ECT Lecture

- Neutrino Oscillation at reactors
- Probing the ‘solar’ sector
- Probing the ‘atmospheric’ sector

Thierry Lasserre (Saclay)

Neutrino Oscillations at reactors

Neutrino Oscillation formalism

$$P(\bar{\nu}_x \rightarrow \bar{\nu}_x) = 1 - \sin^2(2\theta_i)\sin^2\left(1.27\frac{\Delta m_i^2\,(eV^2)\,L\,(m)}{E\,(MeV)}\right)$$

Atmospheric — Cross-Mixing — Solar — Majorana ~~CP~~ phases

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} : "atm." mixing angle — θ_{13} — θ_{12} : "solar" mixing angle

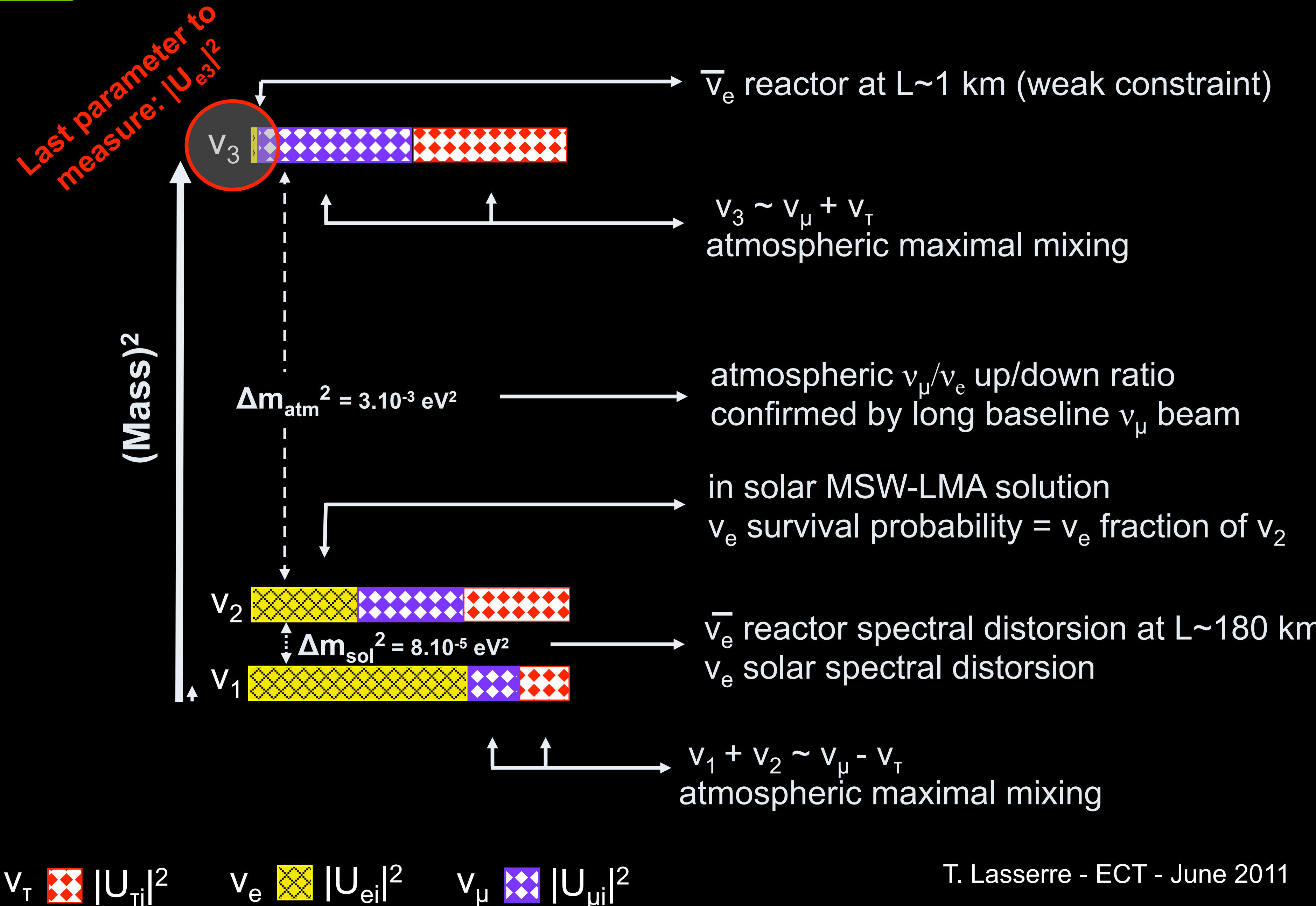
$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

δ Dirac CP violating phase

2 Majorana phases (L violating processes)

- 3 masses m_1, m_2, m_3 : $\Delta m^2_{sol} = m_2^2 - m_1^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2|$
- 3-flavour effects are suppressed because : $\Delta m^2_{sol} << \Delta m^2_{atm}$ (1/30) & $\theta_{13} << 1$

Neutrino Oscillation Status



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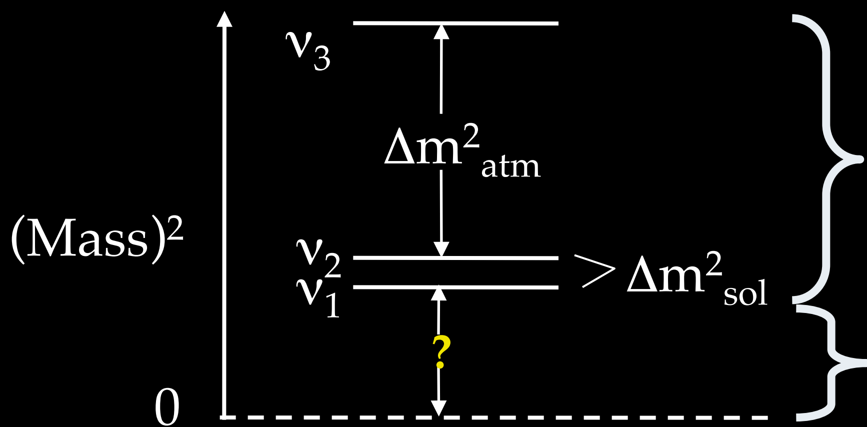
Open questions

- What are the masses of the mass eigenstates ν_i?



ν flavor change

β decay, ββ0ν decay, Cosmology

- Is the spectral pattern (one level on top, two close levels below) or (two close levels on top, one level below) ?

$\overset{(-)}{\nu}$ behavior in earth matter, ββ0ν

- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? ββ0ν

- What are the angles of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic ~~CP~~ responsible for the matter-antimatter asymmetry? →Leptogenesis?

ν flavor change

Neutrino Oscillation at Reactors

- At least 3 active neutrino oscillation but we can simplify the computations by using the two flavor reactor neutrino survival probability (baseline L).

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_i \cdot \sin^2 \left(1.27 \frac{\Delta m_i^2 [eV^2] L[m]}{E_{\bar{\nu}_e}[MeV]}\right)$$

θ_{13} small

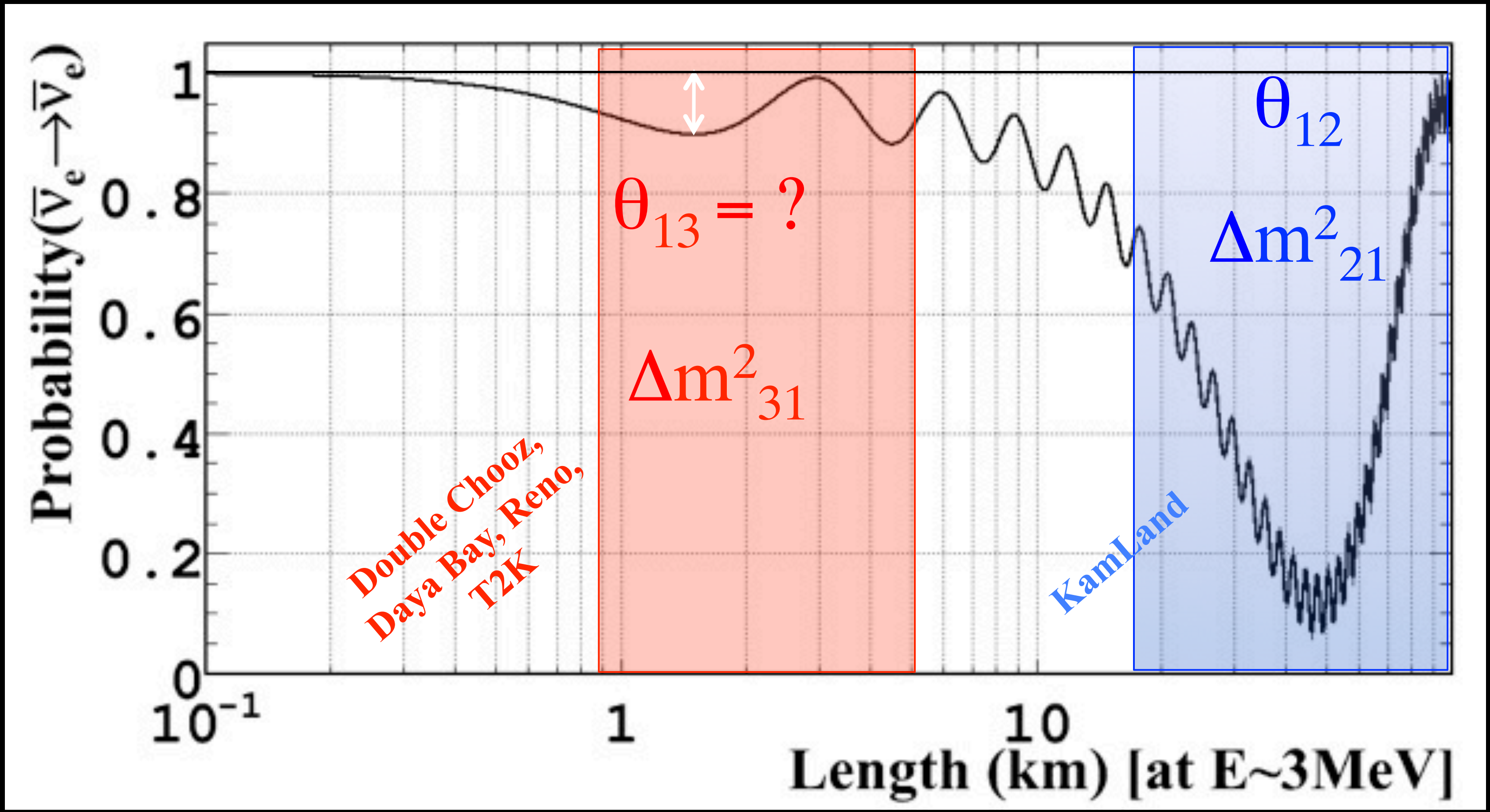
$\Delta m^2_{sol}/\Delta m^2_{atm} \approx 1/30$

- Condition on baseline : L_{osc} (m) = 2.5 E(MeV) / Δm^2(eV^2)
  - L close to $L_{osc}/2$ (optimum): sensitivity to both $\sin^2(2\theta)$ & Δm^2
  - L >> L_{osc} : sensitivity to $\sin^2(2\theta)$ only
  - L << L_{osc} : no sensitivity …

- Three 'decoupled' regimes:
  - Probing 'atmospheric' driven oscillations if the baseline < few kilometers
    - 1.27*3.5/2.5e-3 = 1.7 km $\Delta m_i^2 = \Delta m_{31}^2$ and $\theta_i = \theta_{atm}$
  - Probing 'solar' driven oscillations if the baseline > a few ten's of km
    - 1.27*3.5/8e-5 = 55 km $\Delta m_i^2 = \Delta m_{21}^2$ and $\theta_i \sim \theta_{sol}$
  - Probing 'sterile' driven oscillations if the baseline if a few to a few ten's of m
    - 1.27*3.5/1 ≈ 5 m

Neutrino Oscillation at Reactors

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta)\,\sin^2(\Delta m^2 L/4E)$$



The Ideal Experiment

- The Source
  - Point-like or size<<L_{osc}
  - Emitting a single neutrino flavor
  - High and well know intensity
  - Stable in time
  - monochromatic or with a well know energy spectrum

- The Detector
  - sensitive to
    - the emitting flavor (disappearance experiment)
    - a flavor not (or weakly) emitted by the source (appearance experiment)
  - High and well know detection efficiency
  - Precise and non-biased measurement of the neutrino energy
  - Distance well know from the source
  - low background
  - stable in time

Reactor Experiments

- The Source
  - Source size<<L_{osc} → can be matched easily for 'solar' and 'atm' driven oscillation
    → more difficult for 'eV^2 sterile neutrino'
  - Emitting a single neutrino flavor → 100% electron type antineutrino
  - High and well know intensity → known to 3%, but RAA…
  - Stable in time → Thermal power variation and fuel evolution to be tracked (1%)
  - Well know energy spectrum → within a few %

- The Detector
  - sensitive to
    - the emitting flavor (disappearance experiment)
  - High and well know detection efficiency → (>80%, 1% uncertainty)
  - Precise and non-biased measurement of the neutrino energy → 0.5% E_{scale}
  - Distance well know from the source → 10 cm precision (can be improved)
  - low background → complicated detector design + underground
  - stable in time → sub-percent precision achievable

Sensitivity to Neutrino Oscillation

- On first approximation results of reactor neutrino experiment (RNE) can be analyzed in term of two flavor oscillations

- RNE measure the fraction P of neutrino changing flavor at a given baseline, L
  - $P = \sin^2(2\theta) < \sin^2(\Delta m^2 L/4E) >$
  - $< \sin^2(\Delta m^2 L/4E) >$ → average over neutrino energy spectrum & baselines
    - $L >> L_{osc} = 4\pi E/\Delta m^2$ → $< \sin^2(\Delta m^2 L/4E) > = 1/2$
    - $L << L_{osc} = 4\pi E/\Delta m^2$ → $< \sin^2(\Delta m^2 L/4E) > = (\Delta m^2)^2 <(L/4E)^2>$

- RNE are disappearance experiments
  - N events expected
  - absolute statistical uncertainty is : $N^{1/2}$
  - The minimum fraction P detectable is relative statistical uncertainty is : $P_{min}=1/N^{1/2}$
  - BUT systematic uncertainty provide a lower bound on $P_{min}= \sigma$
  - Experiment is completed when $\sigma = 1/N^{1/2}$

    example: Double Chooz goal σ=0.5% → N=4e4 ($1/N^{1/2}$=0.5%)

Exclusion Contours

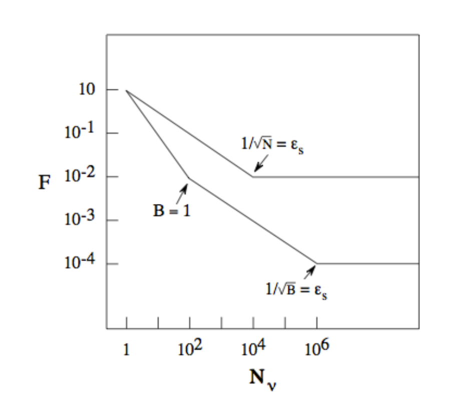
- Exclusions contours are used to display the oscillation parameters consistent with the no-oscillation hypothesis

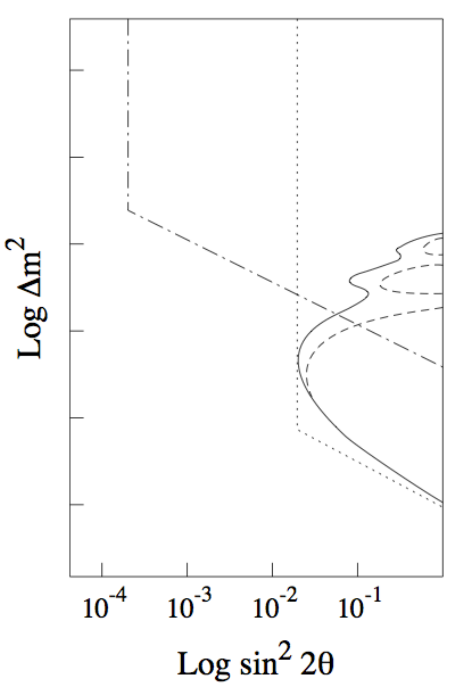
- For ‘historical reason’ they are often given at 90% C.L.

- They are derived from : $P_{min} = \sin^2(2\theta) < \sin^2(\Delta m^2 L/4E) >$

  - For large Δm^2 :
    - $\sin^2(2\theta) = 2\,P_{min}$
    - $\log(\sin^2(2\theta)) = \log(2P_{min})$

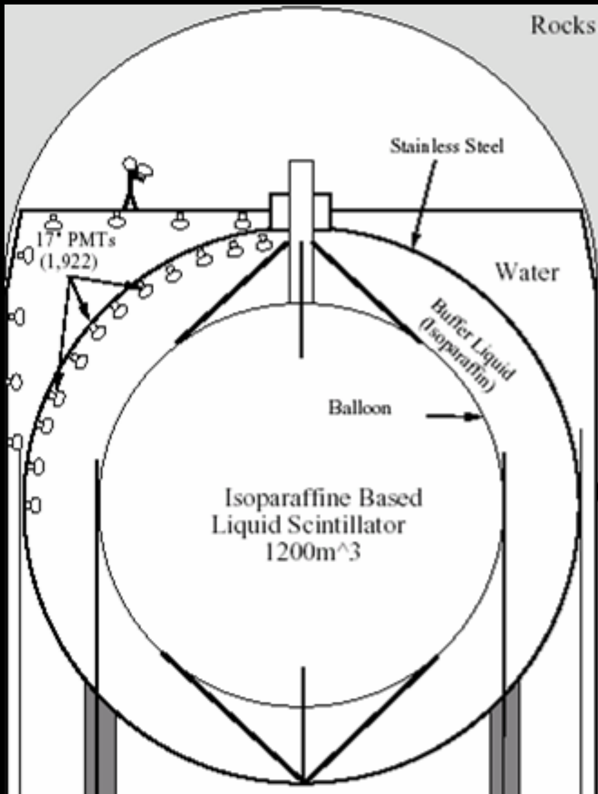
  - For low Δm^2 :
    - $\sin^2(2\theta)\,(\Delta m^2)^2 = P_{min}\,/\,<(L/4E)^2>$
    - $\log(\sin^2(2\theta)) = P_{min}\,/\,<(L/4E)^2> - 2\log(\Delta m^2)$



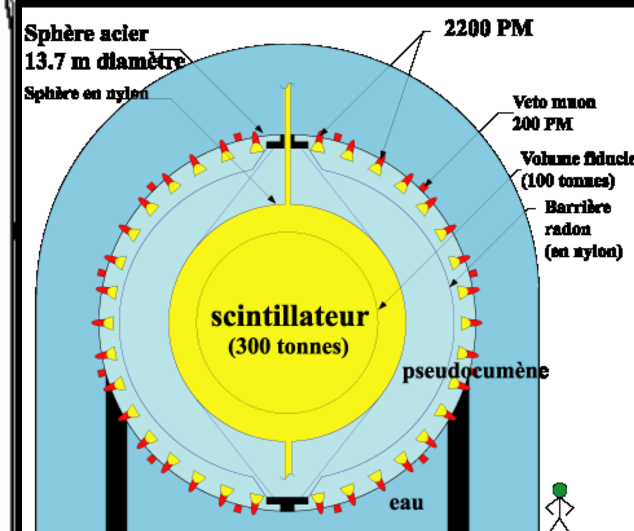


Detectors

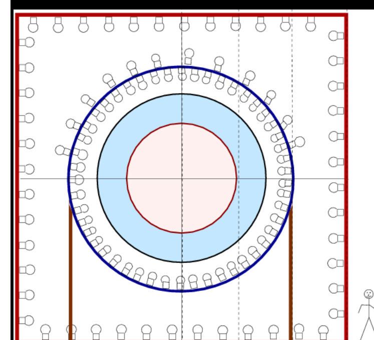
Detectors on the market



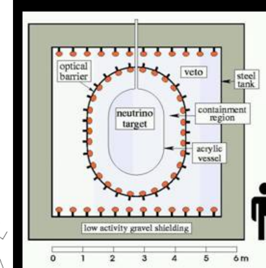
KamLAND
1000 t



Borexino
300 t



Rector/θ_{13}
~20 t

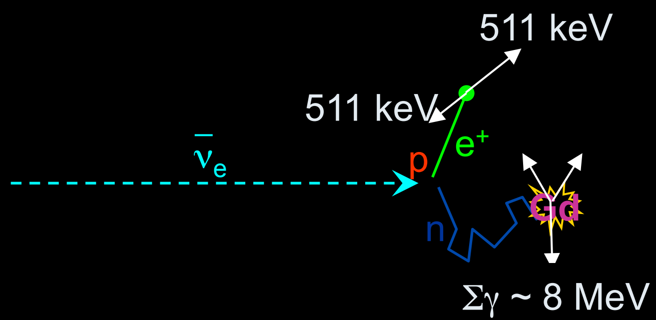


CHOOZ
5 t

$$N(L) = 70\left(\frac{t}{1(\text{day})}\right)\left(\frac{P}{8.4(\text{GW})}\right)\left(\frac{V}{10(\text{m}^3)}\right)\left(\frac{1}{L(\text{km})^2}\right)$$

Backgrounds & Signal

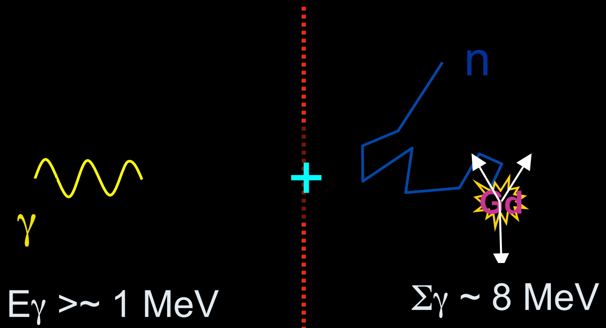
Electron antineutrino signature through inverse beta decay



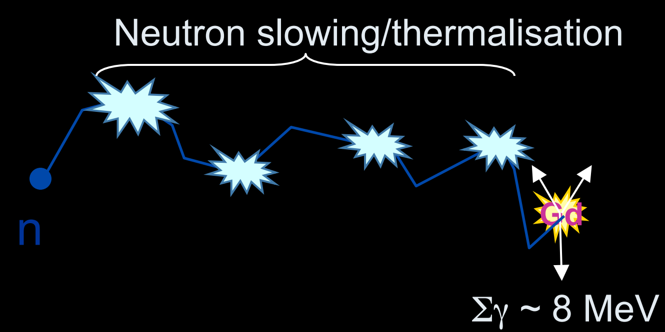
Prompt e^+ (1-8 MeV) Delayed n Gd-capture (8 MeV)

Time correlation: τ~30 μs Space correlation: <1 m

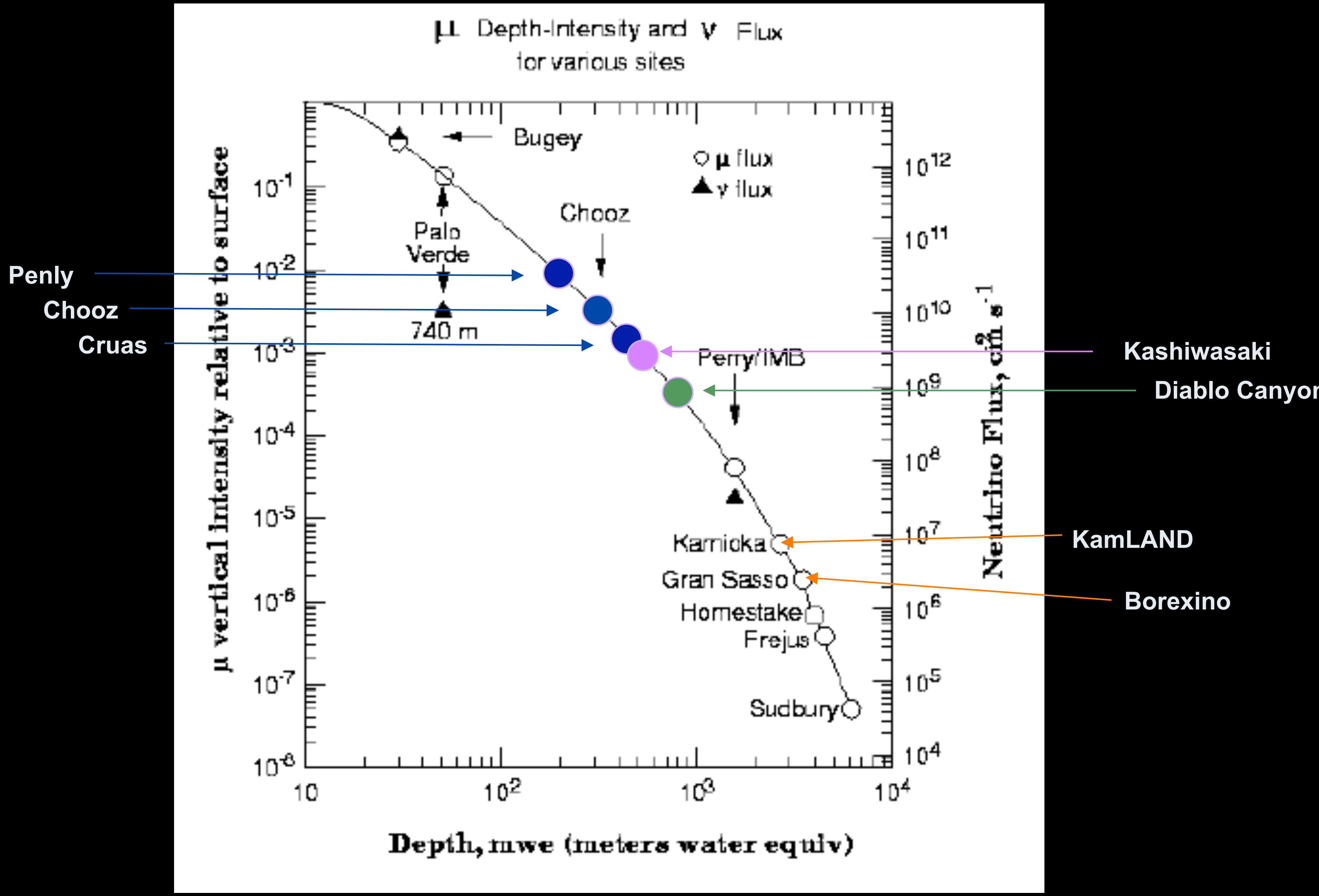
Accidental Background



Correlated Background

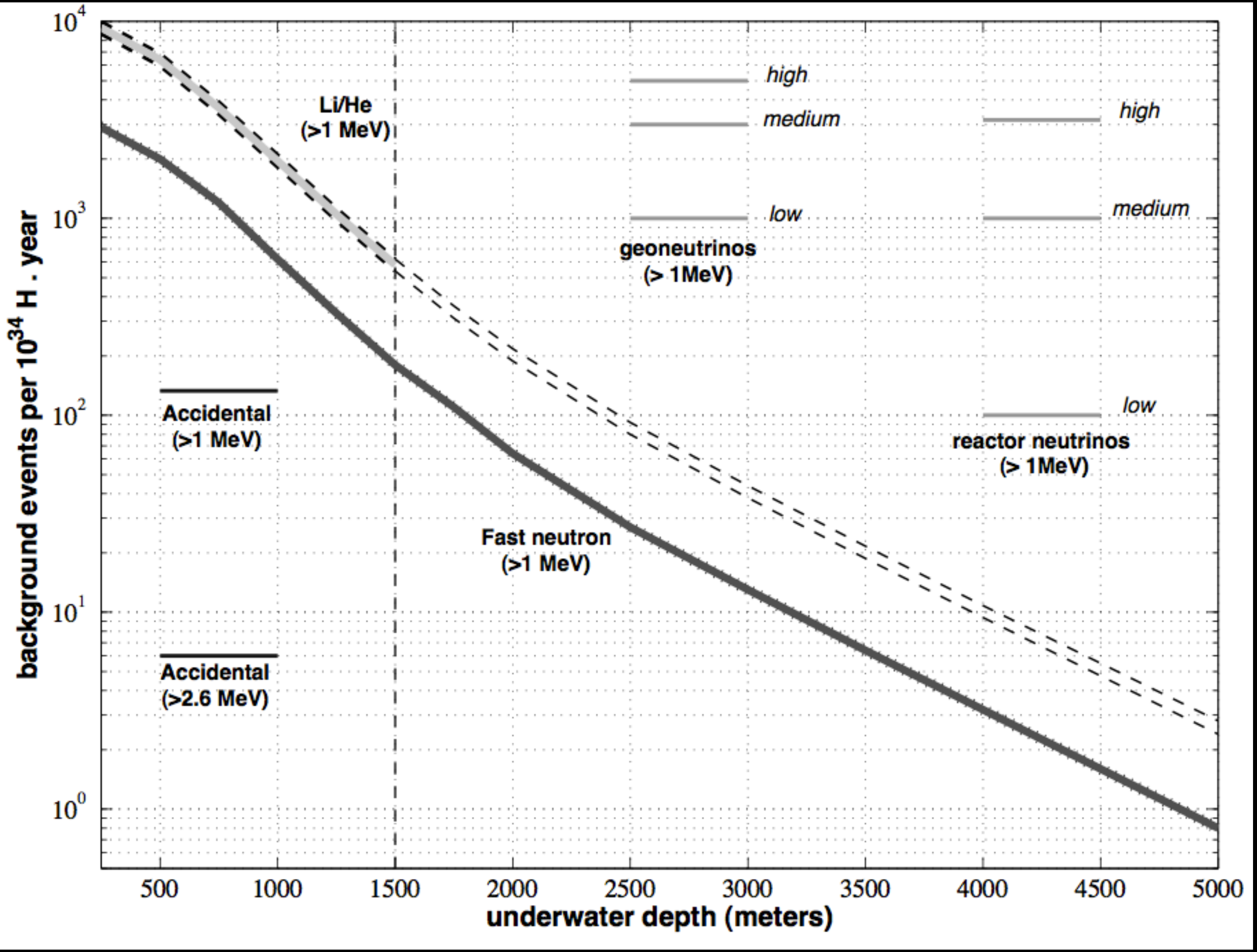


Overburden



μ Depth-Intensity and ν Flux
for various sites
Bugey
μ flux
ν flux
Palo Verde
740 m
Chooz
Perry/IMB
Kamioka
Gran Sasso
Homestake
Frejus
Sudbury
Penly
Chooz
Cruas
Kashiwasaki
Diablo Canyon
KamLAND
Borexino
μ vertical intensity relative to surface
Neutrino Flux, cm^{-2} s^{-1}
Depth, mwe (meters water equiv)

Backgrounds (from arXiv:0145439)

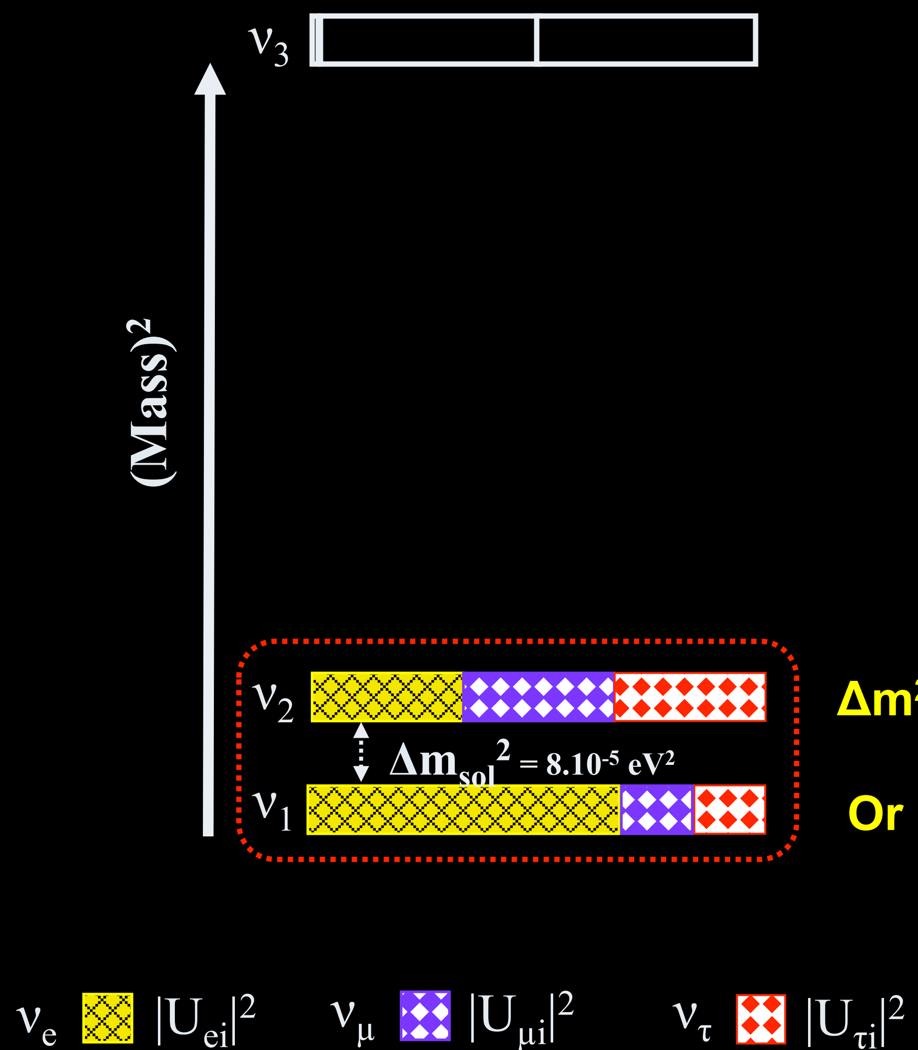


Far Field
(>50km)

Reactor Experiments

Experiment	Baseline	Size
SuperK	Sun	22.500 tons
SNO	Sun	1000 tons
KamLAND	150 km	1200 tons
Borexino	~800 km	300 tons

Δm^2_{21} & θ_{12}



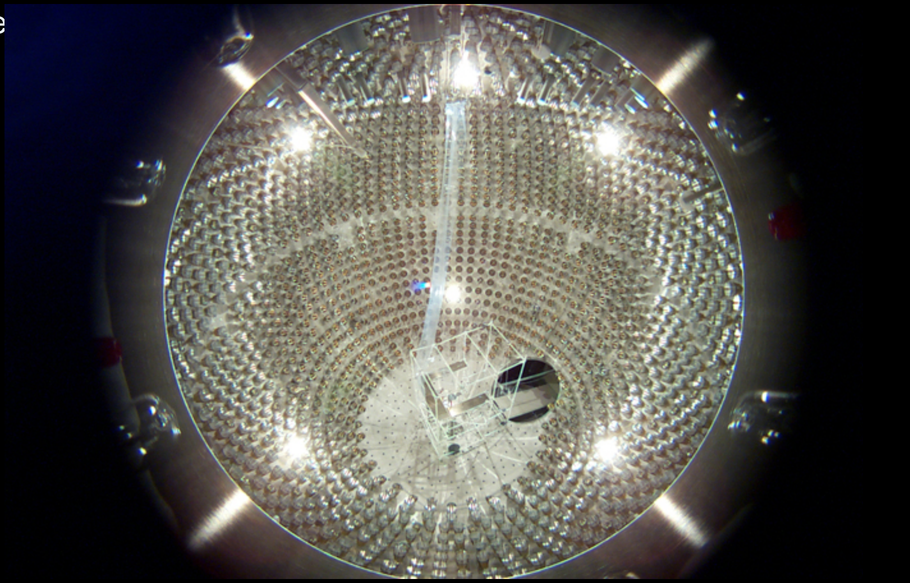
Δm^2 (eV^2) ~ L (km) / E(GeV)

L~100 km & E~MeV

Or MSW 'flavor transition'

Reactor ν's: KamLAND & Borexino

- **Goal** : Measure the disappearance of anti-ν_e from distant reactors with <L> ~ 180-800 km



- **Channel : $\overline{\nu}_e \rightarrow \overline{\nu}_e$** (detected trough IBD)

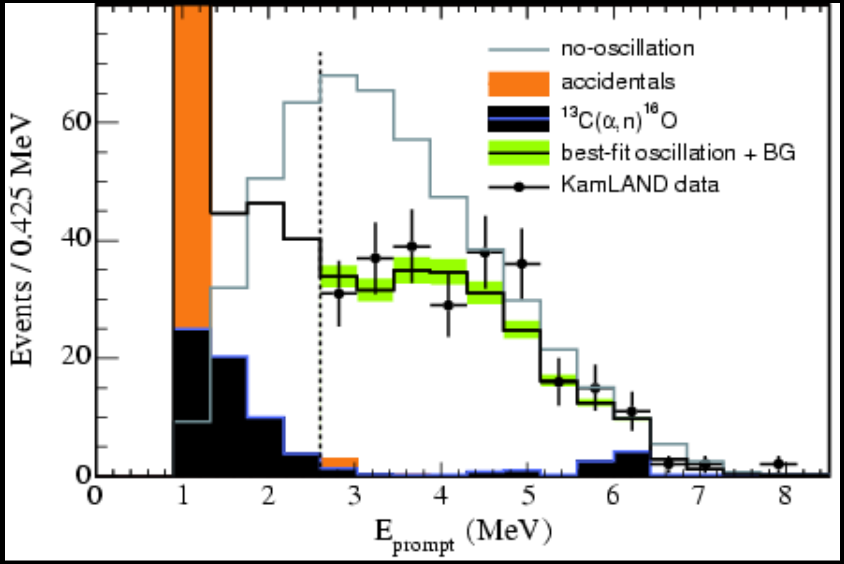
- **Detector**:
  - Liquid scintillator & 2000 PMTs
  - few interactions/day-weeks
  - E range: few 100 keV ~ ten's MeV

- **KamLAND Oscillation Results**

Confirmation of the MSW-LMA solution

Δm^2 =7.58±0.14 (stat) ±0.15 (syst) ×10^{-5} eV^2

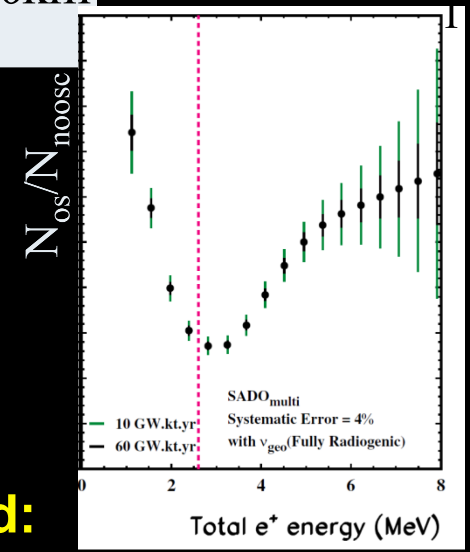
$\tan^2\theta_{12}$=0.56 ±0.08 (stat) ±0.08 (syst)



- **Borexino data taking** (<L> ~ 800 km)
  - No spectrum distortion (no Δm_{21}^2 mes.)
  - Sensitivity to $\sin^2(2\theta_{12})$

Reactor Measurement of θ_{12}

- **Connecting the $\nu_1 - \nu_2$ (solar) neutrino pair with the electron flavor**
  - ➔ Already KamLAND, Borexino, SNO+?
  - ➔ A new dissapearance experiment located at the oscillation maximum : $\text{Baseline} \approx \frac{2\pi E_\nu^{peak}}{\Delta m^2_{21}} \approx 50 - 70\text{km}$

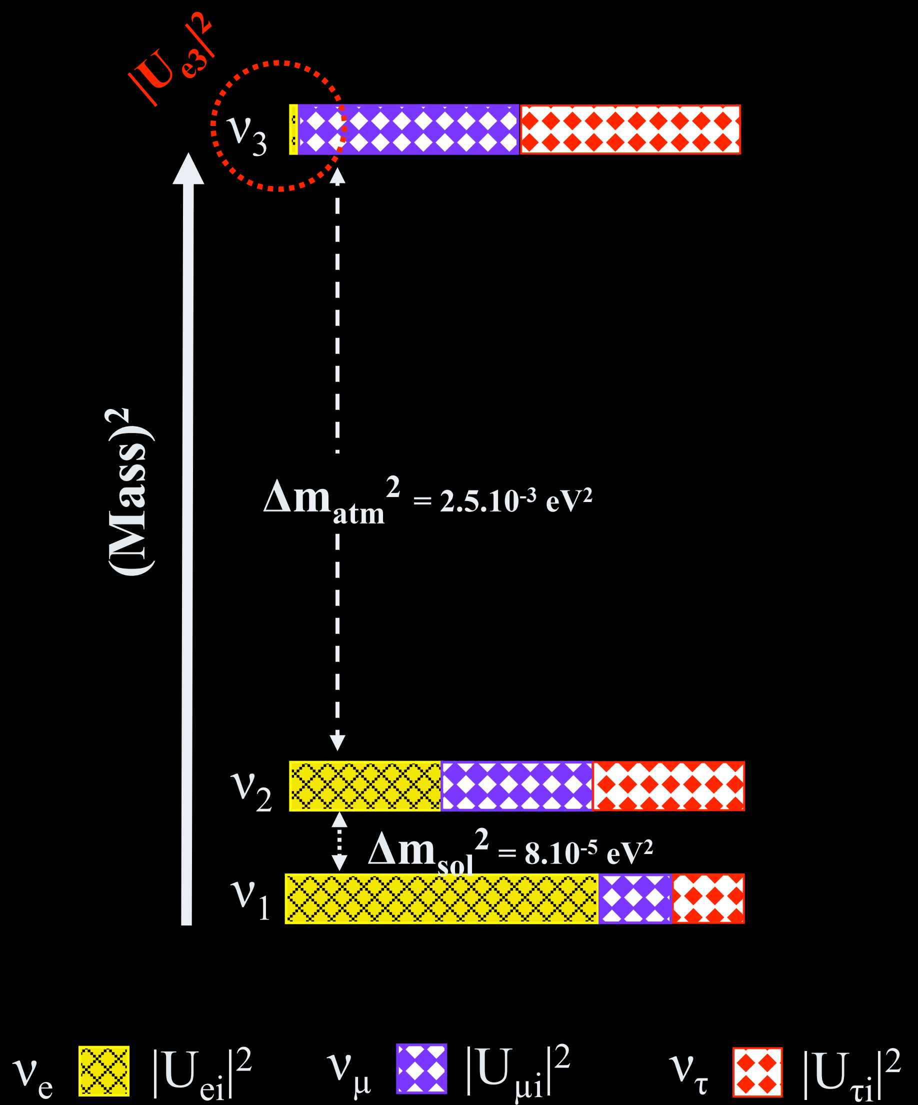


- **Sensitivity (see Phys. Rev. D 71, 013005 2005)**
  - ➔ Exposure: 60 GW_{th} . Ton . Year
  - ➔ 4% systematics, error on $\sin^2(\theta_{12})$: **2%** (1σ)

- **No project funded but a few sites have been discussed:**
  - ➔ Sado Island (Japan), 55 km from Kashiwasaki power plant
  - ➔ San Onofre (US), with the Hano Hano detector underwater
  - ➔ Future experiment close to the Daya-Bay reactors

Middle Field
(1-2 km)

θ_{13}



$|U_{e3}|^2$
ν_3
$(\text{Mass})^2$
$\Delta m_{atm}^2 = 2.5.10^{-3}\ eV^2$
ν_2
$\Delta m_{sol}^2 = 8.10^{-5}\ eV^2$
ν_1
ν_e $|U_{ei}|^2$
ν_μ $|U_{\mu i}|^2$
ν_τ $|U_{\tau i}|^2$

The Current Central Role of θ_{13}

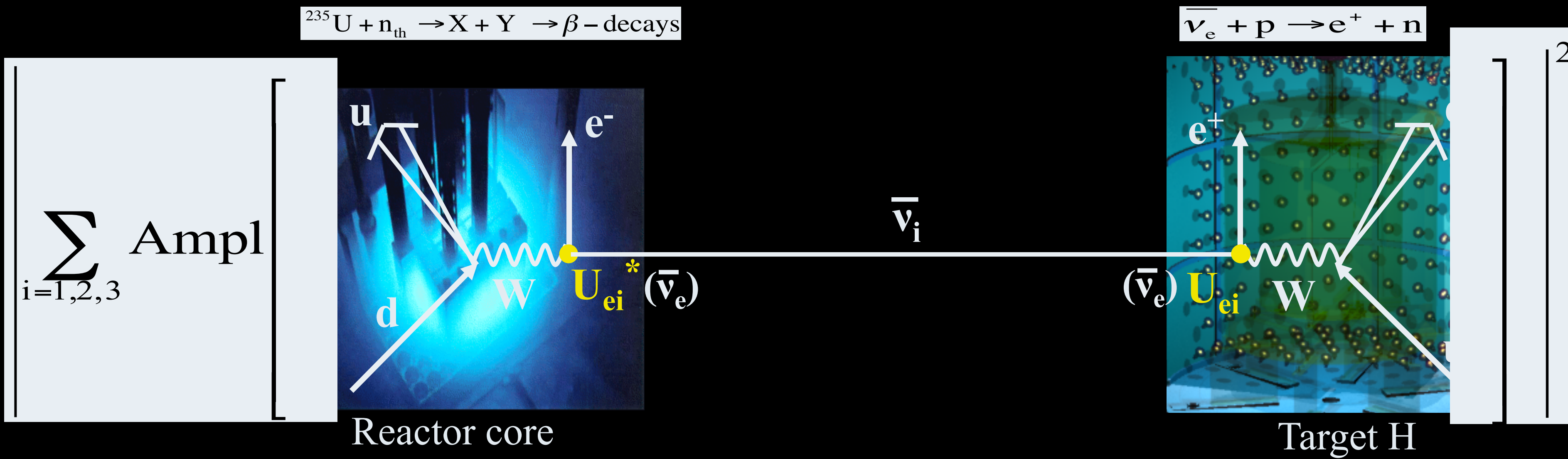
- **θ_{13} is the last neutrino oscillation parameter to measure**
  - θ_{12} & θ_{23} >> θ_{13} → a guideline for oscillation models
  - Improvement of mass parameters (m_e, $m_{\beta\beta}$) & astrophysical sources

- **The θ_{13} quest is an mandatory step prior searching for CP violation in the electroweak sector. Branching point around 2015:**
  - $\sin^2(2\theta_{13}) > 0.02$ → conventional neutrino beam ($\pi \rightarrow \mu\ \nu$, 1% contamination)
  - $\sin^2(2\theta_{13}) < 0.02$ → neutrino factories ($\mu \rightarrow \nu$ or ${}^{A}X \rightarrow e + \nu$, pure beams)

- **Experimentally: need to connect the ν_e flavour with the isolated neutrino (Δm_{atm}^2)**
  - L~1 km, E~MeV reactor neutrino experiments (Double Chooz, Daya Bay, Reno)
    - Disappearance expt. ;
    - θ_{13} only → 'clean'
  - L~1000 km, E~GeV accelerator experiments (T2K, Nova)
    - Appearance expt. ;
    - (θ_{13}, NH/IH, δ_{CP}) → correlations & degeneracies

→Complementary projects (absolutely needed)

Underlying Oscillation Physics

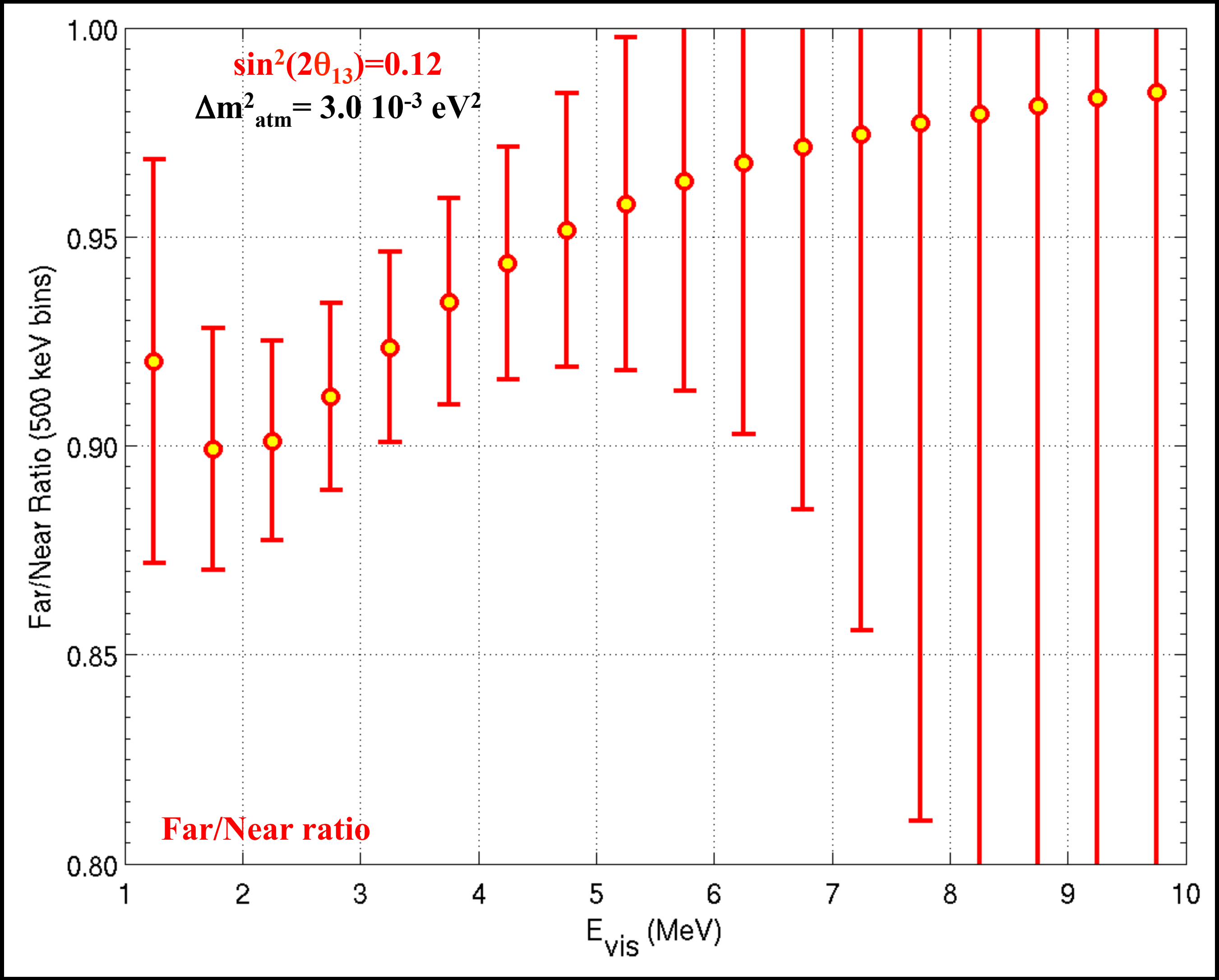


$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \left[\sum_i U_{ei}^{*} e^{-i m_i^2 \frac{L}{2E}} U_{ei}\right]^2 = 1 - \sin^2(2\theta_{13})\left[\sin\left(1.27 \frac{\Delta m_{atm}^2 \,(eV^2)\, L\,(m)}{E\,(MeV)}\right) + O\left(\frac{\Delta m_{sol}^2}{\Delta m_{atm}^2}\right)\right]$$

- Simple oscillation formula
- ➔ depends $\sin^2(2\theta_{13})$ & Δm_{atm}^2, weakly on Δm_{sol}^2
- MeV electron antineutrinos ➔ only disappearance experiments
- ➔ $\sin^2(2\theta_{13})$ measurement independent of δ-CP
- MeV neutrinos + 1 km baseline → negligible matter effects $O[10^{-4}]$
- ➔ $\sin^2(2\theta_{13})$ measurement independent of sign(Δm^2_{13})

‘clean’ θ_{13} information

The oscillation signal



Reactor Neutrino Experiments

Experiment	Baseline	Size	Power	Channel
Double Chooz	400 m / 1.1 km	10 m^3	8.6 GW (2)	
Reno	350 / 1.4 km	20 m^3	16.4 GW (6)	$\overline{\nu}_e \rightarrow \overline{\nu}_e$
Daya Bay	400 / 1.7 km	100 m^3	17.4 GW (6)	

Improving CHOOZ: key facts

Best Sensitivity @CHOOZ: R = 1.01 ± 2.8%(stat)±2.7%(syst)

Statistical error

Luminosity incerase: $L = \Delta t \times P(GW) \times N_{Target\ H}$

	CHOOZ	Double Chooz
Target volume	5,55 m^3	10,3 m^3
Target composition	6,8 10^{28} H/m^3	6,5 10^{28} H/m^3
Data taking period	Few months	3-5 years
Event rate	2700	Far: 40000 / Near: 500000 (3 y)
Statistical error	2,7%	0,5%

Systematic & Background errors

- **Two Detector Concept**
- **Improved detector design:** Lower threshold, e+ and n Efficiencies, Calibration
- **Lower Background:** Shielding, Radiopurity

Syst. error	CHOOZ	Double Chooz
Reactor	1.9%	---
Target H	0.8%	0.2%
efficiency	1.5%	0.5%

CHOOZ

- Channel: anti-$\nu_e \rightarrow$**anti-ν_e**
- Isotrope anti-ν_e flux from $^{235/238}U$ & $^{239/241}Pu$

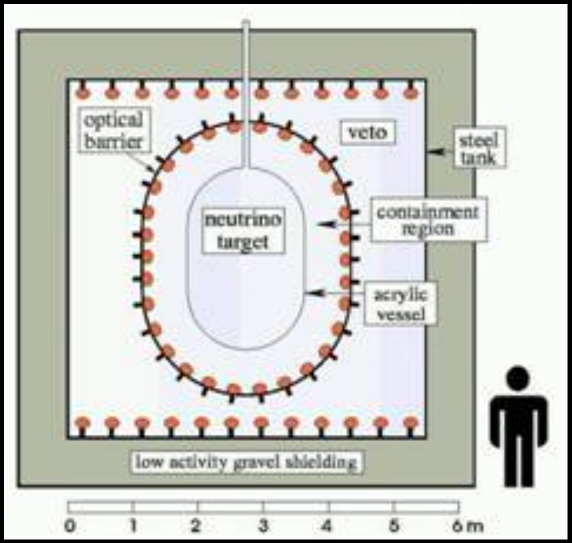
10^{21} ν_e/s for Chooz nuclear power Station (France)

- anti-ν_e + p ➔ e^+ + n, <E>~3.5 MeV, E_{thr}=1.8 MeV

Disappearance experiment: search for a departure from the $1/L^2$ behavior

- **Atmospheric ν_μ do not ocillate in ν_e**
- **ν_e is made of 2 mass eigenstates only**

- **An impressive by-product on θ_{13}**

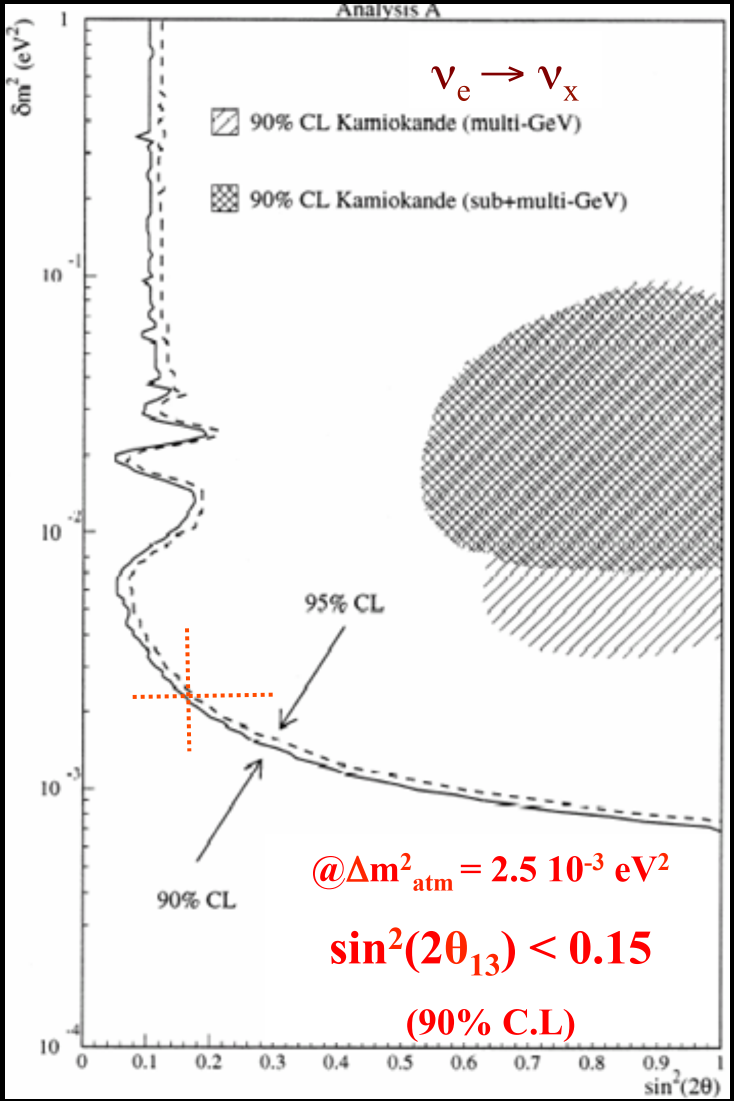


P_{th}= 8.4 GW_{th}

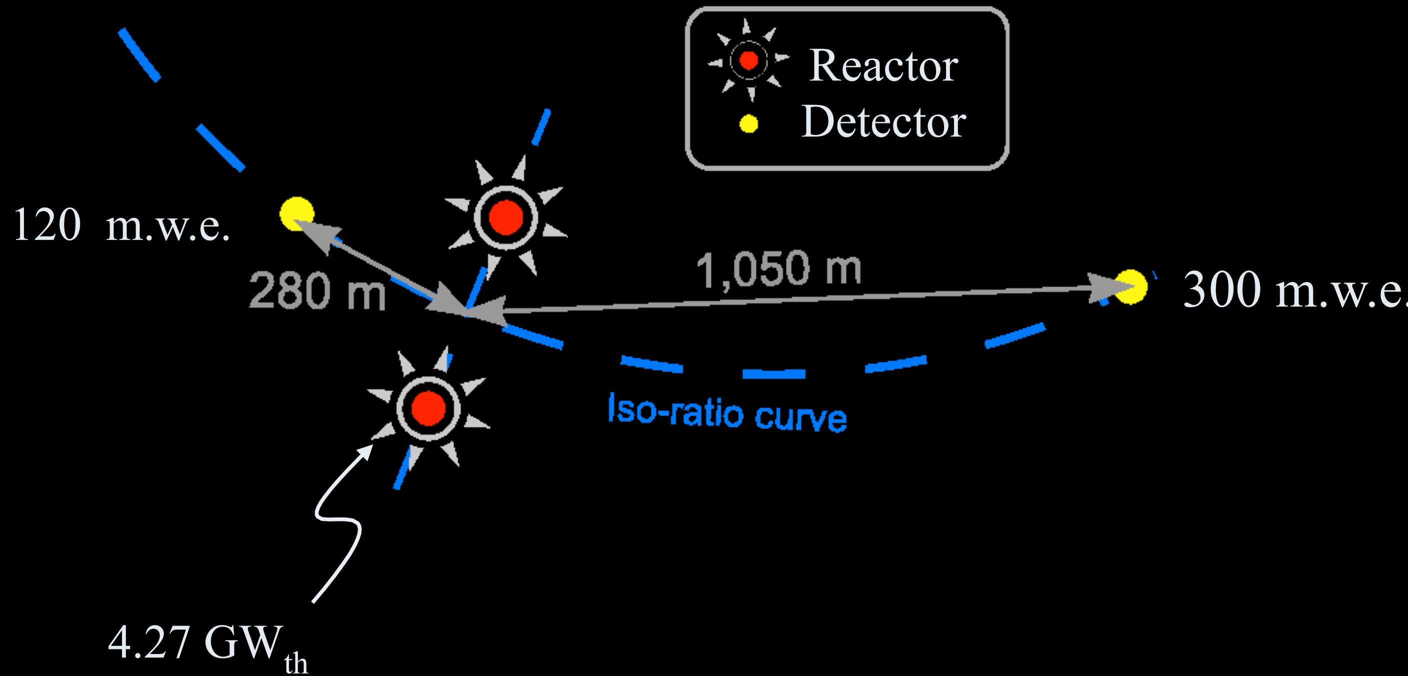
D = 1 km

M = 5 tons

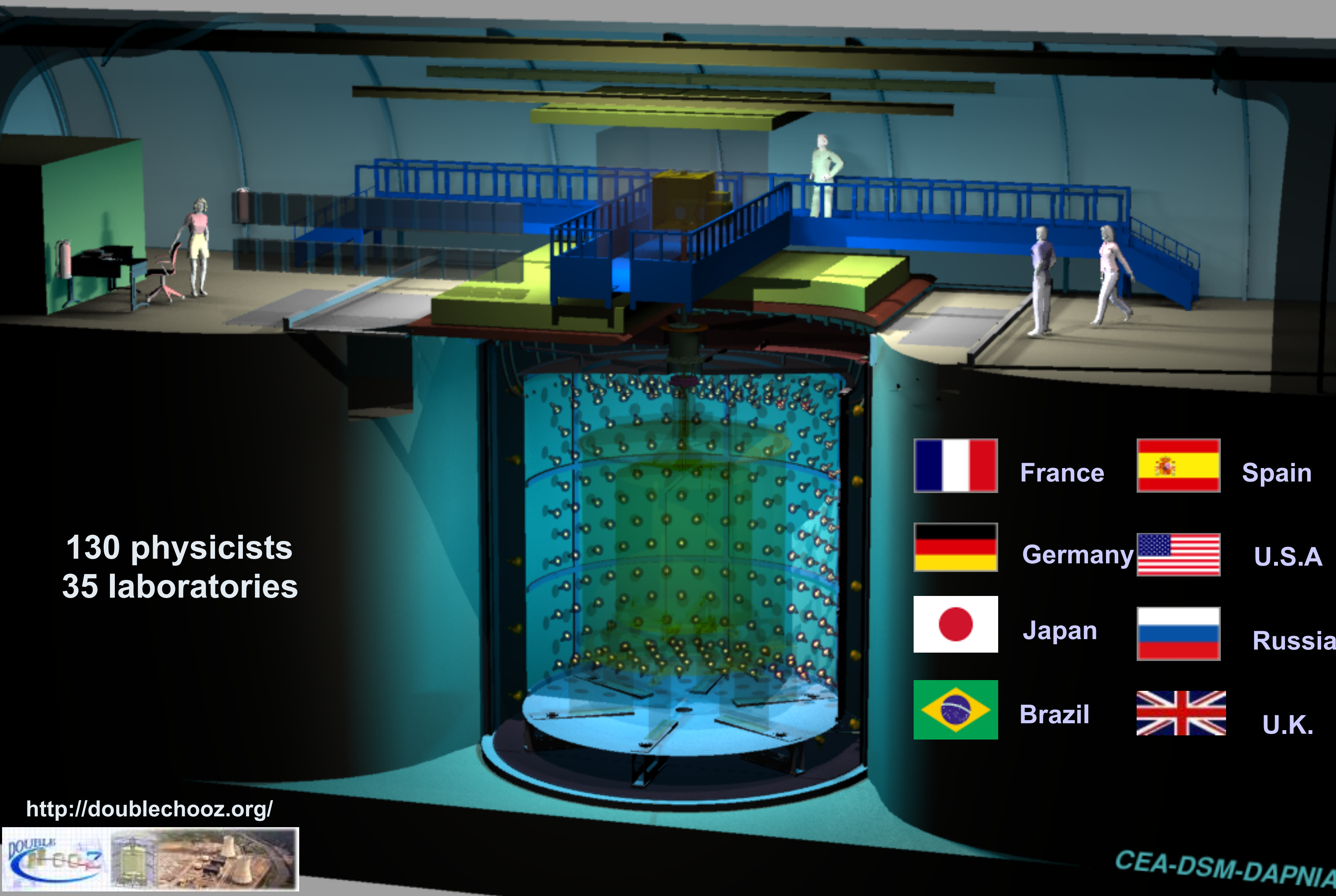
300 mwe



Double Chooz



Double Chooz



130 physicists
35 laboratories

France
Spain
Germany
U.S.A
Japan
Russia
Brazil
U.K.

http://doublechooz.org/

CLOSE DETECTOR 400 m
DISTANT DETECTOR
1 km
WEST REACTOR
EAST REACTOR
$\bar{\nu}_e$
© CEA/DSM/IRFU - DCom/L.COLOMBEL

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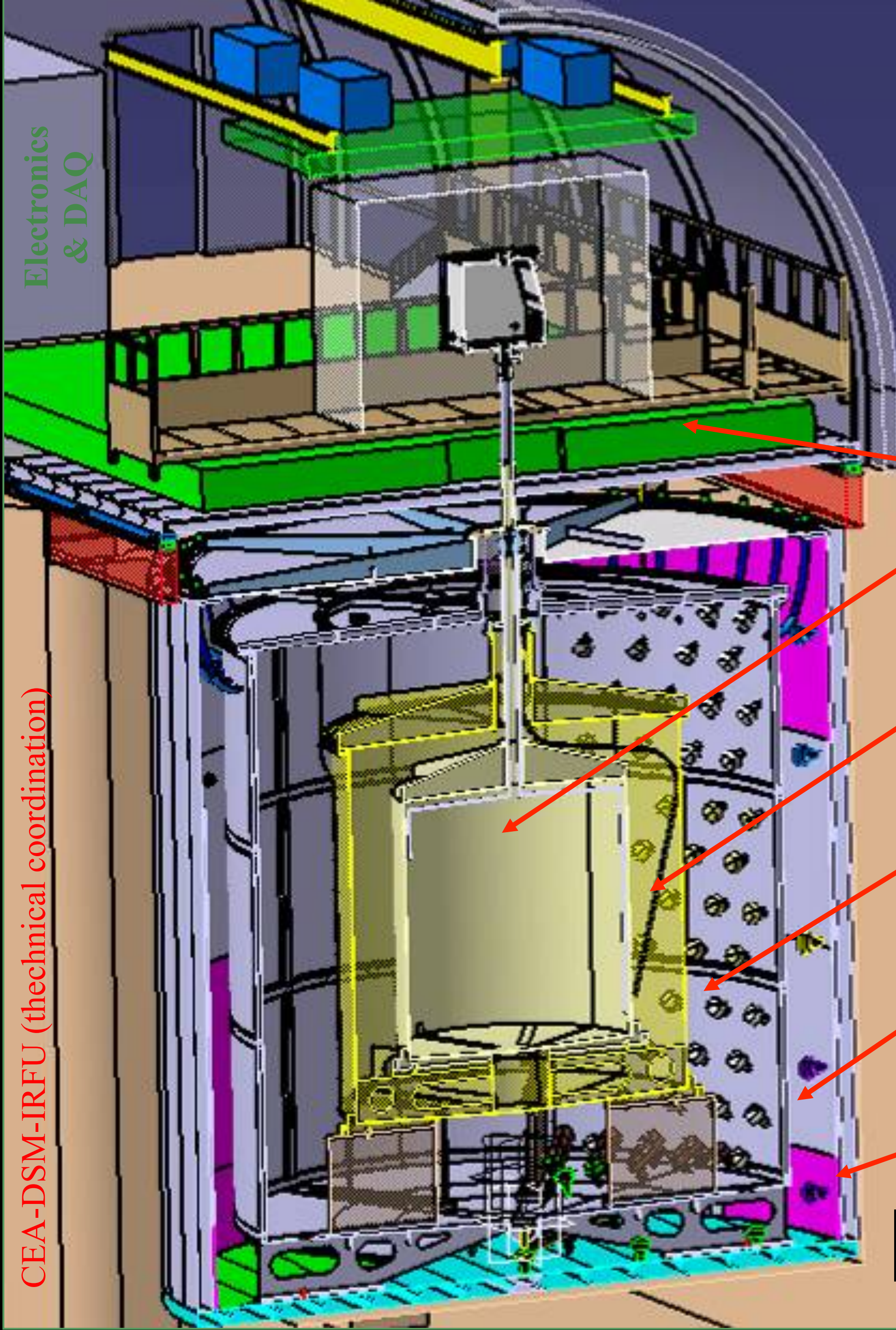
Detector Design



New 4-region large detector concept from Double Chooz Coll. (2003)

http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre1.doc

Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 1g/l of Gd compound in an acryclic vessel (8 mm)

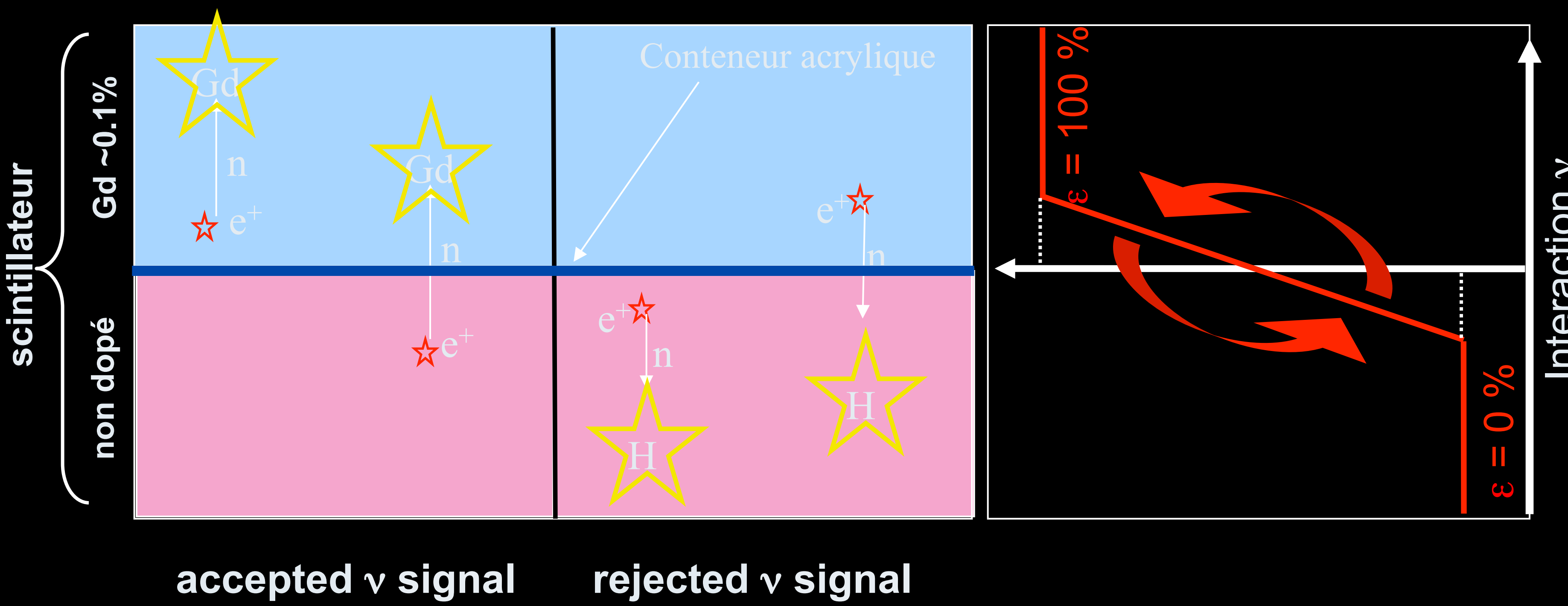
γ-Catcher: 22,3 m^3 scintillator in an acrylic vessel (12 mm)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & Steel Shielding (150 mm)
(4 liquid densities adjusted within 0.1%)

Spill in/out



scintillateur
Gd ~0.1%
non dopé
Gd
n
e+
Gd
n
e+
Conteneur acrylique
e+
n
H
e+
n
H
ε = 100 %
ε = 0 %
Interaction ν
accepted ν signal
rejected ν signal

250 ton Steel Shielding

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Inner Muon Veto

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Inner Veto PMTs & Buffer Vessel

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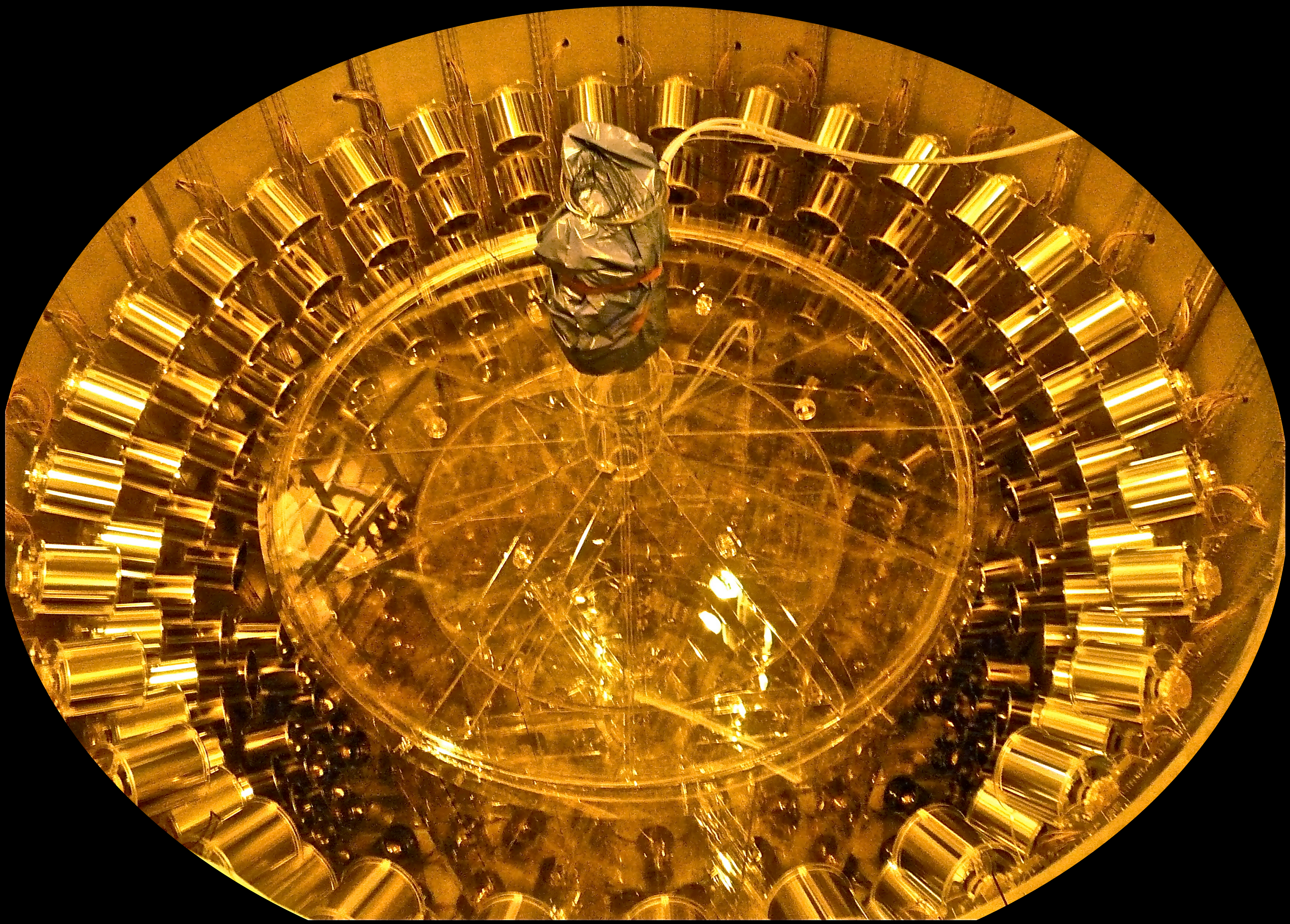
Inner Detector – May 2009

Integration…

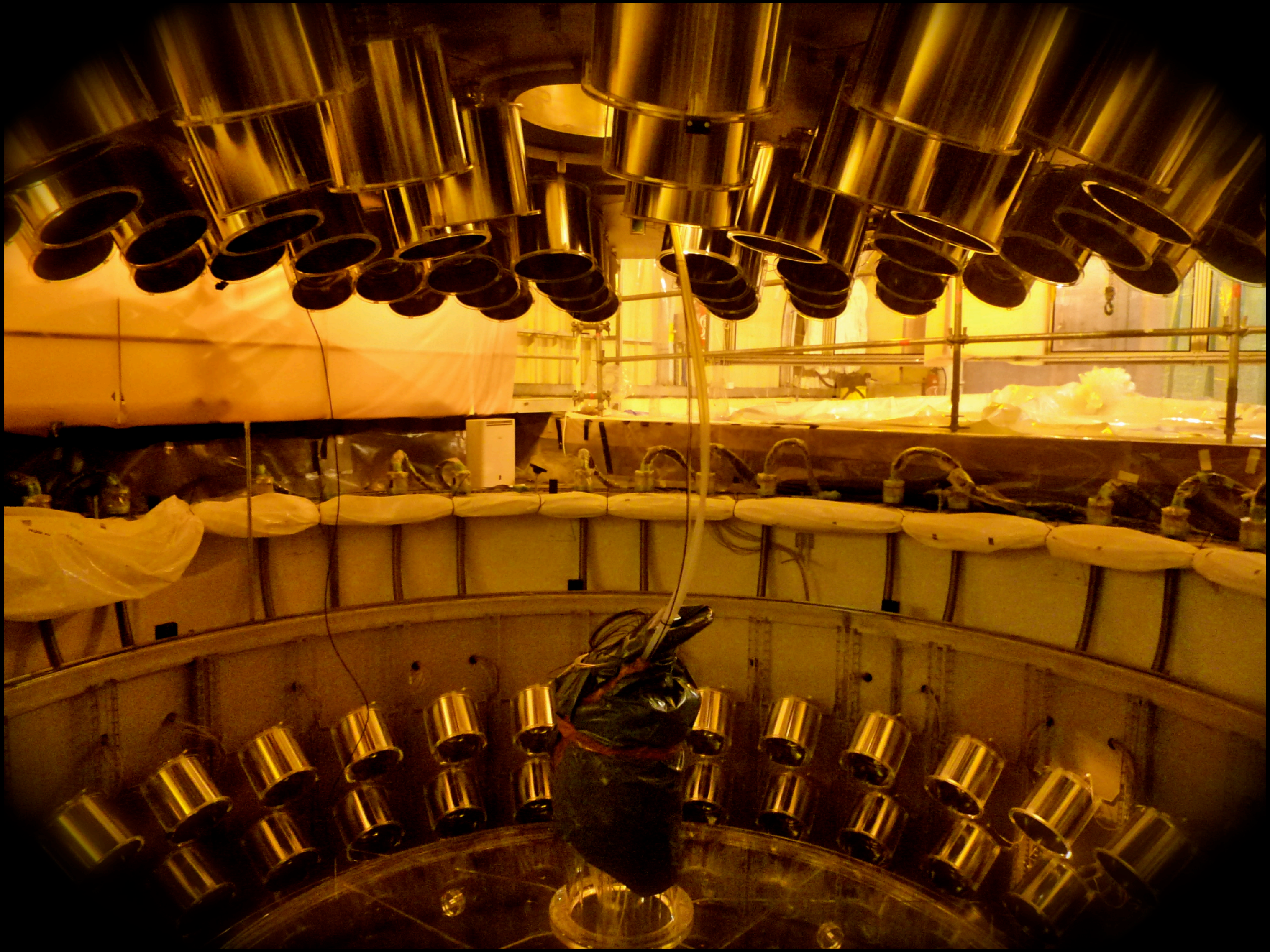
R. Quéval (PH.D)

Detector Interior



T. Lasserre - 04/02/2011

Detector Closing

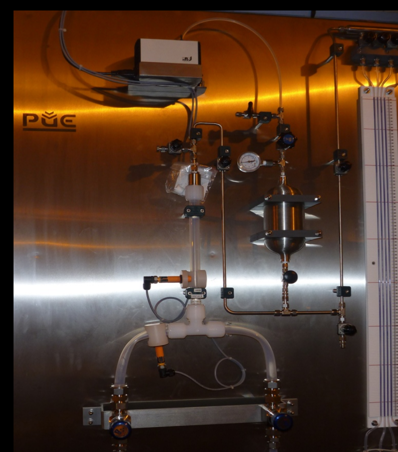


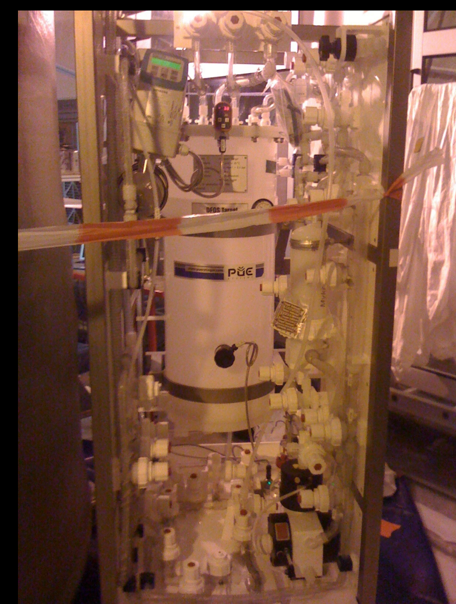
Top Shielding

Next: Outer Muon Veto, Glove Box for in situ Calibration (Feb-June 2010)

Outer Muon Veto

Detector Filling

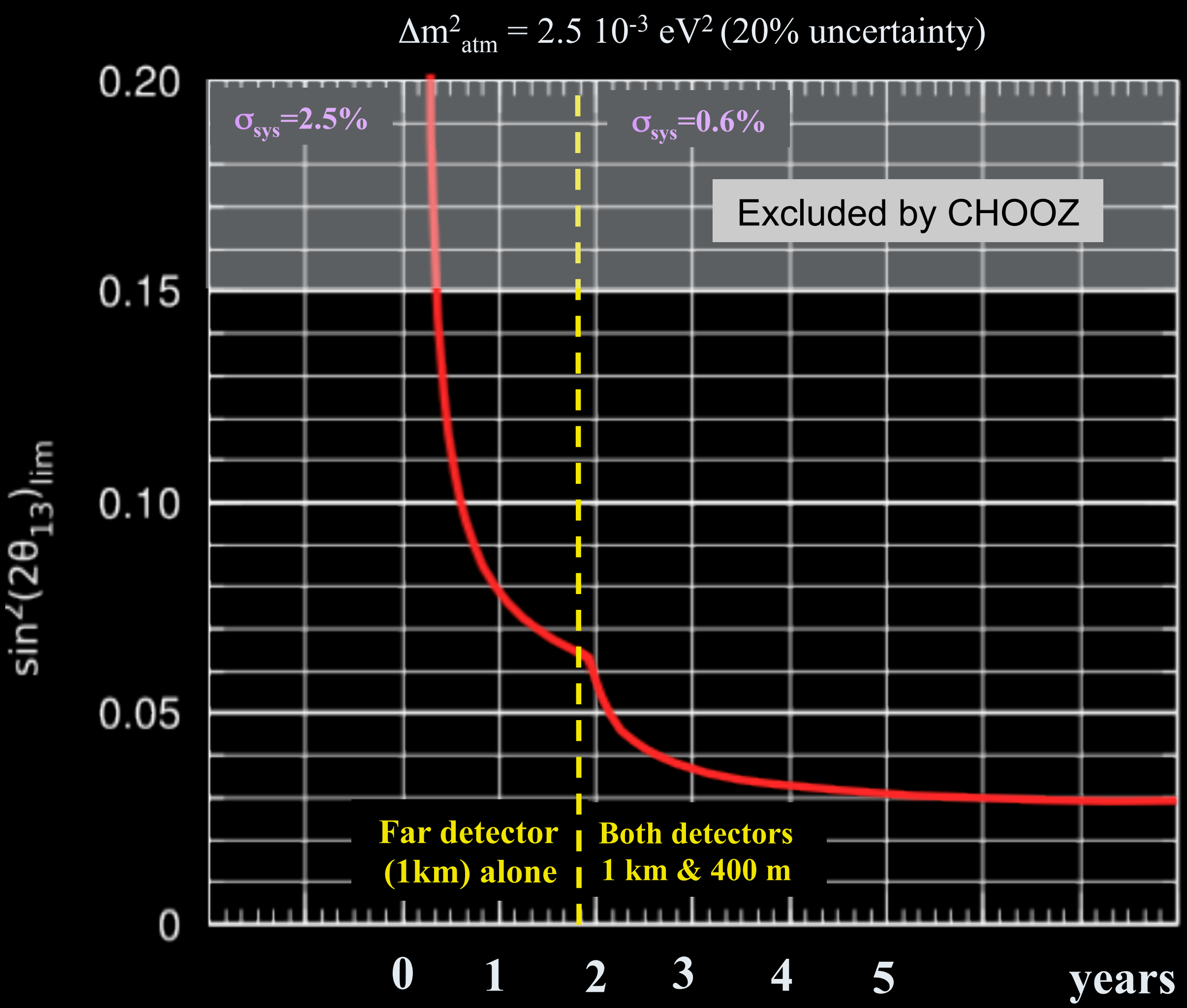




Detector Filling: October-December 2010

Near Laboratory Excavation (06/2011)

Sensitivity (Limit) Timeline

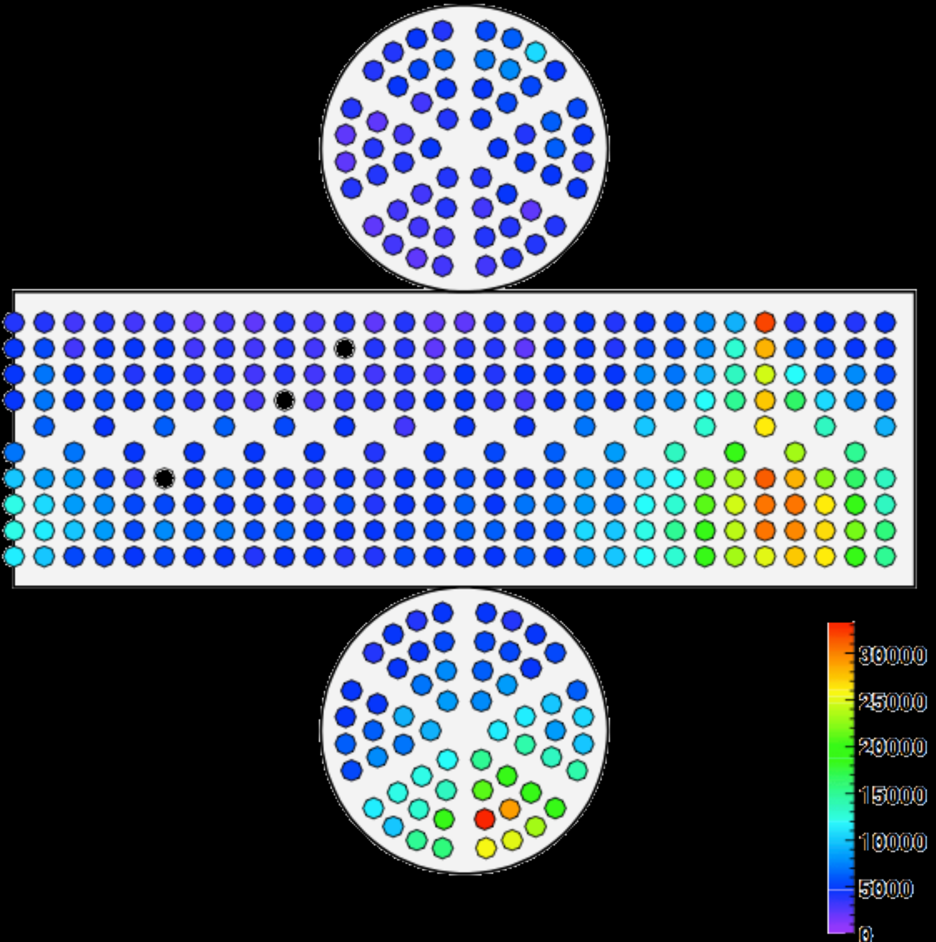


- Efficiencies included
- 1% 'bin-bin' uncorrelated error on background subtraction.
- Systematics 1Det = CHOOZ
- Systematics 2Det:
- σ_{abs} = 2.0%
- σ_{rel} = 0.6%
- σ_{scl} = 0.5%
- σ_{shp} = 2.0%
- $\sigma_{\Delta m^2}$ = 20%

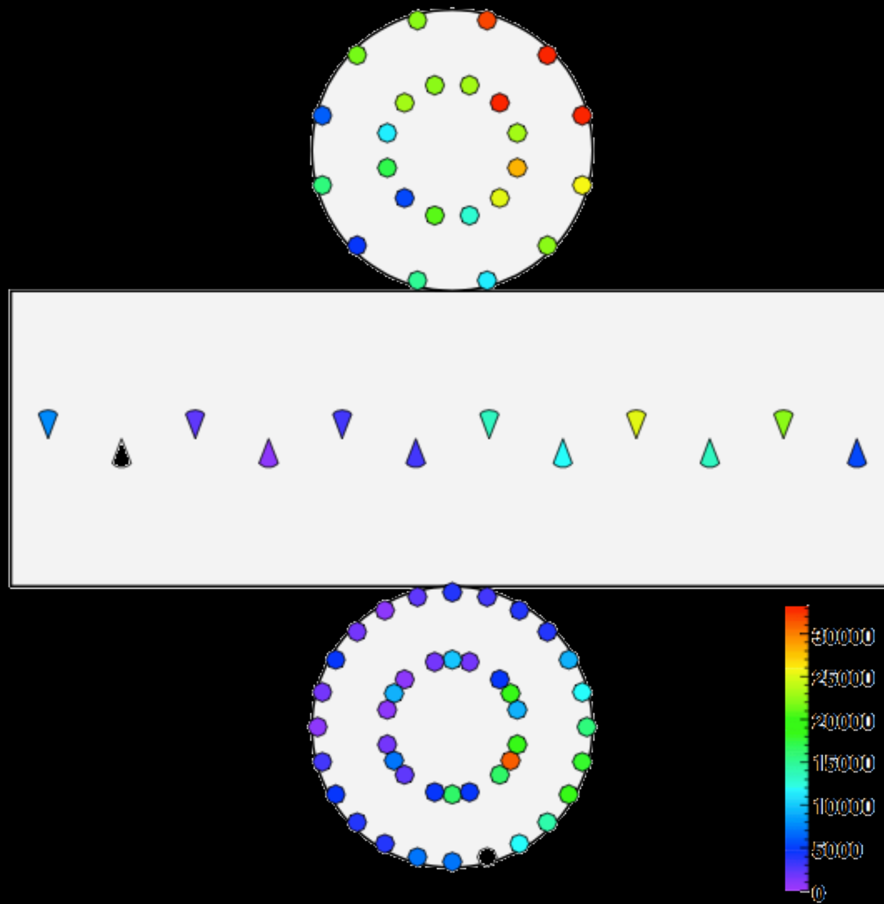
T. Lasserre 09/11/2009

Muon Candidate

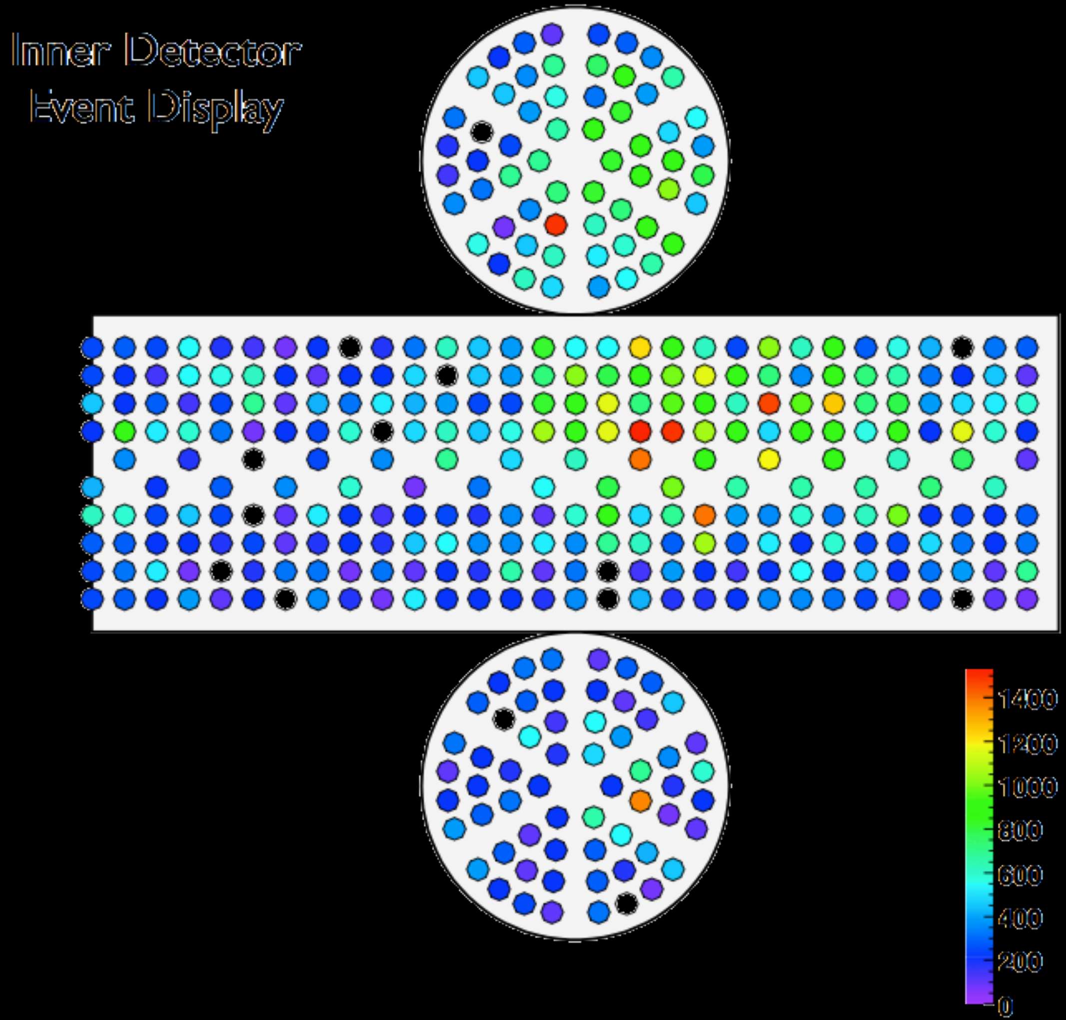
Inner Detector
Event Display



Inner Veto
Event Display



Contained Single Event



- **2009** → Far detector construction & intégration

- **12/2010** → Start of phase I : Far 1 km detector alone

  $\sin^2(2\theta_{13}) < 0.06$ after 1,5 y (90% C.L.) if no-oscillation

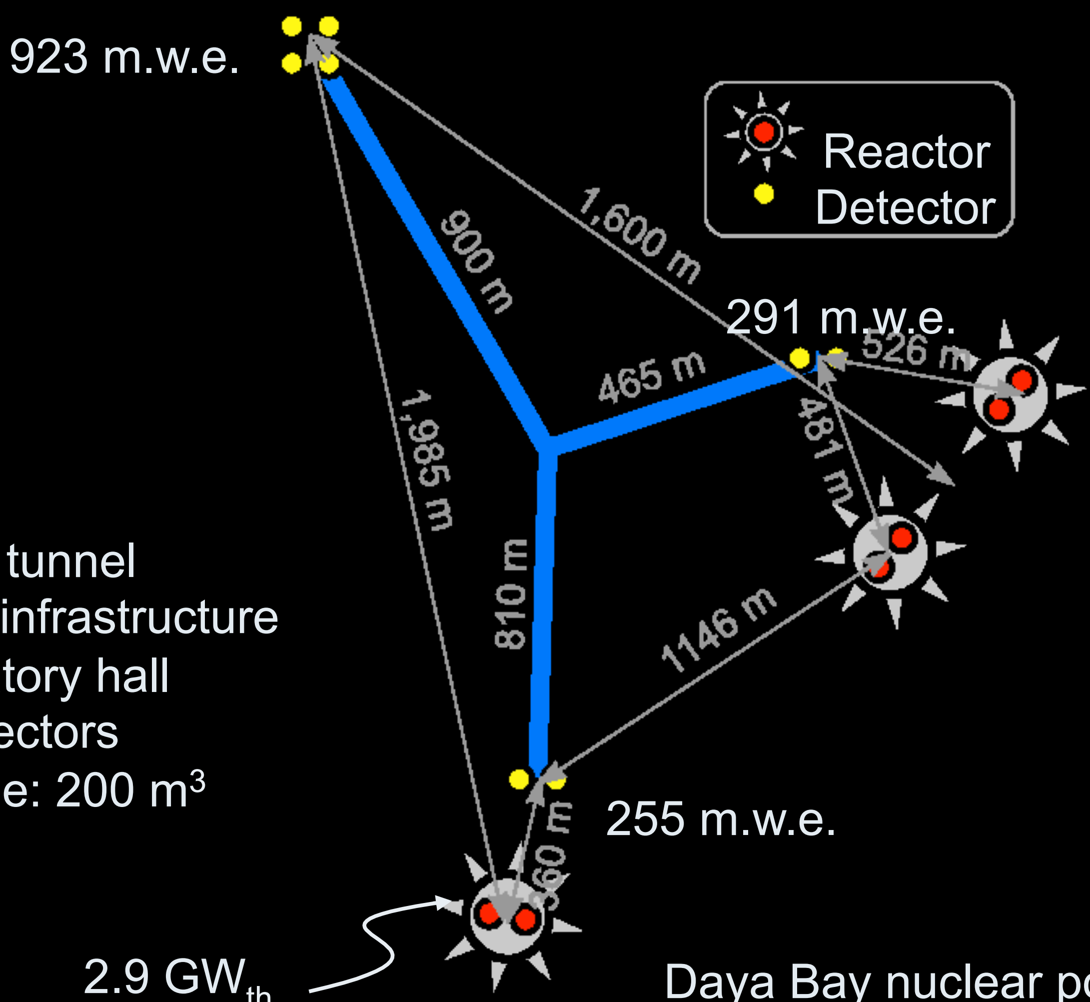
- **2011** → Near Lab Excavation

  → Near Detector Integration

- **2012** → Start of phase II : both near and far detectors

  $\sin^2(2\theta_{13}) < 0.03$ after 3 y (90% C.L.) if no-oscillation

Daya Bay



>3 km tunnel
New surface infrastructure
3 laboratory hall
8 detectors
Gd-volume: 200 m^3

Daya Bay nuclear power station in China

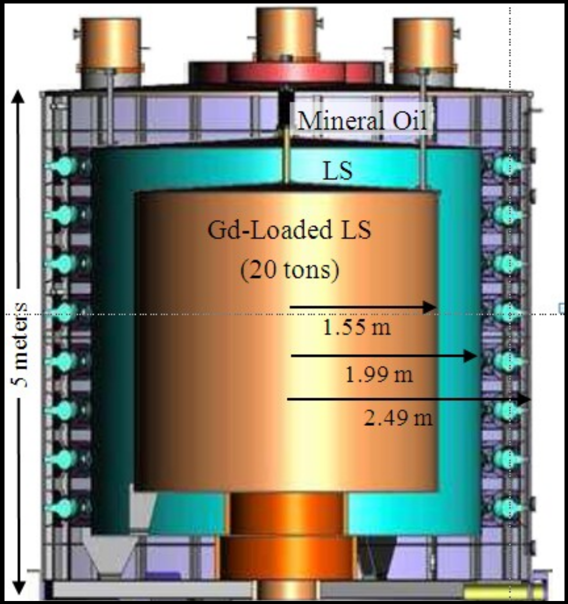
Status of Daya Bay

- **Four reactor cores**
  P=4 x 2.9 = 11.6 GW_{th}
  2 new cores for 6 GW_{th} in 2010-11

- **Civil construction**
  Near: 1 km tunnel + laboratory
  Far: 2 km tunnel + laboratory
  Total length: 3370 m

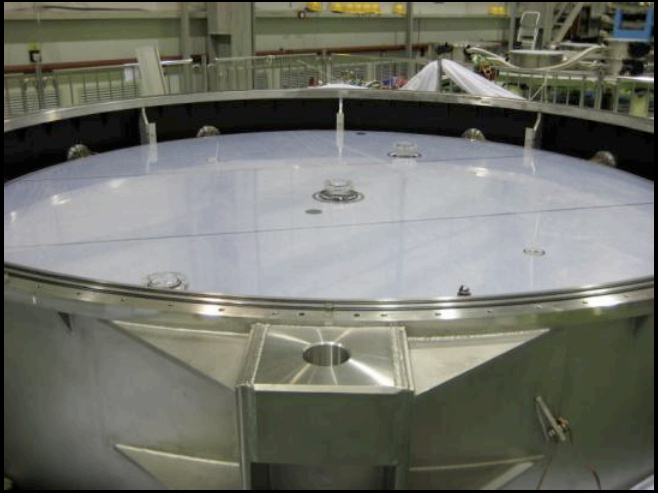
- **8x20 tons detector modules (fiducial)**
  Near: 4x20 tons – 360-500 m – 200 mwe
  Far: 4x20 tons - 1.6-1.9 km – 1000 mwe
  Movable detector concept (in water pools)

- **Expected Sensitivity**
  0.36% systematic error
  3 years – low backgrounds
  $\sin^2(2\theta_{13}) < 0.01$ (90% C.L.)



A huge infrastructure

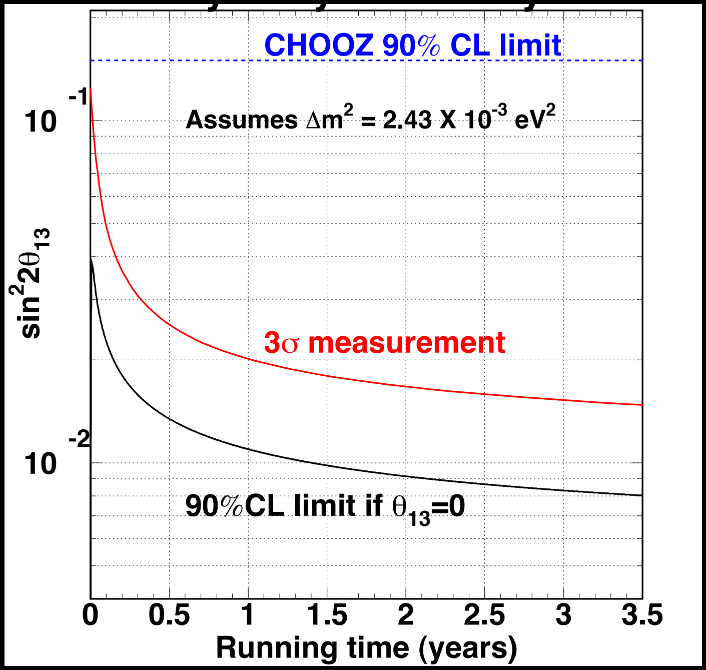
Detector status



Sensitivity & Milestones of Daya Bay

Sensitivity in $\sin^2 2\theta_{13}$:

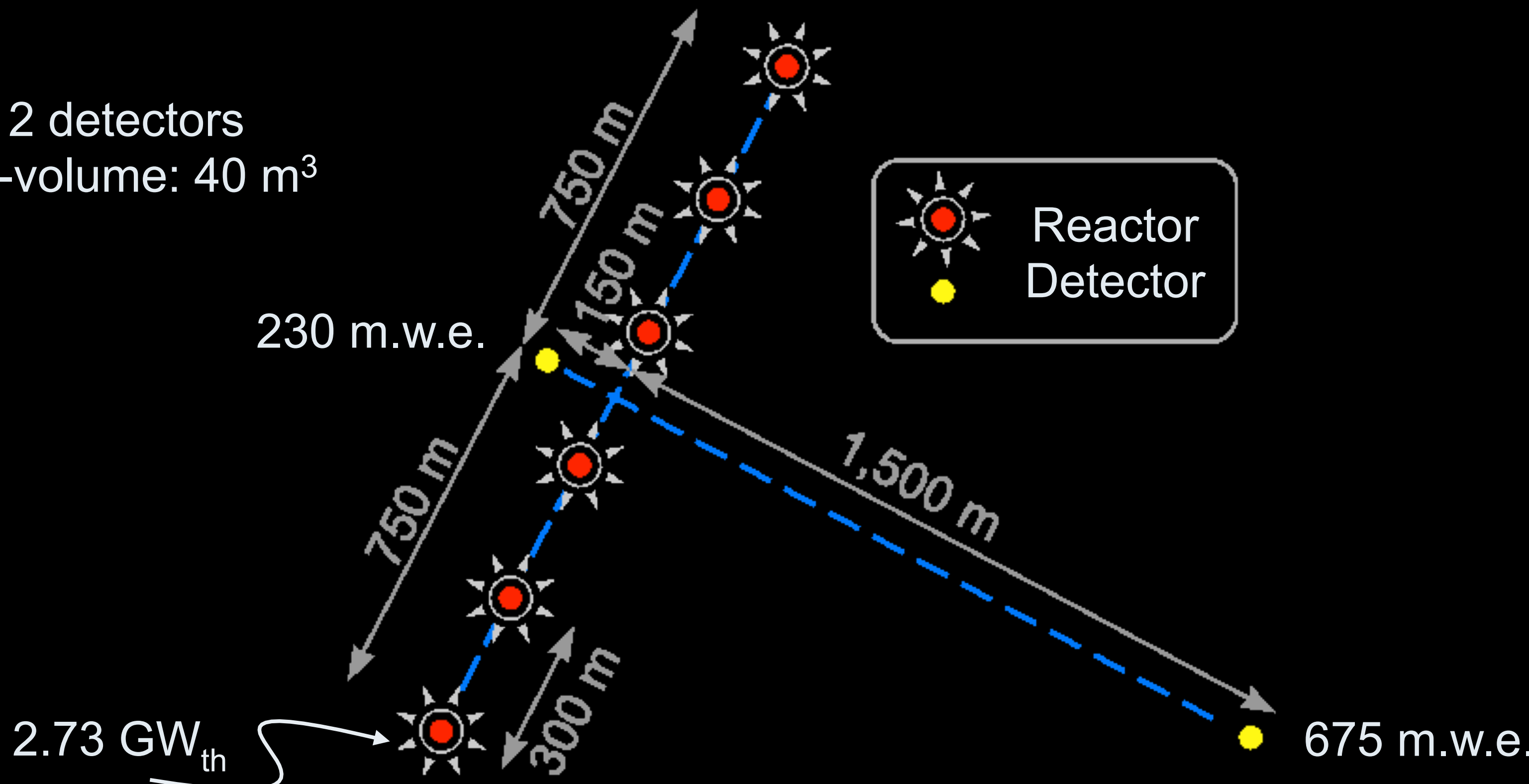
$\sin^2 2\theta_{13} < 0.01$ @ 90% CL
in 3 years of data taking
with 8 detectors running
simultaneously



- **Aug 2009:** Begin detector assembly
- **Fall 2009:** Begin detector installation in experimental halls
- **2011:** Start data taking with first near hall
- **End 2012:** Start data taking with all detectors

RENO

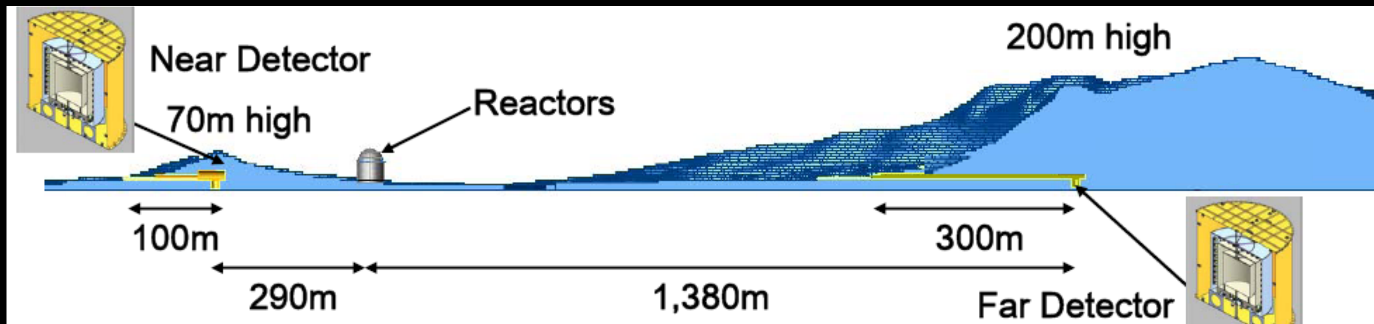
2 detectors
Gd-volume: 40 m^3



Yong gwang nuclear power station in Korea

RENO

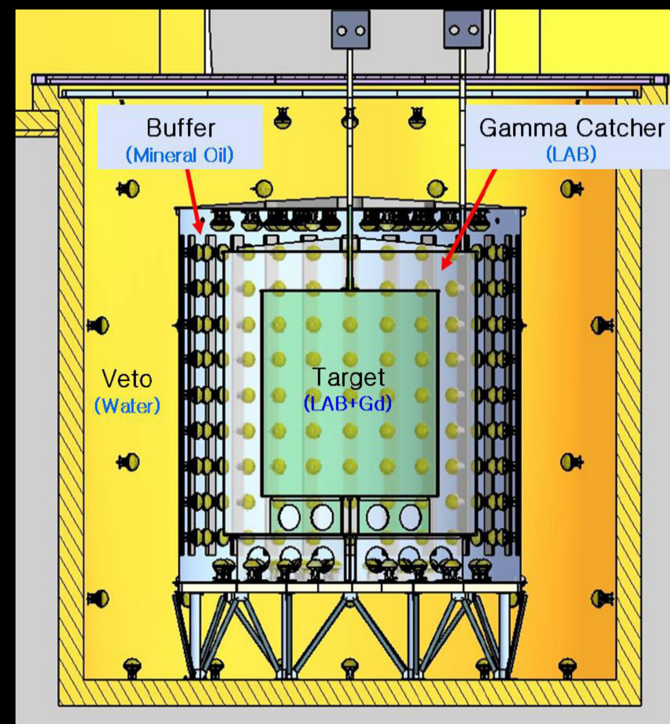
- **Six reactor cores:** P~16 GW_{th} (ND: 90% ν's from 2 cores)



- **Civil construction**
  km tunnel + hall ready!

- **Two 20 tons detectors**
  Near: 20 tons - 300– 200 mwe
  Far: 20 tons - 1.4 km - 700 mwe
  Integration on going

- **Sensitivity**
  0.45% systematic error
  $\sin^2(2\theta_{13}) < \sim 0.02$ (90% C.L.)



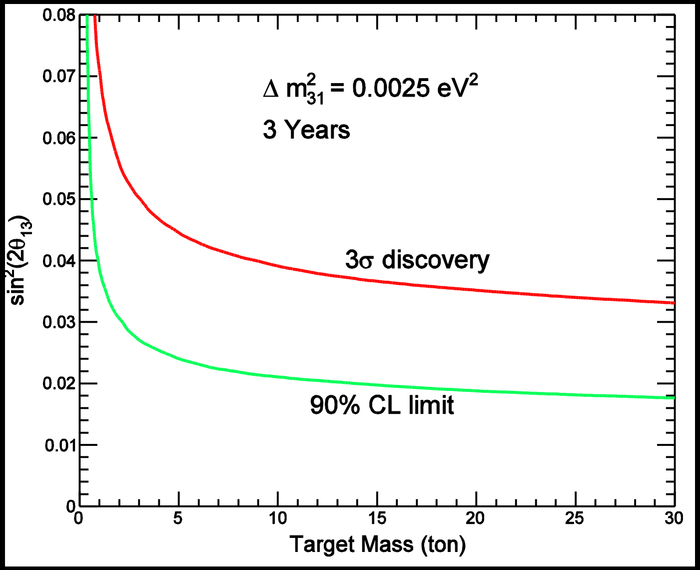
Double Chooz design cut/paste

Near & far tunnels are completed

(construction 2008.6~2009.3) **by Daewoo Eng. Co. Korea**

Status Report of RENO

- RENO is suitable for measuring **$\sin^2(2\theta_{13}) > 0.02$**



- Civil construction completed
- Buffer steel containers are installed
- PMT installation start in Dec. 09
- Acrylic containers will be completed end 2009
- Data taking is expected in 2011

Experimental Comments

- **New 4-region large detector concept from Double Chooz Coll. (2003)**
  (http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre1.doc)
  Concept adopted by Daya Bay and Reno **BUT**
  Double Chooz syst: 0.6% RENO sys:0.45% Daya Bay sys: 0.38%
  → Different expected sensitivities … (without det. Swaping)

- **Double Chooz**
  - Cons: Shorter baseline
  - Pros: 2 cores → reactor OFF periods, calibration, accidental bkg

- **Daya Bay**
  - Cons: 9 baselines / 6 nuclear cores
  - Pros: 160 tons of active volume, opt. baseline, corr. bkg

- **RENO**
  - Cons: Near/Far assymetric configuration, accidental bkg, calibration
  - Pros: Infrastructure ready

Ability to Establish non-zero θ_{13} (2009-16)

OPERA is looking for ν_τ appearance (1 event)

An additional neutrino oscillation clue ; $E_{Beam\ CNGS}$ too high to search for θ_{13}

MINOS is now looking for ν_e appearance.

But limited sensitivity because it is a magnetized iron detector;

current limit from MINOS $\sin^2 2\theta_{13} < 0.27$ (NH) / 0.42 (IH) @90% C.L.

Reactor experiments **Double Chooz, Daya Bay, RENO** will search for ν_e disappearance

No matter effect ; no sensitivity to δ ; clean info concerning $\sin^2 2\theta_{13}$

T2K will search for $\nu_\mu \rightarrow \nu_e$ appearance at low energy / short baseline (295 km, 600 MeV)

Small matter effects ; results = combination of $\sin^2 2\theta_{13}$ and δ

NOvA will search for $\nu_\mu \rightarrow \nu_e$ appearance at mid-energy / long-baseline (810km, 2 GeV)

Larger matter effects → a weak sensitivity to $\pm\Delta m^2_{13}$; results = combination of $\{\sin^2 2\theta_{13}, \pm\Delta m^2_{13}, \delta\}$