Hmotná neutrina

Vít Vorobel, ÚČJF MFF UK

- Úvod (milníky, pojmy)
  - Kinematická měření m_ν
  - Oscilace neutrin (mixování neutrin)
  - Dvojný beta-rozpad (Majorana x Dirac ?)
- Experiment NEMO-3 – dvojný beta-rozpad
- Experiment SuperNEMO
- Experiment Daya Bay – oscilace reaktorových antineutrin

Neutrinové milníky

- **1930 Pauli** – neutrální částice ν β-rozpadu
- 1937 Majorana – co když ν = anti-ν ?
- 1956 Reines, Cowan – pozorování reaktorových anti-ν
- 1957 Pontecorvo – hypotéza oscilací neutrin
- 1968 Davis – pozorování slunečních ν (deficit)

 množství experimentů a trpělivost

- 1998 Super-Kamiokande – pozorování oscilací atmosférických ν
- .....

 80 let poté

- **2010** Hierarchie? Majorana? Hmotnost? Proč tak malá? ...

Základní formalizmus - mísení neutrin

- Slabé stavy $|\nu_\alpha\rangle \qquad \alpha = e, \mu, \tau$
- Hmotnostní stavy $|\nu_i\rangle, \quad m_i \quad i = 1,2,3$
- Směšovací matice Pontecorvo-Maki-Nakagawa-Sakata

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle \qquad |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

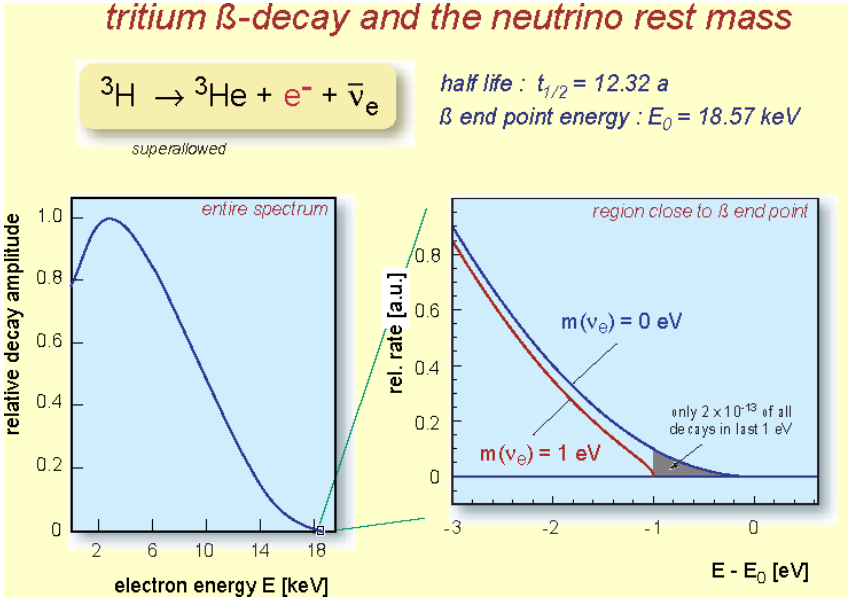
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\cdot e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Informace o hmotnosti neutrin (9 parametrů)
  - Hmotnosti (3) $m_1 \quad m_2 \quad m_3$
  - Parametry PMNS matice
    - Směšovací úhly (3) $\theta_{12} \quad \theta_{23} \quad \theta_{13}$
    - Diracova fáze (1) δ
    - Majoranovy fáze (2) $\alpha_1 \quad \alpha_2$

Kinematická měření $m_{\nu\alpha}^2 = \sum_i |U_{\alpha i}|^2 m_i^2$.

- Beta – rozpad ^{3}H
  - Mainz, Troick, $m_{\nu e} < 2$ eV/c^2
  - KATRINE, plánovaná citlivost 0.2 eV/c^2

$$N(E) \propto F(E,Z) \cdot pE(Q-E) \cdot \sqrt{(Q-E)^2 - m_{\nu_e}^2}$$



- Rozpad π – PSI, $m_{\nu\mu} < 170$ keV/c^2 $\quad \pi^+ \rightarrow \mu^+ + \nu_\mu \qquad m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi\sqrt{p_\mu^2 + m_\mu^2}$
- Rozpad τ – OPAL, DELPHI,ALEPH $\quad \tau \rightarrow \nu_\tau + 5\pi^\pm(\pi^0) \qquad \tau \rightarrow \nu_\tau + 3\pi^\pm$
- $m_{\nu\tau} < 18$ MeV/c^2

Oscilace neutrin $\Delta m_{ij}^2 = m_i^2 - m_j^2 \quad \sin^2 2\theta_{ij}$.

- **Oscilace ve vakuu** - Pontecorvo 1957

$$|\nu_i(\tau_i)\rangle = \exp\left(-\frac{i}{\hbar} m_i c^2 \tau_i\right)|\nu_i(0)\rangle = \exp\left(-\frac{i}{\hbar}(E_i t - px)\right)|\nu_i(0)\rangle \approx \exp\left(-\frac{i}{\hbar}\frac{m_i^2 c^3}{2E} x\right)|\nu_i(0)\rangle \qquad E >> m_i c^2 \quad x \approx ct \quad pc = \sqrt{E^2 - m_i^2 c^4} \approx E - \frac{m_i^2 c^4}{2E}$$

$$|\nu_\alpha(x)\rangle \approx \sum_i U_{\alpha i}^* \exp\left(-\frac{i}{\hbar}\frac{m_i^2 c^3}{2E} x\right)|\nu_i\rangle = \sum_\beta \left[\sum_i U_{\alpha i}^* \exp\left(-\frac{i}{\hbar}\frac{m_i^2 c^3}{2E} x\right) U_{\beta i}\right]|\nu_\beta\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha(x)\rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin^2\left[\frac{\Delta m_{ij}^2 c^3}{4\hbar E} x\right] + 2\sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin\left[\frac{\Delta m_{ij}^2 c^3}{2\hbar E} x\right] \qquad \Delta m_{ij}^2 = m_i^2 - m_j^2$$

2 neutrina:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\pi x}{L}$$

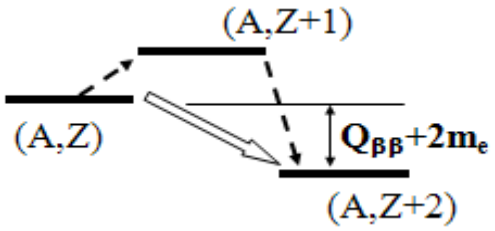
oscilační délka

$$L = \frac{4\pi E \hbar}{\Delta m^2 c^3} = 2.48m * \frac{E(MeV)}{\Delta m^2 (eV^2)}$$

- **Oscilace v hmotném prostředí** - Wolfenstein 1978, Mikheyev-Smirnov 1985 (MSW effect)
  - významný efekt pro sluneční a urychlovačová neutrina
  - Z^0 : ν_e, ν_μ, ν_τ
  - W^+: pouze ν_e
  - Efektivní m_i jsou jiná v prostředí než ve vakuu

ββ-rozpad

$$\langle m_{ve} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$



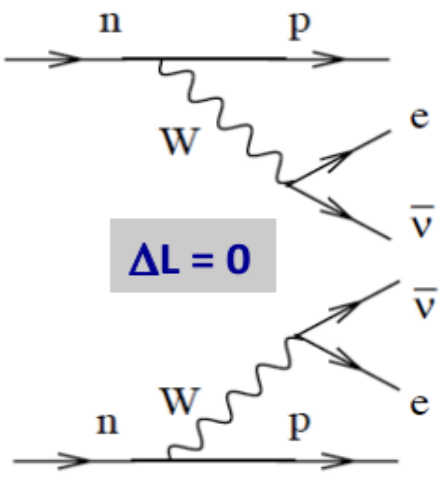
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}, Z) \times \left| M_{0\nu} \right|^2 \times \langle m_{ve} \rangle^2$$

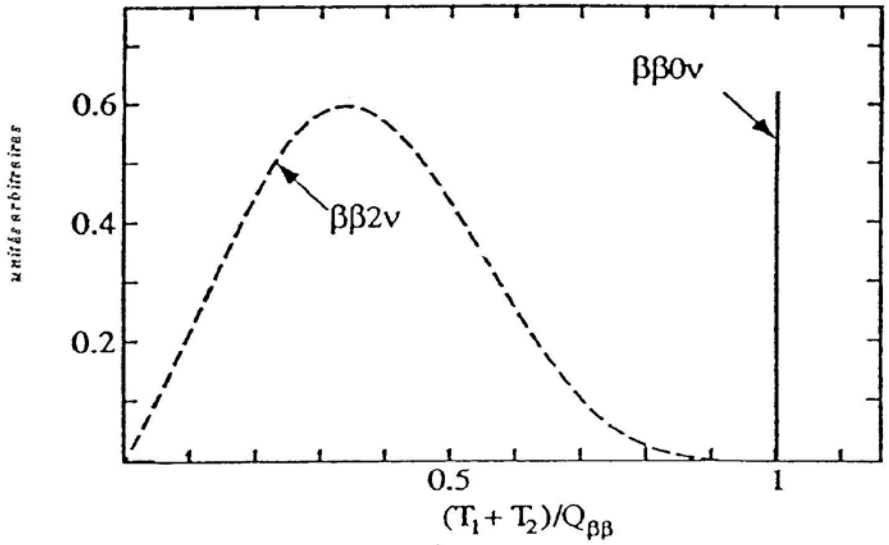
(A,Z)→(A,Z+2) + 2e⁻ + 2ν

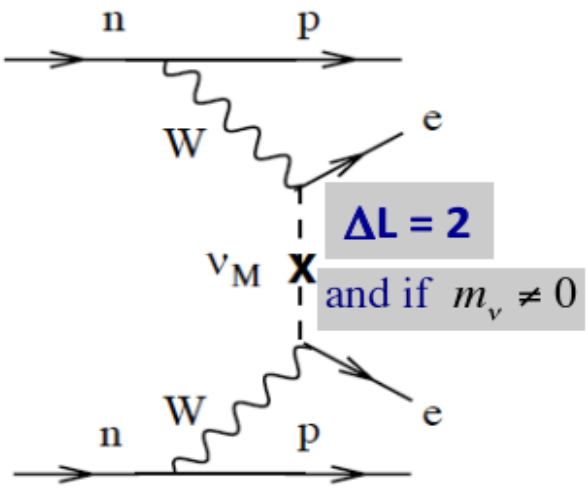
(A,Z)→(A,Z+2) + 2e⁻

ββ2ν: proces dovolený v SM, $T_{1/2} \sim 10^{20}$y

ββ0ν: proces mimo SM, $T_{1/2} \geq 10^{25}$y

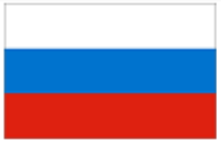


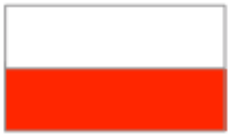


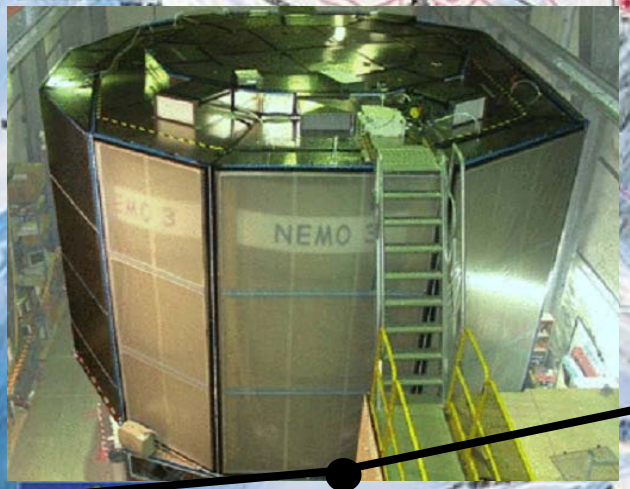
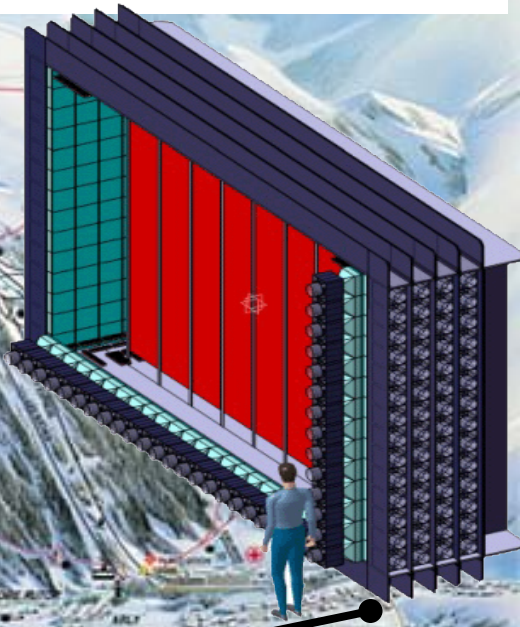


NEMO-3/SuperNEMO collaboration

Neutrino Ettore Majorana Observatory
(Neutrino Experiment on MOlybdenum – historical name)
80 physicists / 30 institutions





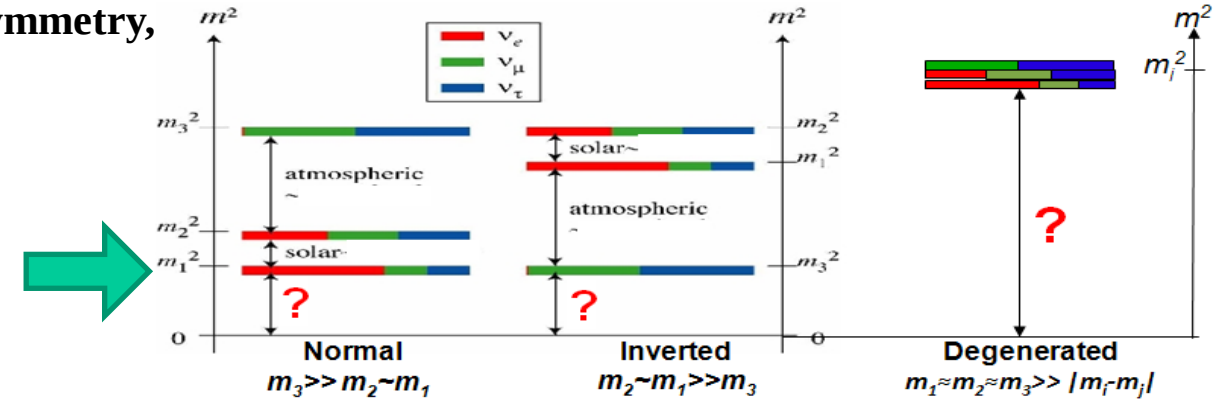
0νββ and neutrino fundamental properties

Probe of neutrino nature.

Neutrinos are Majorana fermions (particle ≡ antiparticle) if ββ0ν takes place ⇒ See-Saw mechanism, Leptogenesis, Baryon asymmetry, CP violation

Neutrino mass hierarchy.

ββ0ν measurements might help to establish the right one.



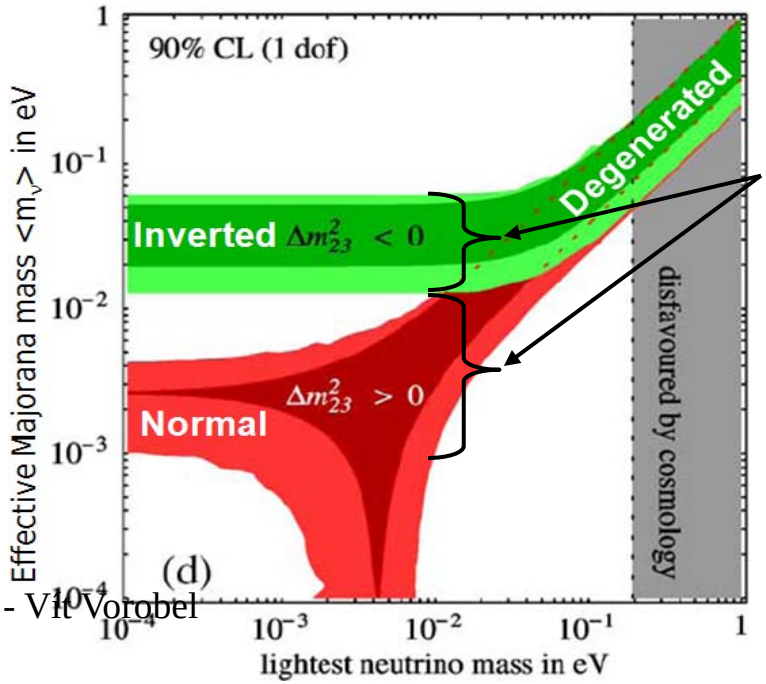
Absolute mass scale.

ββ0ν experiments are among the most sensitive ones.

Beta decay $m_\nu = \left[\Sigma |U_{ei}|^2 m_i^2\right]^{1/2} < 2.3$ eV

Double beta decay $|\langle m_\nu \rangle| = |\Sigma U_{ei} m_i^2| < 0.2 - 0.8$ eV

Cosmology $\Sigma m_i = m_1 + m_2 + m_3 < \sim 1$ eV

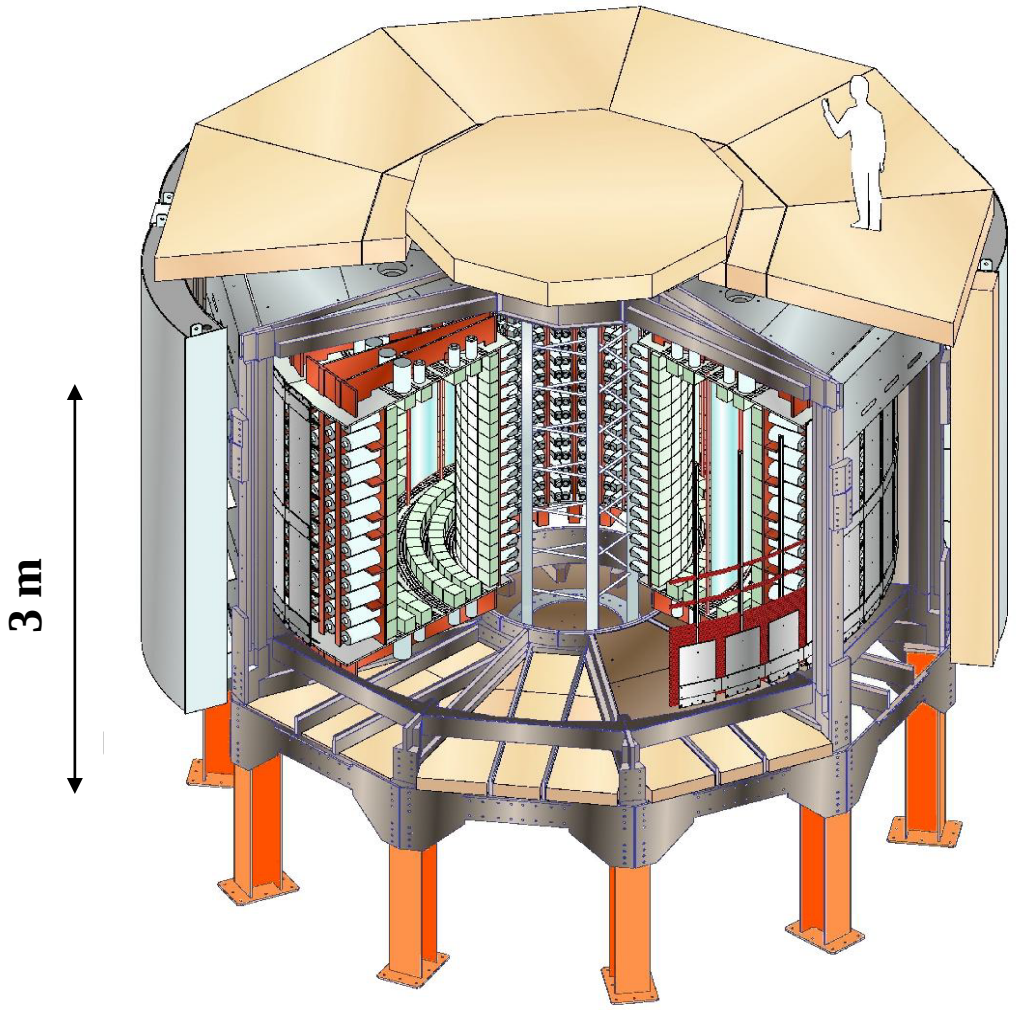


Spreads are due to variations of unknown CP phases

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

20 sectors



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

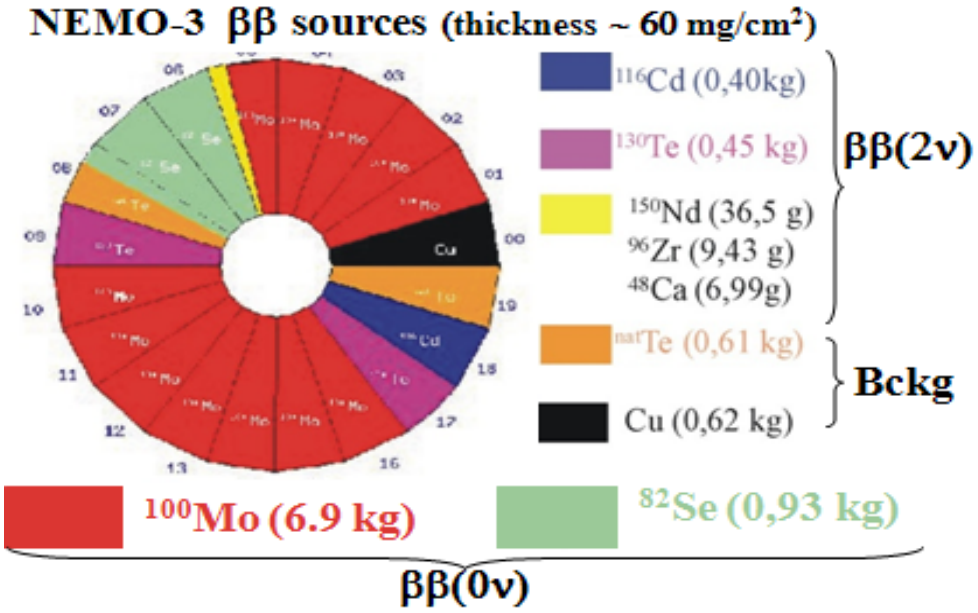
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water (~30 cm) + Wood (Top/Bottom/Gaps between water tanks)

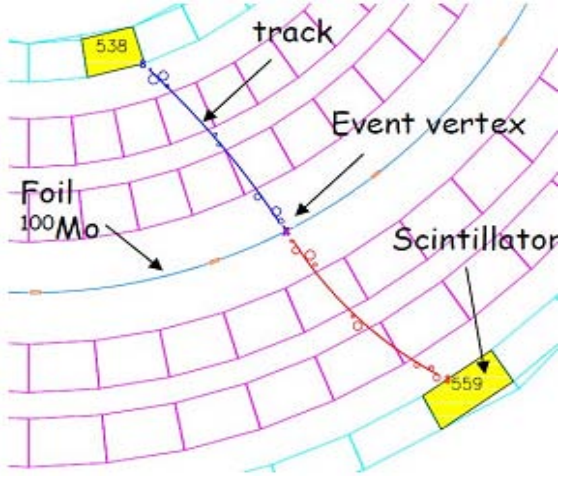
Able to identify e^-, e^+, γ and α–delayed

NEMO3 unique features

Multisource ββ-detector



Measurement of full ββ-event pattern

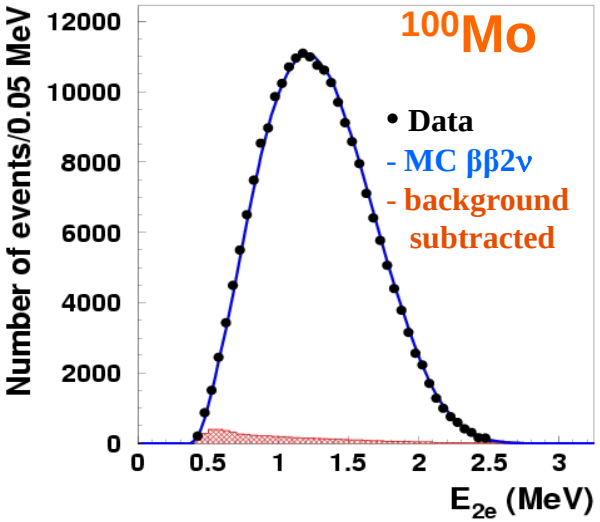


Self-determination of ALL background components measuring independent channels

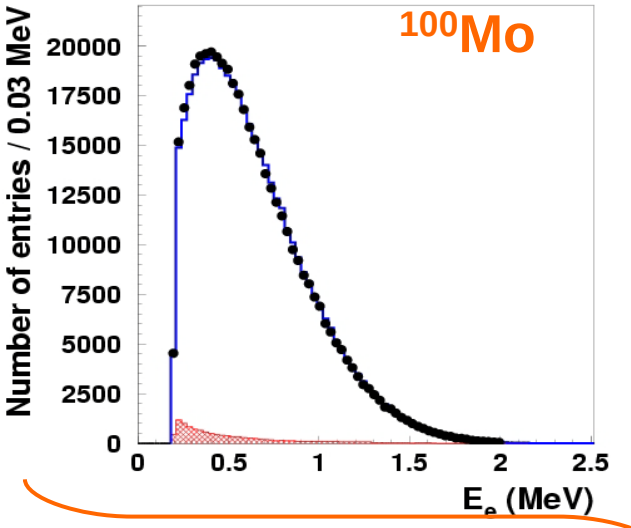
Channel(s)	Background category	Radio-contaminants
$e\gamma_{external}$, $e_{crossing}$	external background	^{40}K, ^{60}Co, ^{226}Ra...
$e\gamma$, $e\gamma\gamma$, $e\gamma\gamma\gamma$	internal background from γ-emitters	^{208}Tl, ^{207}Bi...
$1e$	internal background from pure β-emitters	^{234m}Pa, ^{40}K, ^{90}Y...
$e\alpha(\gamma)$	radon daughters deposited on wires and source foils	^{214}Bi, ^{214}Po

NEMO-3 "2νββ-factory" in action

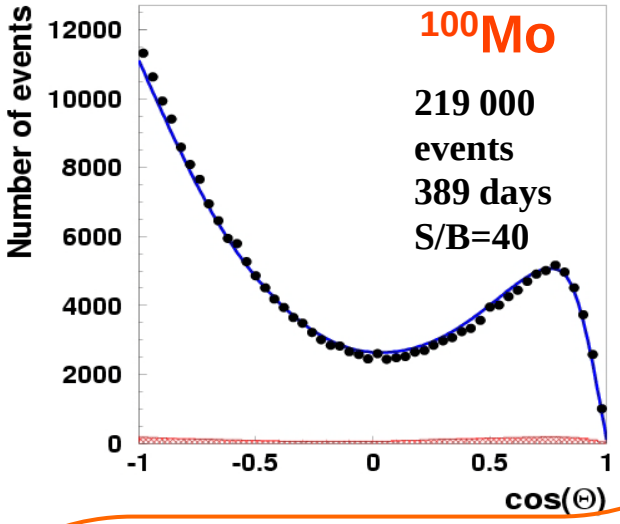
Sum energy spectrum



Single electron energy spectrum

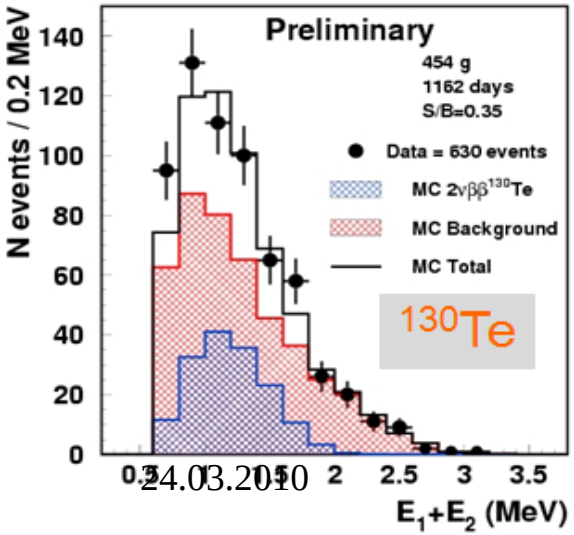


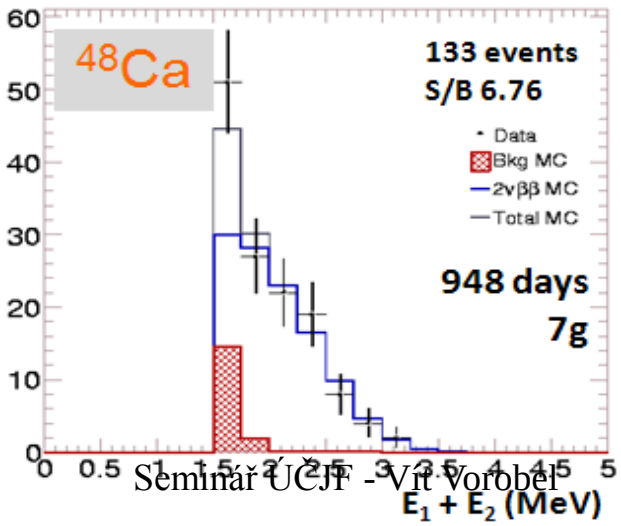
Angular distribution

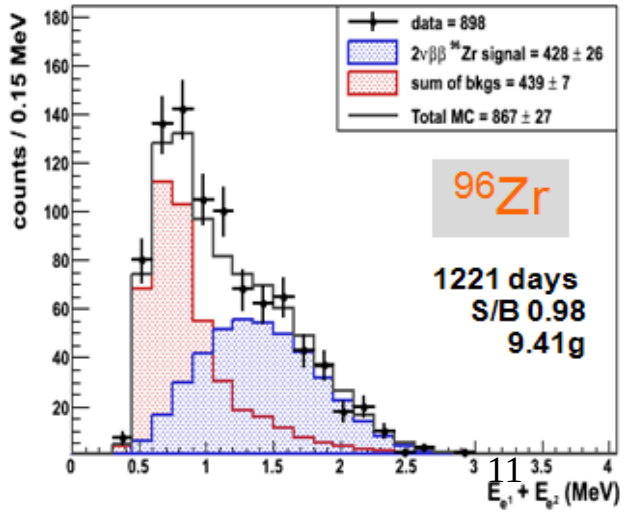


Unique spectra from tracko-calo technique

Latest results:





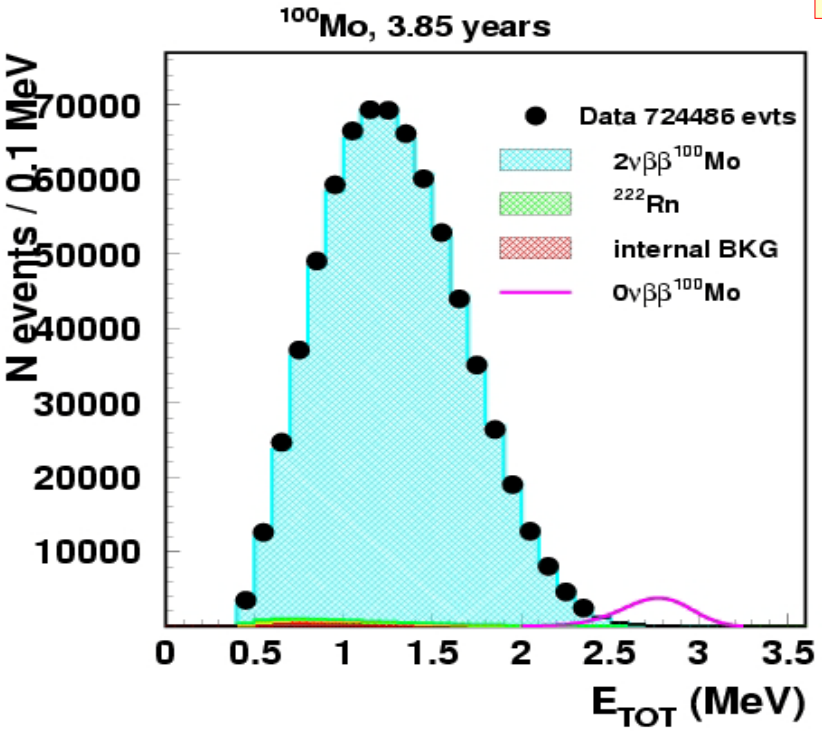


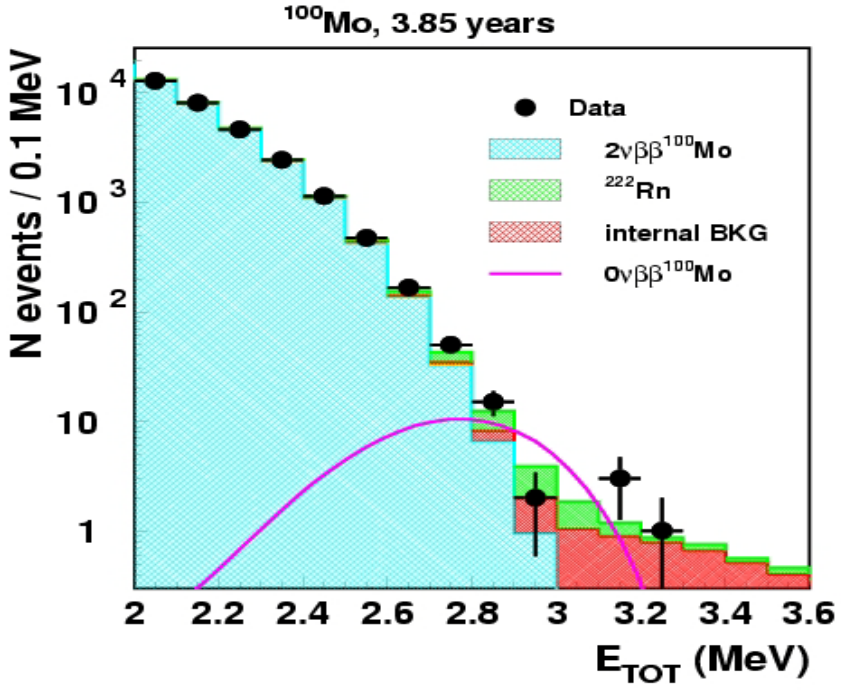
Summary of NEMO-3 2νββ-results

Isotope	Expo-sure, days	Events	S/B	$T_{1/2}(2\nu\beta\beta)$, years
Published				
^{100}Mo	389	219000	40	$(7.11 \pm 0.02(\text{stat}) \pm 0.54(\text{syst})) \cdot 10^{18}$ (SSD favored)
^{100}Mo(0^+_1)	334.3	37,5	4	$(5.7^{+1.3}_{-0.9}(\text{stat}) \pm 0.8(\text{syst})) \cdot 10^{20}$
^{82}Se	389	2750	4	$(9.6 \pm 0.3(\text{stat}) \pm 1.0(\text{syst})) \cdot 10^{19}$
^{116}Cd	168.4	1371	7.5	$(2.8 \pm 0.1(\text{stat}) \pm 0.3(\text{syst})) \cdot 10^{19}$
^{150}Nd	939	2018	2.8	$(9.11^{+0.25}_{-0.22}(\text{stat}) \pm 0.63(\text{syst})) \cdot 10^{18}$
New preliminary				
^{130}Te	1152	236	0.35	$(6.9 \pm 0.9(\text{stat}) \pm 1.0(\text{syst})) \cdot 10^{20}$
^{96}Zr	1221	428	1	$(2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{syst})) \cdot 10^{19}$
^{48}Ca	943.2	116	6.8	$(4.4^{+0.5}_{-0.4}(\text{stat}) \pm 0.4(\text{syst})) \cdot 10^{19}$

Systematic studies of 2νββ process provide crucial knowledge for 0νββ search!

0νββ-results





Isotope	$T_{1/2}(0\nu\beta\beta)$ limit, $\times 10^{24}$years	$\langle m_\nu \rangle$, eV	Experiment	Year
^{76}Ge	> 15.7	<0.3-1.35	IGEX	2002
^{76}Ge	15.	0.17-0.45	HM(KGC)	2004
^{76}Ge	> 15.5	<0.3-1.35	HM(Others)	2005
^{130}Te	>3	<0.2-0.7	CUORICINO	2008
^{100}Mo	>1.1	<0.45-0.93	NEMO-3	2009

From NEMO to SuperNEMO

NEMO-3 successful experience allows to extrapolate tracko-calo technique on larger mass next generation detector to reach new sensitivity level.

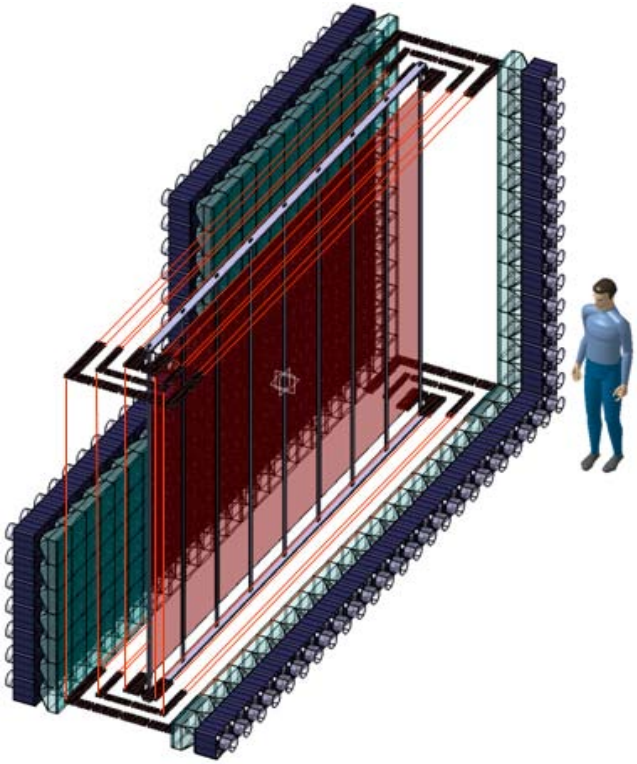
$$T_{1/2}^{0\nu}(y) \propto \frac{a\varepsilon}{W} \times \sqrt{\frac{M \times t}{N_{BGR} \times \Delta E}}$$

NEMO-3	⇒	SuperNEMO
^{100}Mo, 7kg	Isotope, mass	^{82}Se,100-200 kg
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	Background in ββ-foil	^{208}Tl: < 2 μBq/kg ^{214}Bi: < 10 μBq/kg
8%	Efficiency	30%
8% @ 3 MeV	Energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2} > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 0.8$ eV	Sensitivity	$T_{1/2} > 1\text{-}2 \times 10^{26}$ y $\langle m_\nu \rangle < 40 – 100$ meV

SUPERNEMO R&D is in progress since 2006

SuperNEMO basic design

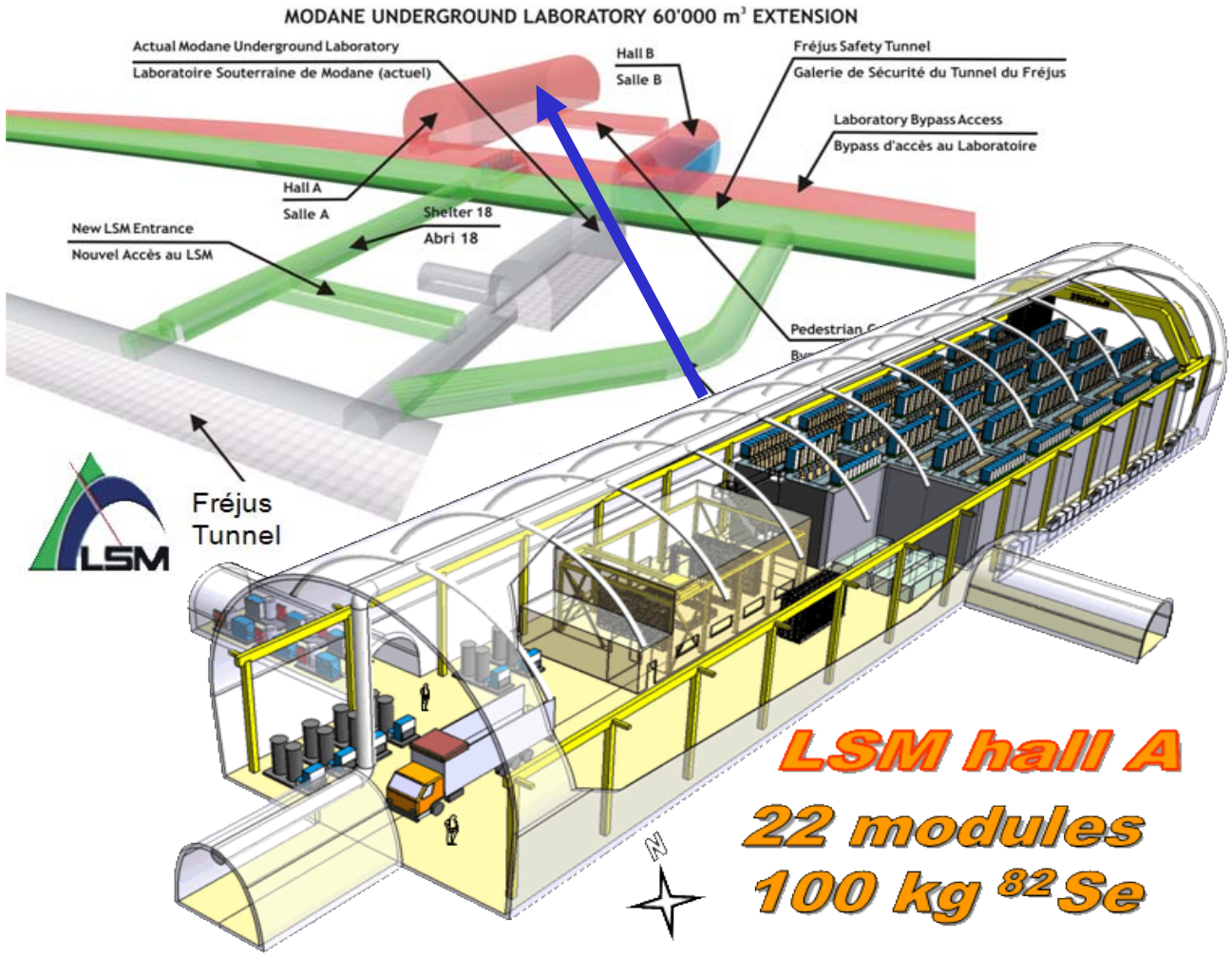
SuperNEMO module



20 modules, each of them hosts:

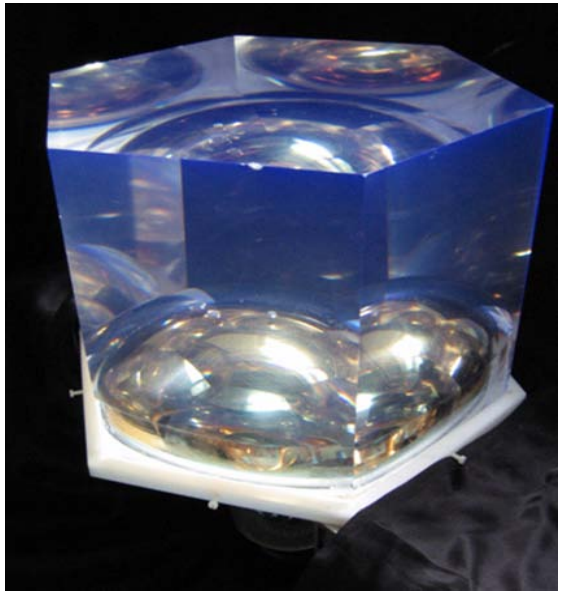
- **5 kg of source foil (^{82}Se, 40mg/cm^2)**
- **2000-3000 Geiger channels**
- **600 Calorimeter channels:**

  PVT Scintillator + 8” PMT



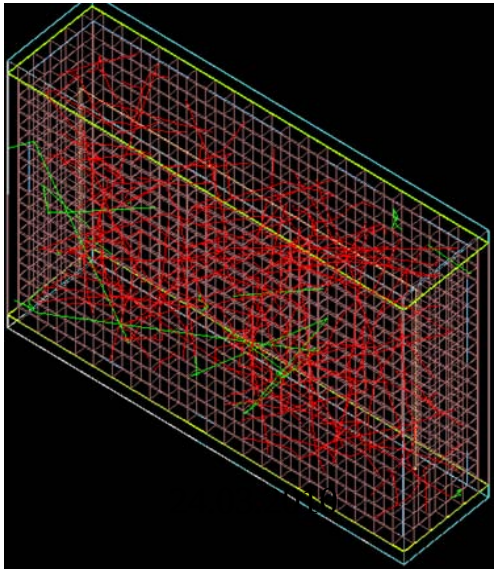
SuperNEMO is the favorite project to be hosted in the new LSM laboratory (hall A) planned to be opened at 2013

SuperNEMO demonstrator

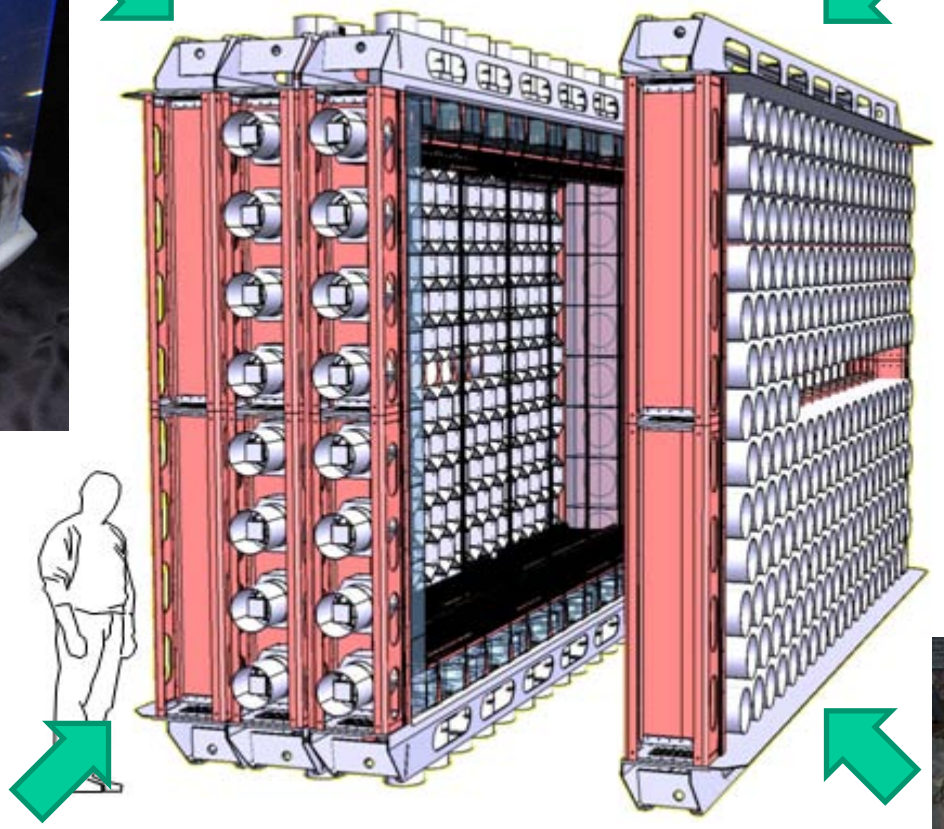


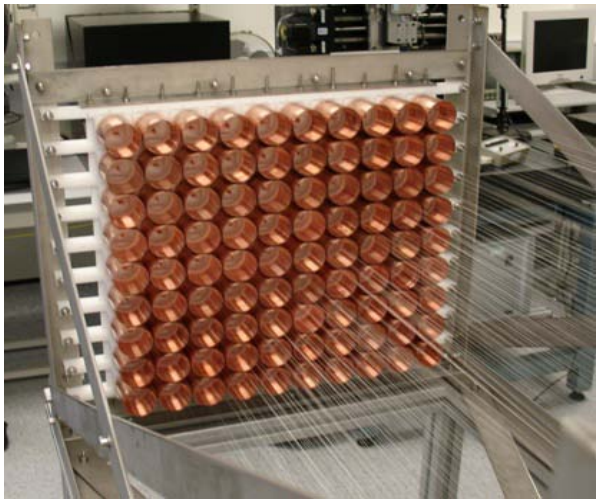
Calorimeter R&D

Simulations



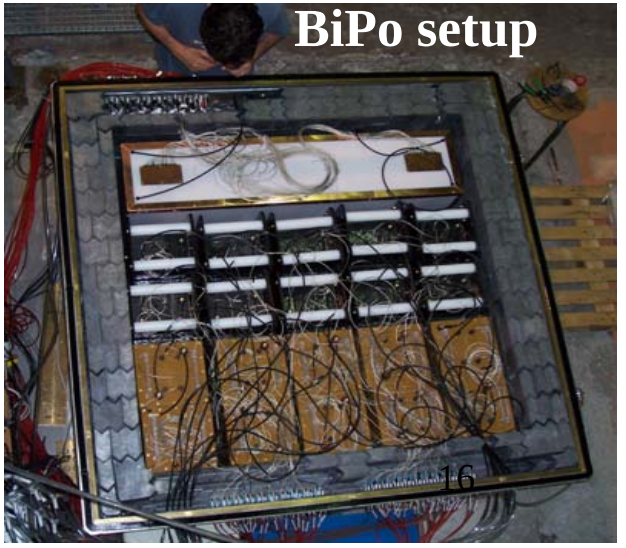
Source: 6.3 kg of ^{82}Se





Tracker R&D

Low background R&D



SuperNEMO demonstrator (first module) being finalizing, which will:

1) **Prove the concept**
2) **Test 0νββ at level of KGC**
3) **Start in 2012**

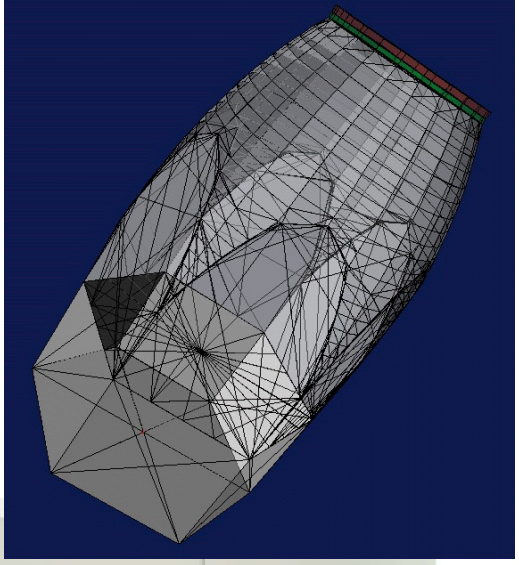
Aktivity MFF UK v NEMO-3/SuperNEMO

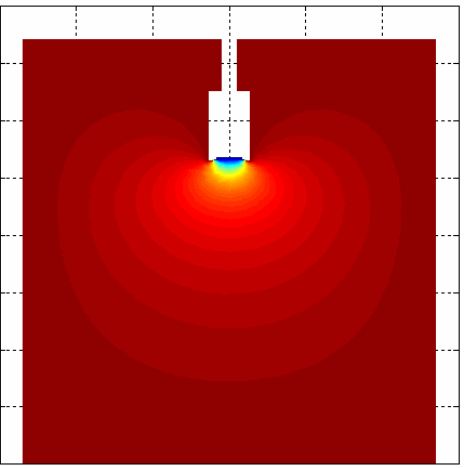
- V úzké spolupráci s UTEF ČVUT

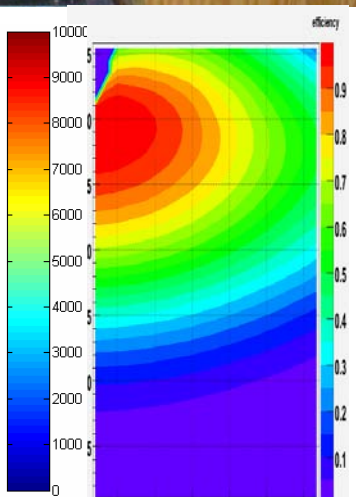
- NEMO-3
  - Simulace a návrh neutronového stínění
  - Koordinace výroby/dodávky nosné konstrukce detektoru (Transporta Chrudim)
  - Koordinace výroby/dodávky „Radon Trapping Facility“ (Hradec Králové)
  - Analýza dat ^{150}Nd (excitovaný stav)

- SuperNEMO
  - Studie alternativní podoby kalorimetru (PD x PMT)
  - Optimalizace tvaru scintilátorů
  - Měření Rn
  - Testování scintilátorů

NEMO 3
Radon
Trapping
Facility
NEMO
Radon
Trapping
Facility
FRAGILE
Mk 5

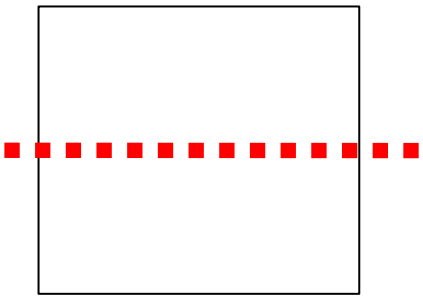


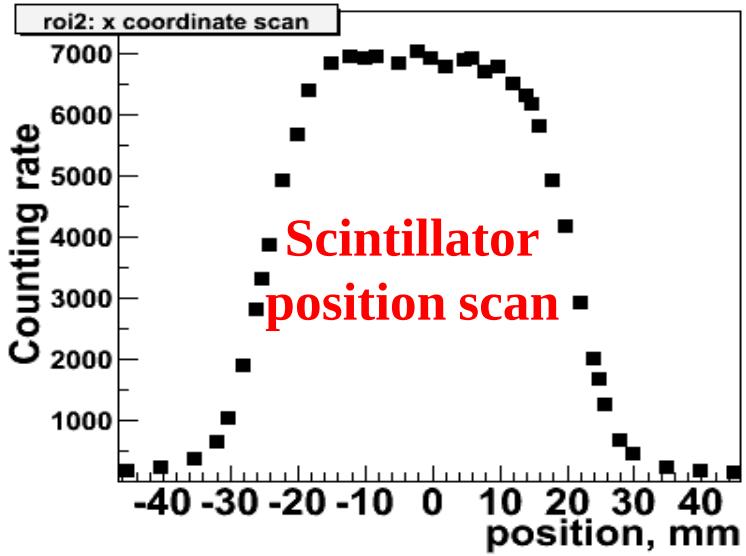

-10
-5
0
5
10
15

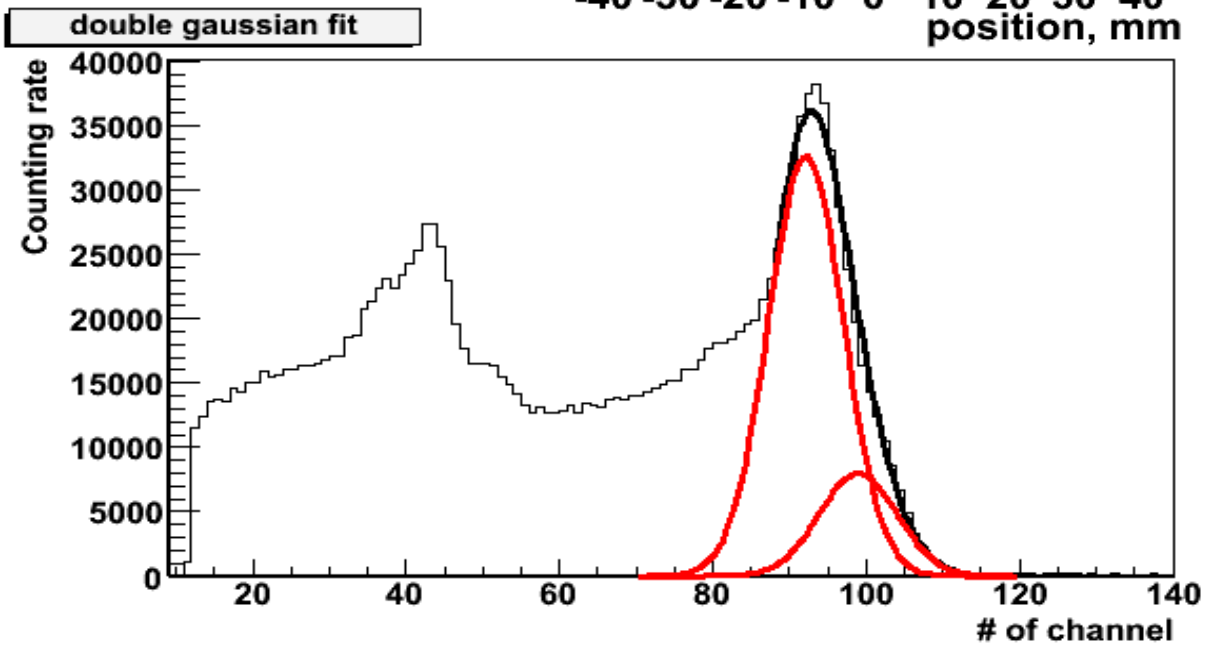

10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0

efficiency
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
4
6
8
10
12
radius [cm]

Scintillator response vs irradiation position



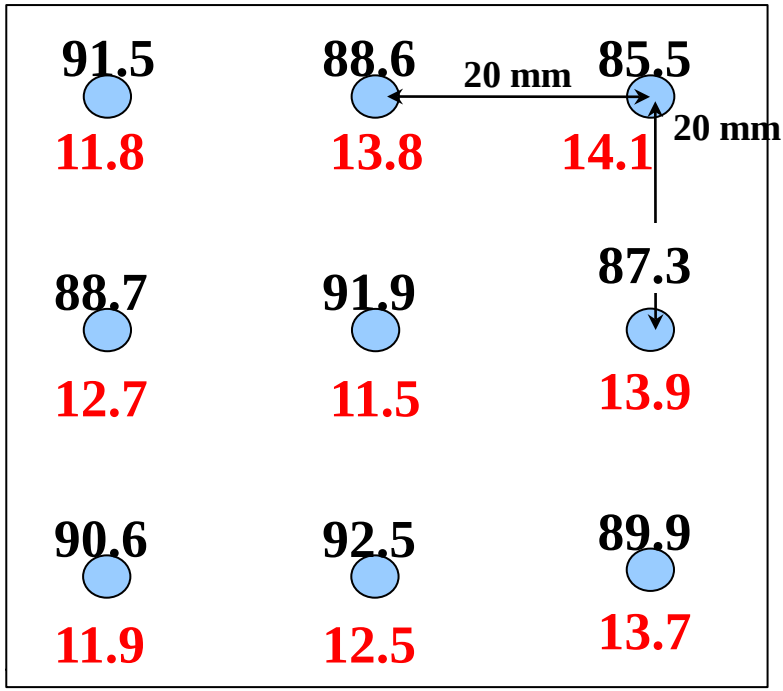




Peak position, ADC

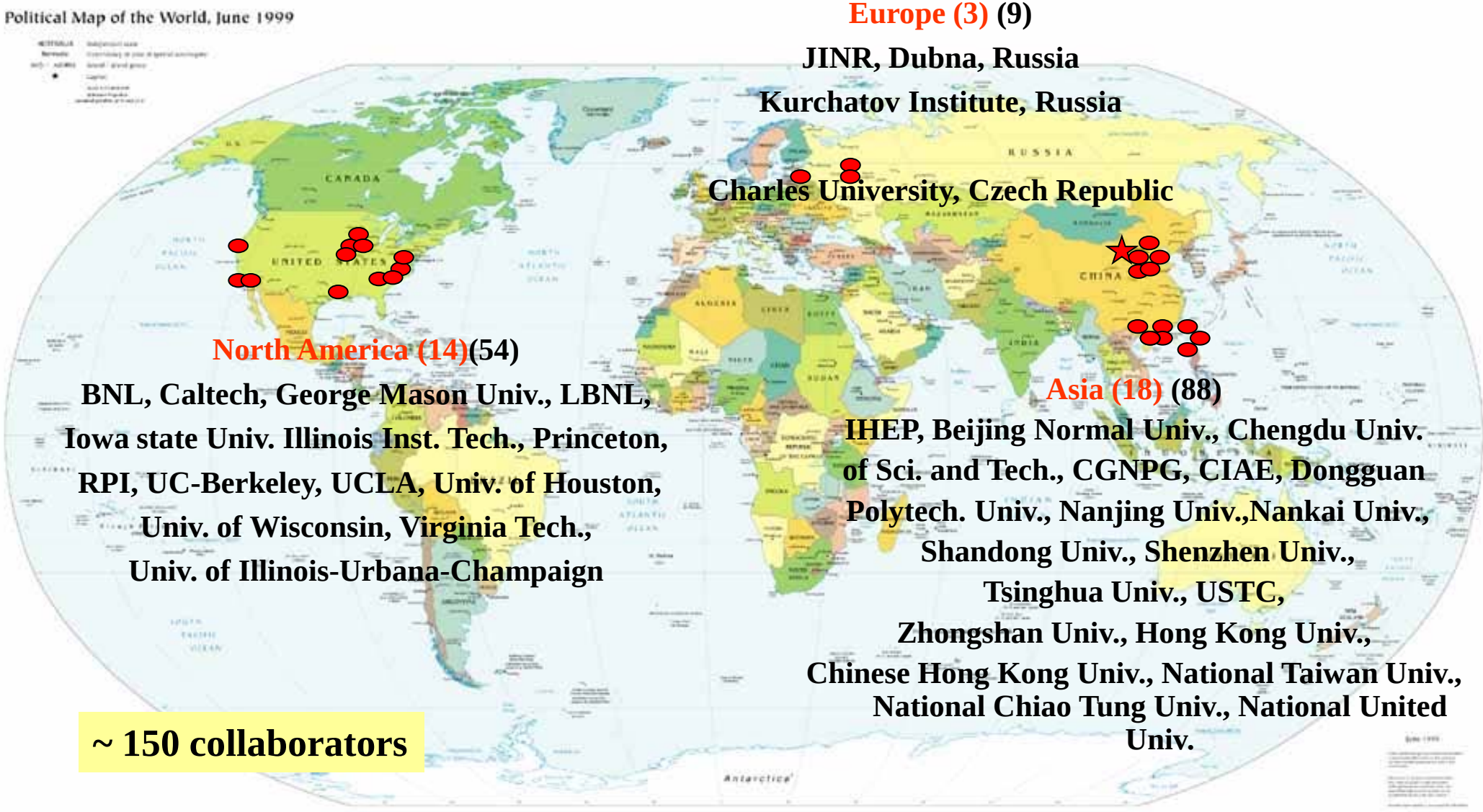
Irradiated area **11.6 mm**

FWHM @ 1 MeV, %



Daya Bay Reactor Antineutrino Oscillation Experiment

The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (14)(54)

BNL, Caltech, George Mason Univ., LBNL, Iowa state Univ. Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (18) (88)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ.,Nankai Univ., Shandong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., National Taiwan Univ., National Chiao Tung Univ., National United Univ.

~ 150 collaborators

θ_{13}: The Last Unknown Neutrino Mixing Angle

U_{MNSP} Matrix
Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} ?$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

atmospheric, accelerator: θ_{23} = ~ 45°

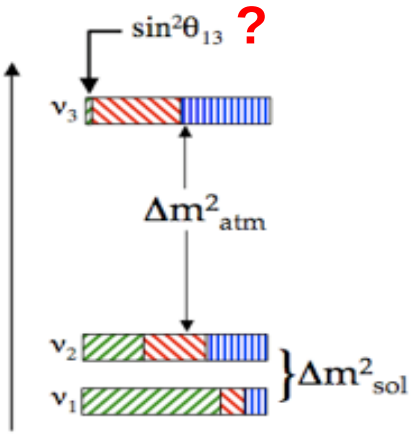
reactor, accelerator: θ_{13} = ?

SNO, solar SK, KamLAND: θ_{12} ~ 32°

$0\nu\beta\beta$

- What is ν_e fraction of ν_3?
- U_{e3} is the gateway to CP violation in neutrino sector:

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta$$



Measuring θ_{13} Using Reactor Anti-neutrinos

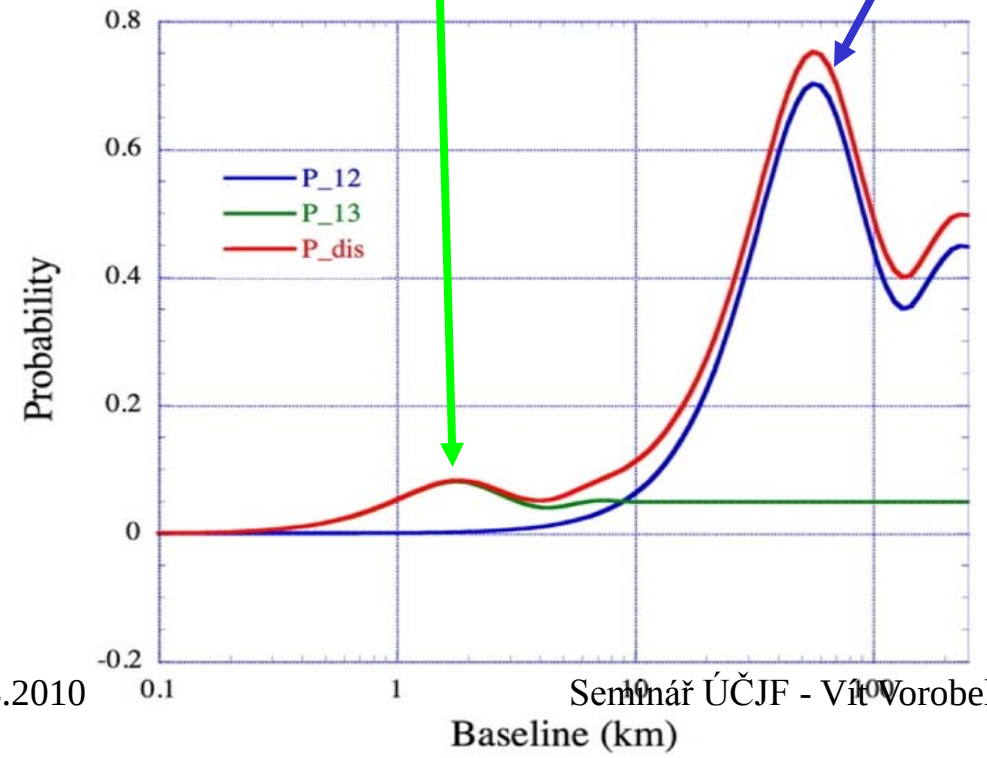
Electron anti-neutrino disappearance probability

$$P_{dis} \approx \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) + \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Small oscillation due to θ_{13}
< 2 km

Large oscillation due to θ_{12}
> 50 km

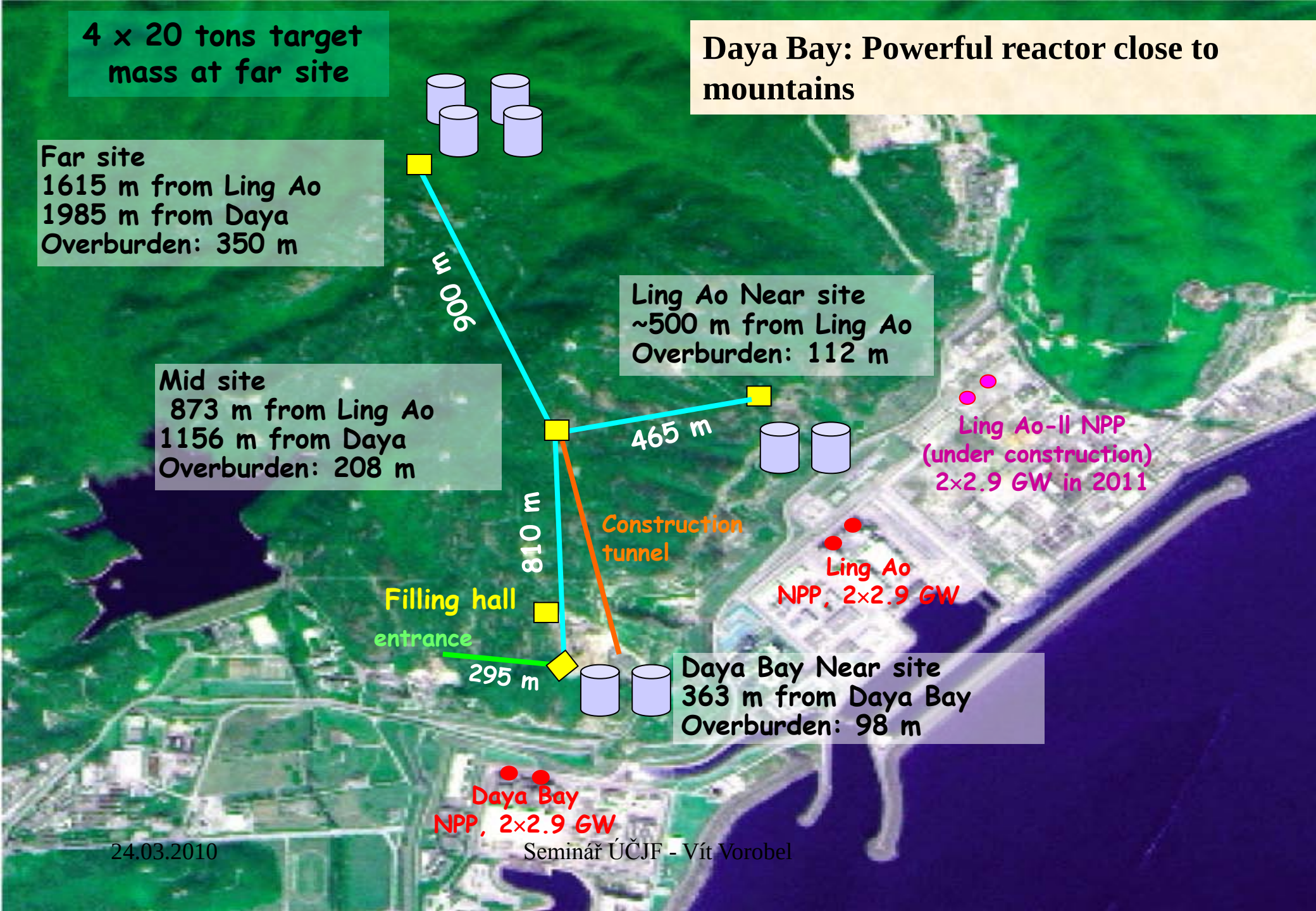
Osc. prob. (integrated over E_ν) vs distance



$\bar{\nu}_e$ disappearance at short baseline(~2 km): unambiguous measurement of θ_{13}

$Sin^2 2\theta_{13}$ = 0.1
Δm^2_{31} = 2.5 x 10^{-3} eV^2
$Sin^2 2\theta_{12}$ = 0.825
Δm^2_{21} = 8.2 x 10^{-5} eV^2

Daya Bay: Powerful reactor close to mountains



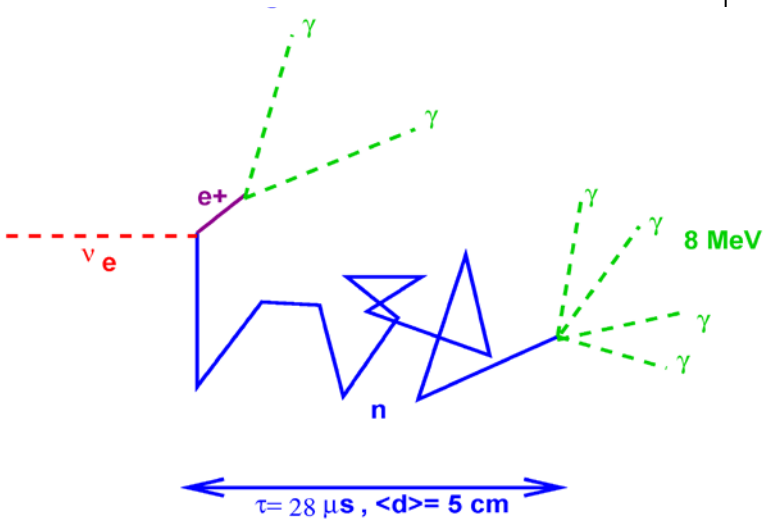
Detection of $\bar{\nu}_e$

Inverse β-decay in Gd-doped liquid scintillator:

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

$\rightarrow$ + p $\rightarrow$ D + γ(2.2 MeV) (t~180μs) 0.3b

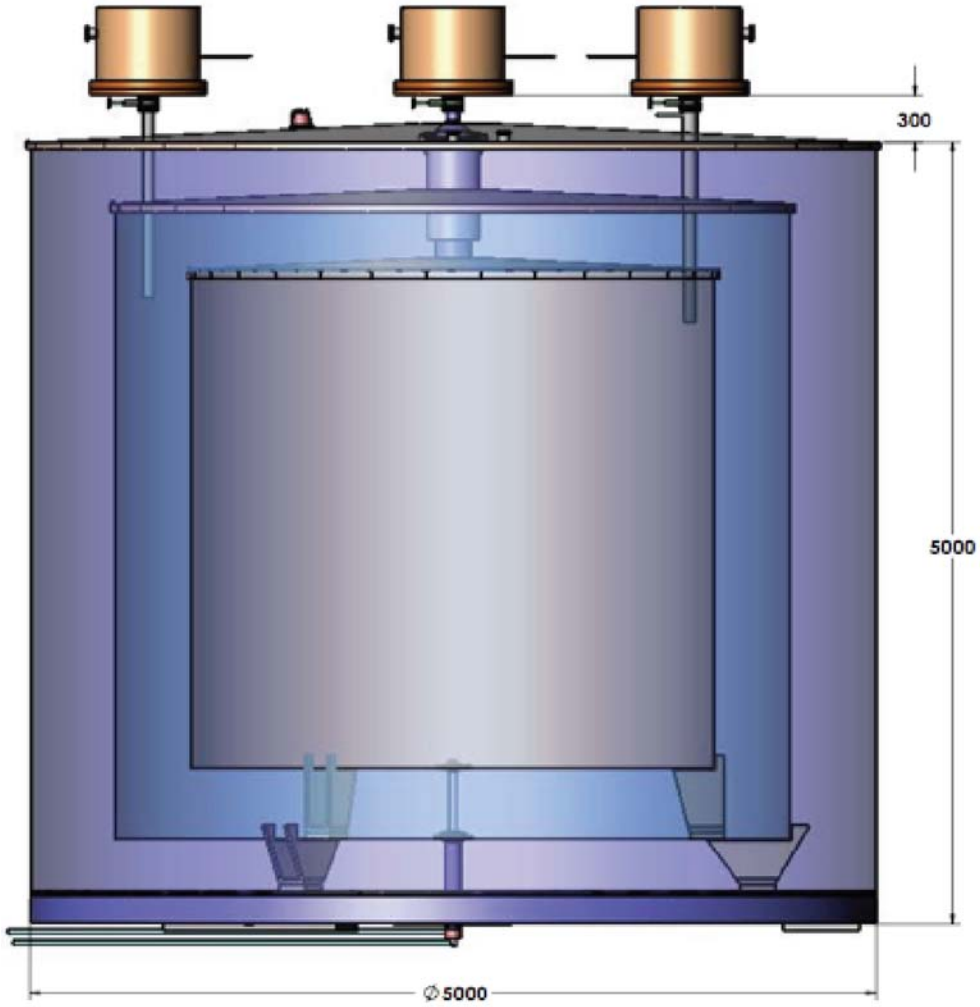
$\rightarrow$ + Gd $\rightarrow$ Gd* $\rightarrow$ Gd + γ's(8 MeV) (t~30μs) 50,000b



Time, space and energy-tagged signal
⇒ suppress background events.

$$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

Antineutrino Detector



Cylindrical 3-Zone Structure separated by acrylic vessels:

I. **Target: 0.1% Gd-loaded liquid scintillator, diameter=height= 3.1 m, 20 ton**

II. **γ-catcher: liquid scintillator, 42.5 cm thick**

III. **Buffer shielding: mineral oil, 48.8 cm thick**

With 192 PMT's on circumference and reflective reflectors on top and bottom:

$$\frac{\sigma}{E} \sim \frac{12.2\%}{\sqrt{E(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 13\mathrm{cm}$$

Inverse-beta Signals

Antineutrino Interaction Rate
(events/day per 20 ton module)

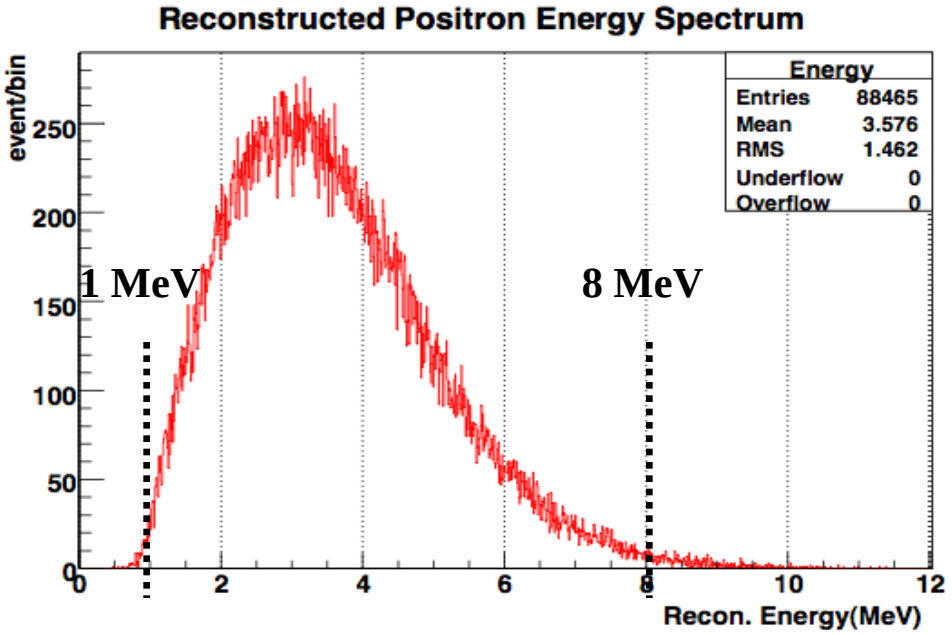
Daya Bay near site	840
Ling Ao near site	740
Far site	90

E_{e+}("prompt") ∈[1,8] MeV

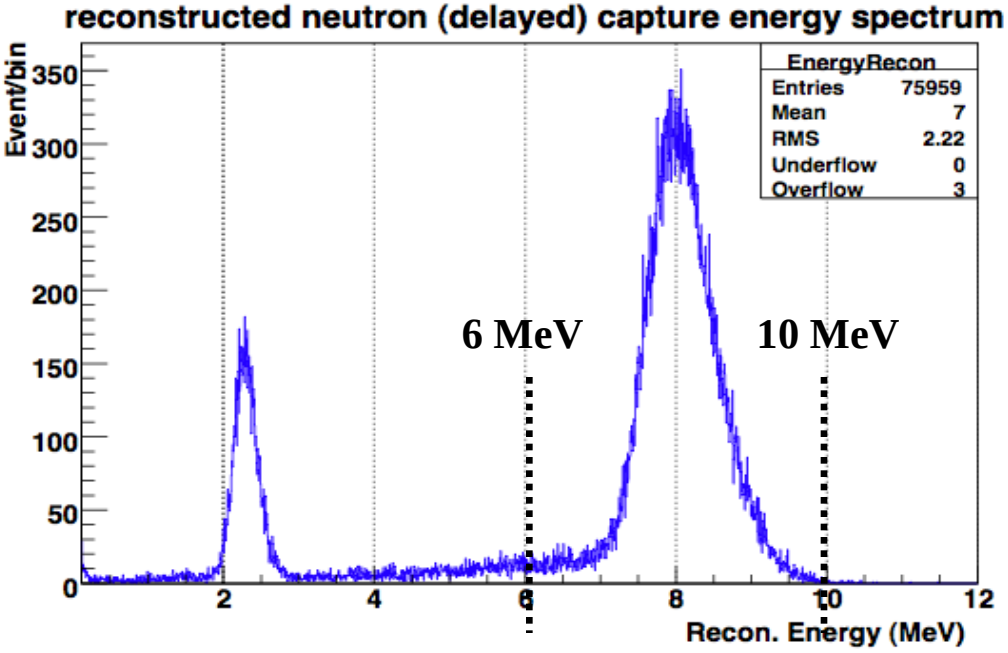
$E_{n\text{-}cap}$ ("delayed") ∈ [6,10] MeV

$t_{delayed}$-t_{prompt} ∈ [0.3,200] μs

Prompt Energy Signal



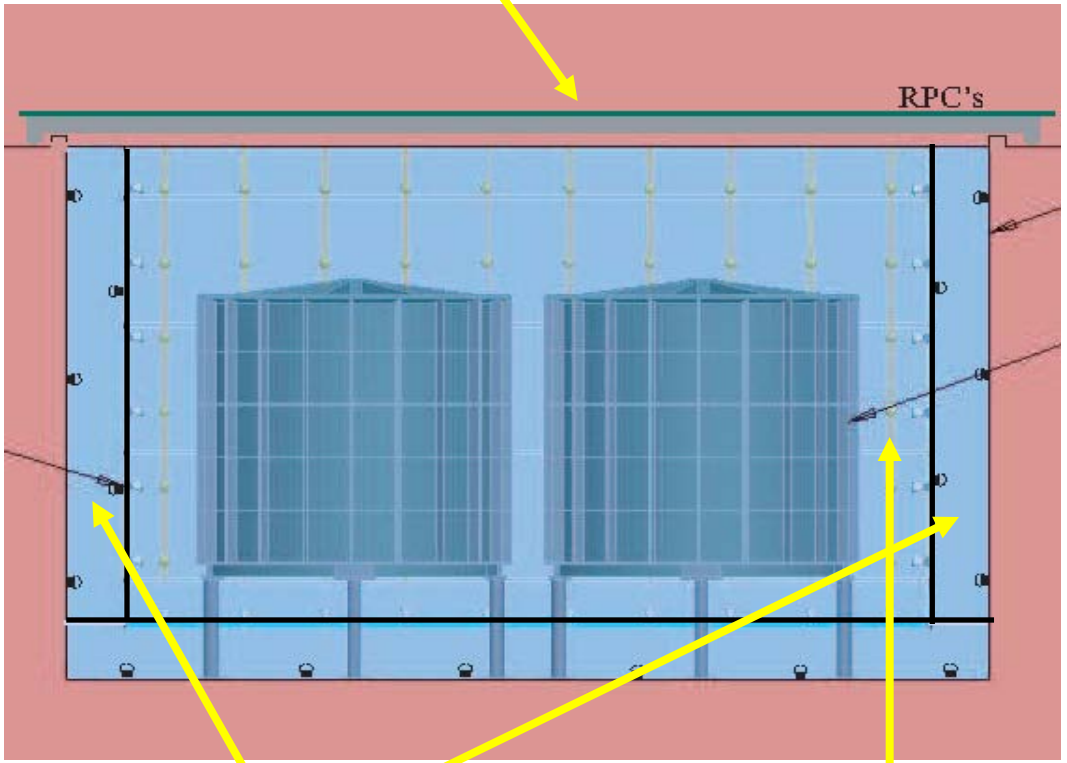
Delayed Energy Signal



MC statistics corresponds to a data taking with a single module at far site in 3 years.

Muon “Veto” System

Resistive plate chamber (RPC)



Outer water shield

Inner water shield

- **Surround detectors with at least 2.5m of water, which shields the external radioactivity and cosmogenic background**
- **Water shield is divided into two optically separated regions (with reflective divider, 8” PMTs mounted at the zone boundaries), which serves as two active and independent muon tagger**
- **Augmented with a top muon tracker: RPCs**
- **Combined efficiency of tracker > 99.5% with error measured to better than 0.25%**

Backgrounds

Background = “prompt”+”delayed” signals that fake inverse-beta events

Three main contributors, all can be measured:

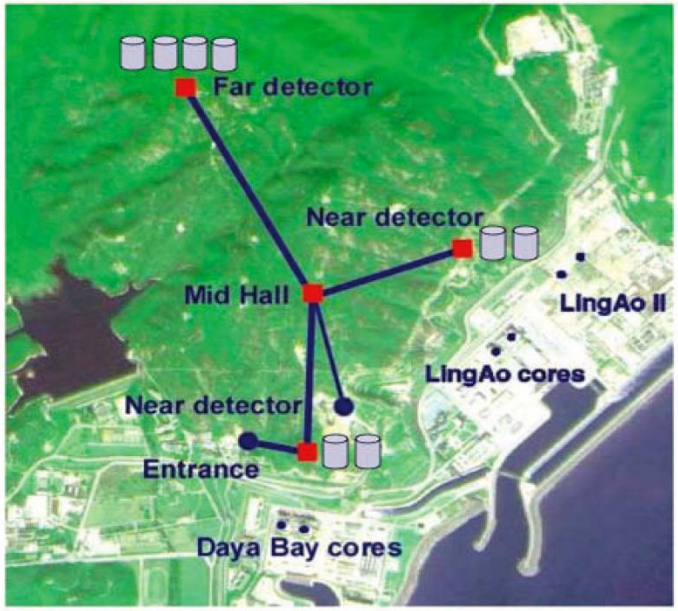
Background type	Experimental Handle
Muon-induced fast neutrons (prompt recoil, delayed capture) from water or rock	>99.5% parent “water” muons tagged ~1/3 parent “rock” muons tagged
^{9}Li/^{8}He ($T_{1/2}$= 178 msec, β decay w/neutron emission, delayed capture)	Tag parent “showing” muons
Accidental prompt and delay coincidences	Single rates accurately measured

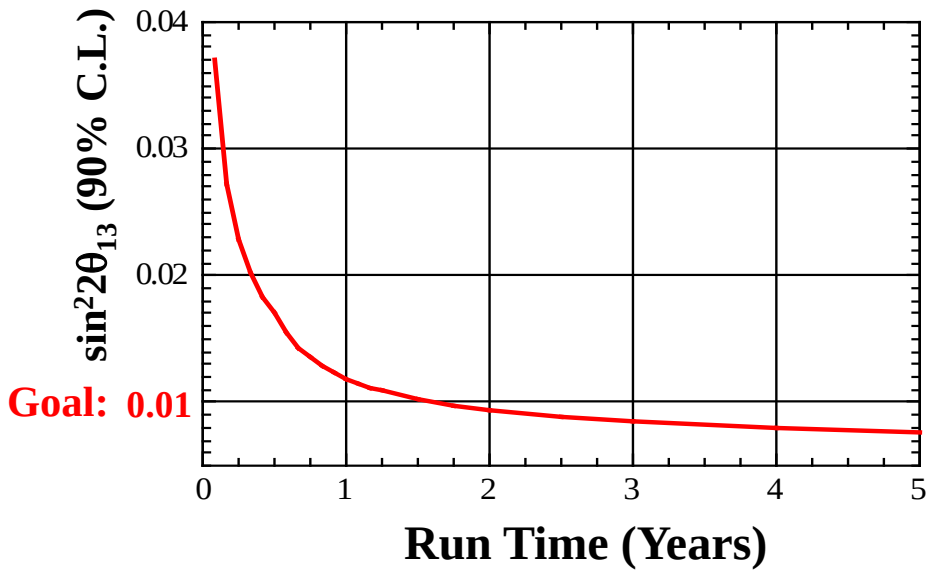
Background/Signal:

	DYB site	LA site	Far site
Fast n / signal	0.1%	0.1%	0.1%
^{9}Li-^{8}He / signal	0.3%	0.2%	0.2%
Accidental/signal	<0.2%	<0.2%	<0.1%

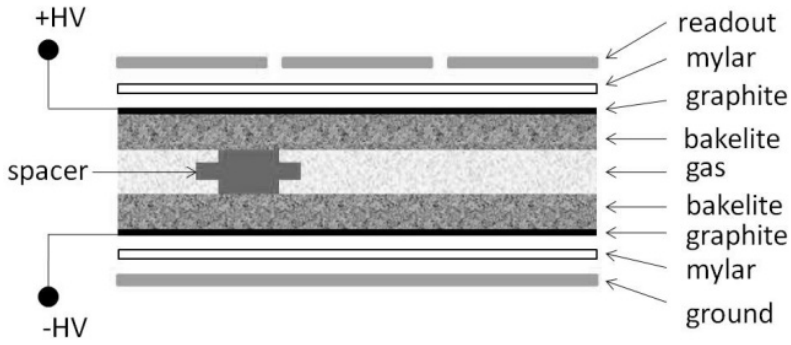
Daya Bay: Status and Plan

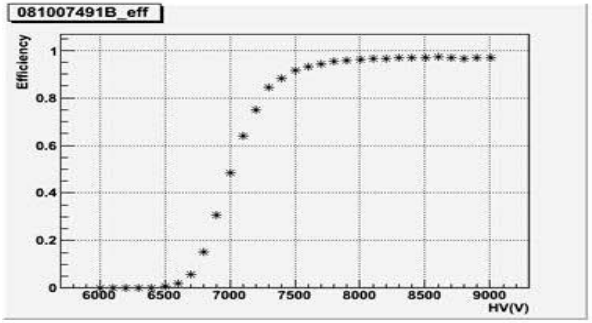
- **Ground Breaking** **Oct 07**
- **CD-3 review comleted** **Spring 08**
- **Surface Assembly Building occupancy** **March 09**
- **Mini Dry Run** **Dec 09**
- **Dry Run** **Spring 09**
- **Daya Bay Near Hall ready for data taking** **2010**
- **All near and far halls ready for data taking** **2011**



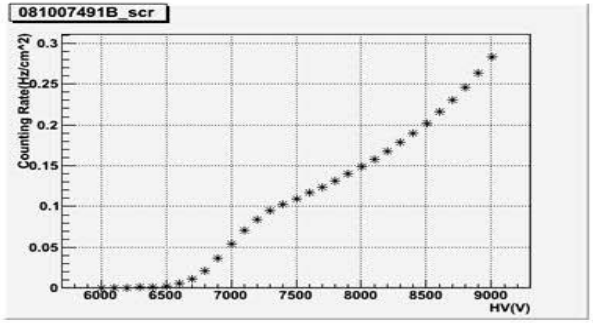


Testování RPC kosmickým zářením – IHEP Peking

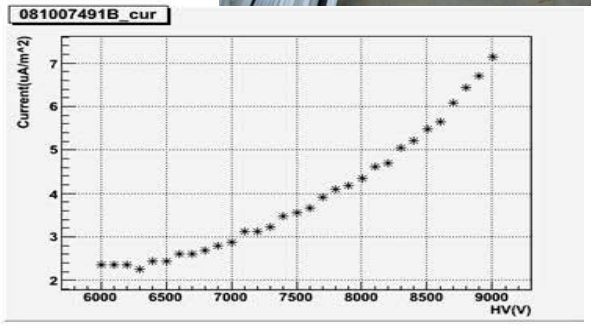




(a)



(b)



(c)

Kritéria testů:

účinnost >95% singles (šum)< 0.8Hz/cm^2 dark current< 10 μA/m^2

Testováno 1600 ks RPC, odmítnuto 15%

谢谢你们！

Děkuji za pozornost !