Neutrinooszillationen

Schule für Astroteilchenphysik,Obertrubach-Bärnfels, 6.10.-15.10. 2004

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Einführung

Lösung der atmosphärischen Neutrinoanomalie:

Neutrinooszillation

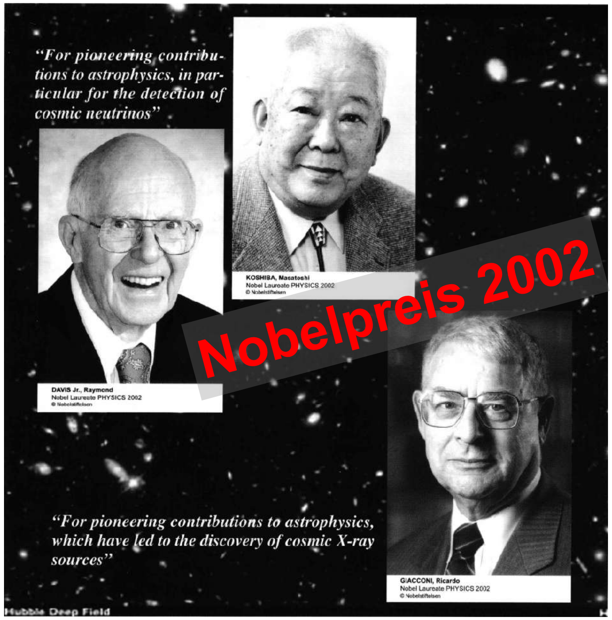
Bestätigung mit Beschleunigerneutrinos

Lösung des solaren Neutrinorätsel

Bestätigung mit Reaktorneutrinos

Offene Fragen für die Zukunft / zukünftige Exp.

Zusammenfassung



Nobelpreis 2002

"For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

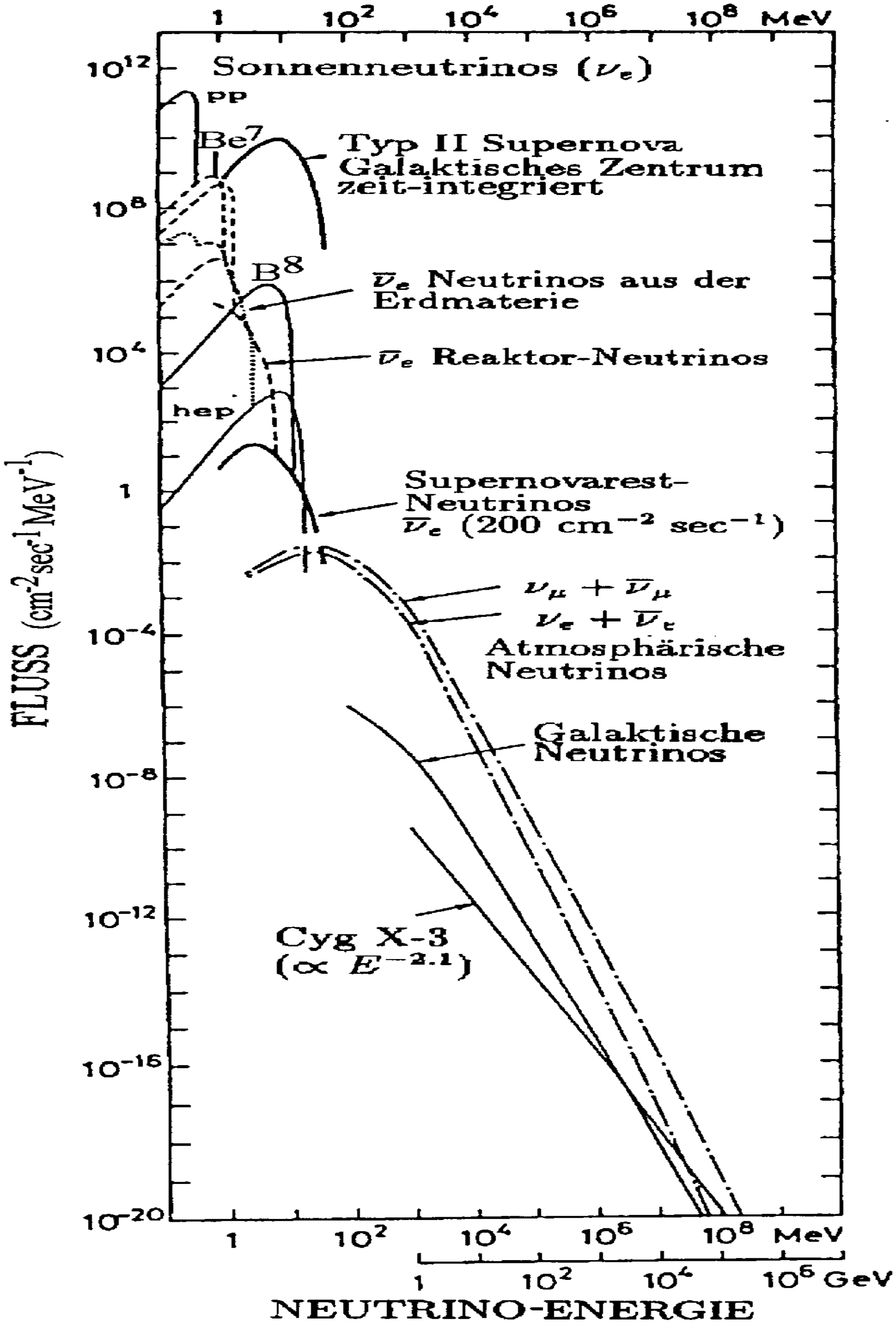
"For pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Meilensteine der Neutrinophysik

1930	Pauli	Neutrino postuliert	
1956	Cowan & Reines	exp. Nachweis des Elektronantineutrinos	
1957/58	Wu, Goldhaber	Verletzung der Parität, Linkshändigkeit des ν	
1962	Lederman, Schwarz, Steinberger	Entdeckung des Myonneutrinos	ν-Beschleunigerphysik
seit 1970	Davis, Nobelpreis 2002	Solares Neutrinodefizit	solare ν-Physik
1987	Kamiokande Nobelpreis 2002	Nachweis von Neutrinos von SN1987a	ν-Astrophysik
1989	LEP-Experimente	aus Z^0-Breite: 3 Neutrinos	
1998	Super-Kamiokande	Nachweis der Oszillation atmosph. ν	$m(\nu) \neq 0$
2000	Donut	Nachweis des Tauneutrinos	
2001,2002	SNO + Super-Kam., Gallex,....,	Evidenz für Oszillation solarer Neutrinos	
2002	KamLAND	Bestätigung der solaren Neutrinososzillation (LMA Lösung)	

⇒ sehr aktives & wachsendes Forschungsgebiet der Kern-, Teilchen- und Astrophysik

Neutrinoquellen und -spektren



solare: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$

Supernova: $e^- + p \rightarrow n + \nu_e$

$Z^0 \rightarrow \nu_x + \bar{\nu}_x$

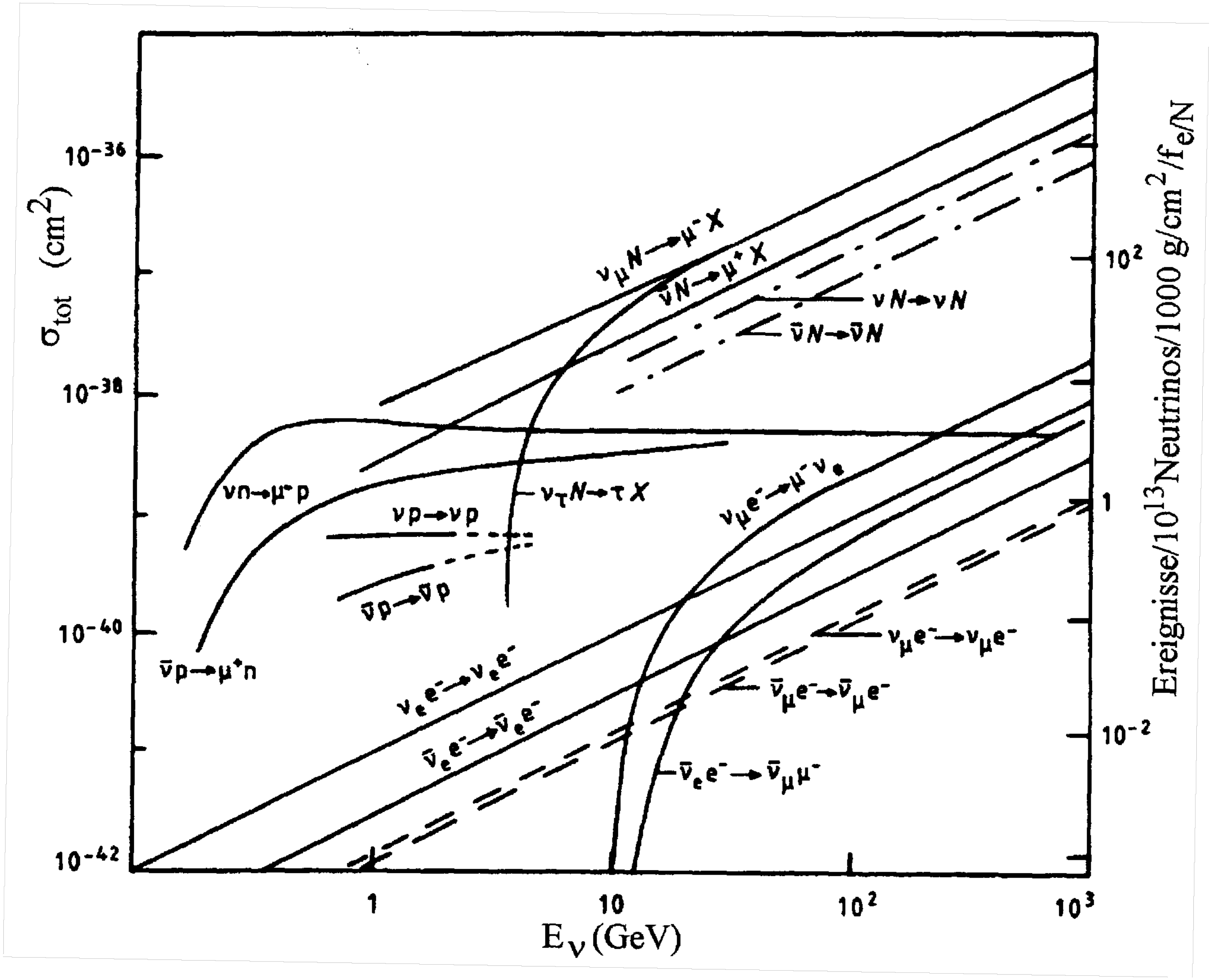
Reaktor: $(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$

Beschleuniger,
atmosphärisch:

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

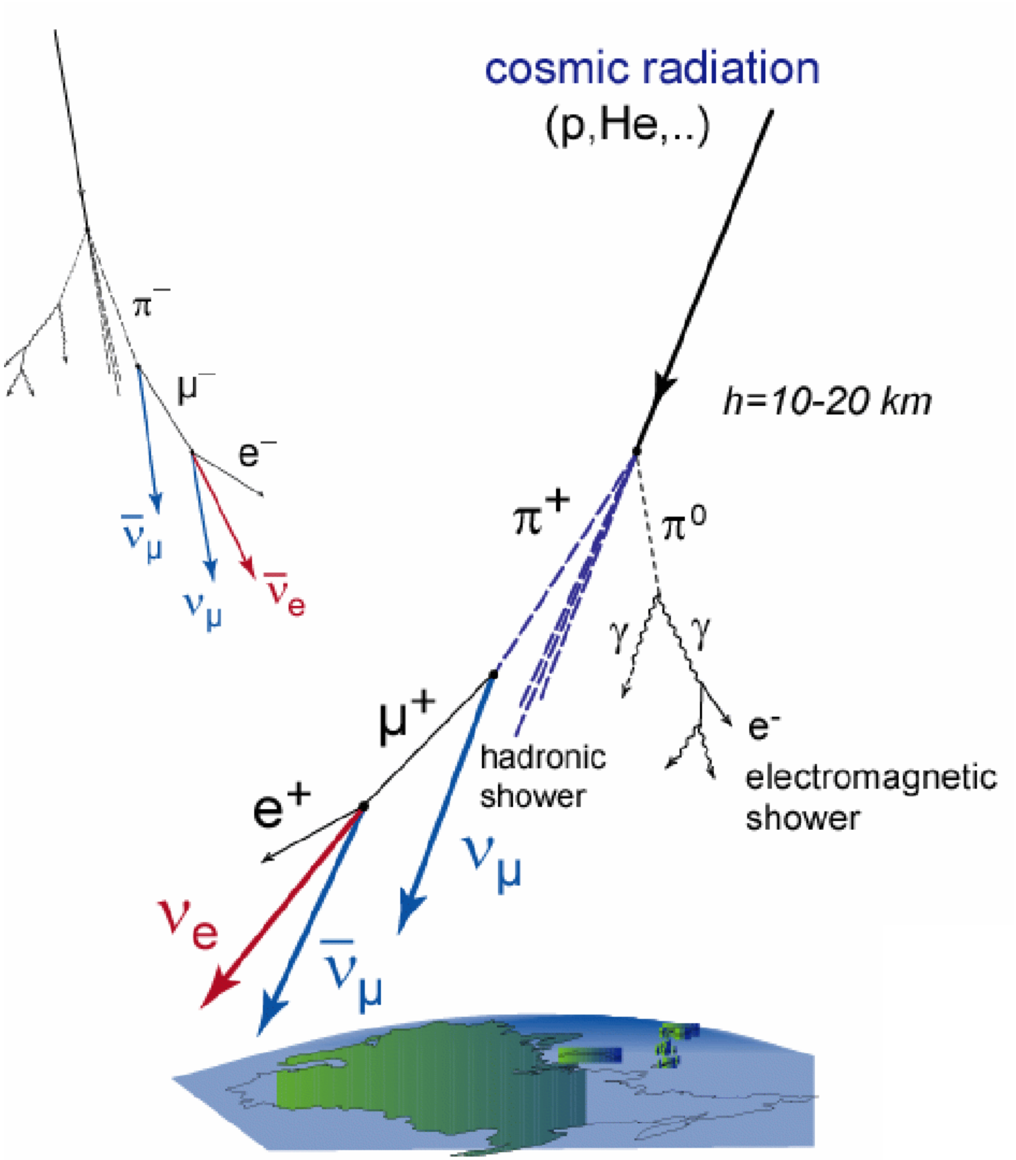
$\rightarrow e^- + \nu_\mu + \bar{\nu}_e$

ν-Wirkungsquerschnitte



ν-Fermion-Wirkungsquerschnitte: $\sigma \propto s = m_f^2 + 2E_\nu m_f$, d.h. $s \propto E_\nu$

Neutrinooszillation: Erste klare Evidenz 1998
Atmosphärische Neutrinos



Wechselwirkung von kosmischer Strahlung (p,α, ..) in äußerer Atmosphäre:

$\Rightarrow$ $\pi^\pm$, $K^\pm$,...

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

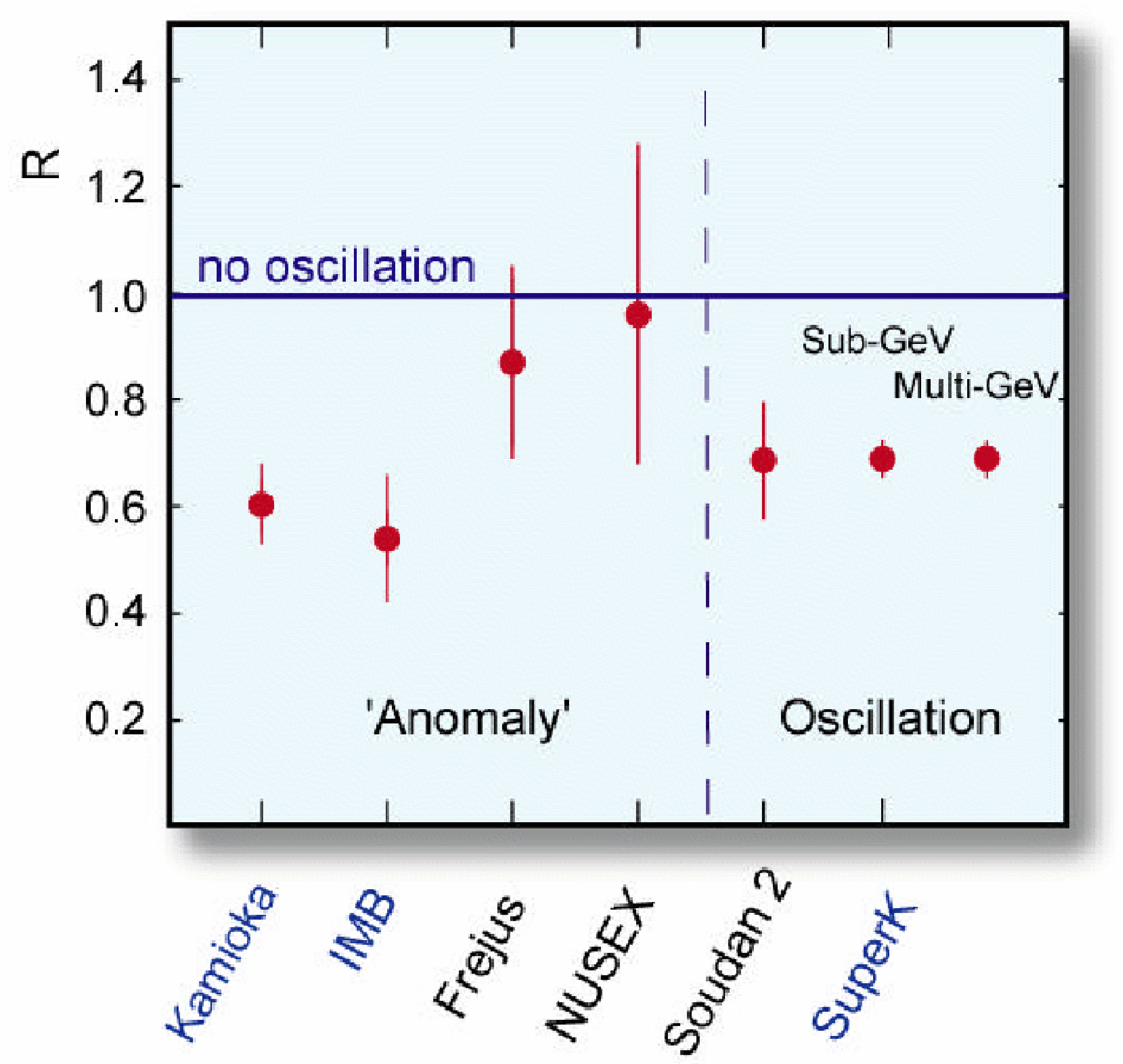
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

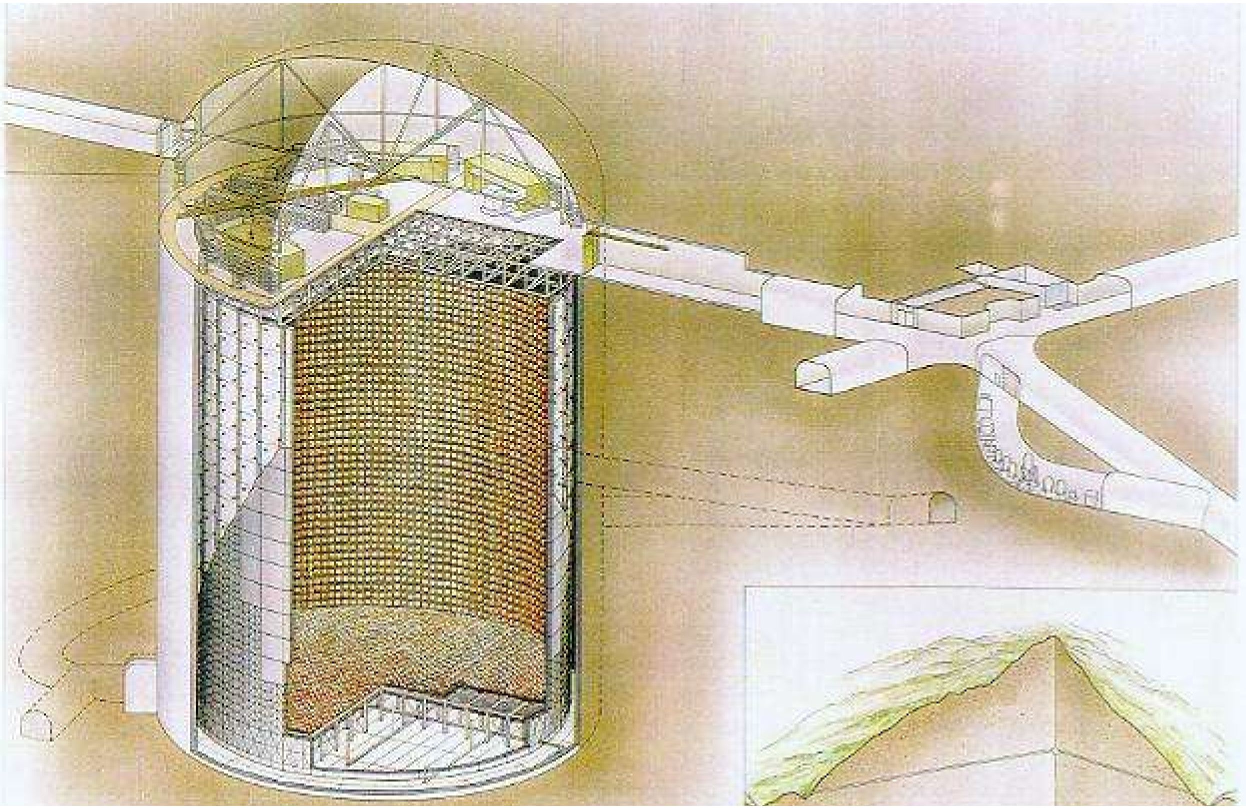
$$\Rightarrow \quad \#\overset{(-)}{\nu}_\mu \,/\, \#\overset{(-)}{\nu}_e \geq 2$$

Erster Hinweis: Verhältnis ν_μ / ν_e :

$$R = \frac{\left(\#\overset{(-)}{\nu}_\mu \;/\; \#\overset{(-)}{\nu}_e\right)_{exp}}{\left(\#\overset{(-)}{\nu}_\mu \;/\; \#\overset{(-)}{\nu}_e\right)_{MC}}$$



Super-Kamiokande

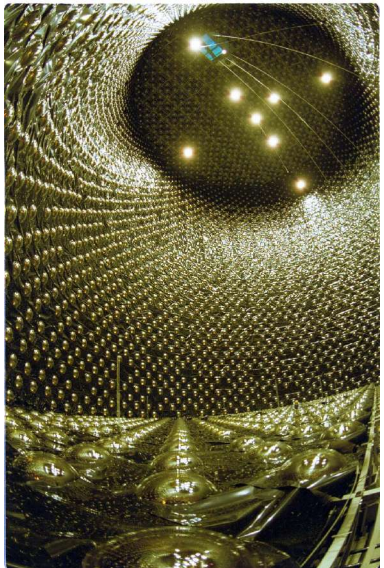


$H_2 0$ Cherenkov-Detektor

$H_2 0$: 50 000 t
40 m hoch, 40 m ∅

11146 Photomultiplier
50 cm ∅

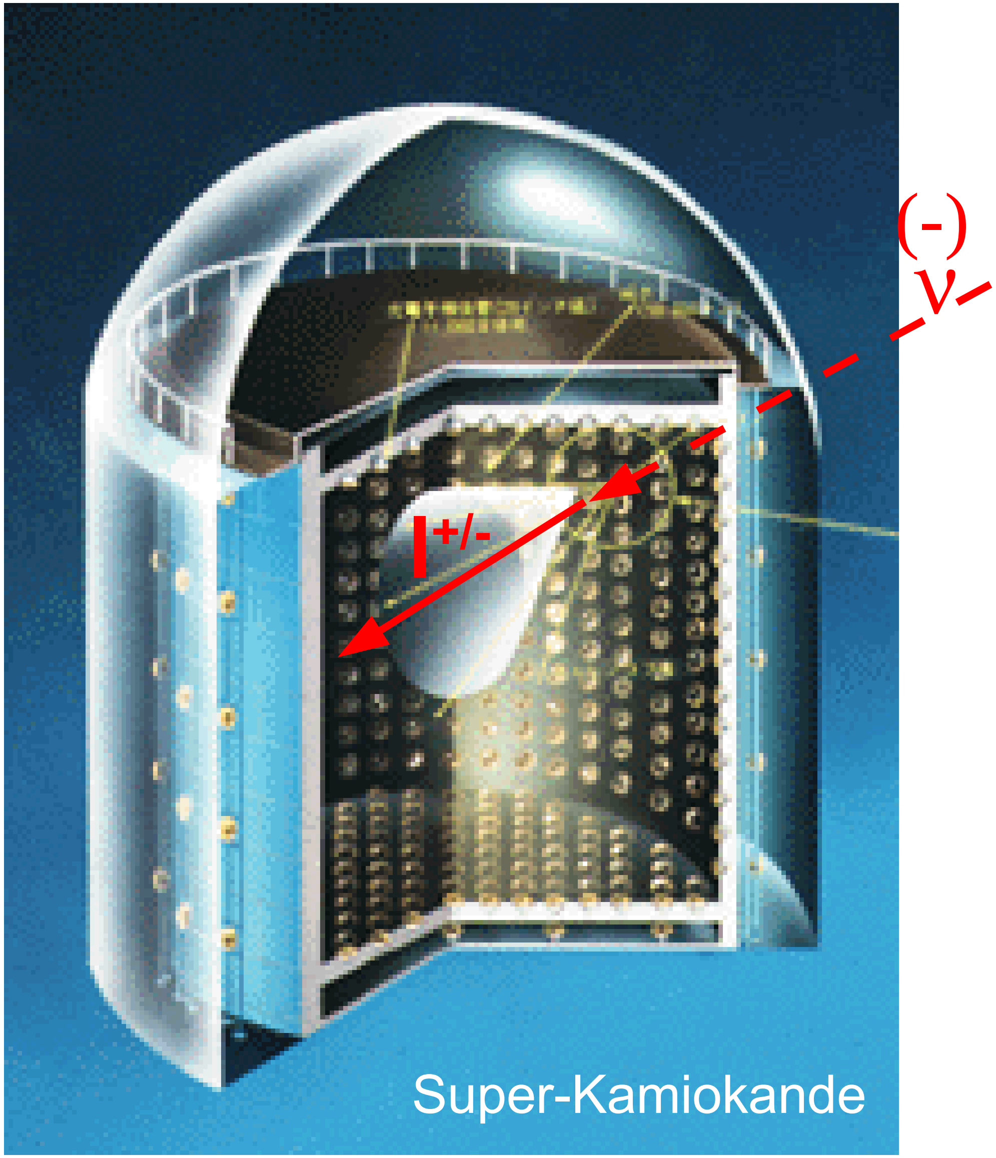
1 km tief in Kamioka Mine, Japan



ab
Dez. 2002
SK II
5200 PMTs

bis Herbst 2001

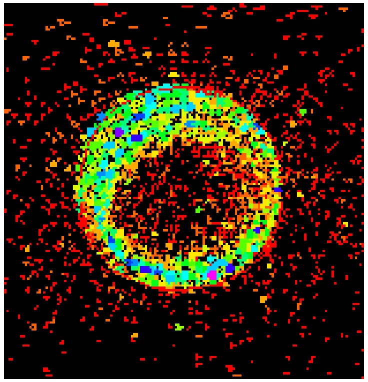
Atmosphärische Neutrinos in SK



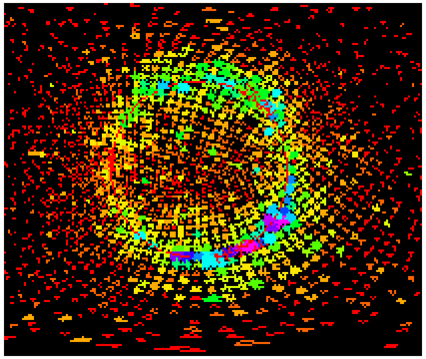
Cherenkov-Kegel:

- Energie
- Richtung
- Elektron/Myon-Unterscheidung

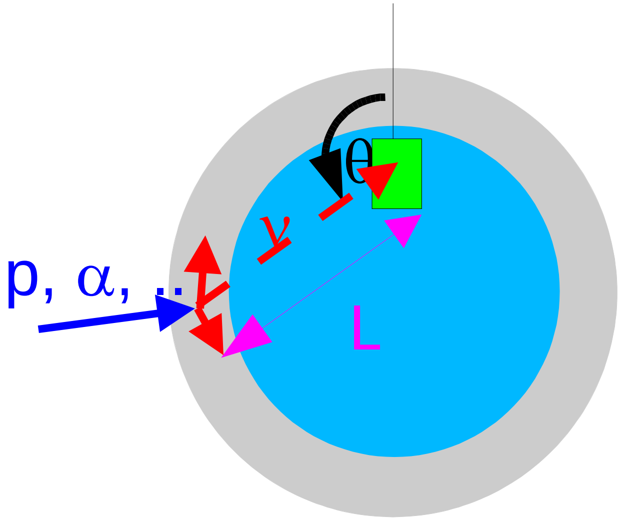
Myonen: scharfer Ring

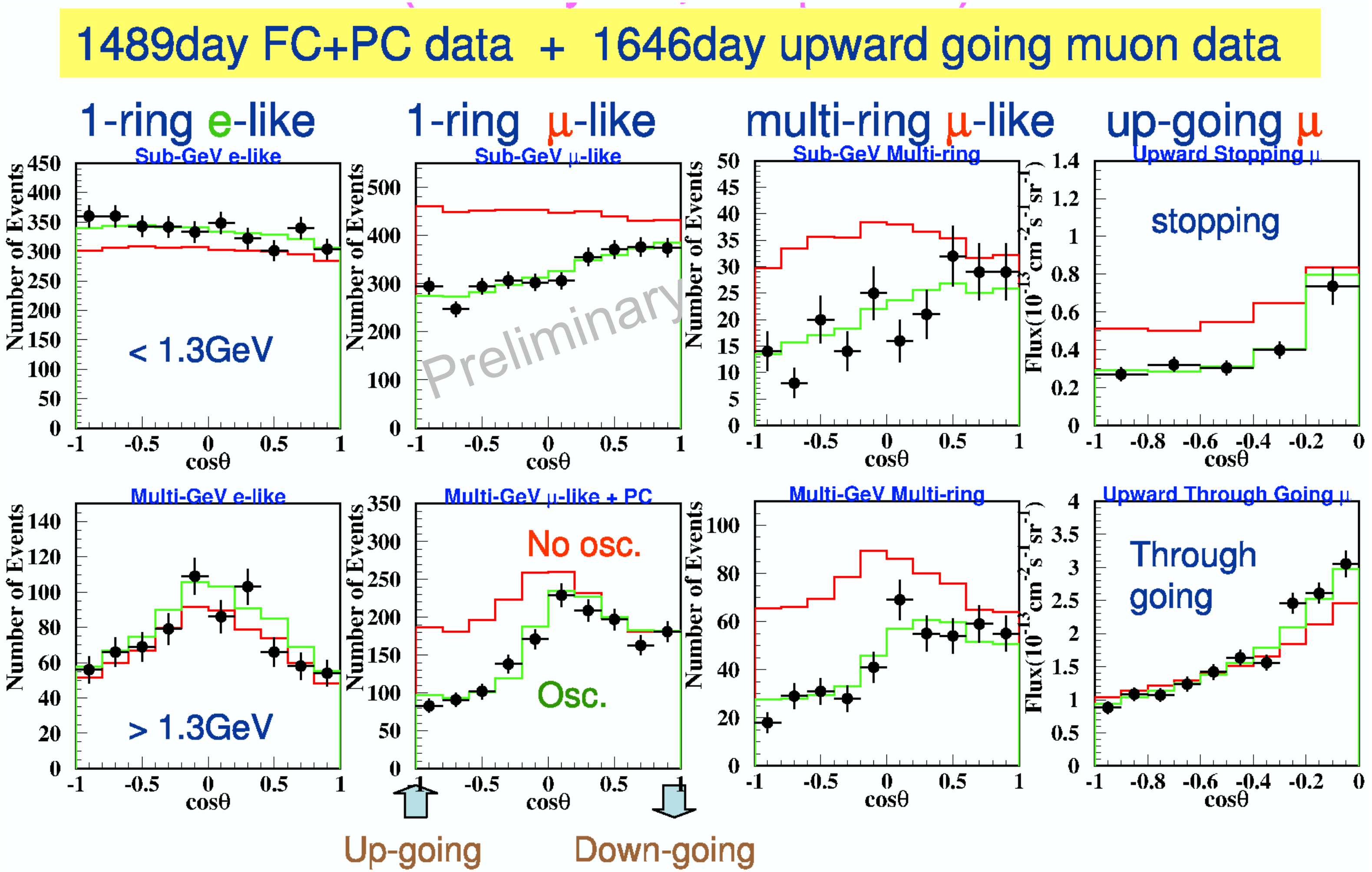


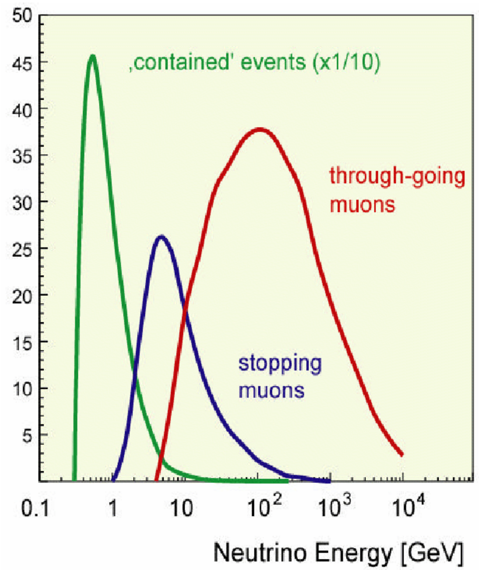
Elektronen: verwaschener Ring
(Vielfach-Streuung, EM-Schauer)



Winkelverteilung von ν_e und ν_μ bei SK




1489day FC+PC data + 1646day upward going muon data



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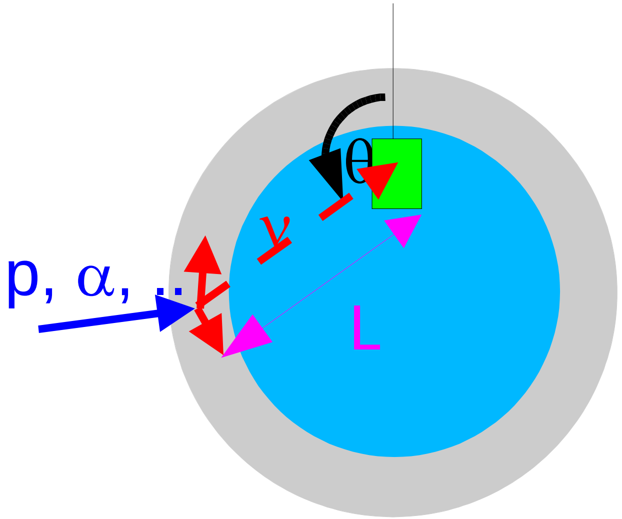

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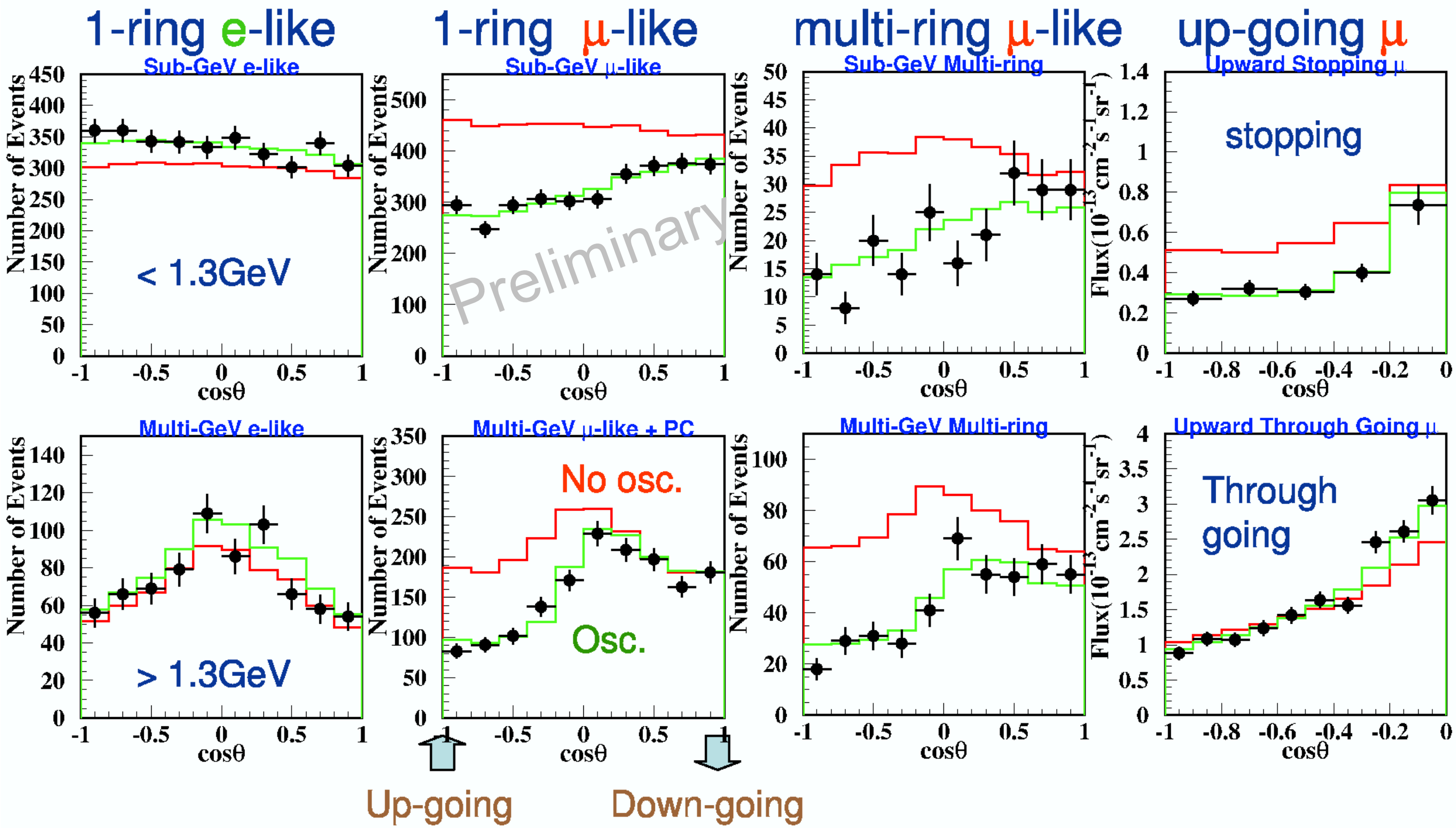


⇒ Klares, energieabh. Defizit von von unten kommenden Myonneutrinos

Alle Datensätze und Analysen (FC, PC, up-going μ, NC enhanced): kompatibel mit $\nu_\mu \rightarrow \nu_\tau$-Oszillation ($\Delta m^2 \approx 2 \times 10^{-3}$ eV^2. $\sin^2(2\theta) \approx 1$)

Neutrinooszillation im Vakuum

Annahmen: **1) ν-Mischung:** $\nu_\alpha = U\,\nu_i$ (α = e,μ,τ; i = 1,2,3, U nicht-trivial)

z.B. 2-Flavor-Mischung: $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

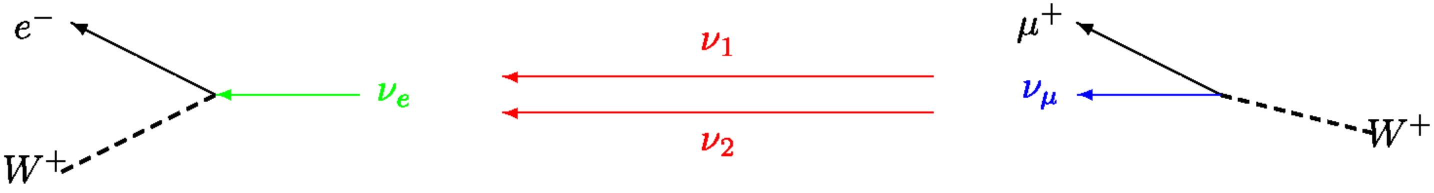
2) $m_i := m(\nu_i)$ sind verschieden ⇒ **mind. ein $m(\nu_i) \neq 0$**

2 Flavour-Fall:

Wechselwirkung von ν_e

Propagation im Ruam als Überlagerung von ν_1 und ν_2

Erzeugung von ν_μ



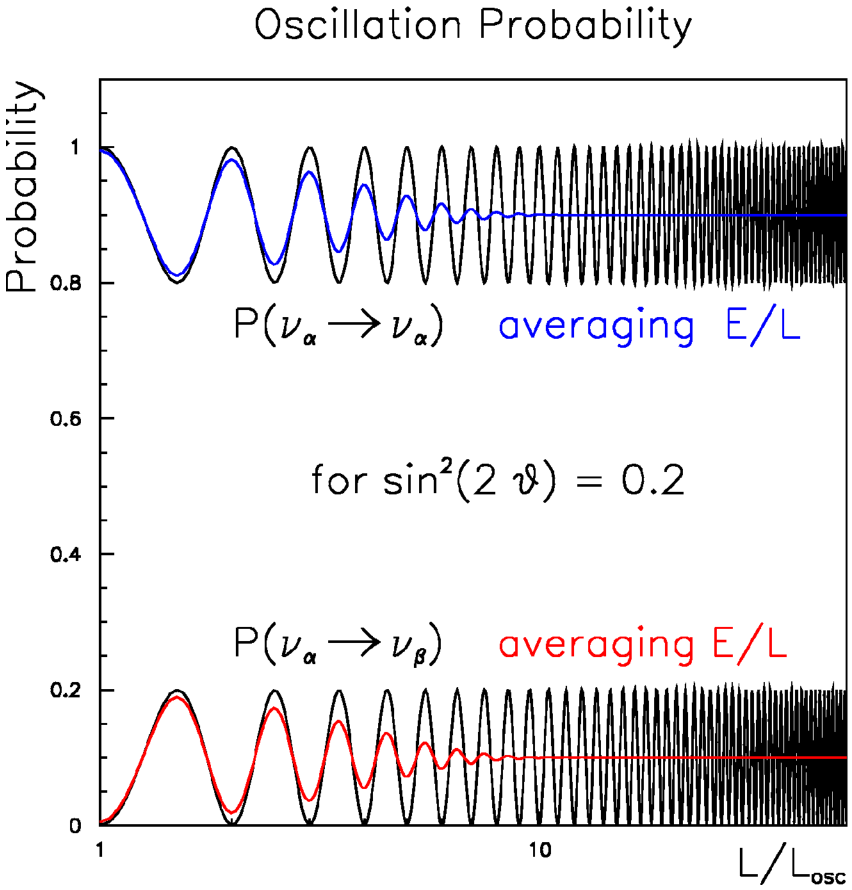
$$\mathrm{P}(\nu_\mu \to \nu_e) = \left| \begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \underbrace{\begin{pmatrix} e^{-iE_1t} & 0 \\ 0 & e^{-iE_2t} \end{pmatrix}}_{\begin{pmatrix} e^{-i\sqrt{p^2+m_1^2}t} & 0 \\ 0 & e^{-i\sqrt{p^2+m_2^2}t} \end{pmatrix} = e^{-i(p+m_1^2/2p)} \cdot \begin{pmatrix} 1 & 0 \\ 0 & e^{-i\frac{m_2^2-m_1^2}{2p}t} \end{pmatrix}} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right|^2$$

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E}\right) = \sin^2(2\theta) \cdot \sin^2\left(\frac{\pi L}{\lambda_{osz}}\right)$$

mit $\lambda_{osz} = \frac{4\pi \cdot E}{\Delta m^2} = 2.5\,km \cdot \frac{E[GeV]}{\Delta m^2[eV^2]}$

Neutrinooszillation

2 Flavour-Fall:



3 Flavour-Mischung:

Generelle Oszillationsformel:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\beta i} \exp^{-i(E_i t)} U^*_{\alpha i} \right|^2$$

From
Alexei Smirnow
DPG-School on Physics
„Neutrino Physics“, 2004

Two aspects of mixing

acuum
mixing
angle

$\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$

$\nu_\mu = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2$

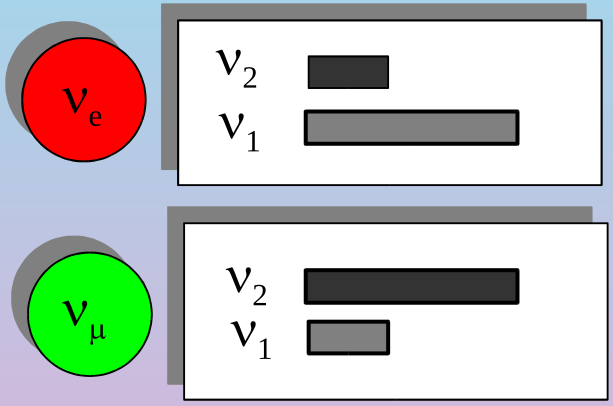
inversely

$\nu_2 = \sin\theta\, \nu_e + \cos\theta\, \nu_\mu$

$\nu_1 = \cos\theta\, \nu_e - \sin\theta\, \nu_\mu$

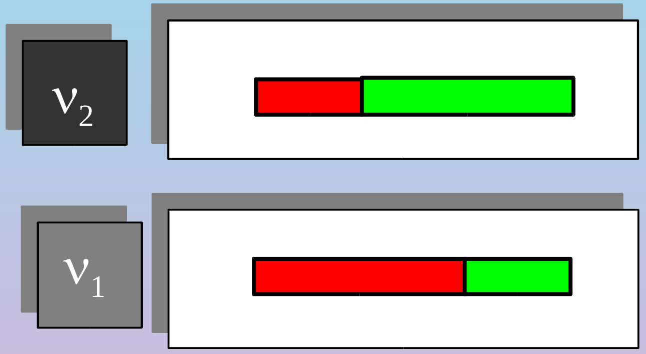
coherent mixtures
of mass eigenstates

flavor composition of
the mass eigenstates

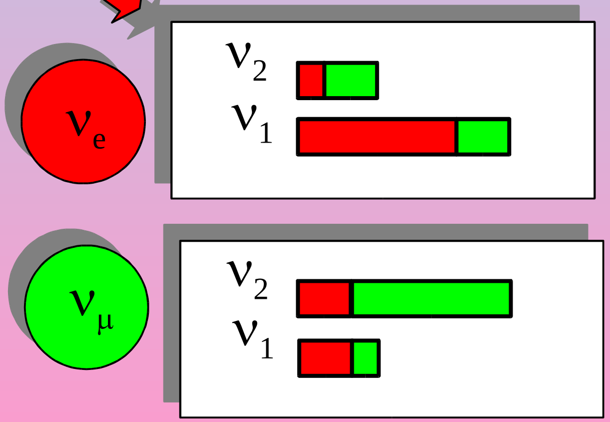


wave
packets

inserting



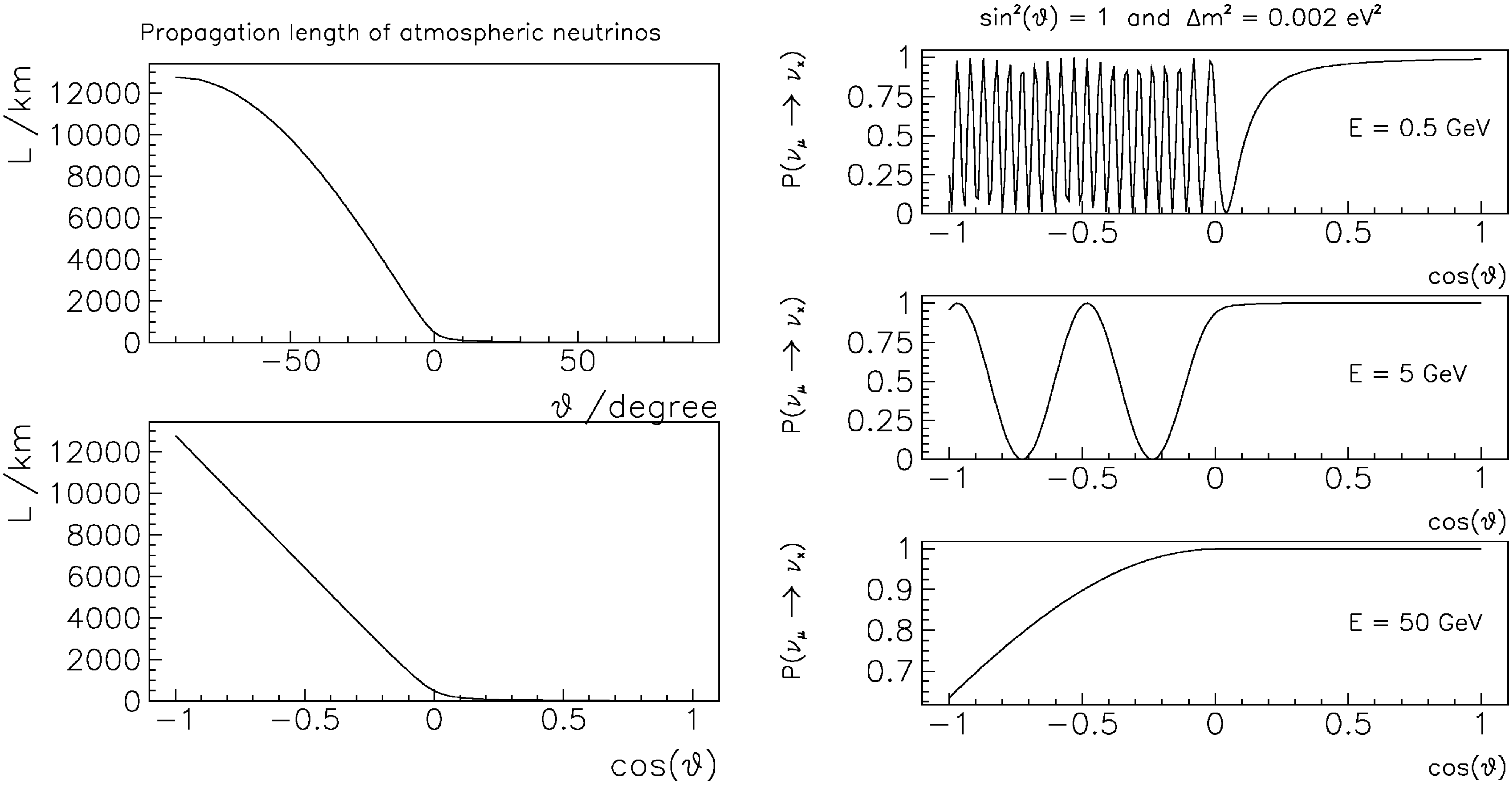
Flavors of eigenstates



The relative phases
of the mass states
in ν_e and ν_μ
are opposite

Interference of the parts of
wave packets with the same
flavor depends on the
phase difference $\Delta\phi$
between ν_1 and ν_2

Erwartung für SK-Daten



Propagation length of atmospheric neutrinos

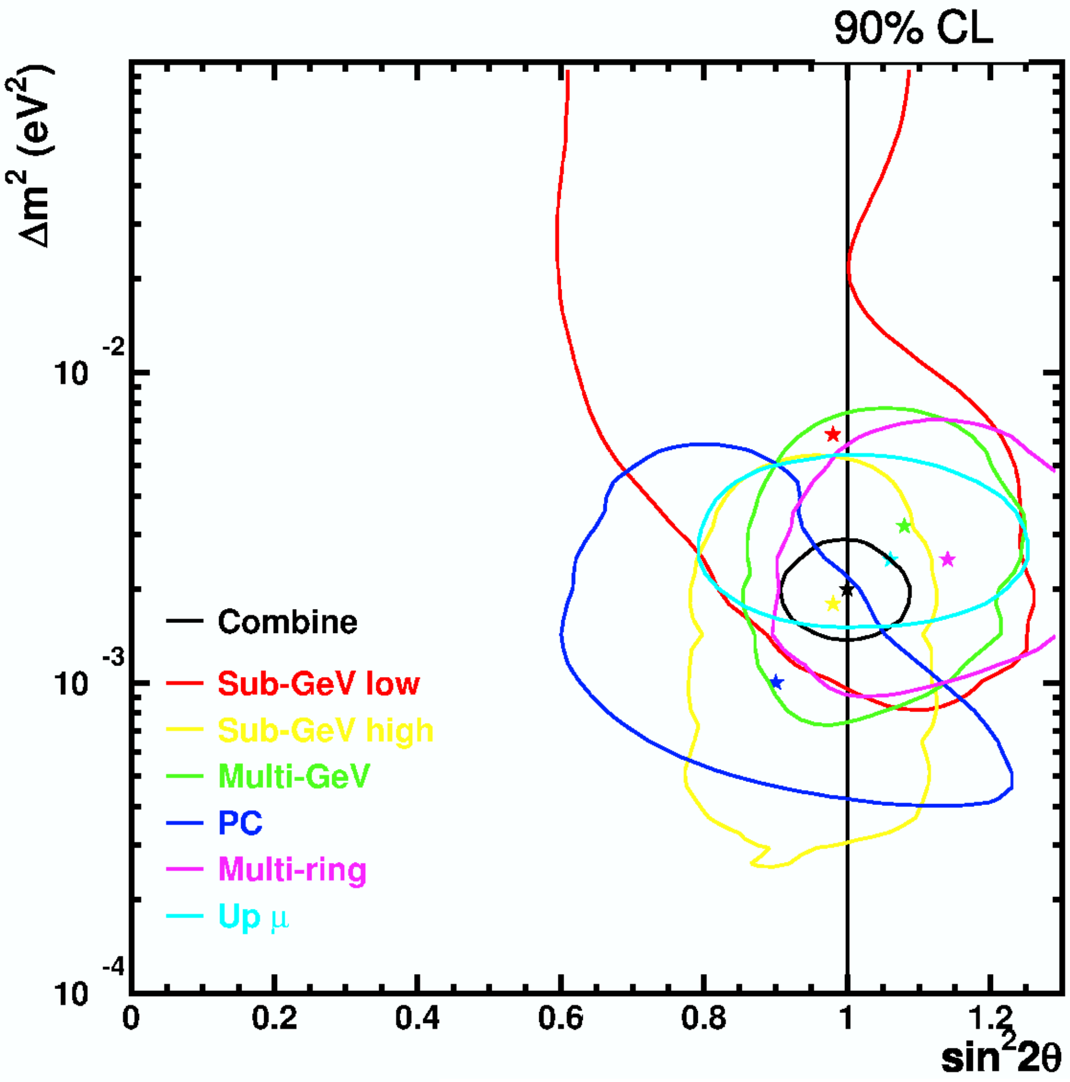
sin²(ϑ) = 1 and Δm² = 0.002 eV²

Analyse der atmosphärischen SK-Daten

Improvements

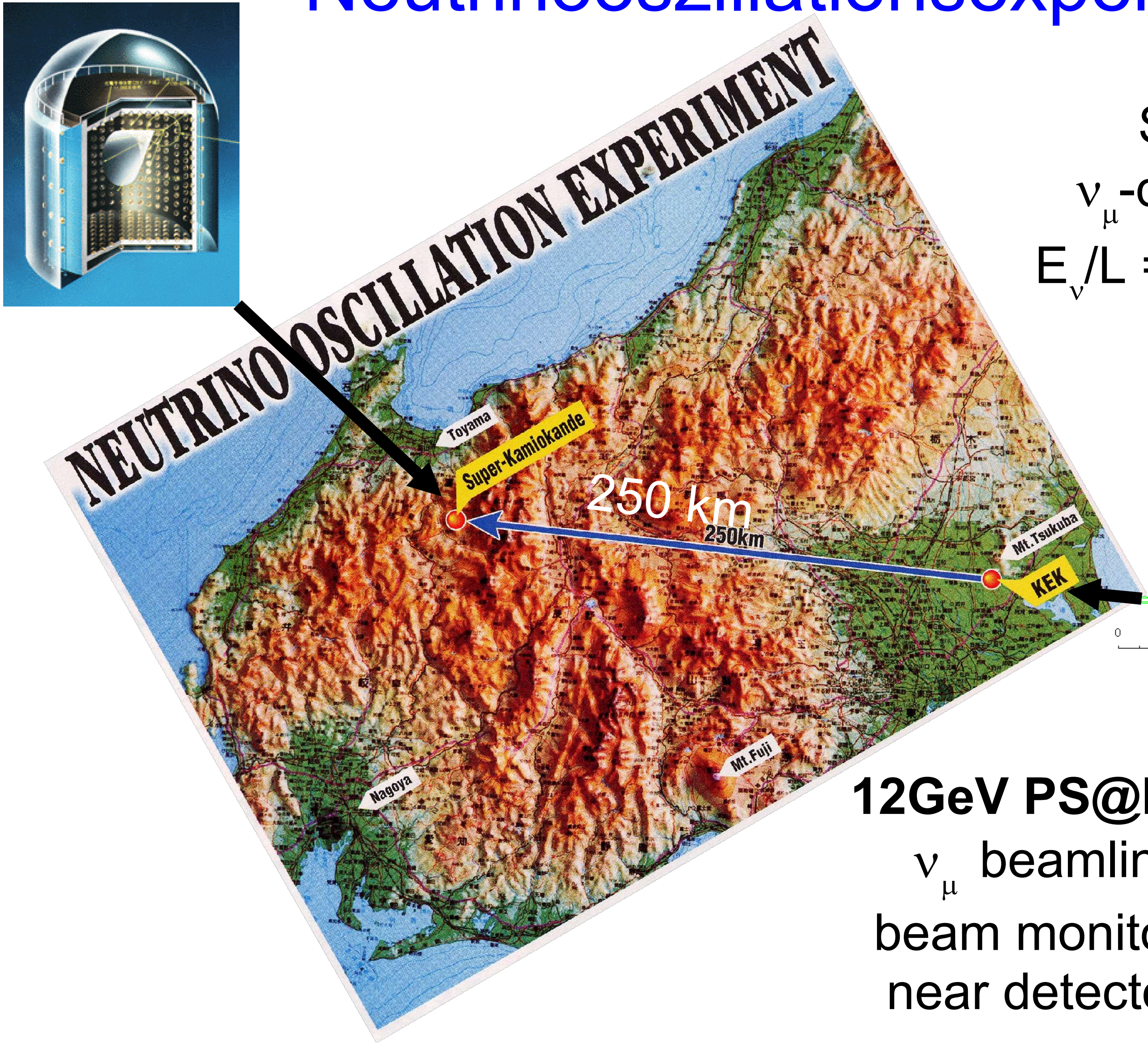
- ν flux
  (1dimensional ➔ 3d.)
- ν interaction models
  (based on K2K near data)
- Detector simulation
- Event reconstruction

Each change contributes to the shift in the allowed (Δm^2) region.

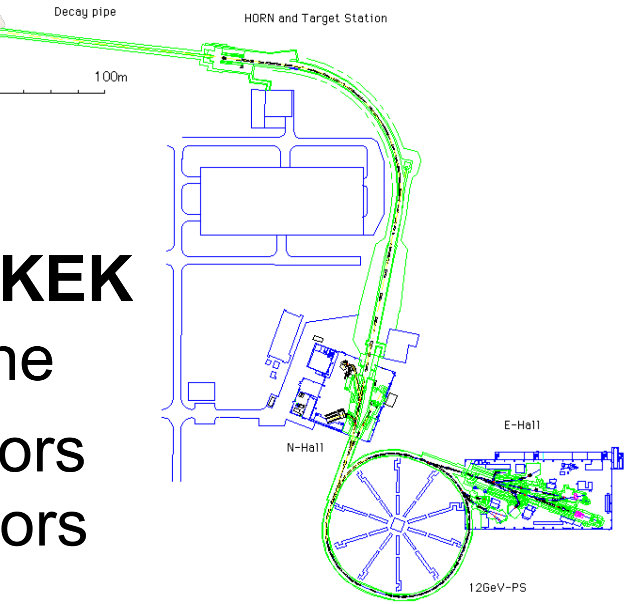


Alle Datensätze und Analysen sind kompatibel mit
$\nu_\mu \rightarrow \nu_\tau$-Oszillation: $\Delta m^2 \approx 2 \times 10^{-3}$ eV^2 und $\sin^2(2\theta) \approx 1$ (maximale Mischung)

Überprüfung durch K2K „long baseline“ Neutrinooszillationsexperiment



Suche nach
ν_μ-disappearance:
E_ν/L = 1.3GeV/250km



12GeV PS@KEK
ν_μ beamline
beam monitors
near detectors

K2K-Ergebnisse

K2K-I

von März 1999 ~ Juli 2001

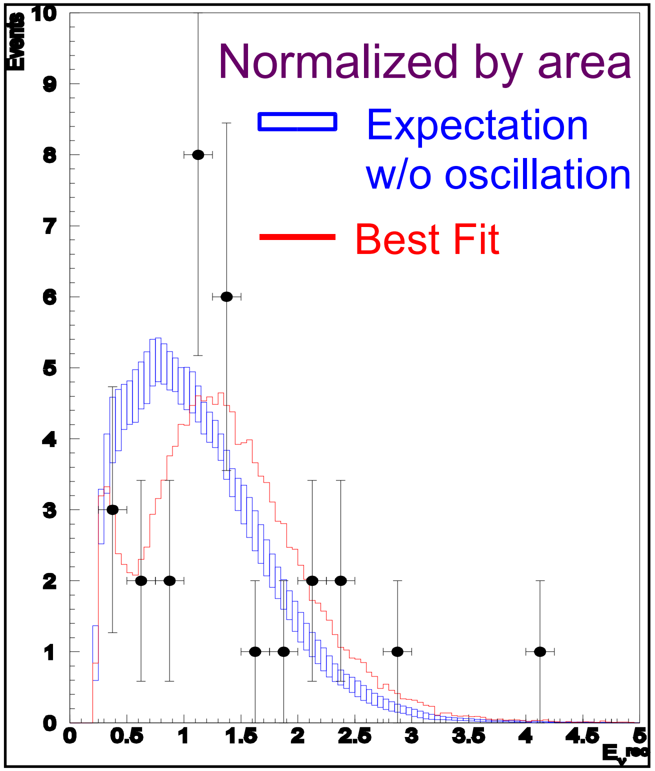
erwartete #: 80.1 +6.2-5.4

gemessen #: 56

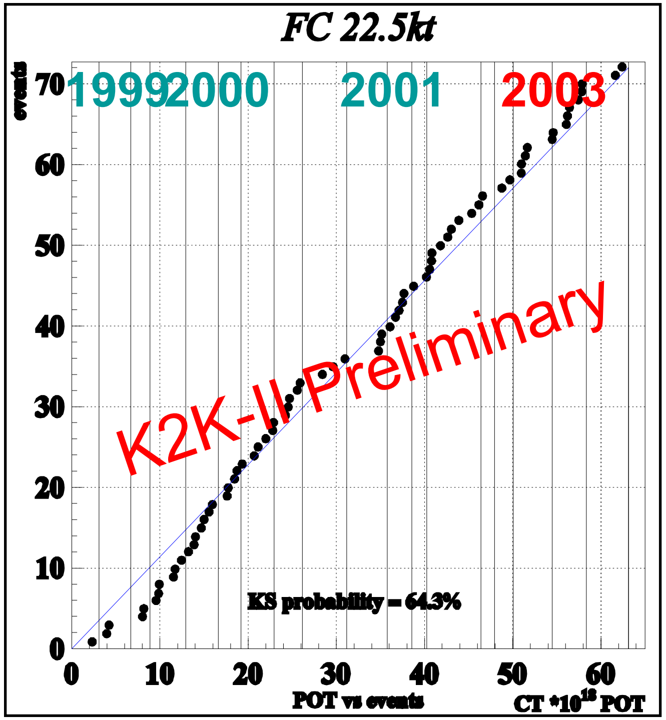
$\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3}\ \mathrm{eV}^2$

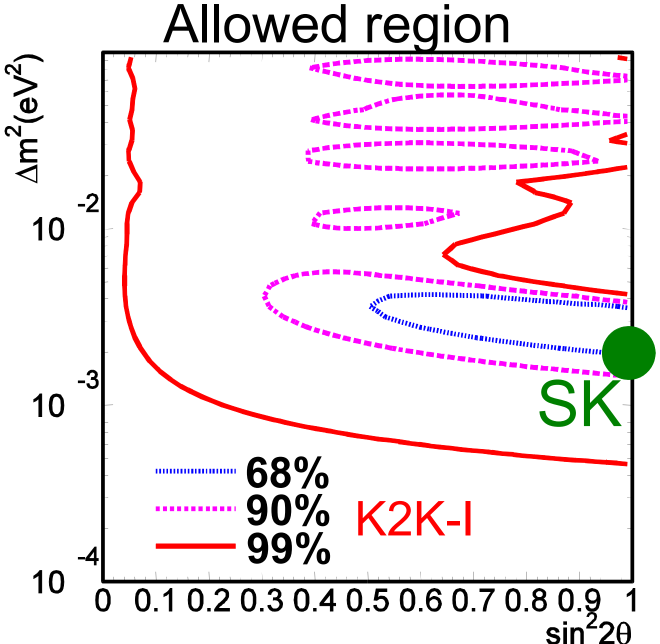
@$\sin^2 2\theta = 1$ (90%CL)

Nullhypothese: <1%



reconstructed E_ν





Atmosphärische Neutrinos: wirklich Neutrinooszillation ?

Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

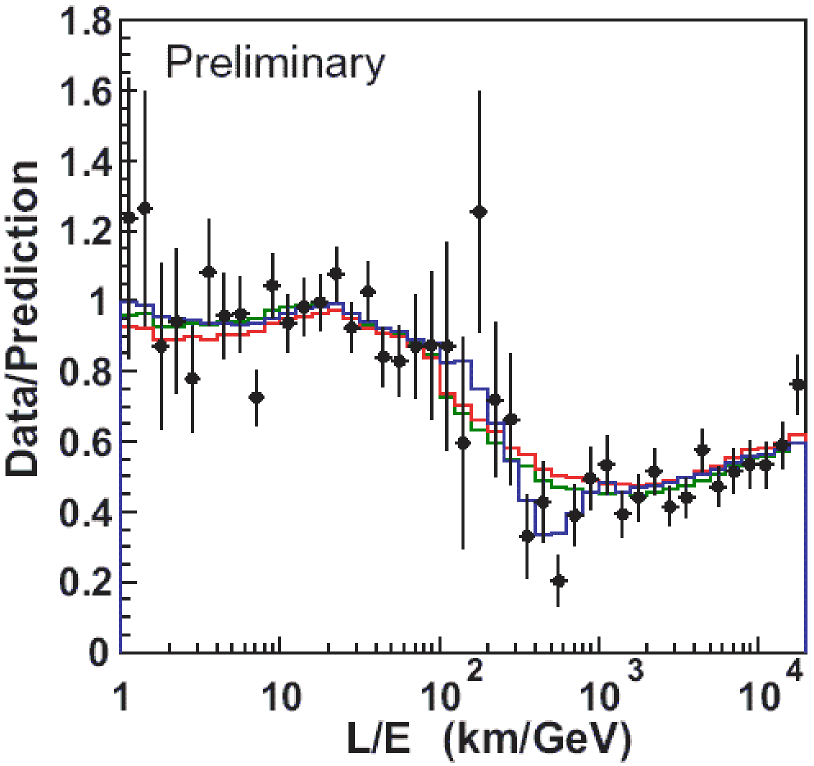
Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \text{ x } \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \text{ x } (1 - \exp(-\gamma_0 \frac{L}{E}))$

— **Oscillation** χ^2_{min}=37.8/40 d.o.f

— **Decay** χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$ =11.4

— **Decoherence** χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$ =14.6



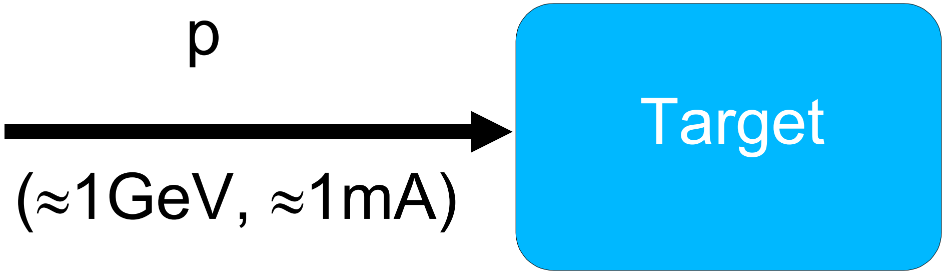
3.4 σ to ν decay

3.8 σ to ν decoherence

First dip observed in data cannot be explained by alternative hypotheses

Ishisuka, NOON2004

$\bar{\nu}_\mu$ - $\bar{\nu}_e$ Neutrinooszillationsexperimente an Beamstop-Quellen (ISIS/RAL, LAMPF/Los Alamos)



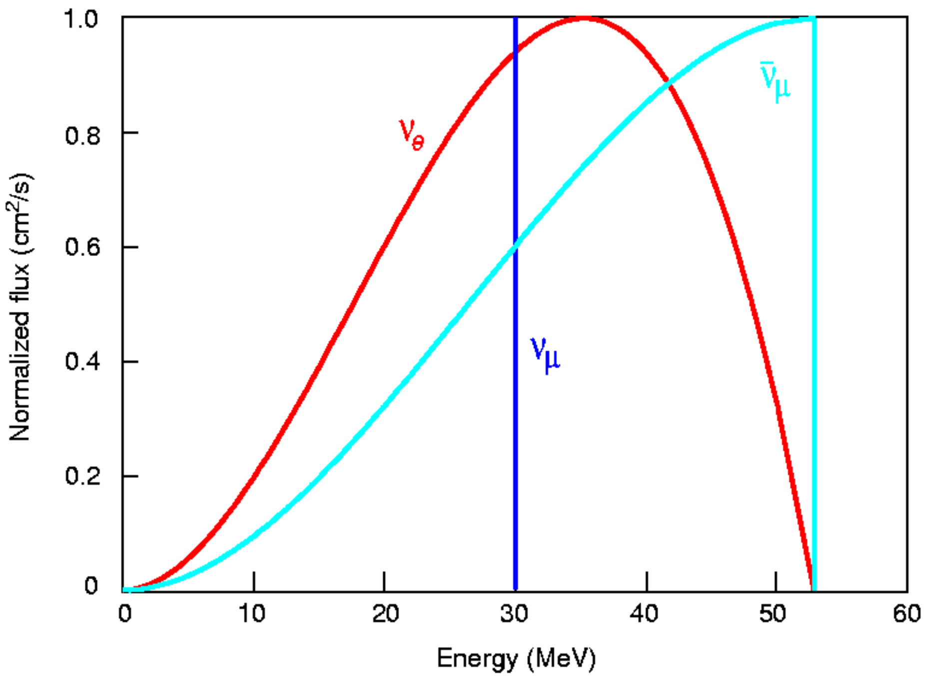
Protonen auf Target $\Rightarrow \pi^\pm$

π^- wird von Kernen absorbiert

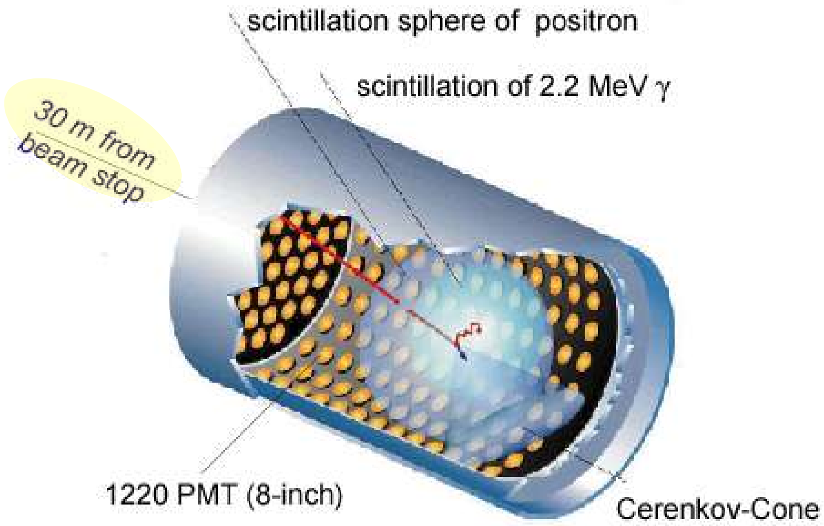
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

$\Rightarrow$ keine $\bar{\nu}_e$!



$\overline{\nu}_\mu$ - $\overline{\nu}_e$ appearance: LSND-Experiment/Los Alamos



167 t diluted scintillator

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e + p \rightarrow e^+ + n$$

$$\downarrow \quad \tau = 186\ \mu s$$

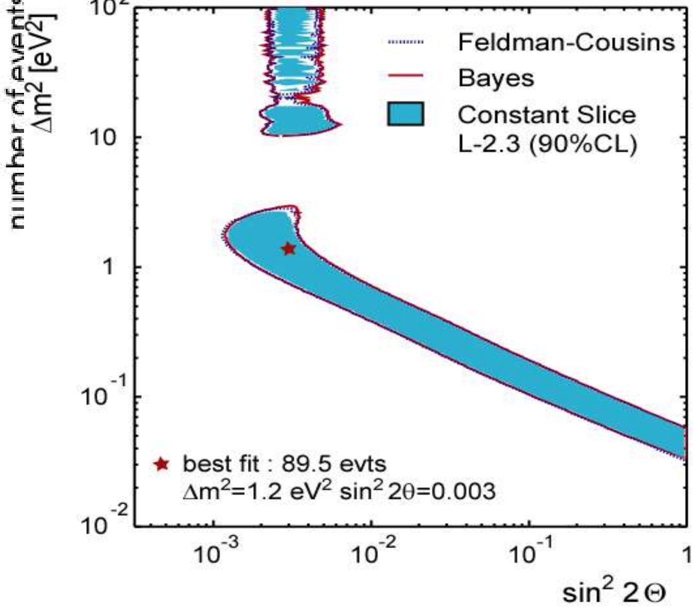
$$p(n,\gamma)d \quad (2.2\ \text{MeV})$$

(49.1 ± 9.4) (beam on-beam off) excess

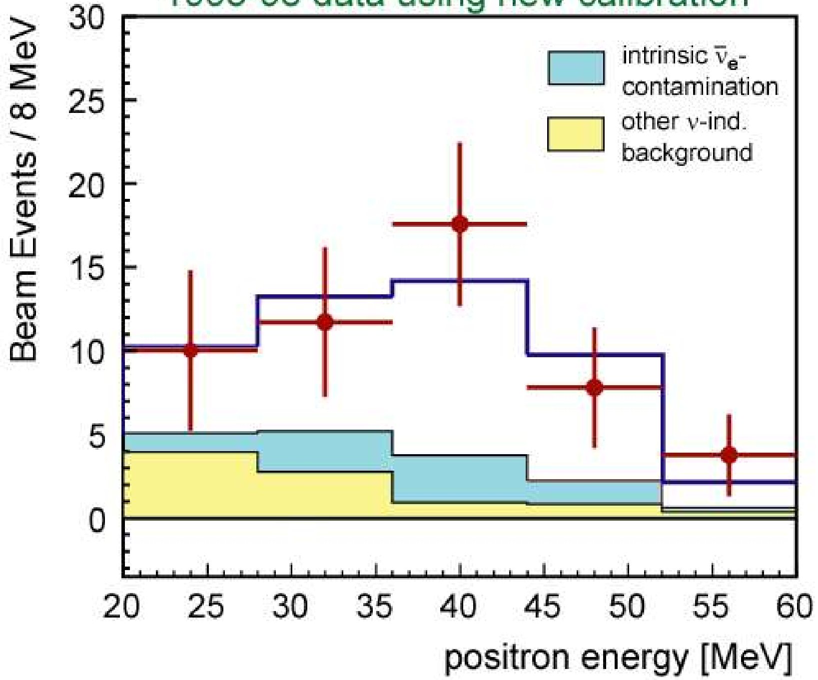
(16.9 ± 2.3) neutrino induced background

(32.2 ± 9.4) event excess (attr. to oscillations)

LSND favoured regions (90%CL)



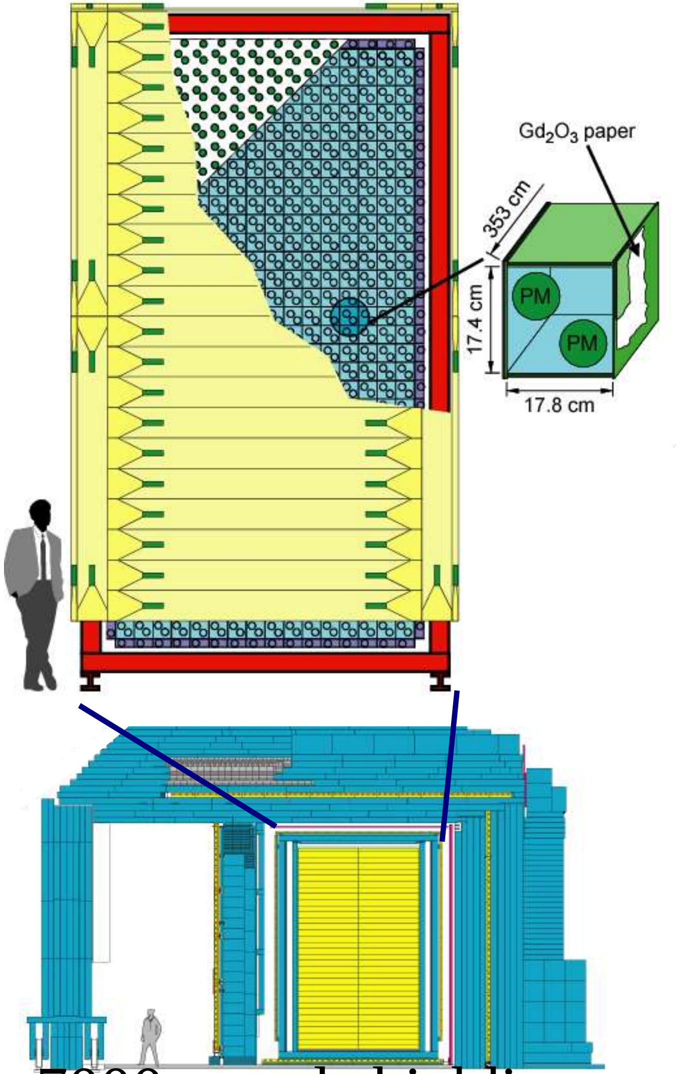
1993-98 data using new calibration



Karmen II am Rutherford Laboratory/UK

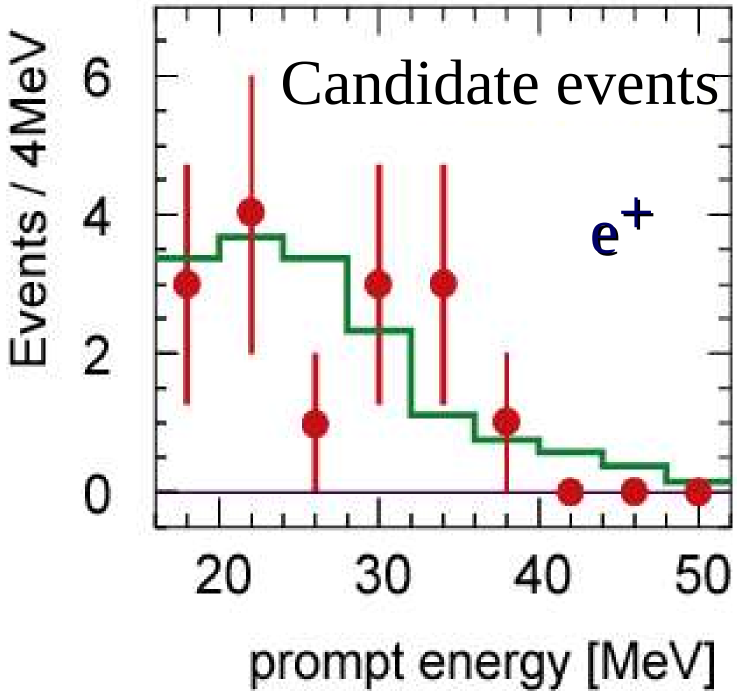
KARMEN2: looking for ν_μ-ν_e appearance at ISIS (1997-2001)

56 t high resolution liquid scintillator at **d=17m**
but: much more compact & simple target (!)



7000 t steel shielding

KARMEN2 oscillation results
4y of measuring after upgrade:



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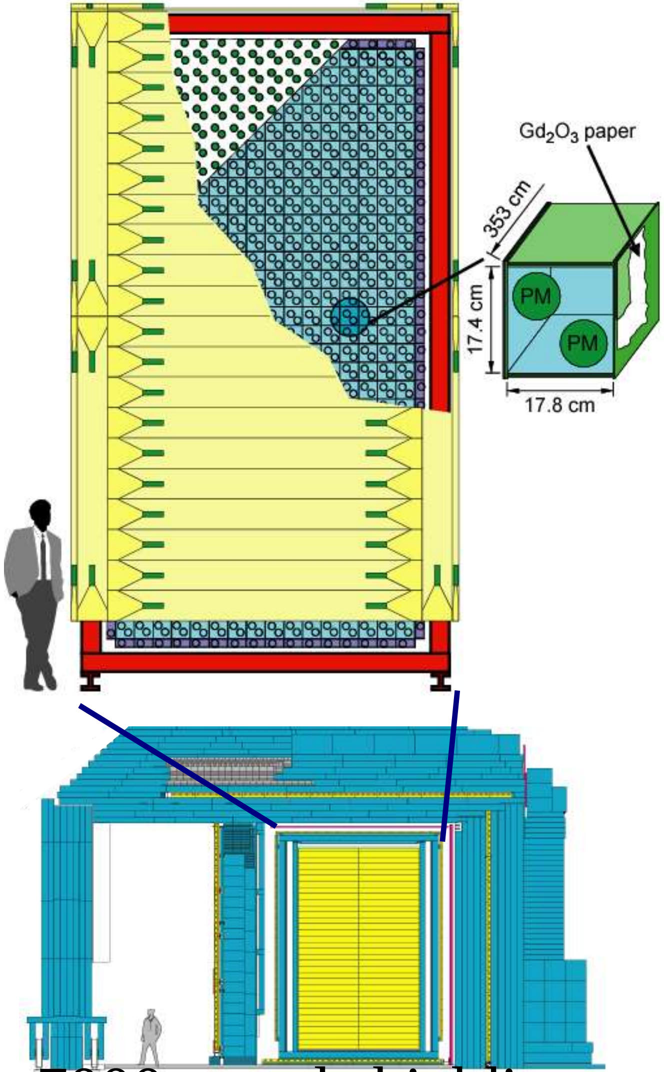


7000 t steel shielding

KARMEN2 oscillation results
4y of measuring after upgrade:

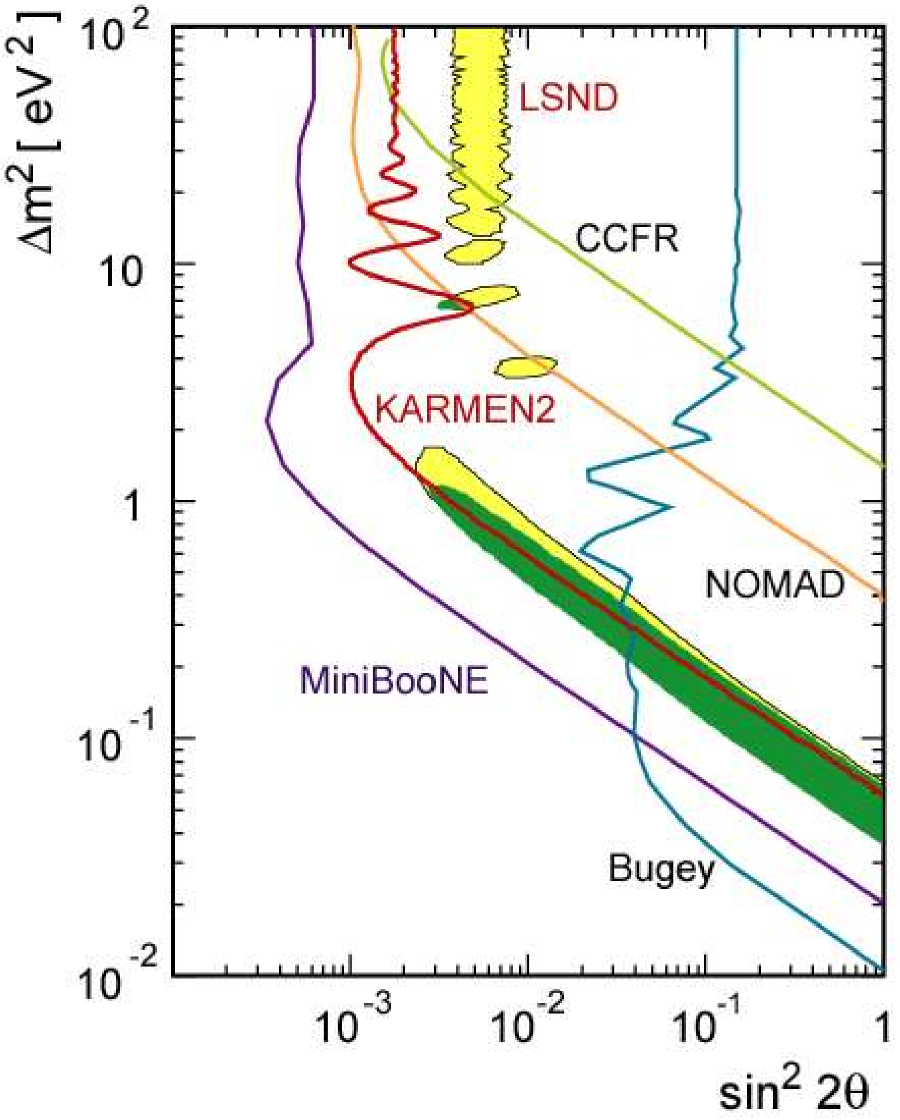
15 candidate events

(15.8 ± 0.5) background
events are expected

cosmic background : 3.9 ± 0.2 evts
ν_e-induc. excl. CC : 5.1 ± 0.2 evts
ν_e-ind. CC & rand. γ : 4.8 ± 0.3 evts
intrin. contamination : 2.0 ± 0.2 evts

no oscillation excess

Endgültige LSND- und Karmen II-Resultate



4y KARMEN2 data taking 2/97 - 2/02

unified (frequentist) approach
Feldman-Cousins

oscillation limit :

$\sin^2 2\theta < 1.7 \times 10^{-3}$ (90% CL.)

large Δm^2

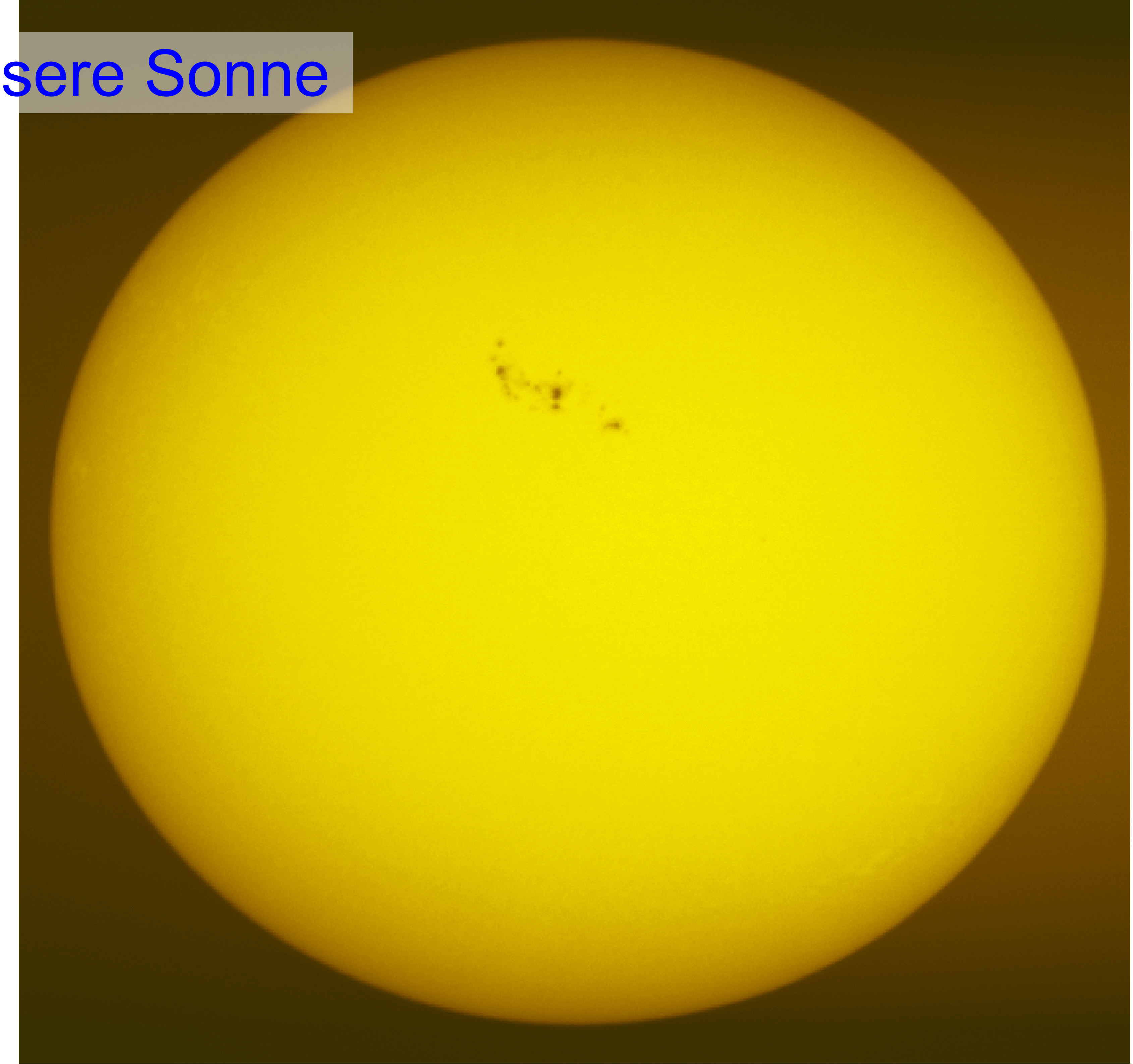
oscillation sensitivity :

$\sin^2 2\theta < 1.6 \times 10^{-3}$ (90% CL.)

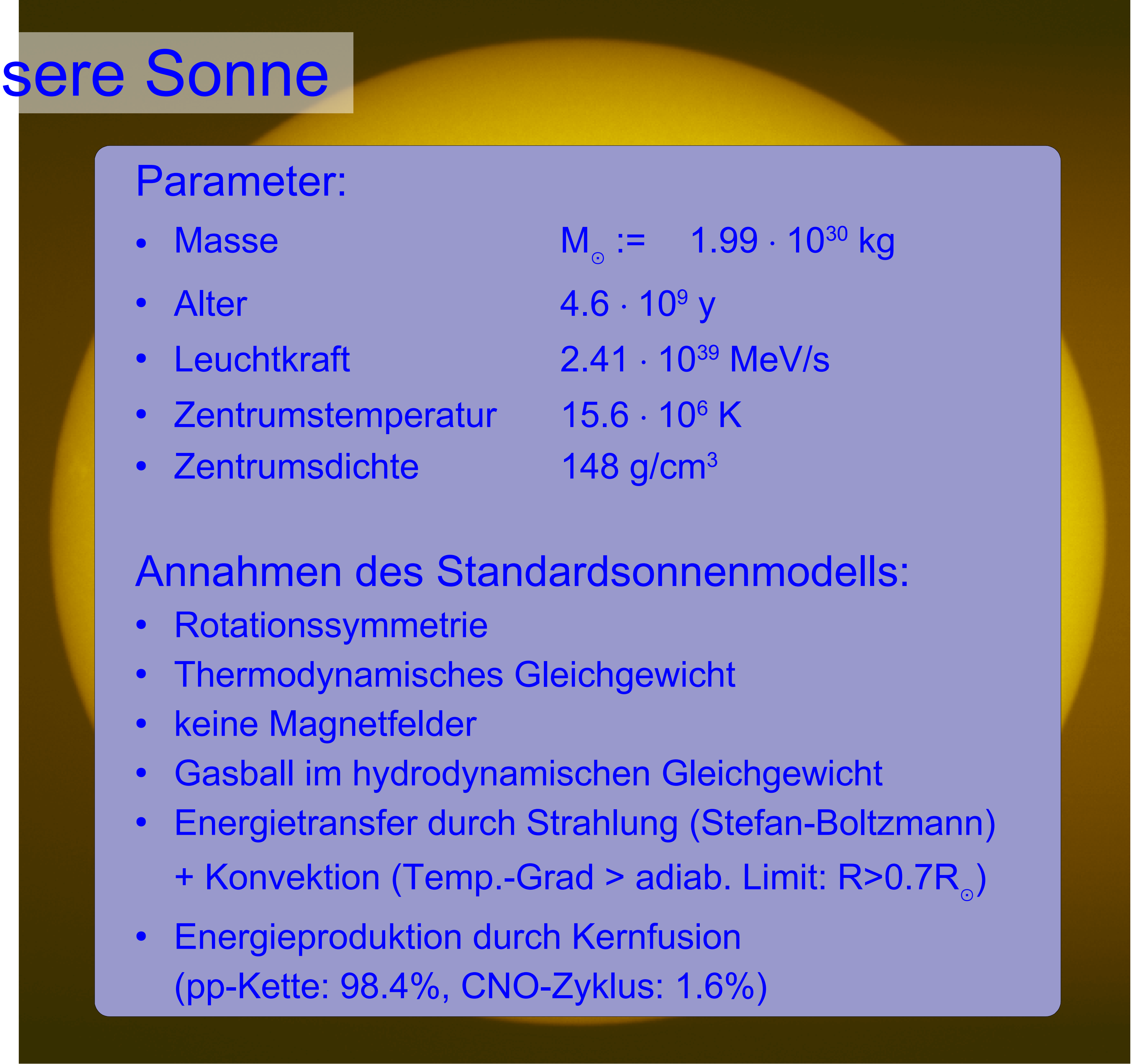
KARMEN2 excludes a significant part of the LSND parameter space

Compatibility analysis:
LSND&KARMEN2
incompatible at individual 64% CL.

Unsere Sonne



Unsere Sonne



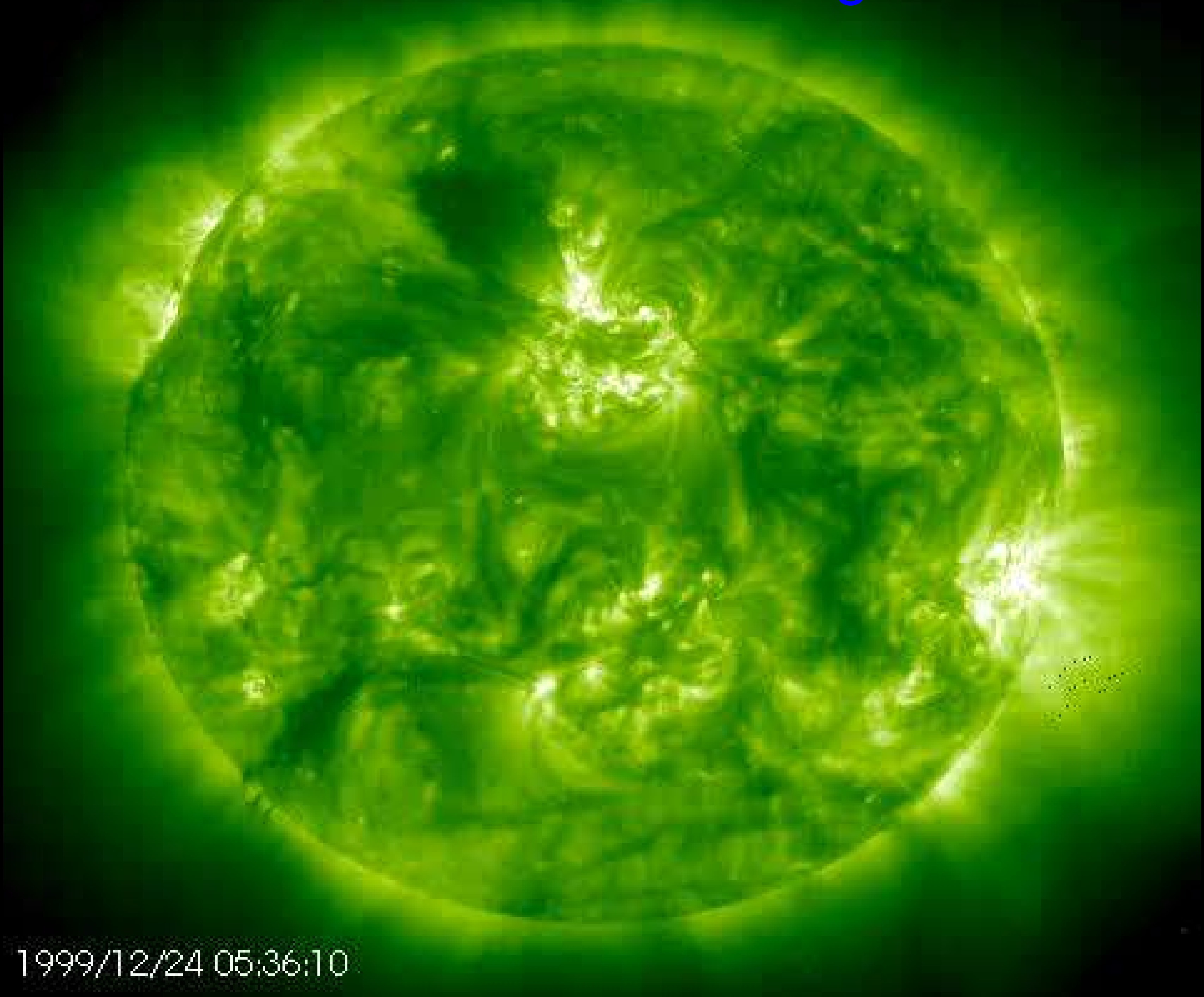
Parameter:

Masse	$M_\odot := \quad 1.99 \cdot 10^{30}$ kg
Alter	$4.6 \cdot 10^{9}$ y
Leuchtkraft	$2.41 \cdot 10^{39}$ MeV/s
Zentrumstemperatur	$15.6 \cdot 10^{6}$ K
Zentrumsdichte	148 g/cm^3

Annahmen des Standardsonnenmodells:

- Rotationssymmetrie
- Thermodynamisches Gleichgewicht
- keine Magnetfelder
- Gasball im hydrodynamischen Gleichgewicht
- Energietransfer durch Strahlung (Stefan-Boltzmann)
  + Konvektion (Temp.-Grad > adiab. Limit: $R>0.7R_\odot$)
- Energieproduktion durch Kernfusion
  (pp-Kette: 98.4%, CNO-Zyklus: 1.6%)

Die Sonne bei einer Wellenlänge von 195Å



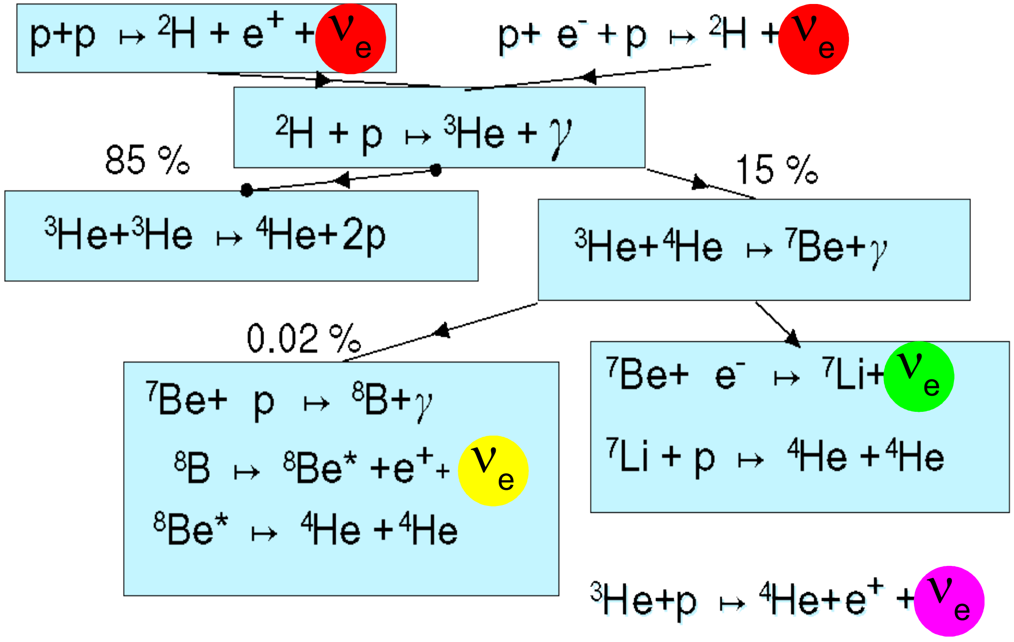
Extreme ultraviolett Imaging Telescope EIT des SOHO Satelliten

Blick ins Innere der Sonne: solare Neutrinos

Kernfusion im Herzen der Sonne:

$4\,p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$ (+ 26.7 MeV)

genauer:



$p+p \mapsto {}^2\mathrm{H} + e^+ + \nu_e$

$p + e^- + p \mapsto {}^2\mathrm{H} + \nu_e$

${}^2\mathrm{H} + p \mapsto {}^3\mathrm{He} + \gamma$

85 %

15 %

${}^3\mathrm{He} + {}^3\mathrm{He} \mapsto {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + {}^4\mathrm{He} \mapsto {}^7\mathrm{Be} + \gamma$

0.02 %

${}^7\mathrm{Be} + p \mapsto {}^8\mathrm{B} + \gamma$

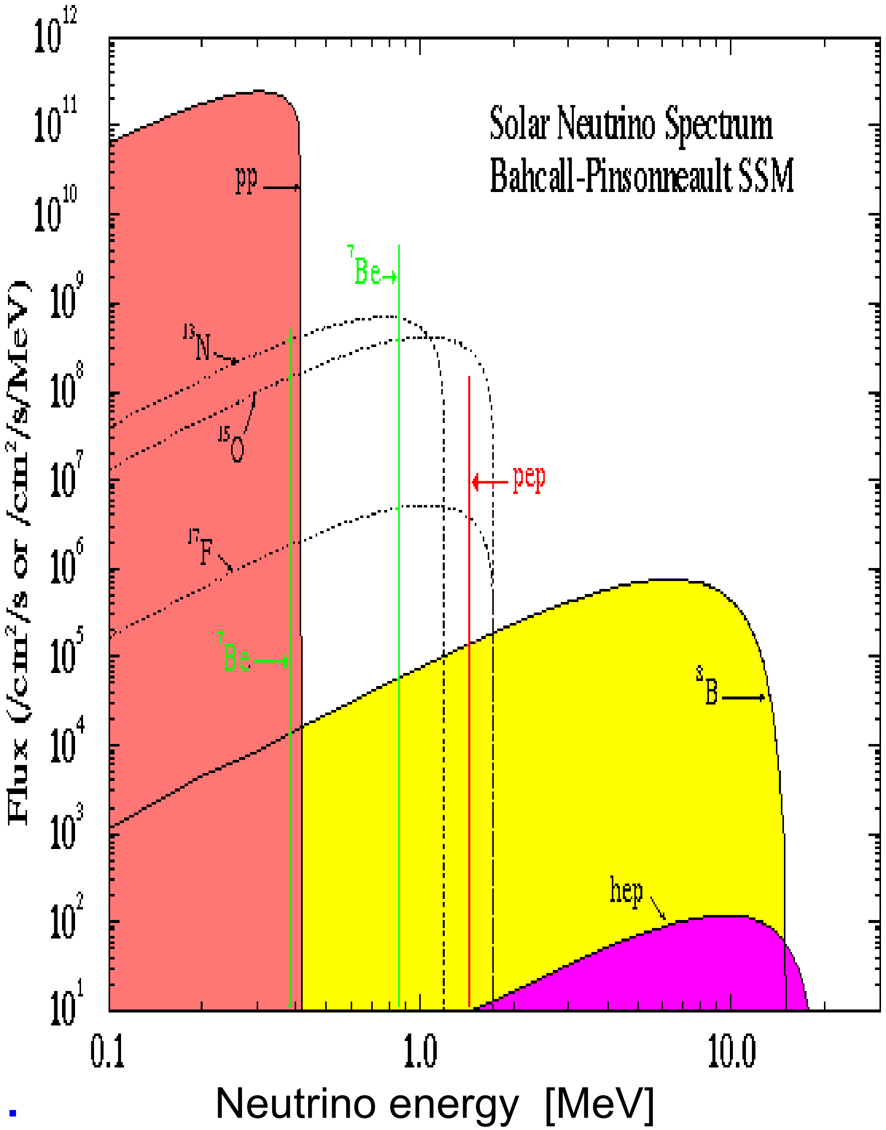
${}^8\mathrm{B} \mapsto {}^8\mathrm{Be}^* + e^+ + \nu_e$

${}^8\mathrm{Be}^* \mapsto {}^4\mathrm{He} + {}^4\mathrm{He}$

${}^7\mathrm{Be} + e^- \mapsto {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Li} + p \mapsto {}^4\mathrm{He} + {}^4\mathrm{He}$

${}^3\mathrm{He} + p \mapsto {}^4\mathrm{He} + e^+ + \nu_e$



Standard-Sonnenmodell: J. Bahcall et al.

auf der Erde:

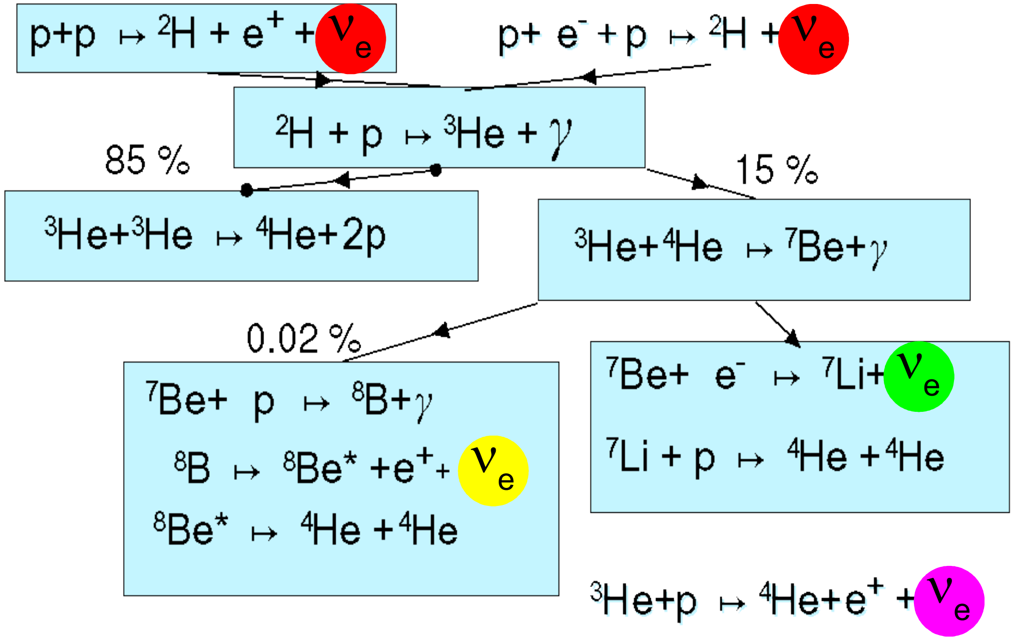
65 Milliarden Neutrinos pro s und cm^2

Blick ins Innere der Sonne: solare Neutrinos

Kernfusion im Herzen der Sonne:

$$4\,p \rightarrow {}^4He + 2e^+ + 2\nu_e \quad (+\,26.7\ \text{MeV})$$

genauer:



$p+p \mapsto {}^2H + e^+ + \nu_e$

$p + e^- + p \mapsto {}^2H + \nu_e$

${}^2H + p \mapsto {}^3He + \gamma$

85 %

15 %

${}^3He + {}^3He \mapsto {}^4He + 2p$

${}^3He + {}^4He \mapsto {}^7Be + \gamma$

0.02 %

${}^7Be + p \mapsto {}^8B + \gamma$

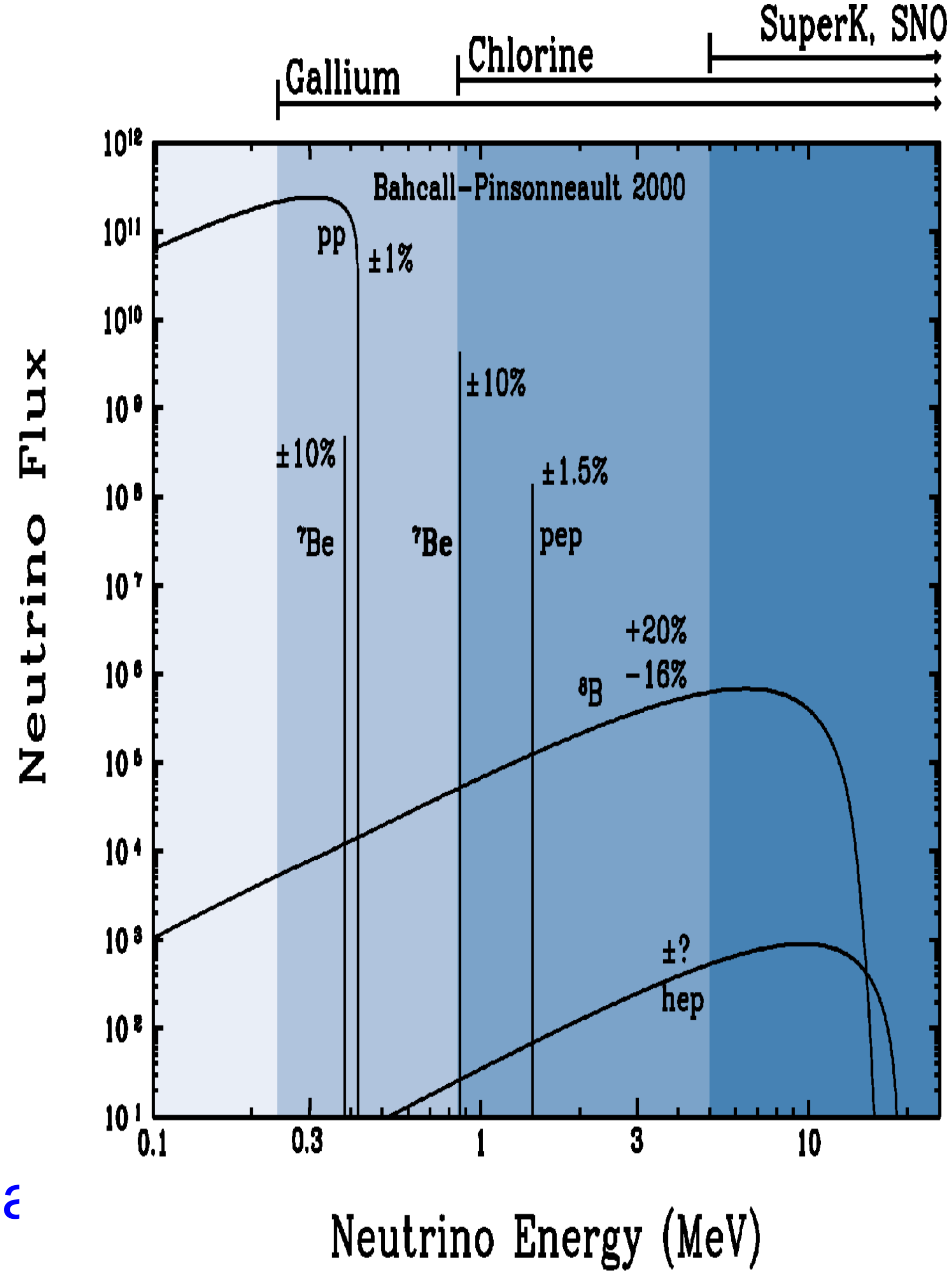
${}^8B \mapsto {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \mapsto {}^4He + {}^4He$

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

${}^7Li + p \mapsto {}^4He + {}^4He$

${}^3He + p \mapsto {}^4He + e^+ + \nu_e$



Standard-Sonnenmodell: J. Bahcall et a

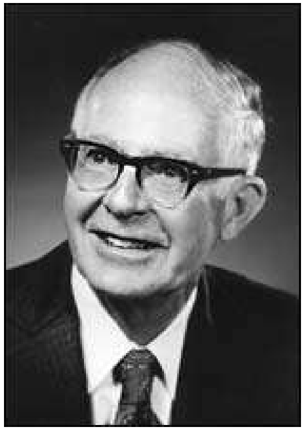
auf der Erde:

65 Milliarden Neutrinos pro s und cm²

Das Chlor Experiment von Ray Davis

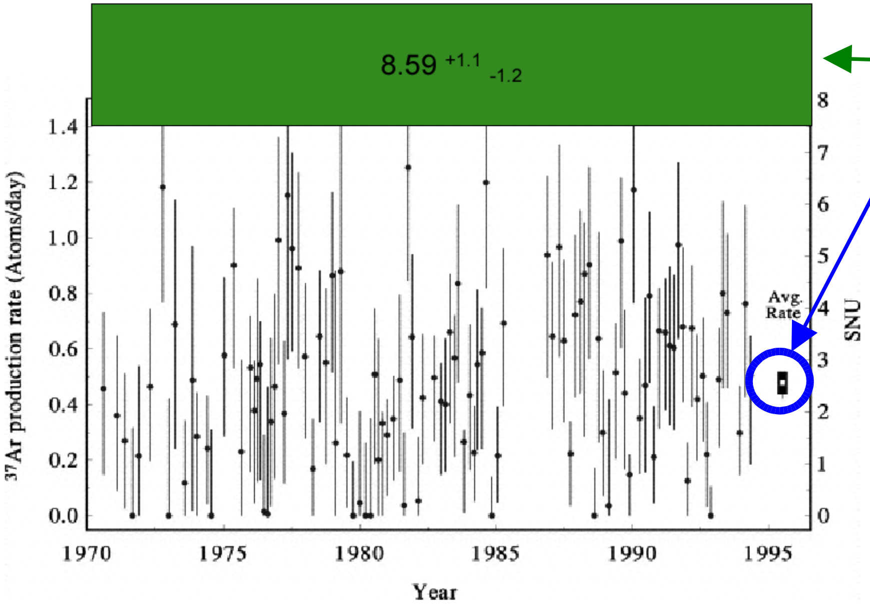
Nobelpreis 2002

380000 l
Perchlorethylen
in der Homestake Miene



$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$

Ausspülen des ${}^{37}\mathrm{Ar}$ (0.5 Atom/Tag !)
und radiochemischer Nachweis



Resultat ist nur 30% von Erwartung

- Ist das Experiment falsch?
- Ist die Theorie der Sonne falsch?
- Verhalten sich die Neutrinos anders?

GALLEX und andere Galliumexperimente

- GALLEX (später GNO), SAGE):
  Inverser β-Zerfall von solaren ν_e an Gallium (^{71}Ga)

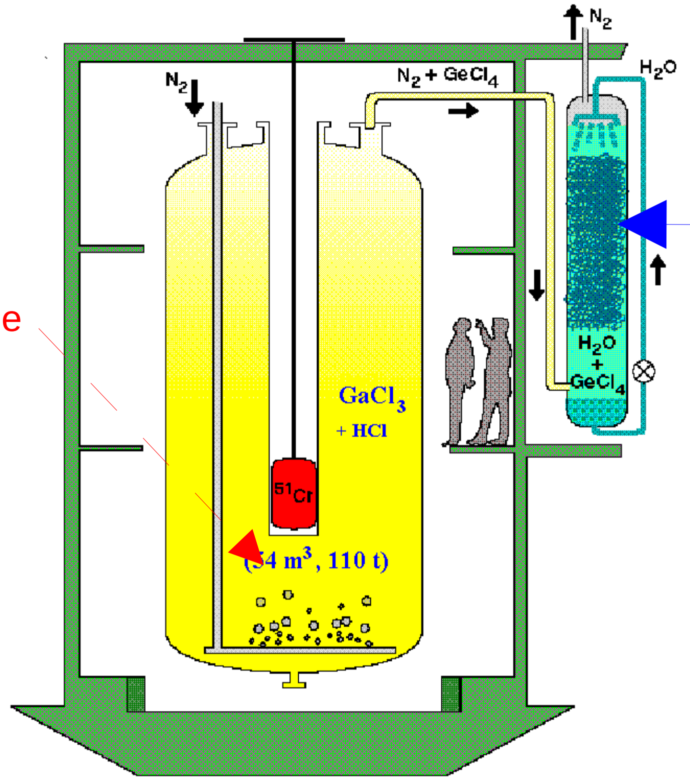
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

radiochemischer Nachweis:

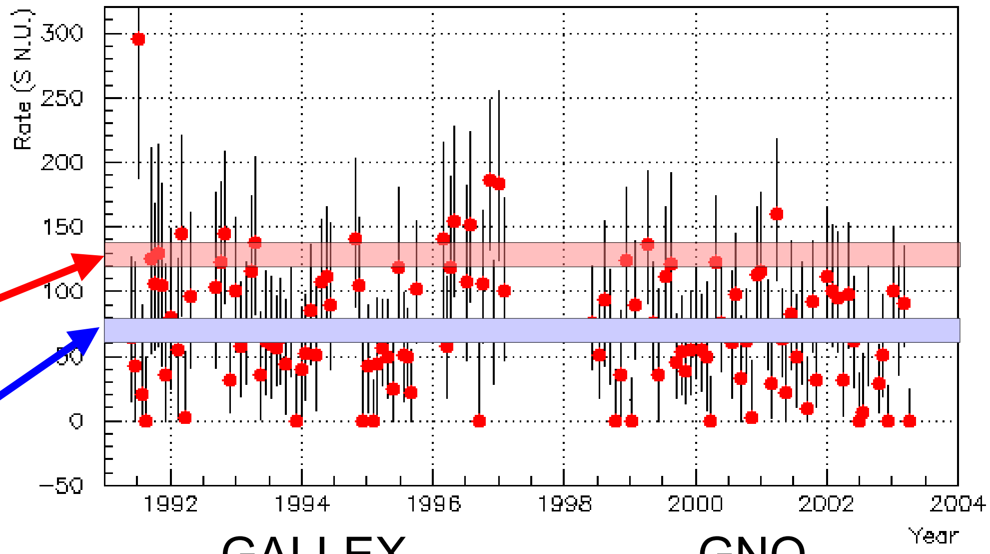
1) Chemische Abtrennung von ^{71}Ge
2) Nachweis durch radioaktiven Rückzerfall
   Nachweiseffizienz ≈ 90 % (geeicht mit ν-Quelle)

GALLEX im Gran Sasso

ν_e



SSM(BP)	128^{+9}_{-7}	SNU
GALLEX	$77.5 \pm 6.2\,^{+4.3}_{-4.7}$	SNU
GNO	$62.9 \pm 5.4 \pm 2.5$	SNU
SAGE	$69.1^{+4.3}_{-4.2}$	SNU

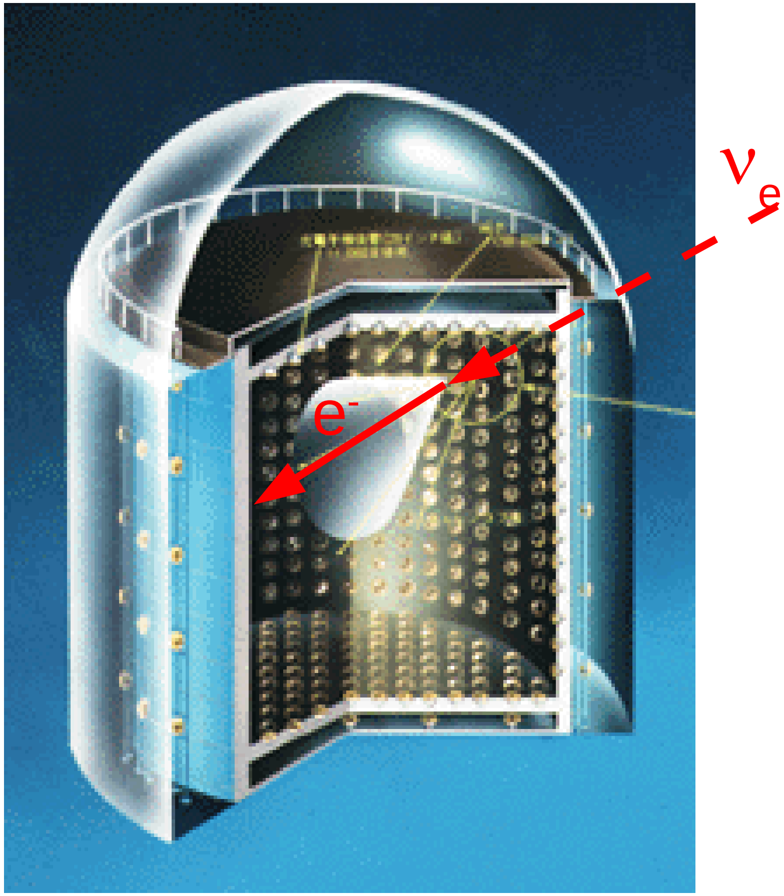


GALLEX
65 solar runs

GNO
58 solar runs

Nachweis von Neutrinos mit Super-Kamiokande

Im Gegensatz zu atmosph. Neutrinos: $\nu_e + e^- \rightarrow e^- + \nu_e$ (elastische Streuung)



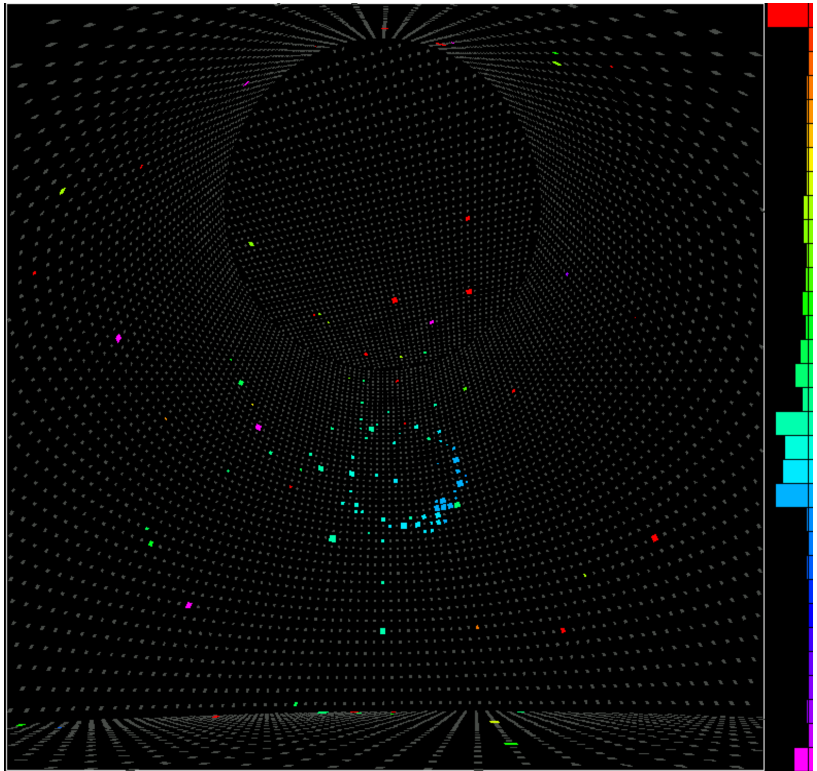
Nachweis der Neutrinos:

ν_e erzeugt ein e^-

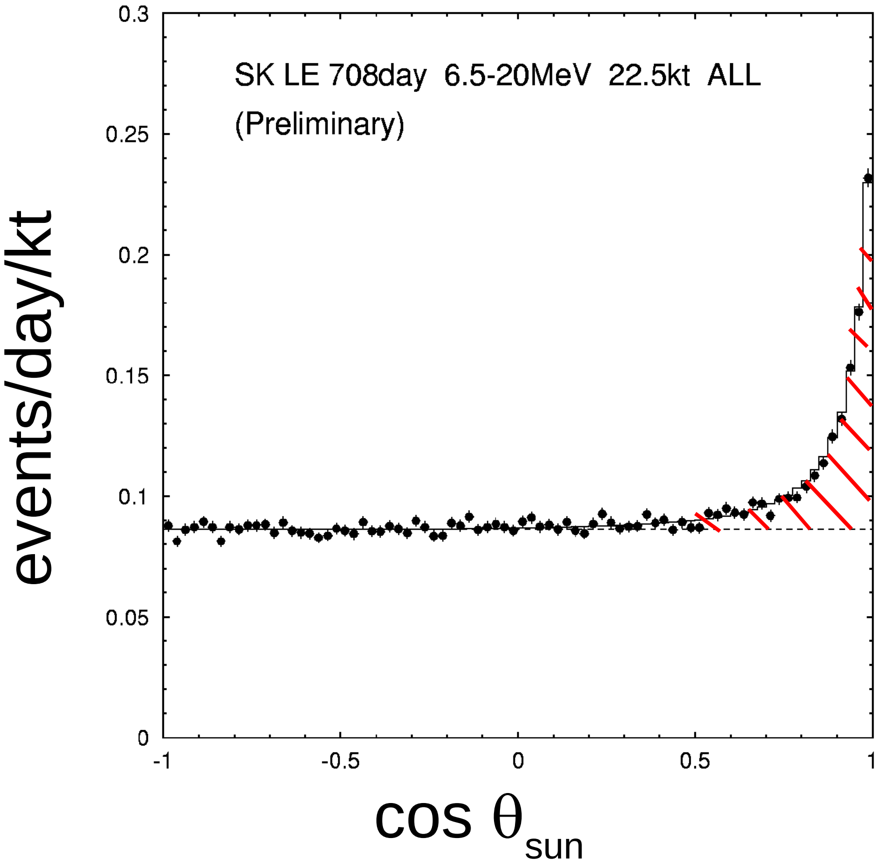
$v(e^-) > c/n$

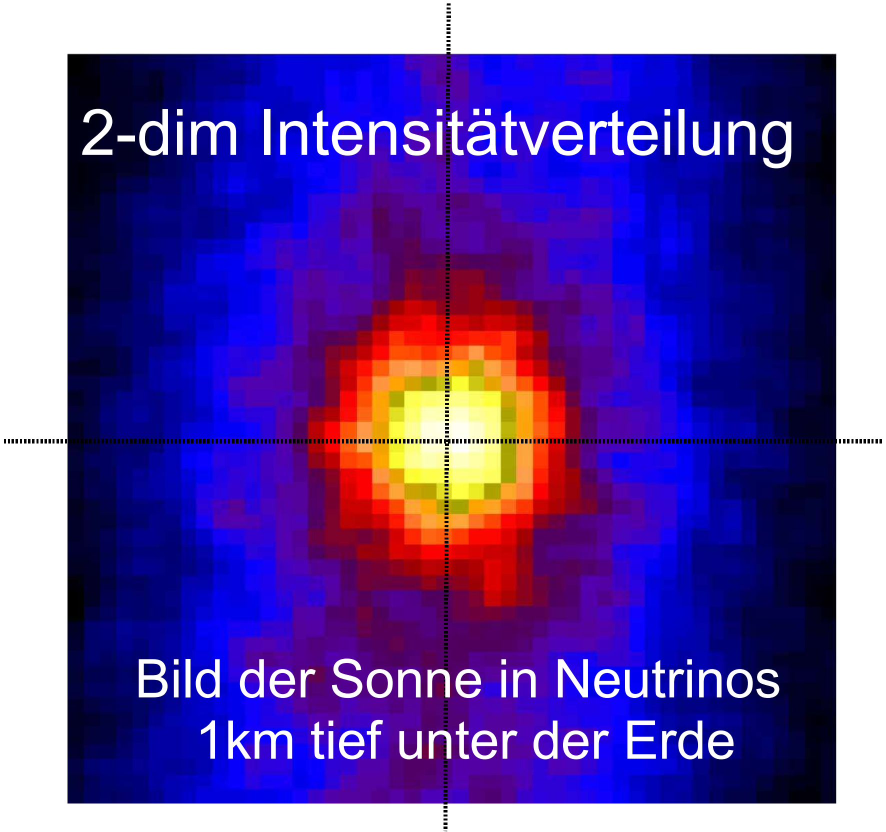
Cherenkov-Kegel:

⇒ Richtung und Energie



Bestimmung des Signals über Winkelverteilung





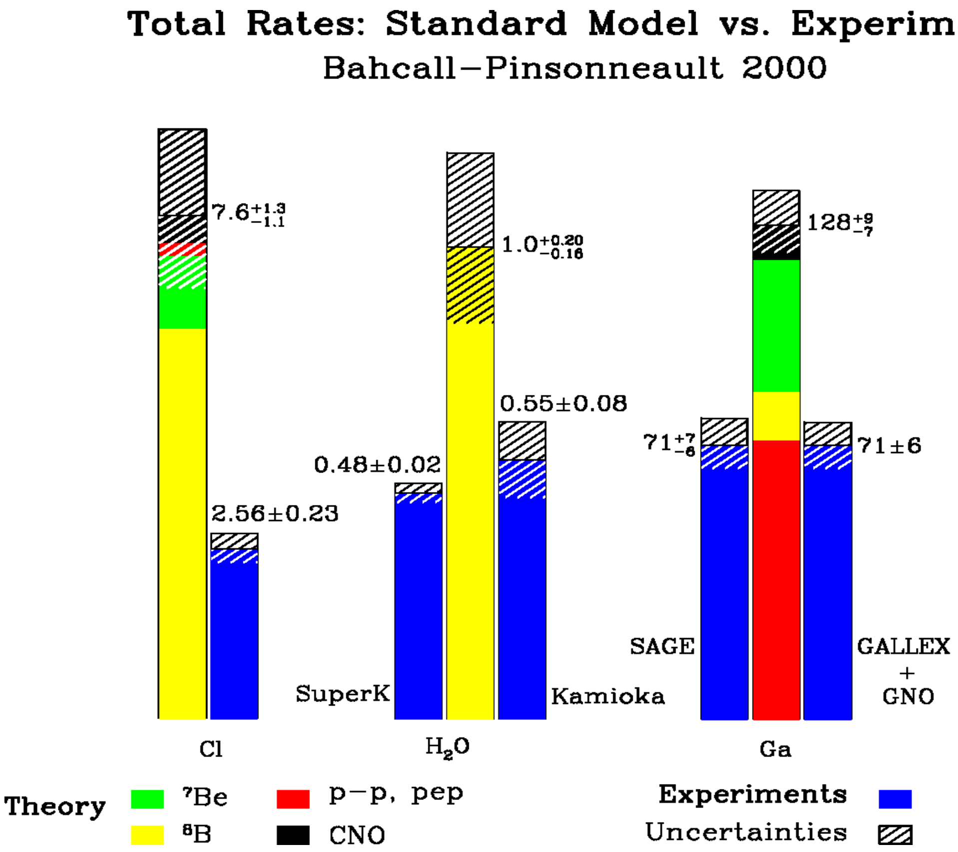
$\Rightarrow$ ν_e kommen wirklich von der Sonne

(erster direkter Beweis der Kernfusion im Inneren der Sonne durch Kamiokande 1990)

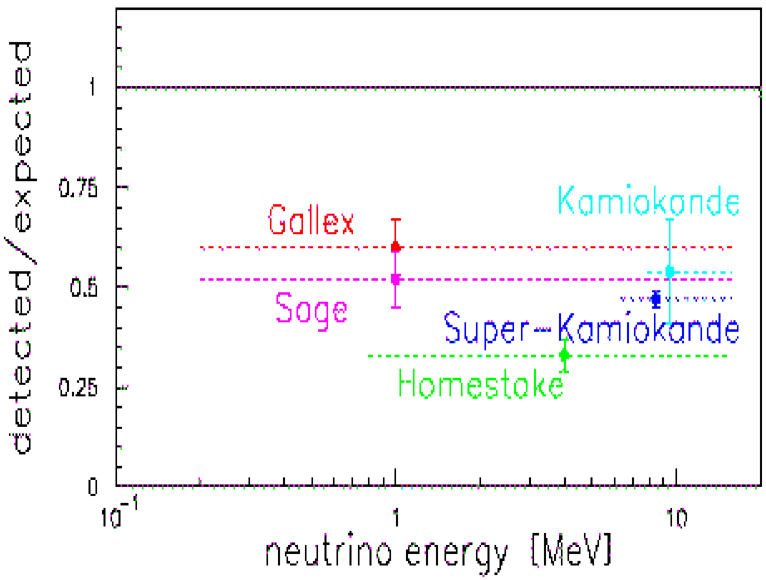
aber deutlich zu wenig:

$\#\nu_{\text{gemessen}} / \#\nu_{\text{erwartet}} = 0.47 \pm 0.20$

Exp. solare Neutrinoraten vor SNO: solares ν-Problem



Exp. haben unterschiedliche Energieschwellen



Reduktion: ≈1/3 ≈1/2 ≈2/3

Was ist falsch ?

- Experimente ?
- Sonnenmodell ? (aber die verschiedenen Reduktionen können nicht durch Änderungen der Einzelflüsse einfach erklärt werden)
- Annahmen über Neutrinos (Neutrinooszillationen) ?

Neutrinooszillation und solares Neutrinoproblem

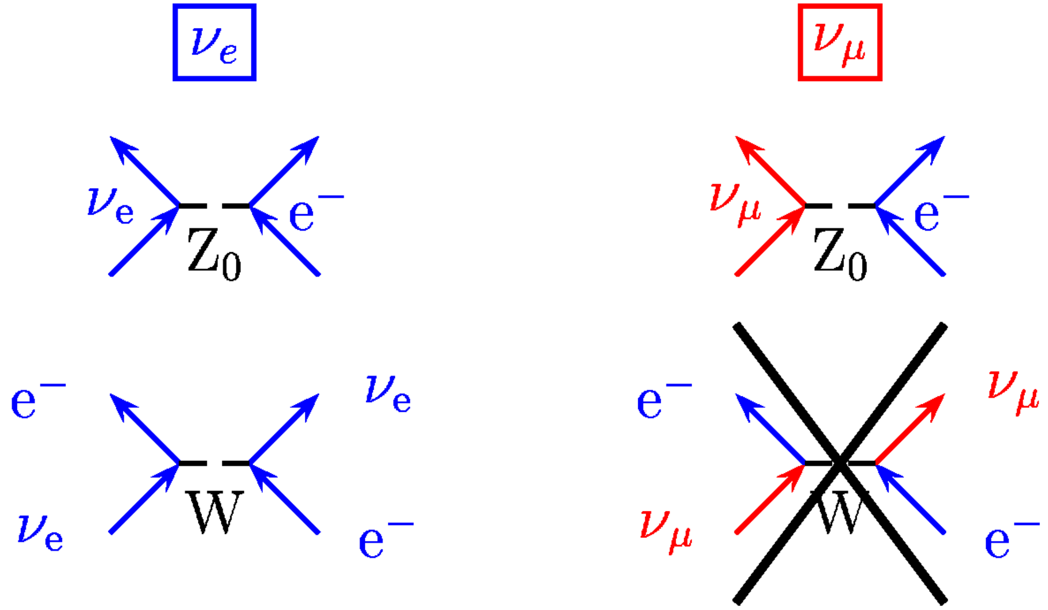
Starke Auslöschung bei Chorexperiment (≈1/3<1/2)

⇒ Abstand Sonne-Erde = $1.44 \cdot 10^{11}$ m $\approx \lambda_{osc}$, mit $E_\nu \approx 10$ MeV

⇒ $\Delta m^2 = 10^{-10}\,\mathrm{eV}^2$ (⇒ Finetuning-Problem)

Lösung: Matterie-verstärkte Oszillation in Materie
(MSW-Effekt, Mirkheyev-Smirnov-Wolfenstein)

Vorwärtsstreung von ν an e^-



→ Unterschiedlicher "Brechungsindex" für ν_e und ν_μ

→ Zusätzlicher Phasenunterschied in der Ausbreitung

→ Neutrinooszillation

MSW-Effekt

Vakuumoszillationen:

$$P(\nu_e \to \nu_\mu) = \left| \begin{pmatrix} 0 \\ 1 \end{pmatrix} \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{U} \underbrace{\begin{pmatrix} e^{-im_1^2/2p\cdot t} & 0 \\ 0 & e^{-im_2^2/2p\cdot t} \end{pmatrix}}_{e^{-i\mathcal{H}_i t}} \underbrace{\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}}_{U^{-1}} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right|^2$$

$$\mathcal{H} = \sqrt{p^2 + m^2} \approx p + m^2/2p = \mathcal{H}_0 + \mathcal{H}_i$$

Mit Materieeffekt:

Zusätzliche CC-Wechselwirkung für ν_e: $\mathcal{H}_{CC} = \sqrt{2} \cdot G_F N_e$

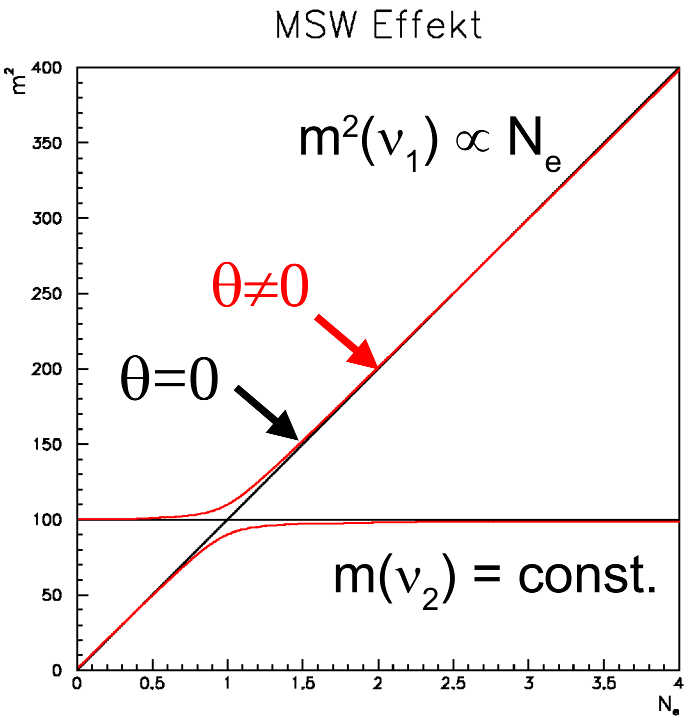
$$\mathcal{H}_{tot} = \mathcal{H}_i + \tilde{\mathcal{H}}_{CC} = \underbrace{\begin{pmatrix} m_1^2/2p & 0 \\ 0 & m_2^2/2p \end{pmatrix} + U^{-1} \begin{pmatrix} \sqrt{2} G_F N_e & 0 \\ 0 & 0 \end{pmatrix} U}$$

$$:= \begin{pmatrix} m_{1m}^2/2p & 0 \\ 0 & m_{2m}^2/2p \end{pmatrix}$$

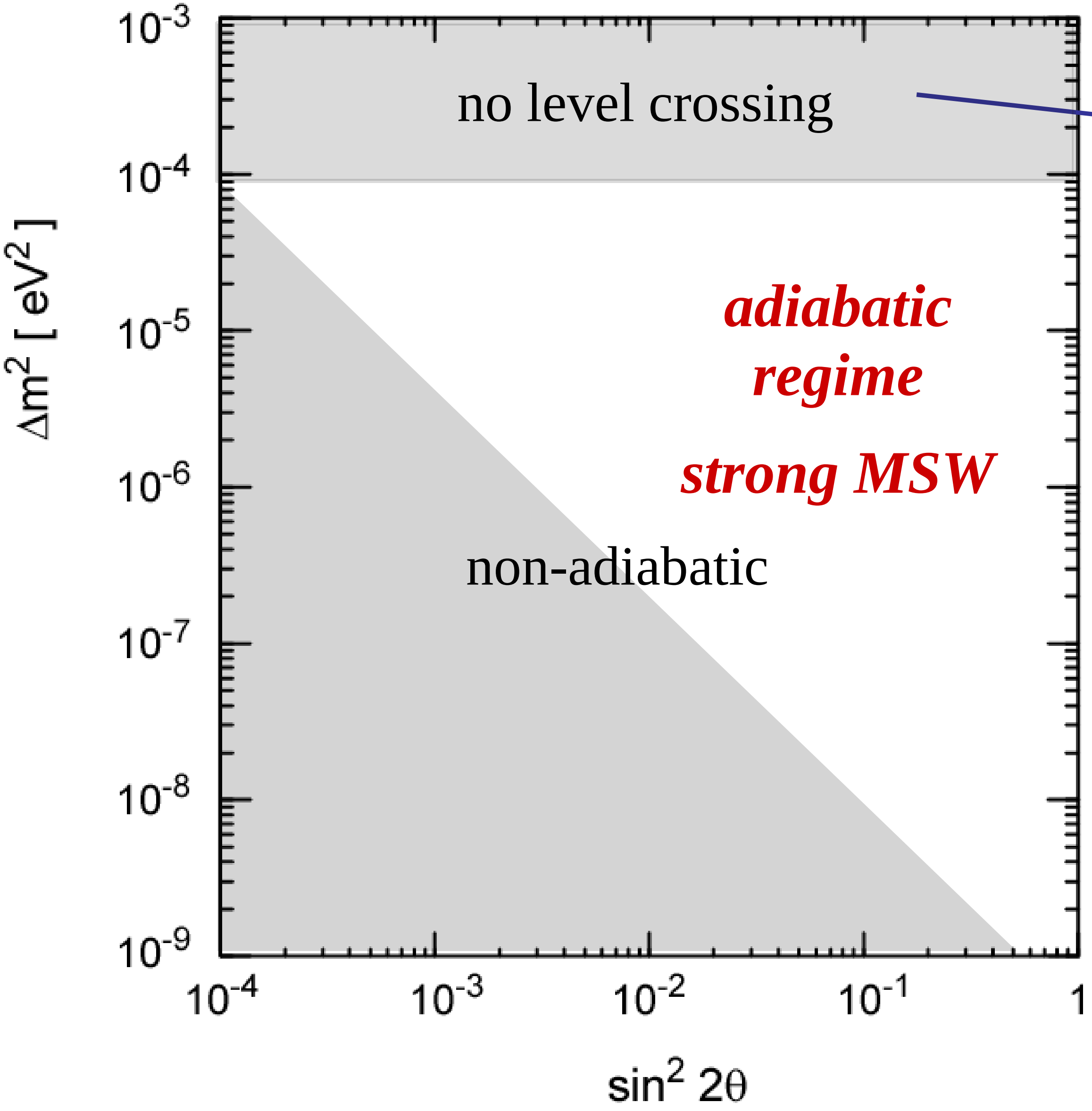
mit $\tan(2\theta_m) = \tan(2\theta) \cdot \left(1 - \frac{\lambda_{osc}}{\lambda_0 \cos(2\theta)}\right)^{-1}$

$$\lambda_m = \lambda_{osc} \cdot \frac{\sin(2\theta_m)}{\sin(2\theta)}$$

$$P(\nu_e \to \nu_\mu) = 1 - \sin^2(2\theta_m) \sin^2 \frac{\pi L}{\lambda_m}$$

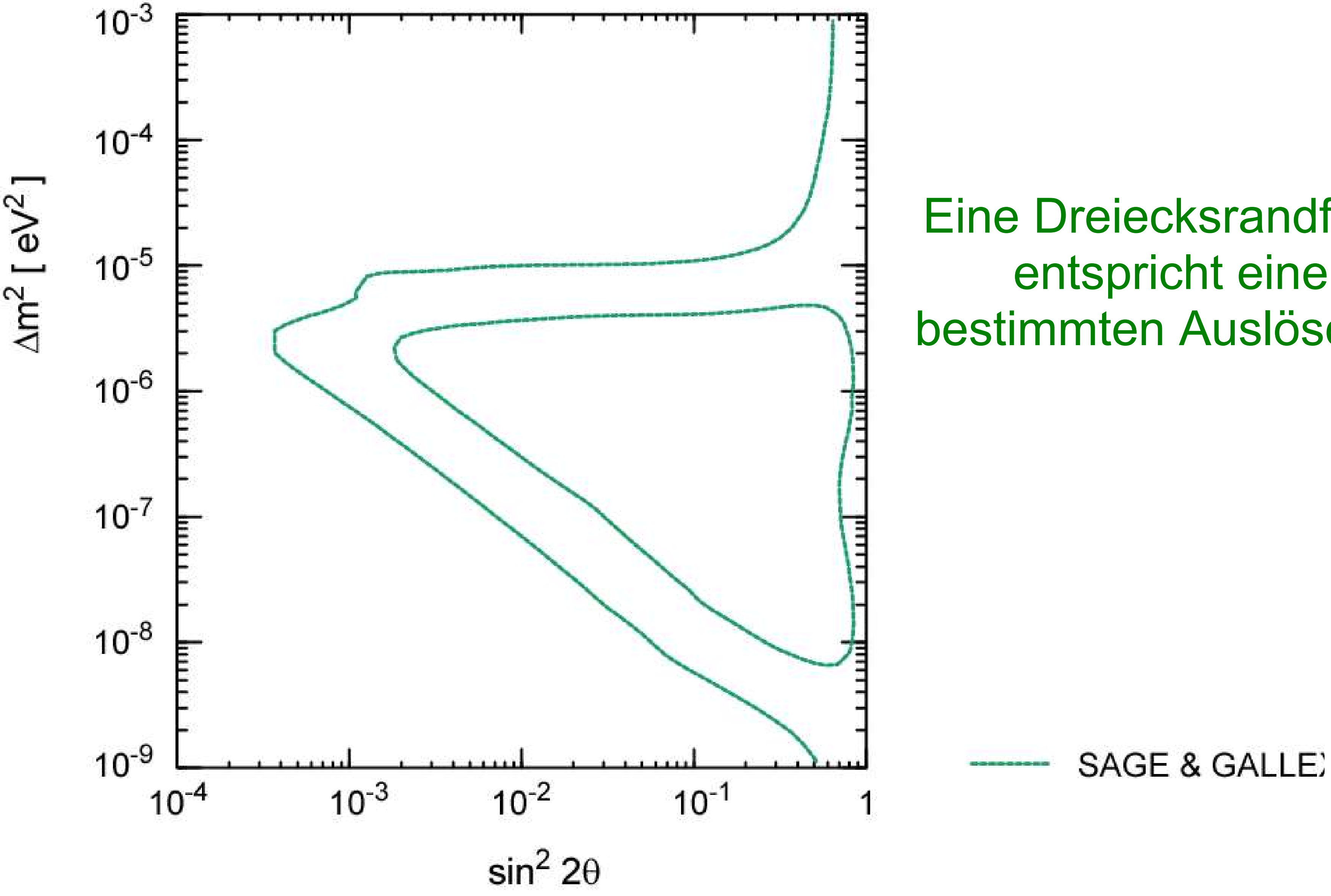


MSW-Effekt und Oszillation solarer Neutrinos



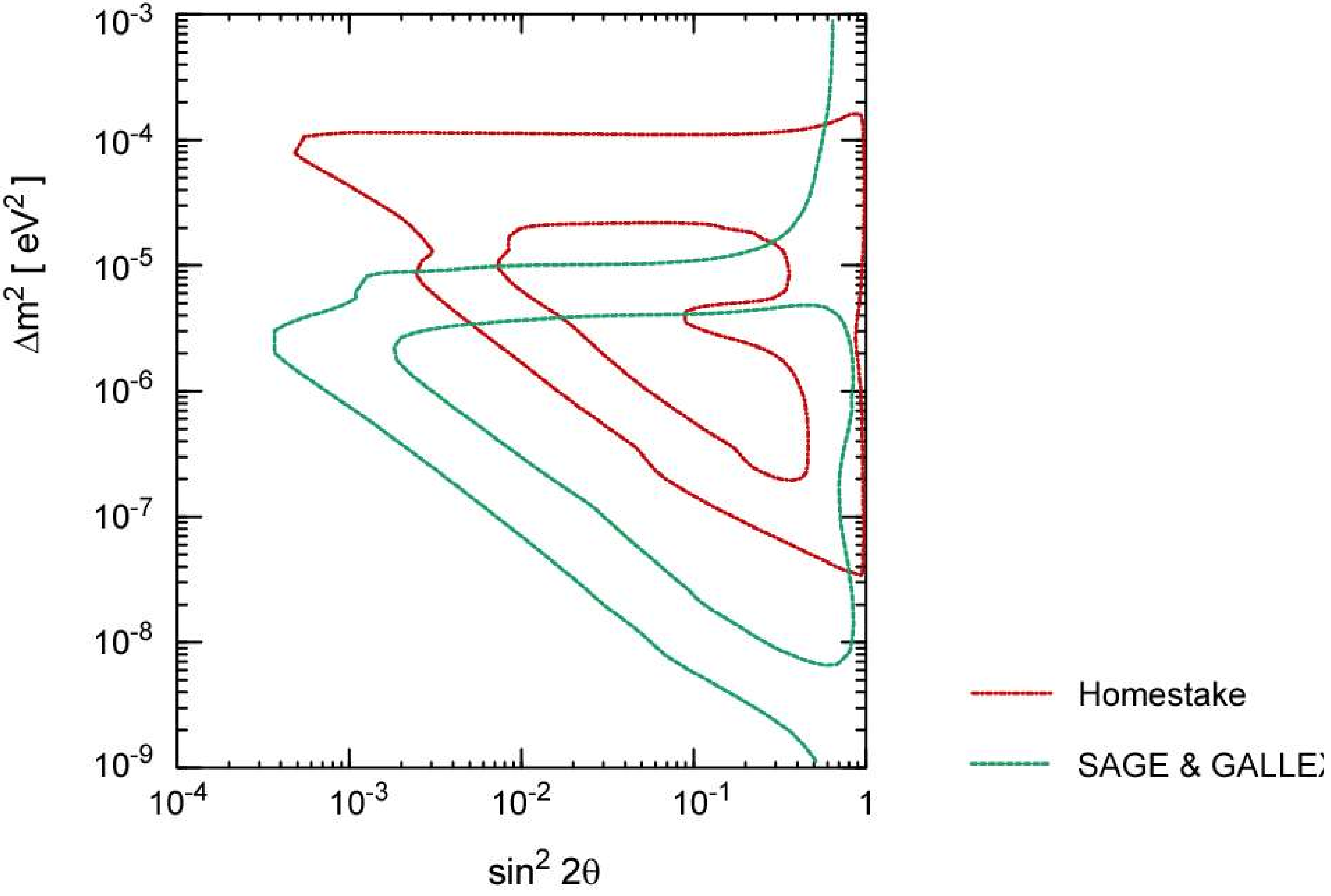
vacuum splitting
of masses too large
to be overcome by matter

MSW-Effekt und Oszillation solarer Neutrinos

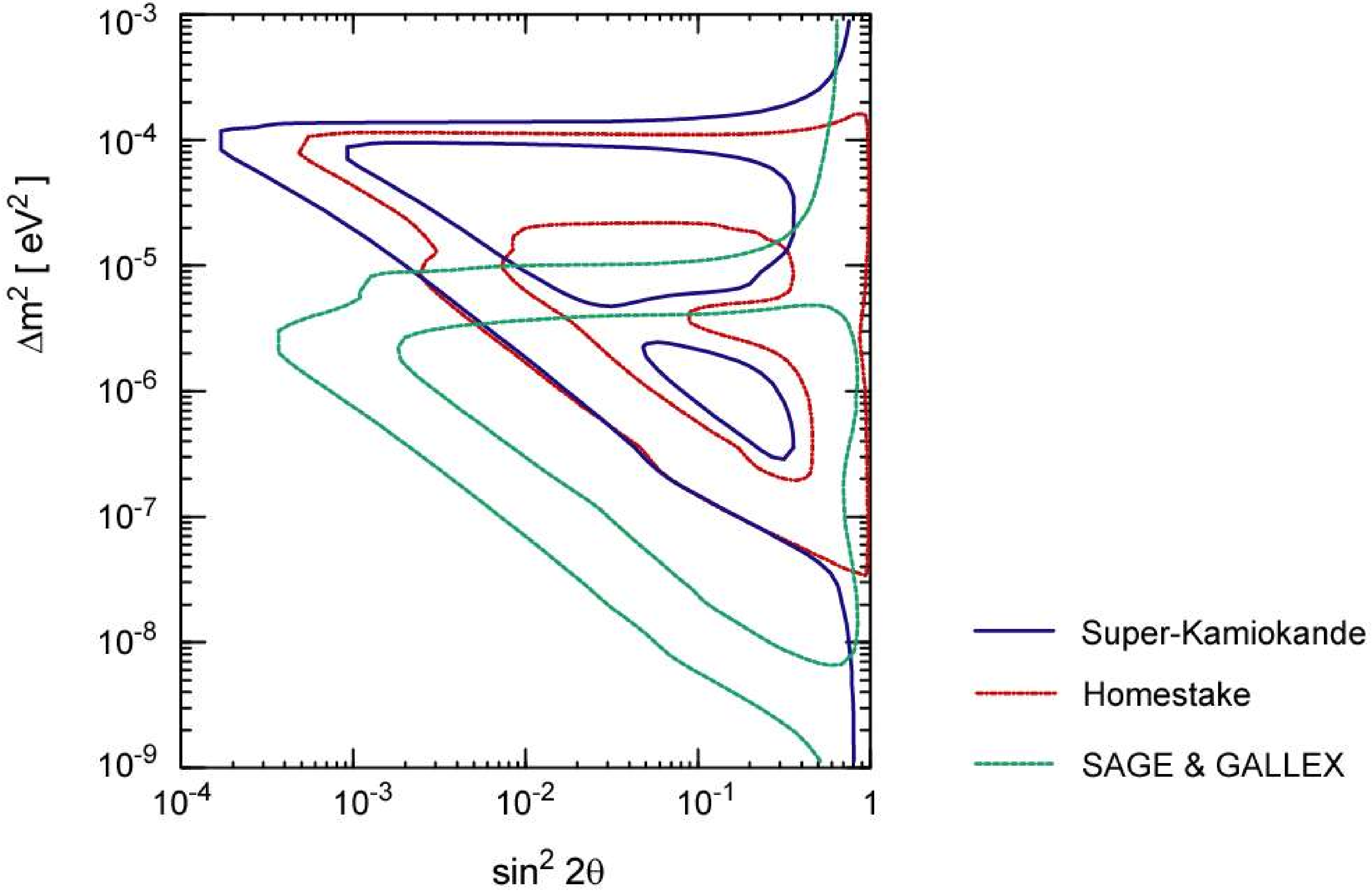


Eine Dreiecksrandfläche
entspricht einer
bestimmten Auslöschung

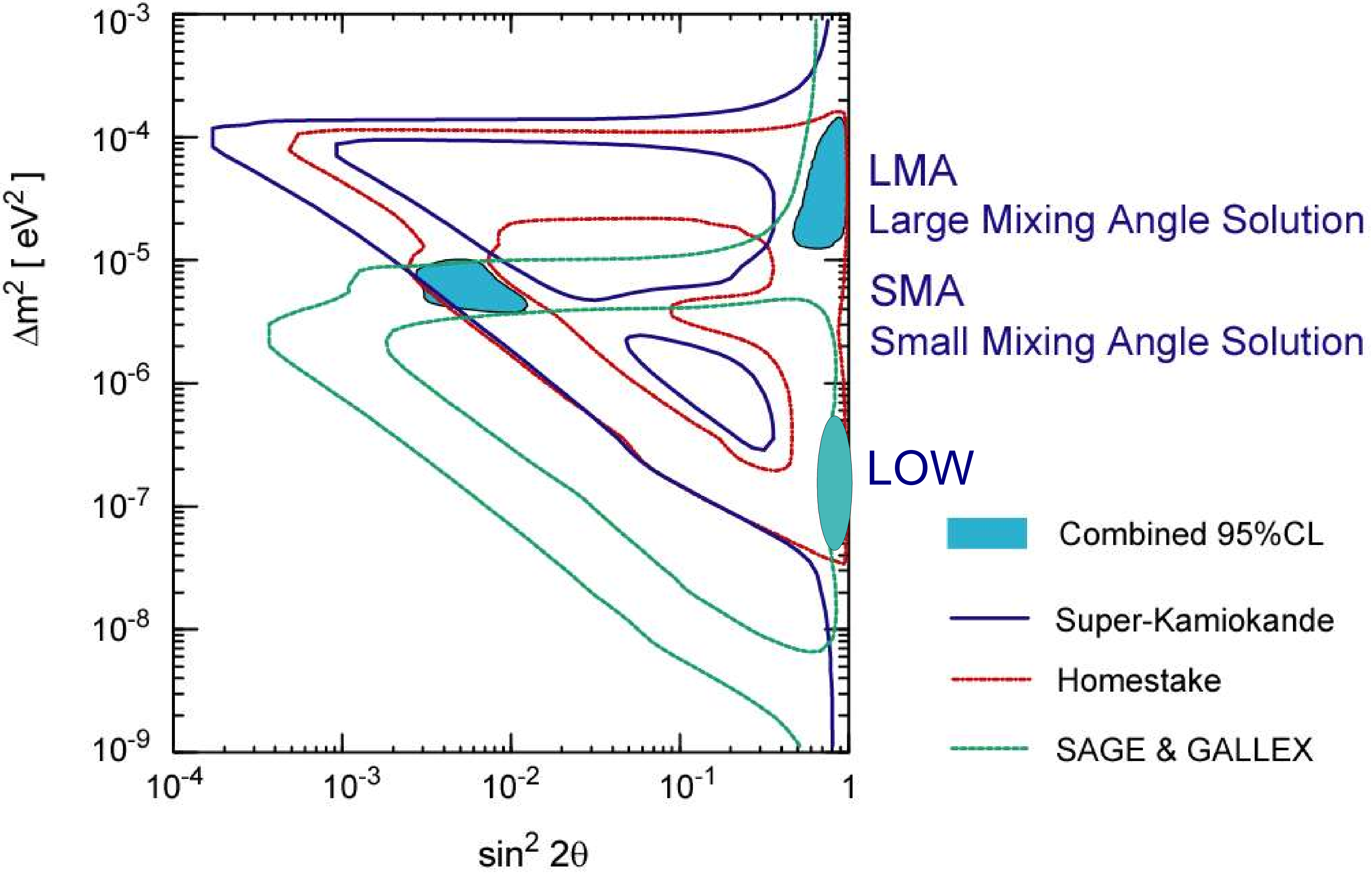
MSW-Effekt und Oszillation solarer Neutrinos



MSW-Effekt und Oszillation solarer Neutrinos



MSW-Effekt und Oszillation solarer Neutrinos

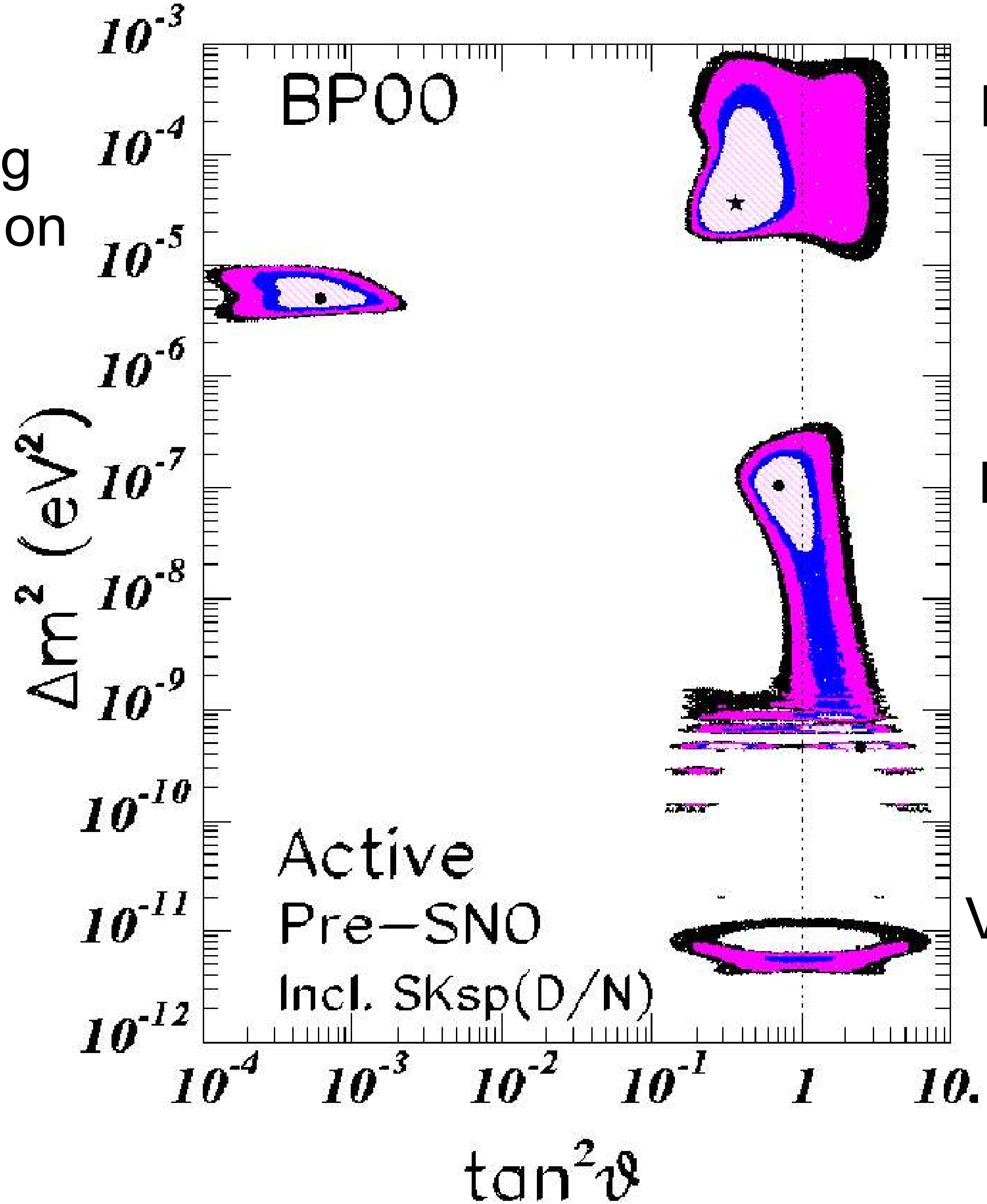


LMA
Large Mixing Angle Solution

SMA
Small Mixing Angle Solution

LOW

MSW-Effekt und Vakuumoszillations-Lösungen für solare Neutrinos



Small Mixing Angle solution (SMA)

Large Mixing Angle solution (LMA)

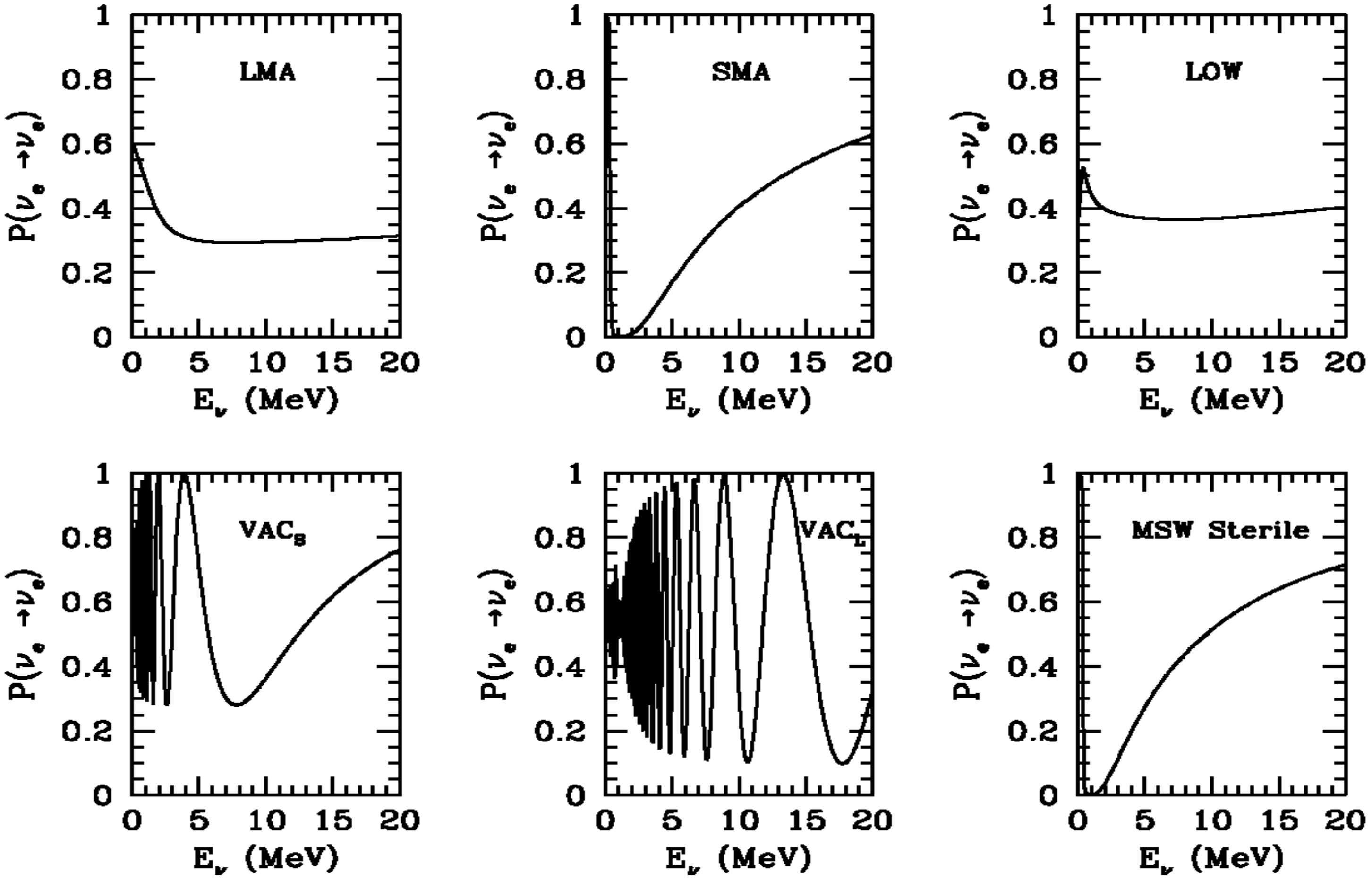
LOW solution (LOW)

Vacuum Oscillation solution (VO)

Solare Neutrinoexperimente der nächsten Generation

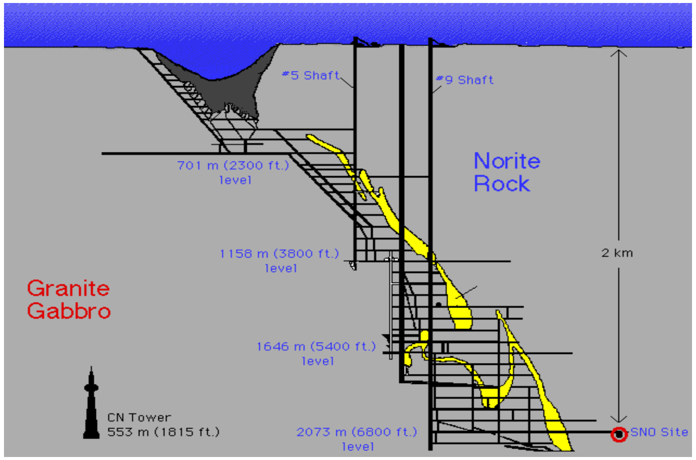
Anforderungen:

- Echtzeit (Tag/Nacht-Asymmetrie, L Variation)
- Spektrale Information

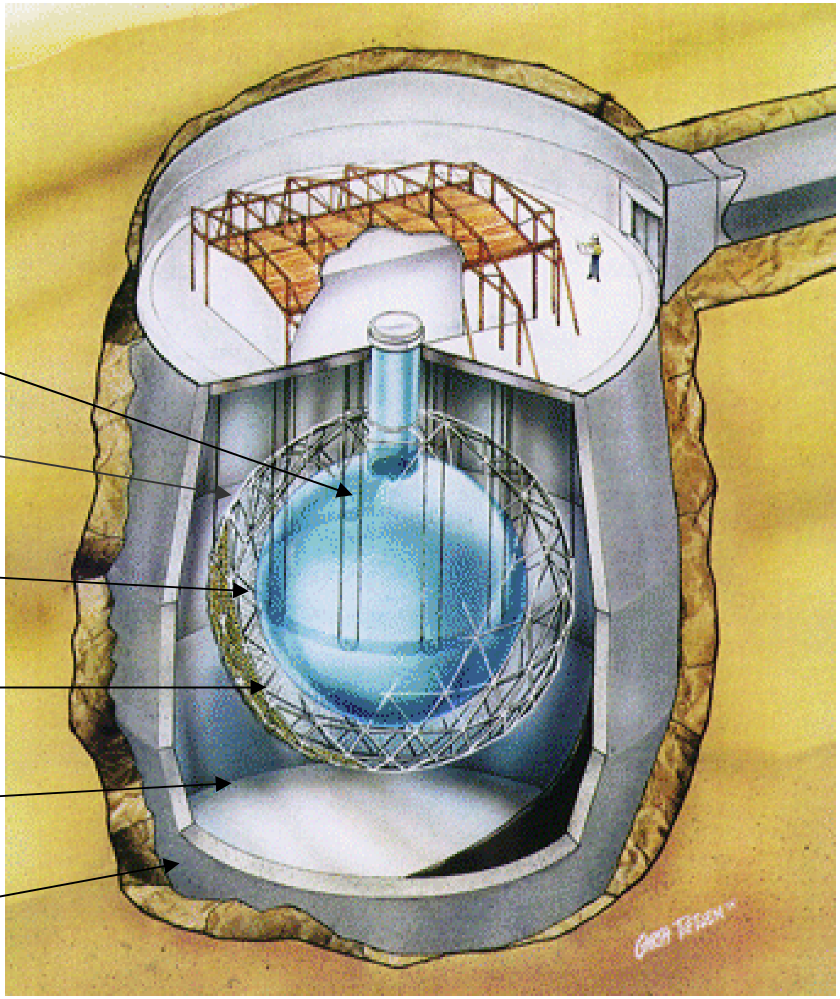


- Flavour Information, zeige: $\nu_e \rightarrow \nu_x$

Das Sudbury Neutrino Observatory SNO



Creighton Mine: 2km tief
in Sudbury, Ontario, Kanada



1000 t D_2O

Haltestruktur für 9500 Lichtdetektoren (Photomultiplier)

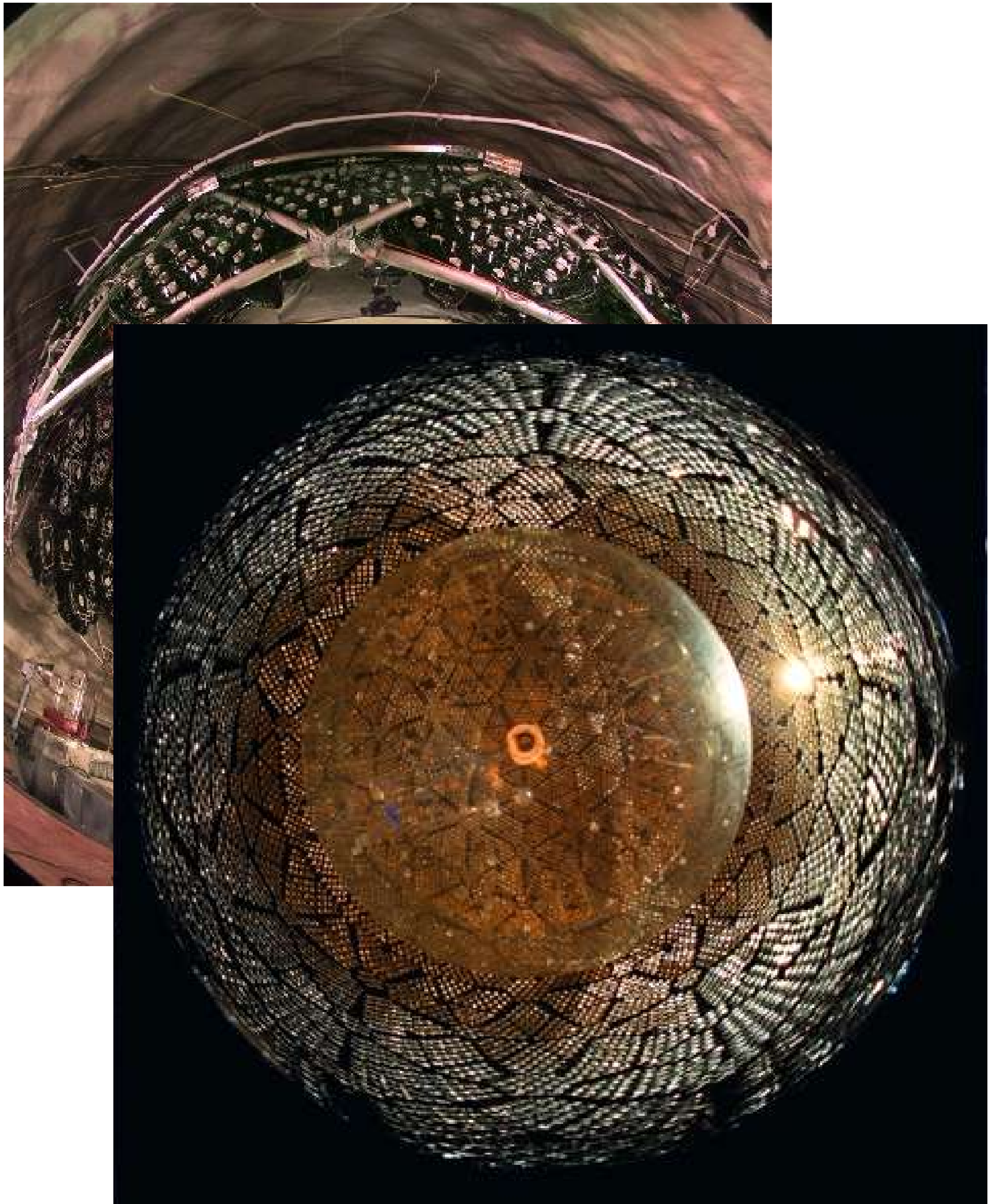
12 m Diameter Acrylic Vessel

1700 t Innere Abschirmung, H_2O

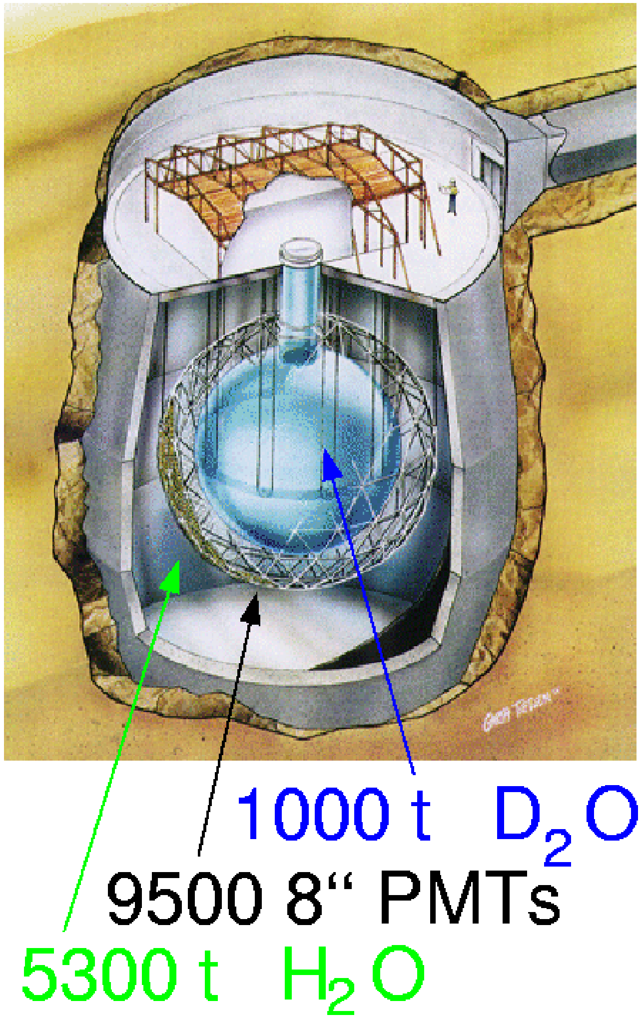
5300 t äußere Abschirmung, H_2O

Urylon Versiegelung

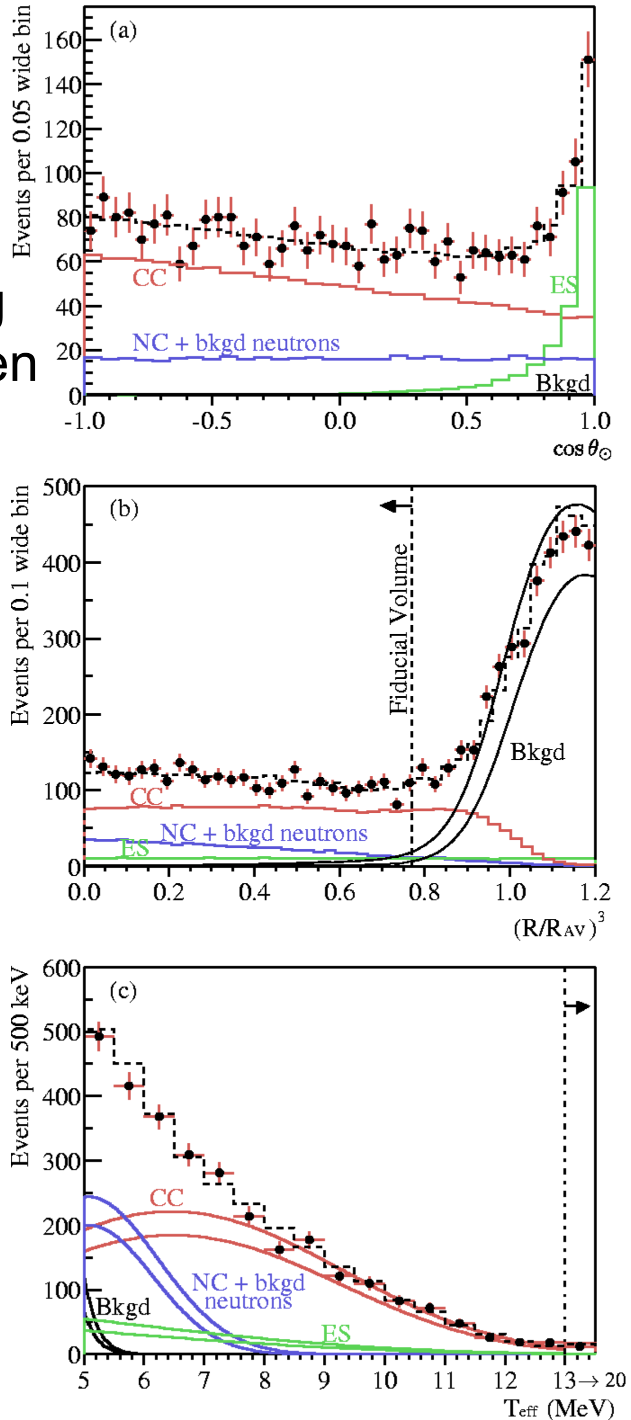
SNO während der Konstruktion
(in einem Klasse 2000 Reinraum)



Das Sudbury Neutrino Observatory SNO



Unterscheidung
der verschiedenen
Reaktionen:



Wasser-Cherenkov-Detektor D_20:

ES $\nu_x + e^- \rightarrow \nu_x + e^-$ ν_e (ν_μ, ν_τ)

CC $\nu_e + d \rightarrow p + p + e^-$ ν_e

NC $\nu_x + d \rightarrow p + n + \nu_x$ ν_e, ν_μ, ν_τ

Neutrino fluxes from SNO (PRL89 (2002) 011301)

Standard solar model [10^6 cm^{-2}s^{-1}]: $\Phi_{SSM} = 5.05\,^{+1.01}_{-0.81}$

Measured fluxes [10^6 cm^{-2}s^{-1}]: $\Phi_{CC} = 1.76\,^{+0.06}_{-0.05}\,^{+0.09}_{-0.09}$

$\Phi_{ES} = 2.39\,^{+0.24}_{-0.23}\,^{+0.12}_{-0.12}$

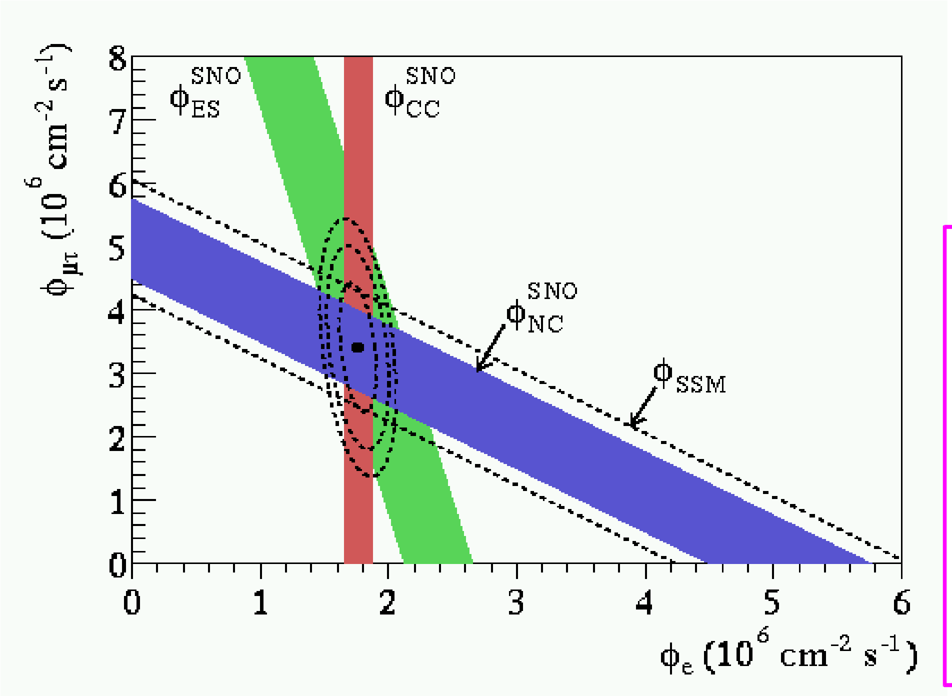
$\Phi_{NC} = 5.09\,^{+0.44}_{-0.43}\,^{+0.46}_{-0.43}$

Neutrino fluxes: $\Phi_e = \Phi(\nu_e)$, $\Phi_{\mu\tau} = \Phi(\nu_\mu) + \Phi(\nu_\tau)$

Relations: $\Phi_{CC} = \Phi_e$

$\Phi_{ES} = \Phi_e + 0.154\,\Phi_{\mu\tau}$

$\Phi_{NC} = \Phi_e + \Phi_{\mu\tau}$



$\Phi_e = 1.76\,^{+0.06}_{-0.05}\,^{+0.09}_{-0.09}$

$\Phi_{\mu\tau} = 3.41\,^{+0.45}_{-0.45}\,^{+0.48}_{-0.45}$ ($\neq 0$ with 5.3 σ)

$\Rightarrow$ ν do oscillate

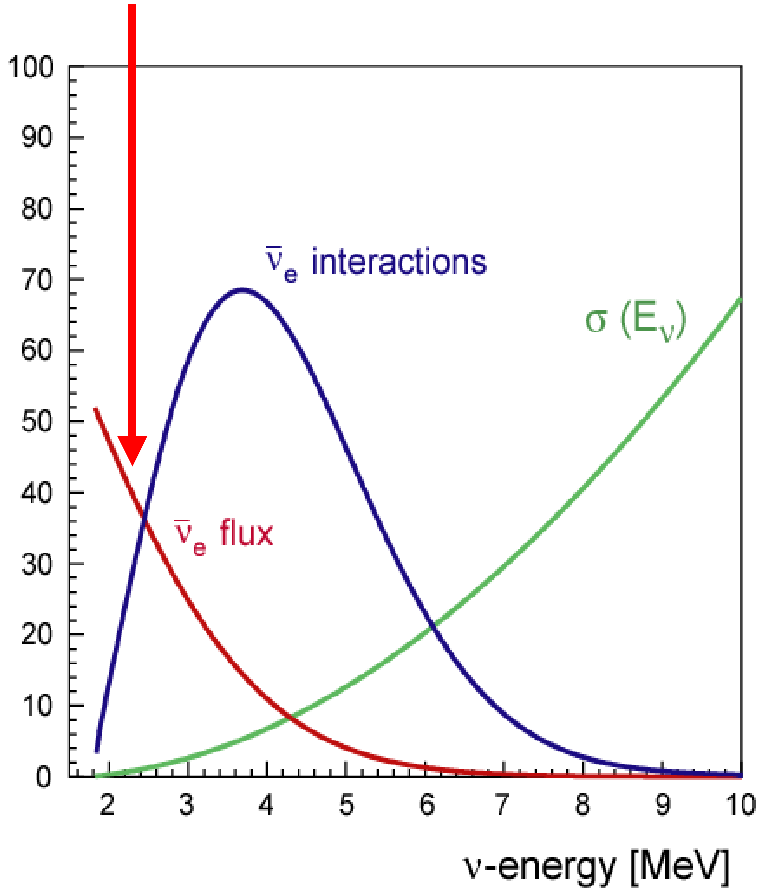
$\Phi_{e\mu\tau} = 5.09\,^{+0.44}_{-0.43}\,^{+0.46}_{-0.43} \approx \Phi_{\mathbf{SSM}}$

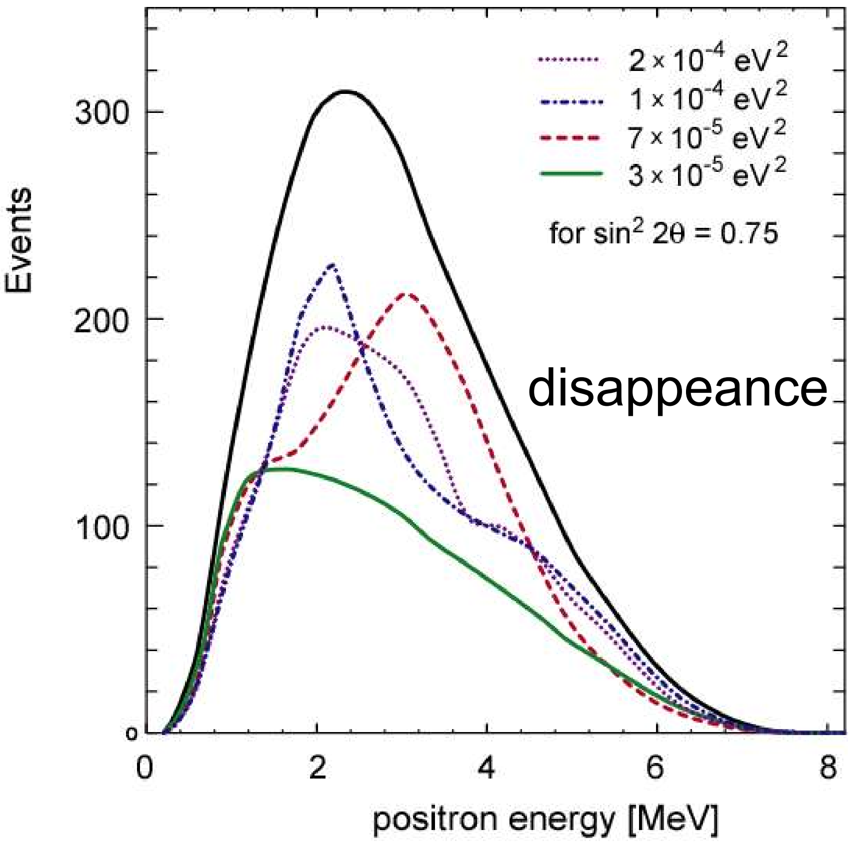
$\Rightarrow$ no solar ν deficit

Reaktor ν-Experimente

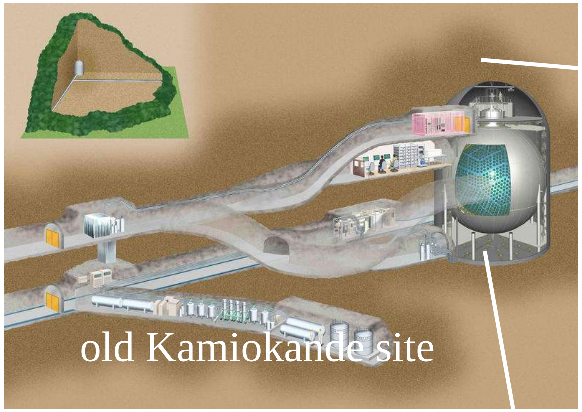
Inverser β-Zerfall: $\bar{\nu}_e + p \rightarrow e^+ + n - 1.80\ MeV$

Summe von β-Spektren der Spaltprodukte





disappeance



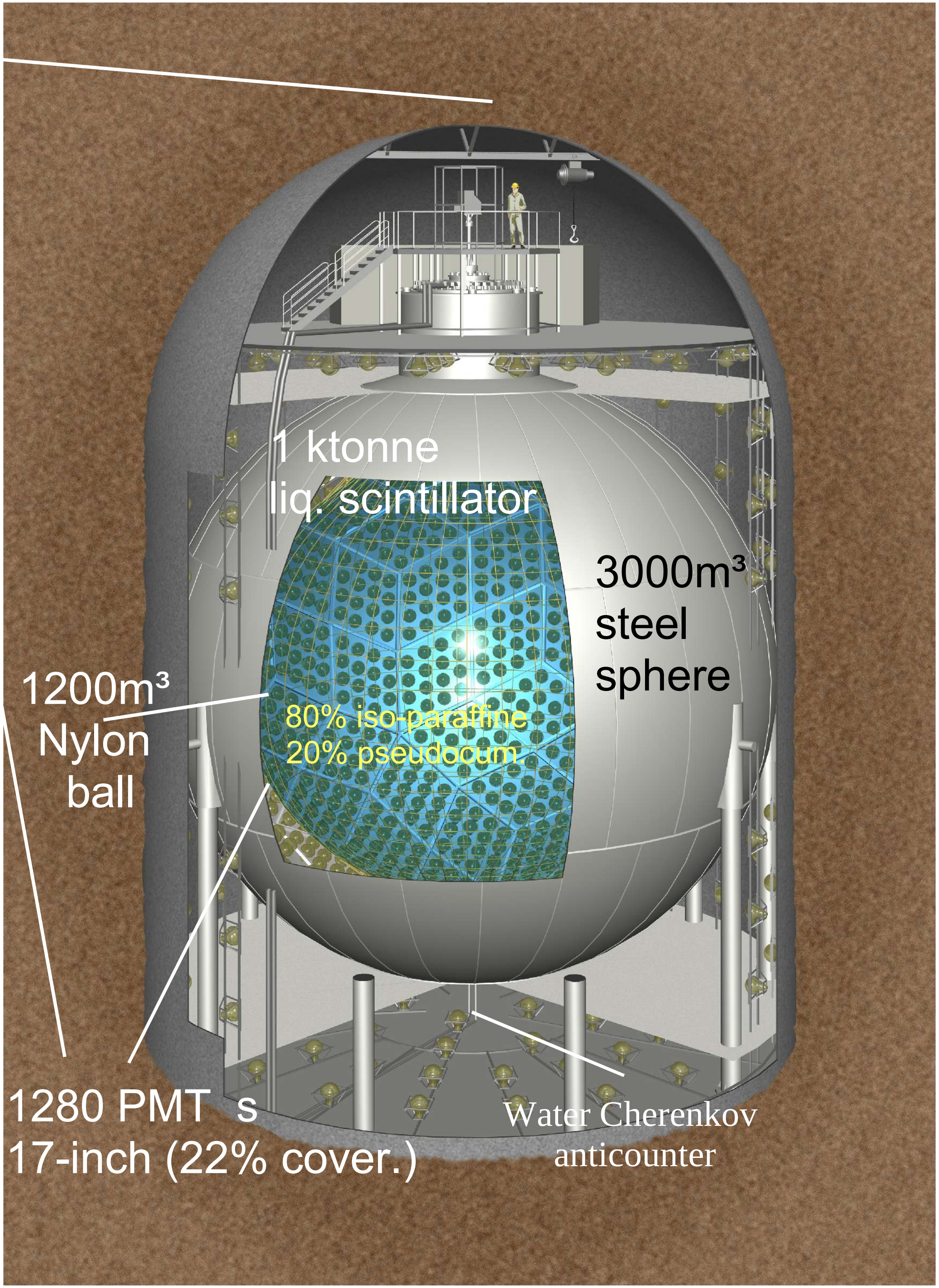
old Kamiokande site

KamLAND

Kamioka Liquid Scintillator
Anti-Neutrino Detector

J-US **long-baseline**
reactor oscillation experiment:
disappearance of reactor ν_e s?

aim: experimental test of
LMA solution of solar ν
using terrestrial neutrinos
(25% of world electr. power)



1 ktonne
liq. scintillator

3000m³
steel
sphere

1200m³
Nylon
ball

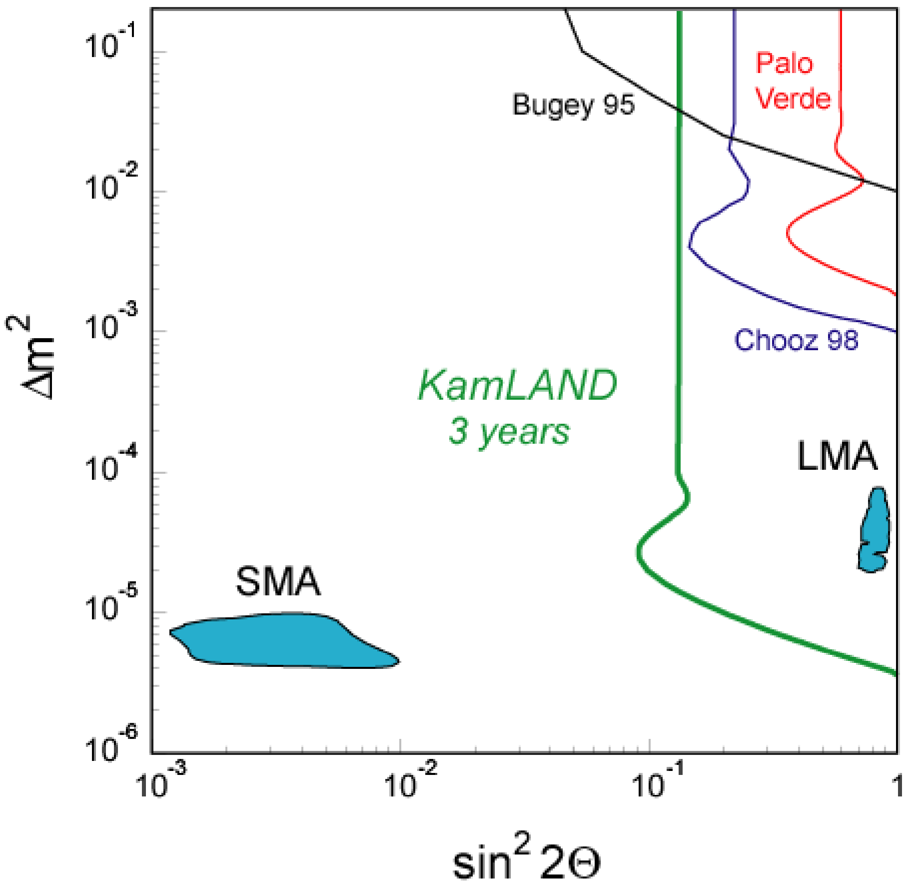
80% iso-paraffine
20% pseudocum

1280 PMT s
17-inch (22% cover.)

Water Cherenkov
anticounter

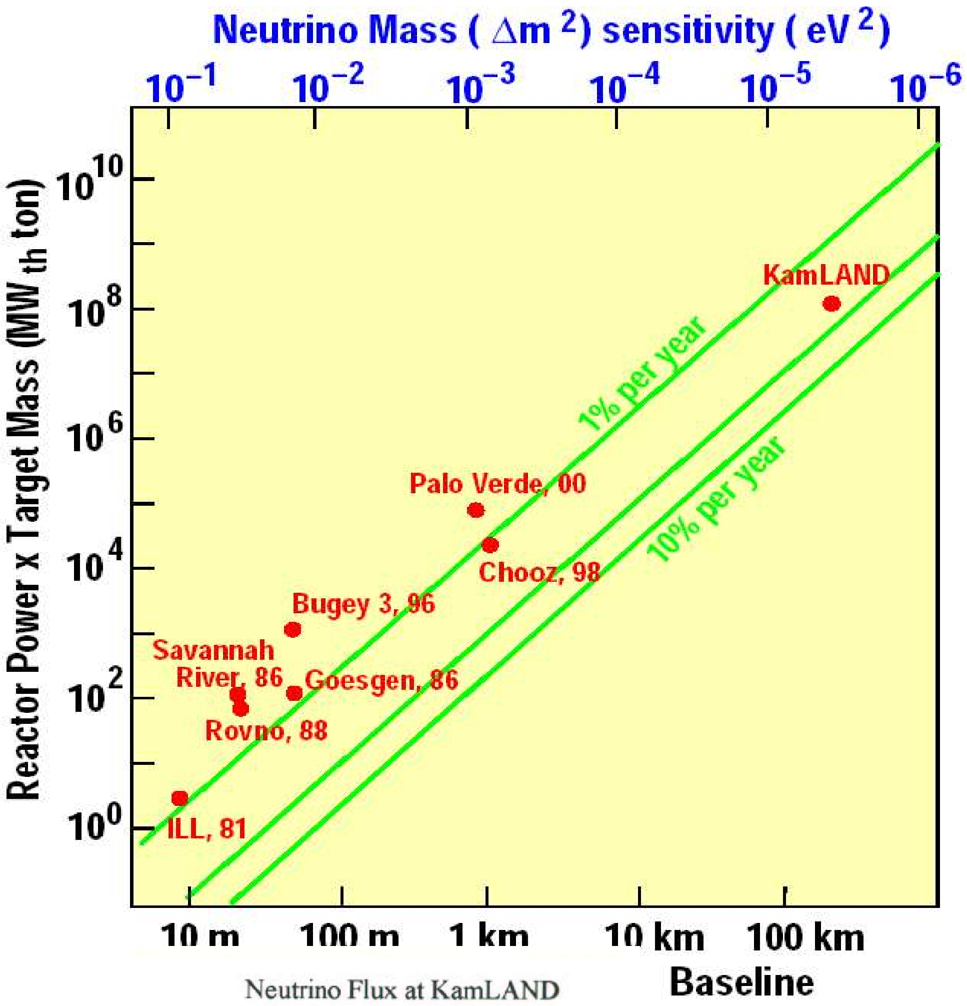
KamLAND: long base-line Reaktorneutrinoexperiment

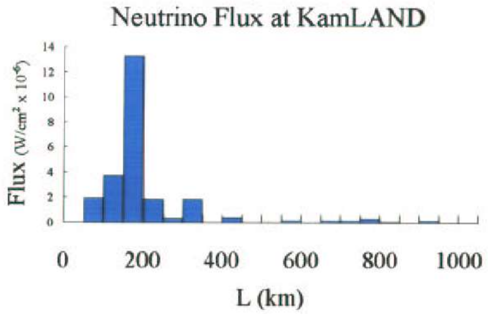
KamLAND sensitivity (3 kt yr)
90% Cl. exclusion limit



Erster Labortest von LMA !

Benutze alle japanischen und koreanischen Reaktoren für KamLAND





KamLAND: Evidenz für $\bar{\nu}_e$ disappearance

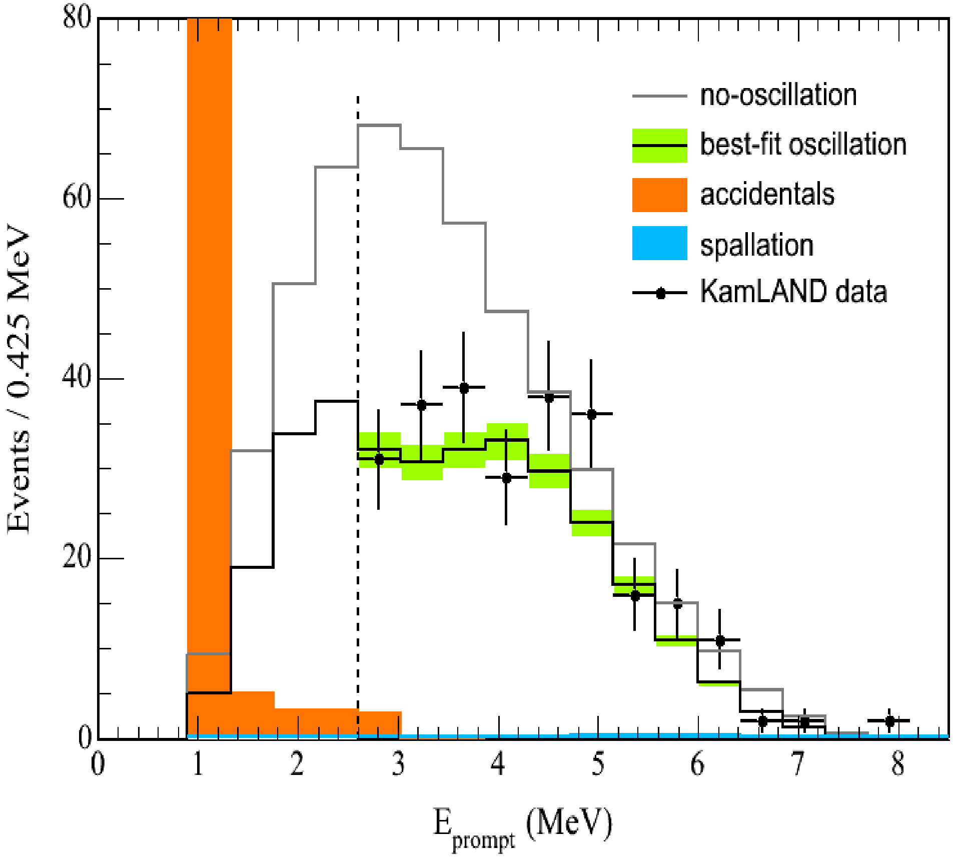
Start Datennahme: Febr. 2002 Ergebnis von Neutrino 2004, Juni 2004

Expected #events: 365 ± 24

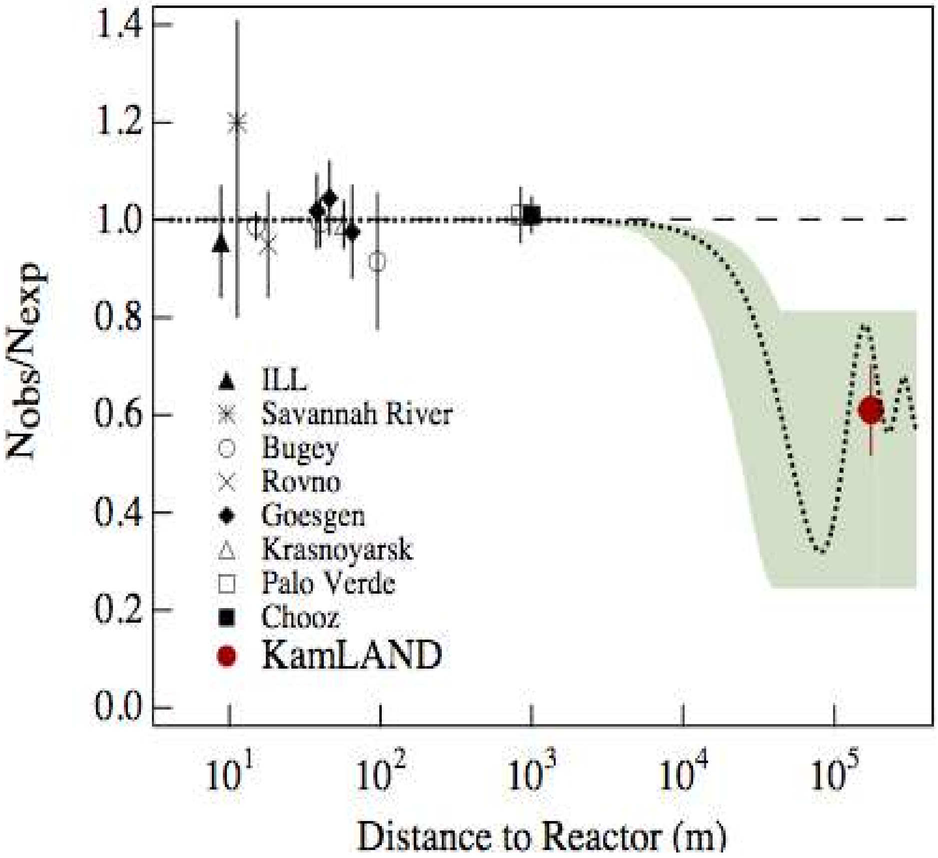
Background #events: 7.5 ± 1.3 ⇒ $R = 0.686 \pm 0.044 \pm 0.045$

Observed #events: 258

515.1 days of data taking



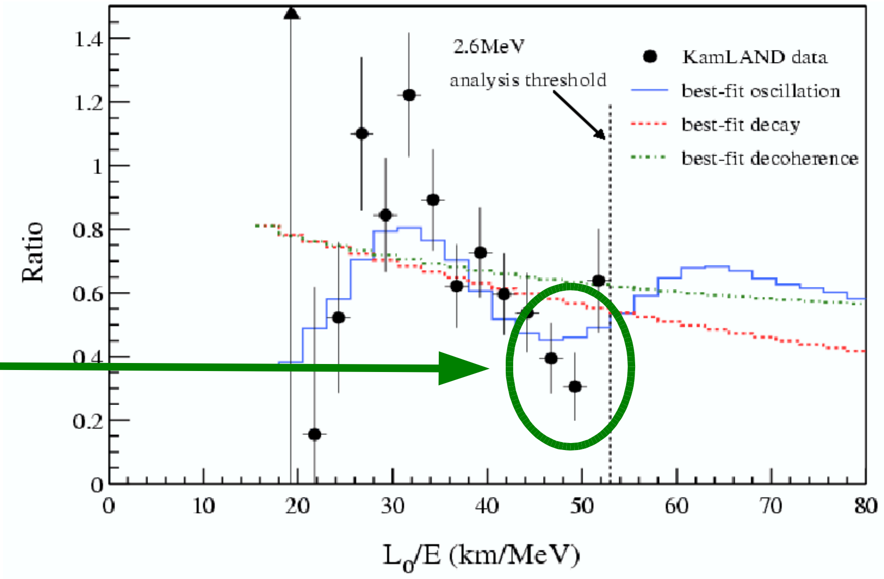
145.1 days of data taking



KamLAND und solare Neutrinoexperimente

KamLAND (Reaktor-ν)

(G. Gratta, Neutrino 2004)

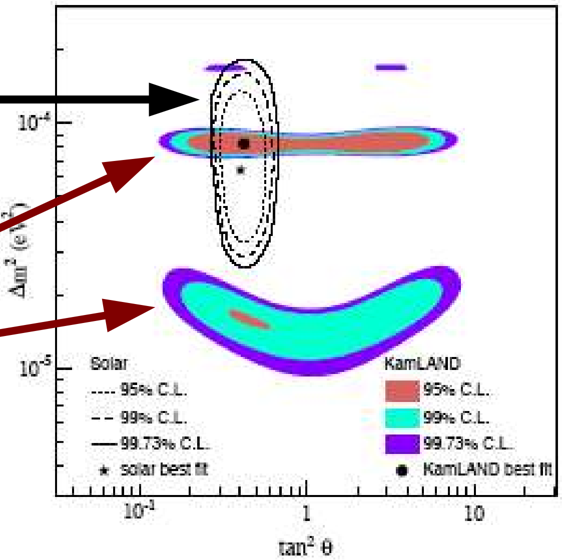


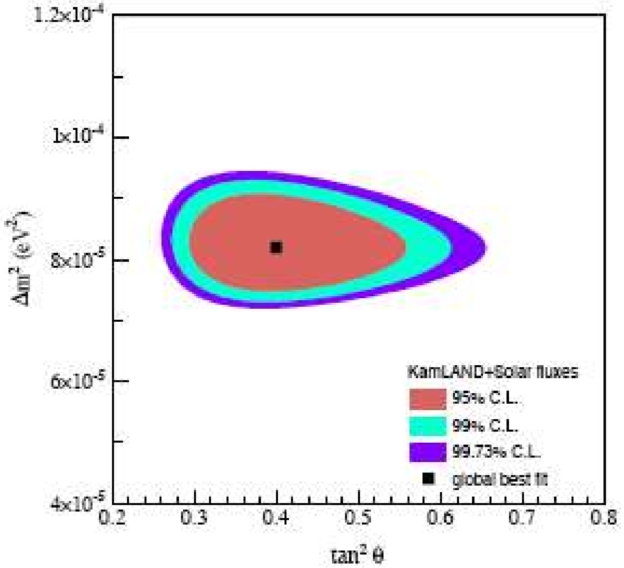
Oszillatorischer Charakter

Übereinstimmung der Oszillationsparameter

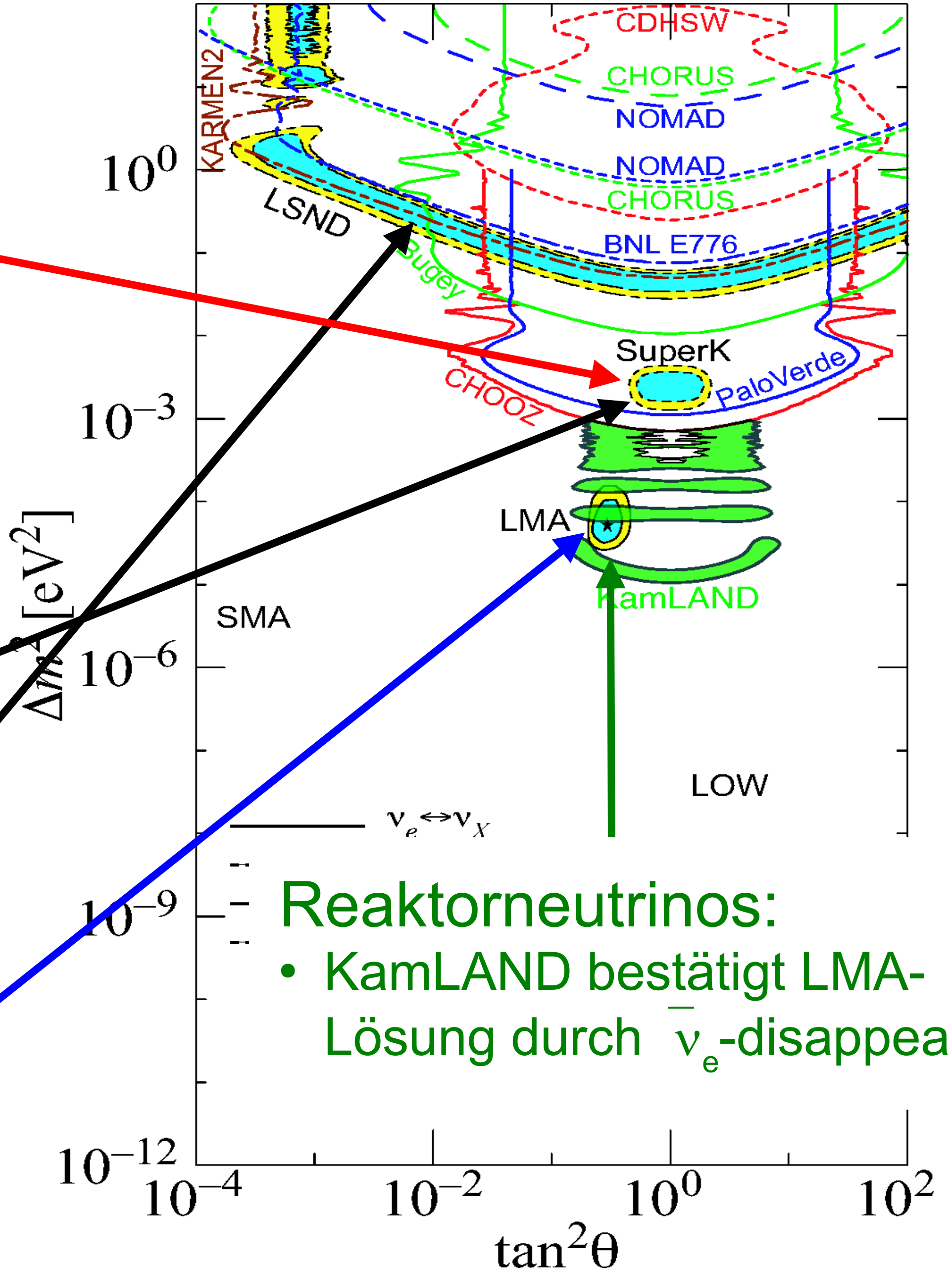
Solare Neutrinos
(SNO et al.)

Reaktor Neutrinos
(KamLAND)





Ergebnisse der Oszillationsexperimente mit atmosphärischen und Beschleunigerneutrinos



Atmosphärische Neutrinos:

- Super-Kamiokande
  $\nu_\mu \rightarrow \nu_\tau$-Oszillation:
  $\Delta m^2 \approx 2 \times 10^{-3}\ \mathrm{eV}^2$ und $\sin^2(2\theta) \approx 1$
- bestätigt durch MACRO, Soudan 2

Beschleunigerneutrinos:

- K2K bestätigt Super-Kamiokande durch ν_μ-Disappearance
- Sieht LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$-Appearance ?

Solare Neutrinos:

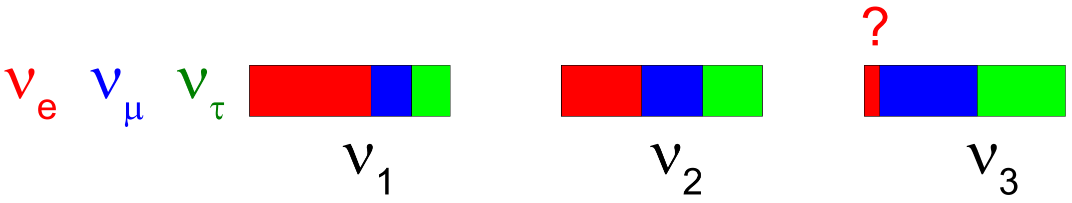
- Homestake, Gallex, Sage, GNO, Kamiokande, Super-Kamiokande SNO: $\nu_e \rightarrow \nu_{\mu\tau}$-Oszillation:
  $\Delta m^2 \approx 8 \times 10^{-5}\ \mathrm{eV}^2$ und $\theta \approx 32^\circ$

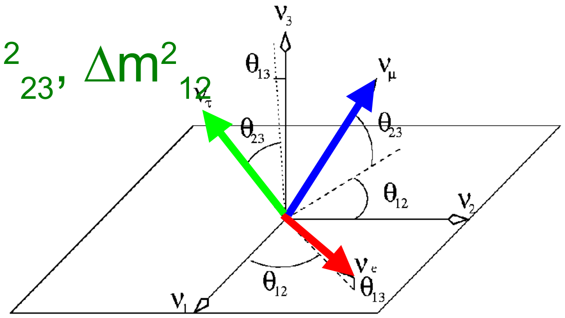
Reaktorneutrinos:

- KamLAND bestätigt LMA-Lösung durch $\bar{\nu}_e$-disappearance

Status und Ausblick der Oszillationsexperimente

Resultate der neuesten Oszillationsexperimente: Θ_{23}, Θ_{12}, Δm^2_{23}, Δm^2_{12}





mit Neutrinomischungsmatrix, i.a. komlex (2 Majorana-, 1 CP-Phase):

$$U = \underbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}}_{wie\ CKM-Matrix} \cdot \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{Majoranaphasen,\ spielen\ bei\ Osz.\ keine\ Rolle}$$

Was fehlt noch:

1) genauere Bestimmung der quadratischen Massendifferenzen und Mischungswinkel
2) Θ_{13}
3) komplexe Phase δ

3 Flavor-Neutrinooszillation

Generelle 3-Flavor Oszillationsformel (ohne Materieeffekt):

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = \left| \sum_{\mathrm{i}} \mathrm{U}_{\beta \mathrm{i}} \exp^{-\mathrm{i}(\mathrm{E_i t})} \mathrm{U}^*_{\alpha \mathrm{i}} \right|^2$$

Reaktor disappearance:

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - 4|U_{e1}|^2|U_{e2}|^2 \cdot \sin^2 \frac{\Delta m^2_{12} L}{4E} \\ &\quad - 4|U_{e1}|^2|U_{e3}|^2 \cdot \sin^2 \frac{\Delta m^2_{13} L}{4E} \\ &\quad - 4|U_{e2}|^2|U_{e3}|^2 \cdot \sin^2 \frac{\Delta m^2_{23} L}{4E} \end{aligned}$$

$$\boxed{= 1 - \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{\mathrm{atm}} L}{4E} - \cos^4(\theta_{13}) \sin^2(2\Theta_{\mathrm{solar}}) \sin^2 \frac{\Delta m^2_{\mathrm{solar}} L}{4E}}$$

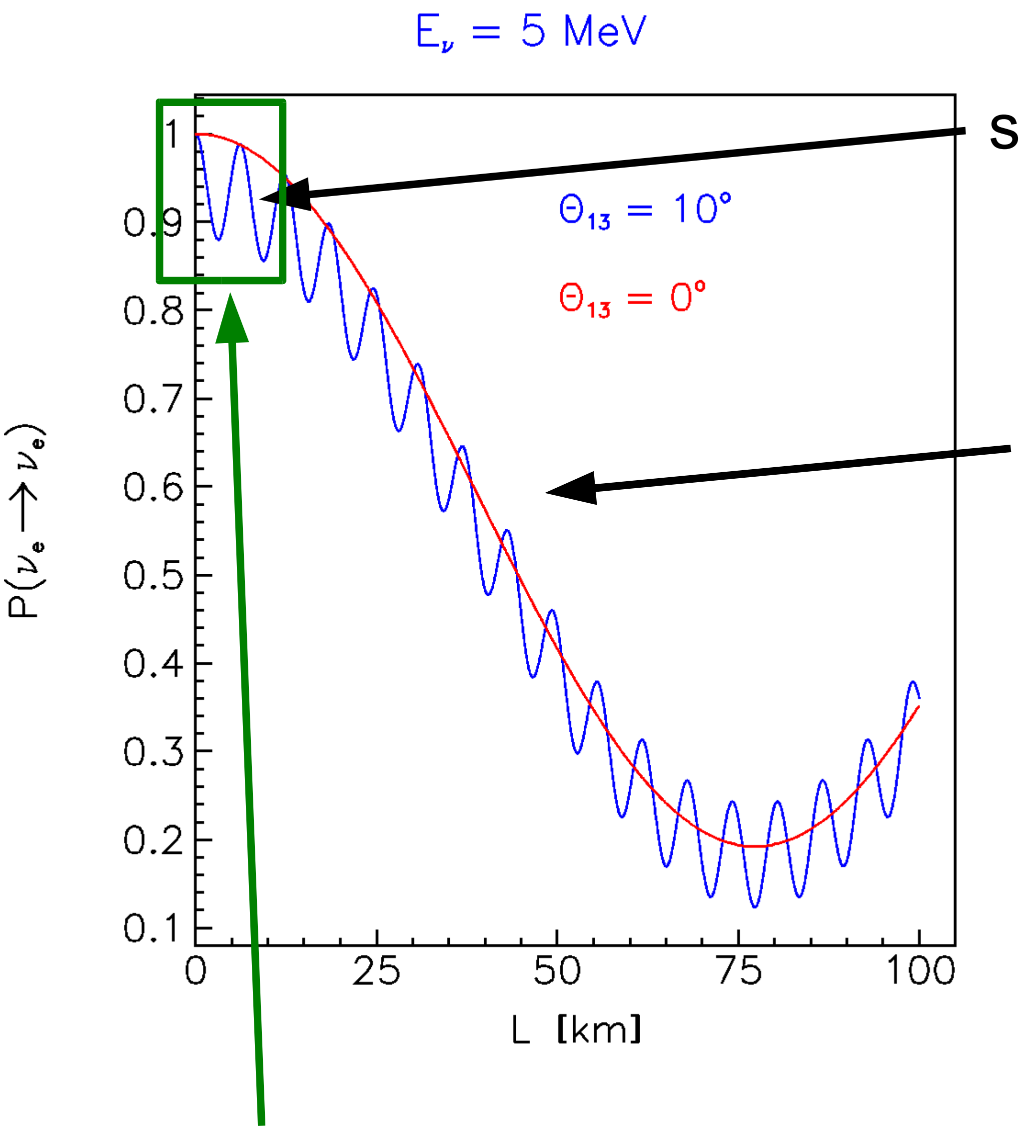
solare: $\Delta m^2_{12} = \Delta m^2_{\mathrm{solar}}$

atmosph: $\Delta m^2_{13} \approx \Delta m^2_{\mathrm{atm}} \approx \Delta m^2_{23}$

mit Neutrinomischungsmatrix, i.a. komlex (2 Majorana-, 1 CP-Phase):

$$U = \underbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}}_{wie\ CKM-Matrix} \cdot \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{Majoranaphasen,\ spielen\ bei\ Osz.\ keine\ Rolle}$$

Bestimmung von Θ_{13}



sub-dominante Oszillation
($\Delta m2_{atmos}$)

dominante Oszillation
(Δm^2_{solar})

Messe Reaktor $\bar{\nu}_e$ disappearance: L ≈ 1km

Neutrinoflussbestimmung mit nahem identischem Detektor,
z.B. Double-CHOOZ-Experiment

Im Aufbau befindliche long baseline Experimente

Fermilab→Soudan (730km): MINOS: ab 2005

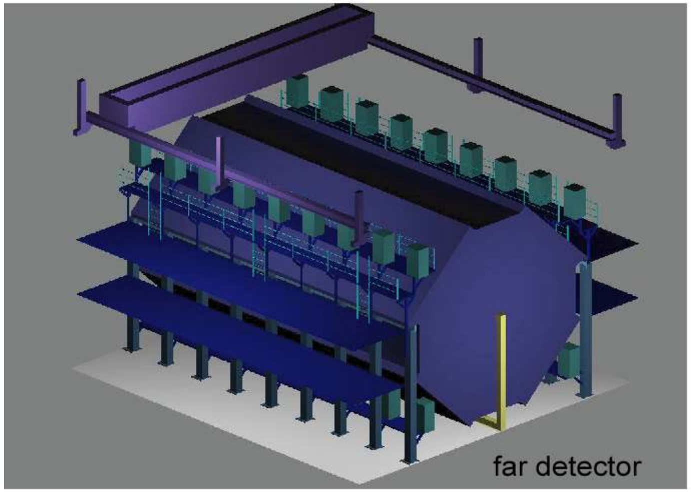
Suche nach ν_μ disappearance und

indirekter ν_τ appearance (NC/CC):

MINOS *Main Injector Neutrino Oscillation Search*

LBL experiment (ν_μ-disappearance) FermiLab-Soudan (732 km)

Main Injector 120 GeV p: 5×10^{13} ppp / 1.9 s horns, 675 m decay tunnel



near detector:
300 m from beam stop

far detector :
5.4 kton iron - scintillator sampling calorimeter

- Magnetized Fe Plates
- Scintillator Strips with WLS read out

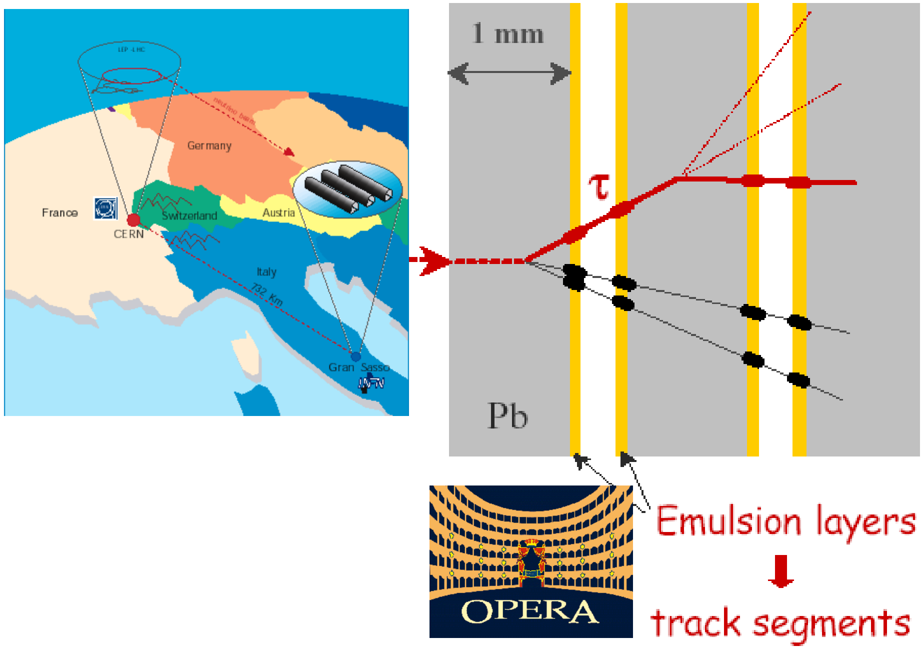
Bestätigung des LSND-Signals:
MiniBoone am Fermilab (seit 2003)

Alle (außer Miniboone) haben auch Θ_{13}-Empfindlichkeit

CERN→Gran Sasso (732 km), ab 2006

ICARUS: Suche nach ν_μ disappearance und indirekter ν_τ appearance

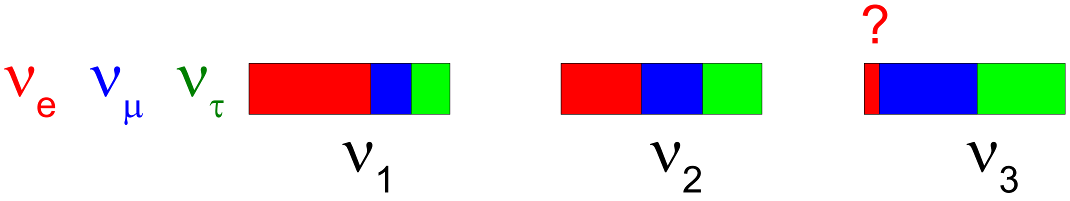
OPERA: direkte ν_τ appearance

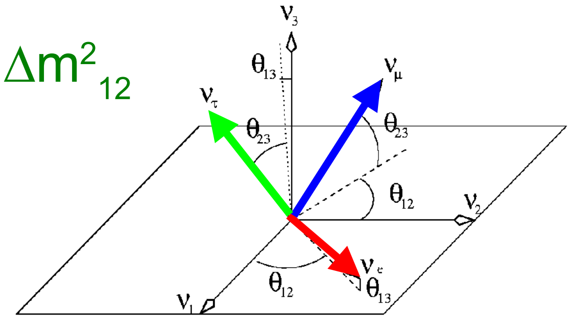


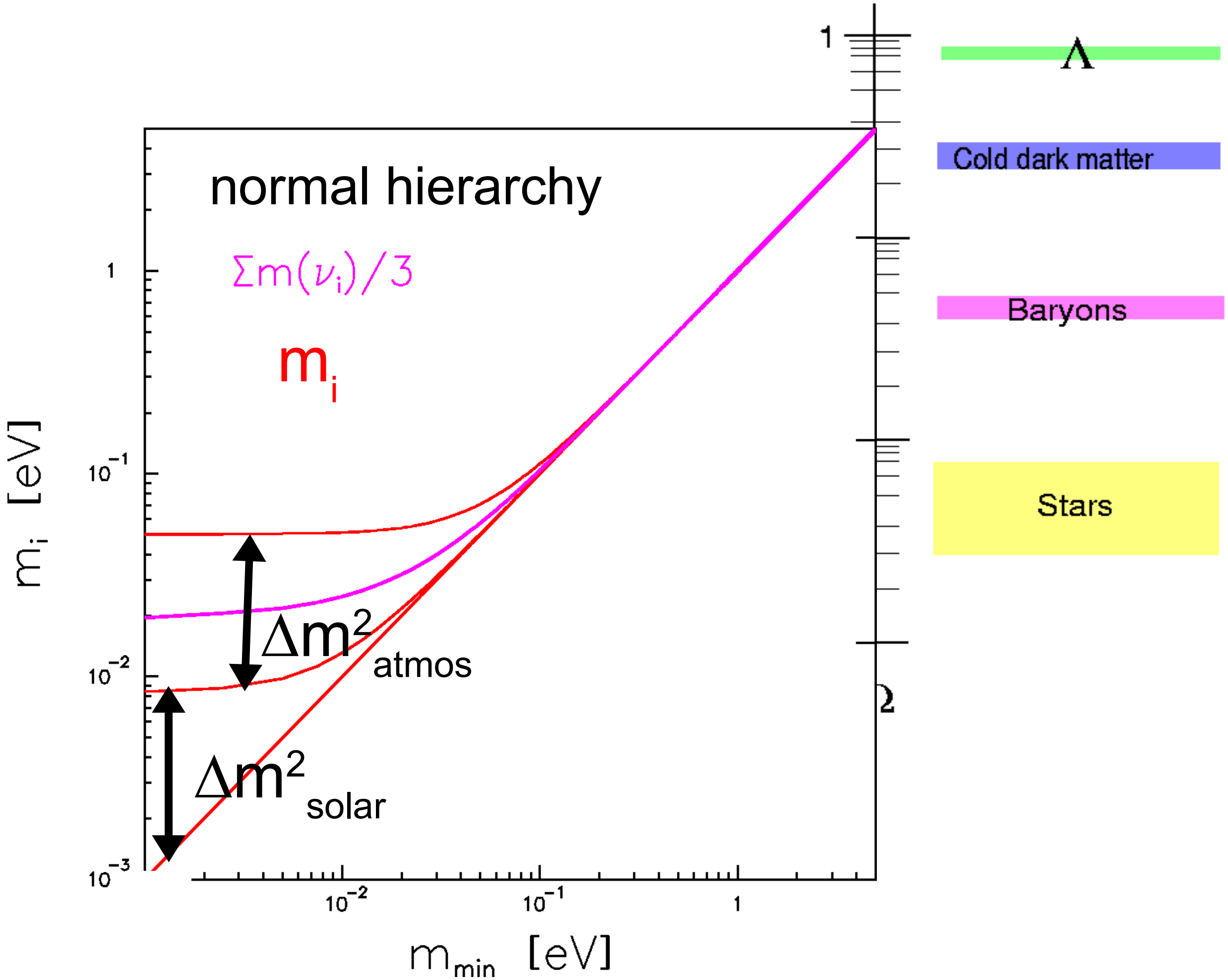
JPARC, ab 2008/9:
JAERI/Tokai → Super-Kamiokande

Absolute ν mass determination

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Δm^2_{23}, Δm^2_{12}







Motivation:

1) distinquish hierarchical and degenerate masses (→ theory beyond SM)
2) check cosmological relevance (→ ν hot Dark Matter)

Absolute ν mass determination

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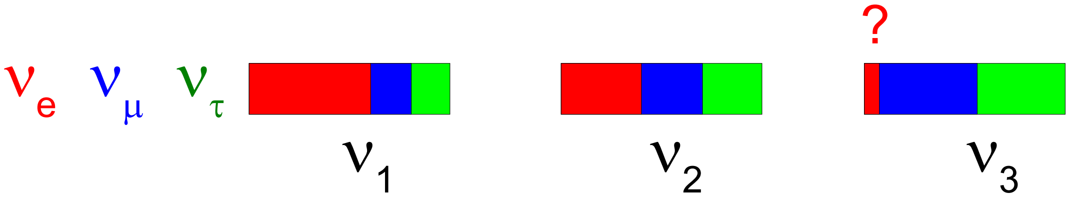

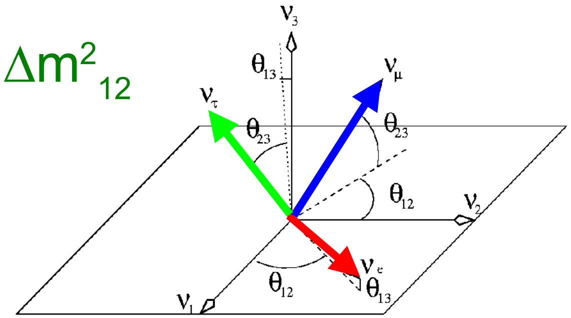

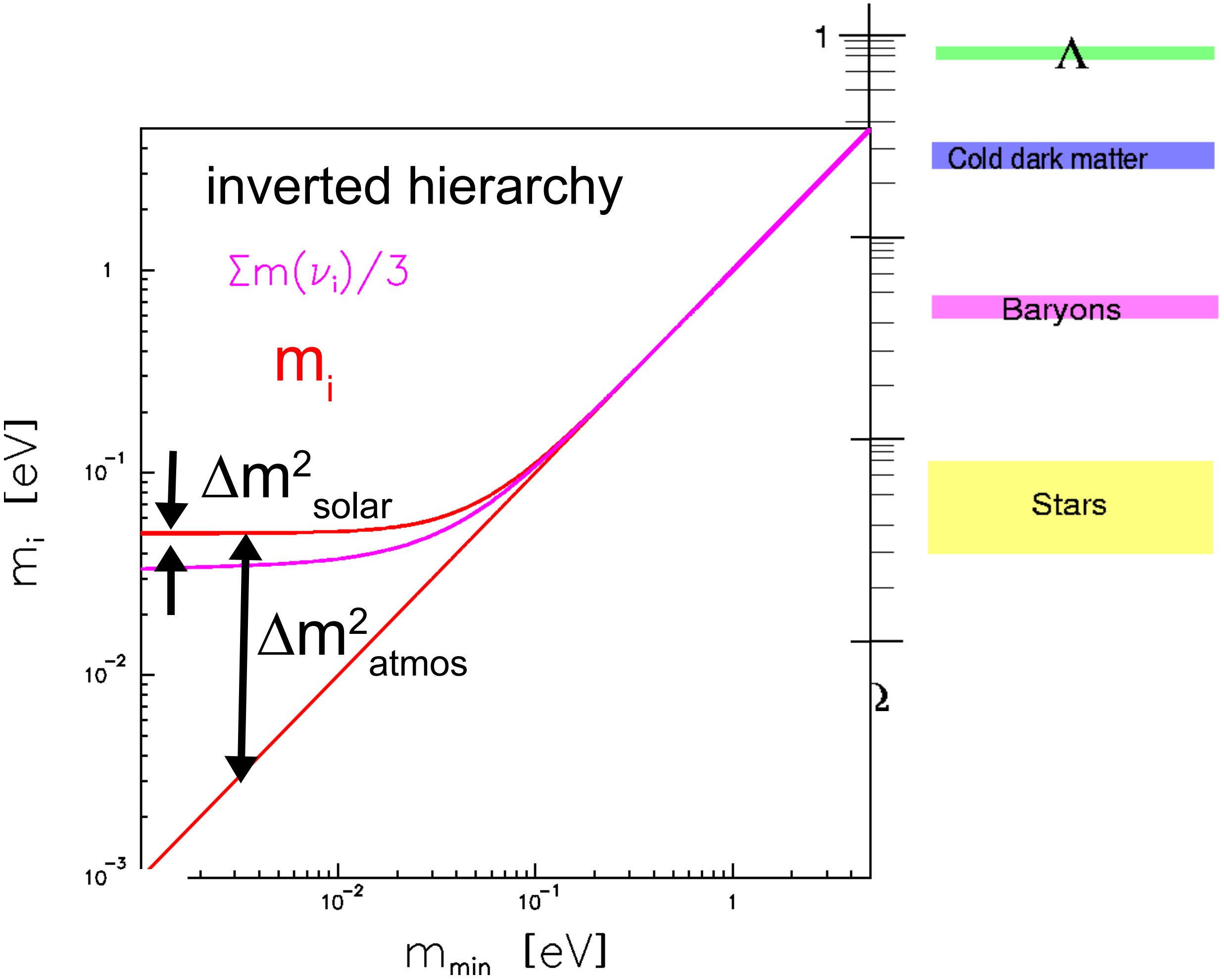

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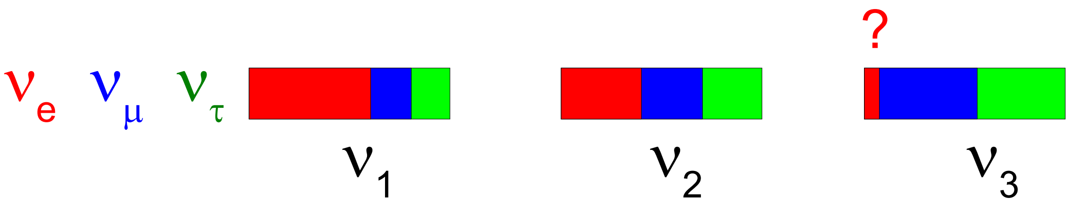

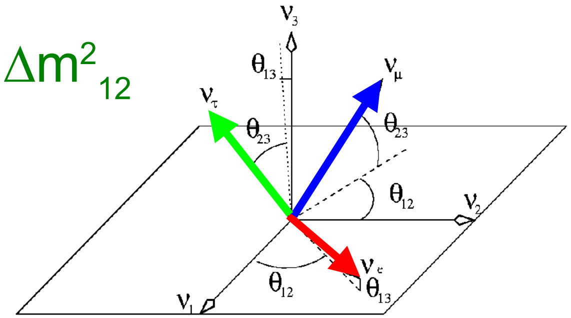

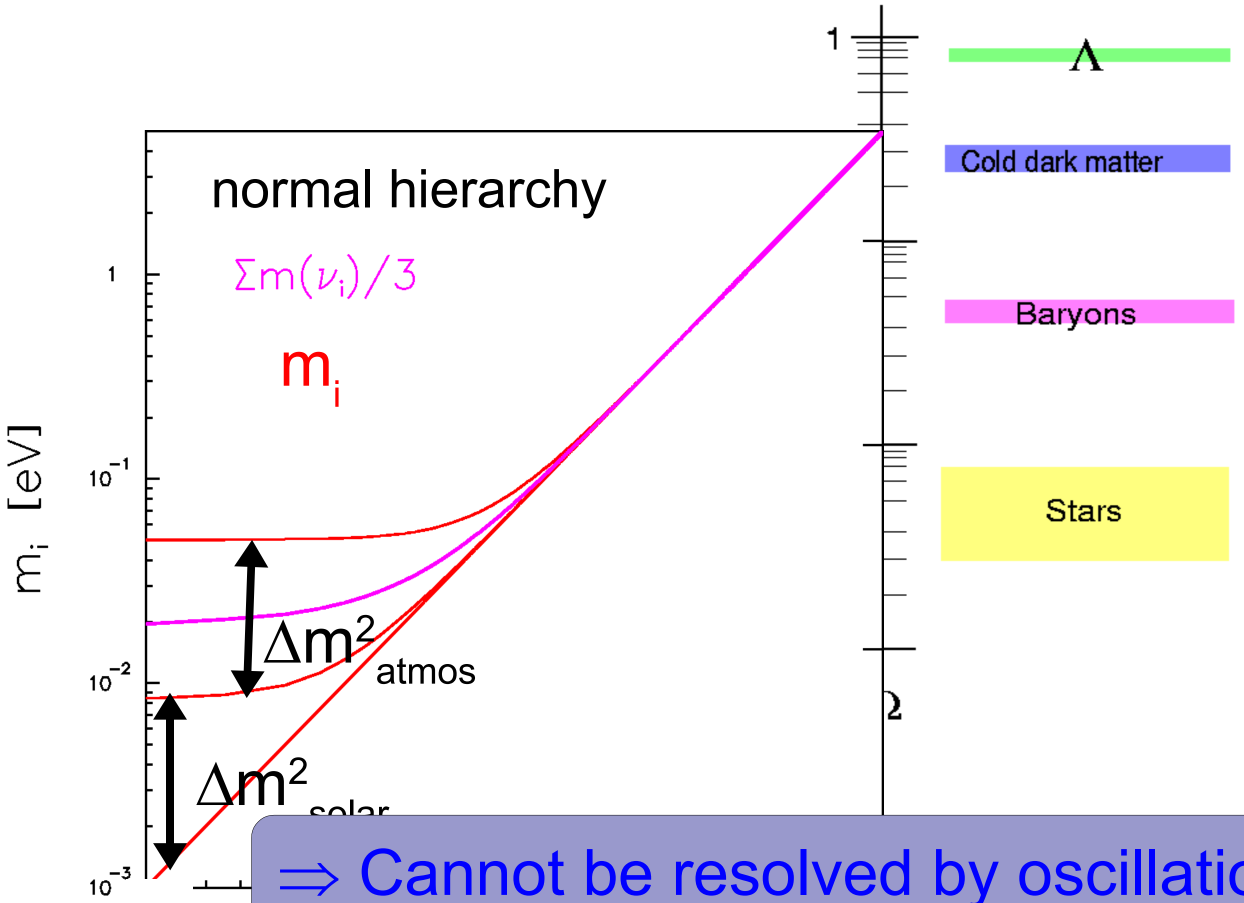

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1) distinquish hierarchical and degenerate masses (→ theory beyond SM)
2) check cosmological relevance (→ ν hot Dark Matter)

⇒ Cannot be resolved by oscillation experiments !
need absolute neutrino mass scale !

Das Karlsruher Tritium Neutrinoexperiment KATRIN

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

(Letter of Intent: hep-ex/0109033)

KATRIN
Karlsruhe Tritium Neutrino Experiment

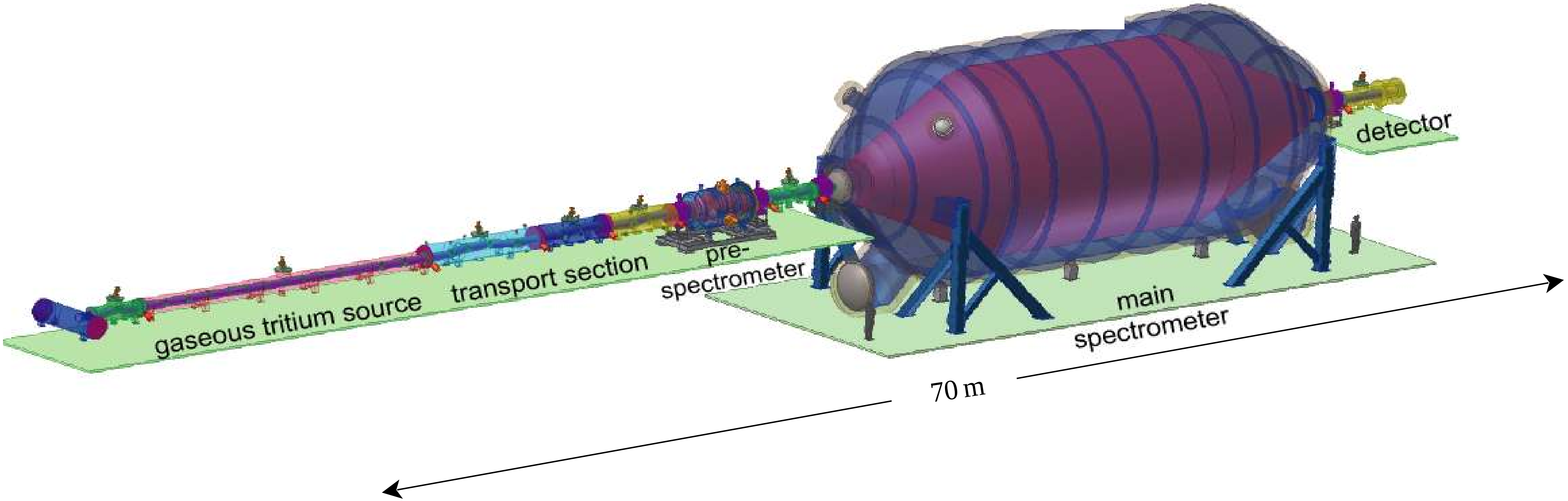
Physikalisches Ziel:

Sensitivität auf Neutrinomassenskala: $m(\nu) \approx 0.2$ eV

- Höhere Energieauflösung: $\Delta E \approx 1$eV
  da $E/\Delta E \sim A_{\text{spectrometer}}$ $\Rightarrow$ größeres Spektrometer
- Relevanter Bereich unterhalb des Endpunkts ist kleiner
  noch weniger Zählrate $dN/dt \sim A_{\text{spectrometer}}$ $\Rightarrow$ größeres Spektrometer

$\Big\}$ $\varnothing$10m

neu, seit 12/2002



Zusammenfassung

Atmosphärische Neutrinos

- Neutrinooszillation $P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \cdot \sin^2(\Delta m^2 L/4E)$

  $\Rightarrow$ Neutrinos mischen und haben Masse !

Beschleunigerneutrinos

- atmosphärische Neutrinooszillation bestätigt
- Keine weiteren starken Evidenzen für Neutrinooszillation (LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?)

Solare Neutrinos

- Rätsel des zu geringen Flusses gelöst: Neutrinooszillation

Reaktorneutrinos

- Bestätigung der solaren Neutrinooszillation durch KamLAND (long baseline)

Aufgaben für die Zukunft:

Absolute Neutrinomassenskala	(→ KATRIN)
Dirac- oder Majorana-Neutrinos	(→ $0\nu\beta\beta$)
Genauere Parameter der Mischungsmatrix	(→ Double-Chooz, long baseline, ...)