Neutrino oscillations:
status & on-going & up-coming experiments

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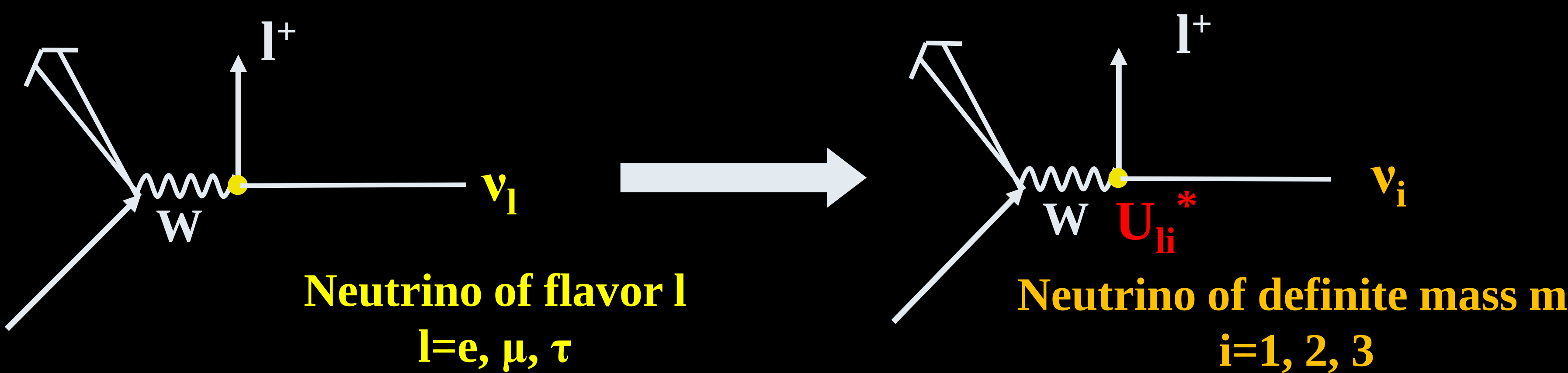
Launch 09
Heidelberg, November 09th 2009

Neutrino Mass and Mixing

- Neutrino: spin ½, neutral, left handed chirality (~helicity), $\sigma \sim 10^{-43}$ cm^2 (reactor-ν)
- For 10 yrs we know neutrinos have tiny masses and mix: 0.04 eV $< m_\nu <$ ~1 eV
- Two views on W decay:



- PMNS mixing matrix U relates mass & flavor bases: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$
- First compelling evidence of physics Beyond the Standard Model

Neutrino Oscillation formalism

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

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

$c_{ij} \equiv \cos\theta_{ij^2}$, $s_{ij} \equiv \sin\theta_{ij}$

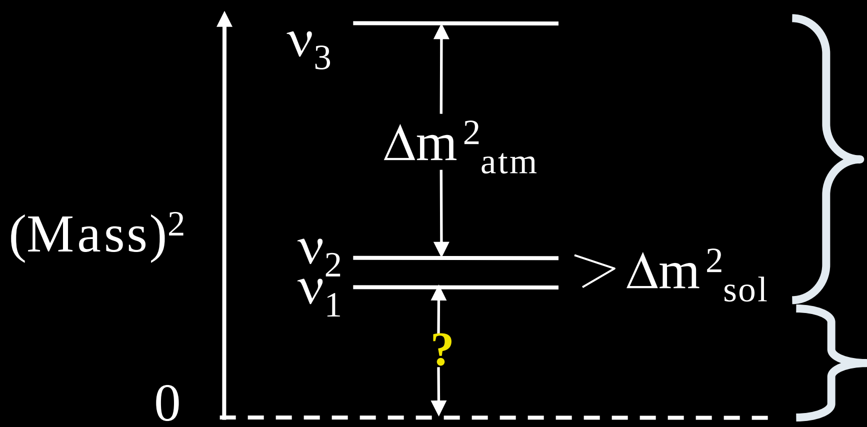
δ Dirac CP violating phase

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) & $\theta_{13} << 1$

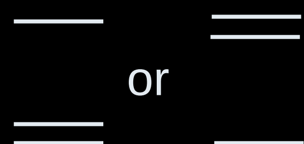
Open questions

- What are the masses of the mass eigenstates ν_i?



ν flavor change (Th. Lasserre)

β decay, ββ0ν decay, Cosmology
(G. Drexlin,) (Y. Wong)

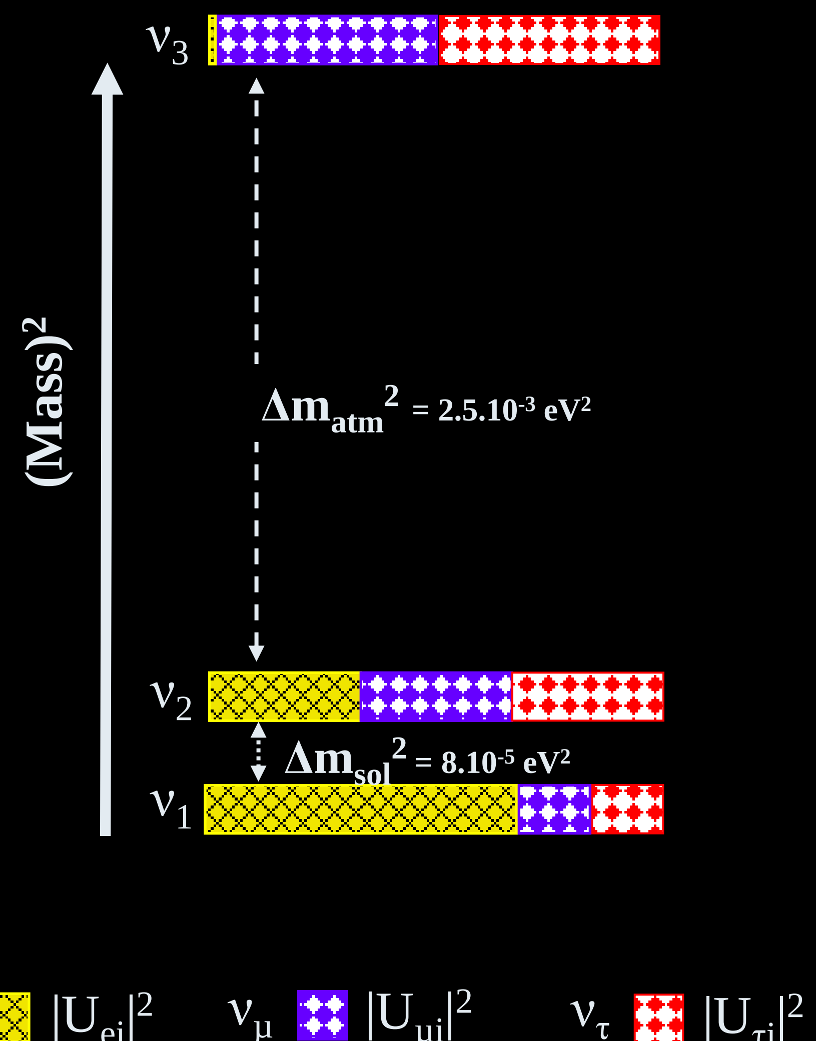
- Is the spectral pattern  ? $\overset{(-)}{\nu}$ behavior in earth matter, ββ0ν (P. Huber)

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

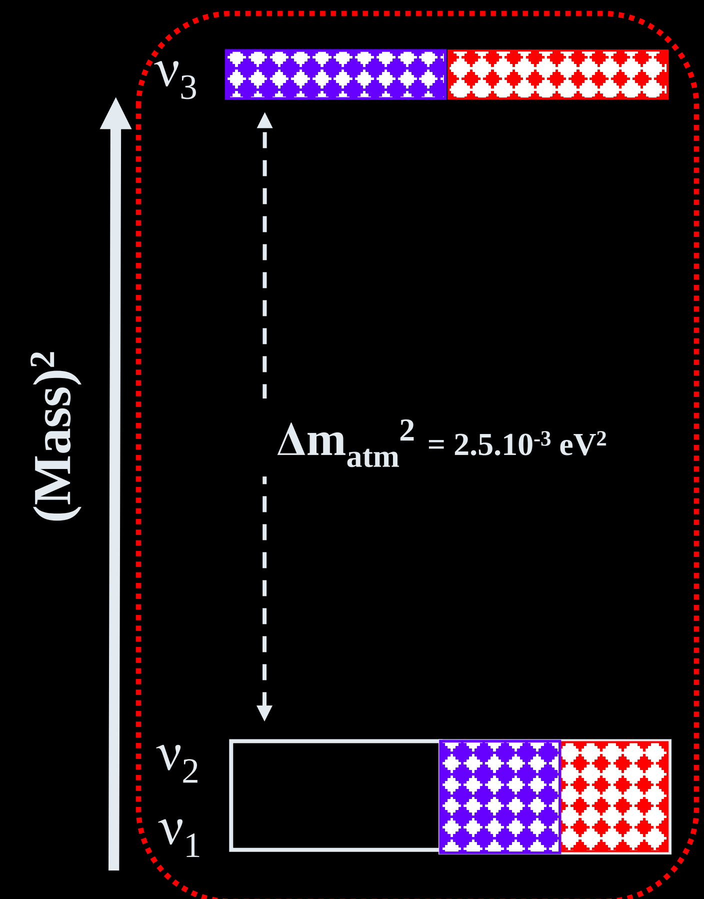
- What are the angles of the leptonic mixing matrix? (Th. Lasserre)
- Do the behavior of ν violate CP? (P. Huber)
- Is leptonic ~~CP~~ responsible for the matter-antimatter asymmetry?
  →Leptogenesis? (A. Kartavtsev)

ν flavor change

Δm^2_{31} & θ_{23}



Δm^2_{31} & θ_{23}



ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$

Δm^2 (eV^2)~ L(km) / E(GeV)

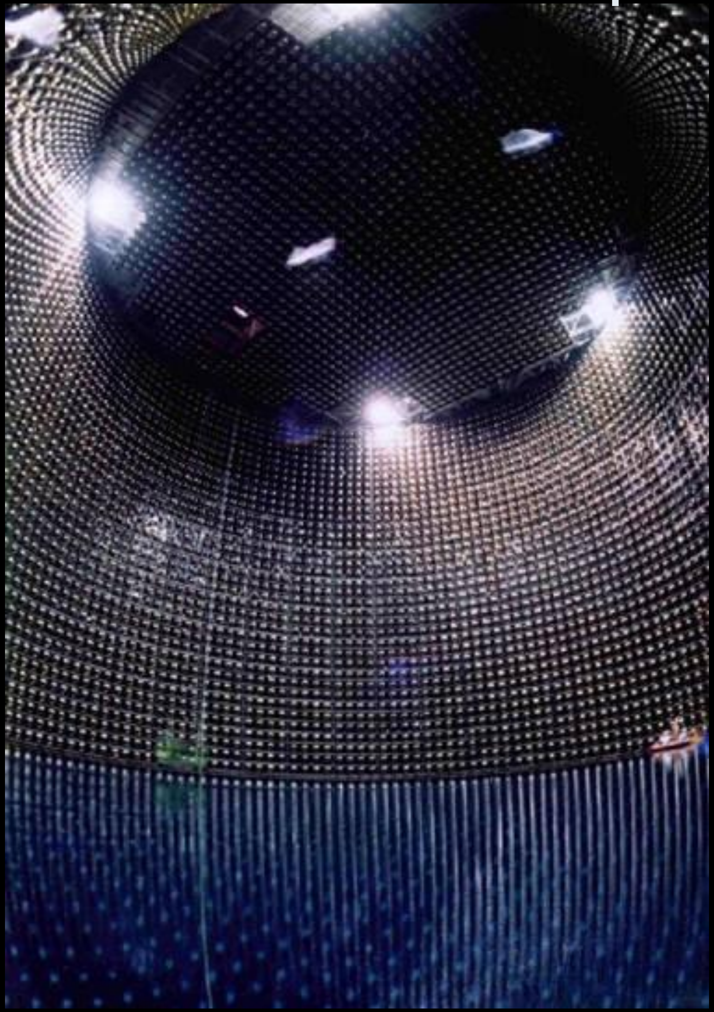
L~10^4 km & E ~ 1-30 GeV
L~1 km & E = ~ 3 MeV
L~1000 km & E ~ 3 GeV

Atmospheric/Beam Experiments

Experiment	Baseline	Size	Channel
SuperK	10-10^4 km	22.5 000 m^3	$\nu_\mu \rightarrow \nu_\mu$
Chooz	1 km	5 m^3	$\overline{\nu}_e \rightarrow \overline{\nu}_e$
K2K	250 km	22.5 000 m^3	$\nu_\mu \rightarrow \nu_\mu$
MINOS	730 km	5.4 ktons	$\nu_\mu \rightarrow \nu_\mu$

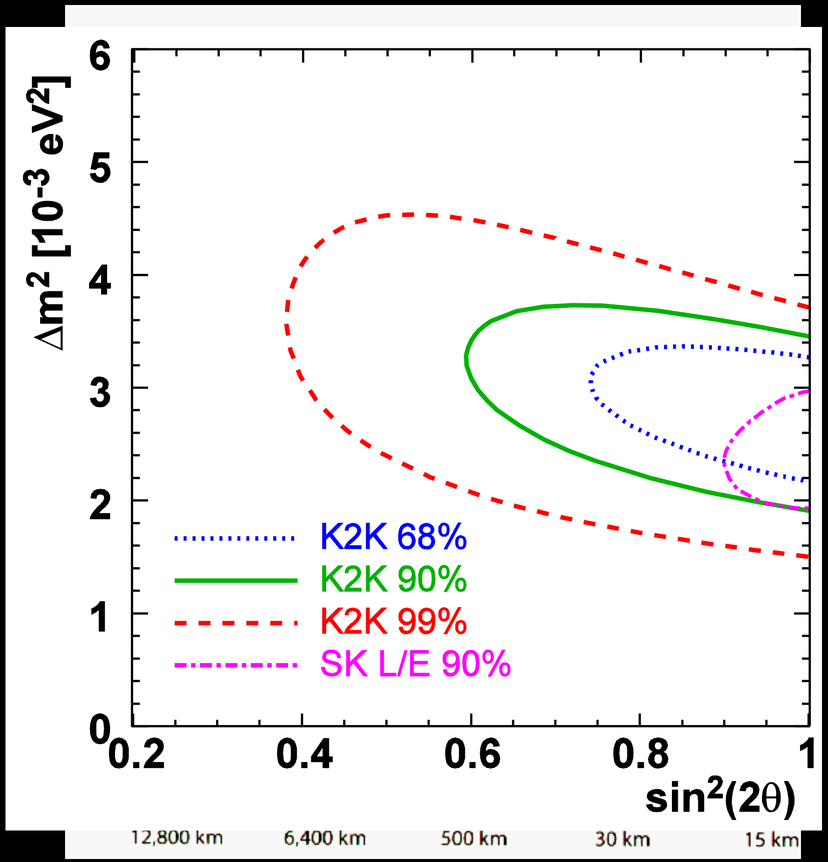
SuperKamiokande 1998 Breaktrough

Water Cherenkov Technique



50 kt of pure water, 12 000 PMTs
Excellent E-resolution
e/μ discrimination at low energy

$$\Phi^{Atm}_{\nu_\mu}(\text{up}) \Big/ \Phi^{Atm}_{\nu_\mu}(\text{down}) = 0.54 \pm 0.04$$



Neutrino do have mass and they oscillate

Remaining question: is ν_3 mostly ν_μ or ν_τ ?

MINOS Muon Neutrino Dissapearance

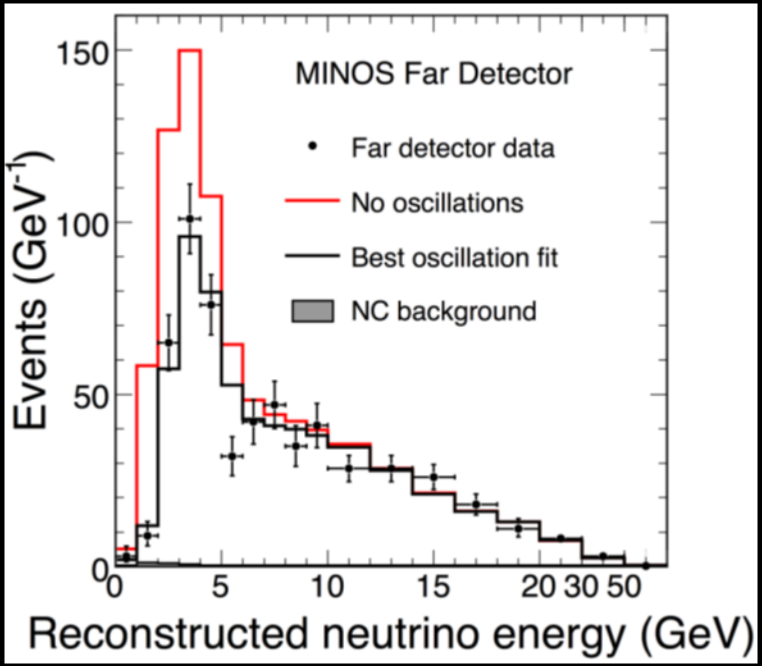
- Channel: $\nu_\mu \rightarrow \nu_\mu$
- Fermilab (US): Main proton Injector (0.3 MW)
  2.5 GeV neutrinos beam
- Baseline: 735km (FNAL → Soudan mine)

- Detectors:
  - Magnetized iron / scintillator tracking calorimeter detectors
  - 5.4kt Far detector / 0.98kt Near detector

- Data-taking since 2005
  - 7×10^{20}POT recorded
  - 3×10^{20}POT analysed

- Results:
  - $\Delta m_{atm}^2 = (2.43 \pm 0.11).10^{-3}\ eV^2$
  - $\sin^2(2\theta_{23}) = 1.00 \pm 0.05$

- Antineutrino run starting
  5σ oscillation confirmation within 1 year



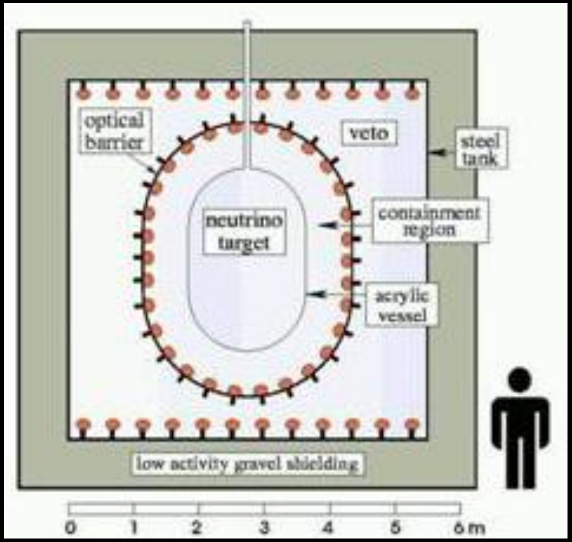
CHOOZ

- 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>~4 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**

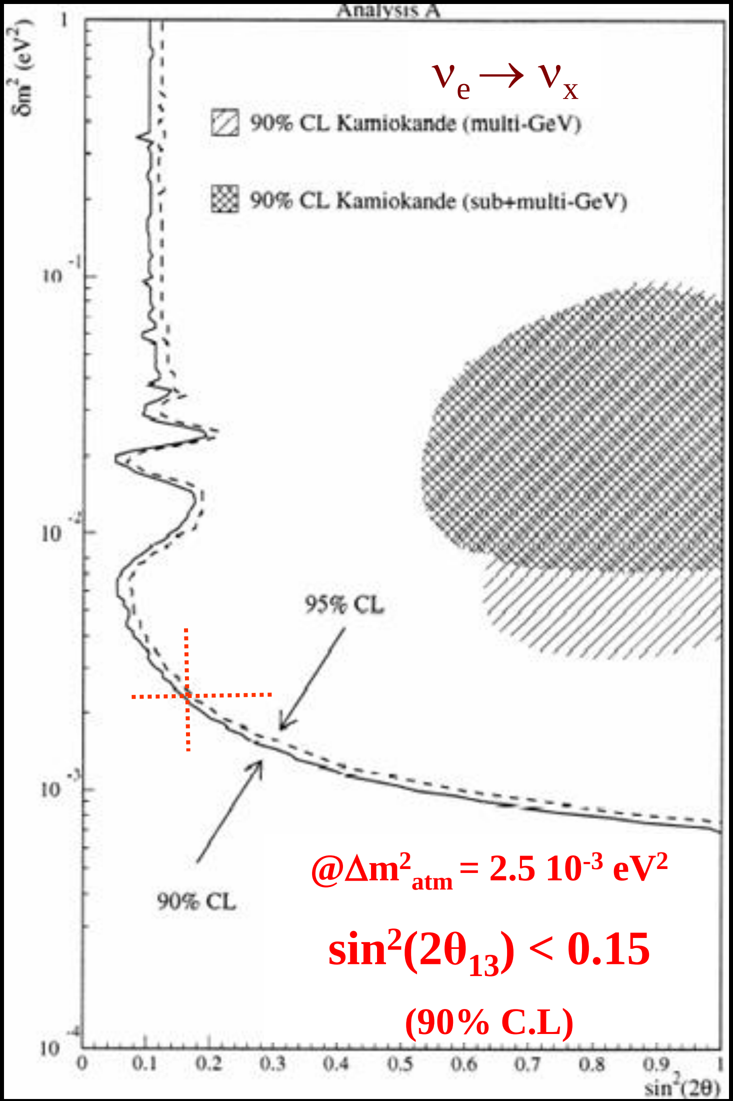
- **An impressive by-product on θ_{13}**



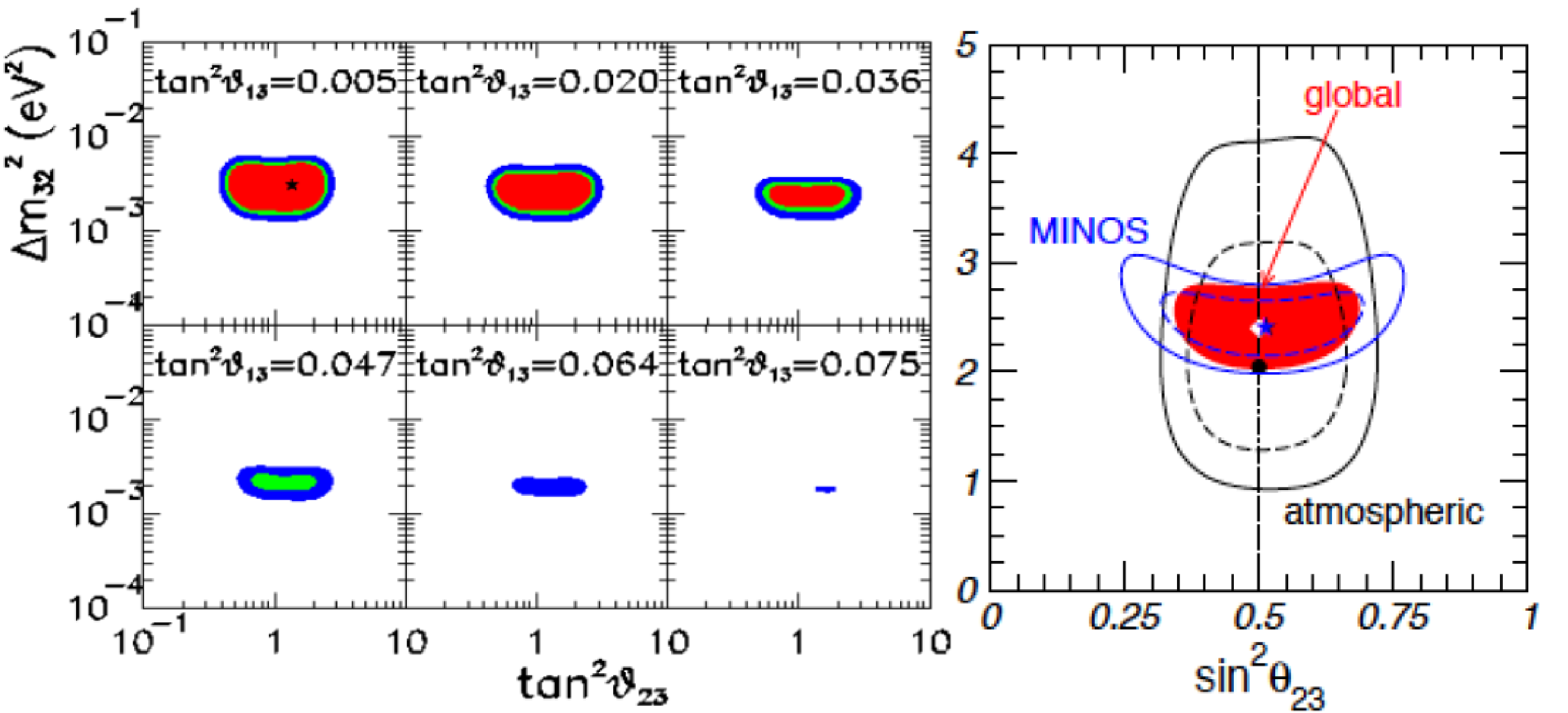
P_{th}= 8.4 GW_{th}

D = 1 km

M = 5 tons
300 mwe



Atmospheric Sector from 2000 to 2009

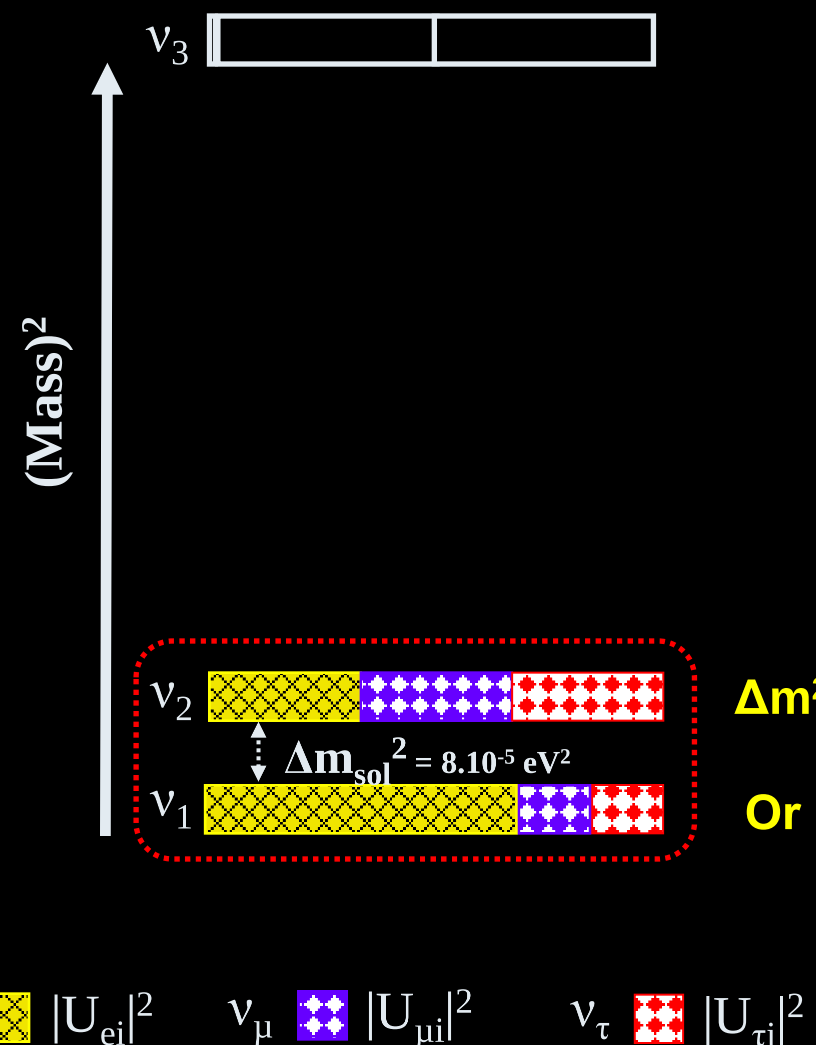


Gonzalez-Garcia et al., 2000 Schwetz et al., 2008

Confident knowledge on Δm_{31}^2 (critical for any terrestrial θ_{13} search)

Is θ_{23} maximal?

Δm^2_{21} & θ_{12}

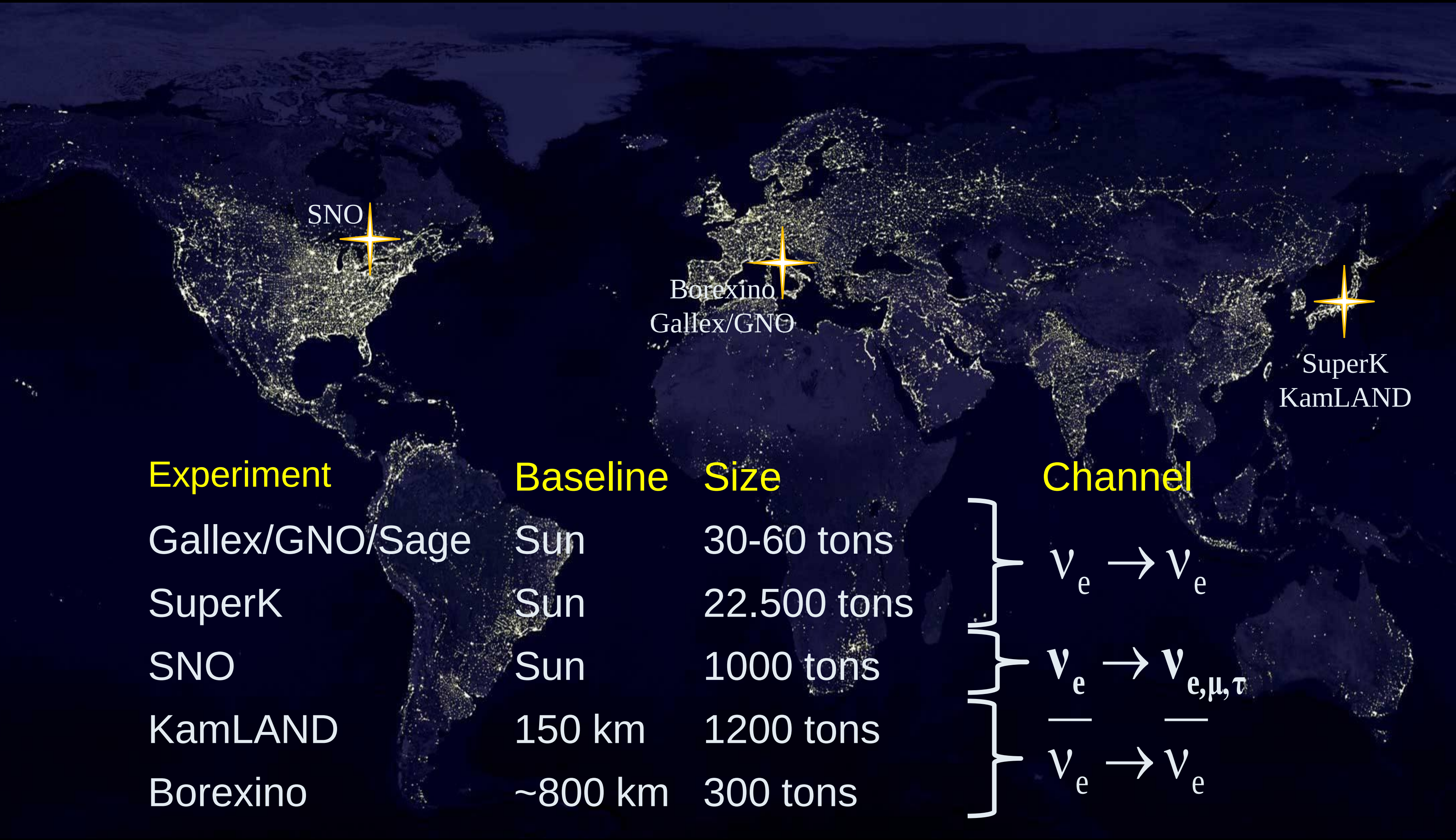


$\Delta m^2\ (eV^2) \sim L\ (km)\ /\ E(GeV)$

L~100 km & E~MeV

Or MSW 'flavor transition'

Solar/Reactor Experiments



Experiment	Baseline	Size	Channel
Gallex/GNO/Sage	Sun	30-60 tons	$\nu_e \rightarrow \nu_e$
SuperK	Sun	22.500 tons	
SNO	Sun	1000 tons	$\nu_e \rightarrow \nu_{e,\mu,\tau}$
KamLAND	150 km	1200 tons	$\overline{\nu}_e \rightarrow \overline{\nu}_e$
Borexino	~800 km	300 tons	

Solar Neutrinos: SNO

- **Goal** : Bore 8 Solar neutrino through CC & NC
  - 3 phases: D_2O, + NaCl, + ^{3}He counters

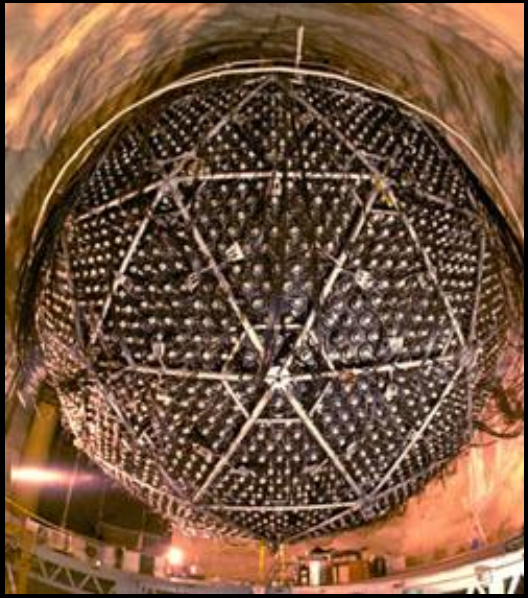
- **Channel/Reaction :**
  - $\nu_e \rightarrow \nu_e$: ν_{sol} D → e p p (CC)
  - $\nu_e \rightarrow \nu_e$, ν_μ, ν_τ : ν_{sol} D → e p n (NC)

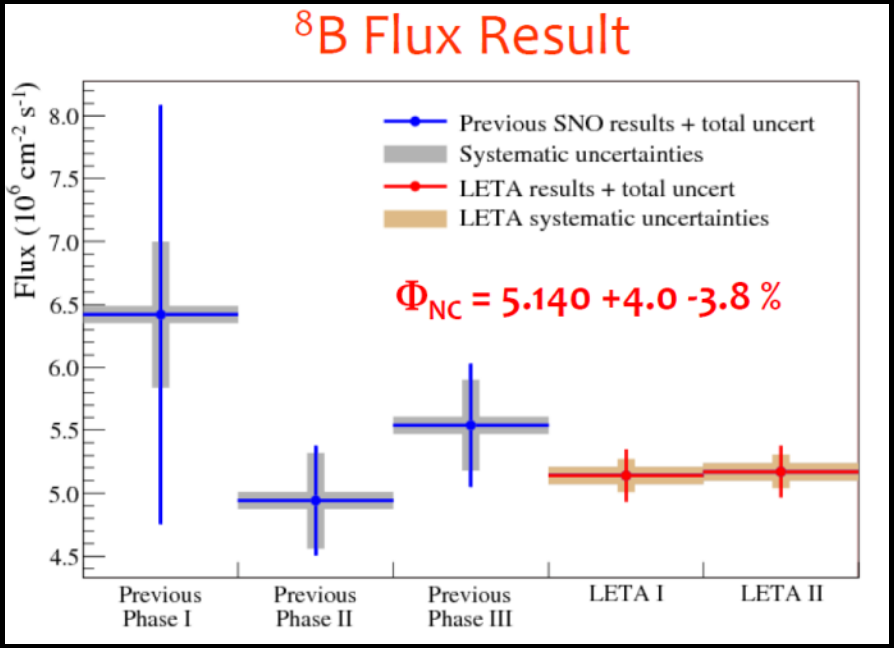
- **Detector in Sudbury mine (Canada)**:
  - 1000 tons of D_2O & 9500 PMTs (54%)
  - move to LS (SNO+)

- **SNO Results**
  - **Tag the MSW-LMA solution**
  - **New LETA analysis (3.5 MeV)**

Δm^2 =5.89±2.13 (stat) ±2.16 (syst) $\times 10^{-5}$ eV^2

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

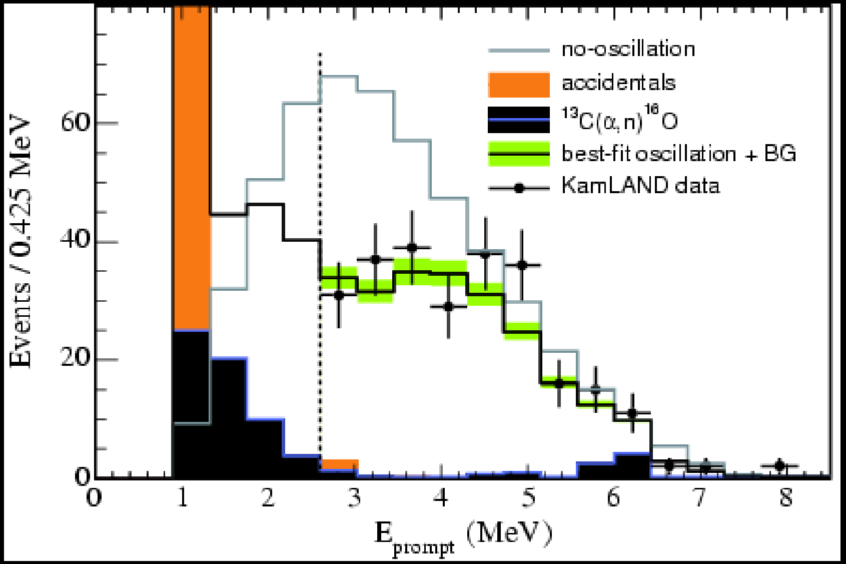




Reactor ν's: KamLAND & Borexino

- **Goal** : Measure the dissapearance of anti-ν_e from distant reactors located <L> ~ 180 km for the Kamioka mine (Japan)

- **Channel : $\bar{\nu}_e \rightarrow \bar{\nu}_e$** (detected trough IBD)
- **Detector**:
  - 1000 tons of liquid scintillator & PMTs
  - 2 interactions/day (no oscillations)
  - E range: few 100 keV ~ ten's MeV
- **KamLAND Results**



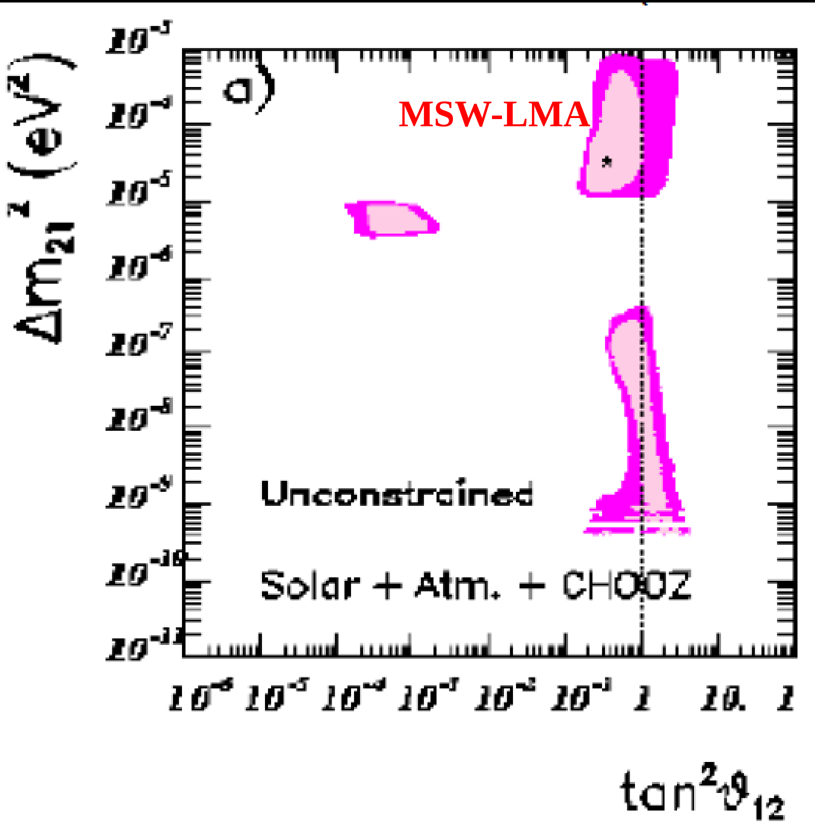
Confirmation of the MSW-LMA solution

$\Delta m^2 = 7.58 \pm 0.14$ (stat) ± 0.15 (syst) $\times 10^{-5}$ eV^2

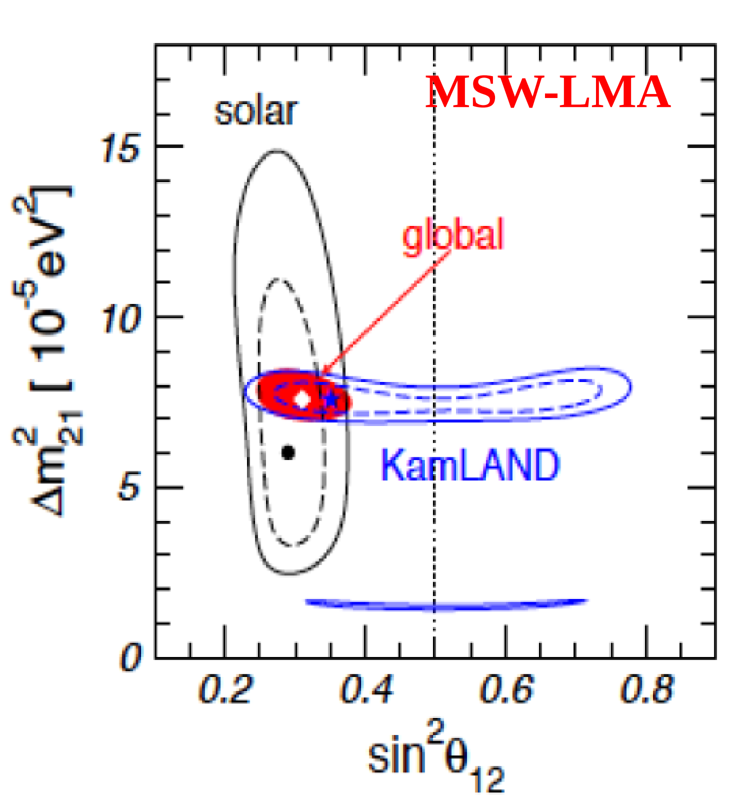
$\tan^2\theta_{12} = 0.56 \pm 0.08$ (stat) ± 0.08 (syst)

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

Solar Sector from 2000 to 2009



Gonzalez-Garcia et al., 2000

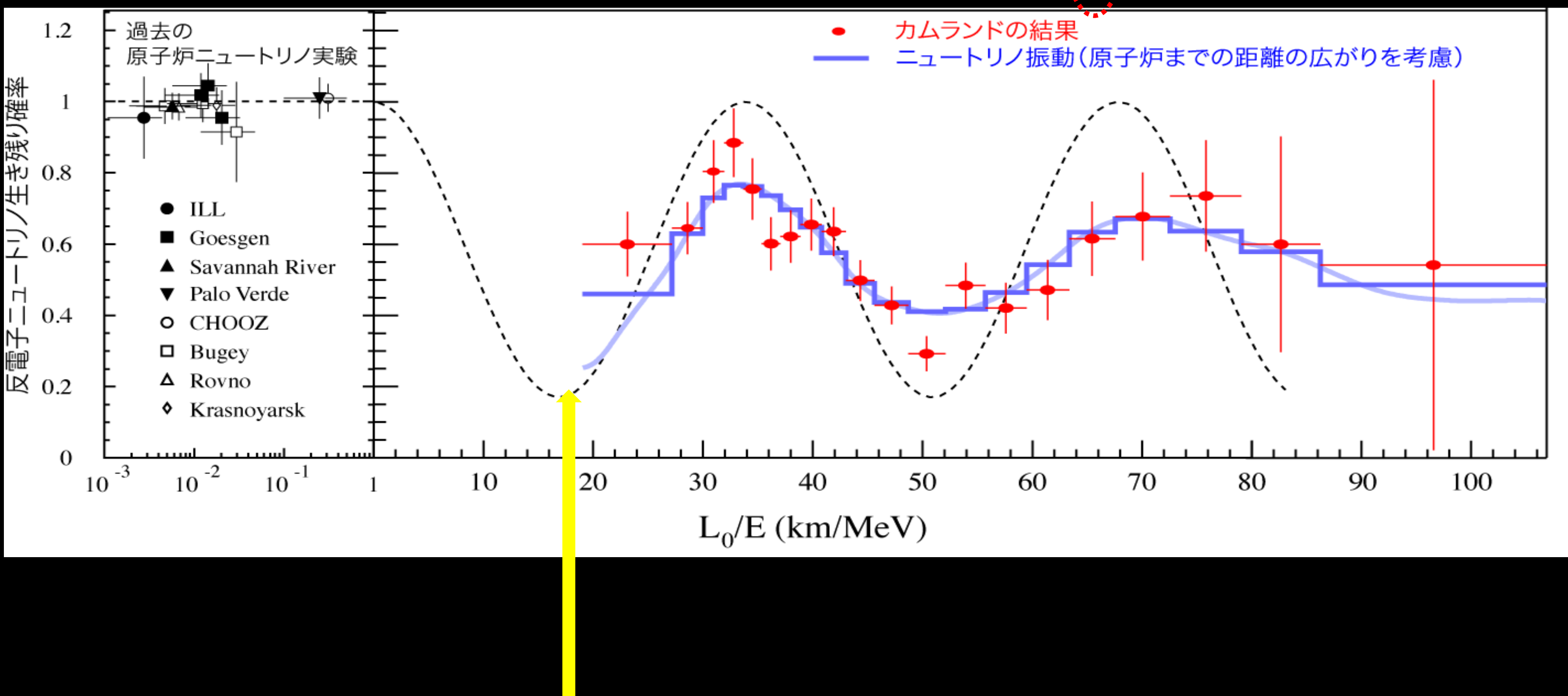


Schwetz et al., 2008

Δm_{21}^2 is ‘large’ but 30 times smaller than Δm_{32}^2
θ_{12} is large but non maximal

KamLAND Oscillatory Behavior

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{12})\left[\sin\left(\Delta m^2_{so}\frac{L}{E}\right)\right]$$

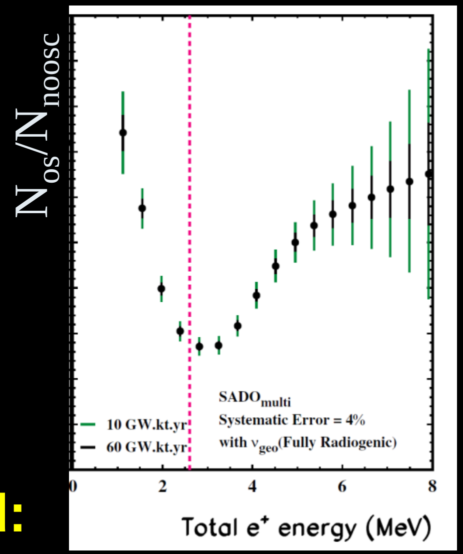


$$\text{Oscillation maximum} \approx \frac{2\pi E_\nu^{peak}}{\Delta m^2_{21}} \approx 50 - 70\text{km}$$

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 : $\text{Baseline} \approx \frac{2\pi E_\nu^{peak}}{\Delta m_{21}^2} \approx 50-70\text{km}$

- **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
  - ➔ Rustrel (500 mwe, France), Cruas (12 GW, 73 km), Tricastin (12 GW, 59 km)

Beam Neutrino Experiments

Experiment	Baseline	Size	Power	Channel
Minos	732 km	5 400 tons	0.3 MW	$\nu_\mu \to \nu_e$
Nova	812 km	15 000 m^3	0.7 MW	&
T2K	295 km	22.5 000 m^3	0.75 MW	$\nu_\mu \to \nu_\mu$

The Beam Channels

- **Silver Channel:** $\nu_\mu \leftrightarrow \nu_\tau$
  - Oscillation Confirmation
  - Test the Unitary Framework

  → **OPERA experiment**

- **Golden Channel:** $\nu_\mu \leftrightarrow \nu_e$ (most of the effort)
  - The best middle term laboratory for neutrino oscillation
  - Precision experiments towards leptonic CP-violation
    - Fraction of ν_e in ν_3 : θ_{13}
    - Mass hierarchy : sign of Δm^2_{13}
    - CP violation : $\sin \delta$

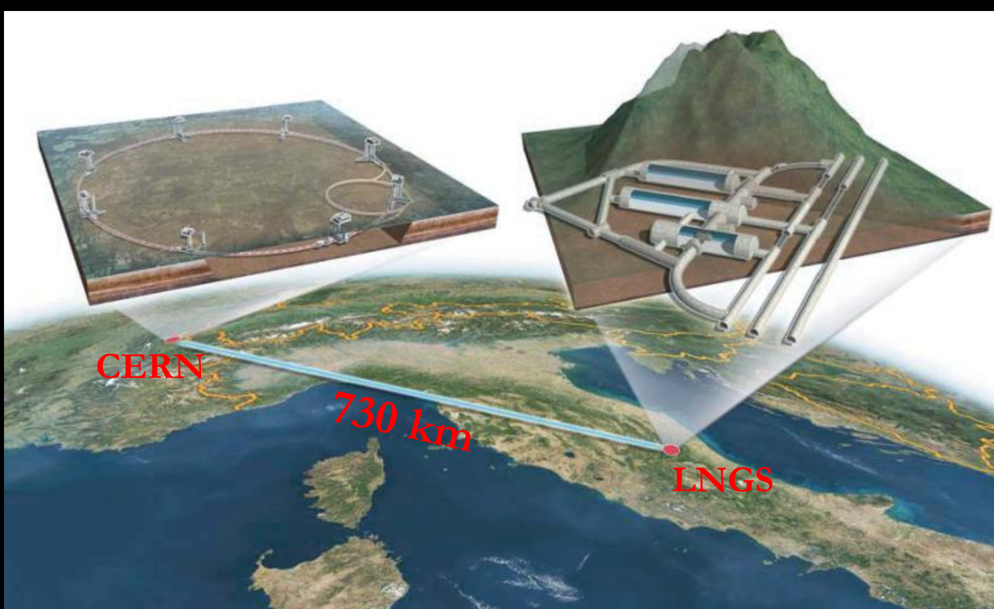
  → **(Minos), T2K, NOvA**

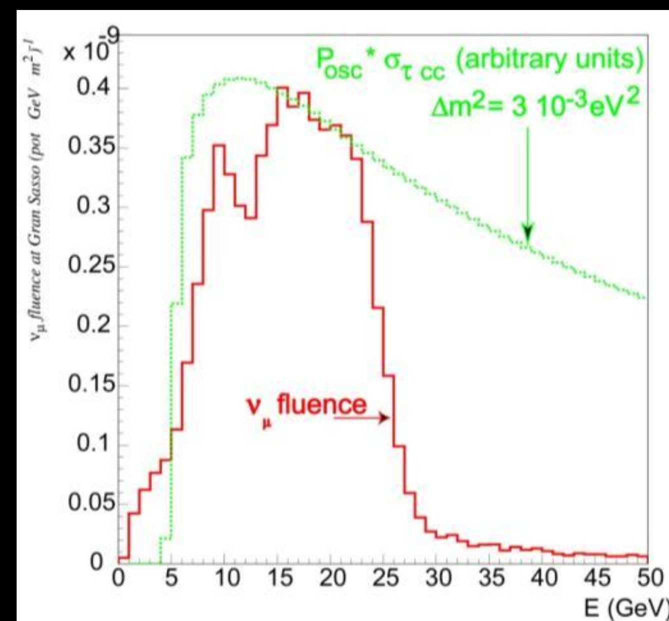
- **Beyond** θ_{13} Physics will be presented in P. Huber's talk

Over-Constraining the Parameter Space

Opera @CNGS

- Channel not yet observed : $\nu_\mu \rightarrow \nu_\tau$ search
- CNGS Beam at CERN; beam: 450 GeV protons, 20 GeV $\pi \rightarrow \mu\nu_\mu$ peak
- Detector: Tau topological ID with 1.25 kt Emulsion Cloud Chamber at LNGS
- Baseline = 730 km (osc. max~1.5 GeV)
- No near detector (low background appearance search)
- Running now for a second year





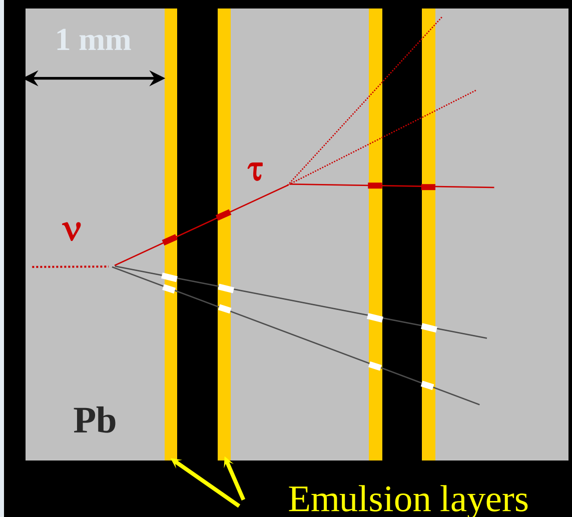
Opera @CNGS

$\nu_\mu \rightarrow \nu_\tau$ search

τ^- decay channels	e(%)	BR (%)	Signal α (Dm^2)^2 Δm^2 = 2.5 x 10^{-3} eV^2	Background
$\tau^- \rightarrow \mu^-$	17.5	17.7	2.9	0.17
$\tau^- \rightarrow e^-$	20.8	17.8	3.5	0.17
$\tau^- \rightarrow h^-$	5.8	49.5	3.1	0.24
$\tau^- \rightarrow 3h$	6.3	15	0.9	0.17
ALL	ε x BR =10.6%		10.4	0.75

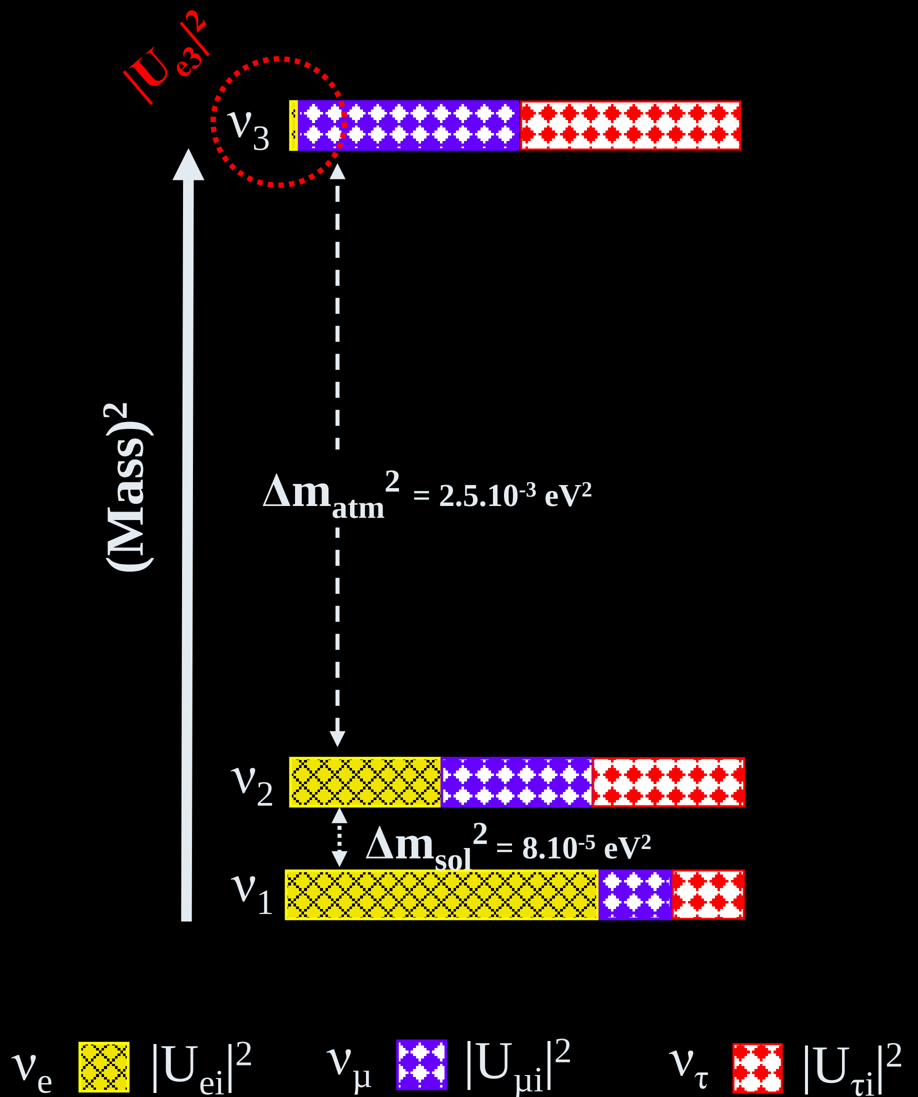
Full mixing, 5 years run,
4.5x10^{19} pot / year , target mass = 1.3 kton

Expected signal



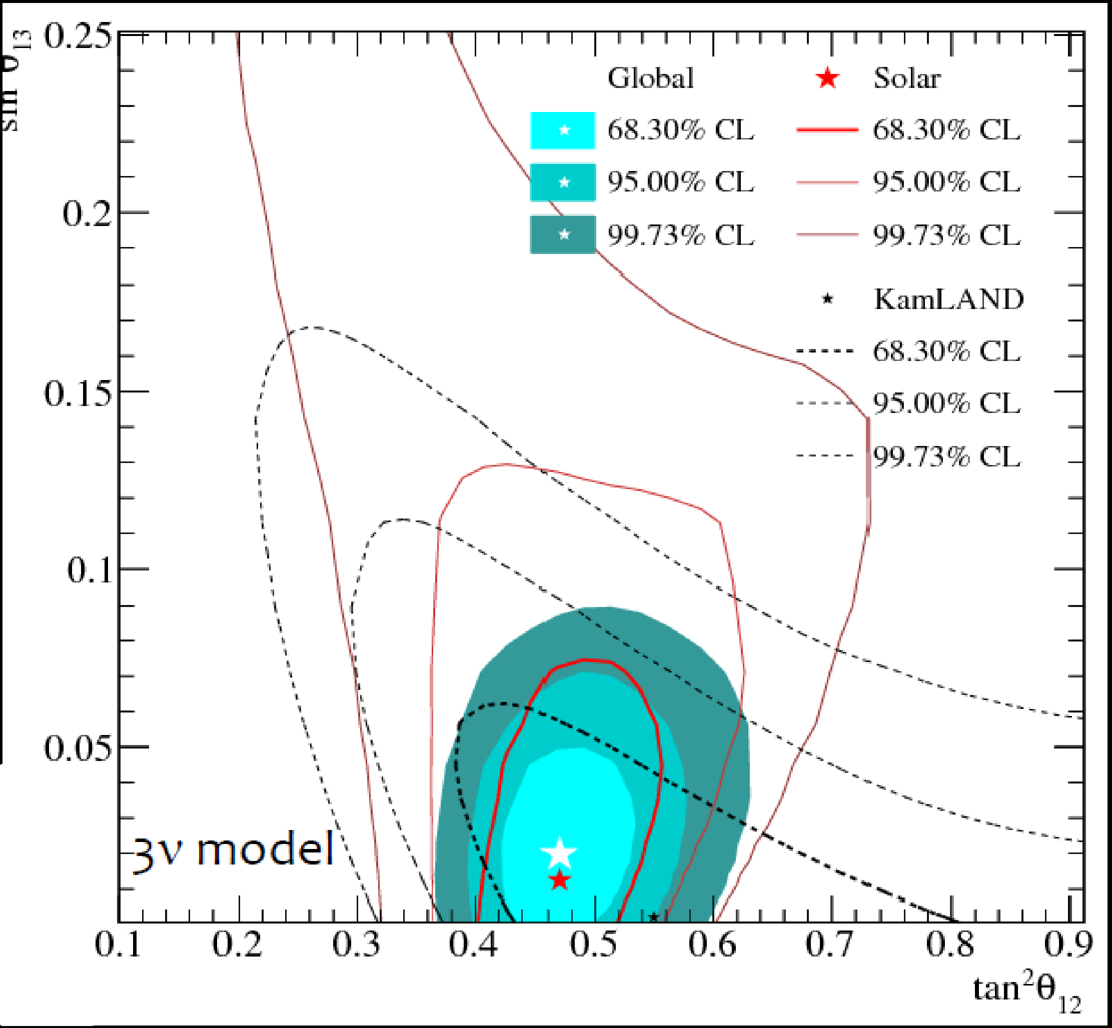
Near term expectation: 4.3 events by end of 2010 (with ~10^{20} p.o.t)

θ_{13}



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

Combined analysis (example)



- 3 flavor analysis
- SNO Combination:
  - SNO LETA paper 2009:
  - SNO LETA joint-phase fit
  - SNO Phase III
  - all solar expts
  - KamLAND
- Best fit
  - $\sin^2 2\theta_{13} = 0.08 \pm 0.07$
- Constaints
  - $\sin^2 2\theta_{13} < 0.24$ (95% C.L.)

Almost no improvement on θ_{13} (global fits → weak positive fluctuation)

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

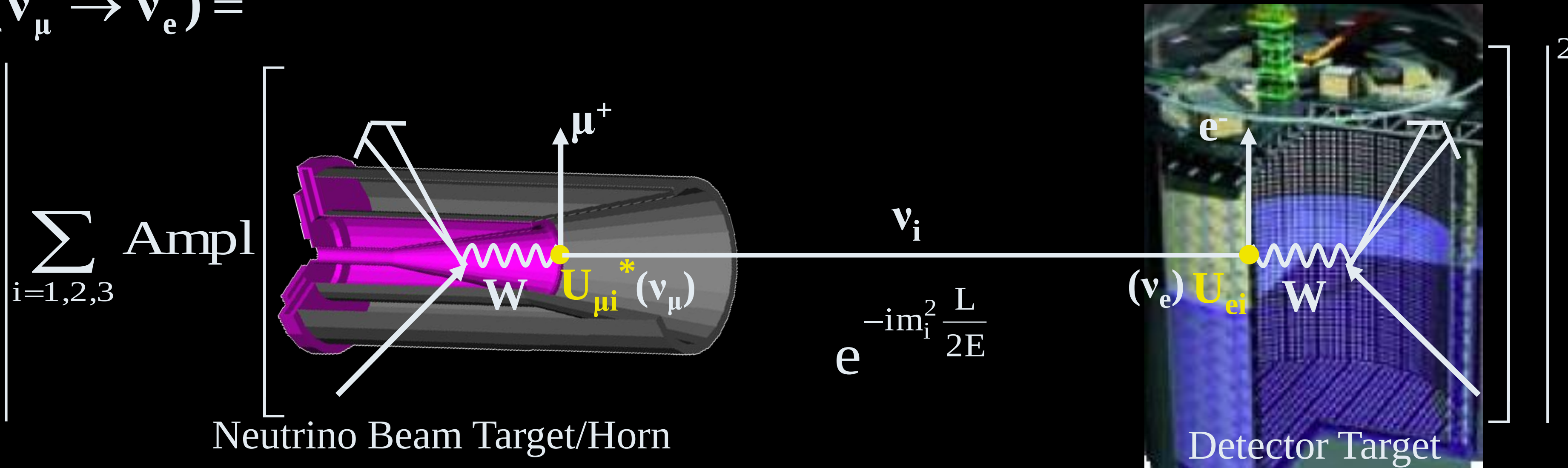
- **The θ_{13} quest is an mandatory step prior searching for CP violation in the electroweak sector. Branching point around 2015:**
  - $\sin^2(2\theta_{13}) \gtrsim 0.02$ → conventional neutrino beam ($\pi \to \mu\ \nu$, 1% contamination)
  - $\sin^2(2\theta_{13}) \lesssim 0.02$ → neutrino factories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

- **Experimentally: need to connect the ν_e flavour with the isolated neutrino (Δm^2_{atm})**
  - 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)

@Beam: Underlying Oscillation Physics

$P(\nu_\mu \rightarrow \nu_e) =$



$$P(\nu_\mu \rightarrow \nu_e) = \left[\sum_i U_{\mu i}^* e^{-im_i^2 \frac{L}{2E}} U_{ei}\right]^2$$

- Complex oscillation formula

➔ depends on $\sin^2(2\theta_{13})$, $\Delta m_{31}{}^2$, sign($\Delta m_{31}{}^2$), δ

- >> MeV muon antineutrinos ➔ appearance experiments

➔ $\sin^2(2\theta_{13})$ measurement depends on δ-CP

- >> MeV neutrinos + 100-1000 km baseline → matter effects

➔ $\sin^2(2\theta_{13})$ measurement independent of sign(Δm^2_{13})

Corrrelation & degeneracies

The electron appearance channel

$$p(\nu_\mu \to \nu_e) =$$

$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CP} - \text{even}$$

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CP} - \text{odd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)} \tag{1}$$

Beam experiment very efficient to detect ν_e appearance BUT information on $\sin^2(2\theta_{13})$ difficult to extract …

MINOS Electron Appearance Results

- **Channel : $\nu_\mu \rightarrow \nu_e$**

- Goal : Search for an excess of ν_e in the Far detector (735km)

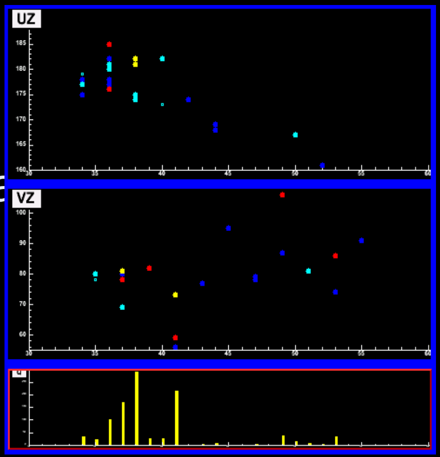
- Two years of data-taking

- Results
  - 35 events in the Far Detector
  - Background prediction of 27 ±5(stat)
  - ±2(sys) based on Near Detector
  - 1.5σ excess of events

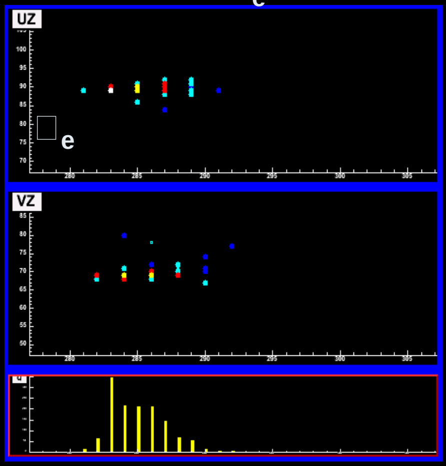
- 90% CL upper limit range
  - **$\sin^2(2\theta_{13})$**< 0.28-0.34 (NH)
  - **$\sin^2(2\theta_{13})$<**0.36-0.42 (IH)
  - CP-phase dependent

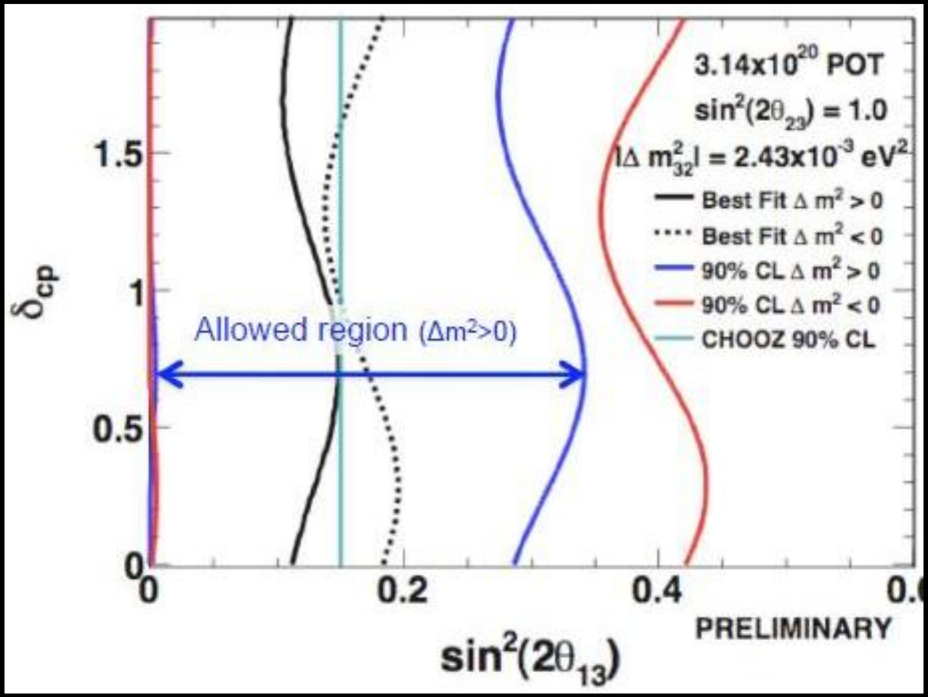
No improvement with respect to CHOOZ

NC Event



ν_e CC Event

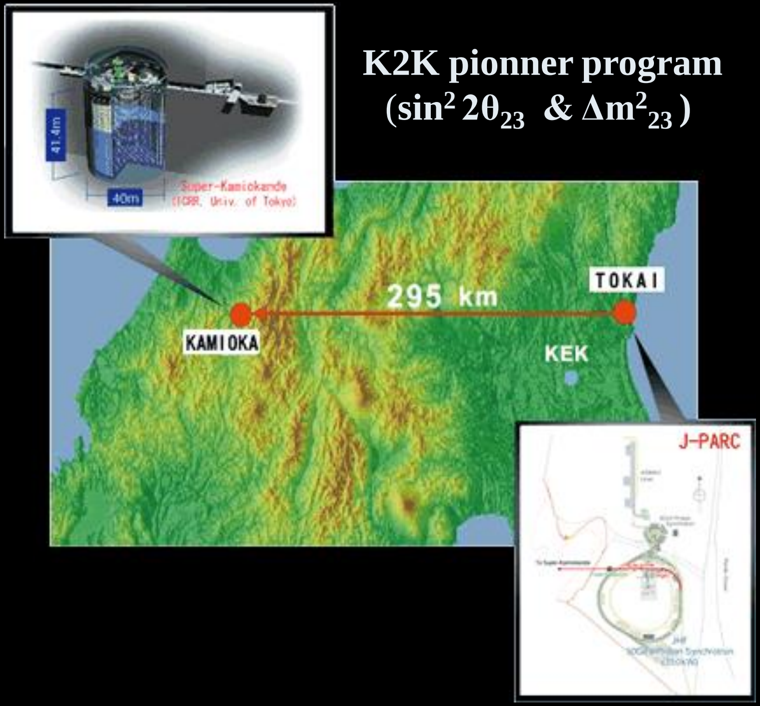




T2K (Tokai to Kamioka) @JPARK

- **CCQE: $\nu_l + n \rightarrow p + l^-$**

- **Channel:** $\nu_\mu \rightarrow \nu_e$ **(1st goal: search for non-zero θ_{13}, beam contamination, NC-1π0)**
- **Channel:** $\nu_\mu \rightarrow \nu_\mu$ **($\sin^2 2\theta_{23}$ @ 1% & Δm^2_{23} @ 2%, single pion production)**

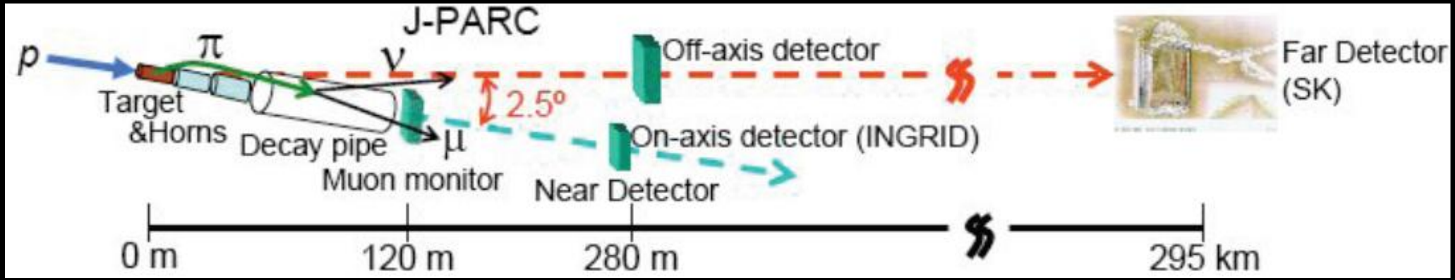


K2K pionner program
($\sin^2 2\theta_{23}$ & Δm^2_{23})

- **Beam Setup:**
  - 750 kW Off-axis beam (2.5°)
  - Quasi-monochromatic ν_μ beam
  - Smaller intrinsic ν_e contamination
  - Reduced high-E non-CCQE backgrounds

- **Far Detector at 295 km: Ready**
  - SuperK with 12000 PMTs & new electronics

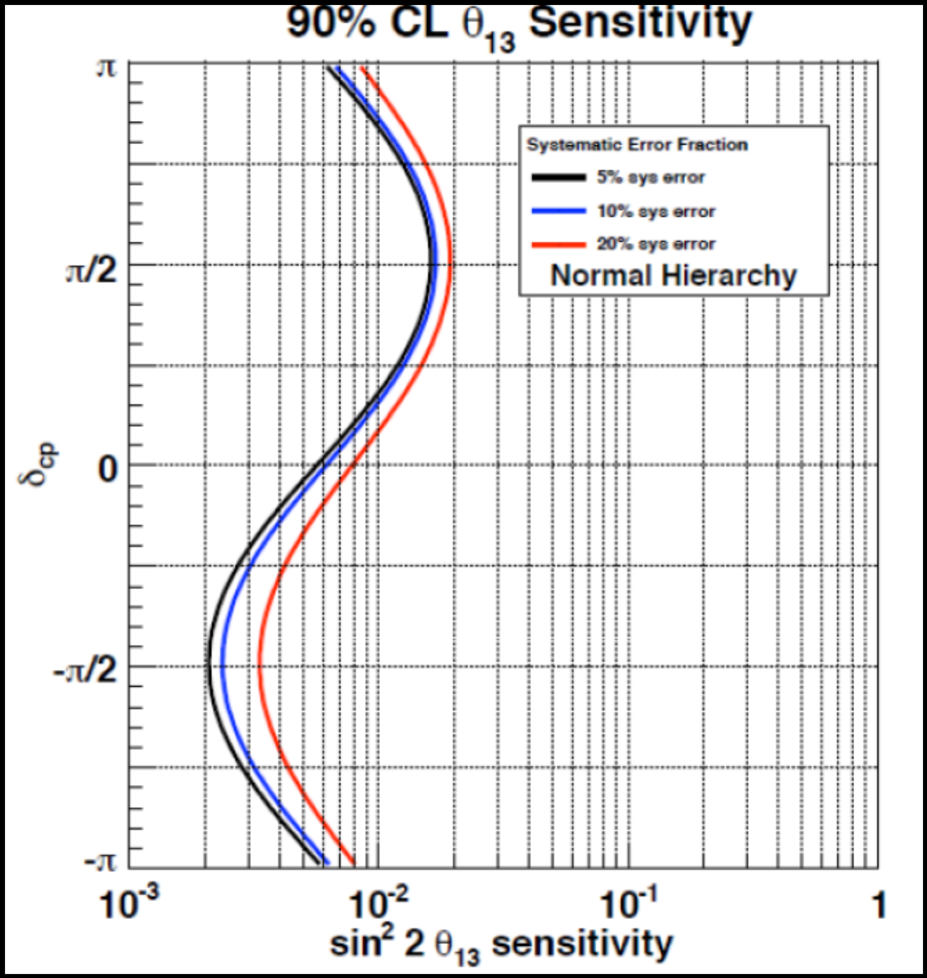
- **Near Detector at 280 m:**
  - On & Off-Axis detectors (Ingrid & ND280)



T2K @JPARK

T2K @JPARK

$\nu_\mu \rightarrow \nu_e$ sensitivity after 5 y at 0.75 MW



- **Beam Status:**
  - Comissionning since 05/2009
  - Subsecant power increase
    - Rep rate @30 GeV
    - LINAC from 181 → 400 MeV

- **Near Detector Status:**
  - Integration started
  - Ready by by mid-2010

- **Expected sensitivity timeline**
  - Physics run in 2010 collecting 100 kW x 10^7s (2 x 10^{20} POT) → $\sin^2(2\theta_{13})$< ~0.06 (δ=0)
  - Proposal: 3750 kW x 10^7s → $\sin^2(2\theta_{13})$< ~0.01 (δ=0)
  - Correlation & degeneracies

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)	$\bar{\nu}_e \to \bar{\nu}_e$
Daya Bay	400 / 1.7 km	100 m^3	17.4 GW (6)	

MeV Reactor Neutrinos

- **Electron antineutrinos Emitted through Decays of Fission Products**
  - FP of: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - $^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \xrightarrow{23\,\mathrm{min}} {}^{239}_{93}\mathrm{Np} \xrightarrow{2.3\,\mathrm{d}} {}^{239}_{94}\mathrm{Pu}$

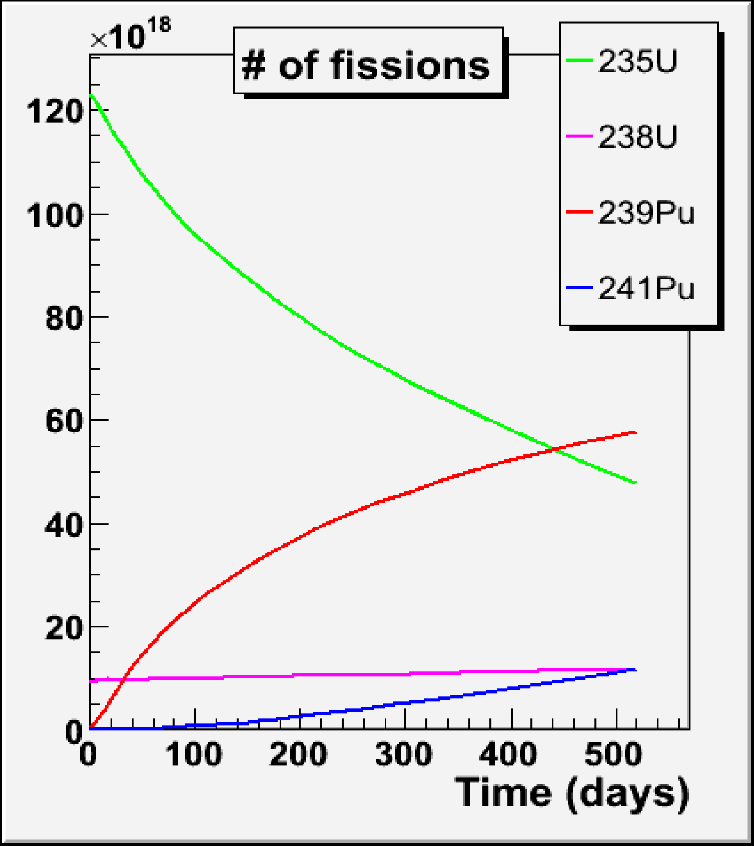
- **Luminosity**

$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$

γ: reactor constant

k : burn up dependent correction
up to 10%

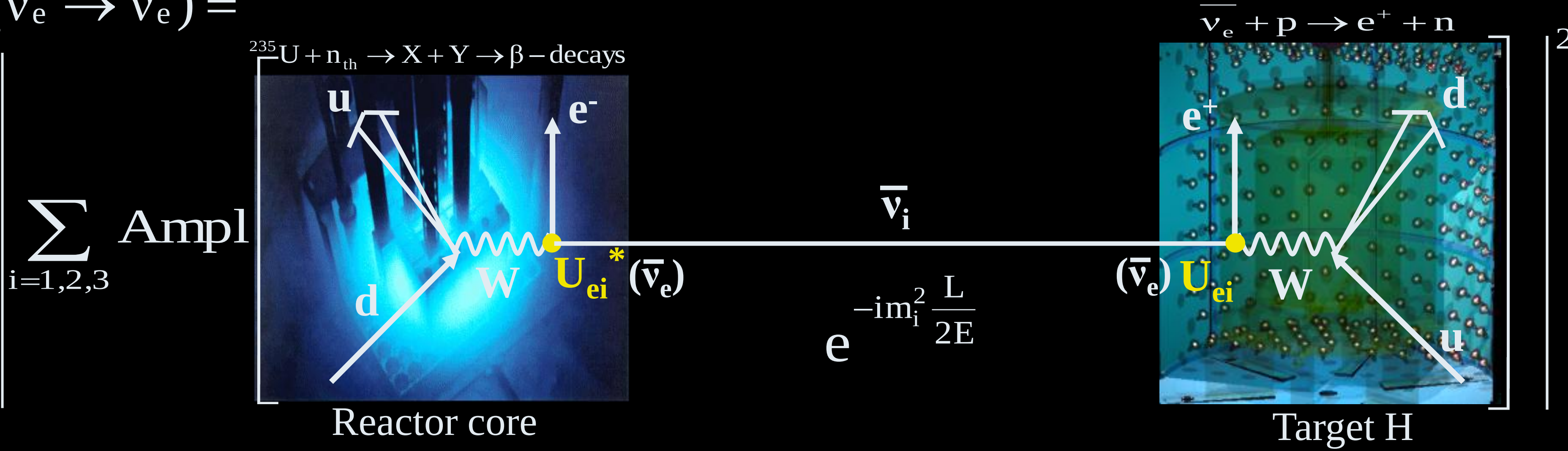
$$1\,\mathrm{GW_{th}} \Leftrightarrow 2\,10^{20}\ \nu/\mathrm{s}$$



t_0: ~3.5% ^{235}U, 96.5% ^{238}U

@Reactor: Underlying Oscillation Physics

$$P(\bar{\nu}_e \to \bar{\nu}_e) =$$



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

- 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

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	6,77 10^{28} H/m^3	6,55 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

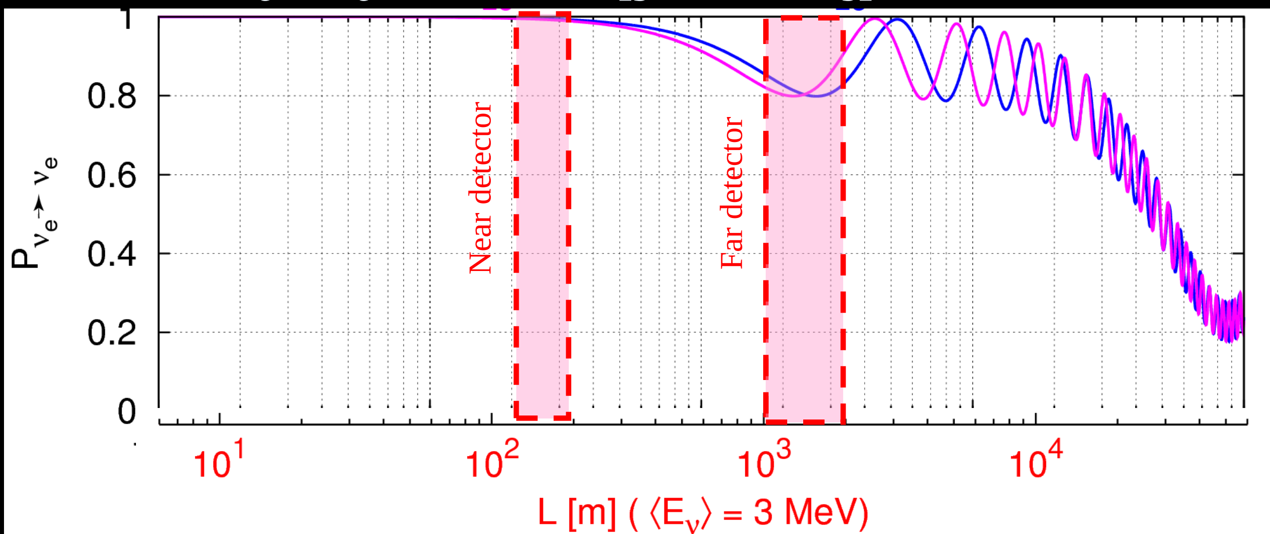
- **Two Detector Concept**
- **Improved detector design:** Lower threshold, e+ and n Efficiencies, Calibration
- **Lower Background:** Shielding, Radiopurity

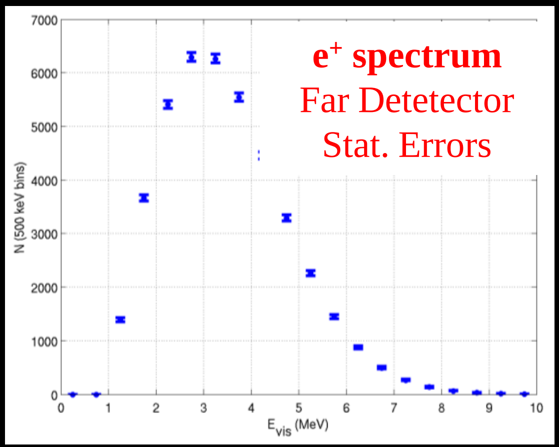
Syst. error	CHOOZ	Double Chooz
Reactor	1.9%	---
Target H	0.8%	0.2%
efficiency	1.5%	0.5%

The experimental concept for θ_{13}

Lev Mikaelyan (Kurchatov, 2000)

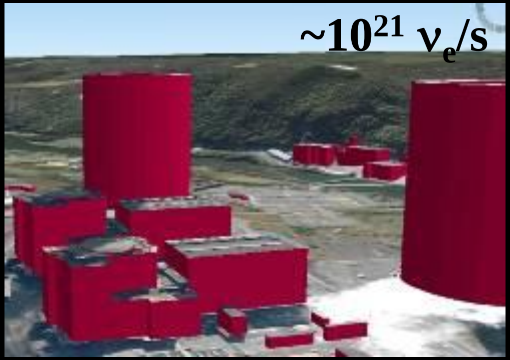
$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31} L/4E)$





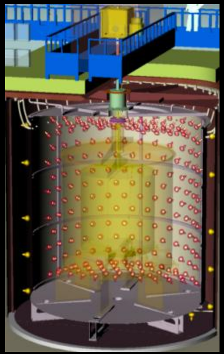
Δm^2_{atm}= 3.0 10^{-3} eV^2

$\sin^2(2\theta_{13})$=0.12



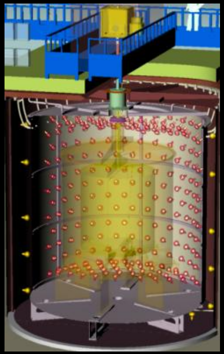
Nuclear Power Station

$\bar{\nu}_e$

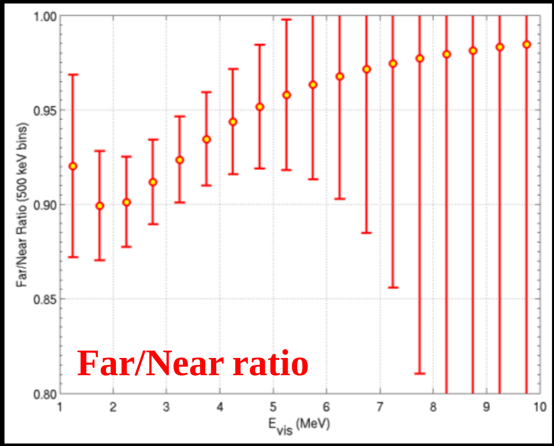


Near detector(s)
<500 m

$\bar{\nu}_{e,\mu,\tau}$

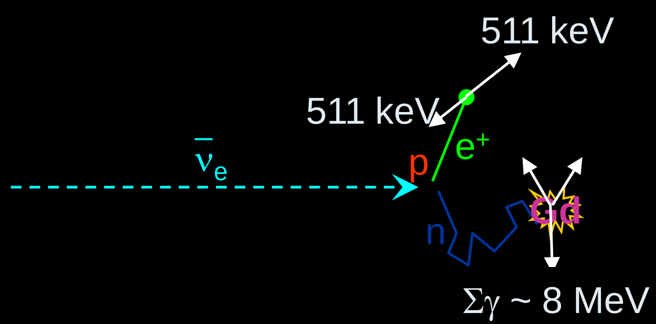


Far detector(s)
1-2 km



Backgrounds & Signal

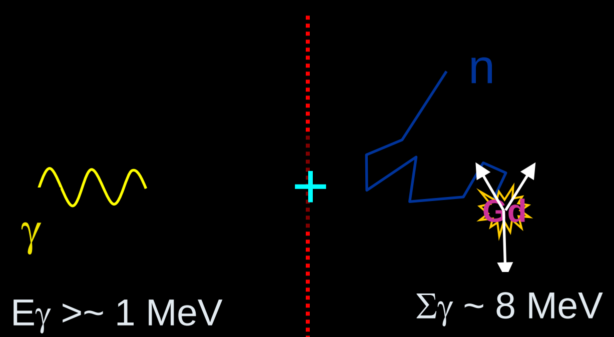
Electron antineutrino signature through inverse beta decay



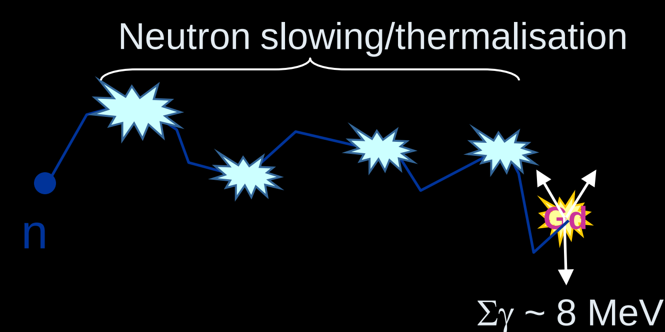
Prompt e^+ (1-8 MeV)   Delayed n Gd-capture (8 MeV)

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

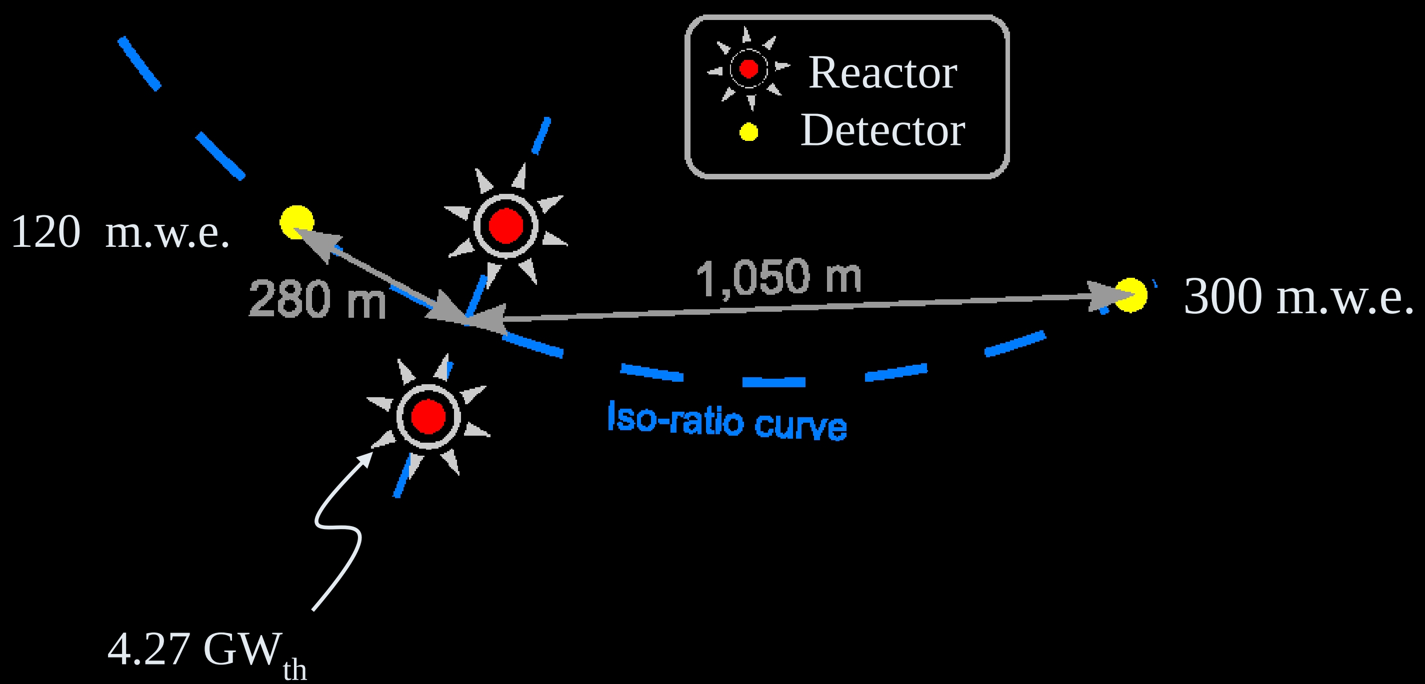
Accidental Background



Correlated Background

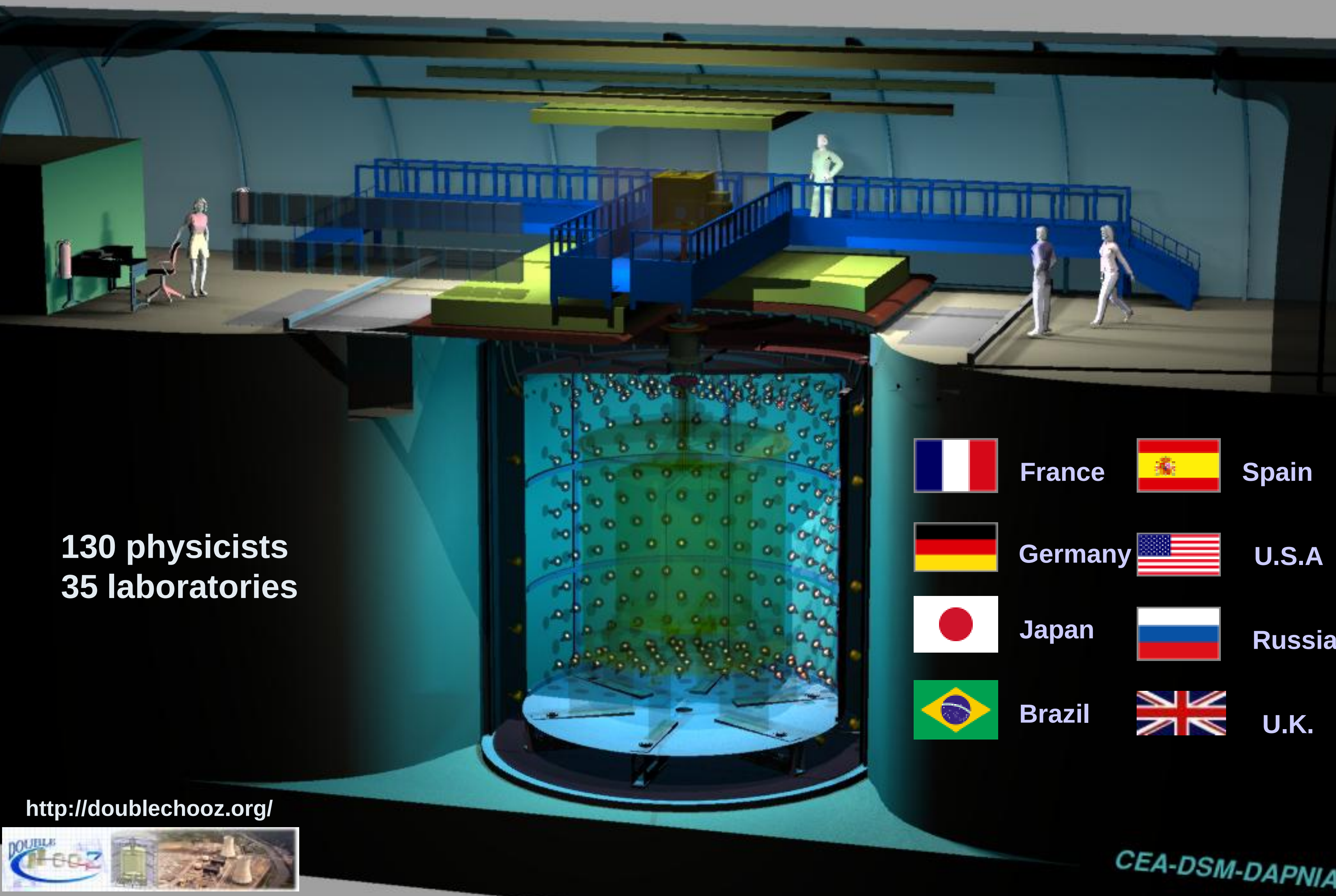


Double Chooz

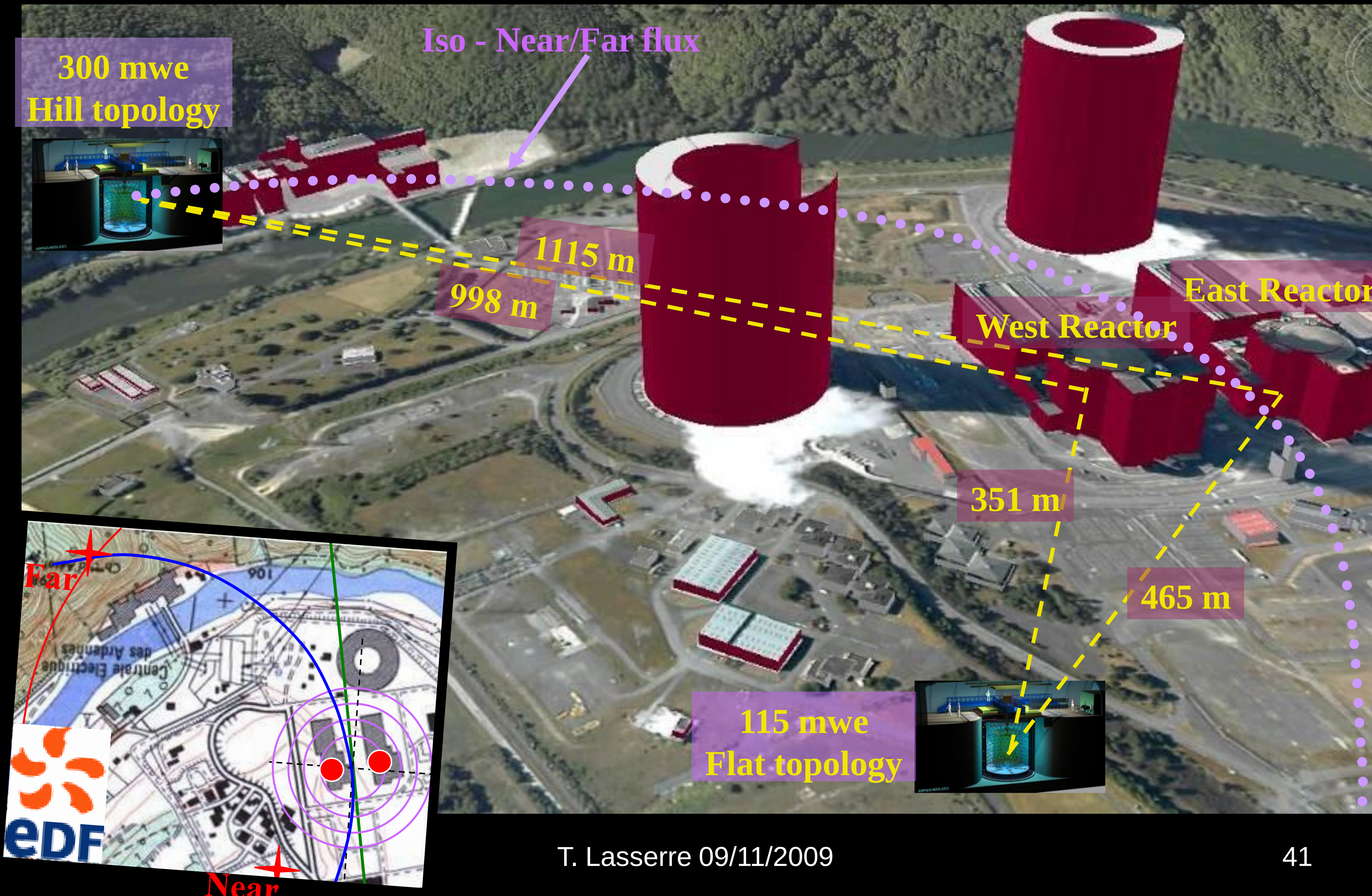


See Talk by Ch. Buck

Double Chooz



Chooz site in French Ardennes



Far Site Status

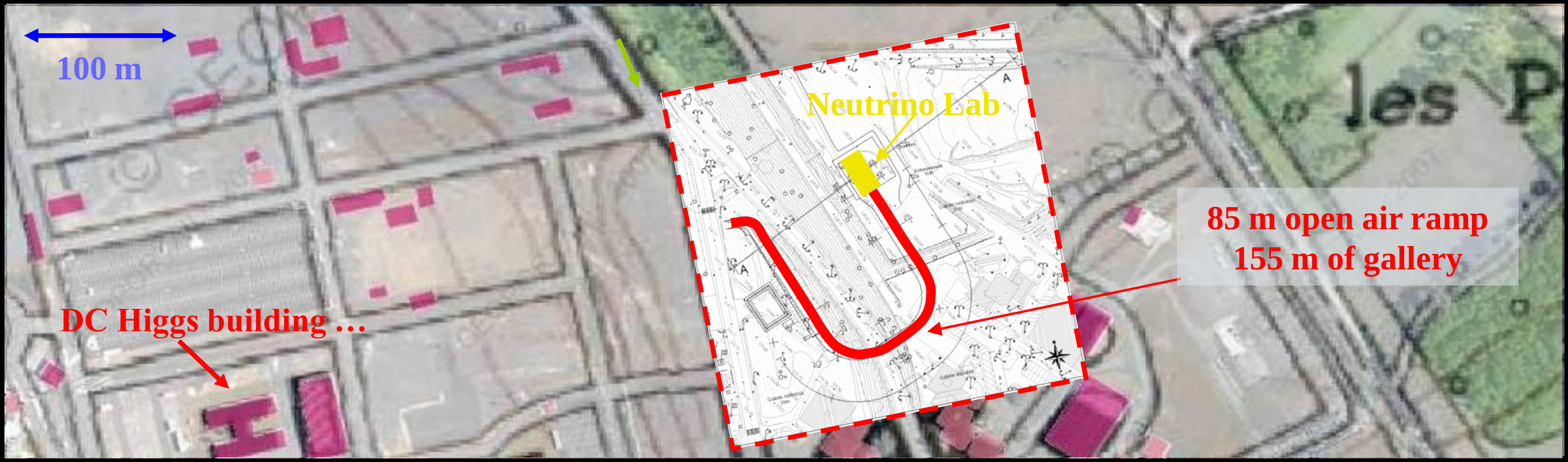
- Laboratory status:
- Site of the CHOOZ experiment

- Features:
- 1 km baseline (15 000 y^{-1})
- 300 mwe. (hill topology)
- µ-Rate: ~20 Hz @IV
- ISO 6 Clean Room

-Liquid storage building

Safety files accepted by French authorities (ASN)

Near Site Status

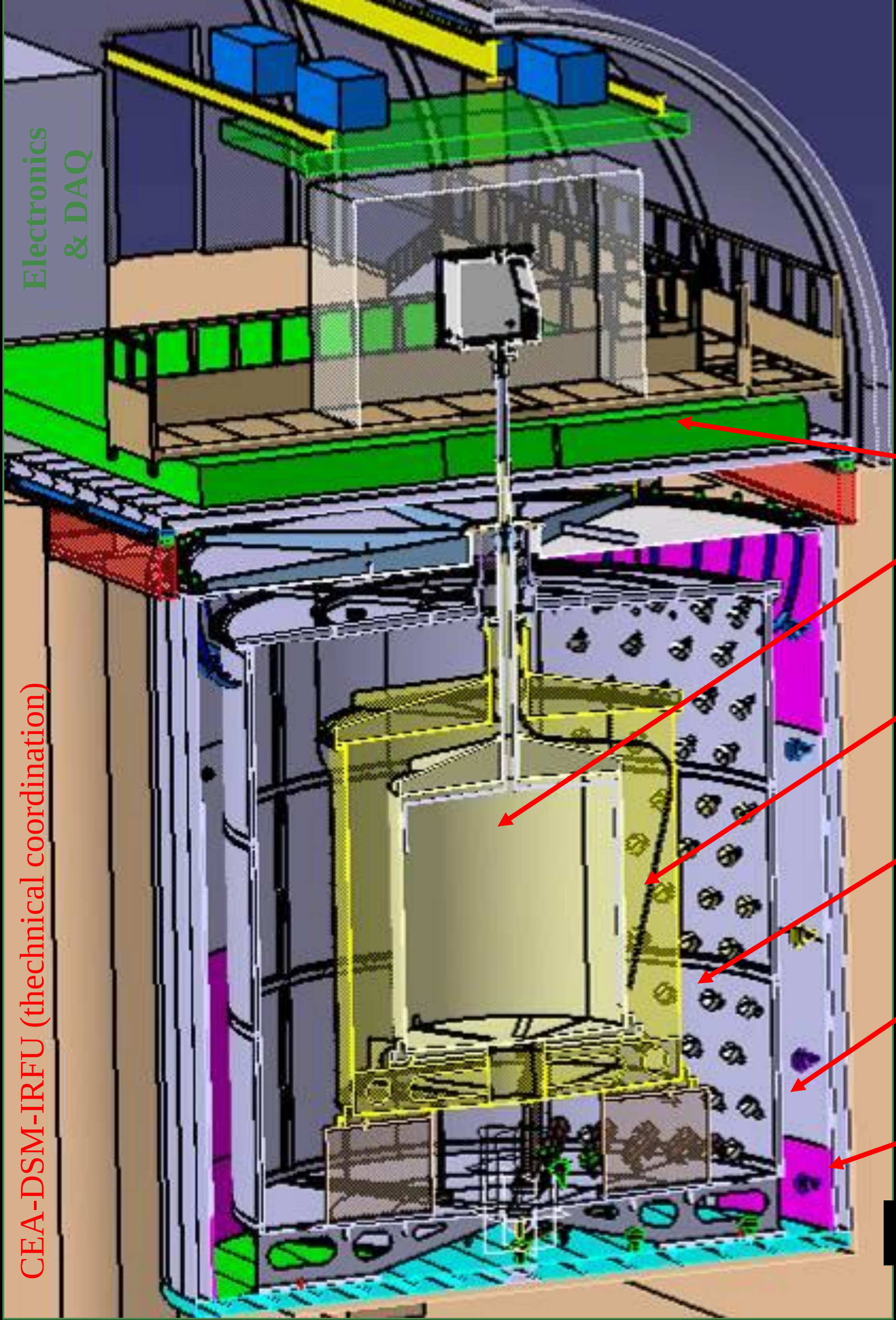


- **Status:**
  - Fully Funded (7 partners)
  - Site Engineering Study Completed
  - Schedule: laboratory delivery mid-2011

- **Features:**
  - 400 m from nuclear cores (150 000 y^{-1})
  - A 155 m tunnel to access the new lab
  - 115 m.w.e (almost flat topology)
  - μ-Rate: ~250 Hz @IV

Schiste-Gres rock

Detector Design



Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 0,1g/l of Gd compound in an acryclic vessel (8 mm)

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

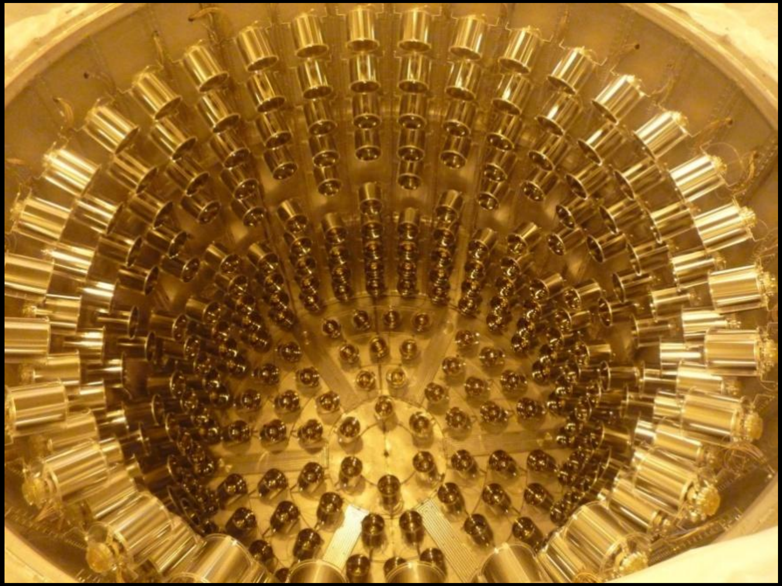
Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

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

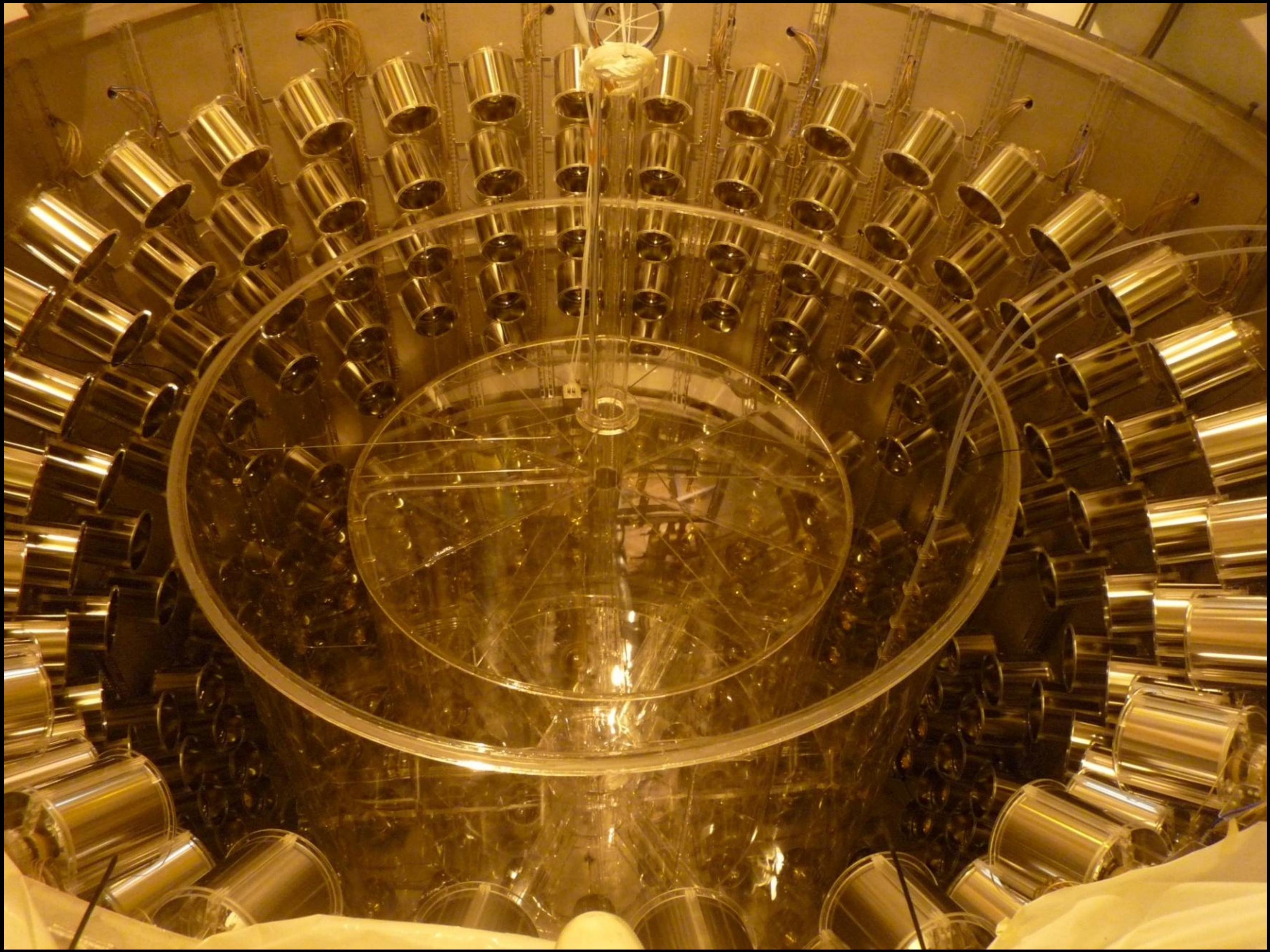
Veto Vessel (10mm) & Steel Shielding (150 mm)

(4 liquid densities adjusted at 0,800±0,005)

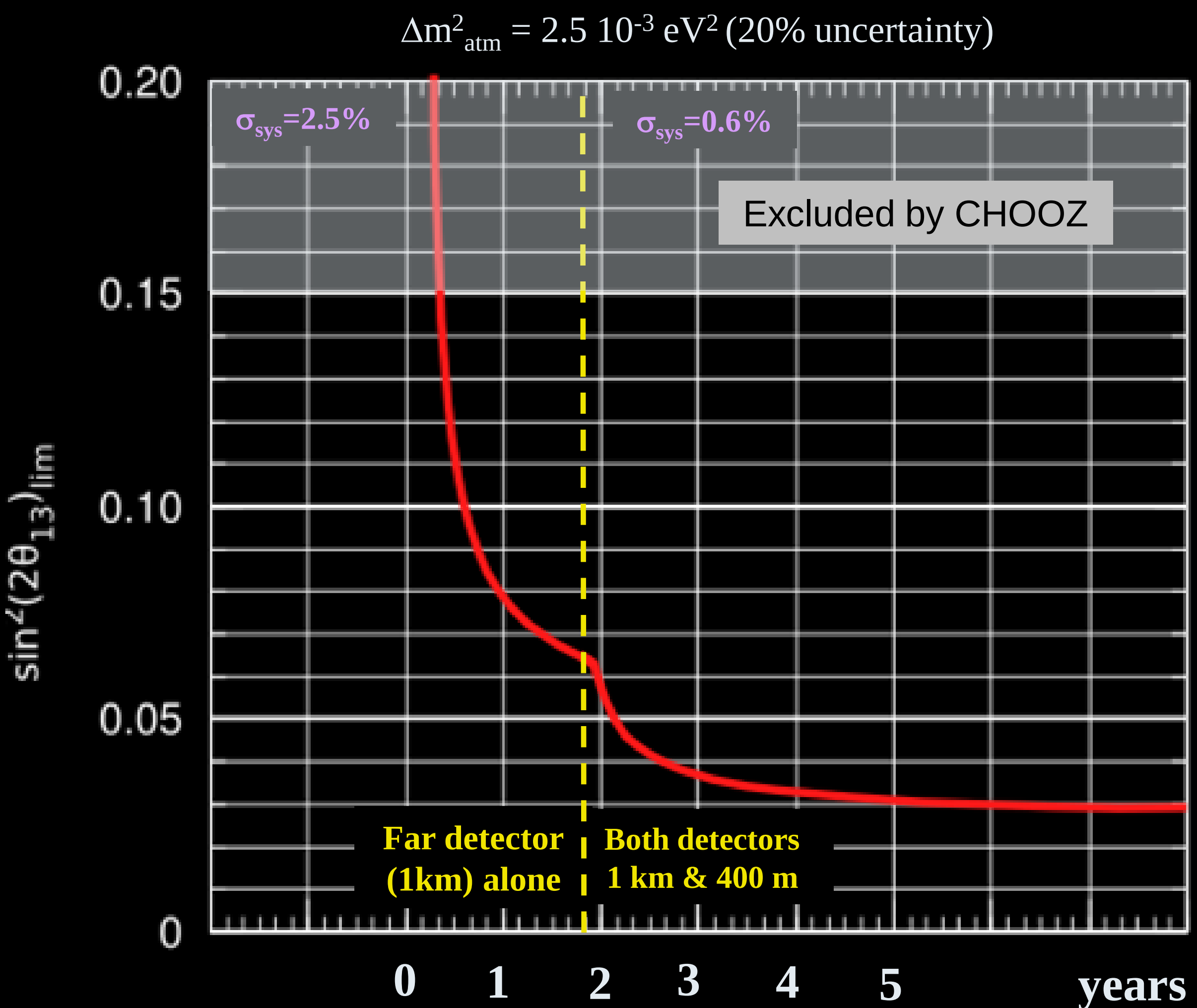
Detector Integration



Target Vessel Integration



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%

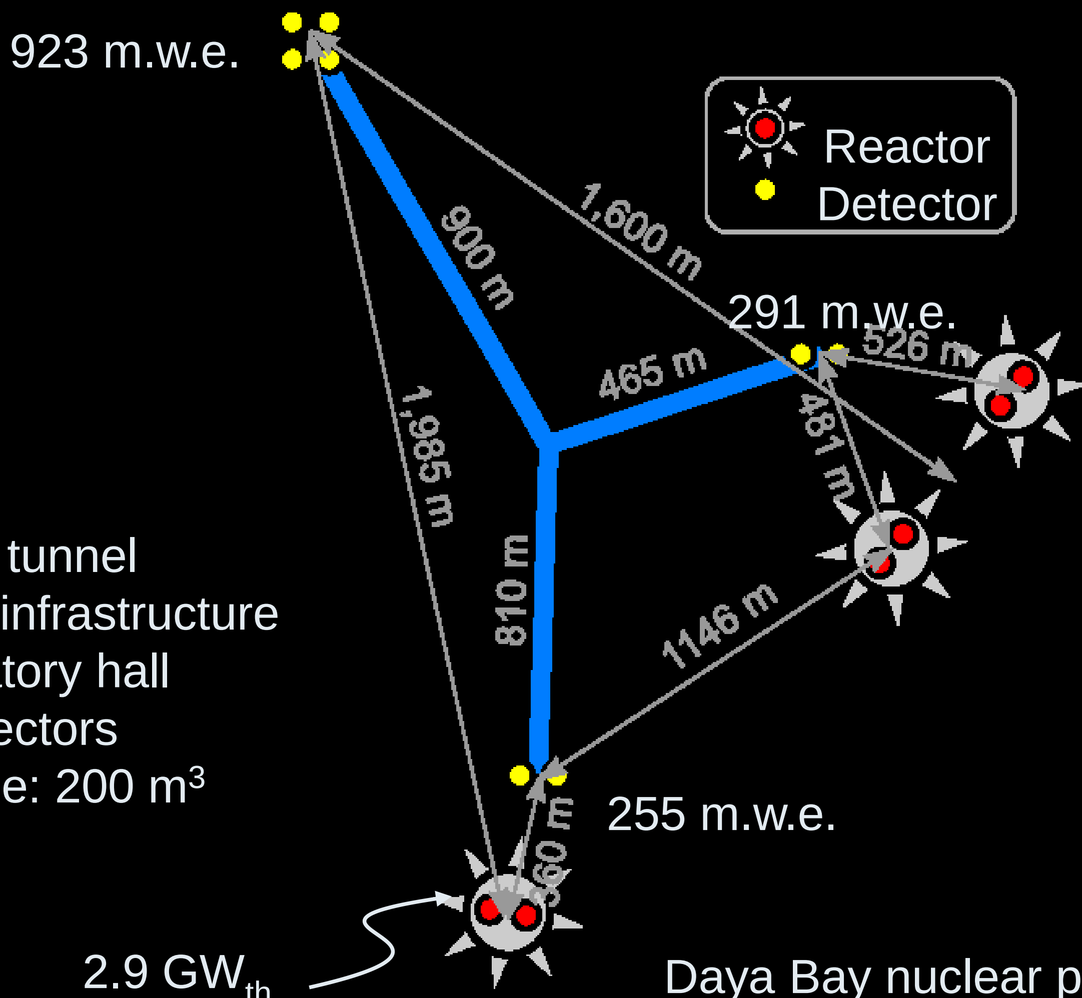
T. Lasserre 09/11/2009

Double Chooz Status

- **2009** → Far detector construction & intégration
- **04/2010** → 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
- **2010/11** → Near Lab Excavation
  → Near Detector Integration
- **2011** → 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

Courtesy : K.. Luk



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

Daya Bay nuclear power station in China

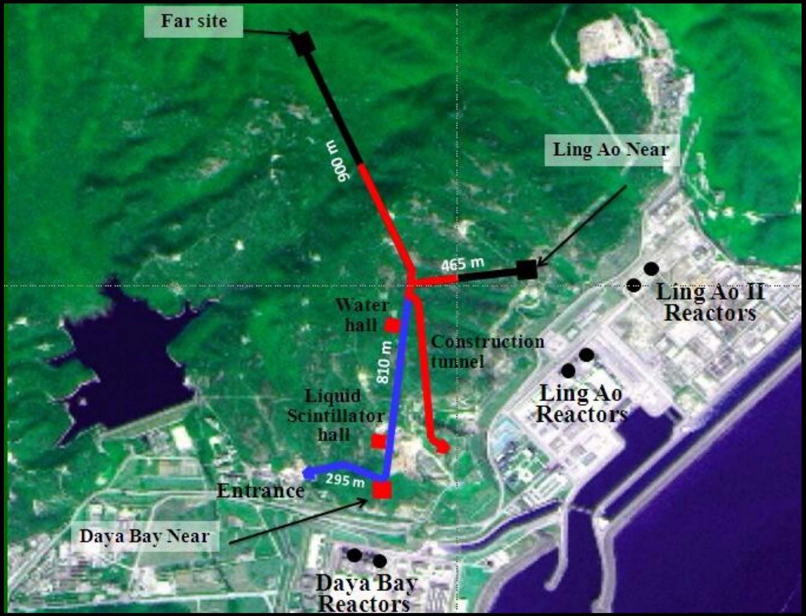
Status of Daya Bay

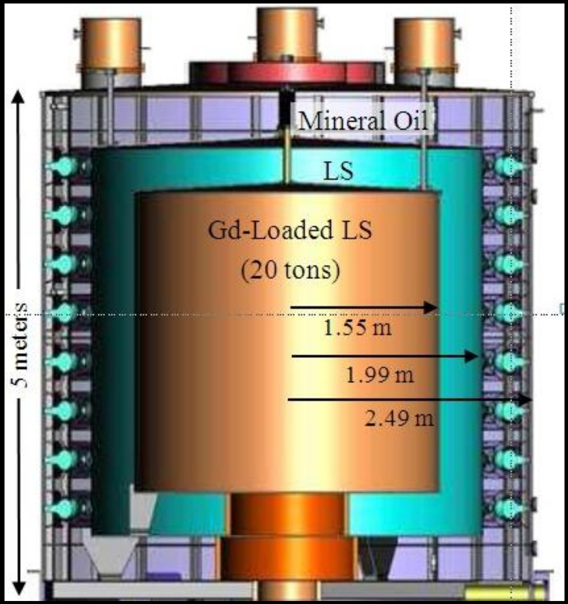
- **Four reactor cores**
  $P = 4 \times 2.9 = 11.6\ GW_{th}$
  2 new cores for 6 GW_{th} in 2010-11

- **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.)





Status of Daya Bay

Construction of near hall

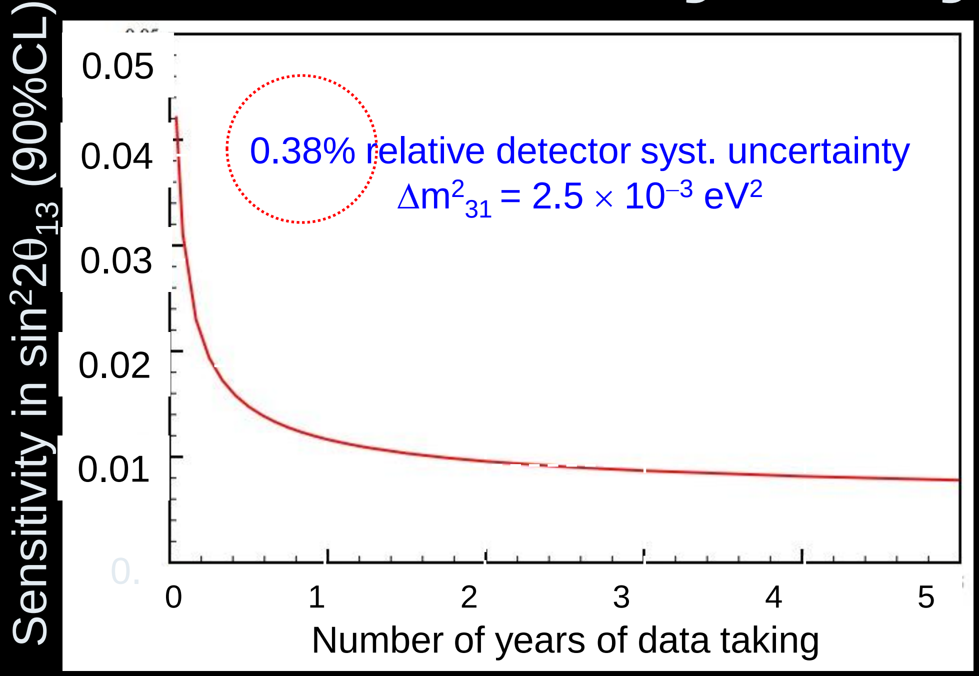
Access tunnel to the underground halls well advanced

Detector mechanics:
5-m SST vessel, 4-m and 3-m acrylic vessels in surface assembly hall

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

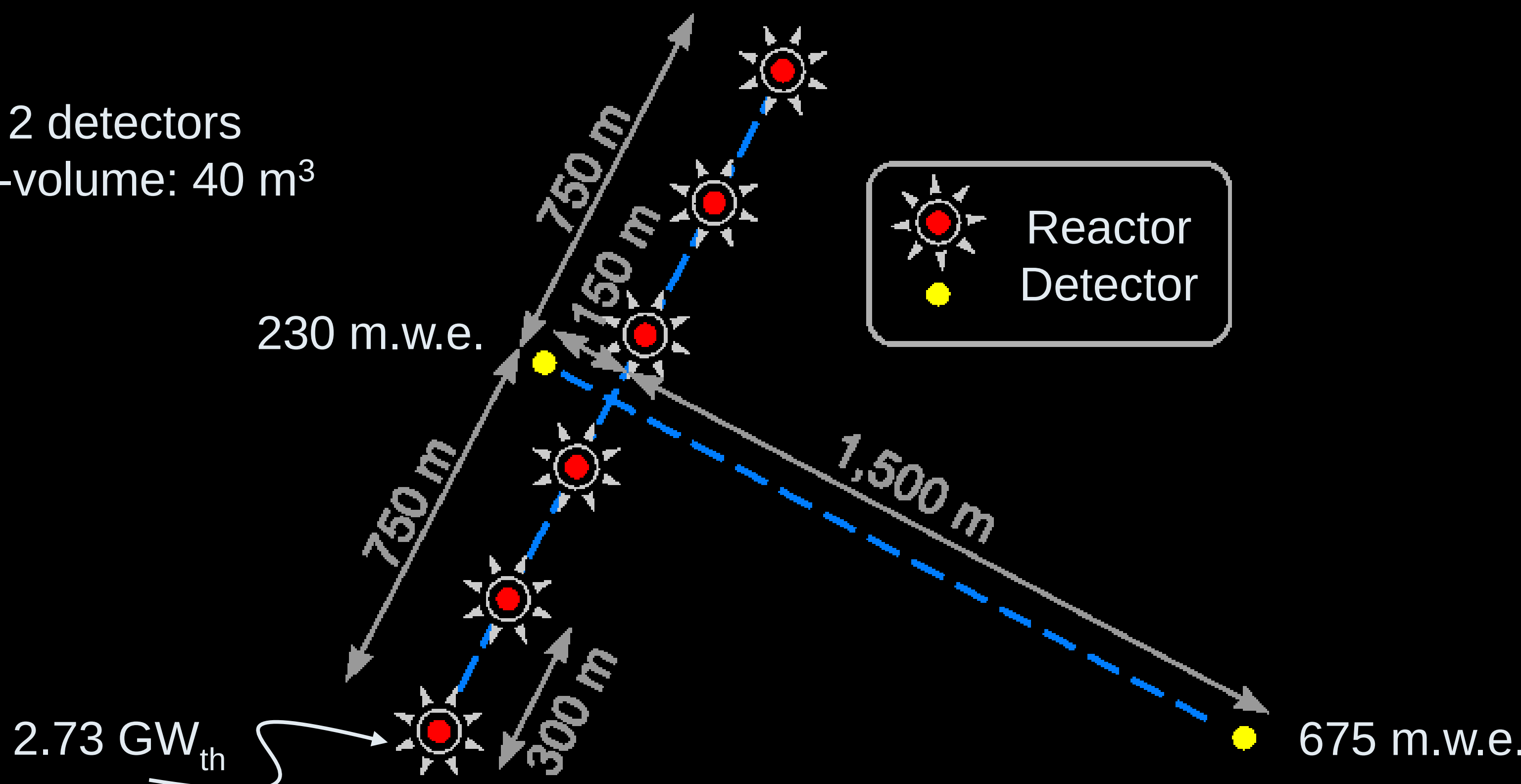


- **Aug 2009:** Begin detector assembly
- **Fall 2009:** Begin detector installation in experimental halls
- **Fall 2010:** Start data taking with first near hall
- **End 2011:** Start data taking with all detectors

RENO

Courtesy : S. B. Kim

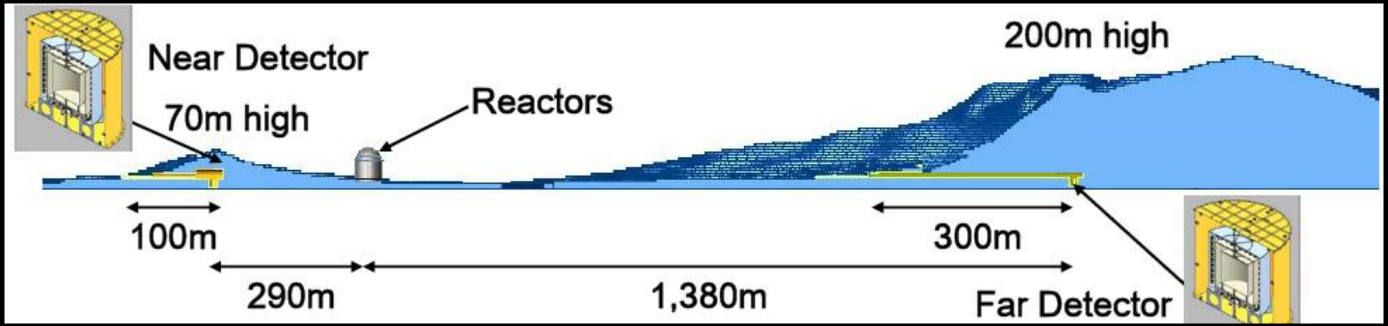
2 detectors
Gd-volume: 40 m³



Yong gwang nuclear power station in Korea

RENO

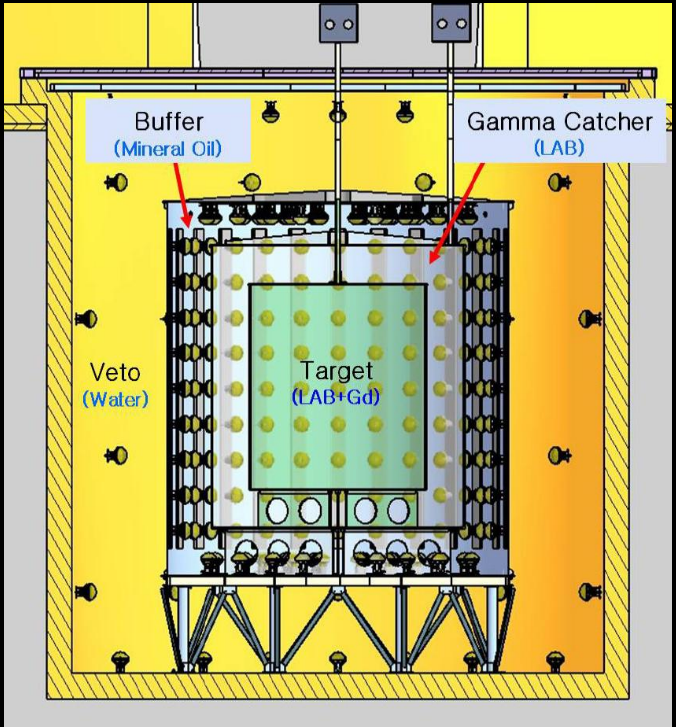
- **Six reactor cores:** P~16 GW_{th} (ND: 90% ν's from 2 cores)



- **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
  $\sin^2(2\theta_{13})$ < ~ 0.02 (90% C.L.)



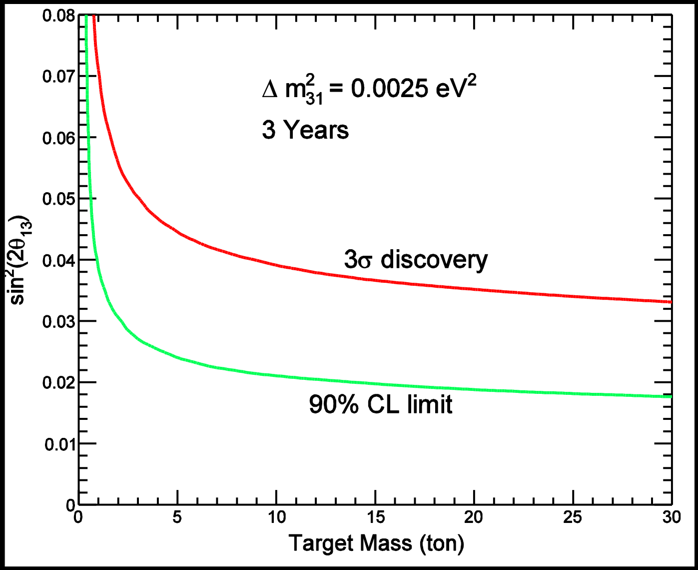
Double Chooz design cut/paste

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 to start in 2010

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)

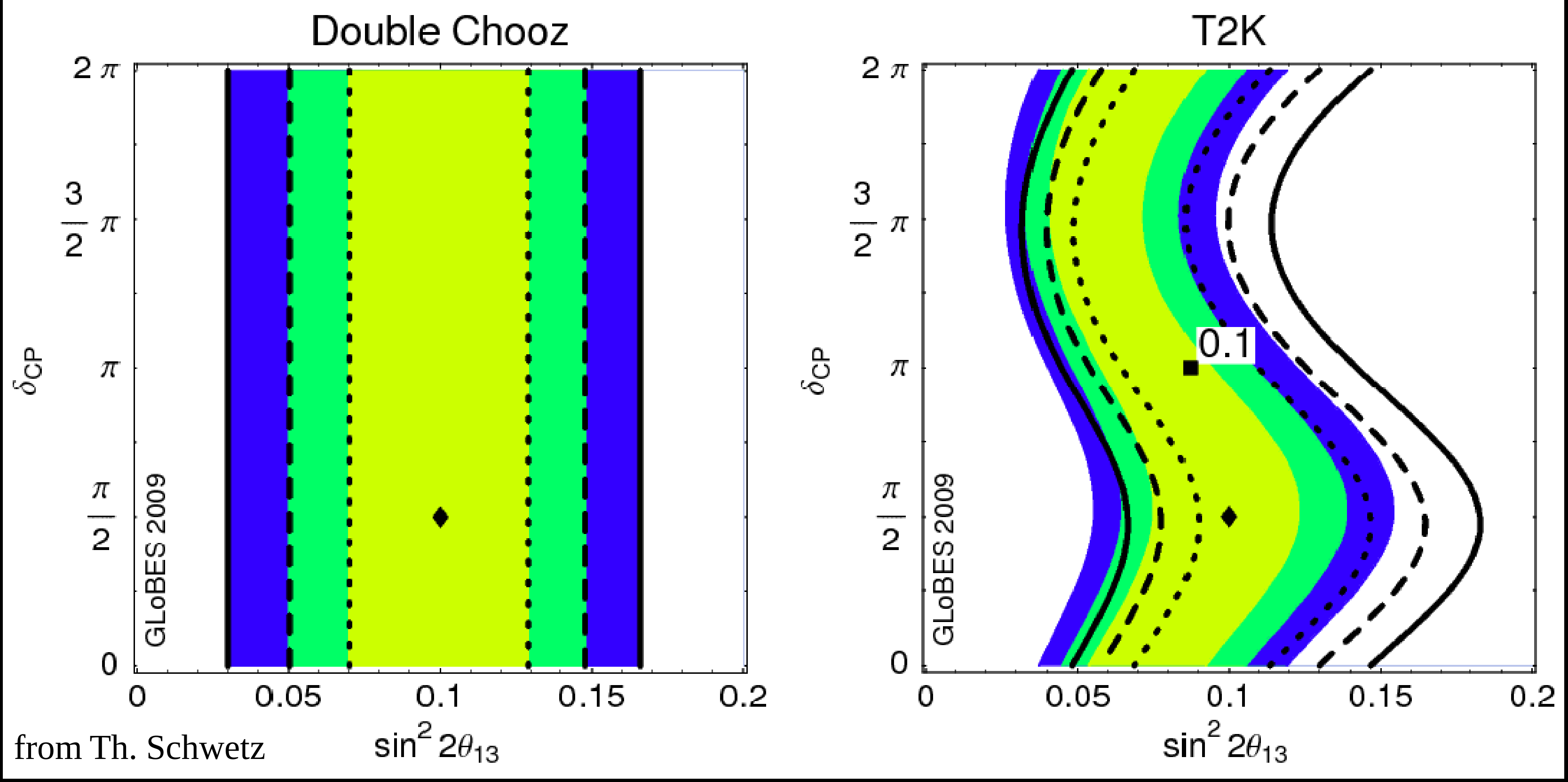
- **Double Chooz**
  - Cons: Shorter baseline
  - Pros: 2 cores → reactor OFF periods, calibration, accidental bkg

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

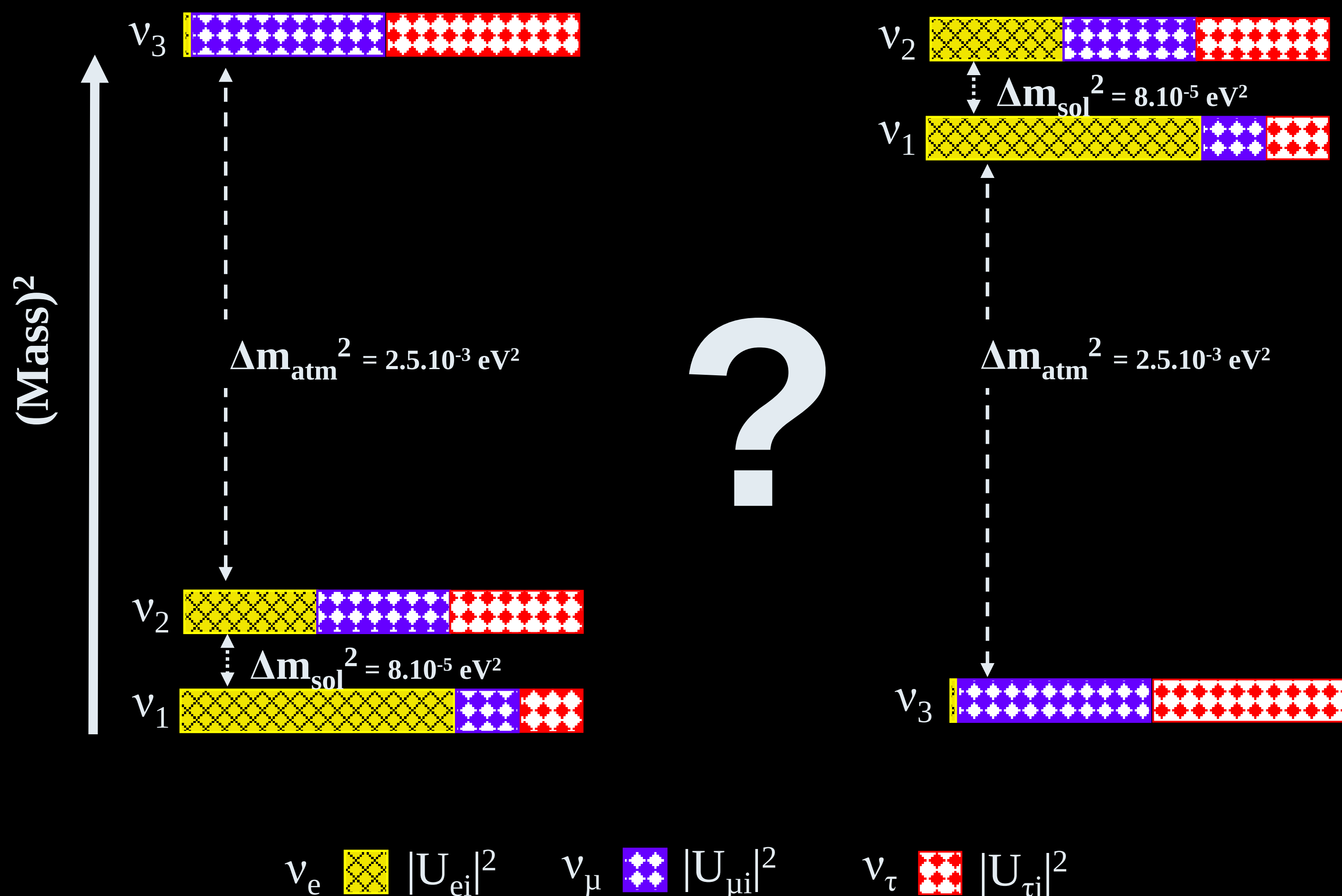
- **RENO**
  - Cons: Near/Far assymetric configuration, accidental bkg, calibration
  - Pros: Infrastructure ready

Complementarity Reactor/Superbeams

$\sin^2(2\theta_{13}) = 0.1$ & $\delta=\pi/2$

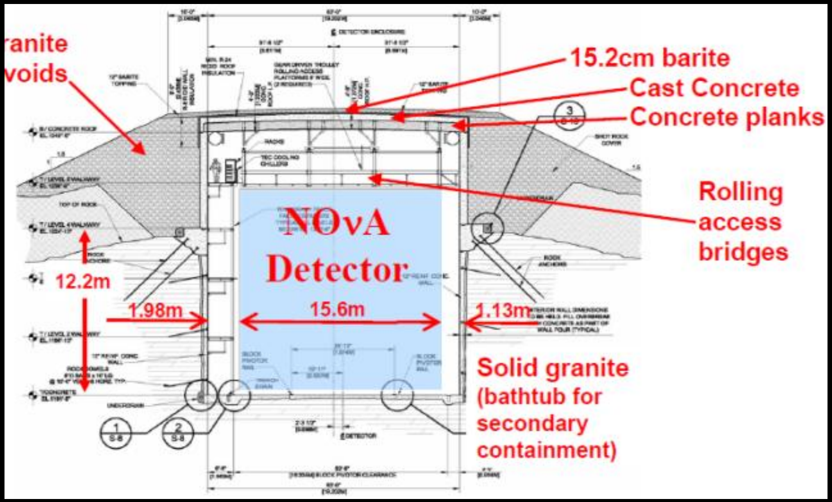


Sign Δm^2_{31}



Nova @NuMi

- **Channel: $\nu_\mu \rightarrow \nu_e$ (1st goal: search θ_{13} & constraint on neutrino mass hierarchy)**
- **Channel: $\nu_\mu \rightarrow \nu_\mu$ ($\sin^2 2\theta_{23}$ & Δm^2_{23})**



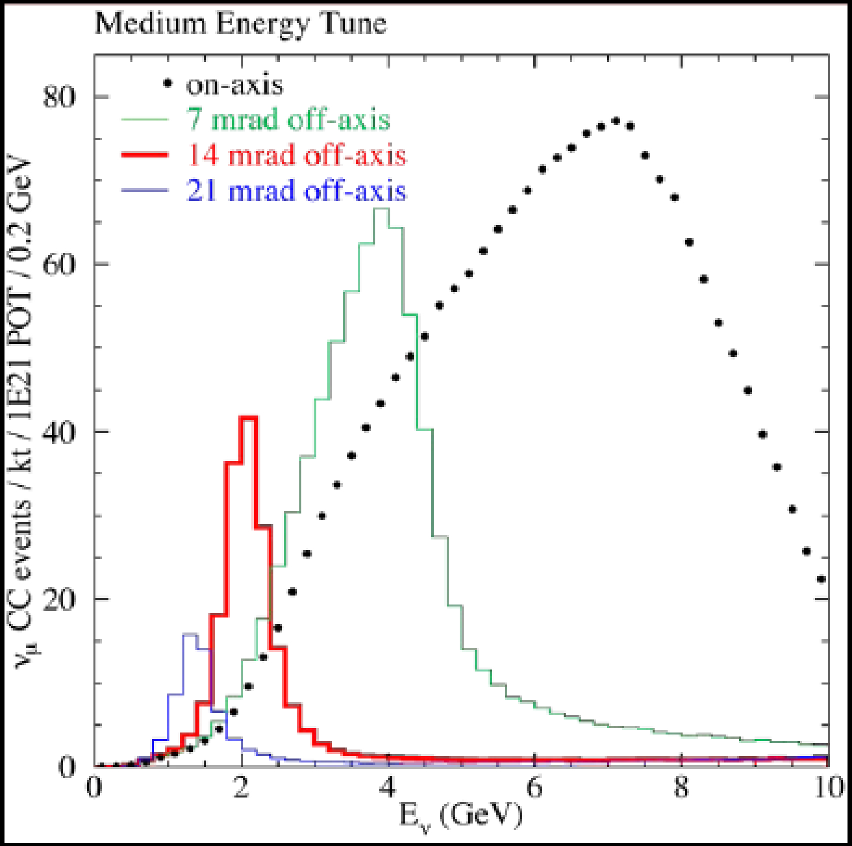
- **Beam Setup:**
  - 700 kW Off-axis beam (14 mrad)
    → improved ν_e CC & NC events discri
  - *6×10^{20} POTs/yr*
  - Plan to run 3yrs ν_μ & 3yrs anti-ν_μ

- **Far Detector (15mx15mx75m) at 800km:**
  - Liquid Scintillator (11000 m^3, 75% active)
    & wavelength-shifting fiber & APDs
  - High E / Long L → Matter effect
  - Ground breaking in May 2009
  - Data taking in 2013

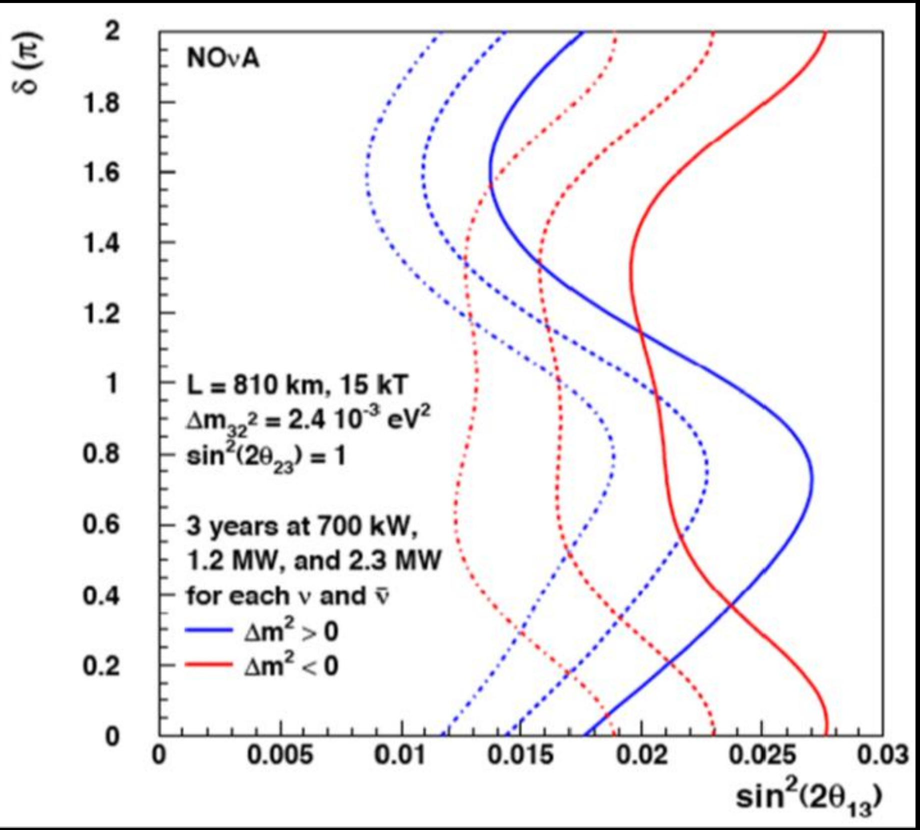
- **Near Detector**
  - Same technology as for the Far detector
  - Surface Data Taking in 2010

Electron appearance at Nova

Off-axis beam



$\nu_\mu \rightarrow \nu_e$ sensitivity after 3 y at 0.7 MW (at 3 σ)



Nova: Matter Effect Perturbation

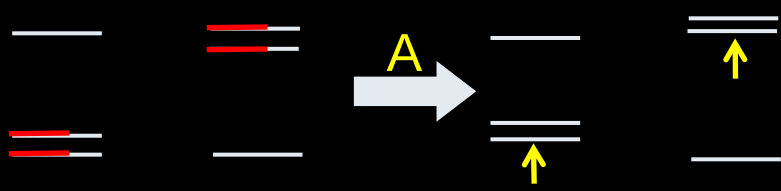
- Coherent neutrino forward scattering from ambient matter

- CC interaction of ν_e with the electrons creates a potential for ν_e

$$A \;\alpha\; \pm G_F N_e E_\nu$$

(+ for ν, - for anti-ν)

- 'A' modifies the mass eigenstates values and thus the oscillation prob.

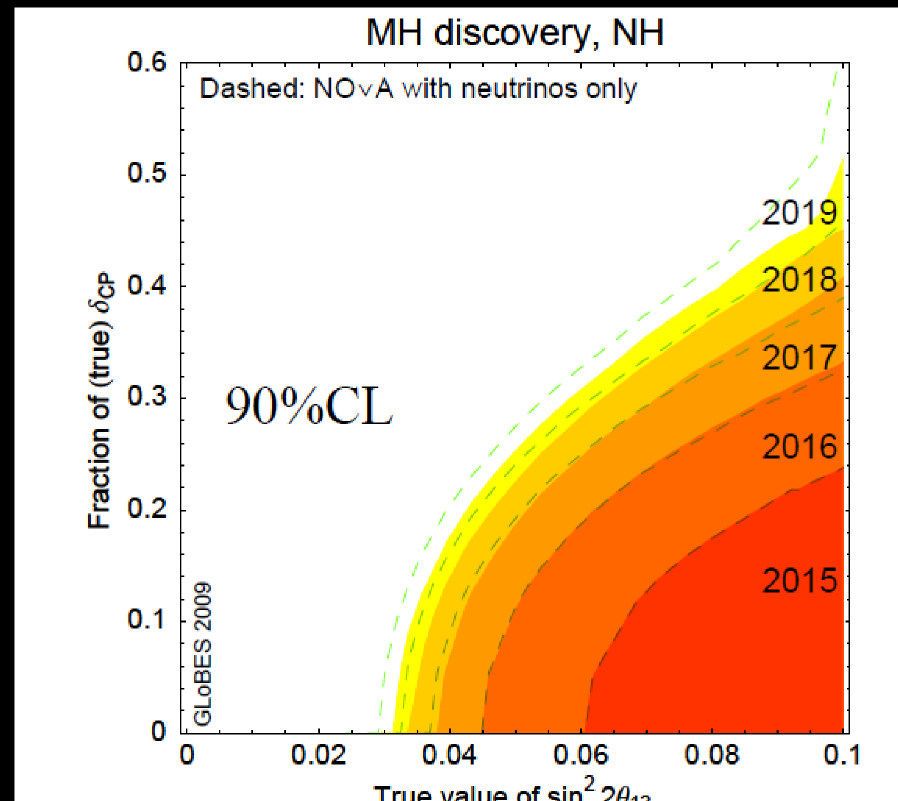


- 'A' lead to $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$

→ Mimicking CP-δ effect

→To be understood to disantangle a CP-like signal

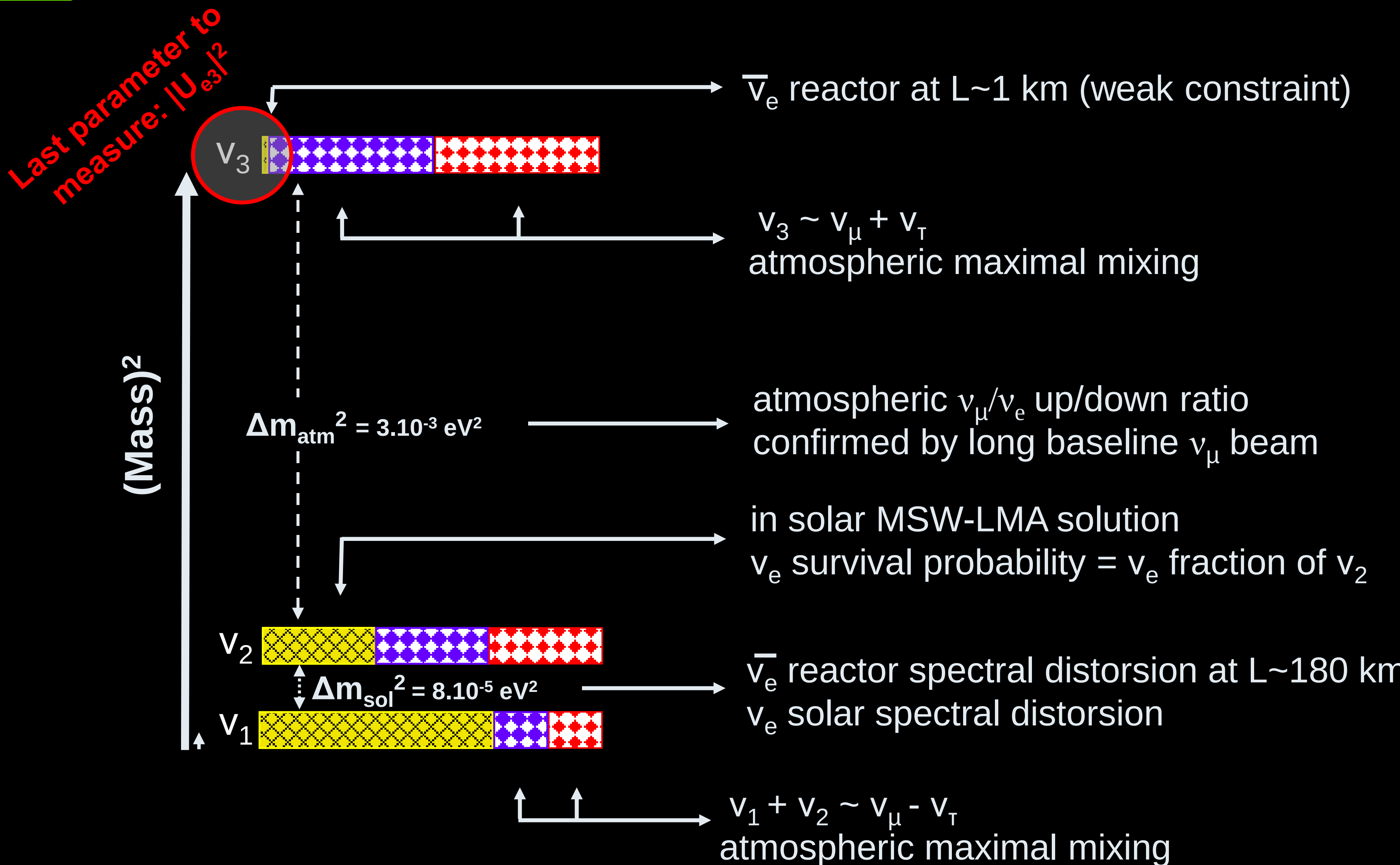
Start probing neutrino mass hierarchy (30% effect, 3 times more than in T2K)



PH, Lindner, Schwetz, Winter, arXiv:0907.1896

Need other experiments

Neutrino Oscillation Status



ν_τ $|U_{\tau i}|^2$ ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$

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

OPERA is looking for ν_τ appearance

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 $\nu_\mu \to \nu_e$ 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 $\nu_\mu \to \nu_e$ appearance at mid-energy / long-baseline (810km, 2 GeV)

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

Towards CP-violation studies

… Requires APPEARANCE experiments (beams but not reactors) …

$$P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\,\sin\delta$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\,\sin\delta$$

$$A_{CP} \,\alpha\, \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)}$$

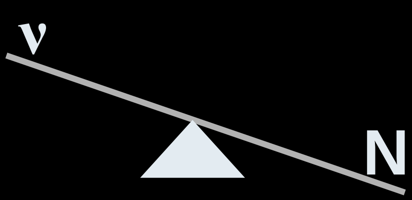
$$A_{CP} = \frac{2\,AS\,\sin\delta}{|A|^2 + |S|^2} = \frac{\sin(\Delta m^2_{12} L/4E)\,\sin\theta_{12}\,\sin\theta_{13}\,\sin\delta}{\sin^2 2\theta_{13} + \text{solar term…}}$$

- Conditions to observe CP with forthcoming/planned beam/detectors
  - Need Large (enough) values of all mixing angles and mass splittings
  - 2002: MSW-LMA
  - 2009-16 : a high enough value of $\sin^2\theta_{13}$?
  - θ_{13} value needed to decide for beam/detector design
- All what you need to know on how to best constrain A_{CP} in P. Huber’s talk

The Neutrino Grail: Leptogenesis

- Is leptonic $\not{CP}$ responsible for the Matter antimatter asymmetry of the universe?
- Quarks Baryogenesis fails… But Leptogenesis is gaining momentum

- Light Majorana neutrinos **ν** through the See-saw Mechanism
  → Heavy Majorana neutrino N (GUT scale)



- Early universe ($<10^{-35}$s) → N production

- $\not{CP}$ → $R(N \to l^- + \Phi^+) < R(N \to l^+ + \Phi^-)$ → L violation (Φ: charged Higgs field)
→ Leptogenesis

- Conversion of the L asymmetry to L & B asymmetries (B-L conserving processes)

- Discovery of CP violation in the light neutrino sector & the majorana nature of the neutrino would give credit to the Leptogenesis scenario

- But: θ_{13} is the last unknown to launch the long term CP effort…

Conclusion & Outlook

- Neutrinos mix and oscillate. A lot's of momentum to understand the neutrino mixing properties ! Neutrino ≠ Quark mixing.

$$U_{CKM} = \begin{bmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{bmatrix} \qquad U_{PMNS} = \begin{bmatrix} 0.8 & 0.5 & \theta_{13}? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

- CP violation in quarks was discovered in 1964, followed a long program to understand and measure it precisely
- Three-neutrino oscillations predict leptonic CP violation: a key ingredient for Leptogenesis. Next step is θ_{13}
- Coming soon: Double Chooz, T2K, RENO, Daya Bay, Nova
- Ultimate Goal: Over-Constrain Parameter Space

Neutrino Oscillation Parameters

parameter	bf$\pm 1\sigma$	1σ acc.	2σ range	3σ range
Δm^2_{21} $[10^{-5} eV^2]$	7.65 ± 0.23	3%	$7.25 - 8.11$	$7.05 - 8.34$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3} eV^2]$	$2.4^{+0.12}_{-0.11}$	5%	$2.18 - 2.64$	$2.07 - 2.75$
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	7%	$0.27 - 0.35$	$0.25 - 0.37$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	14%	$0.38 - 0.64$	$0.36 - 0.67$
$\sin^2\theta_{13}$	–	–	≤ 0.04	≤ 0.056

Best fit values (bf), 1σ errors, relative accuracies at 1σ, and 2σ and 3σ allowed ranges of three-flavor neutrino oscillation parameters from a combined analysis of global data.

M. Maltoni, T. Schwetz *et al.*, arXiv:0812.3161