中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

SURANAREE UNIVERSITY OF TECHNOLOGY

(Reactor) Neutrino Data Analysis (I)

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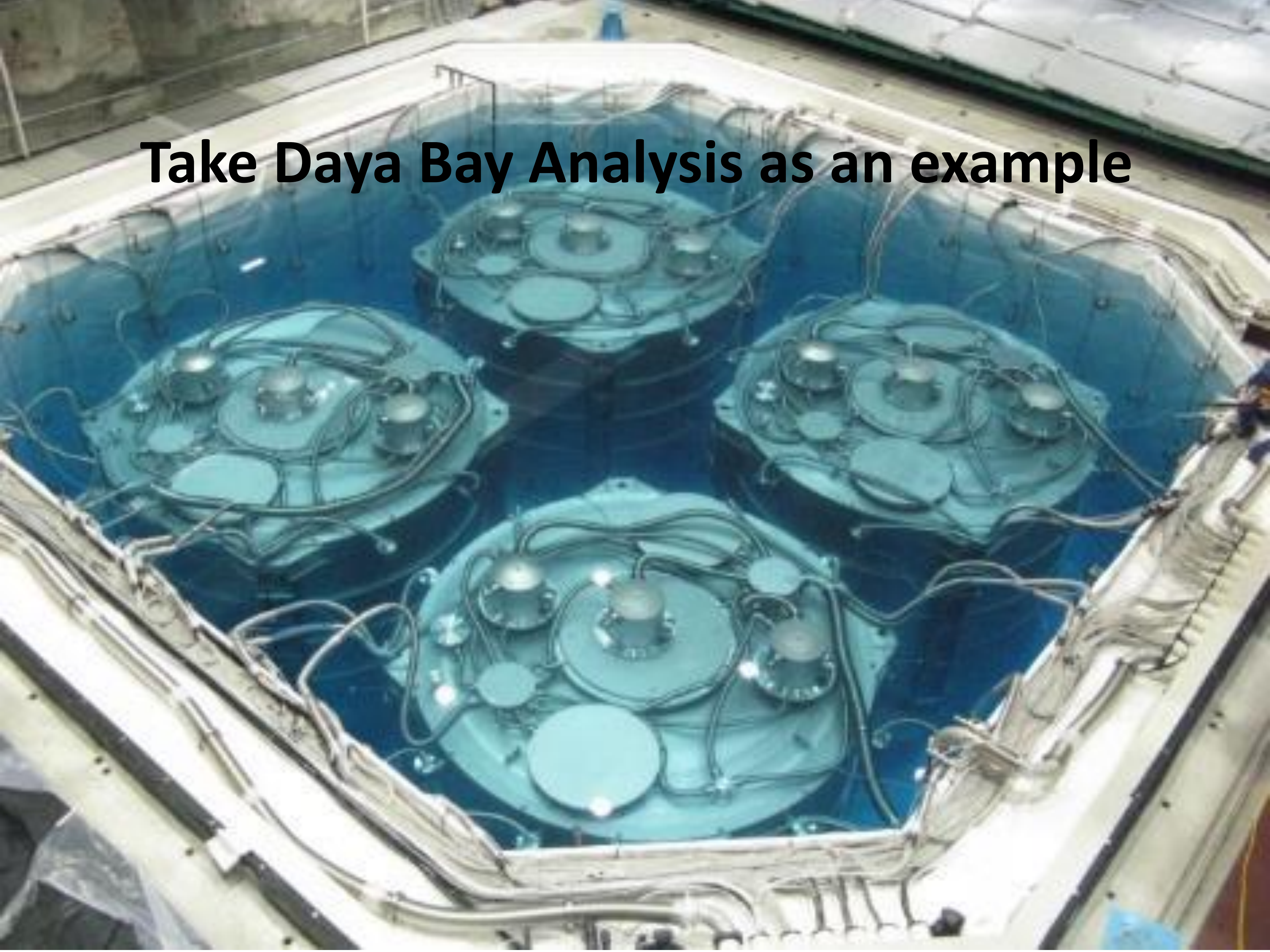
Take Daya Bay Analysis as an example



Signals?

Backgrounds?

Efficiencies?

Fitting?

Systematics?

Outline

- Reactor $\overline{\nu}_e$ Detection
- Natural radioactivity
- Cosmic rays and Cosmogenic Products
- Detector Design

Principles of experimental design and data analysis

- Detector Response and Calibration
- Event Selection
- Backgrounds
- Efficiencies and Uncertainties

$\overline{\nu}_e$ Neutrino Data Analysis

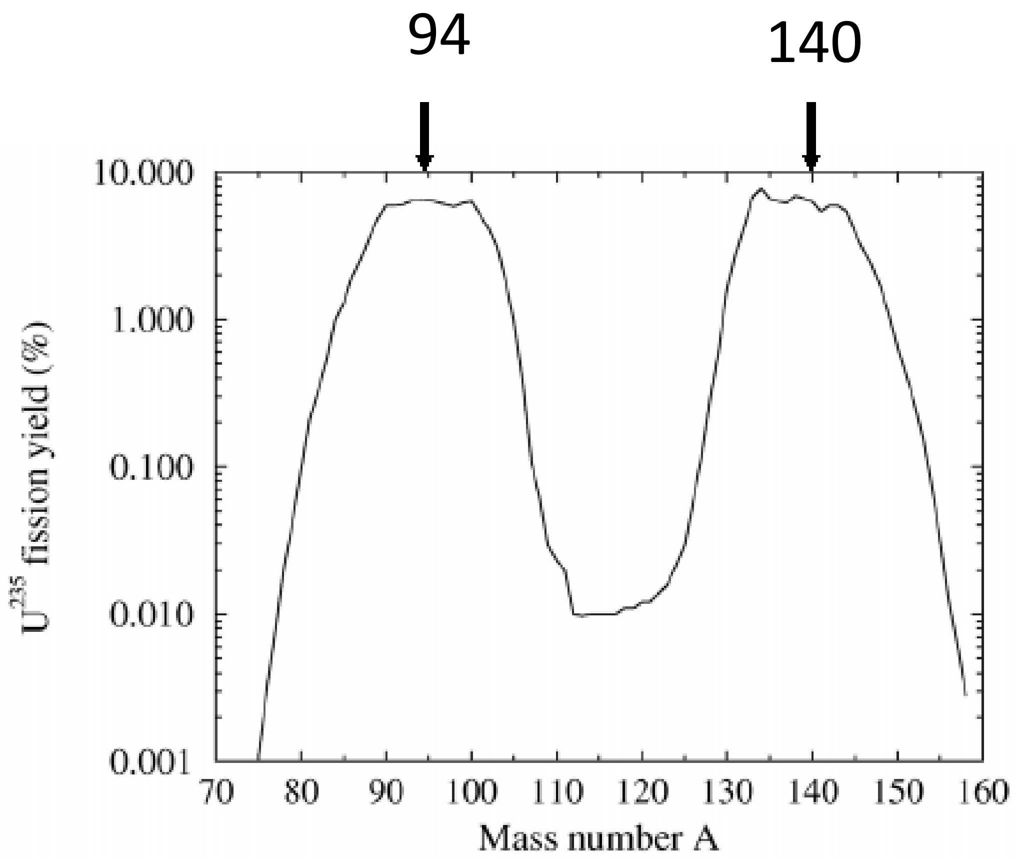
- χ^2 analysis

Get final result

Reactor $\bar{\nu}_e$ Detection

How Neutrinos are produced in reactors?

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



Stable nuclei with A most likely from fission

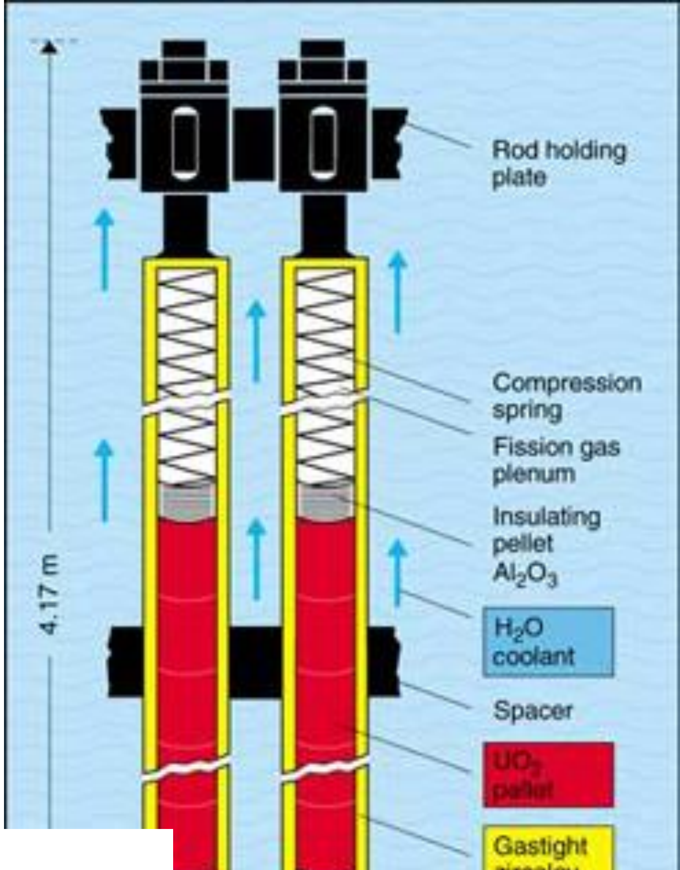
$^{94}_{40}Zr$ $^{140}_{58}Ce$

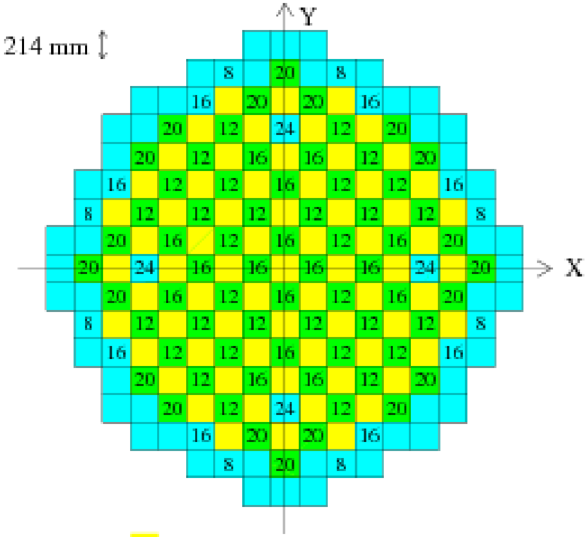
Together these have 98 protons and 136 neutrons

So, on average 6 n have to decay to 6 p to reach stable mater

A typical (light water pressurized) nuclear reactor

- Thermal power: 2.9 GW
- Electrical power: 0.9 GW
- Fuel:
  - 3.5% ^{235}U in the form of UO_2
  - 100t in total
  - Rods: 4m long, 0.5 t each
- Services:
  - Every 12(18) months
  - Each service: ~ 1 month
  - New Fuel: 1/3 rods





						8		20		8						
					16		20		20		16					
				20		12		24		12		20				
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	8		12		12		12		12		12		12		8	
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				20		12		24		12		20				
					16		20		20		16					
						8		20		8						

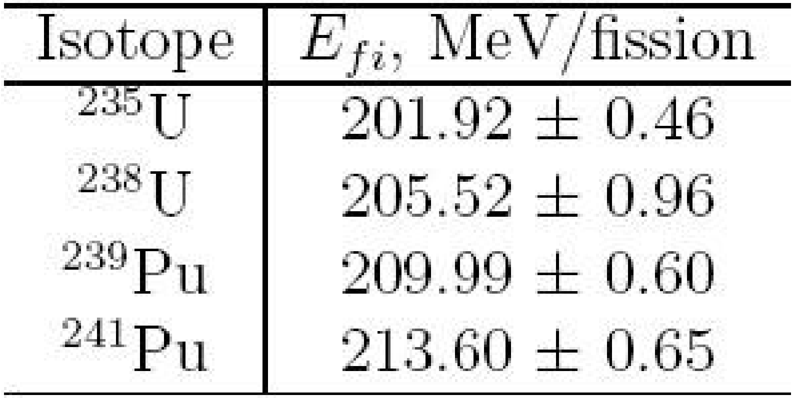
🟨 Region 1: 1.8 % enrichment

Fission Rate in the Reactor

- Sum of fission Energy → Total thermal power

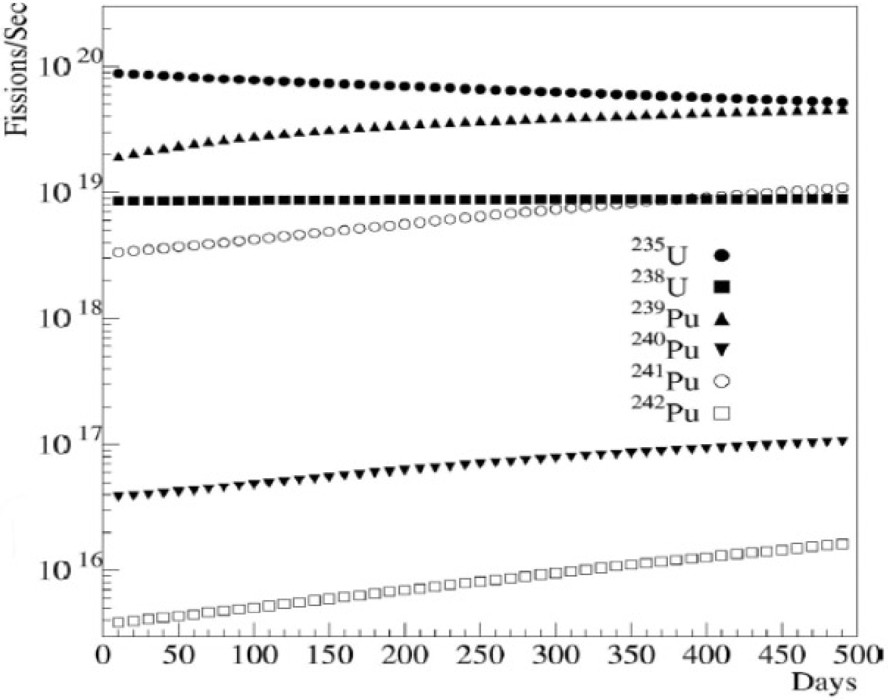
$$W_{th} = \sum_i f_i e_i\ , \qquad F = \sum_i f_i$$

- MC simulation can give reliably relative fission fraction f_i/F
- Absolute normalization factor(F) from measured total thermal power

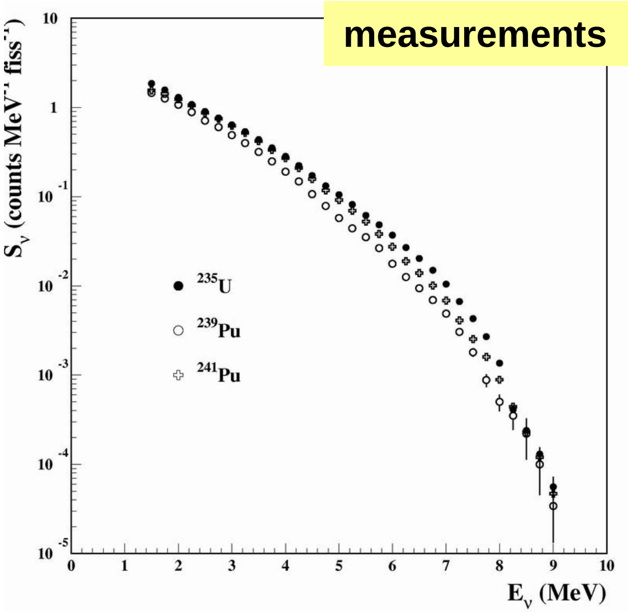


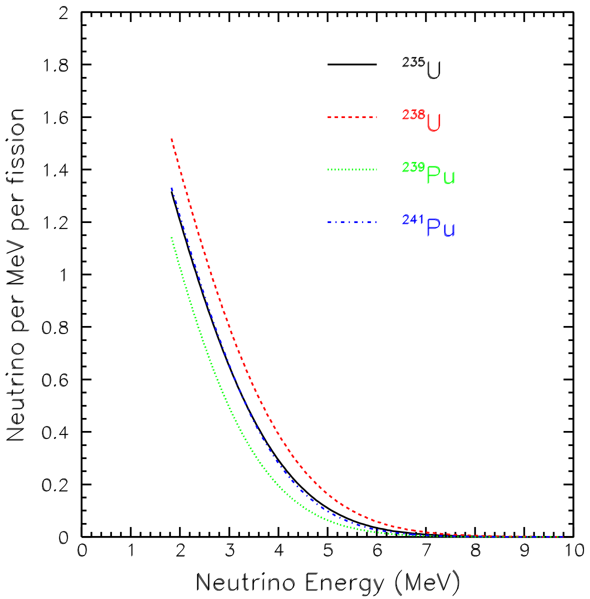
Isotope	E_{fi}, MeV/fission
^{235}U	201.92 ± 0.46
^{238}U	205.52 ± 0.96
^{239}Pu	209.99 ± 0.60
^{241}Pu	213.60 ± 0.65

Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)



Neutrino Flux: ILL model


measurements



- **The method:**
  - **Obtain the Fission rates of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**
  - **Use measured β spectrum of ^{235}U, ^{239}Pu, ^{241}Pu**

K. Schreckenbach et al., PLB160(1985)325
A.A. Hahn et al., PLB218(1989)365

  - **Use calculated β spectrum of ^{238}U**

P. Vogel et al., PRC 24(1981)1543

  - **Convert β spectra to n spectra**

P. Vogel et al., PRC 76(2007) 025504

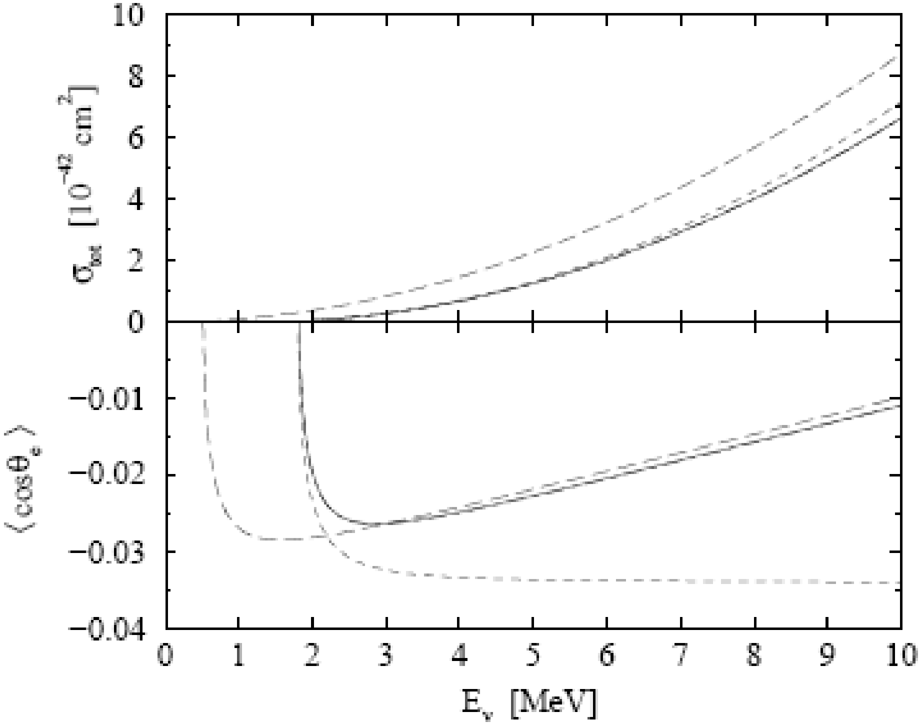
Cross Sections on Target

At tree level, for $\bar{\nu}_e + p \rightarrow e^+ + n$

$$\sigma_{\rm tot}^{(0)} = \frac{2\pi^2/m_e^5}{f^R_{\rm p.s.}\tau_n} E_e^{(0)} p_e^{(0)} = \frac{G_F^2 \cos^2\theta_C}{\pi}(1+\Delta^R_{\rm inner})(f^2+3g^2)E_e^{(0)} p_e^{(0)},$$

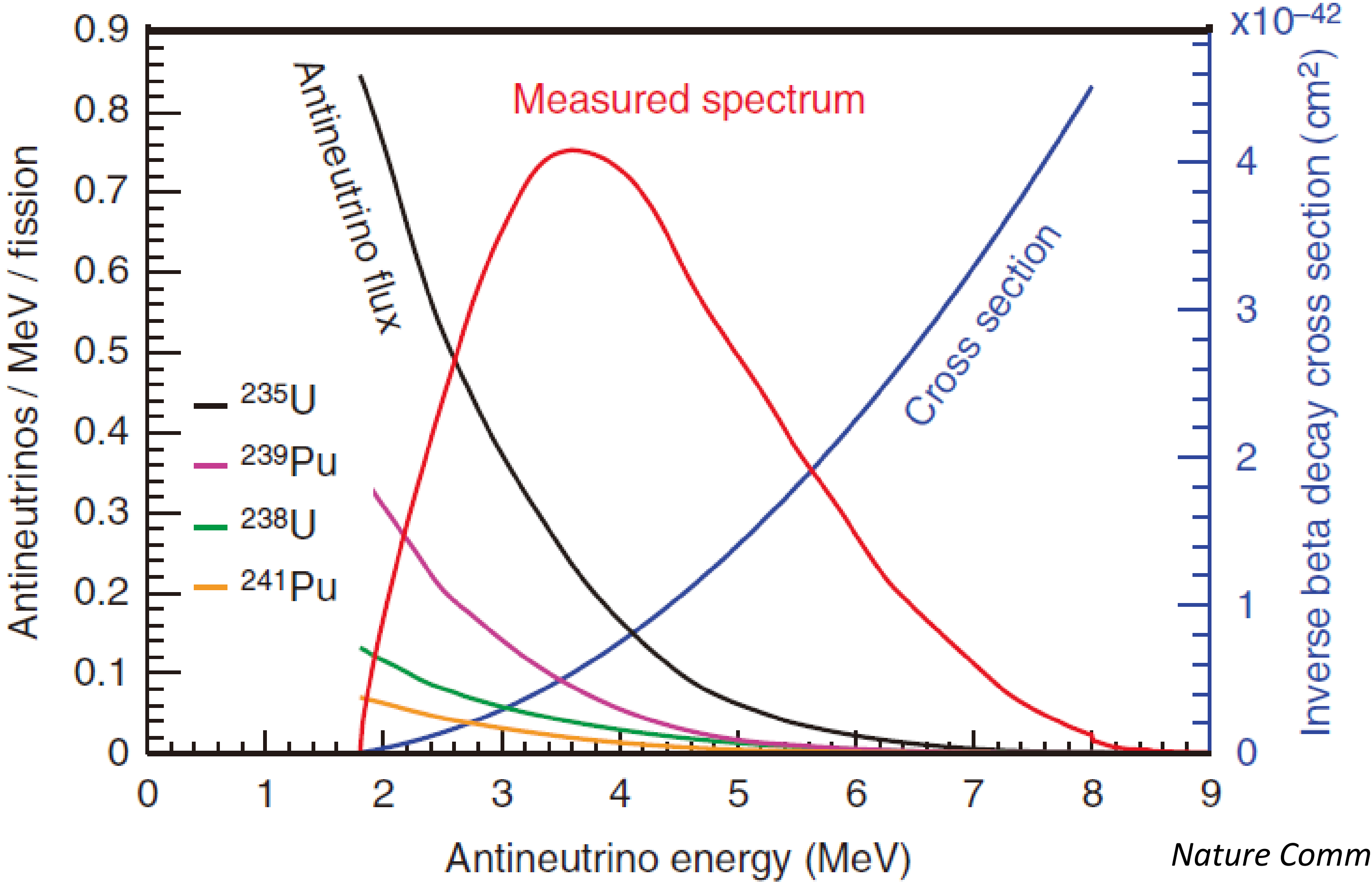
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \simeq 1 + v_e a(E_\nu)\cos\theta\,,$$

$$a^{(0)} = \frac{f^2-g^2}{f^2+3g^2} \simeq -0.10\,,$$



Higher order corrections can be found in P. Vogel et al., PRD60(1999)053003

Expected $\bar{\nu}_e$ Energy Spectrum

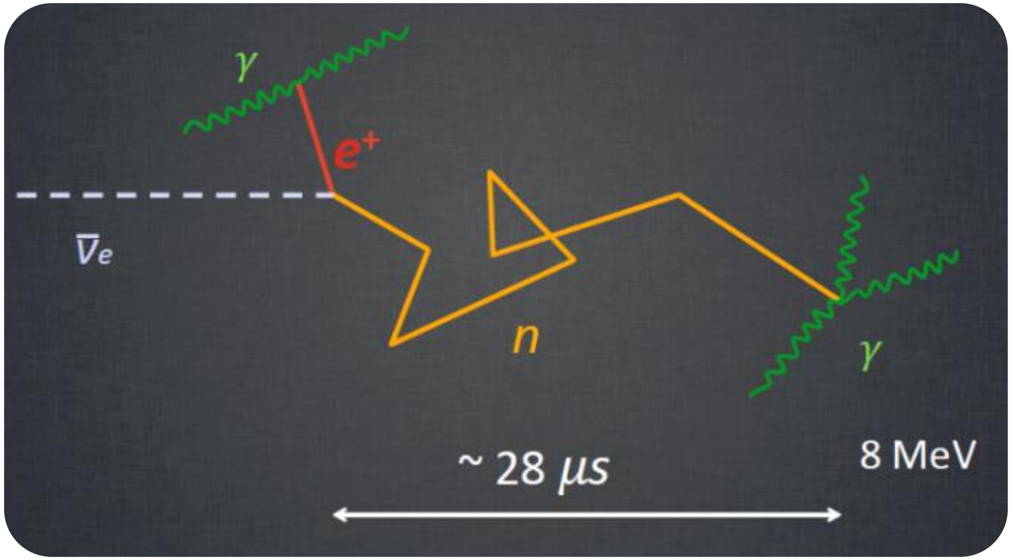


Nature Comms. 6:6935

Inverse-β Decay (IBD)

- Electron anti-neutrino detection via Inverse-β Decay

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



n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ (8 MeV)

Neutrino Event:
Coincidence in time,
space and energy

Neutrino energy:

$$E_{\bar{\nu}} \simeq T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

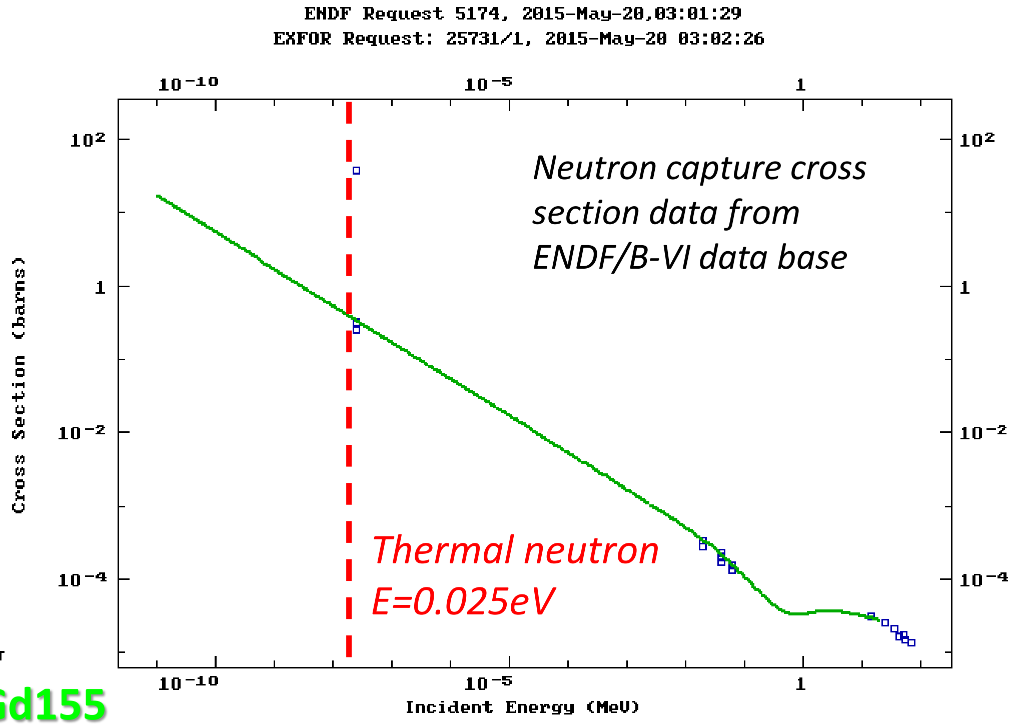
Why Gadolinium?

(1) High Energy of final state gammas

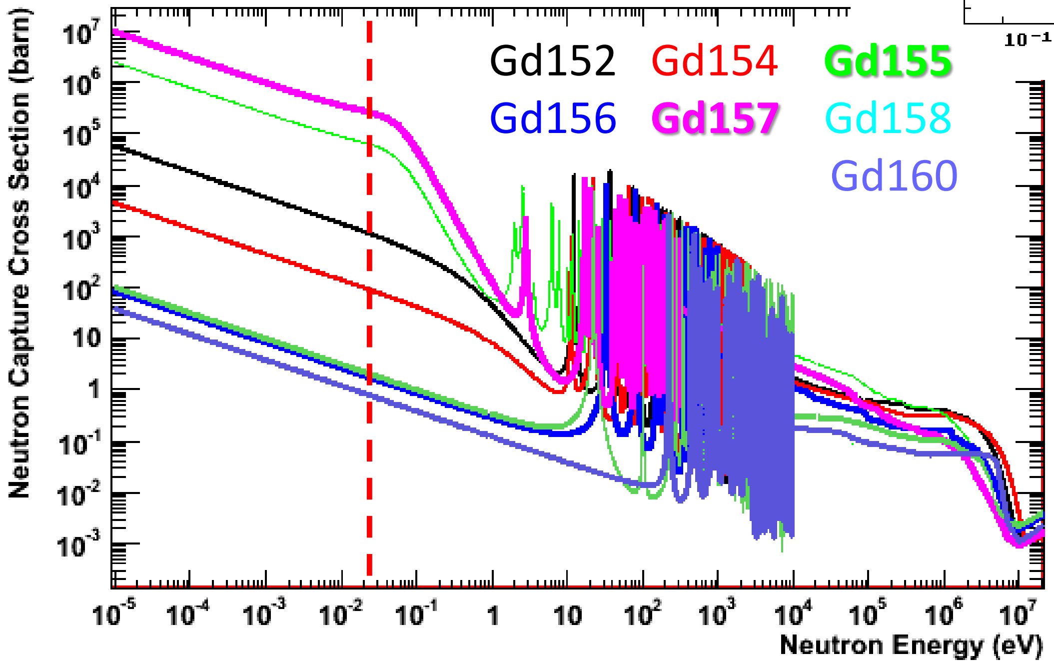
(2) Large neutron capture cross section

(3) Decent abundances

– e.g, ^{157}Gd, ^{155}Gd



Neutron capture cross section data from ENDF/B-VI data base



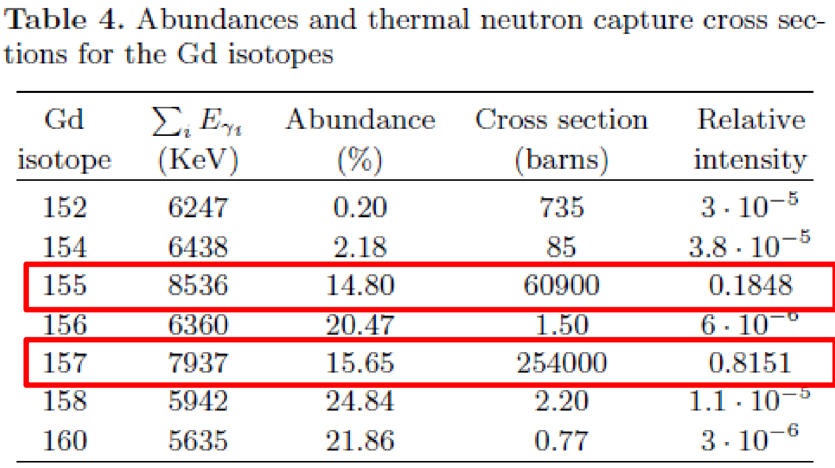
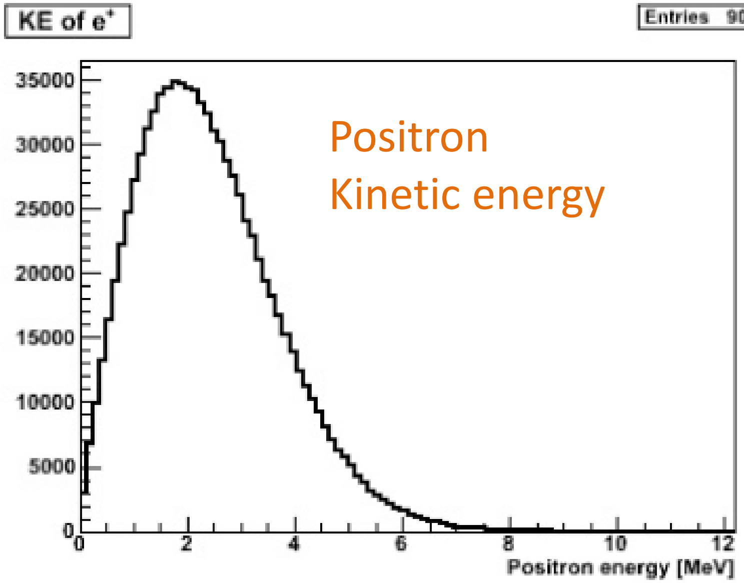


Table 4. Abundances and thermal neutron capture cross sections for the Gd isotopes

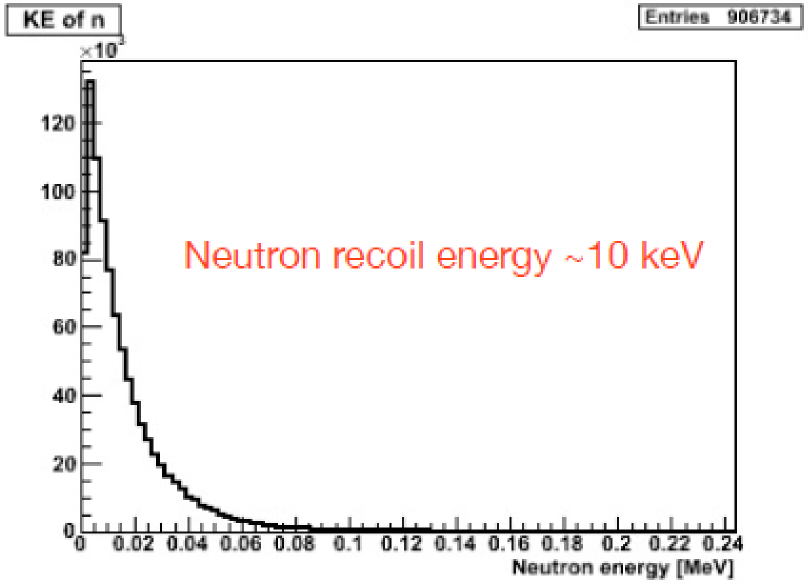
Gd isotope	$\sum_i E_{\gamma_i}$ (KeV)	Abundance (%)	Cross section (barns)	Relative intensity
152	6247	0.20	735	$3 \cdot 10^{-5}$
154	6438	2.18	85	$3.8 \cdot 10^{-5}$
155	8536	14.80	60900	0.1848
156	6360	20.47	1.50	$6 \cdot 10^{-6}$
157	7937	15.65	254000	0.8151
158	5942	24.84	2.20	$1.1 \cdot 10^{-5}$
160	5635	21.86	0.77	$3 \cdot 10^{-6}$

from CHOOZ

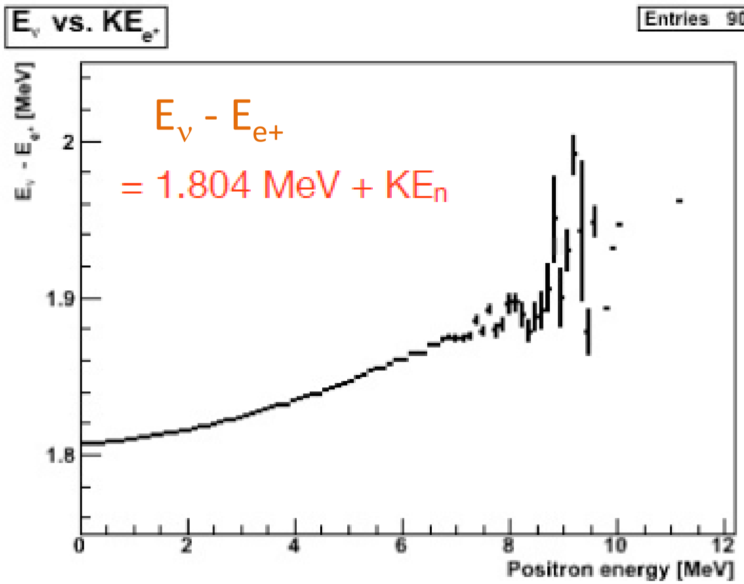
IBD e^+, neutron kinetics



Positron
Kinetic energy

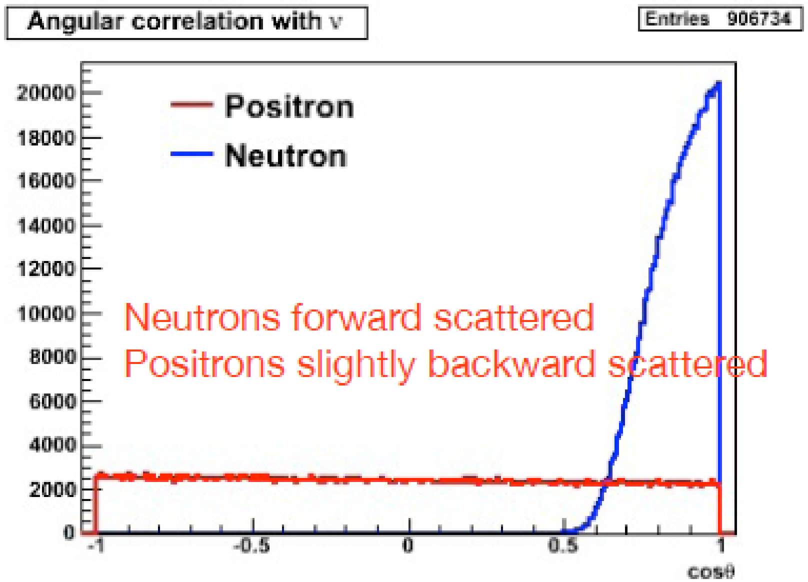


Neutron recoil energy ~10 keV



$E_\nu - E_{e+}$

$= 1.804$ MeV + KE_n

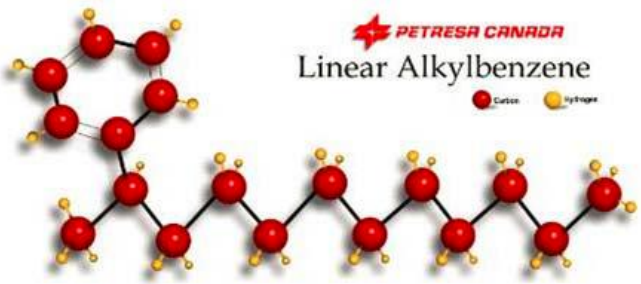


Neutrons forward scattered
Positrons slightly backward scattered

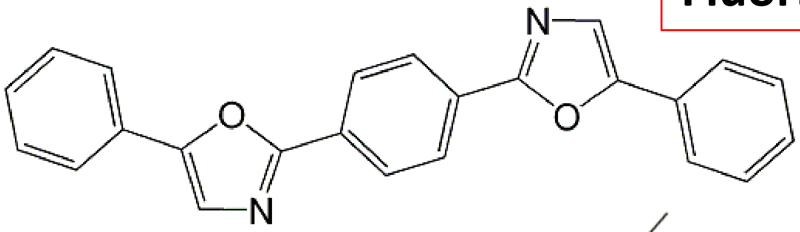
refer to Vogel and Beacom, PRD 60, 053003

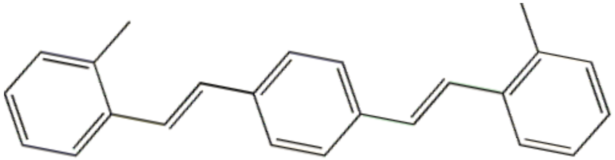
Liquid Scintillator (LS)

Solvent: LAB



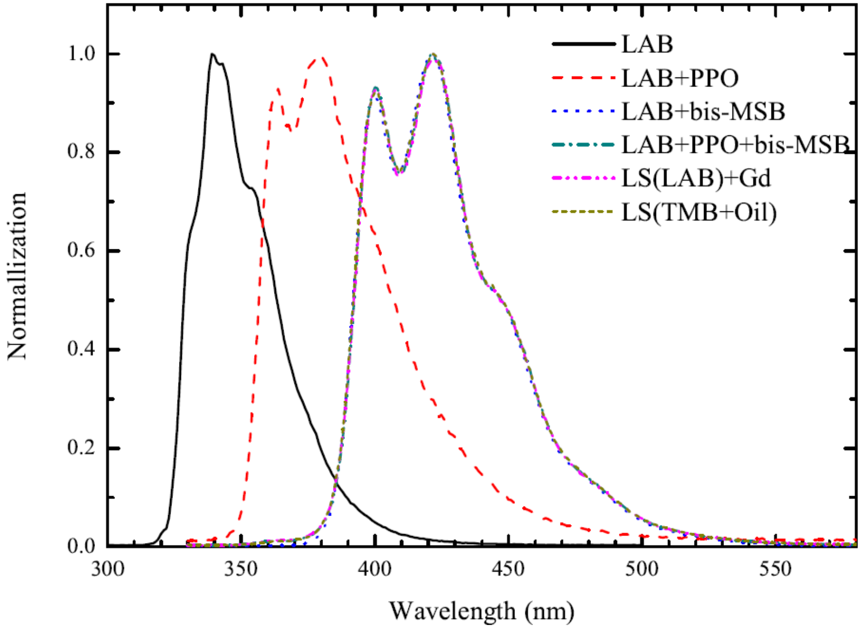
Fluor: PPO

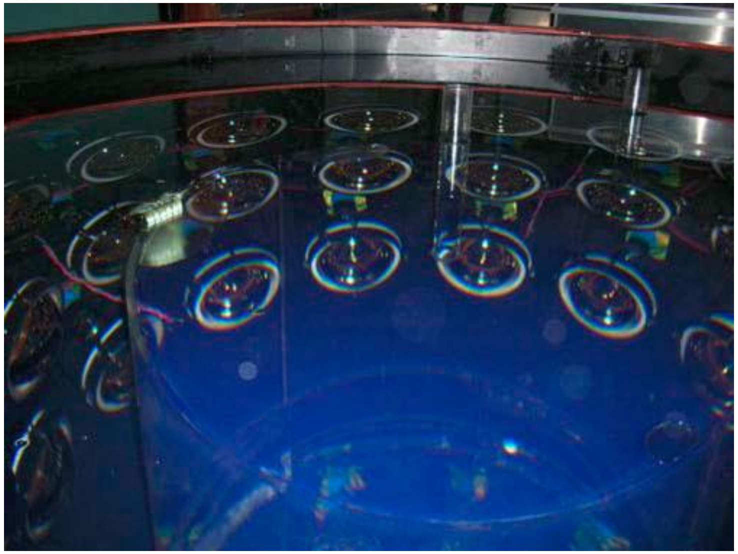




Wavelength shifter: bis-MSB

- Daya Bay Gd-LS
  - LAB + PPO (3g/L) + bis-MSB (15mg/L) + 0.1%Gd





GdLS of the Daya Bay prototype

Energy Response in LS

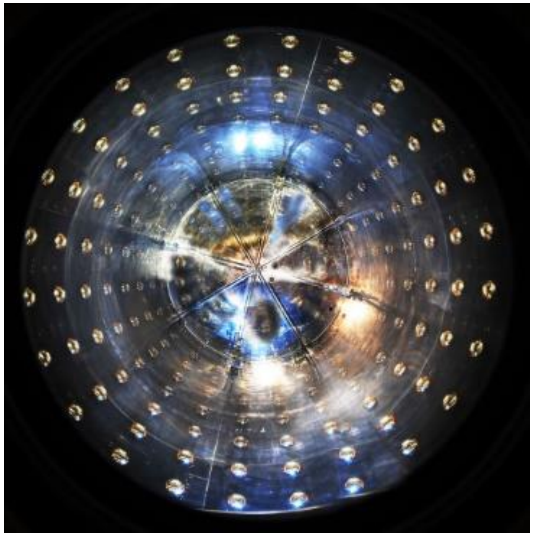
- Energy measurement in LS:
  - charge particle ionization → optical photons → total detected photon electrons → 'Visible Energy'
- Major non-linearity effects
  - Birks' Law (1964)

Energy loss per step

$$dS = A\frac{dE}{1+\boxed{C_1}\delta+\boxed{C_2}\delta^2} \qquad \delta = \frac{dE}{\rho dx} \quad [\mathrm{MeV\,g^{-1}cm^2}]$$

Light produced per step

Birks' constants

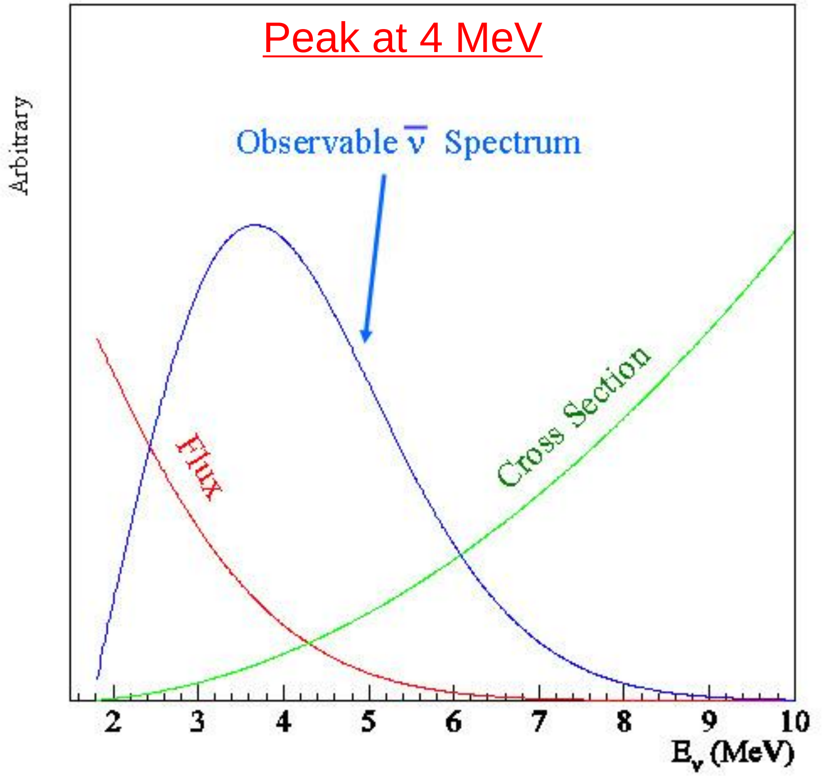

Inside View of Daya Bay detector

  - Absorption – reemission process
    - PPO/bis-MSB can absorb one optical photon (particularly UV photon), then emit a new photon

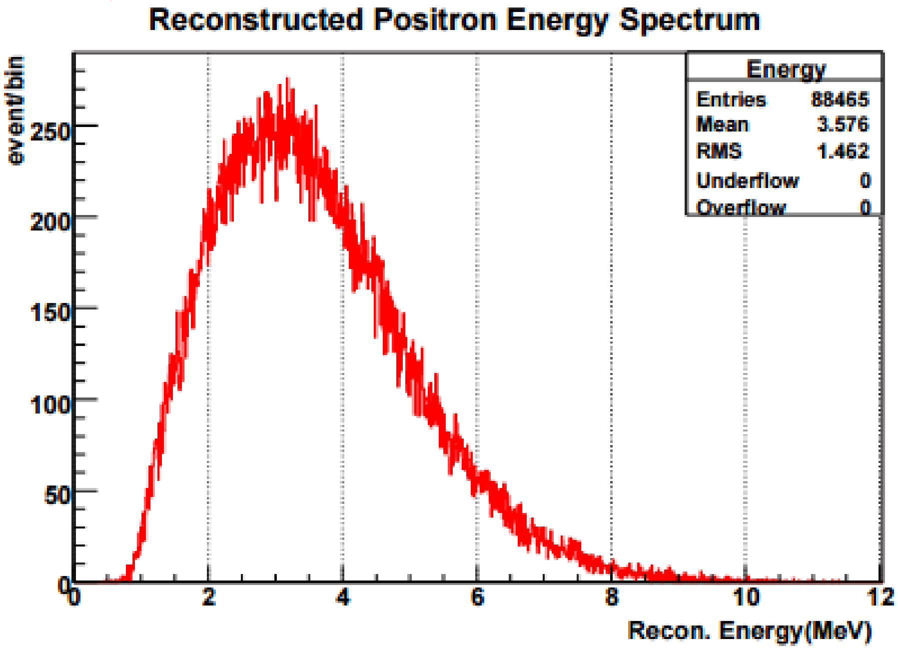
IBD spectrum – Prompt Signal

Neutrino energy:

$$E_{\bar{\nu}} \cong \boxed{T_{e^+}} + \underbrace{T_n}_{\textbf{\textit{10-40 keV}}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\textbf{\textit{1.8 MeV:}}\ \textbf{Threshold}}$$

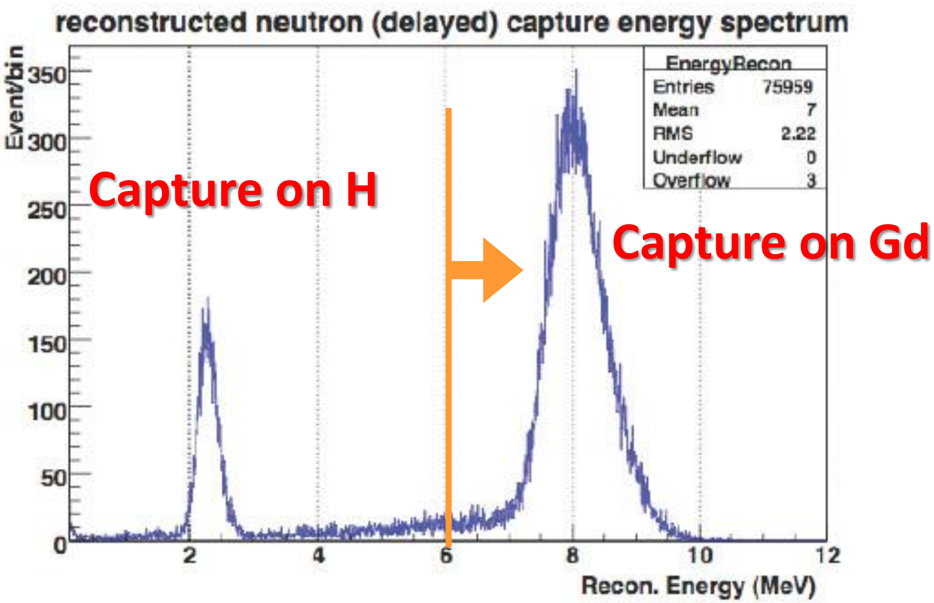

Peak at 4 MeV

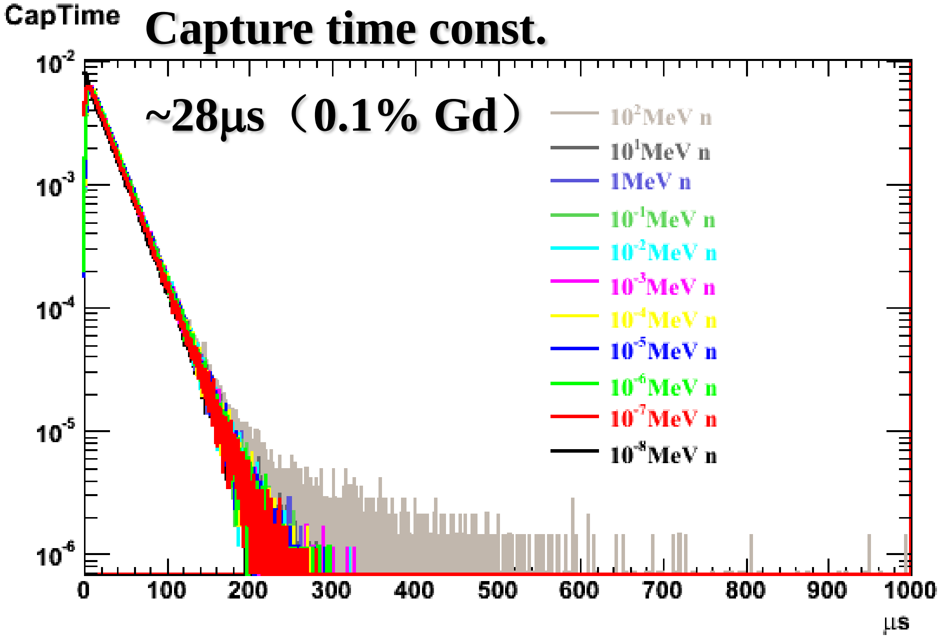
+ 1.022MeV (e+ annihilation energy)

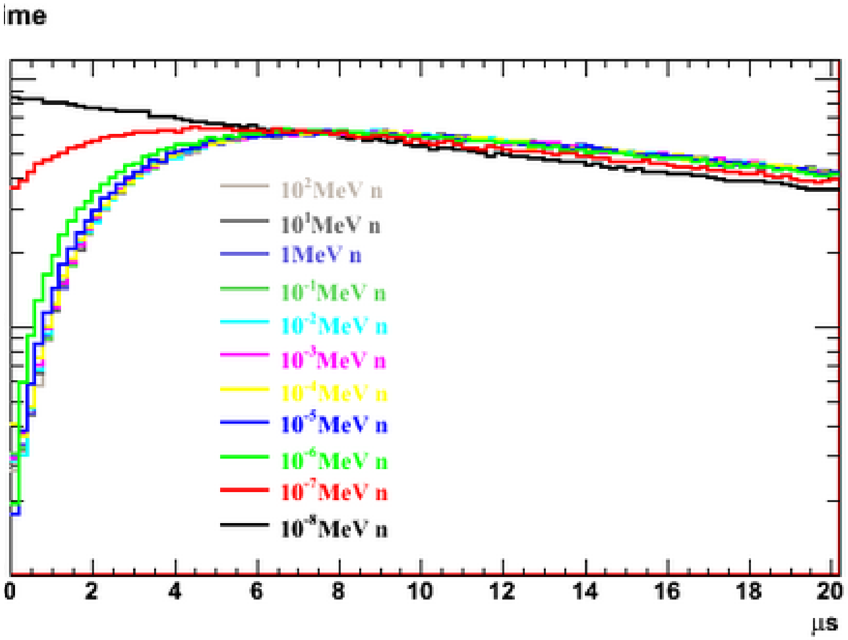


IBD spectrum – Delayed Signal

- Neutron captured on Hydrogen or Gadolinium
  - Proton recoiling during the neutron thermalization will contribute to the prompt signal







Natural Radioactivity

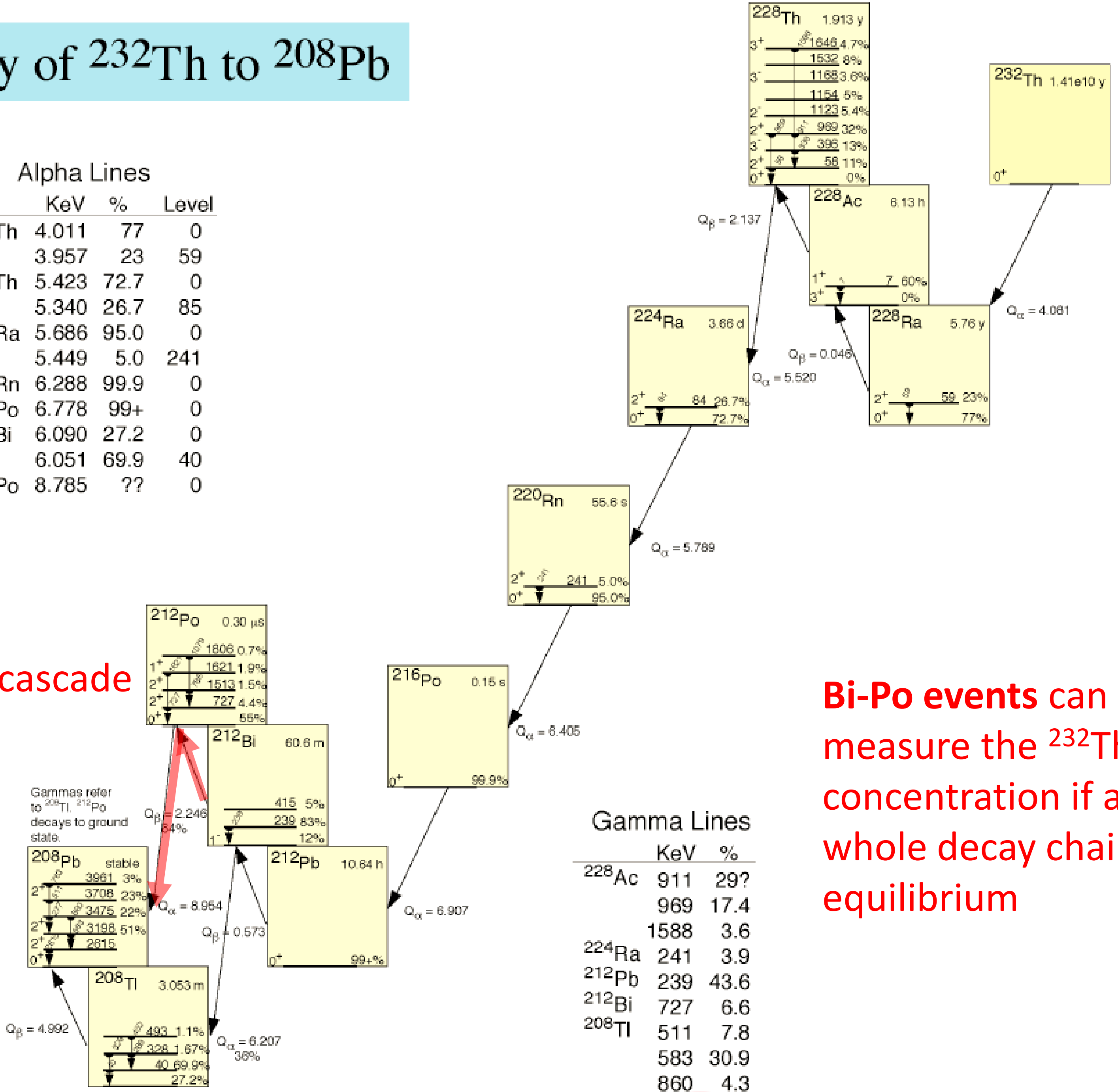
Natural Radioactivity

- ^{40}K, ^{232}Th, ^{238}U average abundances in the earth's crust: 2.4, 9.6 and 2.7 ppm
- Radon from U chain, emanated from rock cracks
- Cosmic activation (e.g, ^{14}C)
- Isotopes from Atmospheric Nuclear tests or reactor spent fuel processing (^{137}Cs, ^{85}Kr, ^{110m}Ag, etc)
  - ^{85}Kr increased in last 50 years due to nuclear power plants and weapons, ~1Bq/m^3 in fresh air
- Artificially introduced radioactivity
  - e.g, ^{60}Co in the steelmaking

Decay of ^{232}Th to ^{208}Pb

Alpha Lines

	KeV	%	Level
^{232}Th	4.011	77	0
	3.957	23	59
^{228}Th	5.423	72.7	0
	5.340	26.7	85
^{224}Ra	5.686	95.0	0
	5.449	5.0	241
^{220}Rn	6.288	99.9	0
^{216}Po	6.778	99+	0
^{212}Bi	6.090	27.2	0
	6.051	69.9	40
^{212}Po	8.785	??	0



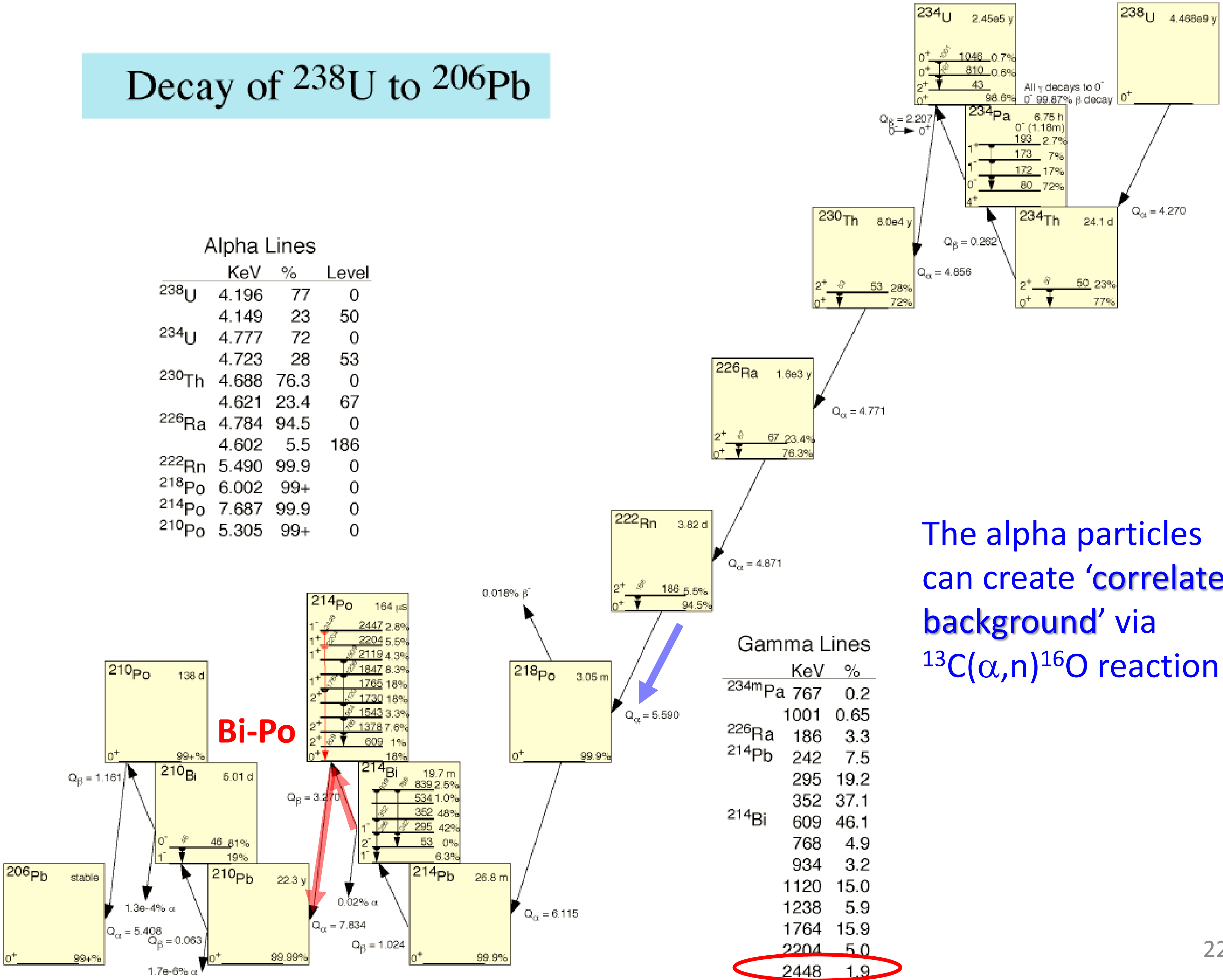
Bi-Po cascade chain

Gamma Lines

	KeV	%
^{228}Ac	911	29?
	969	17.4
	1588	3.6
^{224}Ra	241	3.9
^{212}Pb	239	43.6
^{212}Bi	727	6.6
^{208}Tl	511	7.8
	583	30.9
	860	4.3
	2615	35.9

Bi-Po events can be used to measure the ^{232}Th/^{238}U concentration if assuming the whole decay chain is in equilibrium

Decay of ^{238}U to ^{206}Pb



Alpha Lines

	KeV	%	Level
^{238}U	4.196	77	0
	4.149	23	50
^{234}U	4.777	72	0
	4.723	28	53
^{230}Th	4.688	76.3	0
	4.621	23.4	67
^{226}Ra	4.784	94.5	0
	4.602	5.5	186
^{222}Rn	5.490	99.9	0
^{218}Po	6.002	99+	0
^{214}Po	7.687	99.9	0
^{210}Po	5.305	99+	0

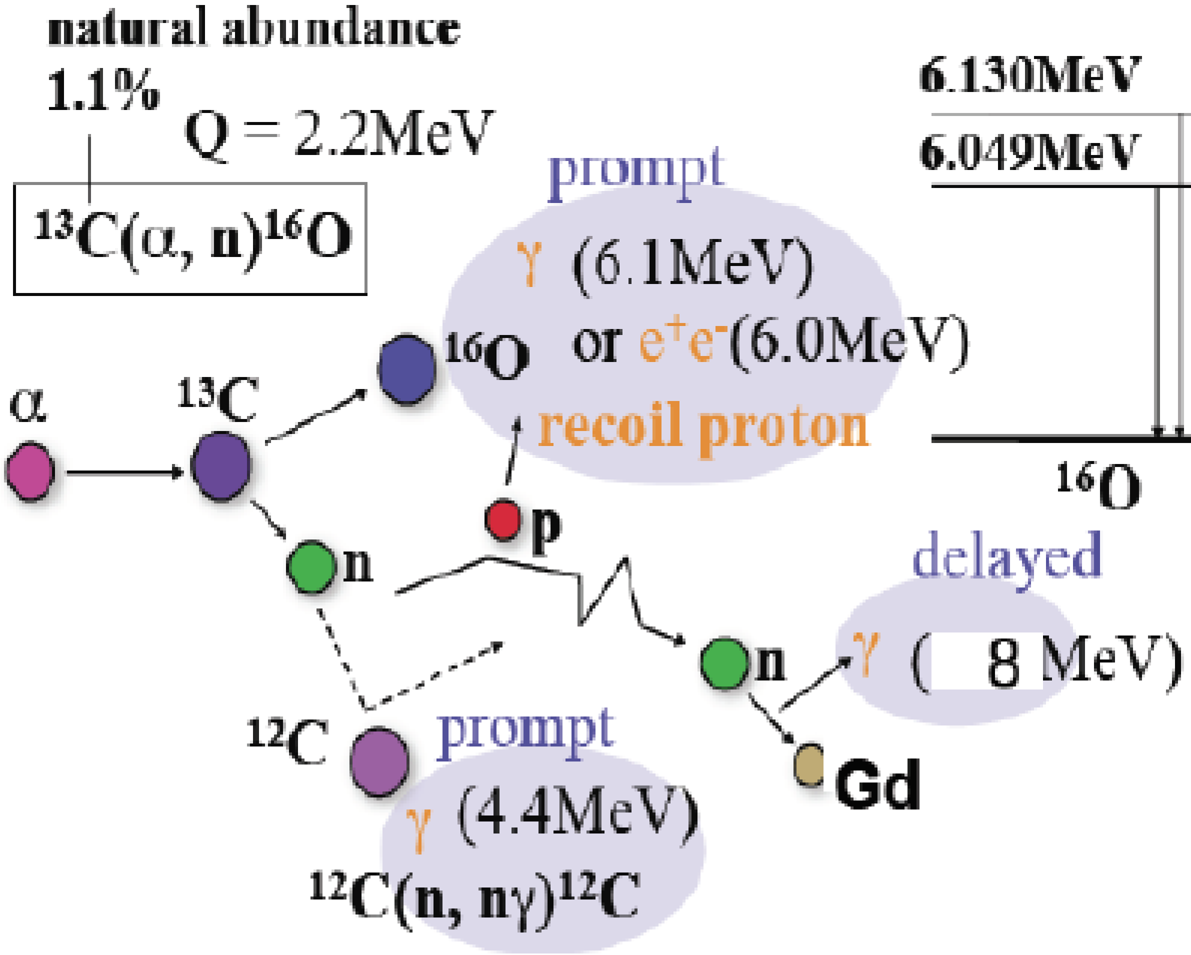
Gamma Lines

	KeV	%
^{234m}Pa	767	0.2
	1001	0.65
^{226}Ra	186	3.3
^{214}Pb	242	7.5
	295	19.2
	352	37.1
^{214}Bi	609	46.1
	768	4.9
	934	3.2
	1120	15.0
	1238	5.9
	1764	15.9
	2204	5.0
	2448	1.9

The alpha particles can create ‘**correlated background**’ via $^{13}C(\alpha,n)^{16}O$ reaction

$^{13}C(\alpha,n)^{16}O$

- $^{13}C(\alpha,n)^{16}O$ can produce ‘correlated background’



$^{13}C(\alpha,n)^{16}O$ in KamLAND

KamLAND 2003, PRL90.021802

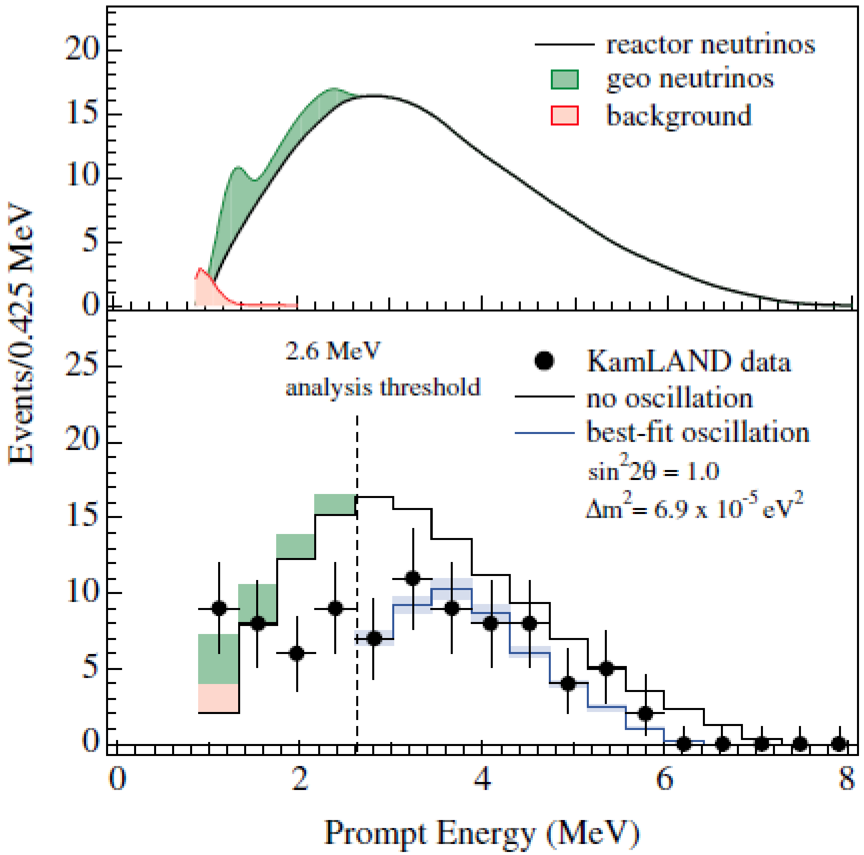
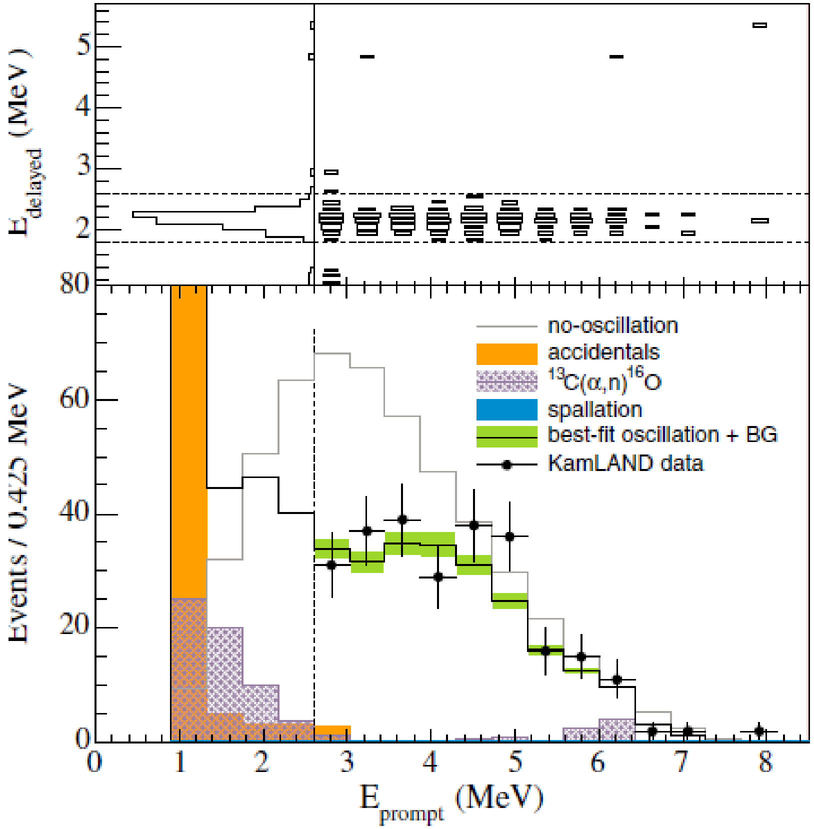


TABLE I. Background summary.

Background	Number of events
Accidental	0.0086 ± 0.0005
$^9Li/^8He$	0.94 ± 0.85
Fast neutron	<0.5
Total B.G. events	1 ± 1

KamLAND 2005, PRL94.081801



α-decay of ^{210}Po, daughter of ^{222}Rn introduced into the LS during construction

$^{13}C(\alpha,n)^{16}O$ in KamLAND

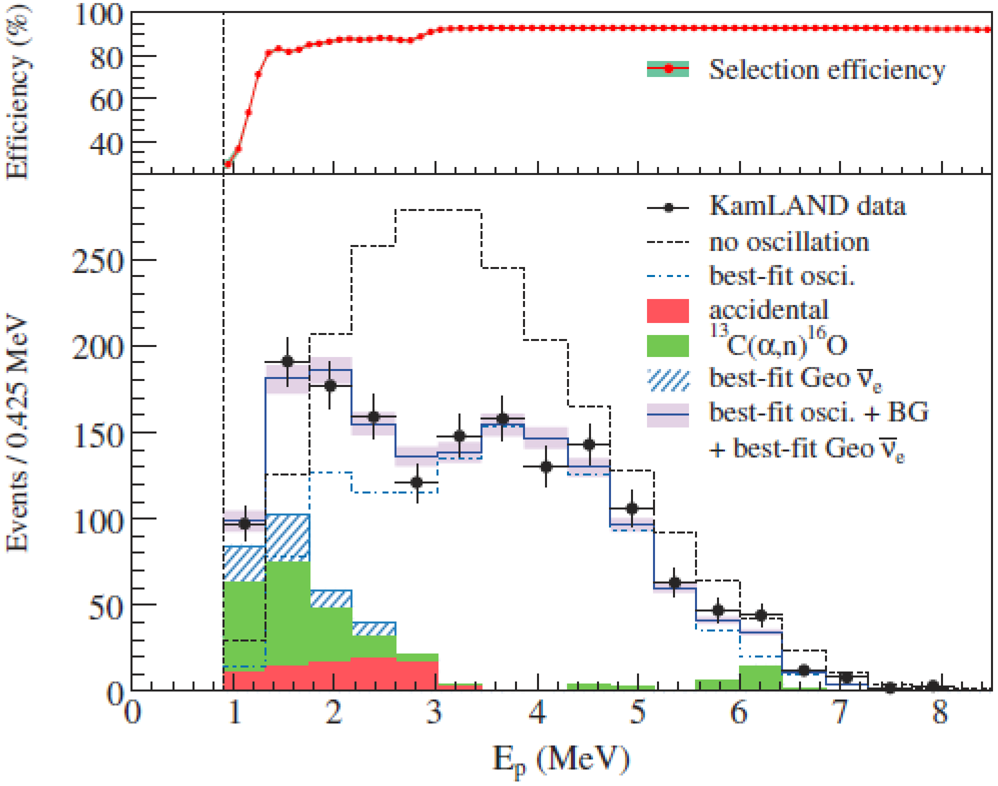


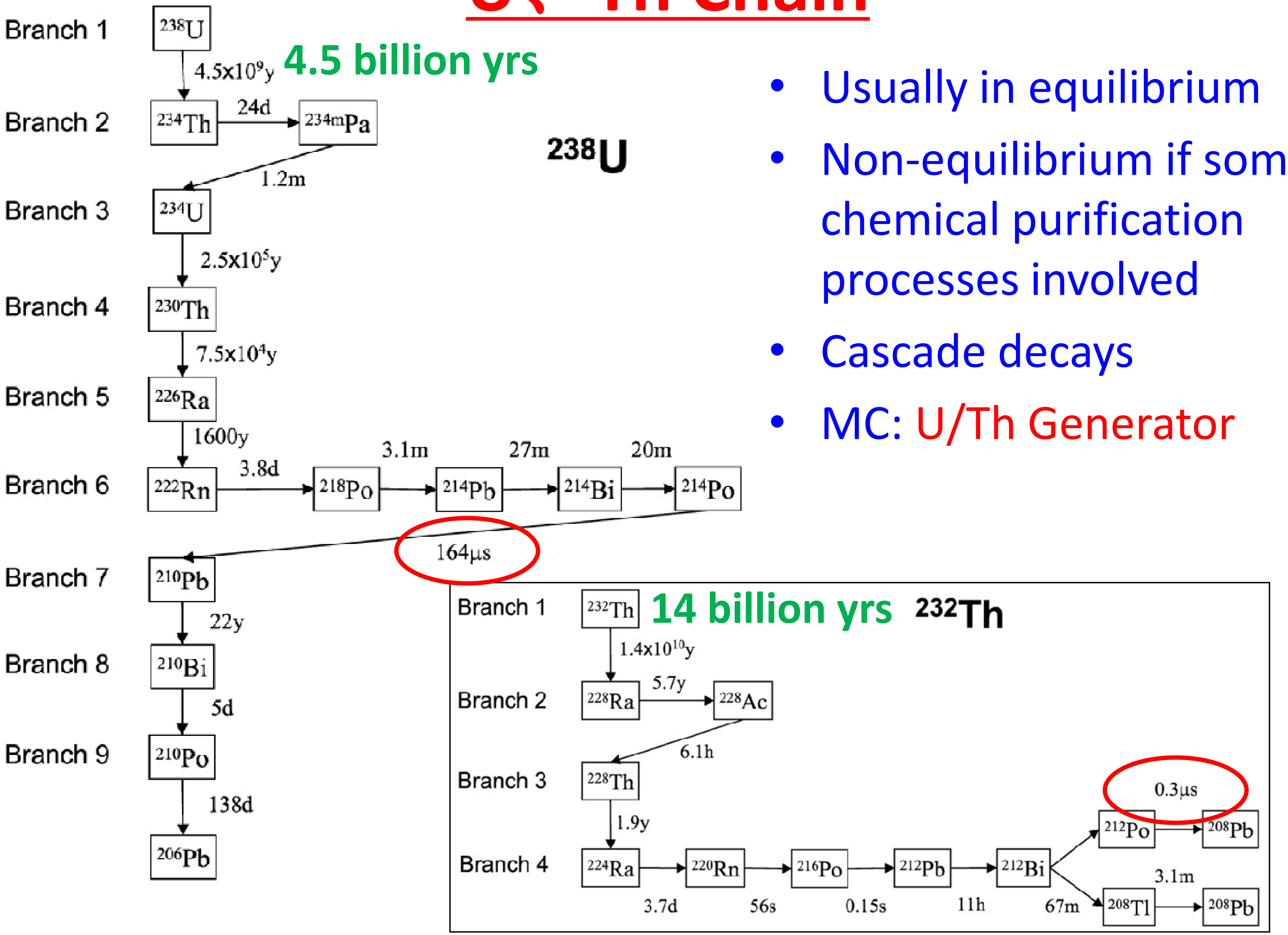
TABLE II. Estimated backgrounds after selection efficiencies.

Background	Contribution
Accidentals	80.5 ± 0.1
$^{9}Li/^{8}He$	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
$^{13}C(\alpha,n)^{16}O_{gs}$, $np \rightarrow np$	157.2 ± 17.3
$^{13}C(\alpha,n)^{16}O_{gs}$, $^{12}C(n,n')^{12}C^{*}$ (4.4 MeV γ)	6.1 ± 0.7
$^{13}C(\alpha,n)^{16}O$ 1st exc. state (6.05 MeV $e^{+}e^{-}$)	15.2 ± 3.5
$^{13}C(\alpha,n)^{16}O$ 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total	276.1 ± 23.5

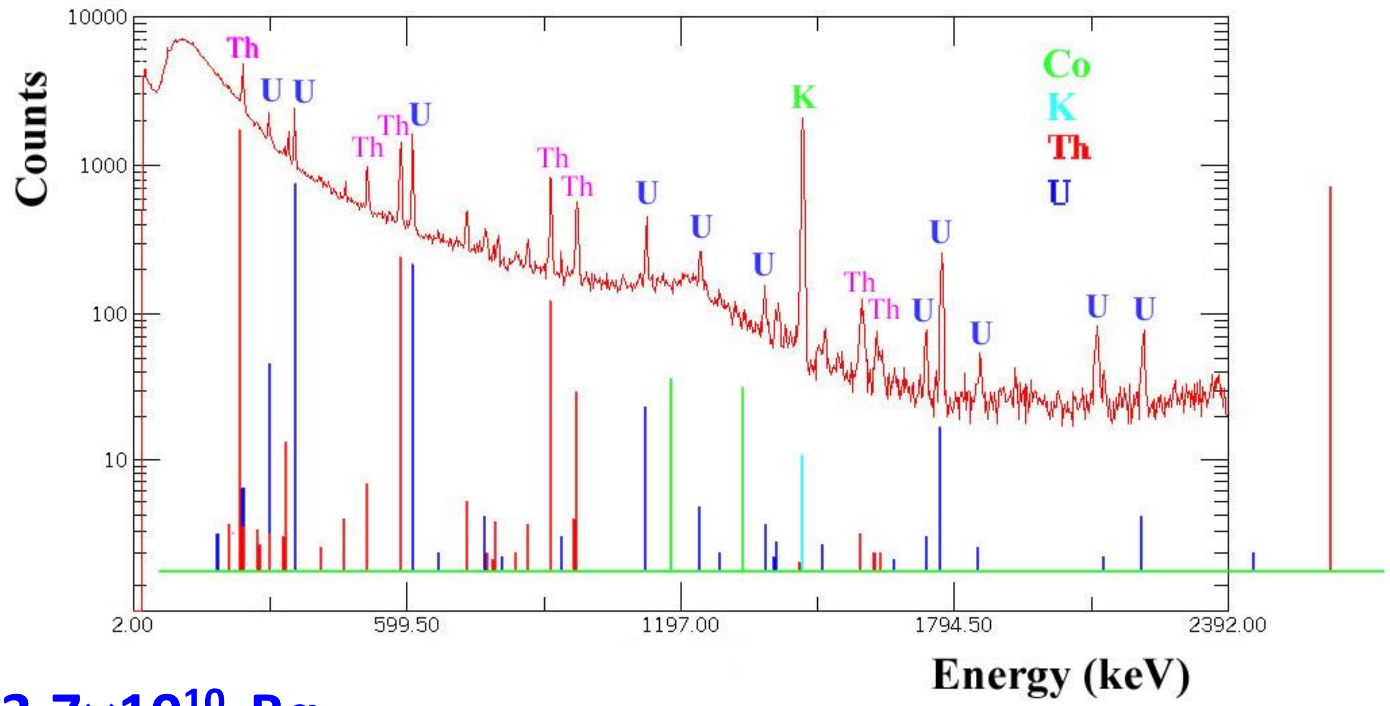
KamLAND 2008, PRL100.221803

U、Th Chain

- Usually in equilibrium
- Non-equilibrium if some chemical purification processes involved
- Cascade decays
- MC: U/Th Generator



γ spectra of Daya Bay Granite



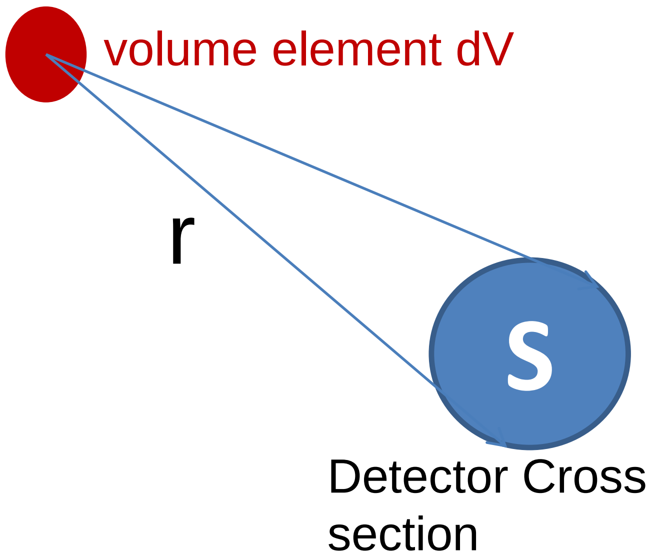
- 1 Ci = 3.7×10^{10} Bq
- ppm, ppb：
  - – 1 ppb 40K = 258.4 mBq/kg
  - – 1 ppb 238U = 12.4 mBq/kg
  - – 1 ppb 232Th = 4.0 mBq/kg

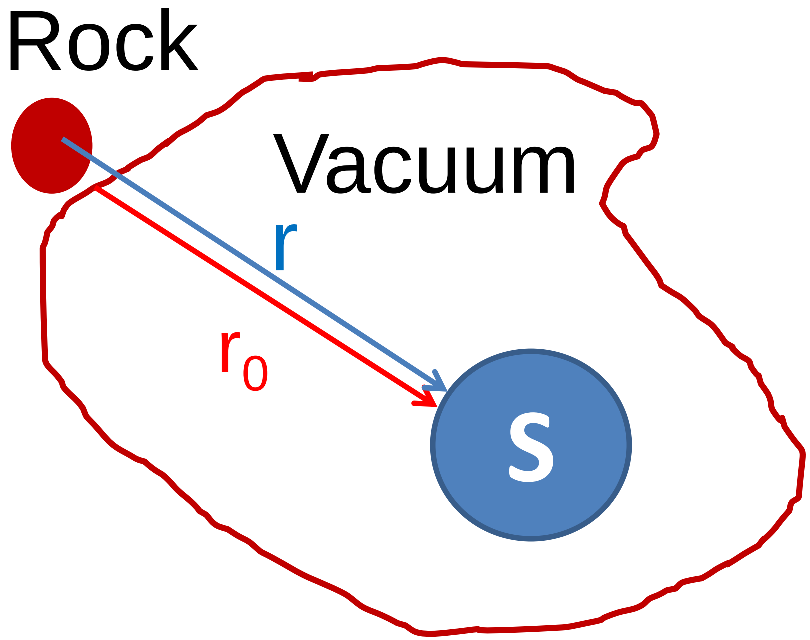
- ◆ Granite has high radioactivity
- ◆ Daya Bay Granite is ~3x of the world average

~10 ppm U

~30 ppm Th

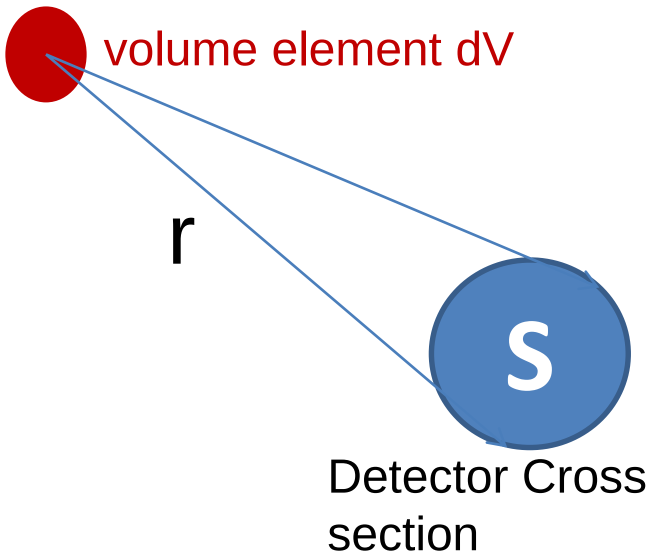
~5 ppm K40

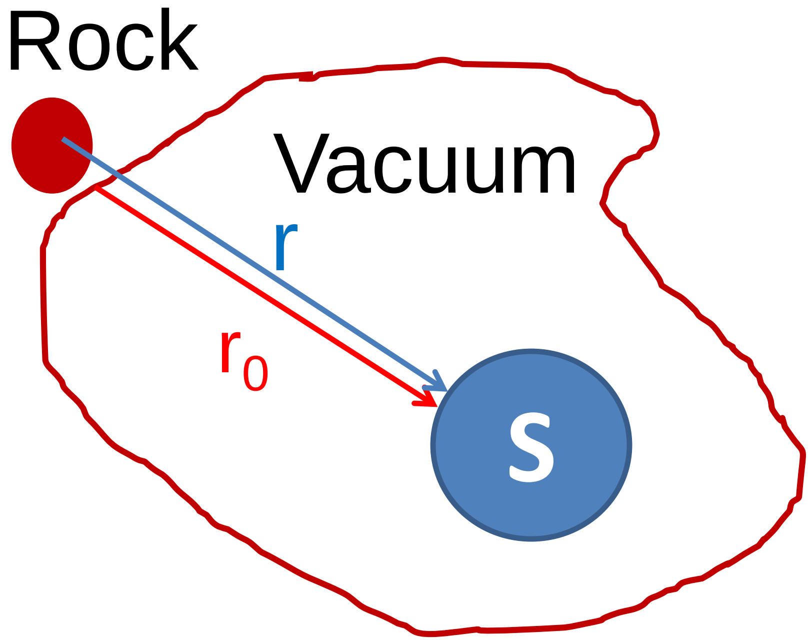




Solve the problem:

Calculate the contribution from gammas in the surrounding rock to the detector. (assume gamma attenuation length in rock is ***L***)





Acceptance of a gamma in dV to detector $f = \frac{S}{4\pi r^2}$

For any given dΩ, $dN = \int_{r0}^{\infty} A d\Omega r^2 dr \cdot \frac{S}{4\pi r^2} \cdot \exp(-\frac{r-r_0}{L})$ $= d\Omega \frac{ASL}{4\pi}$

$A d\Omega r^2 dr$ is activity in dV
$\exp(-(r-r_0)/L)$ is self-absorption of rock where L is gamma attenuation length

Since dN is simply a constant times dΩ, especially not related with r_0, the integral on dΩ is trivial. **N=ASL**. It means that the contribution w/ acceptance and self-absorption taken into account equals to activity in a rock volume of detector cross-section times gamma attenuation length.

Radioactivity Control (I)

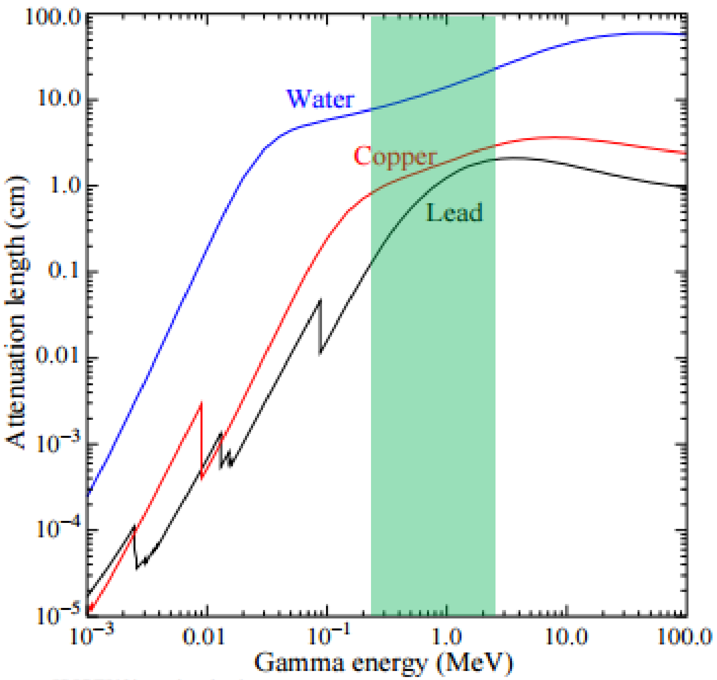
- Sufficient shielding to prevent the rock radioactivity from entering the detector
  - 8.8ppm U, 28.7ppm Th, 4.5ppm K
  - Shielding is very important

Question I:
If you are building the experiment, what material do you choose as shielding material?

Question II:
What thickness do you need to achieve ~ 20 Hz singles rate in the detector?

$$\ell = \lambda(E_\gamma) \cdot \ln f$$

The thickness ℓ required to reduce the external flux by a factor *f > 1*



SPORTS10/atten_lengths_deg.eps

Figure 29.6: γ-ray attenuation lengths in some common shielding materials. The mass attenuation data has been taken from the NIST data base XCOM; see "Atomic Nuclear Properties" at `pdg.lbl.gov`.

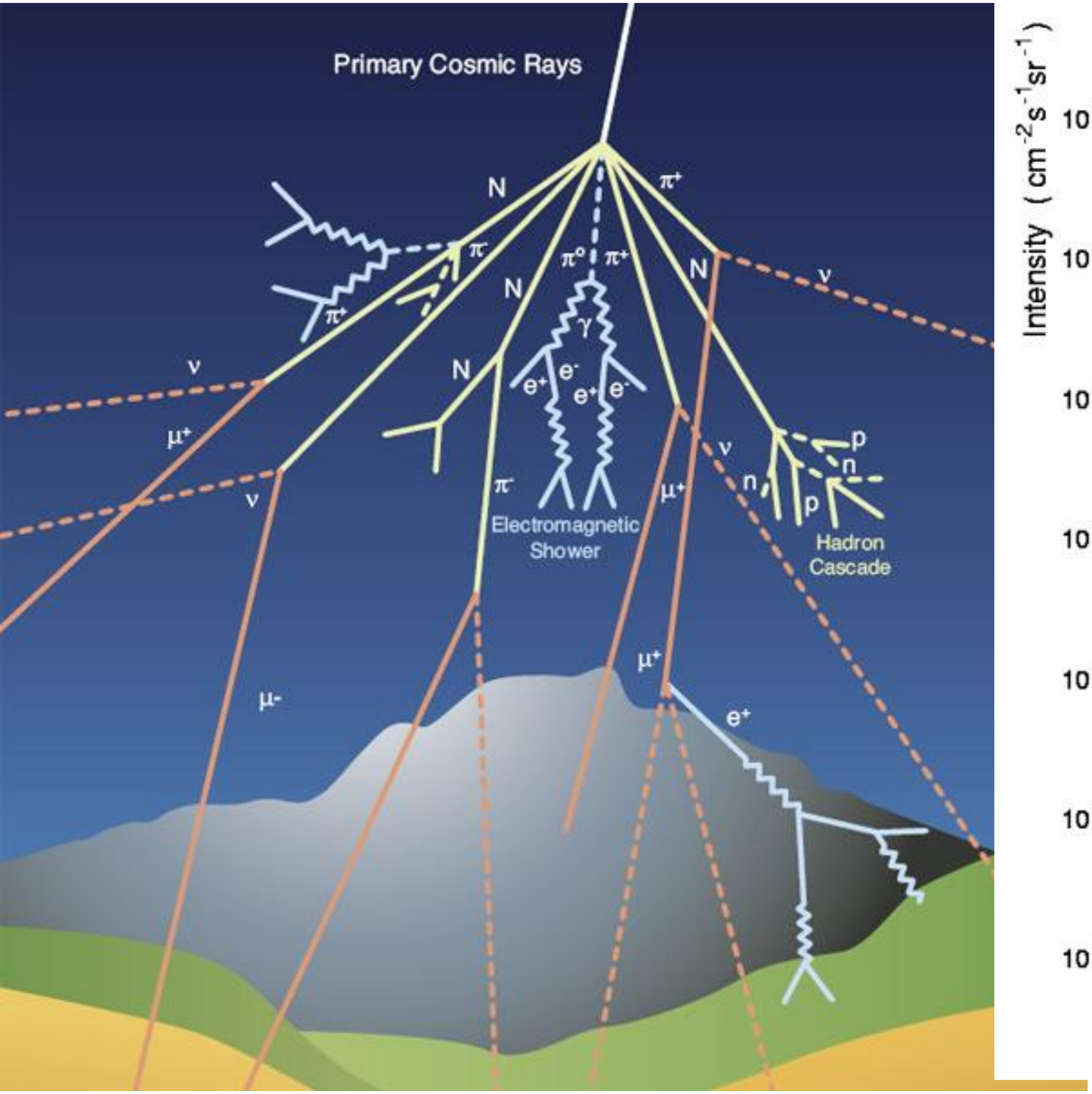
Radioactivity Control (II)

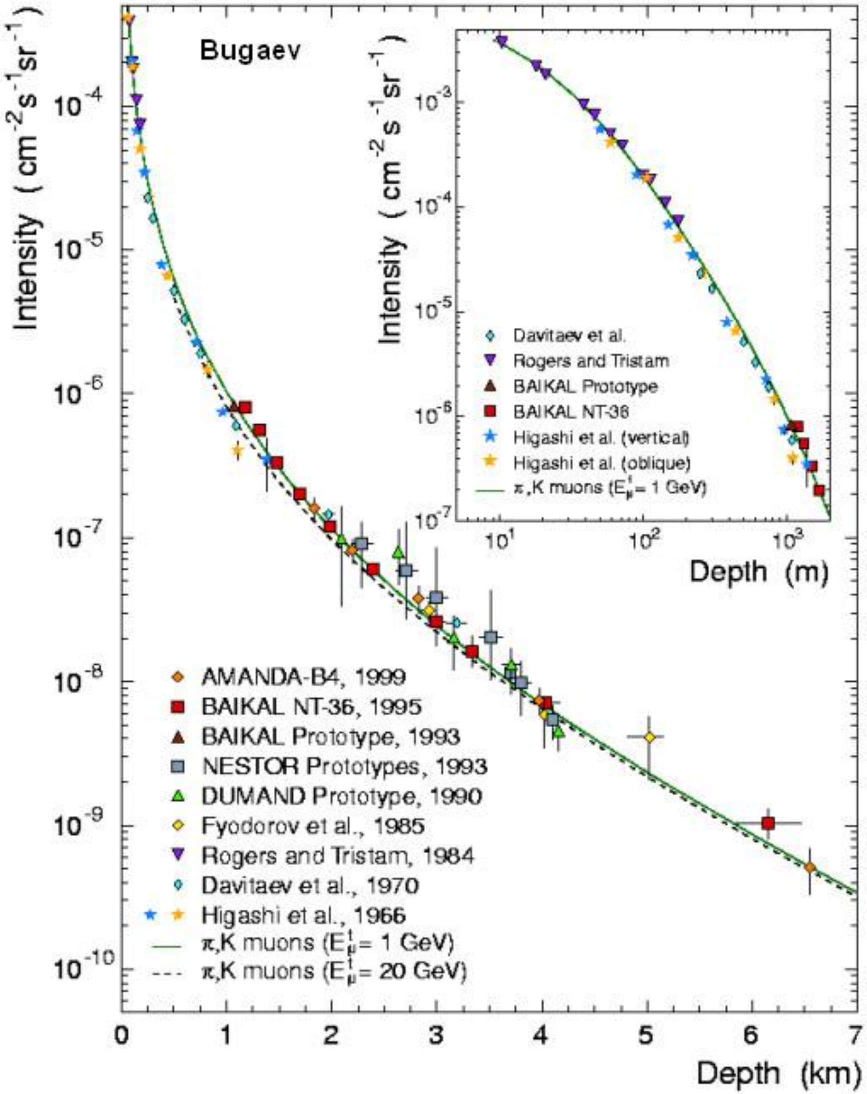
- Measure the radioactivity for every part of the detector, particularly those directly contact with LS. Select the clean material
- PMT glasses: NO direct contact with LS, low radioactivity glass
- Stainless steel: low radioactivity steel and welding material
- NO Aluminum
- Clean room (10k class) for installation
- Ensure the cleanness during LS production and storage
- Radon: Nitrogen flow during Liquid scintillator storage and operation

Solve the problem:
Calculate the ^{40}K radioactivity from ONE drop (0.05ml) of human sweat.

Cosmic Rays

Cosmic Rays





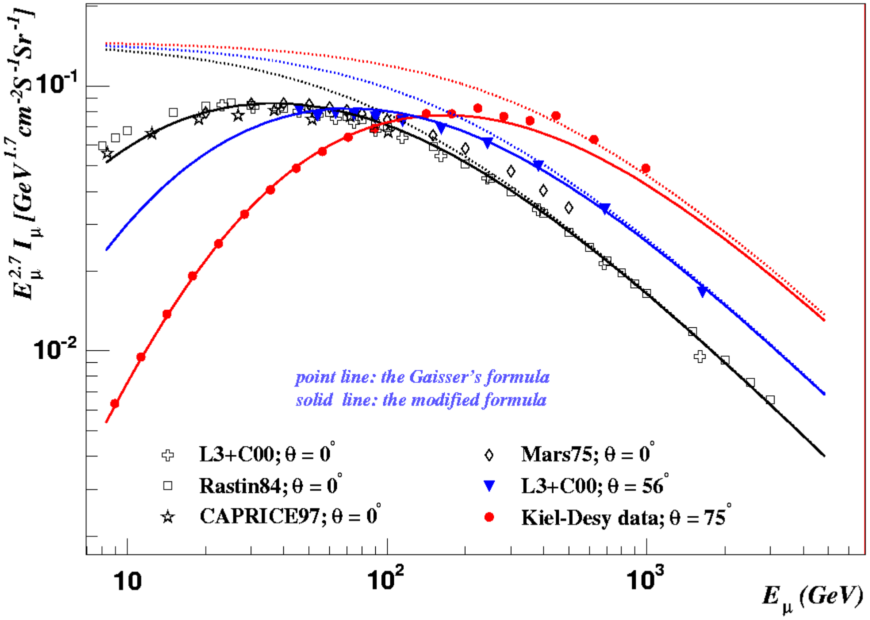
μ flux on ground: ~200Hz/m^2

Muon flux

- **Flux on ground： Gaisser formula**

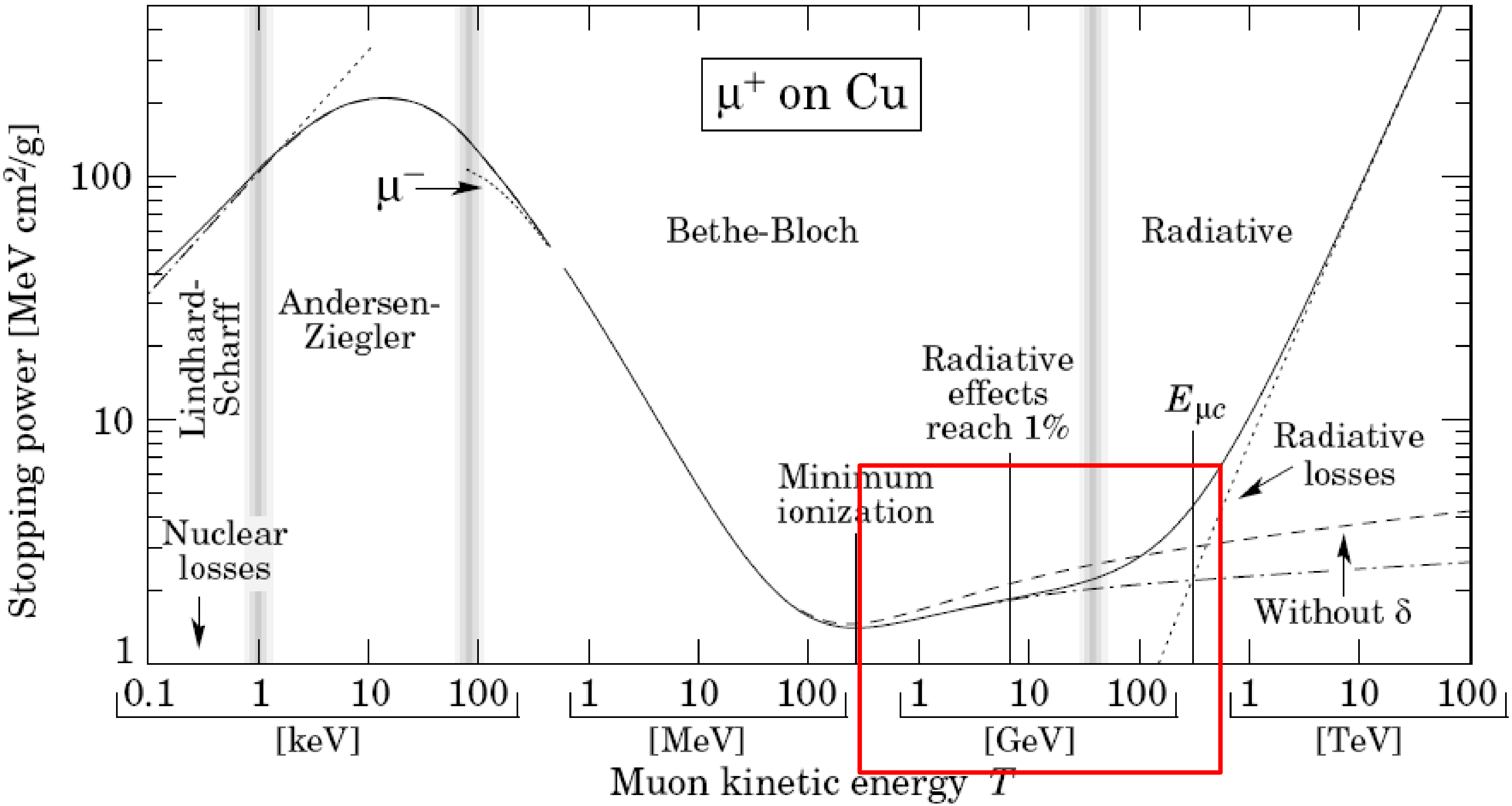
$$\frac{dI_\mu}{dE_\mu d\cos(\theta)} = 0.14\left(\frac{E_\mu}{GeV}\right)^{-2.7}\left[\frac{1}{1+\frac{1.1E_\mu\cos(\theta)}{115GeV}}+\frac{0.054}{1+\frac{1.1E_\mu\cos(\theta)}{850GeV}}\right]$$

$$\frac{dI_\mu}{dE_\mu d\cos(\theta)} = 0.14\left(\frac{E_\mu}{GeV}\left(1+\frac{3.64GeV}{E_\mu[\cos(\theta^*)]^{1.29}}\right)\right)^{-2.7}\left[\frac{1}{1+\frac{1.1E_\mu\cos(\theta^*)}{115GeV}}+\frac{0.054}{1+\frac{1.1E_\mu\cos(\theta^*)}{850GeV}}\right]$$



Modified Gaisser Formula,
(Mengyun Guan et al.)

Stopping Power of Muons



Minimum Ionizing muon: ~200MeV/m.w.e

Muon energy loss

- Continuous process — Ionization

$$\frac{dE}{dx} \approx -[1.9 + 0.08ln(\frac{E_\mu}{m_\mu})]$$

◆ Discrete process — Bremsstrahlung, e^+/e^- pair production, hadron process. Significant when muon energy is high

$$\frac{dE}{dx} = -\frac{E_\mu}{\xi}$$

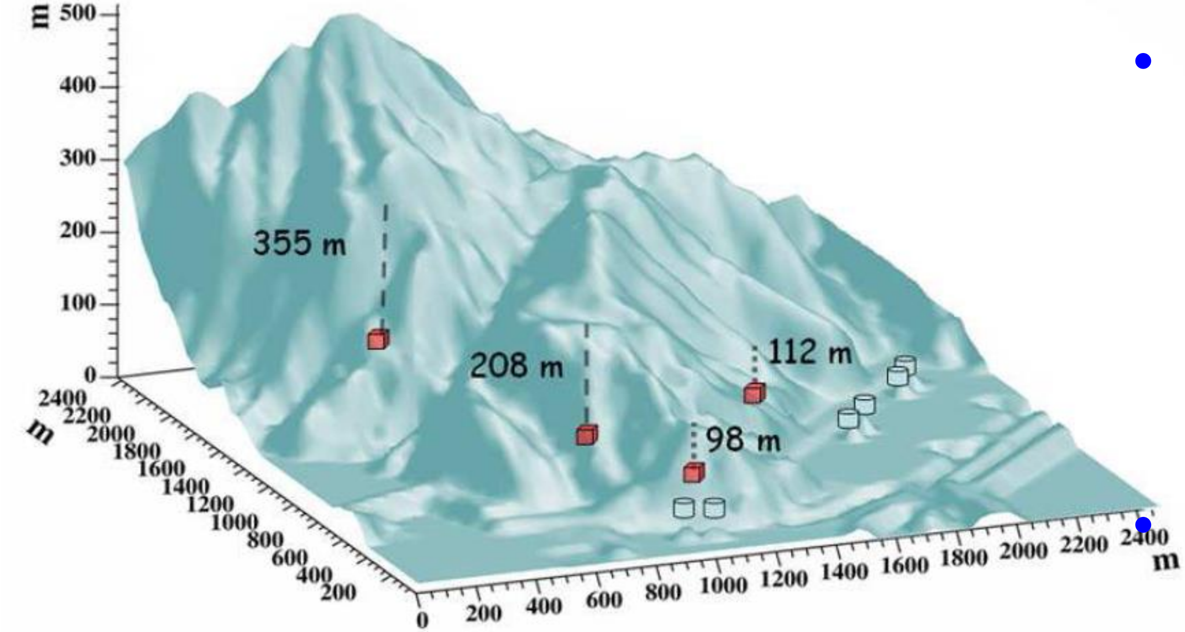
In rock， $\xi \approx 2.5 \times 10^5 g \cdot cm^{-2}$

◆ Minimum energy to pass through x_{min} rock

$$E_0^{min} = \epsilon \left(e^{\frac{x_{min}}{\xi}} - 1 \right)$$

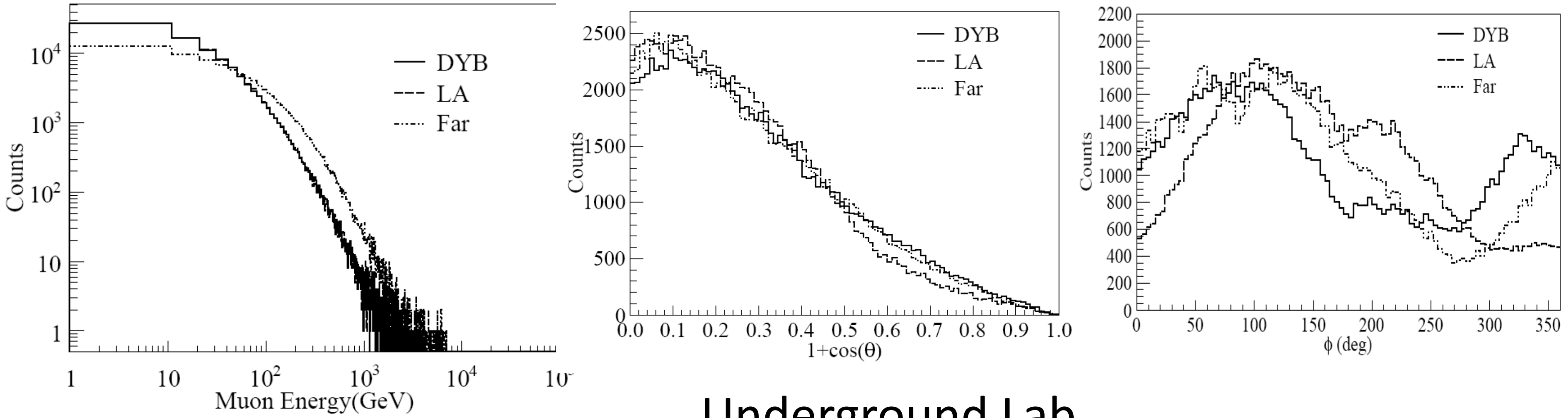
where ε=500GeV， at which the continuous process and discrete process have equal contribution.

Muon Propagation to Underground Lab



- **DYB digitized mountain profile map**
  - 1×2 km high precision survey map（1m）
  - 3×4 km 1:5000 map（5m）
  - 10×10 km SRTM map
- **Muon propagation software： MUSIC**

Rock density： 2.6 g/cm^3

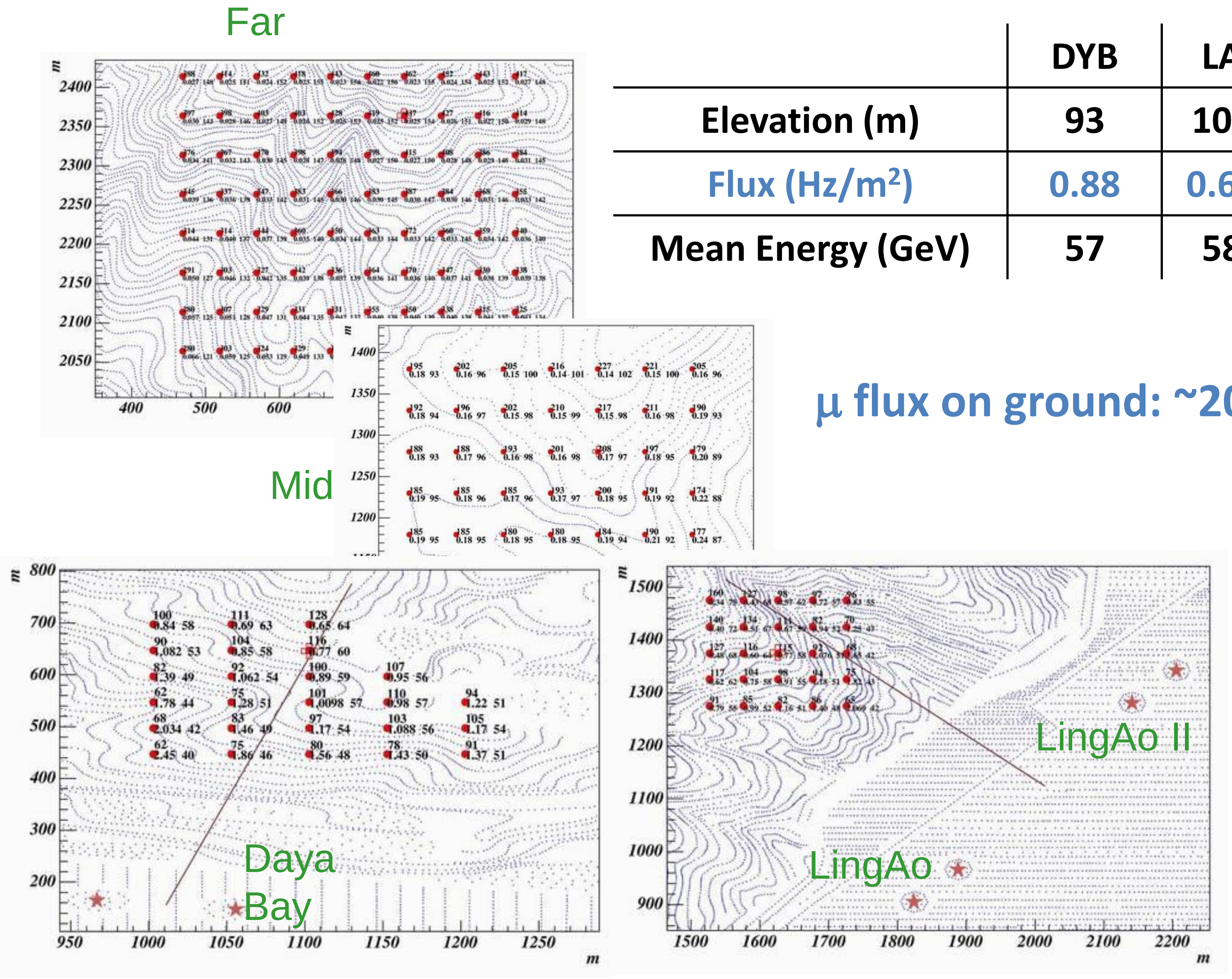


Underground Lab

Muon Simulation

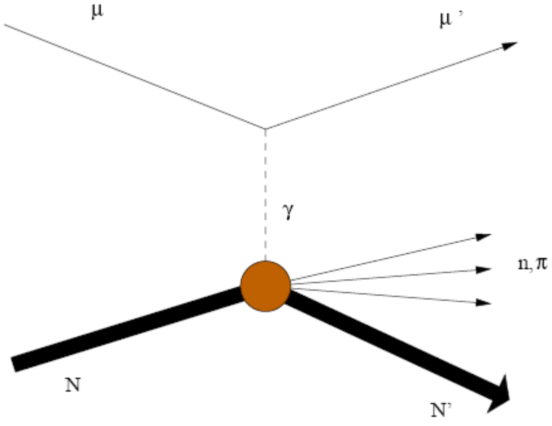
	DYB	LA	Mid	Far
Elevation (m)	93	100	208	324
Flux (Hz/m^2)	0.88	0.69	0.17	0.039
Mean Energy (GeV)	57	58	97	142

μ flux on ground: ~200Hz/m^2

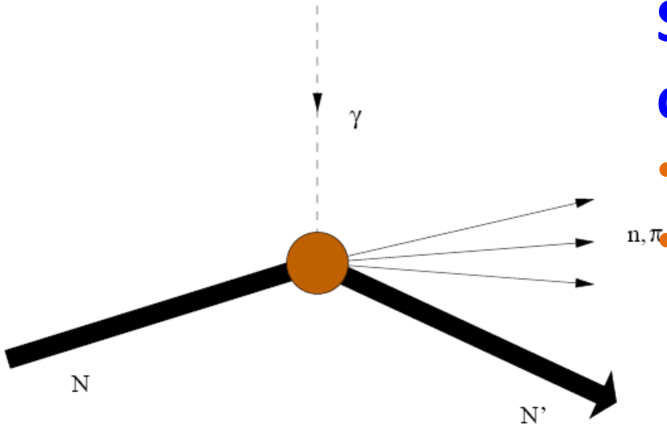


Spallation Neutron

muon spallation



γ-N process



Secondary neutron can be produced by

- **High E Neutrons**
- **Muon capture on Nuclei (low E process)**

- Neutrons from muon spallation is the most important background in those low background experiments
- Estimate the neutron yield: Simulation or Empirical formula

$$N_n = 4.14 E_\mu^{0.74} \times 10^{-6}\, neutron/(muon \bullet g/cm^2)$$

Y.F. Wang et al

neutrons produced by single muon passing 1cm material (ρ=1 g/cm^3)

- Daya Bay Near (Far) neutron production density in the rock
  0.03 (0.001) neutron/m^3/sec

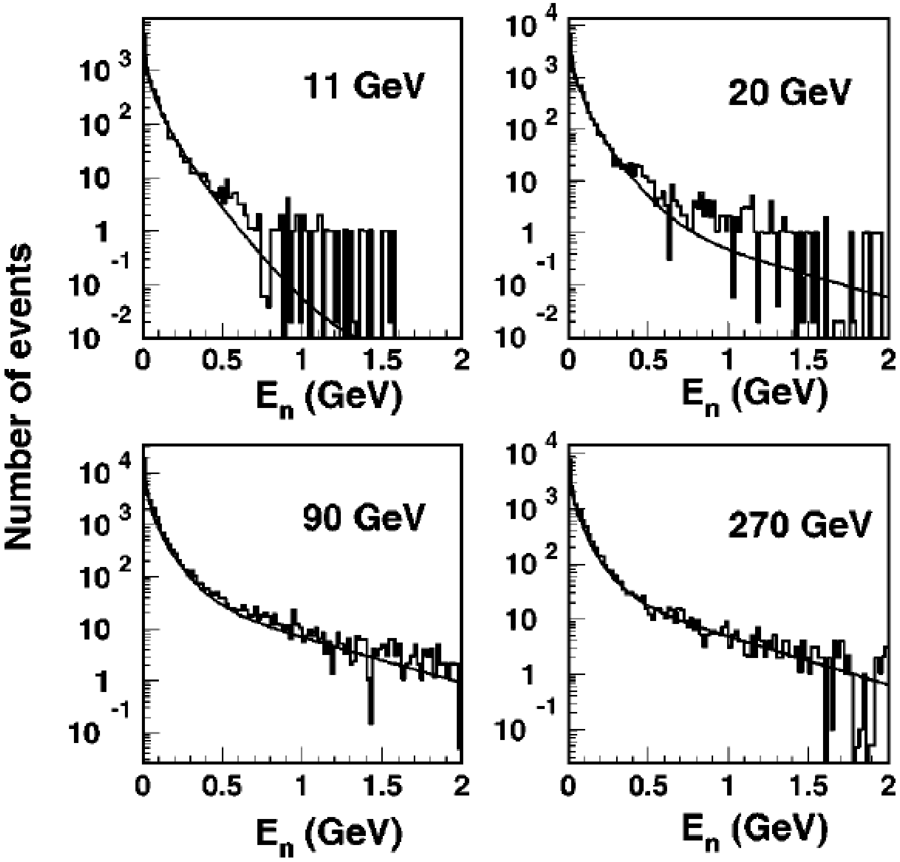
Neutron Energy and Angular Spectra

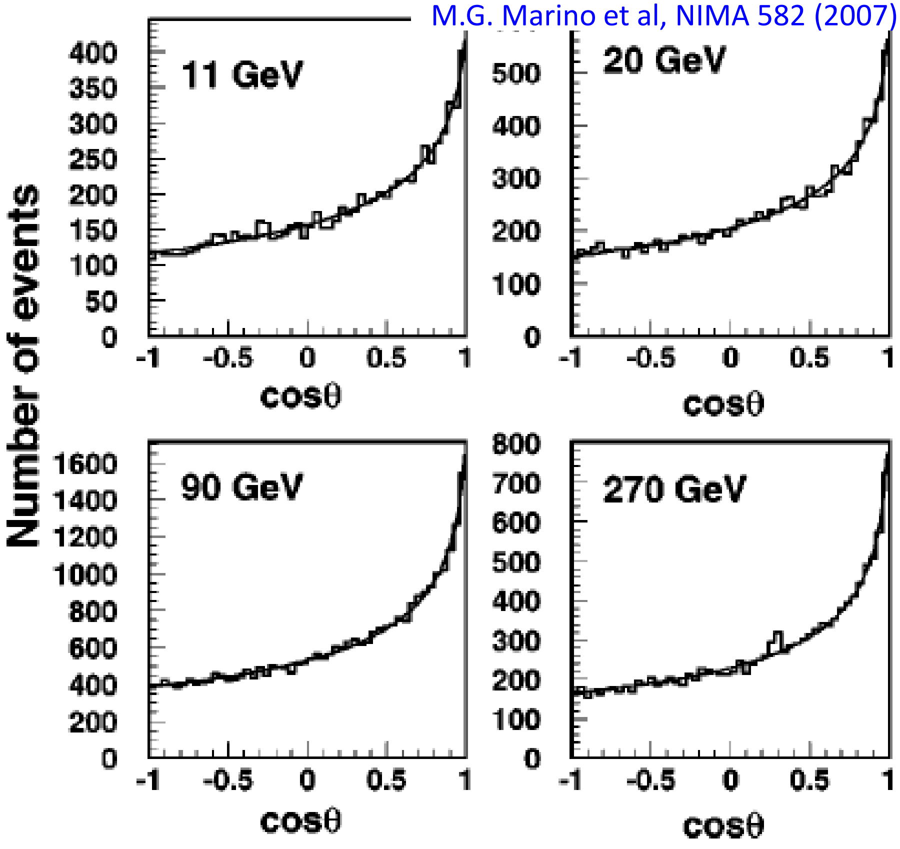
$$\frac{dN}{dE_n} = A\left(\frac{e^{-7E_n}}{E_n} + (0.52 - 0.58e^{-0.0099E_\mu})e^{-2E_n}\right)$$

$$\frac{dN}{d\cos\theta} = \frac{A}{(1-\cos\theta)^{0.6} + 0.699E_\mu^{-0.136}}$$

PHYSICAL REVIEW D **64** 013012

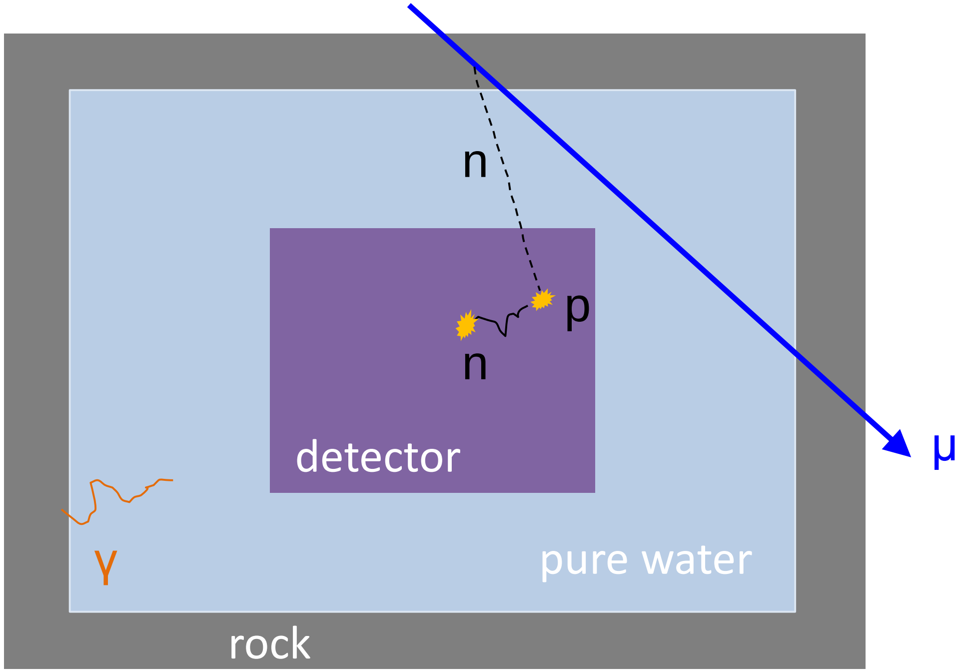
Confirmed by using GEANT4:
M.G. Marino et al, NIMA 582 (2007) 611





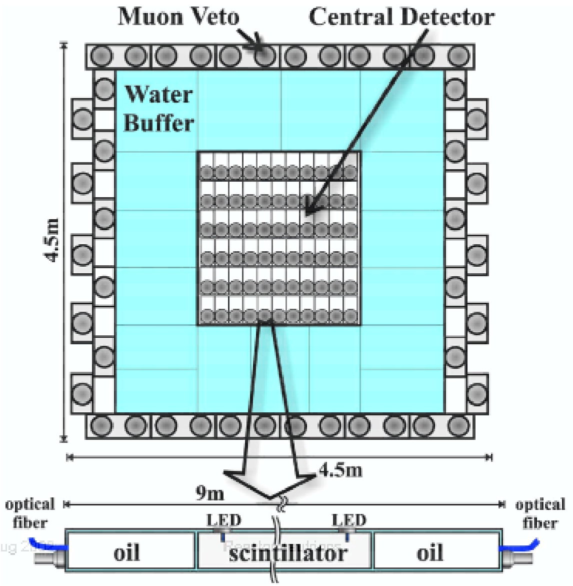
Shield Neutrons

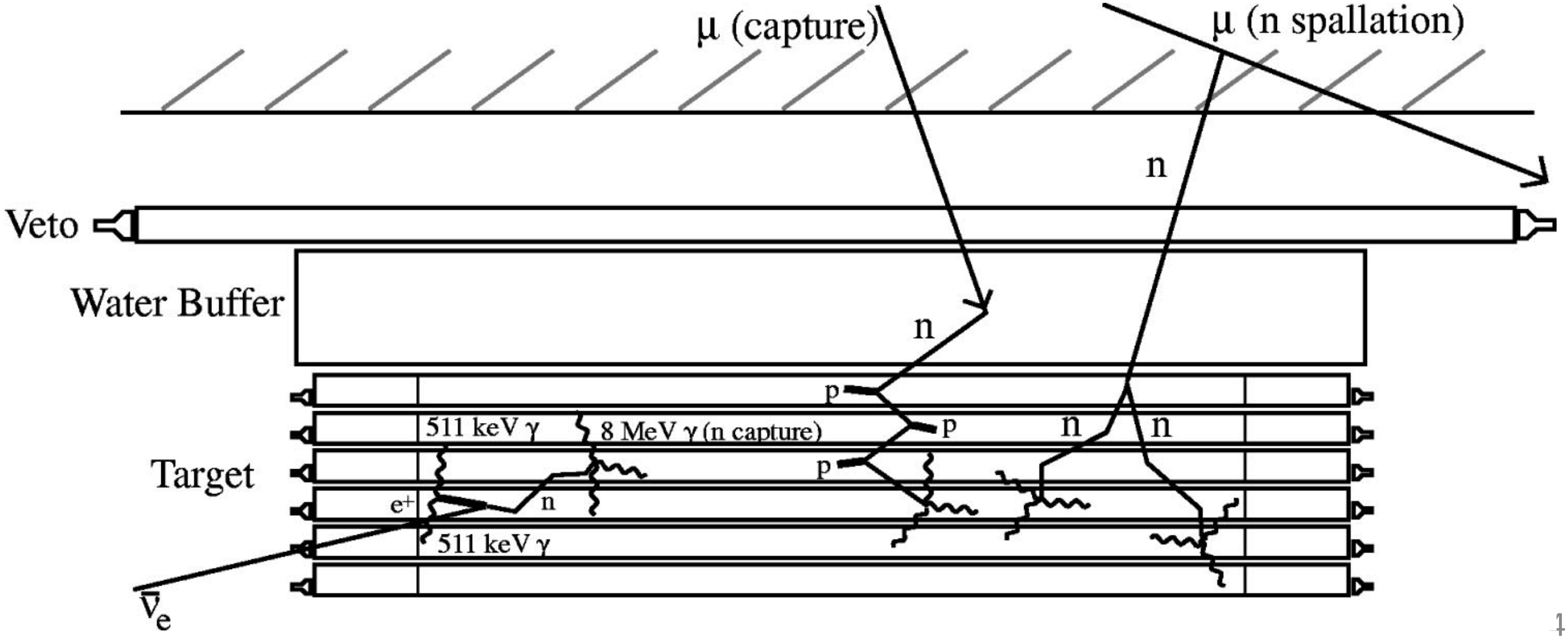
- Active Water is the best
  - Low radioactive backgrounds (<1ppb)
  - Good for neutron moderation
  - Good for neutron veto (tag fast neutrons)
  - Equipped with PMTs → water Cerenkov detector



Need Go Underground

- Experience from Palo Verde
  - Unique triple coincidence due to shallow depth
  - No monochromatic energy peak → difficult for efficiency, systematic errors, …





Muon Capture

- Stopping Muon: $\mu^+ \to e^+ + \nu$， Michele electron， $\tau = 2.19703\ \mu s$
- μ^- first captured by atom, then decay via $\mu^- \to e^- + \bar{\nu}$, or captured by the nuclei

$$\mu^- + p \rightarrow \nu_\mu + n$$

$$\mu^- + {}^{12}C \rightarrow \nu_\mu + {}^{12}B^*$$

元素	μ^- 寿命 (ns)	核俘获率 (s^{-1})	核俘获过程几率 (%)	平均中子个数 (/反应)
C	2026.3	0.388×10^5	7.85	1
H	2194.9	0.420×10^3	0.11	1
O	1795.4	1.026×10^5	18.43	0.98
Fe	201	45.30×10^5	91.08	1.12

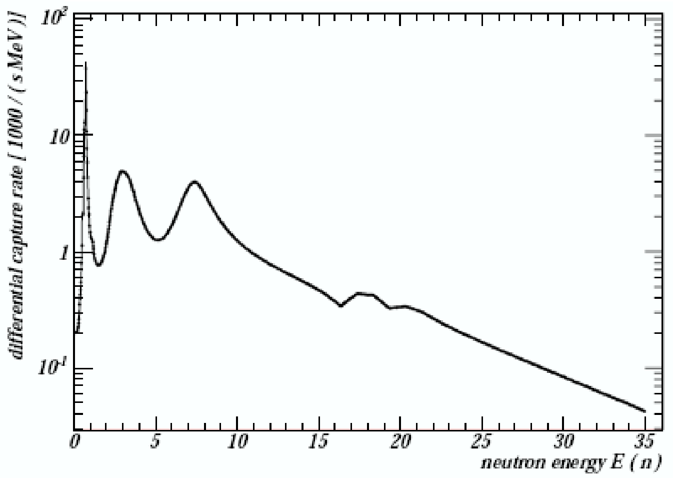


图 1.33: 碳核俘获带负电荷的 μ 子后放出的中子能谱 [64]

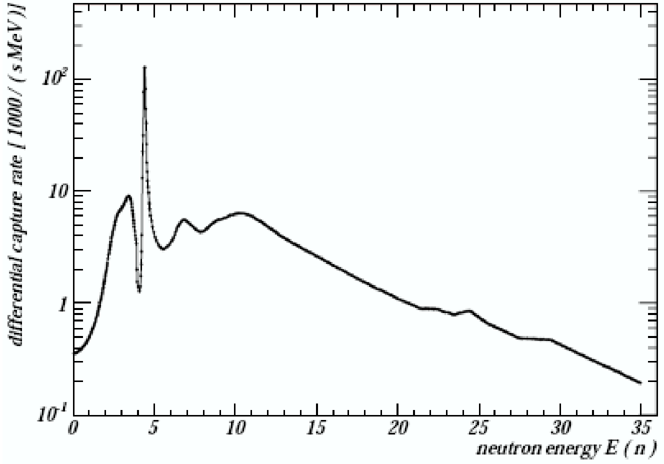
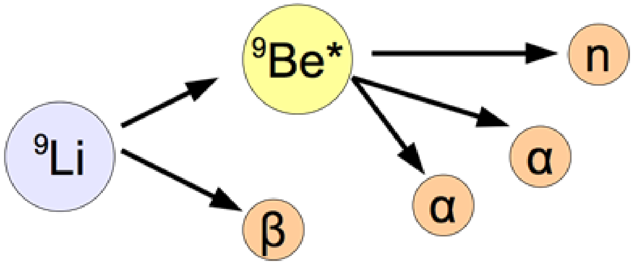


图 1.35: 氧核俘获带负电荷的 μ 子后放出的中子能谱 [64]

Cosmogenic Longlived Isotopes

- **Can not be removed by muon veto**
- **^{8}He/^{9}Li: beta-n emitters, can form correlated background, the biggest background**

$$\boxed{\sigma_{\text{tot}}(E_\mu) \propto E_\mu^{0.73}}$$



	Lifetime in KamLAND LS	Radiation energy (MeV)	Yield ($\times 10^{-7} \mu^{-1}$ g^{-1} cm^{2})		
			Ref. [10]	FLUKA calc.	KamLAND measurement
n	207.5 μs	2.225 (capt. γ)	–	2097 ± 13	2787 ± 311
^{12}B	29.1 ms	13.4 (β^-)	–	27.8 ± 1.9	42.9 ± 3.3
^{12}N	15.9 ms	17.3 (β^+)	–	0.77 ± 0.08	1.8 ± 0.4
^{8}Li	1.21 s	16.0 ($\beta^-\alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6
^{8}B	1.11 s	18.0 ($\beta^+\alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4
^{9}C	182.5 ms	16.5 (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2
^{8}He	171.7 ms	10.7 ($\beta^-\gamma n$)	1.0 ± 0.3	0.32 ± 0.05	0.7 ± 0.4
^{9}Li	257.2 ms	13.6 ($\beta^-\gamma n$)		3.16 ± 0.25	2.2 ± 0.2
^{11}C	29.4 min	1.98 (β^+)	421 ± 68	416 ± 27	866 ± 153
^{10}C	27.8 s	3.65 ($\beta^+\gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9
^{11}Be	19.9 s	11.5 (β^-)	<1.1	0.84 ± 0.09	1.1 ± 0.2
^{6}He	1.16 s	3.51 (β^-)	7.5 ± 1.5	12.08 ± 0.83	–
^{7}Be	76.9 day	0.478 (EC γ)	107 ± 21	105.3 ± 6.9	–

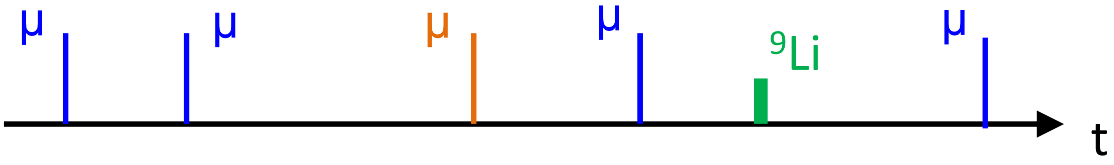
How to deal with ^{9}Li/^{8}He ?

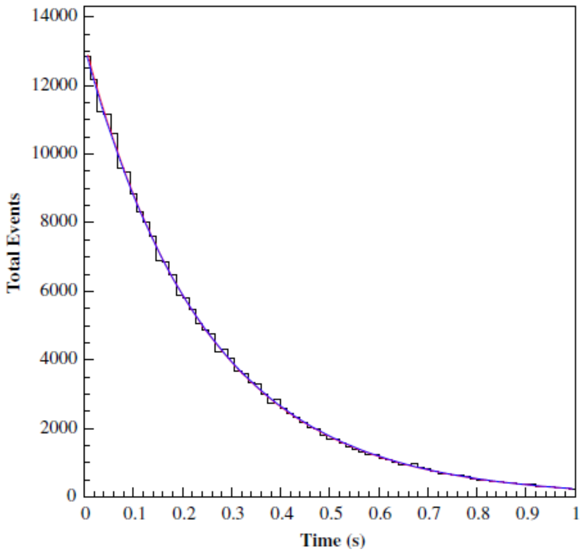
- Measurement in situ:
  - Time since last muon for selected events follows

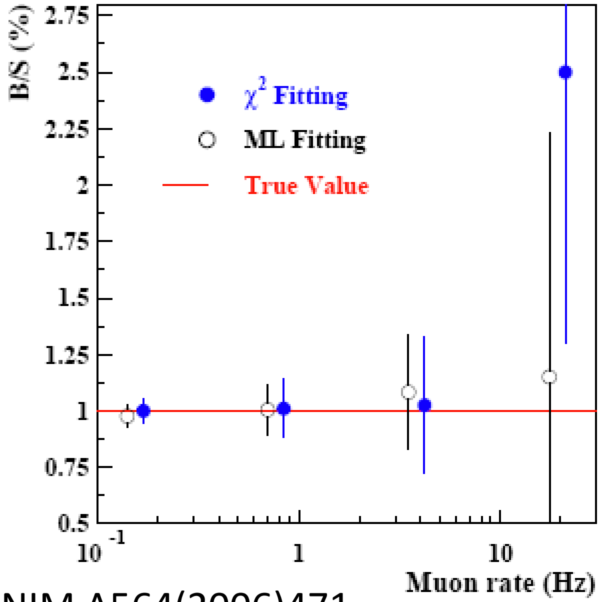
$$f(t) = B \cdot \frac{1}{\lambda} \exp(-t/\lambda) + S \cdot \frac{1}{T} \exp(-t/T)$$

$$\frac{1}{\lambda} = \frac{1}{\tau} + \frac{1}{T}$$

  - Both χ^2 and ML fitting give true values of B
  - The method starts to have difficulty when muon rate is high



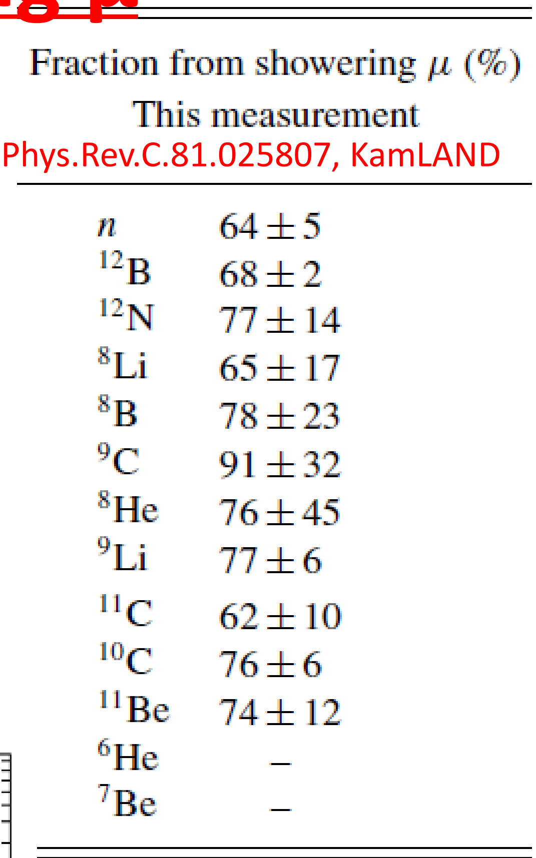




L.J. Wen et al., NIM A564(2006)471

Isotope Production vs. Showering μ

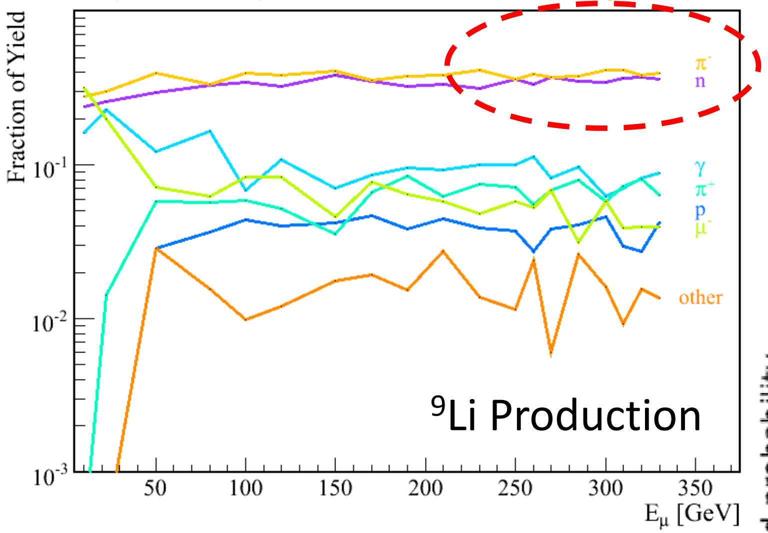
- Showering muons
  - Energy deposit >> minimum ionization *(~200MeV/w.m.e)* . No hard criteria
  - Dominate the isotope production



	Fraction from showering μ (%) This measurement
n	64 ± 5
^{12}B	68 ± 2
^{12}N	77 ± 14
^{8}Li	65 ± 17
^{8}B	78 ± 23
^{9}C	91 ± 32
^{8}He	76 ± 45
^{9}Li	77 ± 6
^{11}C	62 ± 10
^{10}C	76 ± 6
^{11}Be	74 ± 12
^{6}He	–
^{7}Be	–

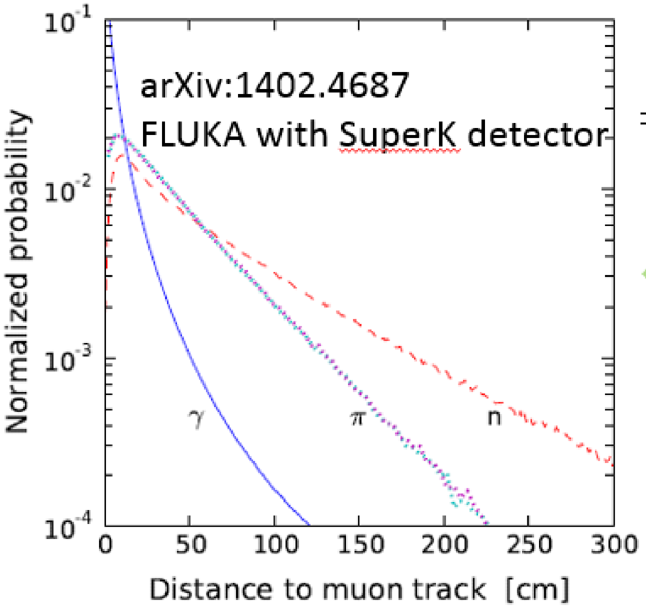
Phys.Rev.C.81.025807, KamLAND

^{12}C(π-, ^{3}He)^{9}Li is a dominant process

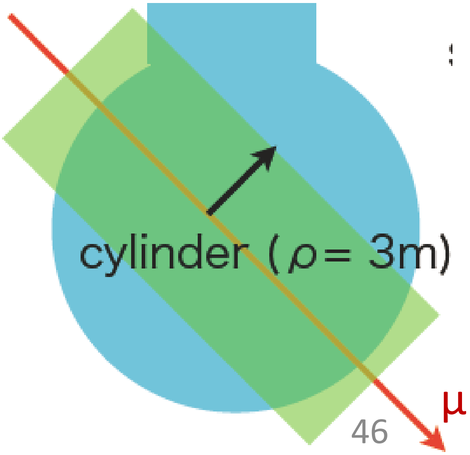


^{9}Li Production

From Lindley Windlow



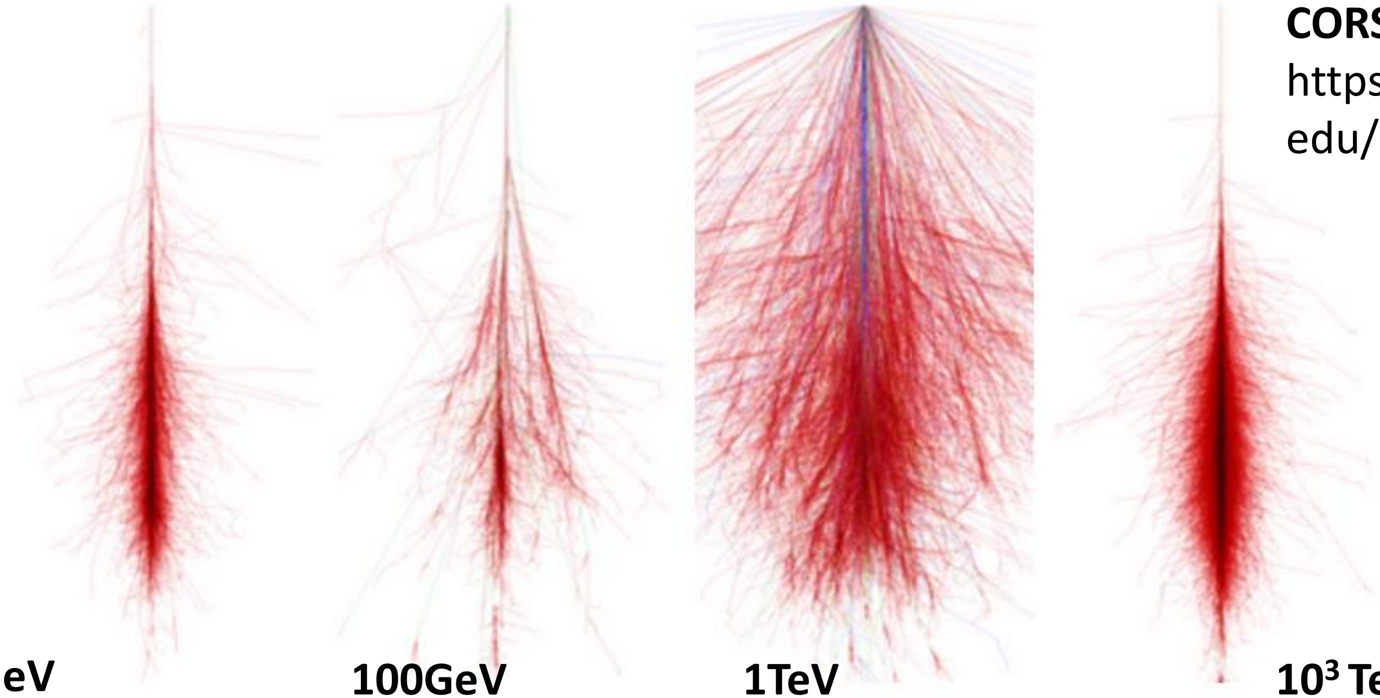
arXiv:1402.4687
FLUKA with SuperK detector



Muon Bundles

- Produced in the air showers initiated by high energy cosmic ray particles. Muons in a bundle can propagate all the way to underground detector

CORSIKA:
https://www.ikp.kit.edu/corsika/



100GeV Photon shower

100GeV Proton shower

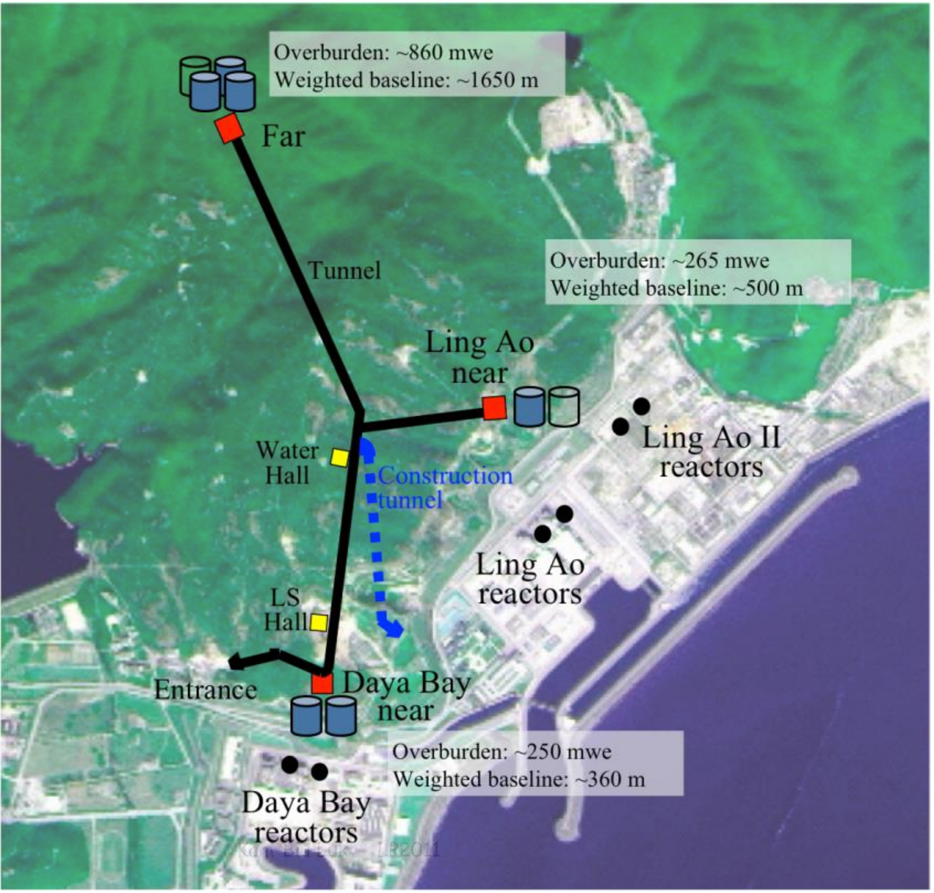
1TeV Iron shower

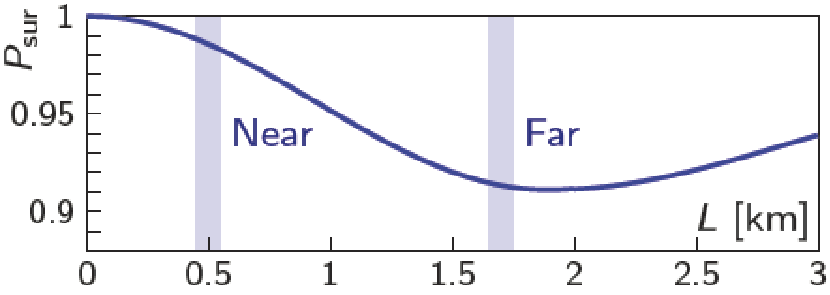
10^3 TeV (PeV) Muon shower

- Not important for small detector (Daya Bay scale)
- Important to measure for large detector (JUNO scale) , ~20%

Detector Design

Relative Measurement

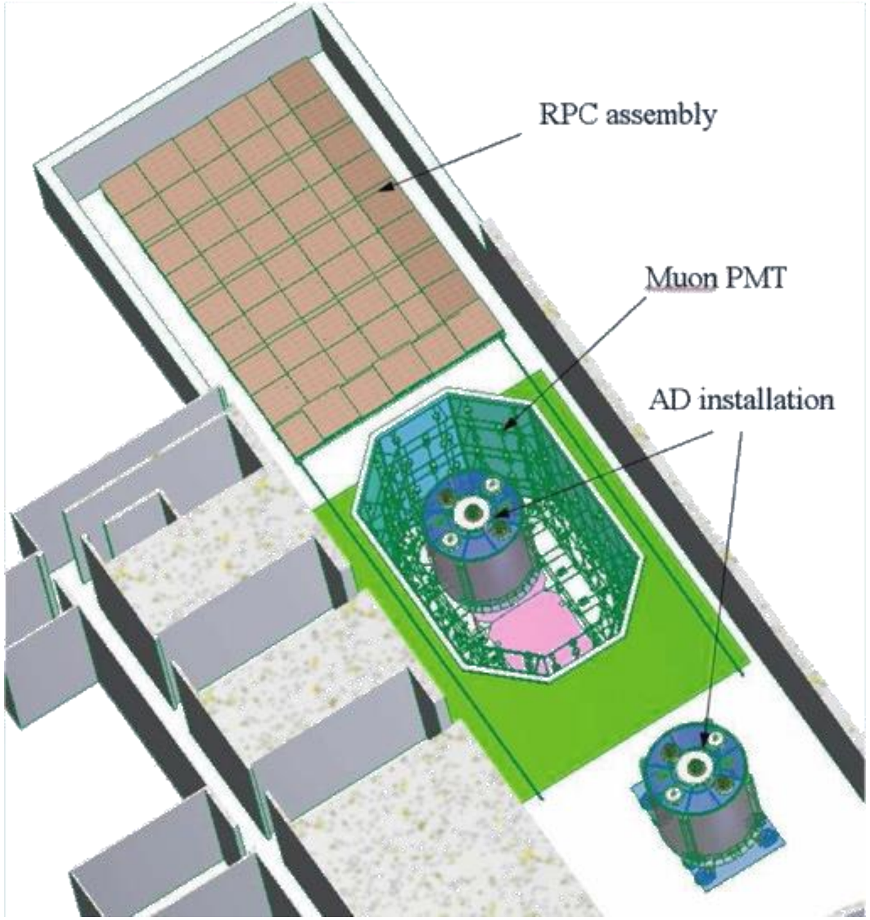




$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \boxed{\left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)} \left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2 \boxed{\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)} \left[\frac{P_\mathrm{sur}(E, L_\mathrm{f})}{P_\mathrm{sur}(E, L_\mathrm{n})}\right]$$

General Concepts

Anti-neutrino events are rare, thus background suppression is a key of the experiment. It's essential to design a good shielding to the Anti-neutrino detector.



◆ Underground Lab to shield cosmic rays

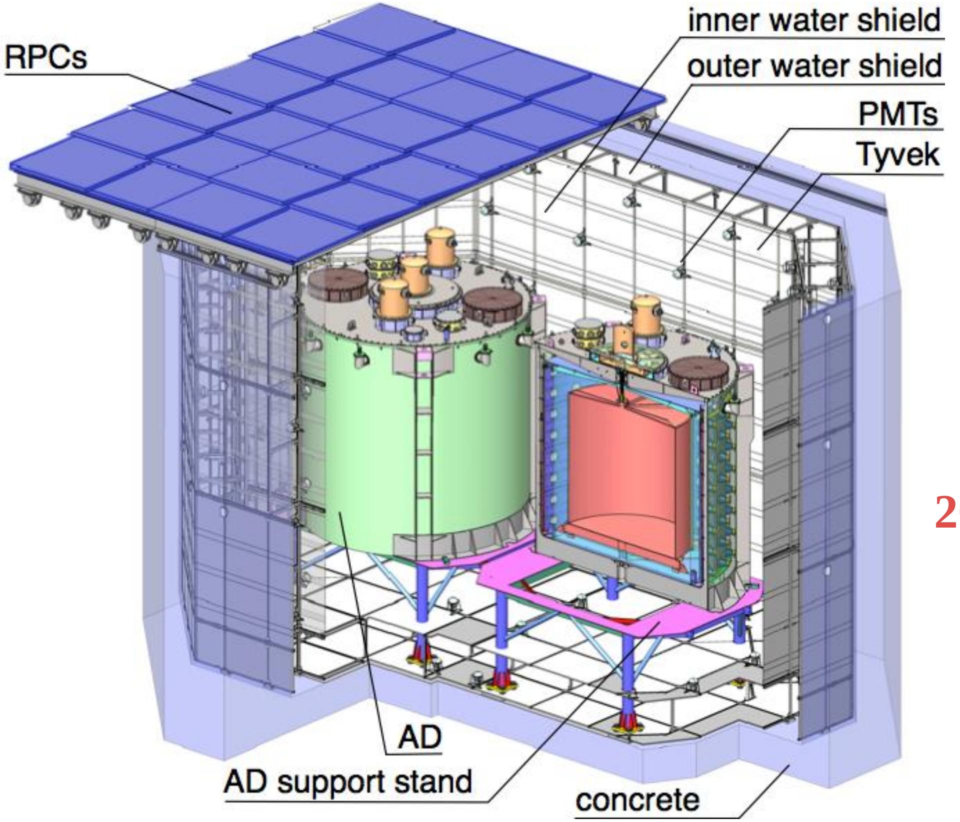
◆ Low-background antineutrino detector (AD)

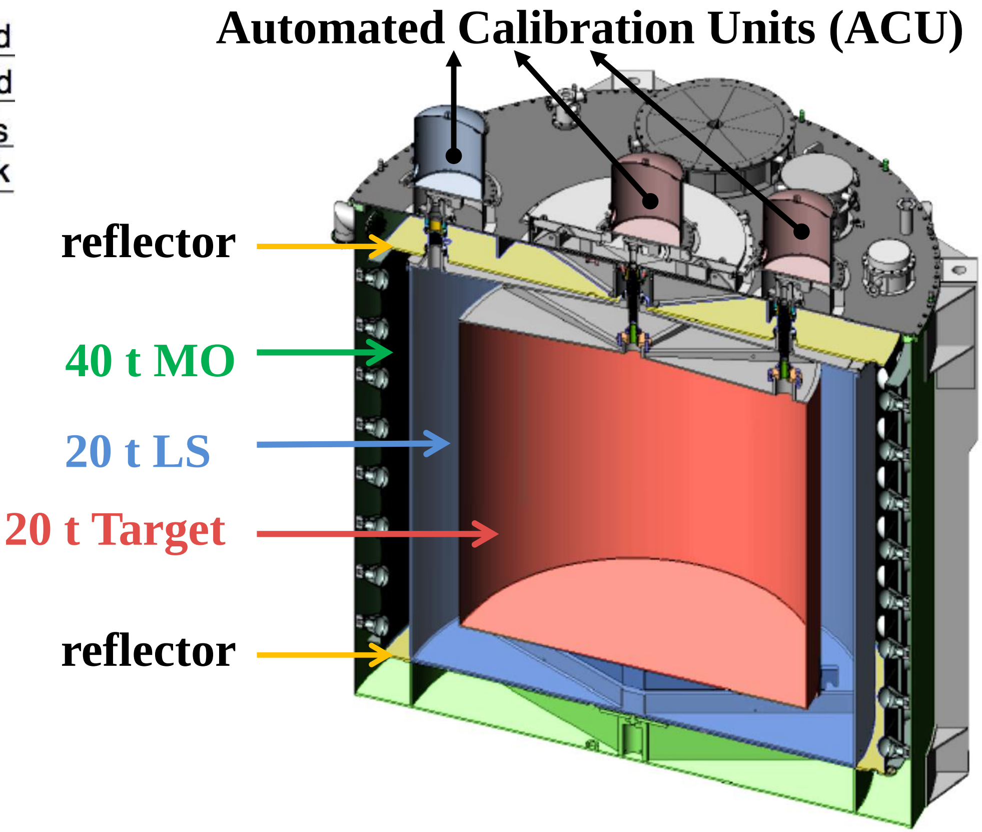
◆ AD merged in water pool (passive shielding)

◆ Water Cerenkov Detector (active shielding)

◆ RPC detector on the top

The Daya Bay Detectors

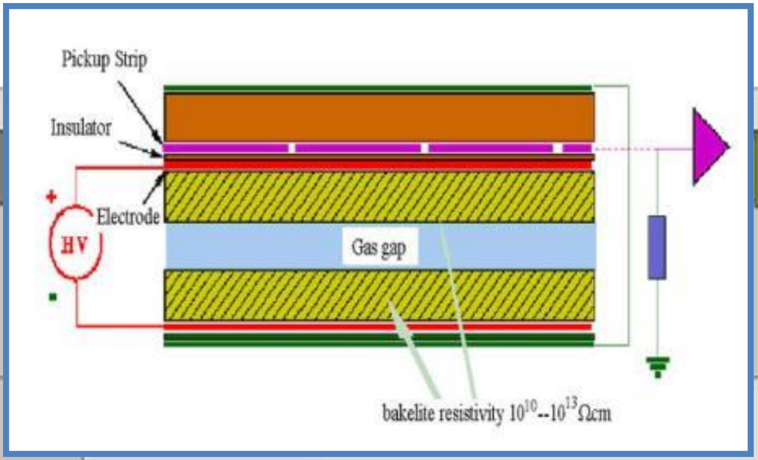


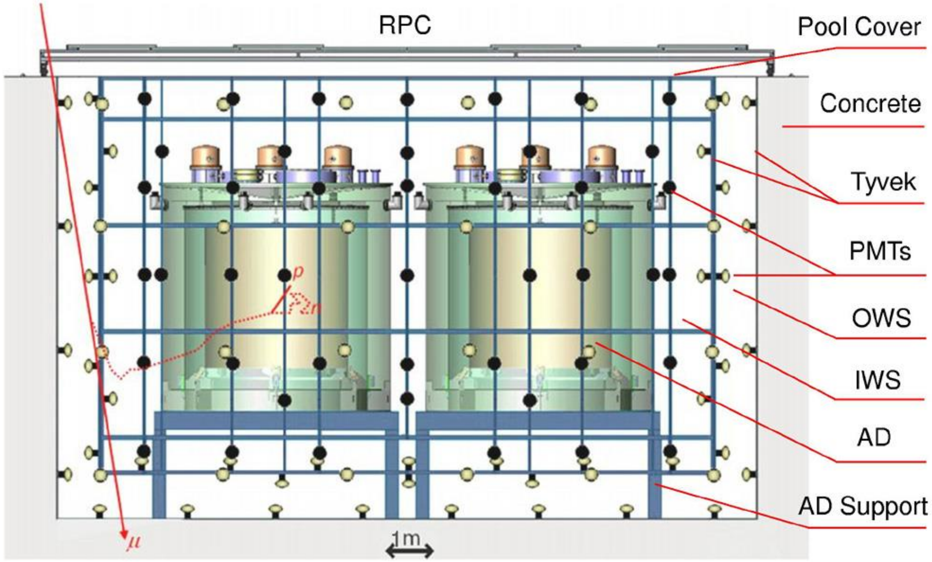


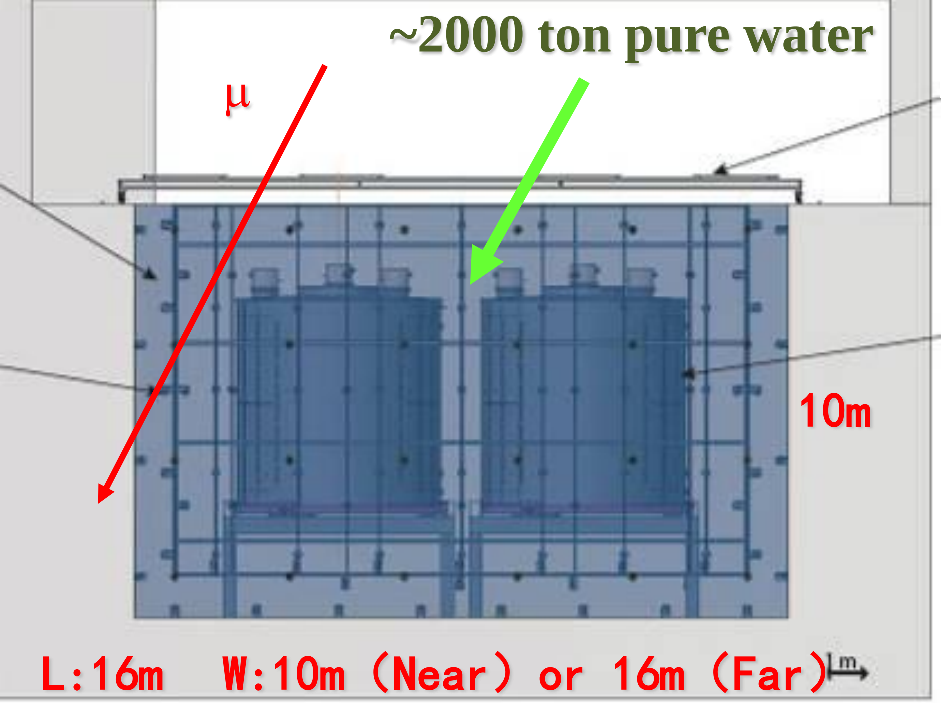
- Multiple AD modules at each site to check Uncorr. Syst. Err.
  - Far: 4 modules， near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov： 2 layers
  - RPC： 4 layers at the top + telescopes

Redundancy !!!

Water Cerenkov Detector

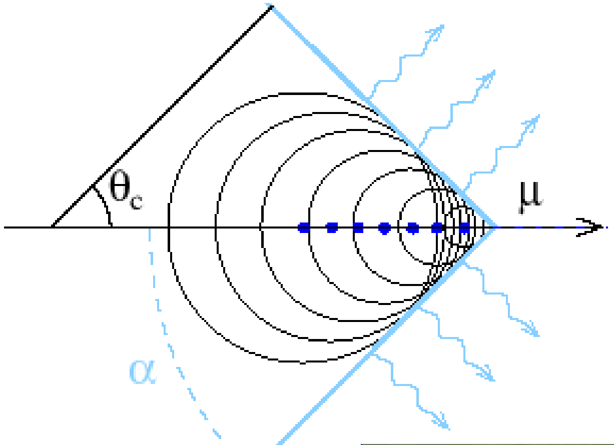






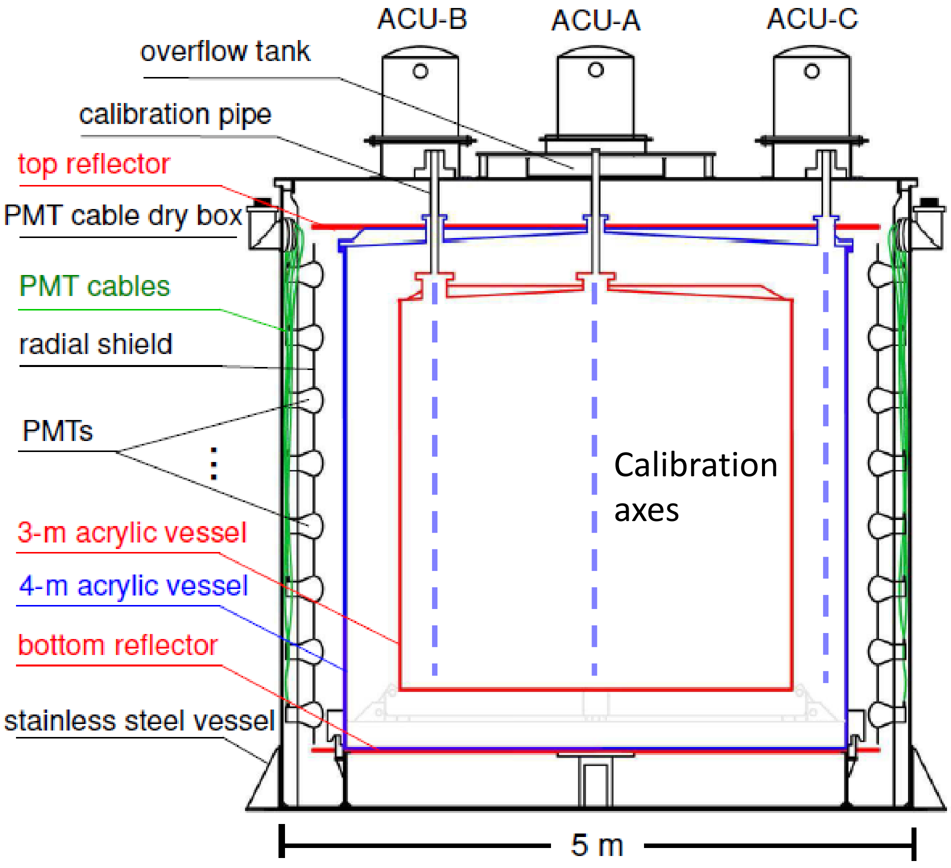
~2000 ton pure water

L:16m W:10m（Near）or 16m（Far）



$$\cos\theta = \frac{c}{nv},$$

Detector Calibration System



- Three calibration axes
  - Energy scale, time-dependence, non-uniformity, efficiency, etc
- Calibration sources
  - **LED** → PMT gain, efficiency
  - ^{68}**Ge** (2 × 0.511 MeV γ's)
  - ^{241}**Am**-^{13}**C** (neutron source) **+** ^{60}**Co** (1.17+1.33 MeV γ's)
- Weekly regular calibration
  - 3 ACU x 5 positions x 3 sources
- Manual 4π calibration system

Thanks!