experimental ν-physics – I : neutrino oscillations

Graduiertentag Tübingen, 13.5.2011

Kepler Center for Astro and Particle Physics

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- neutrino properties
- neutrino oscillations – an introduction
- 3 flavour neutrino mixing
- solar neutrinos: Borexino
- atmospheric neutrinos: OPERA
- reactor neutrinos & θ_{13}: Double Chooz

introduction: neutrino properties

neutrino properties

- parameters of the **three light SM neutrinos** ν_e, ν_μ, ν_τ

intrinsic neutrino properties	
CP properties: Majorana- or Dirac-ν (ΔL = 0, 2)	ν^M or ν^D
absolute masses, (inverted) hierarchy / quasi-degenerated	m_1, m_2, m_3
mixing angles of neutrino mixing matrix	θ_{ij}
(complex) Majorana phases [only for 0νßß]	α_2, α_3
(real) Dirac phase [for ν-oscillations]	δ
life times	τ_1, τ_2, τ_3
decay modes (radiative, non-standard modes)	Γ_i
magnetic dipole moment (static / transition moment)	μ_ν
electric dipole moment	D
mean square charge radius	$\langle r^2 \rangle$
couplings to gauge bosons & Higgs (γ, $W^\pm$, Z^0, H)	g_j

- existence of - sterile neutrinos (beyond the SM)
  - 4^{th} neutrino familiy?

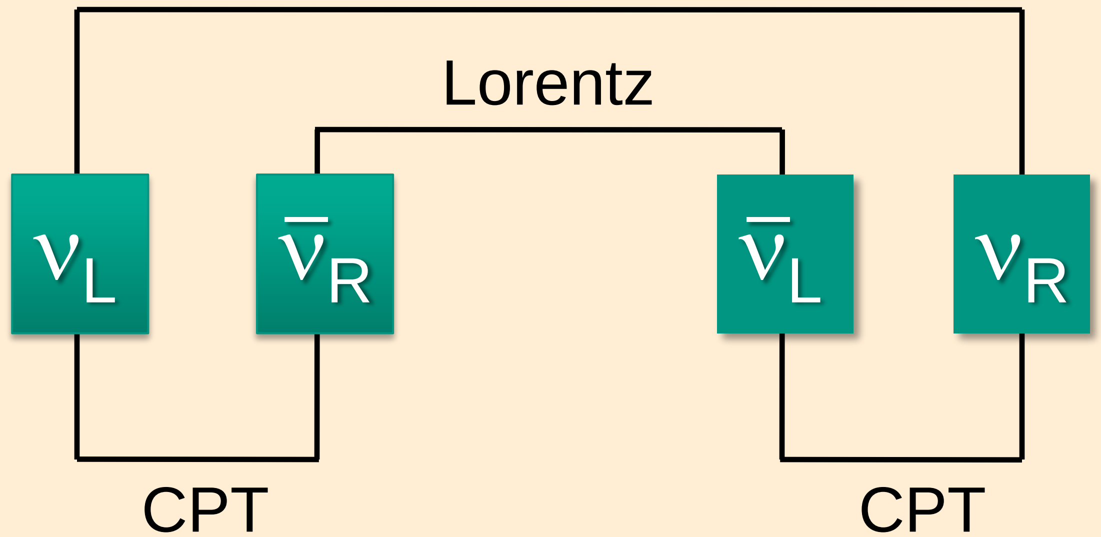
CP properties

- intrinsic **particle-antiparticle symmetry** of SM neutrinos?
  Dirac-ν and Majorana-ν only distinguishable if **$m_\nu \neq 0$**

Dirac neutrino

4 ν states
Lepton number conservation
ΔL = 0
neutrino ≠ antineutrino

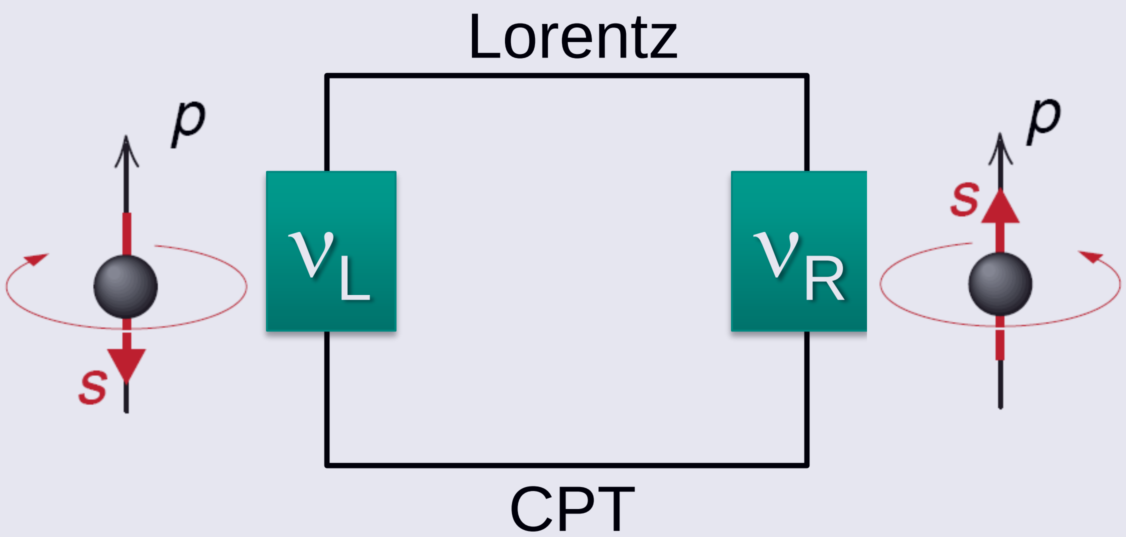
ν^D



Majorana neutrino

2 ν states
Lepton number violation
ΔL = 2
„neutrino = antineutrino"

ν^M



neutrino mass – mechanism?

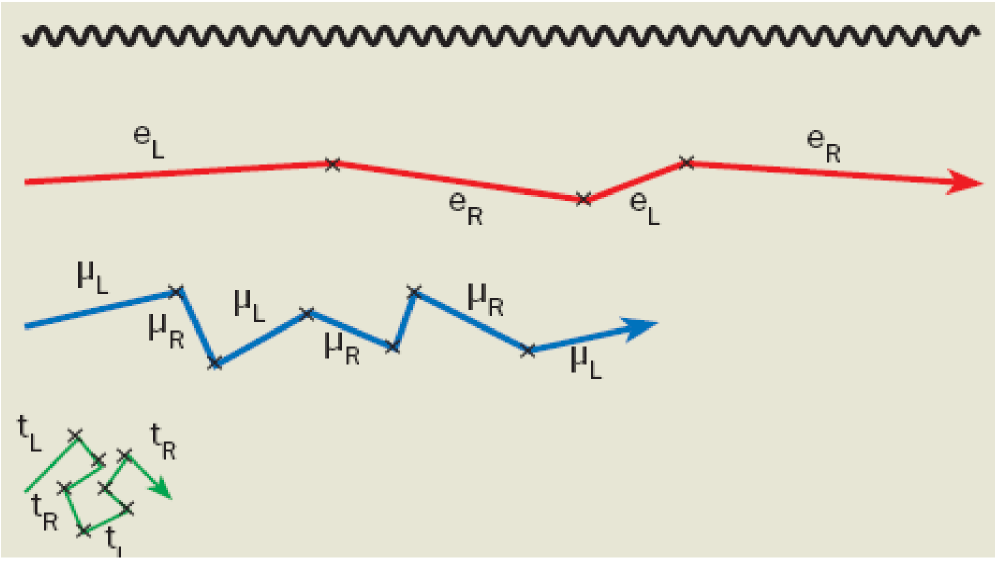
- **Higgs mechanism**: SM particles acquire mass via scalar Higgs boson, this results in a **change of handedness** (lefthanded ↔ righthanded), $\nu_{L,R} \leftrightarrow \nu_{L,R}$
- **see-saw**: light ν_L ⇔ heavy ν_R

γ

e

μ

t



particle	scale	m [MeV]
photon γ	massless	0
electron e	light	0.511
muon μ	medium	105.6
top quark t	heavy	$1.71 \cdot 10^5$

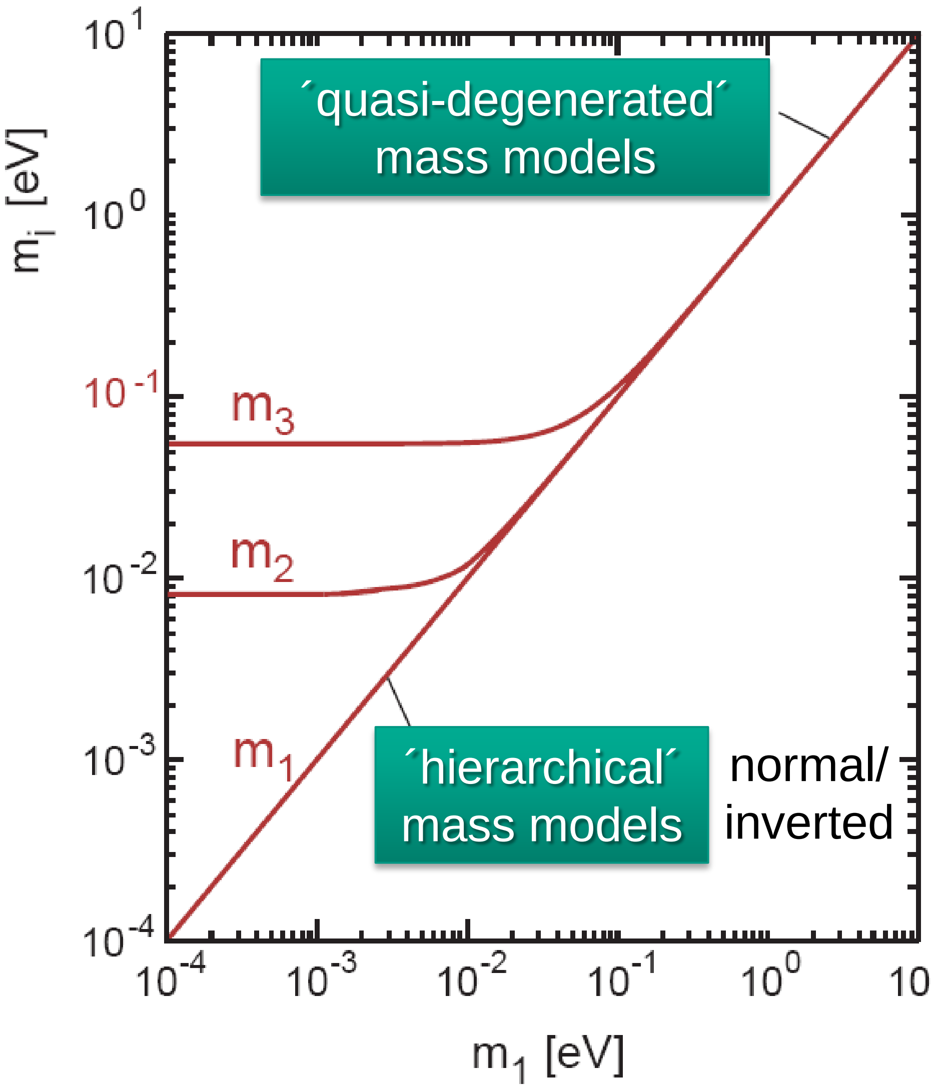
ν

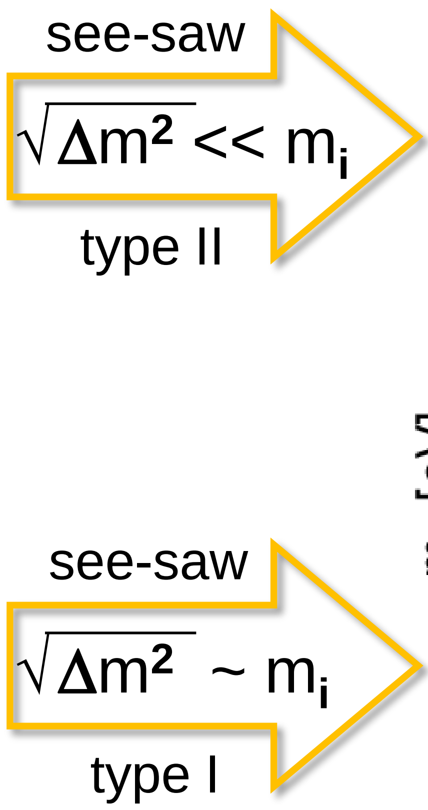
ν_D

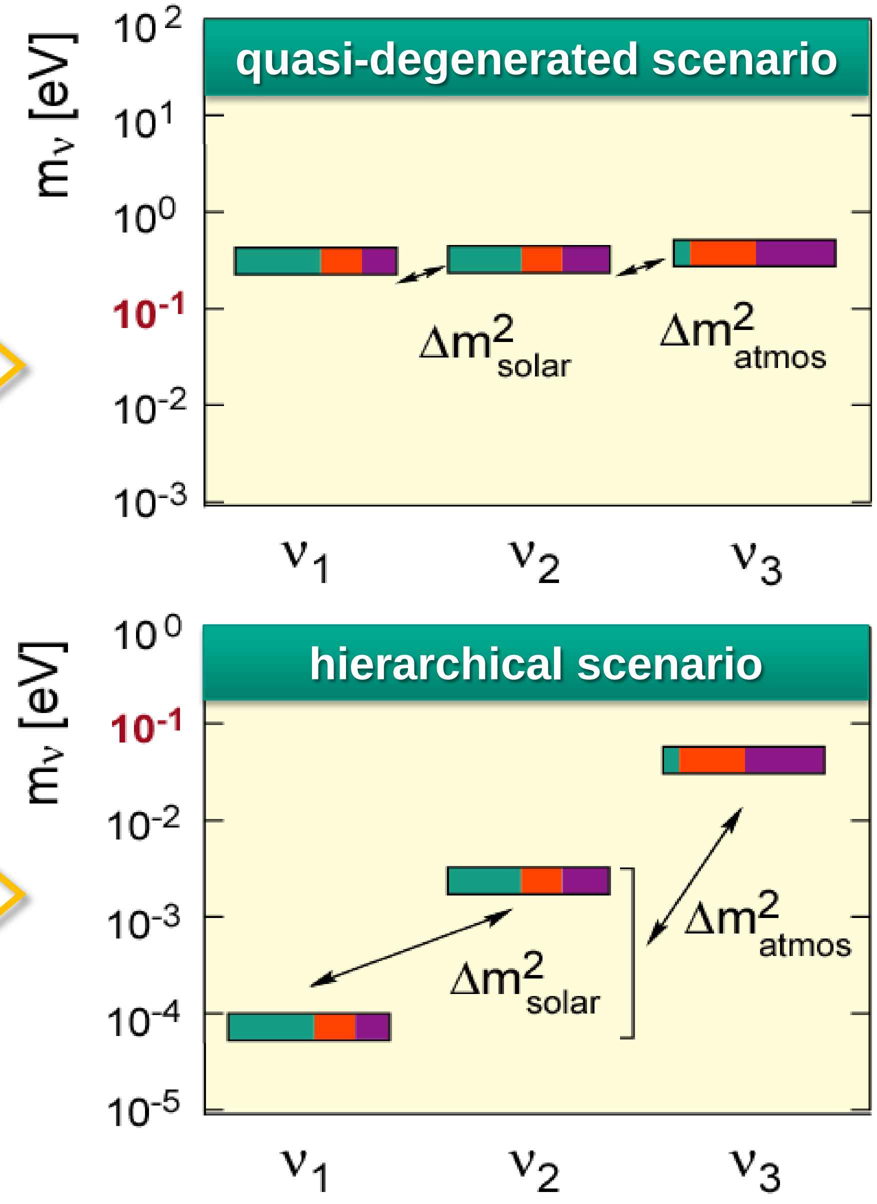
ν_M

neutrino mass – pattern?

- **hierachy** – normal case: $m_1 < m_2 << m_3$, inverted case: $m_3 << m_{1,2}$
  quasi-degenerated – $m_1 \sim m_2 \sim m_3$







neutrino oscillations: an experimentalist´s view

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and

Detecting Neutrinos

Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water ...

... and collide with other particles ...

... producing a cone-shaped flash of light.

The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

LIGHT

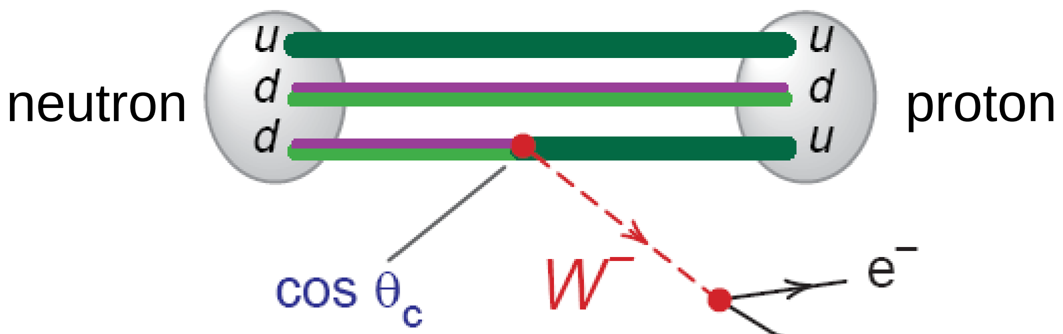
LIGHT AMPLIFIER

And Detecting Their Mass

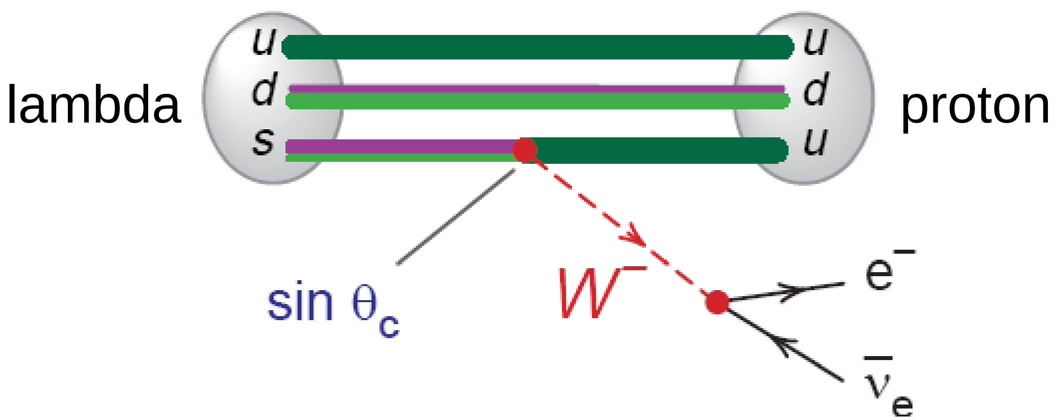
By analyzing the cones of light.

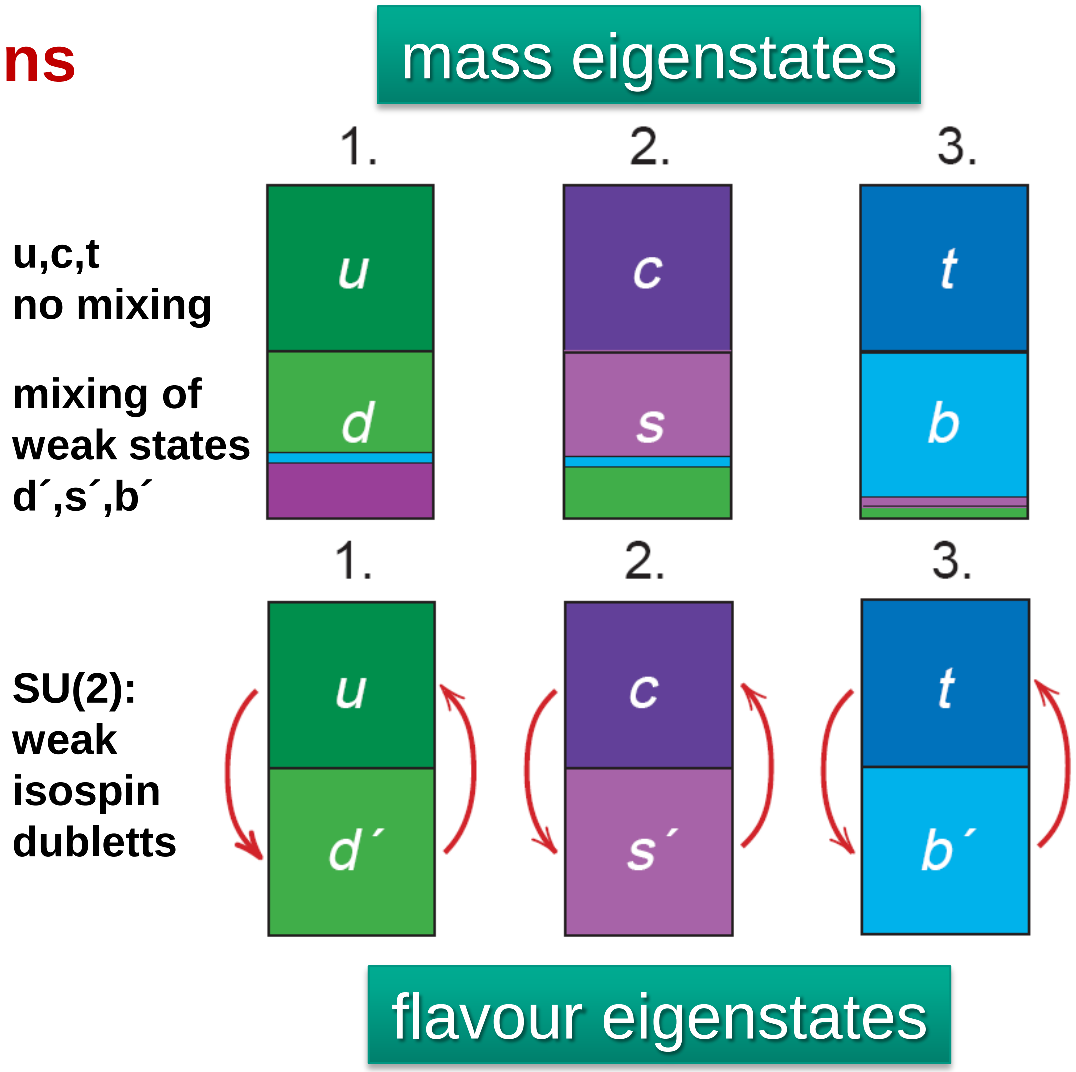
weak interaction – quark mixing

- quarks: mass eigenstates ≠ weak flavour eigenstates (caused by interaction with Higgs-field) ↳ **CKM matrix:** 3 mixing angles & 1 CP phase
  definition: mixing only in d,s,b – Sektor
  - **left-handed quarks, leptons**
  - right-handed anti-particles



Cabibbo angle sin θ_c = 0.22

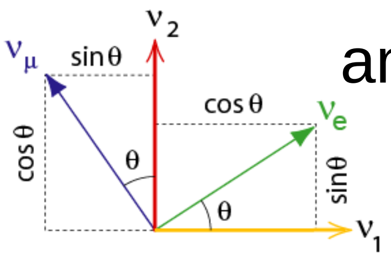




neutrino oscillations – formalism

- **probability P for flavour oscillation** of a ν_μ into ν_e after time t:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L_\nu / E_\nu)$$



amplitude

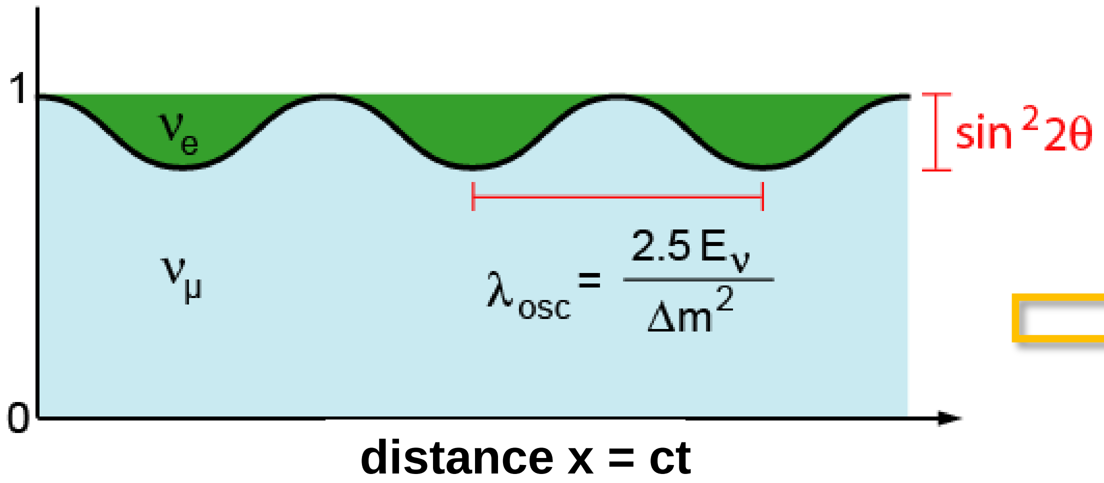
frequency

$$\Delta m_{12}^2 = | m_1^2 - m_2^2 |$$

experimental parameters:

L_ν in units of m [km]
E_ν in units of MeV [GeV]

source



probability that ν_μ transforms to ν_e

probability that ν_μ remains ν_μ

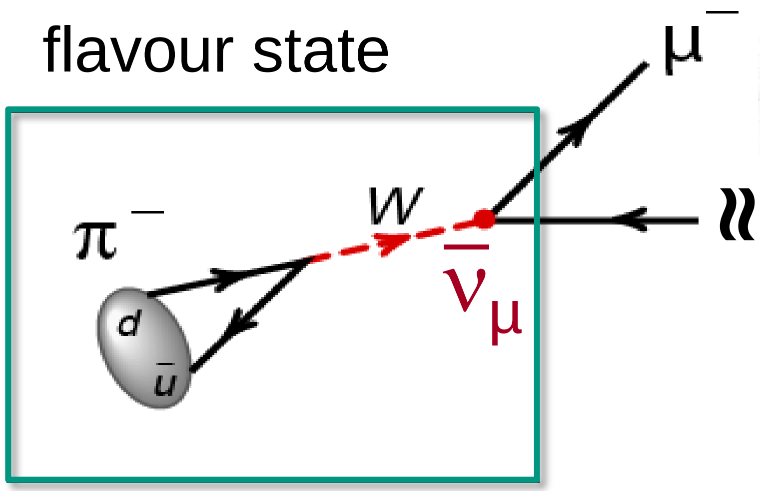
- periodic appearance of a **new** neutrino flavour state (ν_e)
- periodic decrease / increase of original ν-flavour fraction (ν_μ)
- **oscillation length λ ~ ν-energy !**
  λ_{osc} ~ 2.5 E_ν / Δm^2

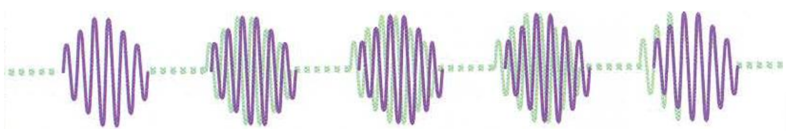
neutrino oscillations – concept

- neutrino oscillations result from the **propagation of mass eigenstates**

ν–source | **ν–oscillations** | **ν–detection**

flavour state



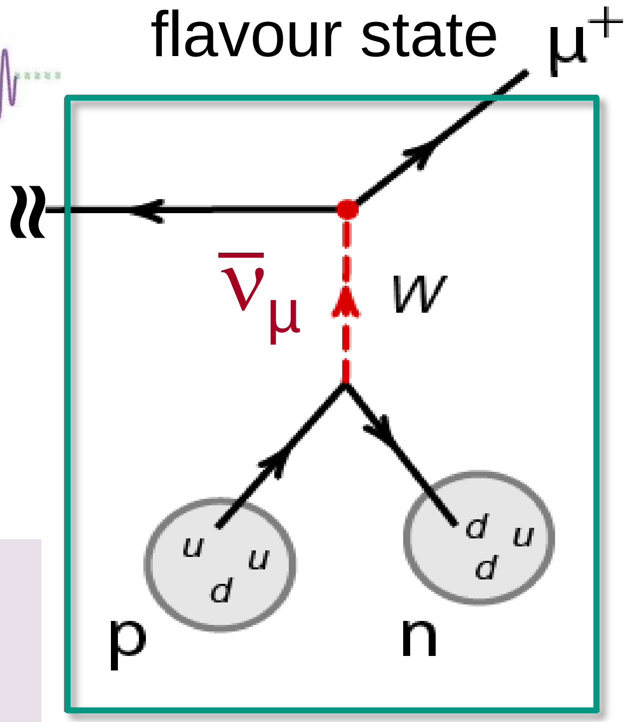


$\nu_{1,2,3}$

propagation of ν–mass eigenstates

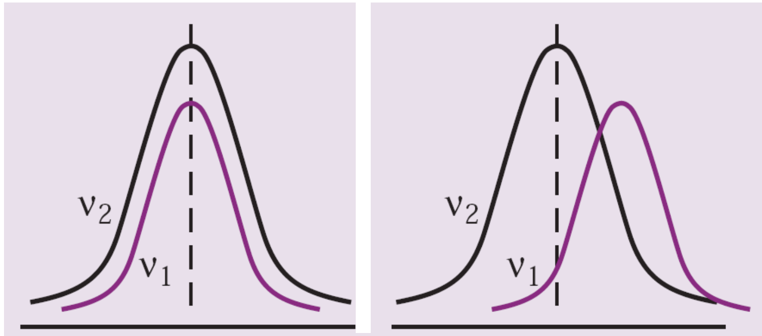
L = 10 m … 10.000 km

flavour state



source parameters to be determined:

ν–energies
ν–fluxes
ν–flavours



emission detection

ν–detection efficiency
ν–energy resolution

appearance & disappearance channel

disappearance channel

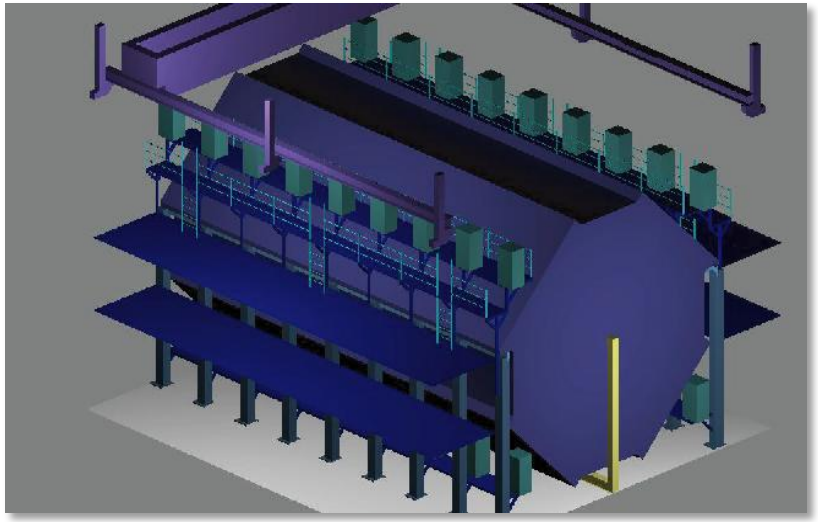
$\nu_\mu \rightarrow \nu_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

statistics: large event ensemble ($N > 10^4$)

systematics: ν–flux & ν–energies?

preferred for **large** mixing amplitudes



example: NuMI beam - MINOS

appearance Kanal

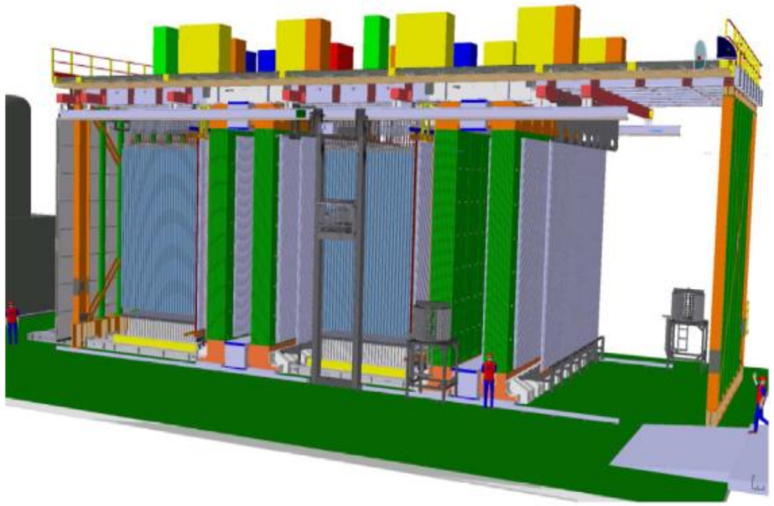
$\nu_\mu \rightarrow \nu_\tau$ appearance

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

statistics: small event ensembles ($N < 100$)

systematics: ν–flavour composition?

preferred for **small** mixing amplitude



example: CNGS beam - OPERA

appearance & disappearance channel

disappearance channel

$\nu_\mu \rightarrow \nu_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

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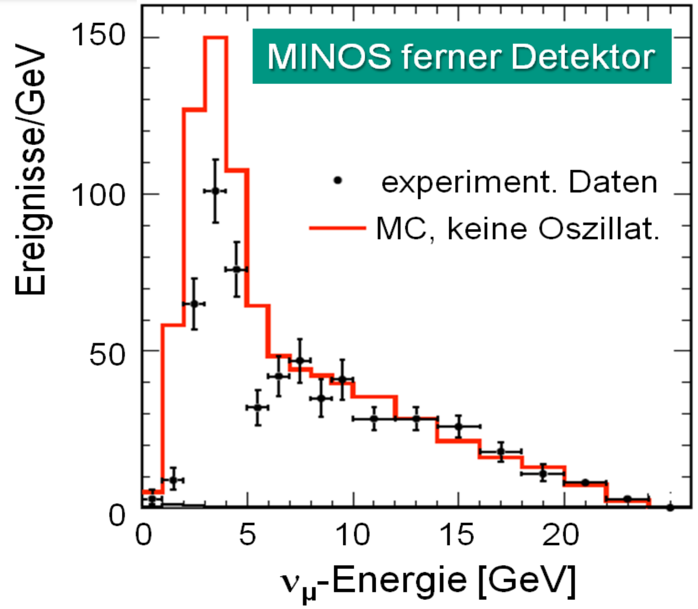

appearance Kanal

$\nu_\mu \rightarrow \nu_\tau$ appearance

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

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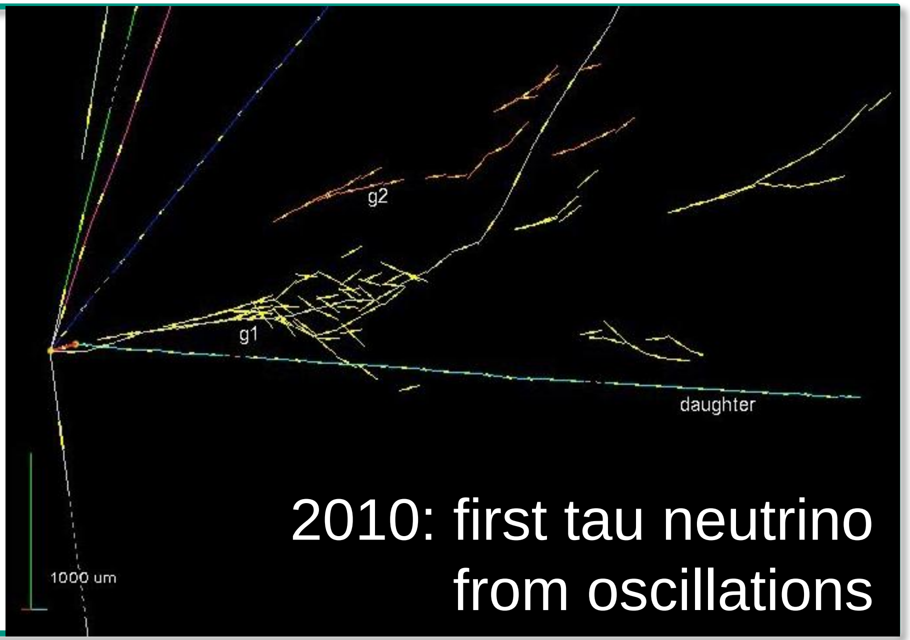
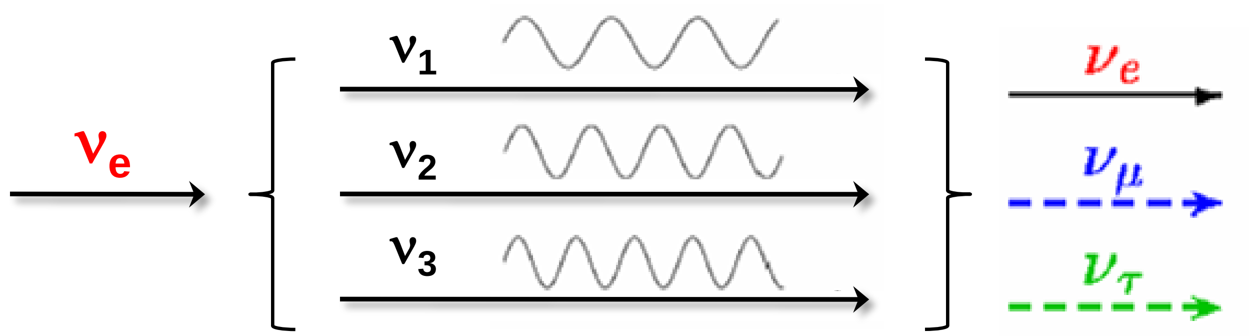


3-flavour mixing

- extension of 2-flavour oscillations to **3 flavour oscillationen**:
  - three mixing angles: θ_{12}, θ_{23}, θ_{13}
  - two independent Δm^2 scales with relation:

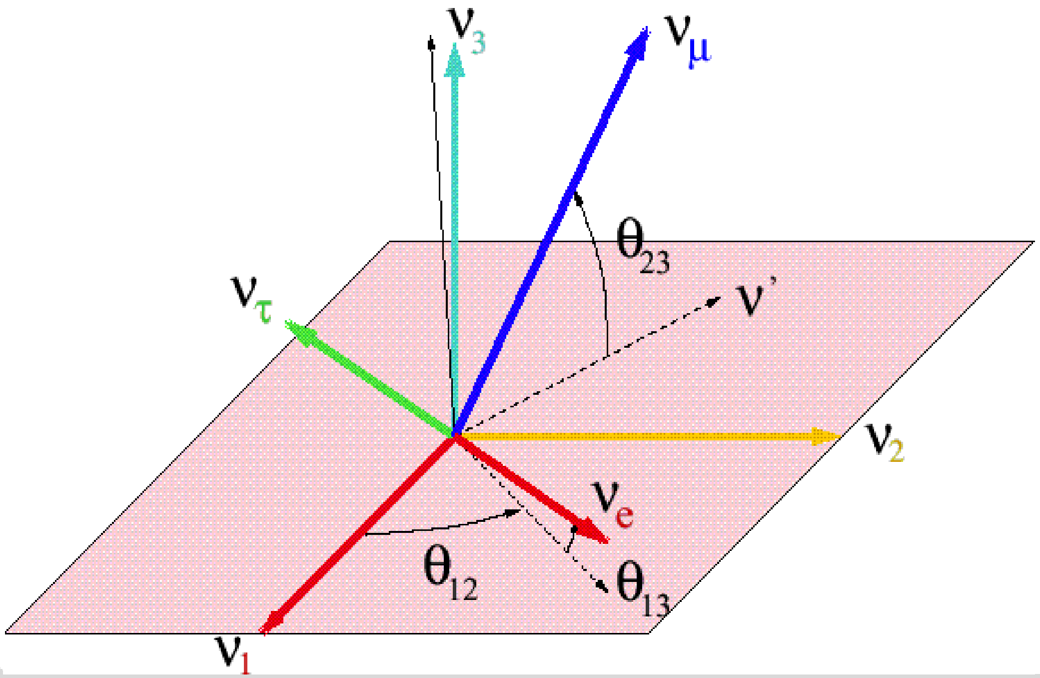
$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$



$\Delta m_{12}^2 = | m_1^2 - m_2^2 |$ 1. & 2. generation

$\Delta m_{23}^2 = | m_2^2 - m_3^2 |$ 2. & 3. generation

$\Delta m_{13}^2 = | m_1^2 - m_3^2 |$ 1. & 3. generation



leptonic mixing matrix:
Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U = unitarity 3 × 3 mixing matrix

3-flavour mixing

- extension of 2-flavour oscillations to **3 flavour oscillationen**:
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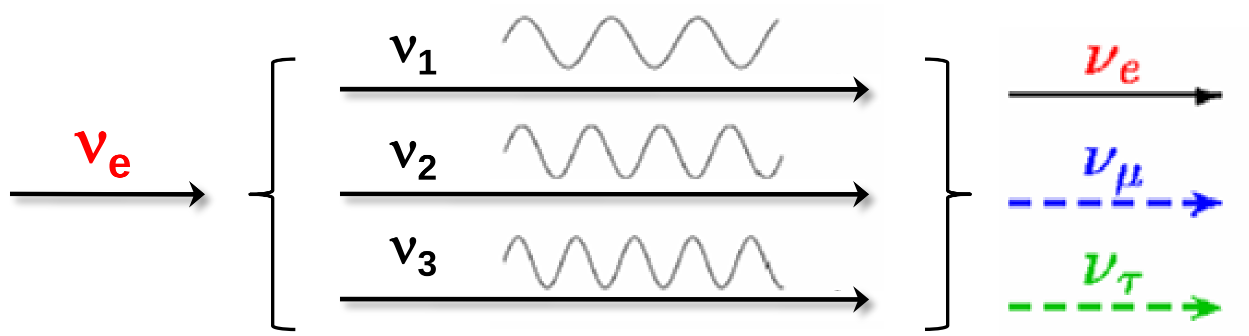
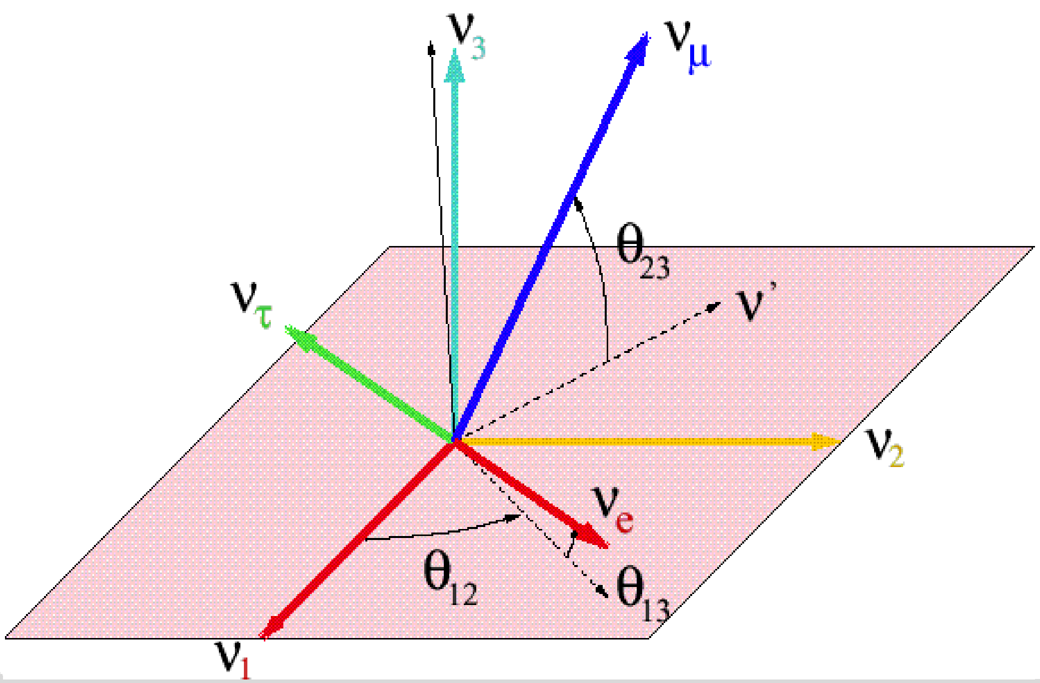


$$\Delta m_{12}^2 = | m_1^2 - m_2^2 |$$ 1. & 2. generation

$$\Delta m_{23}^2 = | m_2^2 - m_3^2 |$$ 2. & 3. generation

$$\Delta m_{13}^2 = | m_1^2 - m_3^2 |$$ 1. & 3. generation



leptonic mixing matrix:
Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.81-0.85 & 0.53-0.58 & 0.00-0.12 \\ 0.32-0.49 & 0.52-0.69 & 0.60-0.76 \\ 0.27-0.46 & 0.47-0.64 & 0.65-0.80 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U = unitarity 3 × 3 mixing matrix

neutrino oscillations: 3-flavour mixing

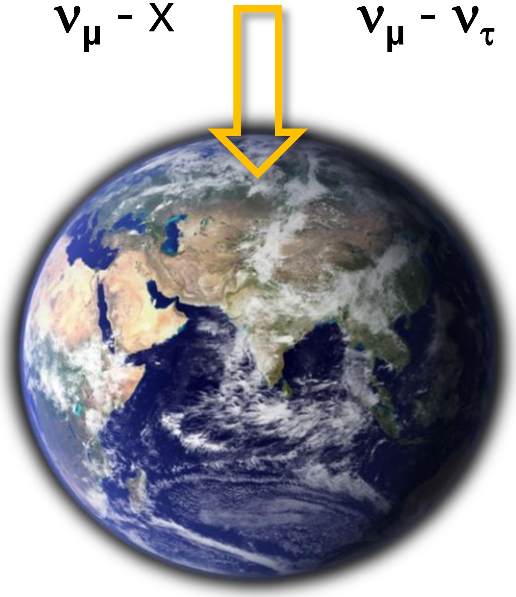
- 3-flavour oscillations ´decouple´ into three separate mixing terms:

δ: CP-phase

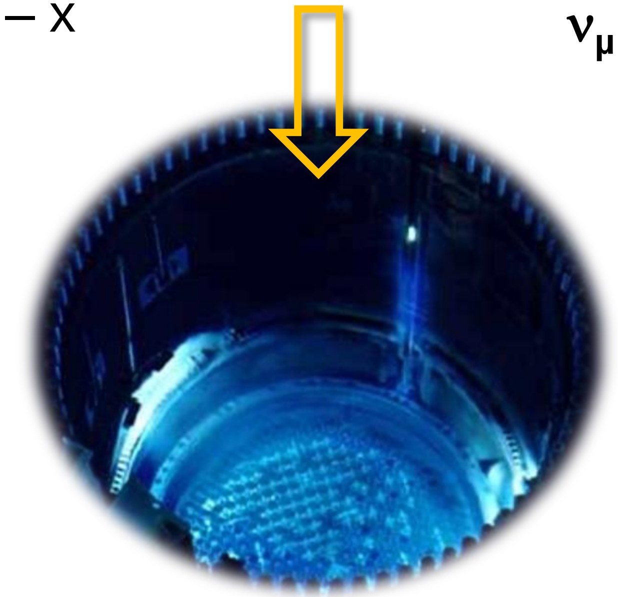
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix}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

2. & 3. generation	1. & 3. generation	1. & 2. generation
atmospheric ν´s	solar / reactor neutrinos	solar neutrinos
long baseline accelerators	long baseline reactor/accelerators	reactor experiments

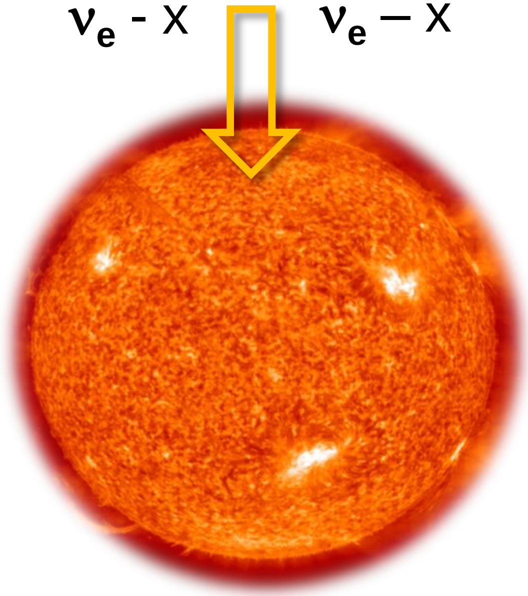
ν_μ - X ν_μ - ν_τ



$\bar{\nu}_e$ – X ν_μ - ν_e

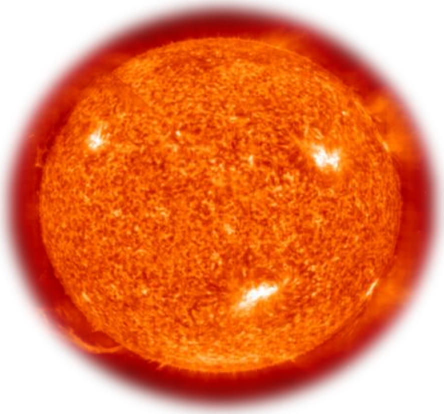


ν_e - X $\bar{\nu}_e$ – X

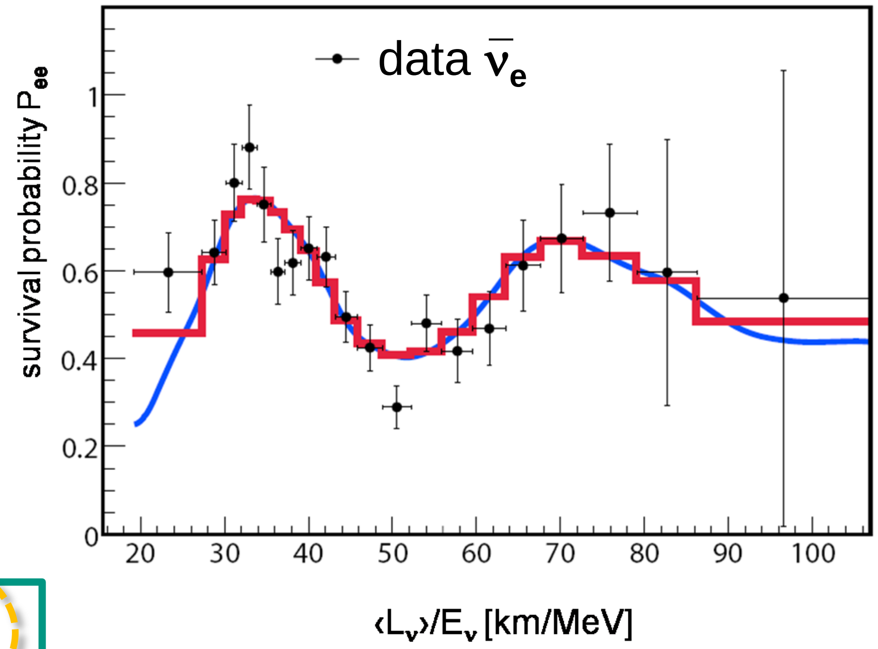


ν-oscillations

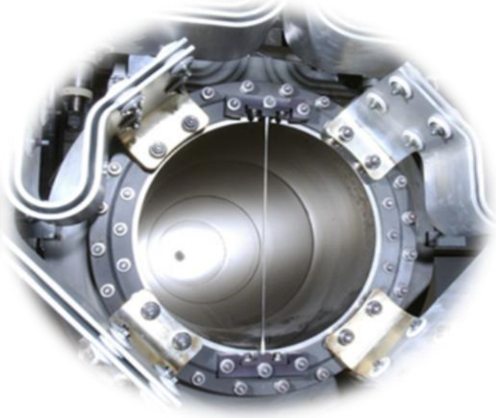
MeV: solar & LBL reactor ν-experiments



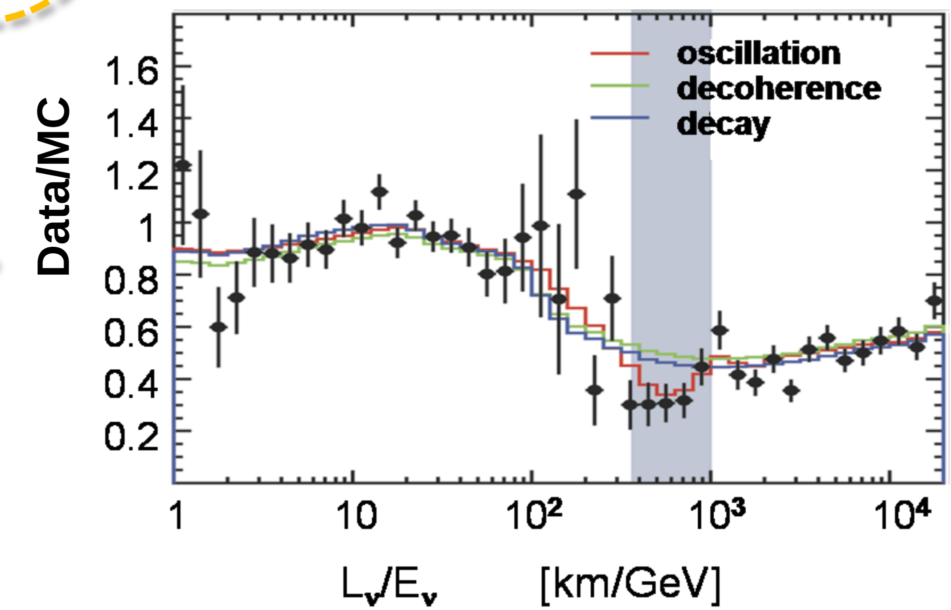
12-mixing



$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{ij} \cdot \sin^2(1.27\ \Delta m^2_{ij} \cdot L_\nu / E_\nu)$$



23-mixing



GeV: atmospheric & LBL accelerator ν´s

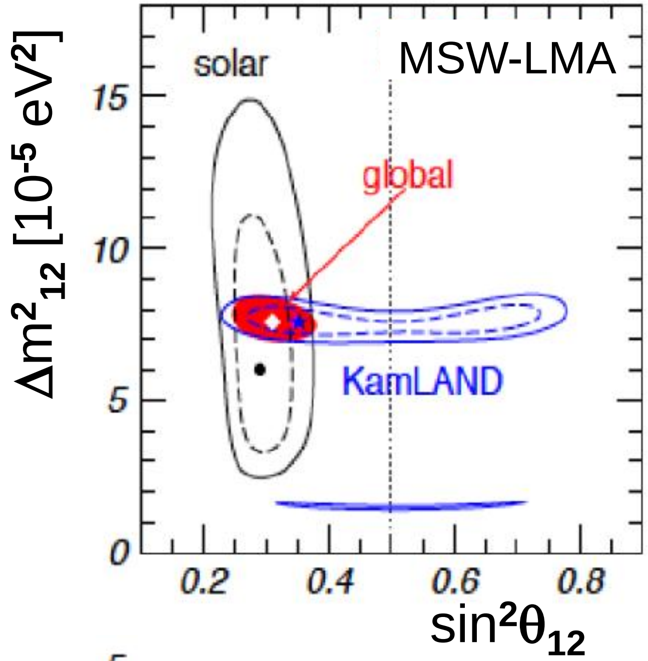
ν-oscillations: mixing parameters

MeV: solar & LBL reactor ν-experiments

$\Delta m^2_{12} = (7.65 \pm 0.23) \times 10^{-5}\ eV^2$

12-mixing

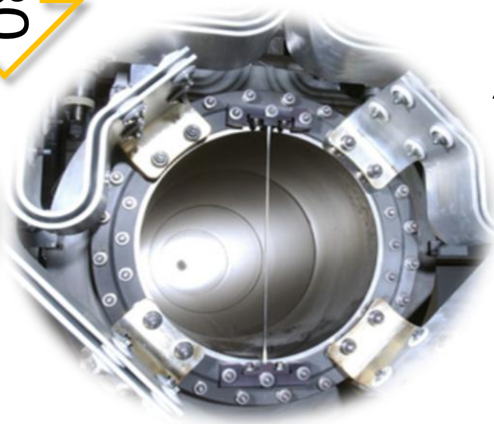
$\sin^2 \theta_{12} = 0.304 \pm 0.02$



decoupled

factor 30

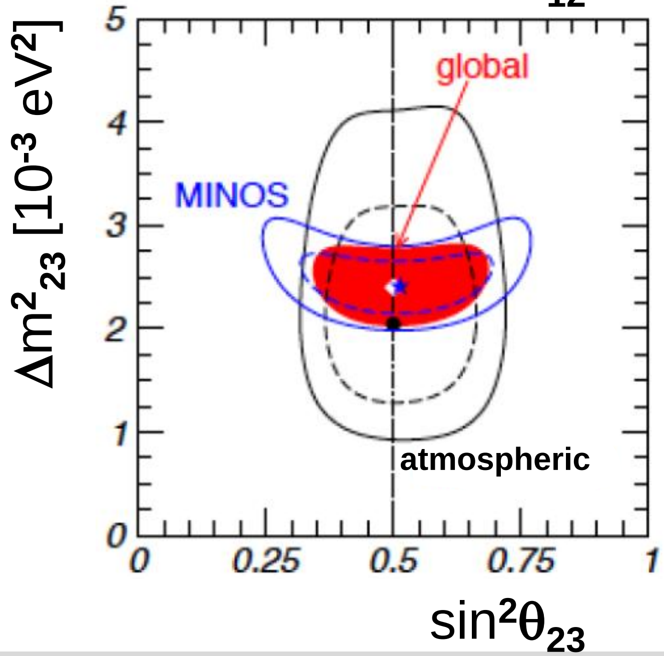
2 flavour oscillations (disappearance)



$\Delta m^2_{23} = (2.4 \pm 0.1) \times 10^{-3}\ eV^2$

23-mixing

$\sin^2 \theta_{23} = 0.50 \pm 0.06$

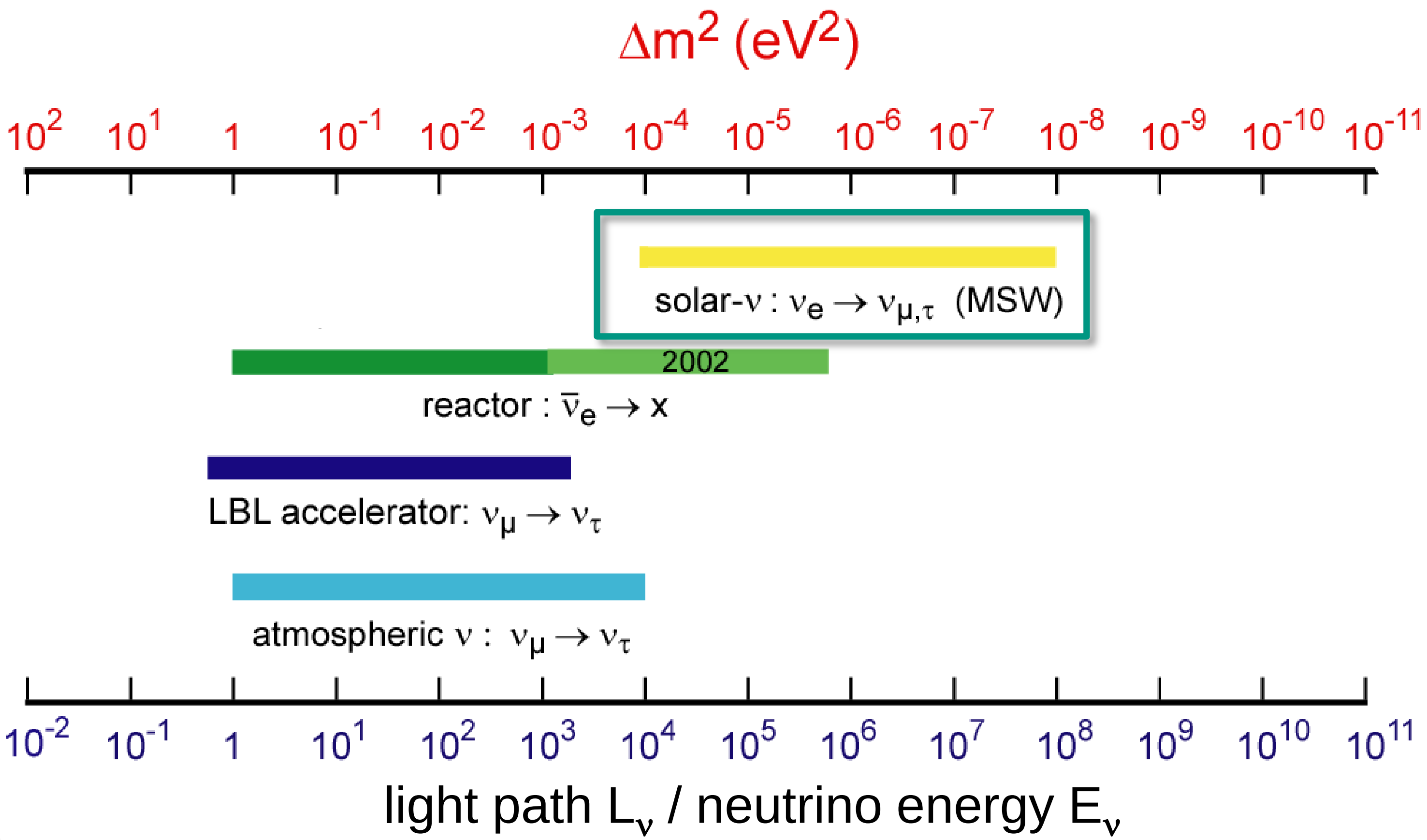


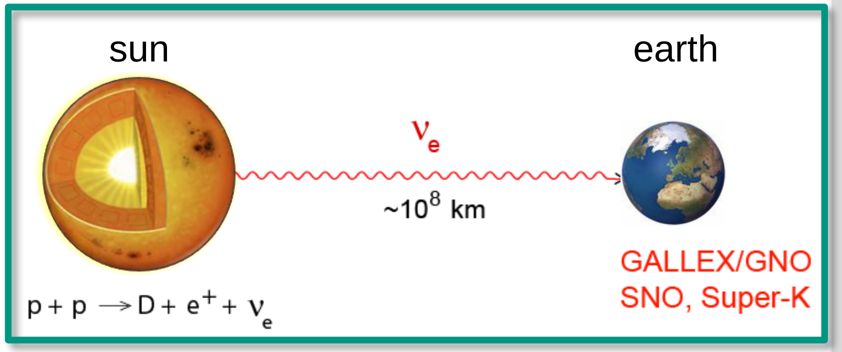
GeV: atmospheric & LBL accelerator ν´s

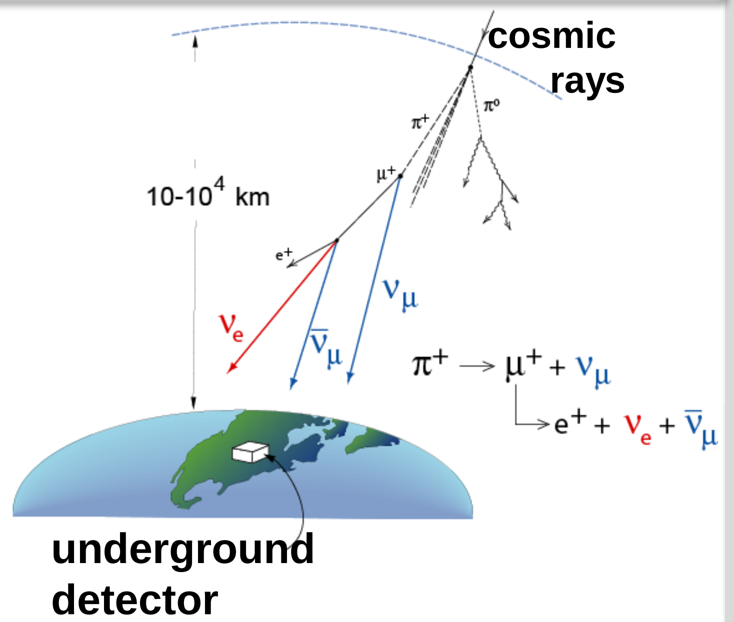
neutrino oscillations: L/E and Δm^2

- coverage of the entire Δm^2-parameter region requires different experiments

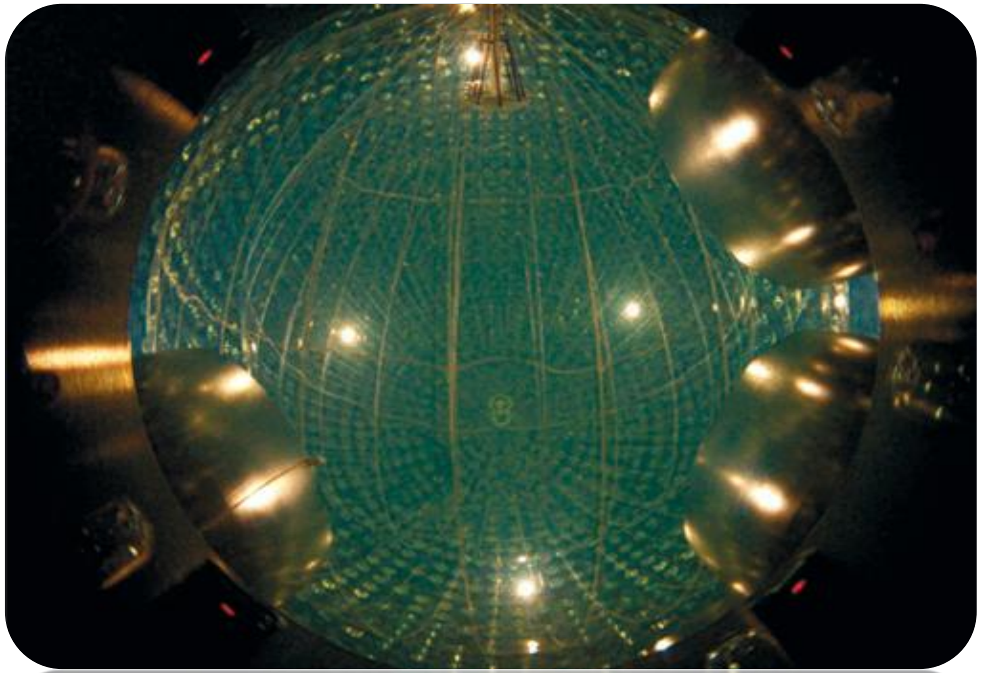
goals: - determination of parameters Δm_{ij}^2, $\sin^2 2\theta_{ij}$
- observation of L_ν/E_ν oscillation pattern
- identification of flavour channels
- matter effects, leptonic CP-violation?







solar neutrinos: θ_{12} oscillations



solar neutrinos – energy spectra & fluxes

Karlsruhe Institute of Technology

- theoretical calculations for solar ν–spectrum, pioneered by J. Bahcall

Standard Solar Model -

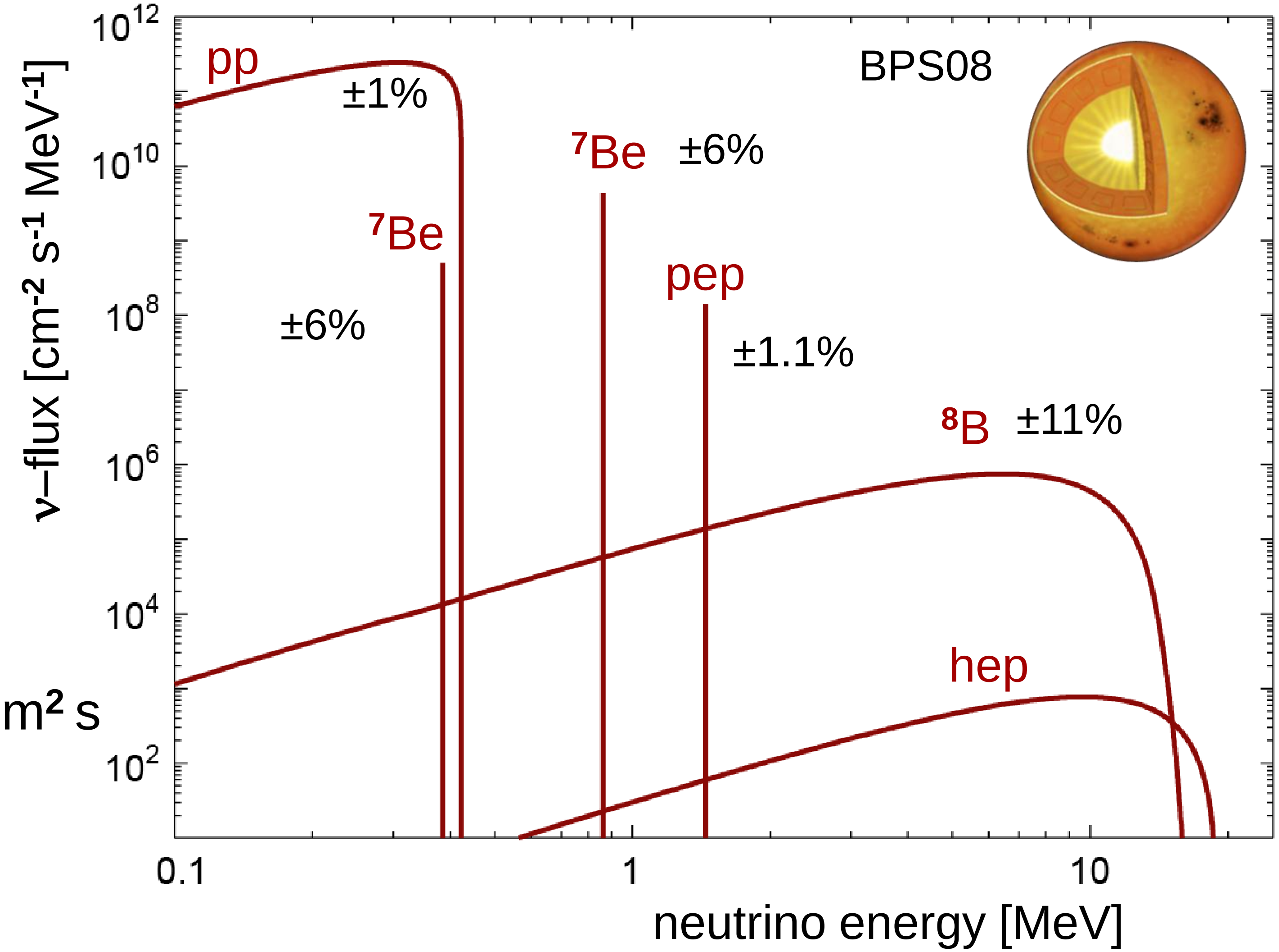
- input parameters: $L_\odot$, ...

  metallicity Z/X:

  high Z: 1.8% ⇔ low Z: 1.65%

- low Z: problems with helioseismology / (SSM)

integral solar ν-flux: $\Phi_\nu = 6.6 \times 10^{10}$ / cm² s



- lower solar metallicity Z

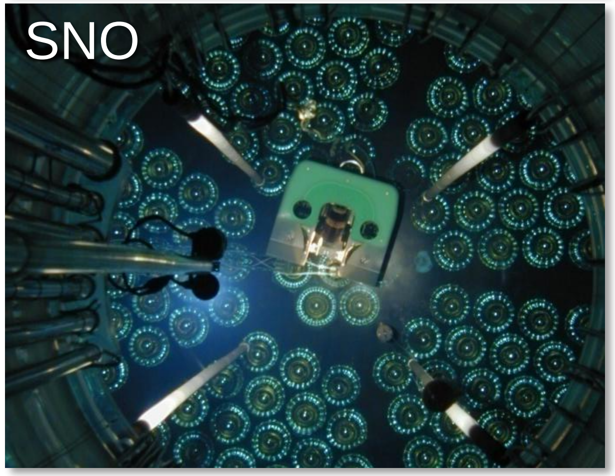
decreases { ^{7}Be by ~10% ; CNO, … }

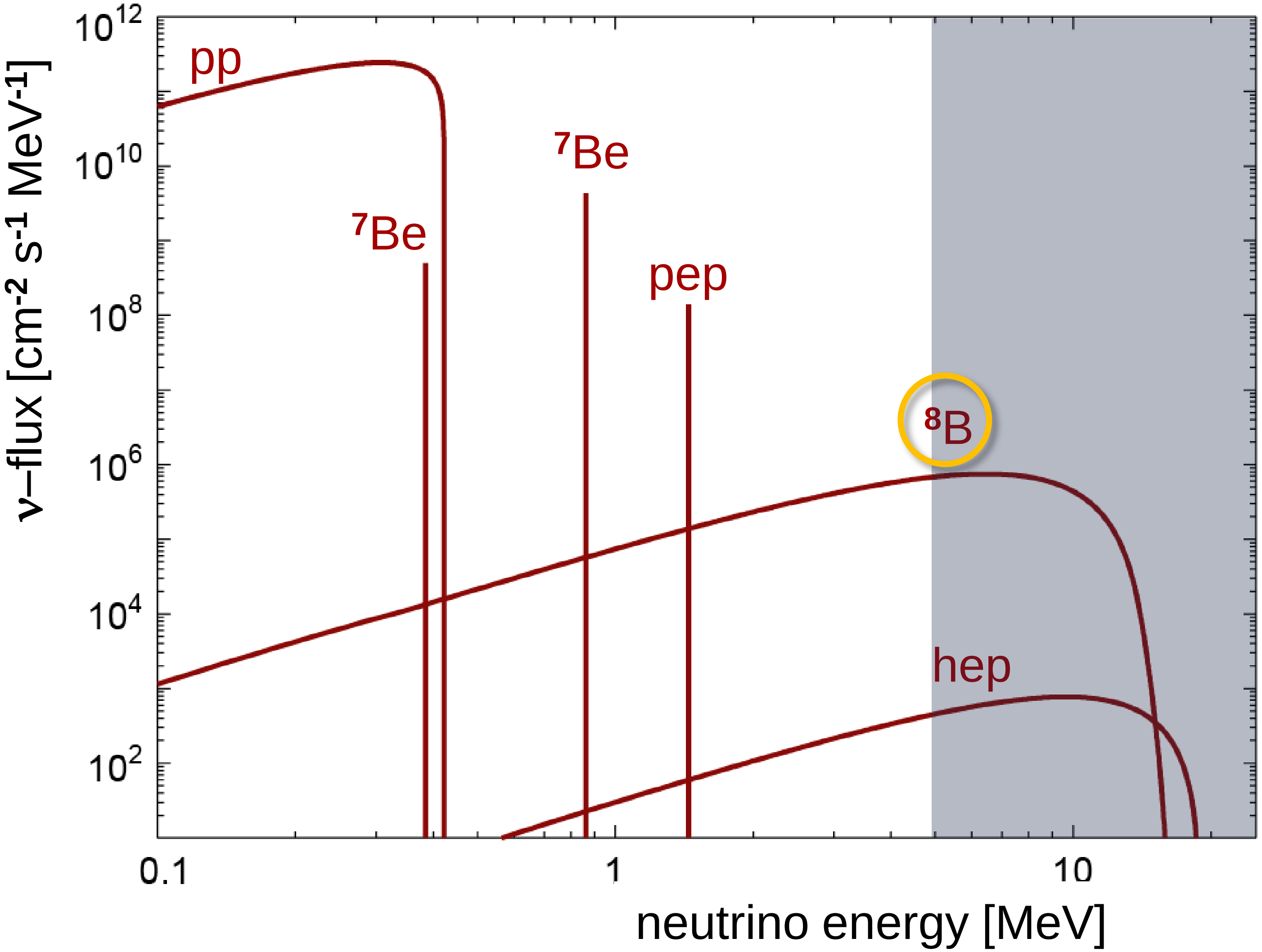
low Z: $\Phi(^7Be) = 4.55$
high Z: $\Phi(^7Be) = 5.07$ $\times 10^9$ /cm² s

(J. Bahcall), C. Pena-Garay & A. Serenelli, 2008, arXiv:0811.2424

solar neutrinos – ^{8}B

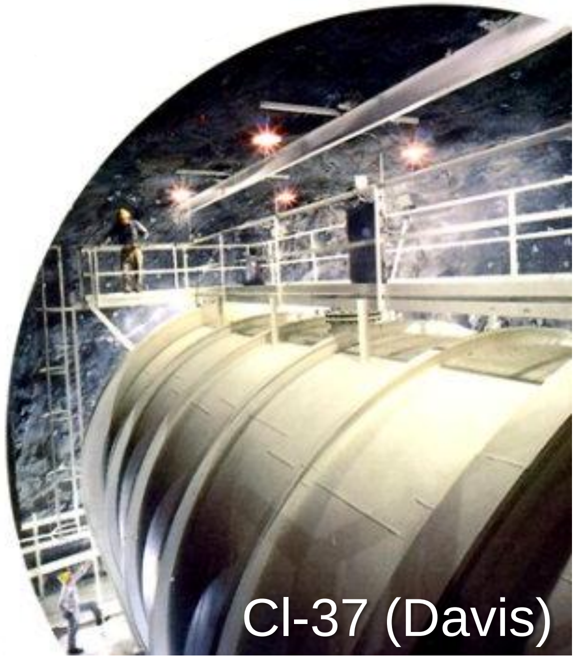
- **water Cherenkov detectors:** ´real-time´ detection of ^{8}B-ν´s
  measurements of : spectral shape, CC rate, NC rate, day-night effects, earth orbit effects, conversion into $\bar{\nu}_e$? (Super-K, SNO)

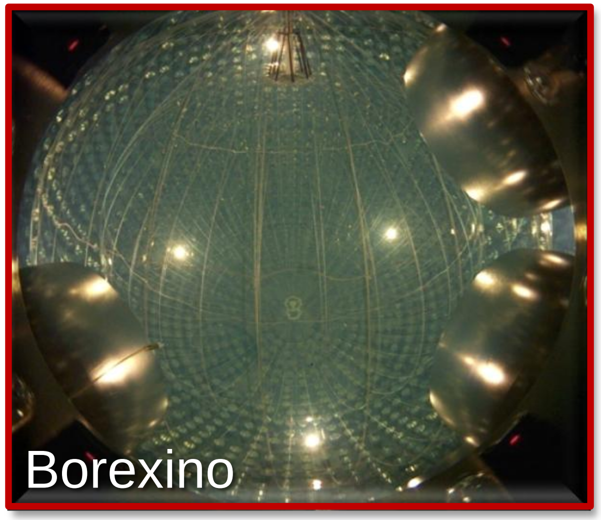


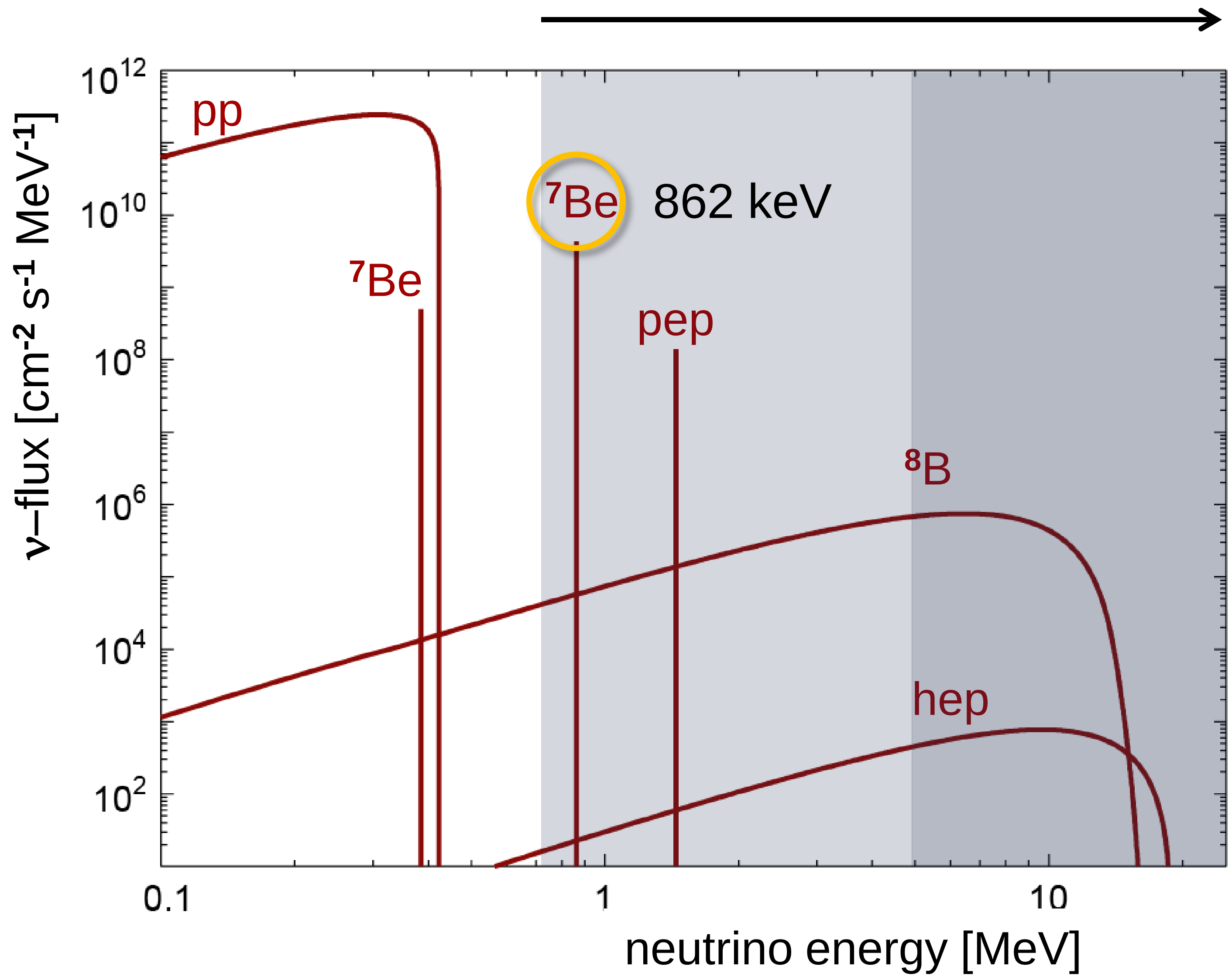


solar neutrinos – ^{7}Be

- **radiochemical detectors:** Cl-37 experiment ⇨ solar ν–problem
  ultra-clean scintillators: Borexino νe-scattering (real-time!)

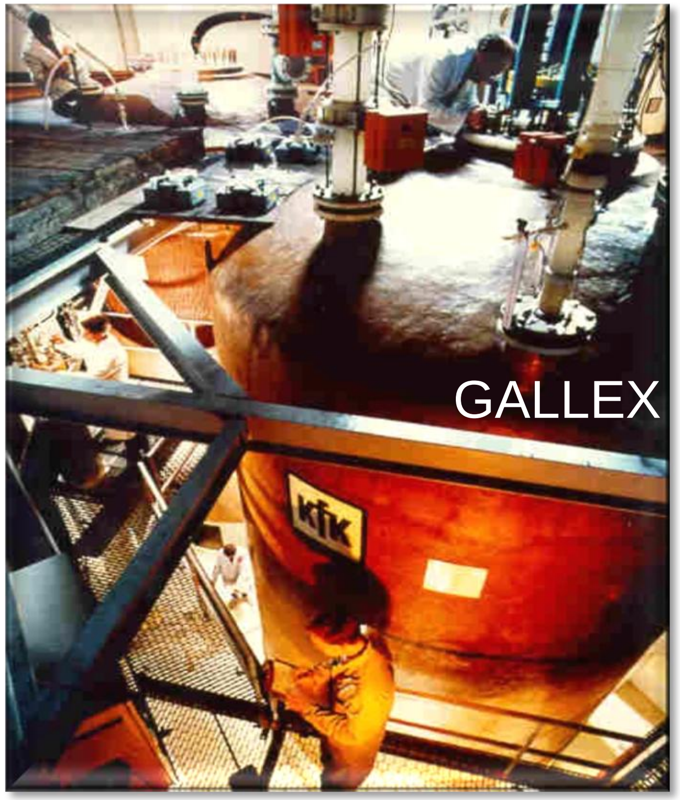

Cl-37 (Davis)

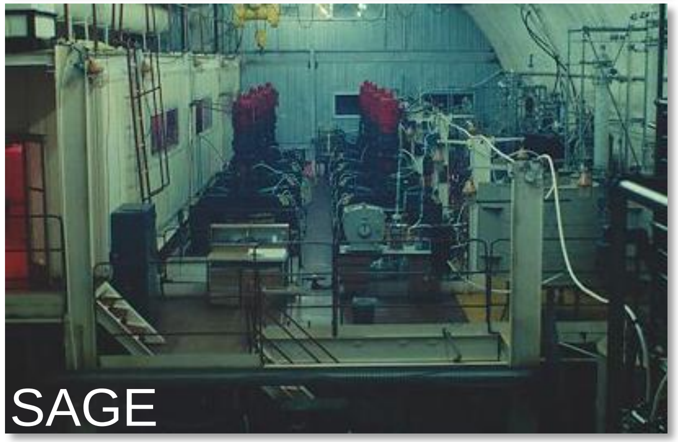

Borexino

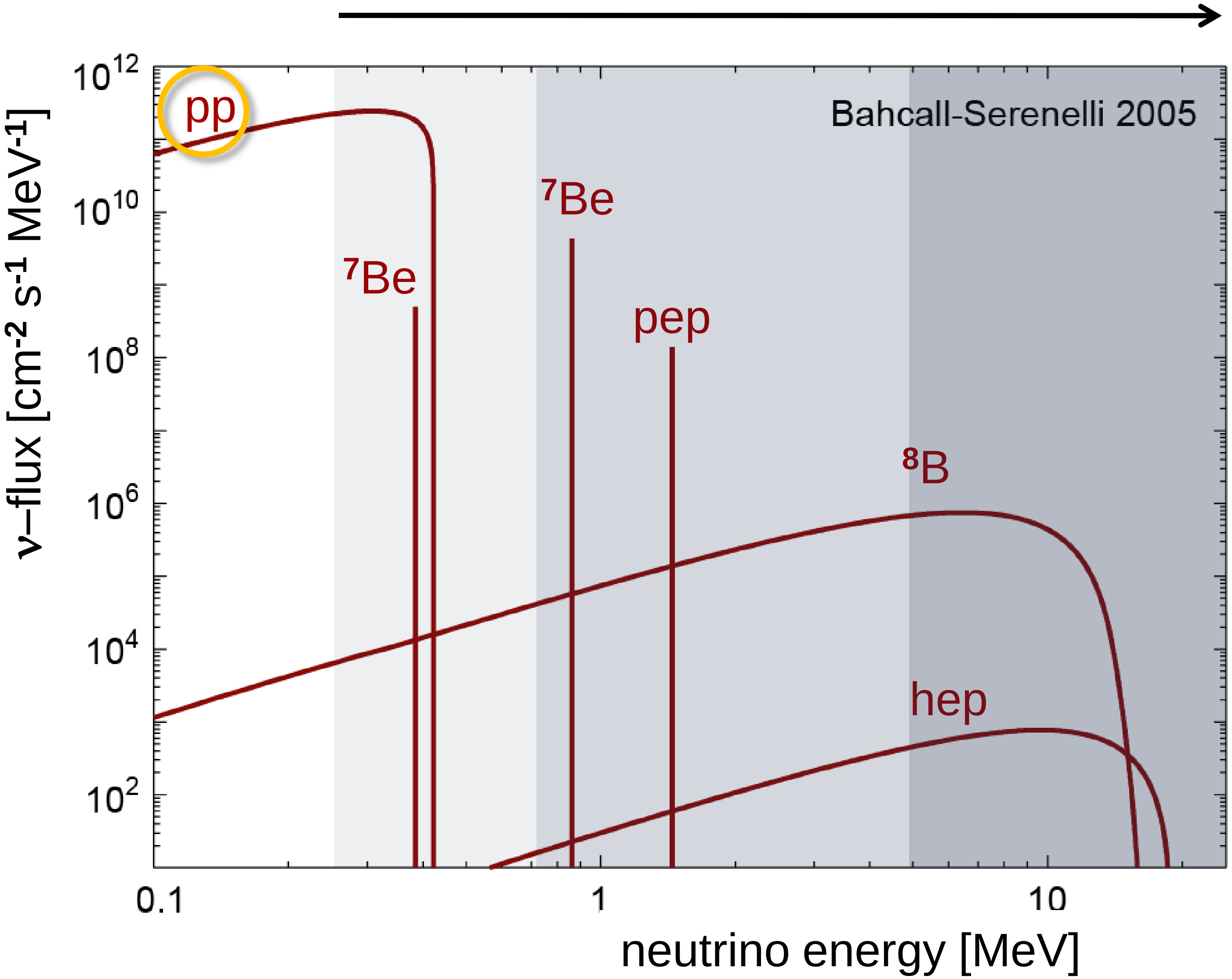


solar neutrinos – pp

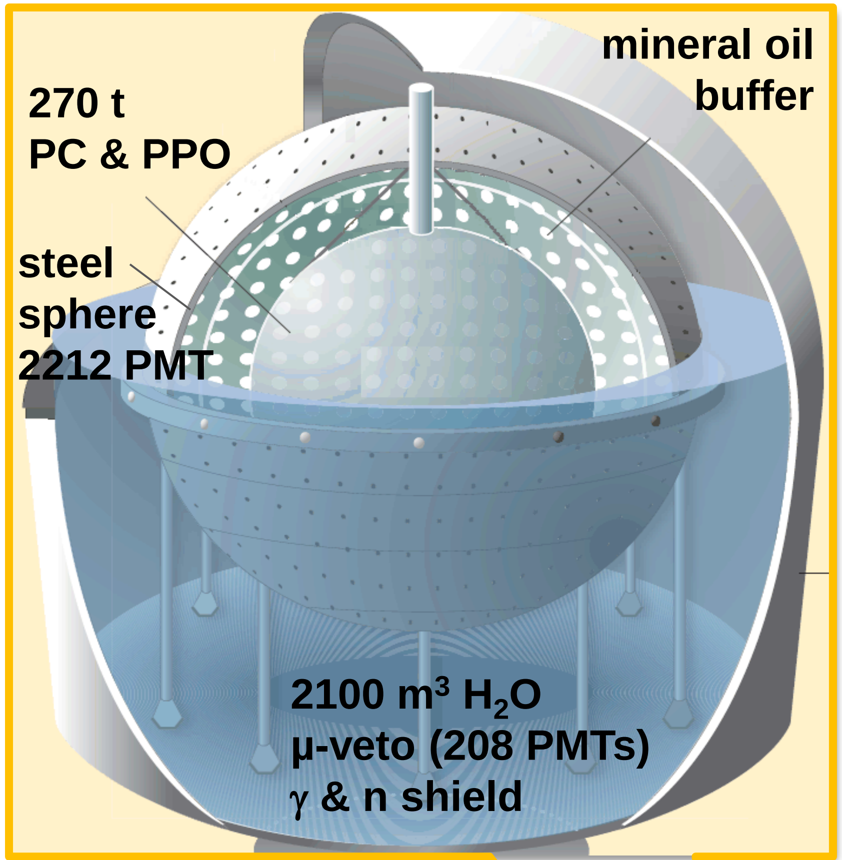
radiochemical detectors: Gallex & SAGE measure low-energy pp-ν´s
successful calibration with ^{51}Cr-ν-source



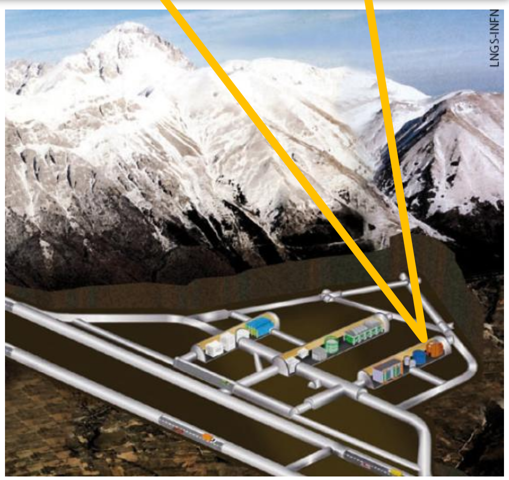




Borexino experiment



at LNGS,
hall C
3500 mwe



■ **objectives: detection of low energy-ν´s via elastic ν-e scattering**

solar neutrinos:

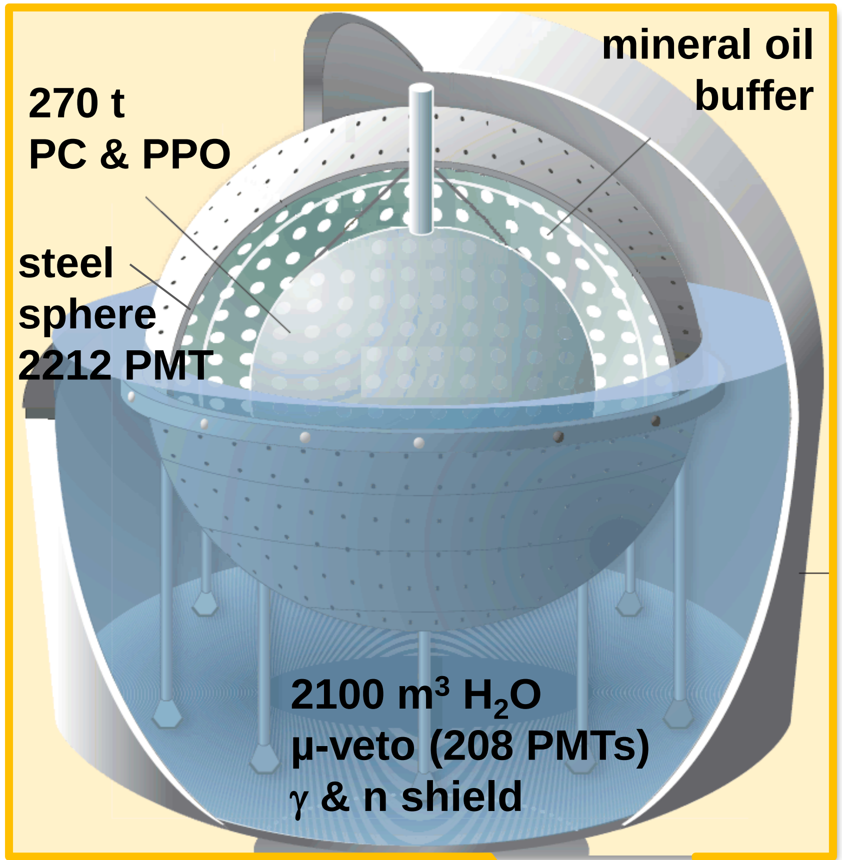
- real-time observation of the **^{7}Be-line**
  - ↳ improved knowledge $\phi(^{7}Be)$ 40 % → < 5 %
  - ↳ astrophysics of the sun (metallicity)
  - ↳ improved precision ϕ(pp), ϕ(CNO)
  - ↳ search for non-standard interactions (NSI)
- measure ^{8}B-ν´s, pep-ν´s
  - ↳ investigation of transition between vacuum oscillations & MSW effect

geo-neutrinos:

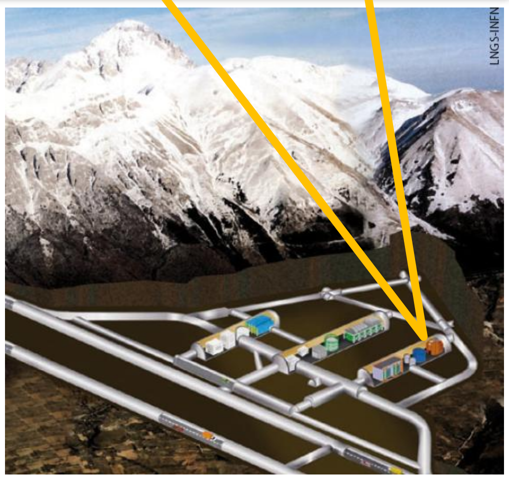
- analysis of energy spectrum at low energies
  - ↳ improved understanding of heat production

[2010: ~10 candidates observed, 4.2σ effect!]

Borexino experiment



at LNGS,
hall C
3500 mwe

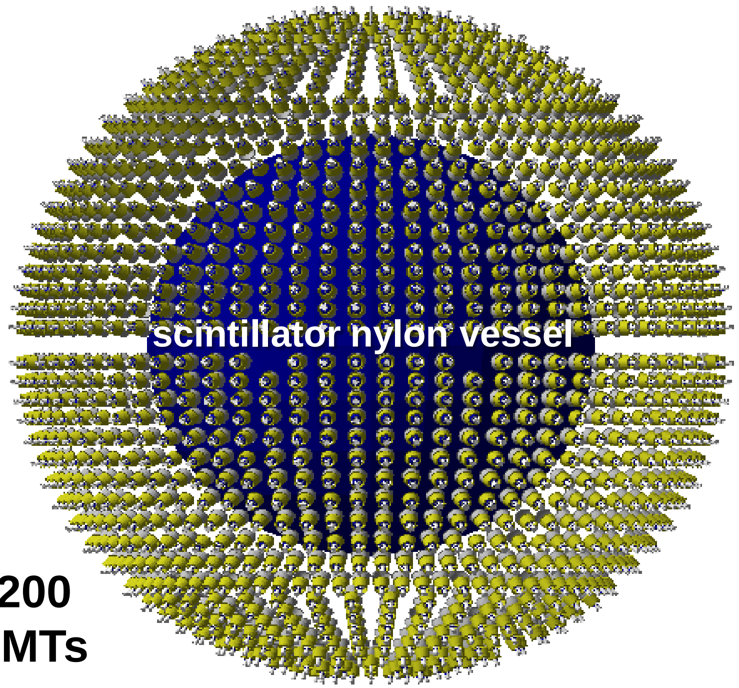


detector: graded shielding principle

ultra-clean liquid scintillator (PC) surrounded by mineral oil buffer and water μ-veto

detector parameters	
light yield	500 p.e./ MeV
resolution	5% @ 1 MeV

Borexino experiment



2200 PMTs


May 15, 2007
Borexino filled with scintillator

detector: graded shielding principle

ultra-clean liquid scintillator (PC) surrounded by mineral oil buffer and water μ-veto

detector parameters	
light yield	500 p.e./ MeV
resolution	5% @ 1 MeV

challenge: extremly small isotope impurities

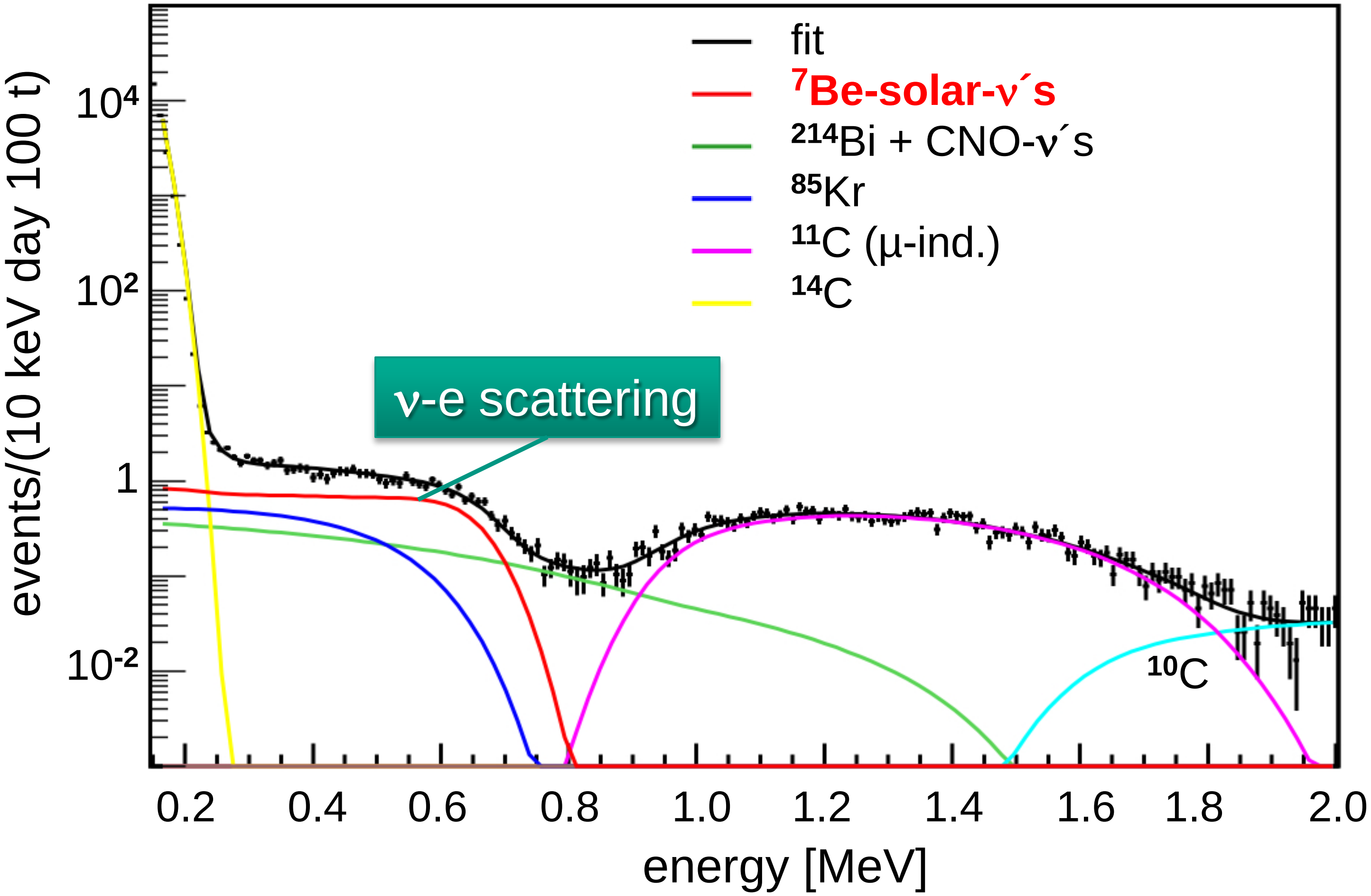
isotope	purity-design	purity-realised	
^{238}U	< 10^{-16} g/g	1.9 ×10^{-17} g/g	
^{232}Th	< 10^{-16} g/g	6.8 ×10^{-18} g/g	⇘ ^{8}B ν´s

^{210}Po: α-decay to ^{206}Pb, E_α = 5.3 MeV, non-eq.
$A(t_0)$ ~ 6000 cts/day/100 t ($t_{½}$ = 138 d)

^{85}Kr: ß-decay to ^{85}Rb, E_0 = 687 keV
A ~ (30 ± 5) cts/day/100 t ($t_{½}$ = 10.7a)

Borexino – initial results for ^{7}Be

- **initial ^{7}Be-analysis**
  data taking 5/07 - 4/08
  192 days = 41.3 t years
- **systematics**
  - **total** **8.5%**
  - detector resp. 6%
  - fiducial mass 6%
  - cut efficiency 0.3%
  - scintillator mass 0.2%



- **initial results**
  parameters of MSW – LMA ☑

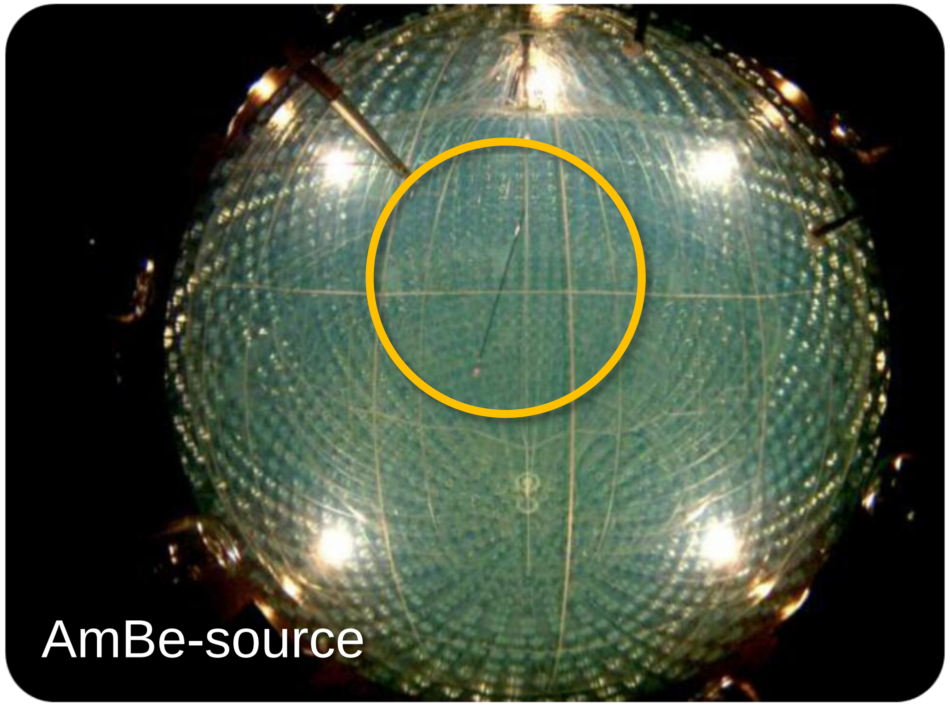
parameter	Borexino result	LMA
^{7}Be-ν rate (per day per 100 t)	49 ± 3 (stat.) ± 4 (syst.)	48 ± 4
^{7}Be-ν flux (× 10^9 cm^{-2} s^{-1})	5.18 ± 0.52	5.1
ν_e-survival probability P_{ee}	0.56 ± 0.10	0.541 ± 0.017

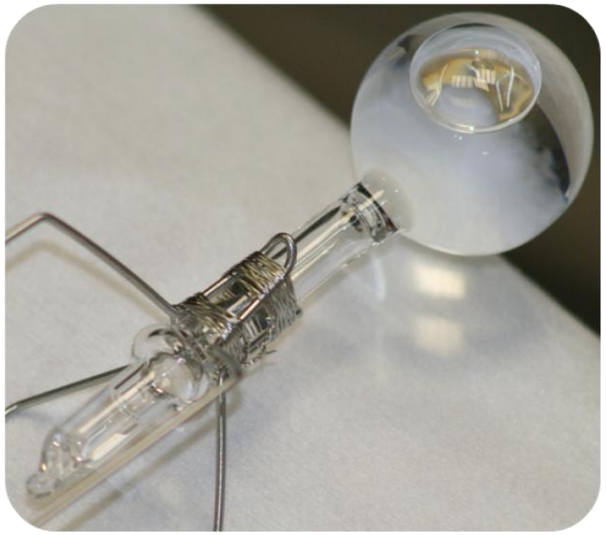
Phys. Rev. Lett. 101 (2008) 09132

Borexino – calibration

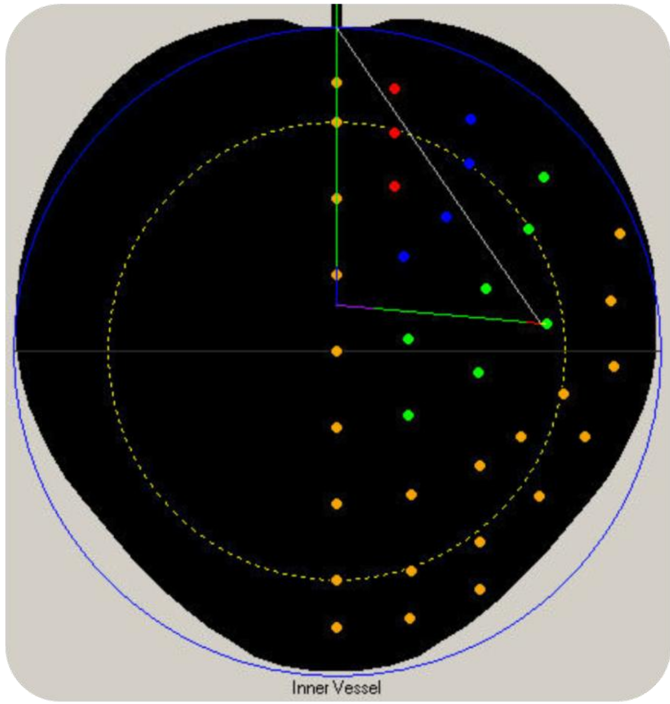
- **2009:** calibration of detector with α,ß,γ and neutron sources:
  - position reconstruction
  - position resolution
    } ↳ fiducial volume
  - energy scale (in particular E < 2 MeV)
    } ↳ detector response

- **results:** reduced systematic error for fiducial volume 6 % → 1.3 %





γ: ^{57}Co, ^{139}Ce, ^{209}Hg, …
ß: ^{14}C, ^{214}Bi, α: ^{214}Po

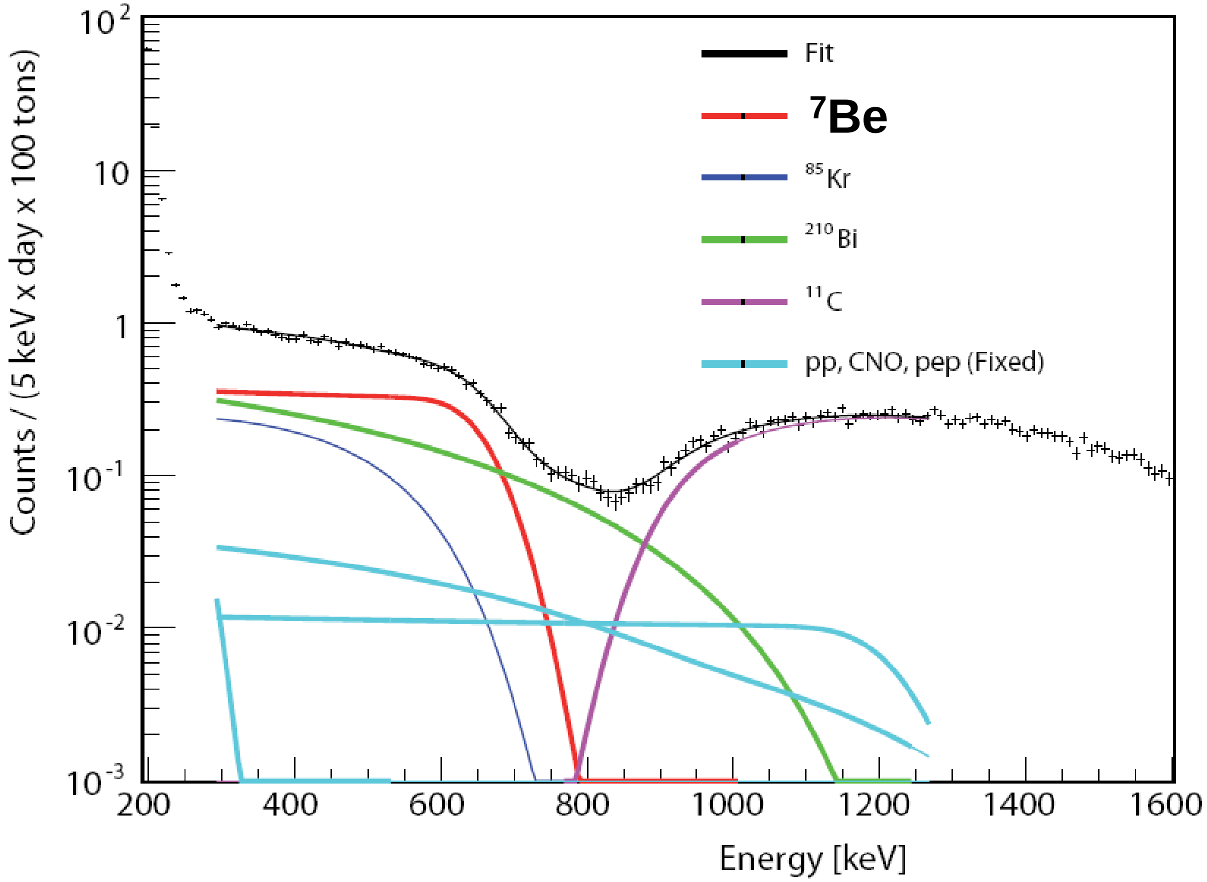


Borexino – preliminary new results for ^{7}Be

- **updated, improved ^{7}Be-analysis**
  ~ 750 days of data
  statistical subtraction of ^{210}Po

- **systematics (after calibration)**

- **total**	**2.7%**
- energy scale	1.3%
- fiducial mass	1.3%
- fit method	1.0%
- fit assumption	1.7%



- **preliminary results**

Parameter	Borexino result	LMA, high Z	LMA, low Z
^{7}Be-ν rate (/day/100 t)	46.0 ± 1.5 (stat.) ± 1.3 (syst.)	48 ± 4	44 ± 4
ν_e-survival P_{ee}	0.51 ± 0.05	E. Meroni, ν-telescopes 2011	

- no discrimination (yet) between high Z / low Z solar metallicity possible

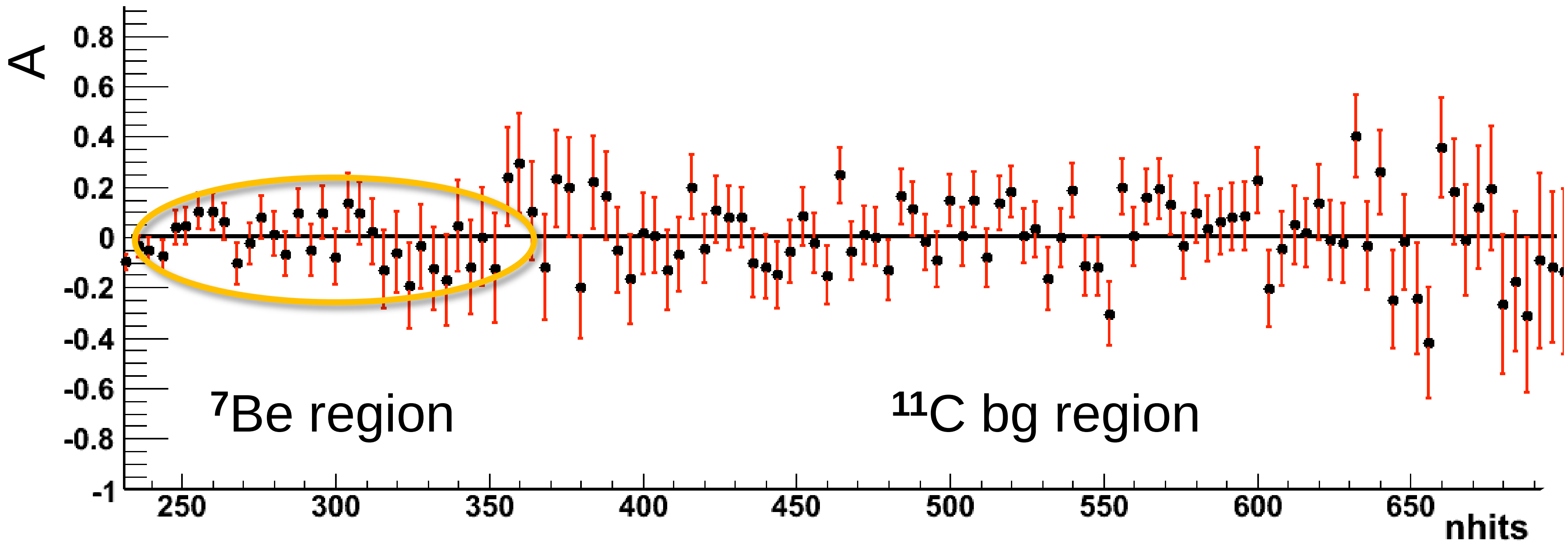
Borexino – ^{7}Be day-night asymmetry

- **^{7}Be-analysis to search for potential day - night asymmetry A**
  - LOW solution (excluded previously by reactor anti-ν´s ´only´)
  - **MaVaN** (**Ma**ss **Va**rying **N**eutrino) models, predicting A = - 0.23
- **^{7}Be-analysis:** day 387.46 days – night 401.57 days

$$A = \frac{N - D}{\frac{1}{2} \cdot (N + D)} = 0.007 \pm 0.0073_{\text{stat}}$$

⇒ MaVaN models ruled out by 3 σ

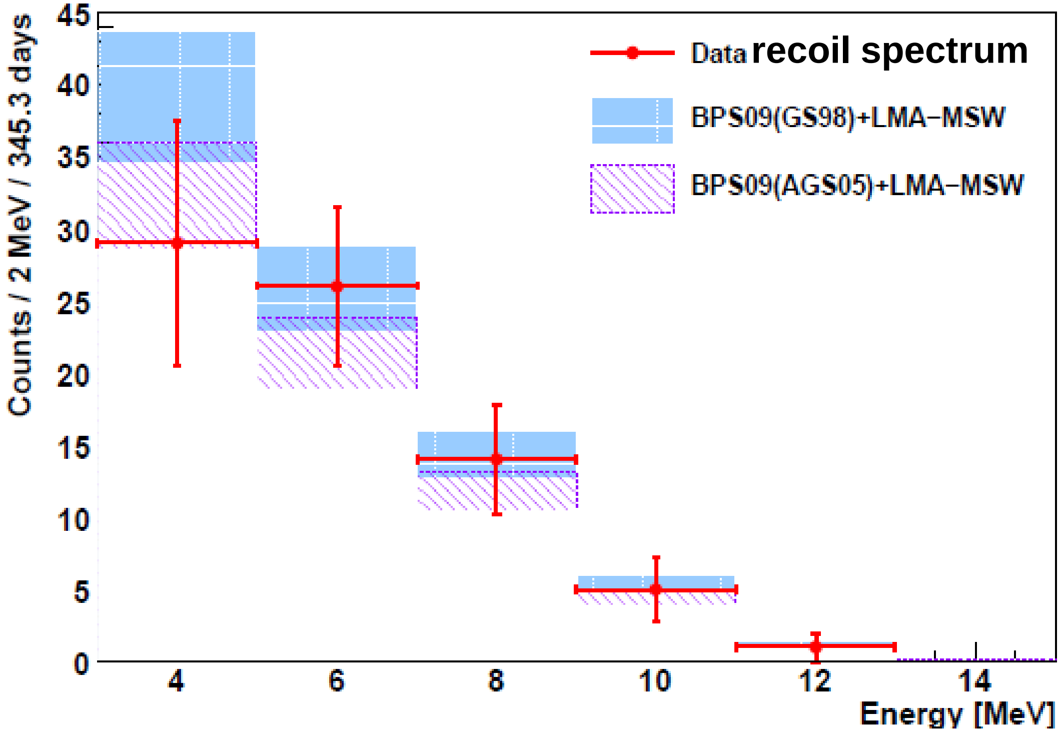
LMA confirmed by solar ν data also



#PMT hits

Borexino – ^{8}B neutrinos with E_{thres} = 3 MeV

- **^{8}B-analysis (E > 3 MeV) to search for transition MSW ⇔ vacuum osc.**
  live time: 345.3 days, expected signal rate R ~ 0.25 cpd/ 100 t (> 3 MeV)
- backgrounds: muons, ^{232}Th, …
- final ^{8}B-sample: **(75 ± 13) events**
  in energy interval 3 – 16 MeV
- results in agreement with
  - LMA solution of MSW effect
  - solar models



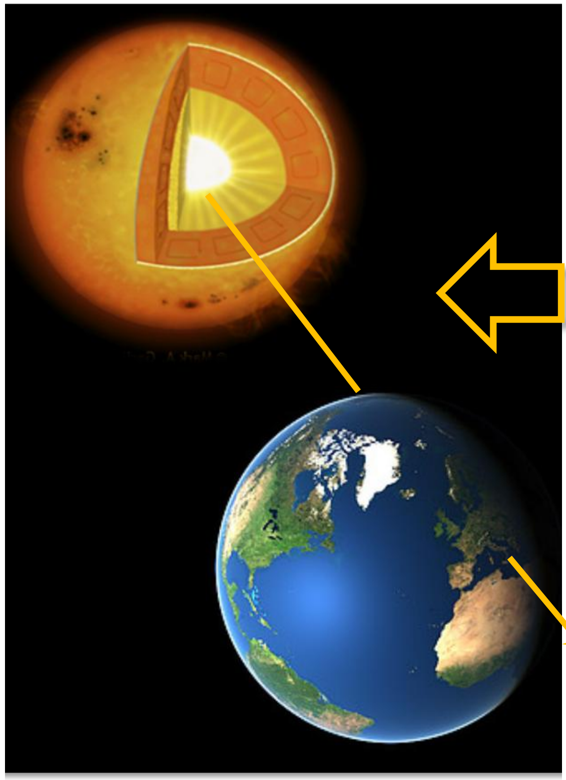
PRD 82 (2010) 033006

parameter	3.0 – 16.3 MeV	5.0 – 16.3 MeV
^{8}B-ν rate (per day per 100 t)	0.22 ± 0.04 (stat.) ± 0.01(syst.)	0.13 ± 0.02 (stat.) ± 0.01(syst.)
^{8}B-ν flux (× 10^{6} cm^{-2} s^{-1})	**2.4 ± 0.4 ± 0.1 [BP: 5.94 ± 0.6]**	2.7 ± 0.4 ± 0.2
exp. signal / SSM + MSW eff.	0.88 ± 0.19	1.08 ± 0.23

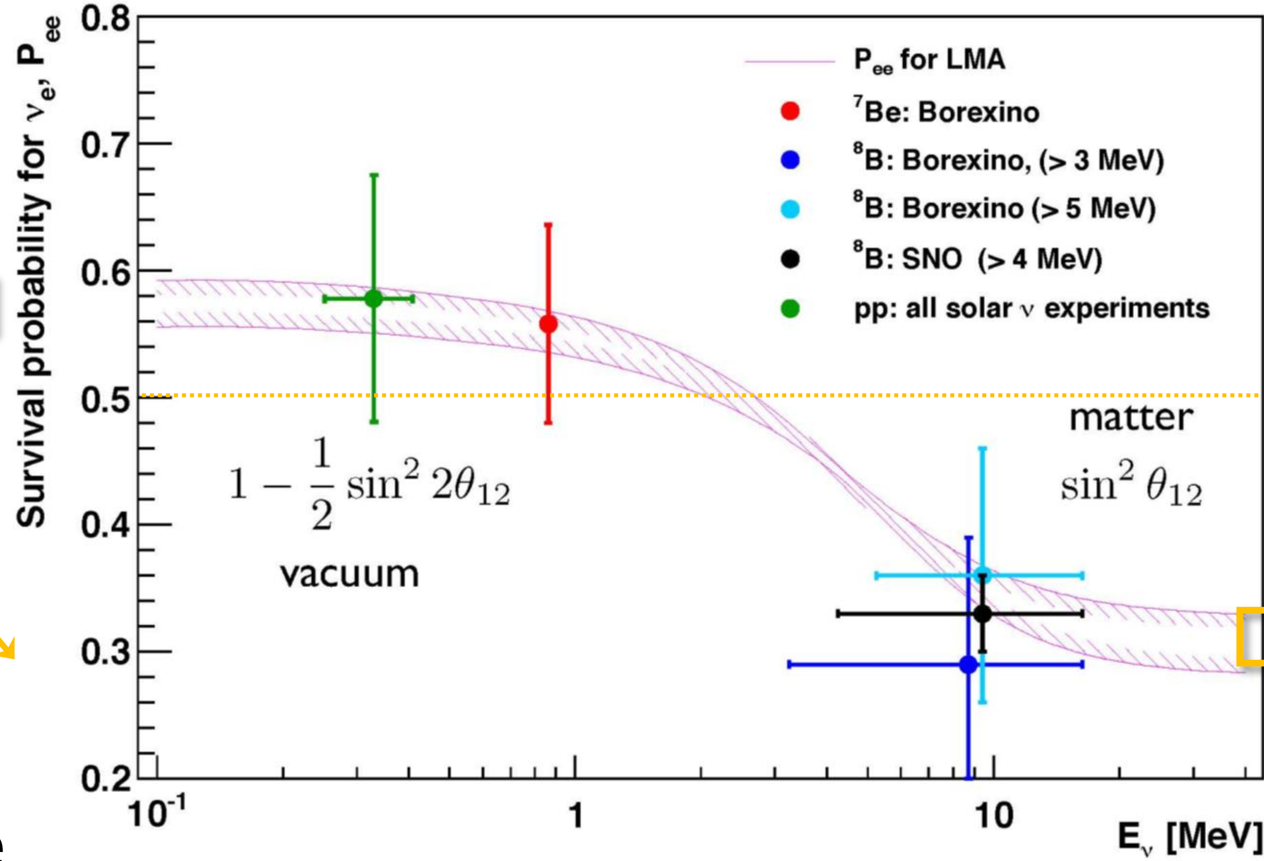
solar ν – transition from MSW to vacuum

■ **Borexino has provided important new information for ^{7}Be, ^{8}B**
- restricts possible sub-dominant contributions from: mass varying neutrinos, FCNC, low-mass sterile ν´s

vacuum oscillation

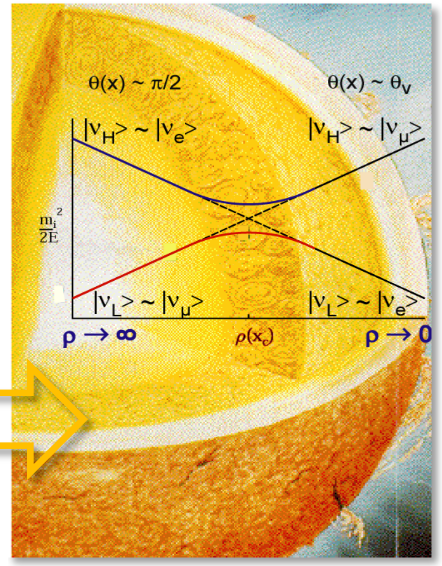


no MSW resonance



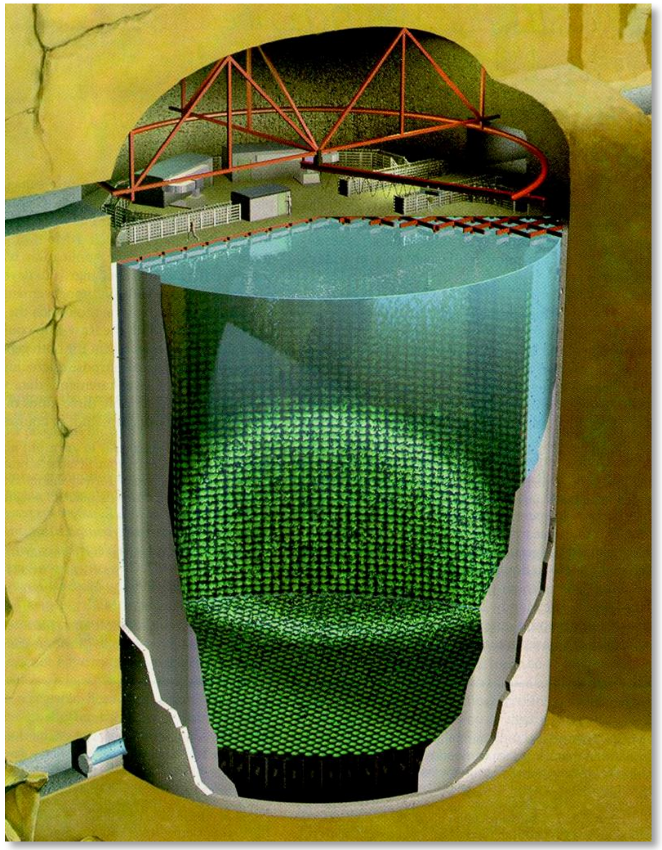
MSW effect

matter effects influence ν-propagation



$V = \sqrt{2}\, G_F \cdot N_e$

atmospheric neutrinos: θ_{23} oscillations

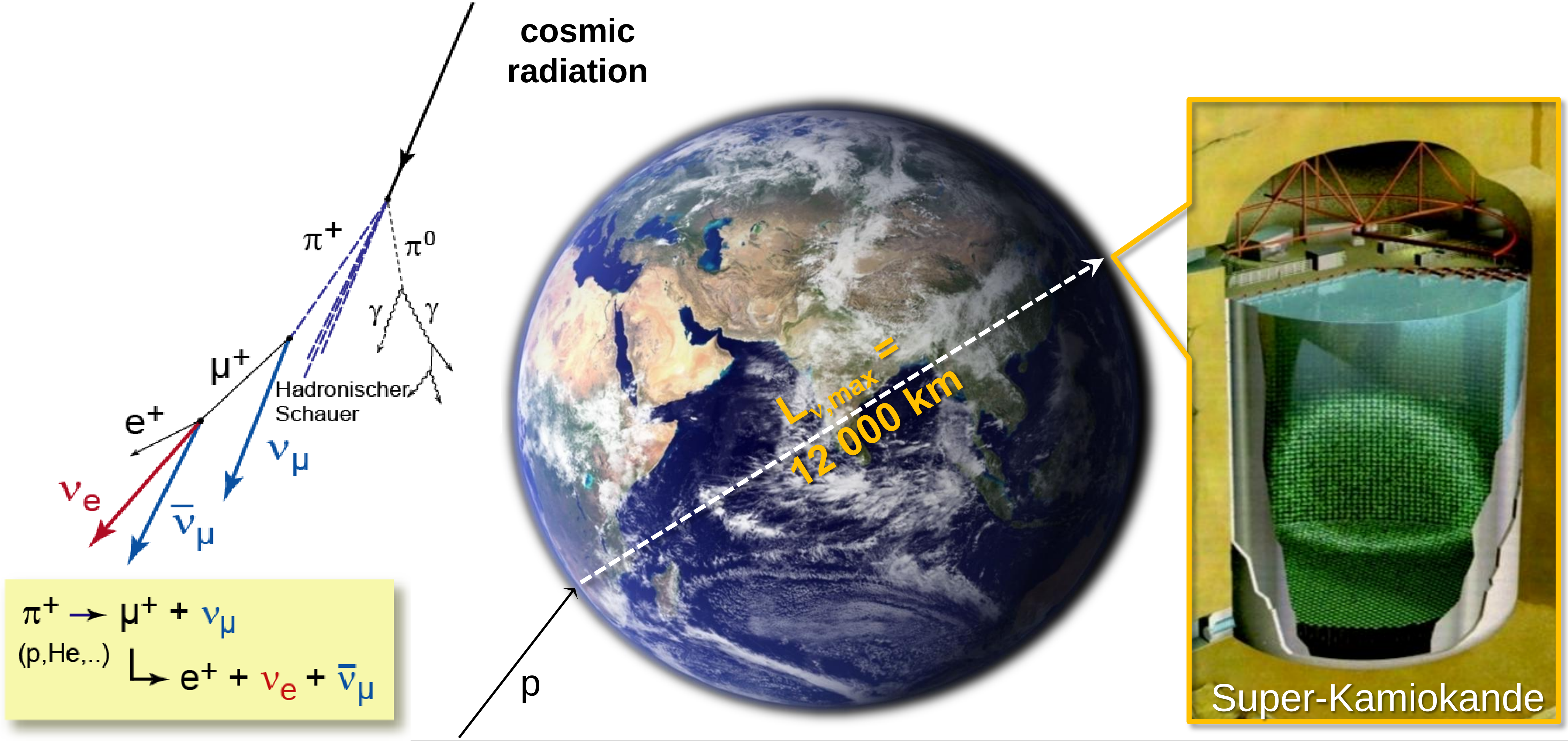


atmospheric neutrinos

- CR generate extensive air showers in upper atmosphere (h ~ 20 km)

energies: Φ_{max} at E_ν = 0.25 GeV, $\Phi_\nu \sim E^{-2.7}$ for higher energies

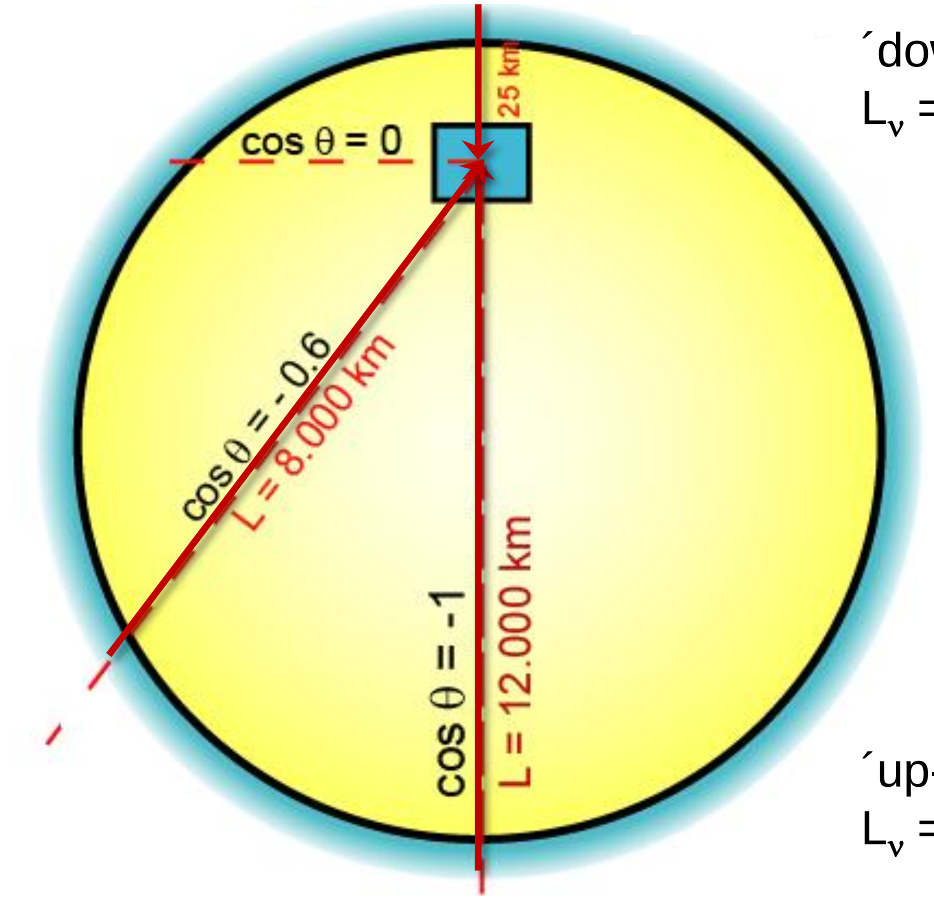
flux: $\Phi_\nu \sim 1\ cm^{-2}\ s^{-1}$ at sea level



atmospheric neutrinos – pathlength L_ν

- **atmospheric neutrinos: an ideal source for ν-oscillations**
  - detector is fully enclosed in a 4π geometry
  - zenith angle θ of neutrino defines ν-pathlength L_ν (20-12.000 km)

azimuth angle θ & pathlength L_ν



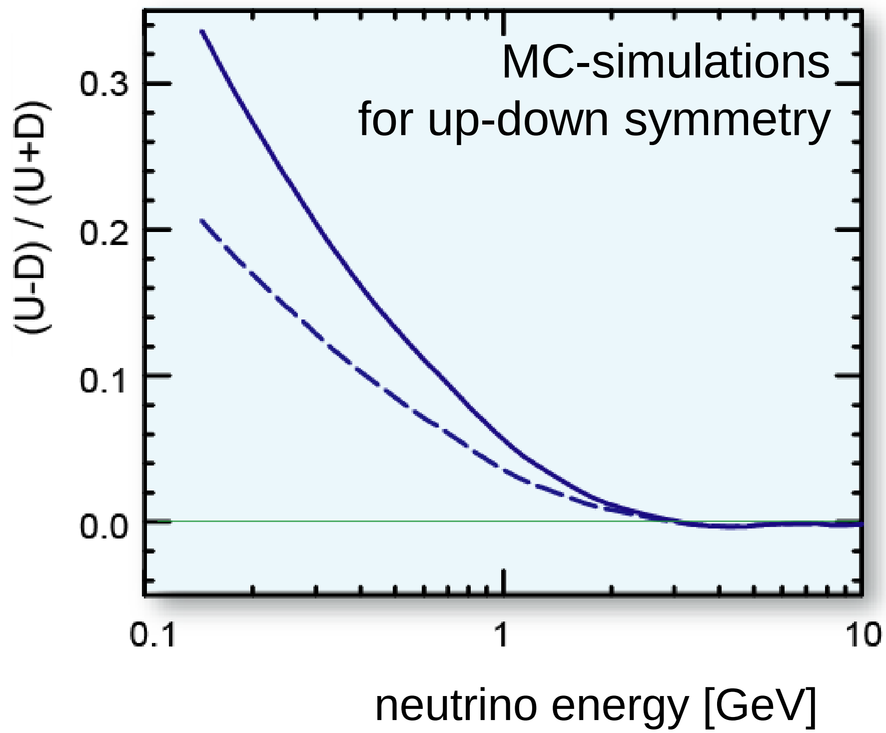
´down-going´ (D)
L_ν = 20-25 km

L_ν ~ 20 – 12 000 km

´up-going´ (U)
L_ν = 12000 km

up/down symmetry

expectation: N(up) = N(down)

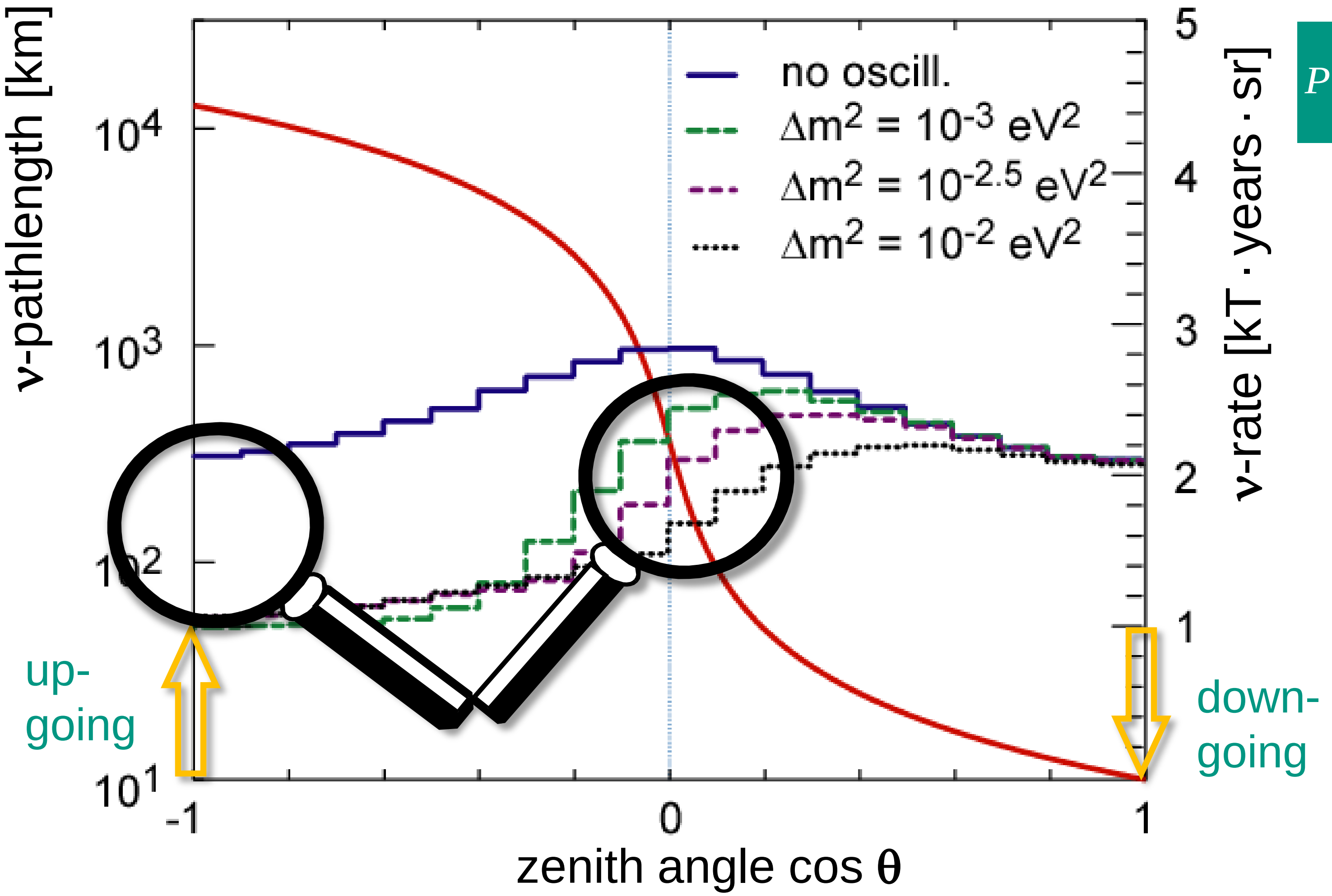


atmospheric neutrinos – zenith angle θ

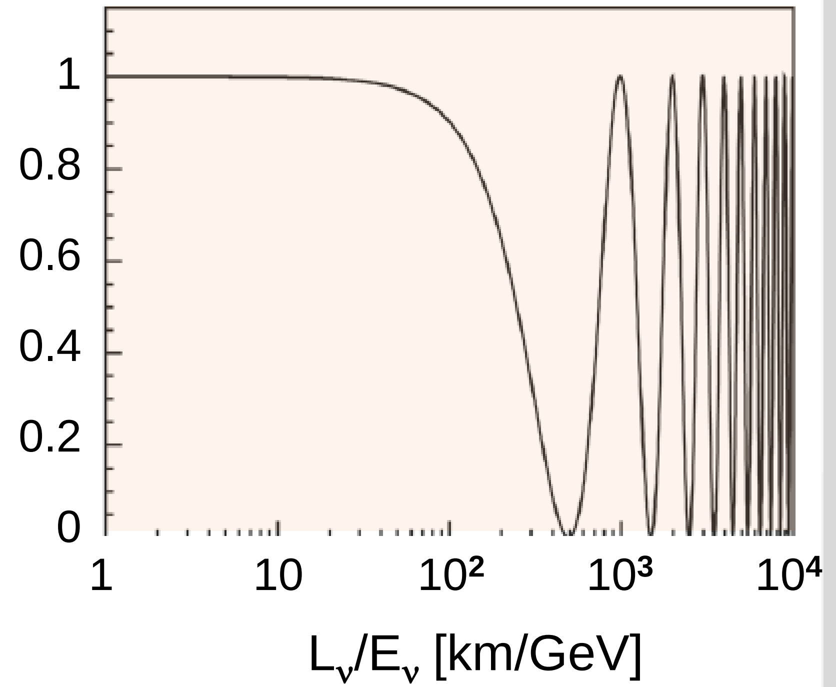
- high-energy multi-GeV ν_{atm}: **close correlation of the angle ν-lepton**

  zenith angles around cos θ = 0 (horizontal ν_μ) ⇨ define scale Δm^2

  zenith angles around cos θ = -1 (up-going ν_μ) ⇨ define scale $\sin^2 2\theta$

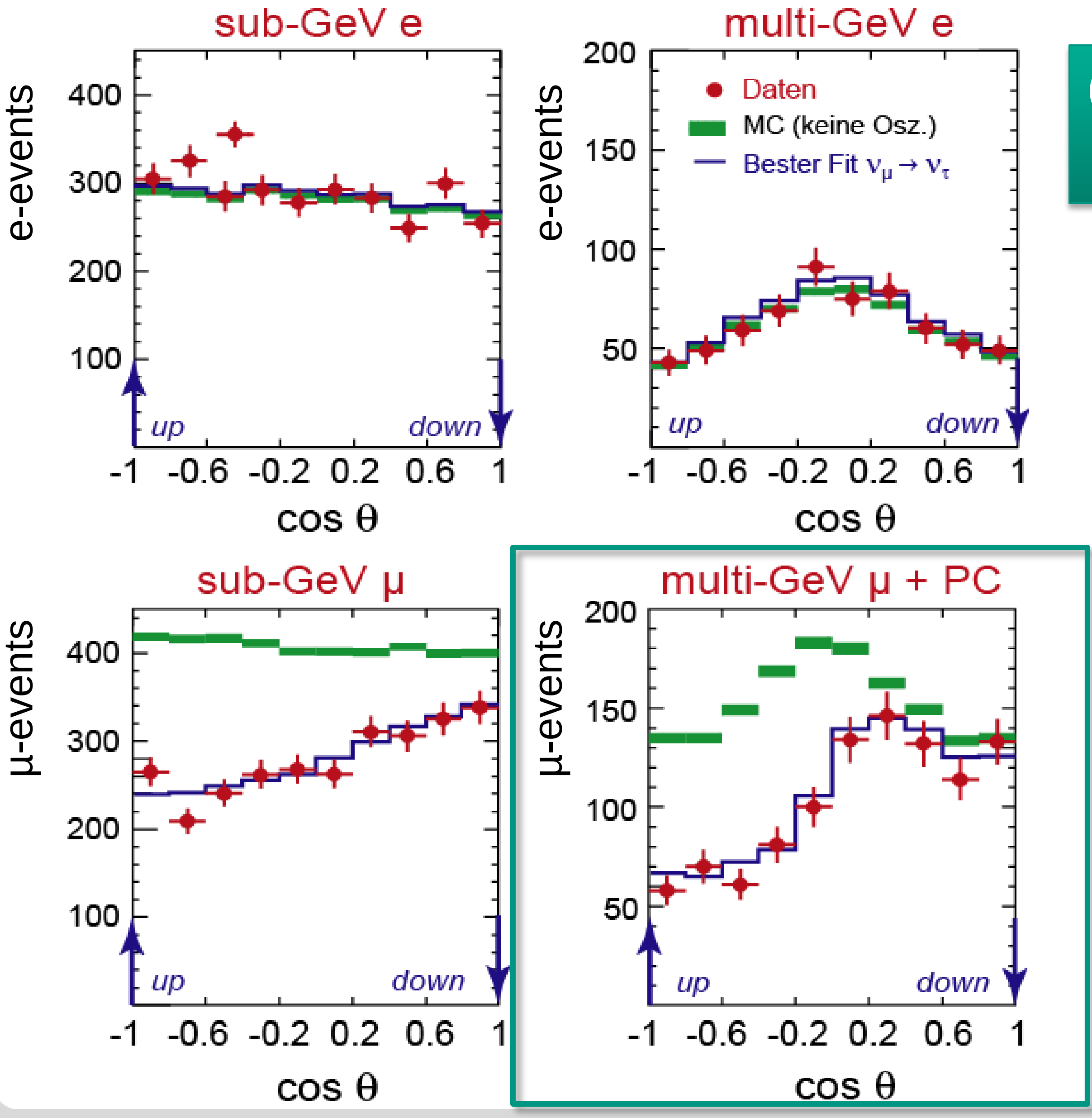


$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

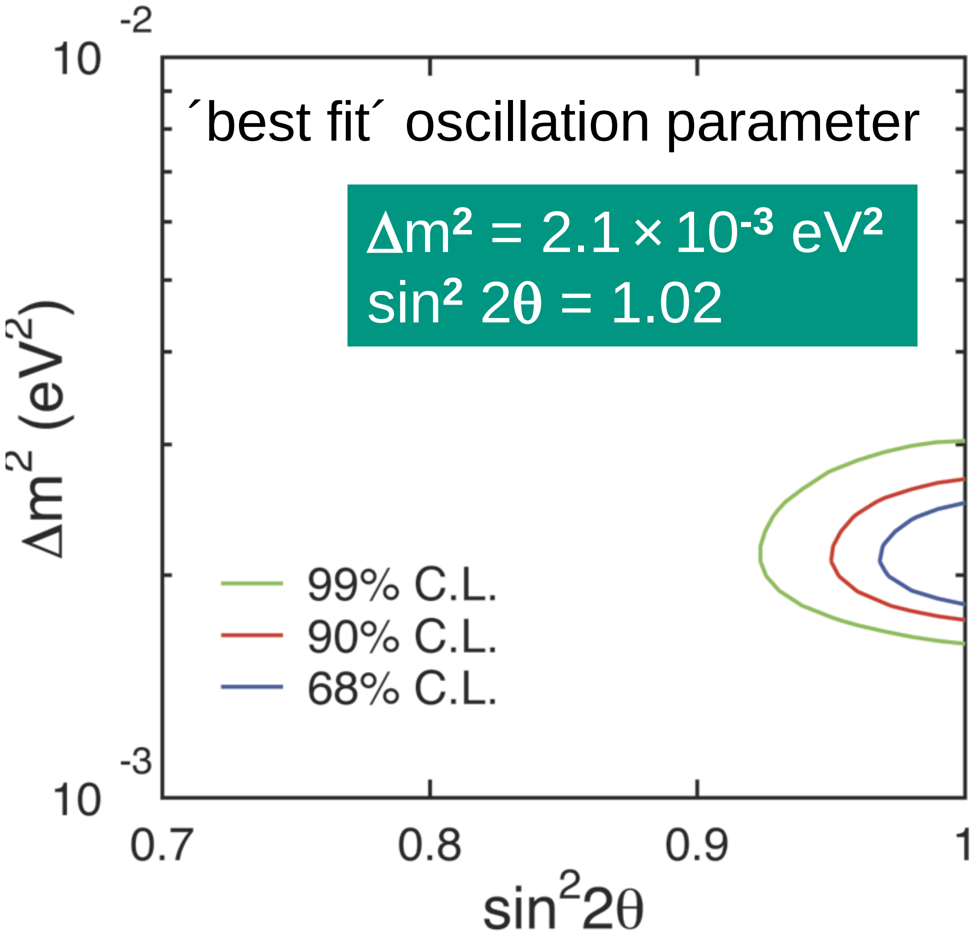


Super-Kamiokande: cosθ distributions

- analysis of Super-Kamiokande-I azimuth angle distributions

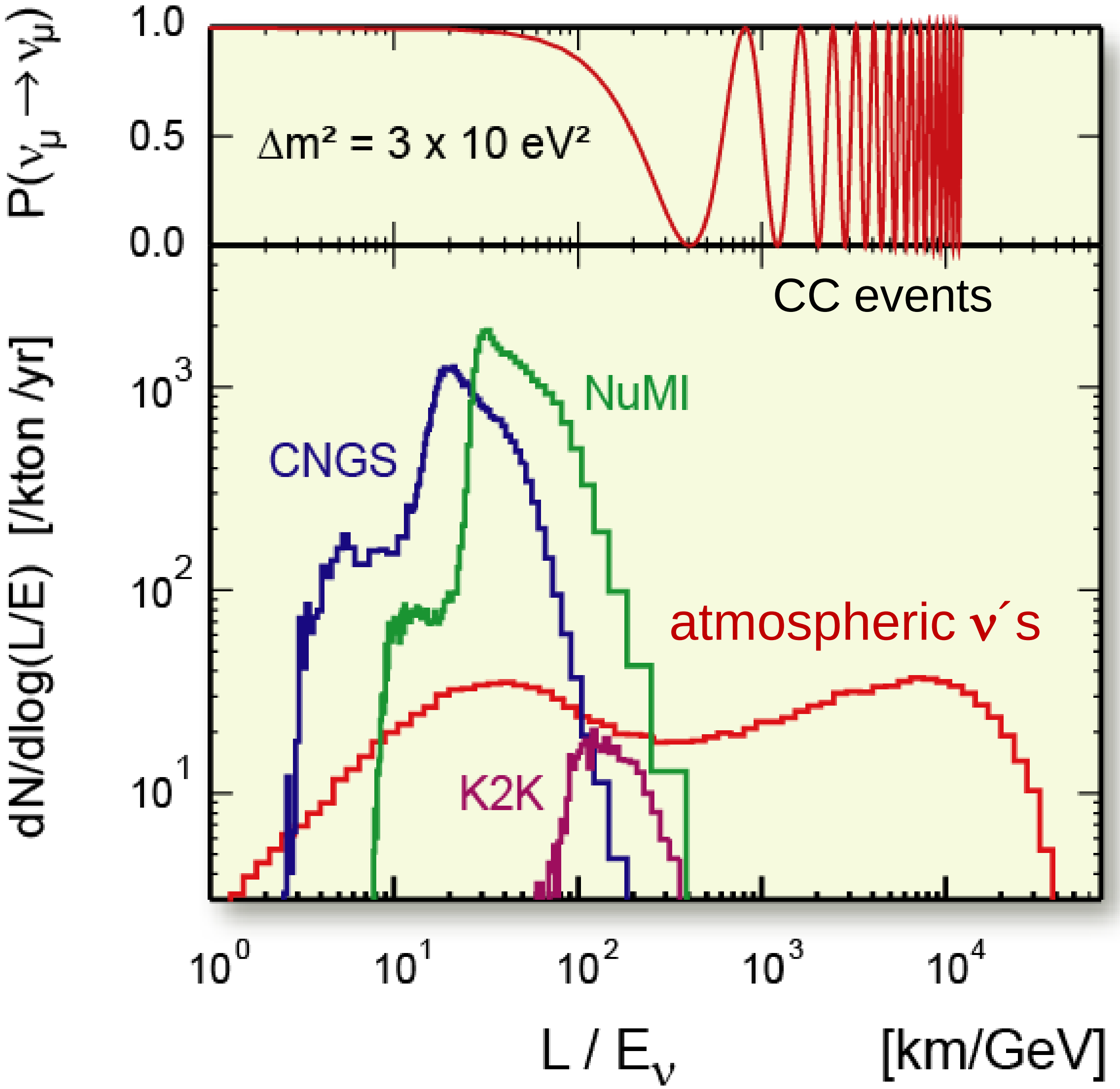


6.6.1998: evidence for oscillations of atmospheric neutrinos!



atmospheric ν´s & accelerators

- cross-checking the results of atmospheric ν´s with longbaseline accelerator-ν-experiments



atmospheric ν´s:

large Δm² (L_ν/E_ν) space

CNGS :

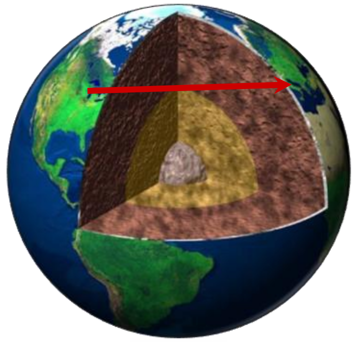
CERN SPS → Gran Sasso

NuMI :

FermiLab → Minos

K2K :

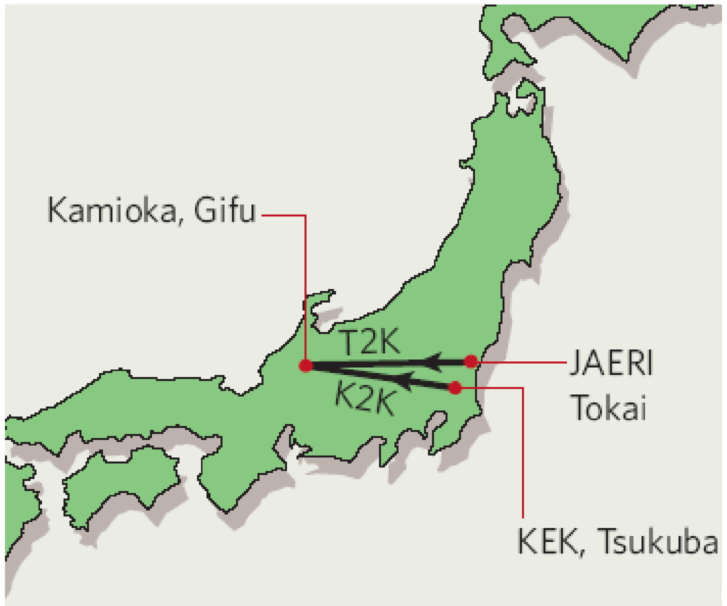
long baseline oscillation experiments

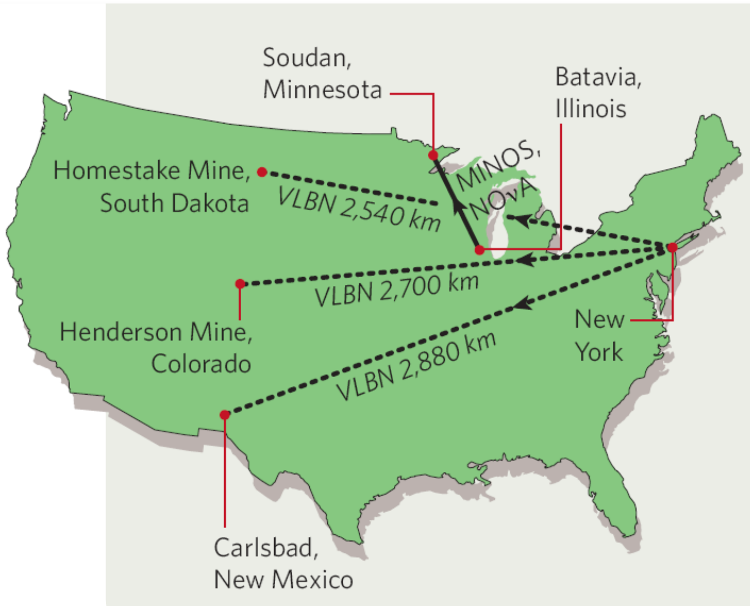


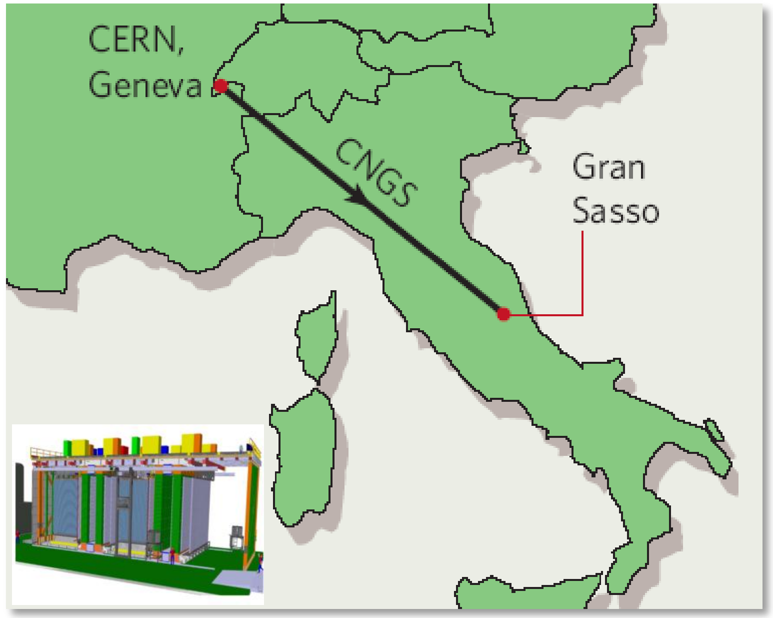
- operating & planned (very) long-baseline accelerator-based ν-oscillation experiments in Japan, US & Europe

long baseline accelerator experiments: overview

LB-ν-beam	place	distance	energy	L/E	start	detector	channel
K2K	J	235 km	1.4 GeV	~150	1999	Super-Kamiokande	ν_μ - x
NuMI	US	735 km	1-30 GeV	50-350	2005	MINOS	ν_μ - x
CNGS	**EU**	**732 km**	**30 GeV**	**50-350**	**2007**	**OPERA**	ν_μ - ν_τ
T2K	J	295 km	~2 GeV	~150	2010	Super-Kamiokande	ν_μ - ν_e





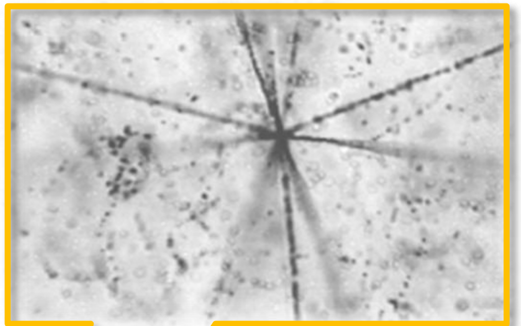


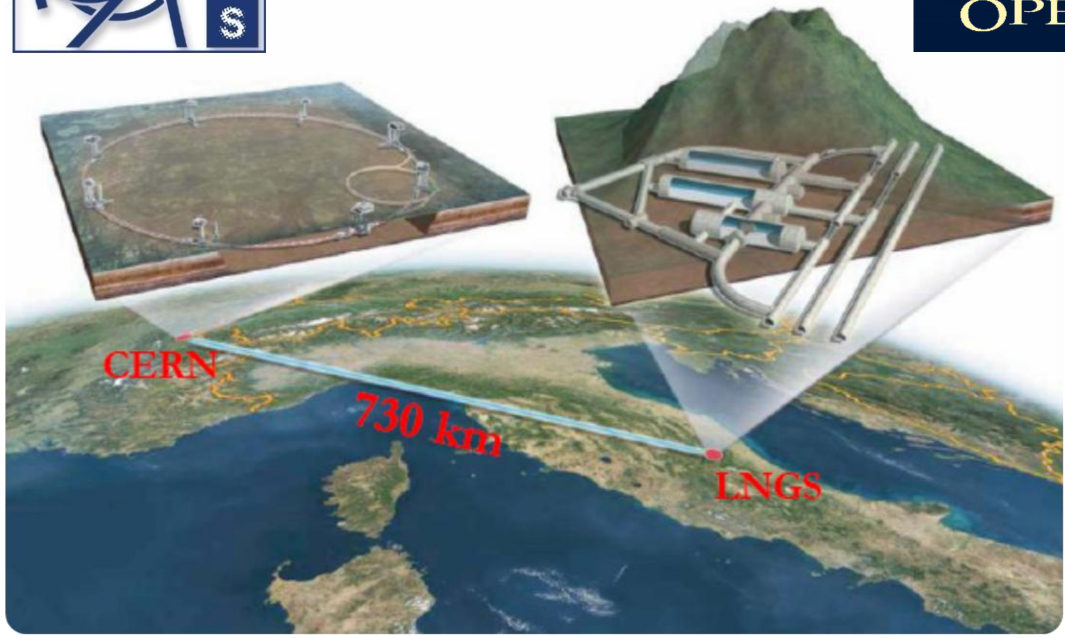
OPERA & CNGS: $\nu_\mu \rightarrow \nu_\tau$ appearance

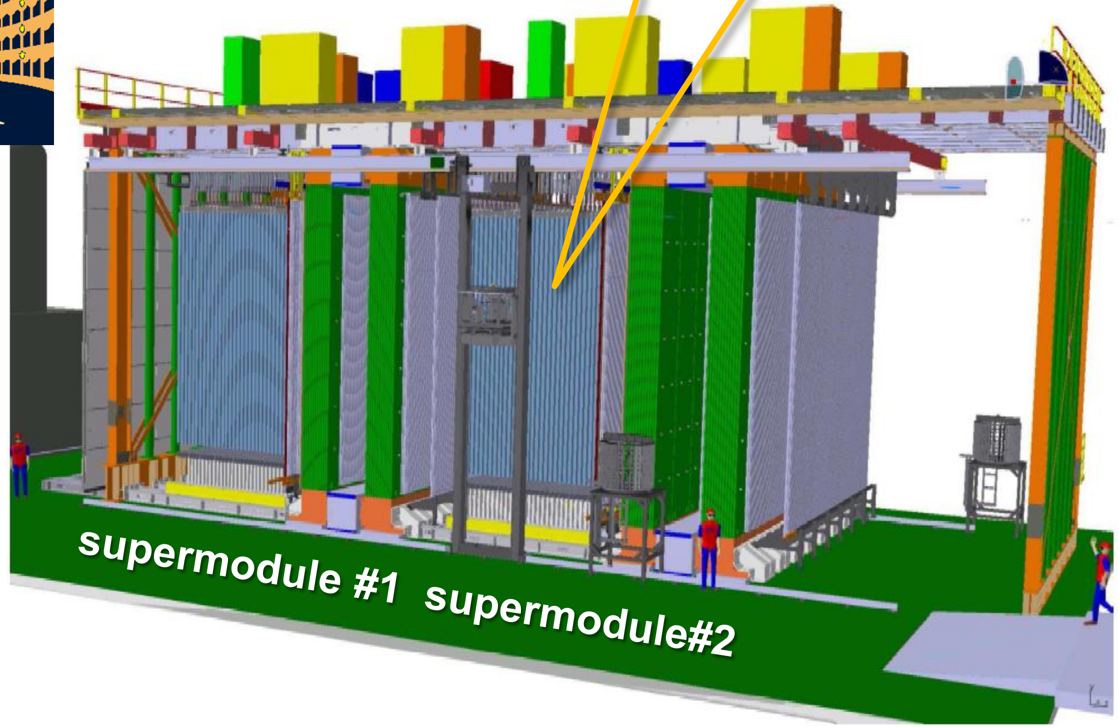
Oscillation **P**roject with **E**mulsion T**R**acking **A**pparatus

beam: - ν_μ beam CERN – LNGS ($L_\nu/E_\nu \sim \Delta m^2_{23}$ scale)
- end of 2010: ~10^{20} p.o.t.

detector: - foto emulsions with Pb-Absorber (bricks)
- tracking detectors (RPCs)
- target mass 1.3 kt

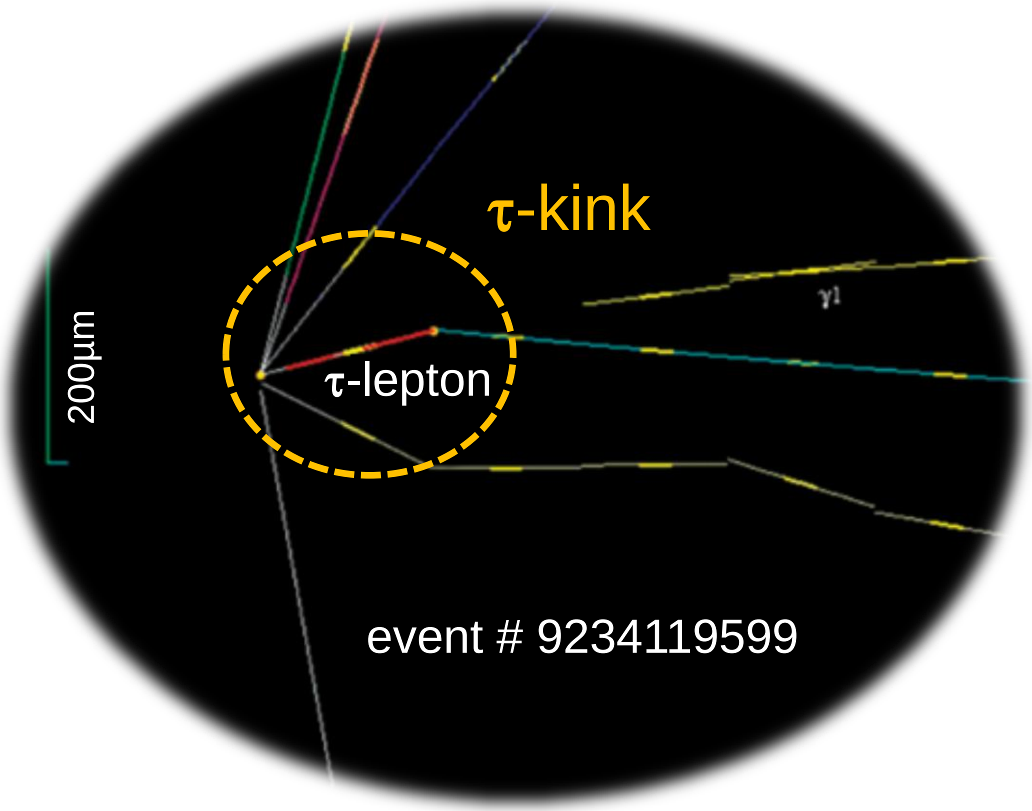


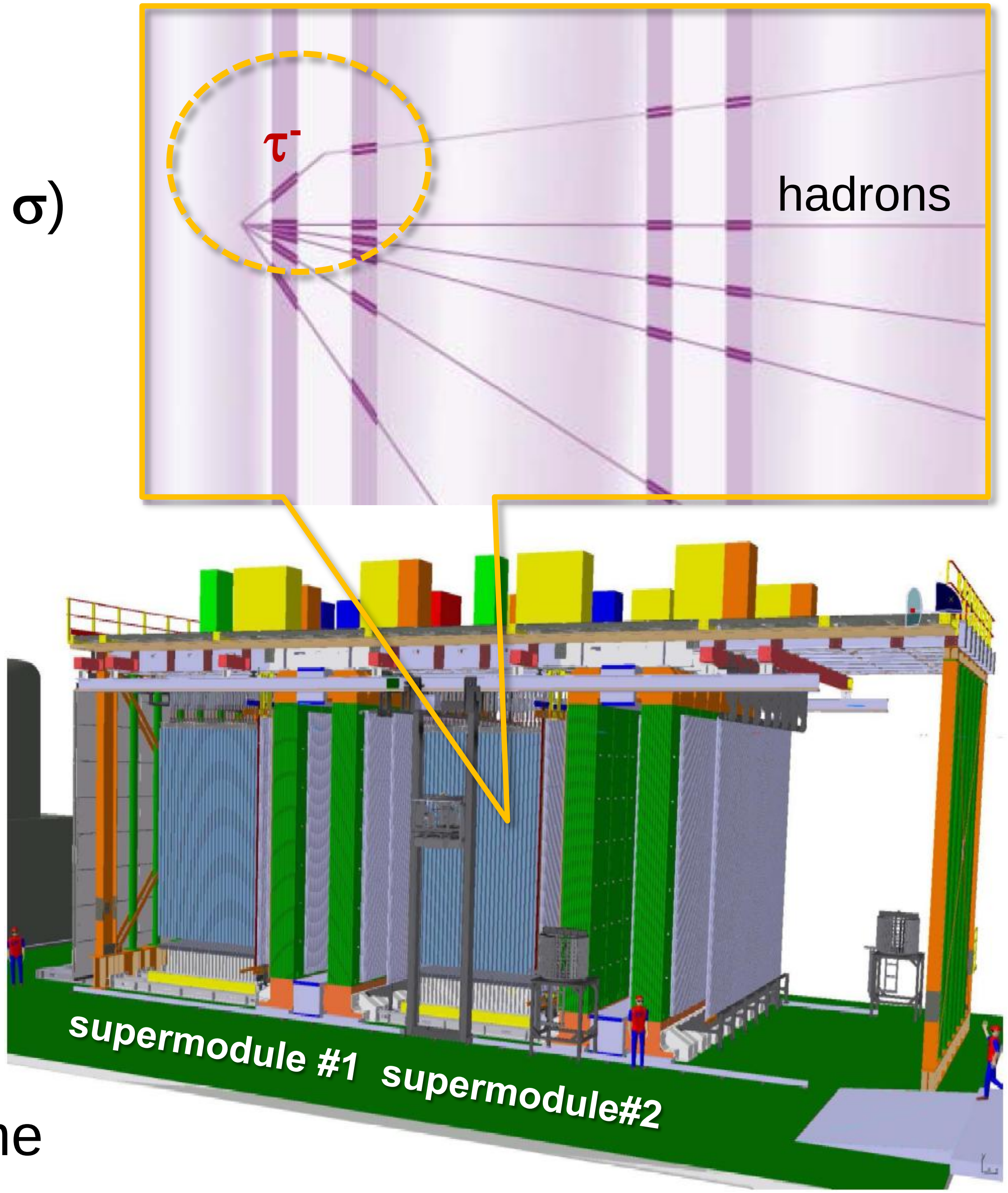




OPERA – first ν_τ candidate

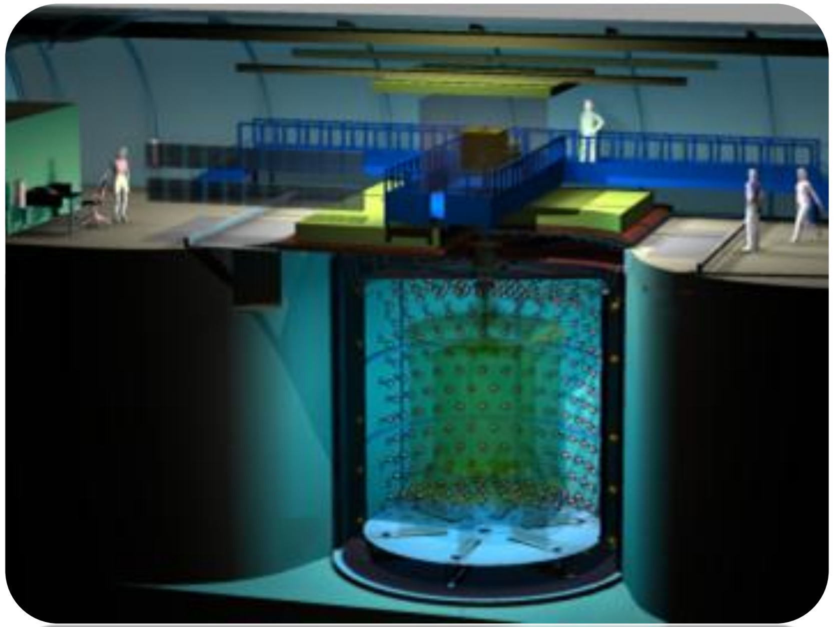
- 2010: detection of **first ν_τ candidate** in an OPERA lead brick
  4.5% probability of a bg-fluctuation (2 σ)





- ~ 2 events/y expected, 5 y running time

3-flavour oscillations – mixing angle θ_{13}

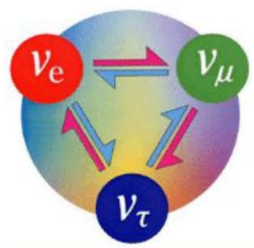


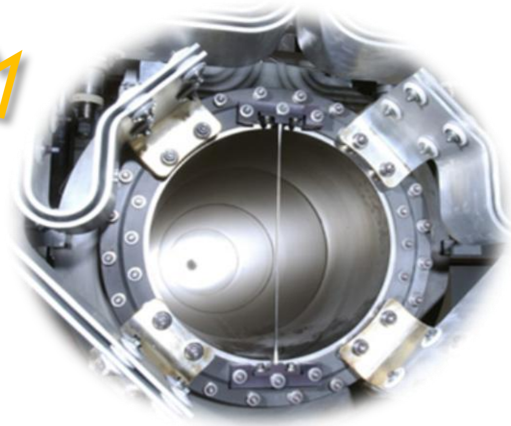
3-flavour neutrino oscillations: θ_{13}

- geniune 3 flavour oscillations ⇔ mixing angle θ_{13}

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

reactor experiments





accelerator experiments

complementary

disappearance channel: $P(\bar{\nu}_e \Rightarrow \bar{\nu}_e)$

- only θ_{13}, no other parameters
- no flavour-´contamination´
- absolute ν-flux (2-/multi- detectors)

appearance Kanal: $P(\nu_\mu \Rightarrow \nu_e)$

$\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, $\pm \Delta m^2_{31}$, δ_{CP} (phase)

- parameters are correlated etc.
- sensitive to matter effects

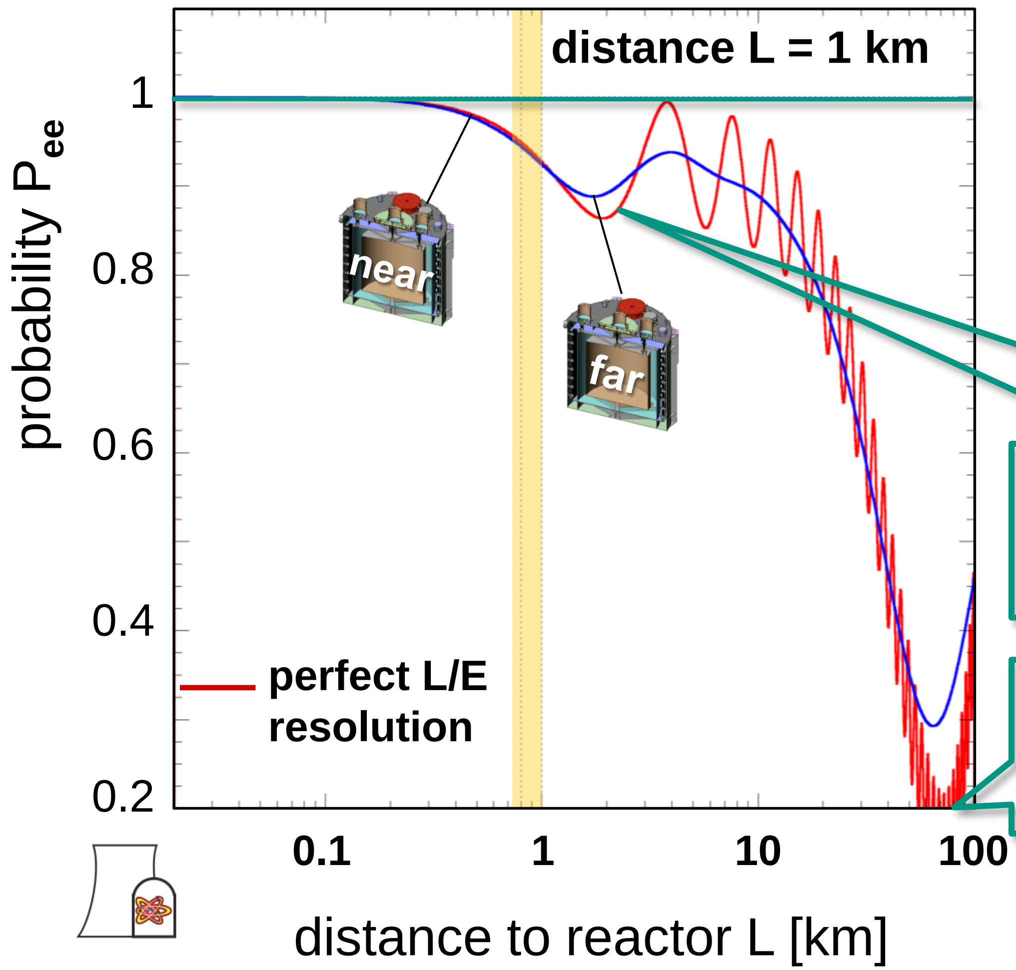
reactor ν–experiments for θ_{13}

- **aim:** measurement of mixing angle θ_{13} via $\bar{\nu}_e$-disappearance
  Δm^2 scale of atmospheric ν´s at $\Delta m^2_{13} \sim 2.4 \times 10^{-3}$ eV²
  L_ν ~ 1 km ‹E_ν› = 3 MeV

´atmospheric´ scale

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{13} \cdot L_\nu}{E_\nu}\right) - \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{12} \cdot L_\nu}{E_\nu}\right)$$

´solar´ scale



1. oscillation maximum due to small θ_{13} mixing

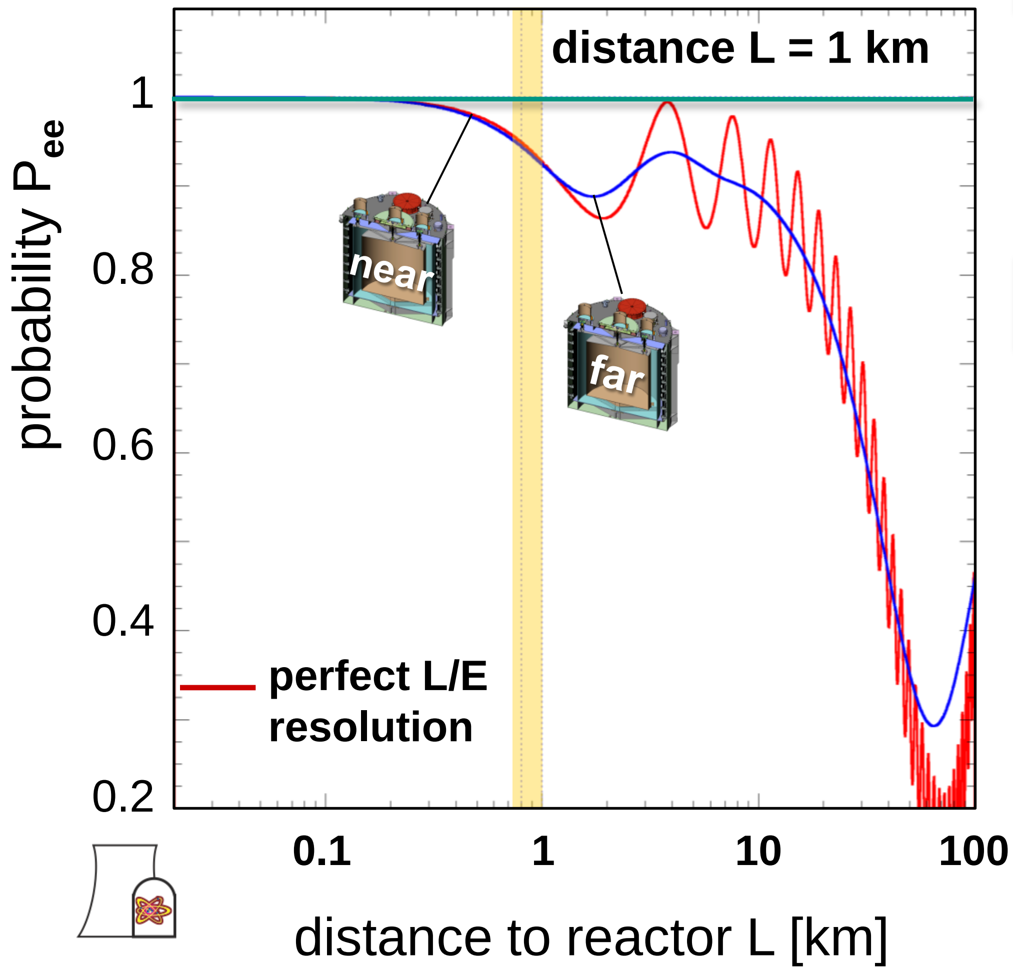
1. oscillation maximum due to strong θ_{12} mixing

observable: near-far ratio

reactor ν–experiments for θ_{13}

Karlsruhe Institute of Technology

- **aim:** measurement of mixing angle θ_{13} via $\bar{\nu}_e$-disappearance
  Δm^2 scale of atmospheric ν´s at $\Delta m^2_{13} \sim 2.4 \times 10^{-3}$ eV²
  $L_\nu \sim 1$ km $\langle E_\nu \rangle = 3$ MeV



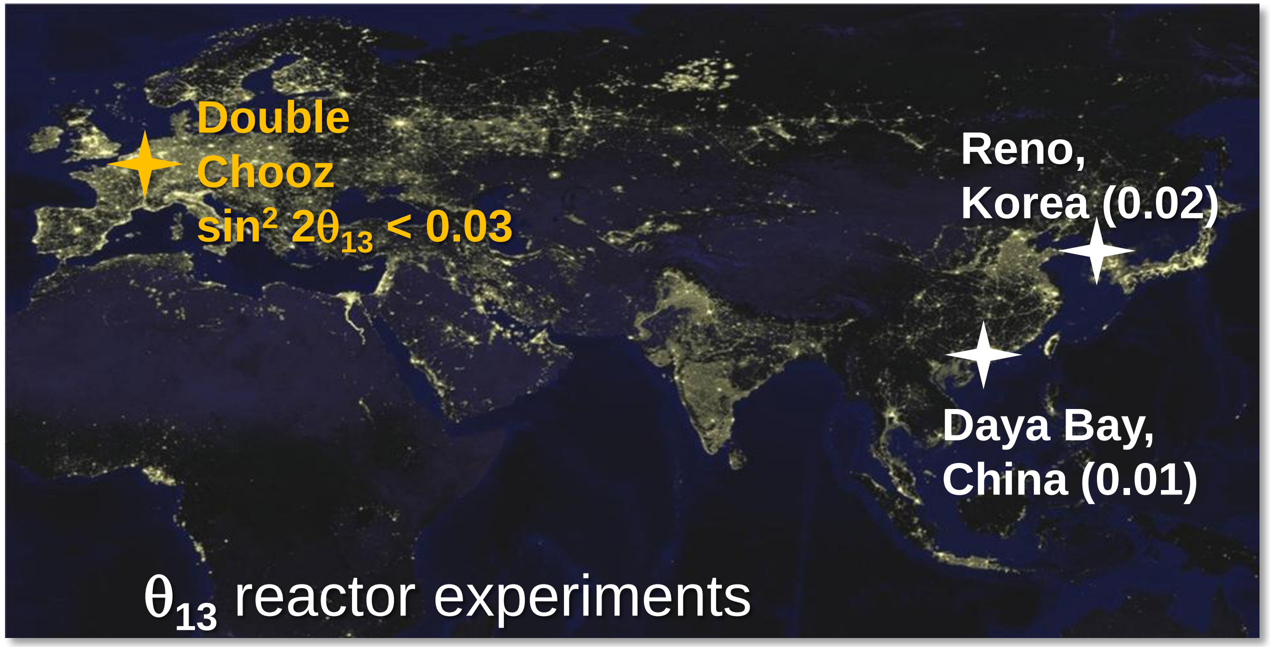
CHOOZ

$\theta_{13} < 12°$ $\sin^2 2\theta_{13} < 0.17$ (90% CL)

global analysis: $\sin^2 \theta_{13} \sim 0.02$ ($\theta_{13} \sim 7°$) ↳ 2σ

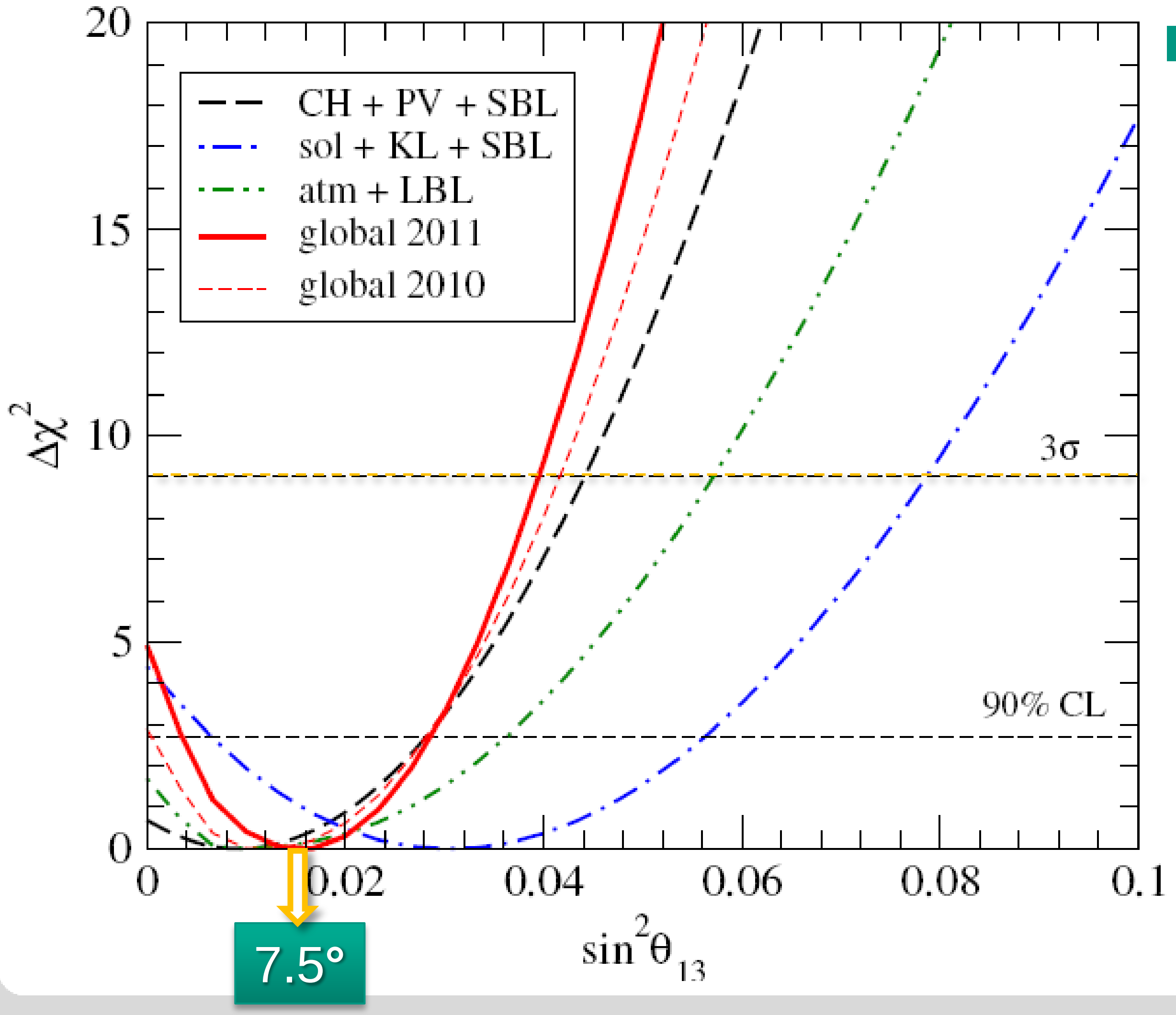
two-/multi-detectors ⇩ **red. systematics**

$\theta_{13} < 3$-$5°$ $\sin^2 2\theta_{13} < 0.01$-$0.03$ (90% CL)



global analysis: first hints for $\theta_{13} \neq 0$?

- **global analysis** of solar ν-data, KamLAND results, MINOS ν_μ-ν_e data, CHOOZ/Palo Verde & other short-baseline reactor data, SK data, including updated 2011 reactor fluxes



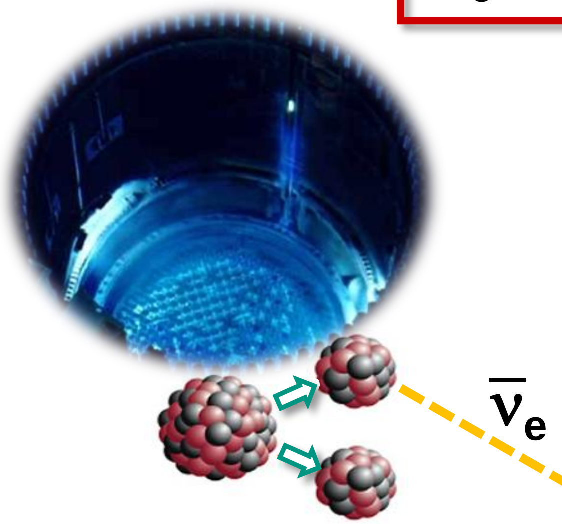
- **most recent results:**
  - combination of different data sets: $\sin^2\theta_{13} = 0.01 - 0.03$ with hints for $\theta_{13} > 0$ (1.8 - 3.2 σ)
  - *normal hierarchy*:
    $\sin^2\theta_{13} = 0.017 \pm^{0.007}_{0.009}$ (**2.2 σ**)
    $\sin^2\theta_{13} < 0.040$ (3 σ bound)
  - *inverted hierarchy*:
    $\sin^2\theta_{13} = 0.020 \pm^{0.008}_{0.009}$ (**2.3 σ**)
    $\sin^2\theta_{13} < 0.044$ (3 σ bound)

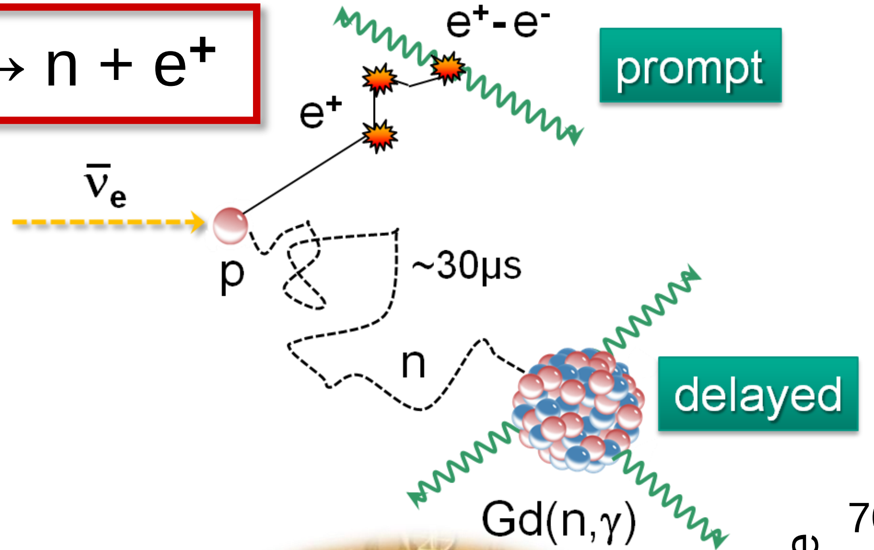
Schwetz, Tortola, Valle, 1103.0734
Th. Schwetz, Neutrino Telescopes 2011

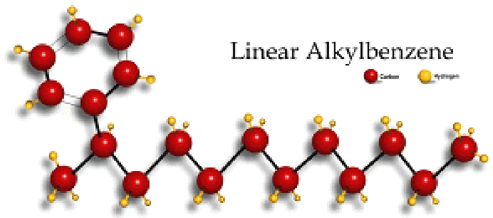
reactor ν–experiments: principle

- detailed calculations of ν-flux & ν-energies from ß-decay of fission products of elements $^{235,238}U$, $^{239,241}Pu$ in fuel rods (burn-up!)

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

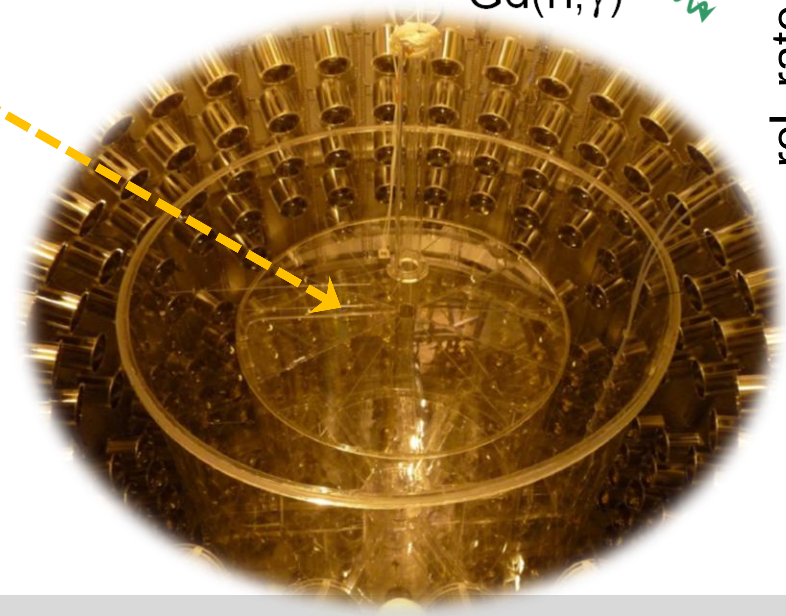


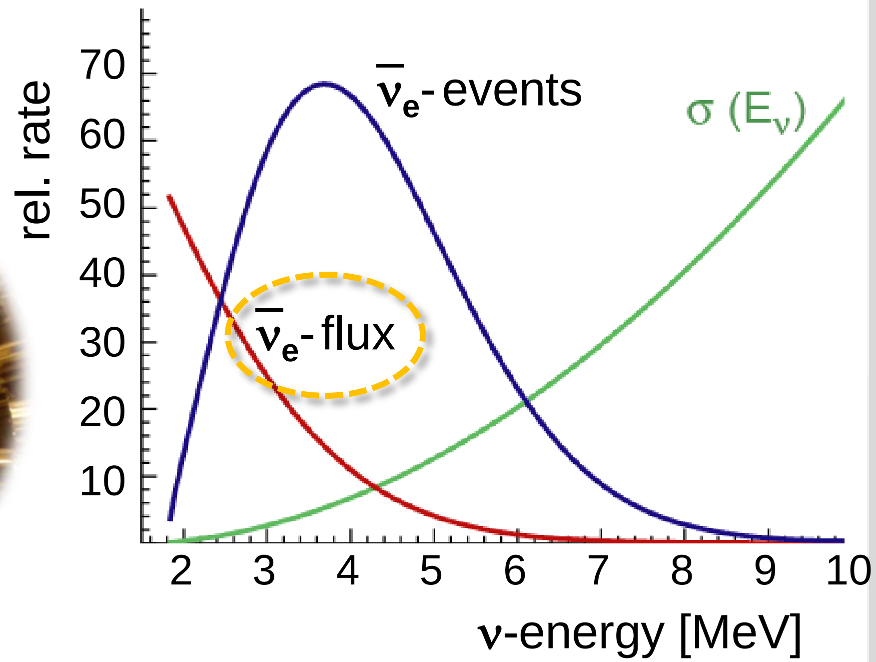




Gd-loaded LS

^AZ	$\bar{\nu}_e$	E_{fiss} [MeV]
^{235}U	1.92	201.7 ± 0.6
^{238}U	1.45	205.0 ± 0.9
^{239}Pu	2.38	210.0 ± 0.9
^{241}Pu	1.83	212.4 ± 1.0





reactor oscillation anomaly

- recent update of reactor ν-fluxes (major changes still possible in 2011!!)
- **reactor neutrino normalisation is increased by +3.5%**
  new calculations of weak magnetism, Coulomb corrections
  for fission product ß-decays
  2% flux uncertainty from ILL electron energy spectra
- update of cross section for $\bar{\nu}_e + p \rightarrow e^+ + n$
  new PDG value for τ_n (decrease by few %), …
- ↳ update of predicted cross section per fission σ_f [10^{-43} cm^2/fission],
  i.e. the **reference value for single detector experiments**

^AZ	$\Delta\Phi(\nu)$
^{235}U	+ 2.5 %
^{238}U	+ 9.8 %
^{239}Pu	+ 3.1 %
^{241}Pu	+3.7 %

^AZ	σ_f (old)	σ_f (new)
^{235}U	6.39	6.61
^{238}U	9.21	10.1
^{239}Pu	4.19	4.34
^{241}Pu	5.73	5.97

if 19 experimental results compraed to new higher theoretical prediction for σ_f:

R = 0.937 ± 0.027

~2 σ deficit of observed $\bar{\nu}_e$!

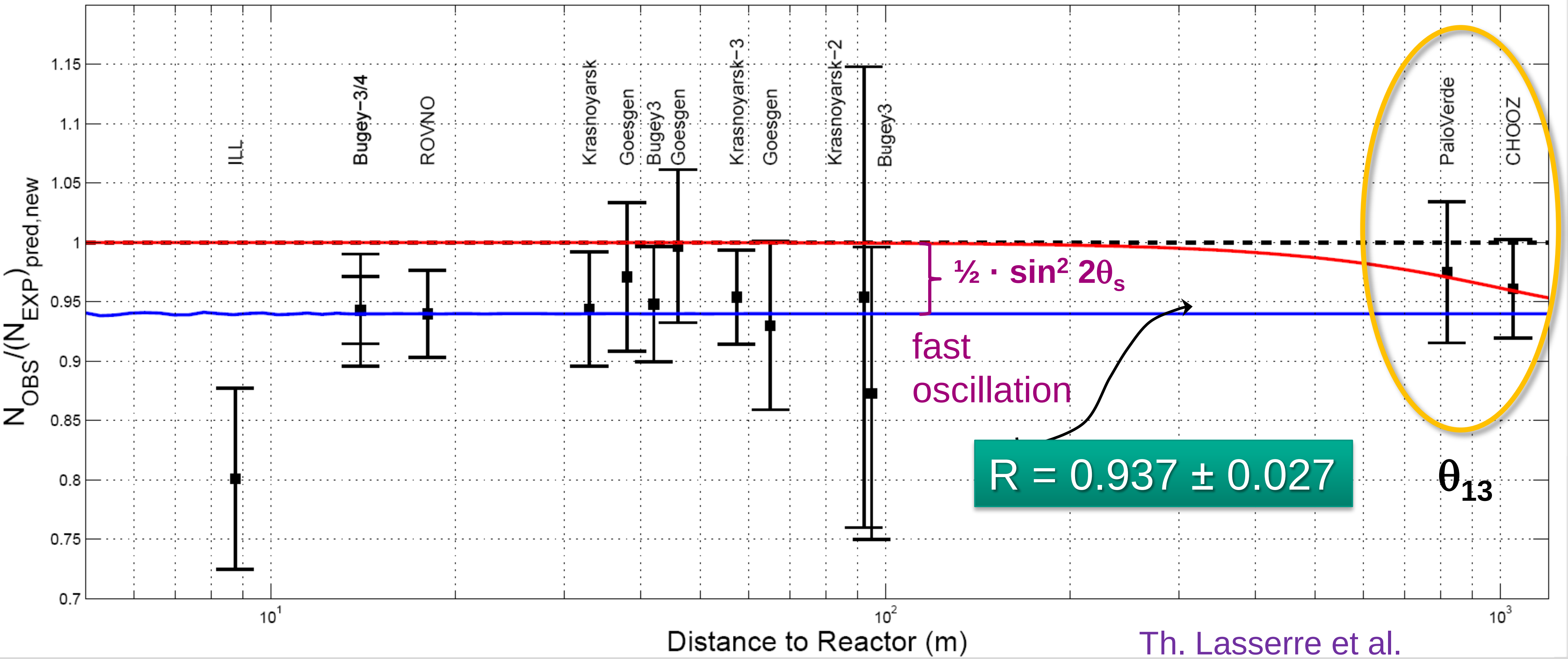
↳ **reactor neutrino anomaly (2011)**

reactor oscillation anomaly

- 2011: **reactor neutrino normalisation is increased by +3.5%**
- Do reactor $\bar{\nu}_e$ data & new prediction point to new physics (sterile ν´s) ?

  3 active ν´s + 0 sterile ν ($\sin^2 2\theta_{13} = 0.06$)

  3 active ν´s + 1 sterile ν $|\Delta m^2_s| > 1.5$ eV², $\sin^2 2\theta_s = 0.16$ ($\sin^2 2\theta_{13} = 0$)



Th. Lasserre et al.

reactor ν–experiments for θ_{13}

Karlsruhe Institute of Technology

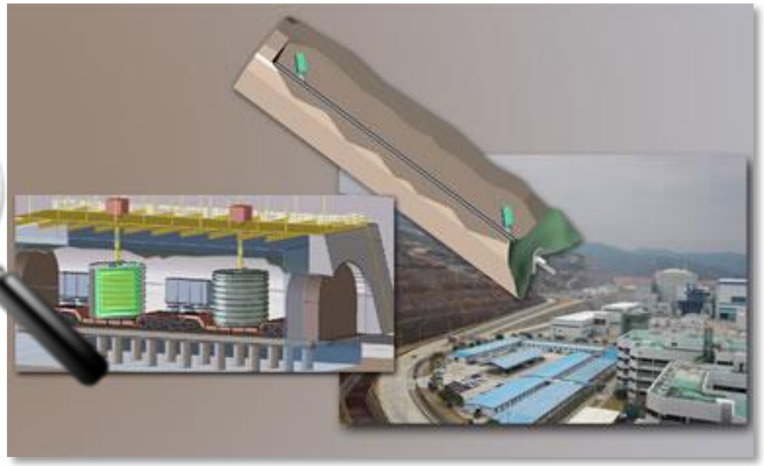
- 3 experiments with two / multi detector set-ups to reduce systematics
  near detector (290-410 m) : high statistics (400-1600 ν´s/d), ´no´ oscillation
  far detector (1050-1985 m) : smaller statistics (50-110 ν´s/d), θ_{13} oscillation
  near – far ratio: understand inter-detector systematics to < 1%!

set-up	P_{th} [GW]	near/far [m]	depth [mwe]	mass [t]	start	$\sin^2(2\theta_{13})$
Double Chooz	**8.7**	**410 / 1050**	**115 / 300**	**8.3/8.3**	**2011/12**	**0.03**
Daya Bay	17.4	360 (500) /1985 (1613)	260 / 910	80	2011/12	0.01
RENO	17.3	290 / 1380	120 / 450	15.4	5/2011	0.02

Double Chooz — near: 400 ν´s / d, far: 50 ν´s / d

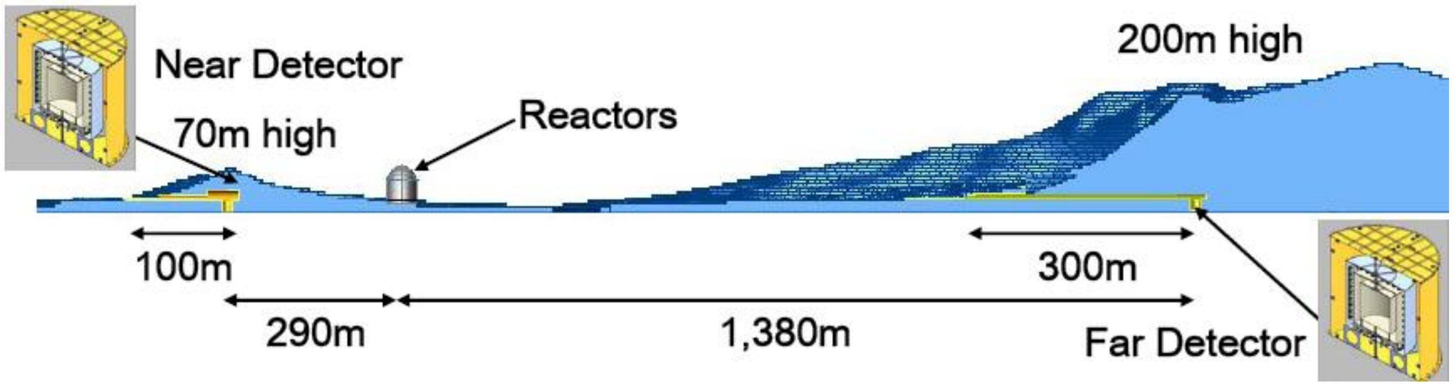
Daya Bay — near: 1580 ν´s / d, far: 90 ν´s / d

RENO — near: 1280 ν´s / d, far: 114 ν´s / d



RENO experiment

- **status**: construction of near and far detector is basically completed
  ready to fill detector with scintillator (Gd-loaded LAB scintillator)
  short-term scintillator stability o.k.



- **sensitivity**:
  $\sin^2 2\theta_{13} = 0.02$ (90% CL)
  $= 0.035$ (3 σ)
- **expected uncertainties**:
  - stat. error: 0.3%
  - syst. error: < 0.5%

near detector
1280 ν´s / day
~10^6 ν´s / 3 a

far detector
114 ν´s / day
~10^5 ν´s / 3 a

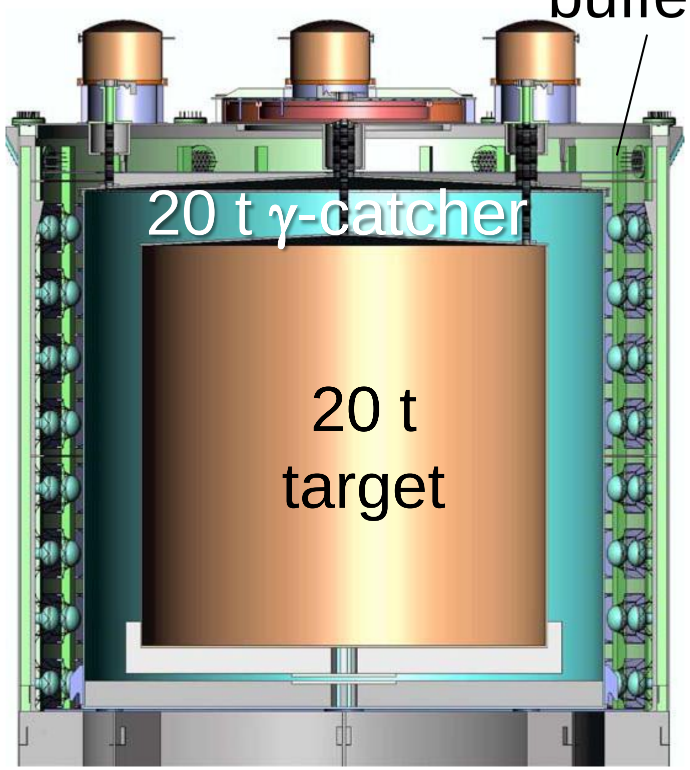
Daya Bay experiment

- **overview**: aim for ´ultimate´ configuration with emphasis on systematics
  - 6 reactor cores at 3 sites (three ´doubletts´ of cores)
  - 1 far site with 4 detectors, 2 near sites, each with 2 detectors
  - 8 identical detectors for cross check (2 already completed)

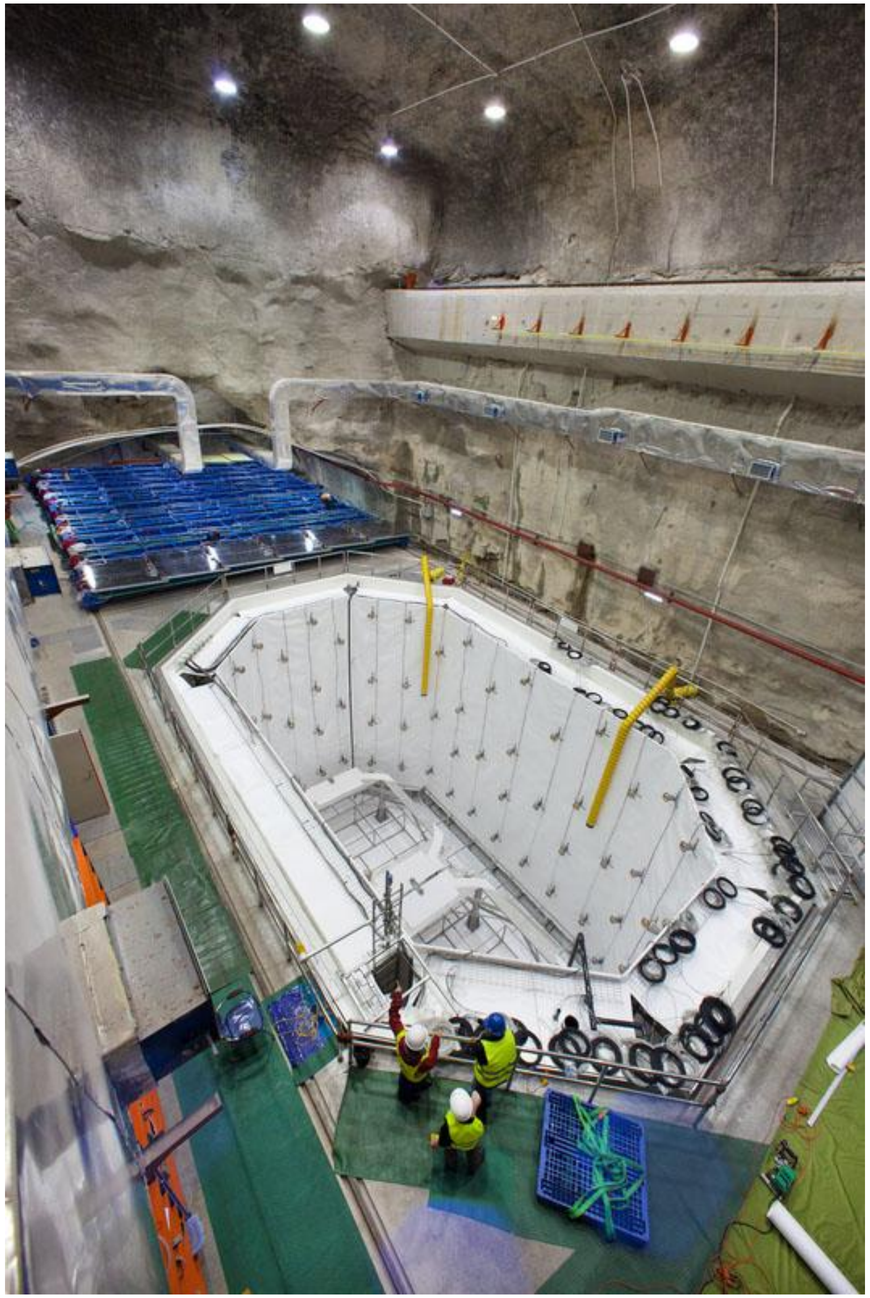
- **status**: near site data taking starting summer 2011

  full data taking (near/far) in 2012

near detector	far detector
DB: 840 ν´s / d	90 ν´s / day
LA: 740 ν´s / d	from DB+LA



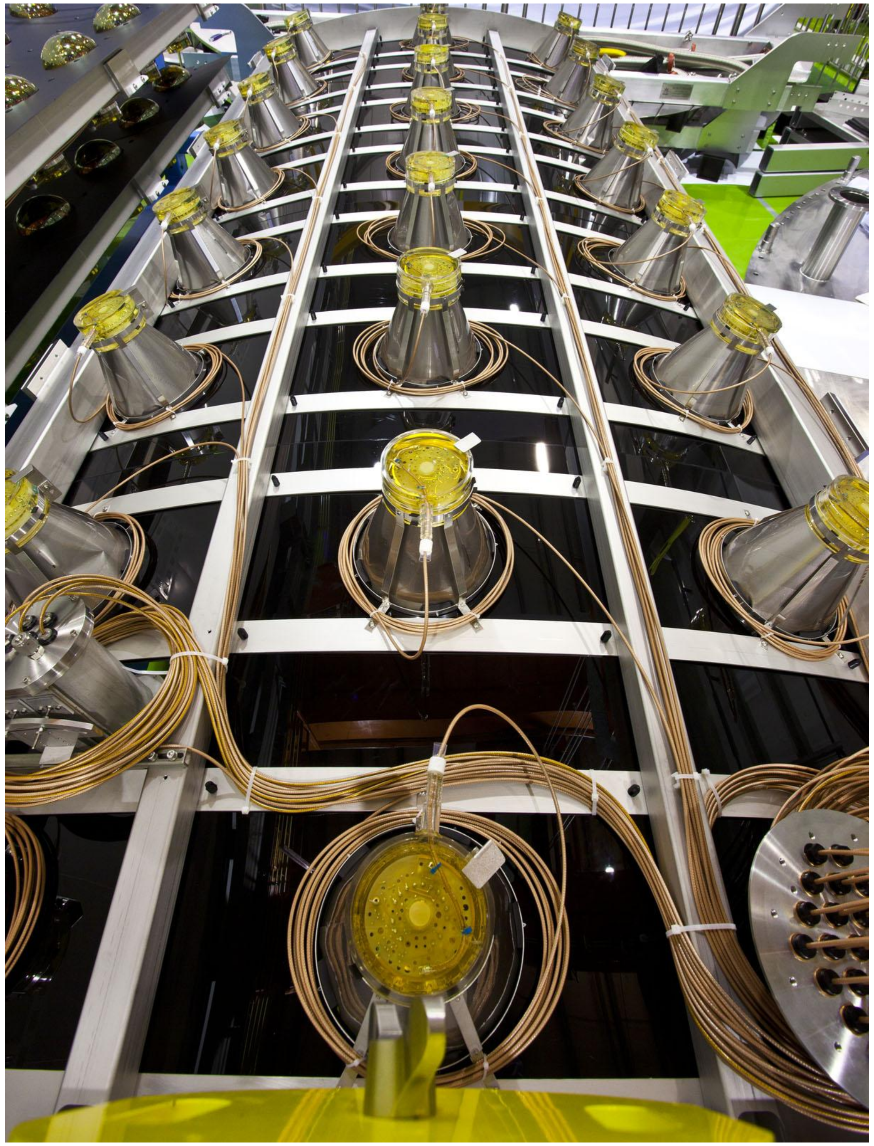
Daya Bay experiment

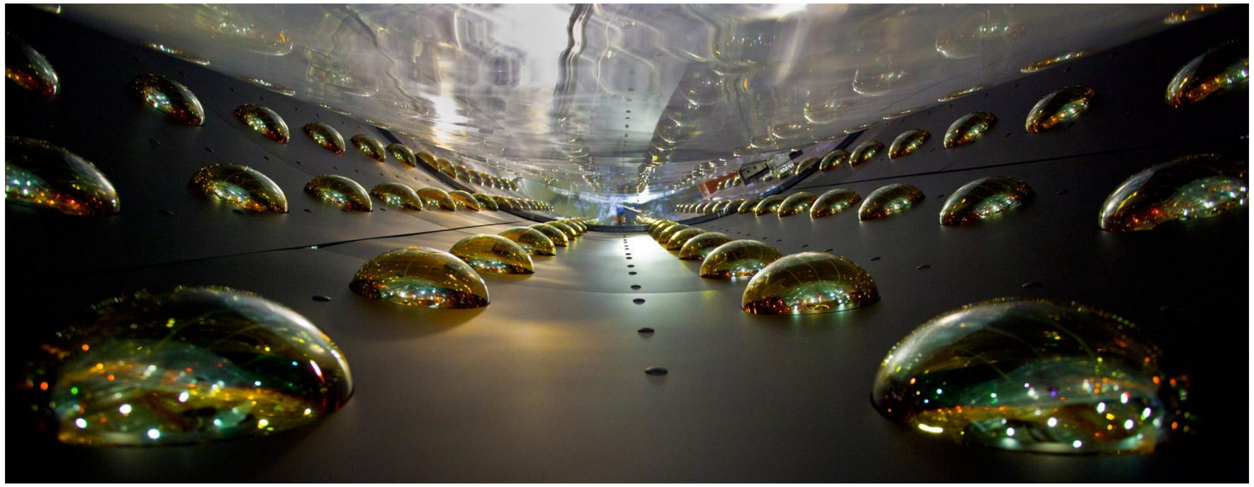


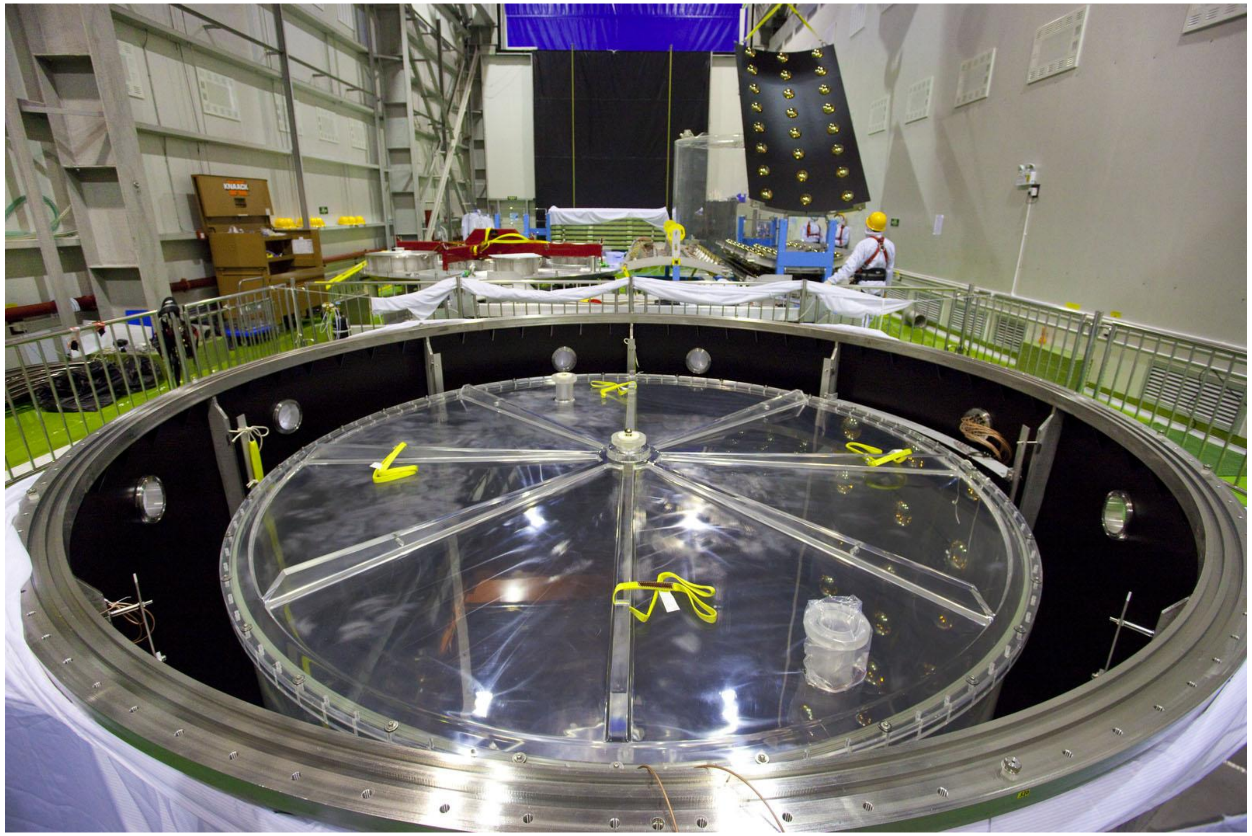
near hall

far hall: to be completed in August 2011
expected begin of data taking: summer 2012

Daya Bay experiment

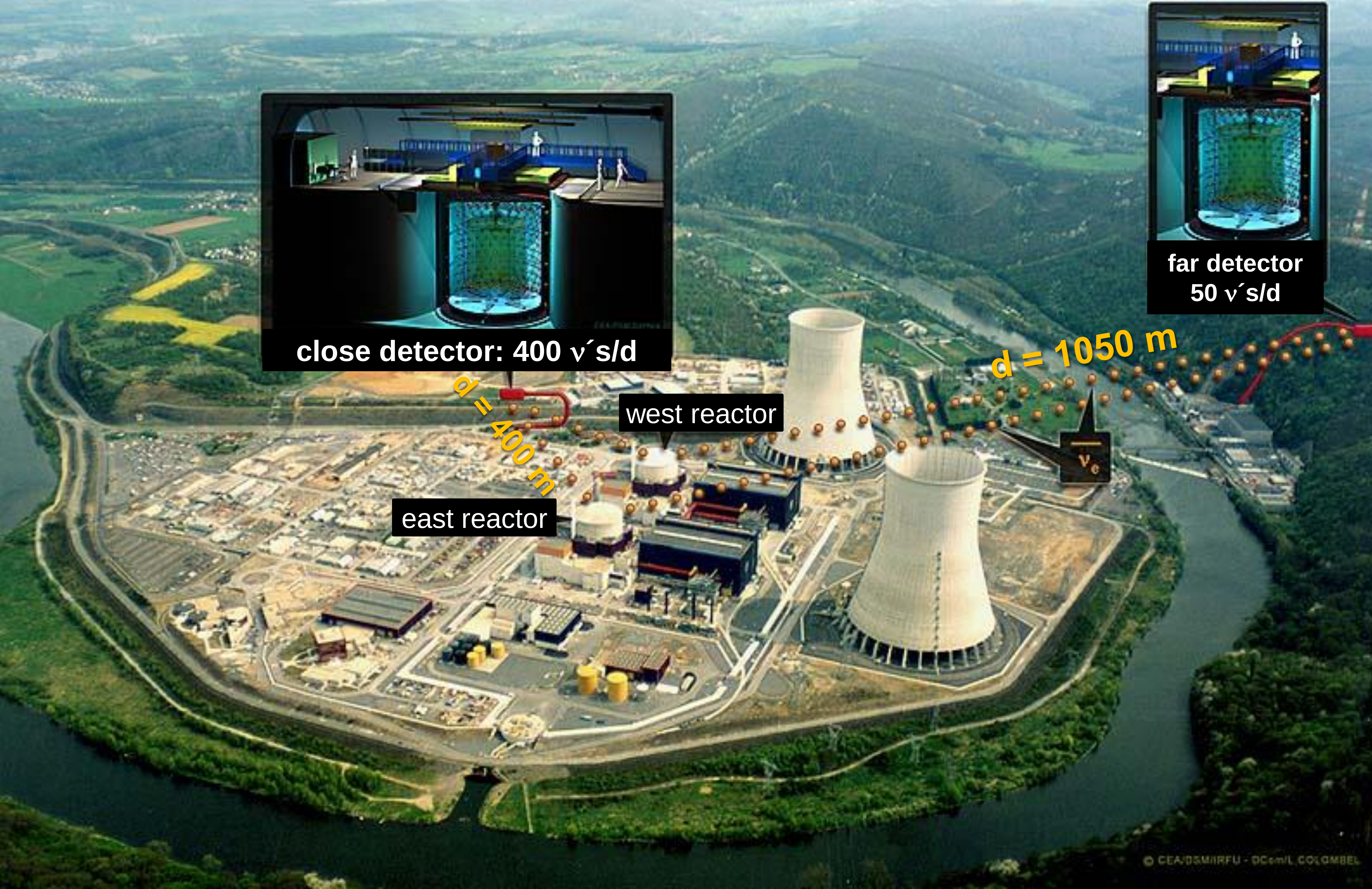






nearly finished “dry” antineutrino detector

Double Chooz



Double Chooz - overview

- two identical detectors at near (L = 410 m) and far (L = 1050 m) site,
  3-fold inner structure: ν-target – γ-catcher – buffer volume
  3-fold veto structure: inner μ-veto – steel shielding – outer μ-veto

outer μ-veto

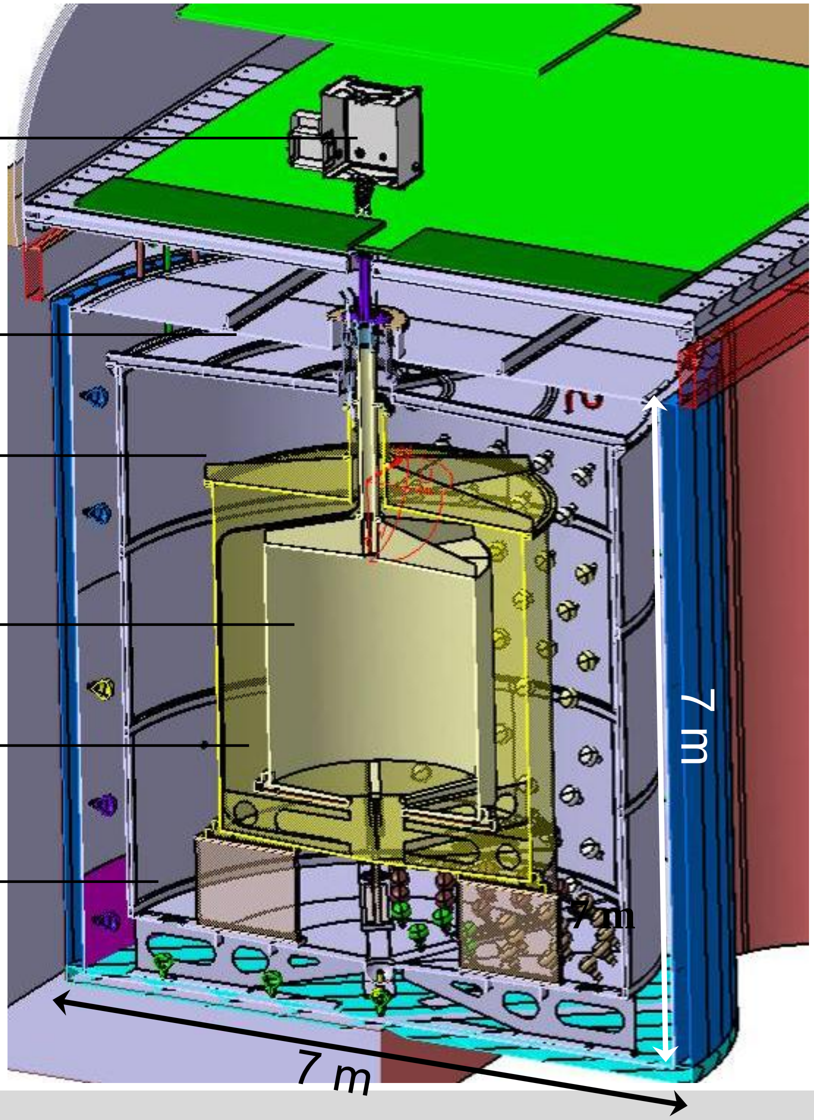
inner μ-veto
(90 m³)

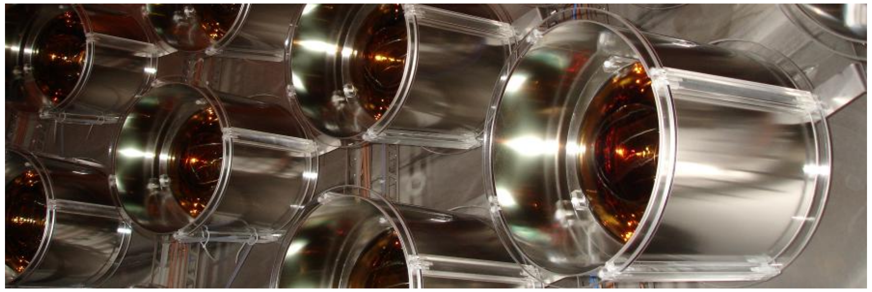
steel shielding
(15 cm against γ´s)

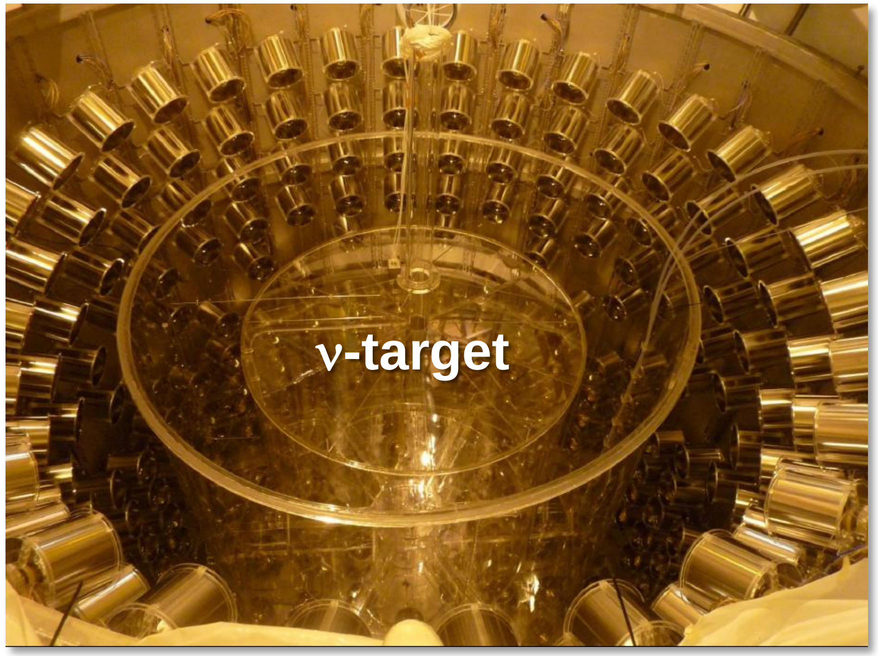
ν-target (LS+0.1%Gd)
(10.3 m³)

γ-catcher (LS)
(22.6 m³)

Buffer (non-scint.)
with 390 PMTs (10´´)
(114 m³)





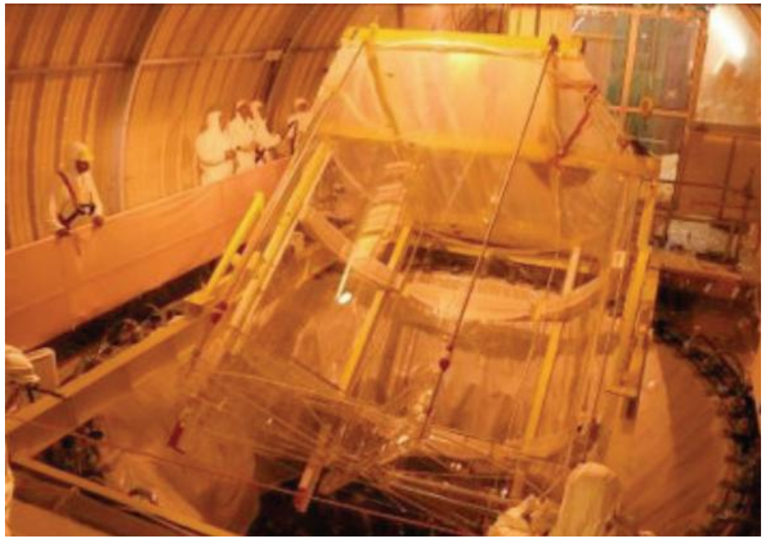


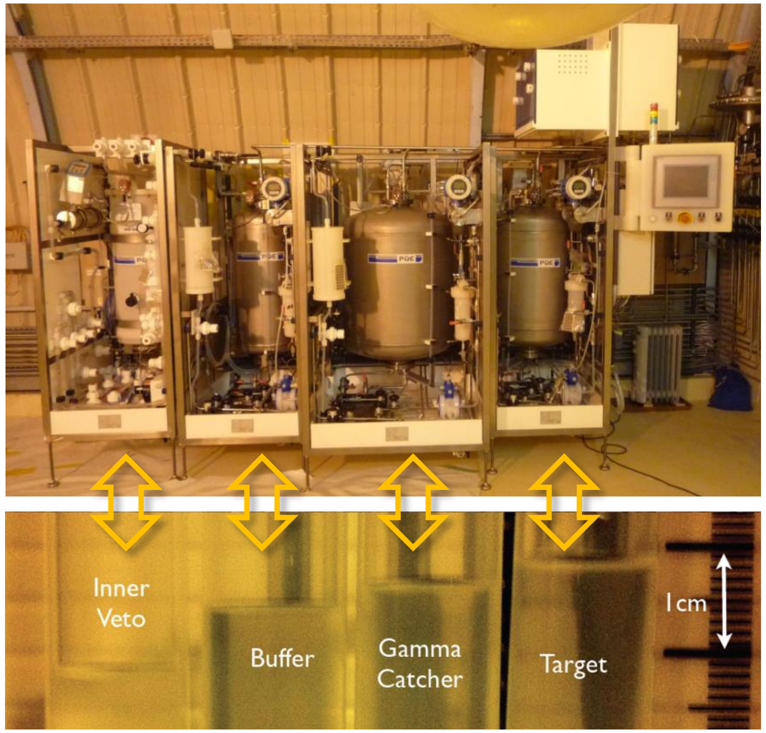
3 fold inner structure DC far detector

Double Chooz – status

- 2009 milestones:
  - 02/09: outer veto installed
  - 04/09: buffer tank installed
  - 07/09: PMTs mounted

2010 milestones
  - 05/10: acrylic γ-catcher installation
  - 10/10: start of filling operations – 4 operating modules, control of
    pressure: $\Delta p \sim 0.1$ mbar
    liquid level: $\Delta h \sim 1$ cm
    density: $\Delta \rho \sim 1$ g/ℓ
  - 12/20: detector filled successfully
    top shield installed

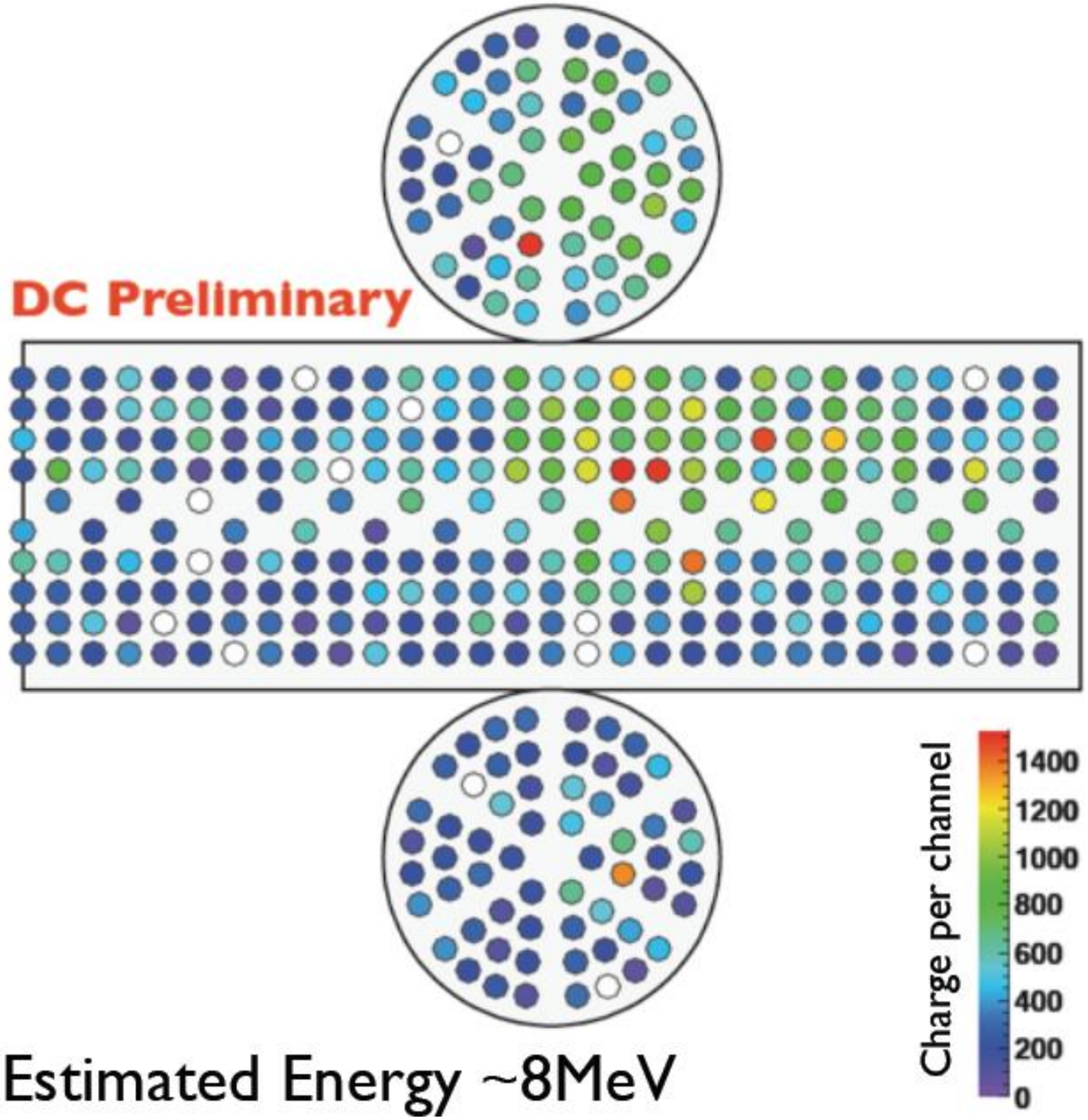


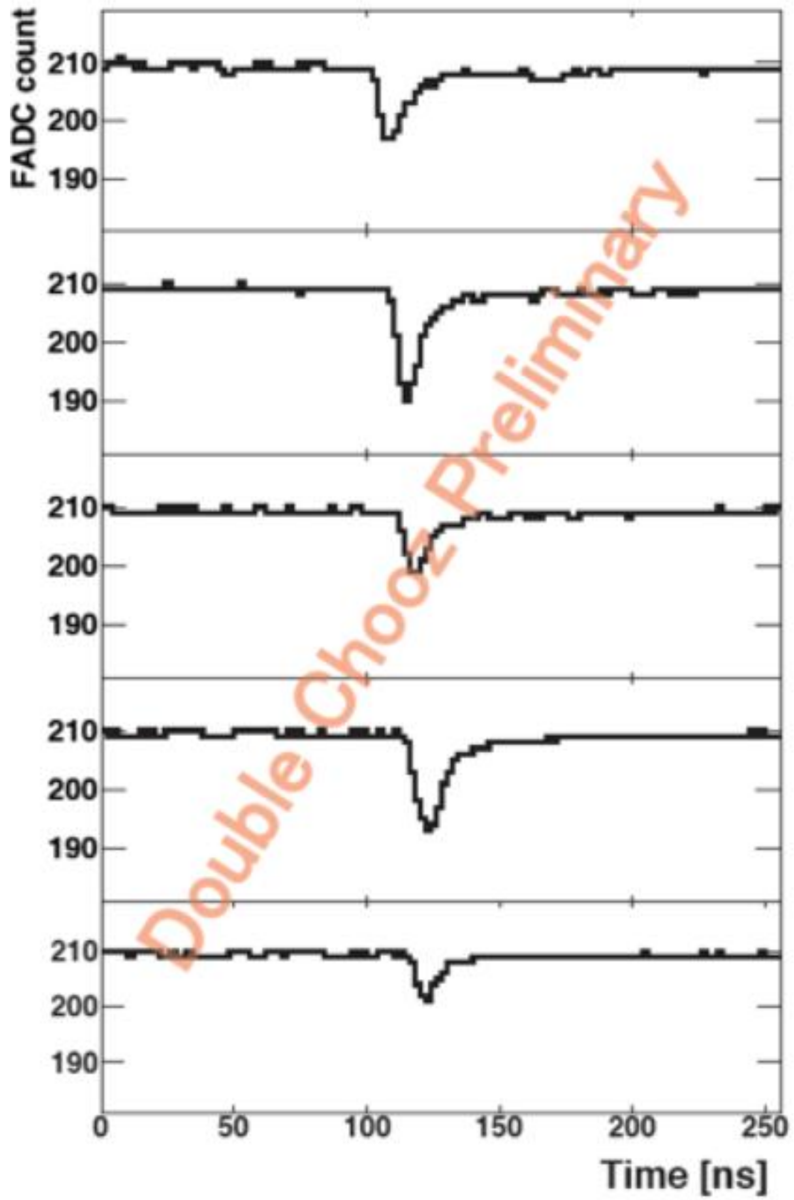


2011 milestones
  - commissioning works: **excellent performance, high-quality data**
  - installation outer μ-veto & glove box, **imminent ν-data taking !**

Double Chooz – first events

- **contained event** from the early DC commissioning period (Jan-Mar 2011)





A. Cabrera, Neutrino Telescopes 2011

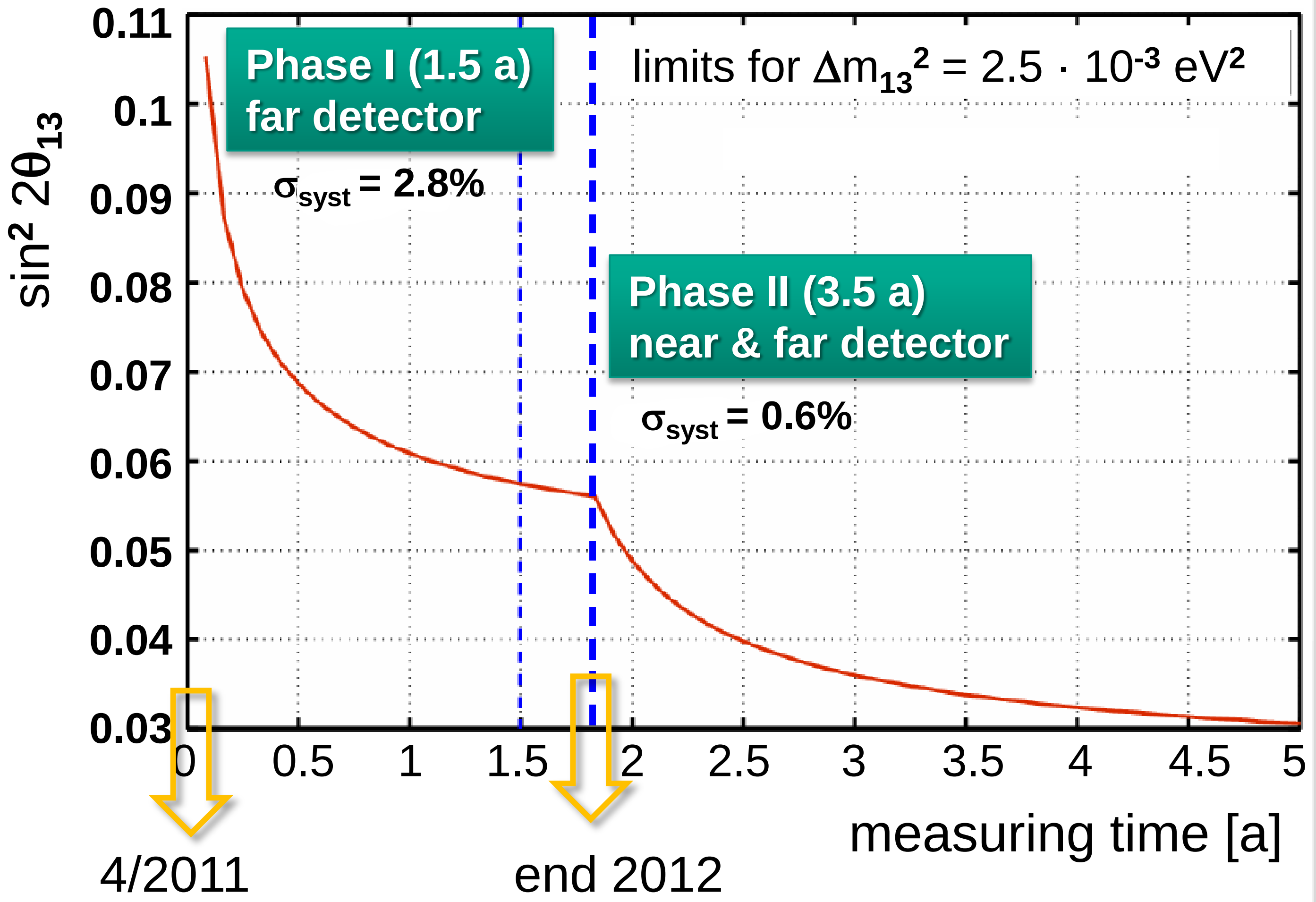
Double Chooz – expected sensitivity

DC – Phase I (far detector only)

- accumulate 10 × more statistics than CHOOZ in 1.5 a
- sensitivity limited by reactor flux uncertainties (rate and shape),
- expected: σ_{syst} = 2.8 % (old fluxes)
- **$\sin^2 2\theta_{13} < 0.054$ (90% CL.)**
- flux normalisation strategy for FD under discussion

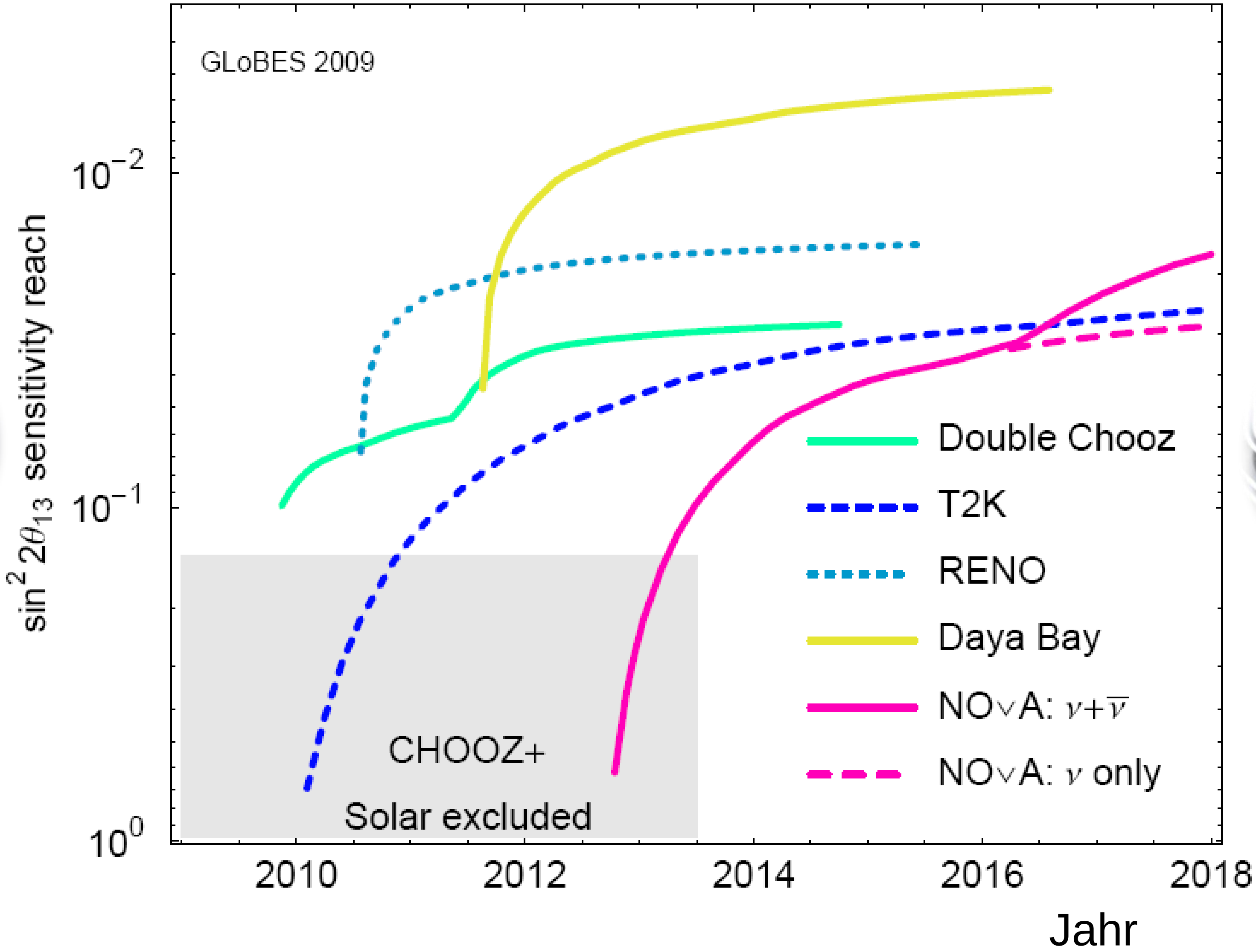
DC – Phase II (near+far)

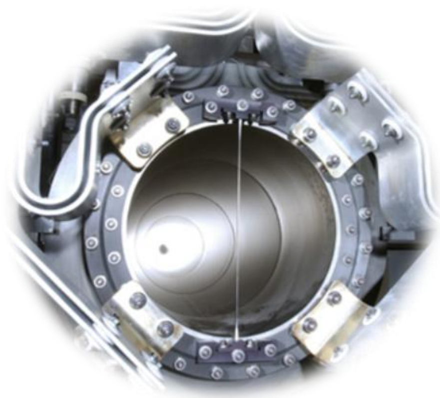
- use near/far ratio (robust)
- sensitivity limited by inner detector normalisation
- expected: σ_{syst} = 0.6 %
- **$\sin^2 2\theta_{13} < 0.03$ (90% CL.)**
  $\sin^2 2\theta_{13} > 0.05$
  (3 σ discovery)



θ_{13} – experimental sensitivities

- **sensitivity limits (90% CL)** for $\sin^2 2\theta_{13}$ (expected)
  comparison of reactor and accelerator experiments



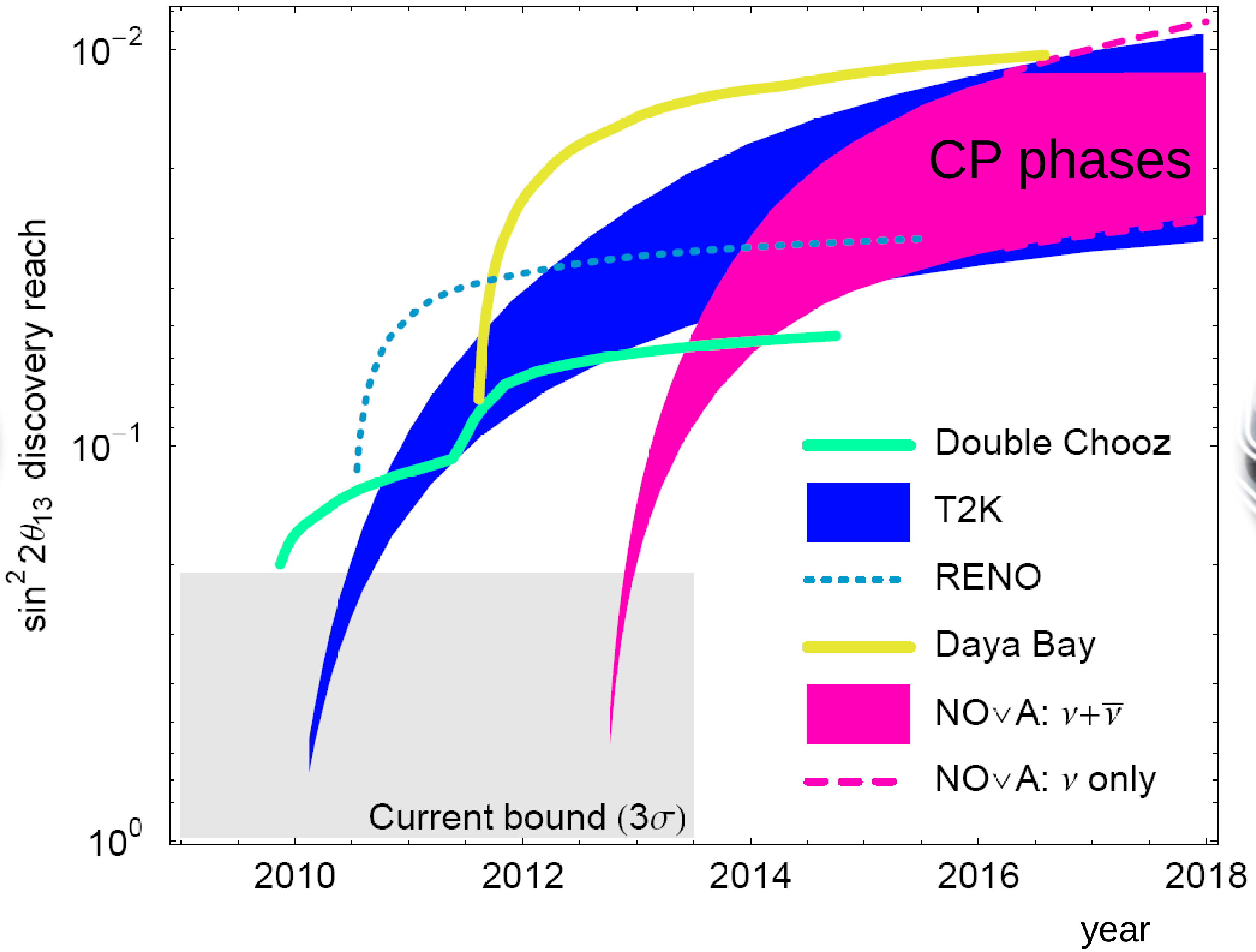


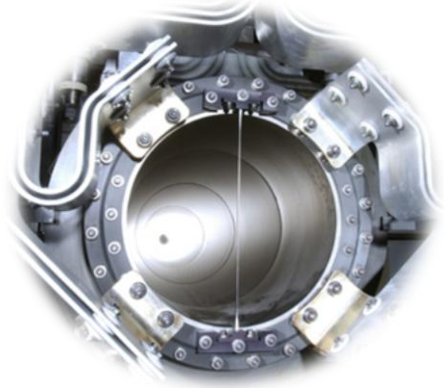
Huber, Lindner 2009

θ_{13} – experimental sensitivities

- comparison of discovery potentials for θ_{13}

normal hierarchy (3σ CL)





Huber, Lindner 2009

additional slides

reactor neutrinos – recent updates

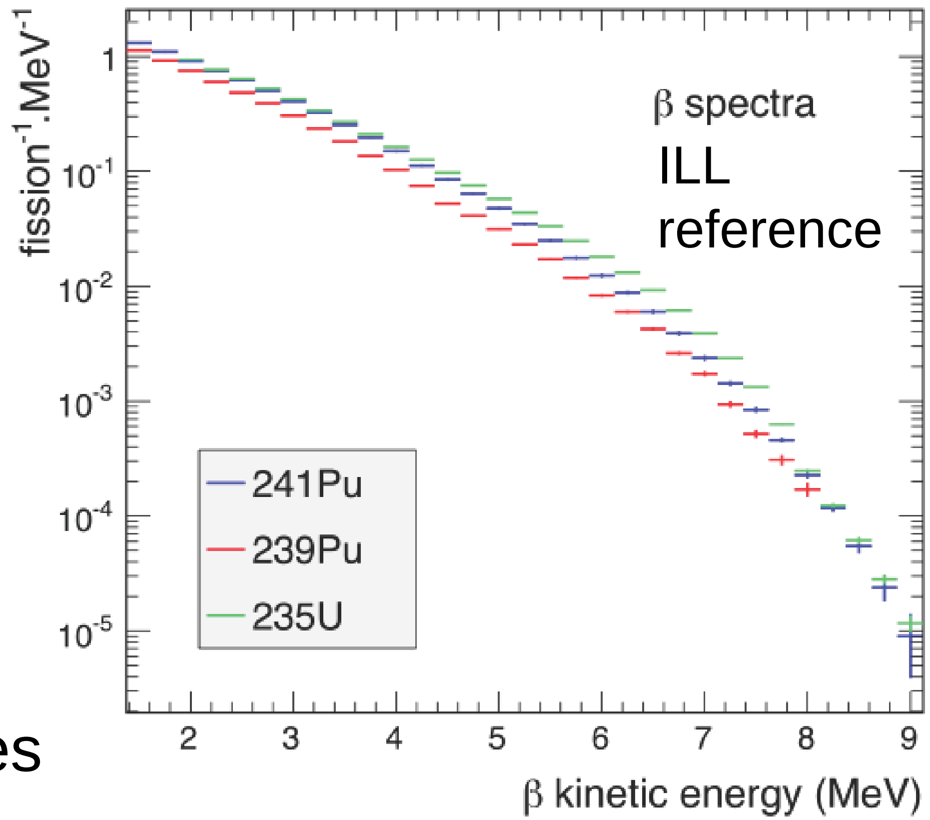
- recent update of reactor $\bar{\nu}_e$ fluxes

Th. A. Mueller, D. Lhuiller et al., arXiv:1101.2663

thermal power   core burn-up

$$\Phi_\nu(E,t) = \frac{\dot{P}_{th}(t)}{\sum_k \alpha_k(t)\, E_k} \times \sum_k \alpha_k(t)\, S_k(E)$$

fission database   ν-spectra

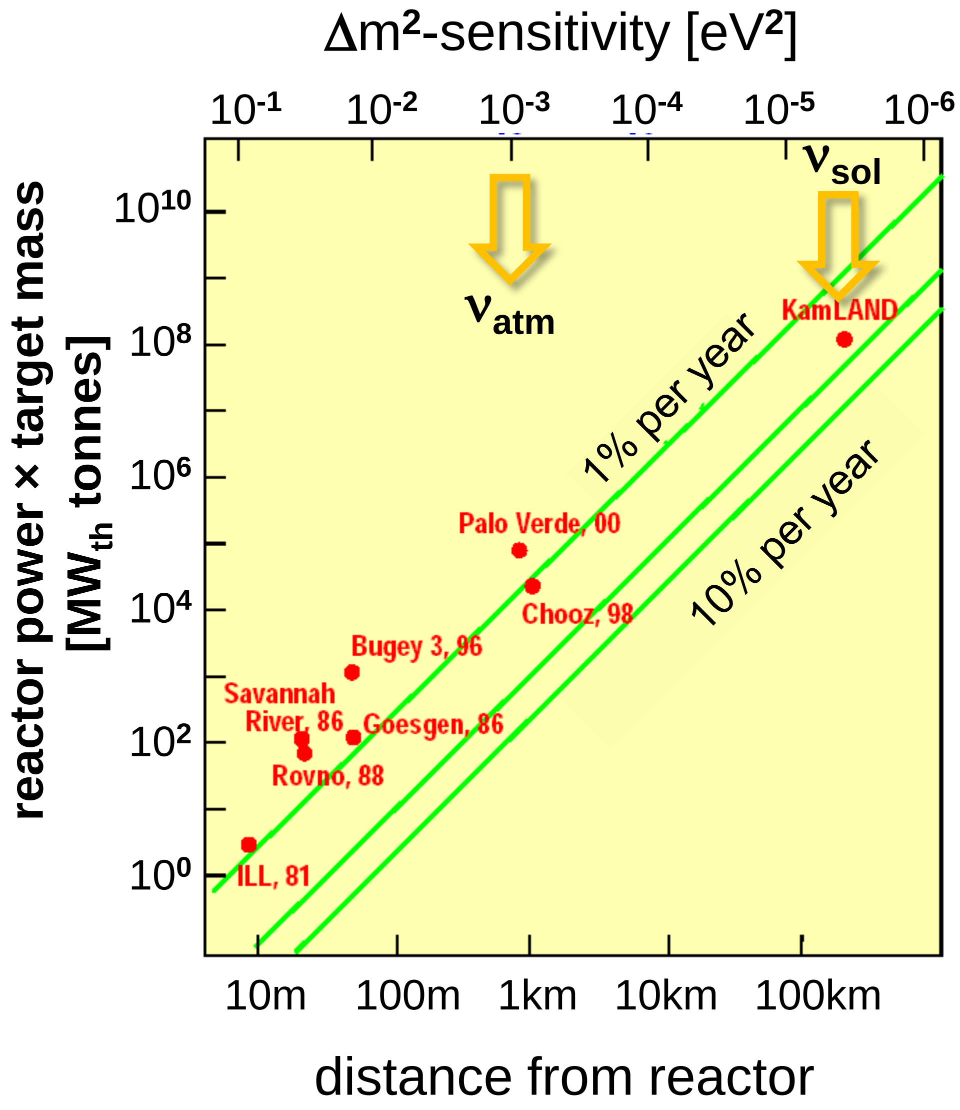


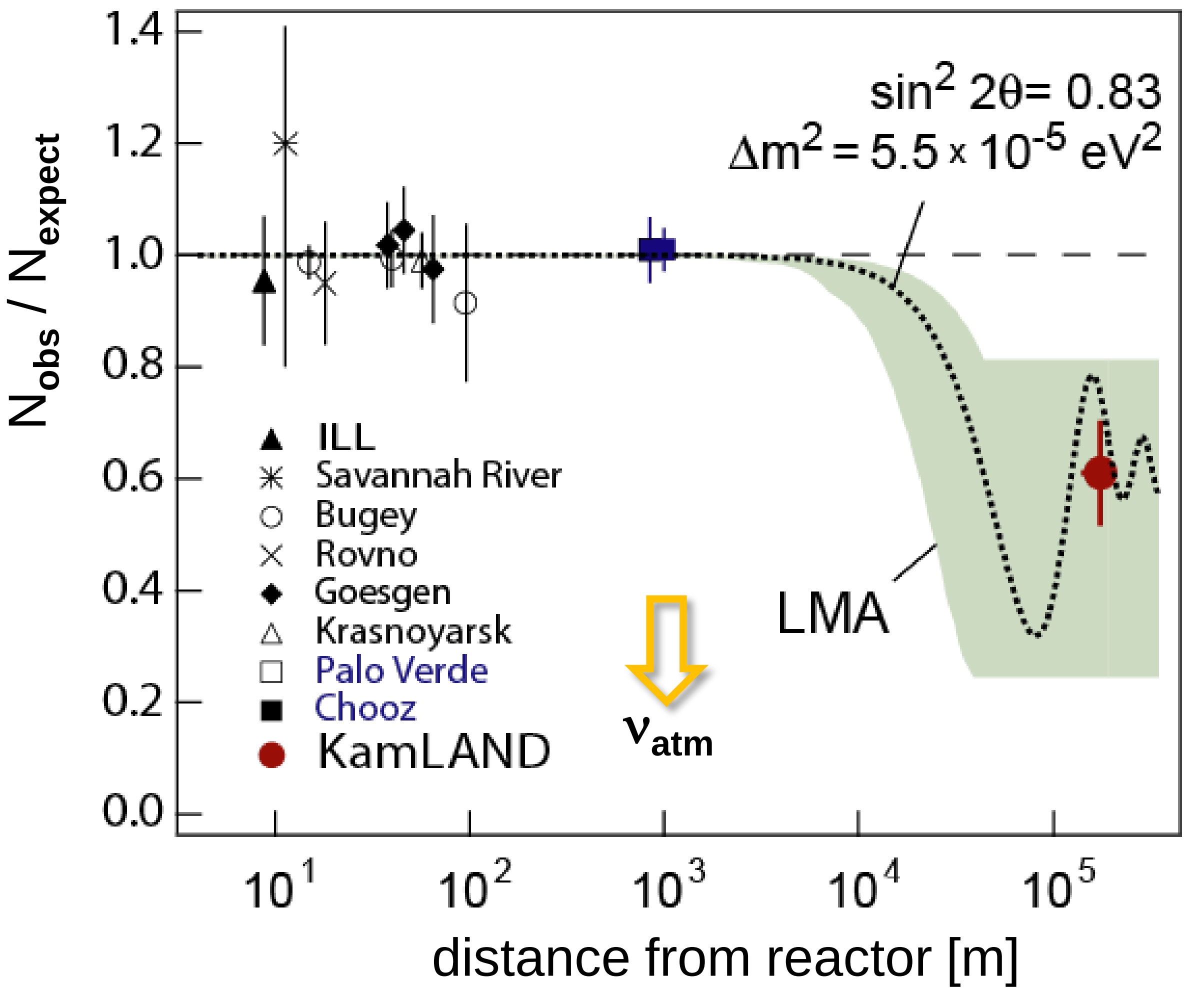
- generation of ν-spectra (previously)
    - exp. reference: ILL **electron spectra**
    - spectra fitted with 30 effective branches
    - conversion of branches to ν-spectra

- generation of ν-spectra (new ´mixed´approach)
    - exp. reference: ILL **electron spectra**
    - ´ab initio´ calculations (database: 800 nuclei & 10.000 ß-branches) reproduce ~ 90% of ILL data, remaining 10%: five effective branches

results from reactor–ν–experiments

- ratio of observed to calculated reactor neutrino events as a function of the distance from the reactor core (10 m – 100 km) & scaling





KamLAND detector

Kamioka Liquid Scintillator Anti-Neutrino Detector (Kamioka mine)

J-US-long-baseline-reactor experiment: **test of the LMA parameter spacee**

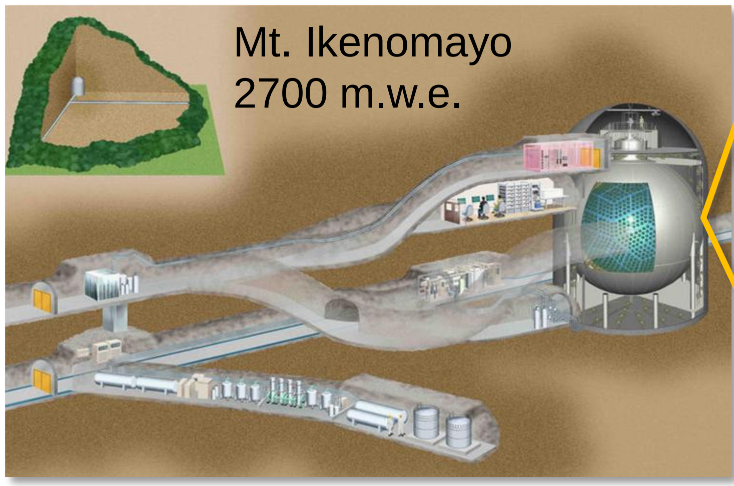
disappearance oscillation of $\bar{\nu}_e$ from all J nuclear reactors (Φ_ν ~ 6 × 10^6 cm^{-2} s^{-1})

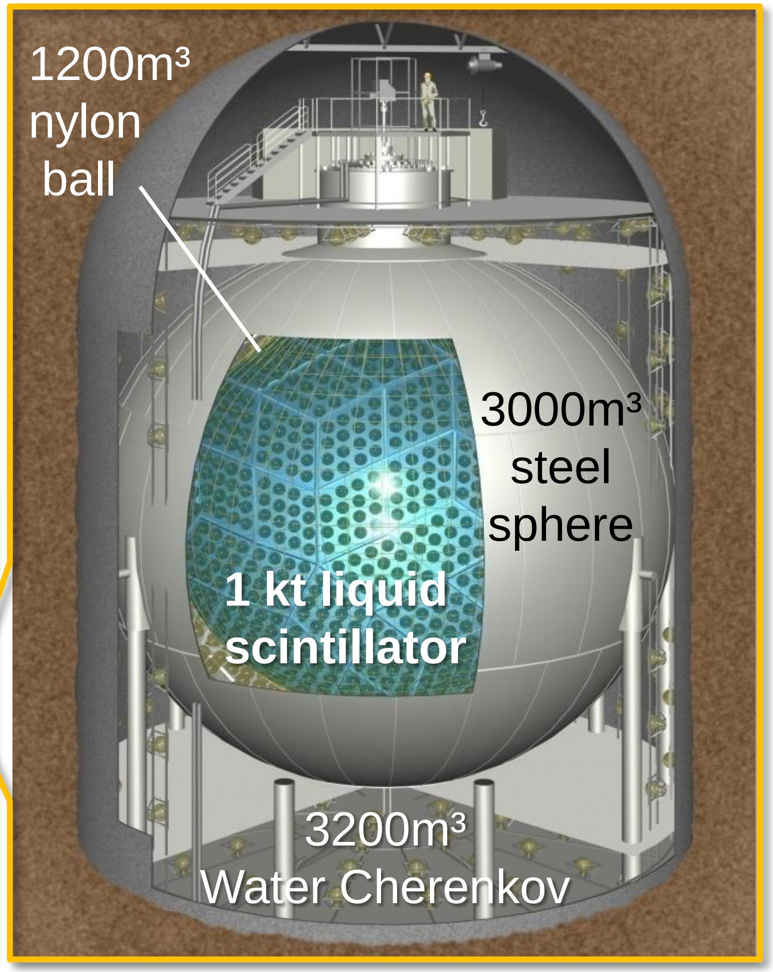
total power: 70 GW (~ 7 % of the world energy!)

distance d = 130 – 220 km, ‹ E_ν › ~ 2-3 MeV

inverse ß-decay

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



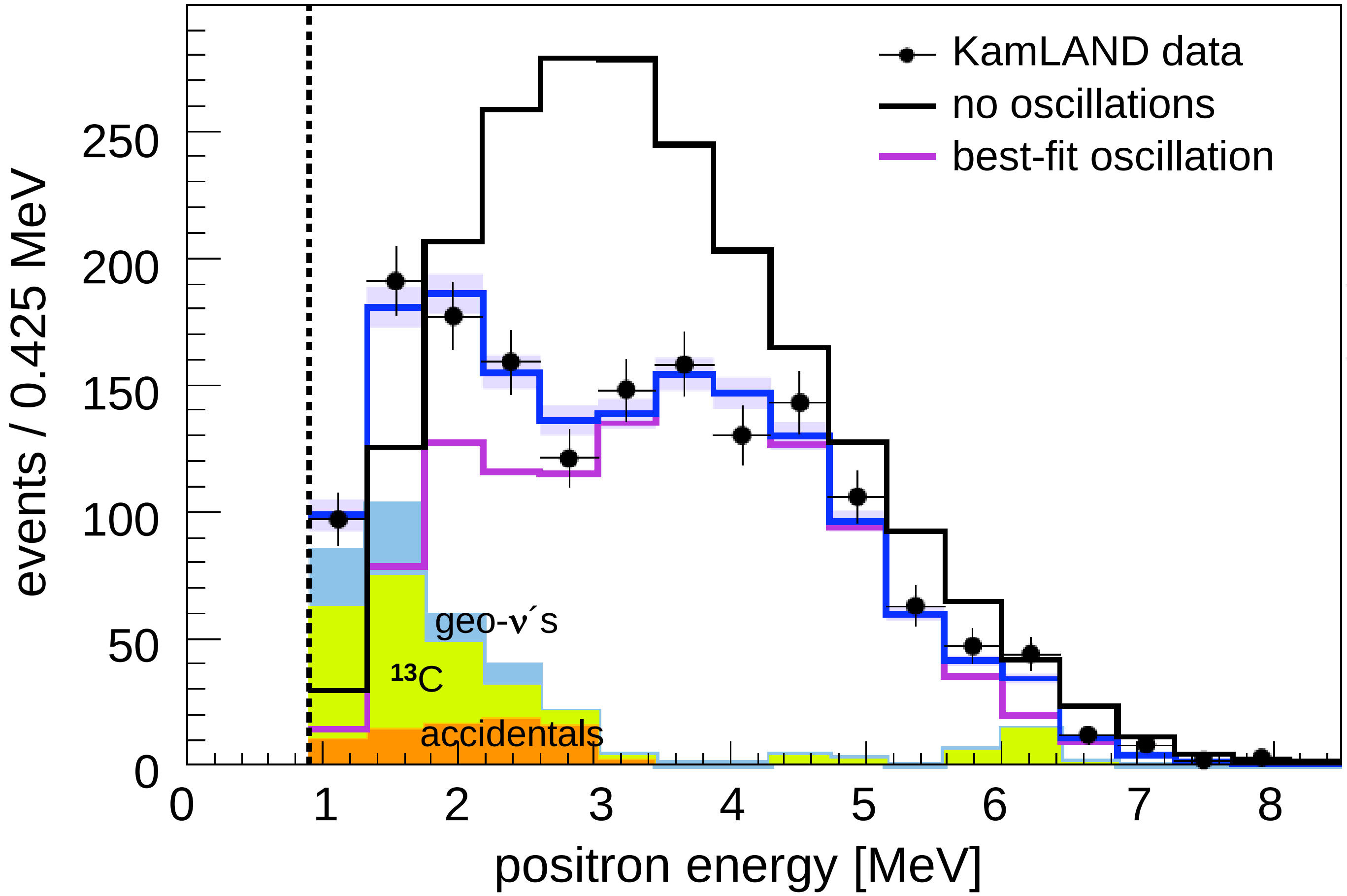


KamLAND – results

- clear & unambiguous evidence for disappearance of reactor neutrinos
  spectrum is fitted with components: reactor-ν´s, geo-ν´s, background

$\Delta m^2 = (7.58 \pm 0.14_{stat} \pm 0.15_{syst}) \times 10^{-5}\ eV^2$
$\tan^2\theta = 0.56 \pm 0.10 \pm 0.10$

KamLAND parameter



KamLAND results	
observed	1609
Background	276.1 ± 23.5
no oscillation	2179 ± 89

KamLAND and solar ν´s: same parameter space

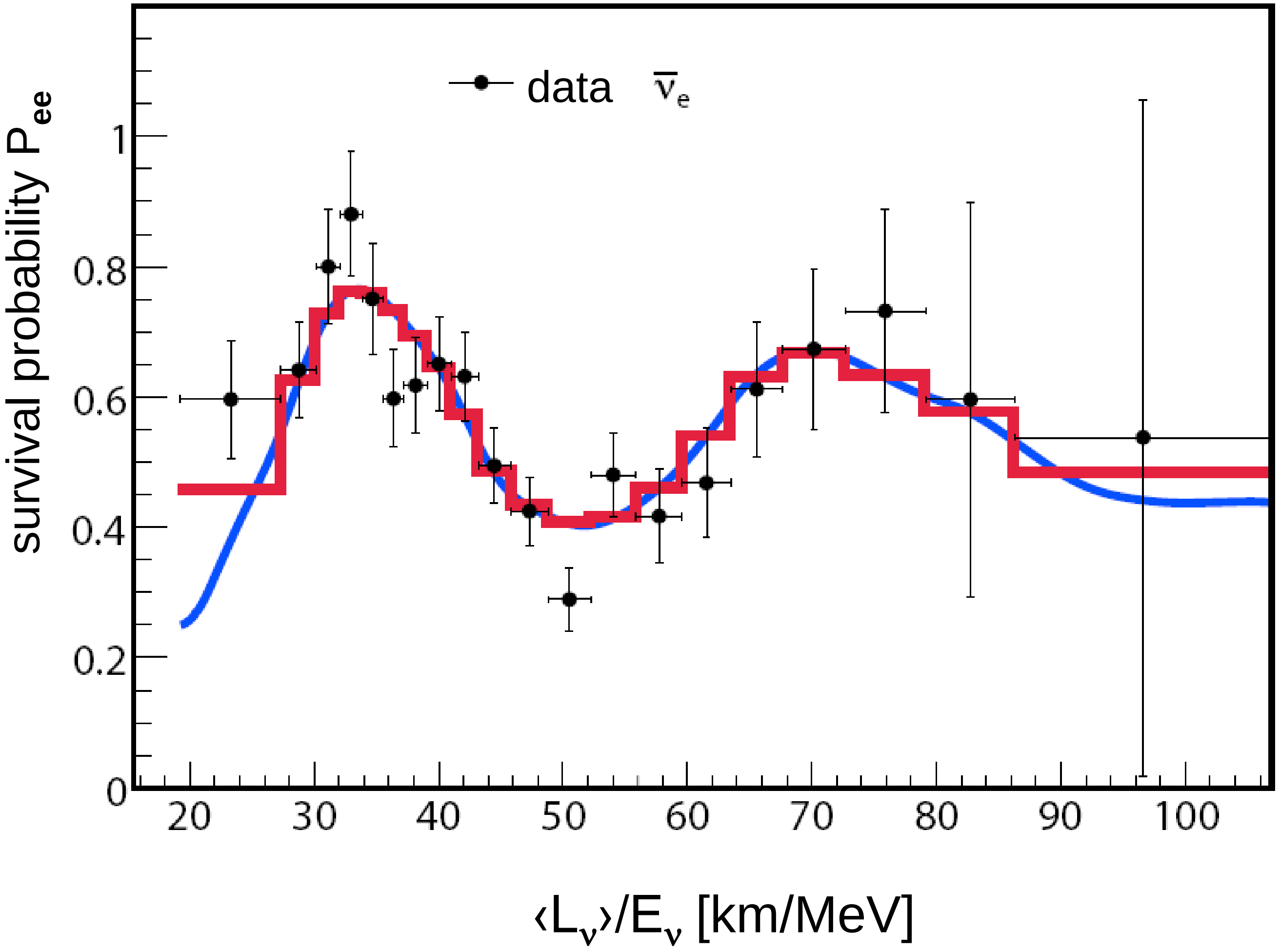
solar ν´s: MSW effect (matter)
reactor-ν´s: vacuum oscillations
CPT symmetry ☑

KamLAND results

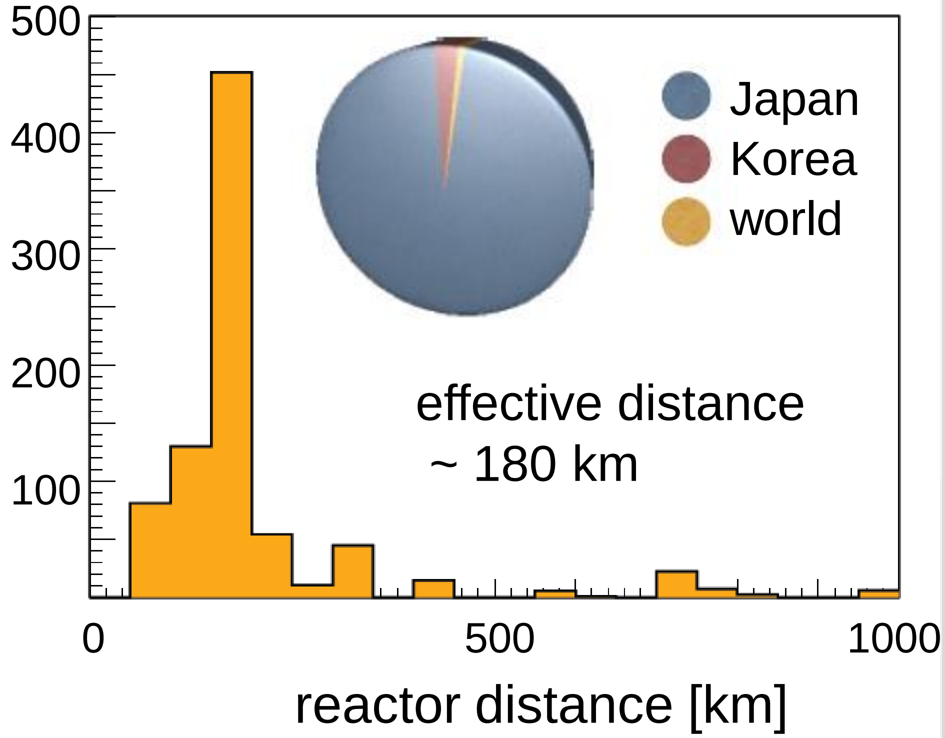
L_ν/E_ν – analysis from KamLAND: L_ν not measurable, effective distance 180 km

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L_\nu}{E_\nu}\right)$$

$\bar{\nu}_e$-disappearance



observation of two oscillation cycles



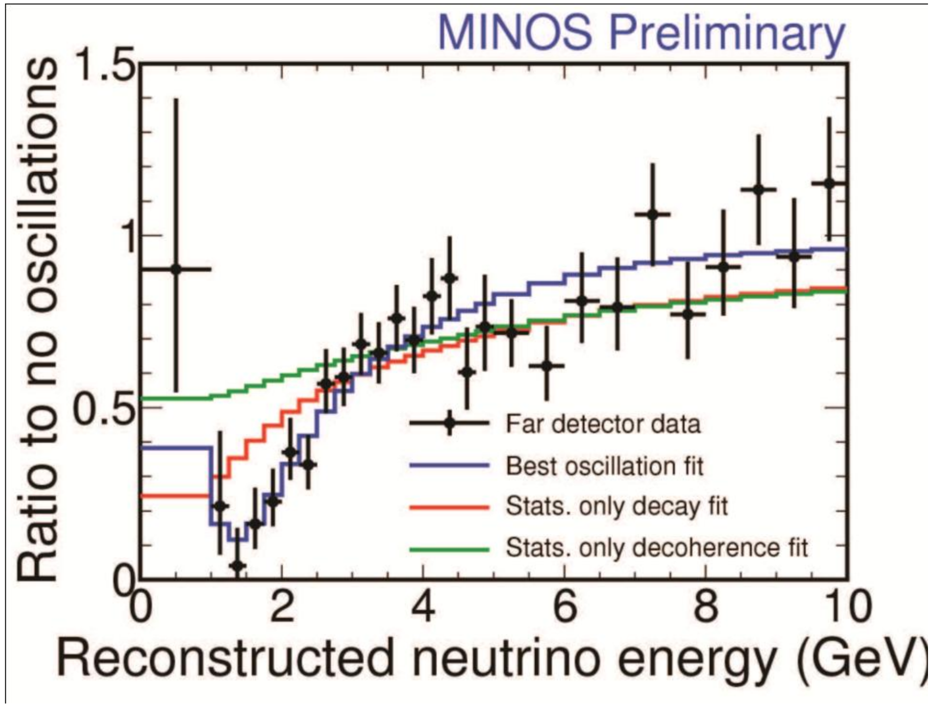
MINOS: hint of CPT violation, ν_e appearance?

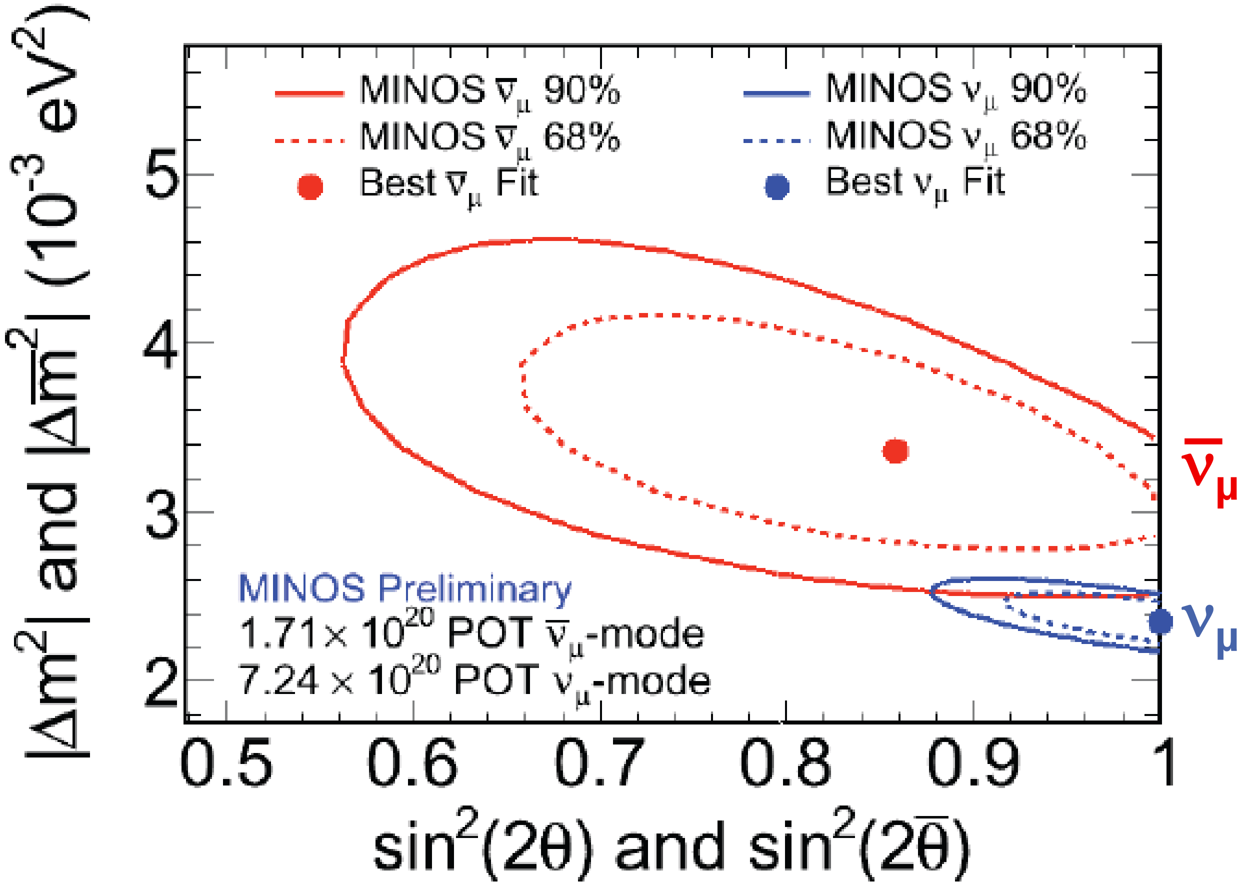
Karlsruhe Institute of Technology

- **surprise: different mixing parameters for ν and $\bar{\nu}_\mu$?**

  2 σ discrepancy at present

  - limited statistics in $\bar{\nu}_\mu$ channel, so far
  - CPT? sterile neutrinos? systematics?





$\Delta m^2 = (3.36 \pm 0.{}^{45}_{40}) \times 10^{-3}$ eV^2

$\Delta m^2 = (2.35 \pm 0.{}^{11}_{08}) \times 10^{-3}$ eV^2

- **ν_μ - ν_e appearance**
  - 54 ν_e events
  - (49.*1*±*7.0*±*2.7) expected*

0.7 σ