3. Neutrino-Oszillationen

3.1 Einleitung

3.2 Neutrinomischung

3.3 Experimentelle Evidenz für Neutrino-Oszillationen

3.4 Bestimmung von Oszillationsparametern

3.5 Zusammenfassung und Offene Fragen

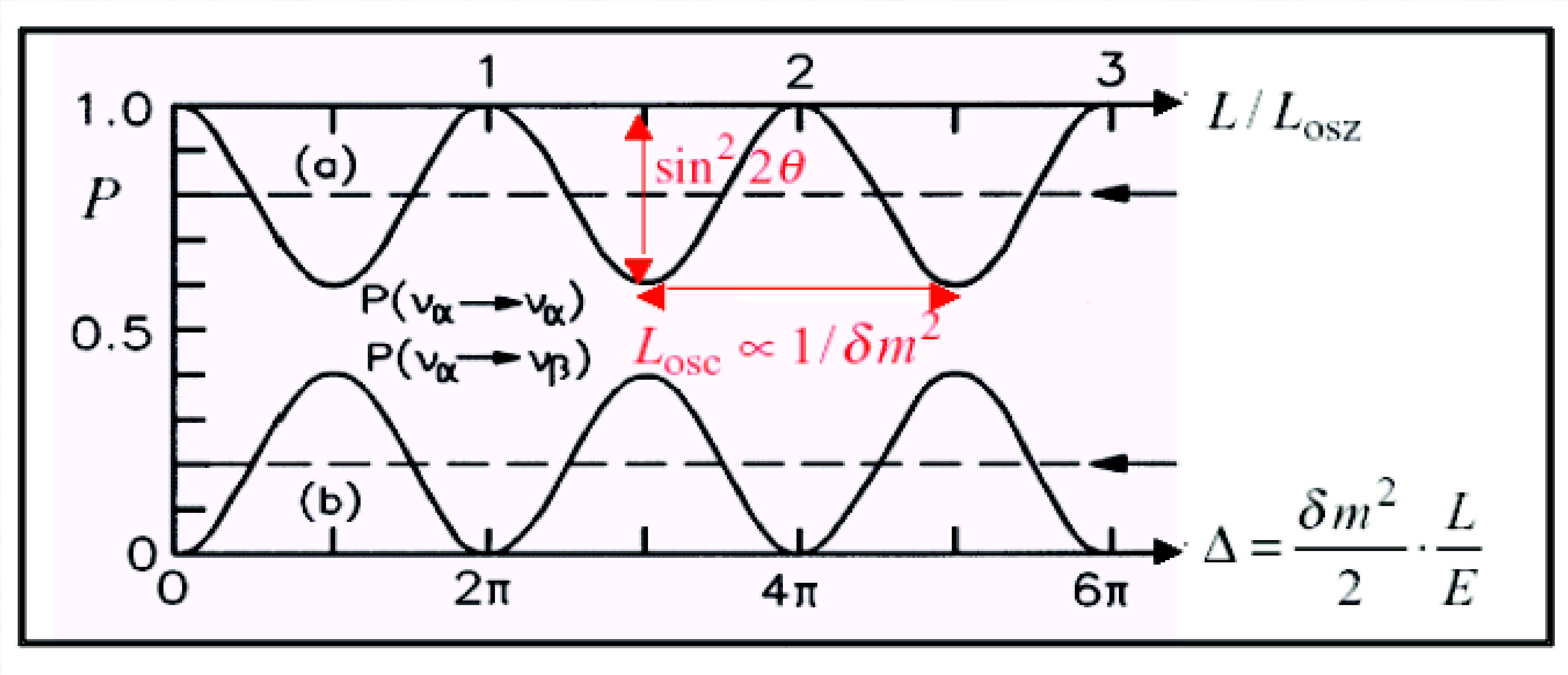
3.3 Experimentelle Evidenz für Neutrino-Oszillationen

3.3.1 Solare Neutrinos

3.3.2 Atmosphärische Neutrinos

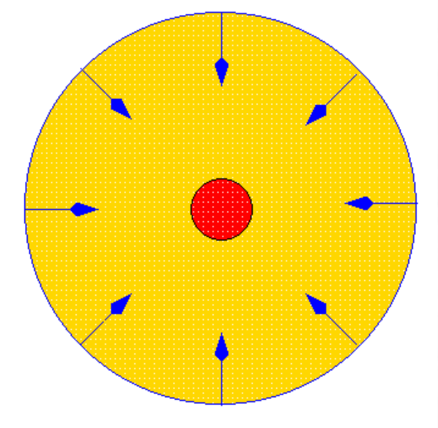
3.3.3 Neutrino-Experimente an Reaktoren

3.3.4 Neutrino-Experimente an Beschleunigern



- Der Mischungswinkel bestimmt die Amplitude
- Δm^2 bestimmt die Oszillationslänge

3.3.1 Solare Neutrinos



- Geburt eines Sterns durch Kontraktion von Gaswolken durch Gravitation
  (Zusammensetzung nach Urknallmodell: ~75% H_2, ~25% He)

- Anstieg der Dichte und Temperatur im Innern

- Zündung von nuklearen Fusionsreaktionen

  Zwei wichtige Fusionsketten: pp – Kette
  CNO-Zyklus

  Bei diesen Kernprozessen entstehen el.magn. Strahlung + Neutrinos

- Stabilität durch Gleichgewicht zwischen Gravitation und Druck (hydrostatisches Gleichgewicht)

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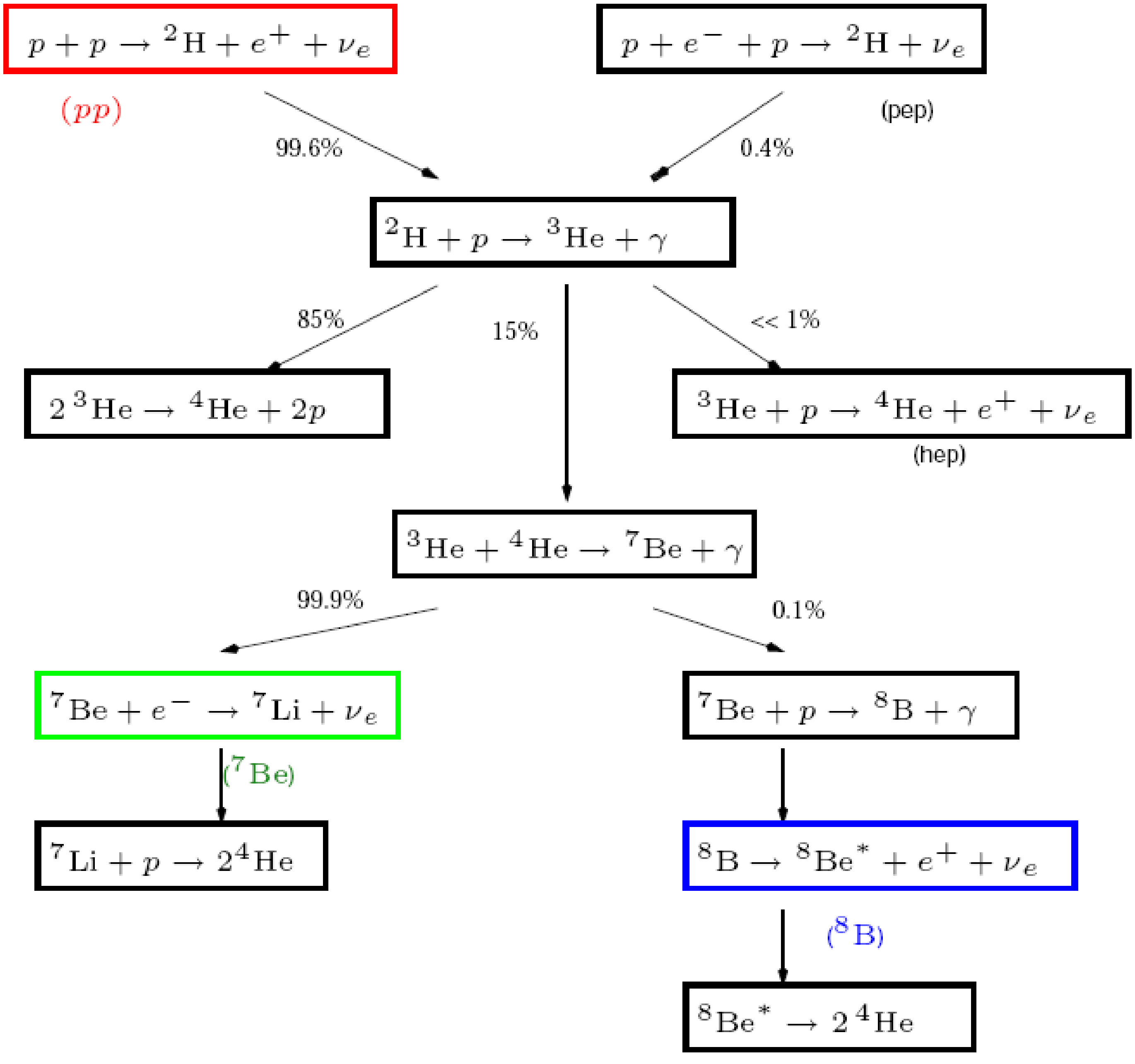
beachte: die heutige sichtbare Luminosität resultiert aus Kernreaktionen, die vor ~ 10^6 Jahren abgelaufen sind.
(Sonne stabil seit ~10^8 Jahren)

Energieproduktion in der Sonne: pp-Kette



Die beiden Fusionsketten:

pp-Zyklus (98.5% von $L_\odot$)

85%:

$p + p \rightarrow e^+ + \nu_e + d$ $\quad$ $p + p \rightarrow e^+ + \nu_e + d$ $\quad$ or (0.4%): $p + e^- + p \rightarrow \nu_e + d$

$p + d \rightarrow \gamma + He^3$ $\quad$ $p + d \rightarrow \gamma + He^3$

$He^3 + He^3 \rightarrow He^4 + p + p$ $\quad$ or (~2x10^{-5}): $He^3 + p \rightarrow He^4 + e^+ + \nu_e$

15%:

$p + p \rightarrow e^+ + \nu_e + d$

$p + d \rightarrow \gamma + He^3$

$He^3 + He^4 \rightarrow \gamma + Be^7$

$e^- + Be^7 \rightarrow \nu_e + Li^7$

$p + Li^7 \rightarrow He^4 + He^4$

or (0.13%):

$p + Be^7 \rightarrow \gamma + B^8$

$B^8 \rightarrow Be^8 + e^+ + \nu_e$

$Be^8 \rightarrow He^4 + He^4$

CNO-Zyklus (zwei Zweige)

$p + N^{15} \rightarrow C^{12} + He^4$ $\quad$ $p + N^{15} \rightarrow \gamma + O^{16}$

$p + C^{12} \rightarrow \gamma + N^{13}$ $\quad$ $p + O^{16} \rightarrow \gamma + F^{17}$

$N^{13} \rightarrow C^{13} + e^+ + \nu_e$ $\quad$ $F^{17} \rightarrow O^{17} + e^+ + \nu_e$

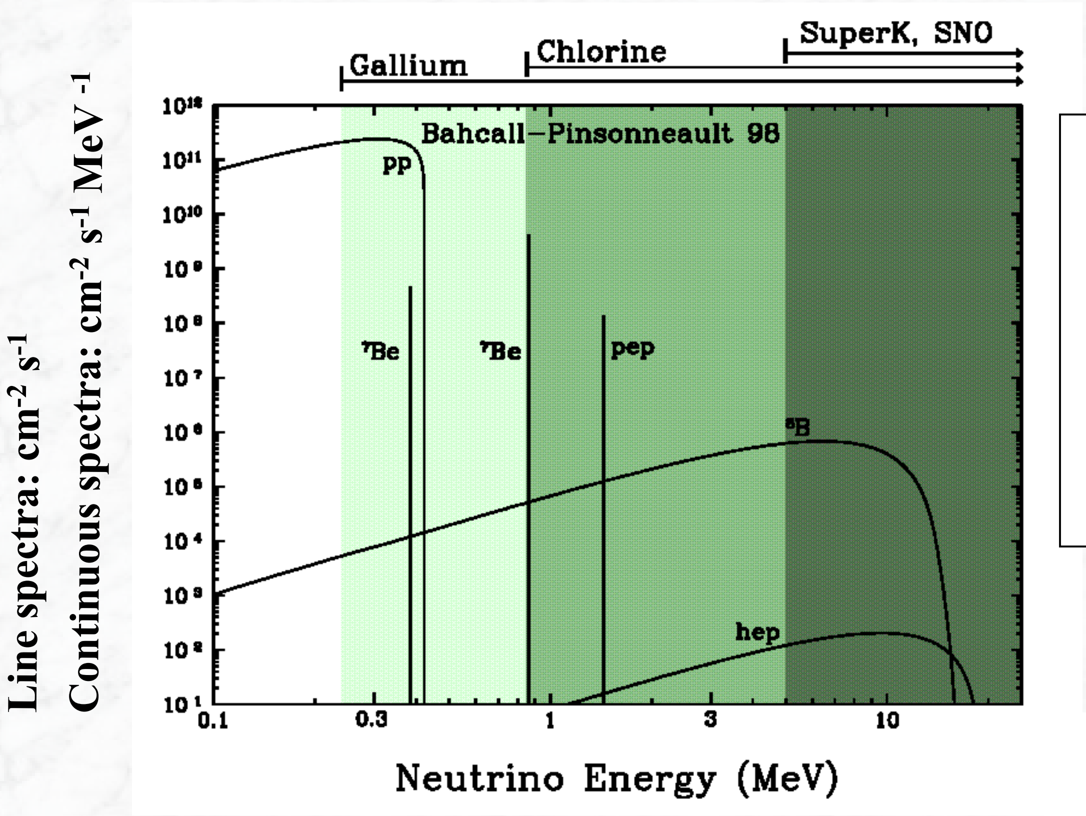
$p + C^{13} \rightarrow \gamma + N^{14}$ $\quad$ $p + O^{17} \rightarrow N^{14} + He^4$

$p + N^{14} \rightarrow \gamma + O^{15}$

$O^{15} \rightarrow N^{15} + e^+ + \nu_e$

In beiden Zyklen liegt die folgende Nettoreaktion vor: $4p \rightarrow He^4 + 2e^+ + 2\nu_e$

Der erwartete Neutrinofluss auf der Erde:



Notation:

pp : $p + p \rightarrow e^+ + \nu_e + d$

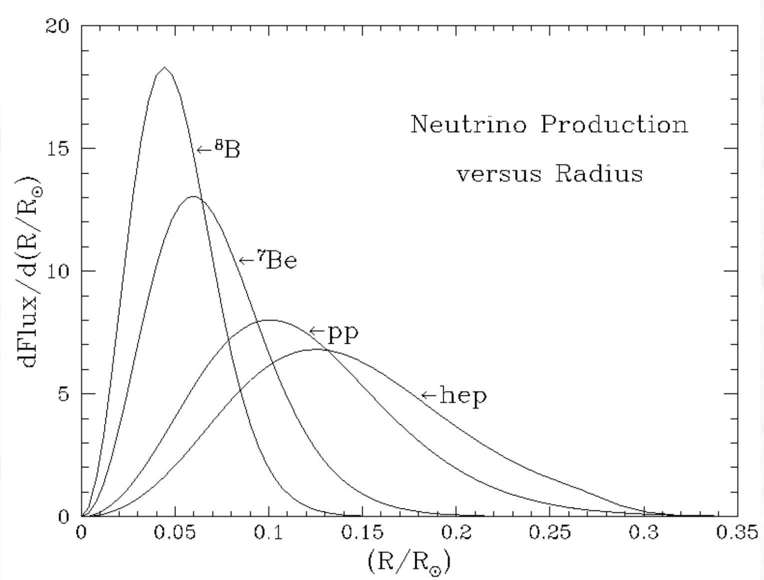
^{7}Be : $e^- + Be^7 \rightarrow \nu_e + Li^7$

pep : $p + e^- + p \rightarrow \nu_e + d$

^{8}B : $B^8 \rightarrow Be^8 + e^+ + \nu_e$

hep : $He^3 + p \rightarrow He^4 + e^+ + \nu_e$

Radiale Verteilung der Neutrinoproduktion in der Sonne (Vorhersage des Standardsonnenmodells)



Endresultat der Fusionsreaktionen:

$$4p \rightarrow He^4 + 2e^+ + 2\nu_e$$

Mittlere, in Form von elektromagnetischer Strahlung, produzierte Energie:

$$Q = (4m_p - m_{He^4} + 2m_e)c^2 - <E(2\nu_e)> \approx 26.1 \text{ MeV}$$

└→ (aus $2e^+ + 2e^- \rightarrow 4\gamma$)

($<E(2\nu_e)> \approx 0.59$ MeV)

Luminosität der Sonne: $L_\odot = 3.846 \times 10^{26}$ W = 2.401×10^{39} MeV/s

Neutrinoemissionsrate: $dN(\nu_e)/dt = 2\, L_\odot/Q \approx 1.84 \times 10^{38}\ s^{-1}$

Neutrinofluss auf der Erde: $\Phi(\nu_e) \approx 6.4 \times 10^{10}\ cm^{-2}\ s^{-1}$

(mittlere Entfernung Sonne-Erde = $1.496 \cdot 10^{11}$ m)

Das Homestake Experiment (1970–1998):
Der erste Nachweis solarer Neutrinos - ein radiochemisches Experiment-

(R. Davis, University of Pennsylvania)

$\nu_e + Cl^{37} \rightarrow e^- + Ar^{37}$ **Energieschwelle $E(\nu_e) > 0.814$ MeV**

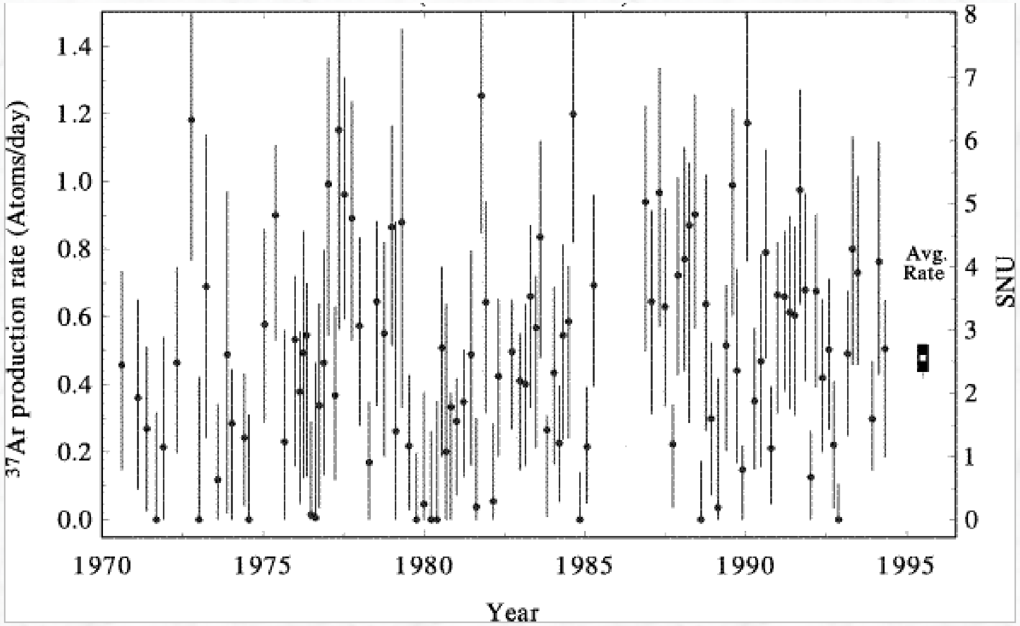
Detektor: 390 m^3 C_2Cl_4 (Perchloroethylene) installiert in einemTank in der Homestake Goldmine (South Dakota, USA) unter 4100 m Wasser-äquivalent (m w.e.)

Erwartete Produktionsrate von Ar^{37} Atomen ≈ **1.5 pro Tag**

Experimentelle Methode:

- Extraktion von Ar^{37} im Abstand von wenigen Monaten, N_2 Spülung, Nachweis des radioaktiven Zerfalls (Elektroneinfangreaktion) der Ar^{37} Atome: $e^- + Ar^{37} \rightarrow \nu_e + Cl^{37*}$ (Halbwertszeit $t_{1/2}$ = 34 Tage)
- Angeregte Cl^{37} Atom im Endzustand emittiert Auger-Elektronen und/oder γ-Quanten Nachweis in einem Proportionalzählrohr
- Kalibration / Vermessung der Nachweiseffizienz: durch Injektion einer bekannten Menge Ar^{37} in den Tank

Ergebnisse von mehr als 20 Jahren Datennahme



SNU (Solar Neutrino Units): Einheit zur Messung der Ereignisrate in radiochemischen Experimenten:

1 SNU = 1 Ereignis s^{-1} pro 10^{36} Target-Atome

Mittelwert aller Messungen:

$R(Cl^{37}) = 2.56 \pm 0.16 \pm 0.16$ SNU
(stat) (syst)

SSM Vorhersage: $7.6^{+1.3}_{-1.1}$ SNU

Solares Neutrino Defizit

(SSM = Standard Solar Model, J. Bahcall et al.)

Der ^{37}Cl-Neutrino-Detektor in der Homestake-Mine   (ca. 1967)


ca. 1966
Raymond Davis
John Bahcall

Echtzeitexperiment unter Benutzung eines Wasser-Cherenkov Detektors zum Nachweis solarer Neutrinos

Elastische Neutrino–Elektron-Streuung: $\nu + e^- \rightarrow \nu + e^-$

Nachweis von Cherenkov-Licht in Wasser, das durch das angestoßene Elektron emittiert wird

(Nachweisschwelle: ~5 MeV, entspricht 2 cm Weglänge in Wasser)

Wirkungsquerschnitte: $\sigma(\nu_e) \approx 6\,\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)$

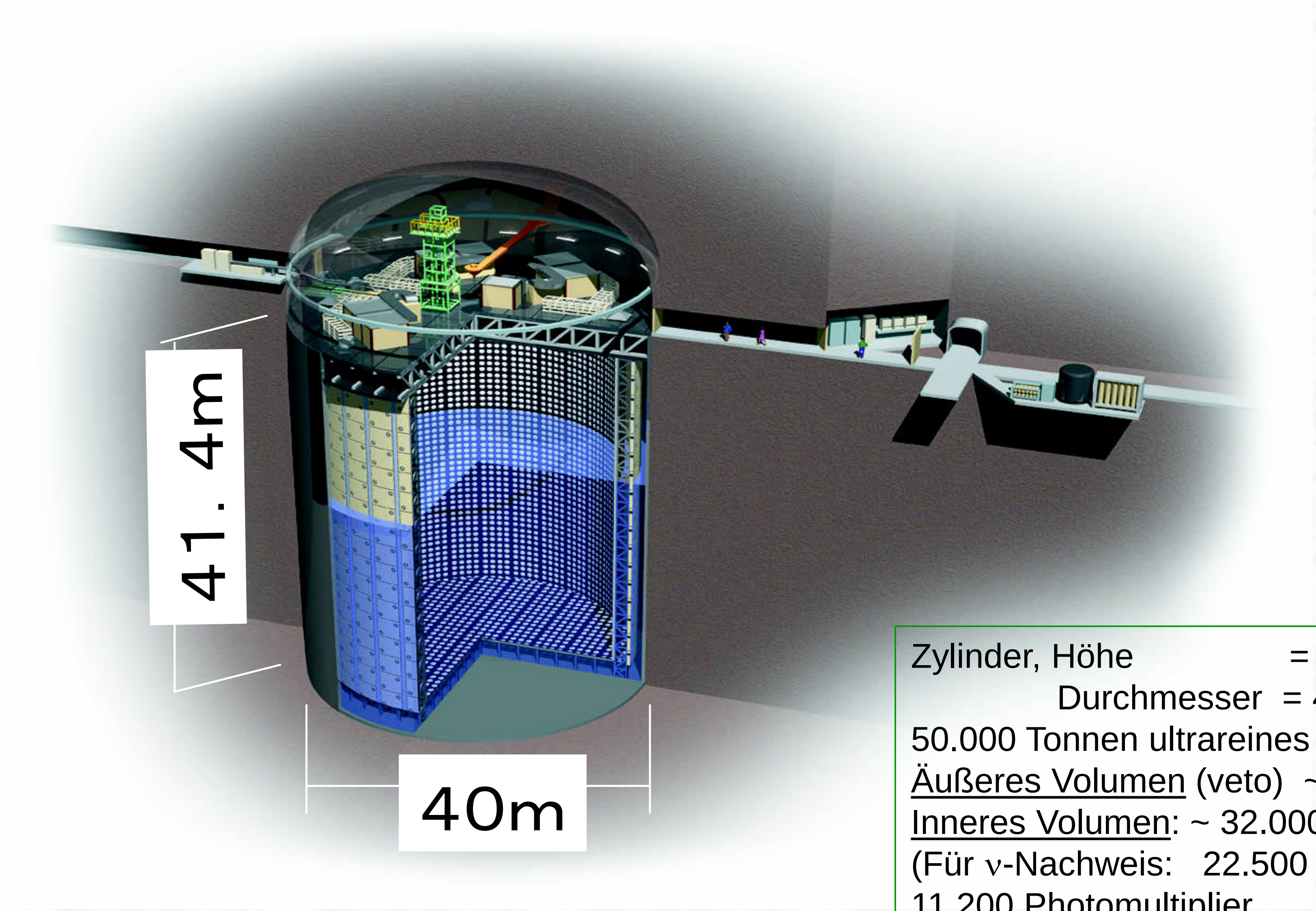
W and Z Austausch — Nur Z Austausch

Zwei Experimente: Kamiokande (1987 – 94), Volumen: 680 m^3

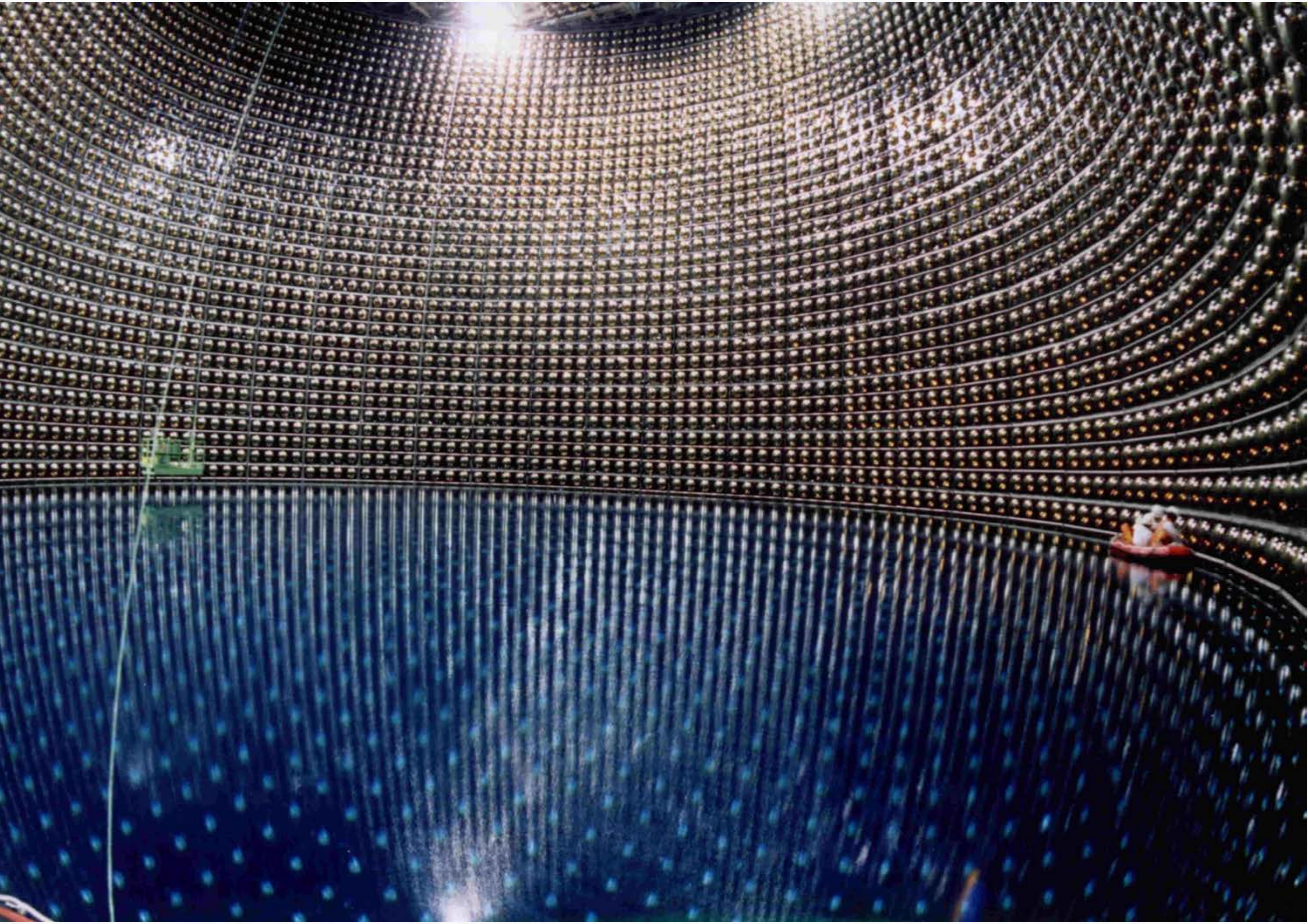
Super-Kamiokande (1996 – 2001) Volumen: 22.500 m^3

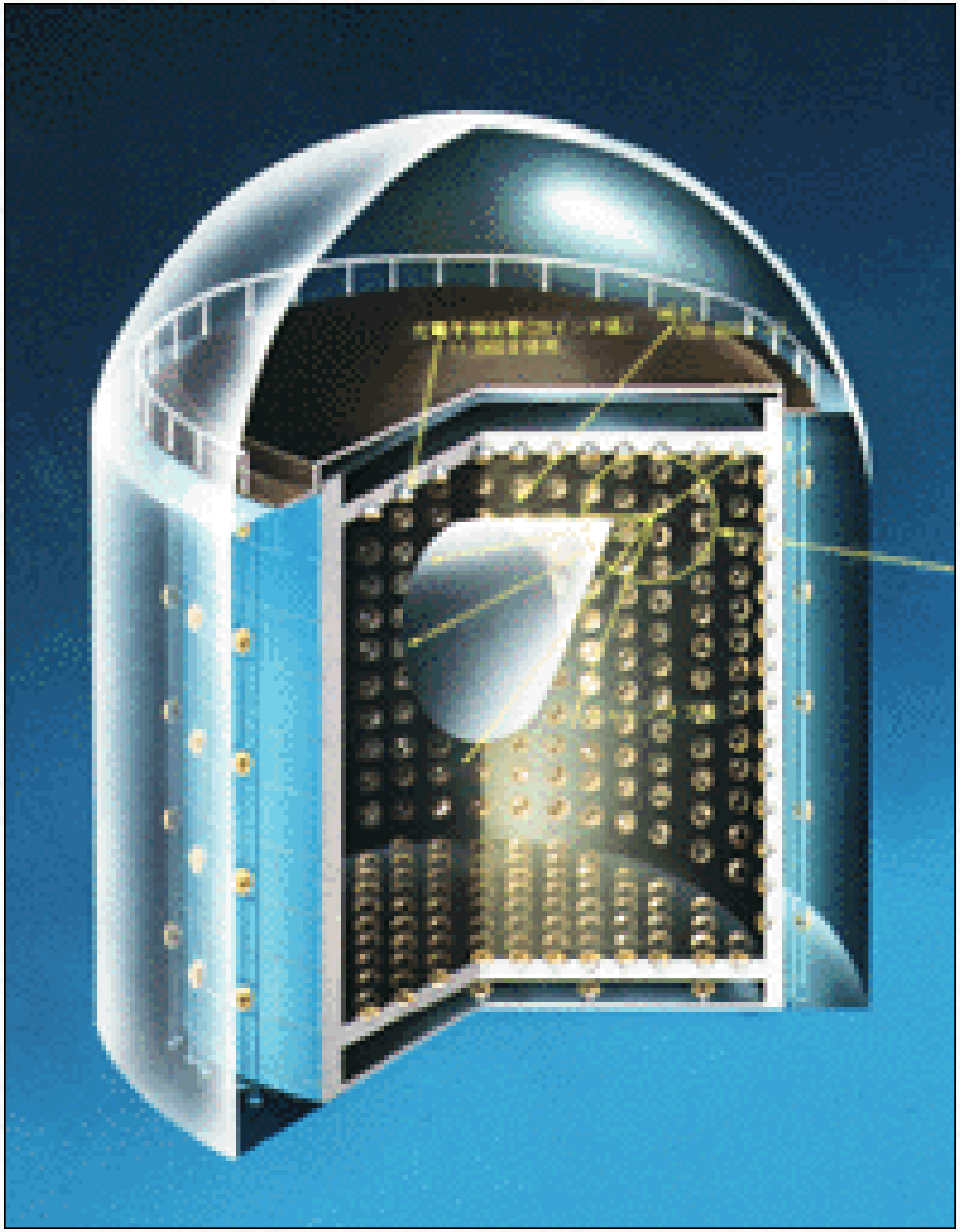
Installiert in der Kamioka-Mine (Japan)
bei einer Tiefe entsprechend 2670 m w.e.

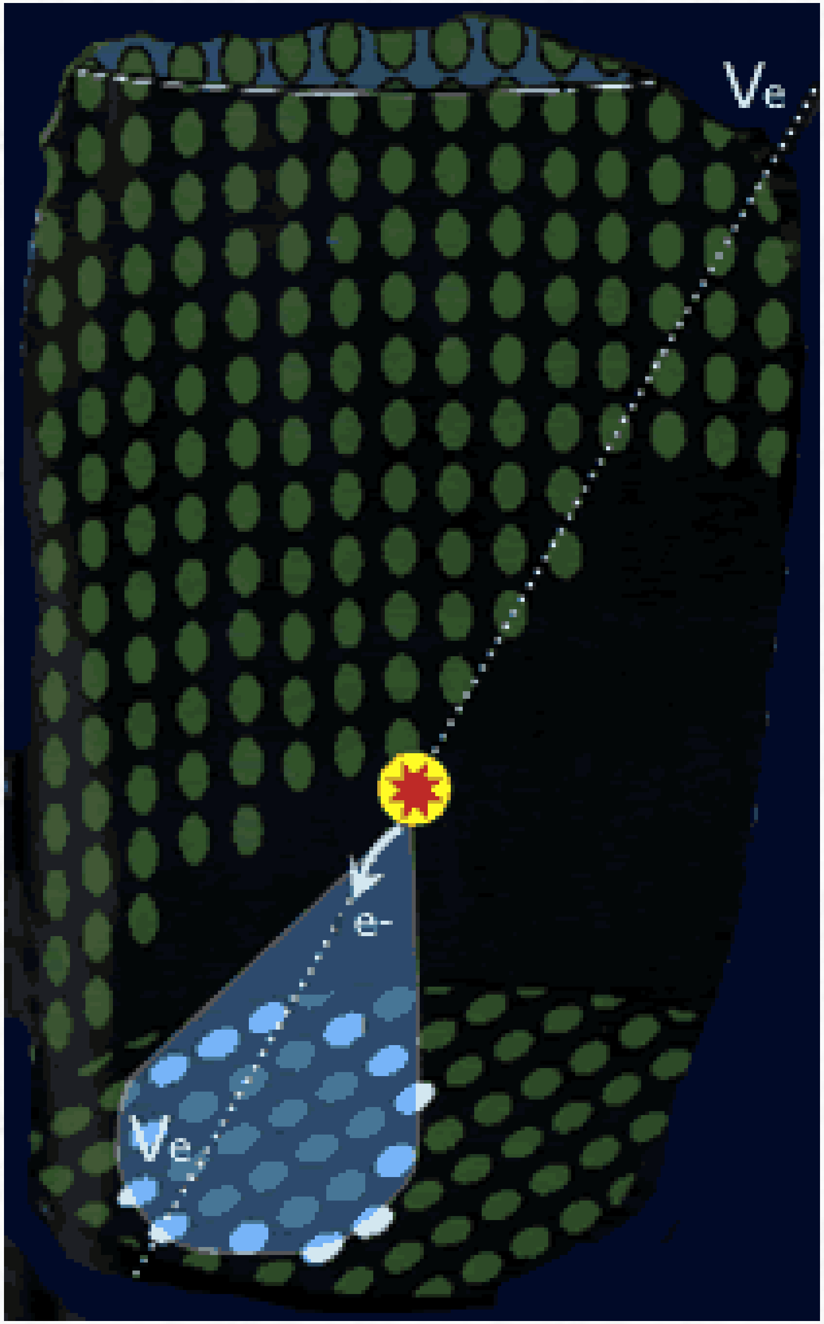
Superkamiokande-Detektor (Japan)



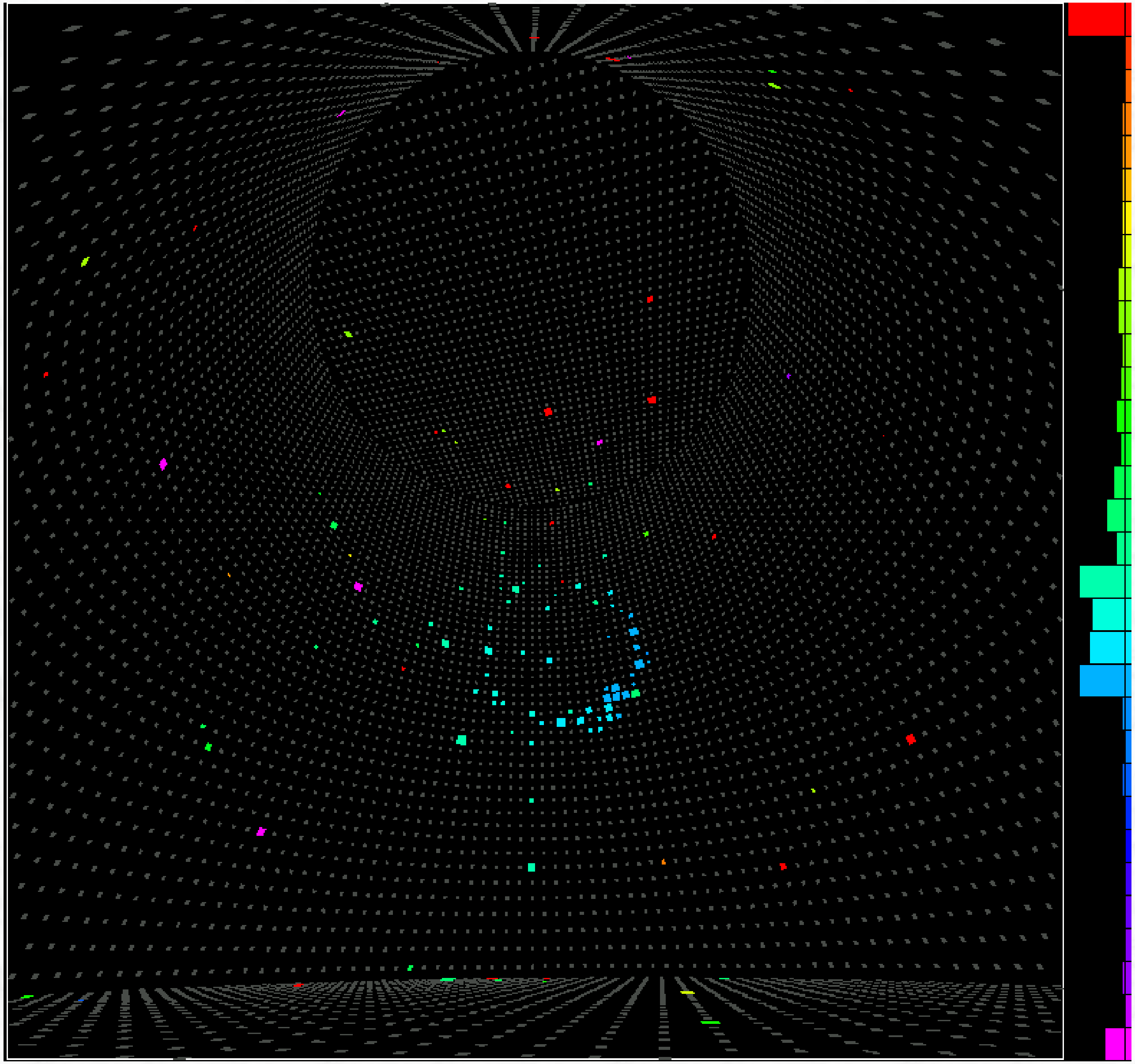
Zylinder, Höhe = 41.4 m
Durchmesser = 40 m
50.000 Tonnen ultrareines Wasser
<u>Äußeres Volumen</u> (veto) ~2.7 m dick
<u>Inneres Volumen</u>: ~ 32.000 Tonnen
(Für ν-Nachweis: 22.500 Tonnen)
11.200 Photomultiplier
Durchmesser = 50 cm







ν_e
e-
ν_e

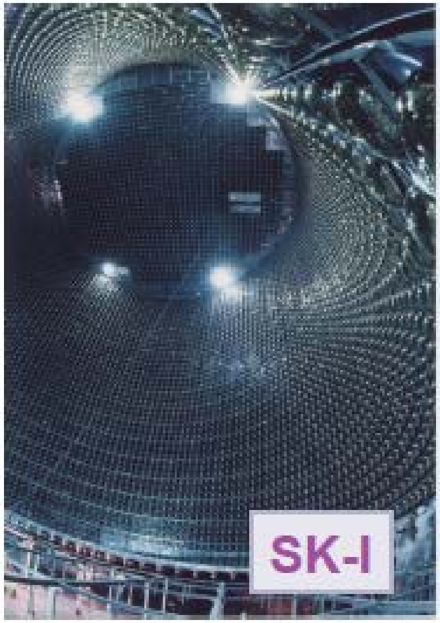


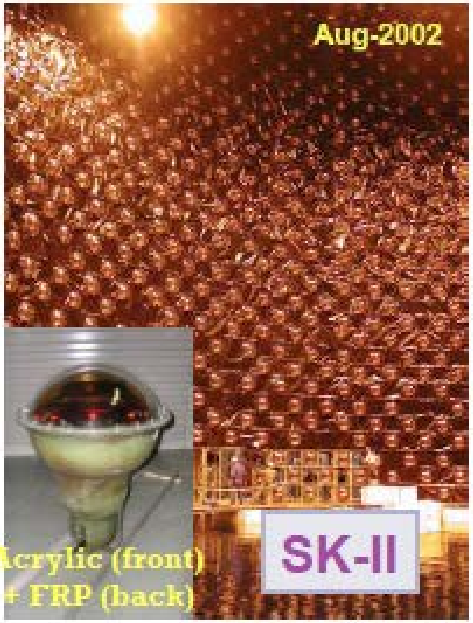
12 MeV
Neutrino
von der Sonne
im SK-Detektor

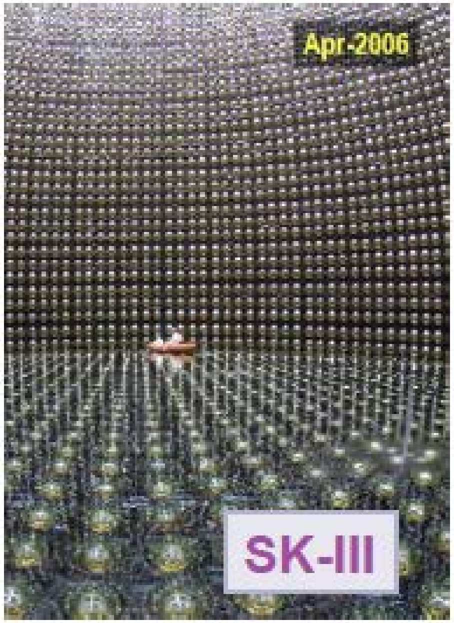
History of Super-Kamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I (Rebuild) SK-II (Rebuild) SK-III SK-IV

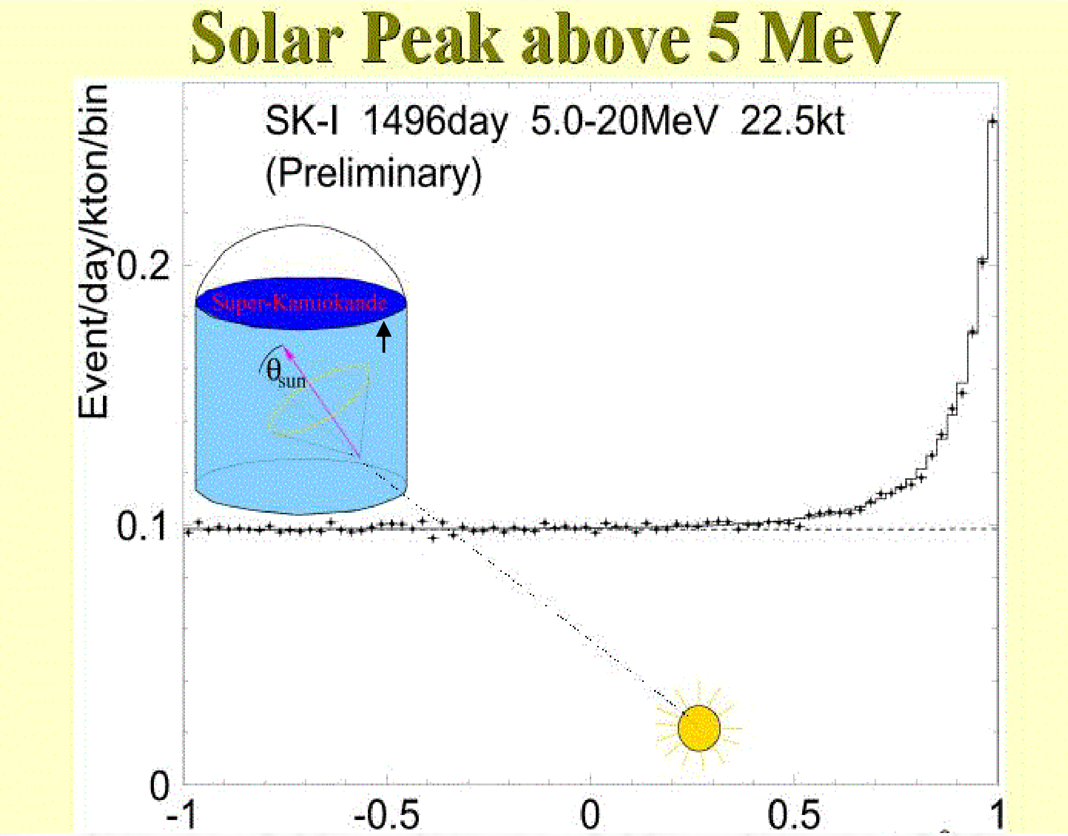






	SK-I	SK-II	SK-III	SK-IV (now)	SK-IV (goal)
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
Threshold: (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV

now goal

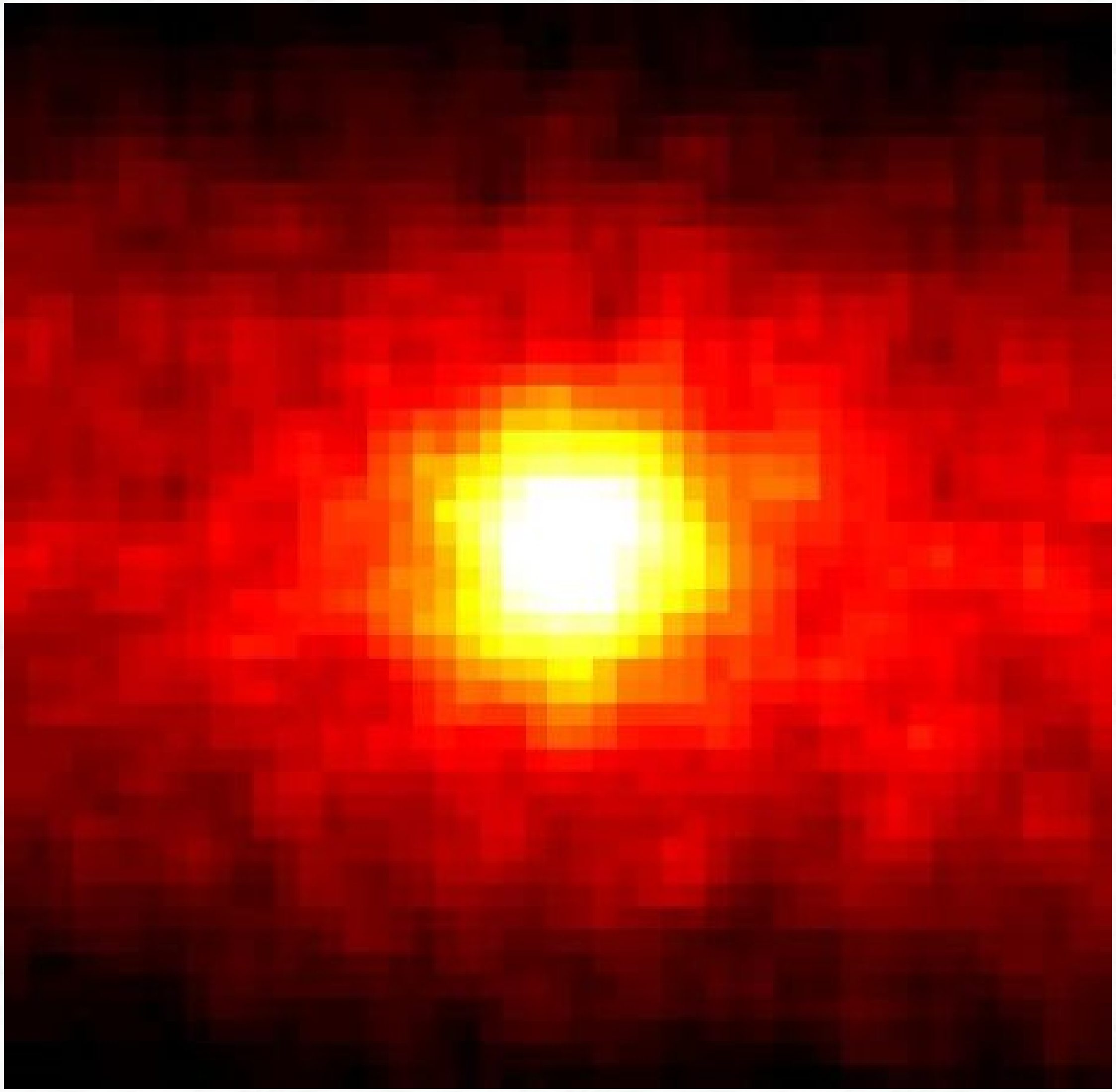


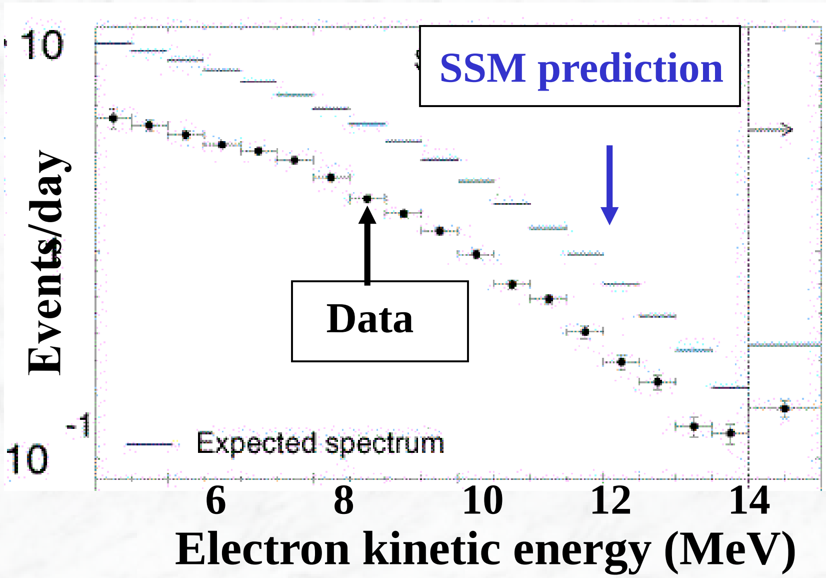
$\cos\theta_{Sonne}$

Bestätigung des solaren Ursprungs der nachgewiesenen Neutrinos:

Winkelkorrelation zwischen der Neutrino-Richtung und der Richtung des gestreuten Elektrons

Die Sonne im Neutrinolicht
(“fotografiert” von Superkamiokande)





1995

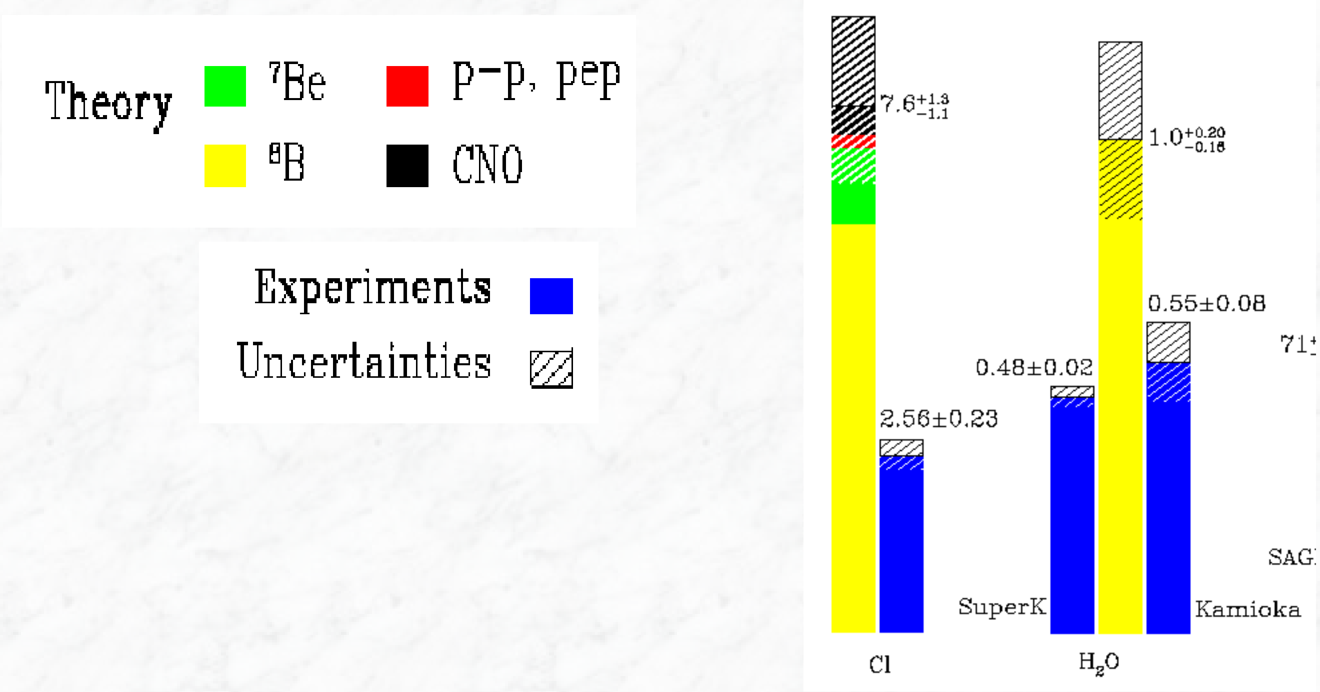
Ergebnisse von 22.400 gemessenen Ereignissen (1496 Tage Datennahme)

Gemessener Neutrino-Fluss (Annahme, alle ν_e): $\Phi(\nu_e) = (2.35 \pm 0.02 \pm 0.08) \times 10^6\ cm^{-2}\ s^{-1}$
(stat) (syst)

SSM Vorhersage: $\Phi(\nu_e) = (5.05\ ^{+1.01}_{-0.81}) \times 10^6\ cm^{-2}\ s^{-1}$

Daten/SSM = $0.465 \pm 0.005\ ^{+0.093}_{-0.074}$ (inkl. theo. Unsicherheiten) → **ν_e Defizit**
(stat)

Vergleich der Homestake- und Kamioka-Ergebnisse mit den Vorhersagen



Homestake and Kamioka Ergebnisse waren bereits Ende der 1980er Jahre bekannt
Allerdings: nur sensitiv auf die hochenergetischen Be- und B-Neutrinos;
Fluss hängt stark von der Temperatur im Innern der Sonne ab.

Nachweis der Neutrinos aus der Proton-Kette ($p + p \rightarrow e^+ + \nu_e + d$) wünschenswert
(Hauptbeitrag zum Neutrino-Spektrum, festgelegt durch die Leuchtkraft der Sonne, geringe theoretische Unsicherheiten)

Gallium experiments: radiochemical experiments to search for

$$\nu_e + Ga^{71} \rightarrow e^- + Ge^{71}$$

Energy threshold $E(\nu_e) > 0.233$ MeV ➡ reaction sensitive to solar neutrinos from $p + p \rightarrow e^+ + \nu_e + d$ (the dominant component)

Three experiments:

- GALLEX (Gallium Experiment, 1991 – 1997)
- GNO (Gallium Neutrino Observatory, 1998 –)

} In the Gran Sasso National Lab
150 km east of Rome
Depth 3740 m w.e.

- SAGE (Soviet-American Gallium Experiment)

In the Baksan Lab (Russia) under the Caucasus. Depth 4640 m w.e.

Target: 30.3 tons of Gallium in HCl solution (GALLEX, GNO)

50 tons of metallic Gallium (liquid at 40°C) (SAGE)

Experimental method:

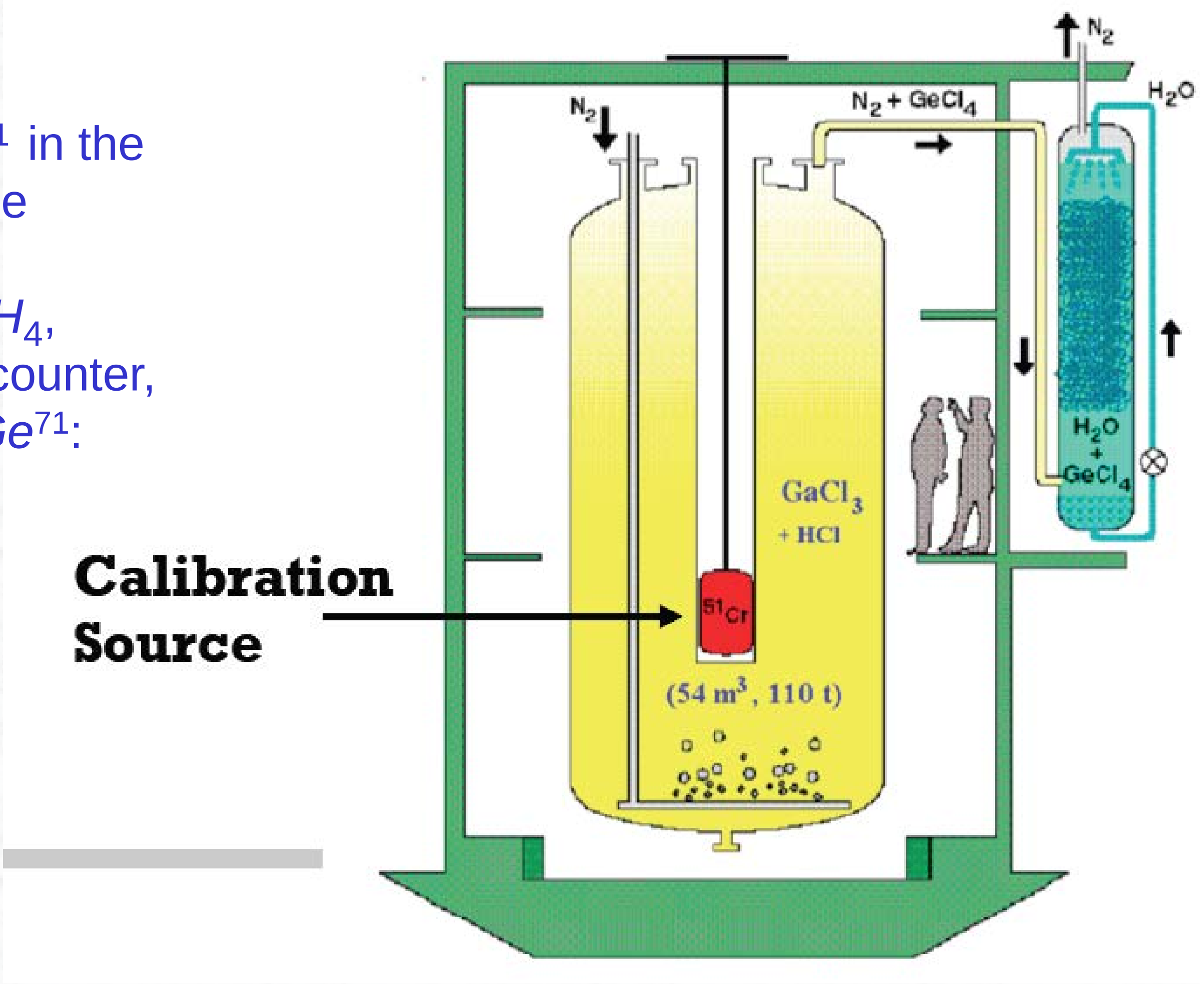
- Every few weeks extract Ge^{71} in the form of $GeCl_4$ (a highly volatile substance),

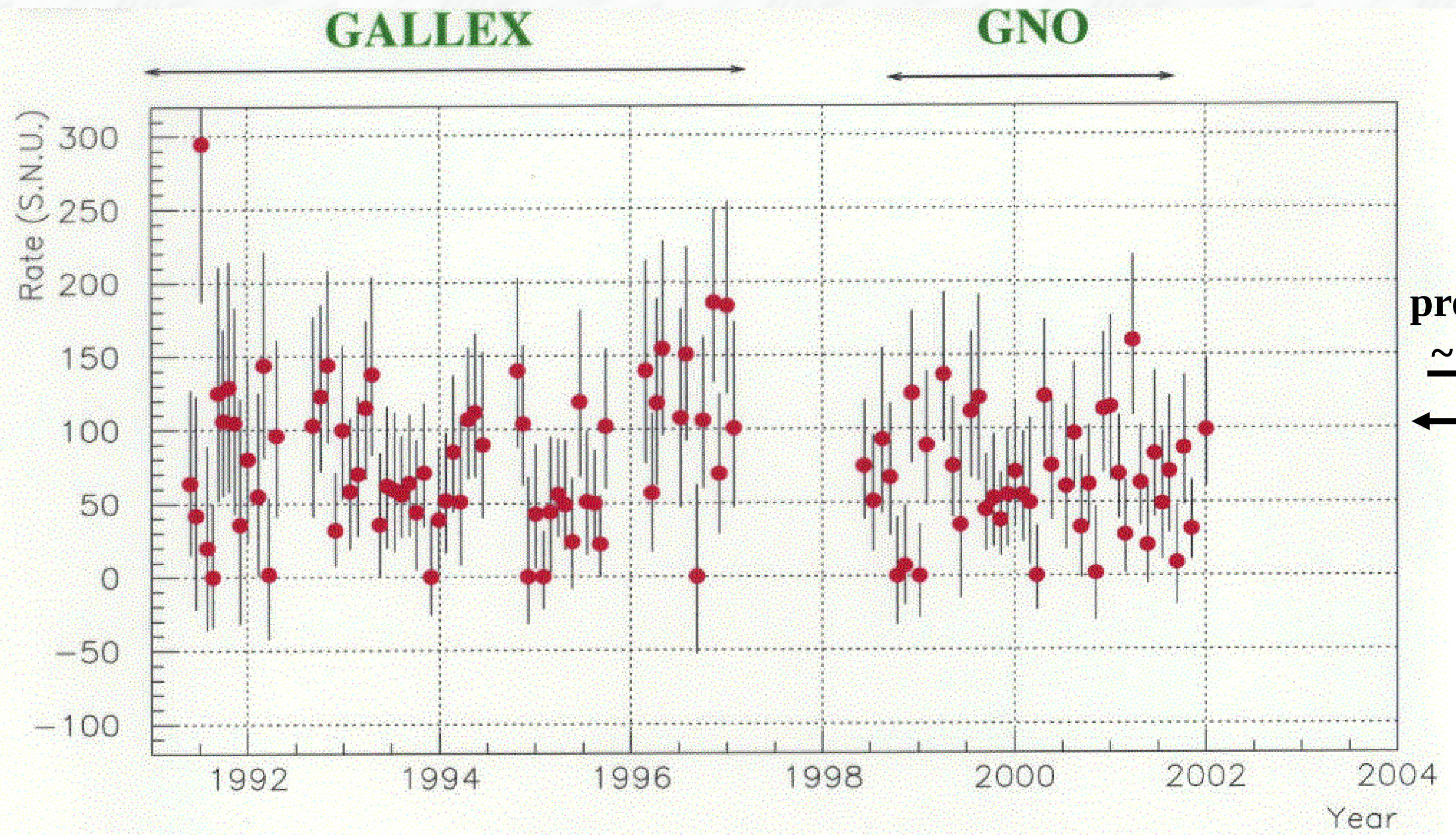
  convert chemically to gas GeH_4,
  inject gas into a proportional counter,
  detect radioactive decay of Ge^{71}:

  $e^{-} + Ge^{71} \rightarrow \nu_e + Ga^{71}$

  (half-life $t_{1/2}$ = 11.43 d)

- Calibrate full procedure with a well defined (and large) β source (^{51}Cr)





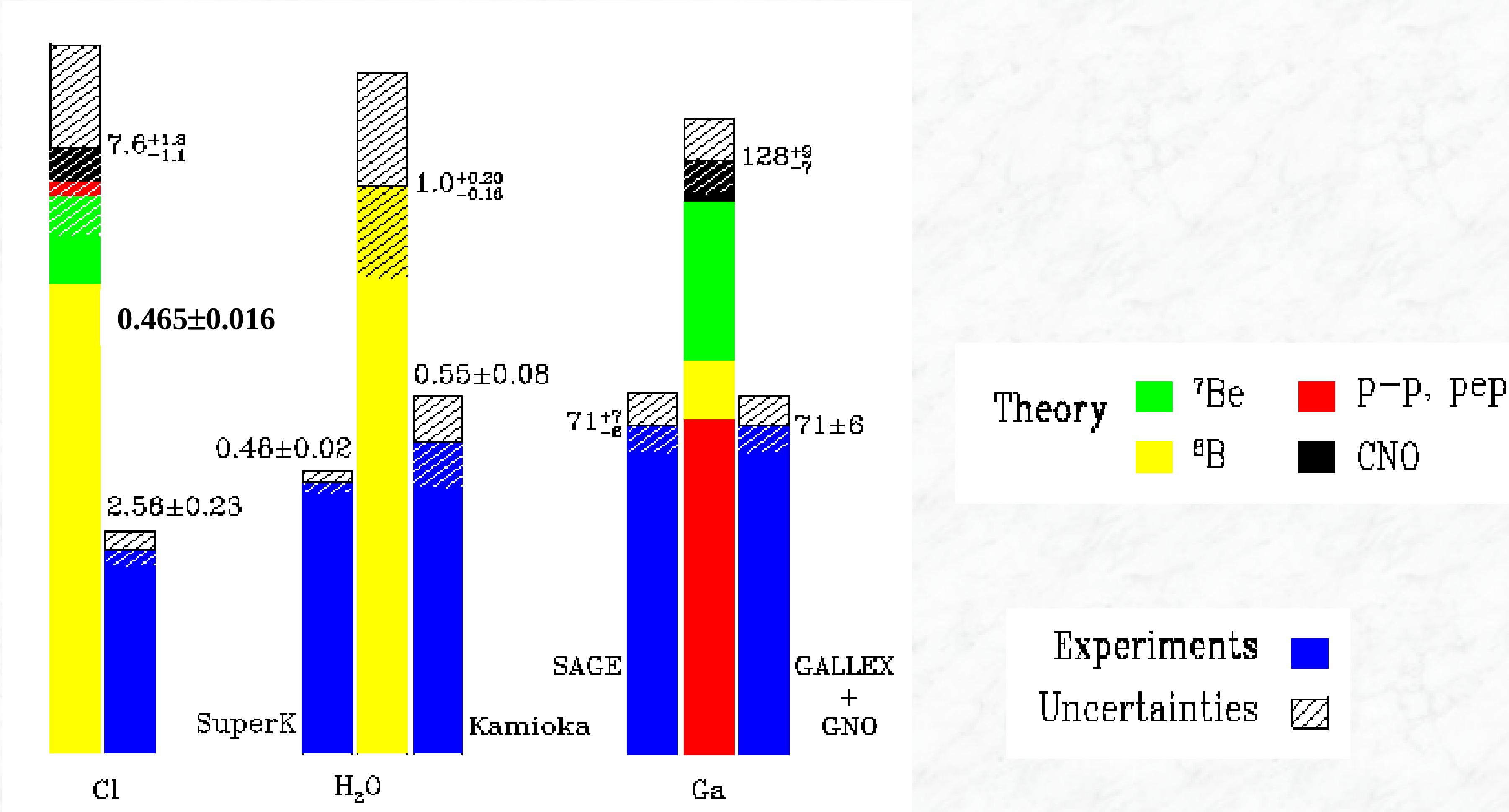
Ge^{71} production rate
~1 atom/day

GALLEX	65 SR	77.5 +– 6.2 (stat) +– 4.5 (sys) SNU
GNO	43 SR	65.2 +– 6.4 (stat) +– 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +– 4.5 (stat) +– 3.8 (sys) SNU

SAGE (1990 – 2001) $70.8^{+6.5}_{-6.1}$ SNU

SSM PREDICTION: 128^{+9}_{-7} SNU

Data/SSM = 0.56 ± 0.05

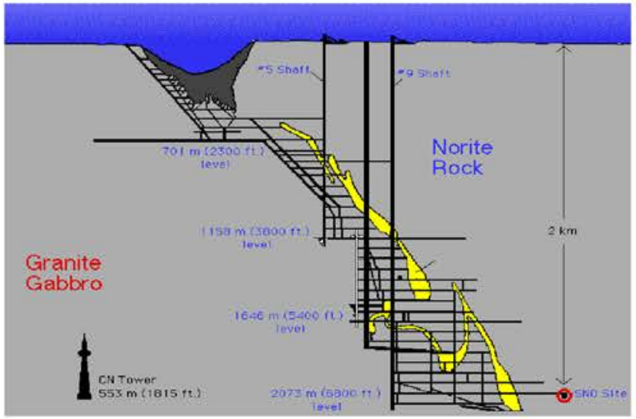

$7.6^{+1.3}_{-1.1}$
0.465±0.016
2.56±0.23
Cl
0.48±0.02
$1.0^{+0.20}_{-0.16}$
0.55±0.08
SuperK
Kamioka
H_2O
128^{+9}_{-7}
71^{+7}_{-6}
71±6
SAGE
GALLEX + GNO
Ga
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

Further experiments to explore the solar neutrino puzzle:

- SNO experiment
  measurement of the total ν flux from the sun
  (ν_e should turn into ν_μ or ν_τ in case of oscillations)
  Key experiment !

- BOREXINO experiment
  Measure the flux of the Be and B neutrinos directly

The SNO Experiment



Sudbury Neutrino Observatory

1000 tonnes D_2O

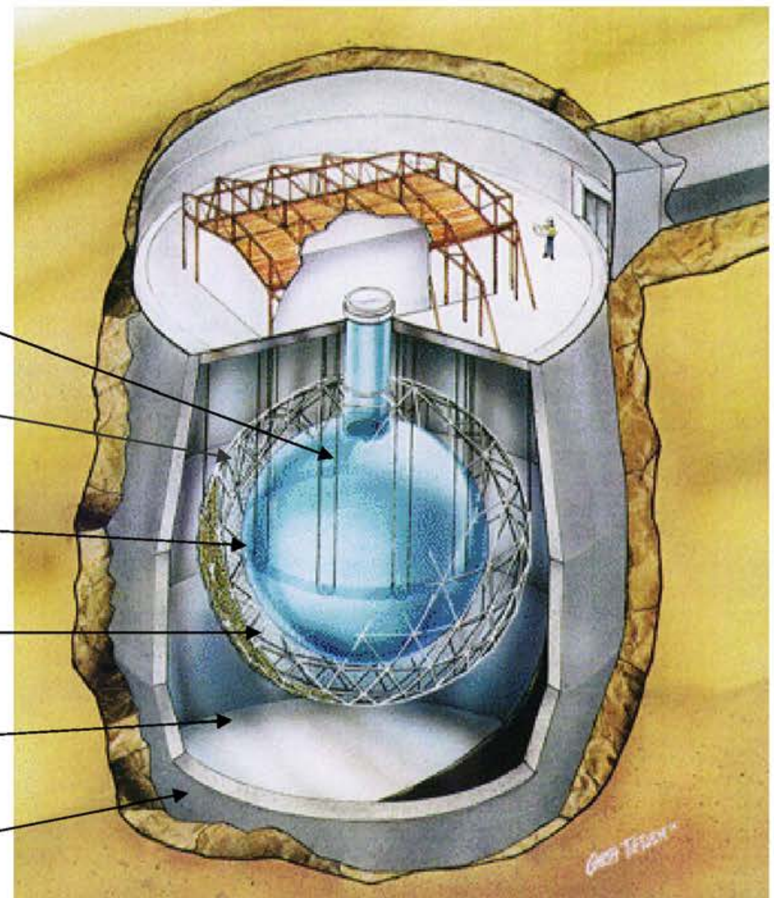
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

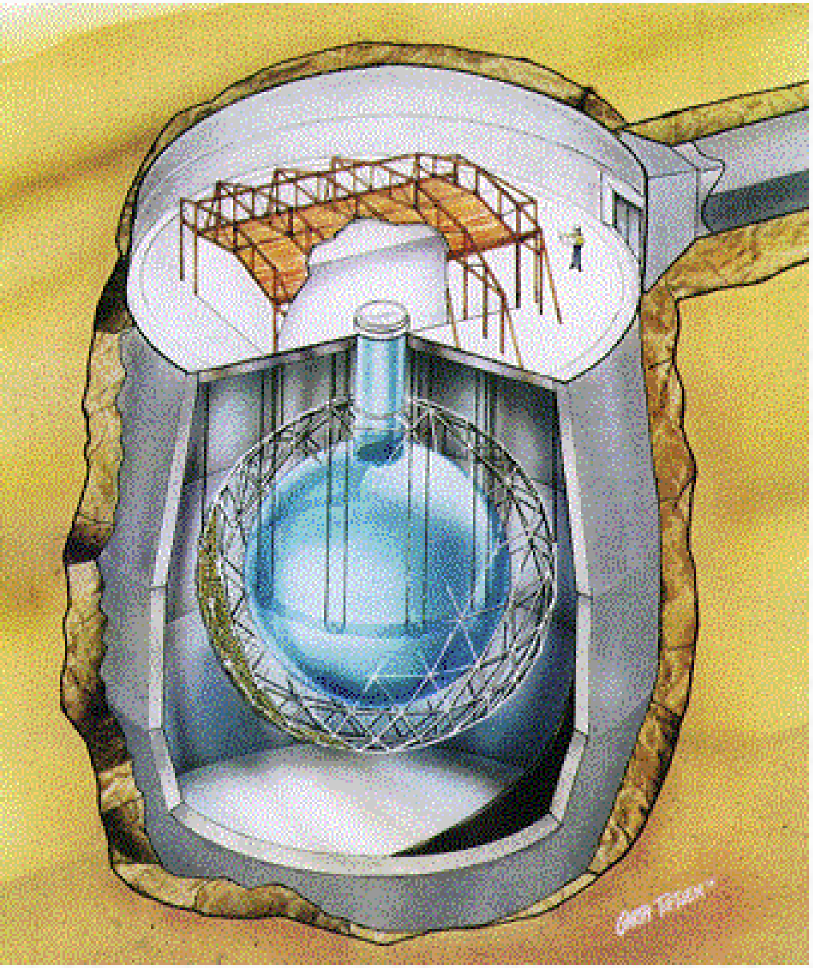
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Unambiguous demonstration of solar neutrino oscillations:



SNO: a real-time experiment detecting Cherenkov light emitted in 1000 tons of high purity heavy water D_2O contained in a 12 m diam. acrylic sphere, surrounded by 7800 tons of high purity water H_2O

Light collection: 9456 photomultiplier tubes, diam. 20 cm, on a spherical surface with a radius of 9.5 m

Depth: 2070 m (6010 m w.e.) in a nickel mine

Electron energy detection threshold: 5 MeV

Fiducial volume: reconstructed event vertex within 550 cm from the centre

Solar neutrino detection at SNO:

1. Neutrino-electron elastic scattering (ES): $\nu + e^- \rightarrow \nu + e^-$

   Directional, $\sigma(\nu_e) \approx 6\,\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)$ (as in Super-K)

2. Charged Current Reaction (CC): $\nu_e + d \rightarrow e^- + p + p$

   Weakly directional: recoil electron angular distribution $\propto 1 - (1/3)\cos(\theta_{sun})$
   Good measurement of the ν_e energy spectrum (because the electron takes most of the ν_e energy)

3. Neutral Current Reaction (NC): $\nu + d \rightarrow \nu + p + n$

   Equal cross-sections for all three neutrino types
   Measure the total solar flux from $B^8 \rightarrow Be^8 + e^+ + \nu$ in the presence of oscillations by comparing the rates of CC and NC events

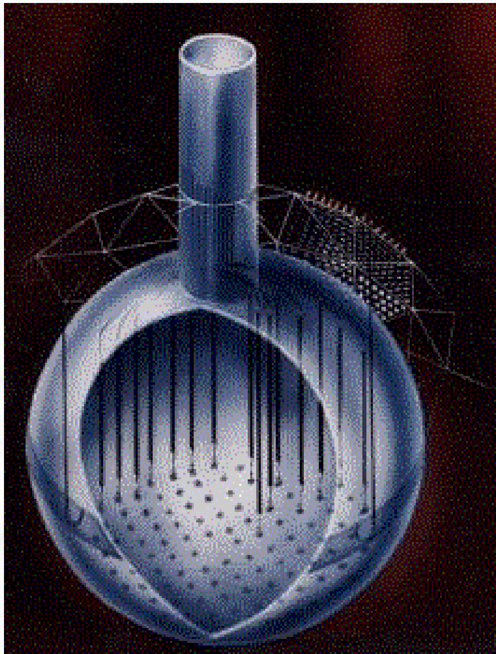
Detection of $\nu + d \rightarrow \nu + p + n$

Detect photons ($\rightarrow e^+ e^-$) from neutron capture at thermal energies:

- First phase (November 1999 – May 2001):
  $n + d \rightarrow H^3 + \gamma$ (E_γ = 6.25 MeV)

- Second phase: add high purity *NaCl* (2 tons)
  $n + Cl^{35} \rightarrow Cl^{36}$ + **γ –** ray cascade ($\Sigma E_\gamma \approx$ 8. 6 MeV)

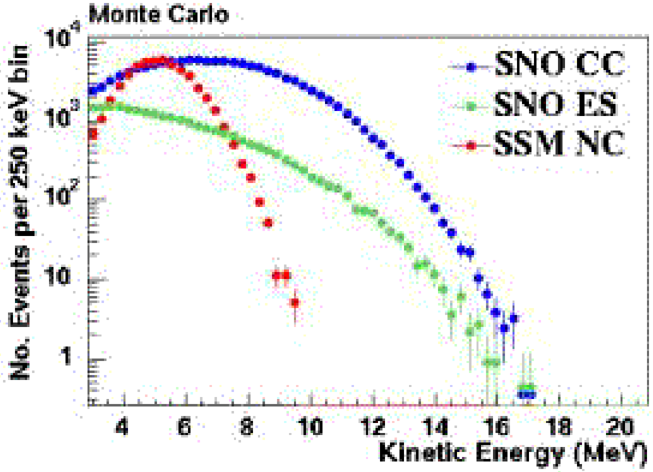
- At a later stage:
  insert He^3 proportional counters in the detector
  $n + He^3 \rightarrow p + H^3$ (mono-energetic signal)



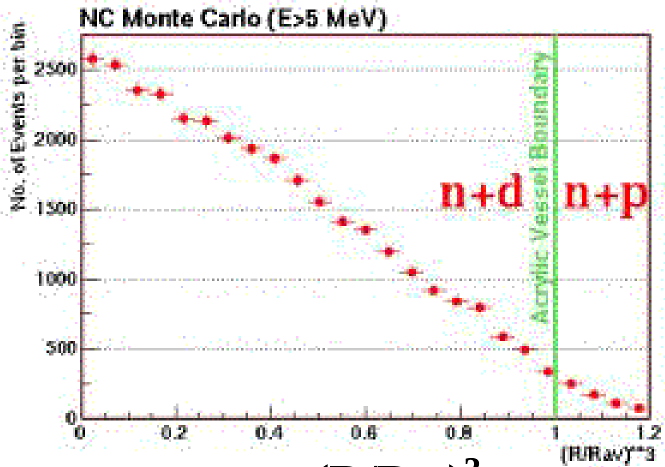
SNO expectations

Use three variables:

- Signal amplitude (MeV)
- $\cos(\theta_{sun})$
- Event distance from centre (R)
  (measured from the PM relative times)

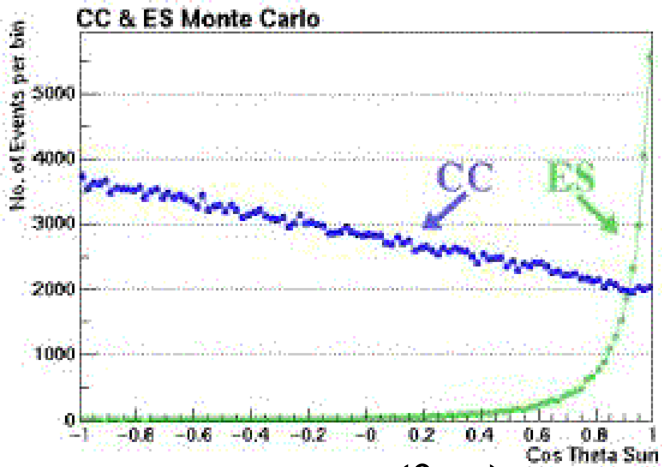


$n + d \rightarrow t + \gamma \ldots \rightarrow e^-$ $(E_\gamma = 6.25$ MeV$)$



$(R/R_{av})^3$

(proportional to volume)



$\cos(\theta_{sun})$

$(R_{av} = 6$ m = radius of the acrylic sphere$)$

Use β and γ radioactive sources to calibrate the energy scale

Use Cf^{252} neutron source to measure neutron detection efficiency (14%)

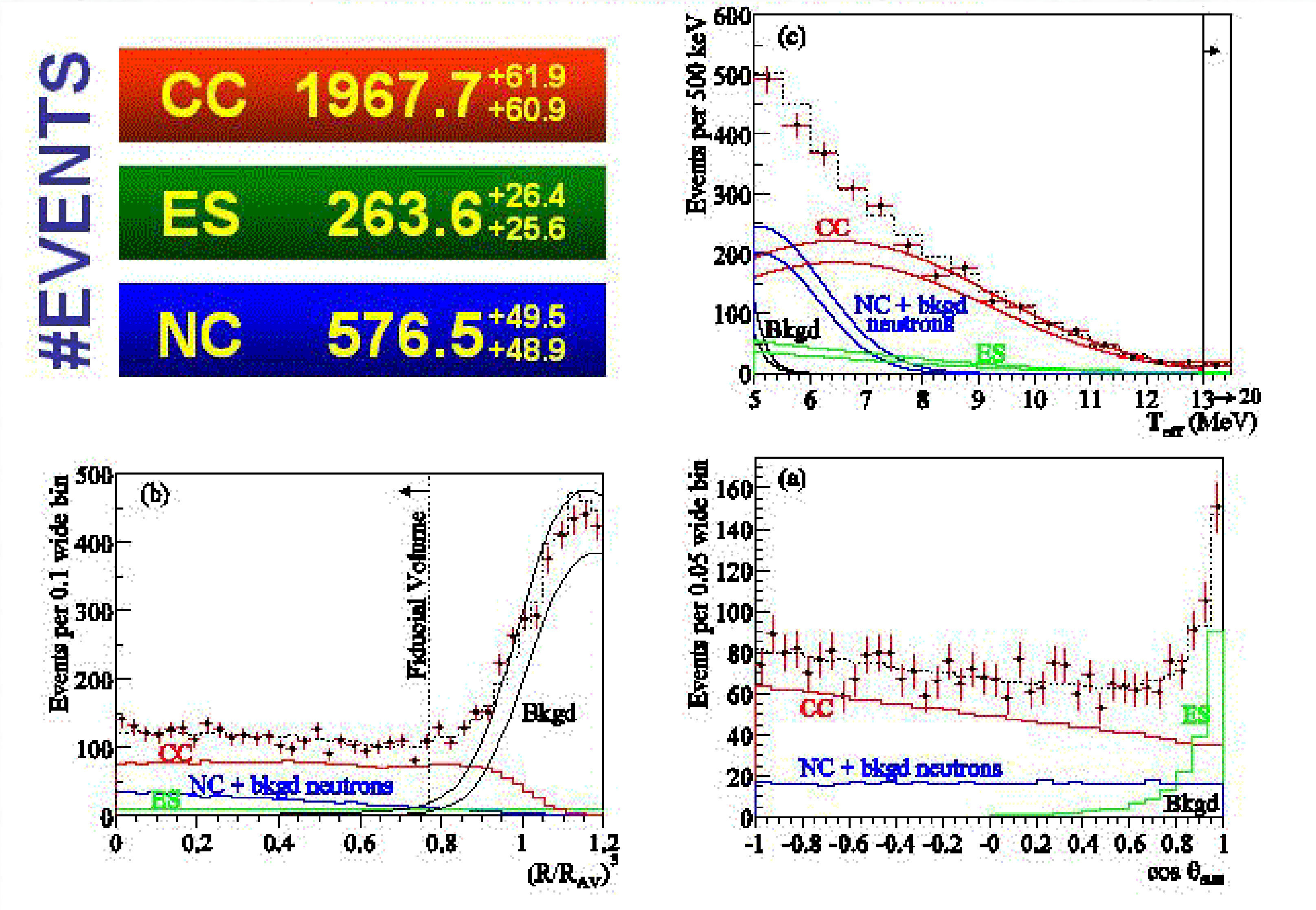
Neutron signal does not depend on $\cos(\theta_{sun})$

From 306.4 days of data taking:

Number of events with kinetic energy $T_{eff} > 5$ MeV and $R < 550$ cm: 2928

Neutron background: 78 ± 12 events. Background electrons 45^{+18}_{-12} events

Use likelihood method and the expected distributions to extract the three signals



Solar neutrino fluxes, as measured separately from the three signals:

$$\Phi_{CC}(\nu_e) = 1.76\,^{+0.06}_{-0.05}\,^{+0.09}_{-0.09} \times 10^6\ \mathrm{cm^{-2}s^{-1}}$$

$$\Phi_{ES}(\nu) = 2.39\,^{+0.24}_{-0.23}\,^{+0.12}_{-0.12} \times 10^6\ \mathrm{cm^{-2}s^{-1}}$$

$$\Phi_{NC}(\nu) = 5.09\,^{+0.44}_{-0.43}\,^{+0.46}_{-0.43} \times 10^6\ \mathrm{cm^{-2}s^{-1}}$$

stat. syst.

Note: $\Phi_{CC}(\nu_e) \equiv \Phi(\nu_e)$

Calculated under the assumption that all incident neutrinos are ν_e

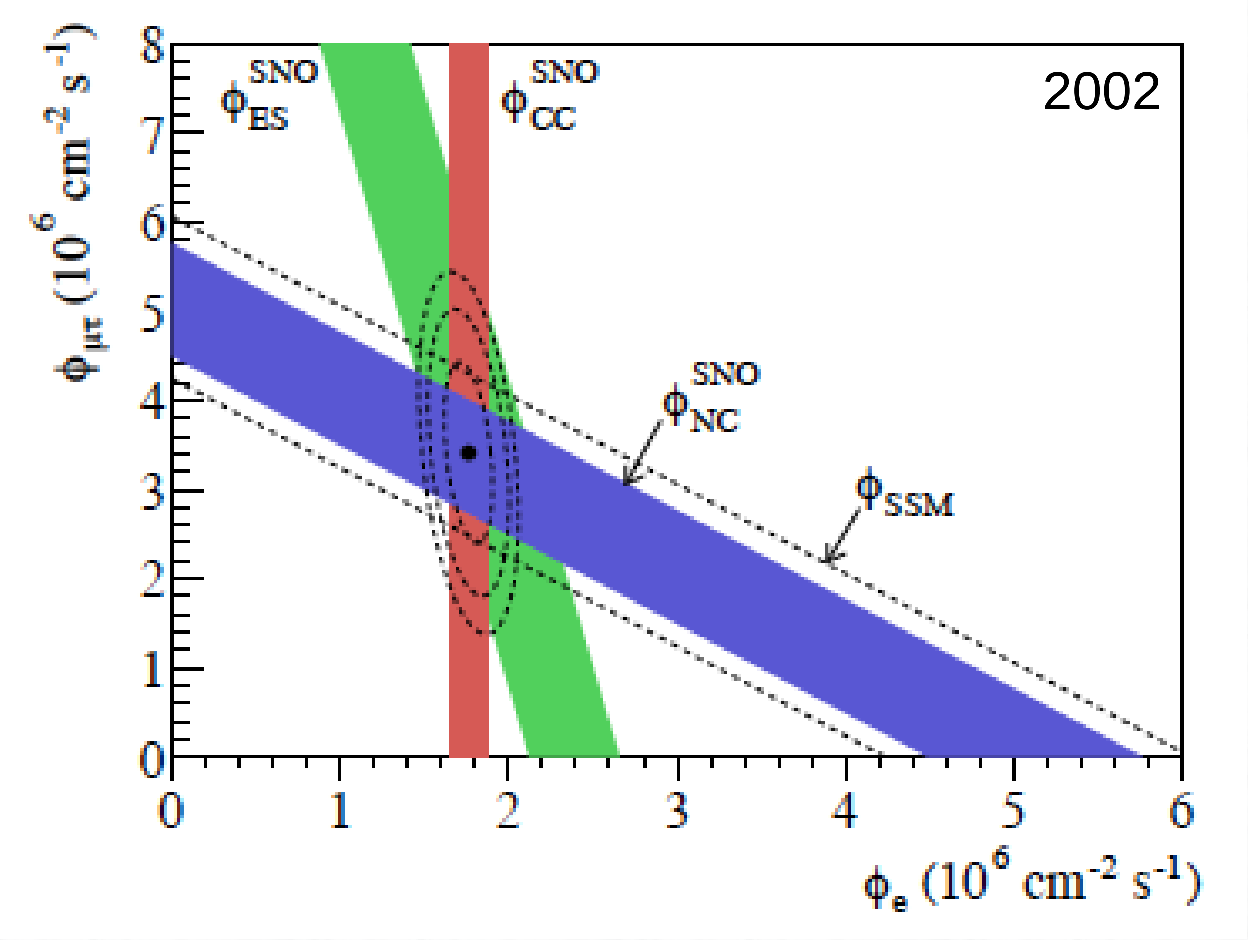
$$\Phi_{SSM}(\nu) = 5.05\,^{+1.01}_{-0.81} \times 10^6\ \mathrm{cm^{-2}s^{-1}}$$

stat. and syst. errors combined

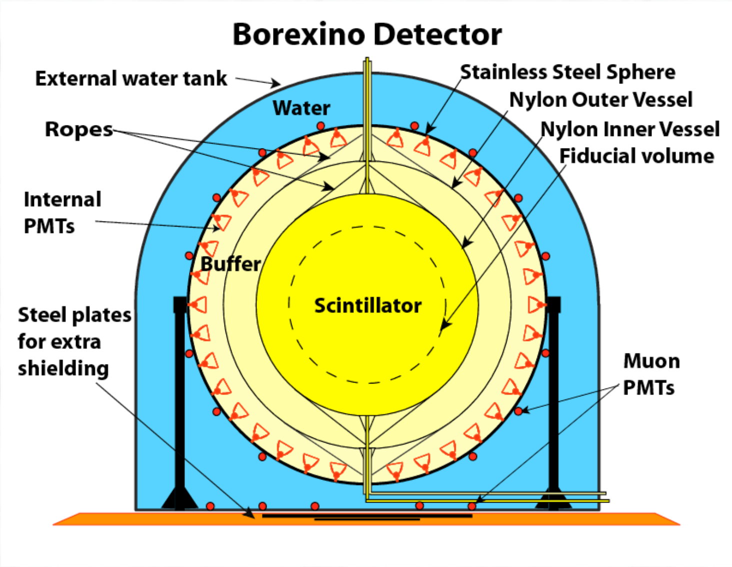
$$\Phi_{NC}(\nu) - \Phi_{CC}(\nu_e) = \Phi(\nu_{\mu\tau}) = 3.33 \pm 0.64 \times 10^6\ \mathrm{cm^{-2}\,s^{-1}}$$

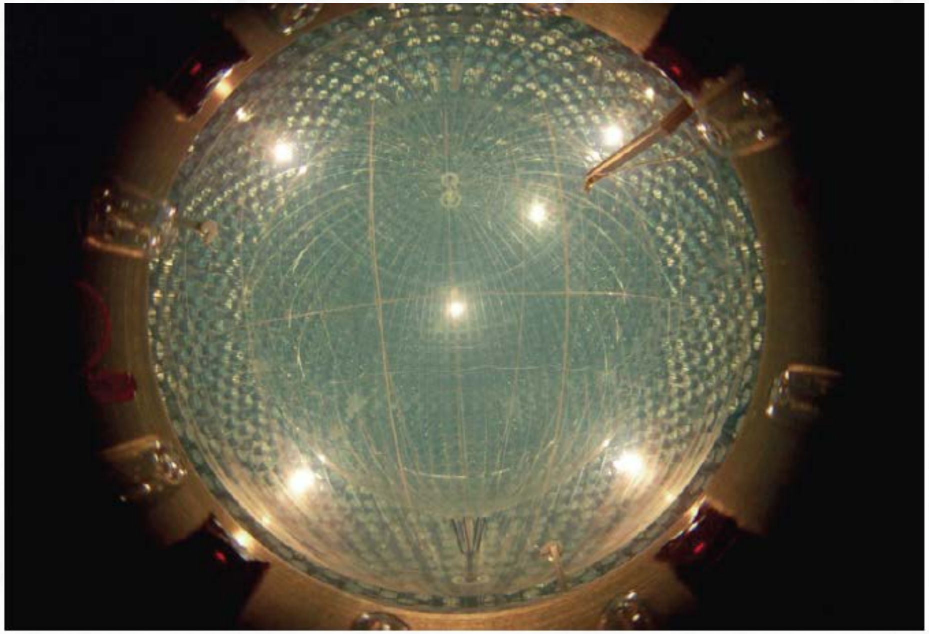
- 5.2 standard deviations from zero
- Evidence that solar neutrino flux on Earth contains sizeable ν_μ or ν_τ component (in any combination)
- Total expected number of neutrinos observed, strong evidence for neutrino oscillations !

Zusammenfassung der Ergebnisse, Konsistenz mit dem Standard-Sonnenmodell



The Borexino Experiment



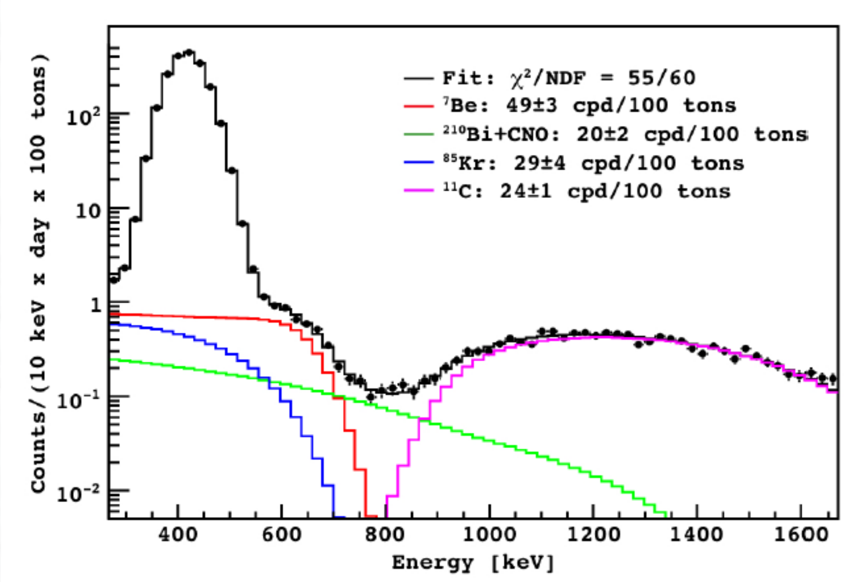


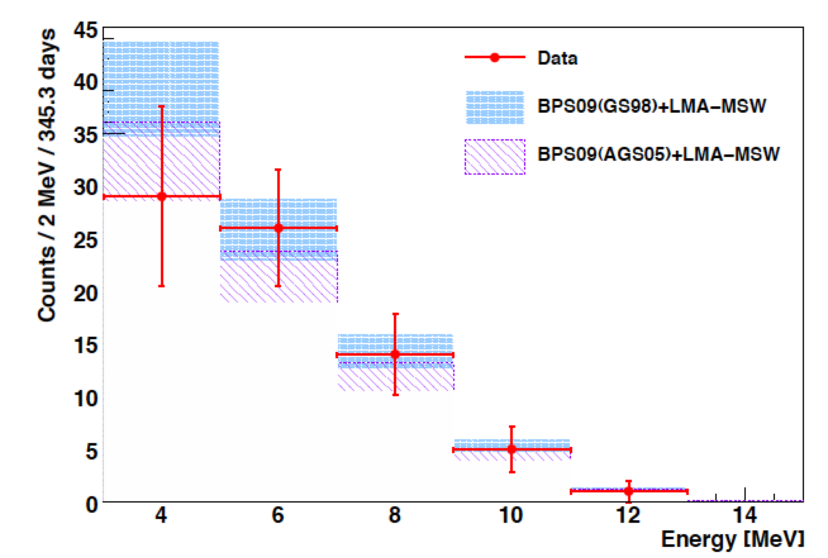
300 kton liquid scintillator
ν-e scattering

- Real-time measurements of sub-MeV flux and spectrum of solar neutrinos
  - Sensitive to: monochromatic ^7Be ν (0.86 MeV) and ^8B, CNO and pp neutrinos

- Energy threshold: 200 keV
- Excellent energy resolution (liquid scintillator): (5% at 1 MeV)
- Very low background level (~120 counts per day per 100 tons)

Results from the Borexino experiment:





Measured energy spectrum
(after 192 days of data-taking)
(Phys. Rev. Lett. 101, 091302 (2008)

- extract Be-component from fit to data, after background subtraction

Measured energy spectrum of ^{8}B neutrinos (3 MeV threshold)
(after background subtraction)
(Phys. Rev. D 82, 033006 (2010)
Data are compared to model calculations assuming oscillations

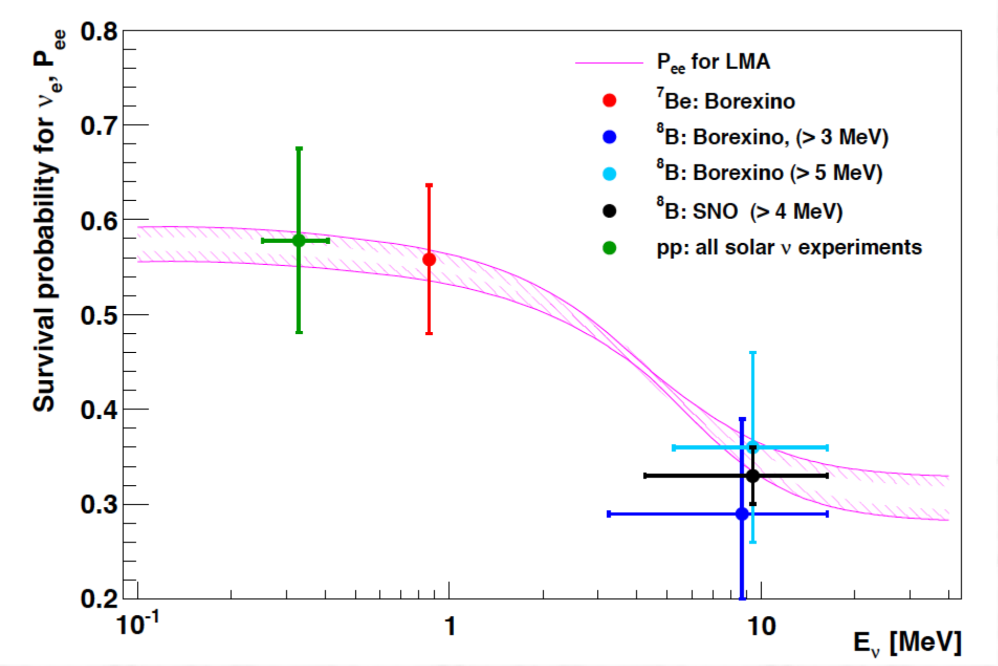
Both measurements show disappearance of electron neutrinos:
Survival probabilities: P_{ee} (^{7}Be) = 0.56 ± 0.10
P_{ee} (^{8}B) = 0.29 ± 0.10

Global picture from solar neutrino measurements

- Electron neutrinos disappear on their way from the centre of the sun to the earth (all experiments)

- The total neutrino flux is consistent with expectations (SNO experiment) (ν_e must oscillate into ν_μ or ν_τ)

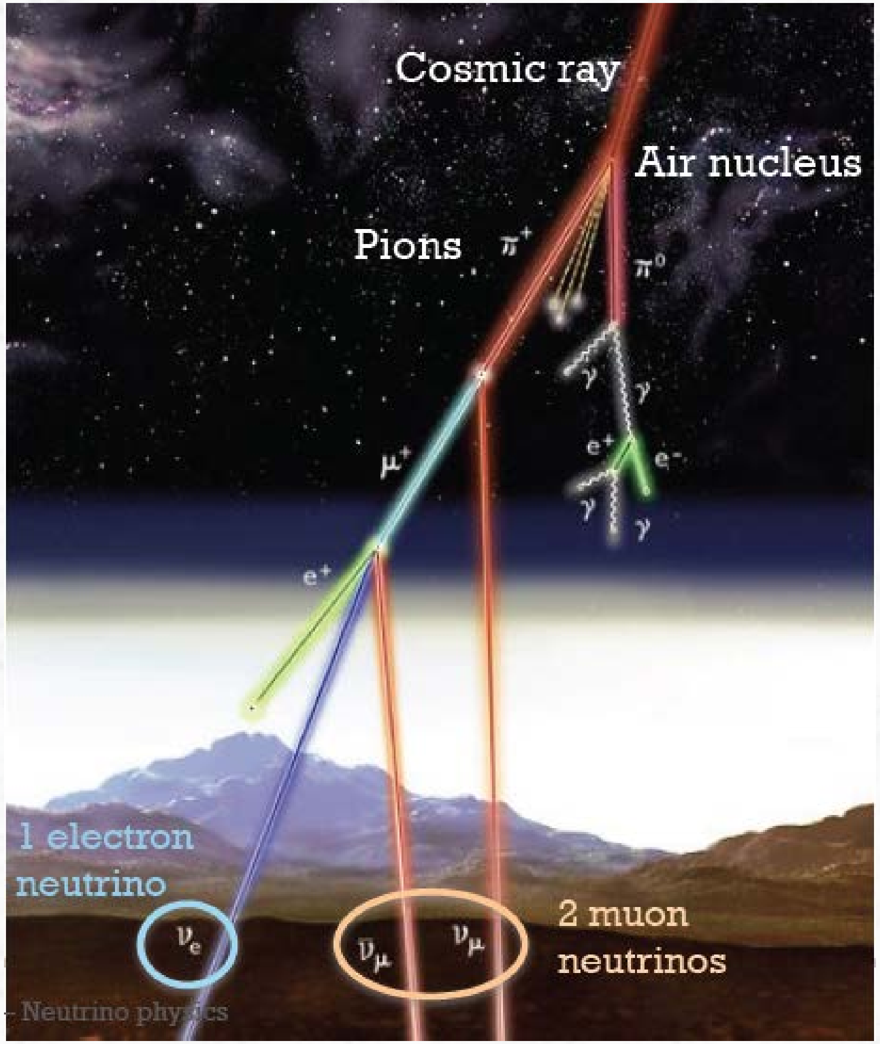
- The survival probability depends on the energy of the neutrinos (Borexino experiment)

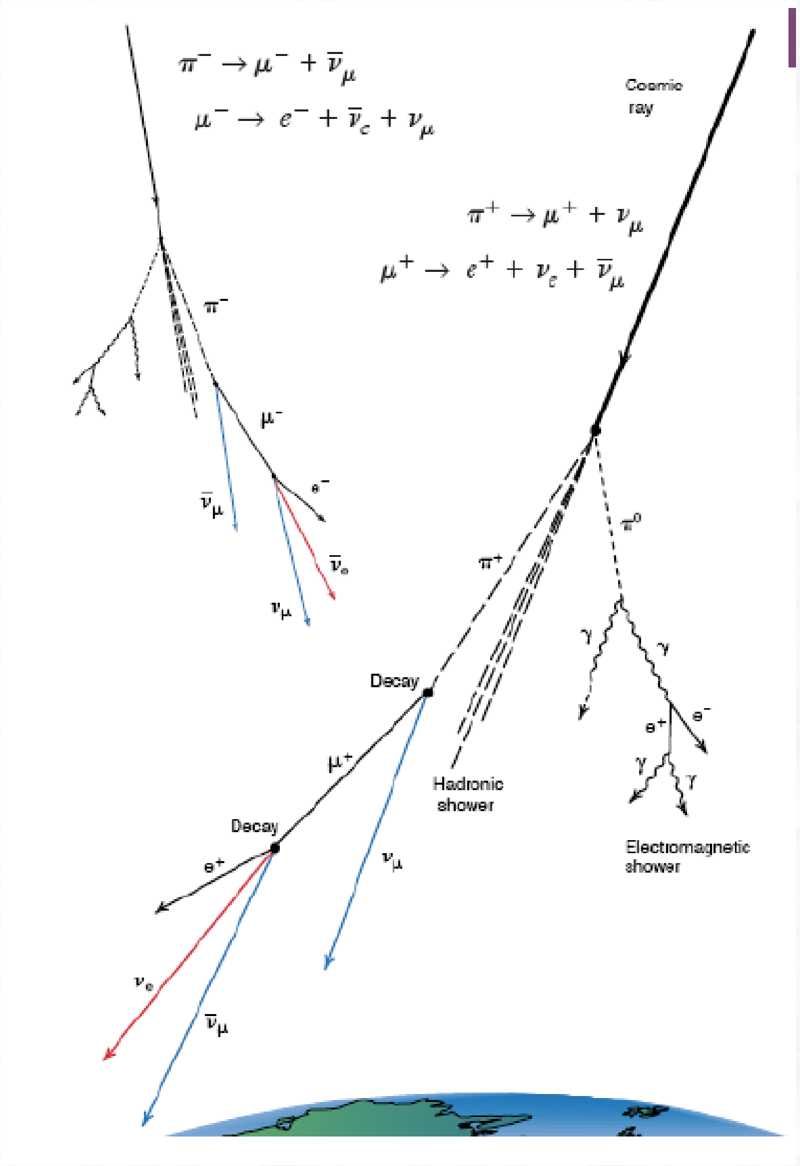


All data can be explained, if ν oscillations with $\Delta m^2 \sim 7\ 10^{-5}\ eV^2$ and $\theta \sim \pi/6$ are assumed

(to explain these data, matter effects on neutrino oscillations in the sun must be taken into account)
Mikheyev, Smirnov, Wolfenstein (MSW) effect

3.3.2 Atmosphärische Neutrinos





“Atmospheric” Neutrinos

The main sources of atmospheric neutrinos:

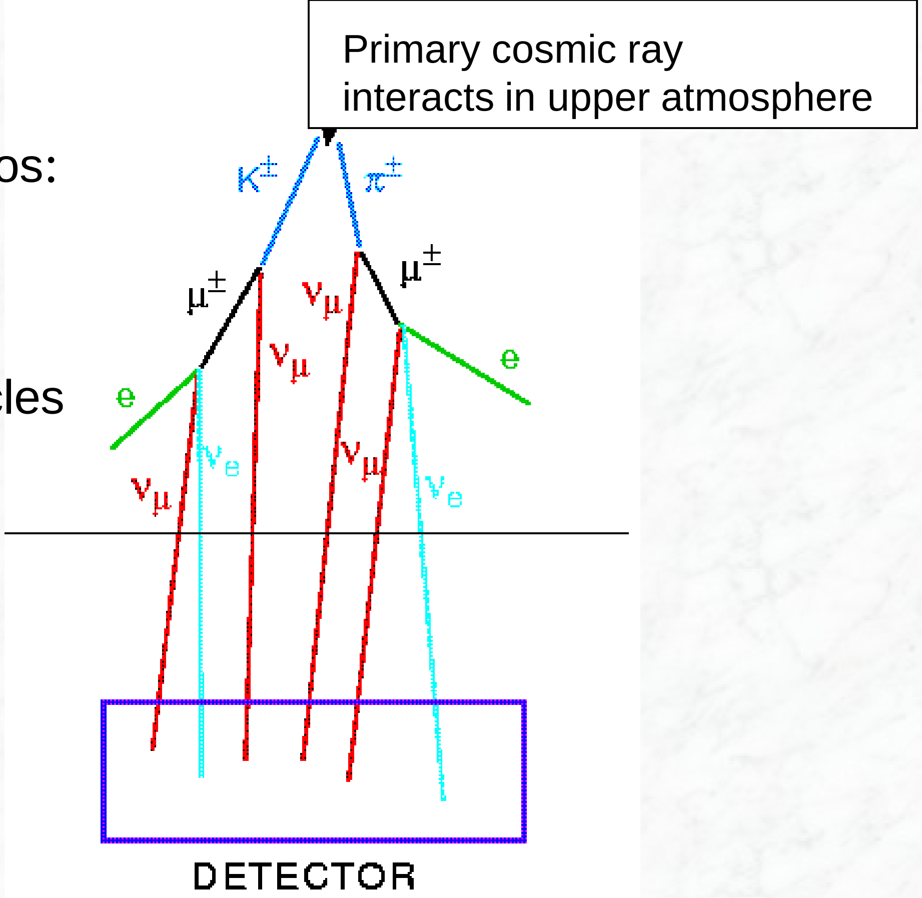
$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\quad\quad\quad\quad \hookrightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

At energies E < 2 GeV most parent particles decay before reaching the Earth

$$\frac{\nu_{\mu} + \bar{\nu}_{\mu}}{\nu_{e} + \bar{\nu}_{e}} \approx 2$$

At higher energies, most muons reach the Earth before decaying:

$$\frac{\nu_{\mu} + \bar{\nu}_{\mu}}{\nu_{e} + \bar{\nu}_{e}} > 2$$ (increasing with E)



Energy range of atmospheric neutrinos: 0.1 — 100 GeV

Very low event rate: ~100 /year for a detector mass of 1000 tons

Uncertainties on calculations of atmospheric neutrino fluxes: typically ± 30%
(from composition of primary spectrum, secondary hadron distributions, etc.)

Uncertainty on the ν_{μ}/ν_{e} ratio: only ±5% (because of partial cancellations)

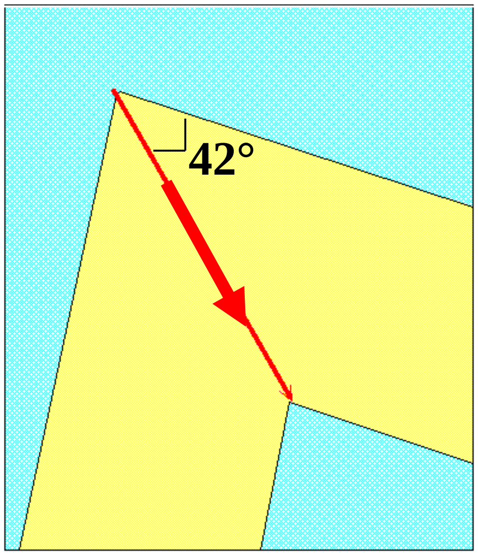
Detection of atmospheric neutrinos

ν_μ + Nucleon $\rightarrow$ μ + hadrons: presence of a long, minimum ionizing track (the μ)

$\nu_e + n \rightarrow e^- + p, \quad \bar{\nu}_e + p \rightarrow e^+ + n$: presence of an electromagnetic shower

$\longrightarrow$

Particle identification in a water Cherenkov counter



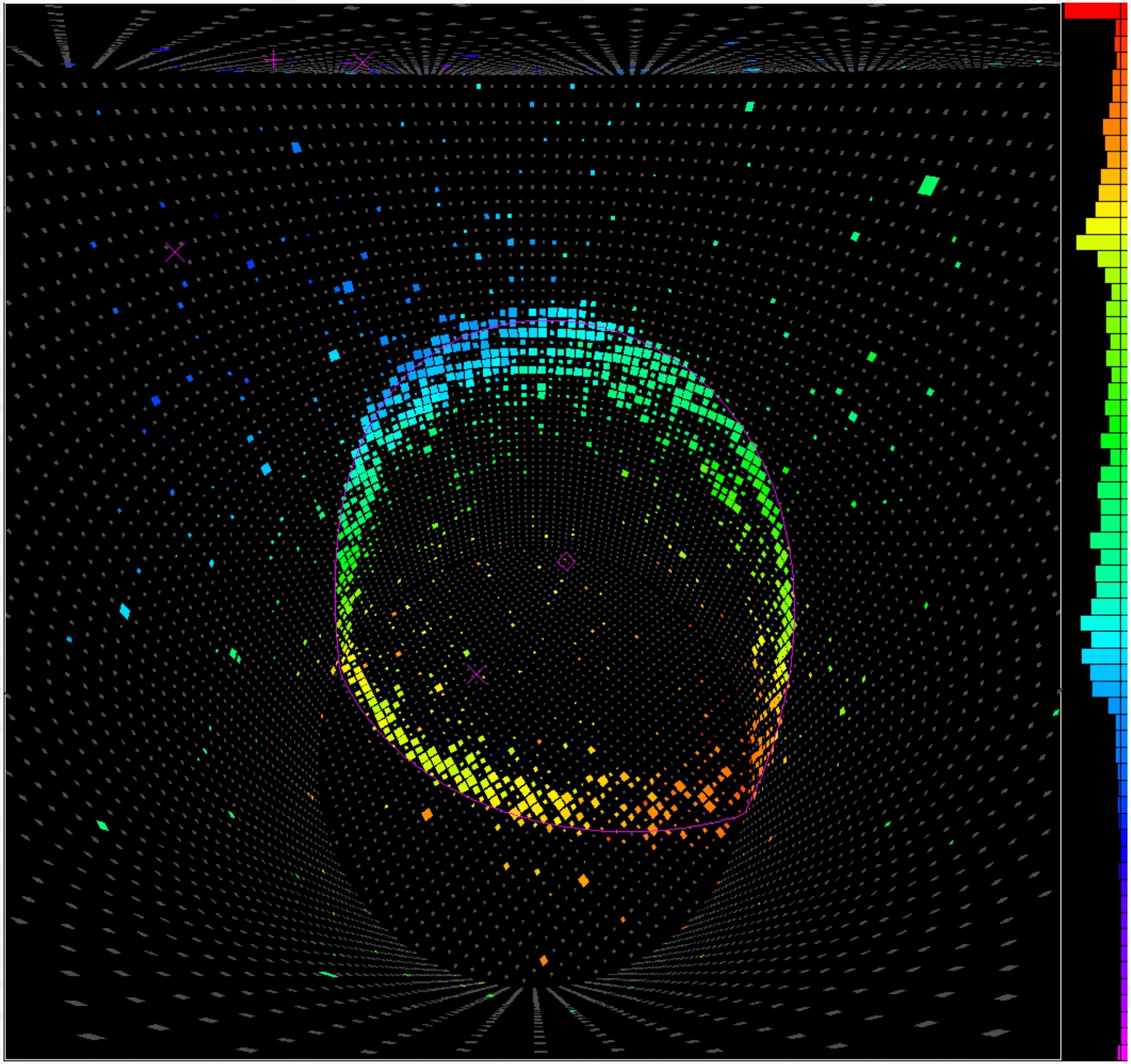
muon track:

- dE/dx consistent with minimum ionization
- sharp edges of Cherenkov light ring

electron shower:

- high dE/dx
- “fuzzy” edges of Cherenkov light ring (from shower angular spread)

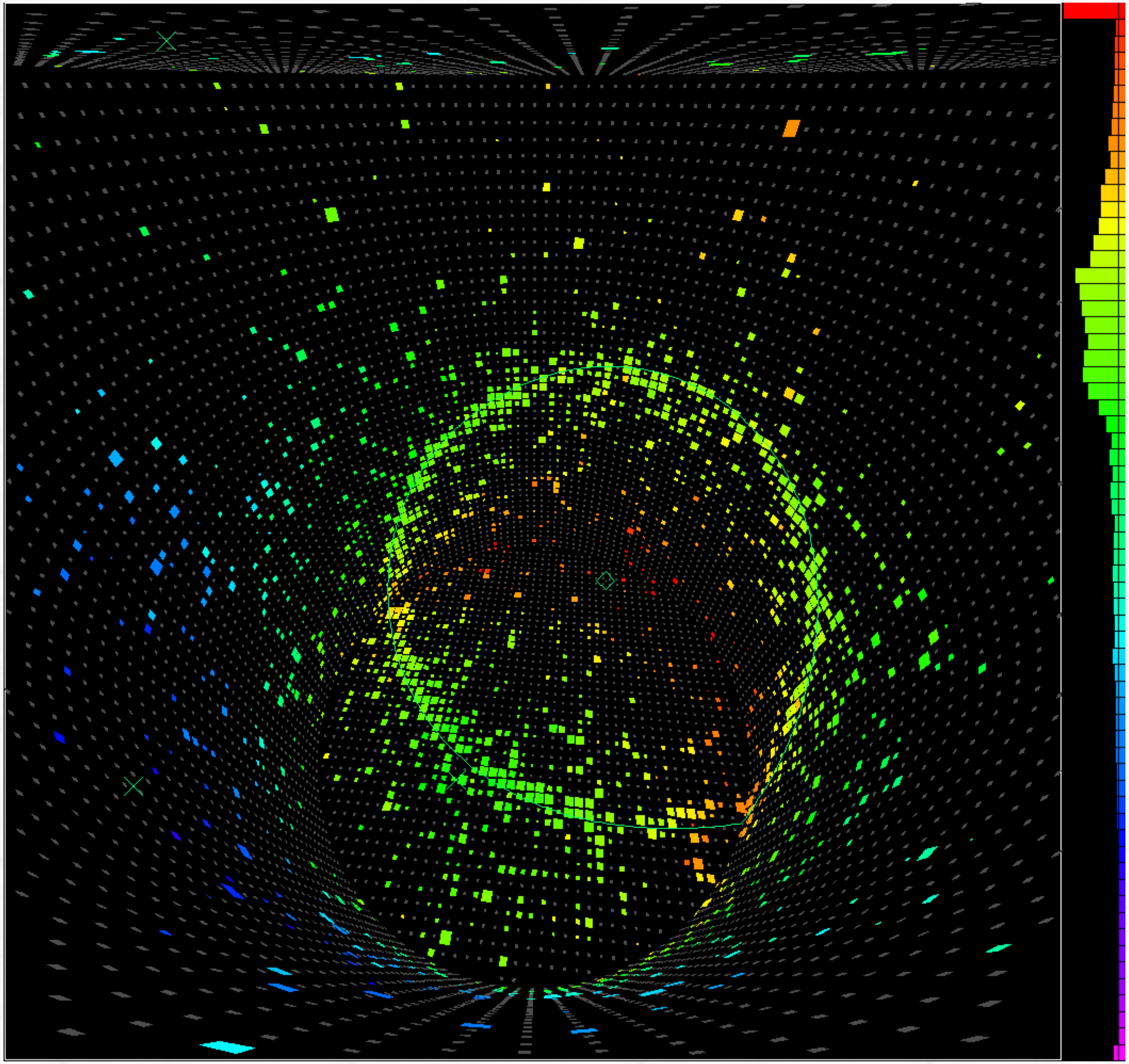
Measure e/μ separation by exposing a 1000 ton water Cherenkov counter (a small Super-K detector) to electron and muon beams from accelerators. Probability of wrong identification ~2%



603 MeV

atmospheric muon ν

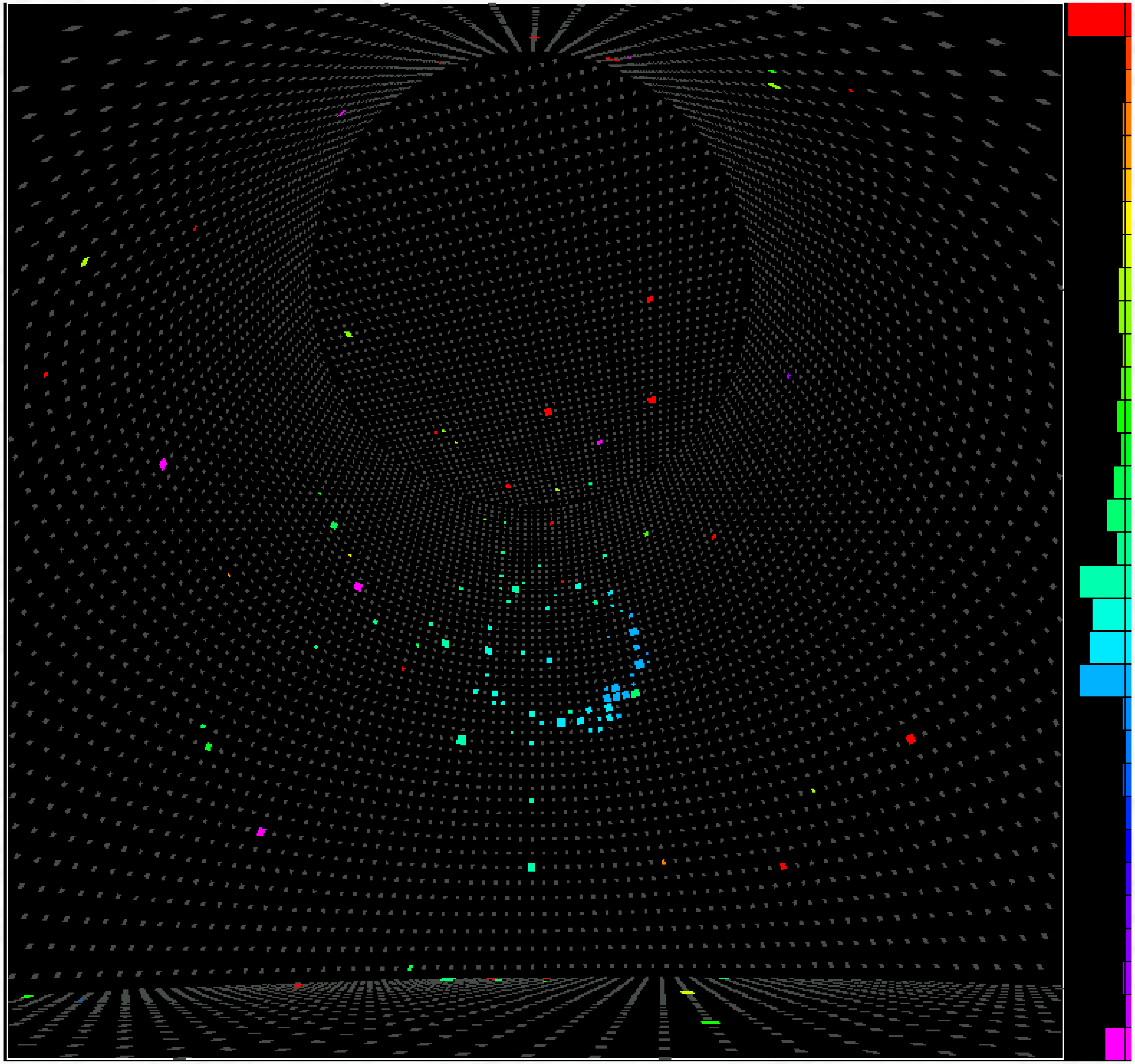
Note sharp edge of ring from the muon produced by ν_{μ}-nucleon interaction



492 MeV atmospheric electron ν

Note diffuse edge of ring from electron produced by ν_e-nucleon interaction

Zum Vergleich:



12 MeV
solar ν

Result of ν-e elastic scattering: points back in solar direction

Measurements of the ν_μ/ν_e ratio:

First hints for a new phenomenon

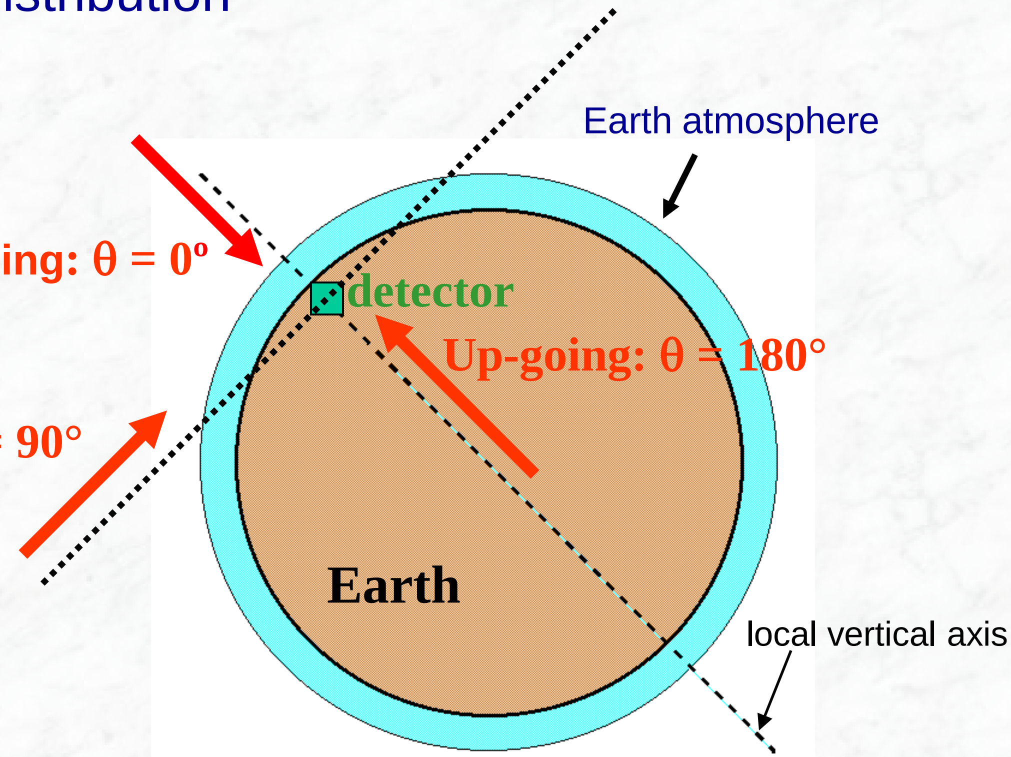
- Water Cherenkov counters: Kamiokande (1988), IMB (1991), Super-K (1998)

- Conventional calorimeter (iron plates + proportional tubes): Soudan2 (1997)

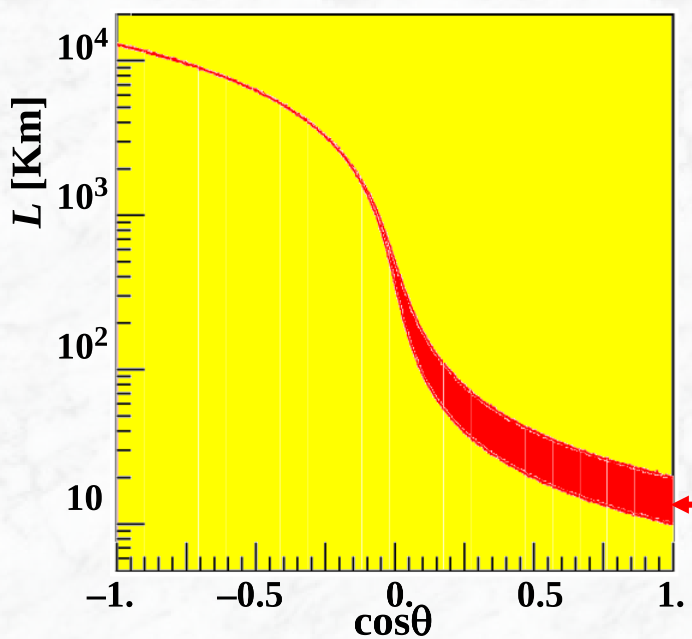
$$\mathbf{R} = \frac{(\nu_\mu/\nu_e)_{\text{measured}}}{(\nu_\mu/\nu_e)_{\text{predicted}}} = \mathbf{0.65 \pm 0.08}$$

Measurement of zenith angle distribution

Definition of zenith angle θ:
Polar axis along the local vertical axis, directed downwards

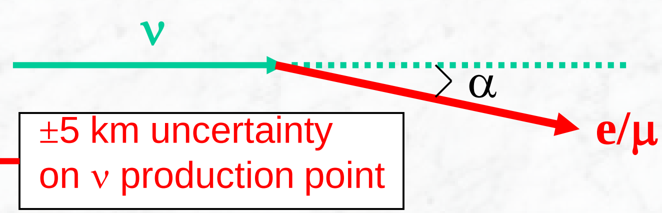


Baseline *L* (distance between neutrino production point and detector) depends on zenith angle



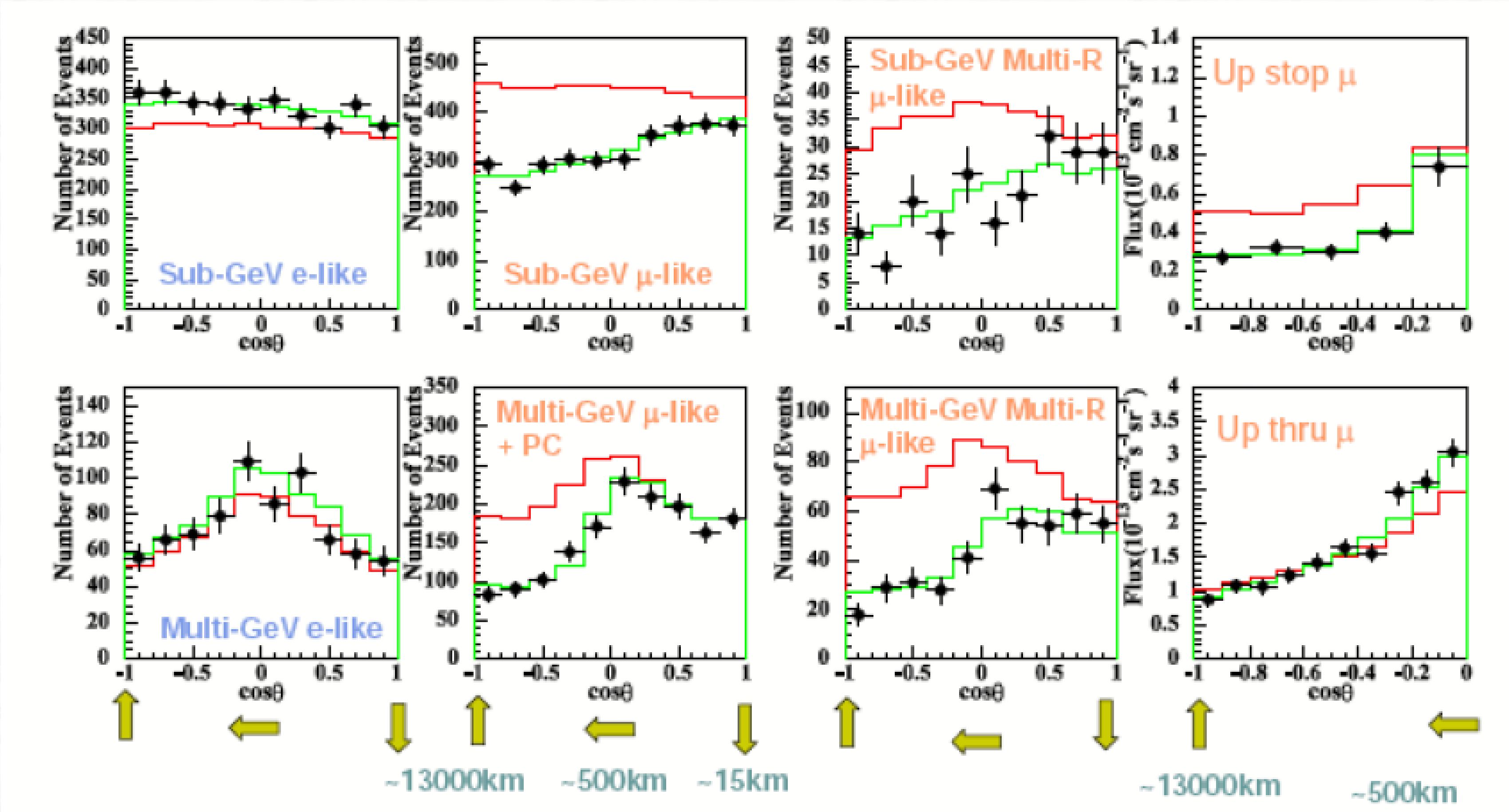
L varies between ~10 and ~12800 km as θ varies between 0º and 180º ➡ search for oscillations with variable baseline

Strong angular correlation between incident neutrino and outgoing electron/muon for *E* > 1 GeV:



α ≈ 25° for *E* = 1 GeV;
α → 0 as *E* increases

Super-K zenith angle distributions



No oscillation (χ^2 = 456.5 / 172 degrees of freedom)

$\nu_\mu - \nu_\tau$ oscillation best fit: $\Delta m^2 = 2.5 \cdot 10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$

χ^2 = 163.2 / 170 degrees of freedom

3.3.3 Reactor experiments

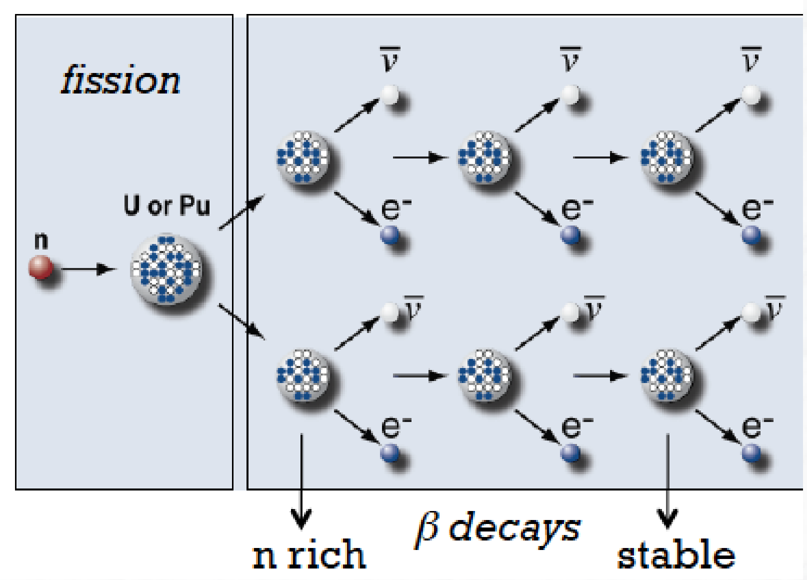
Or: "Can these results be confirmed with man-made neutrinos
- under better controlled conditions-?"

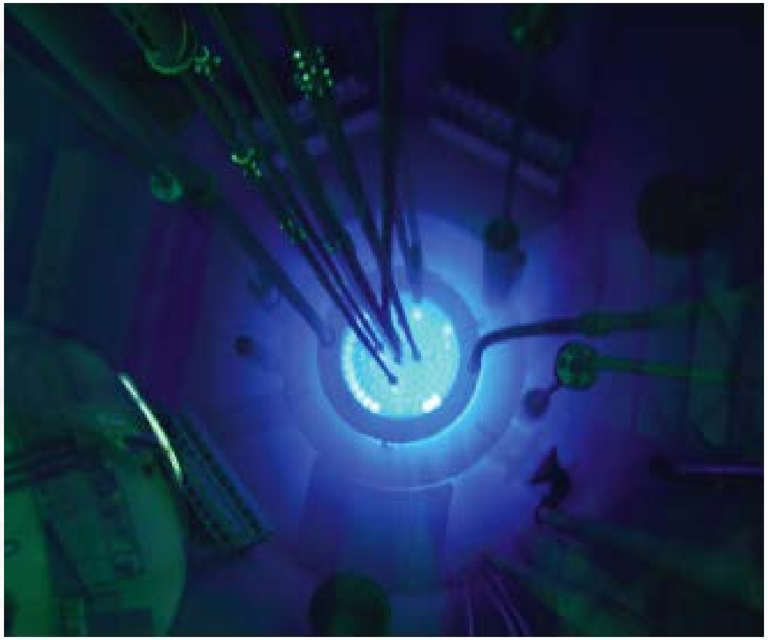
- Can we convincingly verify oscillation with man-made neutrinos?
- Hard for low Δm^2

  Need long distance, large detector mass; L~100 km, 1kt
- Need low E_ν, high Φ_ν

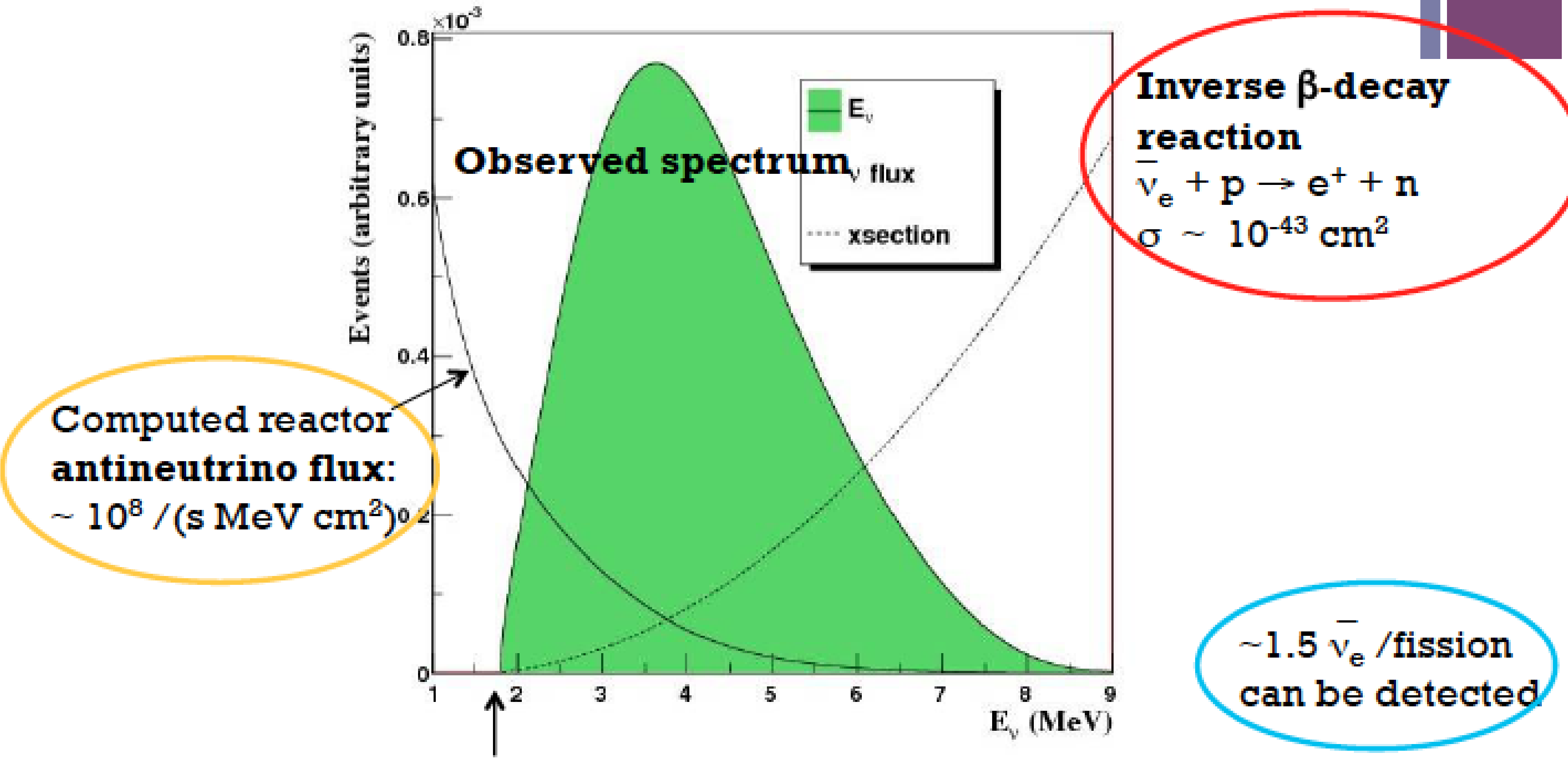
- Nuclear reactors are very intense, pure and isotropic sources of anti-electron neutrinos from the neutron-rich fission products

  ~2 10^{20} ν_e s^{-1} GW_{th}^{-1}



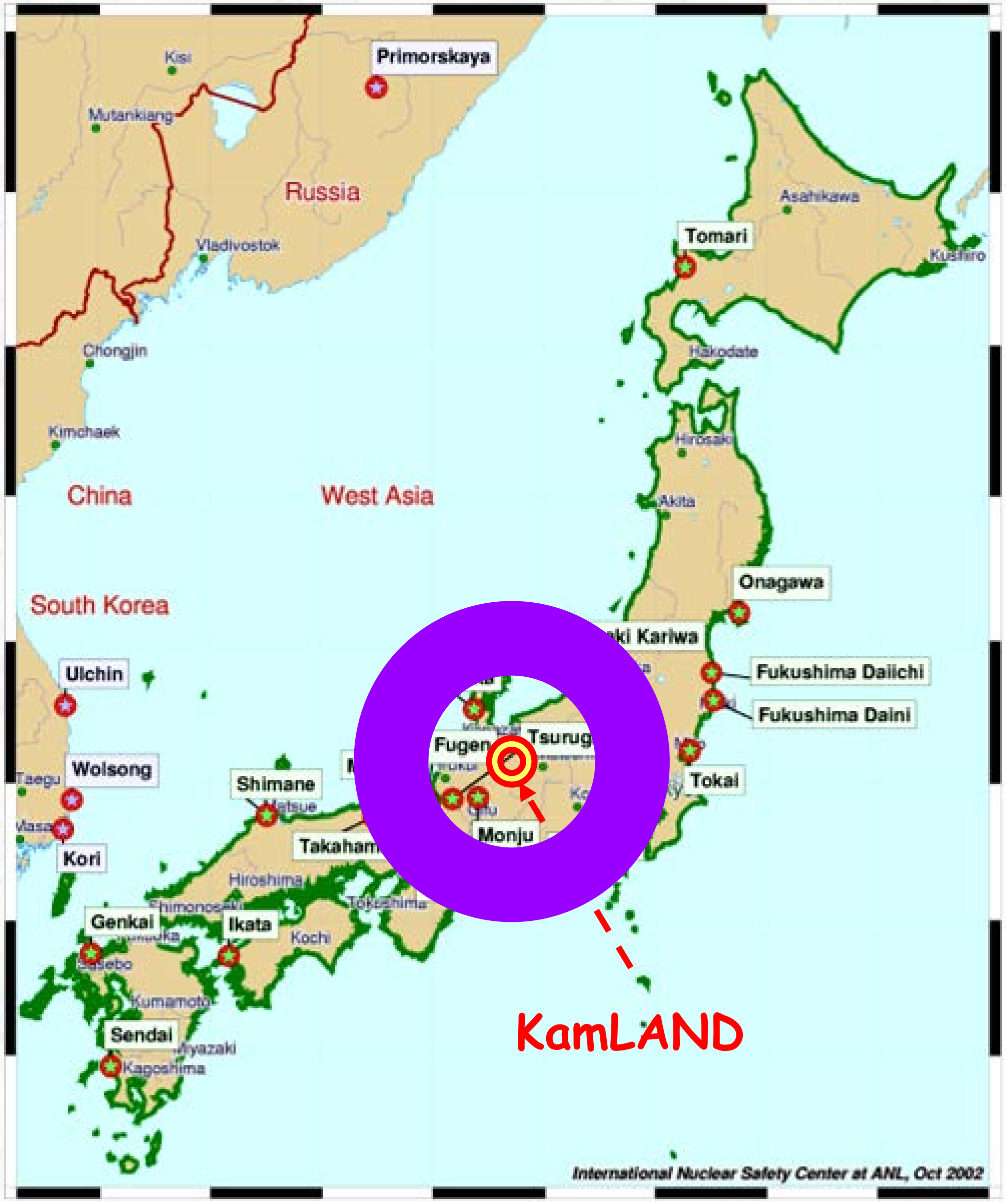


- Anti-electron neutrinos (link via CPT to electron neutrinos)

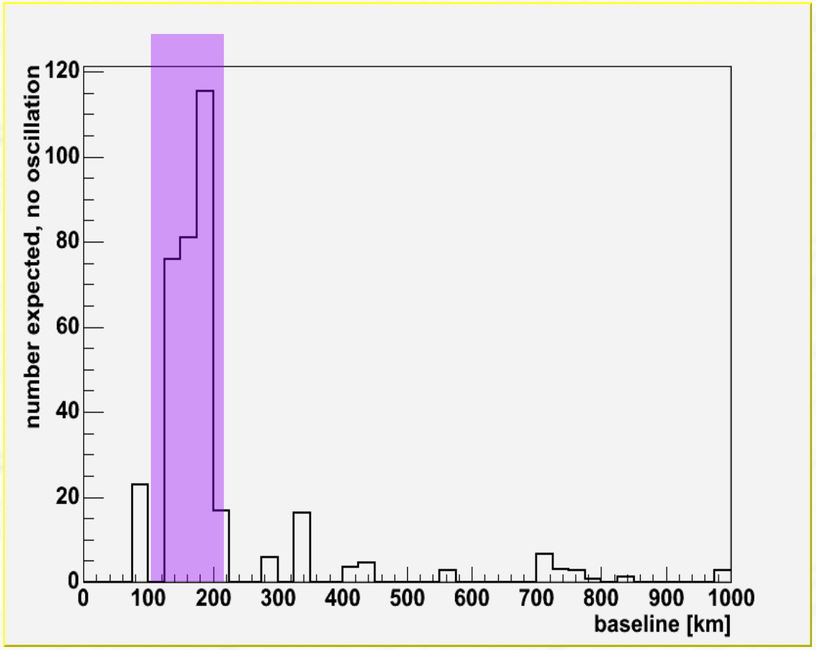


Neutrinos with E < 1.8 MeV are not detected

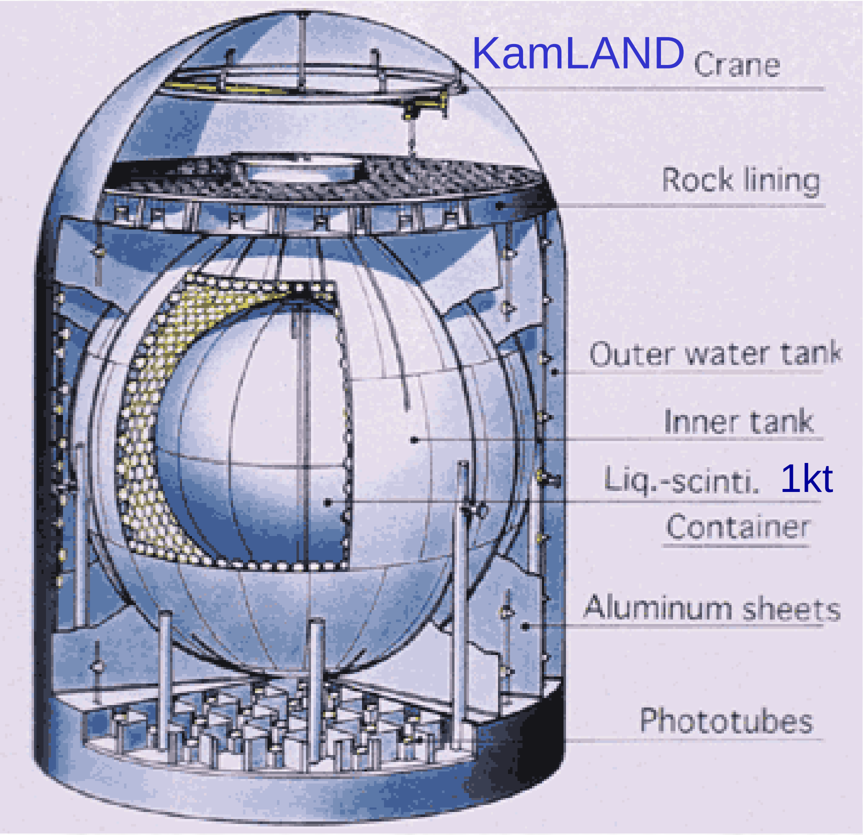
Locations of the nuclear power stations



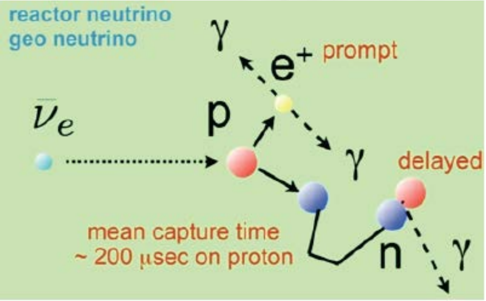
80 % of the expected $\bar{\nu}_e$ from distances of 140-210 km



KamLAND detector



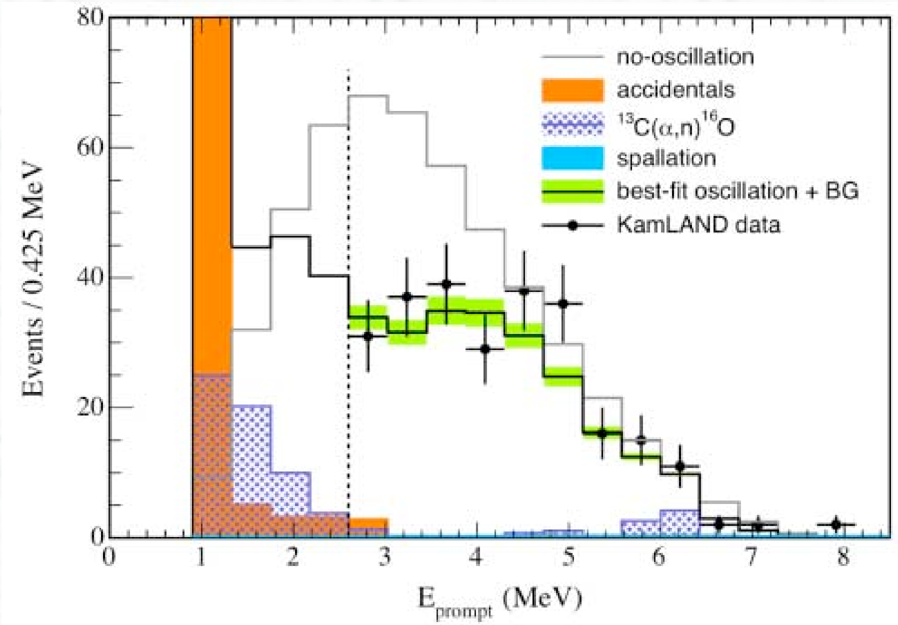
- Goal: Look for disappearance of ν_e (sensitivity to solar oscillations)
- First long-baseline reactor neutrino experiment (L = 180 km)
- Large detector (1kton liquid scintillator)
- Deep underground (2.700 m w.e.)
- Started in 2002

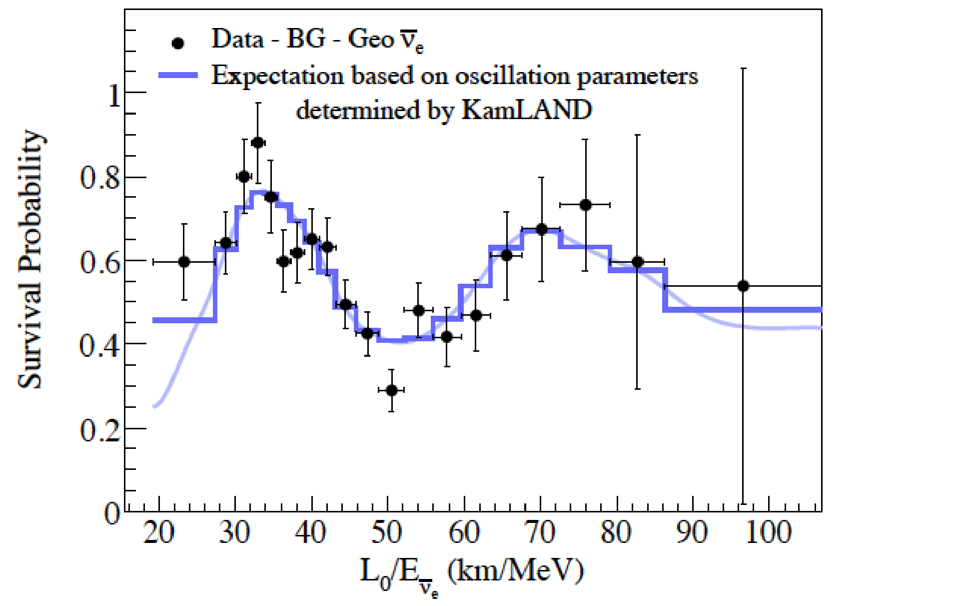


well established detection principle

Results from the KamLand experiment:

2002 - 2005

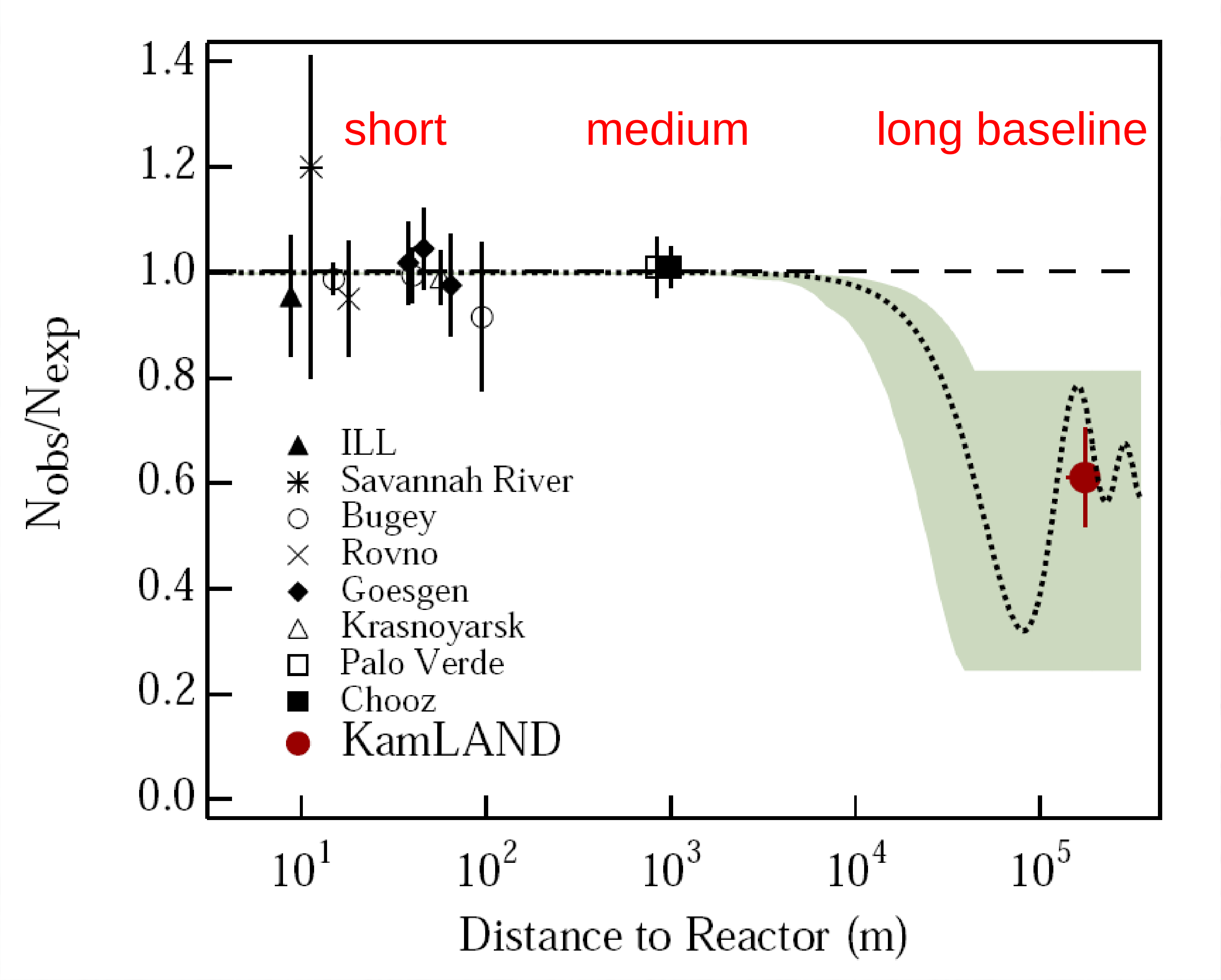


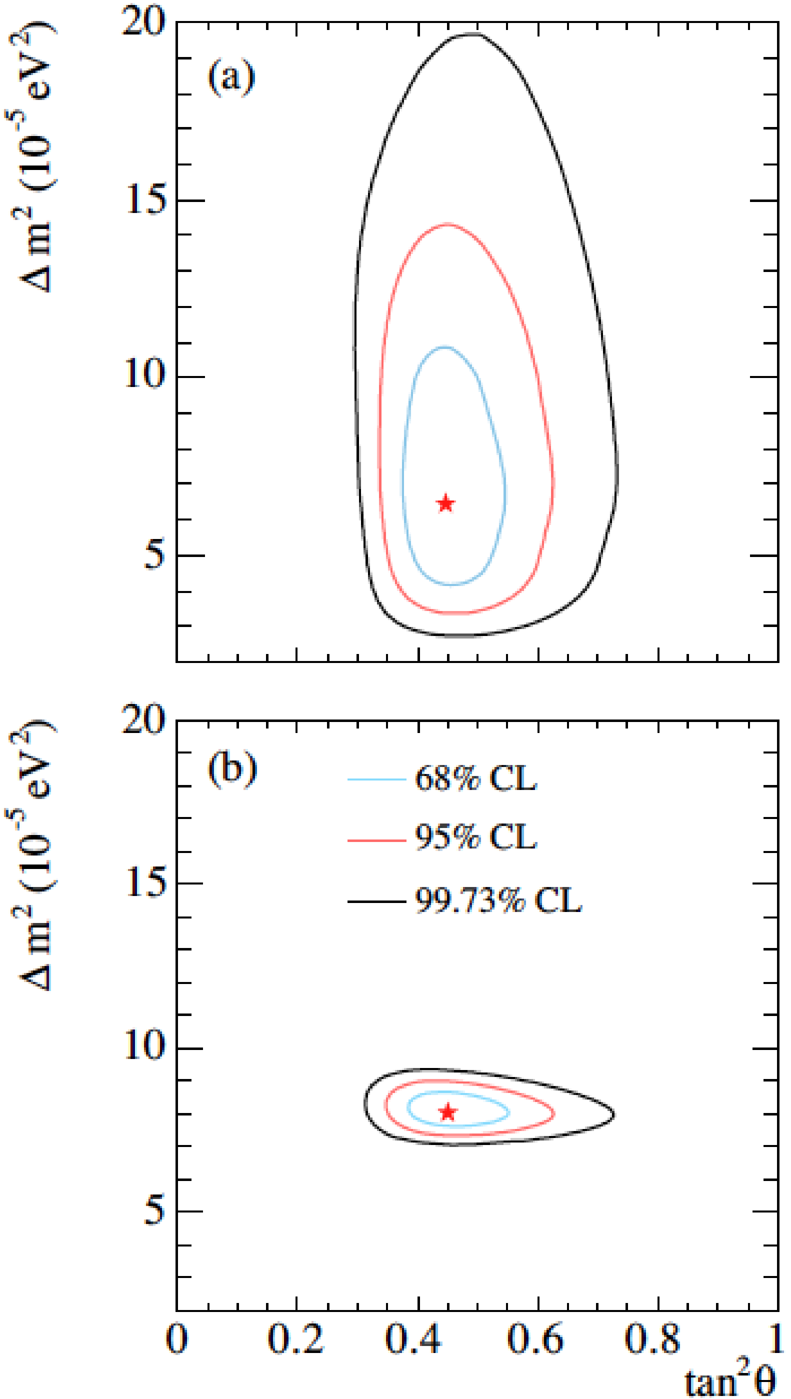


258 $\bar{\nu}_e$ events for $\bar{\nu}_e$ > 3.4 MeV
365.2 ± 23.7 (syst.) evts expected (no-osc)
17.8 ± 7.3 background events
Exposure = 766 ton · yr

- Clear evidence for disappearance of anti-electron neutrinos
- L/E oscillation, as expected, almost two oscillation cycles observed
- Oscillation parameters Δm and $\sin^2(2\theta)$ in agreement with those from solar neutrino observations

Summary of results from past reactor experiments





Solare Experimente

Man beachte: Materieeffekte in der Sonne beeinflussen die Neutrinooszillationen;

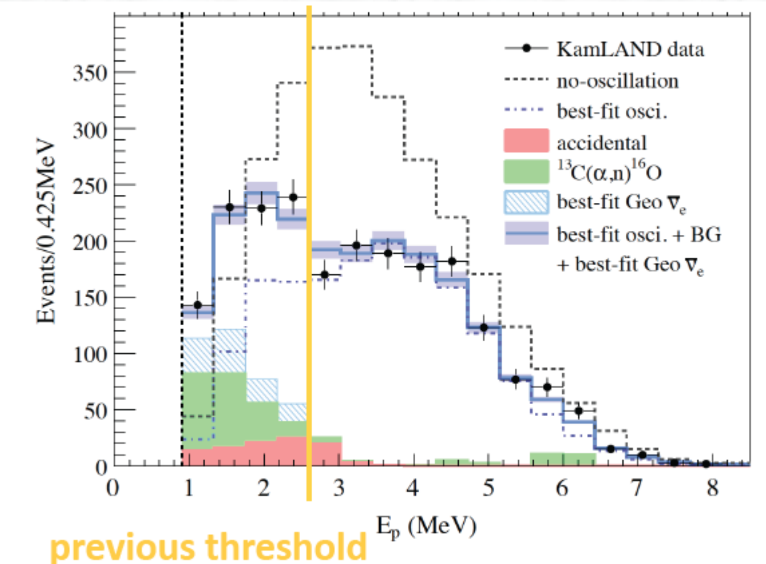
Effekt ist hier berücksichtigt (MSW-Effekt, Mikheyev-Smirnov-Wolfenstein)

Solare Experimente + KamLand (2004)

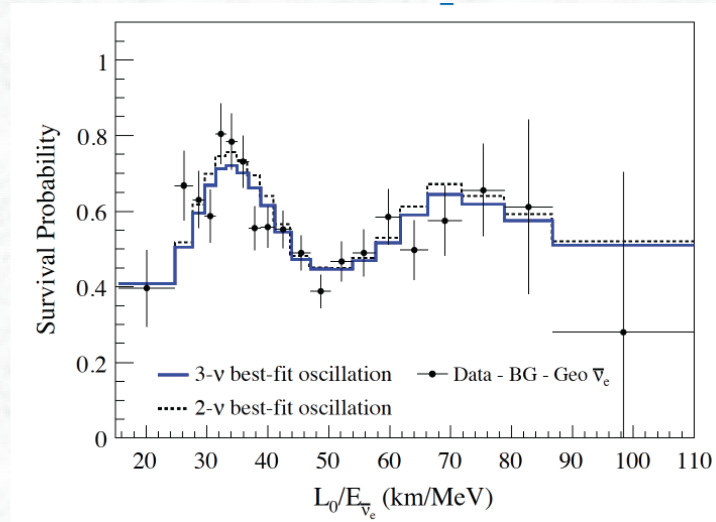
Solare Oszillationsparameter:

$\Delta m^2 = (7.59 \pm 0.21) \times 10^{-5}\ eV^2$
$\tan^2\theta = 0.47 \pm 0.06$

Updated results from KamLand (2010)



Energy threshold lowered to 0.9 MeV



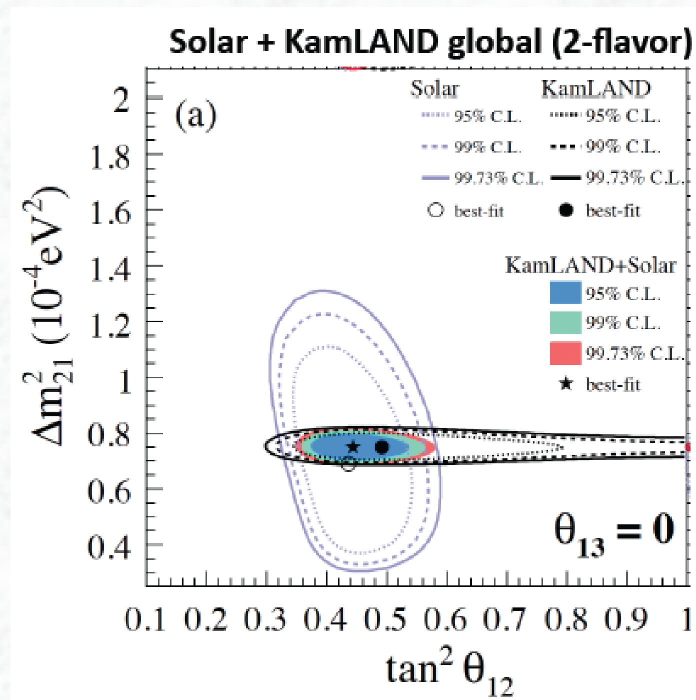
Best fit value

(solar + KamLAND, 3-flavor)

$$\Delta m^2_{12} = 7.50^{+0.19}_{-0.20} \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$$

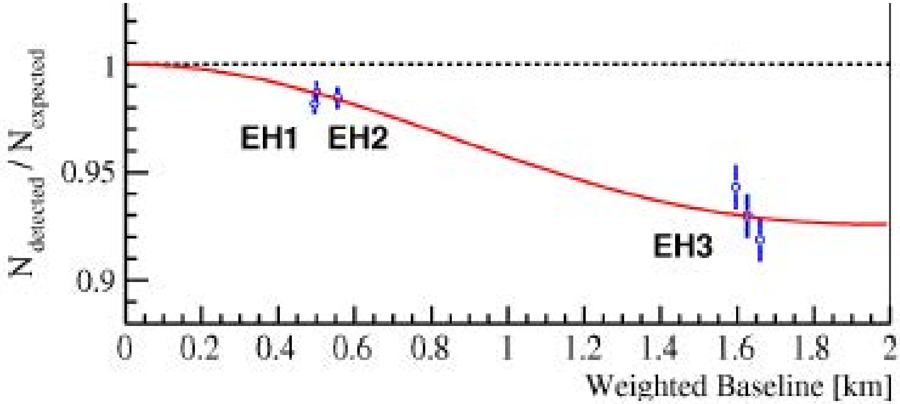


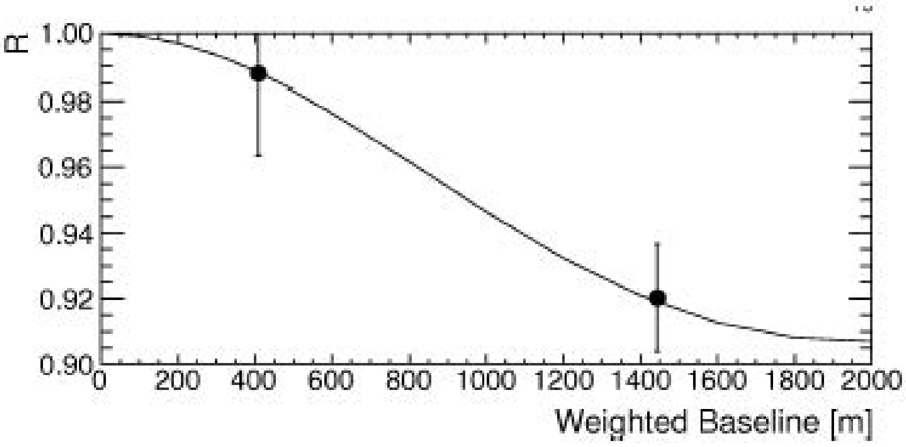
$\bar{\nu}_e$ disappearance with medium baseline

-Daya Bay (China) and RENO reactor experiments (USA)-

Daya-Bay

Reno



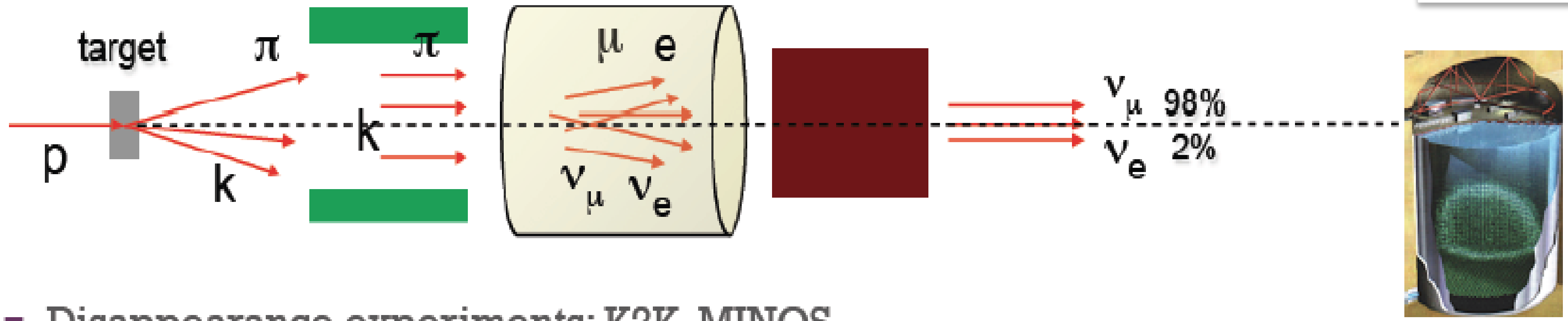


3.3.4 Neutrinos from accelerators

Goals:
- Confirmation of atmospheric oscillation parameters
- Flavour appearance

- *K2K* in Japan
- T2K in Japan
- MINOS / USA (Fermilab)
- Gran Sasso / Italy (CERN)

- Conventional neutrino beam:



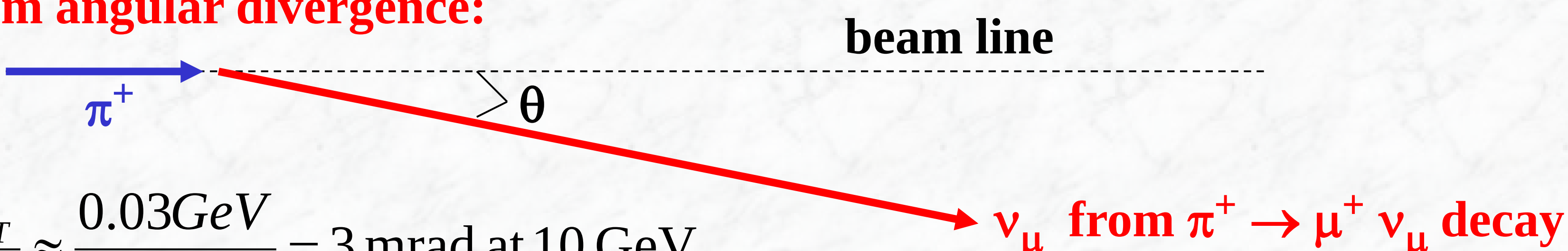
- Disappearance experiments: K2K, MINOS
  - NOT enough energy to produce lepton in CC reaction
- Appearance experiments: MiniBooNE, OPERA
  - Enough energy to produce lepton in CC reaction
- Detector techniques:
  - Near/far detectors in disappearance exp.
  - Emulsions, liquids
  - Magnetized detectors

Long baseline accelerator experiments
(in progress or in preparation)

Project	Baseline L	$\langle E_\nu \rangle$	Status
K2K (KEK to KAMIOKA)	250 km	1.3 GeV	Data taking: 1999 - 2004
MINOS (Fermilab to Soudan)	735 km	few GeV	Data taking since 2005
CERN to Gran Sasso	732 km	17 GeV	Data taking since 2007

- Threshold energy for $\nu_\tau + N \rightarrow \tau^- + X$: $E_\nu > 3.5$ GeV
- Typical event rate ~1 $\nu_\mu \rightarrow \mu^-$ event / year per ton of detector mass

  ⟶ need detectors with masses of several kilotons
- ν_μ beam angular divergence:



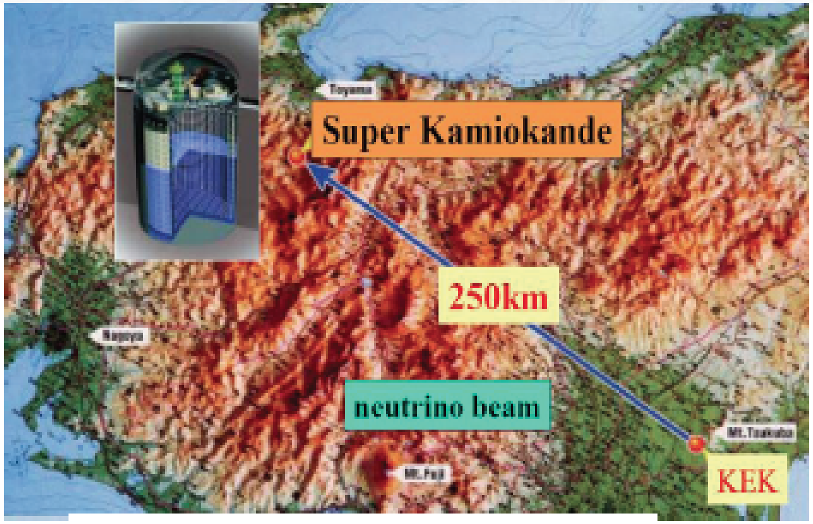
$$\theta \approx \frac{p_T}{p_L} \approx \frac{0.03 GeV}{E_\nu [GeV]} = 3\,\mathrm{mrad\ at\ 10\ GeV}$$

Beam transverse size: 100 m – 1 km at L > 100 km

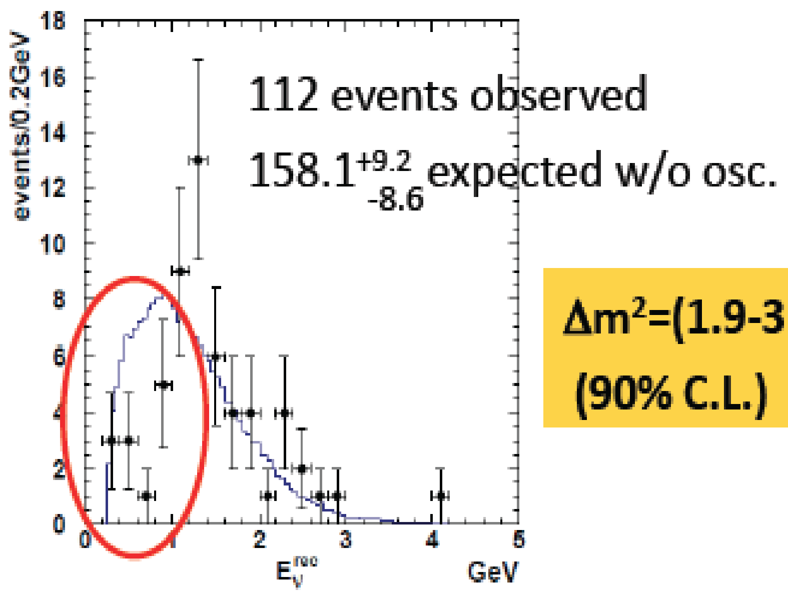
⟶ **no problems to hit the far detector**

but neutrino flux decreases as L^{-2} at large L

K2K experiment



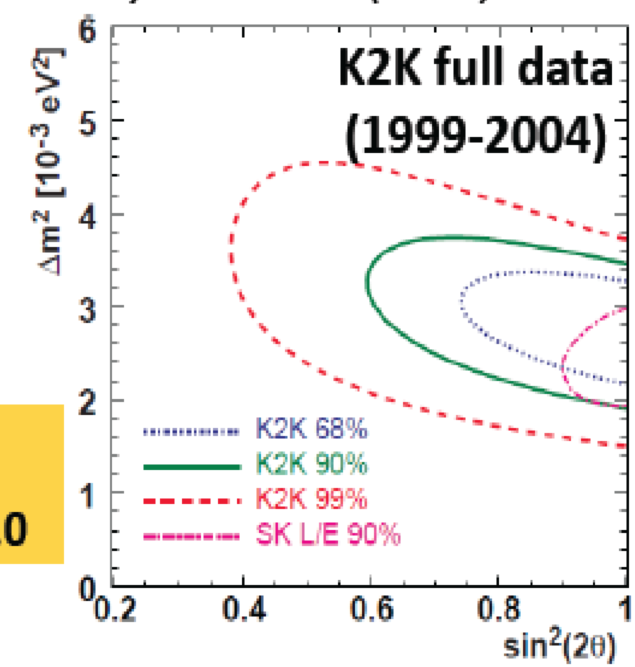
- First experiment with a neutrino beam at long distance (250 km); $E_\nu = 1.3$ GeV, ν_μ beam ~ 98%
- Look for ν_μ disappearance
- Comparison between near and far detectors



$\Delta m^2=(1.9\text{-}3.5)\times10^{-3}$ eV^2

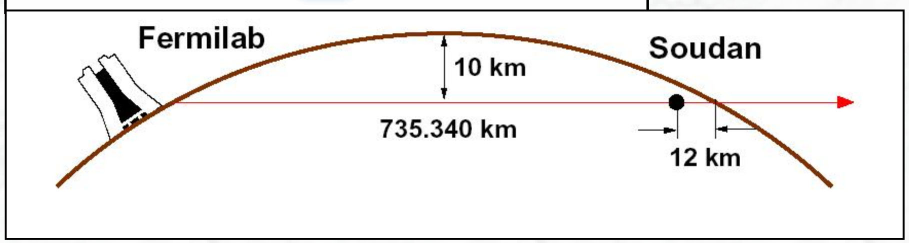
(90% C.L.) @ $\sin^2 2\theta=1.0$

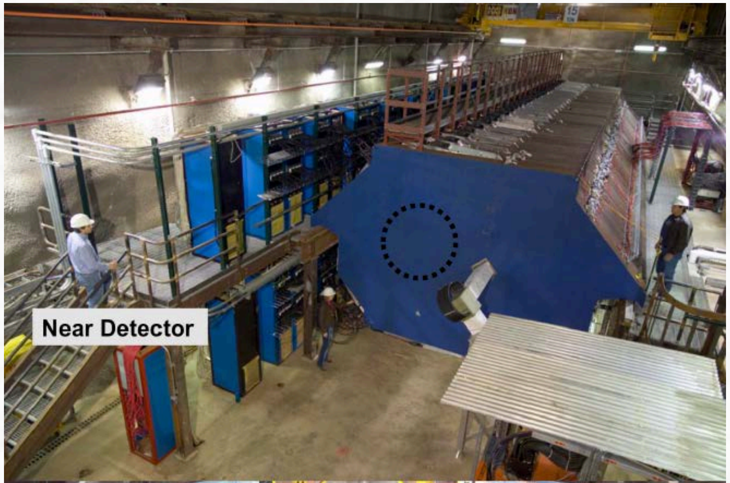
Phys. Rev. D74 (2006) 072003

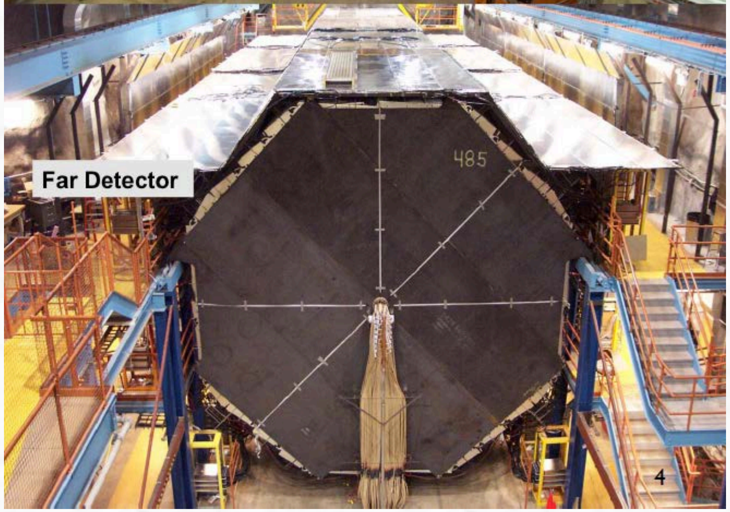


Results are consistent with those from Super-Kamiokande

Fermilab – MINOS Experiment





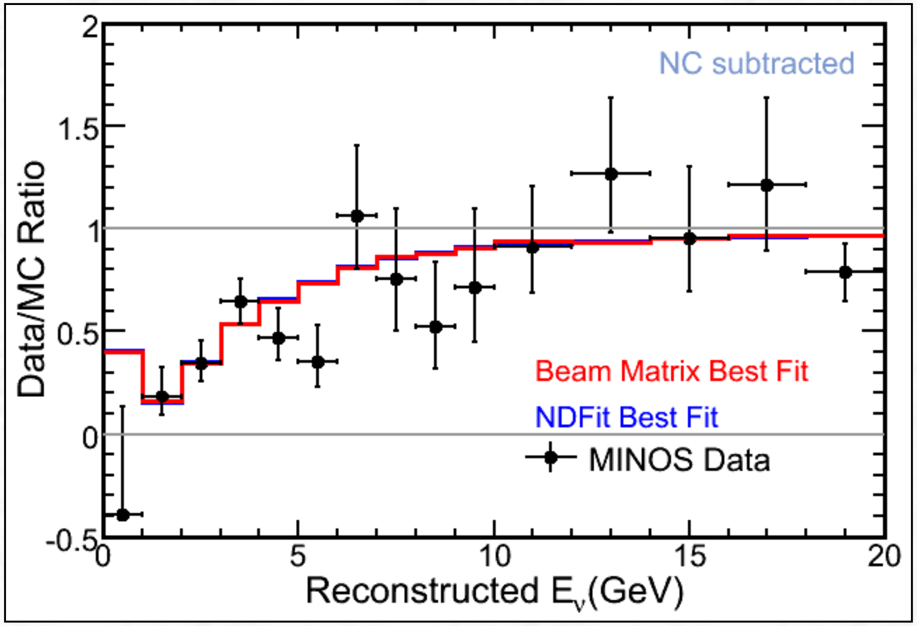


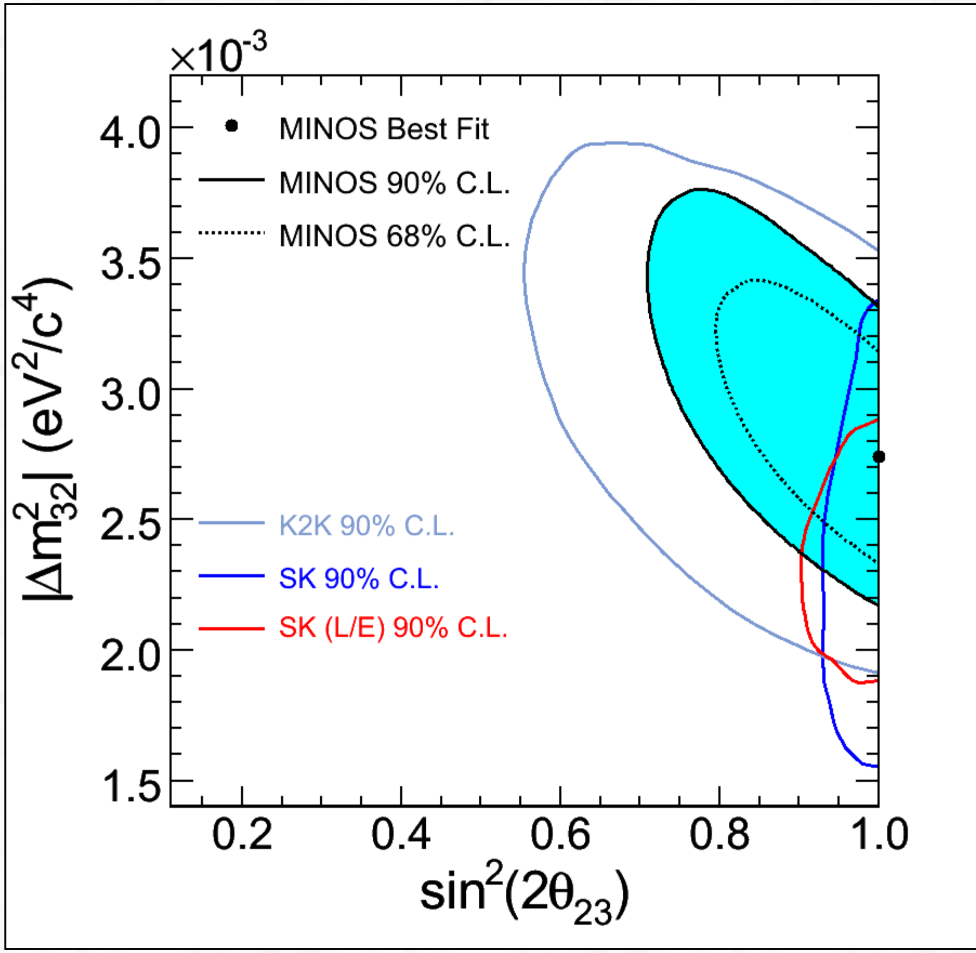
Fermilab Main Injector (MI): 120 GeV proton synchrotron

High intensity: $4x10^{13}$ protons per cycle,
repetition rate: 1.9 s,
$4x10^{20}$ protons on target,
decay tunnel:

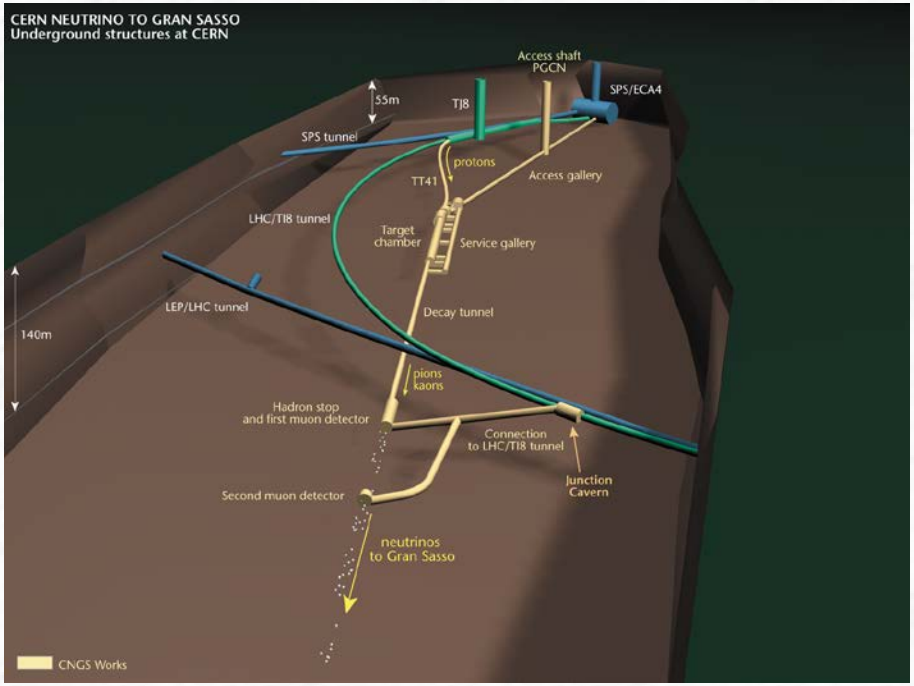
Two detectors: Near: 1.04 km from target
Far: 735 km from target

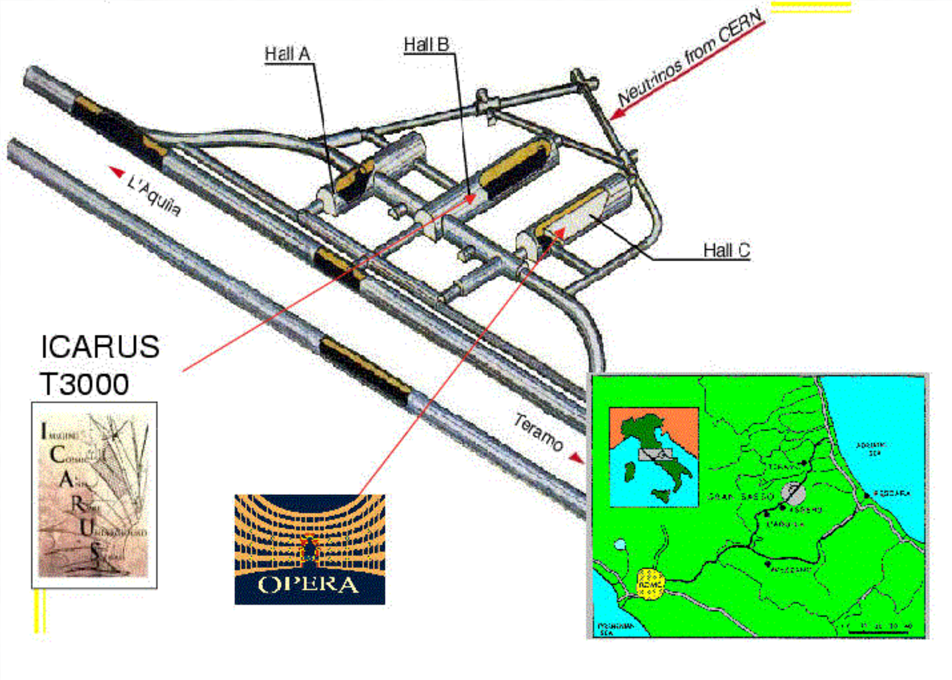
- MINOS Ergebnis 2006: gute Übereinstimmung
- Verschwinden von ν_μ





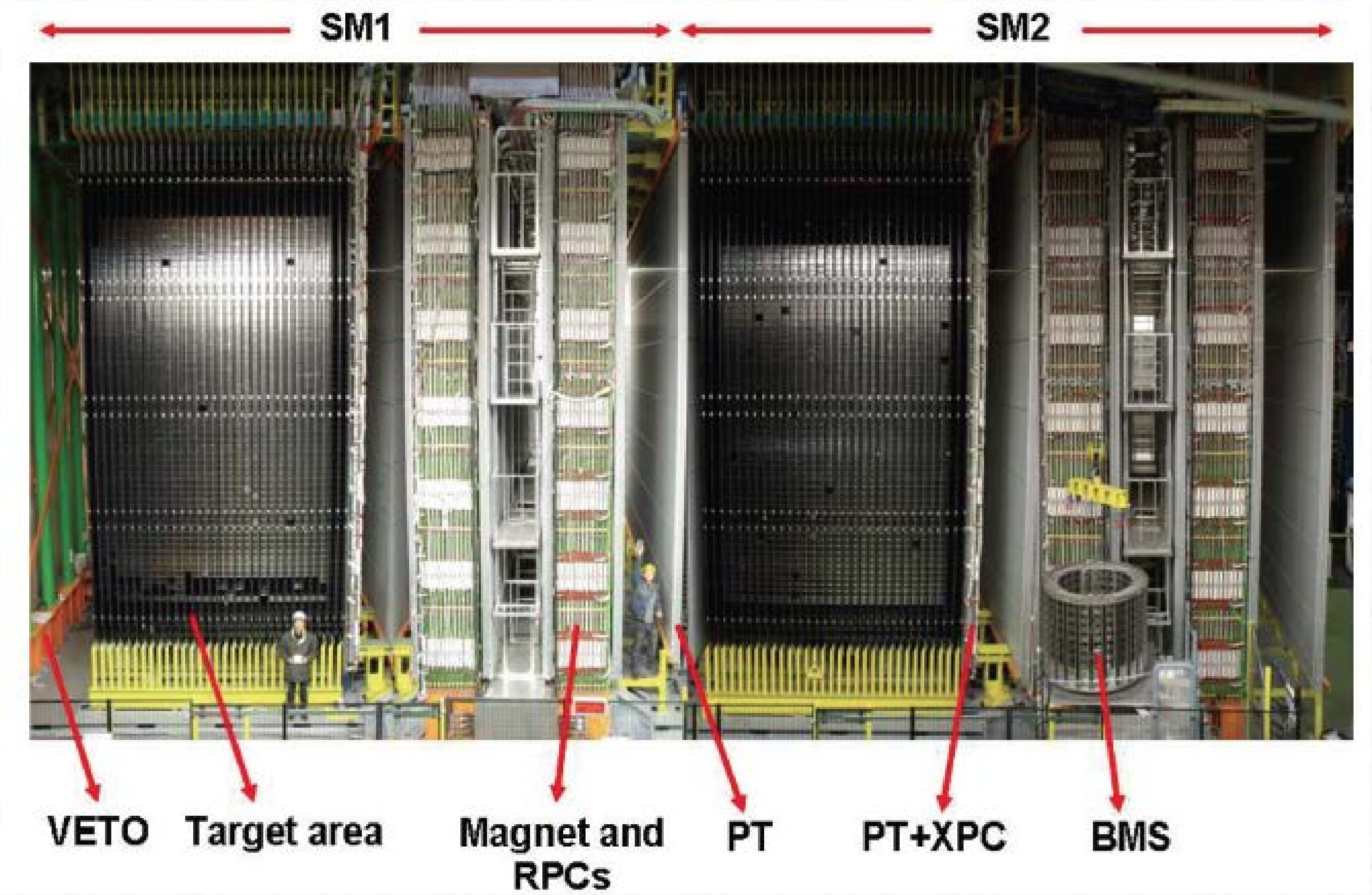
CNGS (CERN Neutrinos to Gran Sasso)



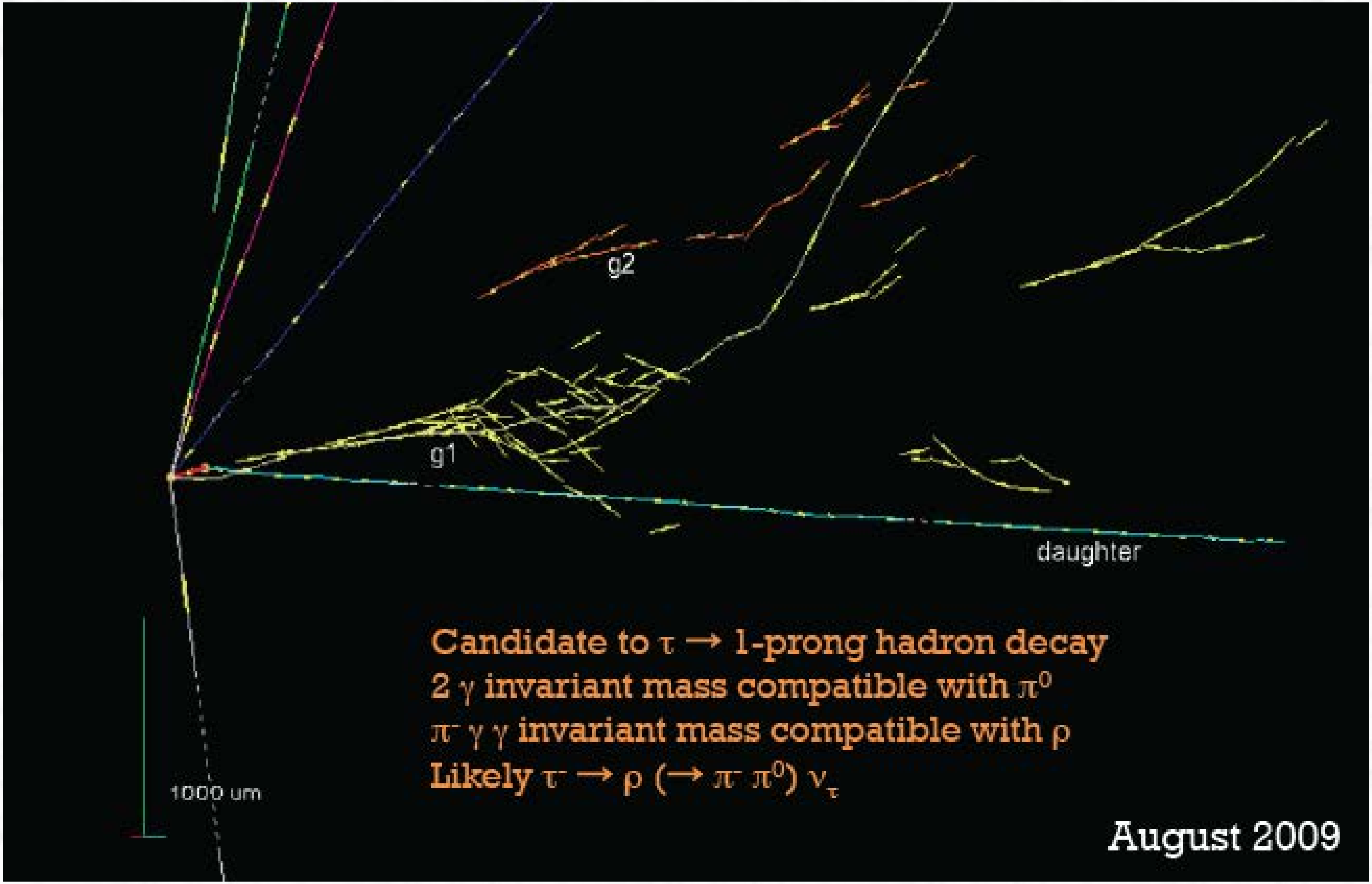


Main goal: Detection of ν_τ appearance after 732 km

OPERA Experiment in Gran Sasso



Candidate event for ν_τ appearance in OPERA



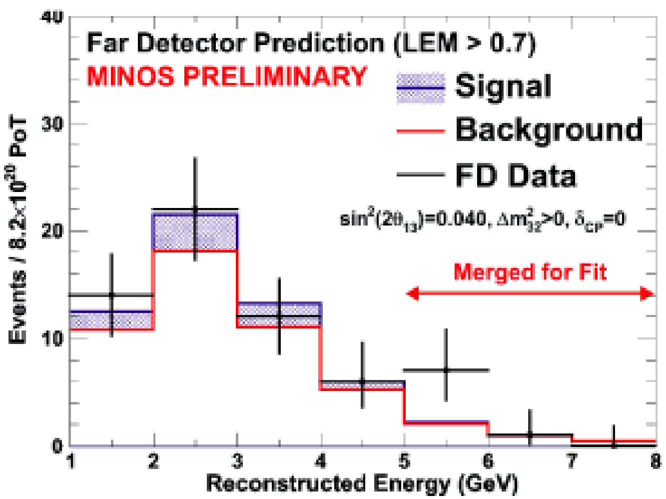
ν_e appearance in long baseline experiments

(important to access all elements of mixing matrix)

T2K	ν_μ at KEK	SK	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=735 km

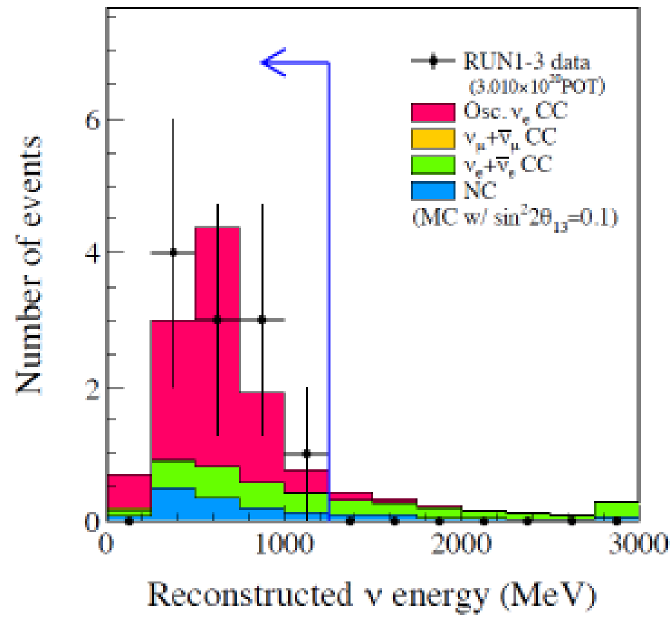
- Observation of $\nu_\mu \to \nu_e$ transitions with $E/L \sim 10^{-3}$ eV^2

MINOS



1.7 σ effect

T2K



3.2 σ effect

3.4 Determination of oscillation parameters

- Global fit to all experimental results
- Interpretation in three-flavour mixing scenario
- Assume neutrinos to be Dirac particles

(not compelling, neutrinos might be their own antiparticles and behave as Majorana particles)

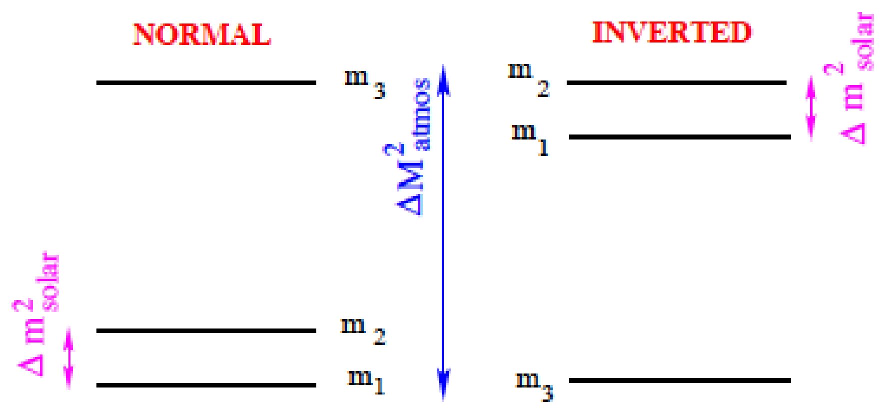
→ 3 x 3 Mixing matrix, analogous to Cabibbo-Kobayashi-Maskawa matrix in the quark sector

→ Three mixing angles, one complex phase (relevant for CP violation)
(for Majorana neutrinos two additional phases would appear)

Parametrisation and dependencies

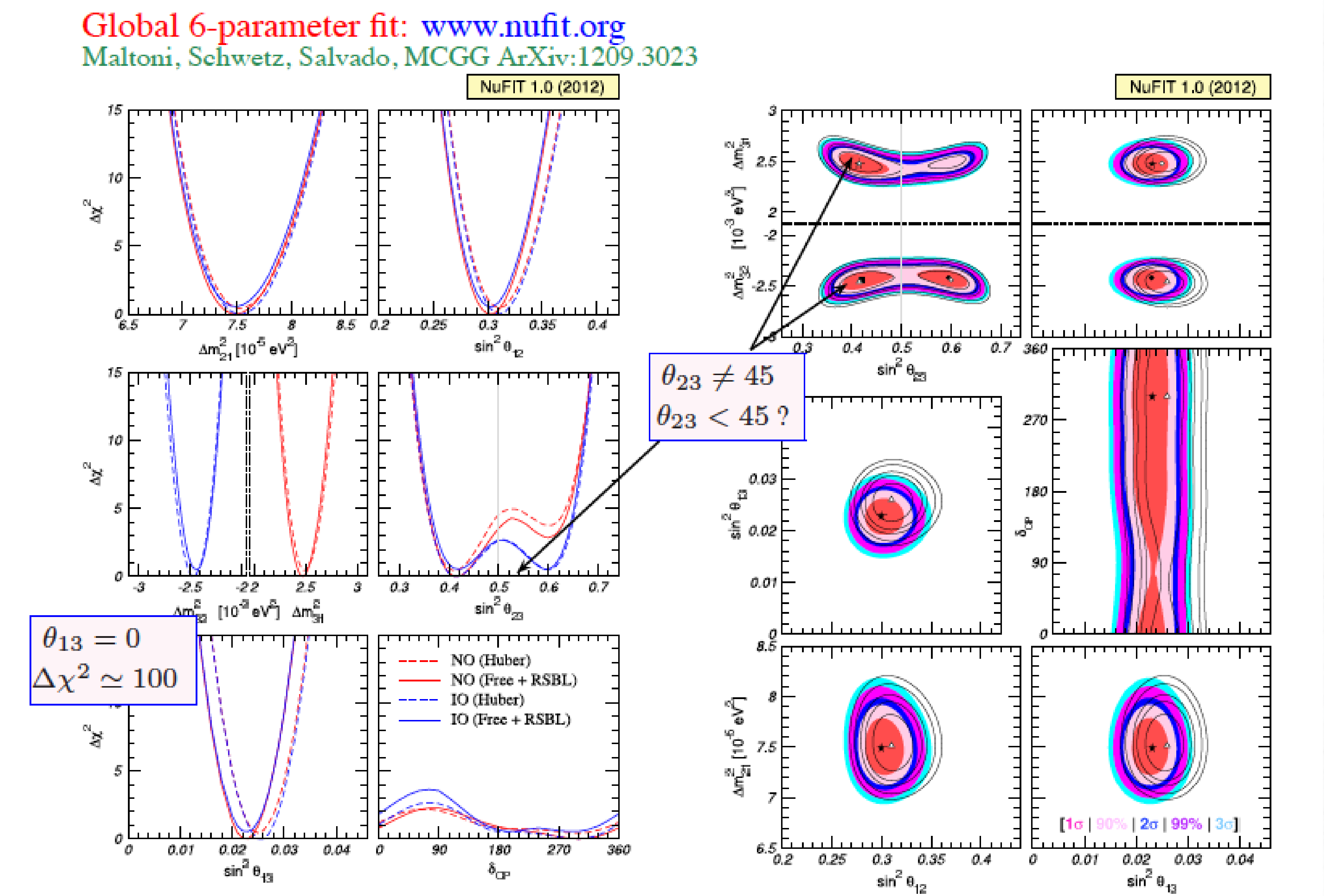
$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Two Possible Orderings



Experiment	Dominant Dependence	Important Dependence
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13}, $\delta_{\rm cp}$
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\rm atm}$	θ_{23}
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21}, θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12}, θ_{13}
Accelerator LBL ν_e App (Minos,T2K)	$\rightarrow \delta_{\rm cp}$	θ_{13}, θ_{23}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$

Present status of global fit to all results

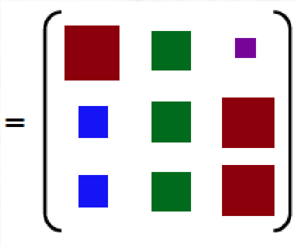


Present status of global fit to all results (cont.)

- The derived ranges for the six parameters at 1σ (3σ):

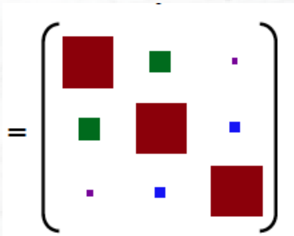
$$
\begin{aligned}
\Delta m^2_{21} &= 7.5 \pm 0.19 \left({}^{+0.59}_{-0.50}\right) \times 10^{-5}\ \mathrm{eV}^2 & \theta_{12} &= 33.4^\circ \pm 0.8^\circ \left({}^{+2.5^\circ}_{-2.3^\circ}\right) \\
\Delta m^2_{31}(\mathrm{N}) &= 2.47^{+0.071}_{-0.067} \left({}^{+0.22}_{-0.20}\right) \times 10^{-3}\ \mathrm{eV}^2 & \theta_{23} &= 40.0^\circ{}^{+2.1^\circ}_{-1.5^\circ} \left({}^{+14.8^\circ}_{-4.2^\circ}\right) \\
|\Delta m^2_{32}|(\mathrm{I}) &= 2.43^{+0.065}_{-0.042} \left({}^{+0.22}_{-0.20}\right) \times 10^{-3}\ \mathrm{eV}^2 & \theta_{13} &= 8.7^\circ \pm 0.45^\circ \left({}^{+1.3^\circ}_{-1.5^\circ}\right) \\
 & & \delta_{\mathrm{CP}} &= 300^\circ{}^{+66^\circ}_{-138^\circ} \left({}^{+60^\circ}_{-300^\circ}\right)
\end{aligned}
$$

$$
|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}
$$



- Good progress but still precision very far from:

$$
|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}
$$



matrices look quite different

3.5 Zusammenfassung und Offene Fragen

- Überzeugende Evidenz für Neutrino-Oszillationen von Experimenten mit solaren und atmosphärischen Neutrinos;

- Hervorragende Bestätigung durch Experimente an Beschleunigern und Reaktoren;

- Evidenz für zwei verschiedene Parametersätze, zwei Δm^2 (für drei Neutrinos)
  Neutrinos haben Masse !

  Das Standardmodell der Teilchenphysik muss entsprechend modifiziert werden;

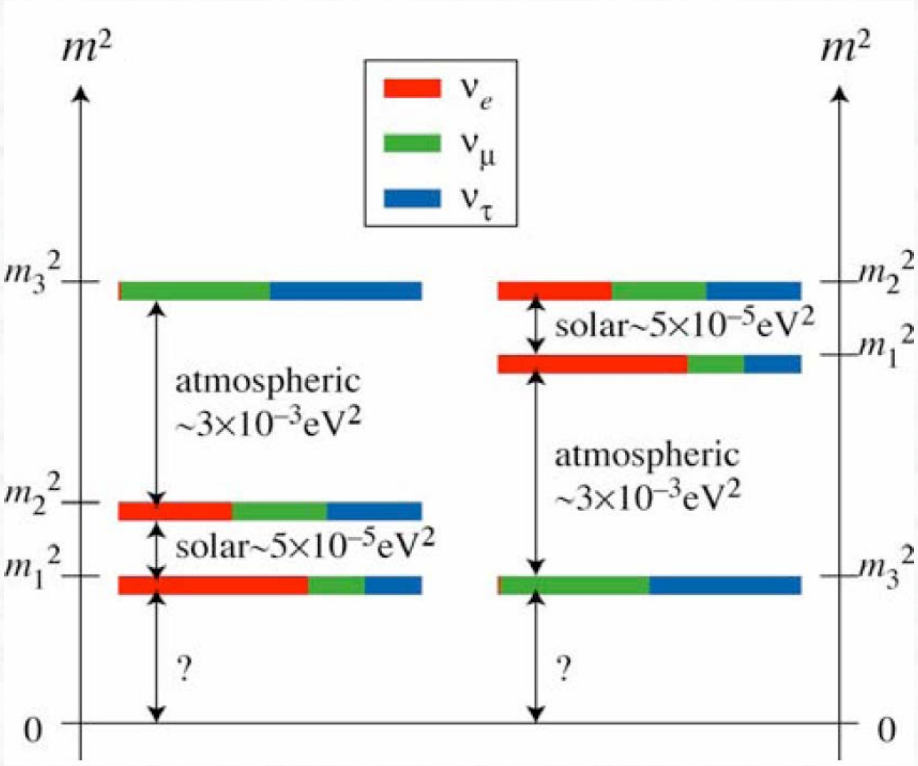
- Die gemessenen Massendifferenzen sind klein;
  (man beachte, dass aus Oszillationsexperimenten keine Aussagen über die Absolutwerte der Massen (offset) gemacht werden können)

- Die gemessenen Mischungswinkel sind groß;
  (sehr verschieden zum Quark-Sektor, wo der größte Mischungswinkel, der Cabibbo-Winkel, 13° beträgt)

- Die erhaltenen Ergebnisse sind mit folgendem Mischungsszenario kompatibel:

ν_e besteht hauptsächlich aus ν_1 und ν_2, kleine Beimischung von ν_3, da der kürzlich gemessene Mischungswinkel θ_{13} relativ klein ist)

ν_μ und ν_τ bestehen zu fast ≈50% aus ν_3



Mögliche Massenhierarchien

Offene Fragen

- Absolutwerte der Neutrinomassen ?
  Ist eine direkte Massenmessung möglich ?

  → Tritium-Zerfallsexperiment KATRIN am Forschungszentrum in Karlsruhe

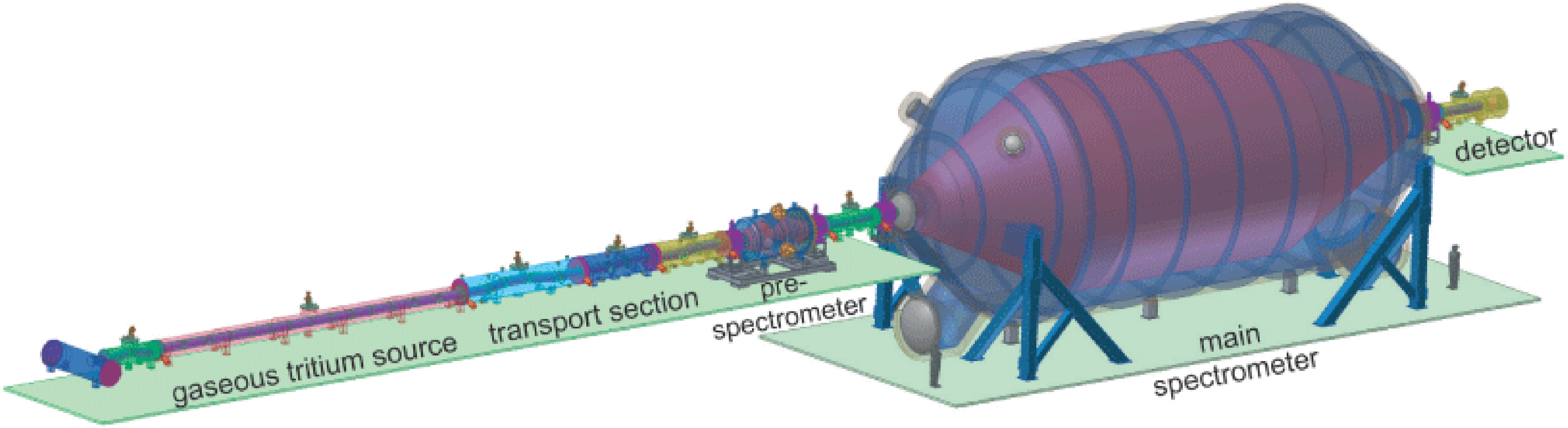
- Präzisionsmessungen der Parameter der Neutrino-Mischungsmatrix;

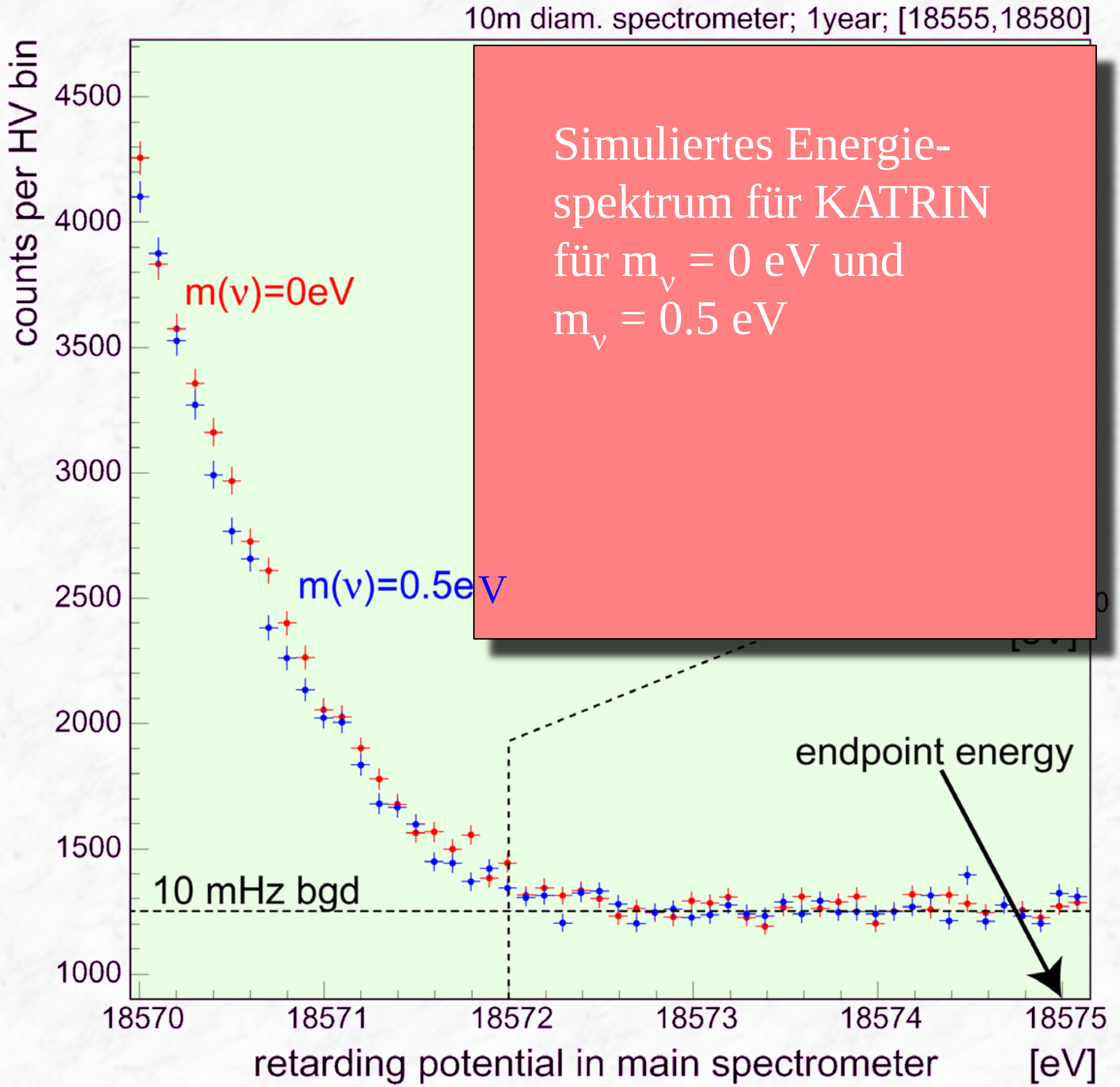
  → Fortführung der Reaktor- (Europa, China, USA)
  und neue Beschleunigerexperimente (USA, Europa ?)

- Sind Neutrinos Dirac- oder Majorana-Teilchen ?

  → Suche nach dem neutrinolosen doppelten β-Zerfall

KATRIN: Karlsruhe Tritium Neutrino Experiment





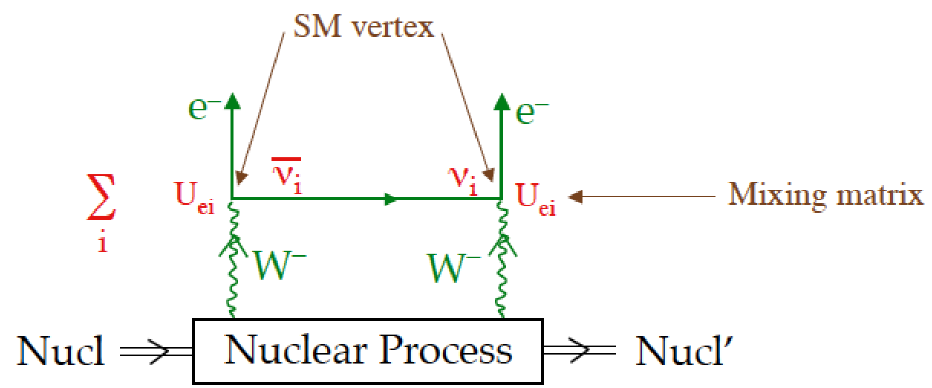
Simuliertes Energie-
spektrum für KATRIN
für m_ν = 0 eV und
m_ν = 0.5 eV

Neutrinoloser doppelter Betazerfall

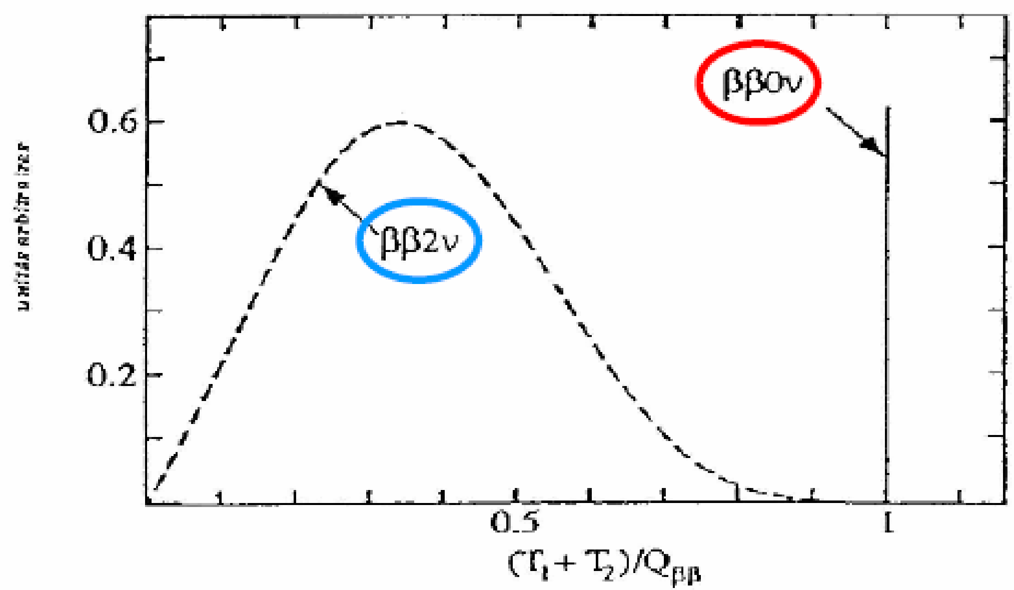
2νββ : $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

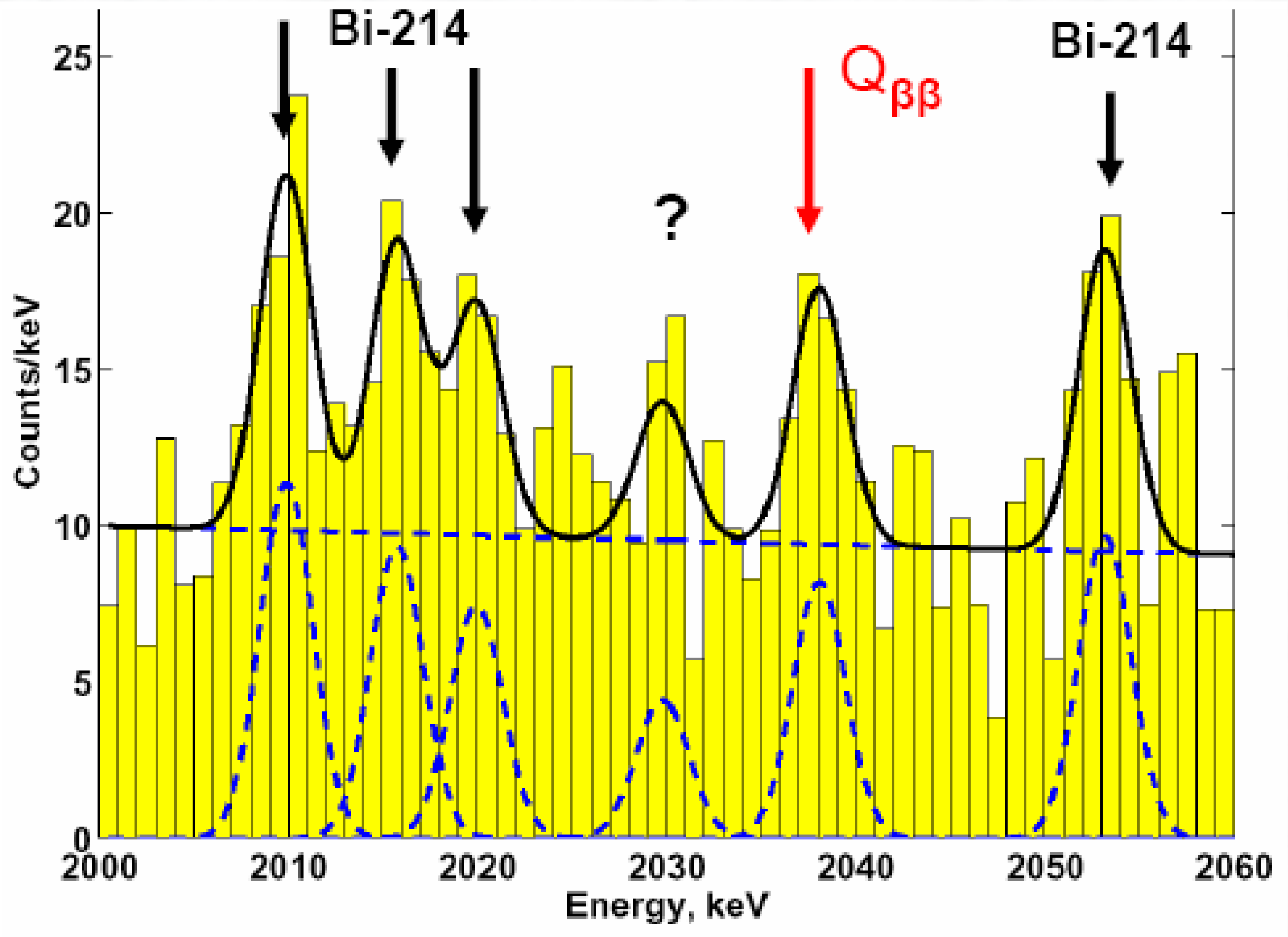
2^{nd} order process, observed, $T_{1/2} \sim 10^{19}$-10^{21} yrs

0νββ : $(A, Z) \rightarrow (A, Z+2) + 2e^-$



Ge-76: $Q_{\beta\beta}$=2039 keV





$T^{0\nu}_{1/2} = (0.69 - 4.18) \cdot 10^{25}$ y (3σ range)

$\langle m_{ee} \rangle$ = 0.2 – 0.6 eV (99.73% C.L.)

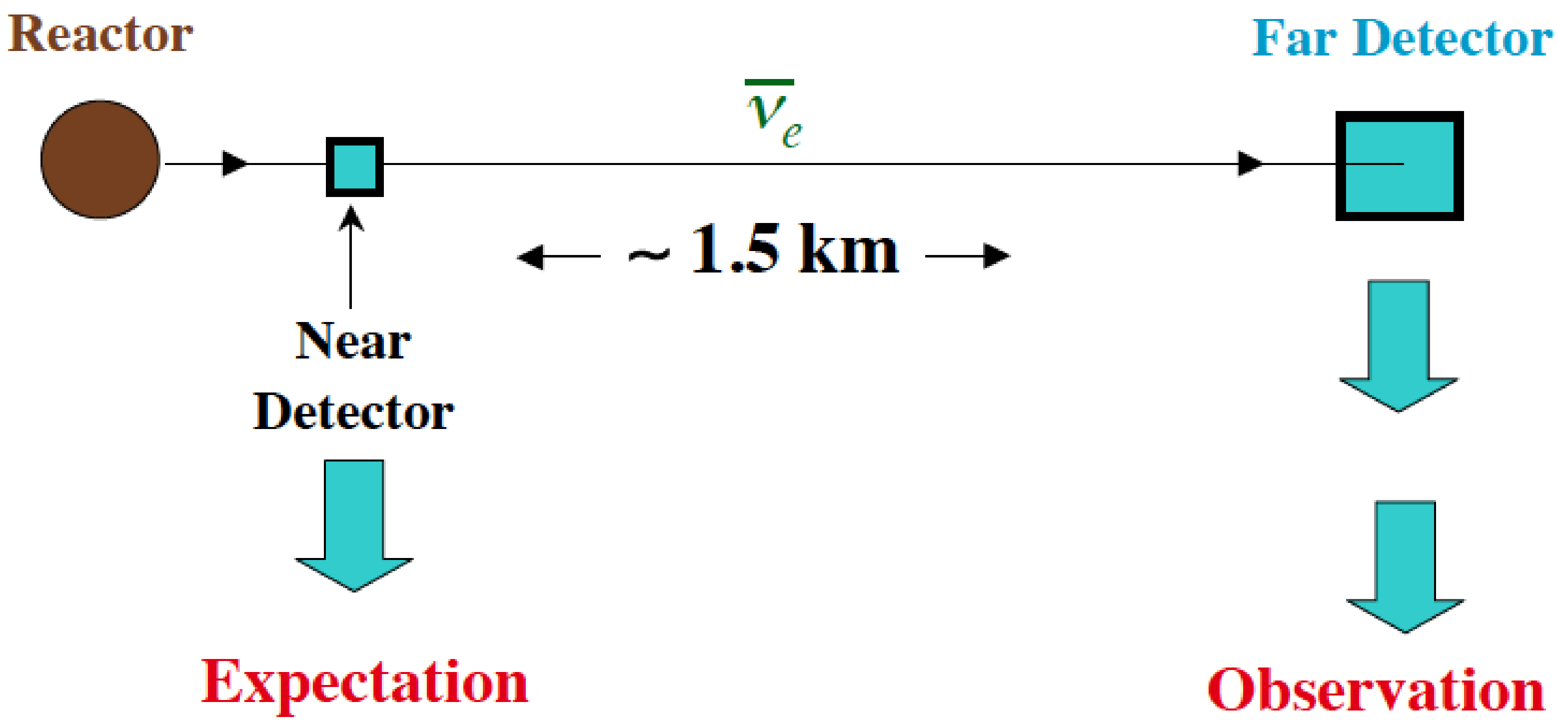
= 0.1 – 0.9 eV (nucl. m.e. depend.)

kontrovers

Überprüfung durch weitere Experimente notwendig

Additional Slides

The Reactor – Neutrino Experiments



Reactor $\overline{\nu}_e$ have $E \sim 3$ MeV, so if $L \sim 1.5$ km,

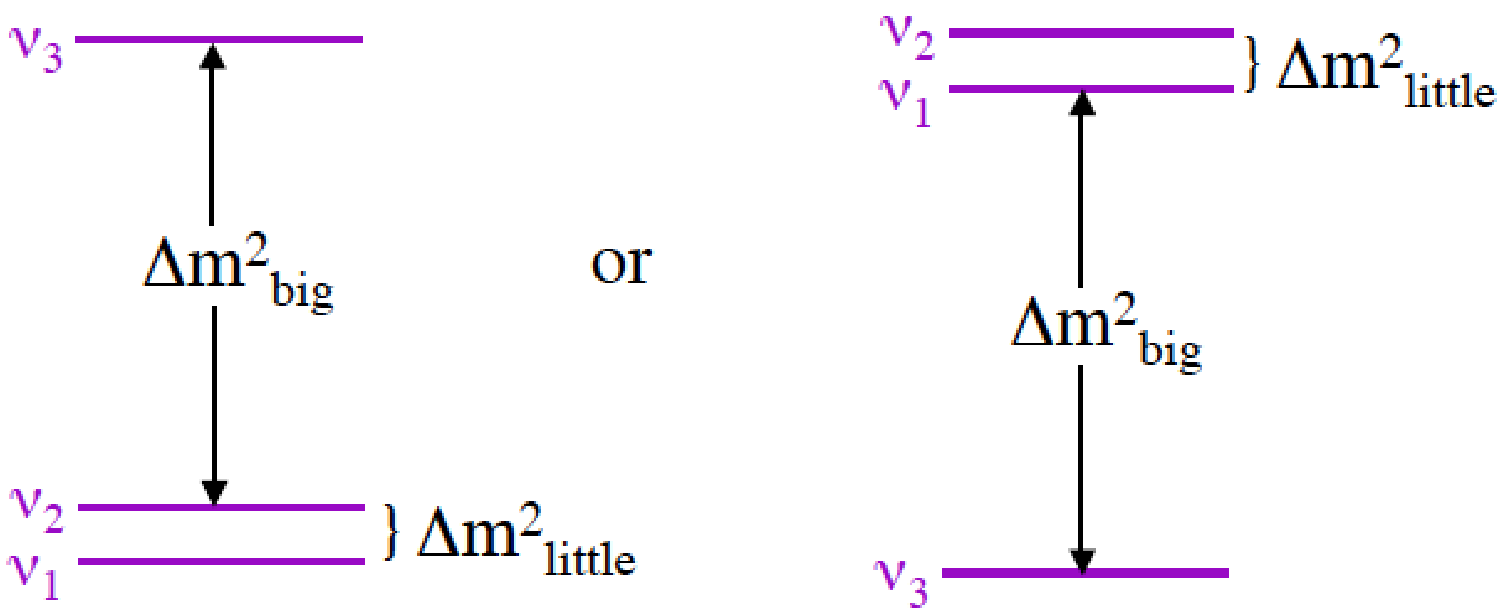
$\sin^2\left[1.27\Delta m^2 \frac{L(\text{km})}{E(\text{GeV})}\right]$ will be sensitive to —

$$\Delta m^2 = \Delta m^2_{\text{big}} = 2.4 \times 10^{-3}\text{eV}^2 \approx \frac{1}{400}\text{eV}^2$$

but not to —

$$\Delta m^2 = \Delta m^2_{\text{little}} = 7.5 \times 10^{-5}\text{eV}^2 \approx \frac{1}{13{,}000}\text{eV}^2.$$

In —



the little splitting is invisible. Then —

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - 4|U_{e3}|^2\left(1 - |U_{e3}|^2\right)\sin^2\left[1.27\Delta m^2_{\text{big}} \frac{L(\text{km})}{E(\text{GeV})}\right]$$

$$= 1 - \sin^2 2\theta_{13} \sin^2\left[1.27\Delta m^2_{\text{big}} \frac{L(\text{km})}{E(\text{GeV})}\right]$$