Aspects on Neutrino (Mass-) and Mixing

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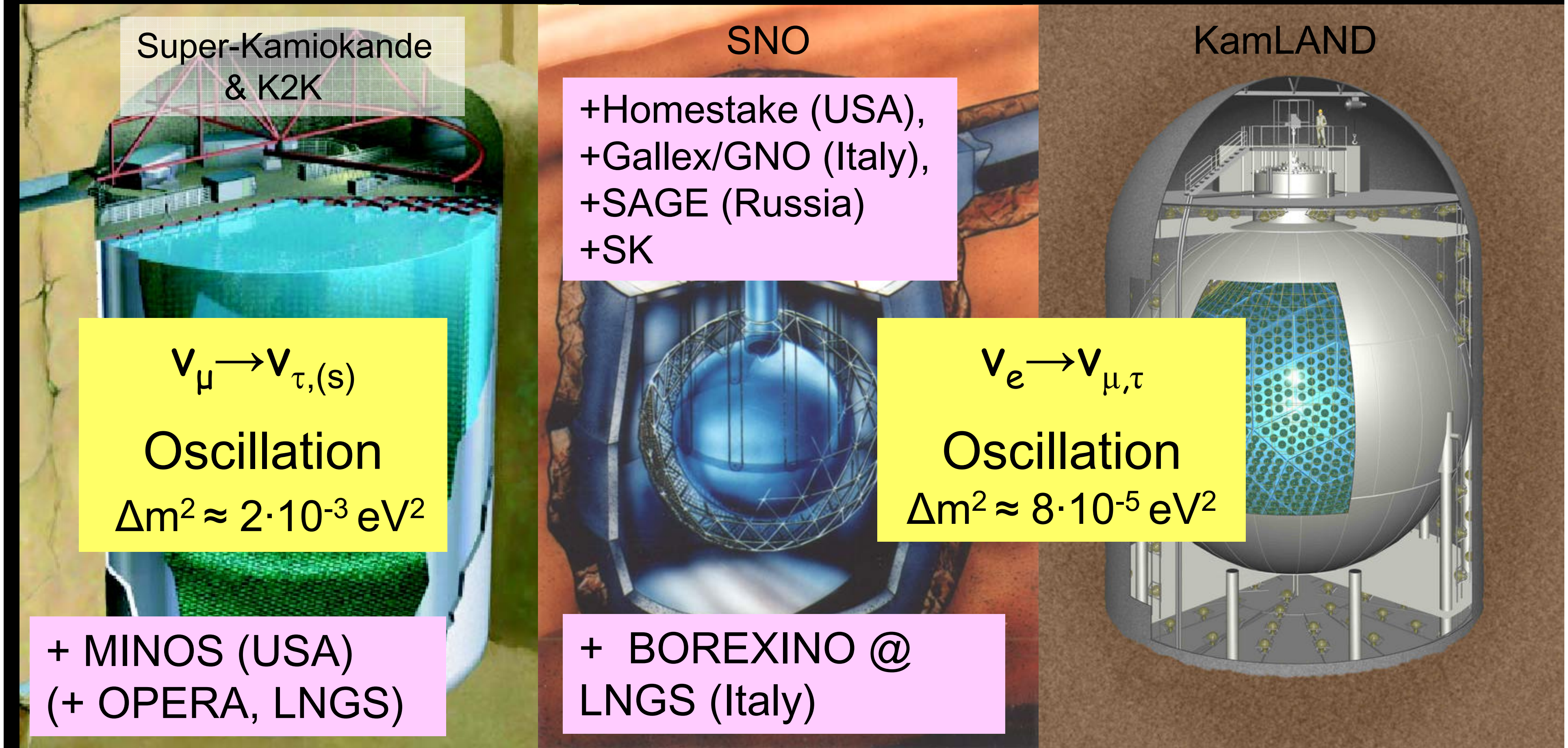
- Introduction: neutrino mass and mixing
- Neutrino Oscillation (I): mu – tau mixing
  - atmospheric neutrinos
  - present neutrino beam experiments:
    - MINOS (NuMi beam: Fermilab – Soudan Mine)
    - OPERA (CNGS beam: Cern – LNGS)
- Neutrino Oscillation (II): e – mu mixing
  - solar neutrino experiments
    - short review on past experiments (SNO)
    - Borexino
    - reactor experiment: KamLand
- Neutrino Oscillation (III): Future prospects (theta13 and CPV)
  - reactor experiments: Double Chooz and Daya Bay
  - off-axis (super)beams: T2K and NovA
  - (neutrinofactory and beta beams)
- (Neutrino Oscillation (IV): Problems?)
  - (LSND / MiniBoone)
  - (GSI anomaly)
  - (NuTeV anomaly)
- Nature of neutrino mass: Majorana or Dirac?
  - Double beta decay

Neutrino Oscillations have been observed
→ Add Neutrino Mass & Mixing to SM

JAPAN | CANADA | JAPAN



atmospheric neutrinos
accelerator neutrinos

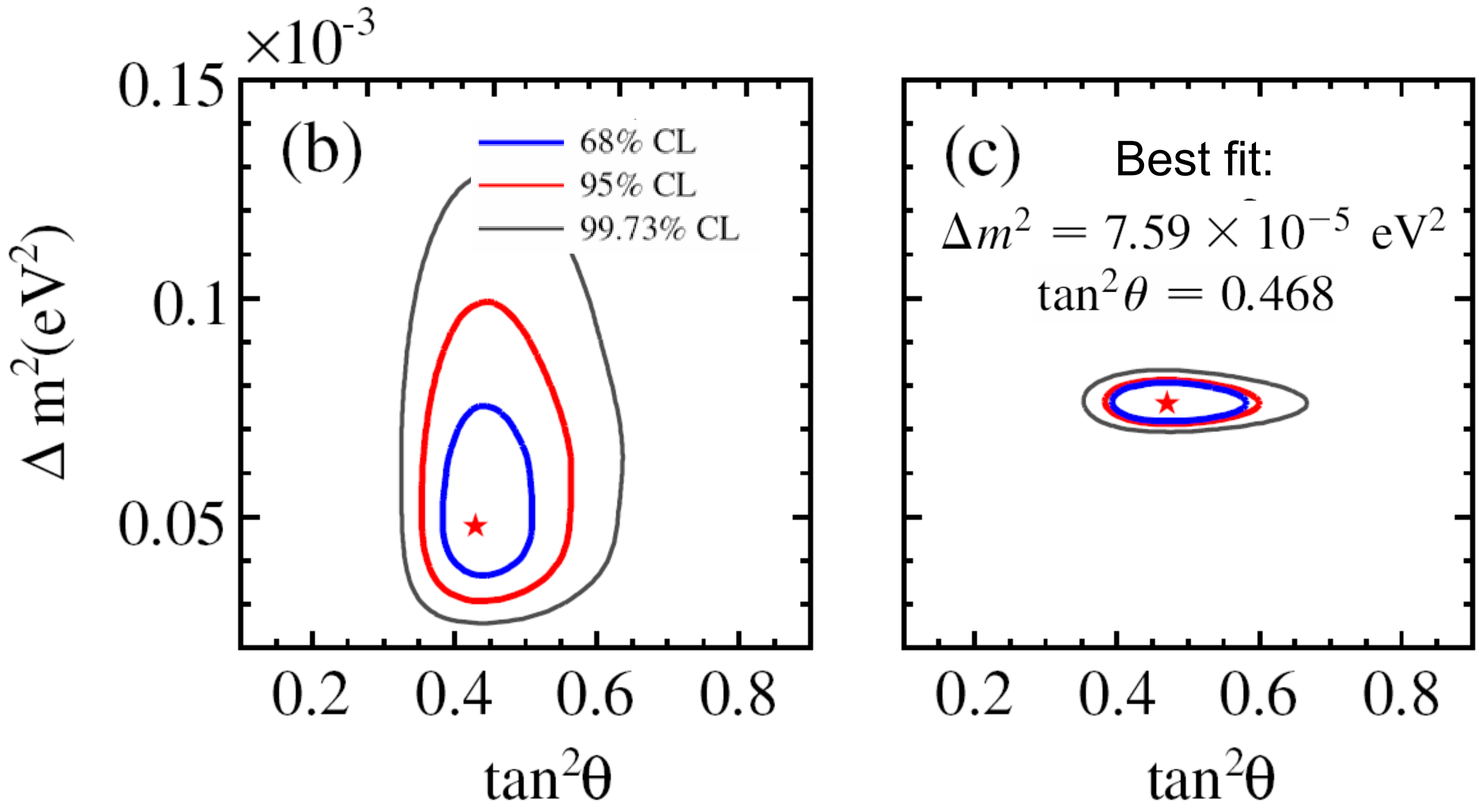
solar neutrinos

reactor neutrinos

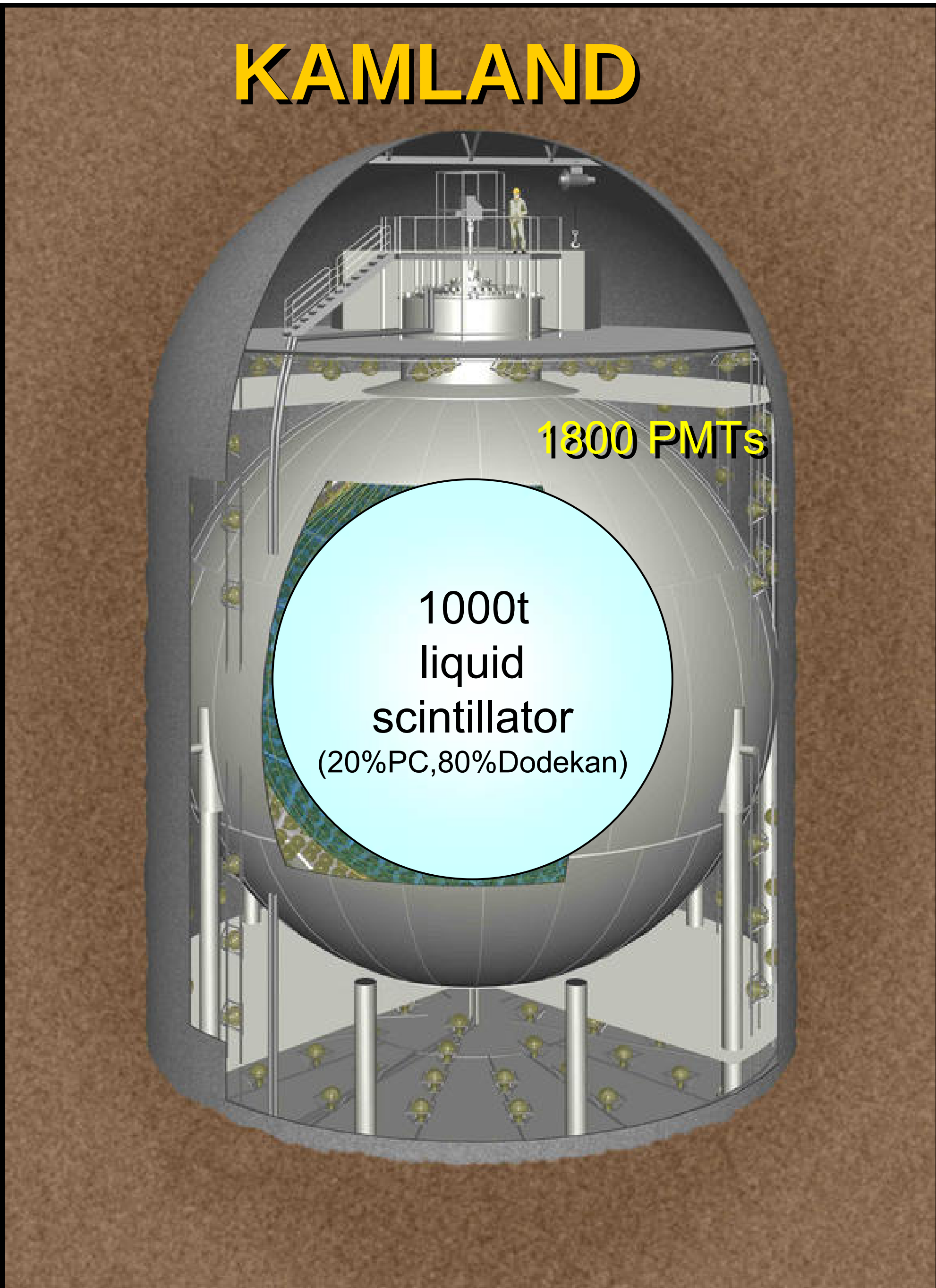
Neutrino Oscillation Analysis (after SNO)

b) Global Analysis using data from SNO, SK, Cl, Ga, Borexino

c) Global Analysis using data from solar exp. & KamLand

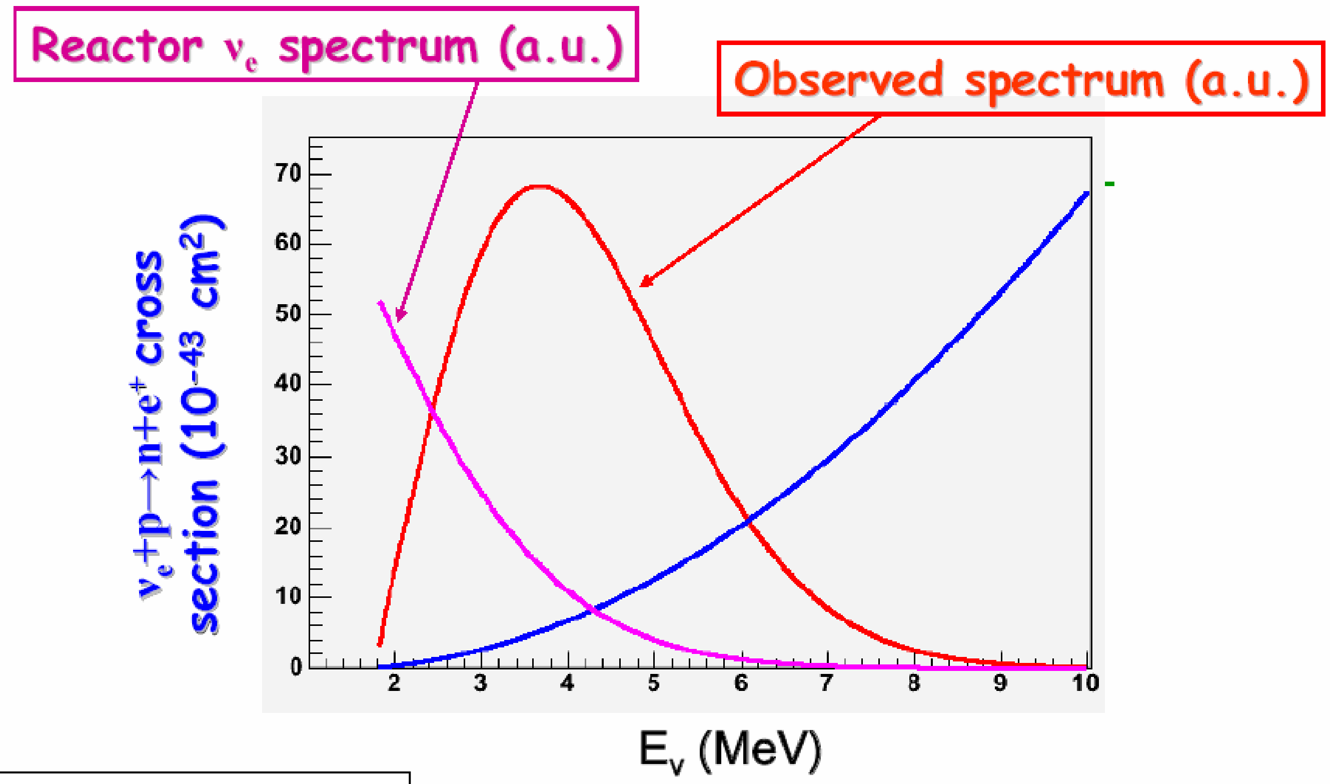


SNO coll., PRL 101, 111301 (2008)



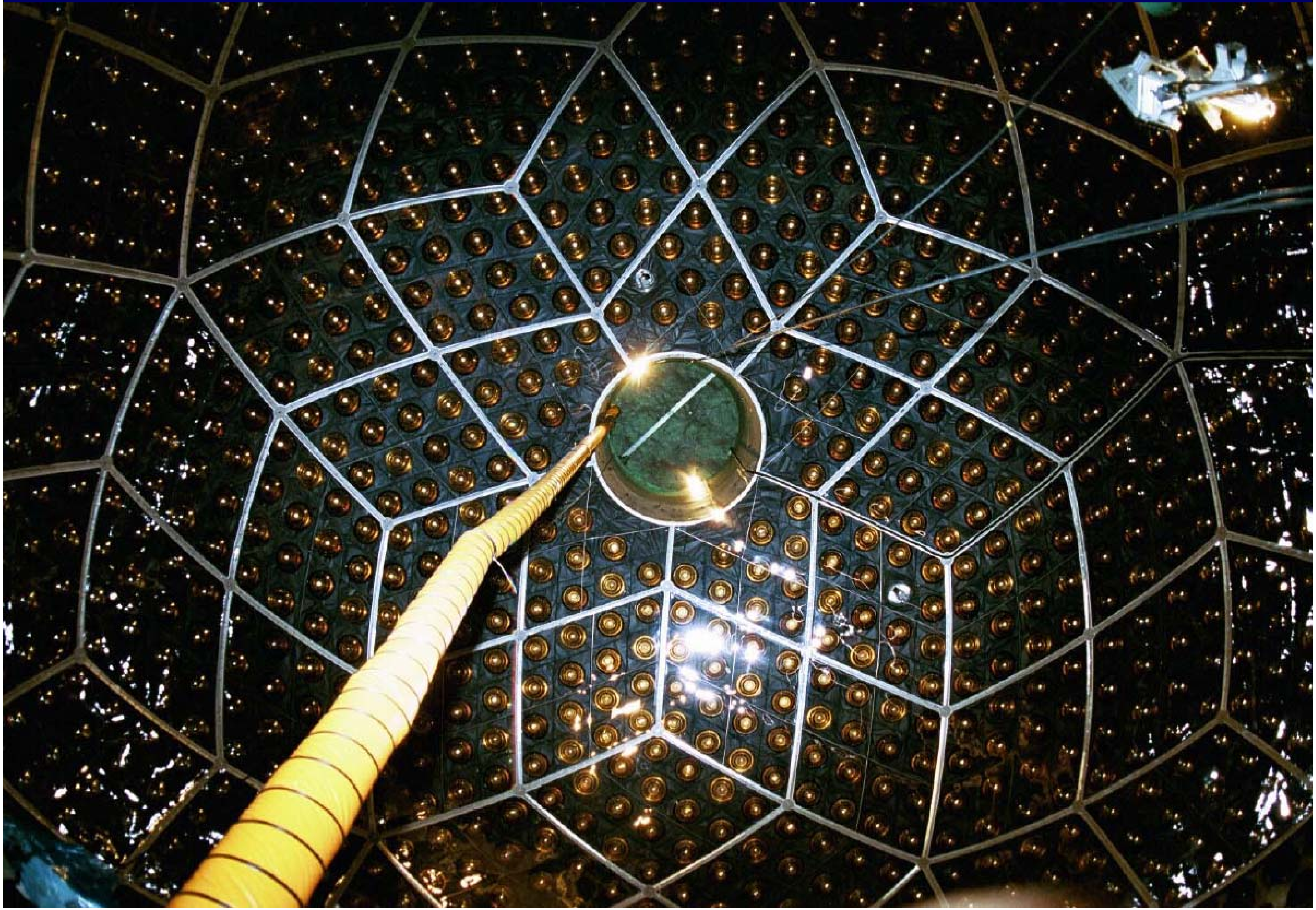
Kamioka Liquid Scintillator Anti-Neutrino Detector

How to detect reactor neutrinos



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

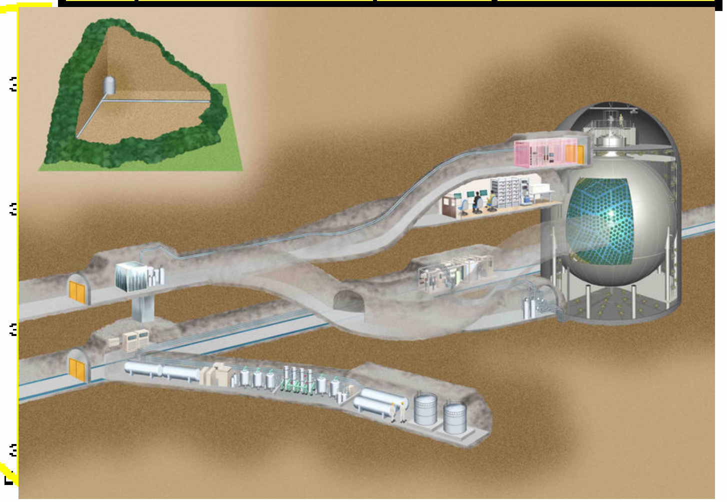
prompt signal	delayed signal
E_ν – 0.8 MeV	$n + p \rightarrow d + \gamma(2.2\text{MeV})$



Reactor distances & event rates

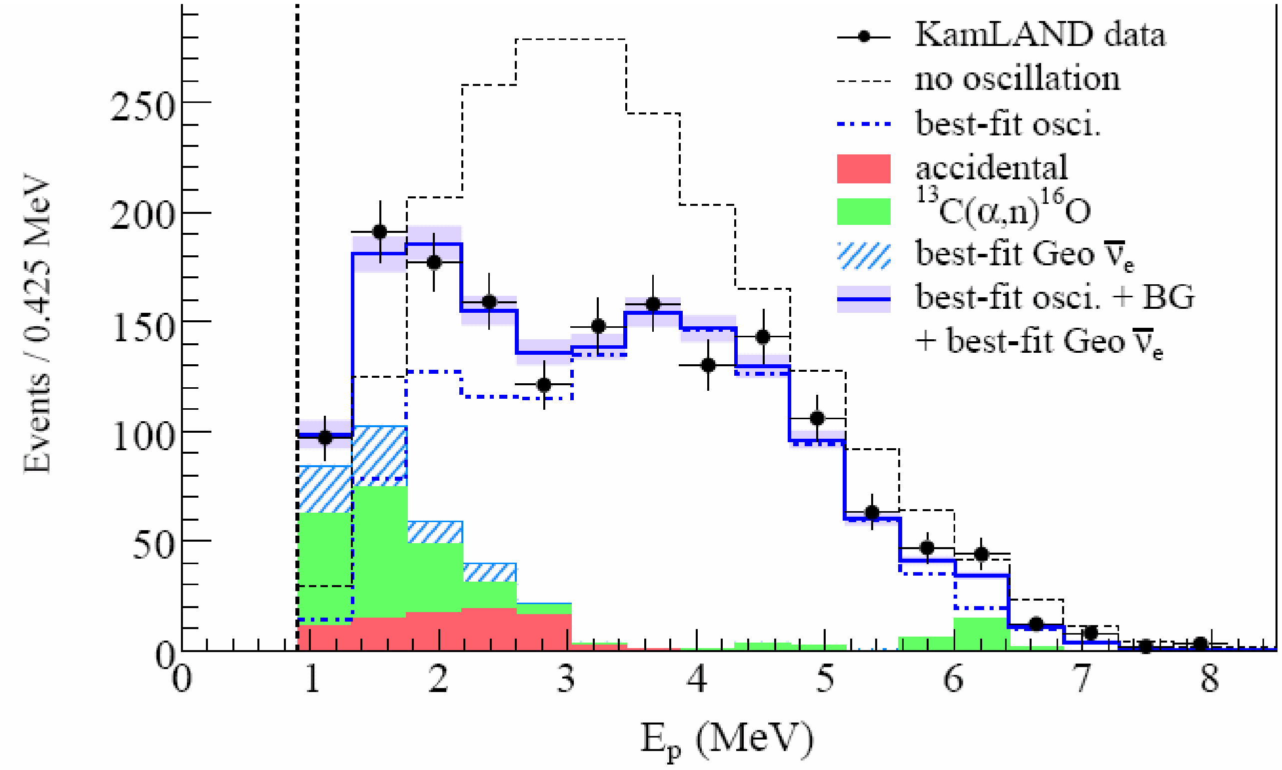
Average distance of reactors from Kamland: 180km

	Site	Dist (km)	Rate noosc* (yr^{-1} kt^{-1})
Japan	Kashiwazaki	160	254.0
	Ohi	179	114.3
	Takahama	191	74.3
	Tsuruga	138	62.5
	Hamaoka	214	62.0
	Mihama	146	62.0
	Sika	88	55.2
	Fukushima1	349	31.1
	Fukushima2	345	29.5
	Tokai2	295	10.1
	Onagawa	431	9.3
	Simane	401	6.3
	Ikata	561	5.1
	Genkai	755	4.8
	Sendai	830	2.1
	Tomari	783	1.4



KamLAND result (2008)

prompt event energy spectrum of anti-ν_e candidates



best fit: $\Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\mathrm{stat})^{+0.15}_{-0.15}(\mathrm{syst}) \times 10^{-5}\ \mathrm{eV}^2$

$$\tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\mathrm{stat})^{+0.10}_{-0.06}(\mathrm{syst})$$

„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008

Background in KamLAND:

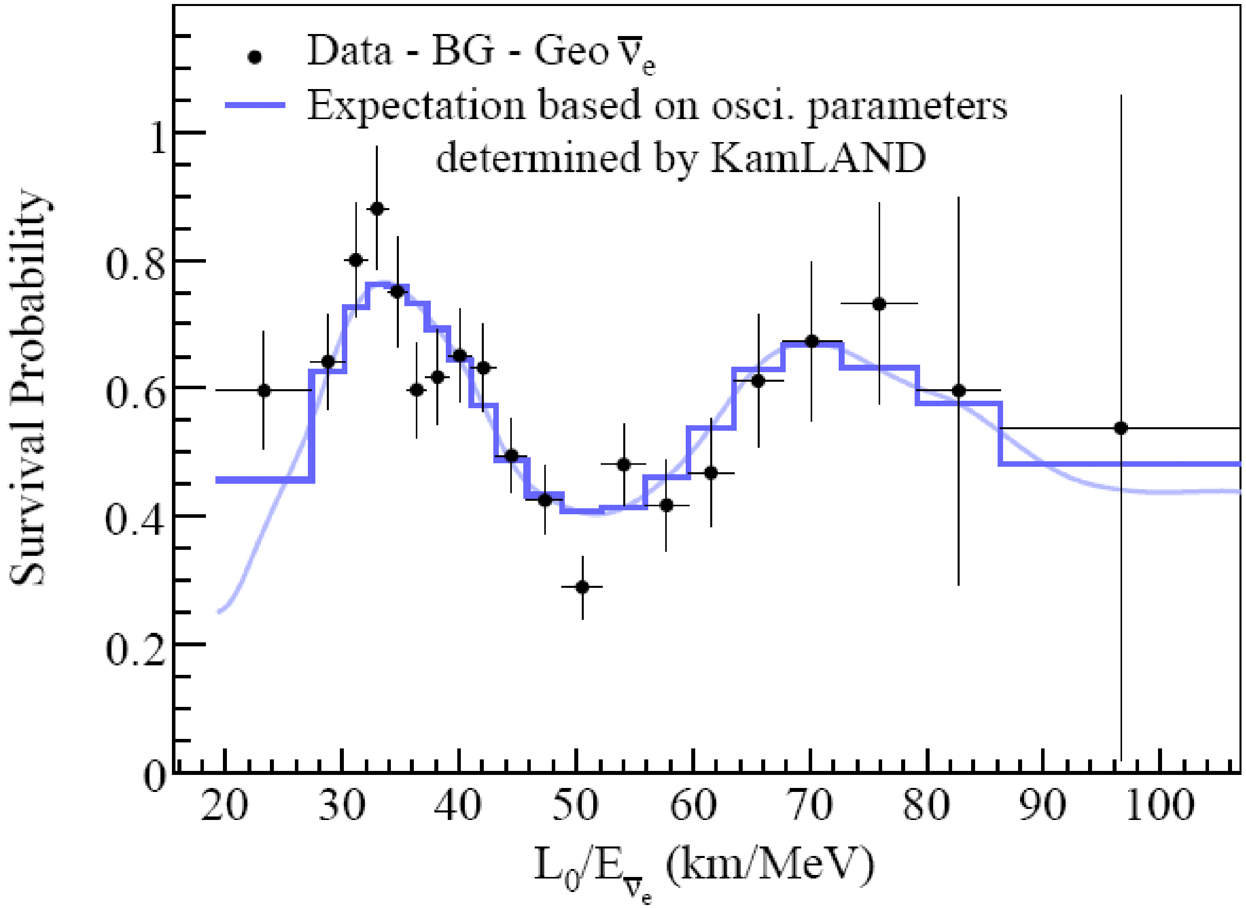
from 2002 - 2007:
Expected events from reactors: 2179 ± 89(syst)
Observed events: 1609

TABLE II: Estimated backgrounds after selection efficiencies.

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

KamLAND result (2008)

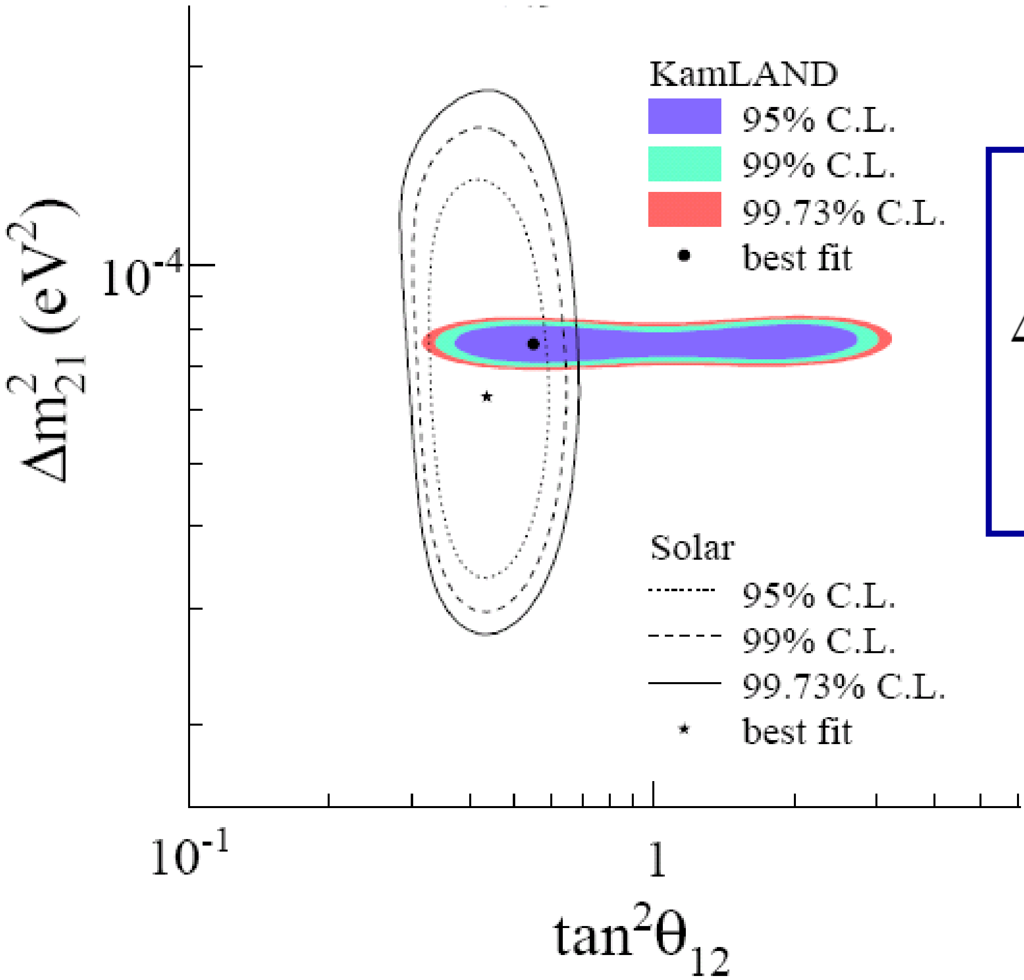
„Precision Measurement of Neutrino Oscillation Parameters with KamLAND", Phys.Rev.Lett.100:221803,2008



L_0 is the „effective" baseline = flux-weighted average of distance = 180km

KamLAND result (2008)

„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008



KamLAND + solar:

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$$

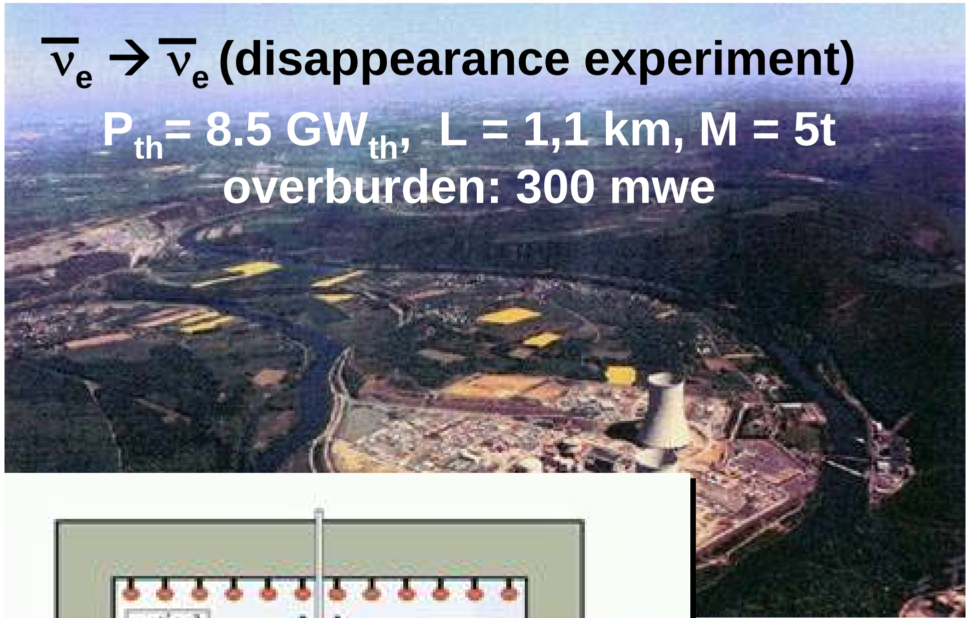
$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

Neutrino Oscillations: the unknown sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

?

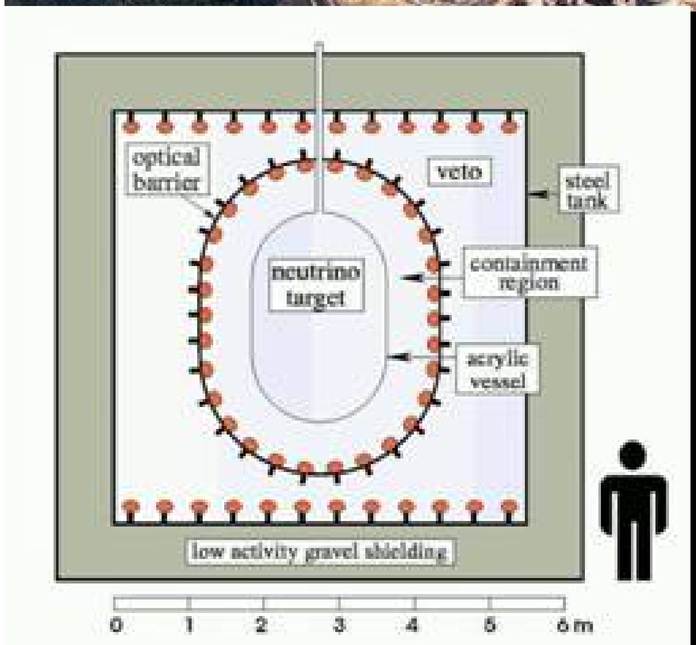
Best Limit on θ_{13}: CHOOZ



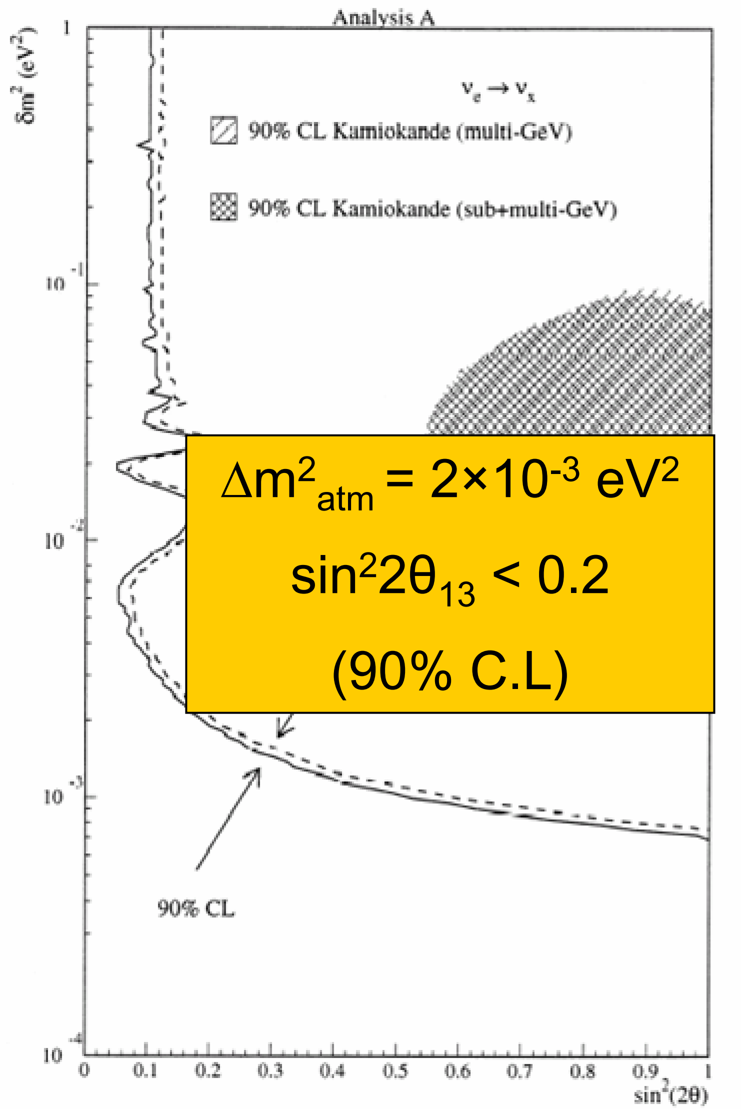
$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment)

P_{th} = 8.5 GW_{th}, L = 1,1 km, M = 5t

overburden: 300 mwe



Target: 5t Gd loaded (0.09%) Scintillator



$\Delta m^2_{atm} = 2\times10^{-3}$ eV^2

$\sin^2 2\theta_{13} < 0.2$

(90% C.L)

M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374

Global analysis: Hints of $\theta_{13} > 0$ (I)

„SNO, KamLAND and neutrino oscillations: theta(13)", **Fogli, Lisi, Marrone, Palazzo, Rotunno**, arXiv:0905.3549

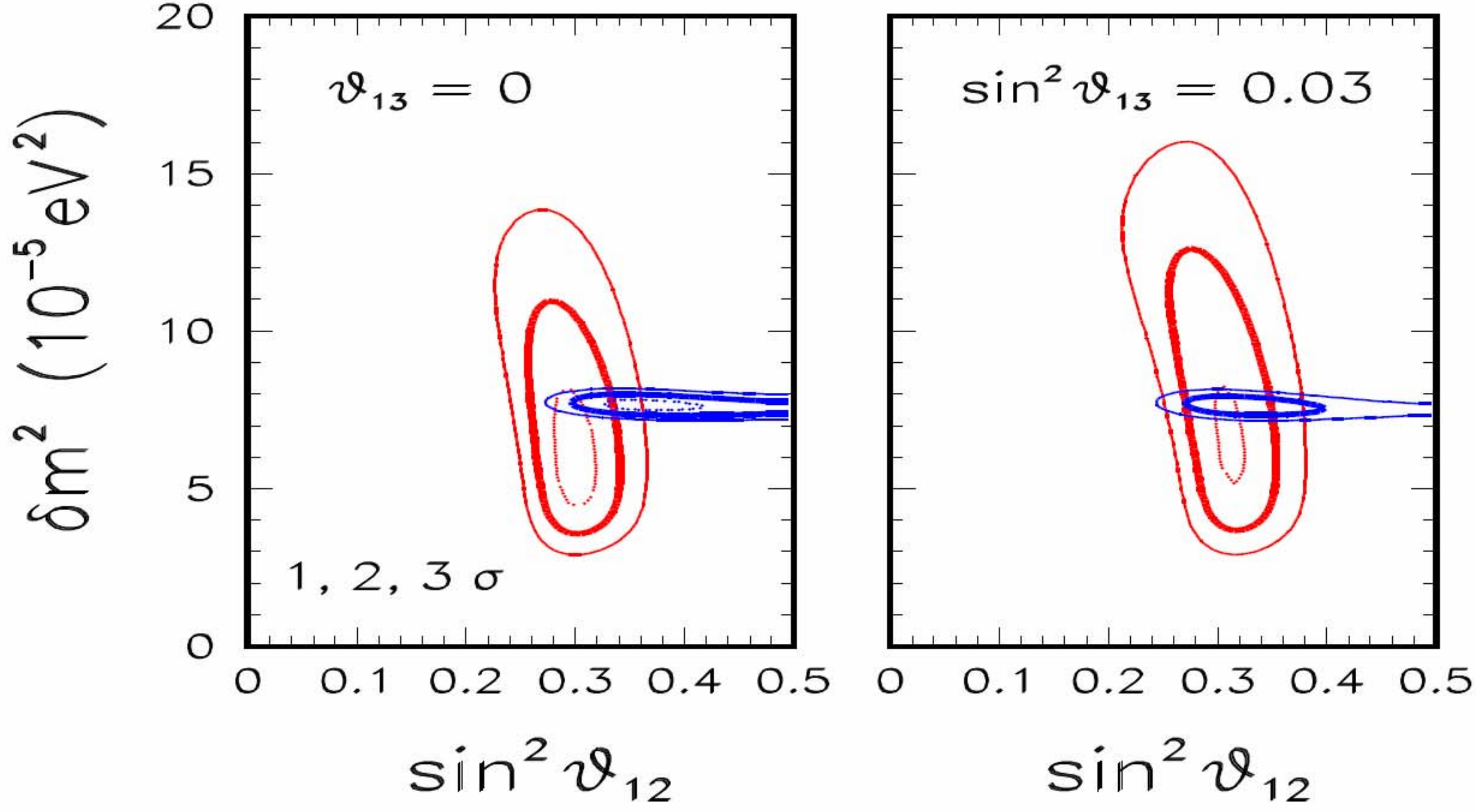
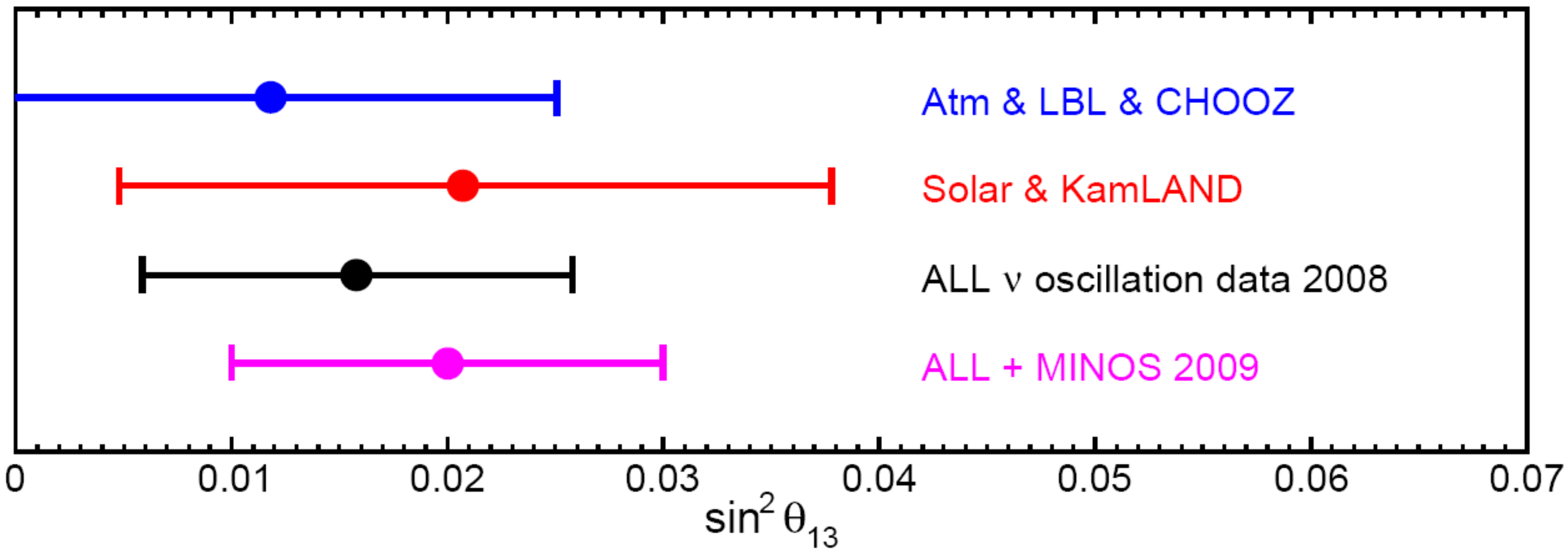


Figure 1: Comparison of n-σ regions allowed by the latest (2008) solar and KamLAND data in the $(\delta m^2, \sin^2\theta_{12})$ plane, for two fixed values of θ_{13}.

Global analysis: Hints of $\theta_{13} > 0$ (II)

„SNO, KamLAND and neutrino oscillations: theta(13)“, **Fogli, Lisi, Marrone, Palazzo, Rotunno**, arXiv:0905.3549



Methods to measure θ_{13}, CPV:

synergies

neutrino super beams: appearance of ν_e in ν_μ beam

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \approx\ & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\
& +\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)
\end{aligned}
$$

nuclear reactors: disappearance of anti-ν_e

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\Delta - \alpha^2\Delta^2\cos^4\theta_{13}\sin^2 2\theta_{12}$$

$\alpha = \Delta m^2_{21} / \Delta m^2_{31} << 1$

$\Delta = \Delta m^2_{31} L / 4E$

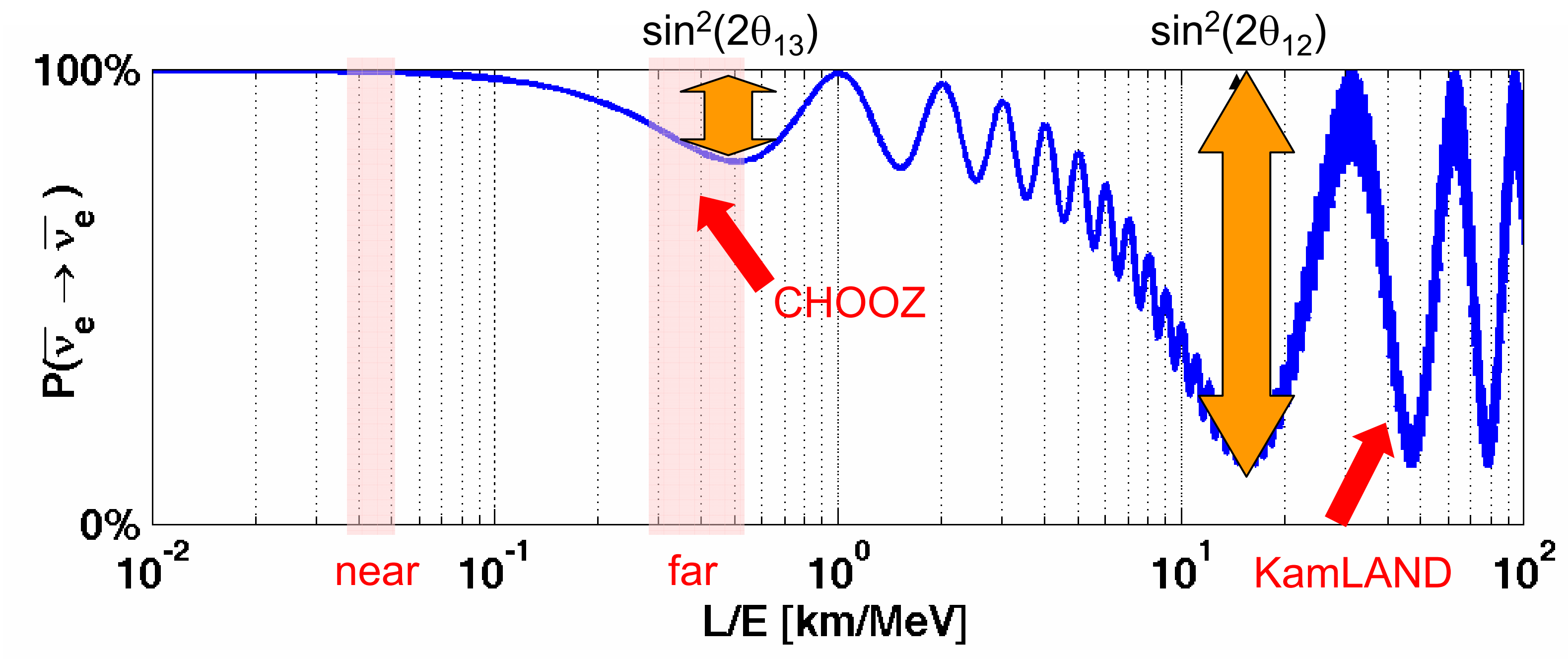
matter dependent quantities:

$\hat{A} = 2VE / \Delta m^2_{31}$

$V = \sqrt{2} G_F n_e$, with electron density n_e (assumed constant)

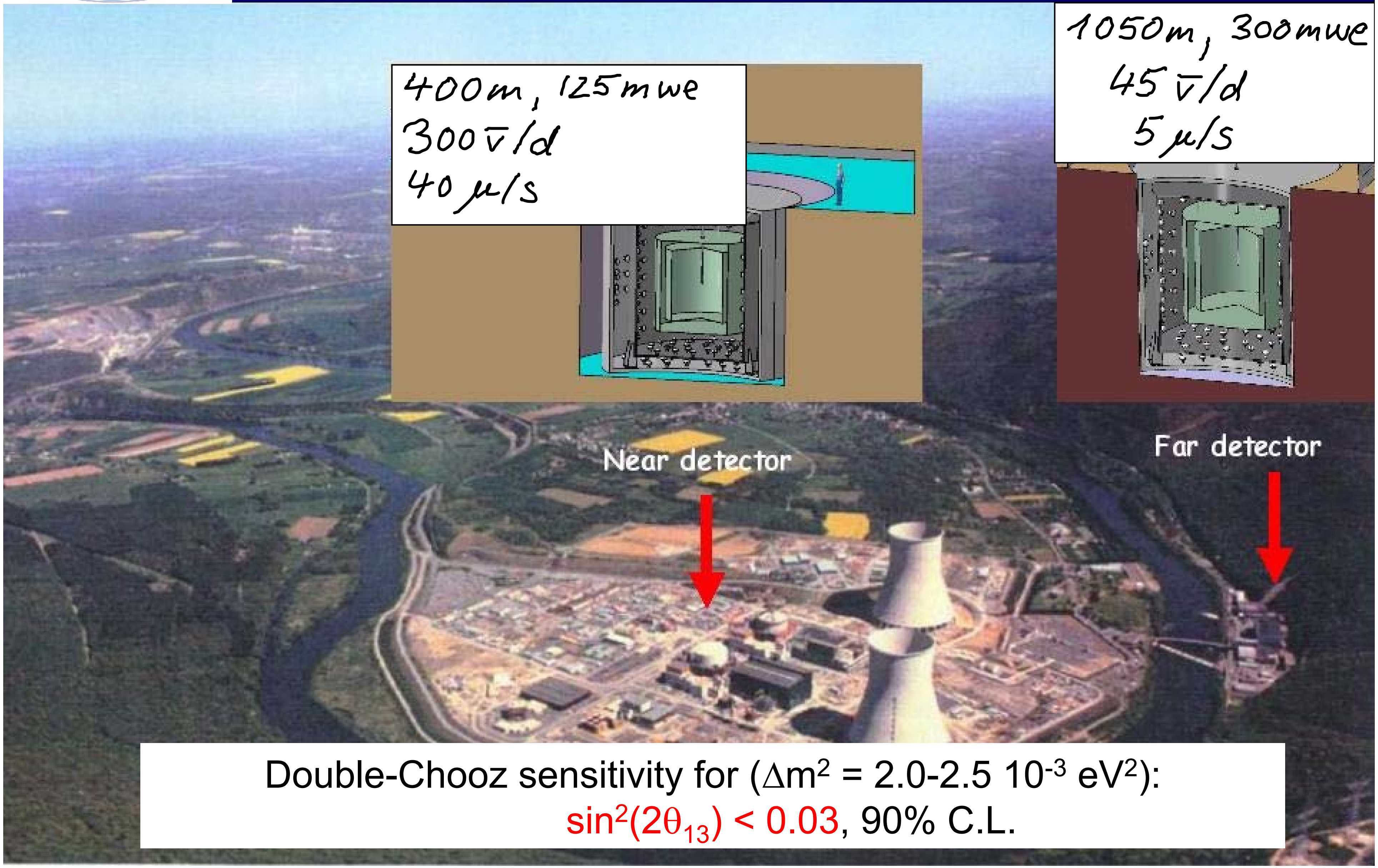
Oscillations of reactor neutrinos and θ_{13}

$$P(\overline{\nu_e} \to \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\bar{\nu}}} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E_{\bar{\nu}}}$$



- max. sensitivity on θ_{13}: E_ν ~ 4 MeV, Δm_{atm}^2 ➔ $L_{osc}/2$ ~ 1.5 km

Double-CHOOZ



Double-Chooz sensitivity for ($\Delta m^2 = 2.0\text{-}2.5\ 10^{-3}\ eV^2$):
$\sin^2(2\theta_{13}) < 0.03$, 90% C.L.

Double Chooz

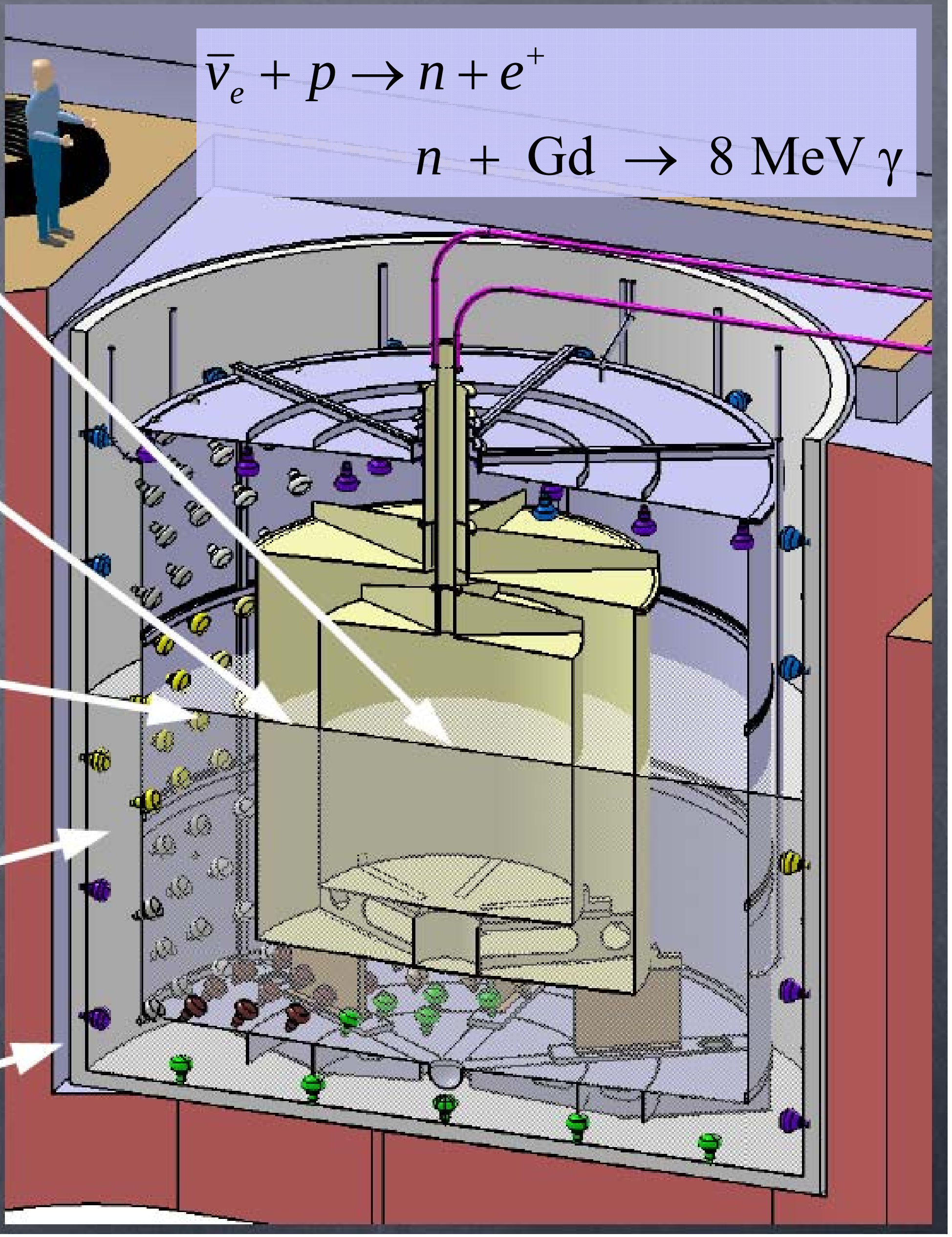
How can one reduce the systematic uncertainty to <1% ?

- comparison of (almost identical) near and far detector:
  many uncertainties cancel, e.g.
  neutrino flux and –spectra.
- Larger target (increased from 5 to 10m^3) and
  longer measurement (5 years), higher statistics.
- Improved detector design and special choice of materials (radioactive purity) based on experience from CHOOZ.

	CHOOZ	Double Chooz
Reactor fuel cross section	1.9%	–
Reactor power	0.7%	–
Energy per fission	0.6%	–
Number of protons	0.8%	0.2%
Detection efficiency	1.5%	0.5%
TOTAL	2.7%	0.6%

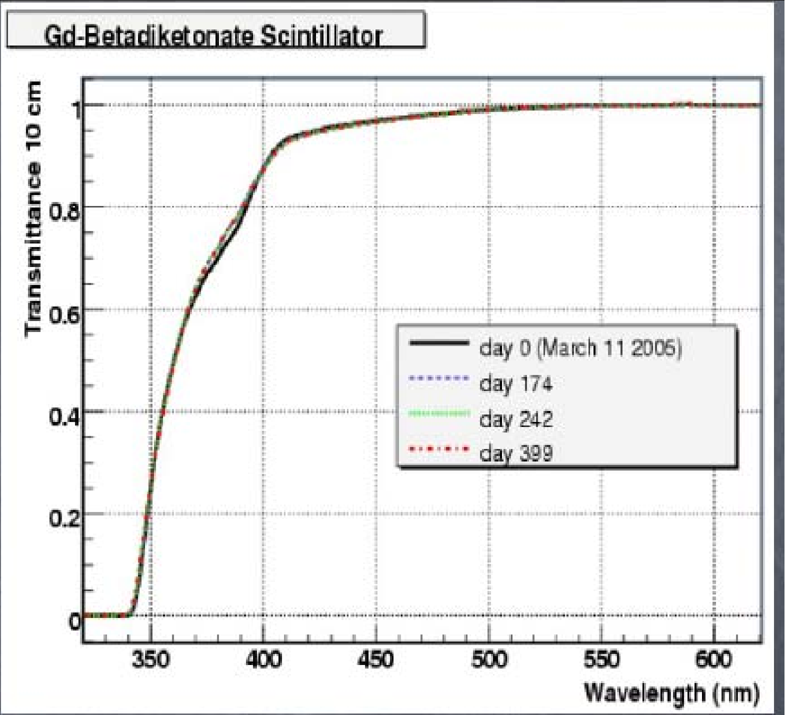
Double CHOOZ Detector

- Inner Detector design:
  - target: ~8t of Gd-doped scintillator in acrylics vessel
  - γ-catcher: 55 cm wide undoped scintillator in acrylics vessel
  - buffer: 105 cm wide, mineral oil in stainless steel vessel
  - inner veto: 50 cm wide, undoped scintillator in painted steel vessel
  - shield: 17 cm of steel slideable on top

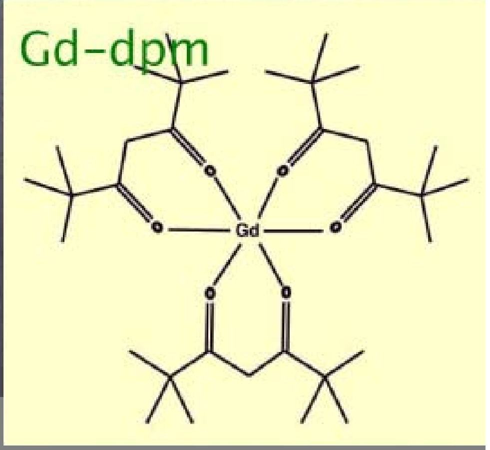


Double CHOOZ: Scintillator R&D

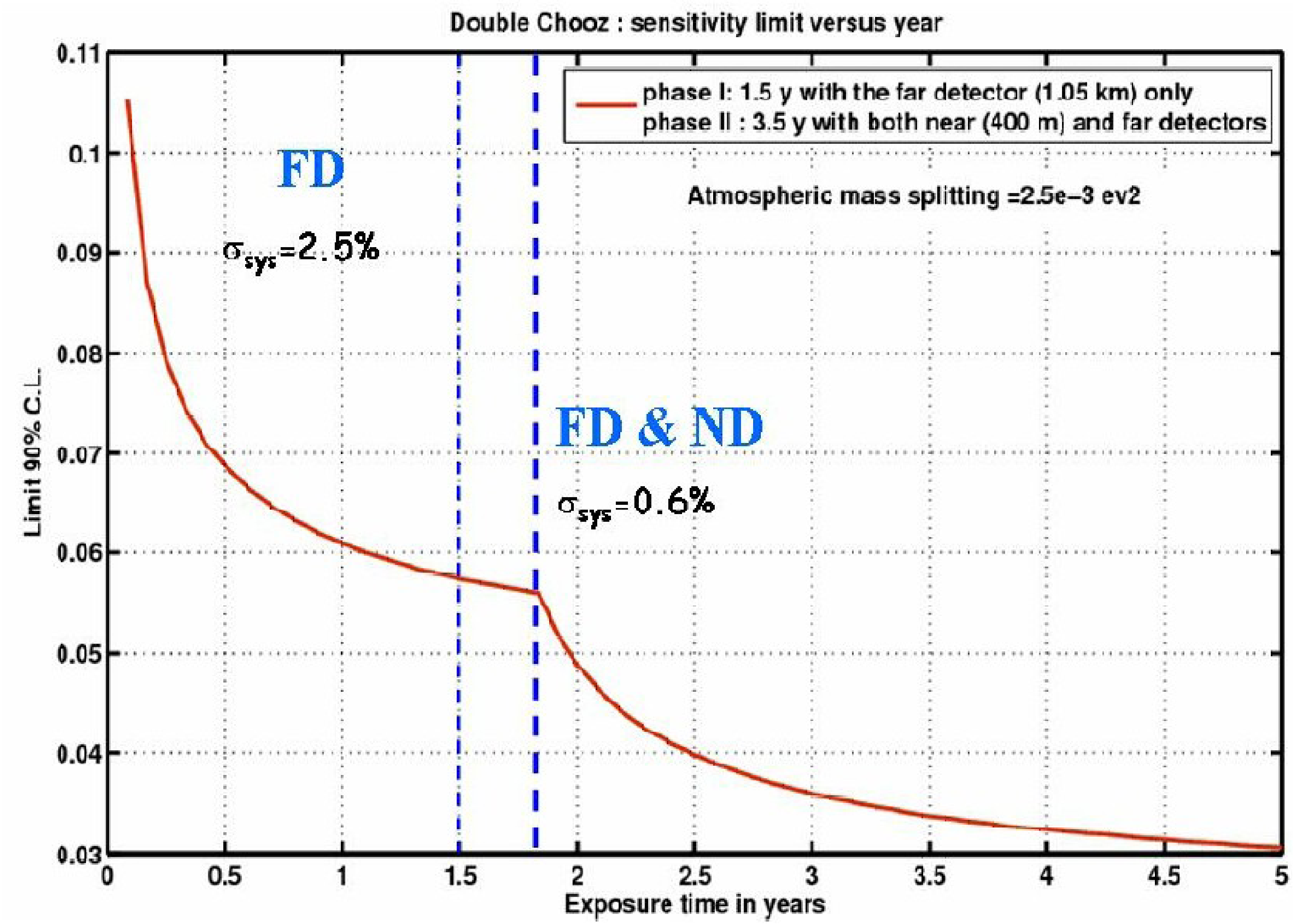
- Attenuation length ~10 m
- Light yield ~ 6000 photons/MeV, target and γ catcher (uniformity!)
- Stability over several years!
  → long term tests @ different temperatures to study aging



- Target composition: 80% Dodecane + 20% PXE + 6g/l PPO + 20m g/l bis-MSB + Gd component, in total ~ 0.1% Gd
- Total amount of required liquid ~ 250 m³ per detector
  → dedicated building @ MPIK constructed,



Double CHOOZ sensitivity



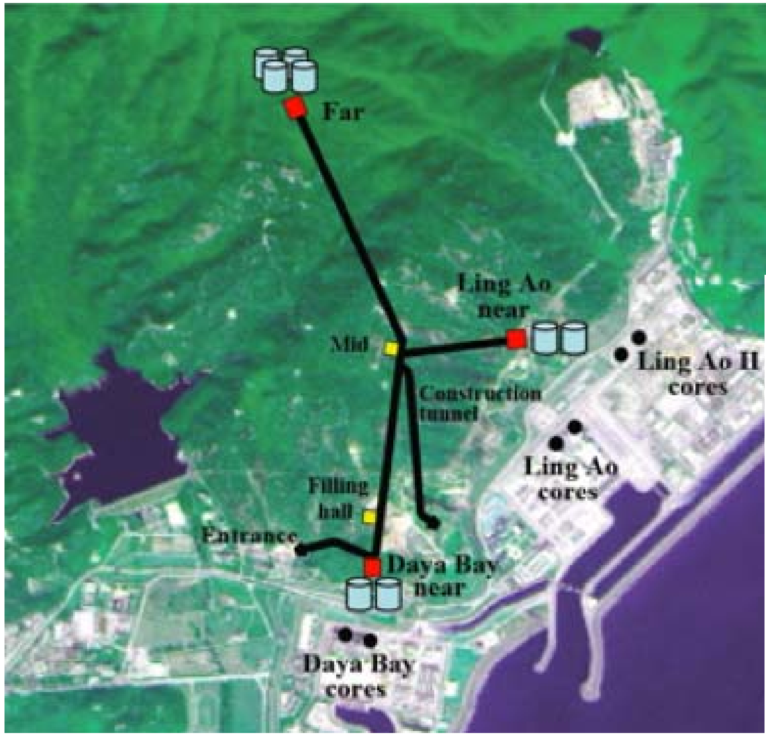
Double CHOOZ Status

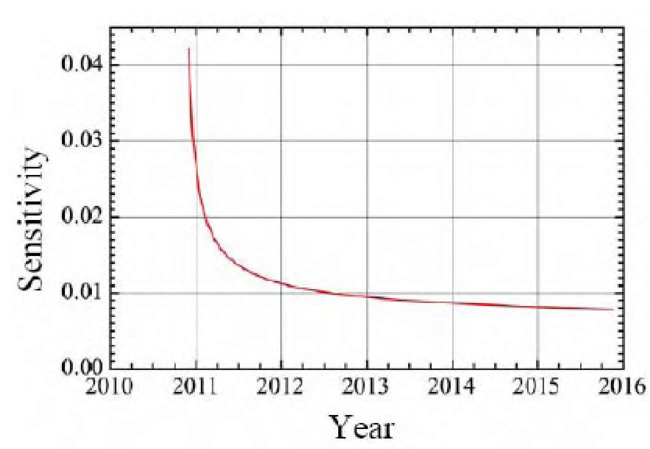
- Installation of far detectors ongoing, PMT's installed.
  end 2009: start commissioning of far detector.

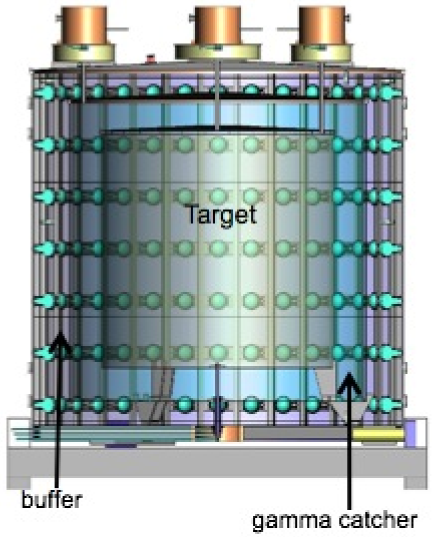
- Design of near detector lab complete.
  2011 commissioning of near detector.

Daya Bay Experiment (USA & China)

Guangdong Daya Bay nuclear power station:
P_{th} = 11.6 GW (now), 17.4 GW(2011) 6th most powerful worldwide





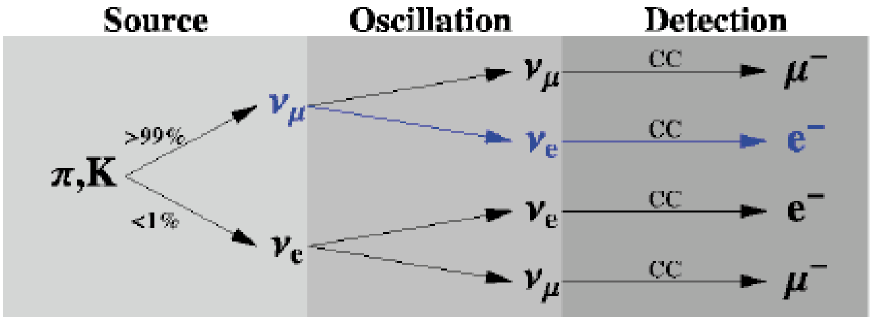


Goal: sensitivity on $\sin^2 2\theta_{13} < 0.01$

Commissioning of the detectors in 1st hall in 2009.
Construction will last about two years, installation of the last detector in 2010.

New neutrino beams

Pion Decays $\pi^+ \rightarrow \mu^+\nu_\mu, \pi^- \rightarrow \mu^-\bar{\nu}_\mu$ **Superbeam**

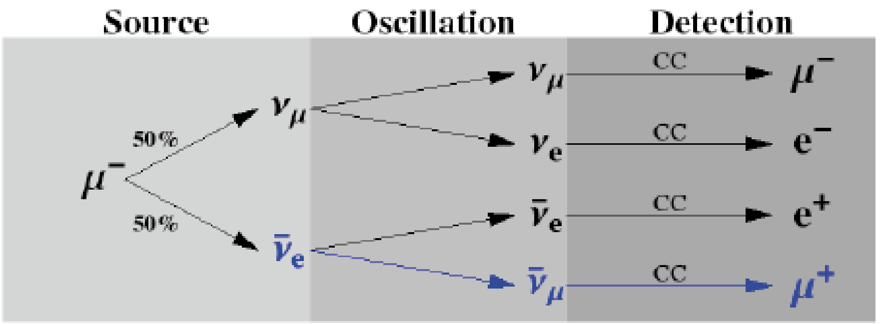


$\nu_\mu \rightarrow \nu_e$ oscillation most interesting
ν_e contamination ⇔ off-axis
good electron detection efficiency
good NC background rejection
near detector
$\bar{\nu}$-beam $\simeq$ different experiment

Beta Decays ${}^Z_A X \rightarrow {}^{Z-1}_A Y e^+ \nu_e,\ {}^Z_A X \rightarrow {}^{Z+1}_A Z e^- \bar{\nu}_e$

Beta Beam

Muon Decays $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu, \mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$ **Neutrino Factory**



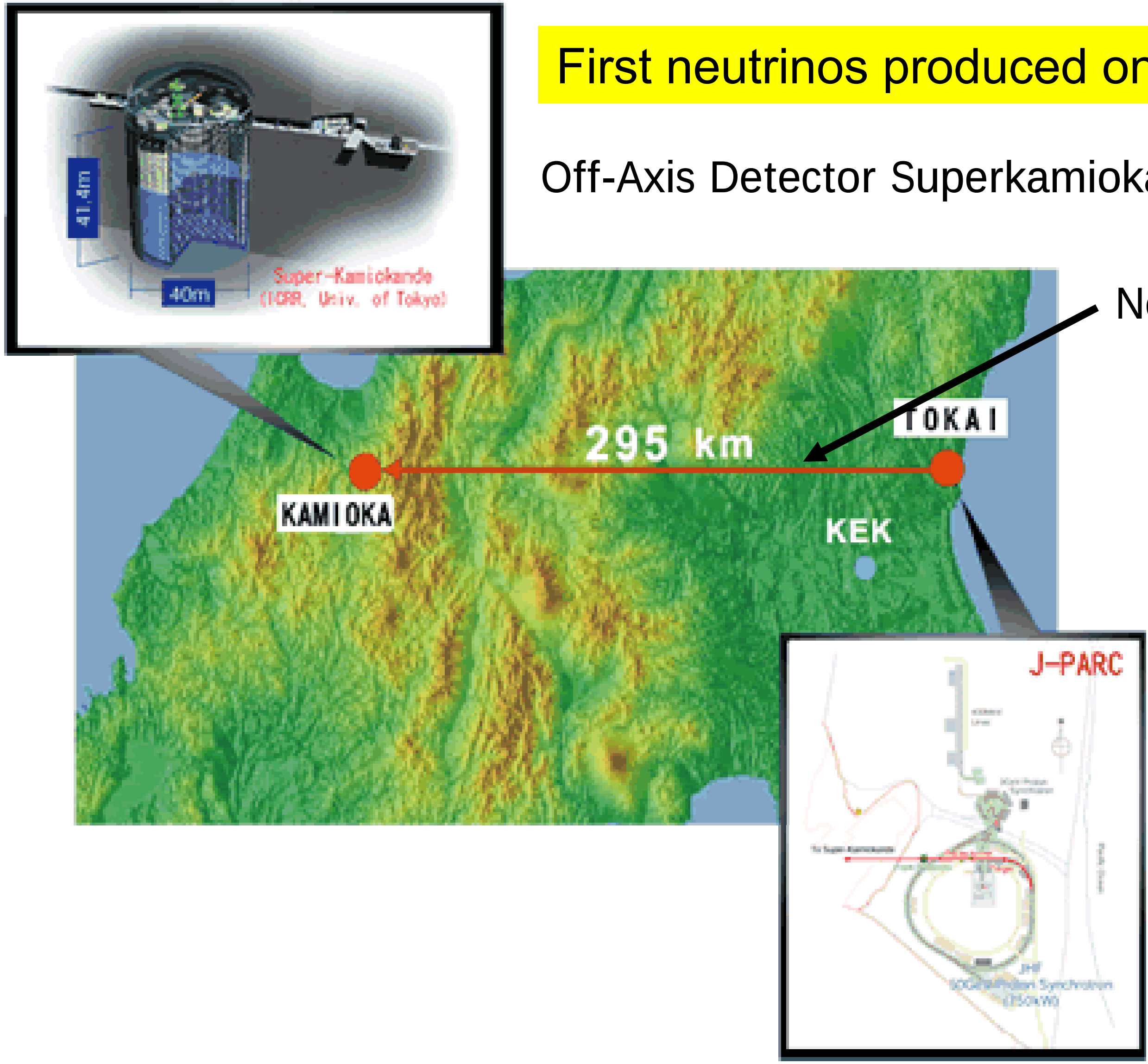
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation most interesting
excellent beam properties
very good charge ID required
good NC background rejection
μ^+ mode very symmetric

T2K (Tokai to Kamioka)

First neutrinos produced on April 23rd 2009!

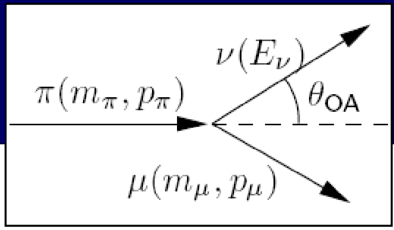
Off-Axis Detector Superkamiokande

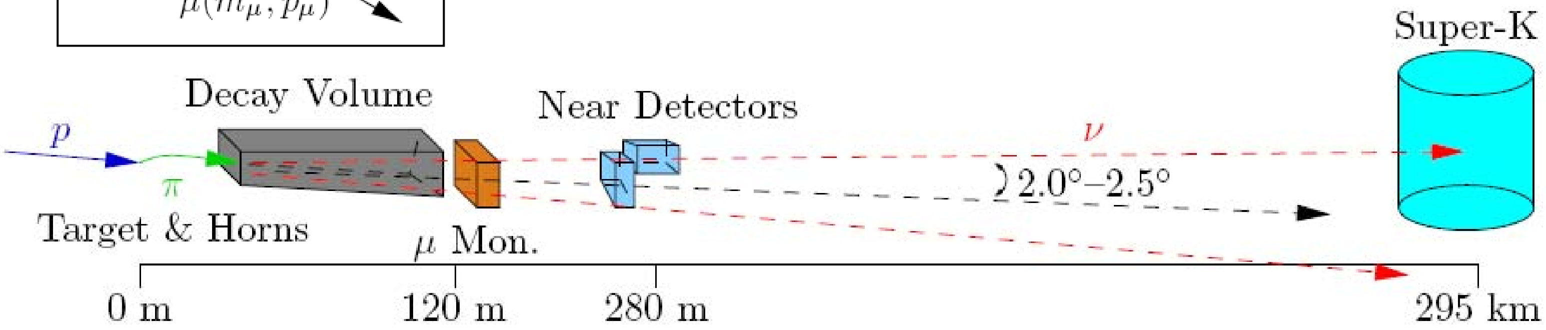
Neutrino Super Beam

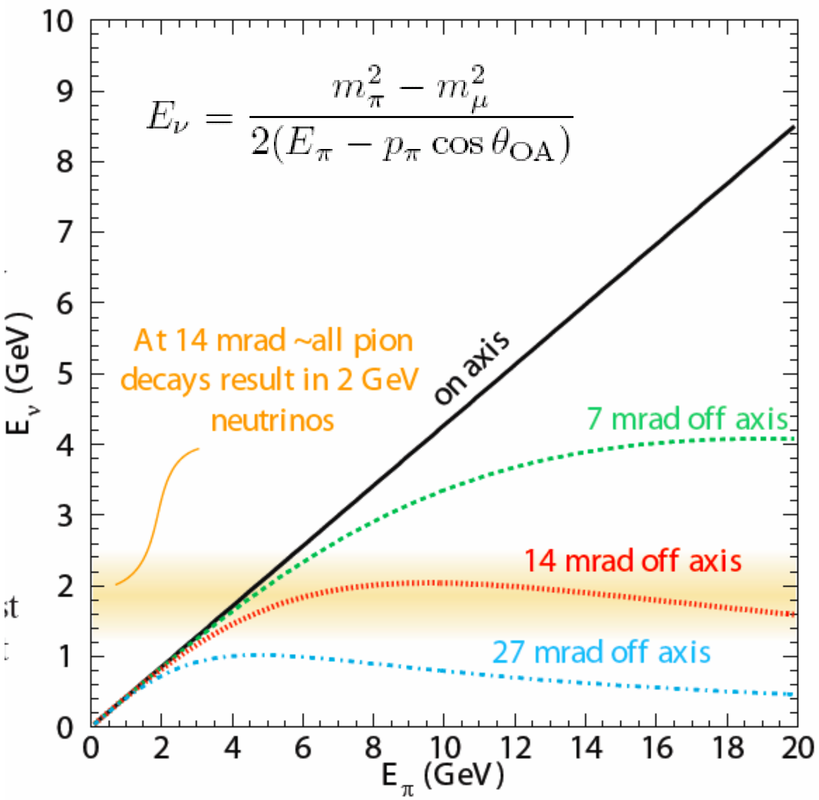


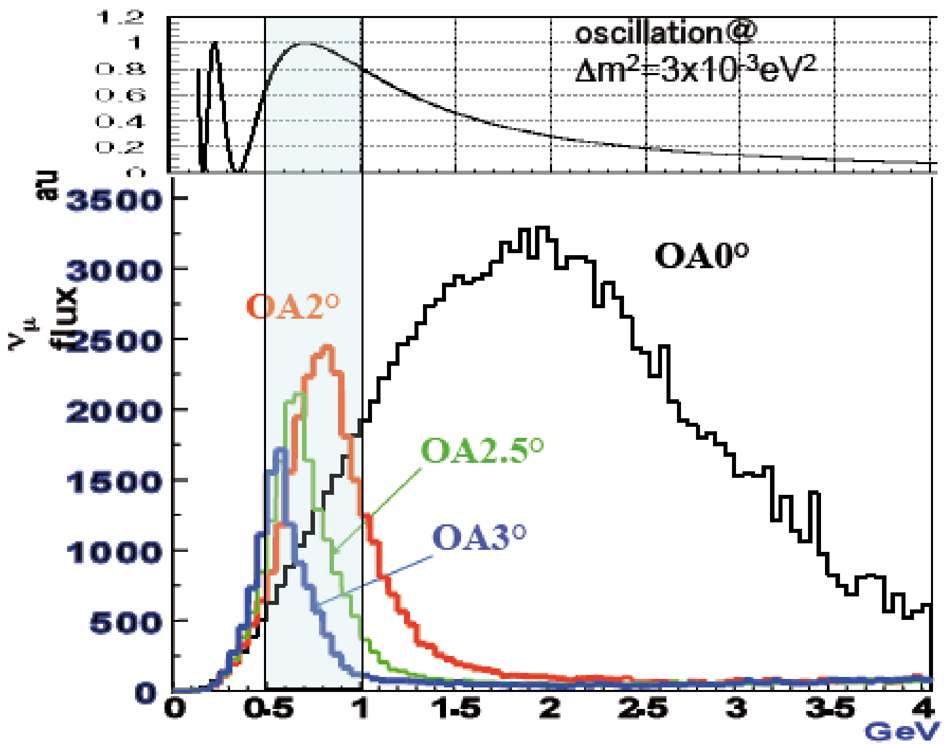
Proton driver

Off axis beams



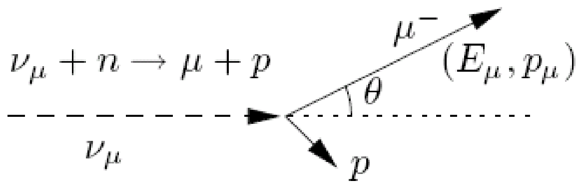


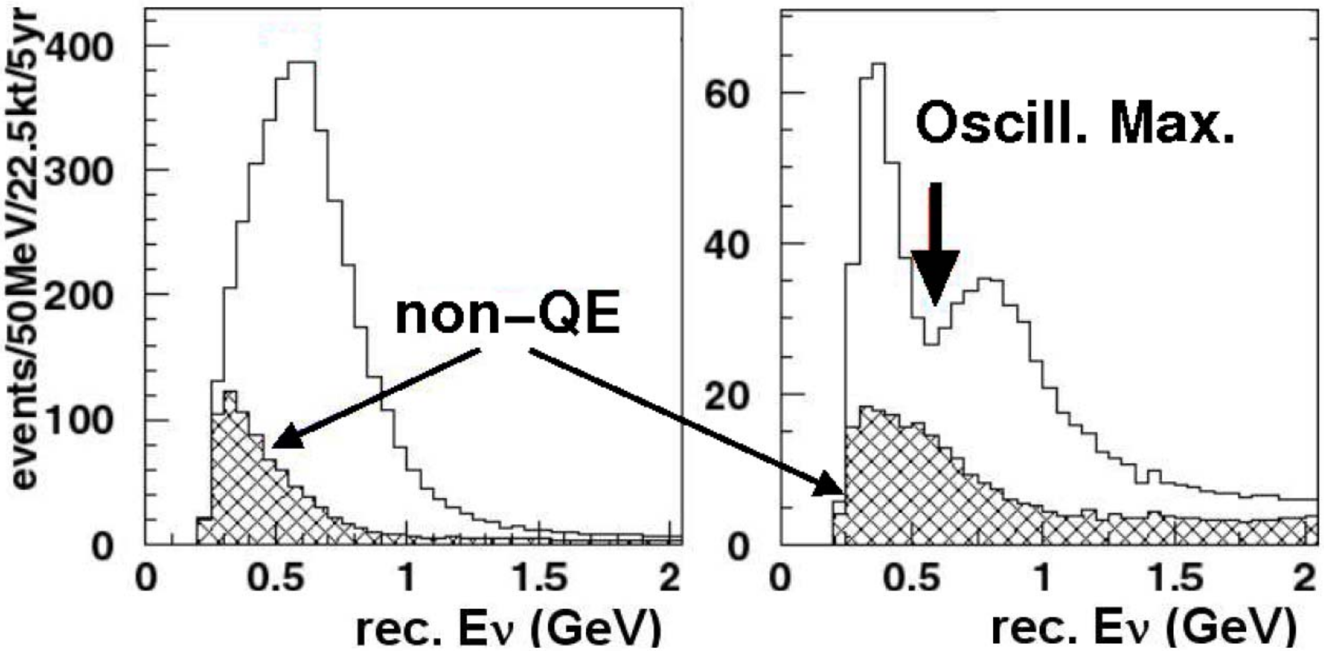




T2K: expected precision on Δm^2_{23} and θ_{23}

use quasi-elastic events:

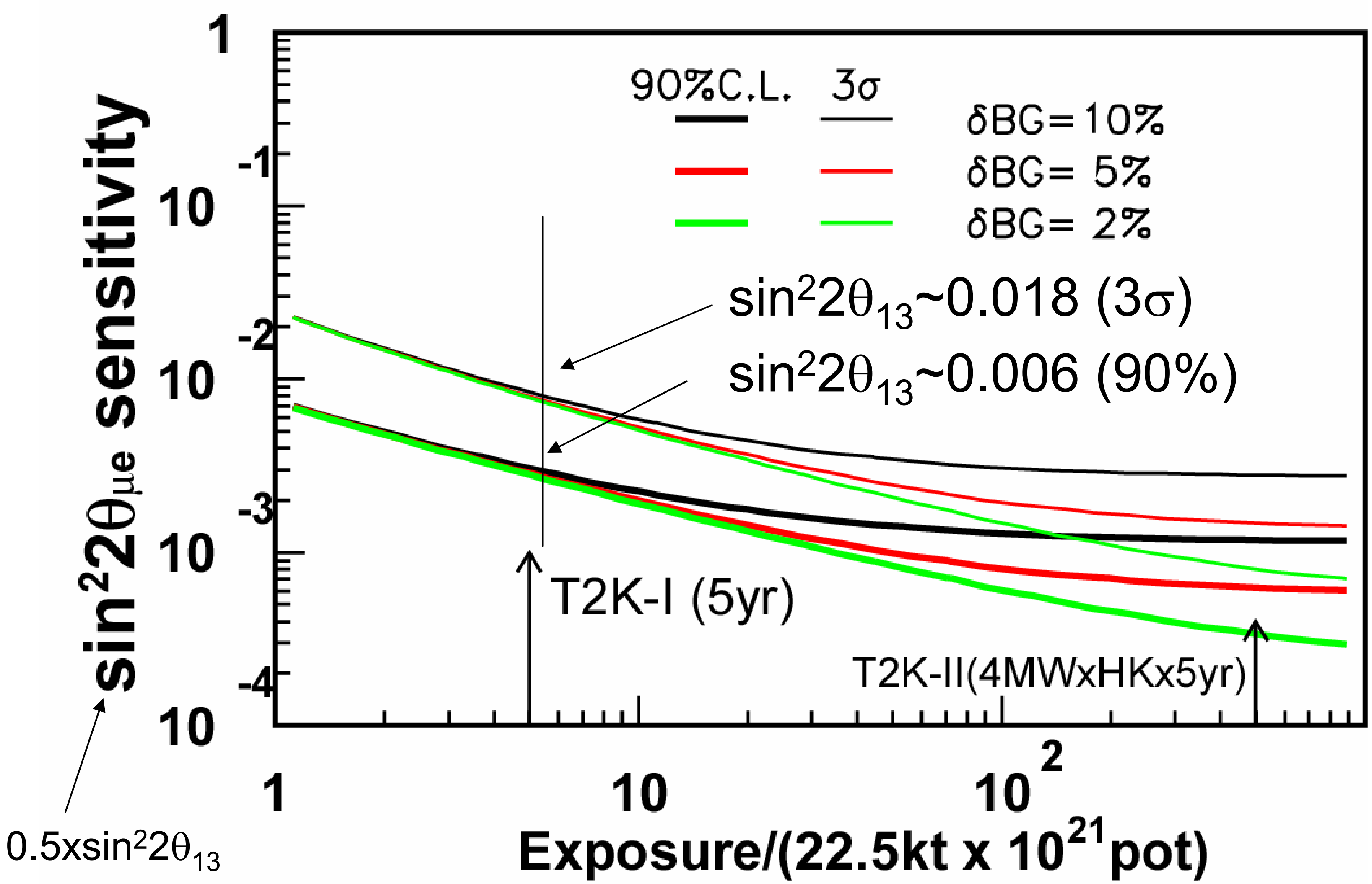




$$\delta(\sin^2 2\theta_{23}) \simeq 0.01$$

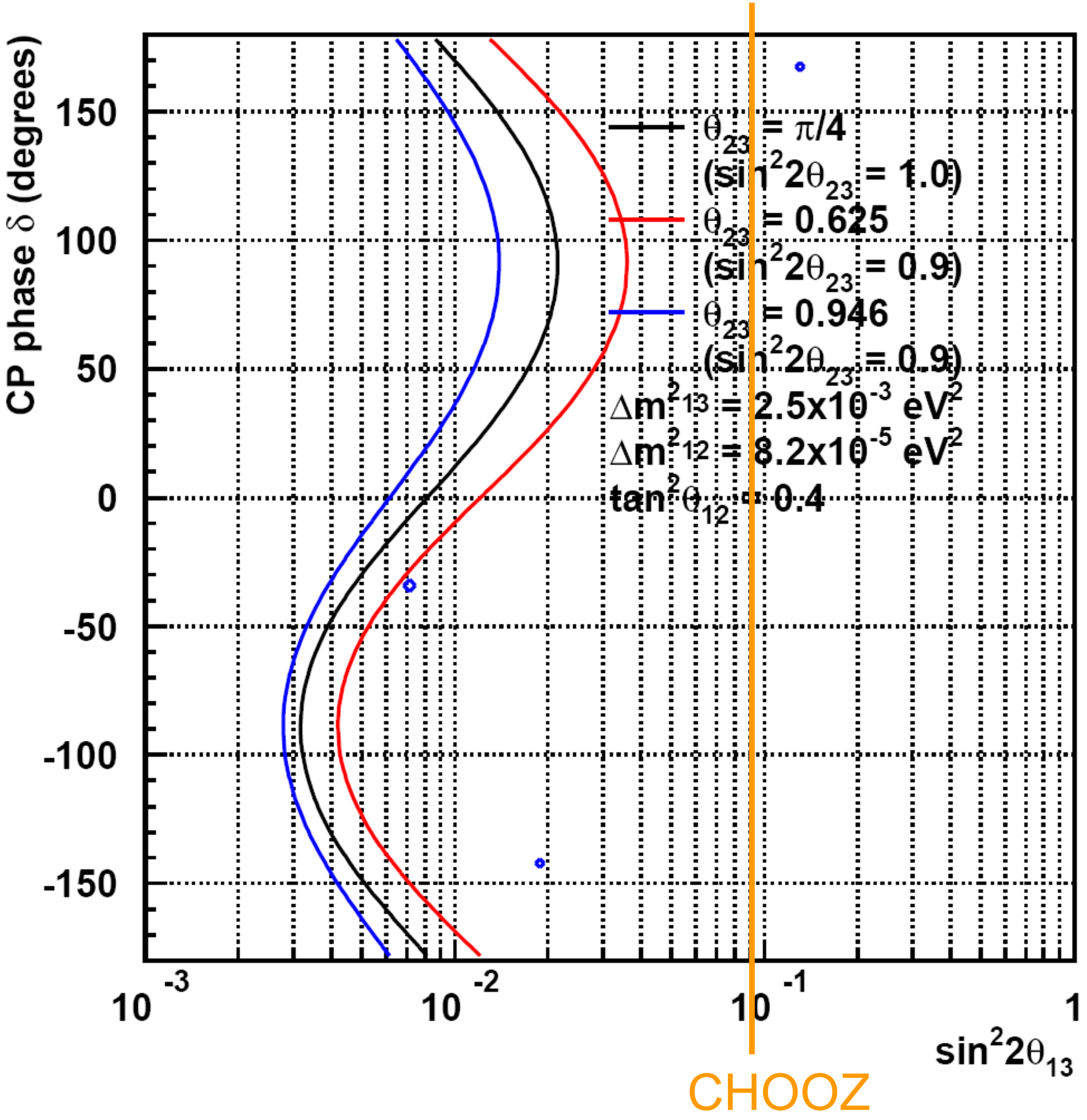
$$\delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$$

T2K: Sensitivity for θ_{13}



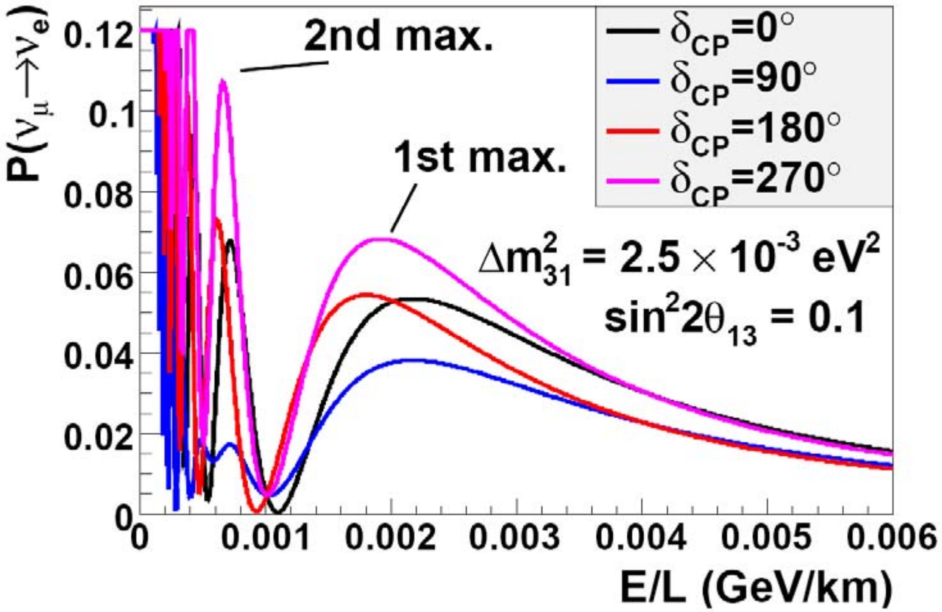
$\sin^2 2\theta_{13} < 10^{-3}$ can be searched if syst err ~ few %

T2K: expected sensitivity for θ_{13} and δ_{CP}

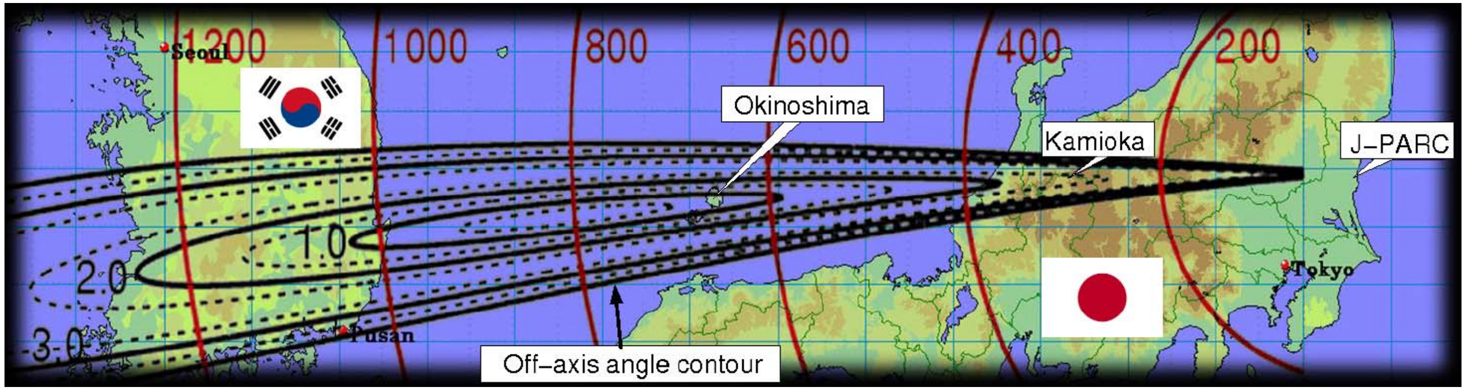


Future plans to upgrade T2K

Idea: use ratio (1st max)/(2nd max) to measure δ_{CP}:
→ need to observe also 2nd max in E (different energy = different off axis angle)

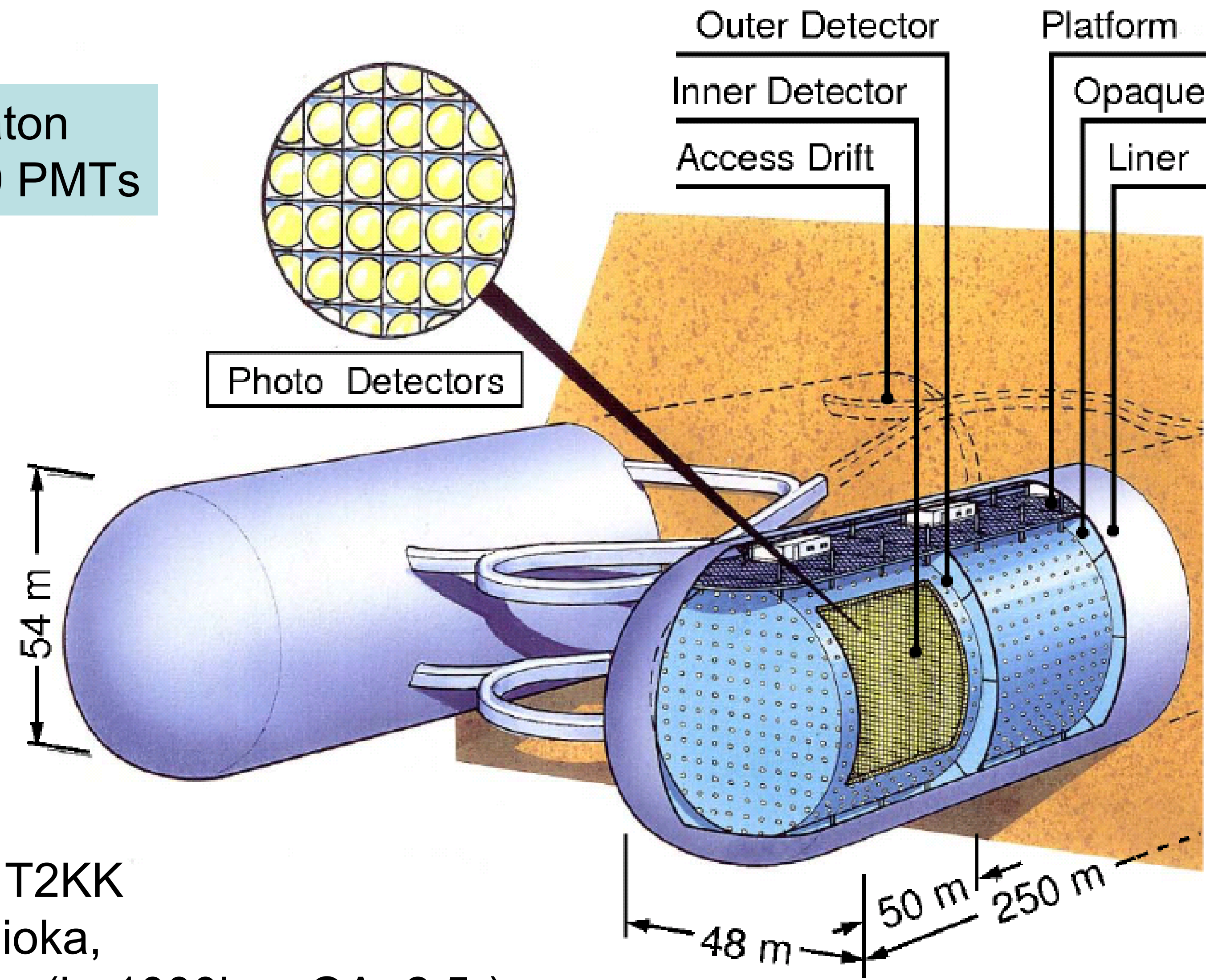


Could be realized with Liquid Argon TPC @ island Okinoshima (L = 658km, OA=0.76°)



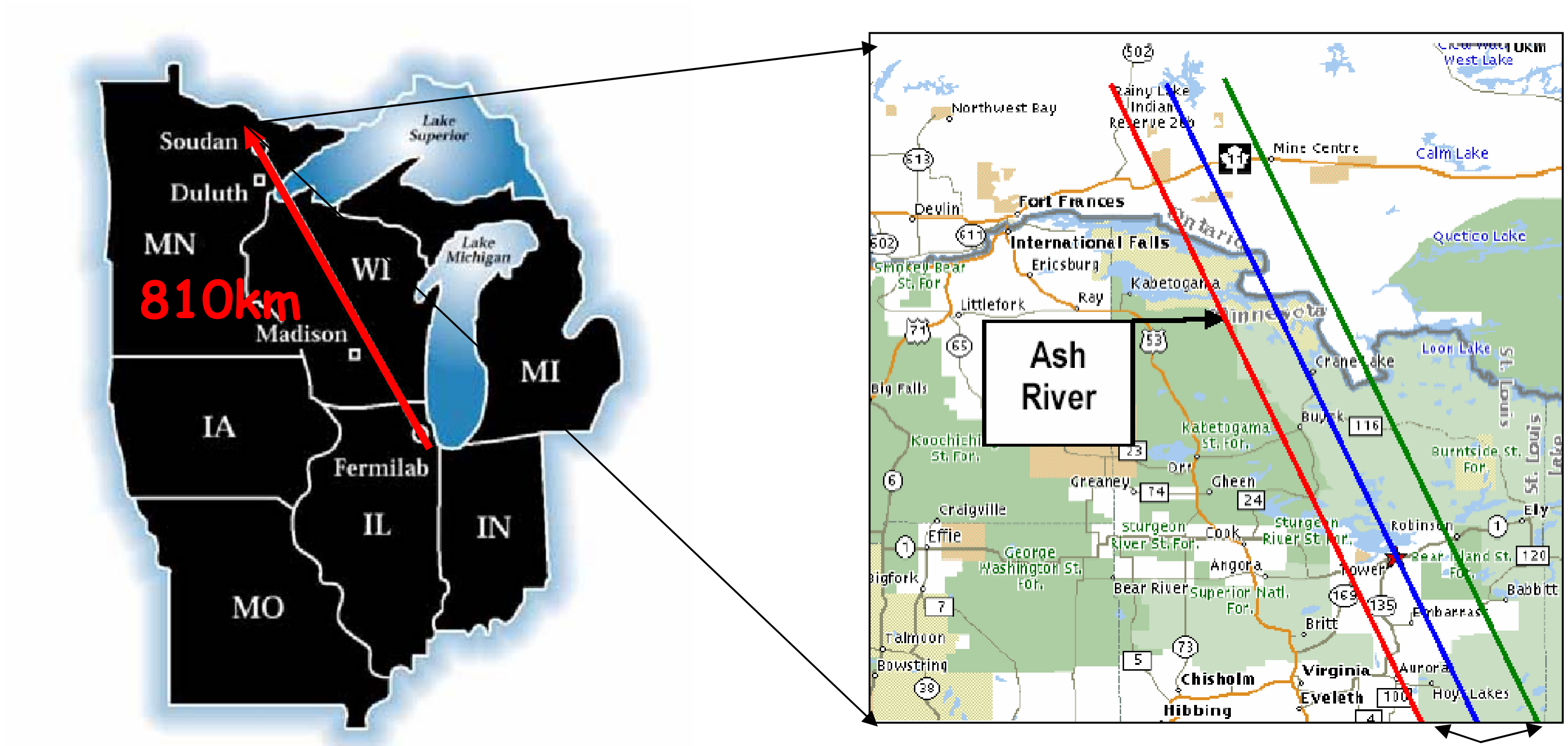
Future plans to upgrade T2K: Hyper-Kamiokande

1 Megaton
200000 PMTs



Possible project: T2KK
1 HyperK in Kamioka,
1 HyperK in Korea (L=1000km, OA=2.5°)

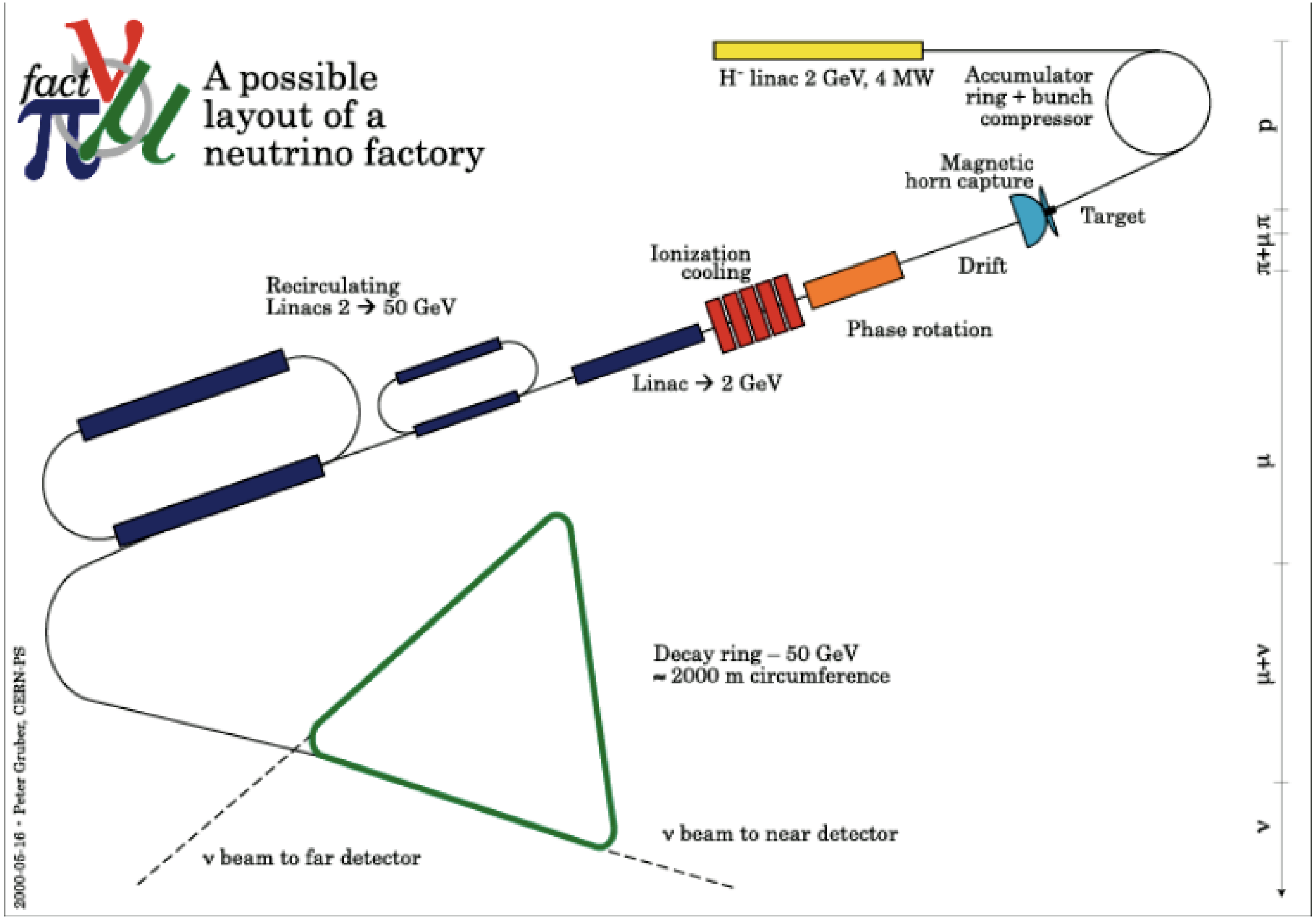
NOvA



16mrad off-axis

@Fermilab: increase beampower from 400kW to 700kW
far detector: 15 kton liquid scintillator (groundbraking jan 09)
construction complete in 2014, 6 years measurement.

Neutrino factories



Neutrino factories

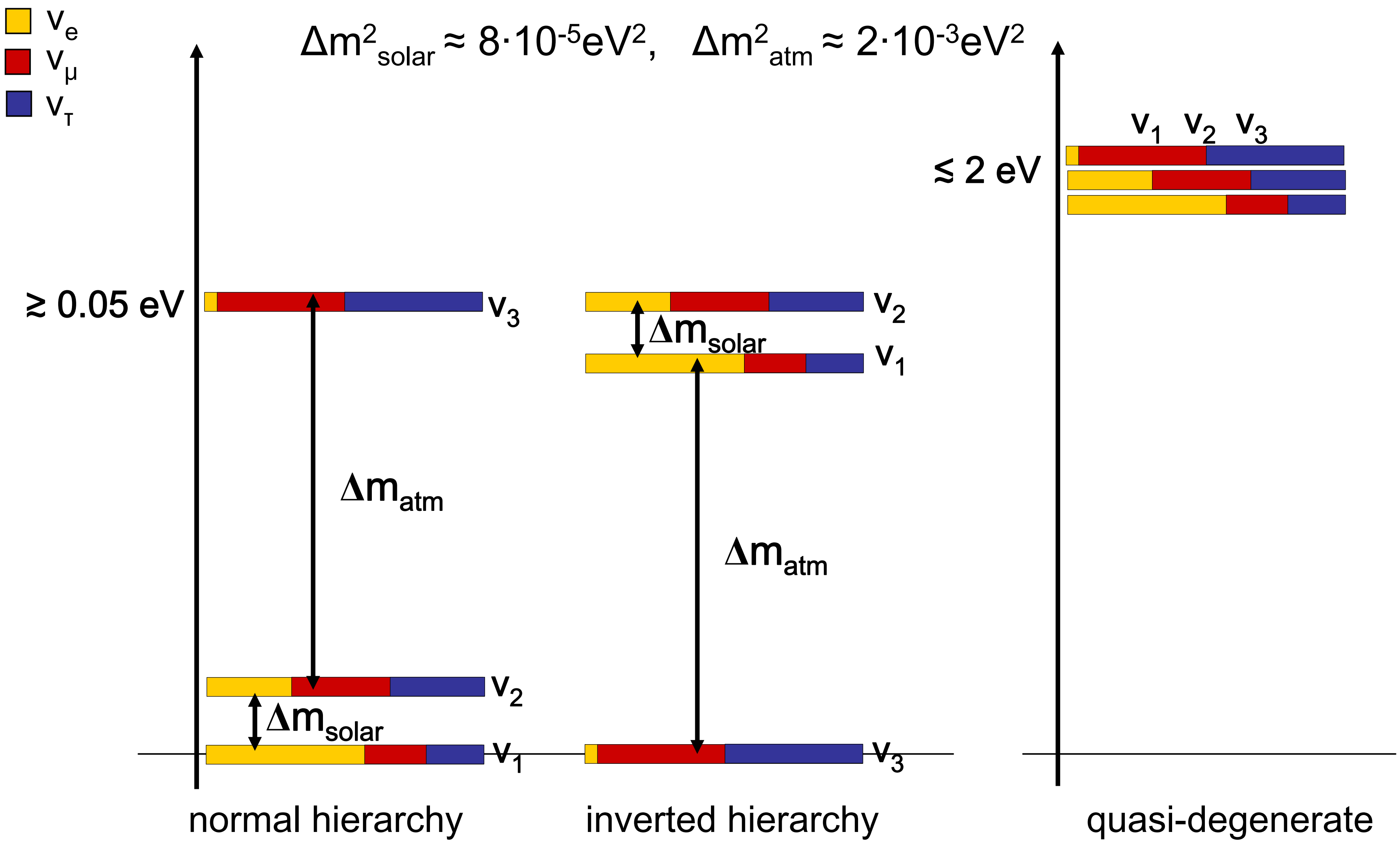
12 Oscillation Processes in a Neutrino Factory

12 Oscillation Processes from (simultaneous) beams of positive and negative muons in a neutrino Factory.

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \bar{\nu}_e \nu_\mu$		
$\overline{\nu}_\mu \to \overline{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance	
$\overline{\nu}_\mu \to \overline{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)	
$\overline{\nu}_\mu \to \overline{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation	platinum
$\nu_e \to \nu_e$	$\overline{\nu}_e \to \overline{\nu}_e$	disappearance	
$\nu_e \to \nu_\mu$	$\overline{\nu}_e \to \overline{\nu}_\mu$	appearance: “golden” channel	golden
$\nu_e \to \nu_\tau$	$\overline{\nu}_e \to \overline{\nu}_\tau$	appearance: “silver” channel	silver

What do we know about neutrino masses?

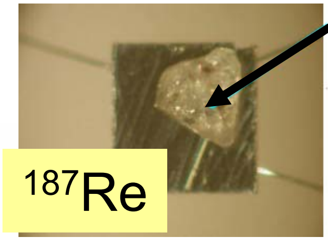
$\Delta m^2_{solar} \approx 8 \cdot 10^{-5} eV^2, \quad \Delta m^2_{atm} \approx 2 \cdot 10^{-3} eV^2$

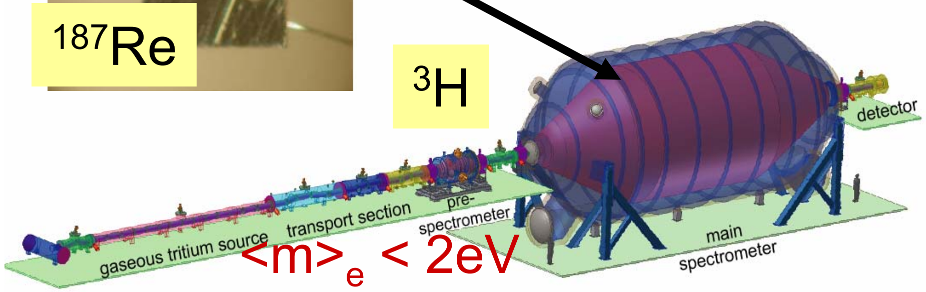


Neutrino Mass Measurements Strategies

β decay kinematics:

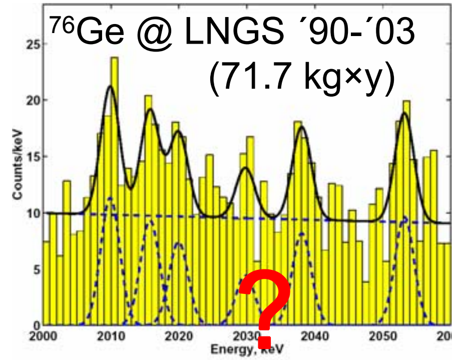
- Microcalorimeters
- MAC-E spectrometers

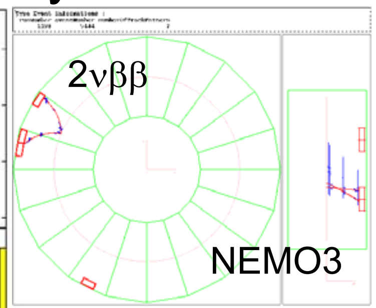




$<m>_e < 2eV$

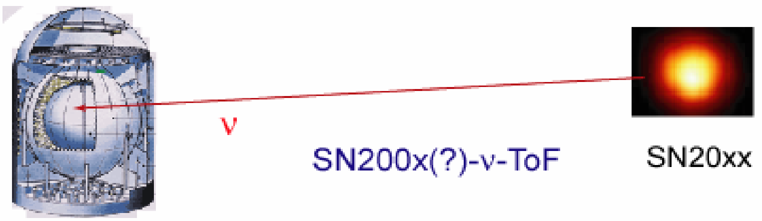
0νββ decay:





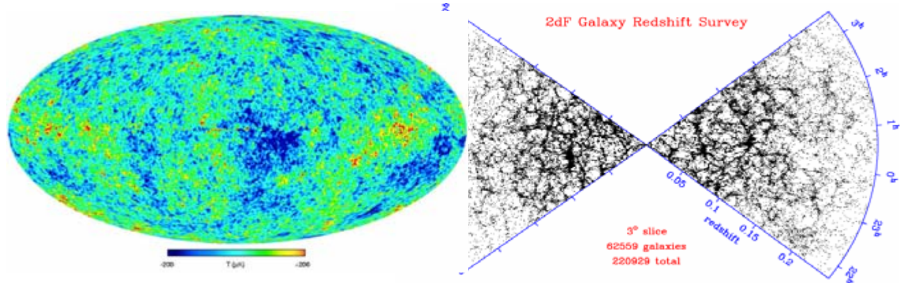
$|m_{ee}|=0.44^{+0.13}_{-0.2}$ eV

astrophysics: supernova time of flight measurements



SuperK, SNO, OMNIS + grav.waves:
potential for ~1eV sensitivity?

cosmology &structure formation

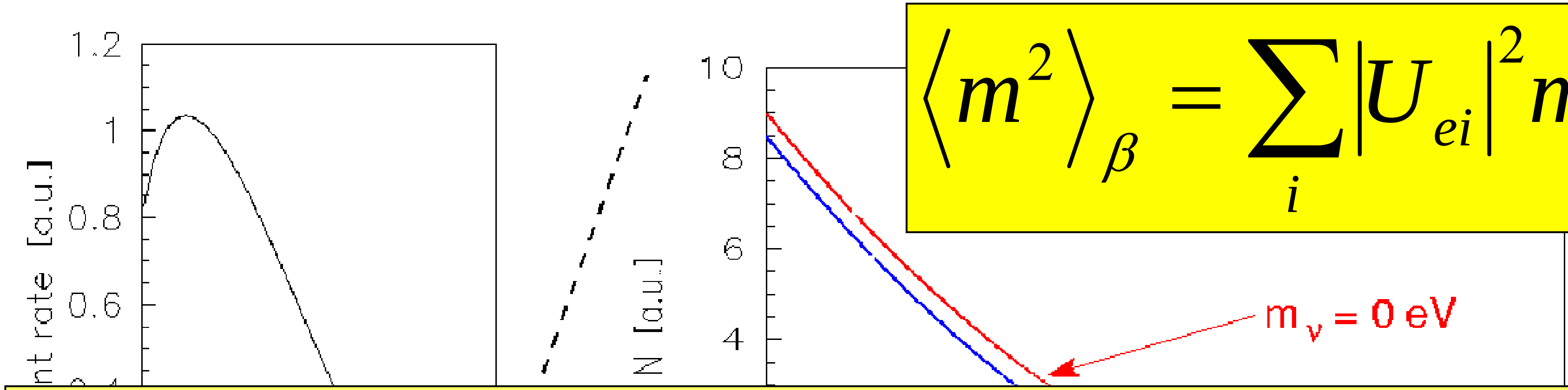


D.N. Spergel et al: $\Sigma m_\nu < 0.69$ eV (95%CL)
S.W. Allen et al: $\Sigma m_\nu = 0.56$ eV (best fit)

Tritium β-Decay: Mainz/Troitsk

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{e}^{-} + \overline{\nu}_e \qquad E_0 = 18.6\ \mathrm{keV}$$

$$dN/dE = K \times F(E,Z) \times p \times E_{tot} \times (E_0 - E_e) \times [\, (E_0 - E_e)^2 - \mathbf{m_\nu^2} \,]^{1/2}$$



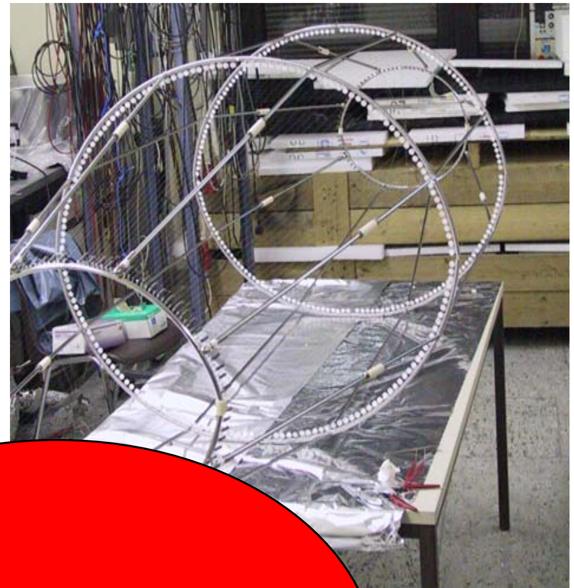
$$\left\langle m^2 \right\rangle_\beta = \sum_i \left| U_{ei} \right|^2 m_i^2$$

Mainz Data (1998,1999,2001)

$$\left\langle m^2 \right\rangle_\beta = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2 \quad \Rightarrow \quad \left\langle m \right\rangle_\beta < 2.2\mathrm{eV}\ (95\%\mathrm{CL})$$

KATRIN Main Spectrometer

- stainless steel vessel (Ø=10m & l=22m) on HV potential
- minimisation of bg → UHV: p ≤ 10^{-11} mbar
  → „massless“ inner electrode system



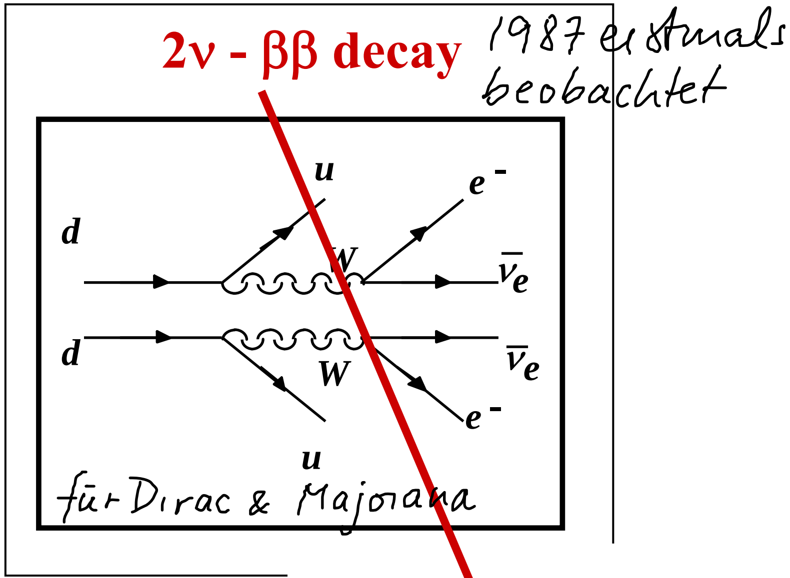
UHV requirements:
outgassing < 10^{-13} mbar l/s
inner surface ~ 800m²
volume to pump ~ 1500m³

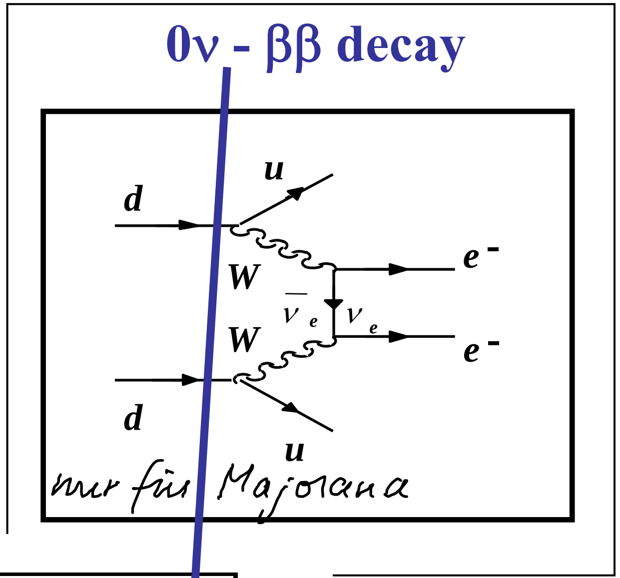
goal:

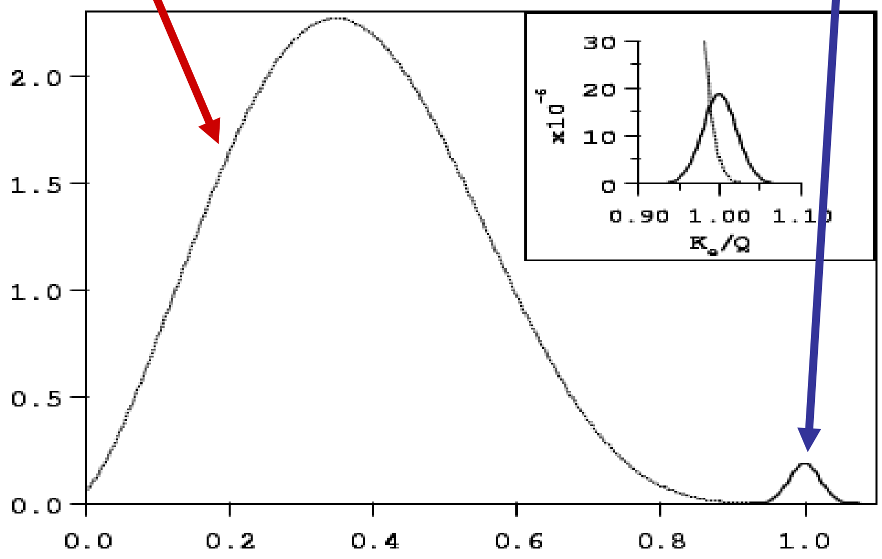
$$\langle m \rangle_\beta < 0.20\,\mathrm{eV}$$

KATRIN: delivery of vacuum vessel

2ν and 0ν double beta - decay

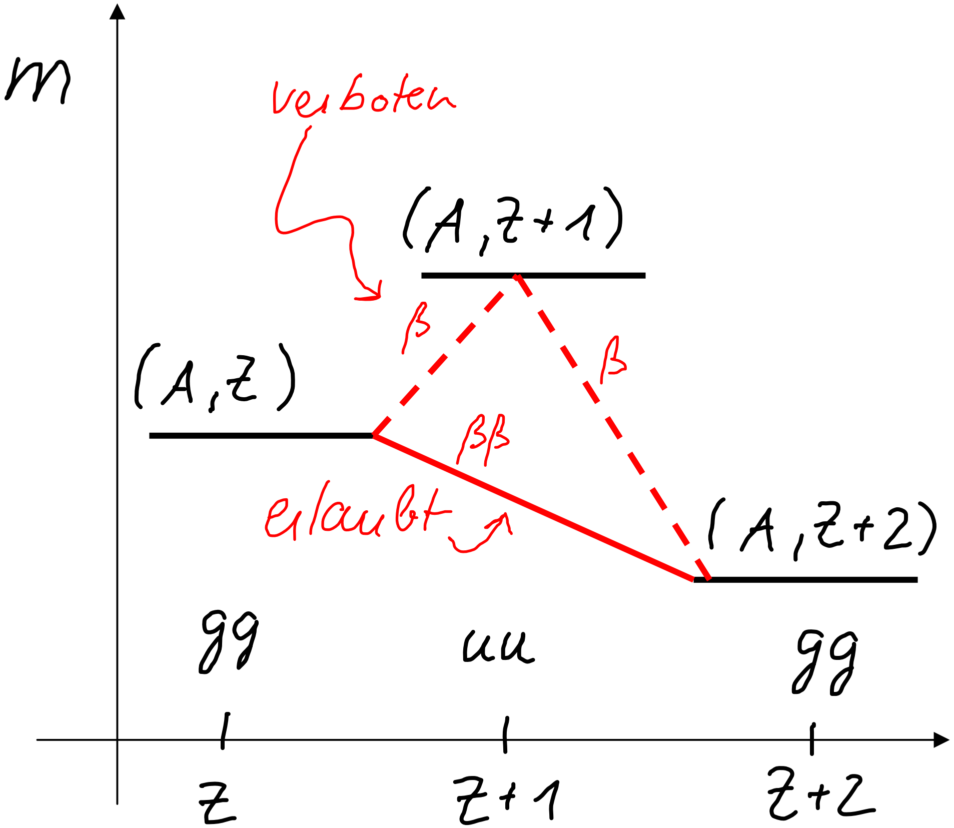


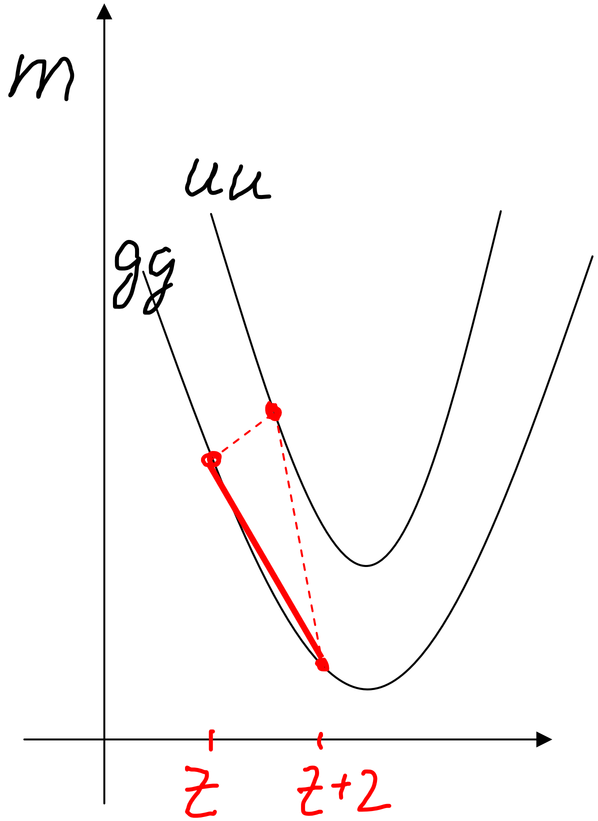




Sum energy of electrons (E/Q)

Which isotopes undergo ββ-transition?





z.B ^{76}Ge, ^{100}Mo, ^{130}Te, ^{150}Nd, ^{116}Cd

Neutrinoless Double Beta Decay

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \right|^2 \langle m_\nu \rangle_{\beta\beta}^2$$

Phase space factor

Transition matrix element

Effective neutrino mass

Effective neutrino mass in 0νββ-decay:

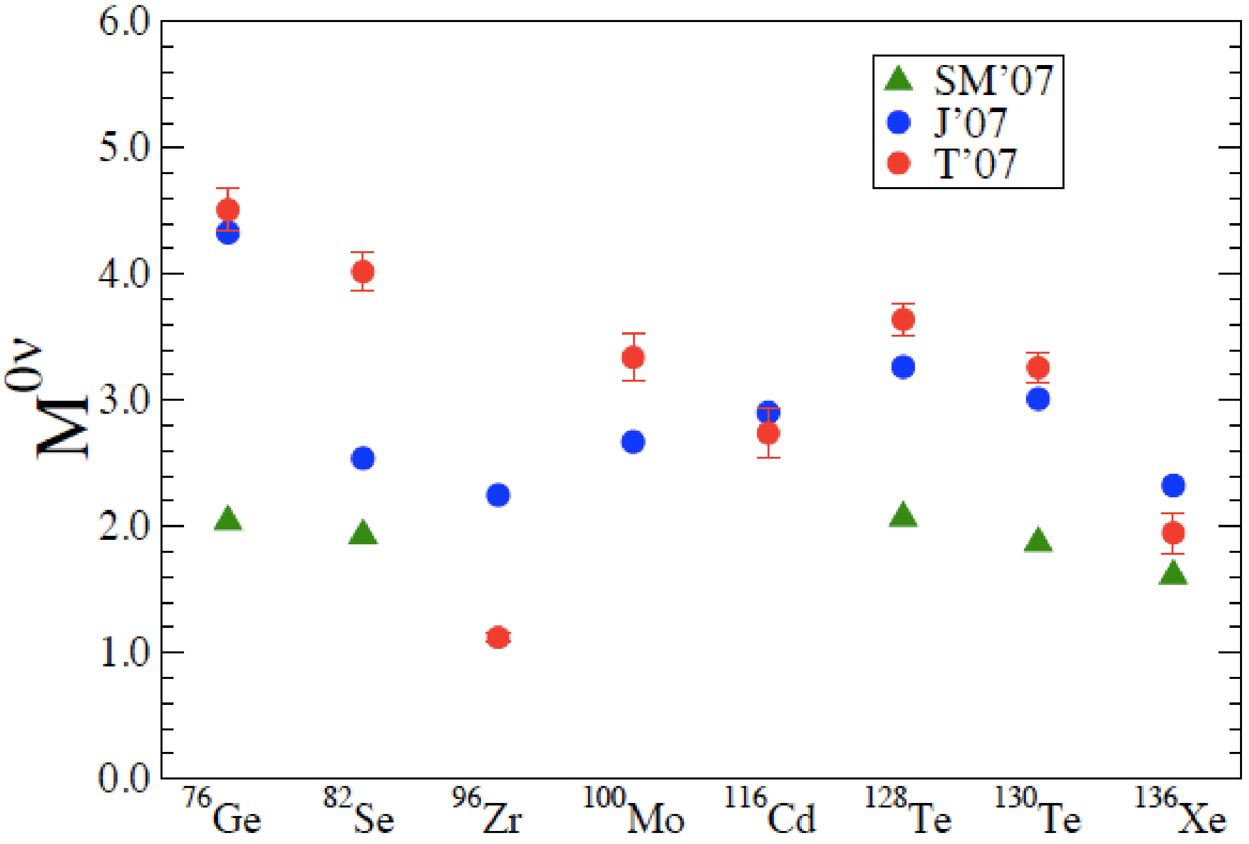
$$\langle m \rangle_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

Compare to β-decay:

$$\langle m^2 \rangle_\beta = \sum_i m_i^2 \left| U_{ei} \right|^2$$

Problem: trasition matrix elements

Must be calculated, still large uncertainties



Complex phases in the mixing matrix

Dirac CP-Phase

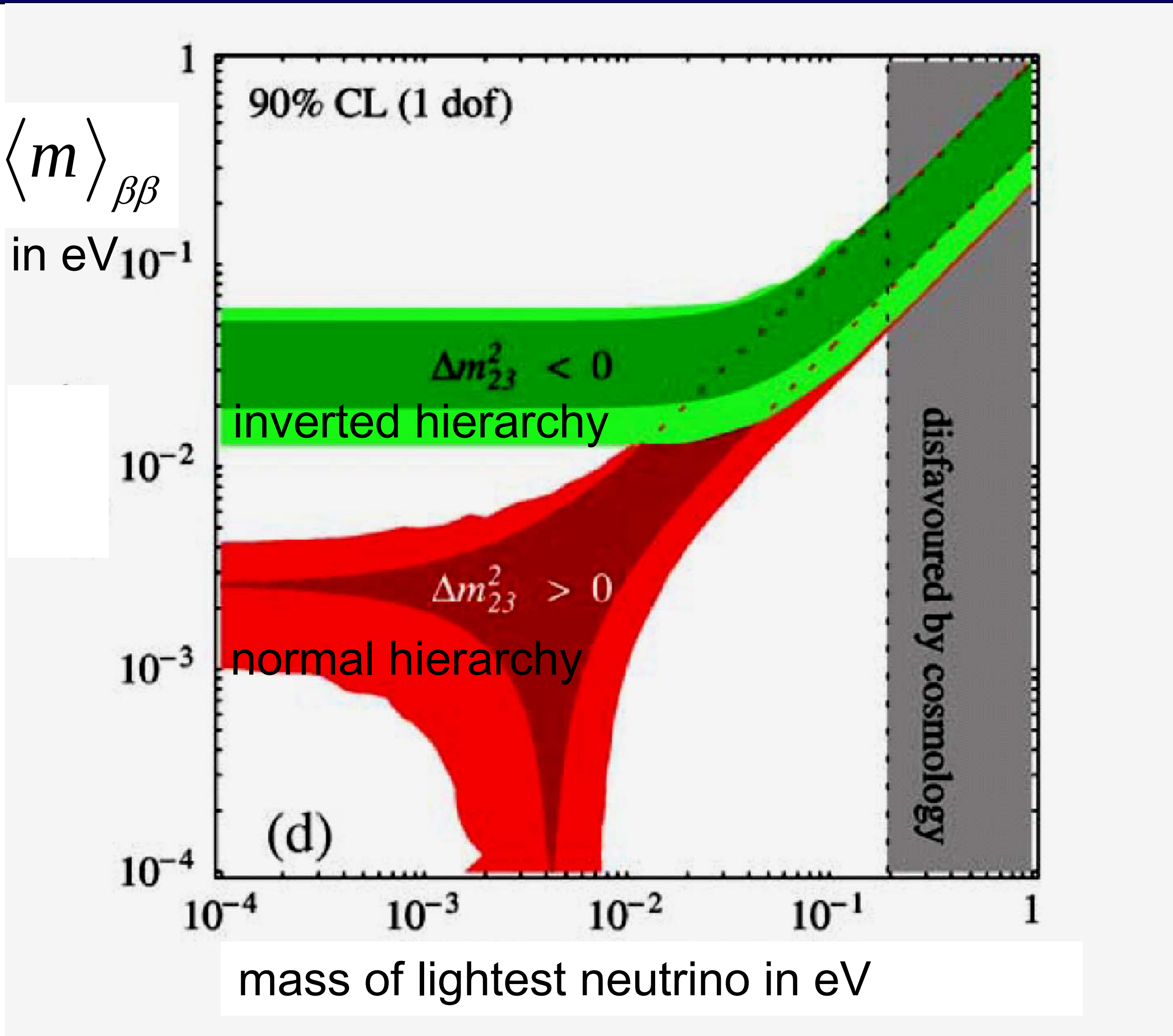
Majorana CP-Phases

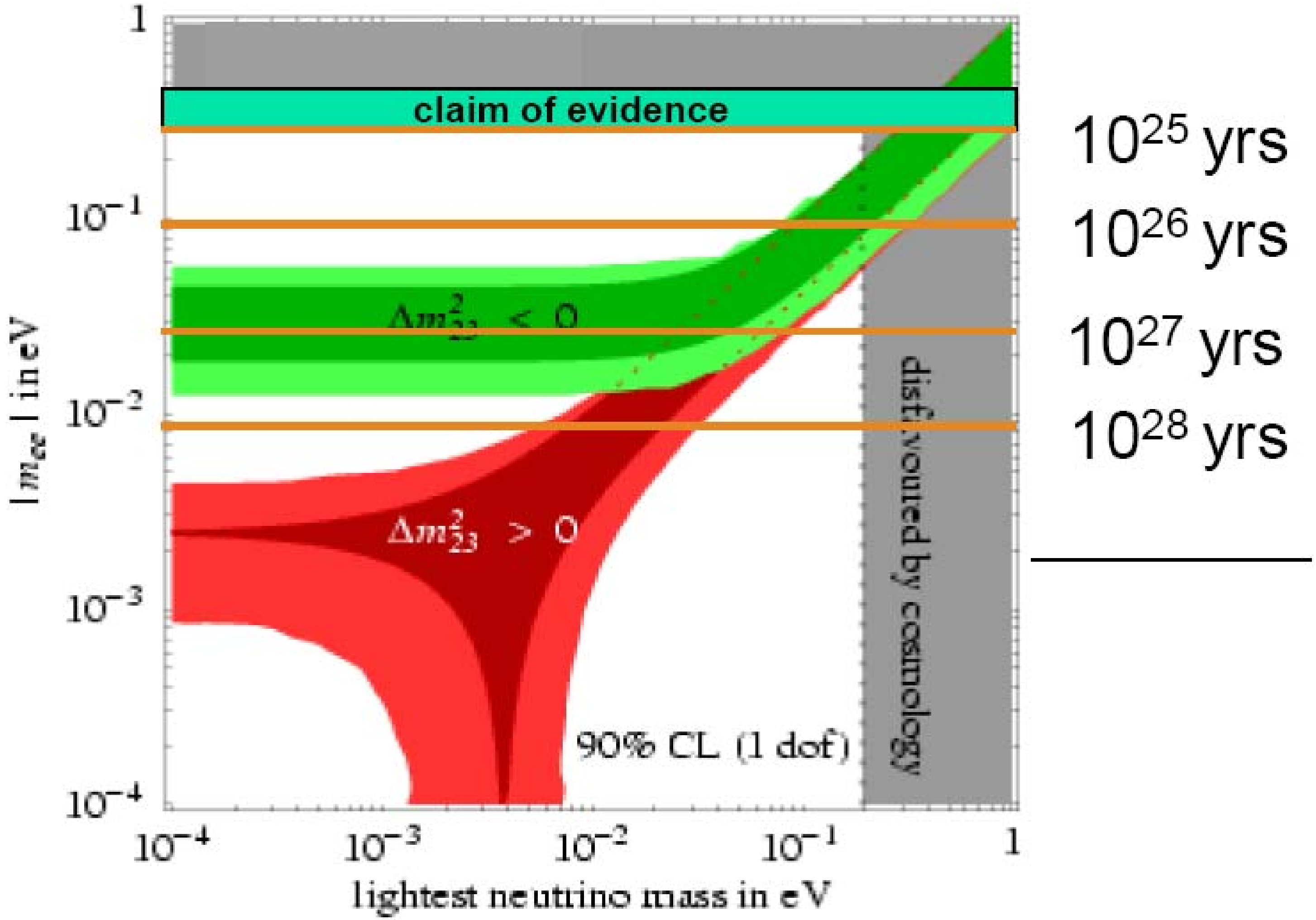
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha_1} & s_{13}e^{-i\delta}e^{i\alpha_2} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & [c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & s_{23}c_{13}e^{i\alpha_2} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & [-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & c_{23}c_{13}e^{i\alpha_2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\langle m \rangle_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right| = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{i\alpha_1} + m_3 U_{e3}^2 e^{i\alpha_2} \right|$$

Cancellation possible!

What does ßß-decay tell about mass of lightest neutrino?




claim of evidence
$\Delta m^2_{23} < 0$
$\Delta m^2_{23} > 0$
90% CL (1 dof)
disfavoured by cosmology
$|m_{ee}|$ in eV
lightest neutrino mass in eV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{25} yrs
10^{26} yrs
10^{27} yrs
10^{28} yrs

0ν Doppel-Beta experiments: results

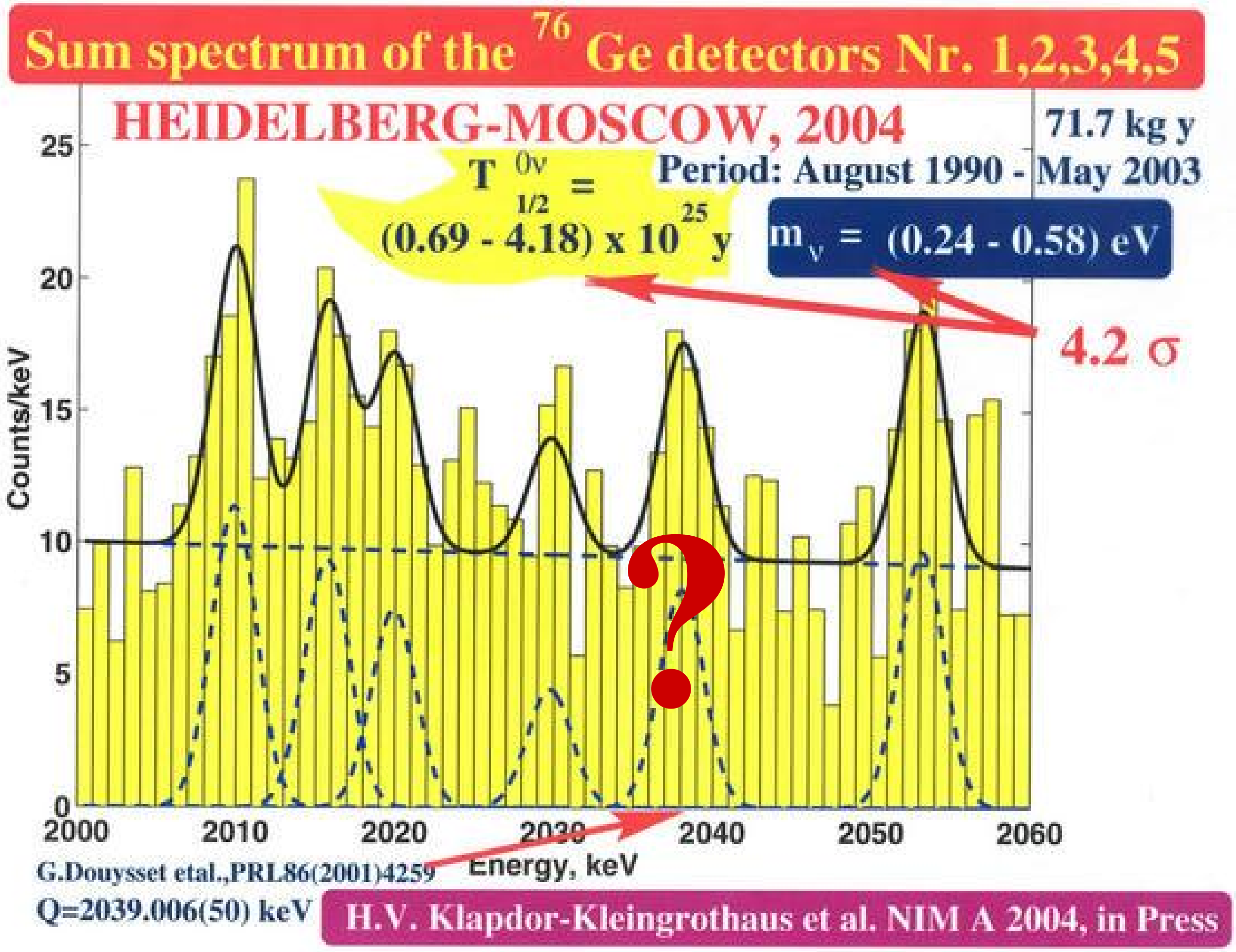
$$\langle m \rangle_{\beta\beta} < 0.35\,\text{eV} \quad (90\%\ \text{CL})$$

Heidelberg-Moskau Collaboration, Eur.Phys.J. A12 (2001) 147
IGEX Collaboration, hep-ex/0202026, Phys. Rev. C59 (1999) 2108

Isotope	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 9.5 \times 10^{21}$(76%)	< 8.3
^{76}Ge	$> 1.9 \times 10^{25}$ HM-K	< 0.35
	$> 1.6 \times 10^{25}$ IGEX	$< 0.33 - 1.35$
^{82}Se	$> 2.7 \times 10^{22}$(68%)	< 5
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
^{116}Cd	$> 7 \times 10^{22}$	< 2.6
^{128}Te	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
^{130}Te	$> 2.1 \times 10^{23}$	$< 0.85 - 2.1$
^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{150}Nd	$> 1.2 \times 10^{21}$	< 3

all 90%CL

But: Part of HdM collaboration has published evidence for 0ν double - beta decay!



(Q = 2039 keV for ^{76}Ge)

Heidelberg-Moskau Experiment (HDM)

5 Ge-Detektoren
(angereichert mit ^{76}Ge)

„Die Detektoren zerfallen!"

Future Projects

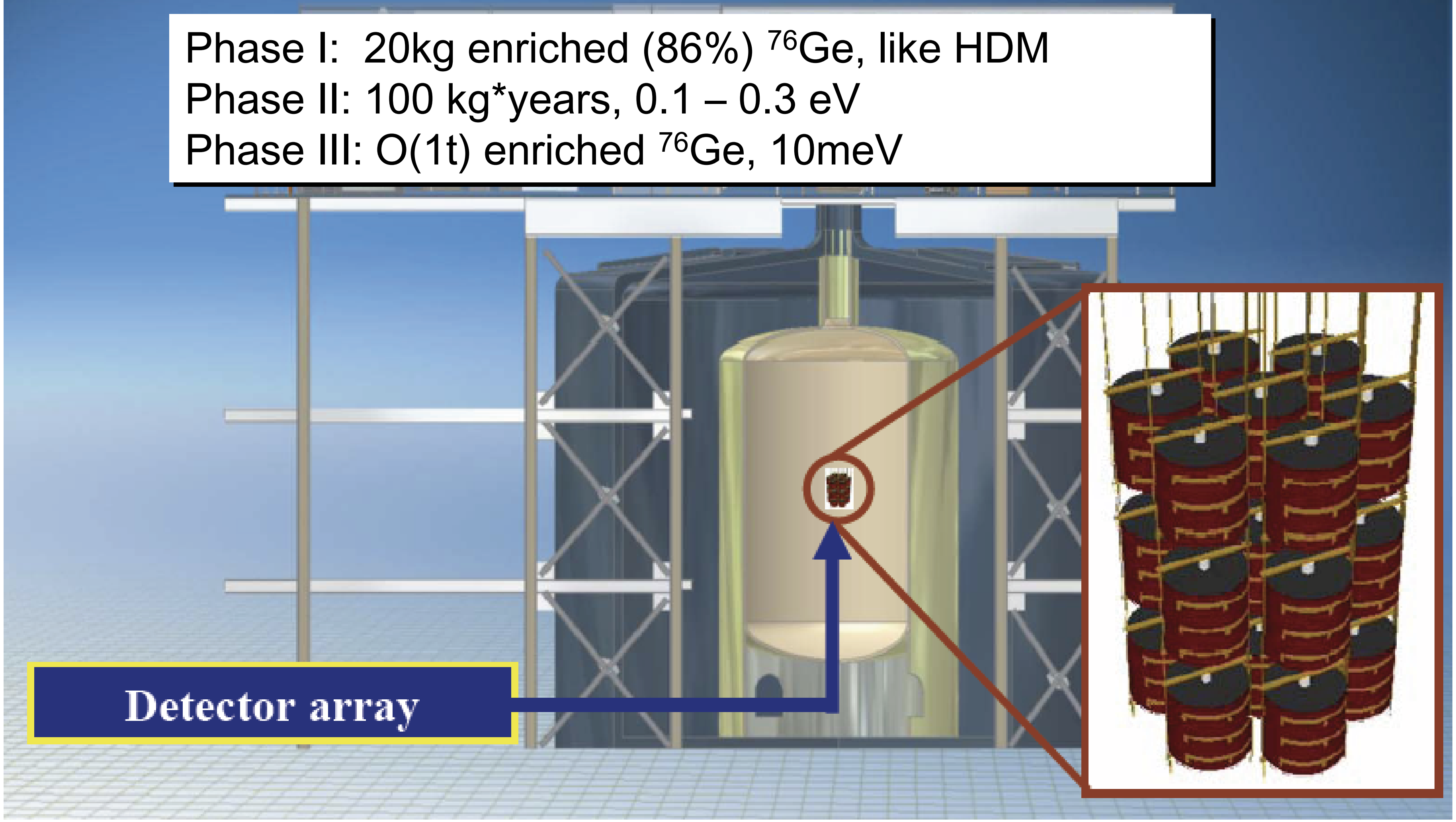
Experiment	Isotope	Experimental approach
CANDLES	48Ca	Several tons of CaF_2 crystals in Liquid scintillator
CARVEL	^{48}Ca	100 kg $^{48}CaWO_4$ crystal scintillators
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors
→ CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers Cuoricino (bis Juni 08)
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)
→ GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, expand to larger masses
GSO	^{160}Gd	2t Gd_2SiO_3:Ce crystal scintillator in liquid scintillator
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses
MOON	^{100}Mo	several tons of Mo sheets between scint.
→ SNO++	^{150}Nd	1000 t of Nd-loaded liquid scint.
→ SuperNEMO	^{82}Se	100 kg of Se foils between TPCs NEMO-3
Xe	^{136}Xe	1.56 t of Xe in liquid scint.
XMASS	^{136}Xe	10 t of liquid Xe

Aus K. Zuber, Acta Polonica B 37, 1905 (2006)

GERDA @ LNGS

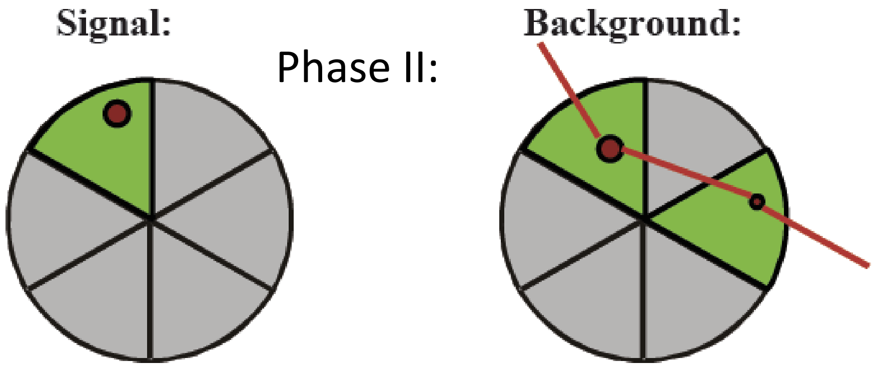
➢Place array of naked HPGe-detectors enriched in ^{76}Ge in the center of a stainless cryostat filled with LAr.

Phase I: 20kg enriched (86%) ^{76}Ge, like HDM
Phase II: 100 kg*years, 0.1 – 0.3 eV
Phase III: O(1t) enriched ^{76}Ge, 10meV

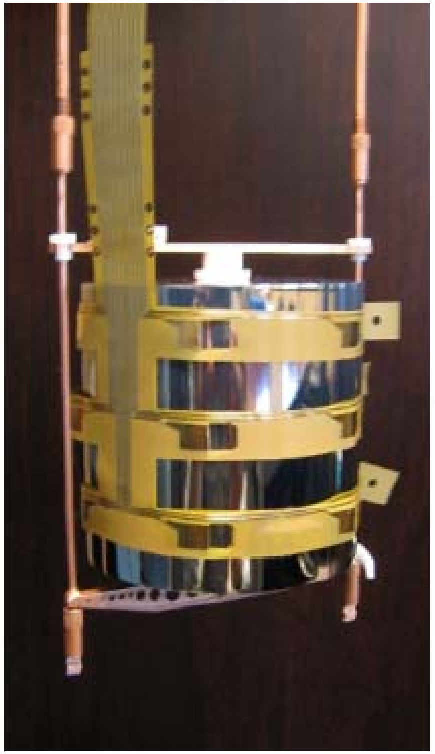


Status GERDA

GERDA Detectors



Phase II:



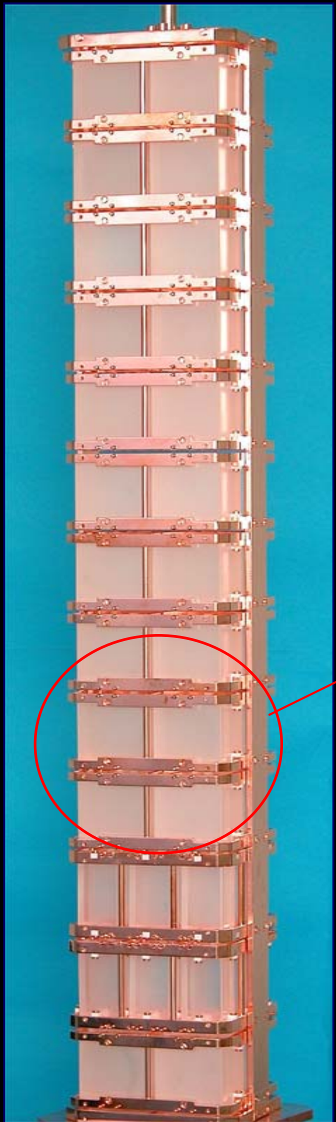
18 fold segmented detector to run in LAr

CUORICINO → CUORE

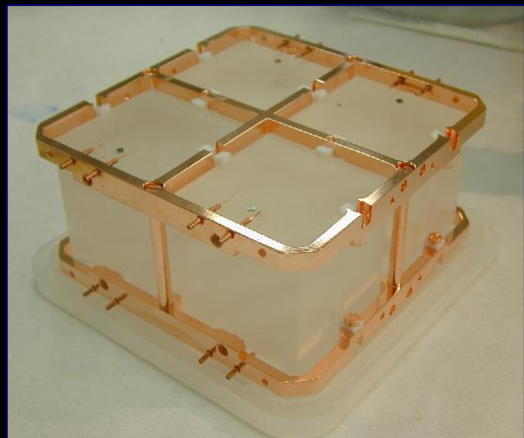
2v double beta with ^{130}Te (Q=2529 keV)

18 crystals 3x3x6 cm3 + 44 crystals 5x5x5 cm3
40.7 kg of TeO_2 → 750 kg TeO_2
from 2003-2008 ↳ 203 kg ^{130}Te

search for 0v double beta:
$T_{1/2}^{0v}$ (^{130}Te) > 7.5 x 10^{23} y
$<m_v>$ < 0.3 - 1. 6 eV

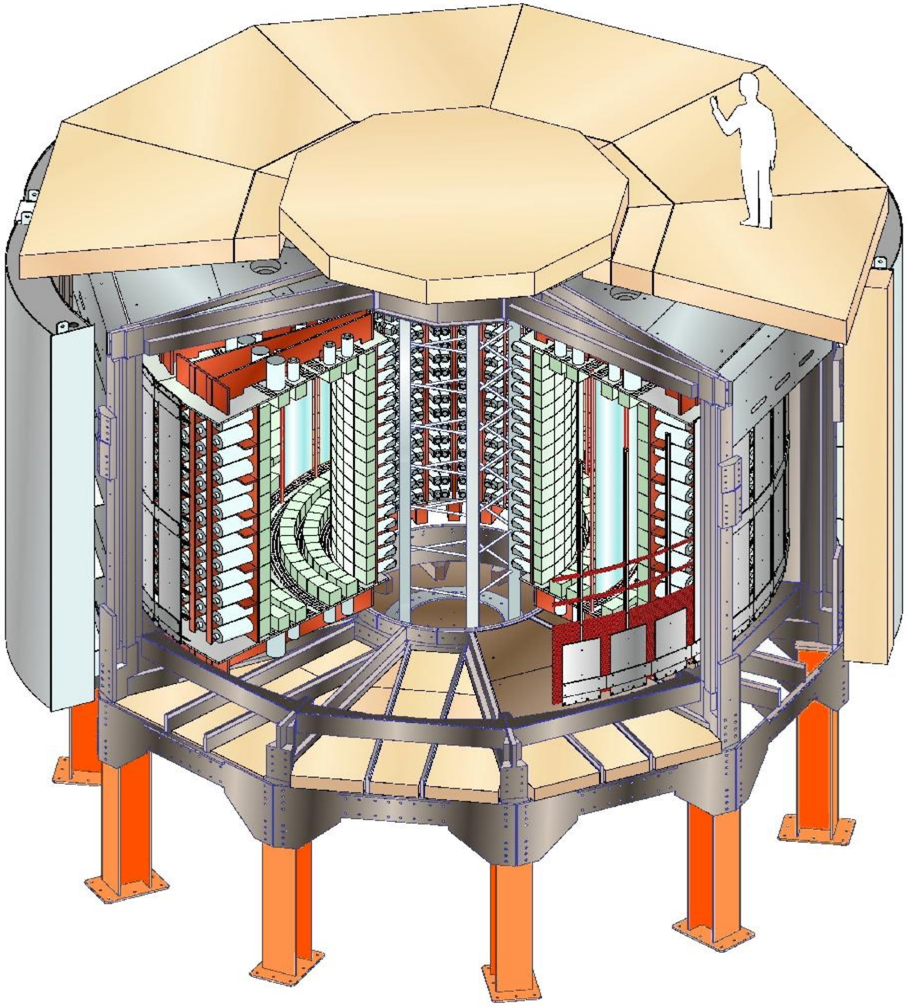


2 modules, 9 detector each,
crystal dimension 3x3x6 cm^3
crystal mass 330 g
9 x 2 x 0.33 = 5.94 kg of TeO_2



11 modules, 4 detector each,
crystal dimension 5x5x5 cm^3
crystal mass 790 g
4 x 11 x 0.79 = 34.76 kg of TeO_2

NEMO-3 @ Frejus Lab

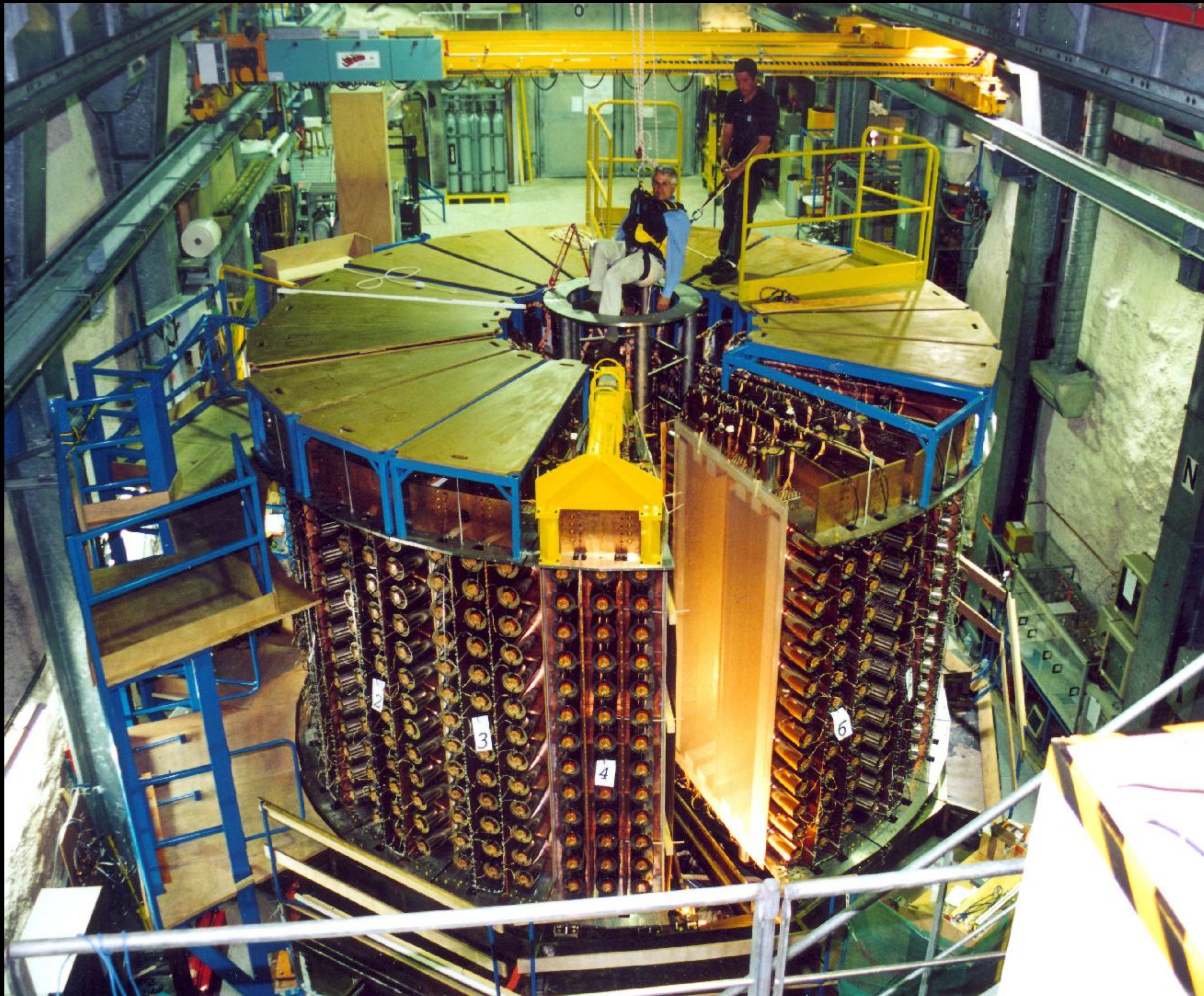


Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², e ~ 60 mg/cm²

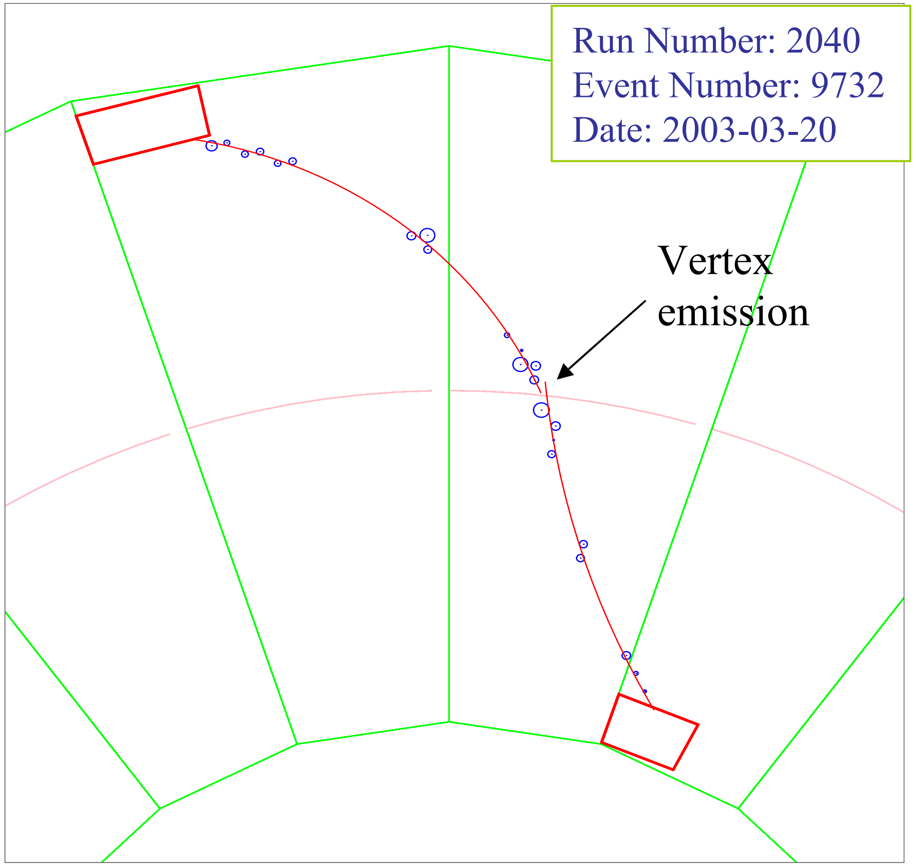
Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

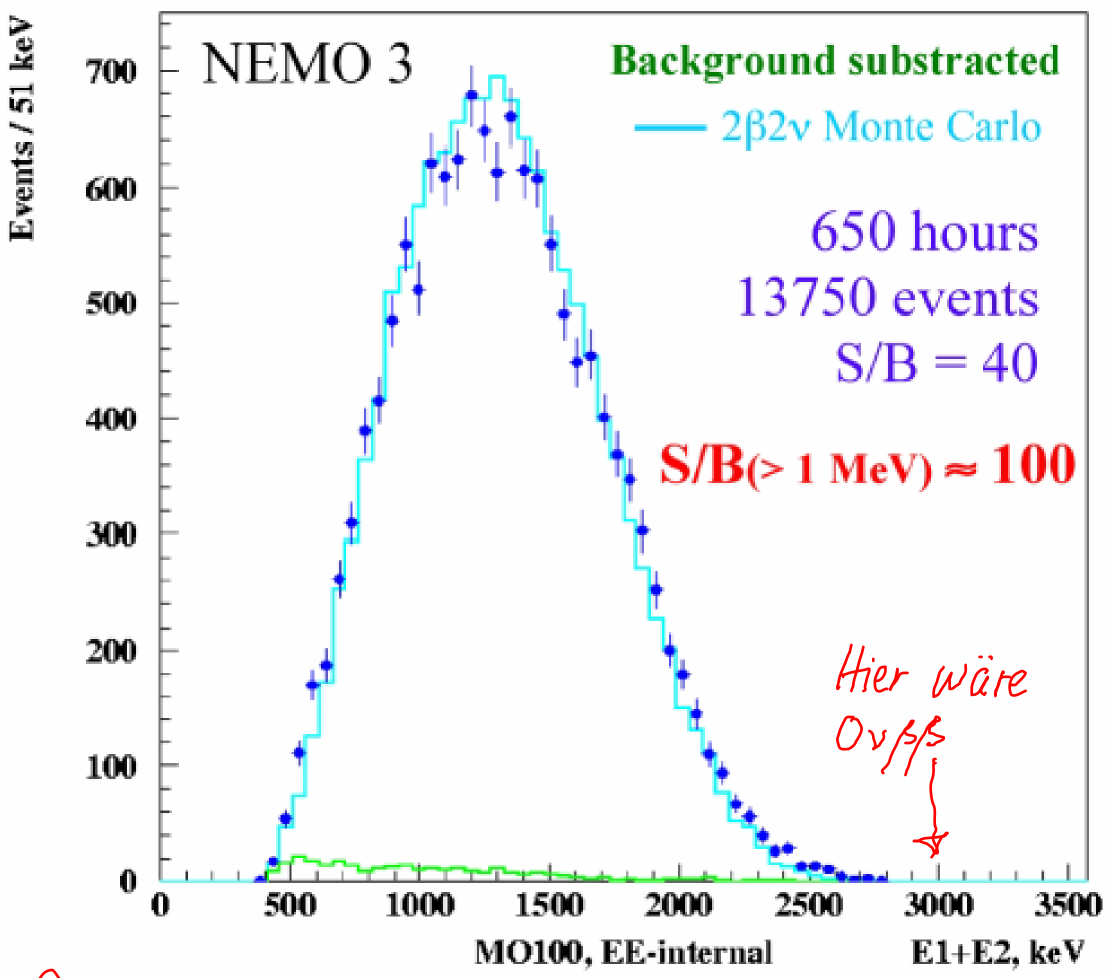
Magnetic field: 25 Gauss
Gamma shield: Pure Iron (e = 18 cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)


2
3
4
6

^{100}Mo: 2νββ-event in NEMO-3

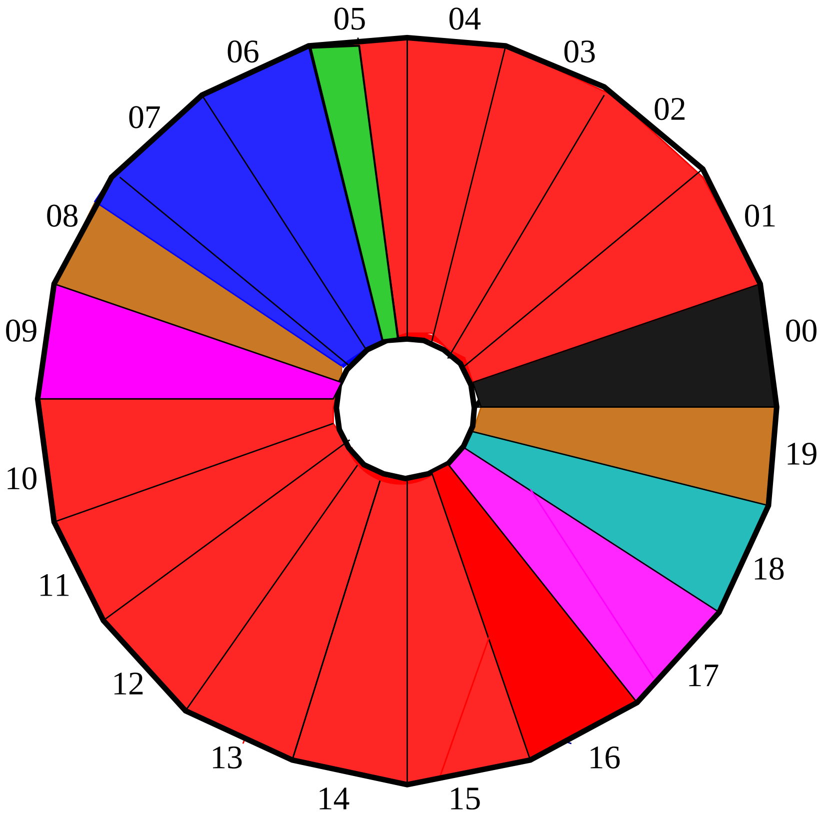


2νββ-decay of ^{100}Mo in NEMO-3



Abgeleitete Grenze für 0νββ: $\langle m_\nu \rangle_{ee} < 0.7 - 1.2$ eV

Overview Isotopes in NEMO-3



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

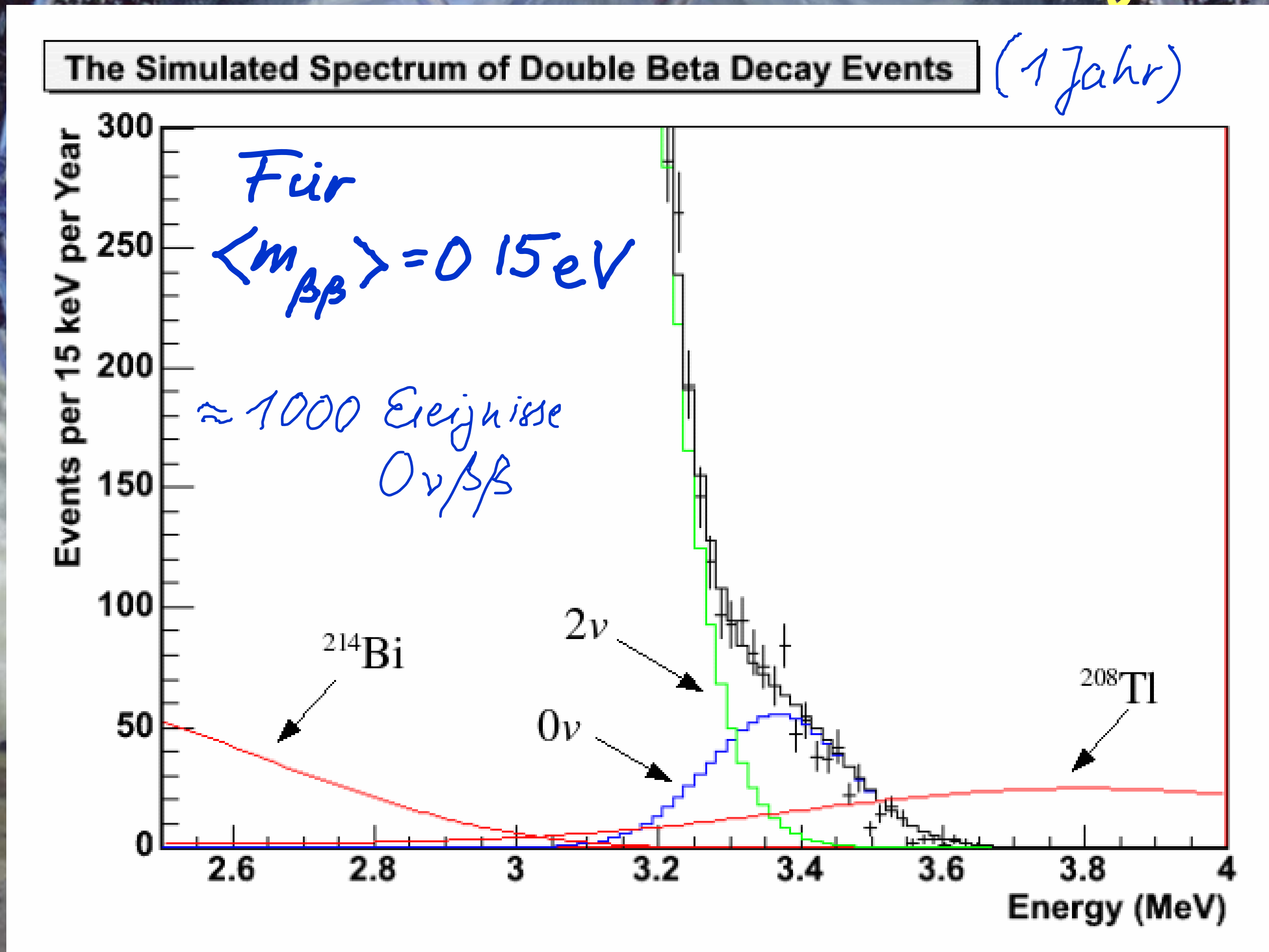
Cu 621 g

External bkg measurement

(All the enriched isotopes produced in Russia)

SNO+

D_2O wird durch Flüssig-Szintillator ersetzt
↳ Beladung mit Nd



(1 Jahr)

Für $\langle m_{\beta\beta} \rangle = 0.15\,eV$

$\approx$ 1000 Ereignisse $0\nu\beta\beta$