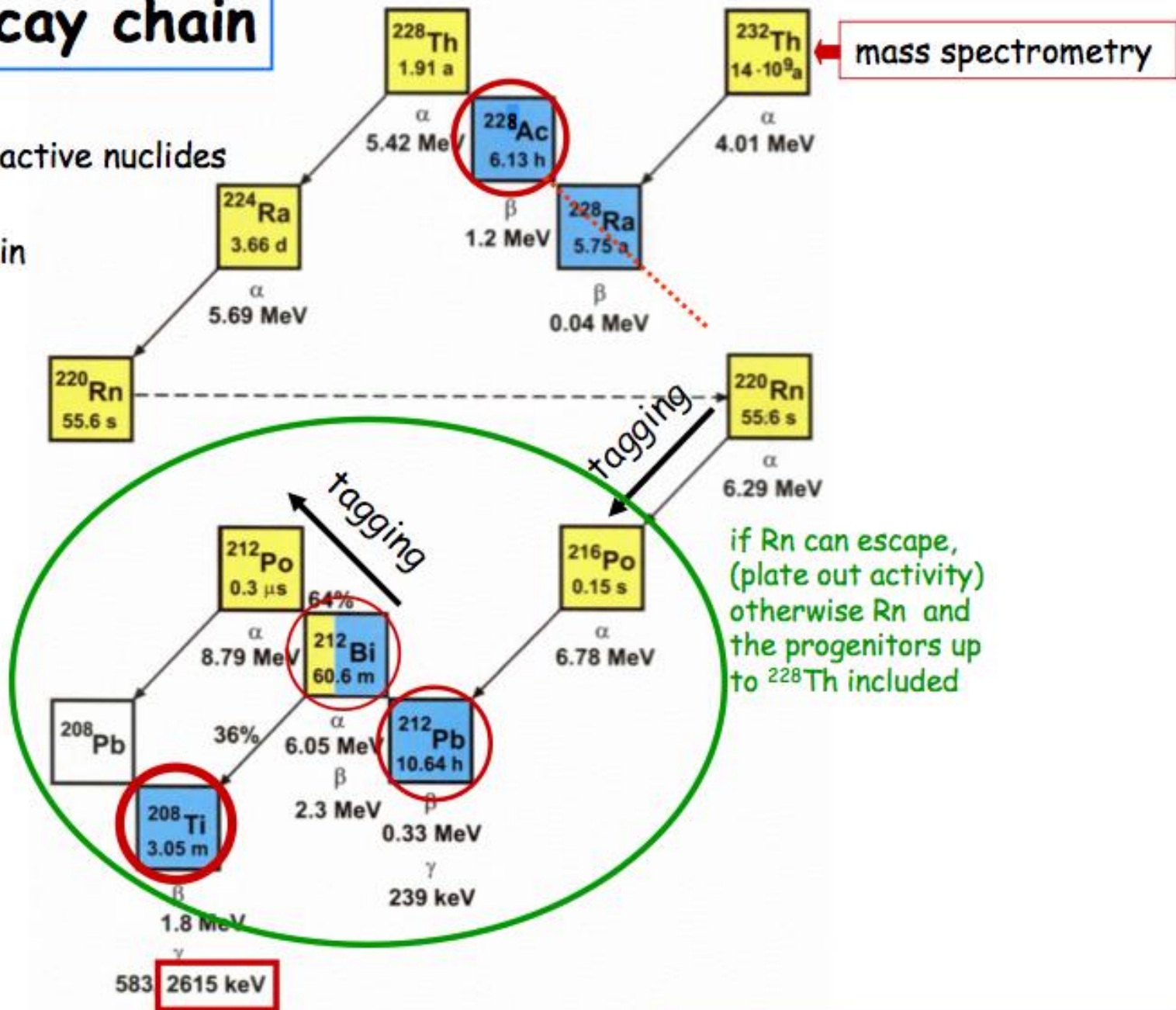
242,295,352 keV  
609,1120,1764 keV

# 232Th decay chain

 ▶ gamma active nuclides

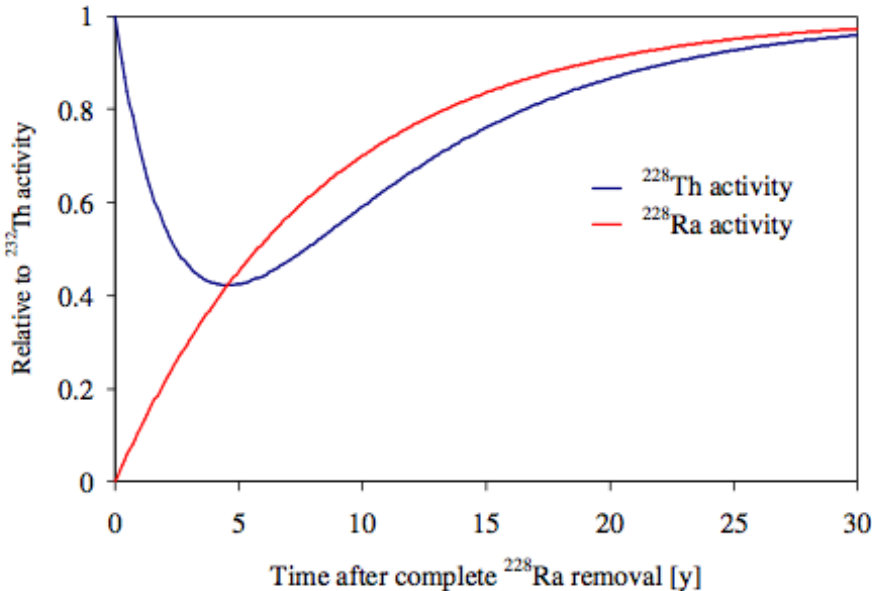
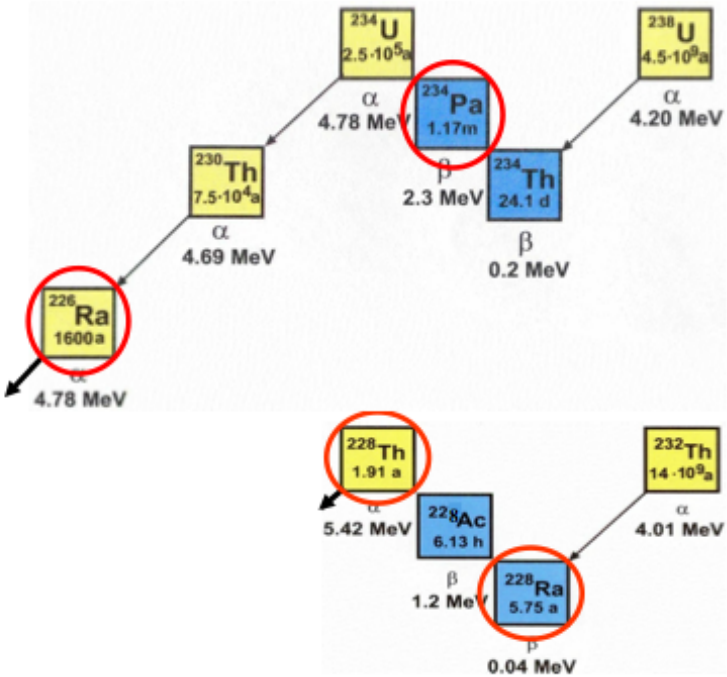
 ▶ sub chain

 equilibr. breaking

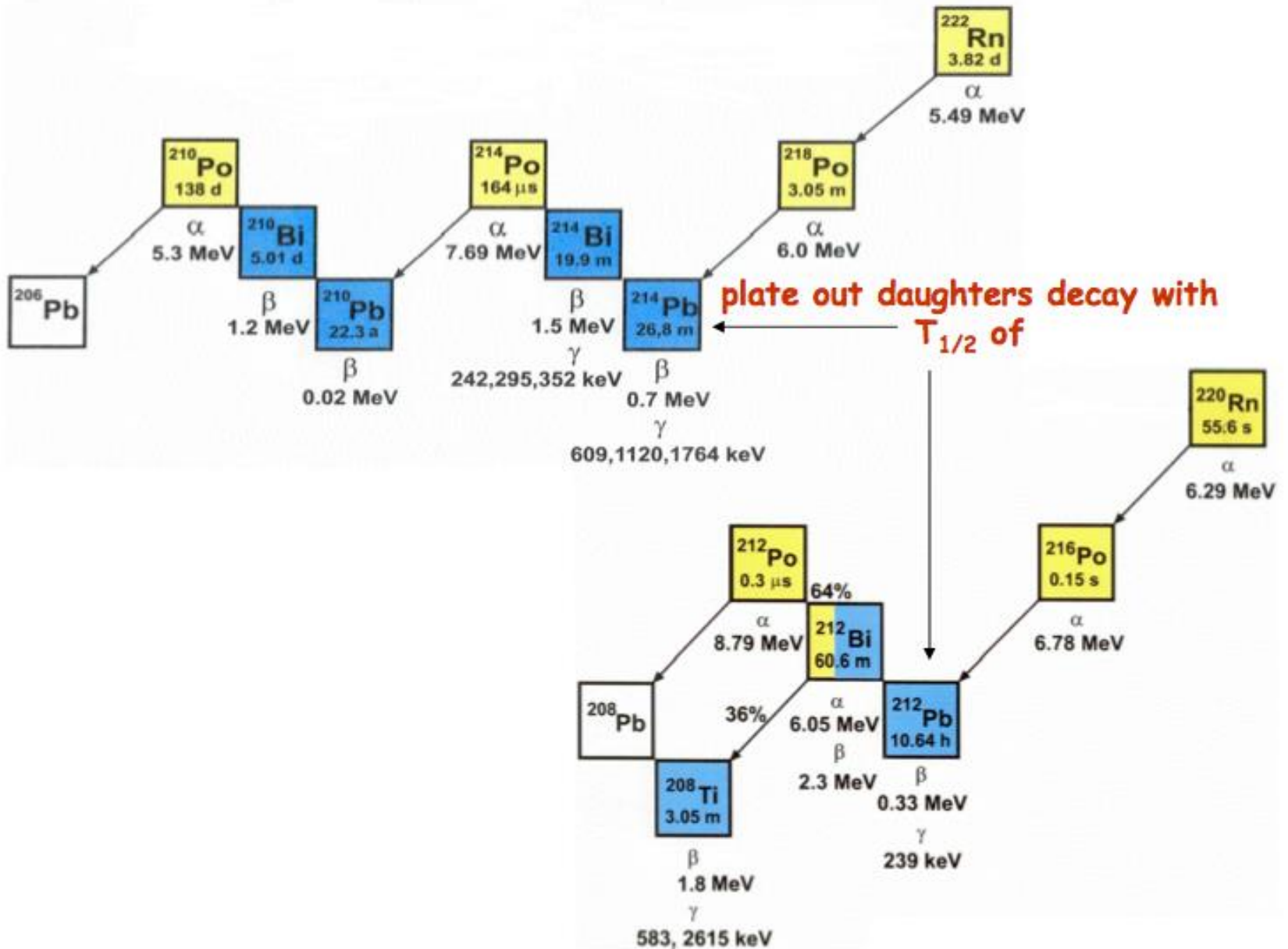


# disequilibrium in natural decay chains

sample	activity of U/Th progenies [mBq/kg] and their ratios					
	$^{234m}\text{Pa}$	$^{226}\text{Ra}$	$^{234m}\text{Pa}/^{226}\text{Ra}$	$^{228}\text{Th}$	$^{228}\text{Ra}$	$^{228}\text{Th}/^{228}\text{Ra}$
WTS steel	121±18	0.99±0.15	122±26	3.7±0.4	1.7±0.2	2.18±0.35
pre WW1 steel	5.7±1.4	0.15±0.02	38±11	0.46±0.07	0.47±0.05	0.98±0.18

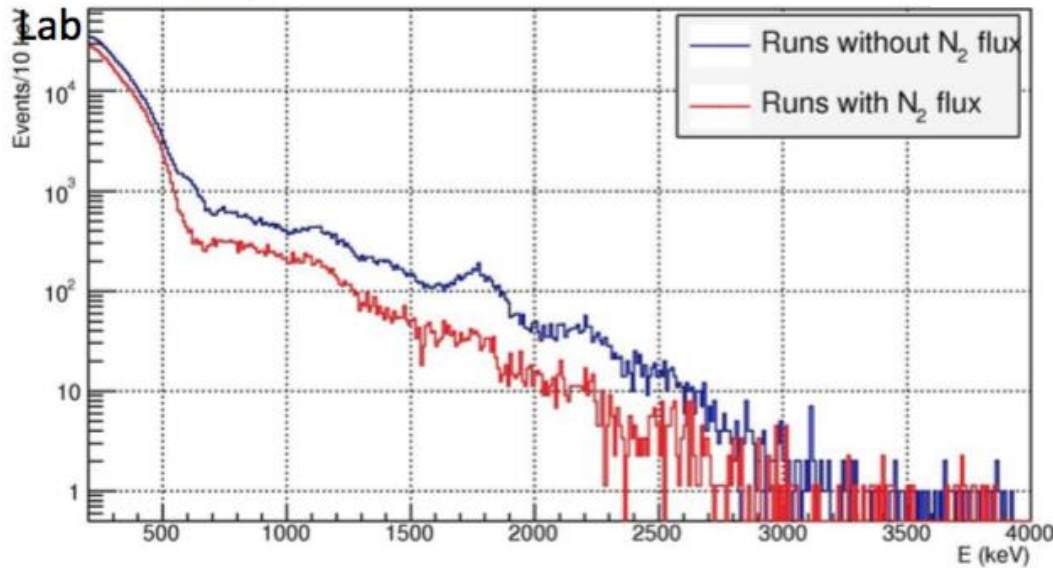


# Rn and its progenies and other airborne radionuclides



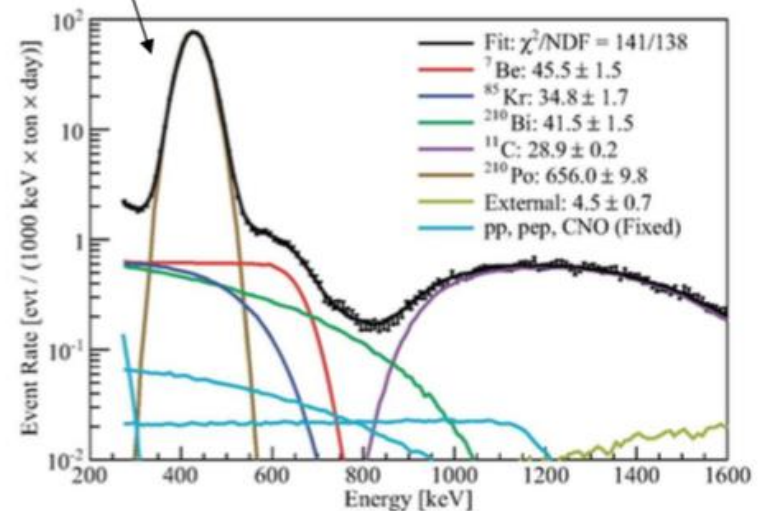
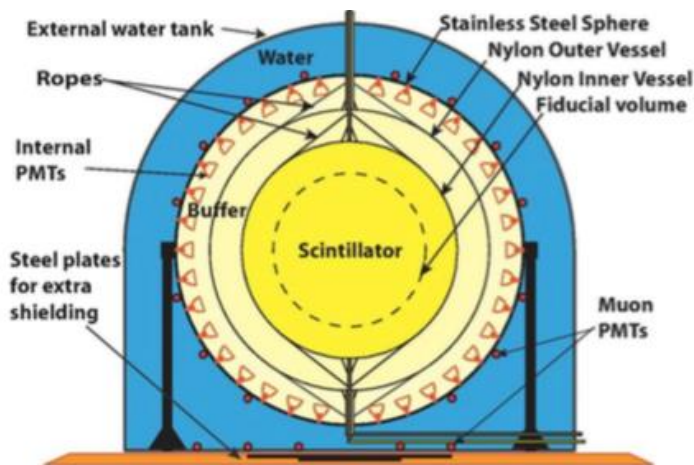
# Rn and its progenies

$^{116}\text{CdWO}_4$  crystal scintillator in the DAMA Cryst at Gran Sasso Lab



Rn in Borexino

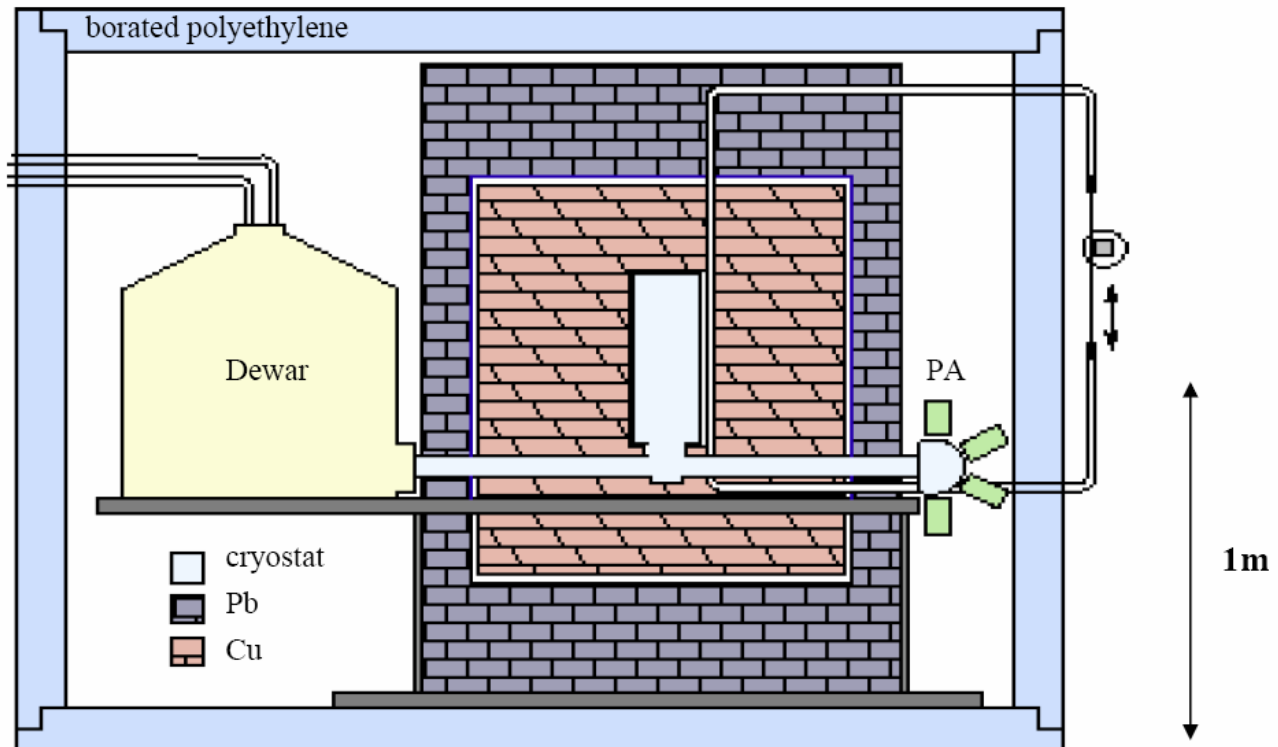
$^{210}\text{Po}$  (daughter of  $^{210}\text{Pb}$ ) appear in Borexino as result of Radon penetration / emanation



# Suppression of background

## 3) External shielding:

- against  $\gamma$  - Pb, Cu, Fe (20-50 cm)
- against neutrons - polyethylene (borated, lithium dopped)

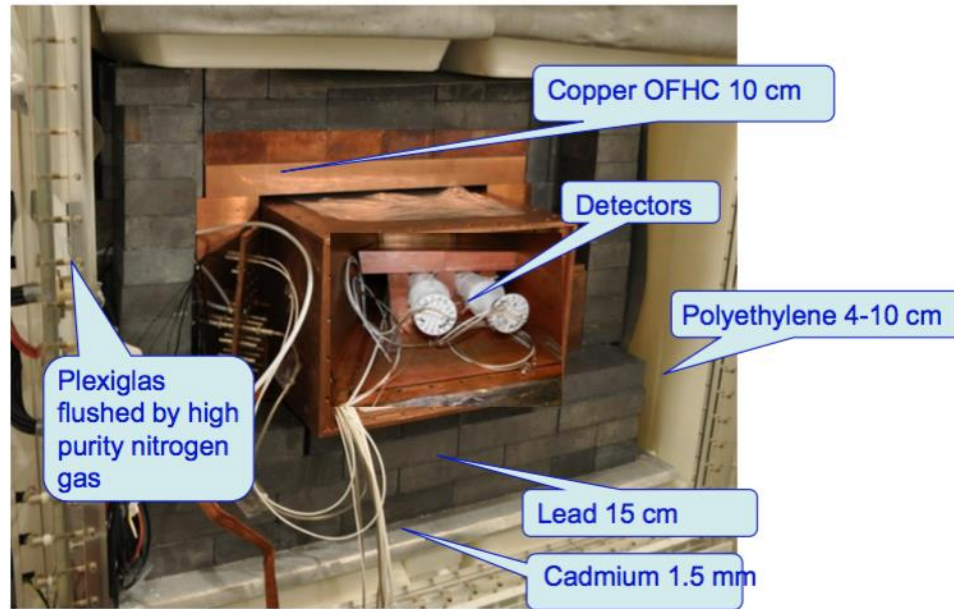


## Measurement of lead with GeMPI

lead sample	weight [kg]	time [d]	specific activity [ $\mu\text{Bq/kg}$ ]				
			$^{226}\text{Ra}$	$^{228}\text{Th}$	$^{40}\text{K}$	$^{207}\text{Bi}$	$^{210}\text{Pb}$
<b>DowRun</b>	144.6	101.7	< 29	< 22	$440 \pm 140$	$98 \pm 24$	$(2.7 \pm 0.4) \times 10^7$
<b>Boliden</b>	144.3	75.0	< 46	< 31	$460 \pm 170$	< 13	$(2.3 \pm 0.4) \times 10^7$
<b>roman</b>	22.1	37.2	< 45	< 72	< 270	< 19	< $1.3 \times 10^6$
	bolometric measurement: Allesandrello et al. NIM B142 (1998) 163						< $4 \times 10^3$



# DAMA R&D passive shield

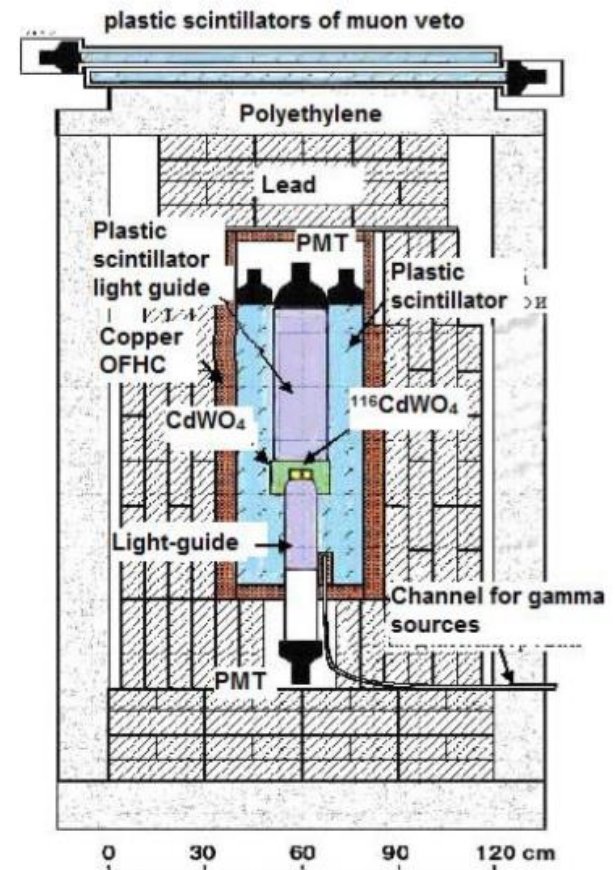


Passive shield typically is made of a few layers to shield against gamma and neutrons, sealing from radon, and to minimize cost

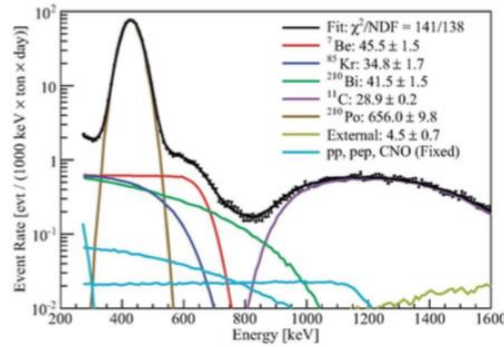
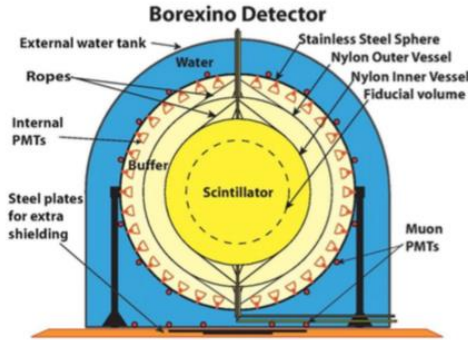
- Combination of different materials in passive shield is reasonable to minimize cost (e.g. OFHC is more expensive than that lead), and to provide shield both from  $\gamma$ s and neutrons
- One should foreseen possibilities for calibration by radioactive sources

## Some examples of shields (passive shield)

Solotvina experiment: passive shield



# Water shield in Borexino



## Some examples of shields (active shields)

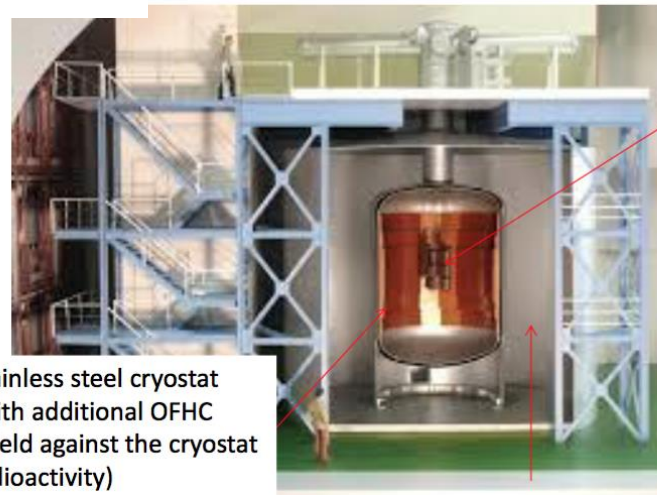
- The external layer of the detector serves as an active shield
- Outer water Cherenkov detector (cosmic muons veto)

Water can be deeply purified by complex approach (e.g. in Borexino):

- filtering (0.1  $\mu\text{m}$ )
- Osmosis unit
- De-ionization
- Current flow of high purity nitrogen in a stripping column

Water is unavoidable for very large set-ups due to high cost of metals

## GERDA water shield



Stainless steel cryostat (with additional OFHC shield against the cryostat radioactivity)

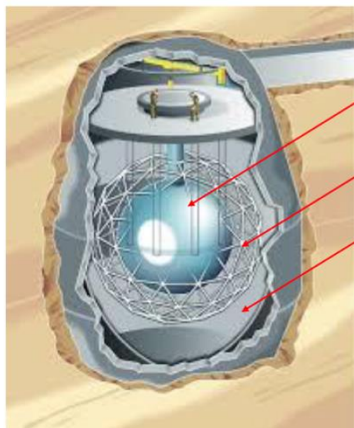
Ultra-pure water passive shield, acts also as active Cherenkov muon veto

Bare HPGe detectors  $^{76}\text{Ge}$



Question: for what reason bare detectors were chosen?

## SNO (Sudbury Neutrino Observatory) heavy water Cherenkov detector to measure solar neutrino ( $\nu_e, \nu_\mu, \nu_\tau$ )



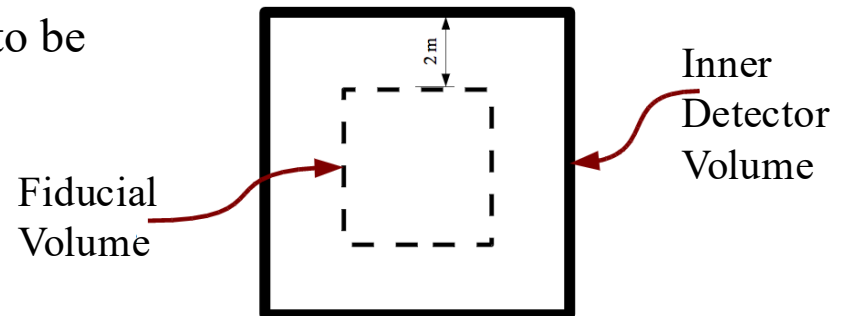
- Acrylic vessel with  $10^3$  ton of heavy water
- Support construction for  $\sim 10^4$  PMTs
- Outer vessel filled with light water as passive shield

# Active shield (veto)

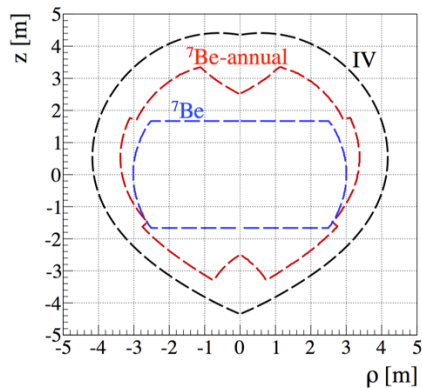
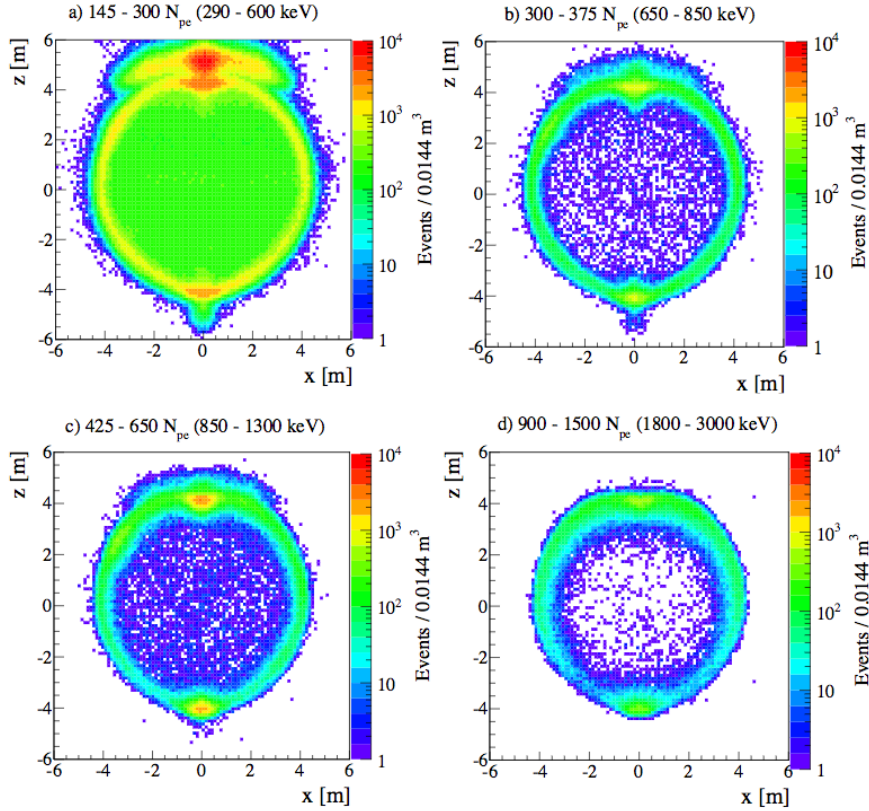
- Plastic scintillators
- Liquid scintillators
- Inorganic scintillators (NaI(Tl), CsI(Tl), BGO, CdWO<sub>4</sub>)
- Cherenkov counter

## Use of Fiducial Volume (FV)

1. The volume used to make physics measurements
2. The volume where the detector is assumed to be well understood
3. For our purpose: the volume where the background is reduced

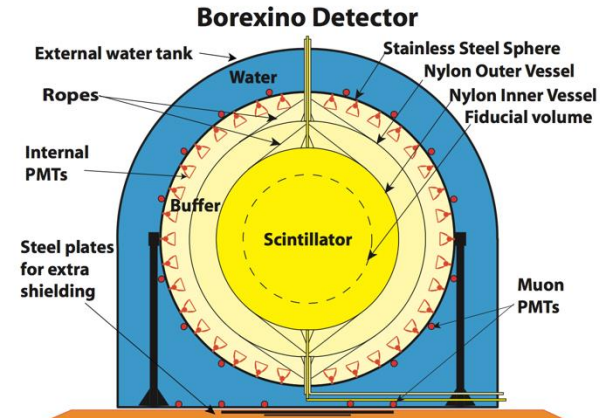
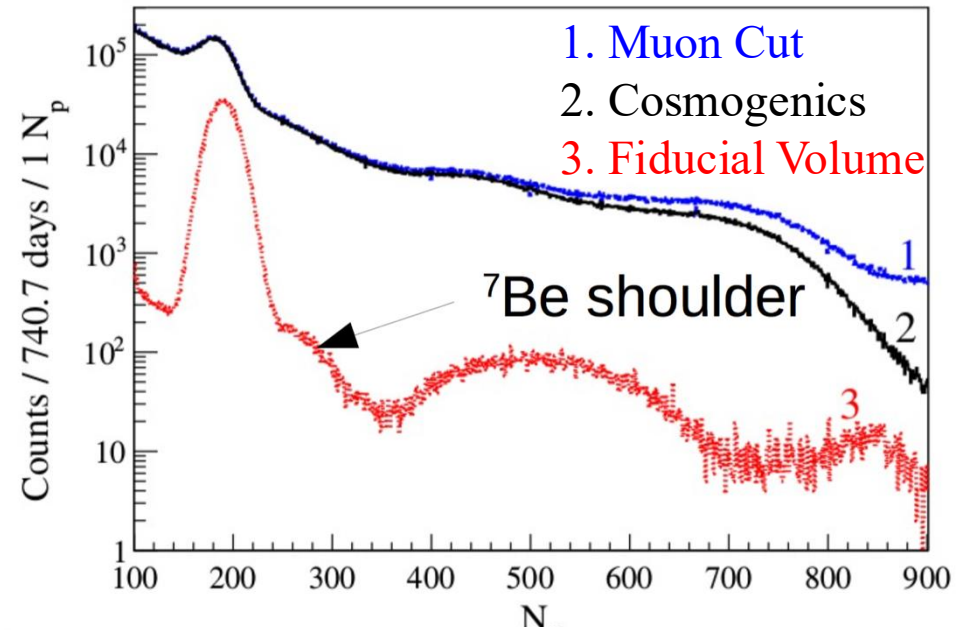


# Fiducial Volume



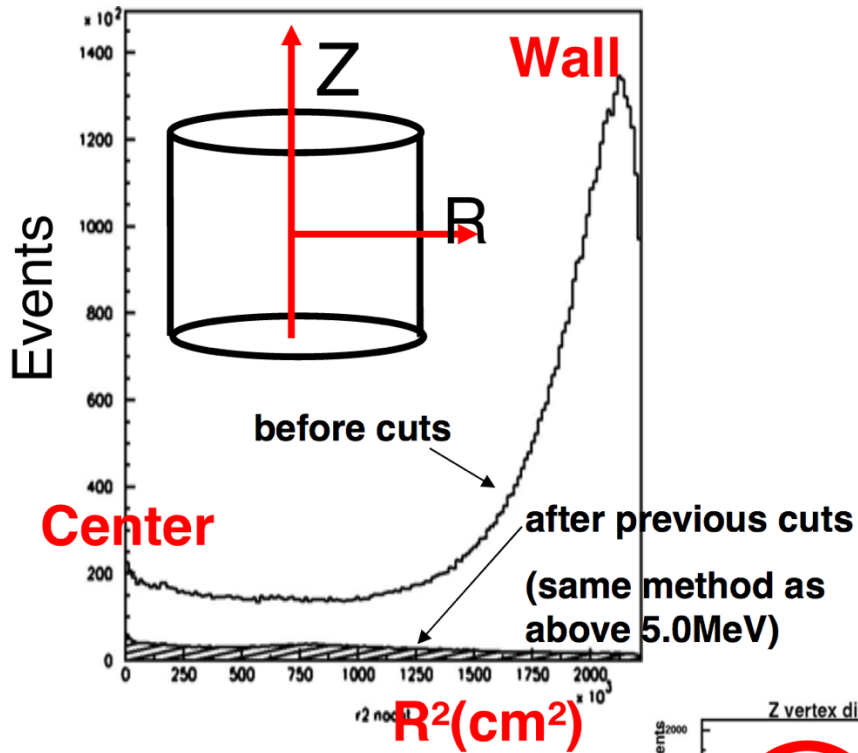
- The choice of the FV is related to the effect searched for
- Trade-off between high exposure and low bckg

## The case of Borexino

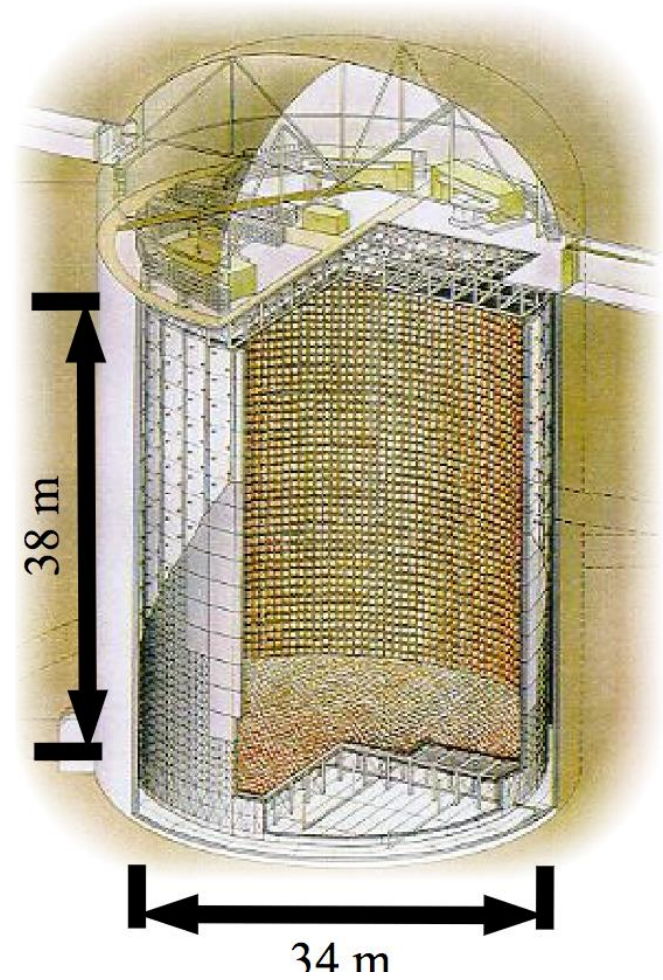
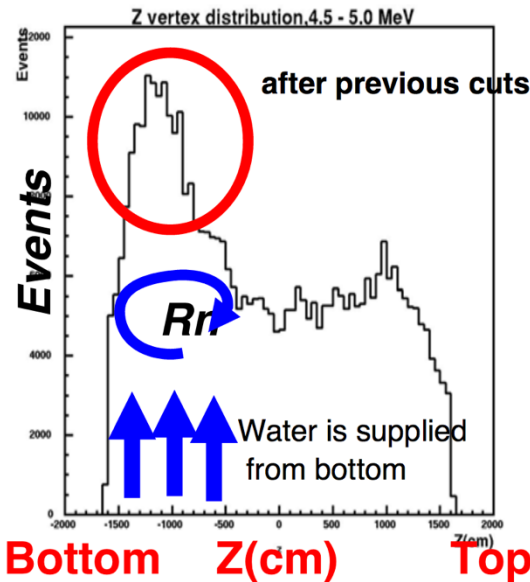


# Fiducial Volume

The case of SuperKamiokande

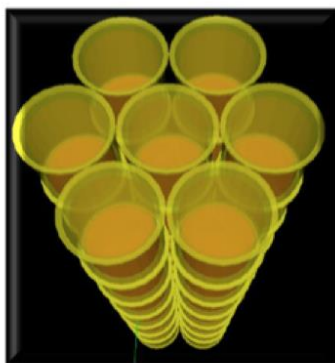
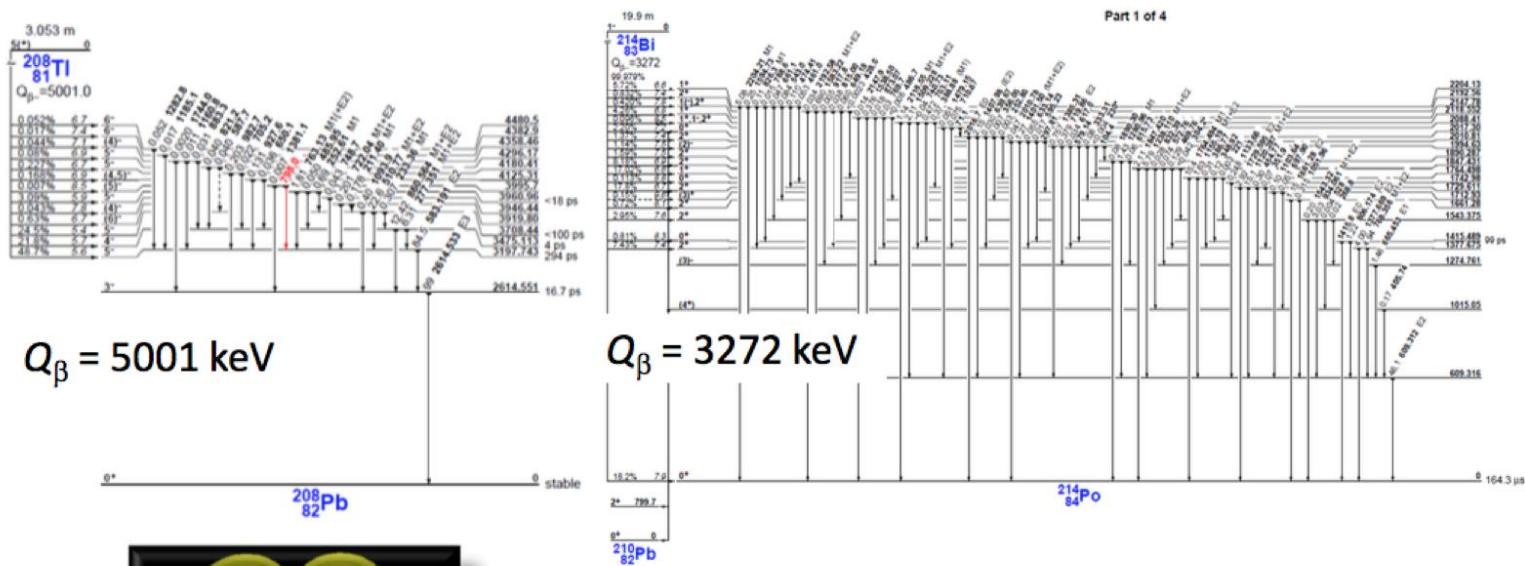


- Analysis of lower energy region in SK-I
- Vertex position distribution of background (4.5 – 5.0 MeV)
- Tighter cuts to reduce external bckg
- Improved vertex reconstruction program.
- Remove high radon periods.



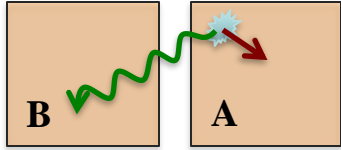
# Coincidence techniques

## Reduction of internal $^{208}\text{Tl}$ and $^{214}\text{Bi}$



Anticoincidence can reduce background by factor 2-10 (depending on 1) energy threshold, 2) presence of passive materials between detectors, 3) multiplicity of the set-up

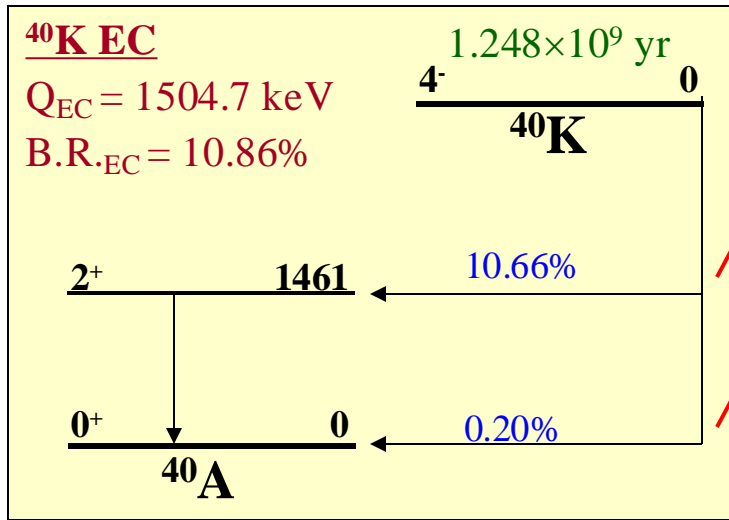
# Coincidence techniques



residual  $^{nat}\text{K}$

$^{40}\text{K}$ :  $\delta = 0.0117 \%$

$T_{1/2} = 1.248 \times 10^9 \text{ yr}$  (EC = 10.86%;  $\beta^- = 89.14 \%$ )



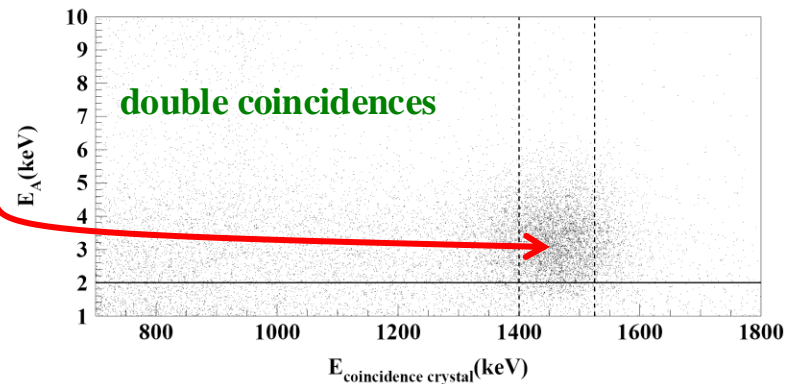
$\Rightarrow 1 \text{ ppb } ^{nat}\text{K}: a(^{40}\text{K}) = \frac{1000 \cdot 10^{-9} \cdot N_A}{39.1} \delta \frac{\ln 2}{T_{1/2}} = 31.7 \mu\text{Bq/kg}$

**L1461:**  $\text{EC}_K = 76.3\%$ ;  $\text{EC}_L = 20.9\%$ ;  $\text{EC}_{M+} = 2.74\%$

**L0:**  $\text{EC}_K = 87.9\%$ ;  $\text{EC}_L = 8.6\%$ ;  $\text{EC}_{M+} = 1.26\%$

The 1461 keV  $\gamma$  can escape from one detector (A) and hit another one causing a double coincidence. X-rays/Auger electrons give rise in A to a 3.2 keV peak

**r**  
 The probability for  $^{40}\text{K}$  EC from shell K to the 1461 keV level of  $^{40}\text{Ar}$  is:  $P_{^{40}\text{K} \text{ EC} \rightarrow 1461} = 10.66\% \times 76.3\% = 8.1\%$  in such a case a 1461 keV  $\gamma$  is emitted together with the 3.2 keV X-rays/Auger electrons from shell K of  $^{40}\text{Ar}$  (this last is contained in the detector with efficiency  $\sim 1$ )



The 3.2 keV peak offers also the proof of the physical threshold of the detectors and an intrinsic calibration for each one in the lowest energy region

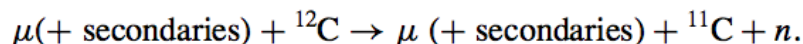
# Coincidence techniques

The case of cosmogenic in-situ  $^{11}\text{C}$  in Borexino

## Three-Fold-Coincidence

Muon track

Spherical cut  
around neutron  
capture to reject  $^{11}\text{C}$  event



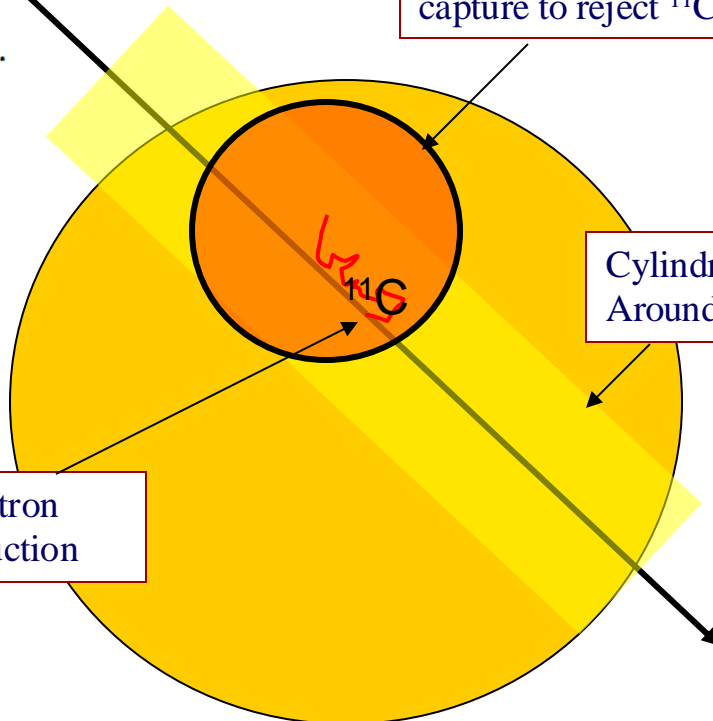
Triple coincidence among:

1. The muon
2. The neutron capture by H
3. The  $^{11}\text{C}$  decay

Cylindrical cut  
Around muon-track

$^{11}\text{C}$   $\beta^+$  decays with a mean life of 29.4 min  
and an end-point energy of 0.96 MeV

Neutron  
production



Muons crossing the LS  
produce at least one neutron  
in 95% of cases

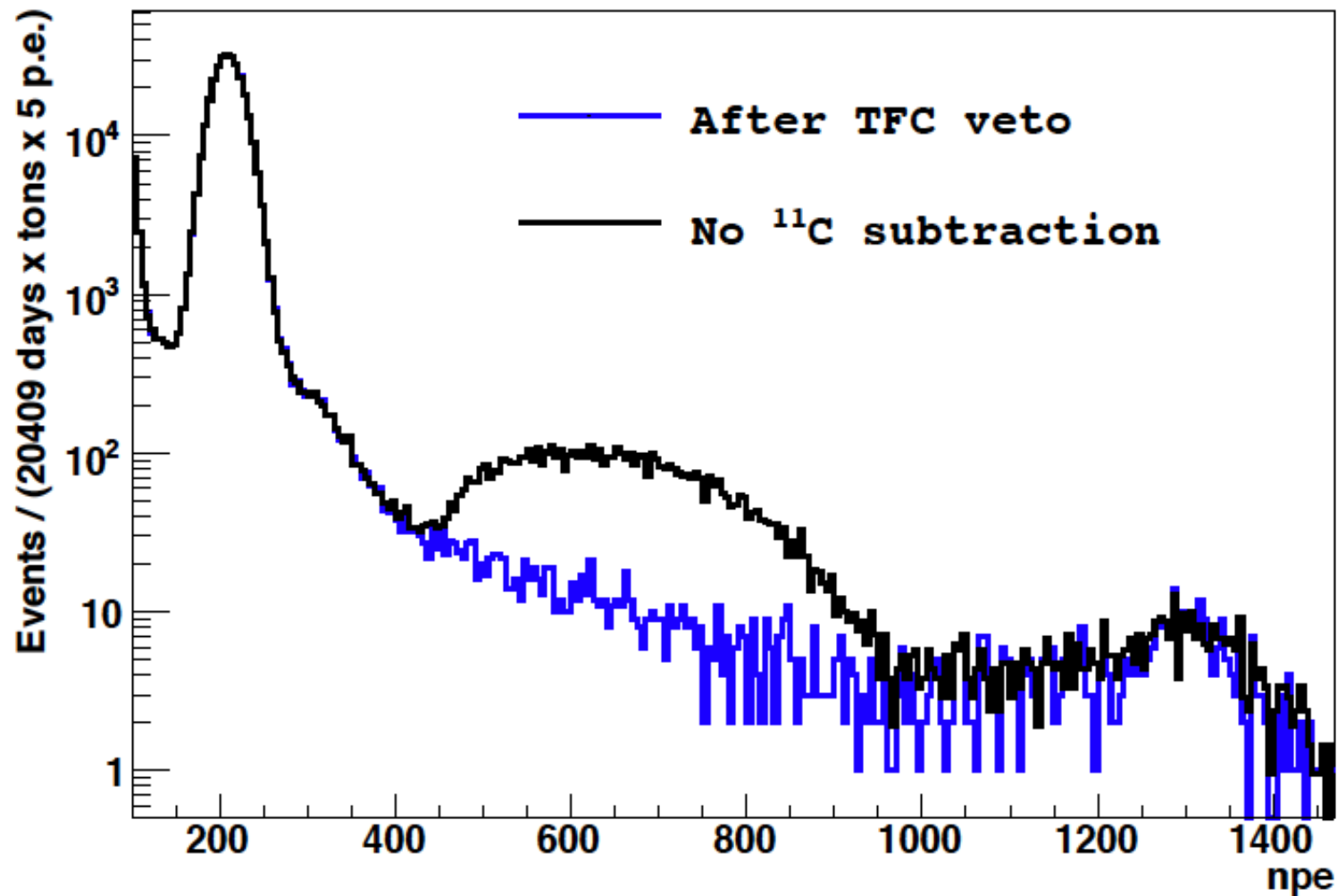
**Goal:** reduce  $^{11}\text{C}$  background

*Borexino coll: CNO and pep neutrino spectroscopy in Borexino: measurement of the deep-underground production of cosmogenic  $^{11}\text{C}$  in an organic liquid scintillator, Phys. Rev. C 74, 045805 (2006).*

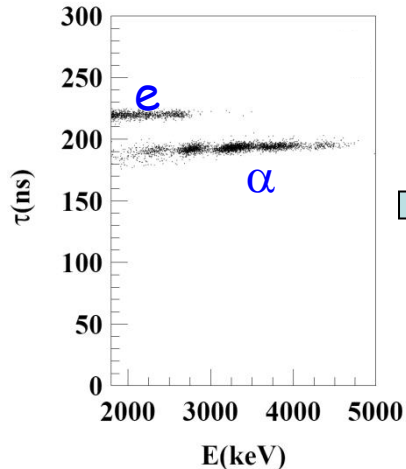
TFC decreases  $^{11}\text{C}$  rate to  $\sim 10\%$  of its original value with  $\sim 50\%$  loss of exposure.

Limiting background internal  $^{210}\text{Bi}$ .

### Energy spectrum in FV



# Pulse Shape Discrimination (PSD)



$\alpha/e$  pulse shape discrimination has practically 100% effectiveness in the MeV range



The measured  $\alpha$  yield in the new DAMA/LIBRA detectors ranges from 7 to some tens  $\alpha$ /kg/day

$^{238}\text{U}$  residual contamination in NaI(Tl) of DAMA/LIBRA

$$t = \frac{\int_0^t t \times f(t) dt}{\int_0^t f(t) dt} \gg \frac{\dot{a}_i h_i t_i}{\dot{a}_i h_i}$$

First estimate: considering the measured  $\alpha$  and  $^{232}\text{Th}$  activity, if  $^{238}\text{U}$  chain at equilibrium  $\Rightarrow$   $^{238}\text{U}$  contents in new detectors typically range from 0.7 to 10 ppt

But, hypothesis of equilibrium is not confirmed by the study of the  $\alpha$  particles energy distributions:

Example:  
5  $\alpha$  peaks

1.  $^{232}\text{Th}(Q_\alpha=4.08 \text{ MeV}) + ^{238}\text{U}(4.27 \text{ MeV})$
2.  $^{234}\text{U}(4.86 \text{ MeV}) + ^{230}\text{Th}(4.77 \text{ MeV}) + ^{226}\text{Ra}(4.87 \text{ MeV})$
3.  $^{210}\text{Po}(5.41 \text{ MeV}) + ^{228}\text{Th}(5.52 \text{ MeV}) + ^{222}\text{Rn}(5.59 \text{ MeV}) + ^{224}\text{Ra}(5.79 \text{ MeV})$
4.  $^{218}\text{Po}(6.12 \text{ MeV}) + ^{212}\text{Bi}(6.21 \text{ MeV}) + ^{220}\text{Rn}(6.41 \text{ MeV})$
5.  $^{216}\text{Po}(6.91 \text{ MeV})$

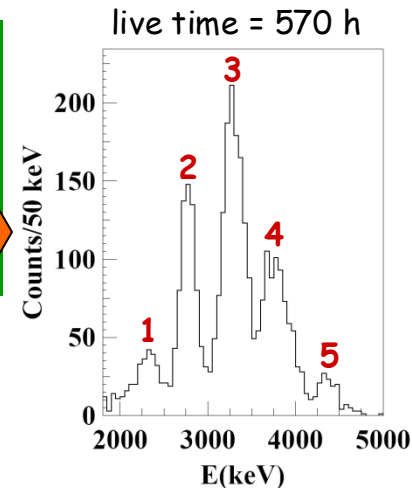


$^{238}\text{U}$  chain splitted into 5 subchains:  $^{238}\text{U} \rightarrow ^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow ^{210}\text{Pb} \rightarrow ^{206}\text{Pb}$

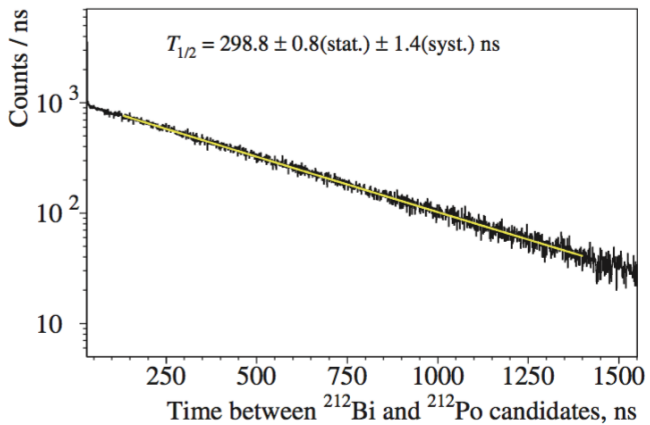
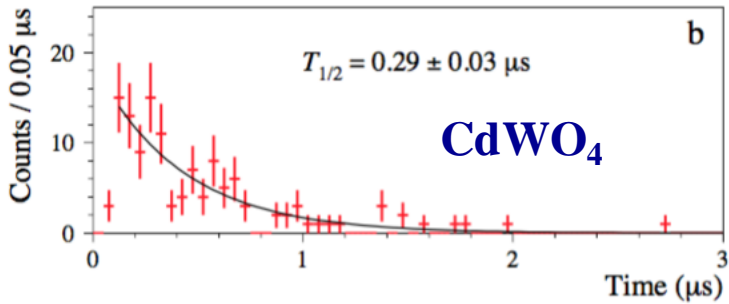
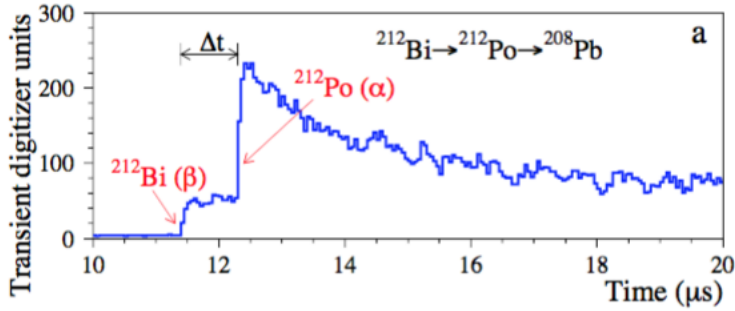


Thus, in this case:  $(2.1 \pm 0.1)$  ppt of  $^{232}\text{Th}$ ;  $(0.35 \pm 0.06)$  ppt for  $^{238}\text{U}$

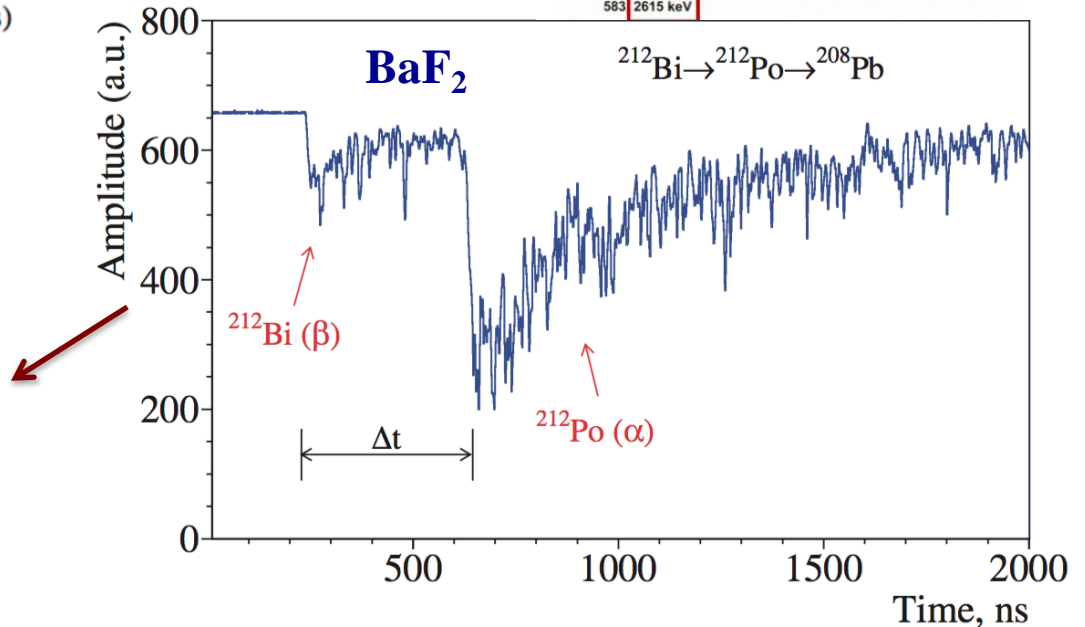
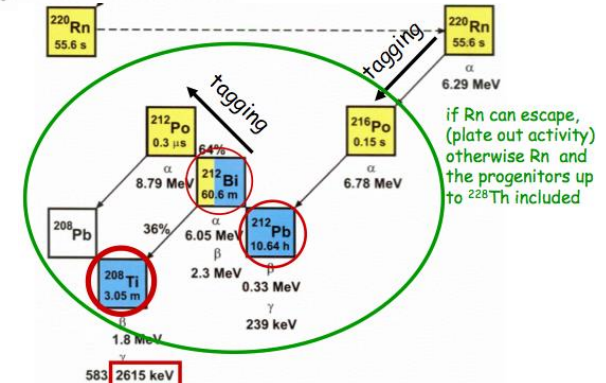
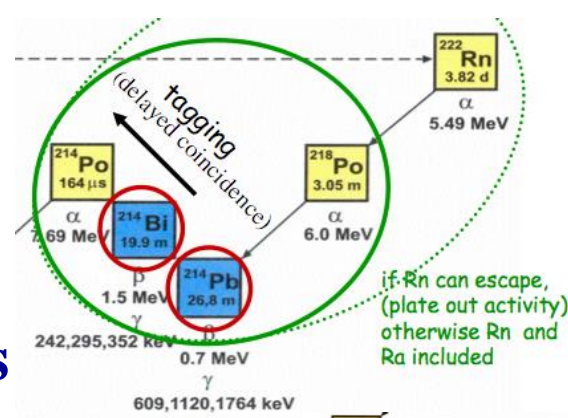
and:  $(15.8 \pm 1.6) \mu\text{Bq/kg}$  for  $^{234}\text{U} + ^{230}\text{Th}$  subchain;  $(21.7 \pm 1.1) \mu\text{Bq/kg}$  for  $^{226}\text{Ra}$  subchain;  $(24.2 \pm 1.6) \mu\text{Bq/kg}$  for  $^{210}\text{Pb}$  subchain.



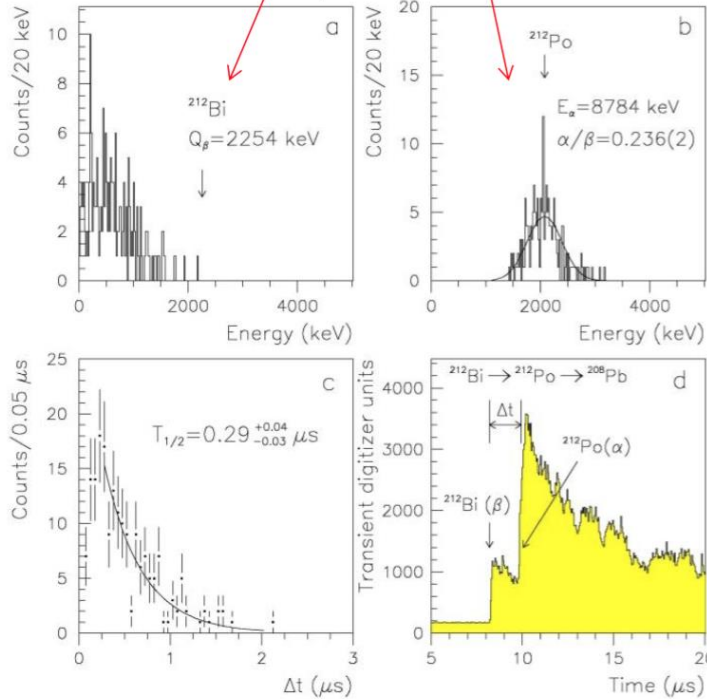
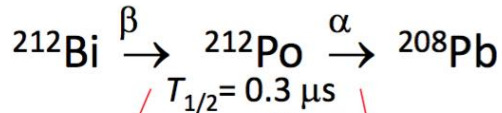
# Time Amplitude Analysis



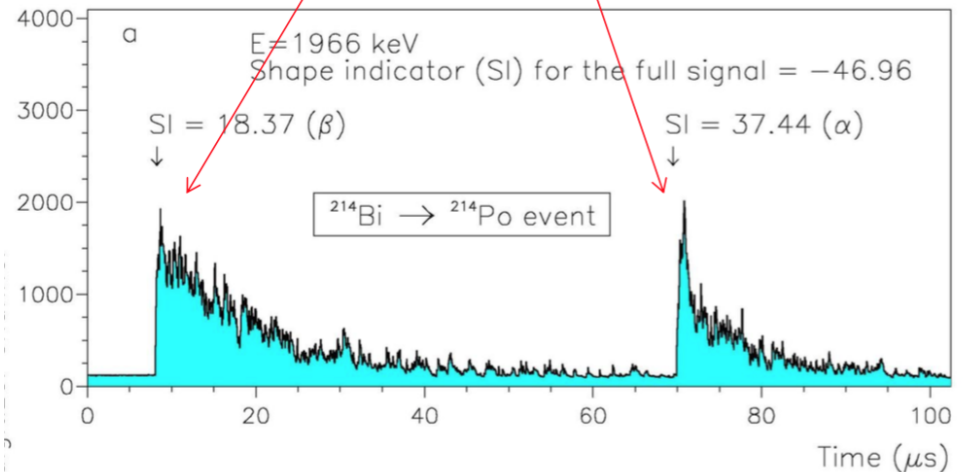
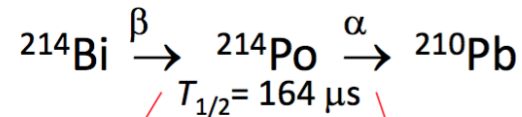
## Bi-Po events



# $^{212}\text{Bi}$ - $^{212}\text{Po}$ in $^{116}\text{CdWO}_4$



# $^{214}\text{Bi}$ - $^{214}\text{Po}$ in $^{116}\text{CdWO}_4$



# Summary

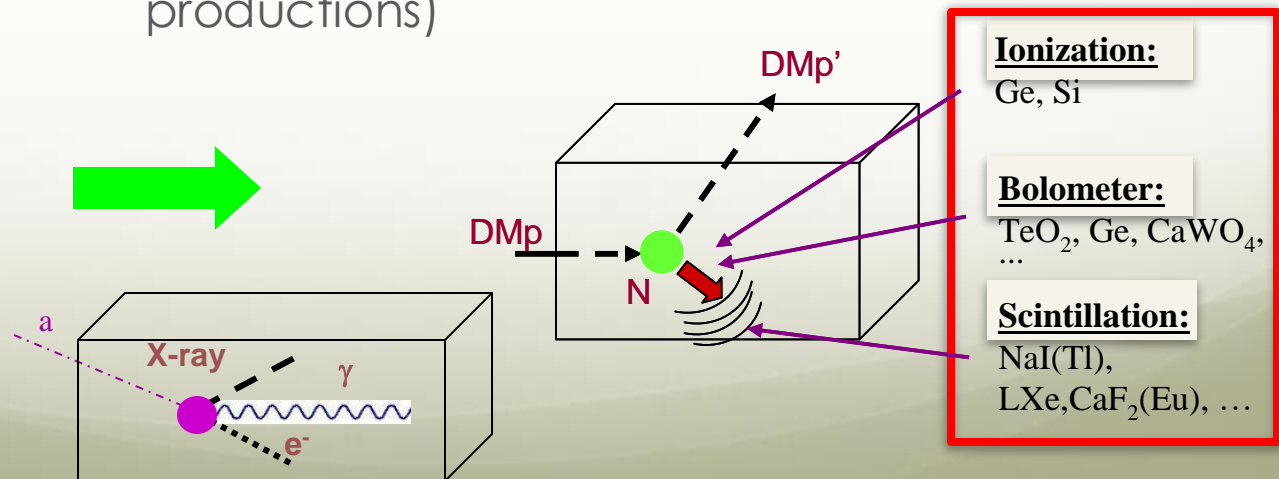
- Surface contamination is rather dangerous source of background
- Pulse-shape and time-amplitude analyses are powerful approaches to analyze internal radioactive contamination of detectors
- Noise can be rejected by pulse-shape discrimination, stability (time and energy) should be checked
- Monte Carlo simulation is a useful tool to analyze background spectra (learn GEANT4, EGS4, etc)
- Crystal scintillators are detectors with rather wide range of radioactive contamination (13 orders of magnitude). Composition and chemical properties are the most crucial issues
- Deep purification of materials is strongly requested by low counting experiments: crystallization in aqueous solutions, distillation, zone melting, recrystallization

# Direct detection experiments

The direct detection experiments can be classified in **two classes**, depending on what they are based:



1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a **model-independent signature**
2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)



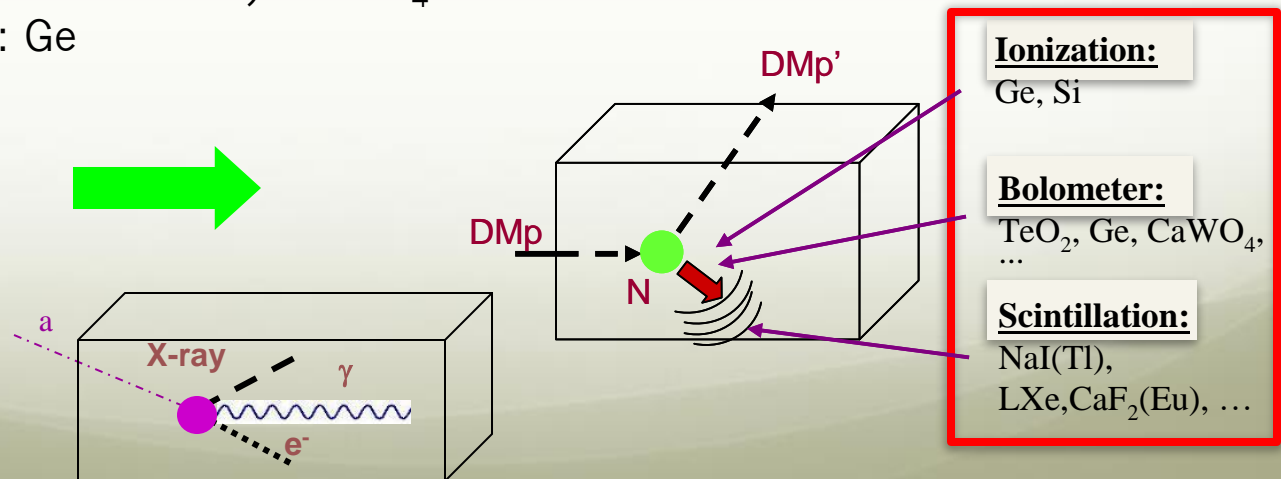
# Direct detection experiments

## Summarizing, the detectors for DM:

- must have very low-energy thresholds (order of keV at least)
- must have very low intrinsic bckg
- must be well shielded by external environmental radiation (muons, neutrons, gammas, ...)
- must be stable with time
- must have very good experimental features (energy resolution, check of the energy scale, uniformity of the detector, and many others)

## Many techniques/experiments on the market:

- Scintillation detectors: NaI(Tl) ...
- Liquid noble gases: LXe, LAr, LNe
- Bolometers (heat vs ionization): Ge, Si
- Bolometers (heat vs scintillation): CaWO<sub>4</sub>
- Ionization detectors: Ge
- and others...



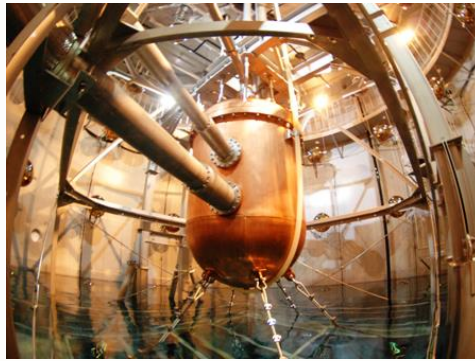
# Experiments using liquid noble gases

## PSD in single phase detector:

- pulse shape discrimination  $\gamma$ /recoils from the UV scintillation photons



DAMA/LXe



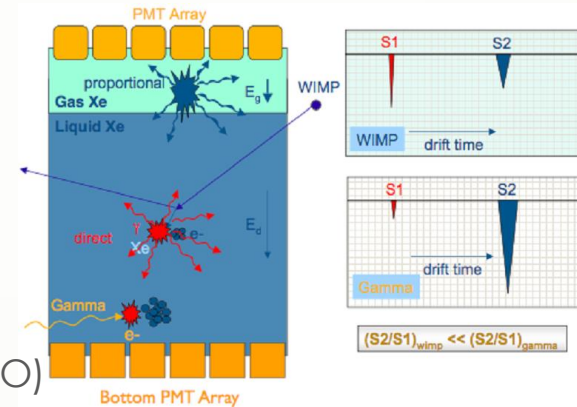
XMASS

WARP, XENON10, -100, -1T, -nT, LUX, PANDAX, DarkSide-50, DEAP-3600, CLEAN, ArDM → towards larger target masses (LZ, Darwin, DS-20k, ARGO)

## in dual phase detector:

- prompt signal (S1): UV photons from excitation and ionization
- delayed signal (S2):  $e^-$  drifted into gas phase and secondary scintillation due to ionization in electric field

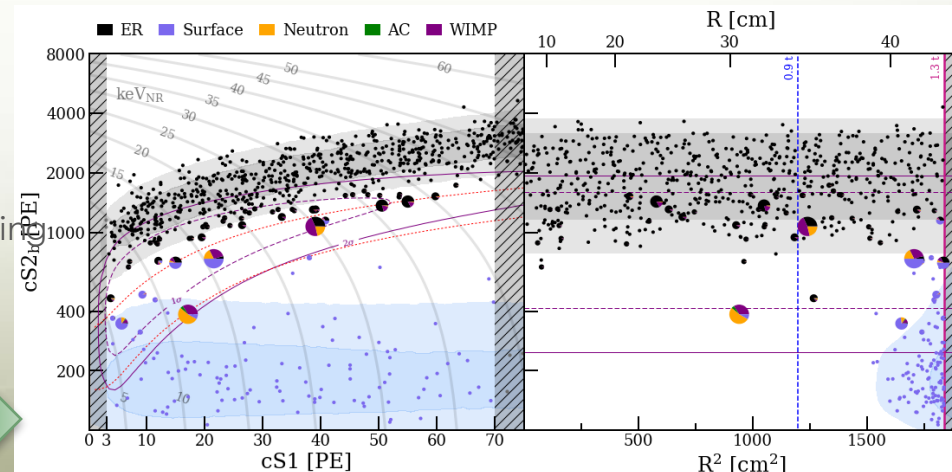
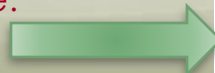
Statistical rejection of e.m. component of the counting rate



- **Non-uniform** response of detector: intrinsic limit
- **UV light, nonlinearity** (more in larger volumes)
- **Correction** procedures applied; **Systematics**
- Physical **energy threshold not robust**
- Poor energy **resolution**
- **Light responses** for electrons and recoils at low energy
- **Quenching factors** measured with a much-more-performing detector **cannot be used** straightforward
- Etc.

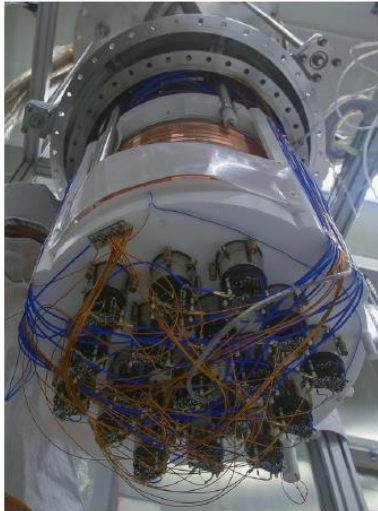
Many cuts applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?

After many cuts few events survive: intrinsic limit reached?



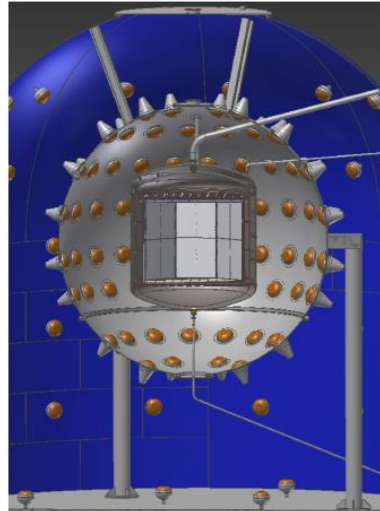
# LAr at LNGS: DarkSide

The DarkSide Program at Gran Sasso Lab



**DarkSide-50**

150/50/30 kg total/active/fiducial  
Sensitivity <math><10^{-44}</math> cm<sup>2</sup>  
Data: 2013-present



**DarkSide-20k**

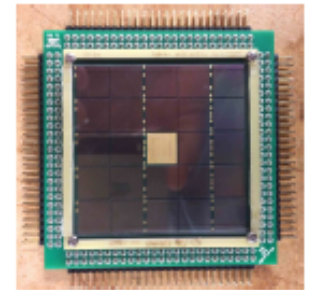
30/23/20 T tot/act/fiducial  
Sensitivity <math><10^{-47}</math> cm<sup>2</sup>  
Data: ~2021

...toward DarkSide-20k



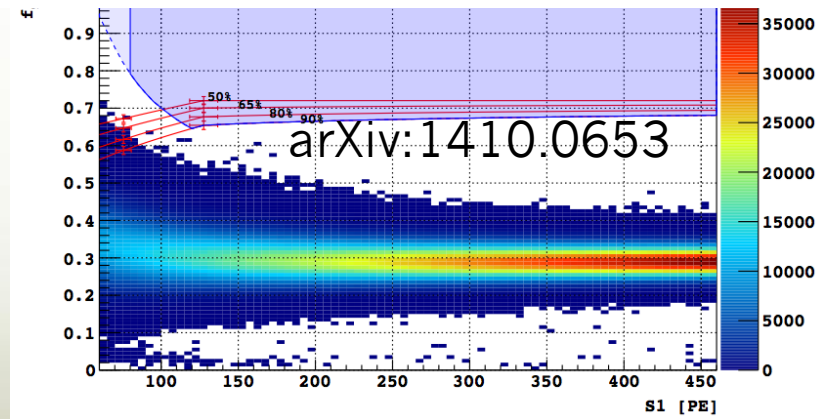
← Massive effort to extract and purify UAr

SiPMs  
replace →  
PMTs



## DarkSide

- Operated DarkSide-10 prototype for 1 year
- Constructed as part of DarkSide-50:
  - 1000 tonnes water Cherenkov muon veto
  - 30 tonnes organic liquid scintillator neutron veto
  - two Rn-free clean rooms for final preparation of the detector
  - argon recirculation, purification, and recovery systems
- All facilities built sized to house DarkSide-G2

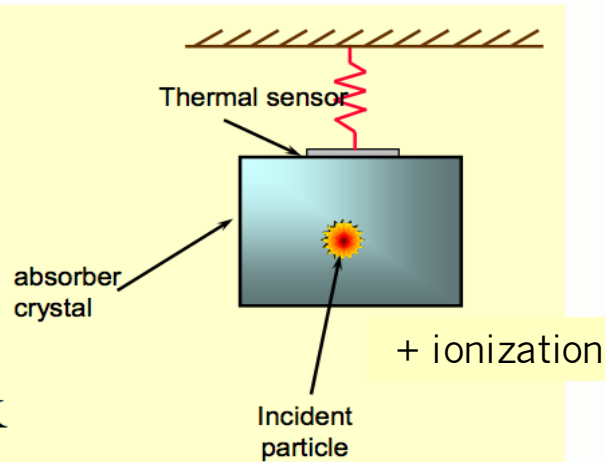


Technical comments similar as for XENON are expected (see above)

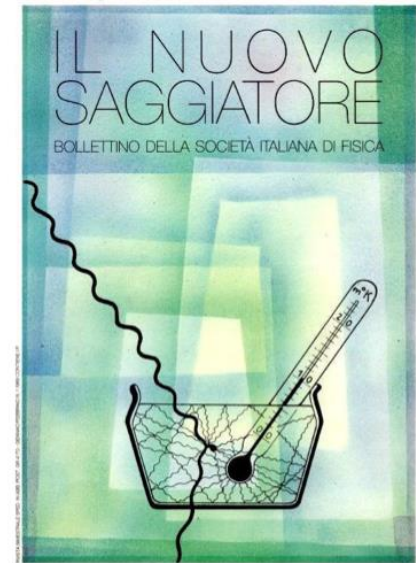
# Double read-out bolometric technique (ionization vs heat)

$$\Delta T = \frac{Q}{C_V}$$

$$C_V = 1944 \frac{V}{v_m} \left(\frac{T}{\Theta}\right)^3 \text{ J/K}$$

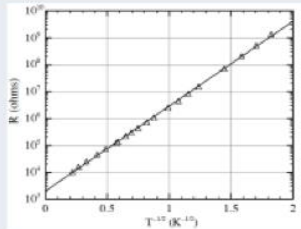


Energy resolution      <1 eV ~2eV      @ 6 keV  
 ~10 eV ~keV      @ 2 MeV

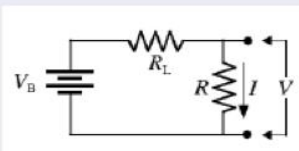


5\*1989\*1

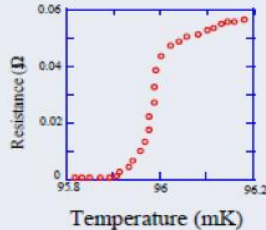
## Doped Semiconductors



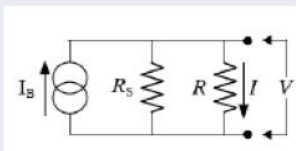
- $\alpha$  negative;  $|\alpha| < 10$
- Resistance large
- Current bias and read voltage



## Superconducting transition-edge

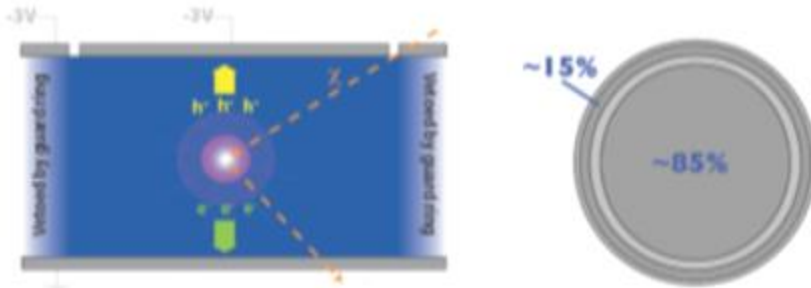


- $\alpha$  positive;  $10 < \alpha < 1000$
- Resistance small
- Voltage bias and read current



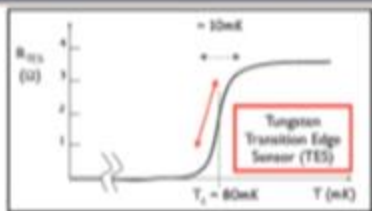
# Double read-out bolometric technique (ionization vs heat)

## ZIP Detectors: Charge



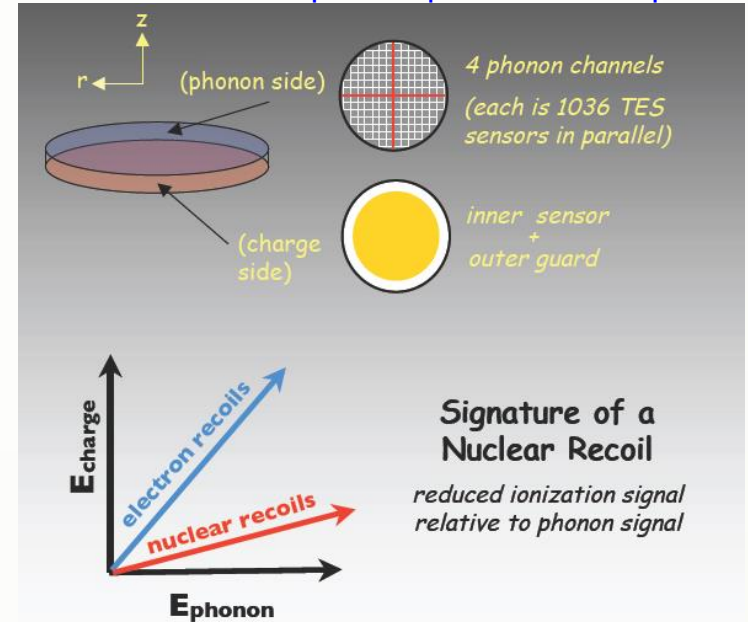
Inner Channel: ionization measurement  
Outer Channel: fiducial volume

## ZIP Detectors: Phonons

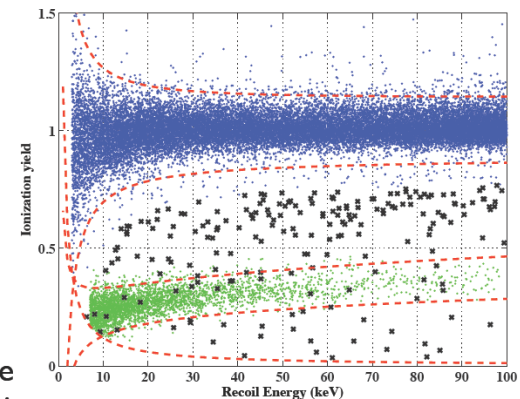


4 SQUID readout channels, each reads out 1036 TESs in parallel

## CDMS: detection principle and response



- Most backgrounds ( $e, \gamma$ ) produce electron recoils
- WIMPs and neutrons produce nuclear recoils.
- Ionization yield (ionization energy per unit phonon energy) strongly depends on particle type.



- Particles that interact in the “surface dead layer” result in reduced ionization yield.

# Double read-out bolometric technique (ion. vs heat)

- CDMS-Ge: Soudan, 3.22 kg Ge, 194.1 kg x day;  $E_{th}=10$  keV + other attempts at lower  $E_{th}$
- SuperCDMS: Soudan, 9 kg Ge, 577 kg x day
- Edelweiss: LSM, 3.85 kg Ge, 384 kg x day;  $E_{th}=20$  keV + search for low-mass WIMPs, ;  $E_{th}\sim 1$  keVee
- CDMS-Si: 1.2 kg Si, 140.2 kg x day;  $E_{th}=7$  keV

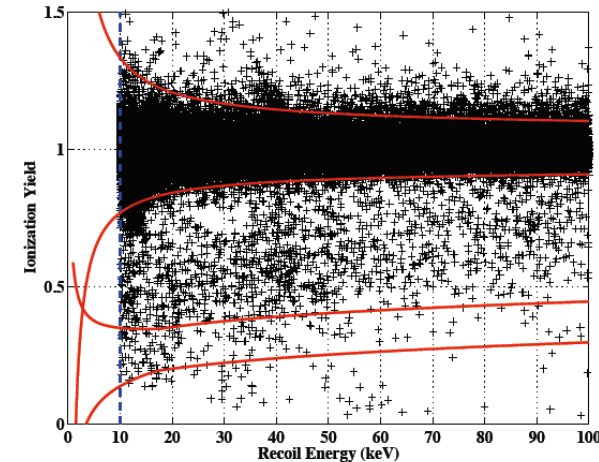
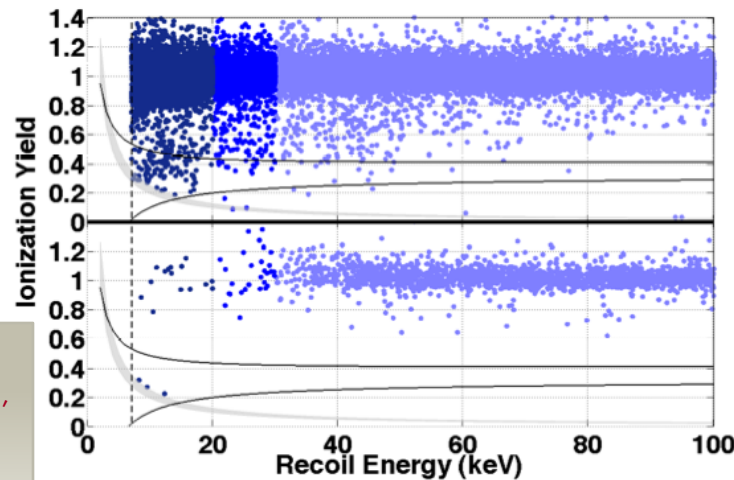


Thermal sensors:

- superconductor thermistors (highly doped SC): NTD Ge → **EDELWEISS**
- superconducting transition sensors: TES → **CDMS, CRESST**

Towards low energy thresholds → **CDMSlite**: no charge collection, HV enhancement of the phonon signal (Neganov-Luke effect)

- **Many cuts on the data**: how about systematics?
- The **systematics** can be variable along the data taking period;
- **Poor detector performances**: many detectors excluded in the analysis
- **Critical stability of the performances**
- **Non-uniform** response of detector: intrinsic limit
- **Surface electrons**: PSD needed with related uncertainty



Anyhow, after many cuts few (two in CDMS-Ge, eleven in SuperCDMS, five in Edelweiss and three in CDMS-Si) events survive: positive hints or intrinsic limit reached?

# Double read-out bolometric technique (scintillation vs heat)

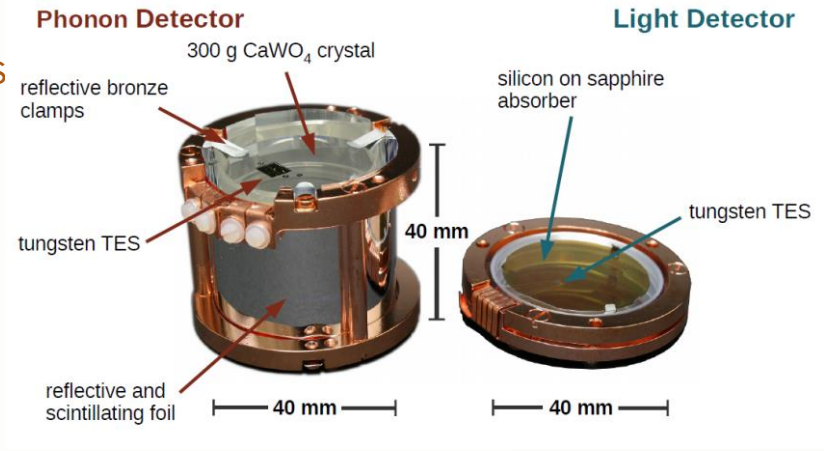
Experimental site: Gran Sasso (LNGS)

Detector: 33  $\text{CaWO}_4$  crystals (10 kg mass data from 8 detectors)

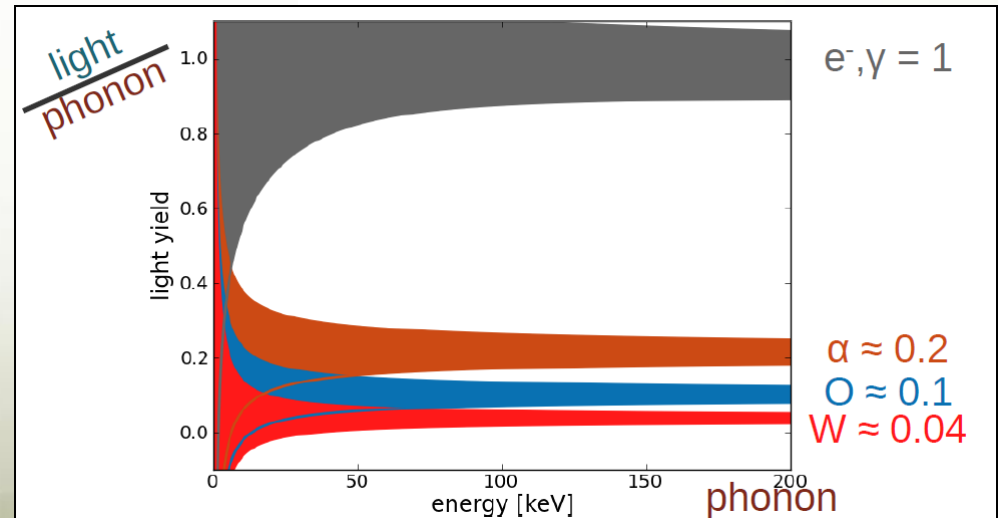
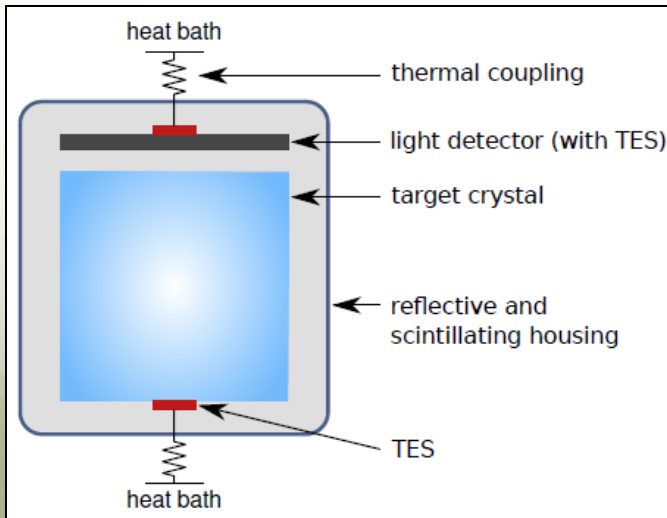
Exposure:  $\approx 730 \text{ kg} \times \text{day}$

Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light:

- Phonon:  $\text{CaWO}_4$  crystals read out with TES
- Light: recorded by separate light detector also read out with TES

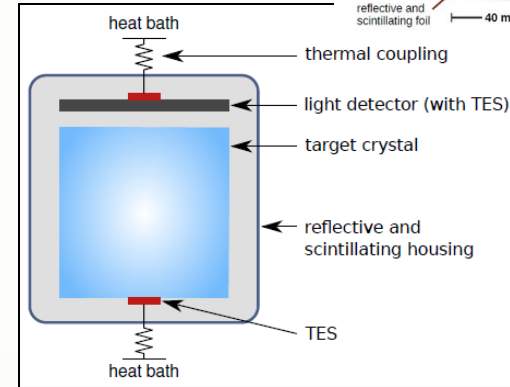
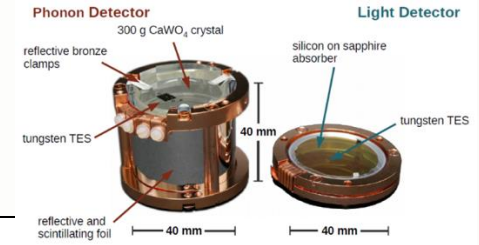


$$\text{Light Yield} = \frac{E_{\text{Light}}}{E_{\text{Phonon}}}$$

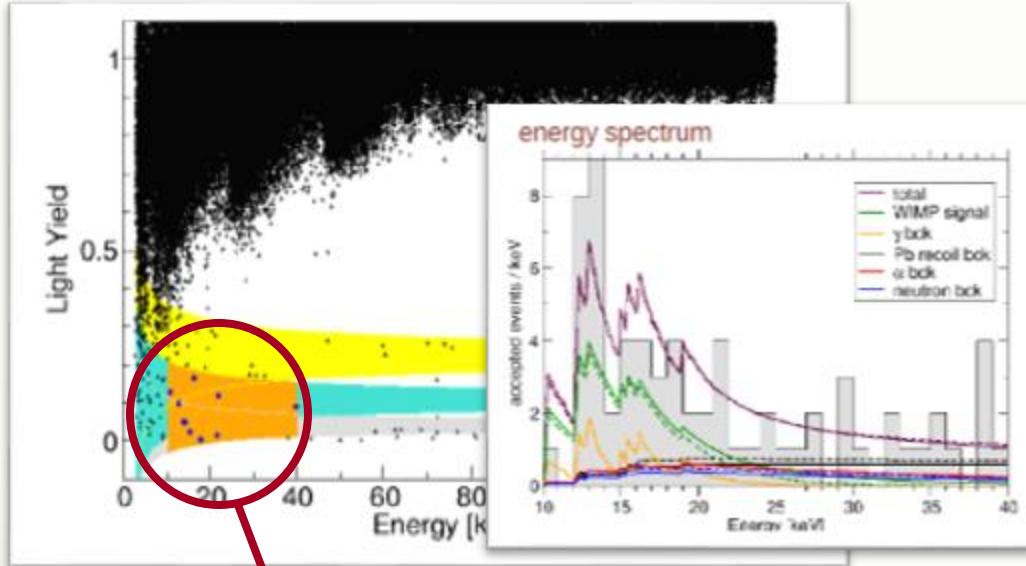


# Double read-out bolometric technique (scintillation vs heat)

CRESST at LNGS: 33  $\text{CaWO}_4$  crystals (10 kg mass)  
 data from 8 detectors. Exposure:  $\approx 730 \text{ kg} \times \text{day}$   
 Data from one detector

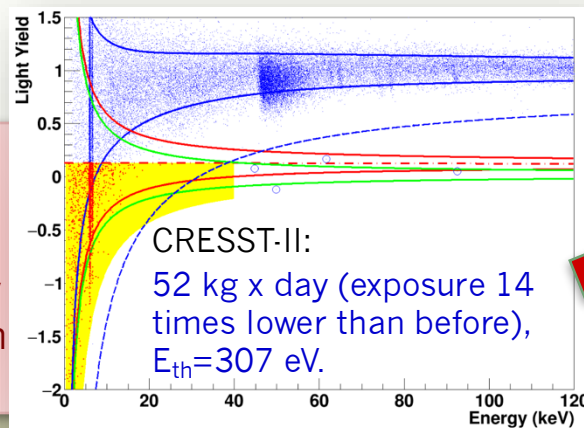


**Efficiencies + stability + calibration, crucial role**

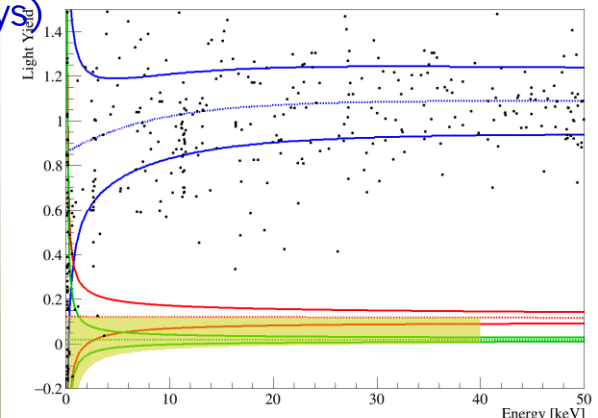


67 total events observed in O-band

Systematics in previous runs (?):  
 Following run with lower exposure and lower energy threshold does not confirm this  $3.5\sigma$  excess!!!



CRESST-III (new detector modules, 24 g each, 100 eV thr, 2.39 kg days)

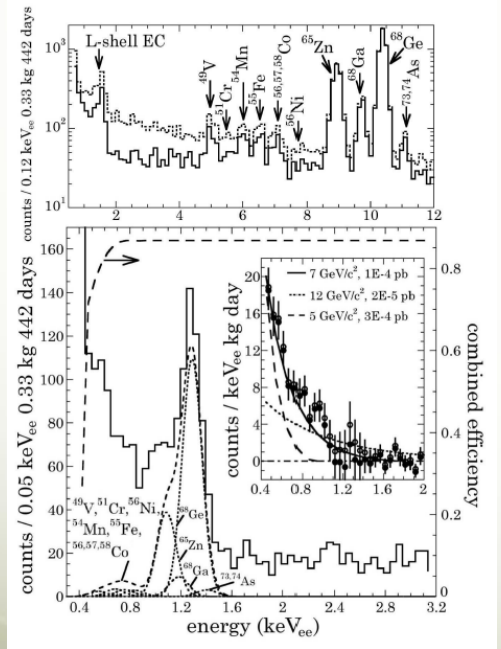


# Positive hints from CoGeNT (ionization detector)

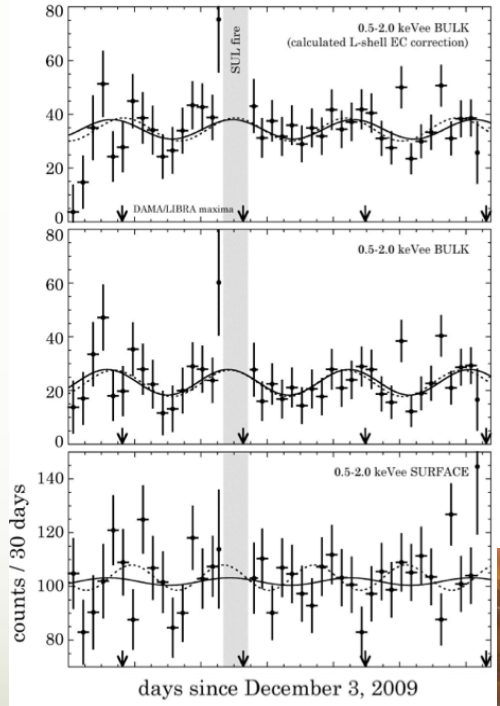
Experimental site: Soudan Underground Lab (2100 mwe)  
 Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold  
 Exposure: 146 kg x day (dec '09 - mar '11)



✓ Irreducible excess of bulk-like events below 3 keVee observed;



✓ annual modulation of the rate in 0.5-4.5 keVee at  $\sim 2.2\sigma$  C.L.

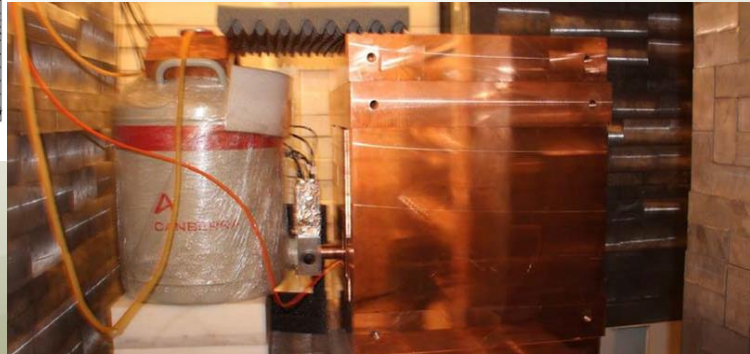


format. A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation ( $\sim 90\%$  SA for  $\sim 90\%$  BR)

Unoptimized frequentist analysis yields  $\sim 2.2\sigma$  preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...

Other Ge activity:  
 Texono, CDEX @ CJPL

- CoGeNT upgrade: C-4
- C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab



# Nal(Tl) scintillating detectors

These experiments were motivated to reproduce the more-than-20-years DAMA results with its ULB Nal(Tl). They are at well different R&D stages. Intrinsically not enough sensitivity

**ANAIS-112:** 3x3 matrix of Nal(Tl) scintillators 12.5 kg each to study DM annual modulation at Canfranc (LSC); 1.5 yr of data taking released (exposure: 157.55 kg x yr)

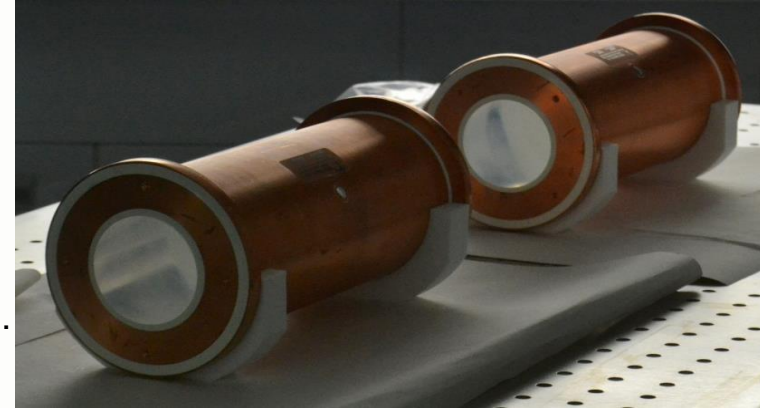
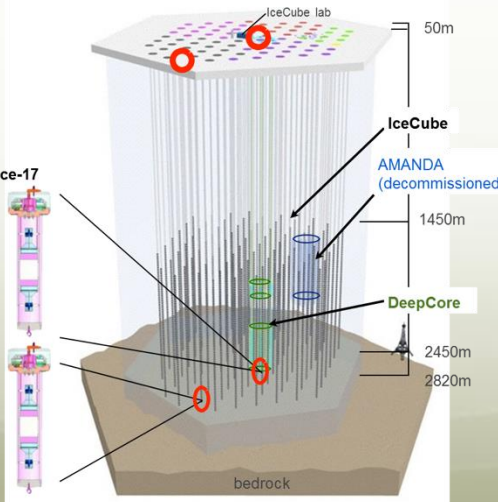


**KIMS:** CsI(Tl) crystals since 2000 at Yangyang (Y2L), Korea. Afterwards, KIMS-Nal joining Cosine

**COSINE-100:**  $\approx 100$  kg Nal in Y2L, released 1.7 years collected with five of the eight crystals ( $\square 60$  kg)  $\Rightarrow 97.7$  kg x yr.

**DM-ICE:** Nal(Tl) deployed at the South Pole; exposure: 60.8 kg x yr

**SABRE:** two sites: LNGS in Northern and SUPL in Southern hemisphere (but the effect does not depend on hemisphere); PoP (5 kg) ready to start



Warning: PSD with CsI(Tl), Nal(Tl), ... sometimes overestimated sensitivity; claimed high rejection power, but existing systematics drastically limit the reachable sensitivity.

Key points: not only residual contaminants but also long-term/high-level stability, etc.

**COSINUS:** cryogenic calorimeters with pure Nal; dual readout; R&D phase 50 g to 300 g but scintillation different from standard temperature and doped conditions.

+ **picoLON**

**DAMA/LIBRA-phase3:** R&D under completion

Even very small **systematics** in the data selections and statistical discrimination and rejection procedures can be difficult to estimate;

**e.m. component** of the rate can contain the signal or part of it

Even assuming pure recoil case and ideal discrimination on an event-by-event base, the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well **known existing recoil-like indistinguishable background**

Therefore, even in the ideal case the “excellent suppression of the e.m. component of the counting rate” can **not** provide a “signal identification”

## A model independent signature is needed

**Directionality** Correlation of Dark Matter impinging direction with Earth's galactic motion due to the distribution of Dark Matter particles velocities

very hard to realize



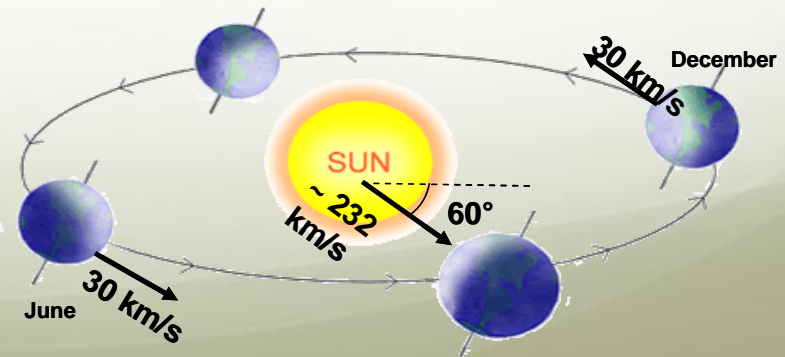
**Diurnal modulation** Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

only for high  $\sigma$



**Annual modulation** Annual variation of the interaction rate due to Earth motion around the Sun

at present the only feasible one, sensitive to many DM candidates and scenarios



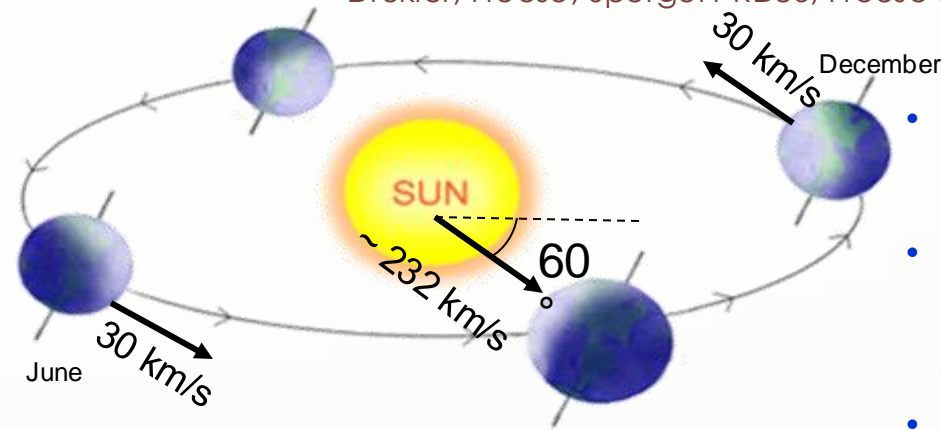
# The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Drukier, Freese, Spergel PRD86; Freese et al. PRD88

## Requirements of the annual modulation

- 1) Modulated rate according cosine
- 2) In a definite low energy range
- 3) With a proper period (1 year)
- 4) With proper phase (about 2 June)
- 5) Just for single hit events in a multi-detector set-up
- 6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios



- $v_{\text{sun}} \sim 232 \text{ km/s}$  (Sun vel in the halo)
- $v_{\text{orb}} = 30 \text{ km/s}$  (Earth vel around the Sun)
- $\gamma = \pi/3$ ,  $\omega = 2\pi/T$ ,  $T = 1 \text{ year}$
- $t_0 = 2^{\text{nd}} \text{ June}$  (when  $v_{\oplus}$  is maximum)

$$v_{\oplus}(t) = v_{\text{sun}} + v_{\text{orb}} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

# A toy model on the velocity distribution

$$I(E_R) = \int_{v_{\min}(E_R)}^{\infty} \frac{f(v)}{v} dv$$

The simplest velocity distribution for the galactic halo is given by the iso-thermal sphere where  $\mathbf{f}(\mathbf{v})$  is a **Maxwellian** distribution

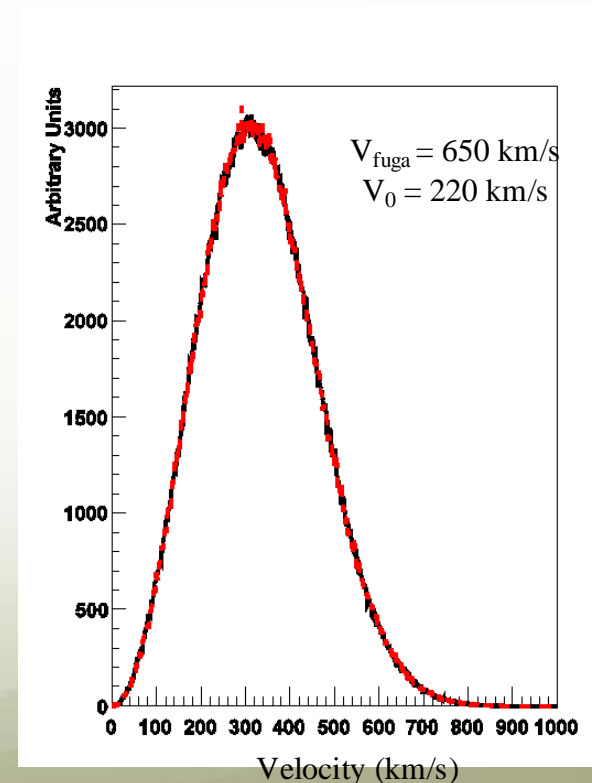
$$f(v)dv = \int_{\Omega} g(\vec{v}) d^3v \quad \rightarrow \quad g(\vec{w}) = \frac{1}{\pi^{3/2} v_0^3} e^{-\frac{w^2}{v_0^2}} \quad (\vec{w} = \vec{v} + \vec{v}_E)$$

$$f(v) = \frac{2v^2}{\sqrt{\pi}v_0^3} e^{-\frac{v^2+v_E^2}{v_0^2}} \int_{-1}^1 e^{-\frac{2vv_E \cos\vartheta}{v_0^2}} d\cos\vartheta =$$

$$= \frac{v}{\sqrt{\pi}v_0 v_E} e^{-\frac{v^2+v_E^2}{v_0^2}} \left( e^{\frac{2vv_E}{v_0^2}} - e^{-\frac{2vv_E}{v_0^2}} \right)$$

$$= \frac{v}{\sqrt{\pi}v_0 v_E} \left( e^{-\frac{(v-v_E)^2}{v_0^2}} - e^{-\frac{(v+v_E)^2}{v_0^2}} \right)$$

**BUT:**  $v_E$  is dependent on time (then, annual modulation of the signal)



The relative Earth speed along the galactic plane is given by:

$$v_E(t) \approx v_{\odot} + v_{\oplus} \cos \gamma \cos[\omega(t - t_0)]$$

Where:

- $v_{\odot} \sim 232$  km/s (Sun velocity in the halo)
- $v_{\oplus} = 30$  km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$ ,  $\omega = 2\pi/T$ ,  $T = 1$  year and  $t_0 = 2^{\text{nd}}$  June (when  $v_{\oplus}$  is maximum)

We define:

$$\eta(t) = \frac{v_E(t)}{v_0} = \eta_0 + \Delta\eta \cos[\omega(t - t_0)]$$

Here  $\Delta\eta \ll \eta_0$ .

We can write  $R$  as a function of  $\eta$  and use Taylor expansion:

$$\frac{dR}{dE} \cong \left[ \frac{dR}{dE} \right]_{\eta_0} + \frac{\partial}{\partial \eta} \left[ \frac{dR}{dE} \right]_{\eta_0} \Delta\eta \cos[\omega(t - t_0)]$$

Expected signal:

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t - t_0)]$$

where (energy bin  $\Delta E_k$ ):

$$\left\{ \begin{array}{l} S_{0,k} = \frac{1}{\Delta E_k} \int_{\Delta E_k} \left[ \frac{dR}{dE} \right]_{\eta_0} dE \\ S_{m,k} = \frac{1}{\Delta E_k} \int_{\Delta E_k} \frac{\partial}{\partial \eta} \left[ \frac{dR}{dE} \right]_{\eta_0} \Delta \eta dE \end{array} \right.$$

In real experiment:

Several experimental parameters to be accounted for, such as energy resolution, q.f. in case DM candidates inducing just recoiling nuclei, etc.

# DAMA set-ups

an observatory for rare processes @ LNGS



- DAMA/LIBRA (DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

*see the next lecture*

## Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev

+ neutron meas.: ENEA

+ in some studies on  $\beta\beta$  decays (DST-MAE and Inter-Universities project):

IIT Kharagpur and Ropar, India