Backgrounds in Underground Experiments

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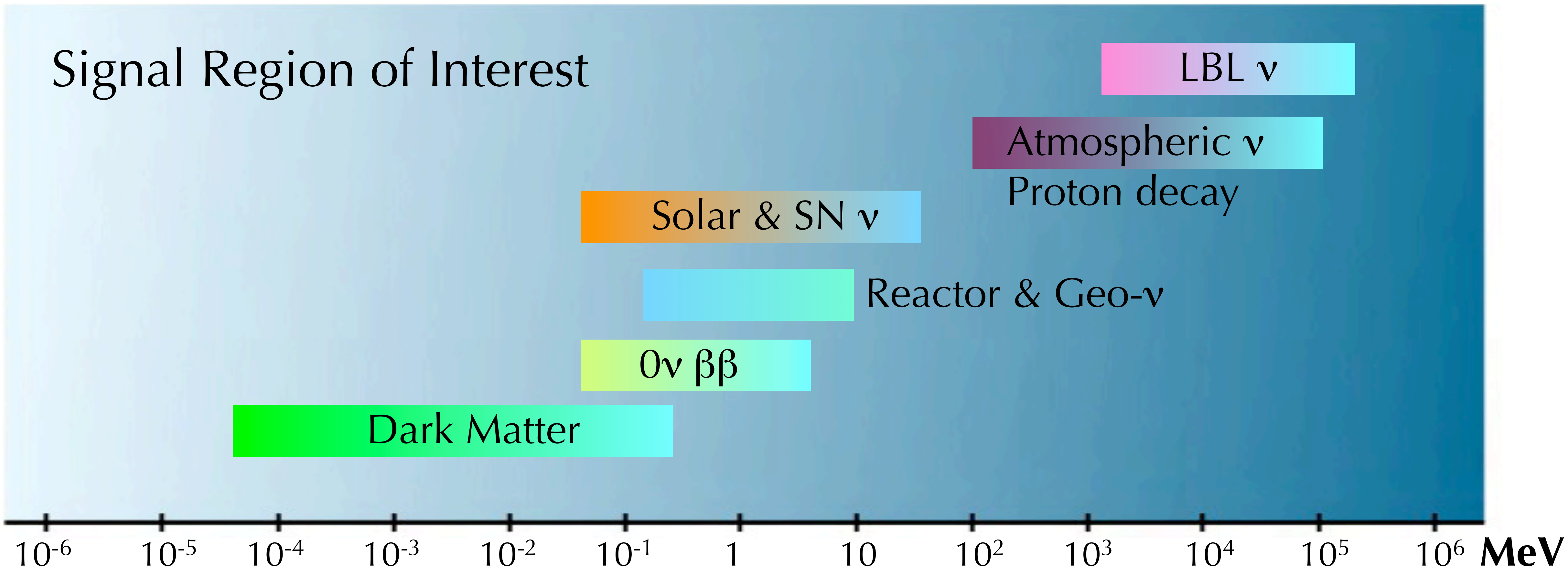
Acknowledgements

Help (and slides) from:

– Joe Formaggio (MIT)
– Aksel Hallin (Alberta)

Types of Experiments and Backgrounds

- Backgrounds:
  - Cosmic-ray primaries and secondaries produced in the atmosphere
  - Cosmic muons
  - Neutrons ("Cosmic" and "Environmental")
  - α, β and γ ("Detector intrinsic" and "Environmental")



Cosmic-ray Primaries & Secondaries

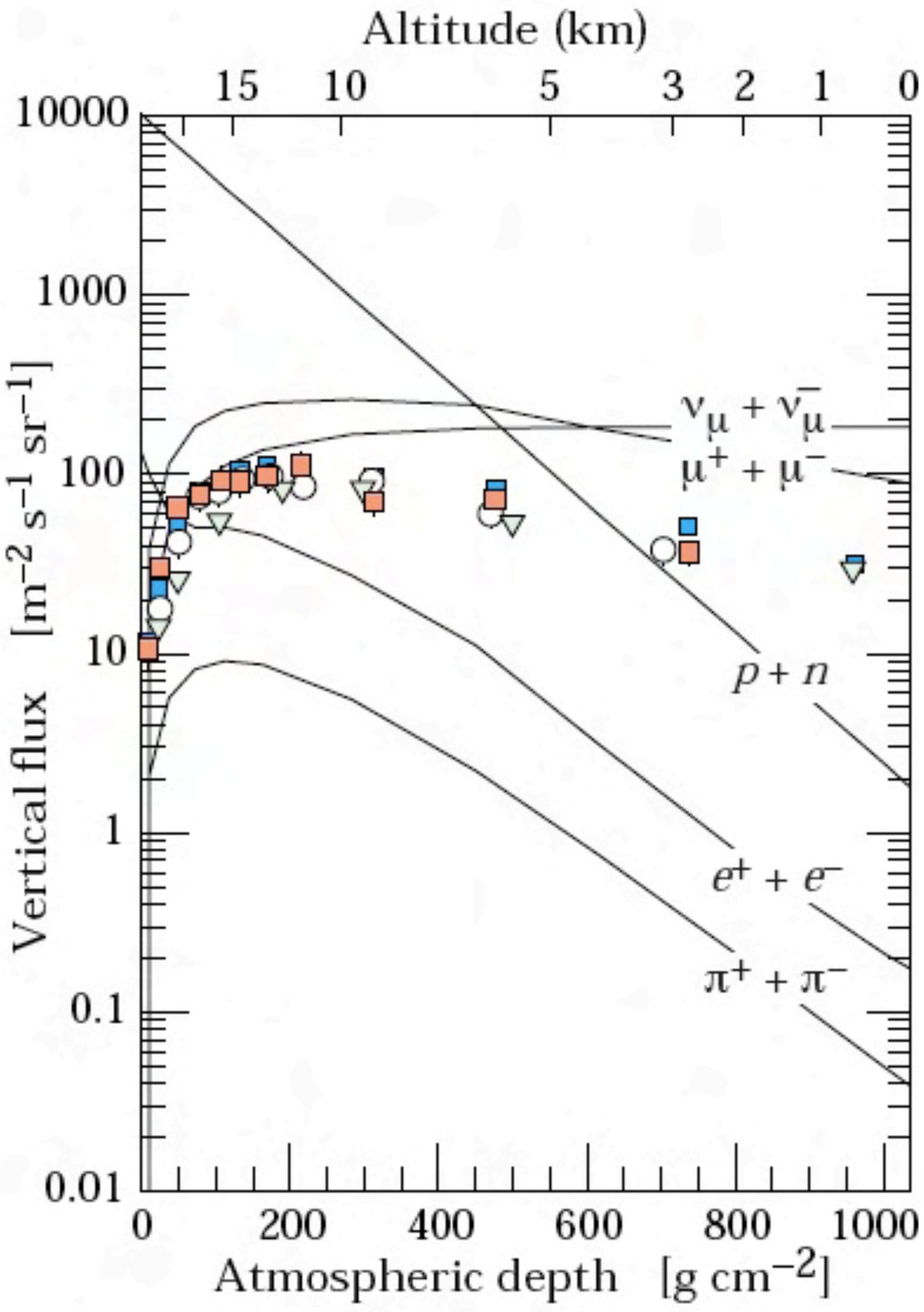


Figure 24.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (24.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [29–32]. See full-color version on color pages at end of book.

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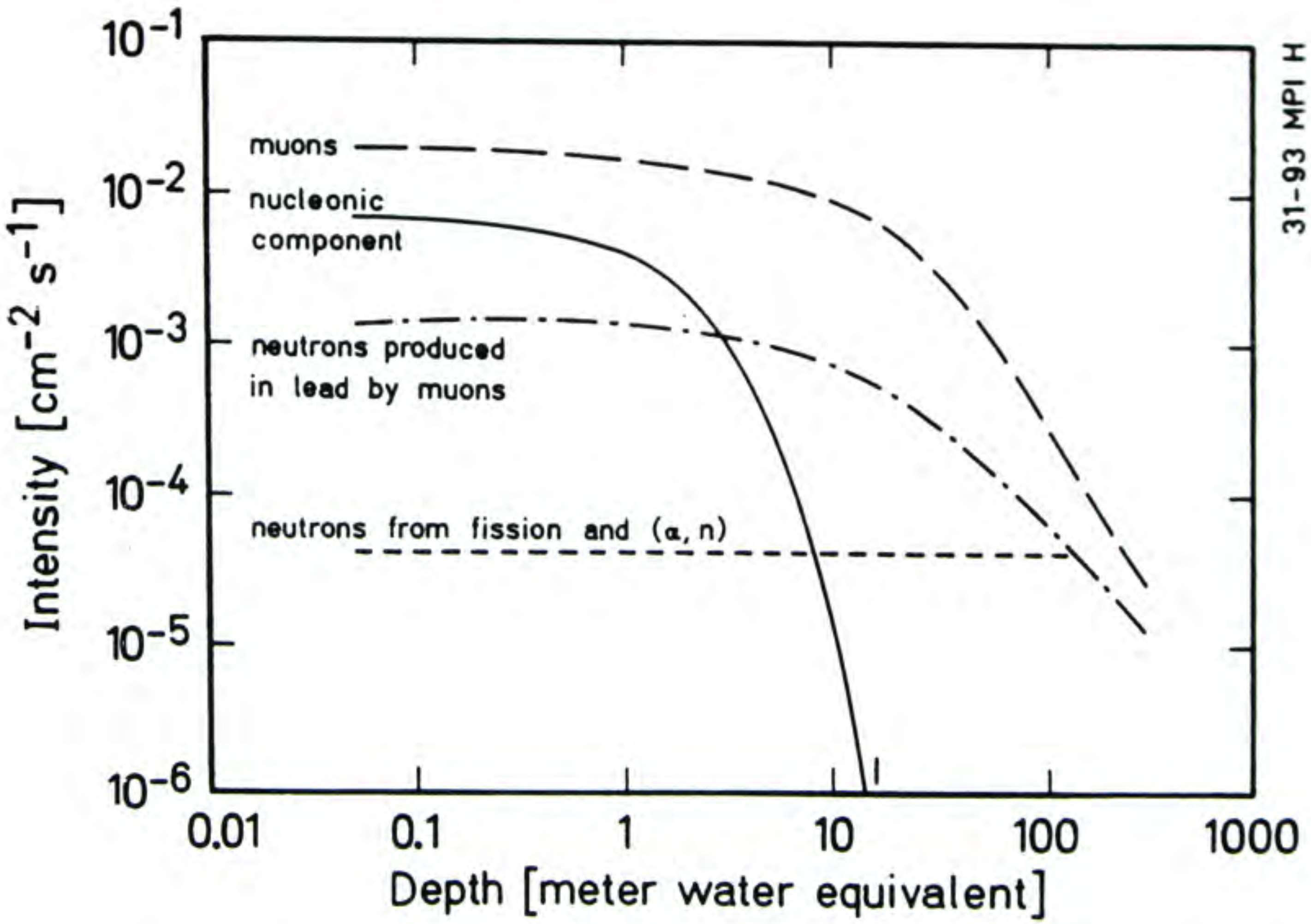
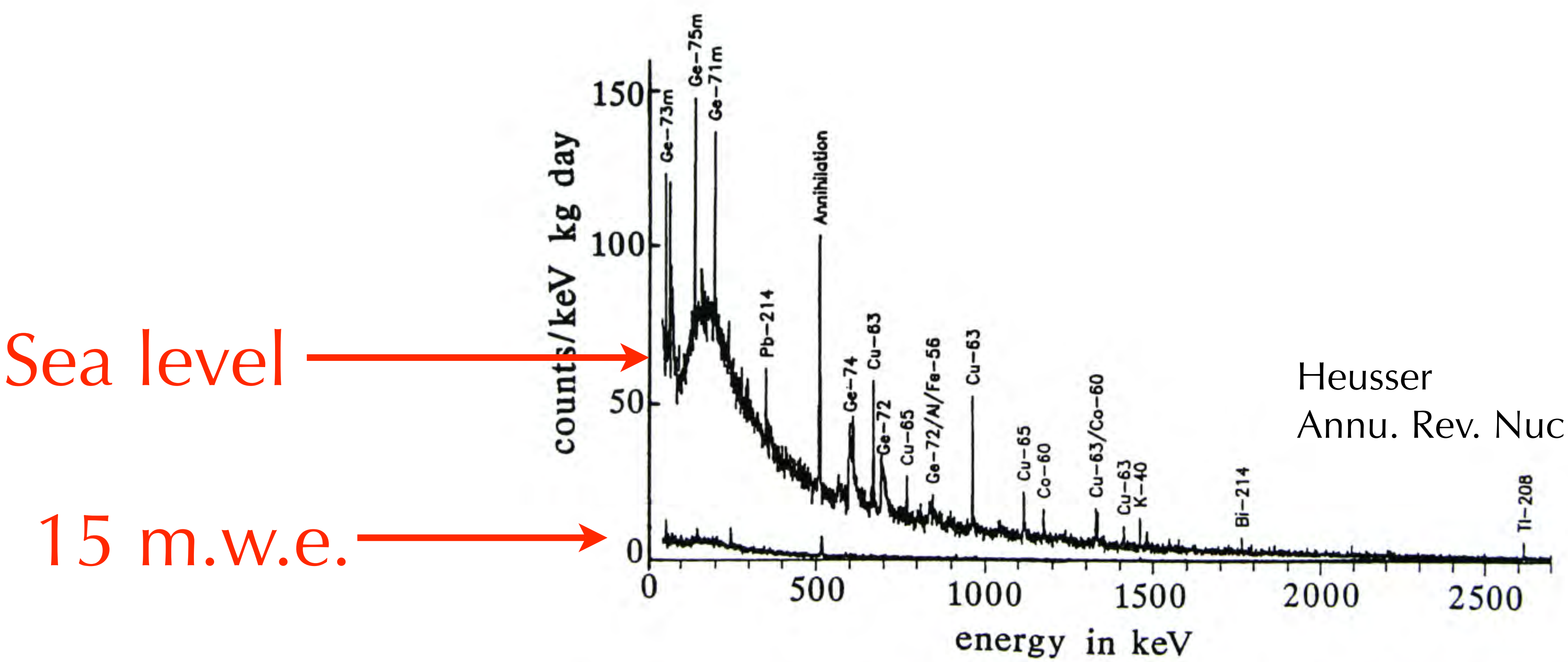


Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shiel vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. Th nucleonic component is more than 97% neutrons.

Heusser, Annu. Rev. Nucl. Part. Sci. 45: 543 (1995)

Cosmic-ray Primaries & Secondaries

- Minimal overhead burden goes a long way in reducing backgrounds induced by nucleonics:



Heusser
Annu. Rev. Nucl. Part. Sci. 45: 543 (1995)

Figure 4 Background spectra of similar Ge spectrometers (0.9 kg active volume) with passive and active shielding at sea level (*top*) and at 15 m.w.e. (*bottom*).

- Even at 25 m.w.e., the muonic and nucleonic contributions to the "star density" (nuclear interactions per gram of material per unit time) are about equal (< ~0.01 inelastic interaction per kg per day). [Lal & Peters 1967]

Why do we care about cosmic muons?

- Cosmic muons are easy to shield and veto if they pass through the detector.

- But cosmic muons can
  - create neutrons, β and γ backgrounds without leaving any traces in the detector
  - produce unwanted radioisotopes
  - increase detector dead-time (if overhead burden is inadequate)

Muon Intensity

- On surface (10 GeV < E_μ < 100 TeV, θ<70°): [Gaisser 1990]

$$\frac{dN_\mu}{dE_\mu d\Omega} \simeq 0.14 E_\mu^{-(\gamma-1)} \left(\frac{1}{1+\frac{1.1 E_\mu \cos\theta}{115\,\mathrm{GeV}}} + \frac{0.054}{1+\frac{1.1 E_\mu \cos\theta}{850\,\mathrm{GeV}}} \right) \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$$

$$\gamma - 1 = 2.78 \pm 0.05$$

Shape uncertainty ~ 5%

Flux uncertainty ~20%

- Energy loss while traveling through rocks (brem., e^+e^- pair production, photonuclear):

$$-\left\langle \frac{dE(E_\mu)}{dX} \right\rangle = \alpha + \beta E_\mu$$

Energy (GeV)	α (GeV g^{-1} cm^2)	β (g^{-1} cm^2)	ϵ (GeV)
10	2.17×10^{-3}	1.90×10^{-6}	1142
100	2.44×10^{-3}	3.04×10^{-6}	803
1000	2.68×10^{-3}	3.92×10^{-6}	684
10000	2.93×10^{-3}	4.35×10^{-6}	674

- Approximate relationship, neglecting energy loss fluctuation [Lipari]:

$$I(X) = I_0 \frac{\epsilon^{1-\gamma}}{\gamma-1} e^{-(\gamma-1)\beta X} (1 - e^{-\beta X})^{1-\gamma} \approx A \left(\frac{X_0}{X}\right)^{\eta} e^{-\frac{X}{X_0}}$$

where $A = (2.15 \pm 0.08) \times 10^{-6} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ $\quad X_0 = \beta(\gamma-1)^{-1} = 1155^{+60}_{-30}\,\mathrm{mwe}$

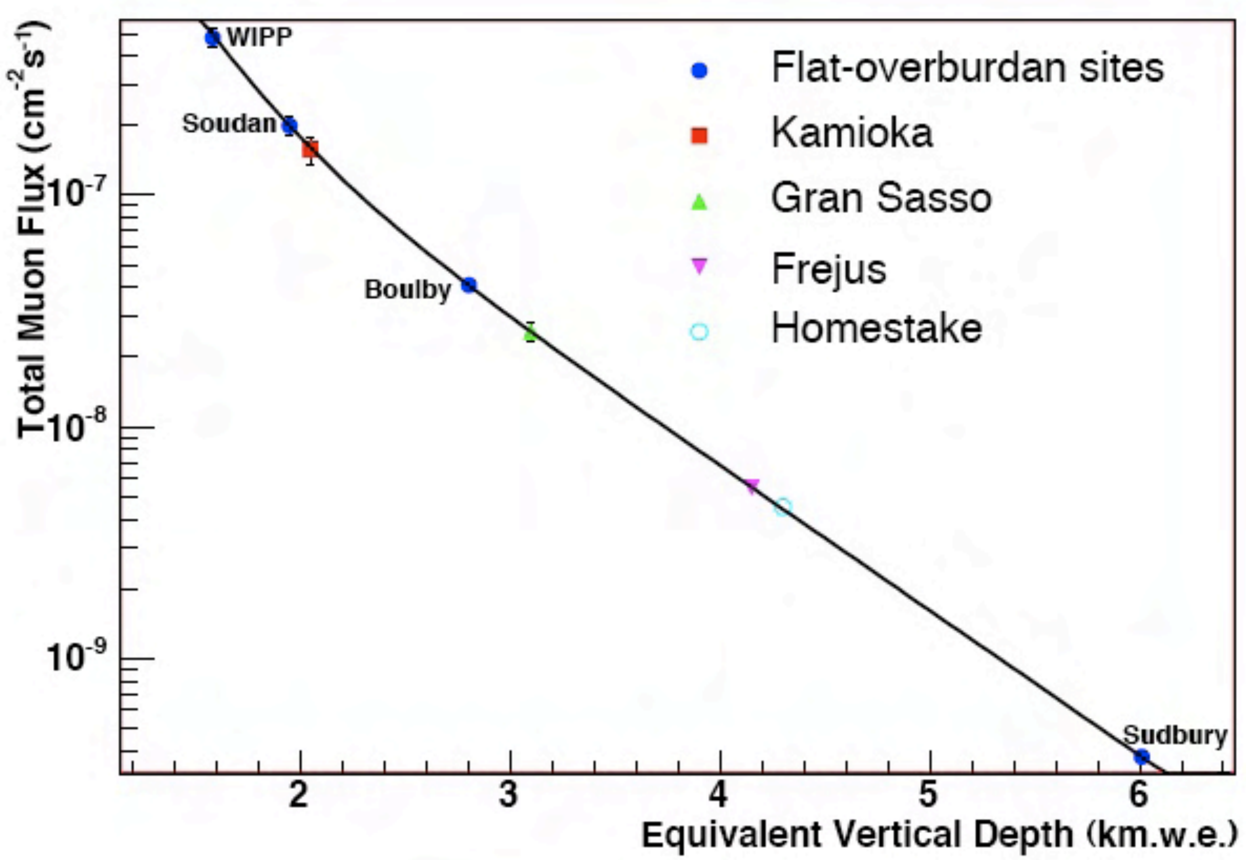
$$\eta = \gamma - 1 = 1.93^{+0.20}_{-0.12}$$

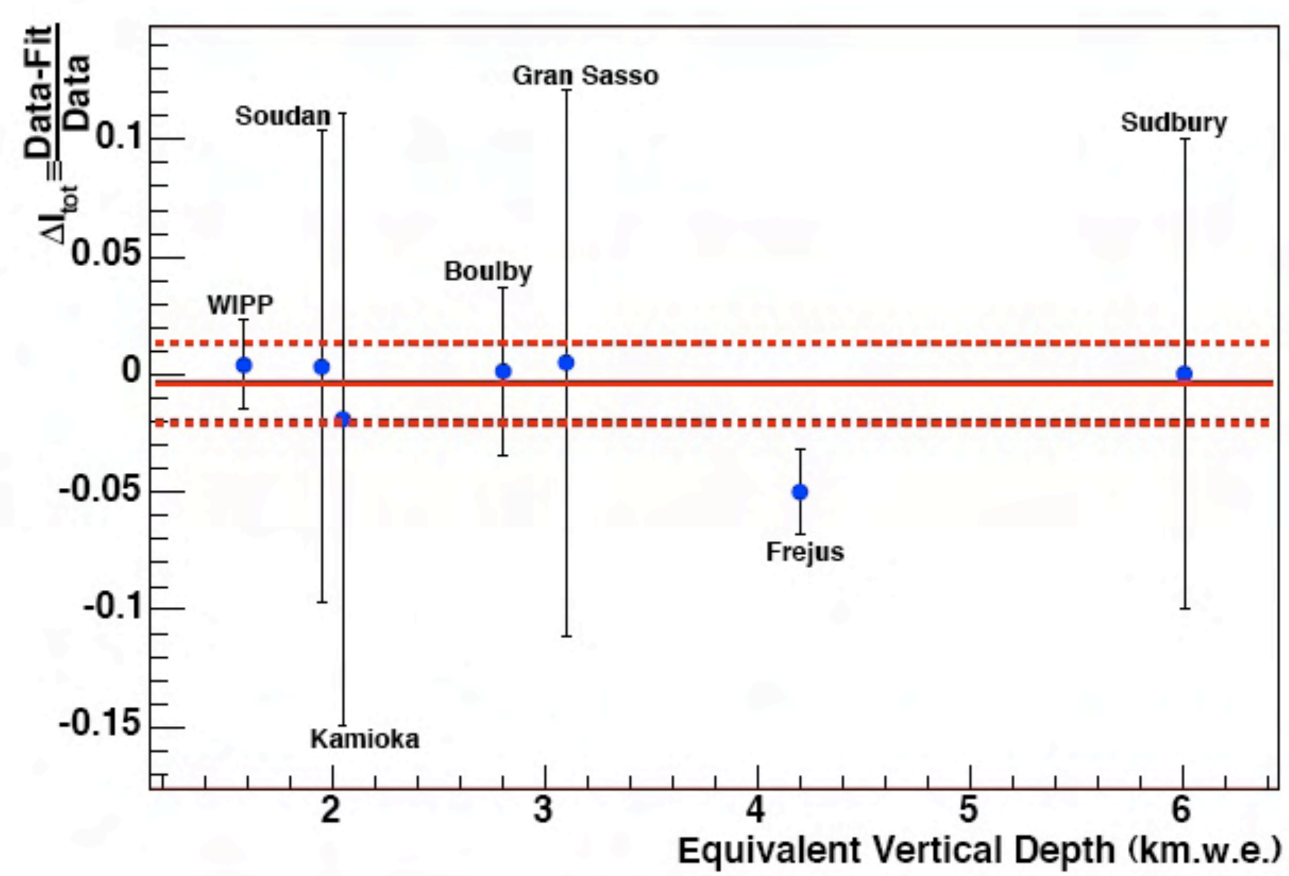
See Chu's talk on site-specific fits

Muon Intensity

- At great depths or in complicated topologies, more detailed calculations are needed (e.g. MUSIC or PROM_MU).
- Empirical fits do exist. For example, Mei and Hime:

$$I_\mu(h_0) = 67.97 \times 10^{-6} e^{\frac{-h_0}{0.285}} + 2.071 \times 10^{-6} e^{\frac{-h_0}{0.698}} \quad \mathrm{cm}^{-2} s^{-1}$$





Muon Intensity

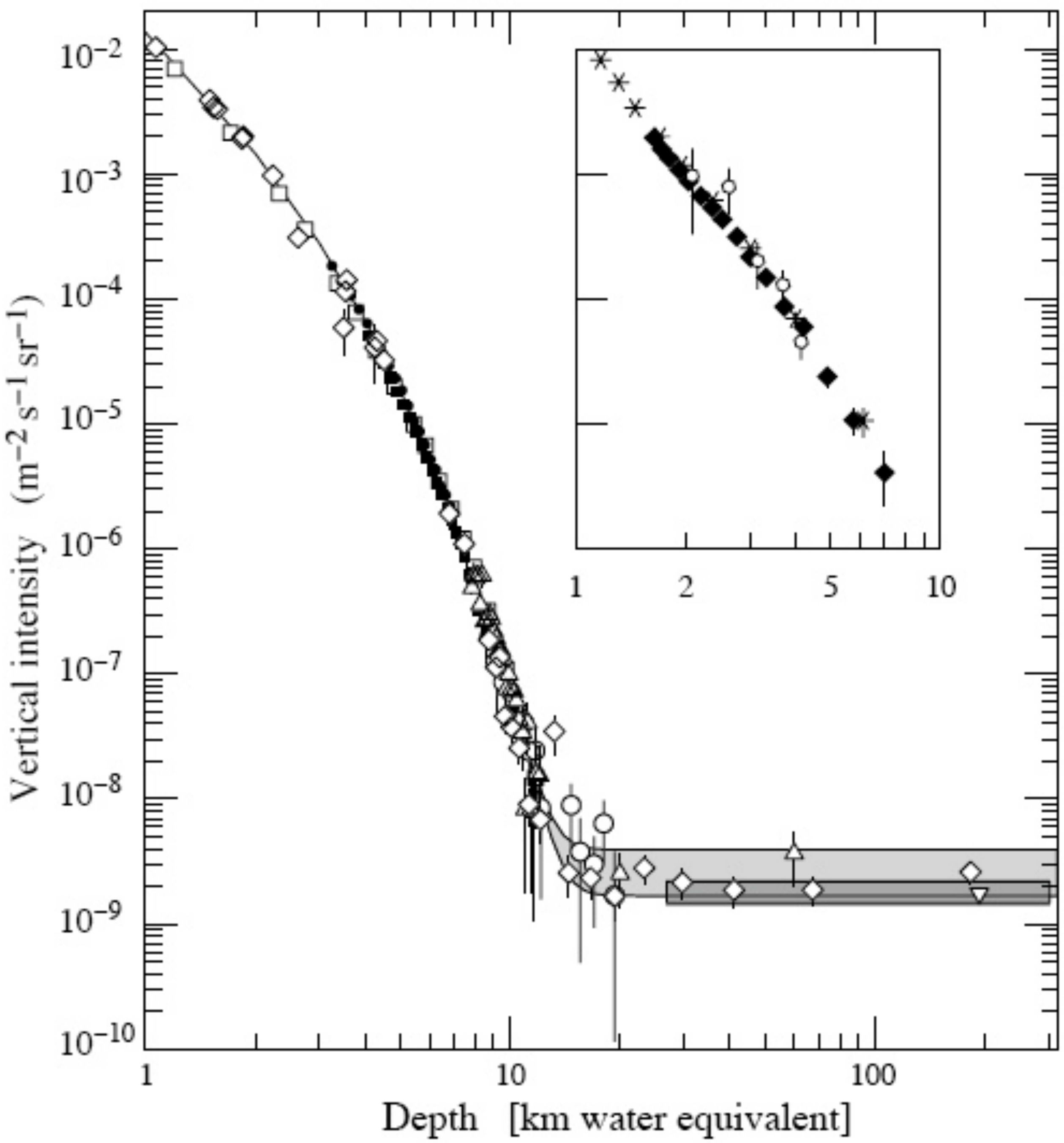


Figure 24.6: Vertical muon intensity vs depth (1 km.w.e. = 10^5 g cm^{-2} of standard rock). The experimental data are from: ◊: the compilations of Crouch [54], □: Baksan [58], ○: LVD [59], •: MACRO [60], ■: Frejus [61], and △SNO [62]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.

PDG 2008

Cosmogenic Production of Radioisotopes

- Production of radioactive nuclei by nuclear interactions of cosmic ray muons
- Example: ^{71}Ge production in $GaCl_3$ (GALLEX solar neutrino experiment):

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

$$^{71}Ge + e^- \rightarrow {}^{71}Ga^* + \nu_e$$

- But ^{71}Ge can be produced cosmogenically. Therefore, one must choose a lab that is deep enough.
- Cosmogenic ^{68}Ge (EC, 271d half-life) was problematic for GALLEX initially. This was a background for ^{71}Ge counting.
- Cosmogenic radioisotope production rate can be calculated with code such as COSMO. Calculations and measurements agree to within a factor of ~2. [Martoff et al., Comput. Phys. Commun. 72:96 (1992)]

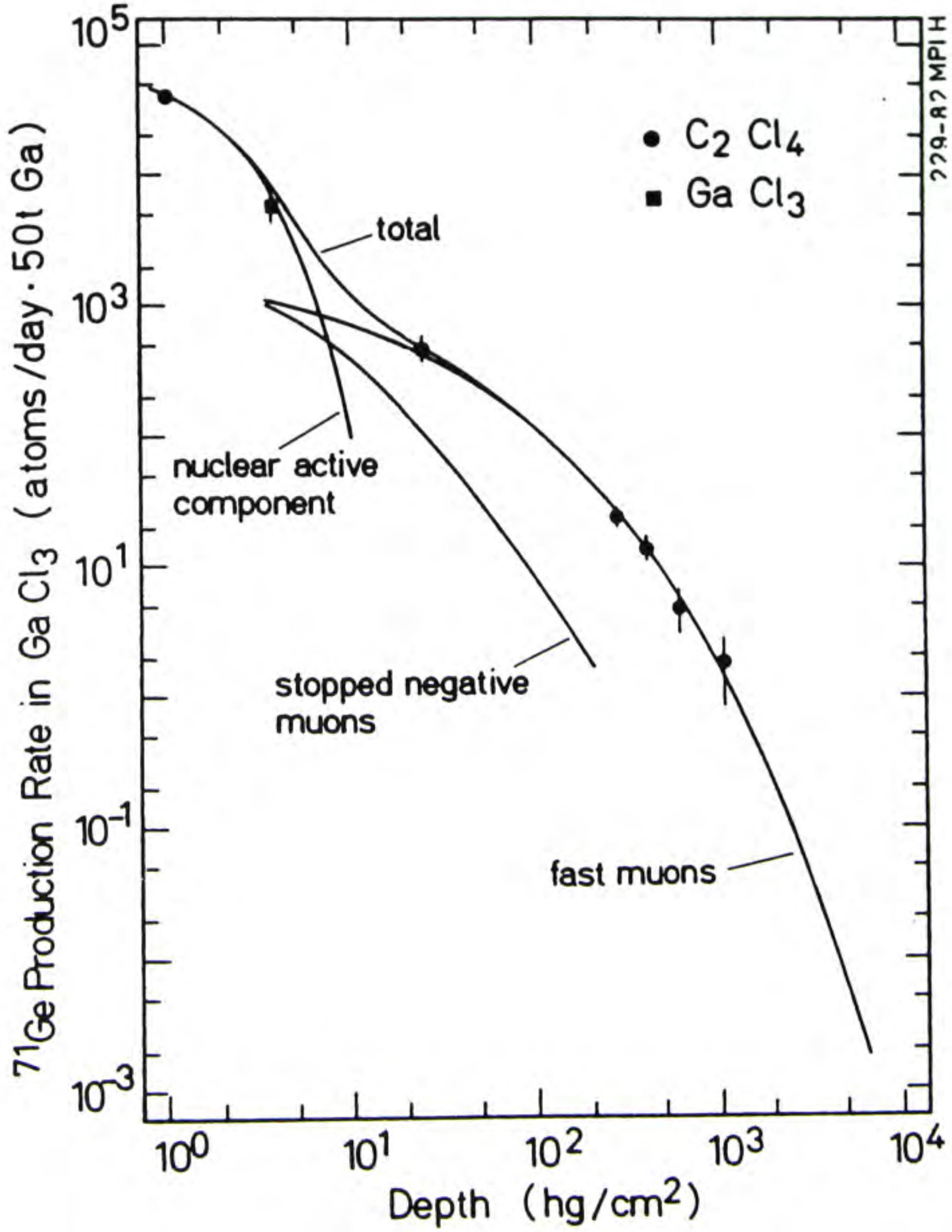
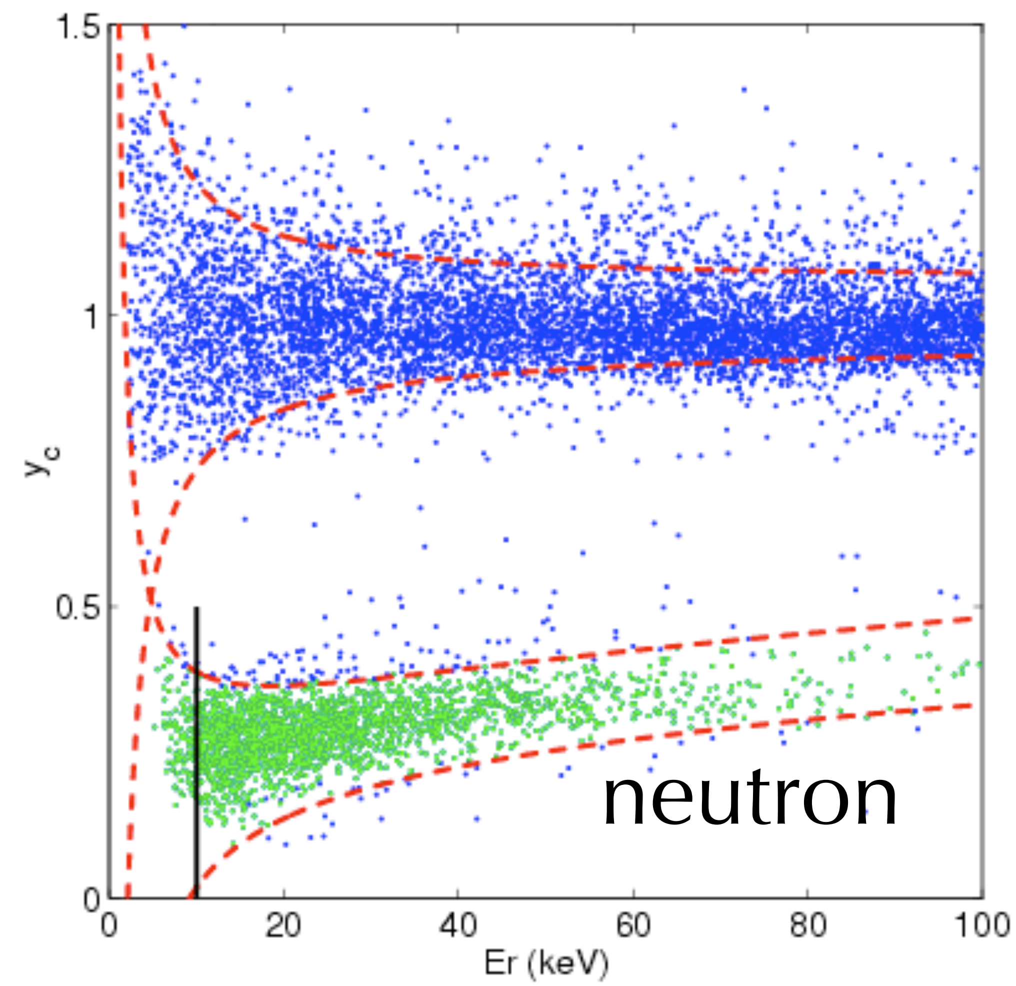


Figure 3 Cosmic ray production of ^{71}Ge in $GaCl_3$ vs shielding depth.

Heusser, Annu. Rev. Nucl. Part. Sci. 45: 543 (1995)

Neutron Backgrounds

- "Cosmic" and "Environmental"
  - Cosmic: muon-induced
  - Environmental: Mostly from U and Th in rock
- Neutrons are hard to tag:
  - No charge
  - can be produced in the surrounding rock
- Why do we care about neutrons?
  - May directly simulate a signal event in many underground experiments, e.g. neutrons as fake WIMPs.
  - May produce gamma rays through (n,γ) and (n,n′γ) processes in the detector or its shielding.
  - May produce long-lived radioactive isotopes



CDMS

Neutron Backgrounds

- At deep sites, the main source of neutron backgrounds is usually the rock.

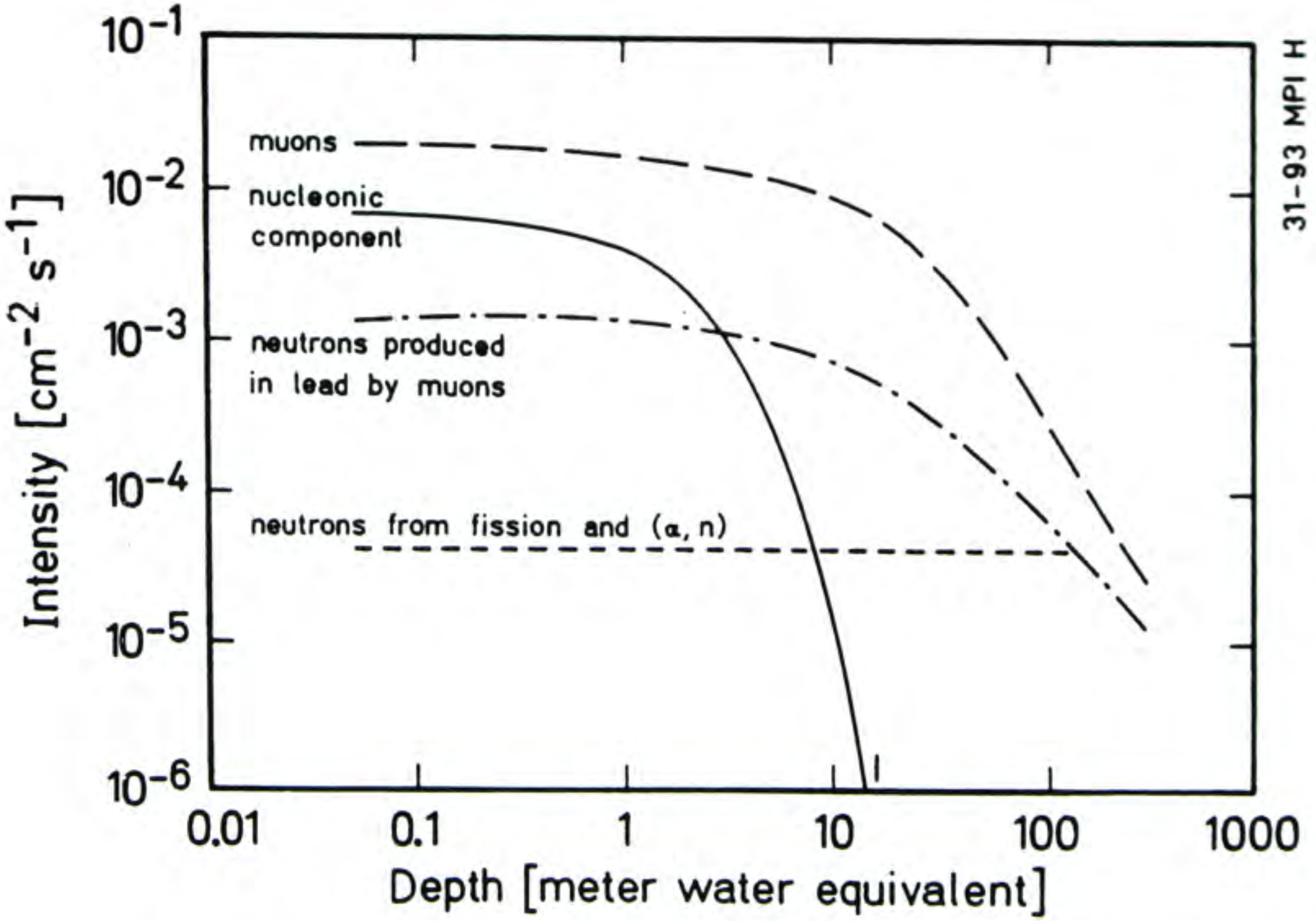


Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.

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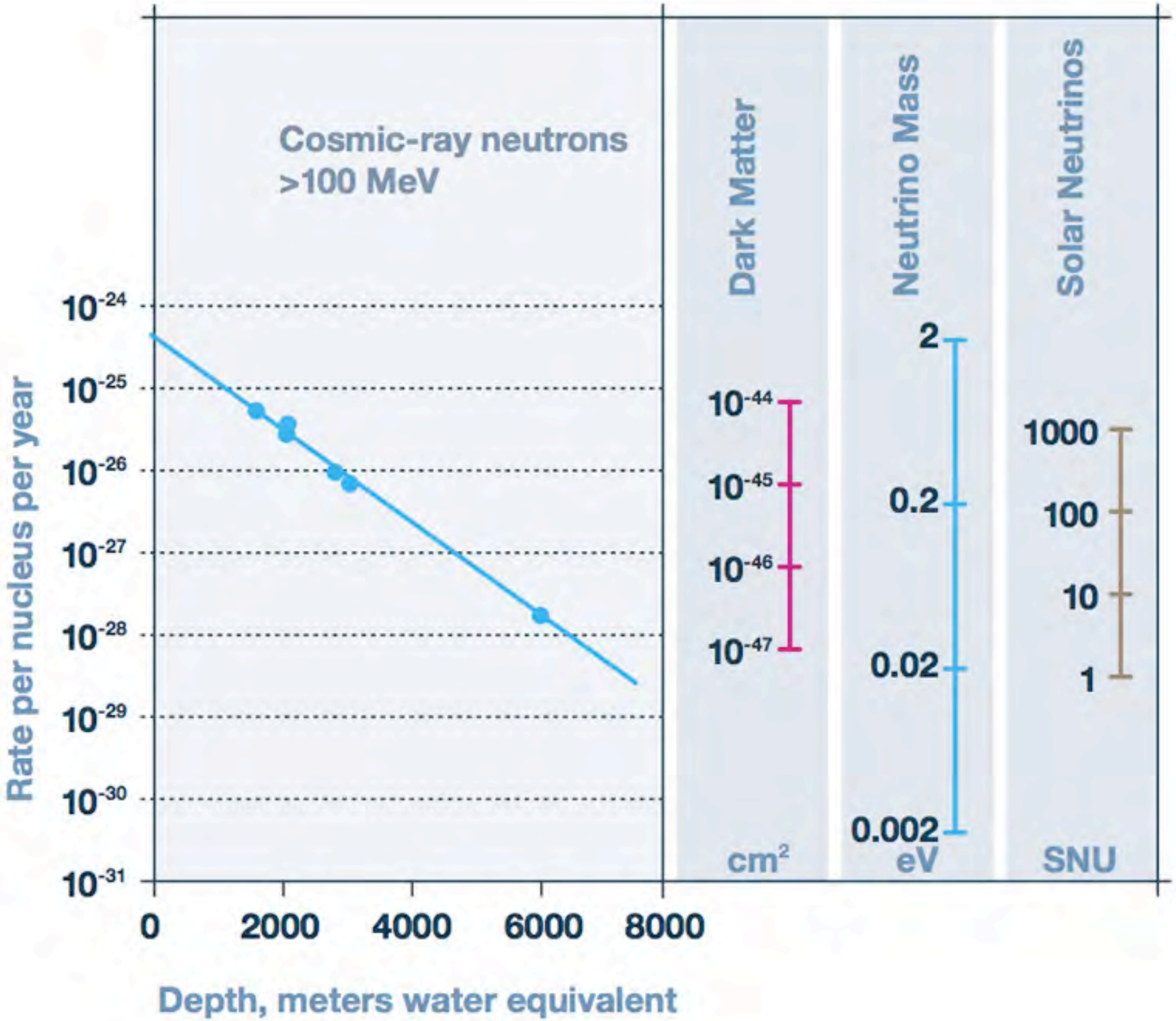
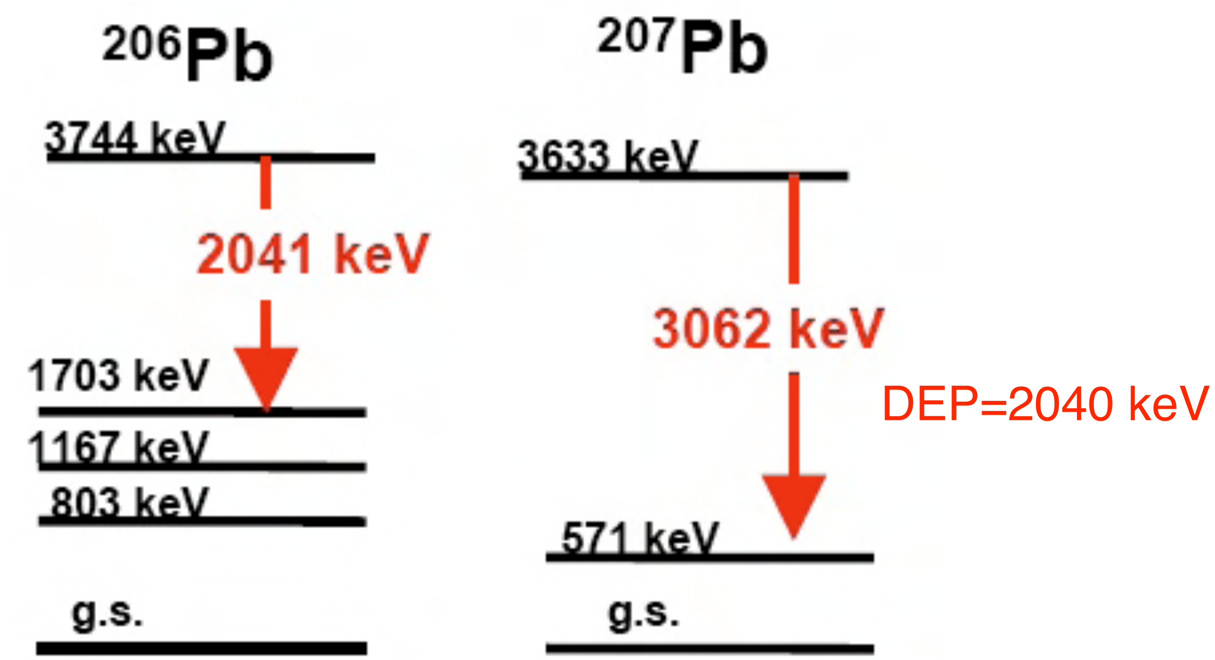
Why do we care about cosmic neutrons?

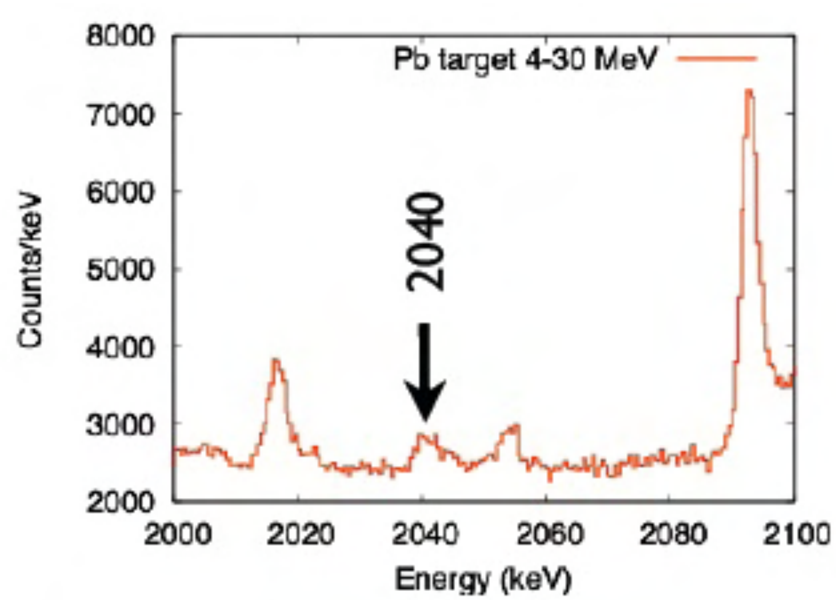


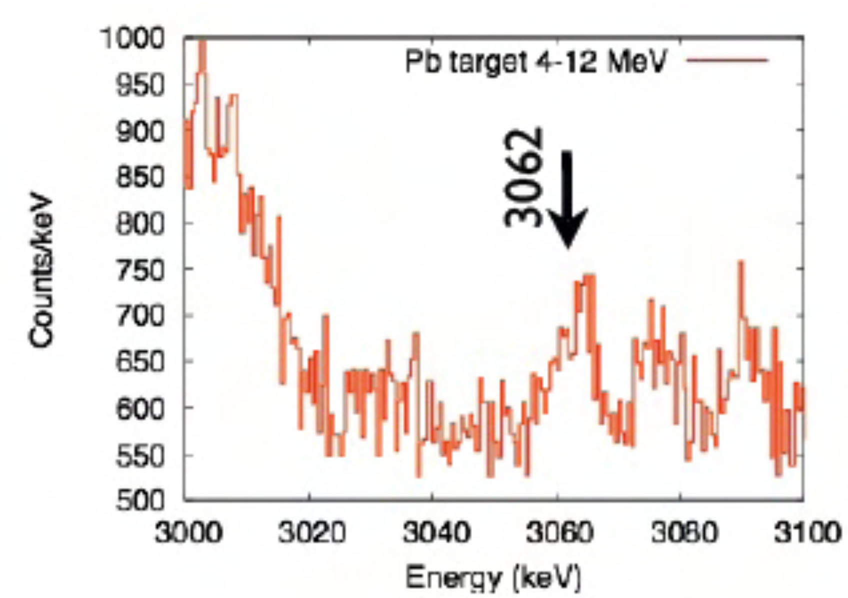
Deep Science

Neutron-Induced Backgrounds (An Example)

- Fast neutron interactions can excite these levels in Pb (a common low background experiment shielding material). See Chan's talk







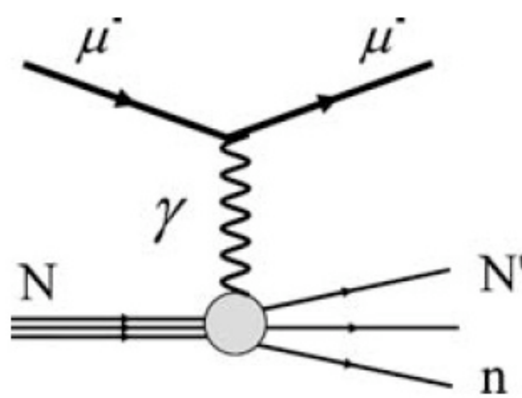
Elliott

The problem: Q value for ^{76}Ge $\beta\beta$ is 2039 keV.

Production of Cosmic-Induced Neutrons

- μ⁻ capture: $\mu^- + \mathrm{A(Z, N)} \rightarrow \nu_\mu + \mathrm{A(Z-1, N+1)}$
  - capture rate ~Z^4
- Electromagnetic showers generated from cosmic μ.
  - cross section ~Z^2
- μ spallation via virtual photon exchange
  - At high energy $\sigma_{\gamma N} = 67.7 s^{0.0808} + 129 s^{-0.4525}$

$$s \equiv 2 m_n E_\gamma$$



- μ-nucleon quasi-elastic scattering

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} G_M^2(-Q^2)\left[\frac{Q^2/4M_n^2}{(1-Q^2/4M_n^2)} + \left(\frac{Q^2}{2M_n^2}\right)\tan\frac{\theta}{2}^2\right]$$

- Secondary neutron production from any of the above processes

Formaggio & Martoff, and references therein

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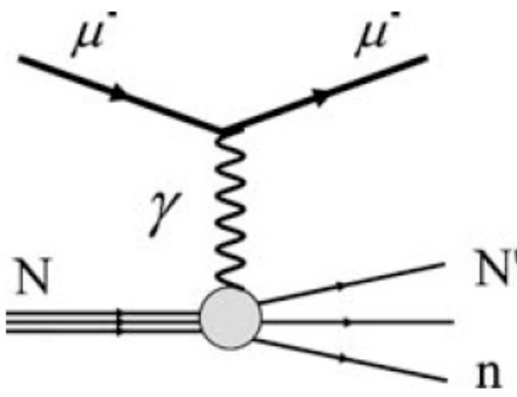

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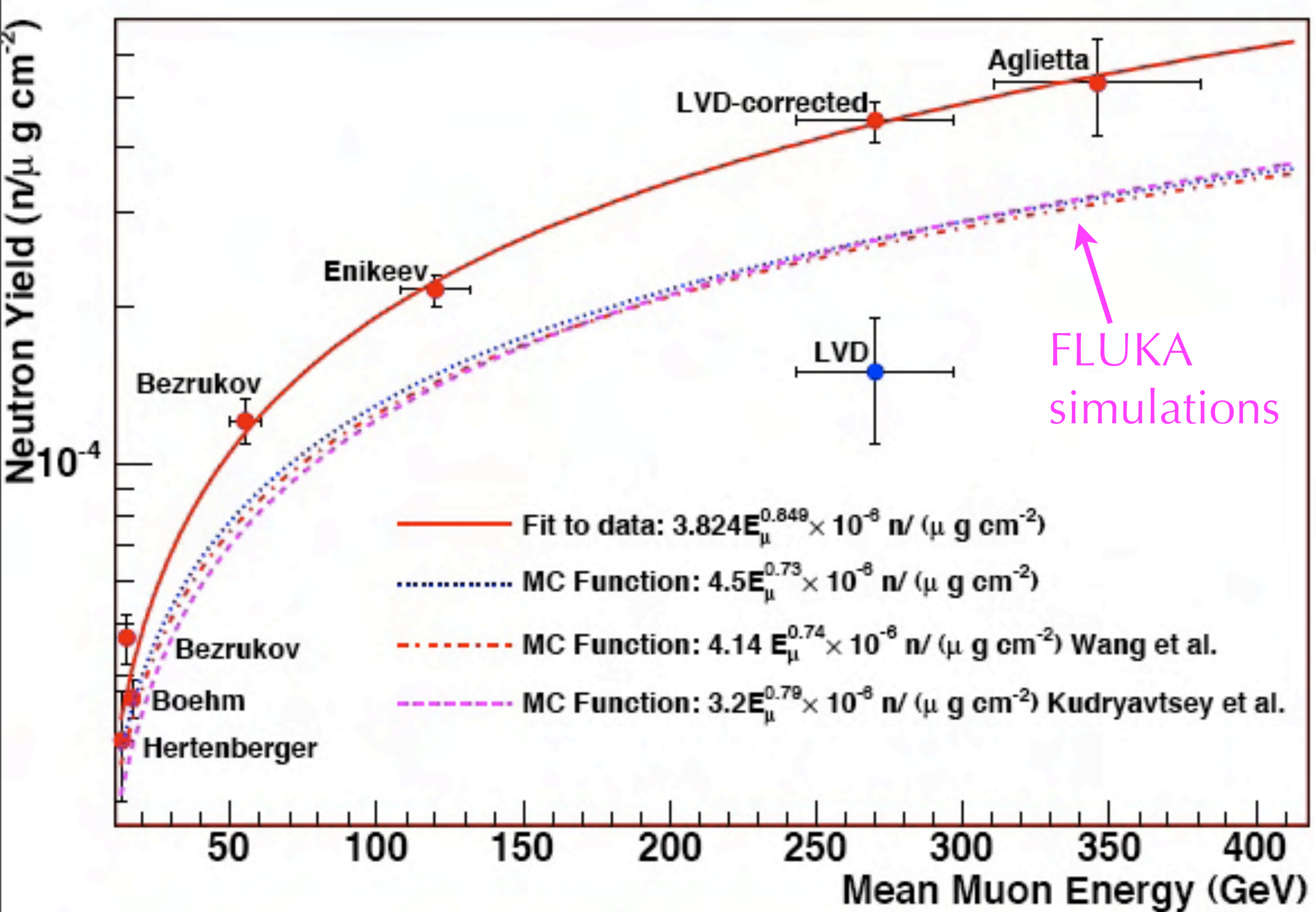
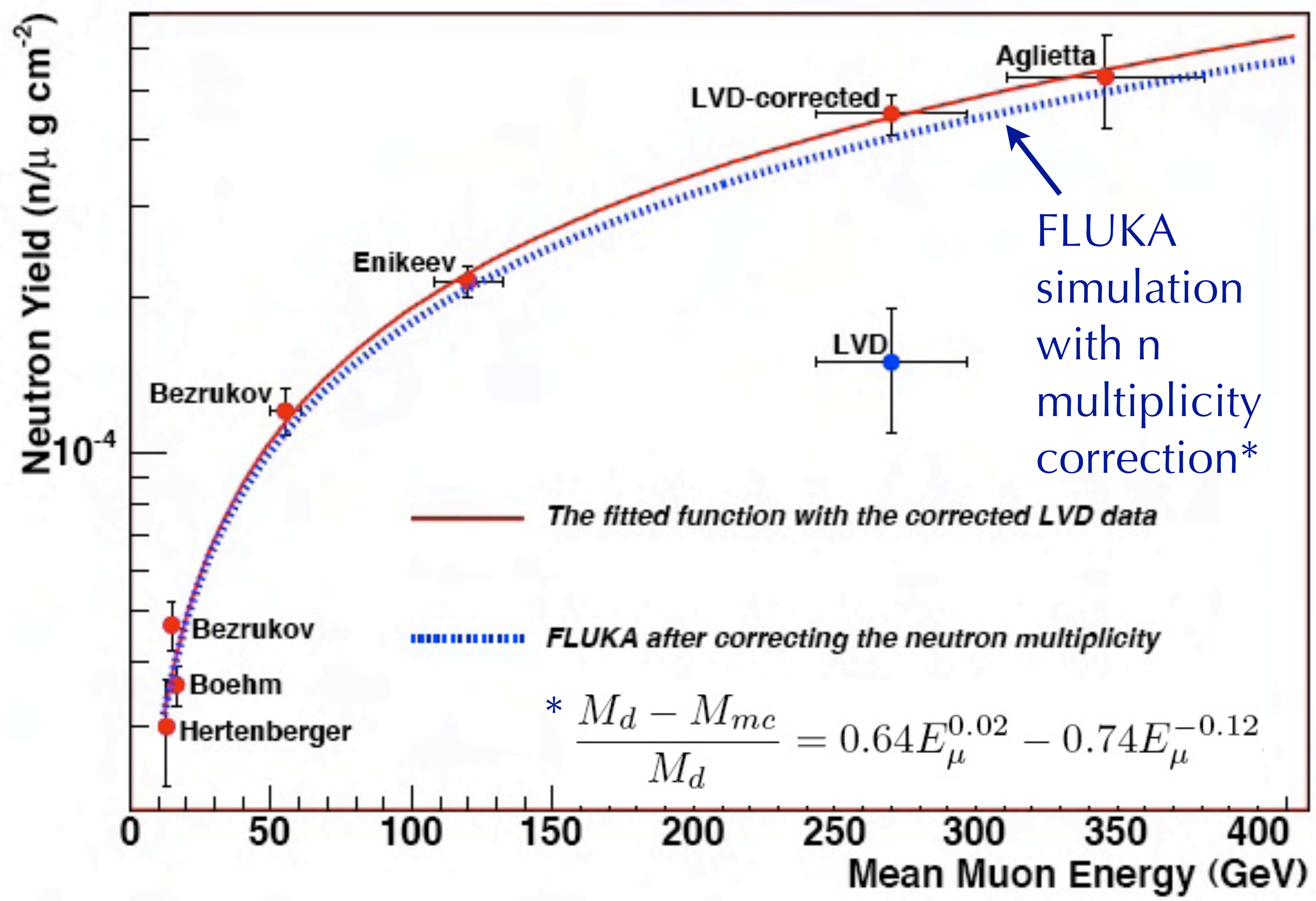
When in doubt, GO DEEP

Formaggio & Martoff, and references therein

Cosmic-Induced Neutrons

Depth Dependence





Mei & Hime, 2005

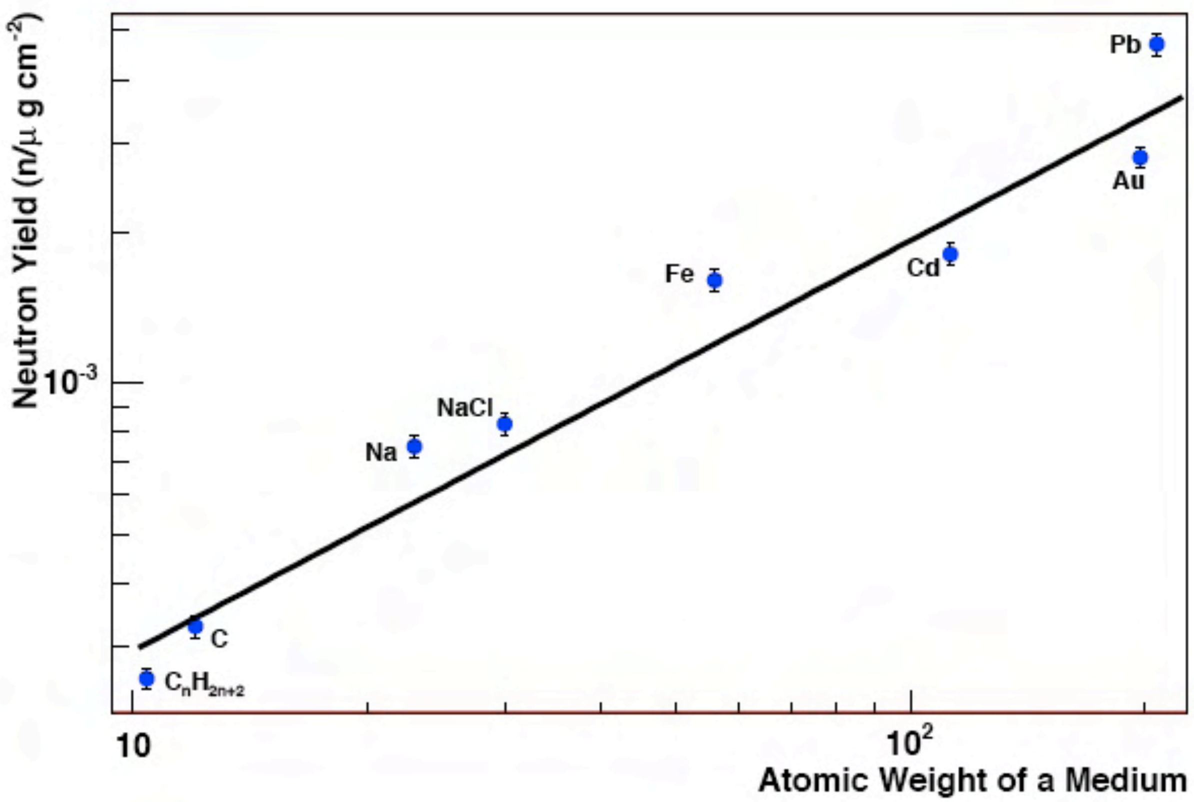
Notes:

- Data are somewhat controversial, and are mostly from light targets
- Models need further tests

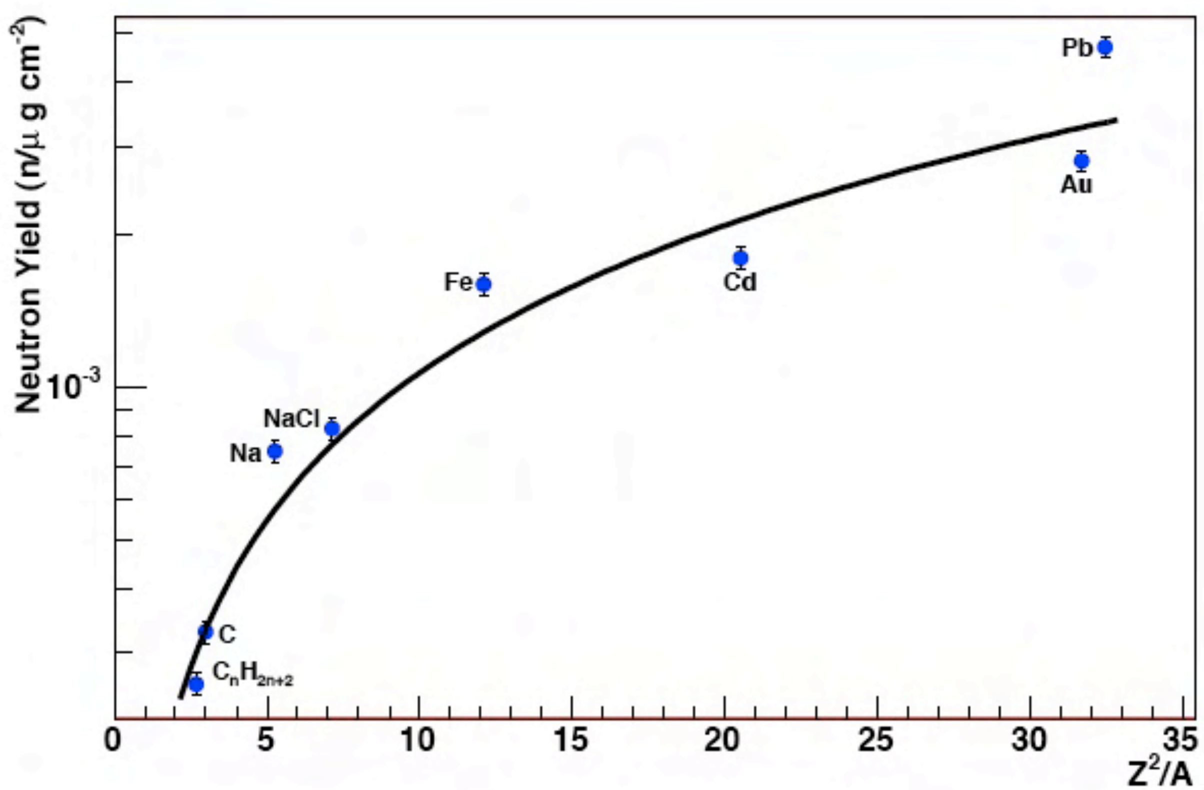
Cosmic-Induced Neutrons

Atomic Weight Dependence

- Usual parameterization for neutron yield is $\sim A^{\beta}$.



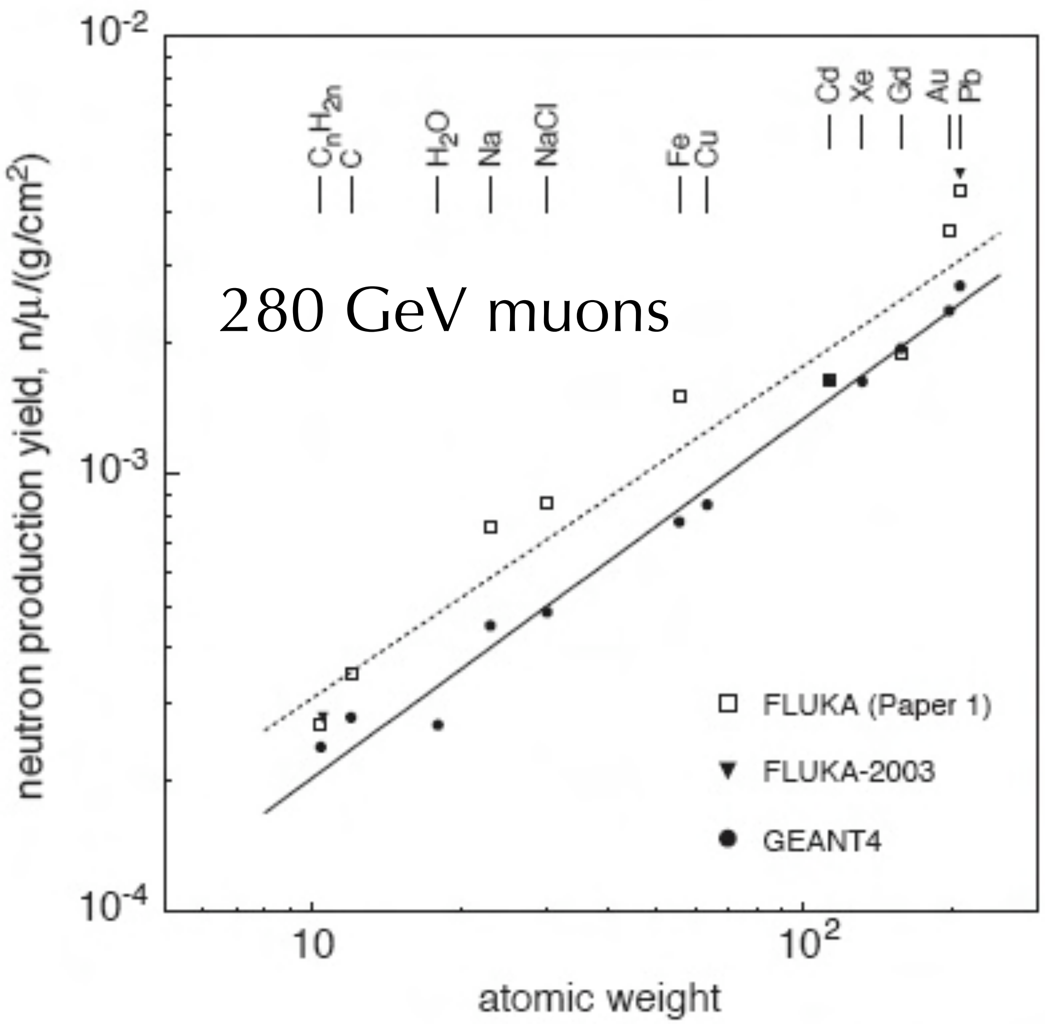
$$< n > = 4.54 \times 10^{-5} A^{0.81} n/(\mu\ g\ cm^{-2})$$



$$< n > = 1.27 \times 10^{-4} (\frac{Z^2}{A})^{0.92} n/(\mu\ g\ cm^{-2})$$

Mei & Hime, 2005

Cosmic-Induced Neutrons



- GEANT4 and FLUKA agree to within a factor of ~2
- They seem to under-estimate the induced neutron flux
- Need underground data as NA55 is a thin-target measurement.

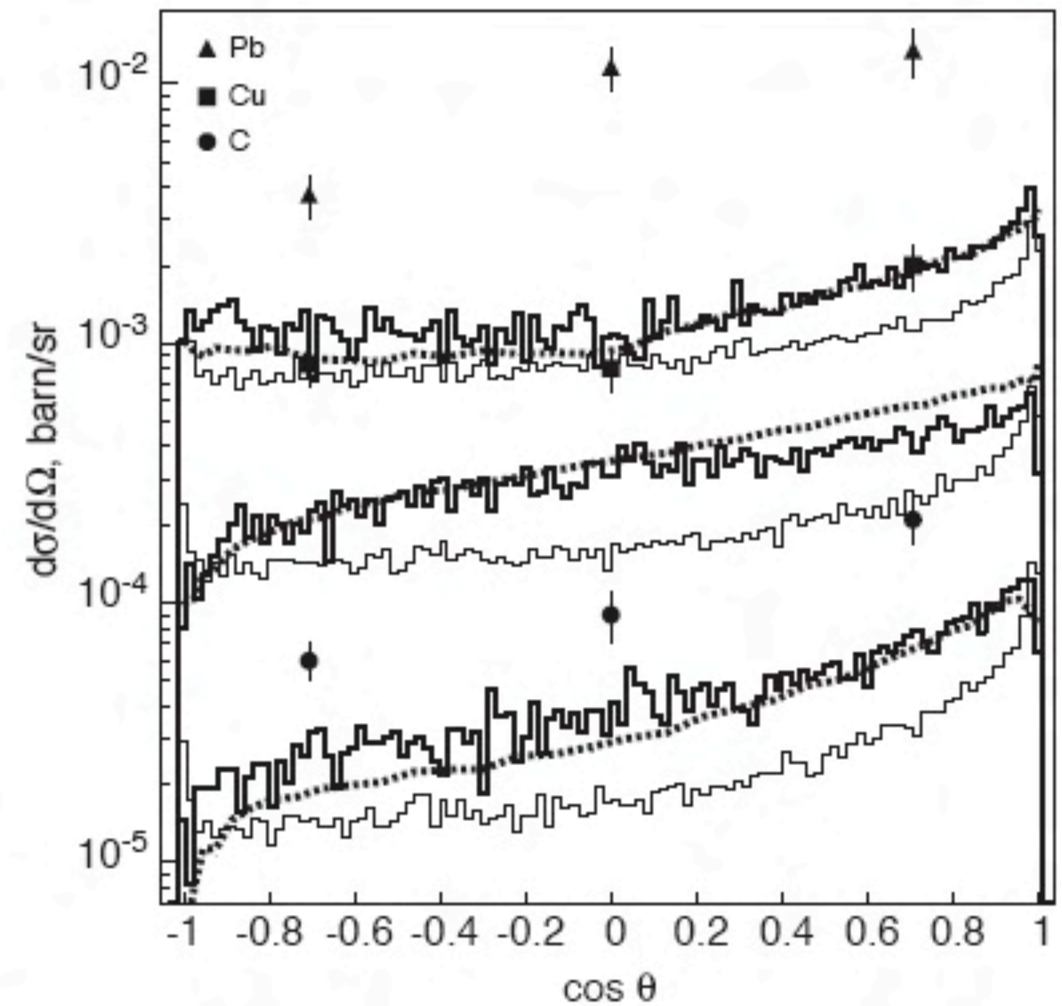
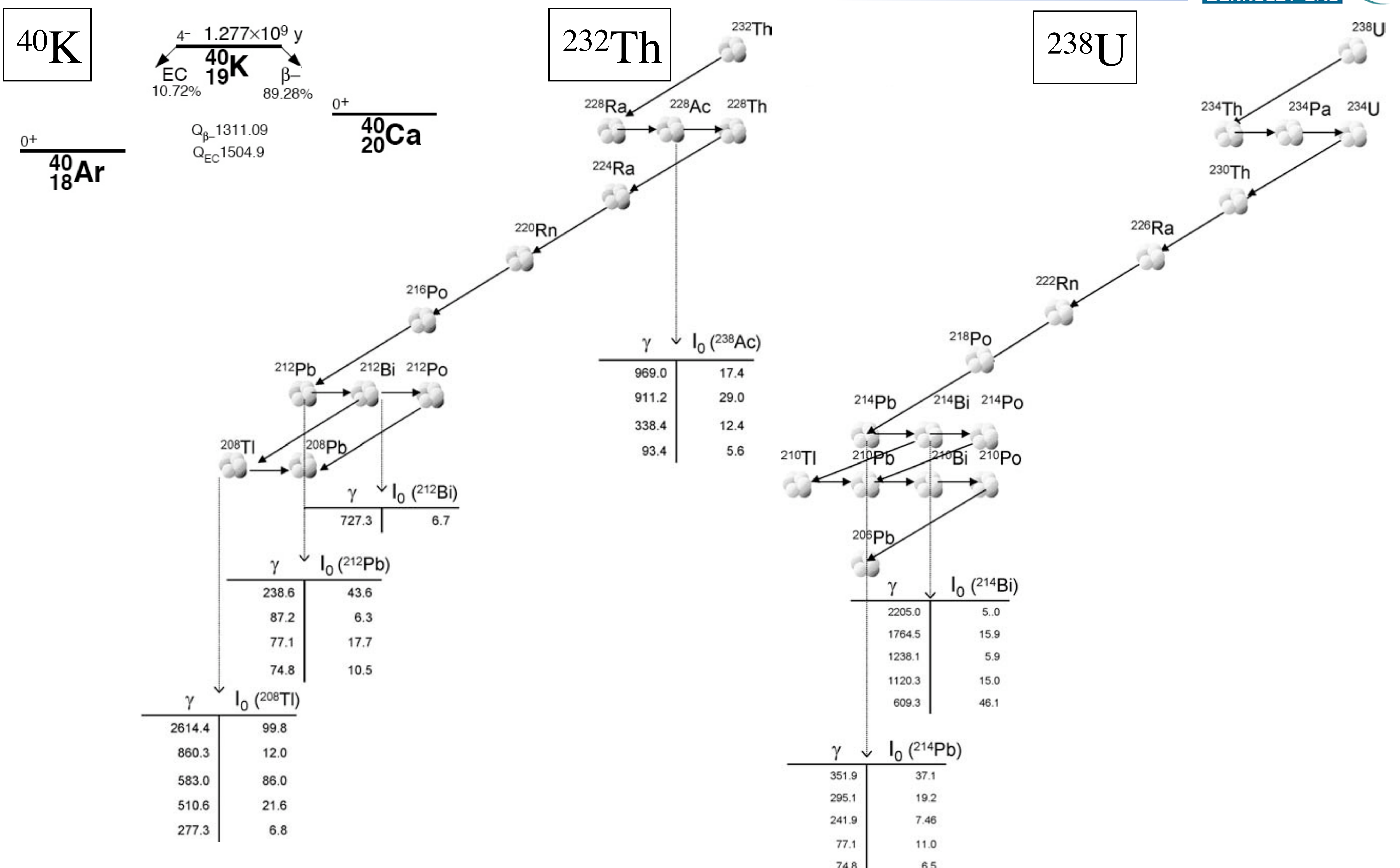


Fig. 7. Differential cross-section of neutron production by 190 GeV muons for a 10 MeV threshold in neutron energy. The data points represent the results of the NA55 experiment. The thin-line histogram shows the GEANT4 simulation considering muon–nucleus interaction only; the thick histogram includes all physics processes. The dashed line represents the FLUKA results for the latter case.

Araujo et al., NIM A545 (2005) 398

Primordial Radioactivities



"Environmental" Neutrons

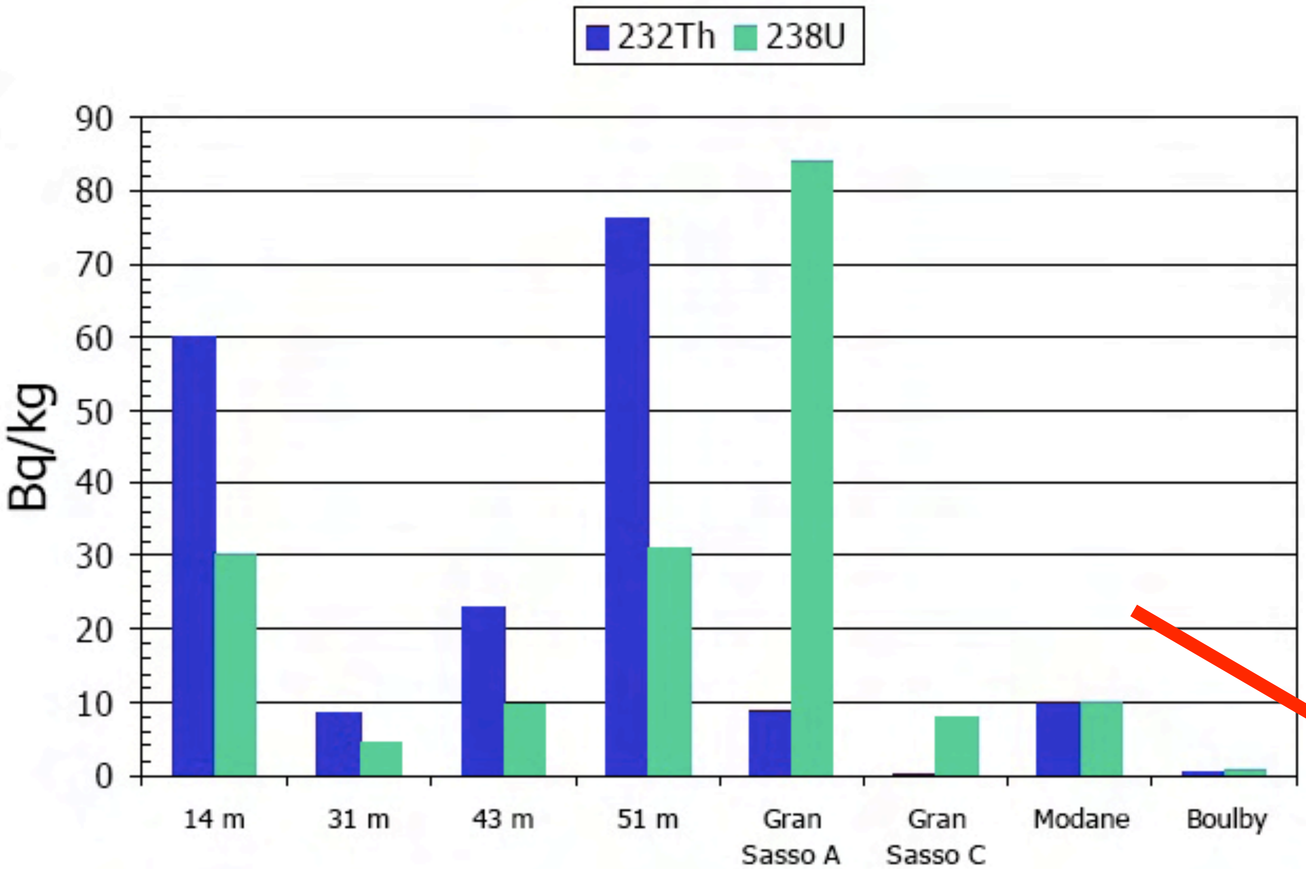
- The origin of the most dominant neutron backgrounds in "deep" underground labs can be traced to primordial U and Th in the rock or construction material of the laboratory:
  - Spontaneous fission of ^{238}U, ^{235}U and ^{232}Th
    - Mostly ^{238}U (SF BR=5.45×10^{-7}, ~2 n/fission)
  - (α,n) reaction
    - U chain: ^{218}Po(6.0 MeV), ^{214}Po(7.7 MeV), ^{210}Po(5.3 MeV)
    - Th chain: ^{216}Po(6.8 MeV), ^{212}Po(8.8 MeV)

TABLE 9 Uranium and thorium concentrations for various types of rocks, along with estimates on neutron production from such sources. Granite types A, B, and C are from rock samples taken in Karkonosze, Poland. Salt types I and II are from Wieliczka Salt Mine, Poland. Tabulation from Reference (144) with permission

Type of rock	U (ppm)	Th (ppm)	U(α, n)	Th(α, n)	Fission	Total yield
	Concentration (ppm)		(neutrons/g/y)			
Granite	5	11	7.85	7.755	2.33	17.9
Limestone	1	1	0.64	0.285	0.467	1.4
Sandstone	1	1	0.837	0.38	0.467	1.7
Granite A	1.32	7.79	2.24	5.92	0.62	8.8
Granite B	6.25	4.59	10.62	3.49	2.92	17.0
Granite C	1.83	4.38	3.11	3.33	0.85	7.3
Salt I	0.30	2.06	1.60	4.77	0.14	6.5
Salt II	0.13	1.80	4.17	0.69	0.06	4.9

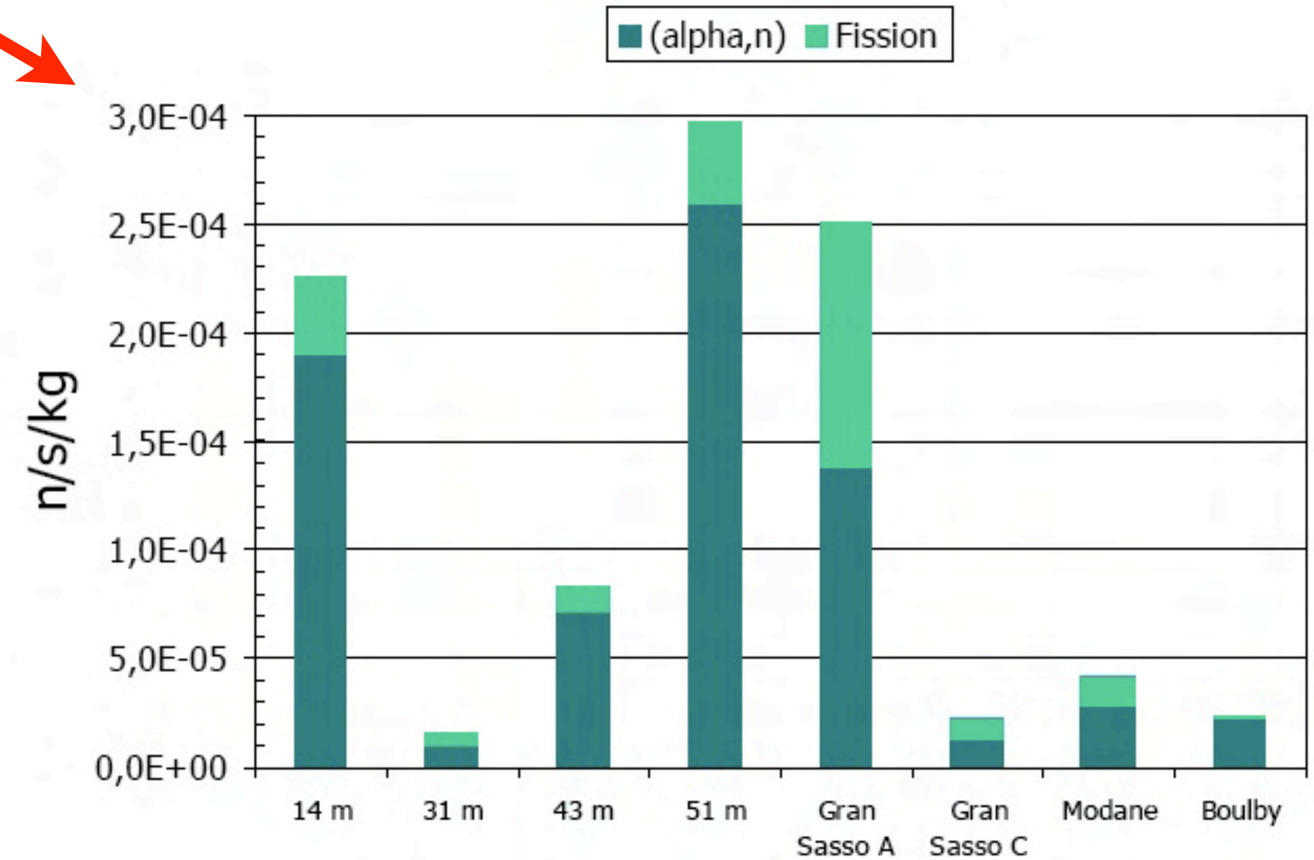
Formaggio & Martoff and references therein

(α, n)



Gran Sasso:	Astroparticle Physics 22 (2004) 313
Modane:	Astroparticle Physics 9 (1998) 163
Boulby:	Astroparticle Physics 22 (2004) 409

(α, n) rate calculation
ALPHN



Gran Sasso:	Astroparticle Physics 22 (2004) 313
Modane:	IDM2002 proceedings
Boulby:	Astroparticle Physics 22 (2004) 409

J. Amare et al.

Primordial Radioactivity

- α, β and γ from radioactive decays of primordial directly impacts most low background experiments.
  - "detector intrinsic"
  - "environment"
- Achieve high levels of radio-purity via:
  - material screening
  - purification
  - careful material handling and cleaning during construction and operation
  - shielding

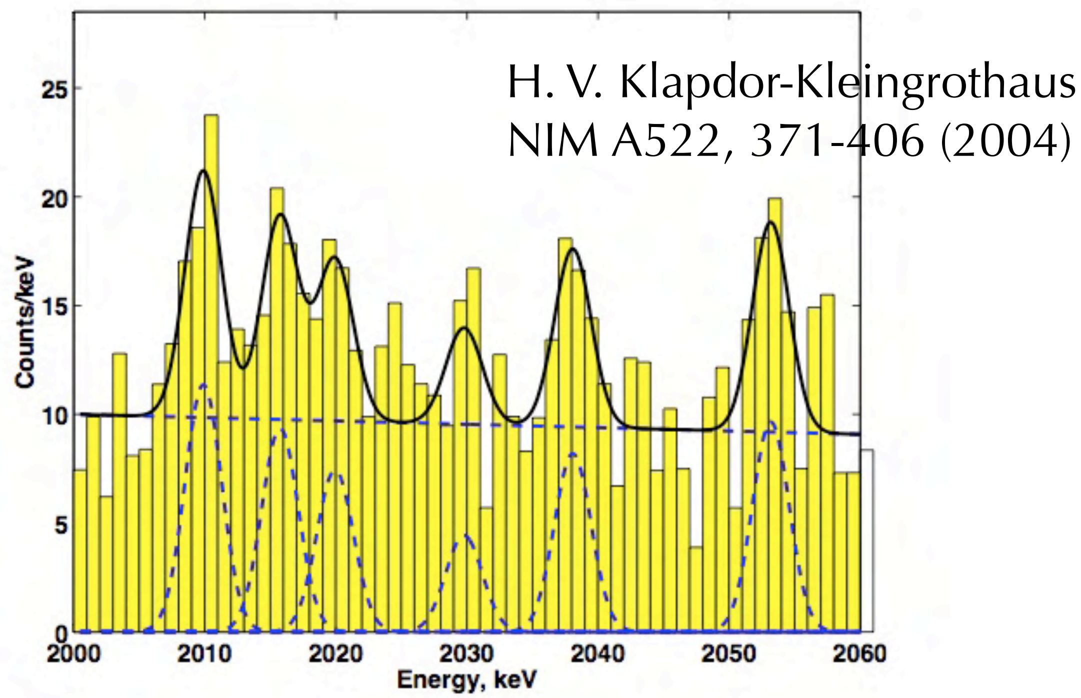


Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

GERDA-II MC
Tomei, DBD06

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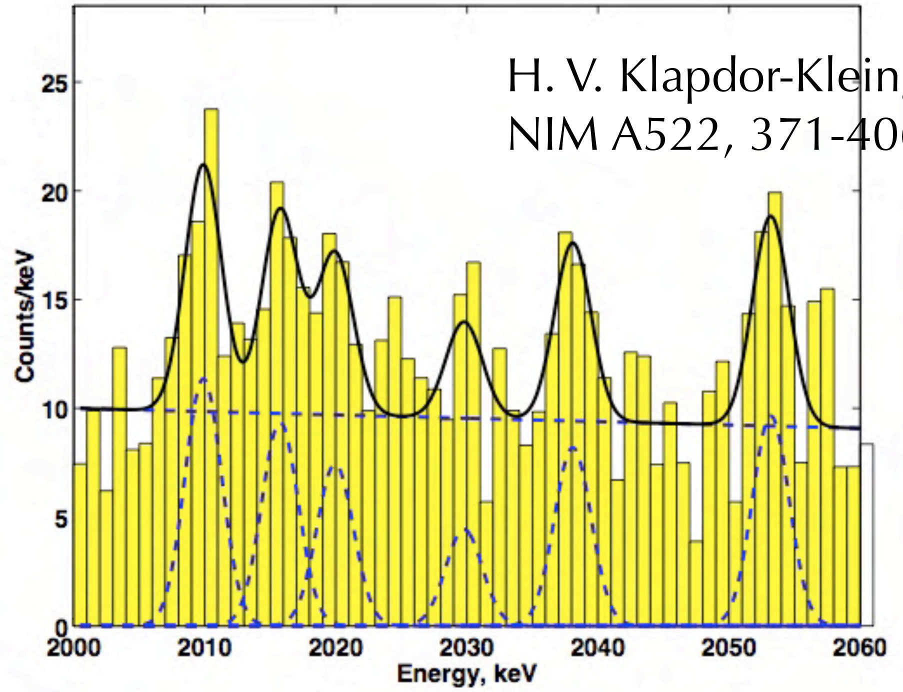

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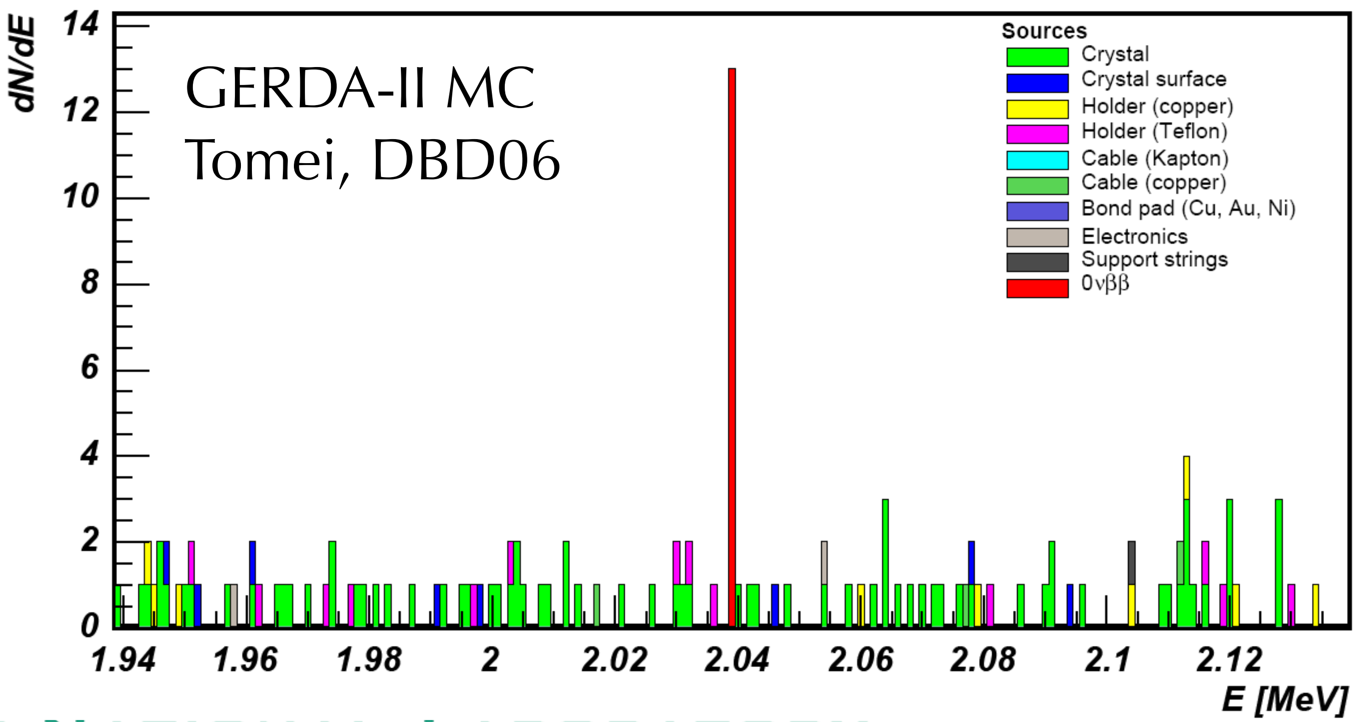


Material Screening

- Individual experiments have to ensure the cleanliness of their systems.
  - Multiple counting methods/facilities
  - Multiple vendors, individual production batches
  - Stockpiling of clean materials in suitable storage
- Example: EXO-200

#	Material	Method	K conc. $[10^{-9} g/g]$	Th conc. $[10^{-12} g/g]$	U conc. $[10^{-12} g/g]$
		Bulk Copper			
1	Norddeutsche Affinerie, NOSV copper made May 2002.	Shiva Inc. GD-MS	0.4	<5	<5
2	Norddeutsche Affinerie, NOSV copper made May 2002.	Ge	<120	<35	<63
3	Norddeutsche Affinerie OFRP copper made May 2006, batch E263/2E1.	ICP-MS	<55	<2.4	<2.9
4	Norddeutsche Affinerie OFRP copper made May 2006 batch E262/3E1.	ICP-MS	<50	<2.4	<2.9
5	Rolled Norddeutsche Affinerie OFRP copper, May 2006 production. Rolled by Carl-Schreiber GmbH.	ICP-MS	-	<3.1	<3.8
6	TIG welded Norddeutsche Affinerie OFRP copper made May 2002. No cleaning after welding. Result are normalized to length of weld.	ICP-MS	-	<9.8 pg/cm	10.2±3.4"pg/cm
7	Valcool VNT 700 metal working lubricant, concentrate.	A.G. Ge	38000±11000	<10000	<3700
8	Water alcohol mixture, lubricant for machining of Cu parts.	A.G. Ge	<44000	<18000	<3800

Nucl. Instrum. Meth. A591:490-509,2008.

Assay Techniques

- "Common" assay techniques:
  - Direct γ counting with Ge detectors [~10^{-12} gU(Th)/g]
  - Neutron Activation Analysis (NAA) [~10^{-14}-10^{-15} gU(Th)/g]
  - Mass Spectroscopy [~10^{-12}-10^{-13} gU(Th)/g]
    - Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS)
    - Gas Discharge-Mass Spectroscopy (GD-MS)
  - Emission Spectroscopy
    - X-Ray Fluorescence
    - Inductively Coupled Plasma-Emission Spectroscopy (ICP-ES)
- Target-specific procedures
  - Example:
    - Extraction of 224Ra and 226Ra using manganese oxide (MnOx) and hydrous titanium oxide (HTiO) compounds to assay water with sensitivity of ~10^{-16} g/g. [NIM A501, 386 (2003), NIM A501, 399 (2003)]

HPGe Counting System

- An example:

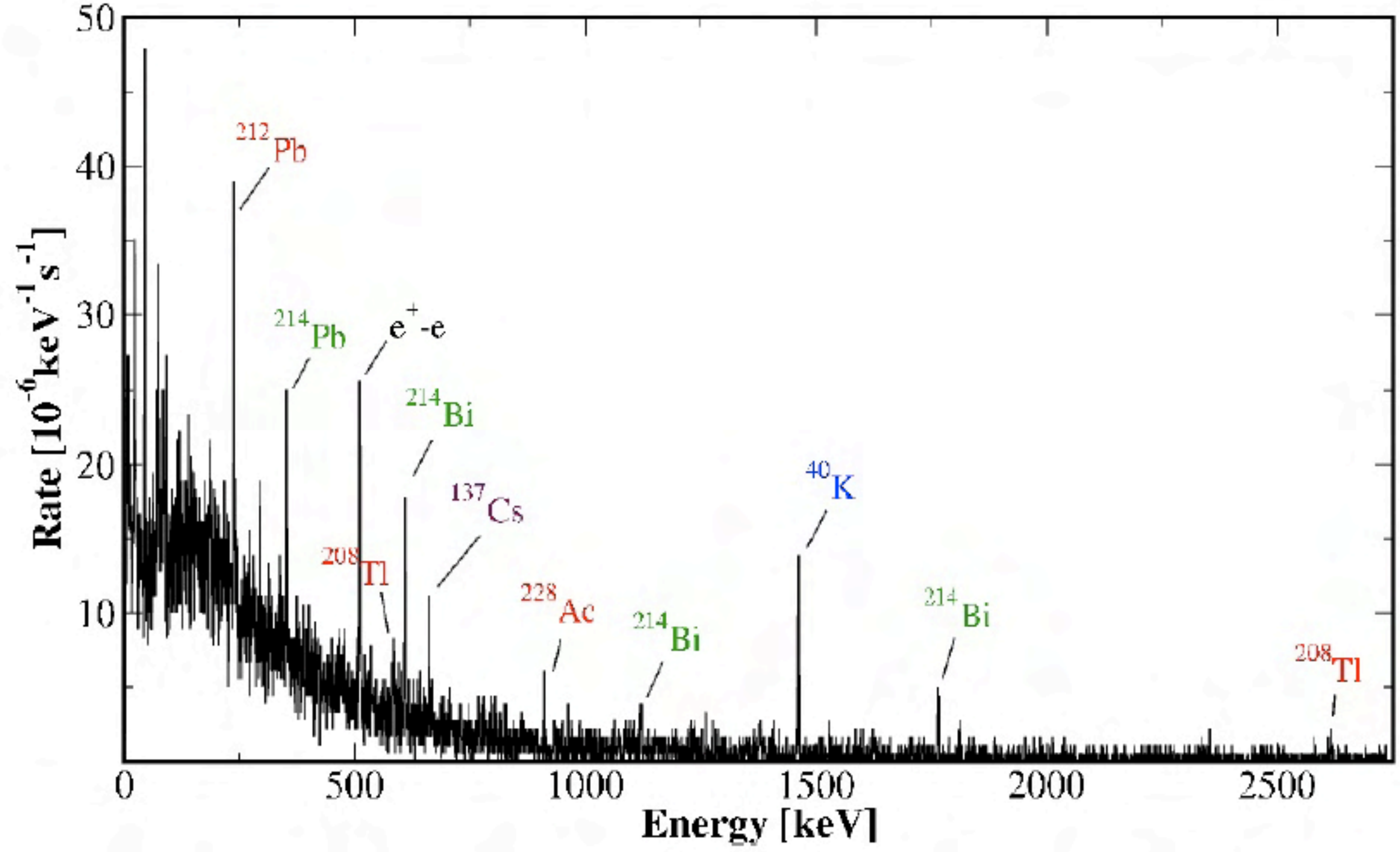
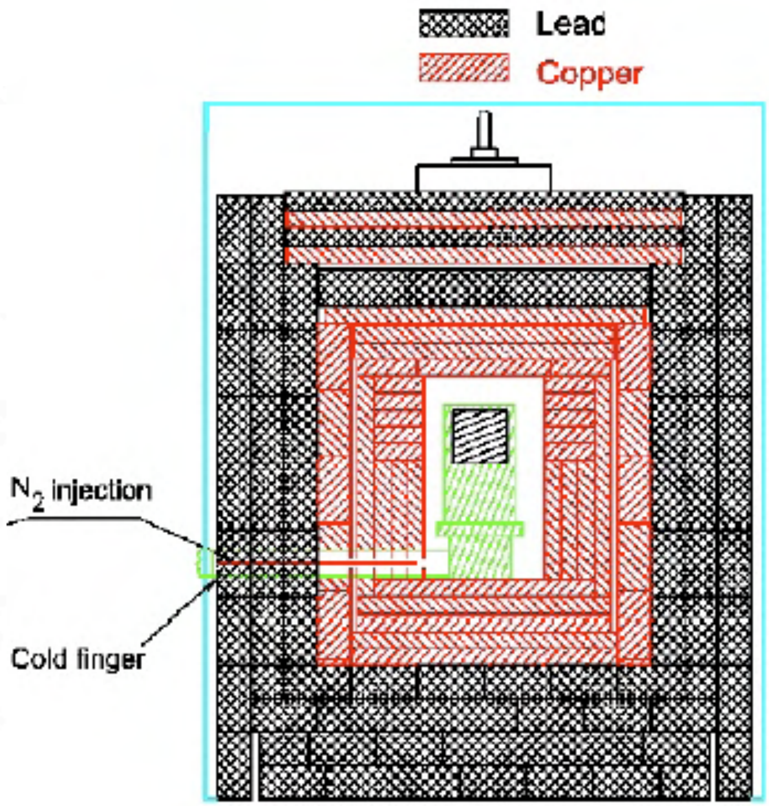


Fig. 3. Underground germanium background spectrum, measured with no sample for 672 h. Gamma lines from natural activities, namely the ^{232}Th (^{208}Tl, ^{228}Ac, ^{212}Pb) and ^{238}U (^{214}Bi, ^{214}Pb) chains, ^{40}K, as well as the ^{137}Cs line from an artificial activity, are indicated.



Nucl. Instrum. Meth. A591:490-509,2008.

Network of HPGe Counting Systems

- Systems with different overhead burden and intrinsic detector backgrounds. Optimize counting efficiency and throughput.

- Example: The Collaboration of European Low Level Underground Laboratories (CELLAR)

- Some collaborations have their own smaller networks.

Table 1
List of the underground facilities of the CELLAR network members

Institute	Underground laboratory	Depth (m w.e.)	HPGe-detectors Integral counting rate [d^{-1} kg^{-1}] (40–2700 keV)	Detector type	Main activity
ARC Seibersdorf research (Schwaiger et al., 2002)	(Austria)	ca. 1	8200 ± 200	p-type extended range	Environmental radioactivity, CTBT
Max-Planck-Institut für Kernphysik, Heidelberg (Heusser, 1986)	Low-level laboratory (Germany)	15	2012 ± 23	p-type coaxial	Rare events research and detector development
IAEA-MEL (Povinec, 2002)	CAVE (Monaco)	35	840 ± 50	p-type well	Environmental radioactivity
VKTA (Niese et al., 1998)	Felsenkeller (Germany)	110	3870 ± 30	p-type well	Environmental radioactivity
University of Iceland (Theodórsson, 2003)	(Iceland)	350	—	—	Studies of background components in radiation detectors
IRMM (Hult et al., 2003)	HADES (Belgium)	500	260 ± 4	p-type coaxial	Reference measurements
PTB (Neumaier et al., 2000)	UDO in the salt mine Asse (Germany)	2100	277 ± 4	p-type extended range	Reference measurements
LNGS (Arpesella, 1996)	Gran Sasso (Italy)	3800	87 ± 1	p-type coaxial	Radiopurity of construction materials to support to rare event experiments
LSCE (Reyss et al., 1995)	Modane (France)	4800	30 ± 1 186 ± 2	p-type coaxial p-type well	Environmental radioactivity

M. Laubenstein et al. / Applied Radiation and Isotopes 61 (2004) 167–172

Radiopurity Database

Welcome to the ILIAS database on radiopurity of materials

This site is part of the ILIAS program, a common European project for the development of the underground science.
Data sources: *UKDM Collaboration (Boulby Mine), ANAIS, CAST, ROSEBUD Collaborations (Canfranc Underground Laboratory), EDELWEISS (Laboratoire Souterrain de Modane), BOREXINO (Gran Sasso)*

The database provides access to radionuclide concentration in materials commonly used in low background experimental set-ups. The measurements have been performed by groups involved in experiments which require extremely low backgrounds.

While this data is an useful guide for material selection, the radionuclide concentration may vary depending on the lot. Therefore, it is necessary to control all used materials when building low background set-ups.

Search radionuclide concentration:

Acrylic | Search

http://radiopurity.in2p3.fr/

Radiopurity Database

- PMT

Material	Measured by	Method	^{238}U (ppb)	^{232}Th (ppb)	^{40}K (ppm)	Comments
PM bulb (Hamamatsu R5912)	Supplier's data	GES?	81	74	97	Measurements reported as Bq/kg or (raw) counts/1000s/100g.
PM bulb (Hamamatsu R7081)	Supplier's data	GES?	537	36	122	
PM tube (Burle 5")	J.C. Barton	GES	< 200	< 200	~ 2000	assume 100g glass.
PM tube, ceramic (EMI) `small'	J.C. Barton	GES	~ 200?	~. 200?	50(50)	U + Th 400 ppm
PM tube, ceramic (EMI) `large'	J.C. Barton	GES	~250?	~250?		U + Th 500 ppm
PM tube, low b/g (EMI)	Supplier's data	GES?	250(40)	200(50)	90(40)	
PM tube, low b/g (EMI 5" 9390B53)	Supplier's data		27(20)	33(8)	74(16)	
PM tube (ET 9823B)	Supplier's data	GES?	245(9)	280(9)	340(17)	
PM tube (ET 9823QB)	Supplier's data	GES?	215(13)	240(13)	1400(110)	quartz window
PM tube, 8" (ET 9354B)	Supplier's data	GES?	30(17)	30(10)	70(17)	low b/g
PM tube (Hamamatsu R1250)	Supplier's data	GES?	307	306	17900	Measurements reported as Bq/kg or (raw) counts/1000s/100g.
PM tube (Hamamatsu R1250)	Supplier's data	GES?	309	306	464	"Low RI" faceplate. Measurements reported as Bq/kg or (raw) counts/1000s/100g.

http://radiopurity.in2p3.fr/

Radon

- What you can't see and smell can kill your experiment.

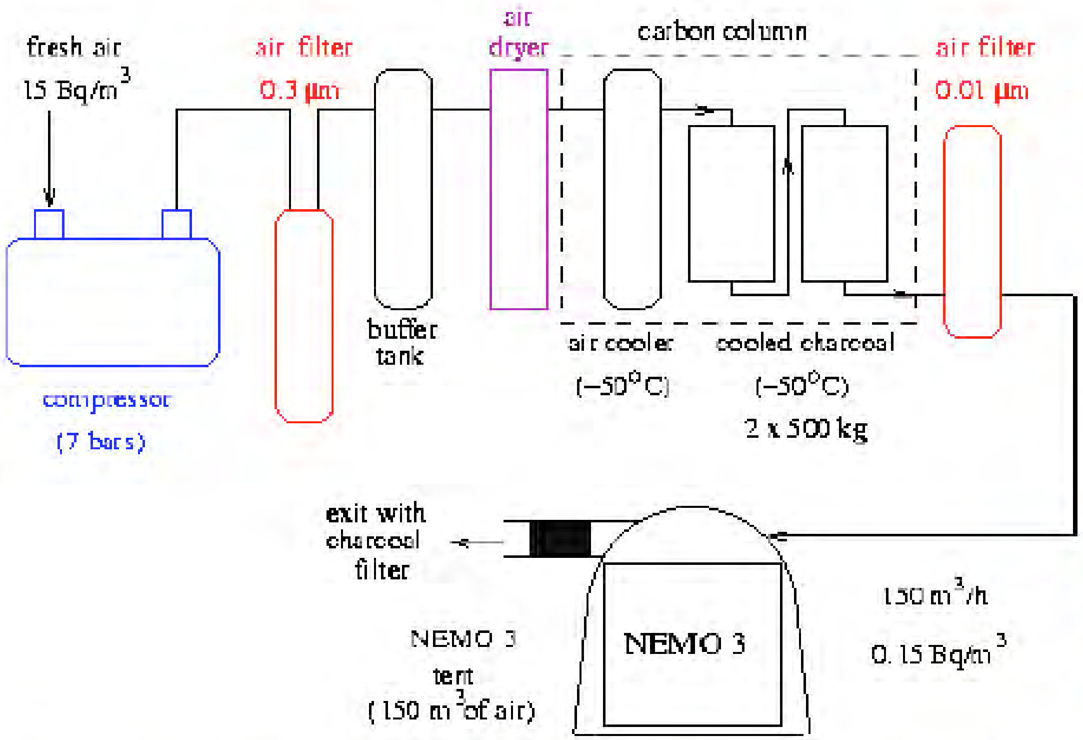
- ^{220}Rn ($\tau_{1/2}$=56 sec)... → ^{212}Pb ($\tau_{1/2}$=11 h)
- ^{222}Rn ($\tau_{1/2}$=3.8 d)... → ^{210}Pb ($\tau_{1/2}$=22 y) A bigger enemy!

Rn

- ^{222}Rn concentration is higher in an underground facility than on surface.
  - Kamioka mine tunnel: ~1200 Bq m^{-3} [Phys. Lett. 452, 418 (1999)]
  - SNO underground lab: 123±13 Bq m^{-3} or 60,000 atoms/l.
  - Surface ~1/10 to 1/20 as much
- Why Rn is a problem?
  - Rn daughters plate out electrostatically onto surfaces
  - Some fraction might be transferred to active detector volume by leaching.
- Techniques based on charcoal adsorption have been used which suppress Radon by about a factor of 10^4-10^5.
  - Pocar et.al. at Princeton developed a pressure swing system
  - Lalanne et.al at Modane developed a cryogenic adsorption system

Free-Radon air factory

Principe:
Air circulation (150 m^3/h) trough a column of charcoal cooled down at -50°C



The specifications of the radon trapping facility are :

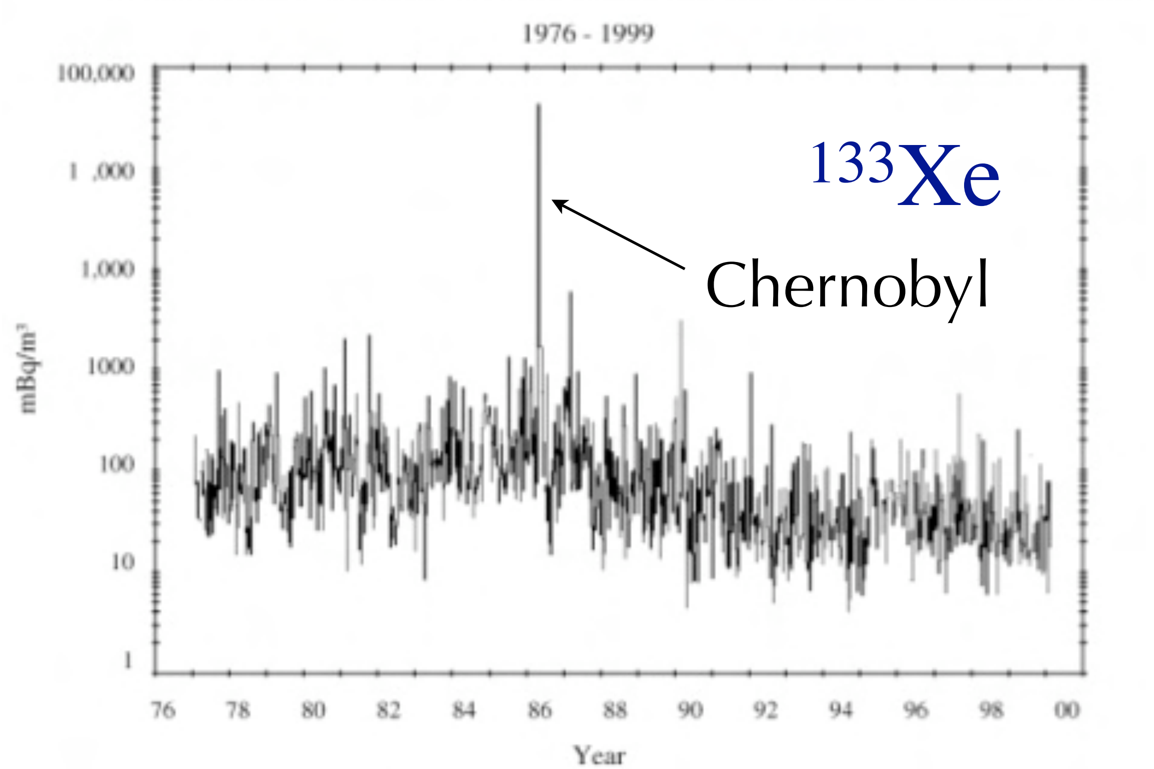
- Compressor (7 bars)
- filtration with oil separator (0.03 µm) and dust separator (0.1 µm)
- Air Dryer with a dew point -70°C for 8.5 bars -30°C at maximum value
- Cooling unit
- Two adsorption columns, with internal diameter of 600 mm and 3 m high
- Charcoal: activated carbon 2x500 kg

The Rn level at exit of the column: 18 mBq/m^3 ⟹ air sent into the tent

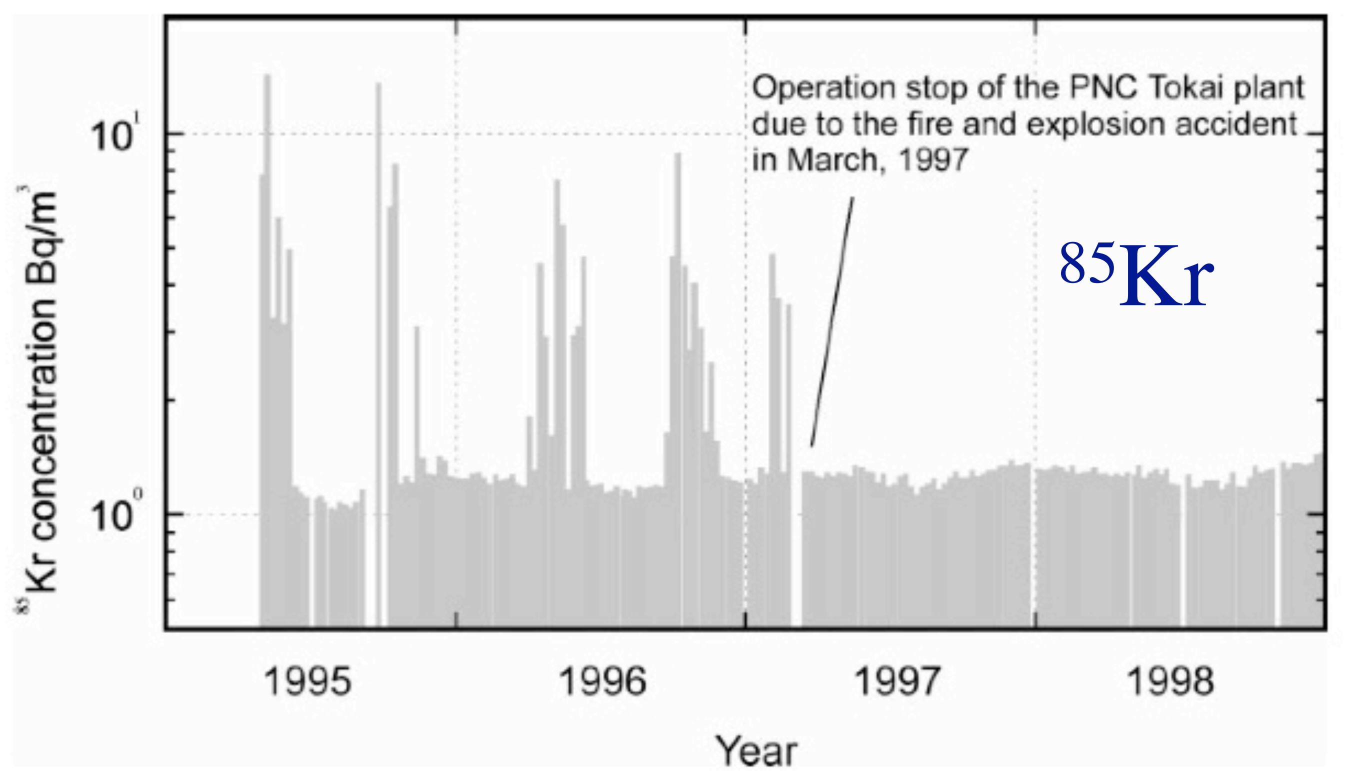
Other Airborne Radioactivity

- Mainly spallation products from nitrogen and oxygen.
- Also airborne radioactivities (^{3}H, ^{14}C, ^{85}Kr, ^{90}Sr, ^{137}Cs) from previous nuclear weapon testings and nuclear power generation.

T.W. Bowyer et al. / J. Environ. Radioactivity 59 (2002) 139–151



Y. Igarashi et al. / J. Environ. Radioactivity 48 (2000) 191–202



- Problematic for certain next-generation dark matter (^{39}Ar and ^{42}Ar) and solar neutrino experiments (^{85}Kr).

Other Airborne Radioactivity

TABLE 11 Atmospheric abundance for selected isotopes*

Isotope	Decay (Max. energy)	Half-life	Activity (Bq/kg)	Flux in atmosphere (atoms cm^{-2} s^{-1})
^{3}H	β^- (18.6 keV)	12.35 y	0.25	
^{7}Be	E.C. (478 keV)	53.4 d	—	8.1×10^{-3}
^{10}Be	β^- (556 keV)	1.6×10^{6} y	—	0.036
^{14}C	β^- (156 keV)	5730 y	400–500	2.2
^{22}Na	β^+ (1275 keV)	2.6 y	—	6×10^{-5}
^{26}Al	β^+ (1809 keV)	7.16×10^{6} y	—	1.7×10^{-4}
^{35}S	β^- (167 keV)	7.16×10^{6} y	—	1.4×10^{-3}
^{36}Cl	β^- (709 keV)	3.0×10^{5} y	—	1.1×10^{-3}
^{39}Ar	β^- (565 keV)	269 y	10^{-6}	Negligible
^{42}Ar	β^- (3525 keV from ^{42}K)	32.9 y	$(0.1–7.0) \times 10^{-6}$	Negligible
^{85}Kr	β^- (514 keV γ emission)	10.7 y	0.5–0.7	Negligible

*Values for ^{39}Ar and ^{42}Ar are from theoretical calculations including the effects of nuclear weapons testing. Value for ^{85}Kr is from direct measurements made in the Northern Hemisphere in 1985.

Formaggio & Martoff

Summary

- This was a whirlwind tour of backgrounds in underground experiments and assay/monitoring techniques.
- When in doubt:
  - Go measure
  - Go deep

Summary

- This was a whirlwind tour of backgrounds in underground experiments and assay/monitoring techniques.
- When in doubt:
  - Go measure
  - Go deep
- Expect the unexpected!