TECHNISCHE UNIVERSITÄT DRESDEN

Neutrino detectors

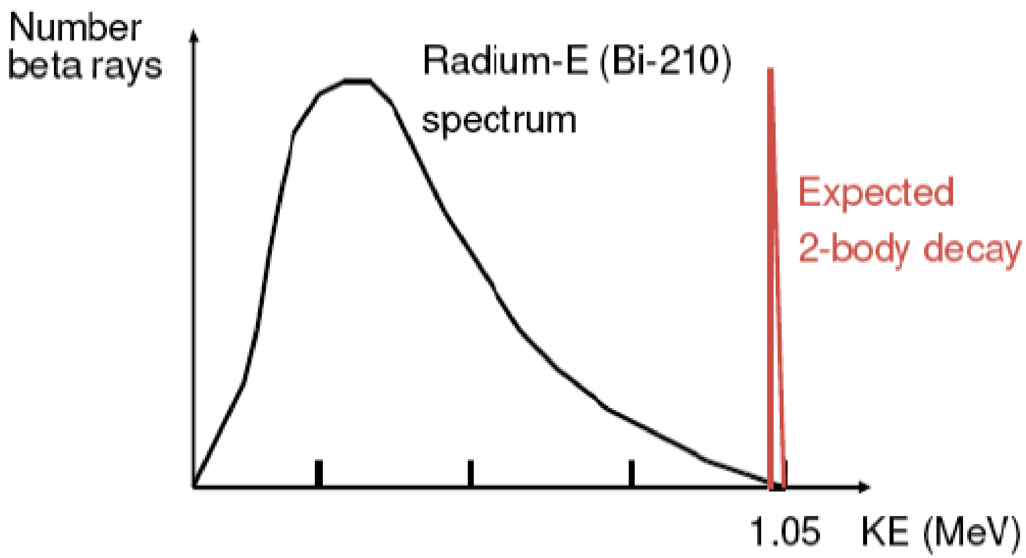
V. Lozza, 5.10.2011

Outline

- Introduction to neutrinos
- Sources of neutrinos
- Detection techniques
- Why we need to go underground?
- Background components
- What to do?
- Summary

A brief of history

1914: Discovery of a continuous energy spectrum for beta decay



The nucleous was thought to be of A protons + (A-Z) electrons

The beta decay was expected to be a two body decay with monoenergetic electron, has was observed for alphas and gammas

A brief of history

Various (wrong) explanations were given:

- L. Meitner: beta undergoes secondary interactionin nucleus, losing energy that goes into additional gamma rays → calorimetric experiments that measured the average energy in the decay (mean energy of beta spectrum)
- N. Bohr: energy is not conserved in beta-decay

Further problems: spin of nuclei (3Li6 and 7N14) measured to be integer

– 3Li6 : 6 protons+3 electrons= 9 fermions

– 7N14: 14 protons + 7 electrons = 21 fermions

A brief of history

4th December 1930: Birth of neutrino idea (Pauli)

Solution?!

4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

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A brief of history

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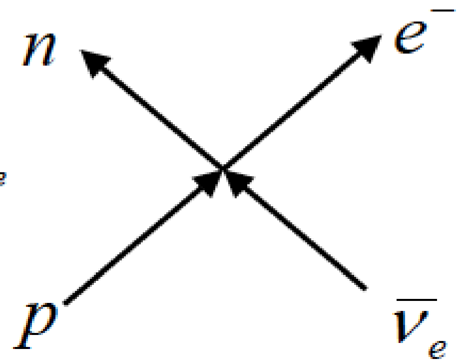
1932: Fermi theory of beta decay

$$n \rightarrow p + e^- + \nu_e$$



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

1953-1959: First reactor antineutrino detection (Reines and Cowan)

1956: Parity violation in Co beta decay → electron is left ended (Wu et al.)

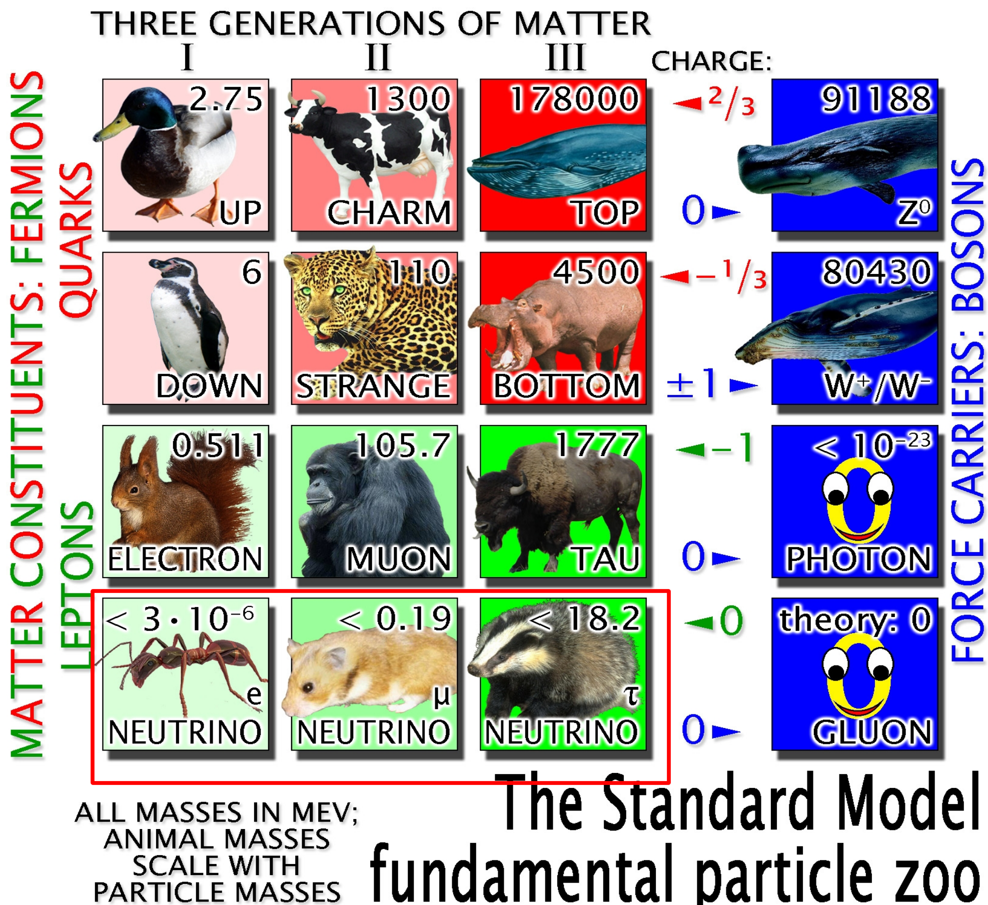
1957: Neutrino have negative helicity (M. Goldhaber)

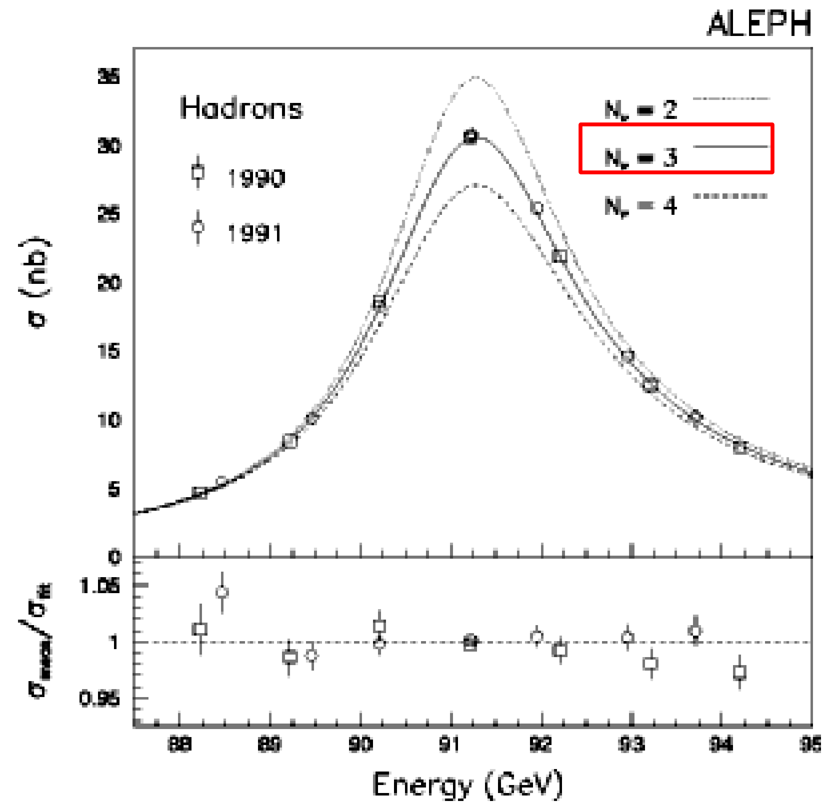
1960: There is more than one type of neutrino (Lee and Yang)

1962: Discovery of muon neutrino (Schartz, Lederman, Stainberger)

Standard Model

1989: LEP → Number of neutrinos

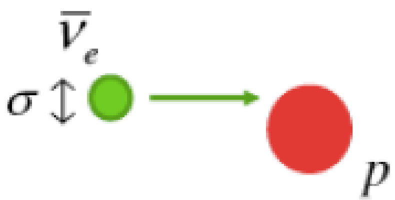




in 2001: N_ν = 2.984 ±0.008

Neutrino cross section

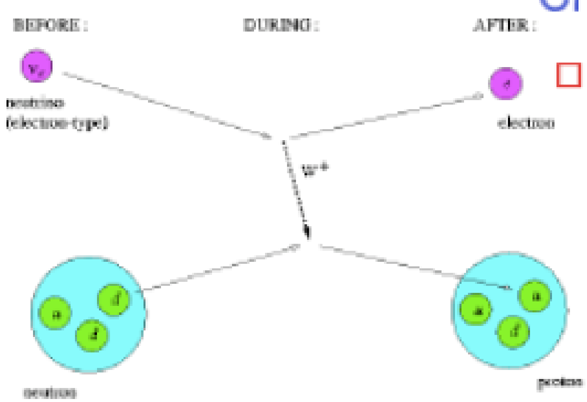
- Bethe-Peierls (1934): calculation of first cross-section for inverse beta reaction $\bar{\nu}_e + p \rightarrow n + e^+$ or $\nu_e + n \rightarrow p + e^-$ using Fermi theory



$$\sigma \approx 10^{-44}\ cm^2 \quad \text{for} \quad E(\bar{\nu}) = 2\ MeV$$

Conversion from natural units: $\hbar c = 197.3\ MeV \cdot fm$

Cross-section: multiply by $(\hbar c)^2 = 0.3894 \times 10^{-27}\ GeV^2 \cdot cm^2$



- Mean free path of antineutrino in water:

$$\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21}\ cm \approx 1600 \quad light-years$$

$$n = \frac{\text{num. free protons}}{\text{volume}} \approx 2 \frac{N_A}{A} \rho$$

In water: $n = \dfrac{2 \times 6 \times 10^{23}}{18} = 6.7 \times 10^{22}\ cm^{-3}$

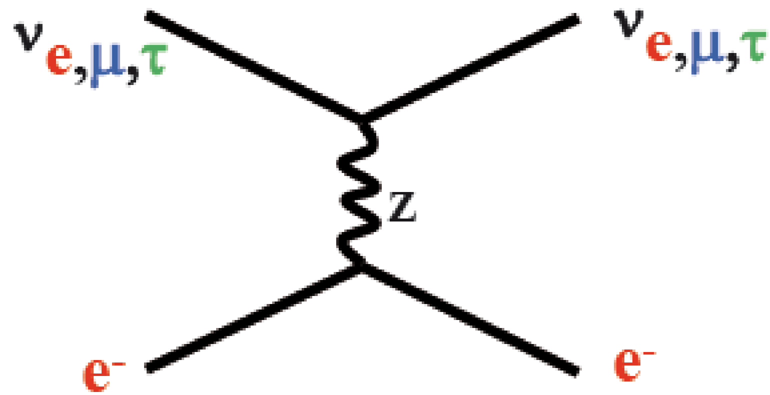
- Probability of interaction:

$$P = 1 - \exp\left(-\frac{L}{\lambda}\right) \approx \frac{L}{\lambda} = 6.7 \times 10^{-20}\ (m\ water)^{-1}$$

Need very intense source of antineutrinos to detect inverse beta reaction.

Neutral/Charge current interaction

At all energy, NC are possible for all neutrinos



CC reactions

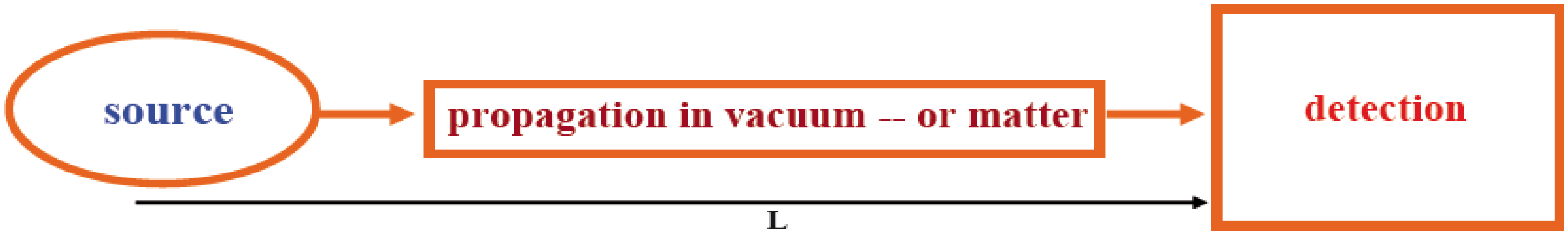
- At low energies (E < 50 MeV) → inverse beta decay
- For 50 < E < 700 MeV → quasi elastic reaction on p or n
- Above → deep inelastic reactions

Threshold for muon reaction is 110 MeV

Threshold for tau recation is 3.5 GeV

Neutrino oscillation

There is a probability that a neutrino created as one flavor being detected as another flavor after travelling a distance L



weak interaction produces 'flavour' neutrinos

e.g. pion decay $\pi \to \mu\nu_\mu$

$|\nu_\mu\rangle = \alpha\, |\nu_1\rangle + \beta\, |\nu_2\rangle + \gamma\, |\nu_3\rangle$

α is noted $U_{1\mu}$

β is noted $U_{2\mu}$

γ is noted $U_{3\mu}$ etc....

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha\, |\nu_1\rangle\ \exp(i\,E_1\,t) + \beta\, |\nu_2\rangle\ \exp(i\,E_2\,t) + \gamma\, |\nu_3\rangle\ \exp(i\,E_3\,t)$$

t = proper time $\propto$ L/E

detection and identification by weak interaction: (CC)

$\nu_\mu\ N \to \mu^-\ X$

or $\nu_e\ N \to e^-\ X$

or $\nu_\tau\ N \to \tau^-\ X$

$$P(\mu \to e) = |\langle \nu_e | \nu(t)\rangle|^2$$

Neutrino oscillation

There is a probability that a neutrino created as one flavor being detected as another flavor after travelling a distance L

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Δm^2 in eV^2

L in km

E in GeV

Solar neutrino problem

The Infamous "Neutrino-burglar"

Neutrino sources

Typical: Neutrino Physics, Dark Matter searches, Rare decays

Dark matter 0-20 keV

Double beta decay: 0-5 MeV

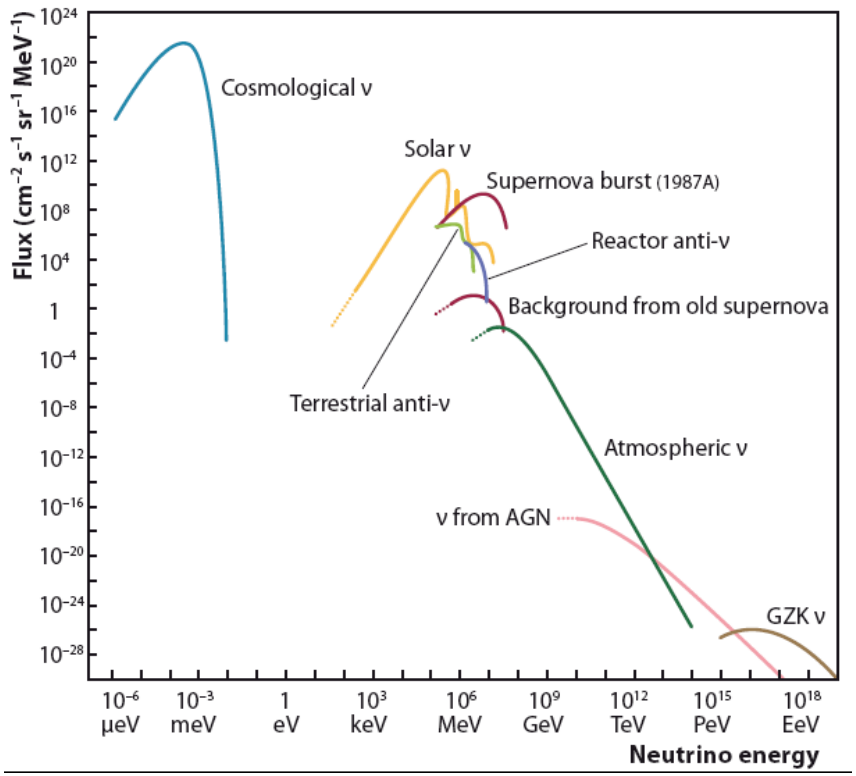
Reactor neutrinos: 0-8 MeV

Solar neutrinos: 0-18 MeV

Supernova neutrinos: 5-30 MeV

Proton decay: 100 – 940 MeV

Atmospheric neutrinos: MeV- GeV



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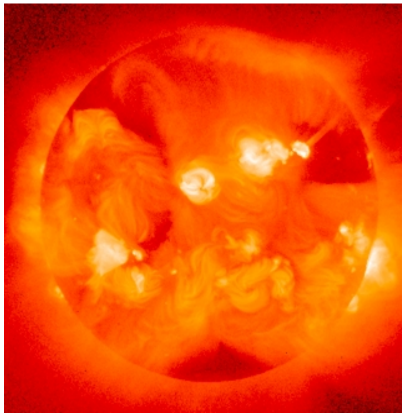
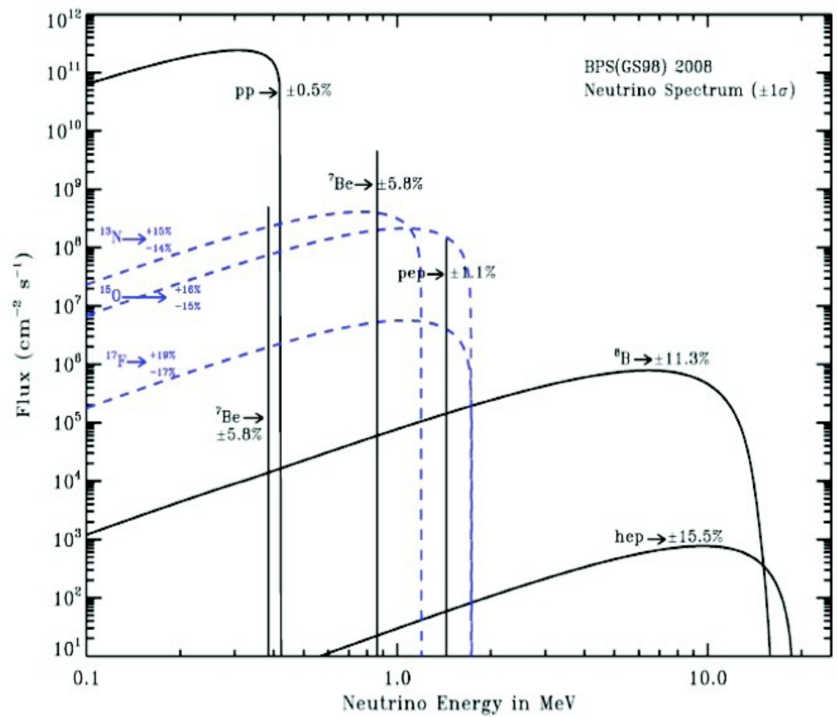
Solar neutrinos





☑ Super-K and SNO measured ^{8}B

☑ Borexino measured ^{7}Be

☑ Subtracting ^{8}B and ^{7}Be, pp comes from Ga experiments

Still missing pep and CNO!

$$Flux\ of\ neutrinos = \frac{N_\nu}{4\pi R^2} = \frac{2\times 9.1\times 10^{37}}{4\pi\times(1.5\times 10^{13})^2} = 6.4\times 10^{10}\ \nu_e\ s^{-1} cm^{-2}$$

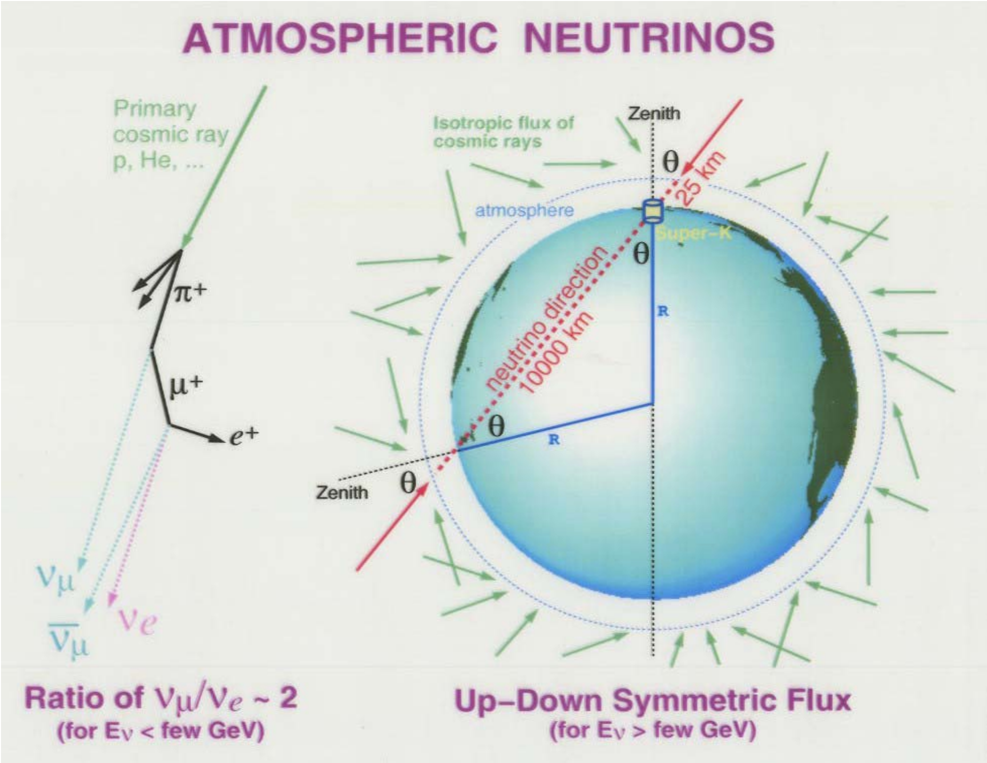
(64 billion neutrinos per second through your finger nail of 1 cm² !!!!)

1 SNU = 1 event per second per 10^{36} target atoms

Atmospheric neutrinos

Atmospheric neutrinos: neutrino production from cosmic rays in atmosphere

Protons hit upper part of atmosphere producing cascade of particles including pions that decay (on average) into 2 muon neutrinos for each electron neutrino produced in an interaction



Example.
12 candidates for 70 days of data taking

Reactor neutrinos

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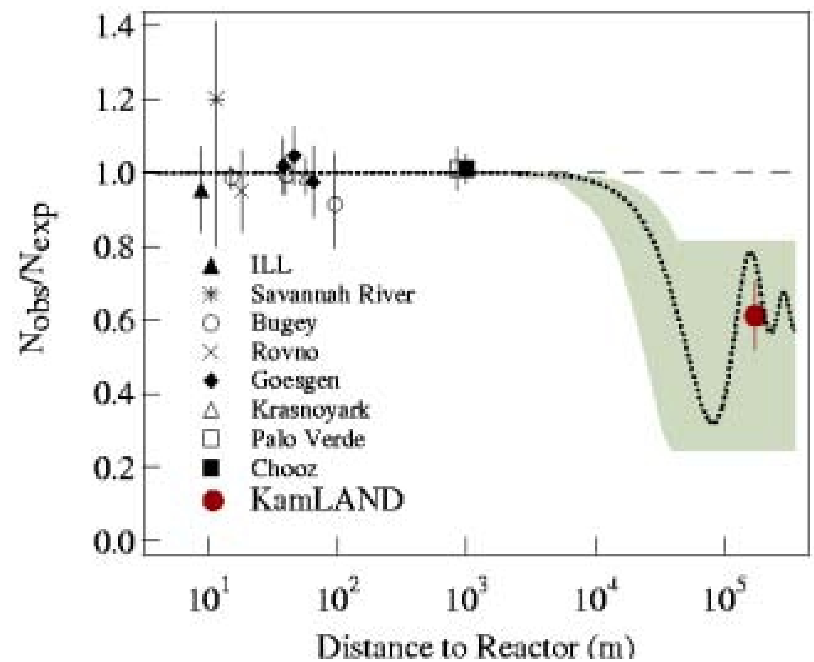
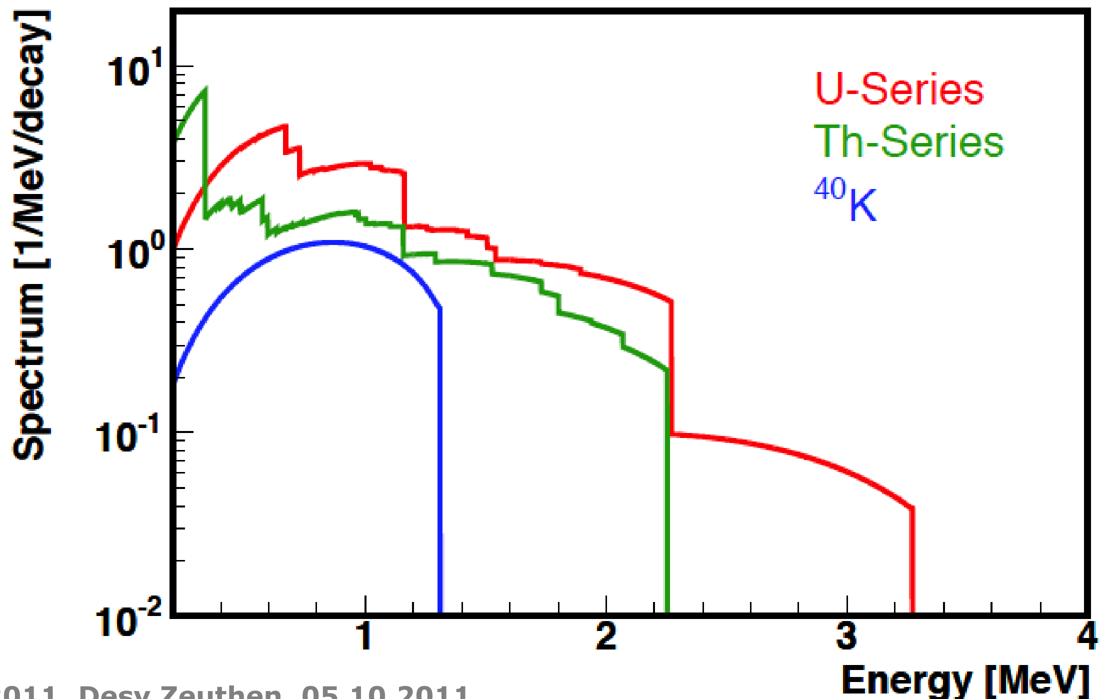
Verify neutrino oscillation model



The total flux is about 2x10^{20} !!e/sec/GW in the range 1.8-7.8 MeV
The estimated number of observed events is about 774 events/year for no mixing

Geo neutrinos

- beta-decays in the U, Th, K decay chains produce electron antineutrinos
- 10.72% of the cases 40K decays via electron capture giving 44 keV electron neutrino in 10.67% of the cases and 1.5 MeV electron neutrino in 0.05% of the cases
- few neutrinos events/yr expected



So, what we expect ...

So, what we expect ...

A small signal in an overwhelming background

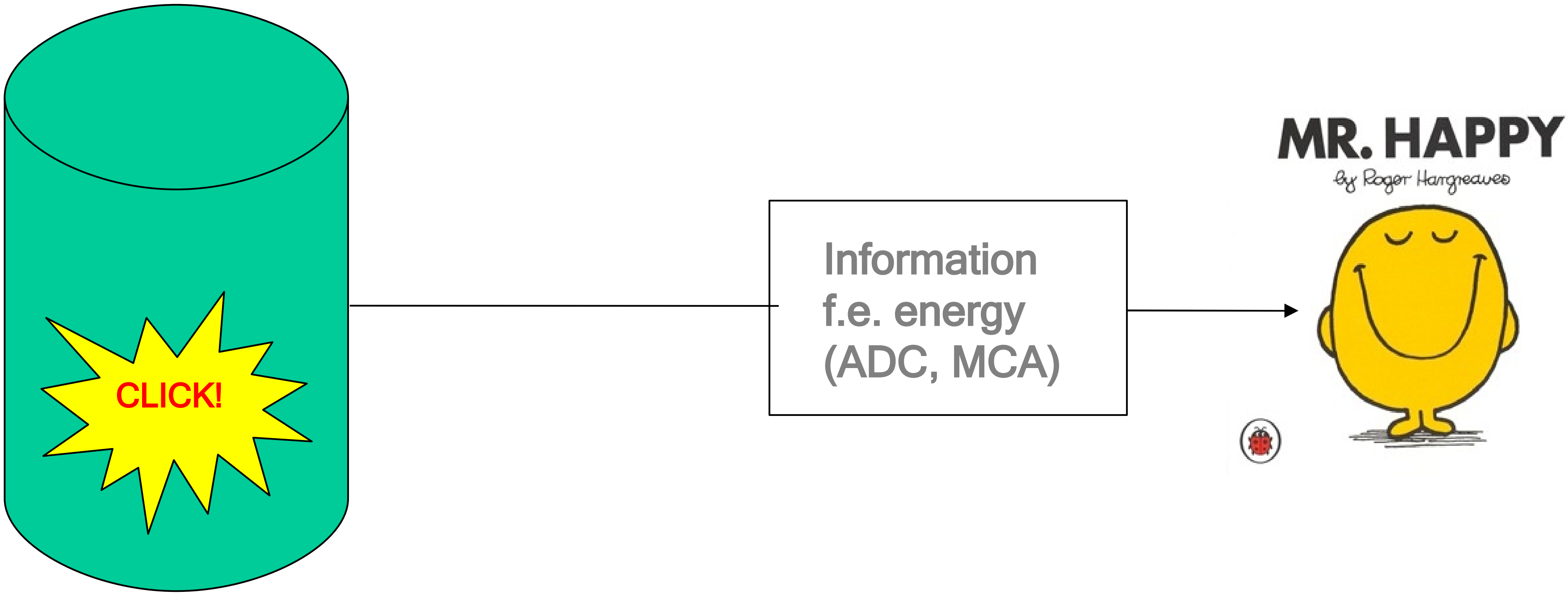
Typical experiment

It seems quite simple ...

A. Some energy deposition in a detector!

B. Processed data

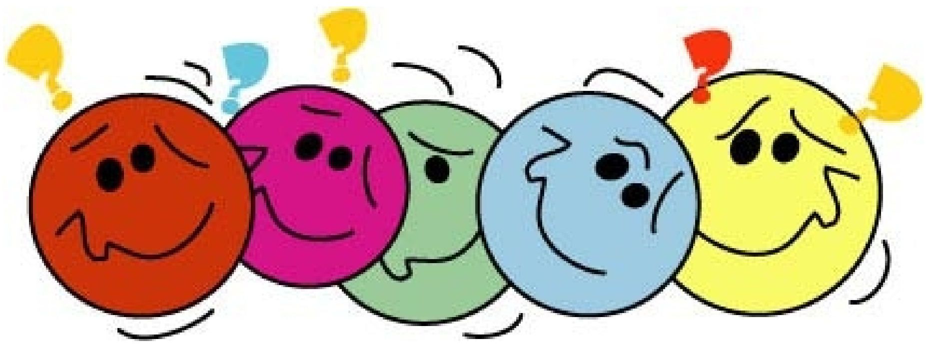
C. Results



BUT....

Typical experiment

Signal might be 1 event per tonne per year!!!

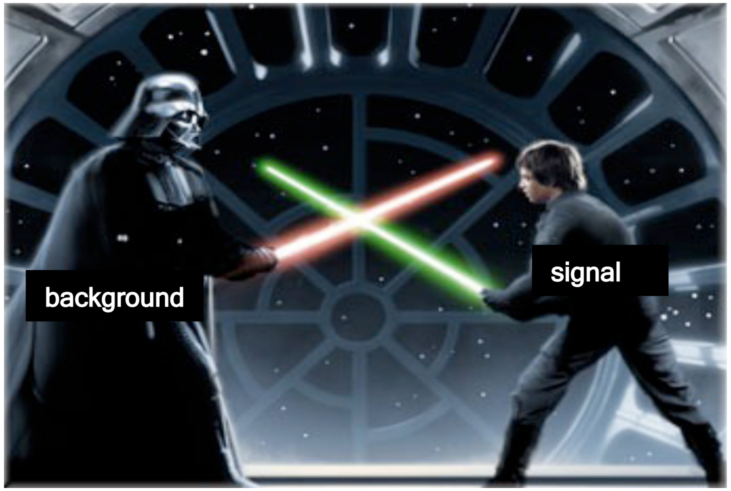


Is this signal or background?

Two options:

Measure additional information

Reduce number of background events



Neutrino detectors

Technologies

Water Cerenkov detector

Liquid Ar TPC

Liquid Scintillator detector

Sampling detectors for neutrino beams

...

Experiments

Atmospheric neutrino exp.

SuperK , HyperK/UNO , INO , TITAND,…

Solar neutrino exp.

GALLEX/SAGE, SNO/SNO+, Borexino, XMASS, …

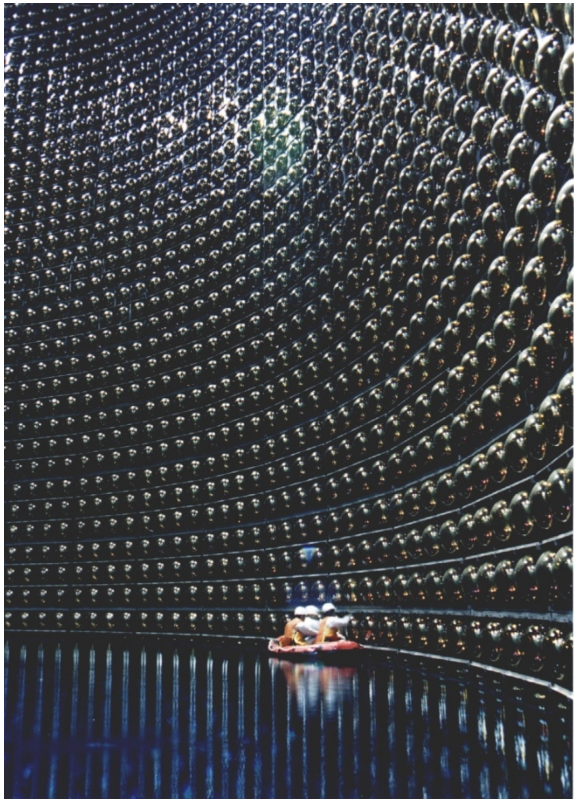
Accelerator neutrino exp.

Minos, OPERA, MiniBooNE, T2K, Nova, …

Reactor neutrino

Water Cherenkov detectors

Successful for atmospheric neutrinos, solar neutrinos, proton decays, supernova, ···



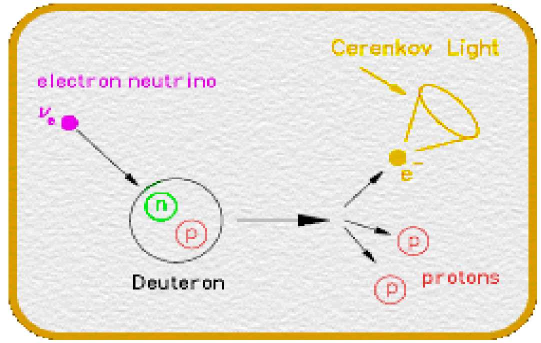
"Ring Imaging" → take advantage of the Cherenkov light produced by charge particles (direction)

Large volume of water/ice surrounded by PMTs

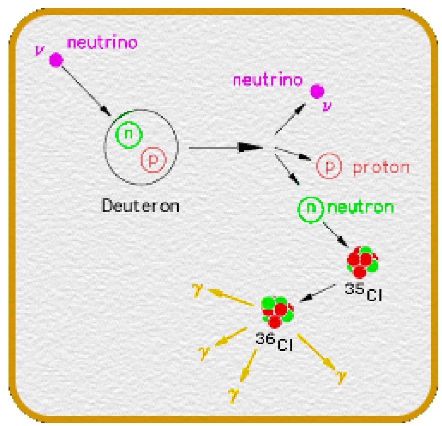
Different ring pattern for electron neutrinos and muon neutrinos.

Water Cherenkov detectors

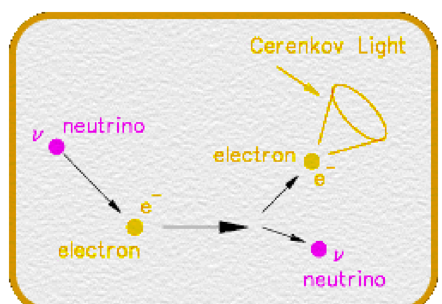
CC: *ne + d ----〉 p + p + e-*



NC: nx + d ----〉 p + n + nx



ES: e- + nx ----〉 e- + nx



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SNO = Sudbury Neutrino Observatory

1000 t of heavy water
Active medium

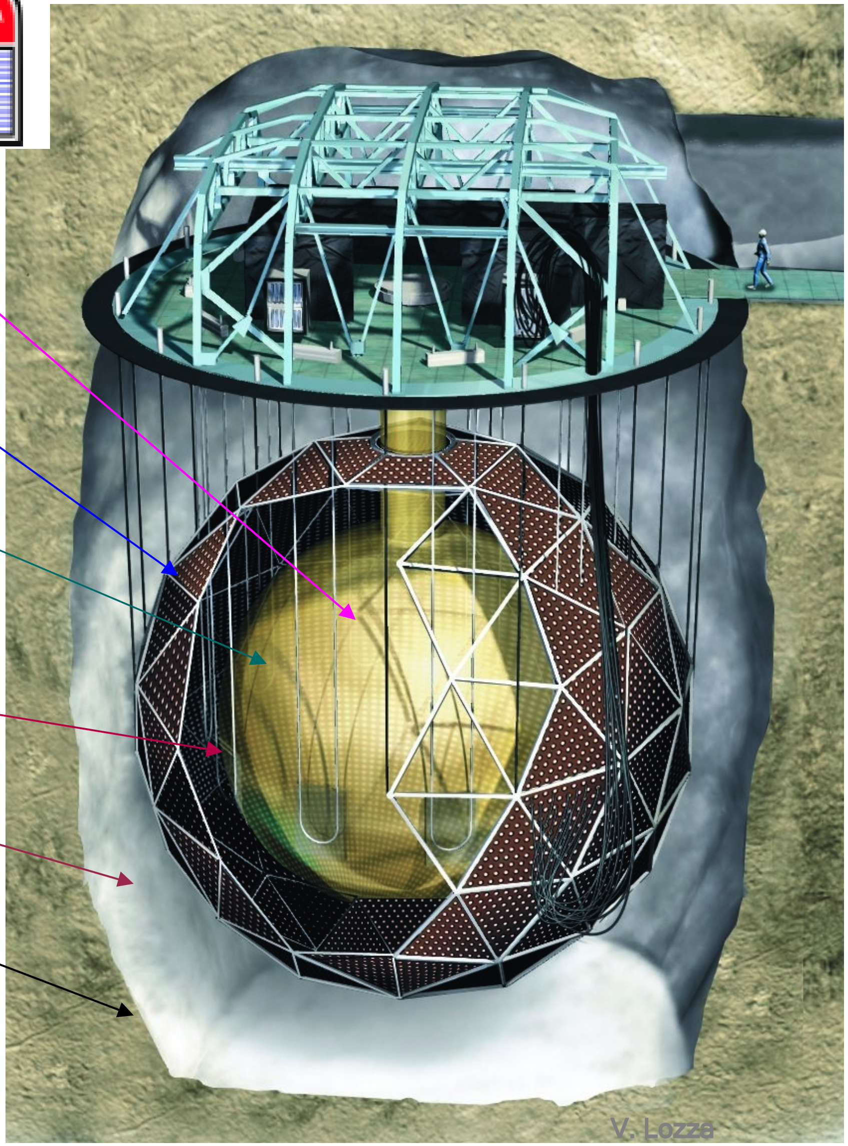
PSUP = PMT Support Structure
~9500 PMT ~ 54% coverage

Acrylic Vessel
ϕ=12 m, thickness = 5 cm

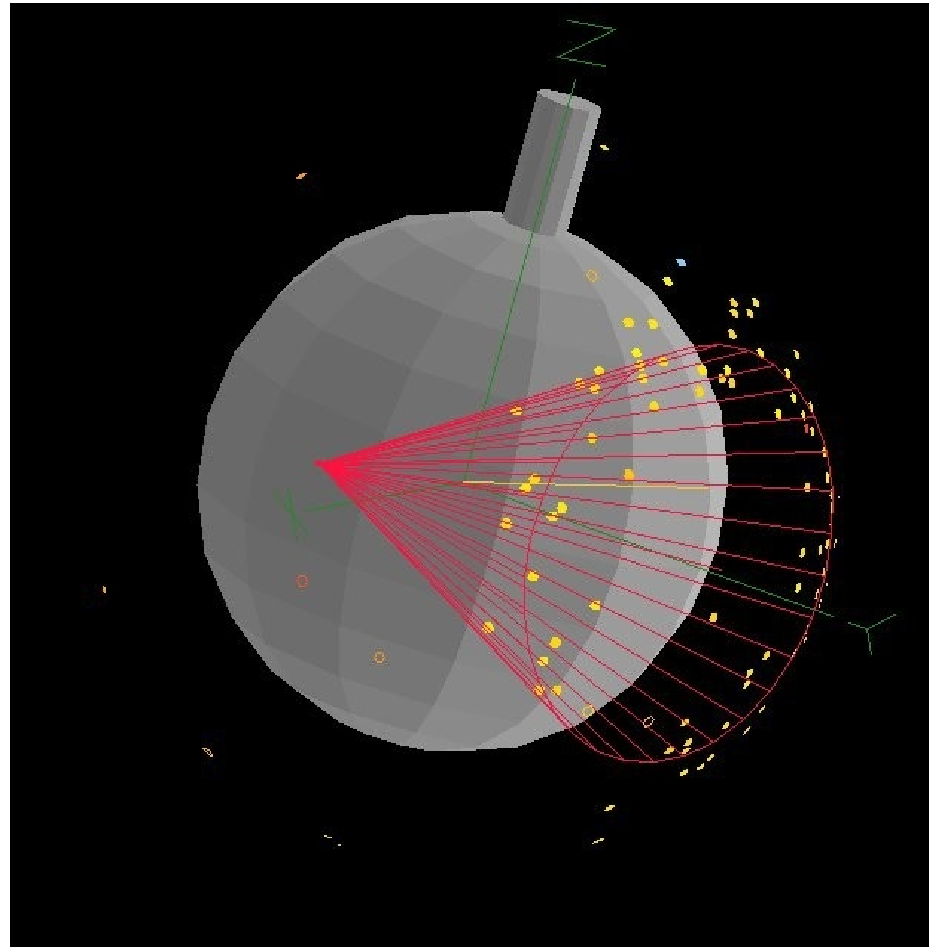
Light water (H_2O) shielding
- 1700t internal
- 5300t external

Urylon Liner and Radon Seal

Location: 2 km underground
Clean room lab → Class 2000



SNO = Sudbury Neutrino Observatory



Liquid scintillator detectors

Successful for atmospheric neutrinos, solar neutrinos, proton decays, supernova, ···

The active material is Liquid scintillator (LAB, PC) → high light yield and lower energy threshold

Detectors are sensitive to low energy solar neutrinos (pep, pp, 7Be)

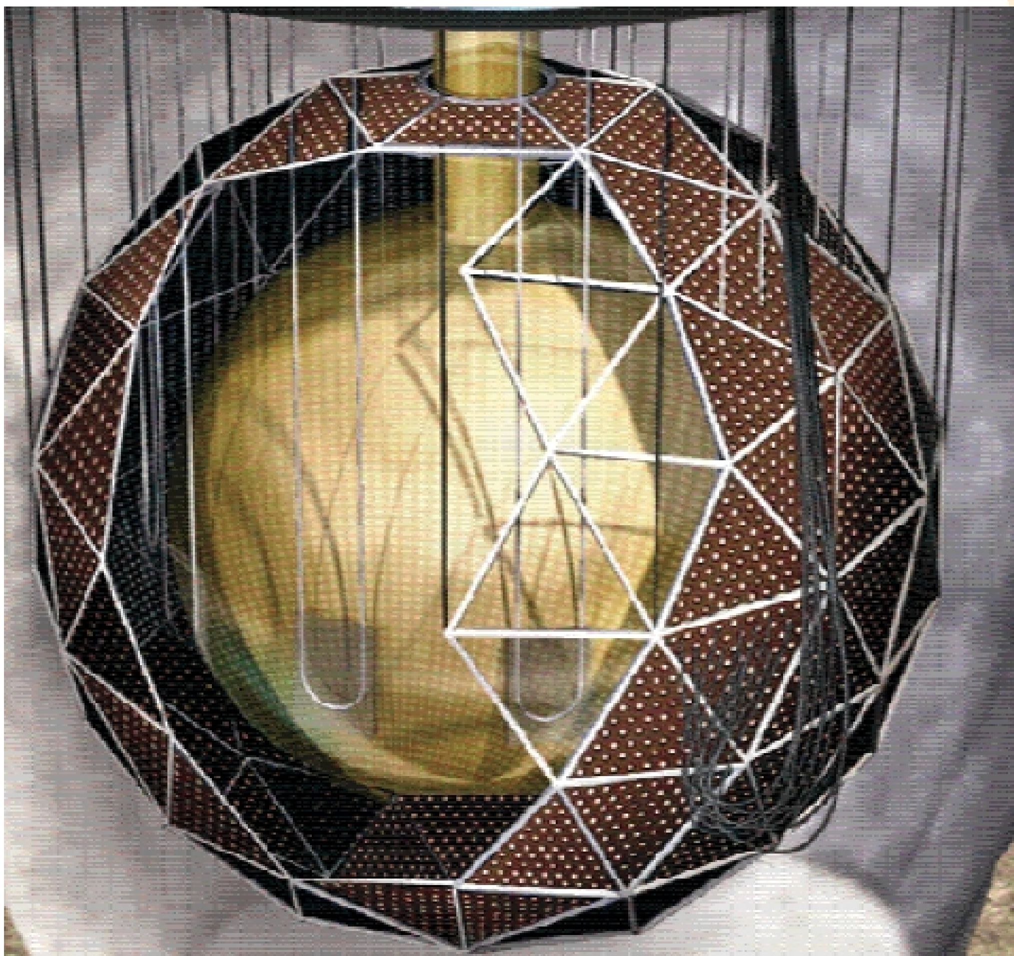
Due to the lower energy threshold, background reduction is more important than for water cherenkov detectors

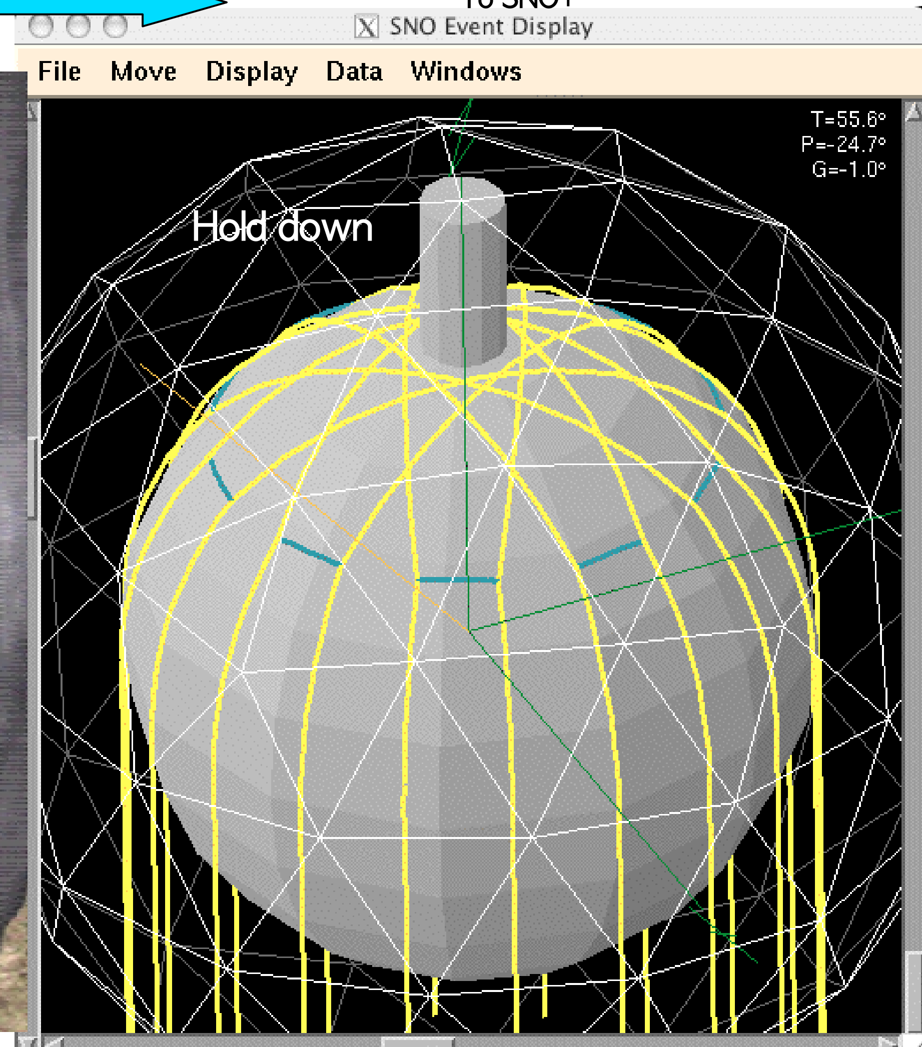
Example: SNO+

Liquid scintillator is lighter than water (ρ =0.86 g/cm^3)

From SNO → To SNO+

Hold up

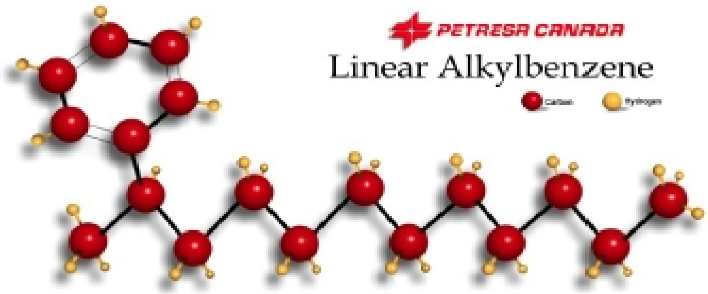




Example: SNO+

Linear alkylbenzene (LAB) identified as the liquid scintillator solvent

- Chemical compatibility with acrylic
- High light yield (50-100 times higher than D_2O)
- Good optical transparency
- Low scattering
- Fast decay, different for alphas and betas
- High purity available
- Safe
- Low toxicity
- High flash point 130° C
- Boiling point 278-314° C
- Environmentally safe
- Low solubility in water 0.041 mg/L
- Inexpensive



Petresa Plant – Bécancour, QC

V. Lozza

0ν2β with Liquid scintillator

Neutrinoless double beta decay with liquid scintillator:

- ☺ Large mass, low background
- ☹ Poor energy resolution (3.5% at Nd endpoint)

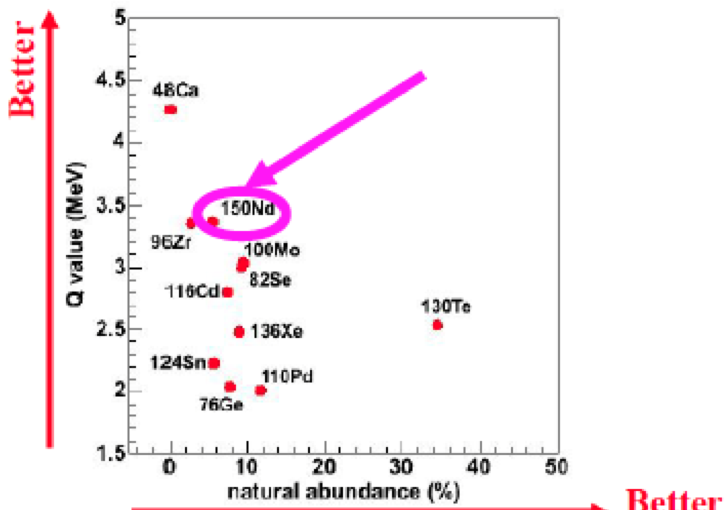
Use 150Nd :

- ☺ High Q-value (3371 keV) → low background

Successfully loaded in LAB.

0.1% loading

Optimized 0.3% under study



Decay candidate	Q value (MeV)	natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

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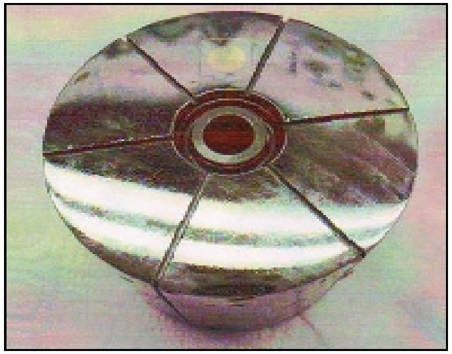
Ge-76 detectors

GERDA

iktp

Experimental Considerations: ^{76}Ge as Source

Very good energy resolution	Background due to 2νββ decay negligible
Source = Detector	High signal detection efficiency (95%)
Very high purity of detector material (zone refinement)	Very low intrinsic background
Considerable experience	Well known and reliable, improvements possible
Natural abundance of ^{76}Ge 7,44%	Enrichment necessary

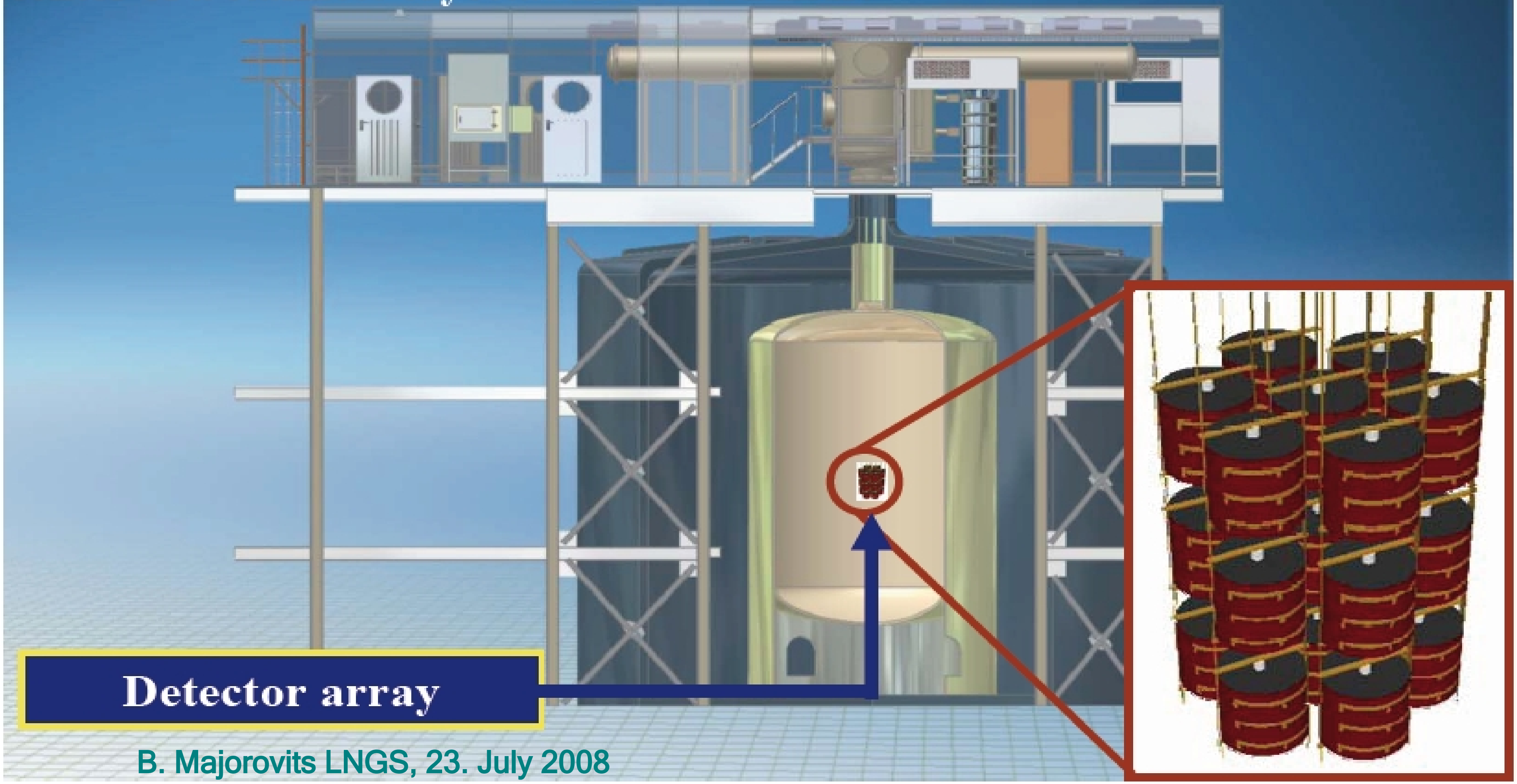


B. Majorovits LNGS, 23. July 2008

Ge-76 detectors

GERmanium Detector Array: GERDA

➢Place array of naked HPGe-detectors enriched in ^{76}Ge in the center of a stainless cryostat filled with LAr.



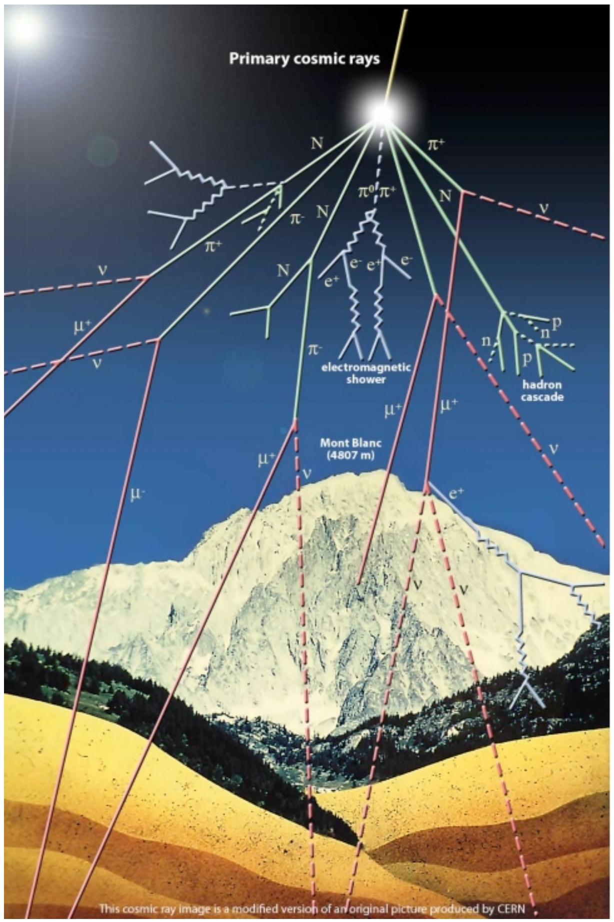
B. Majorovits LNGS, 23. July 2008

Background components

- Cosmic rays
- Atmospheric muons
- Radioisotopes produced by CR spallation (experiment specific)
- Natural Radioactivity (U,Th decay chains, ^{40}K)
- Long living radioisotopes (experiment specific)
- Neutrons
- Other experiment specific background

Cosmic Rays

For some people are a signal …



- The cosmic radiation incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer

- Primary = accelerated at astrophysical sources (e^-, α , p, t, C, O, Fe)

- Secondaries = produced in the interaction with interstellar gas (Li, Be, B)

- Low energy cosmic rays ($E < 10$ GeV) are deflected by solar and terrestrial magnetic field

- Intensity between 10 GeV – 100 TeV

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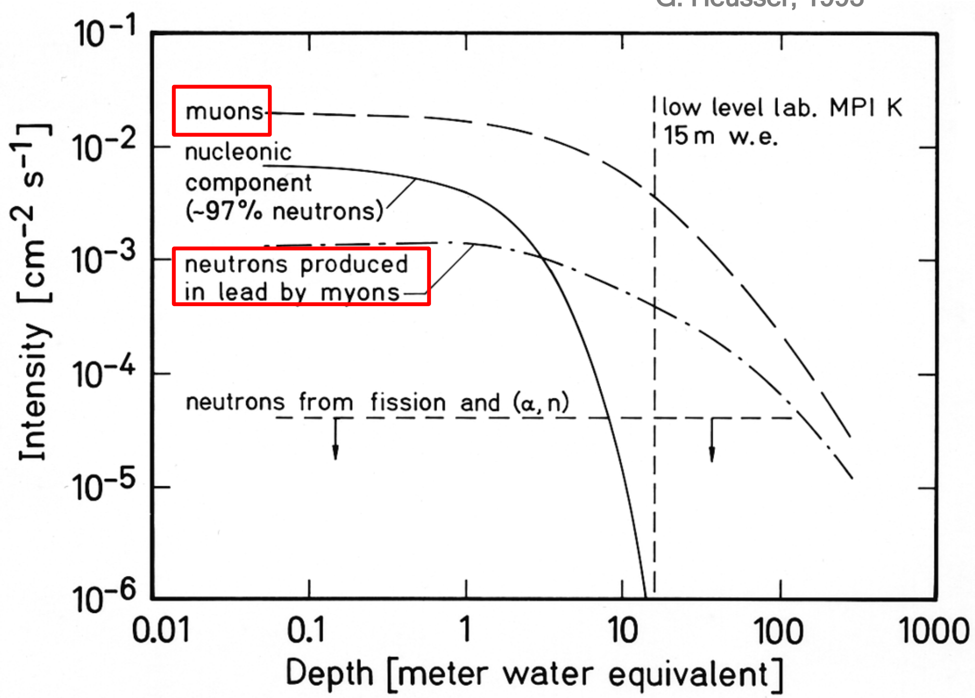
Cosmic Rays

But for low energy neutrinos, they make the detector blind ...

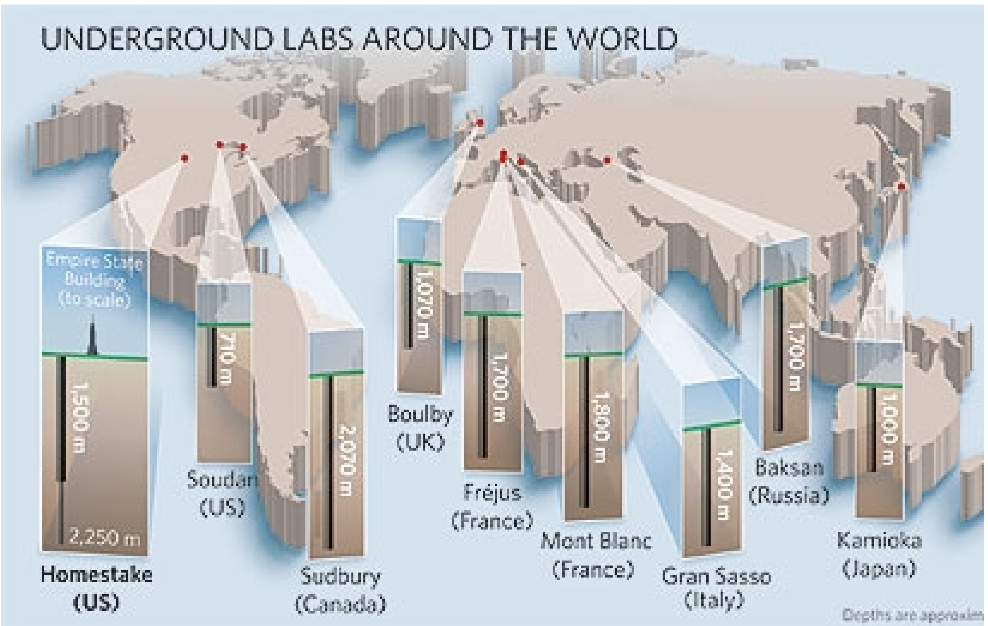
Solution → Depth

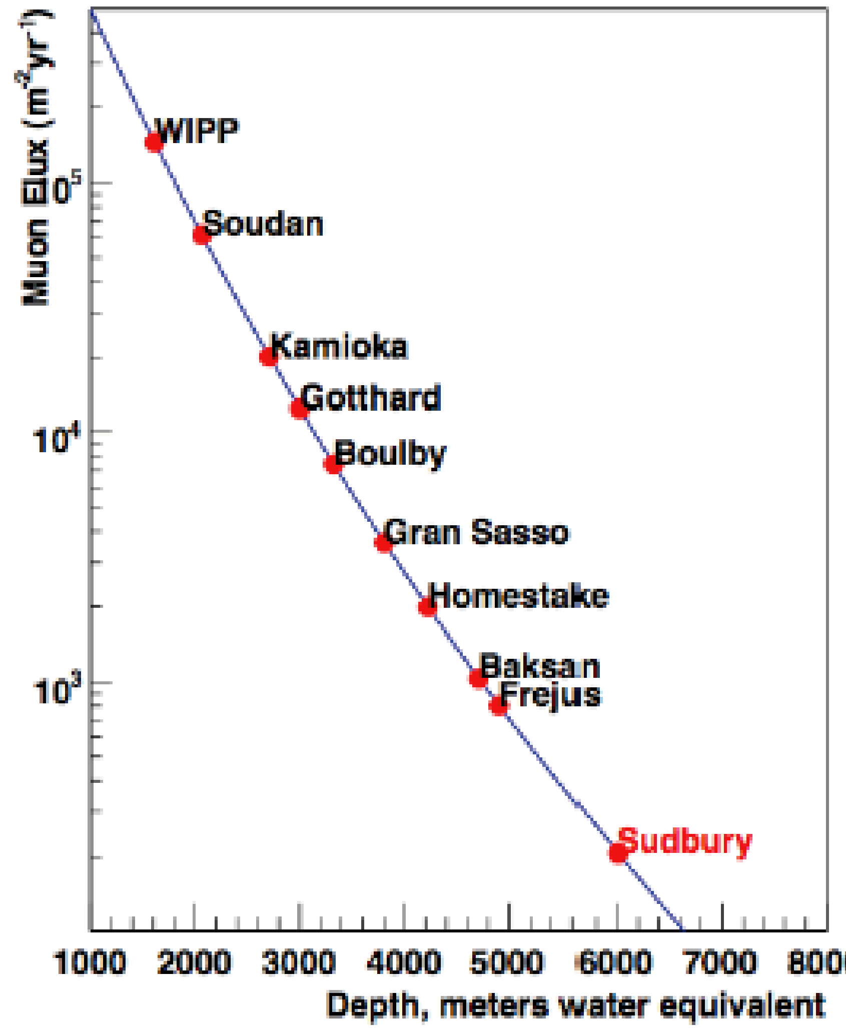
G. Heusser, 1993



Muons are the only cosmic ray particles penetrating deep underground

Cosmogenic muons





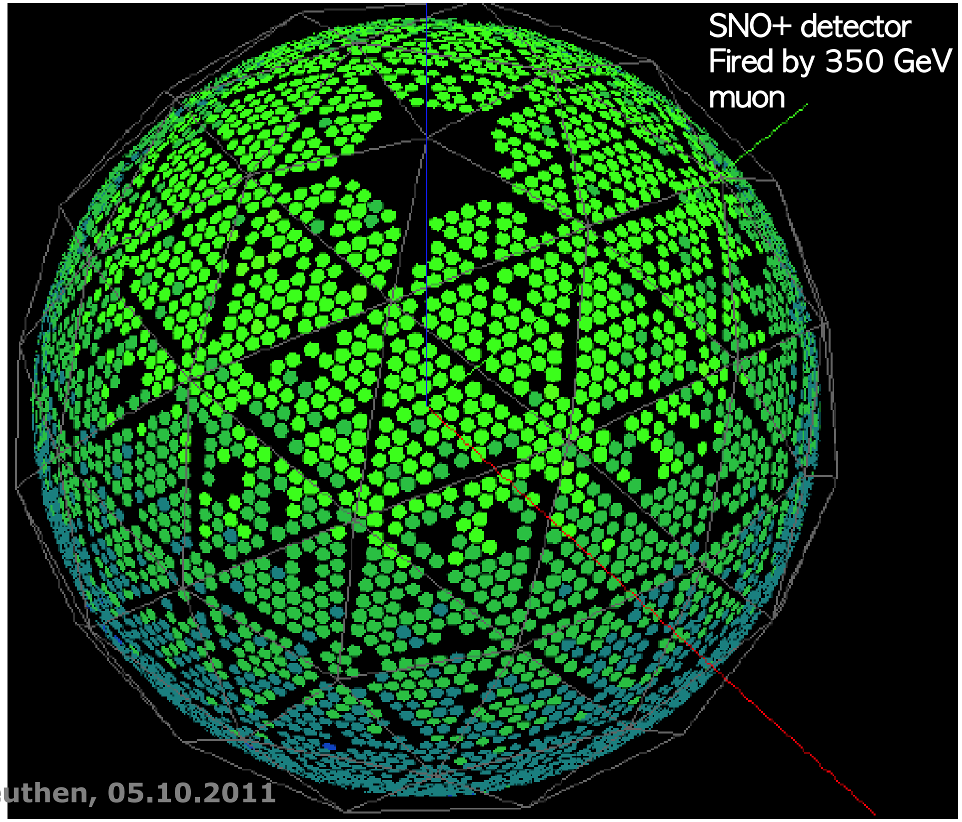
The deeper the better →

Muon background

A. Muons are dangerous as a direct background

All detector PMT are fired → electronic saturation

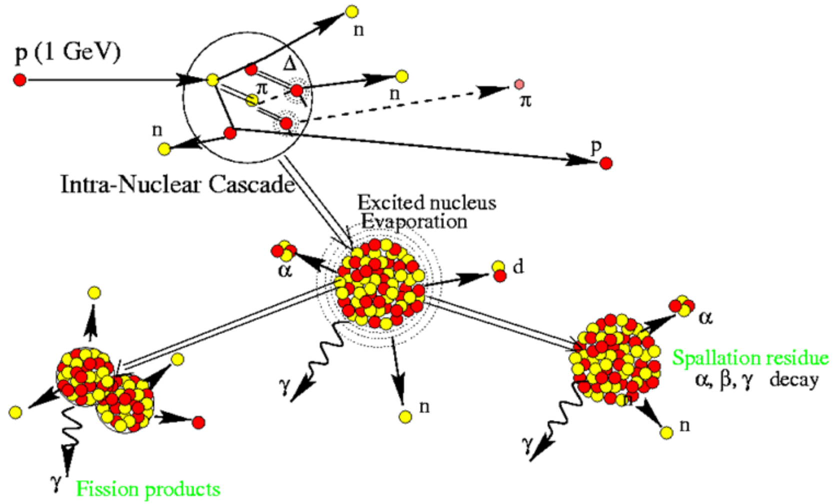
In the mean time the detector is insensitive to another signal

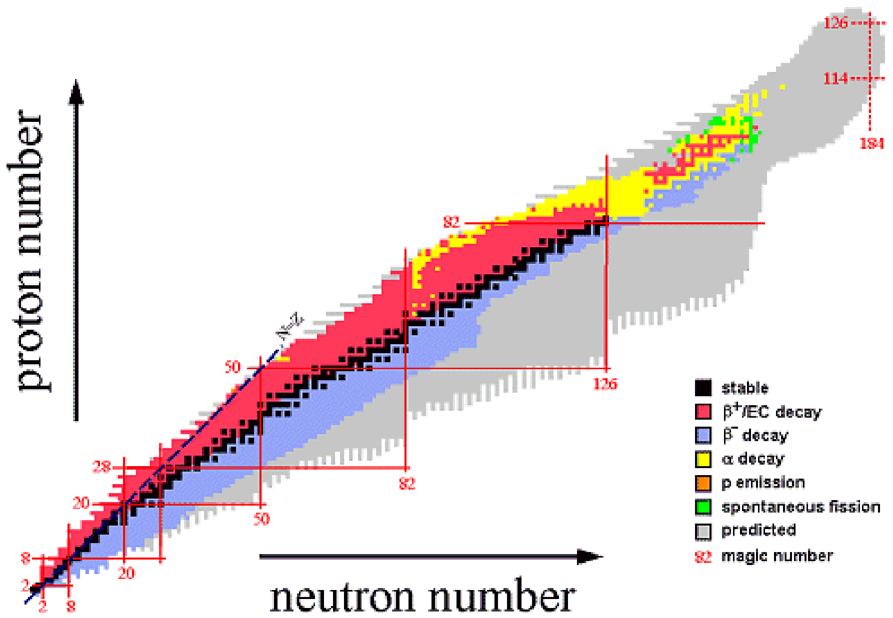


Cosmogenics

B. Muons as well as all the other cosmic rays (neutrons, protons) can induce background, activating detector material

These products are defined as *Cosmogenics = Radioisotopes produced by cosmic ray spallation*

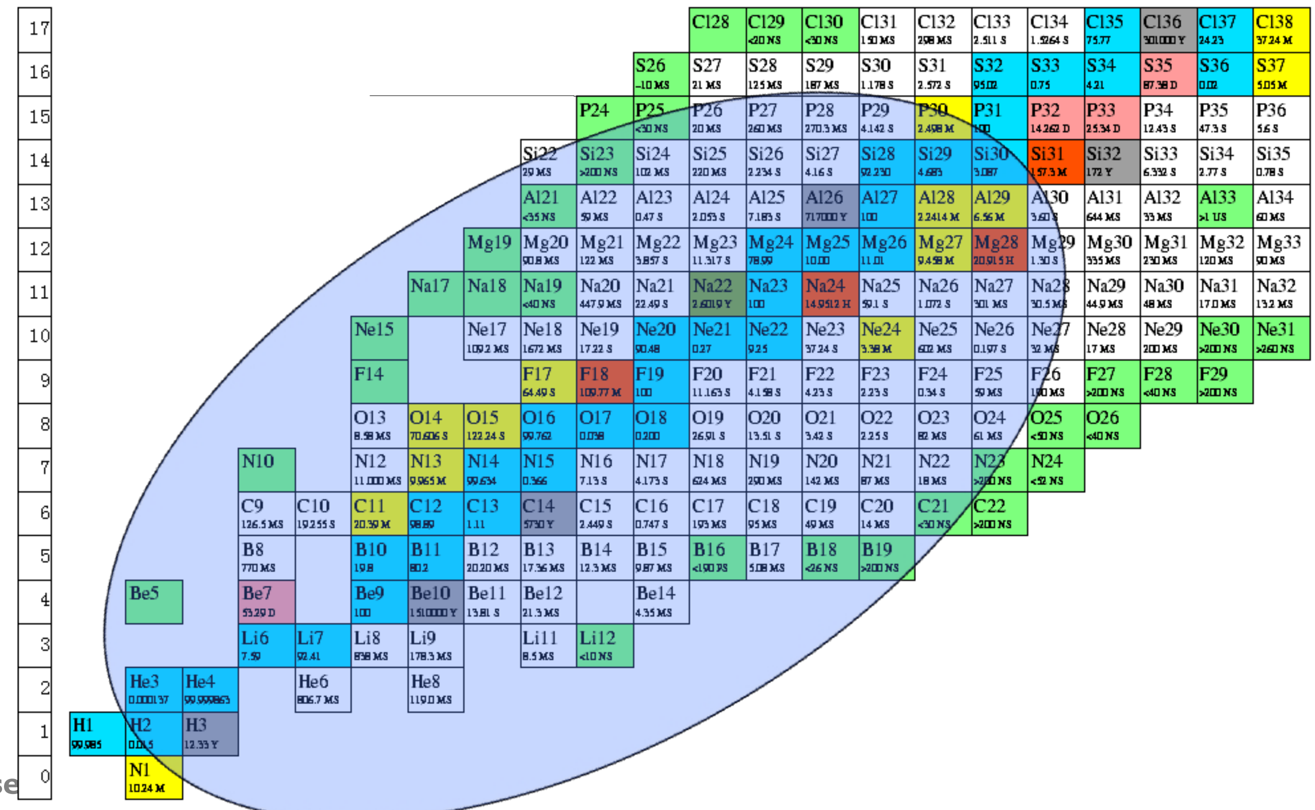




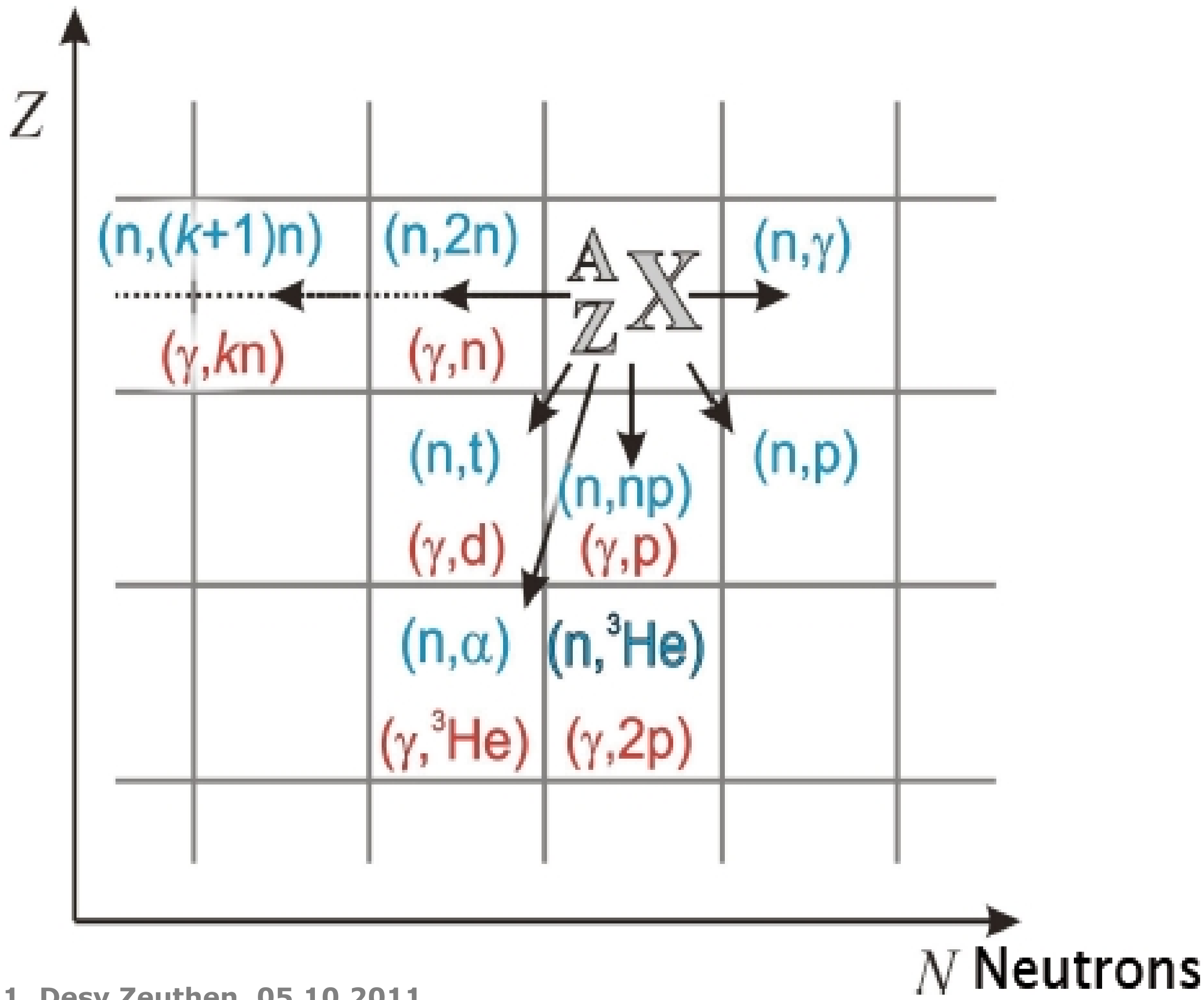
Cosmogenics

Depending on the detector material, some of the cosmogenics can be long living isotopes that remain in the detector during its all data taking life.

The effect on signal discrimination depends both on the rate of the signal search and on the mode in which the isotope decay (beta, alpha or gamma-decay)



Cosmogenics



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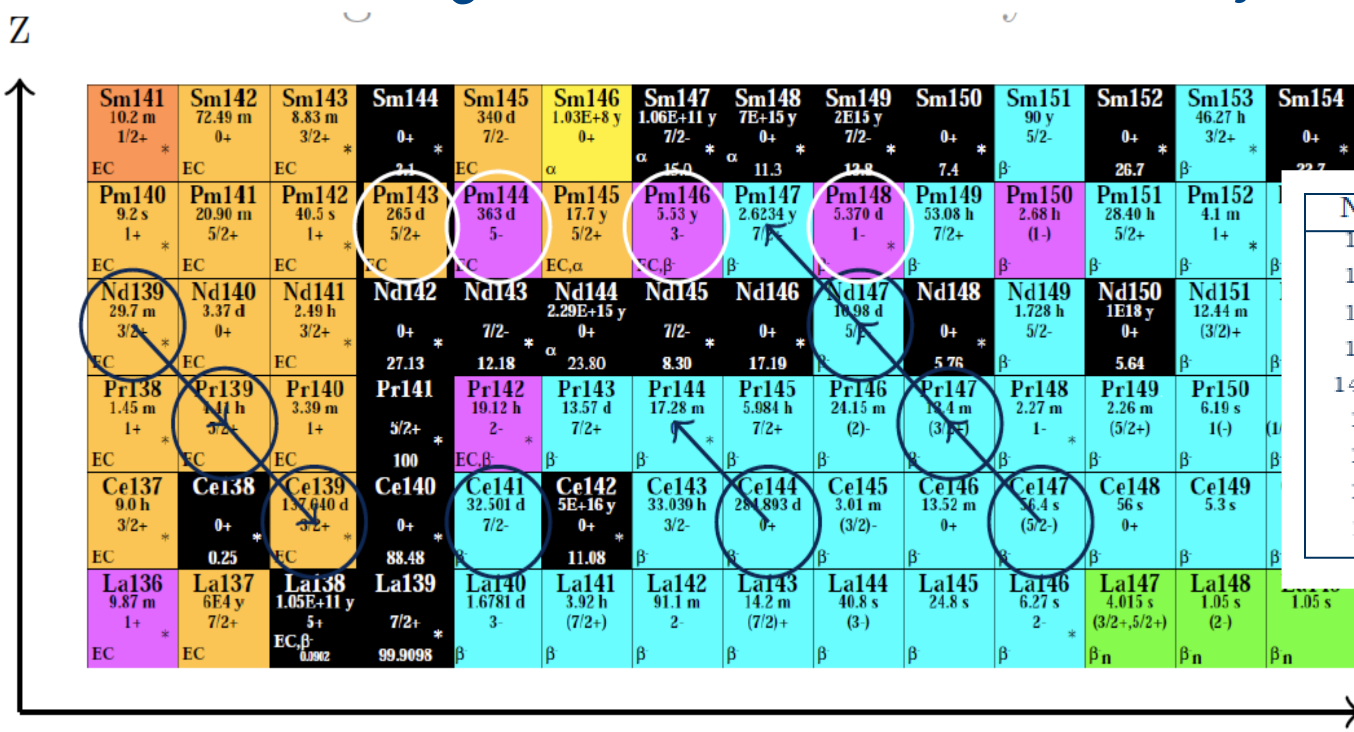
Cosmogenics - example

Neutron induced background in SNO+: activation of neodymium



Nuclide	$T_{1/2}$	Q / keV
^{143}Pm	265 d	1000
^{144}Pm	360 d	2330
^{146}Pm	5.5 a	1400/1500
^{147}Pm	2.6 a	220
^{148m}Pm	41 d	2470
^{139}Ce	140 d	280
^{141}Ce	32.5 d	580
^{144}Ce	285 d	320
^{138}La	10^{11} a	1000/1700

Minimise surface time, don't fly, store underground

V. Lozza

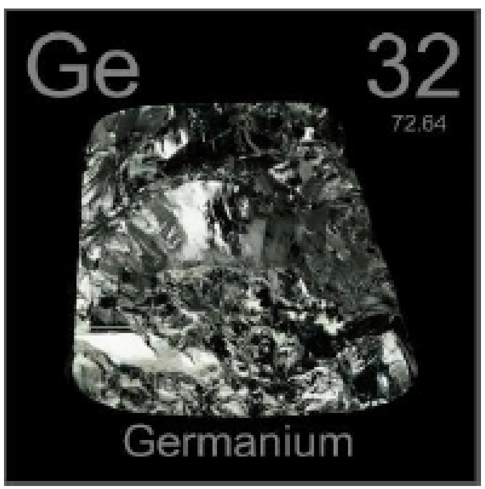
Cosmogenics

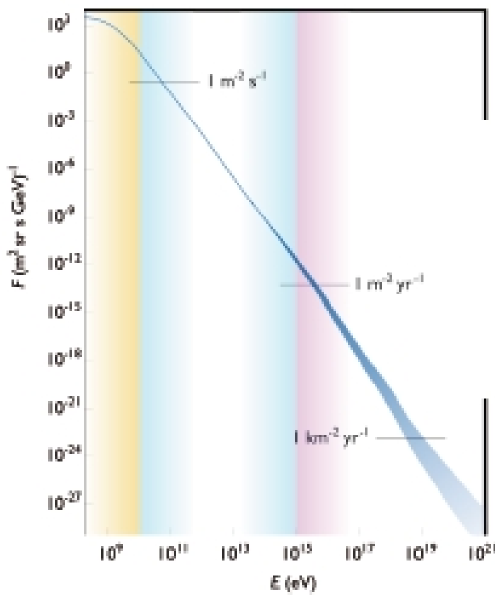
Minor: In situ production, but as background gets lower and lower ...

Radioisotope production due to cosmic rays

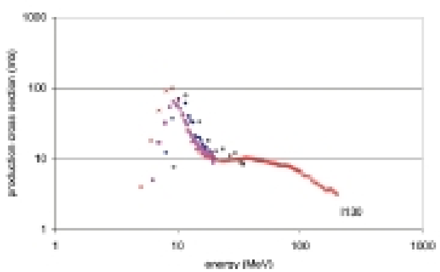
$$R(day) = N_{atom} \times \Phi(E) \times \sigma(E) \times t$$

K. Zuber Padova 2009





?



10^{26} atoms $\quad$ 1 cm^{-2}s^{-1} $\quad$ 10^{-23} cm^{-2}s^{-1} $\quad$ 10^{5}sday^{-1}

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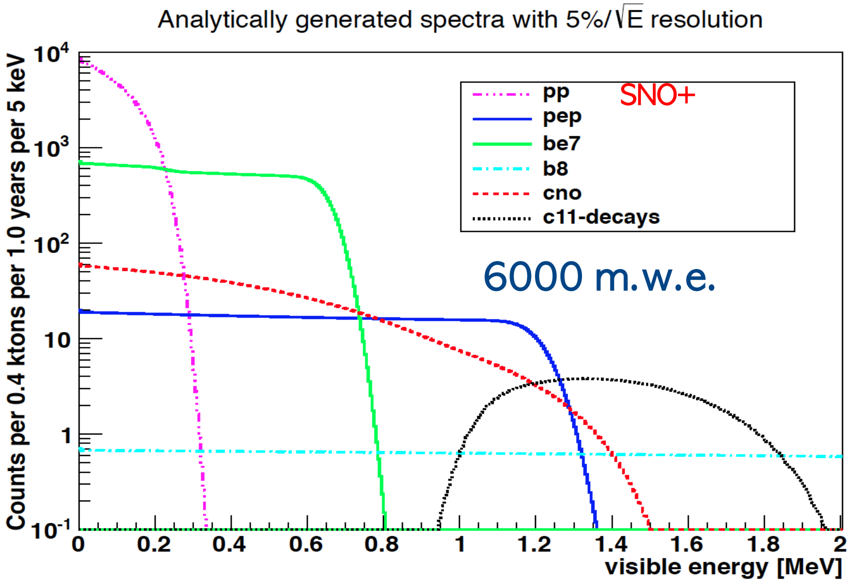
Cosmogenics - example

Muon induced background: 11C

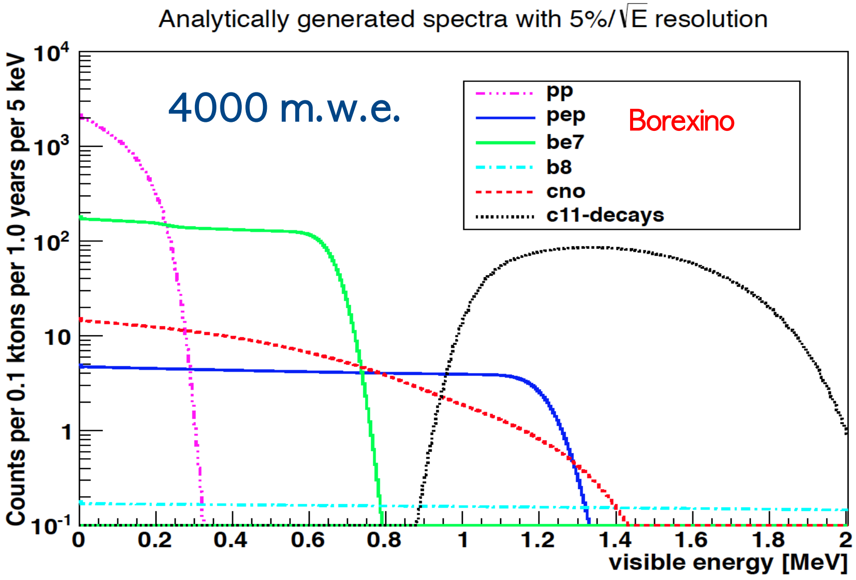
11C are the major source of background for pep solar neutrino (1.4 MeV) measurement being directly in the region of interest

11C has an half life of 20 min

other expected backgrounds not shown



other expected backgrounds not shown

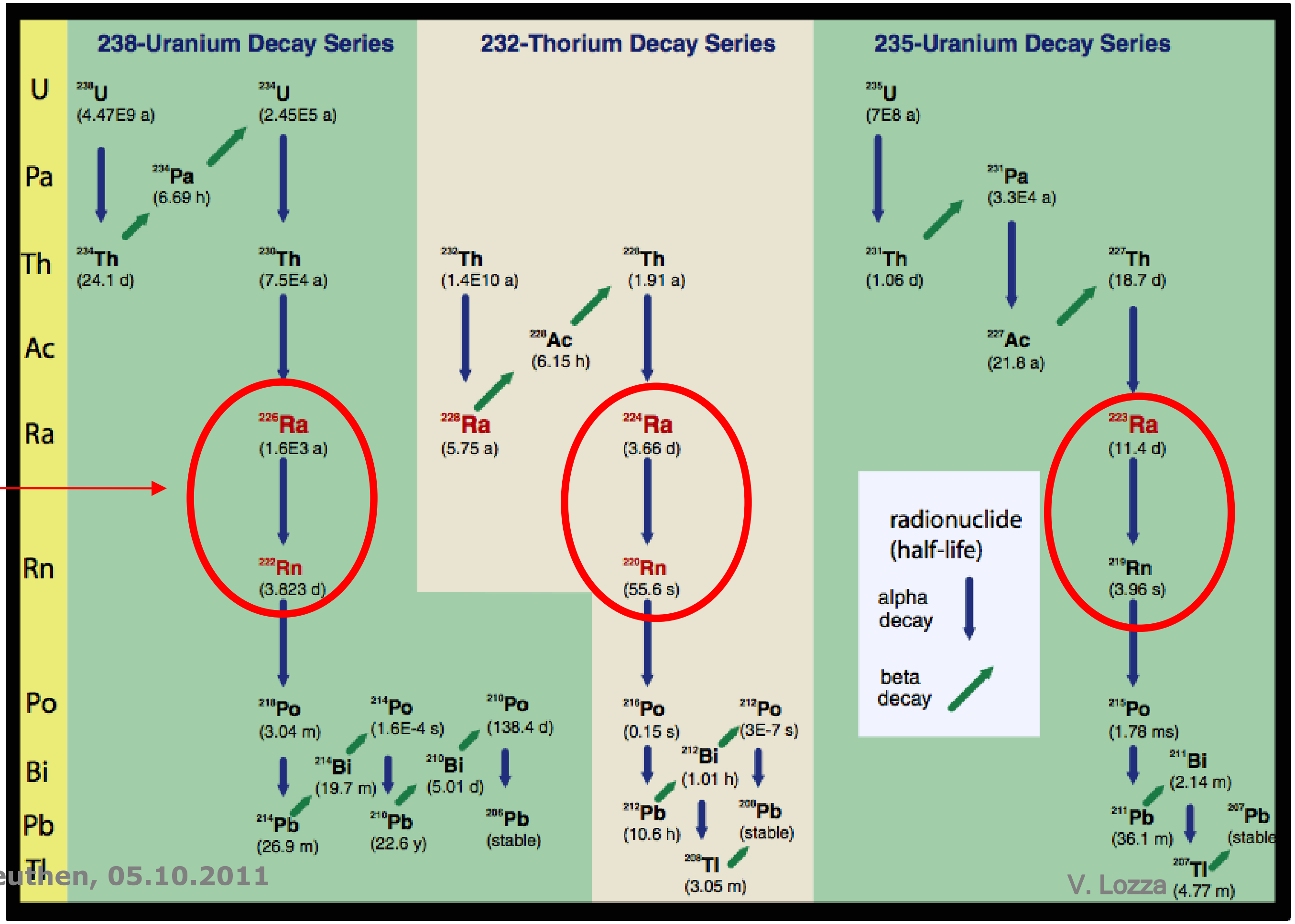


Natural occurring isotopes

All the material used for the construction of the detector MUST be RADIOPURE

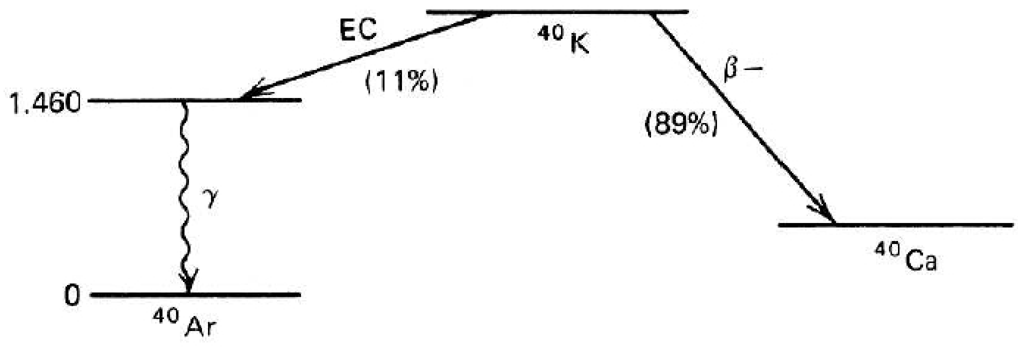
In nature there are 3 main chains of radioactivity: 238U, 235U, 232Th

Bad guys!!
Even worse going deep underground



Natural occurring isotopes

Further primoridal radionuclides 40K, 87Rb (no γ):



Avoid Rn by nitrogen atmosphere, radon traps
- Try to minimize material around detectors

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Neutrons

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Extremely hard to shield, extremely dangerous for dark matter experiment and antineutrino searches in liquid scintillator experiments

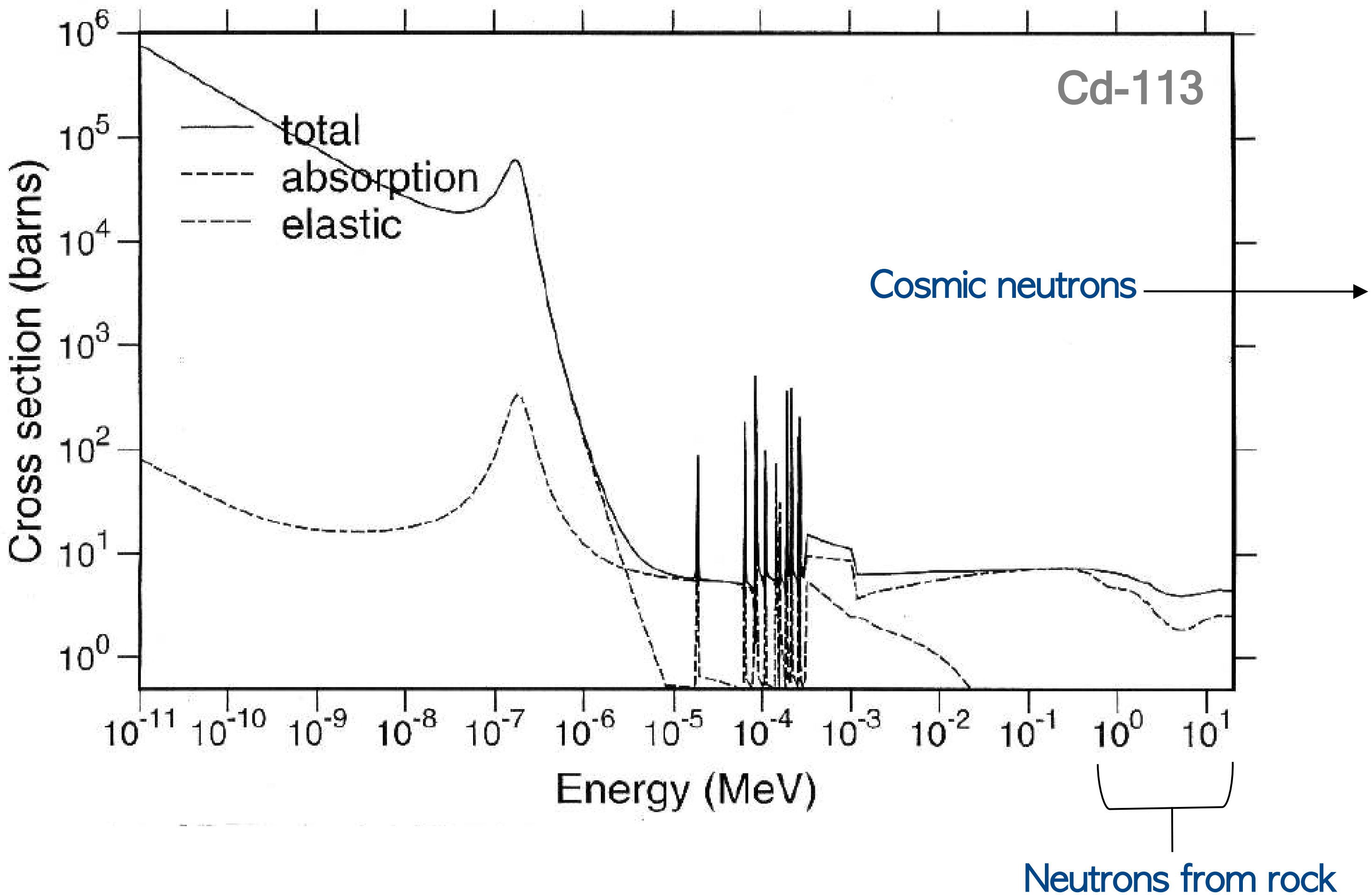
Antineutrino signature = prompt gammas + delayed neutron (hundreds us)

As a direct background neutrons can mimic antineutrino signature

Neutrons can be originated directly from the rock, from muons underground, or from alpha reaction on liquid scintillator

Alpha particles come from the alpha-decay of contaminants in the detector material

Neutrons



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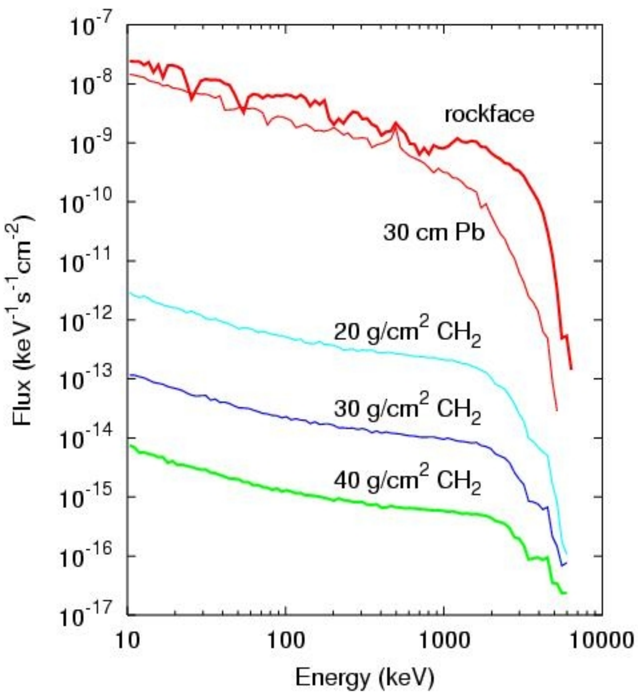
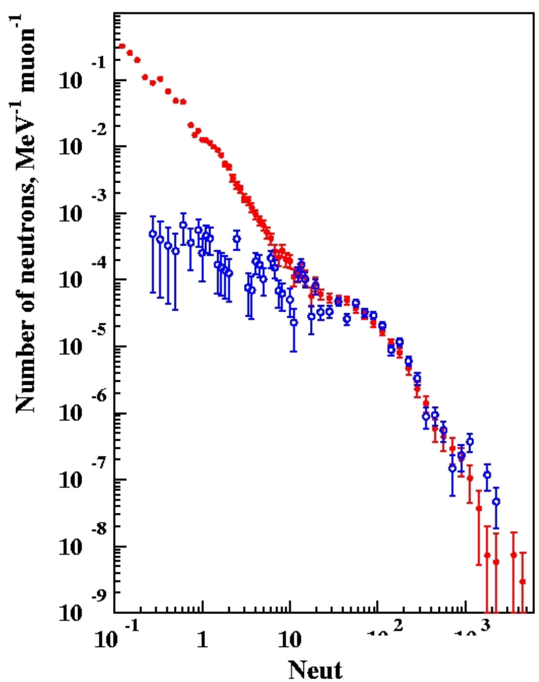
Neutrons underground

Underground sources: (α ,n) reactions from fission, muon-induced neutrons

Shielding strategy = *Moderate*

- Paraffine
- polyethylene (organic molecules)
- capture (n, γ) (Cd, Gd) or (n, α) (B,Li)





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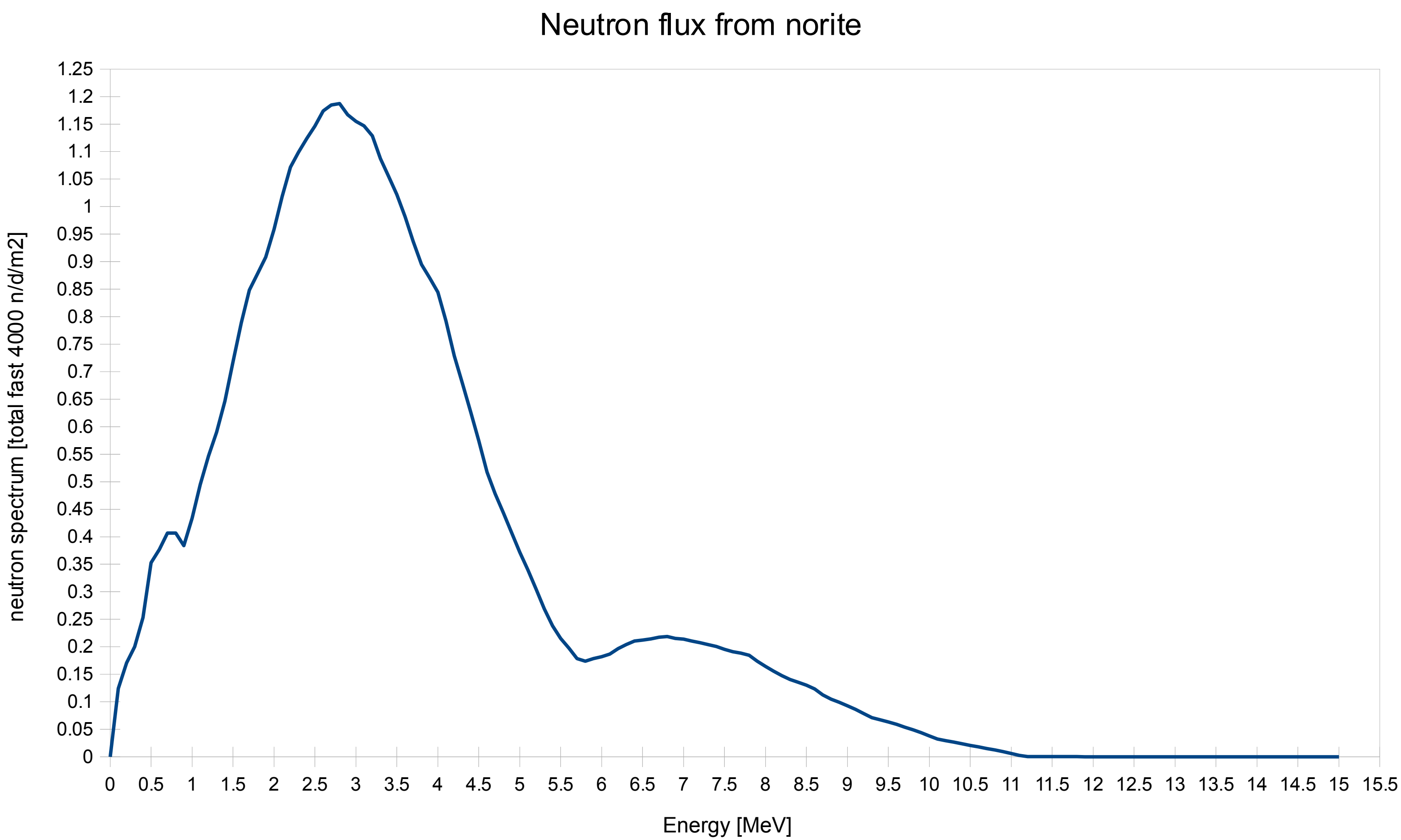
Carson et al, Astroparticle Phys. 21, 667 (2004)

Neutrons from rock



What to do?

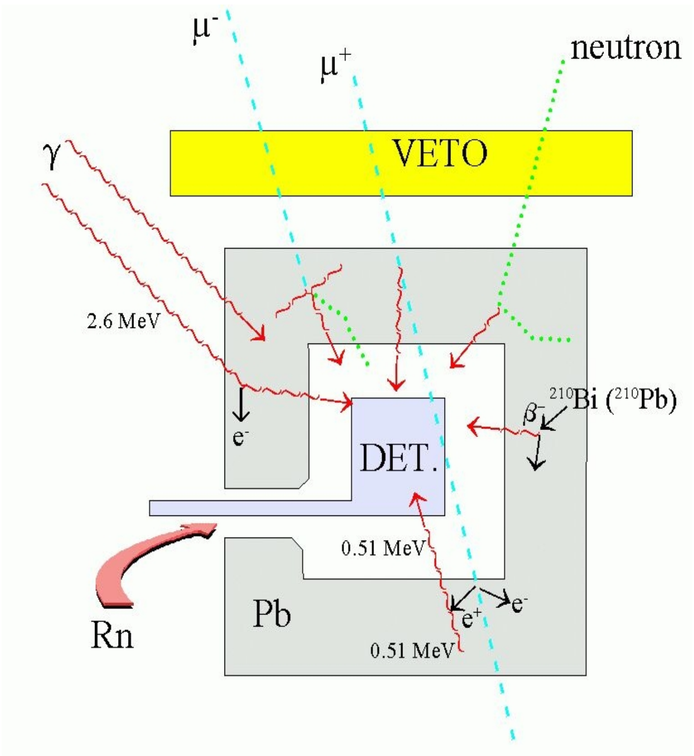
What to do?

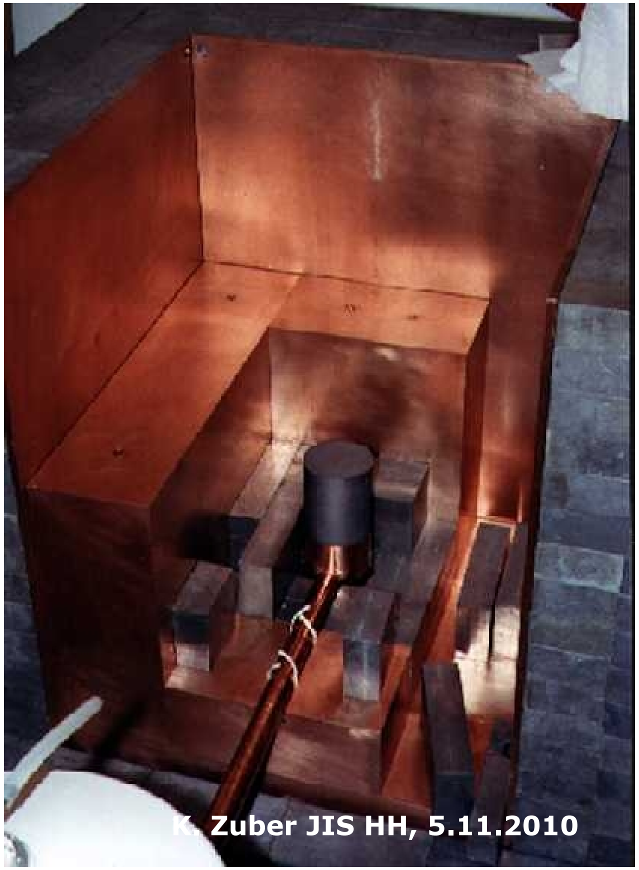
You MUST:

A. Clean the laboratory where you are working in order to avoid contamination from dirty material
B. Clean all the detector part (washing with acid, ultrapure water) several times
C. Count all the detector materials with Ge-counters in order to be sure they respond to the radiopurity requirements
D. If you are underground, flush the detector with Nitrogen in order to avoid Radon contamination
E. Seal you detector
F. Limit your detector exposure to air
G. Sophisticated cleaning methods (water-water extraction, metal scavengers,...) exist in order to reduce U and Th contamination
H. Water shielding

Measure material

Every (!!!) single device/material has to be measured before you can use it!
Use Ge-semiconductor detectors!!! → Fantastic energy resolution





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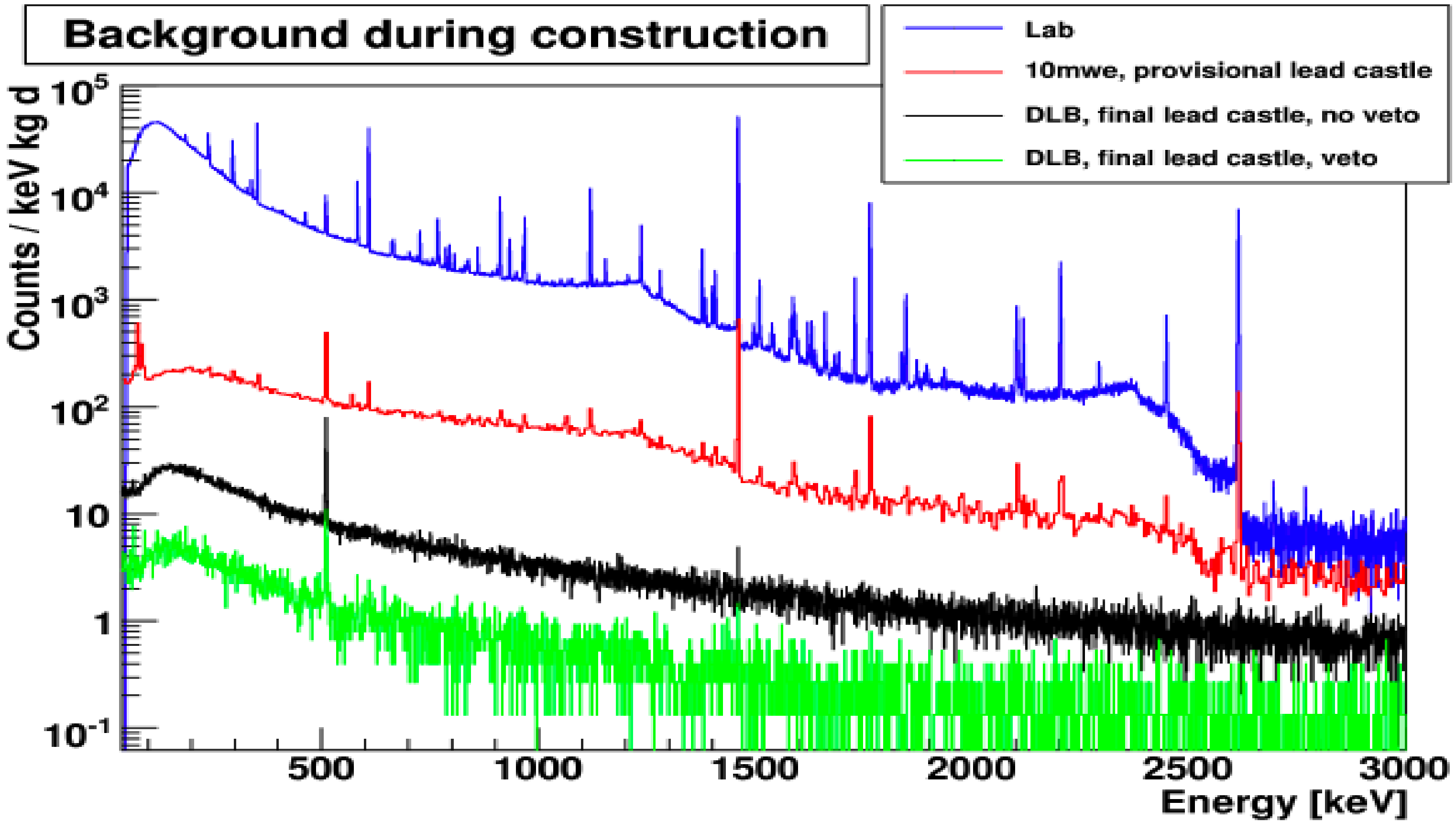
Gamma spectra

Every (!!!) single device/material has to be measured before you can use it!
Use Ge-semiconductor detectors!!! → Fantastic energy resolution



Example

- The expected rate of solar neutrinos in 100tons of BX scintillator is ~50 counts/day which corresponds to ~ 5 10^{-9} Bq/Kg;
- Just for comparison:
  - Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
  - Air is ~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
  - Typical rock is ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

BX scintillator must be 9/10 order of magnitude less radioactive than anything on earth!

B. Caccianiga TAUP2011

Example

Background suppression: 15 years of work

- **Internal background: contamination of the scintillator itself (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)**
  - Solvent purification (pseudocumene): distillation, vacuum stripping with low Argon/Kripton N2 (LAKN);
  - Fluor purification (PPO): water extraction, filtration, distillation, N_2 stripping with LAKN;
  - Leak requirements for all systems and plants < 10^{-8} mbar· liter/sec;
- **External background: γ and neutrons from surrounding materials**
  - Detector design: concentric shells to shield the inner scintillator;
  - Material selection and surface treatement;
  - Clean construction and handling;

Background suppression: achievements

•Contamination from ^{238}U and ^{232}Th chain are found to be in the range of ~10^{-17} g/g and ~5x 10^{-18} g/g respectively;

•**More than one order of magnitude better than specifications!**

•Three backgrounds out of specifications: ^{210}Po, ^{210}Bi and ^{85}Kr. More about it later

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Physicist

What we expect

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Summary

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Search for rare events (neutrinos, dark matter, rare decays) is an essential part of particle physics and particle astrophysics, complementary to accelerator activities.

Expected event rates are extremely small (less than 1 per day in a big detector) normally covered by overwhelming backgrounds

However, field has done enormous progress over the last two decades in selecting clean materials, measuring contaminations in the order of μ Bq/kg, purification procedures, shielding designs

The excitement and interest in the field is reflected by the fact that more and more countries plan or build underground labs (US, China, Poland, Finland, Romania,...)

Interesting to read

RECENT ADVANCES IN LOW LEVEL COUNTING TECHNIQUES[1]

By Ernest C. Anderson and F. Newton Hayes
Biomedical Research Group, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

Ann. Rev.Nucl. Part. 6, 1956

Big issue: 14C: 5000 years

LOW-RADIOACTIVITY BACKGROUND TECHNIQUES

G. Heusser
Max-Planck-Institut für Kernphysik, P.O. Box 103 980, D-69029 Heidelberg, Germany

Ann. Rev.Nucl. Part.45, 1995

Big issue: DBD: 10^{25} years