

Neutrino-Physik

Teil II:

Sonnen- und Reaktor-Neutrinos

Eigenschaften der Neutrinos

	Familien			elektr. Ladung	Kräfte			
					st	em	schw	grav
Quarks	u	c	t	2/3	x	x	x	x
	d	s	b	-1/3	x	x	x	x
Leptonen	ν_e	ν_μ	ν_τ	0	-	-	x	x
	e	μ	τ	-1	-	x	x	x

- im Standardmodell: ν sind masselos
- ν ($\bar{\nu}$) gehorchen nur der Schwachen Wechselwirkung (falls masselos); max. Paritätsverletzung: Helizität -1 (+1)
- Massengrenzen aus Zerfallskinetik:
 - $M(\nu_e) < 2 \text{ eV}/c^2$ (Tritium Endpunkt)
 - $M(\nu_\mu) < 0.19 \text{ MeV}/c^2$
 - $M(\nu_\tau) < 18.2 \text{ MeV}/c^2$
- Massengrenzen aus Kosmologie (Strukturbildung):
 - $\sum M(\nu_e, \nu_\mu, \nu_\tau) < 0.2 \text{ eV}/c^2$

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	d	s	b	-1/3	x	x	x	x
Leptonen	ν_e	ν_μ	ν_τ	0	-	-	x	x
	e	μ	τ	-1	-	x	x	x

- ν könnten ihre eigenen Antiteilchen sein (Majorana Teilchen)
- mögliche Konsequenzen von ν -Massen:
 - flavour-Eigenzustände ν_e ν_μ ν_τ können **Mischung** der Massen-Eigenzustände ν_1 ν_2 ν_3 sein
 - \rightarrow Oszillationen zwischen flavour-Eigenzuständen
 - ν könnten ein (kleines) magnetisches Moment haben
 \rightarrow wechselwirken auch elektromagnetisch?

2-Flavour Neutrino Oszillationen:

$$U = \begin{matrix} & \nu_1 & \nu_2 \\ \nu_\alpha & \cos \theta & \sin \theta \\ \nu_\beta & -\sin \theta & \cos \theta \end{matrix} \cdot$$

z.B.: $|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \sin^2 2\theta \sin^2[1.27 \Delta m^2(L/E)]$$

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha) = 1 - \sin^2 2\theta \sin^2[1.27 \Delta m^2(L/E)]$$

3-Flavour Neutrino Oszillationen:

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

$$c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij} \quad \delta: \text{CP verletzende Phase}$$

es gilt: $\theta_{atm} \cong \theta_{23} \quad \theta_{solar} \cong \theta_{12}$

n.b.: CP Verletzung hängt immer mit s_{13} zusammen!

Neutrino-Quellen:

•Solare Neutrinos

(Entstehen bei den Fusionsreaktionen in der Sonne), ca 2×10^{38} /s,
Fluss auf der Erde $\sim 7 \times 10^{10} \text{ cm}^{-2\text{s}^{-1}}$

•Kosmische Hintergrundneutrinos

Ausfrieren aus thermischen Gleichgewicht $\sim 1\text{s}$ nach dem Urknall
Temperatur $\sim 1.9 \text{ K}$, $\langle E \rangle \sim 5 \times 10^{-4} \text{ eV}$, $\sim 330/\text{cm}^3$

•Kosmische Neutrinoquellen

Supernova-Explosionen, Aktive Galaxien, GRBs...

•Atmosphärische Neutrinos

Entstehung in Luftschauern kosmischer Strahlung

•Geo-Neutrinos

Radioaktiver Zerfall in der Erde, Gesamt-Leistung $\sim 20 \text{ TW}$, Fluss $\sim 10^7 \text{ cm}^{-2\text{s}^{-1}}$

•Von Menschen erzeugte Neutrinos

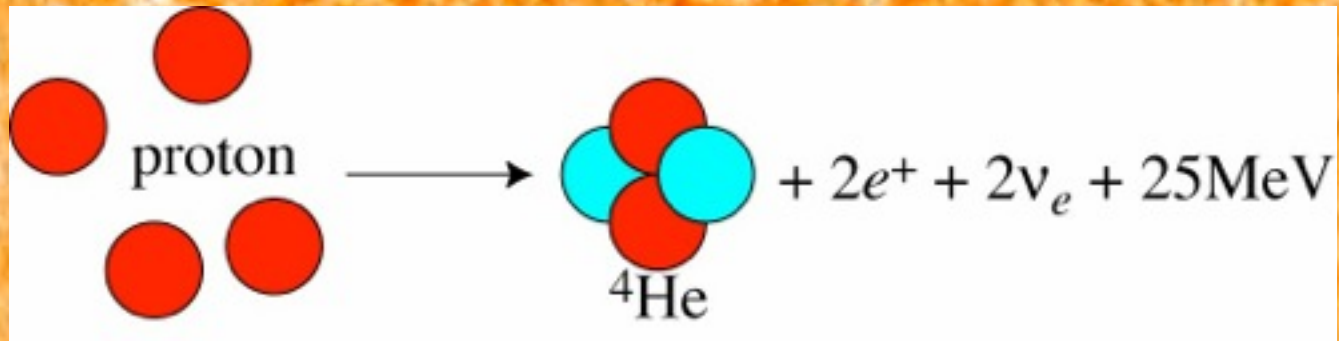
Reaktor-Neutrinos (MeV-Bereich), ca 10^{20} /s;
Beschleuniger (MeV \rightarrow GeV),

Sensitivität verschiedener Oszillationsexperimente

Source	Type of ν	\bar{E} [MeV]	L [km]	$\min(\Delta m^2)$ [eV ²]
Reactor	$\bar{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\bar{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν 's	$\nu_{\mu,e}, \bar{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \sin^2 2\theta \sin^2[1.27 \Delta m^2 (L/E)]$$

Energieerzeugung in der Sonne



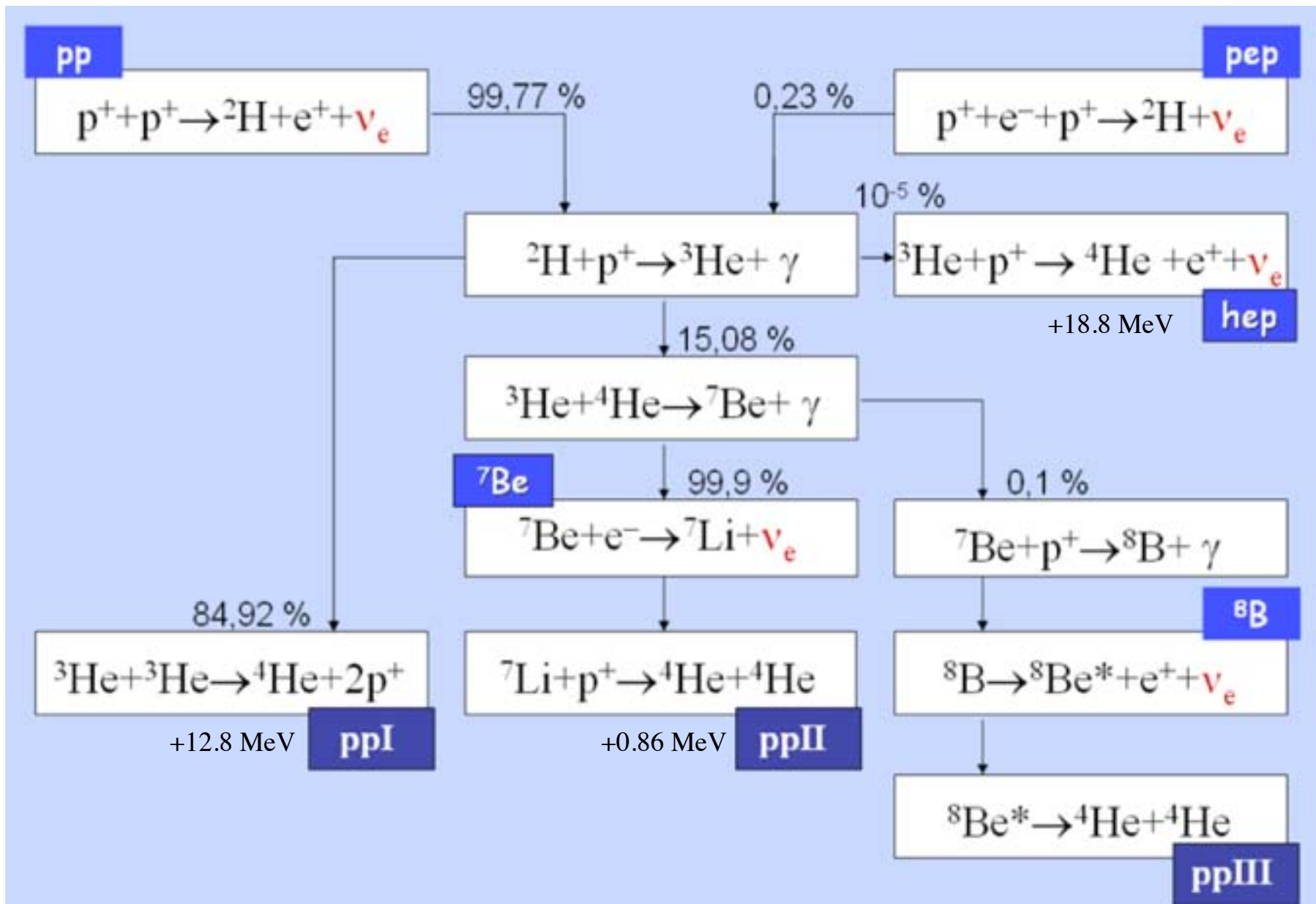
$$\Phi_{\nu} = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7 \cdot 10^{10} \text{ sec}^{-1} \text{ cm}^{-2}$$



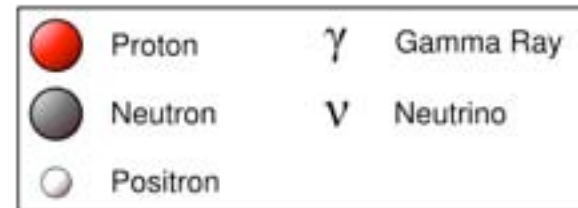
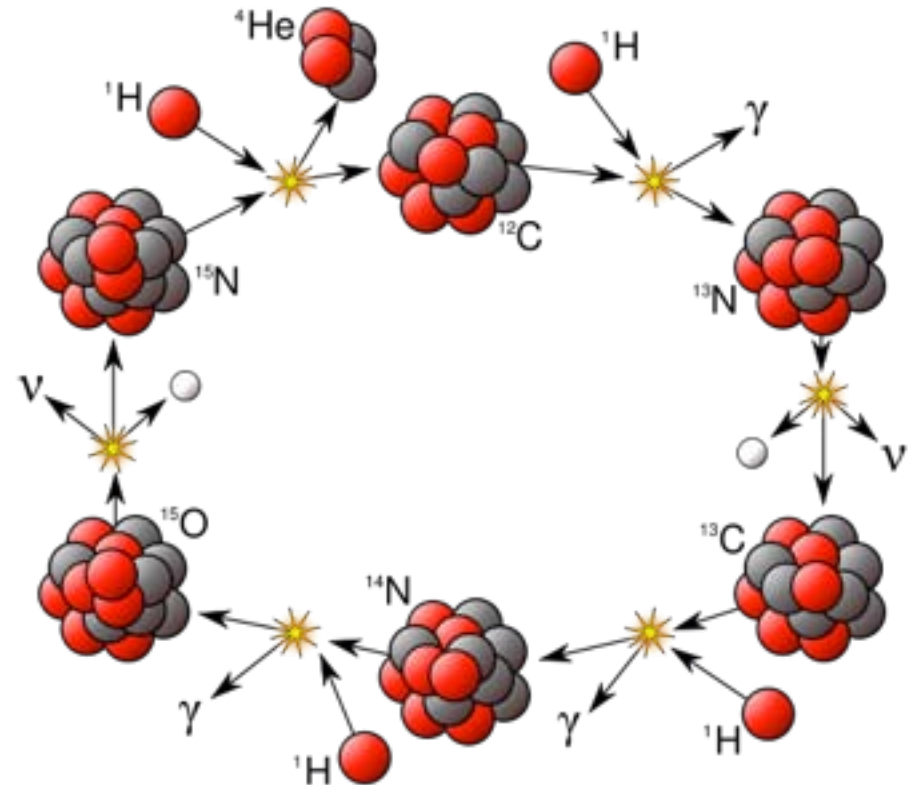
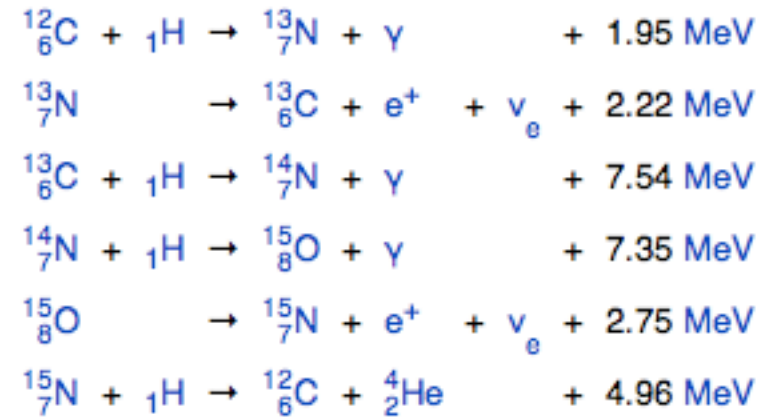
FACT: about 65 billion neutrinos pass through your thumbnail every second.

Learn Something
New Every Day
LSNED.com

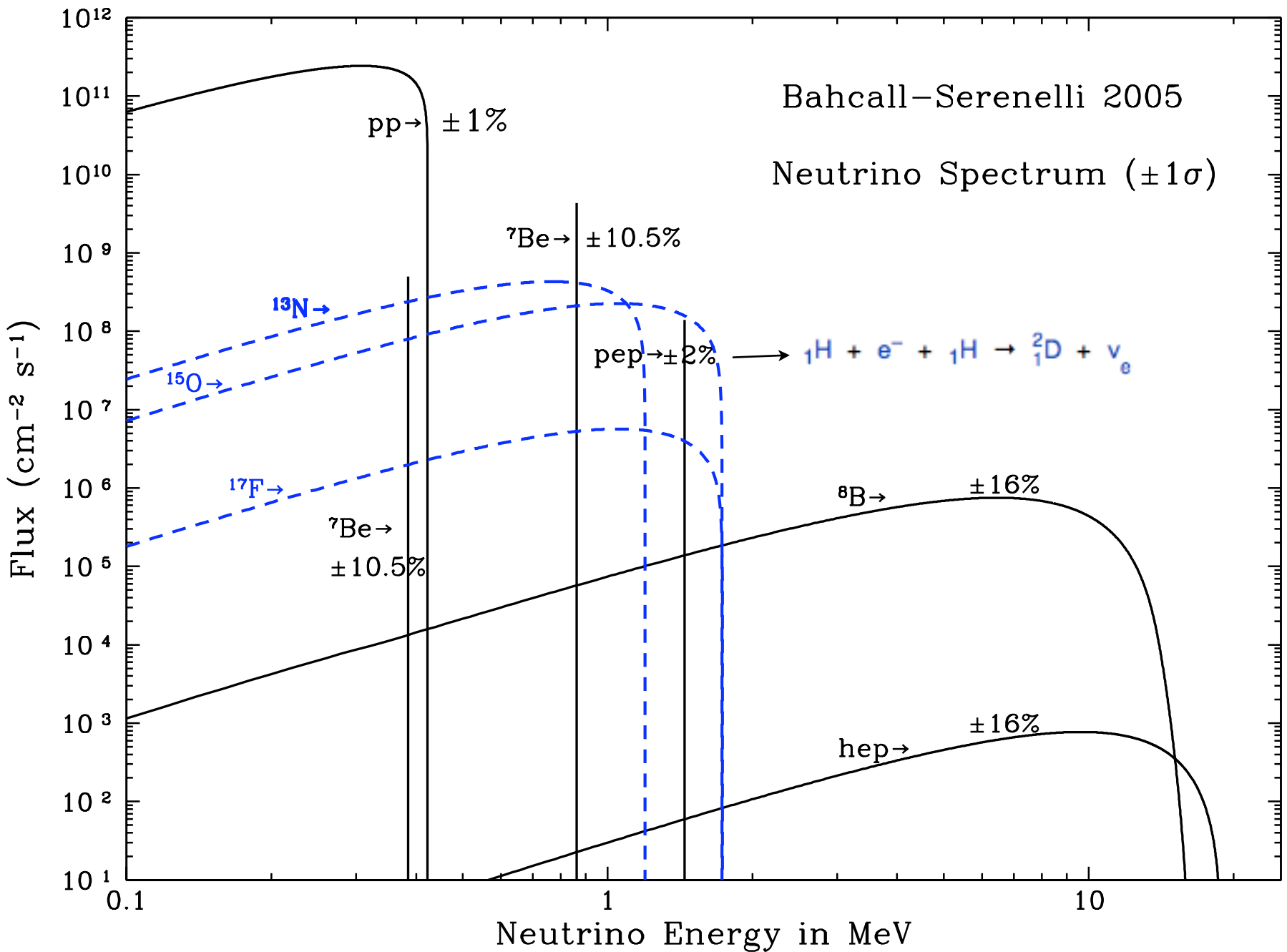
Das solare Standardmodell: Proton-Proton-Kette

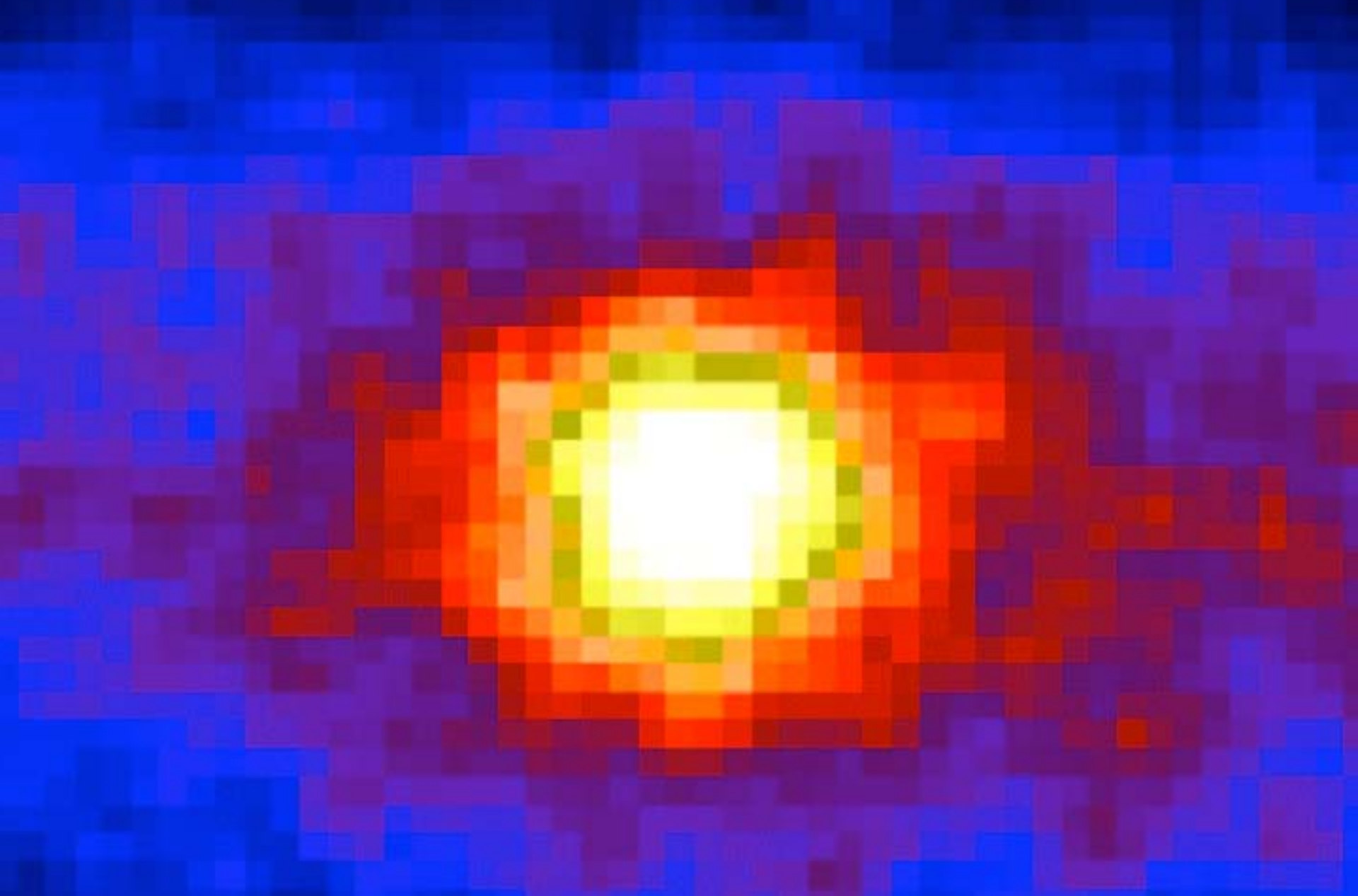


der CNO Kreislauf (Bethe-Weiszäcker)



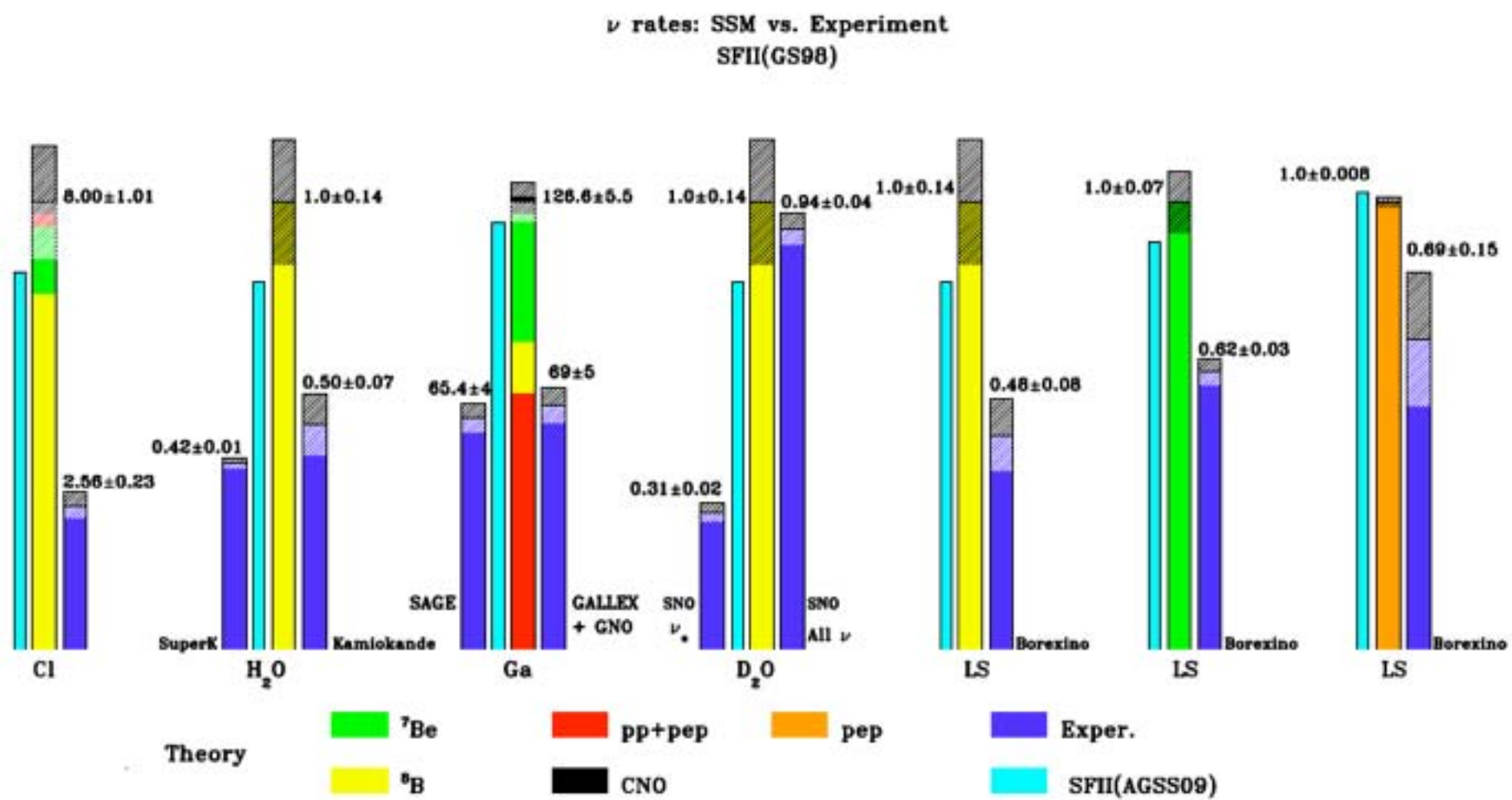
- CNO dominiert in schweren Sternen
- Sonne: ca. 1.7% des ${}^4\text{He}$ durch CNO, sonst p-p.





Die Sonne „gesehen“ mit Neutrinos (SuperK)

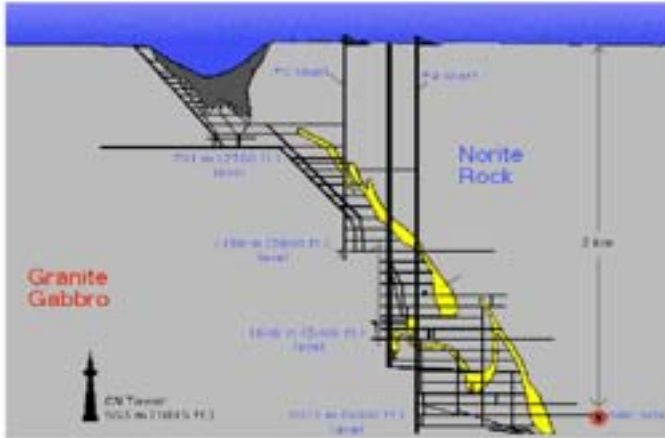
langjährige Messungen: wir sehen signifikant zu wenige Neutrinos von der Sonne!



Quelle: Serenelli, Neutrino 2012, Kyoto

Experimente messen i.w. ^8B Neutrinos

Sudbury Neutrino Observatory (SNO)



1000 tonnes D_2O

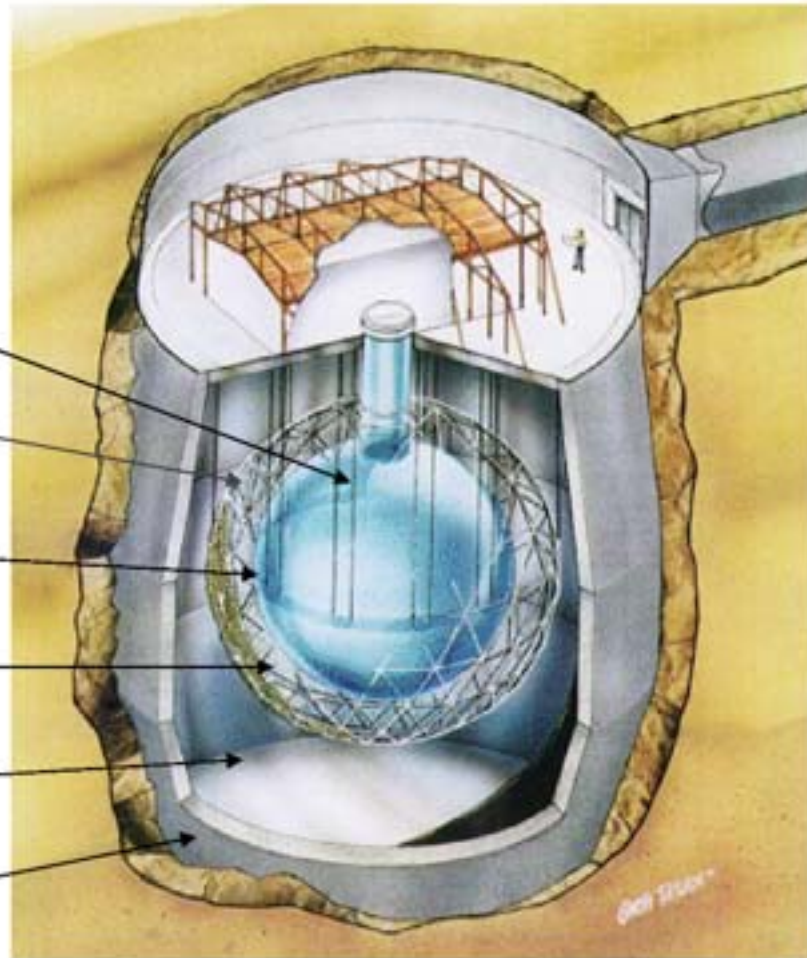
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

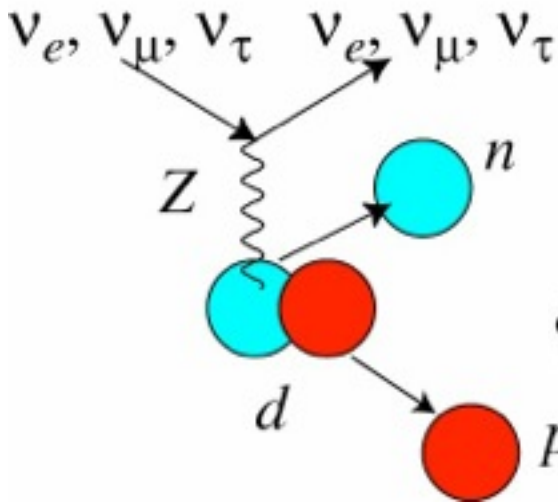
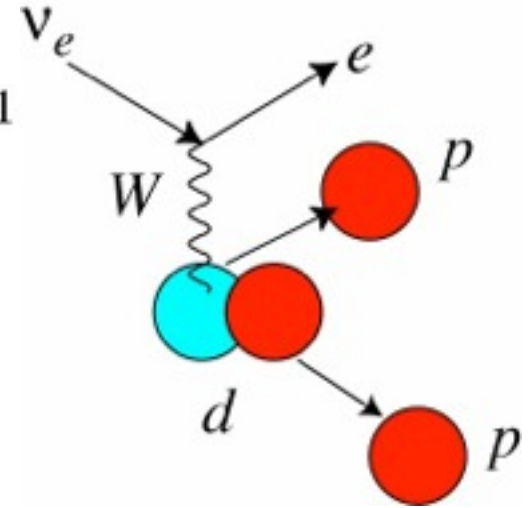
5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



SNO misst Elektron-Neutrino-Raten (cc)
 und Summe aller Neutrinos (nc):

$$\Phi_{CC}^{SNO} = 1.59_{-0.07}^{+0.08} {}_{-0.08}^{+0.06} \times 10^6 \text{cm}^{-2} \text{s}^{-1}$$



$$\Phi_{NC}^{SNO} = 5.21 \pm 0.27 \pm 0.38 \times 10^6 \text{cm}^{-2} \text{s}^{-1}$$

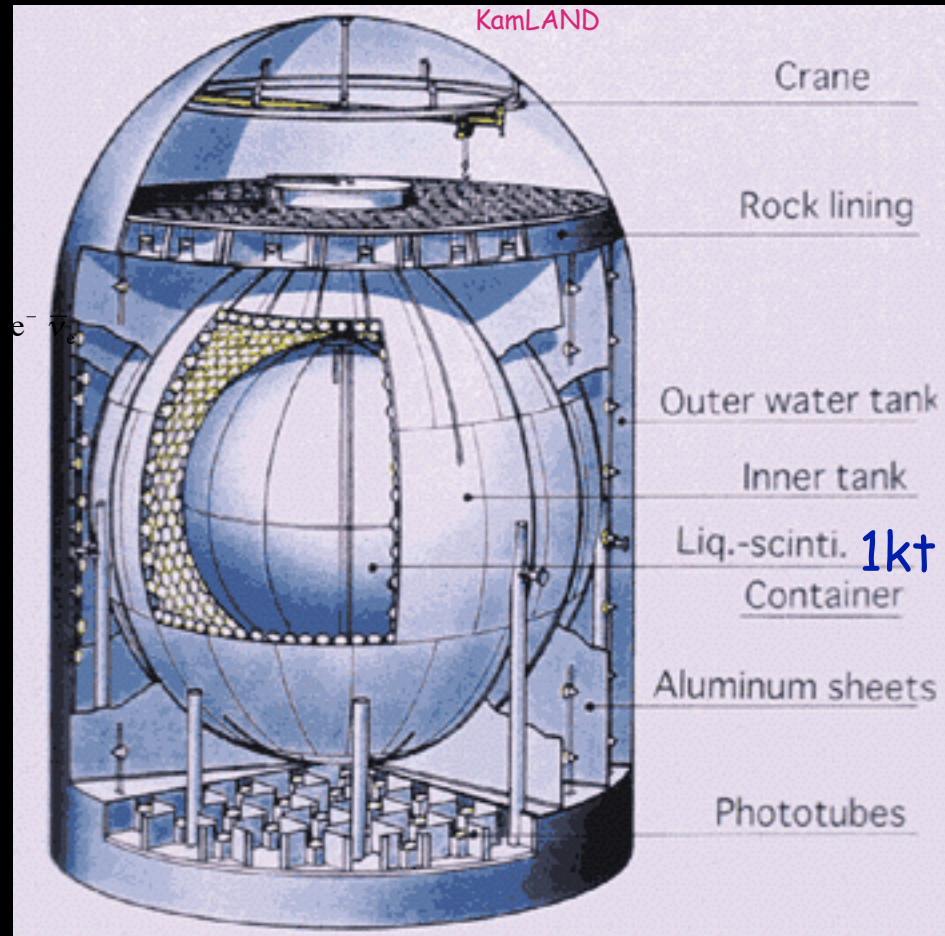
gesamter Neutrinofluss (nc) stimmt gut mit Erwartung aus solarem Standardmodell (SSM) überein, aber nur 1/3 kommt als Elektron-Neutrino an → Oszillationen!

Terrestrische “Solare Neutrinos”: Neutrinos von Kernreaktoren

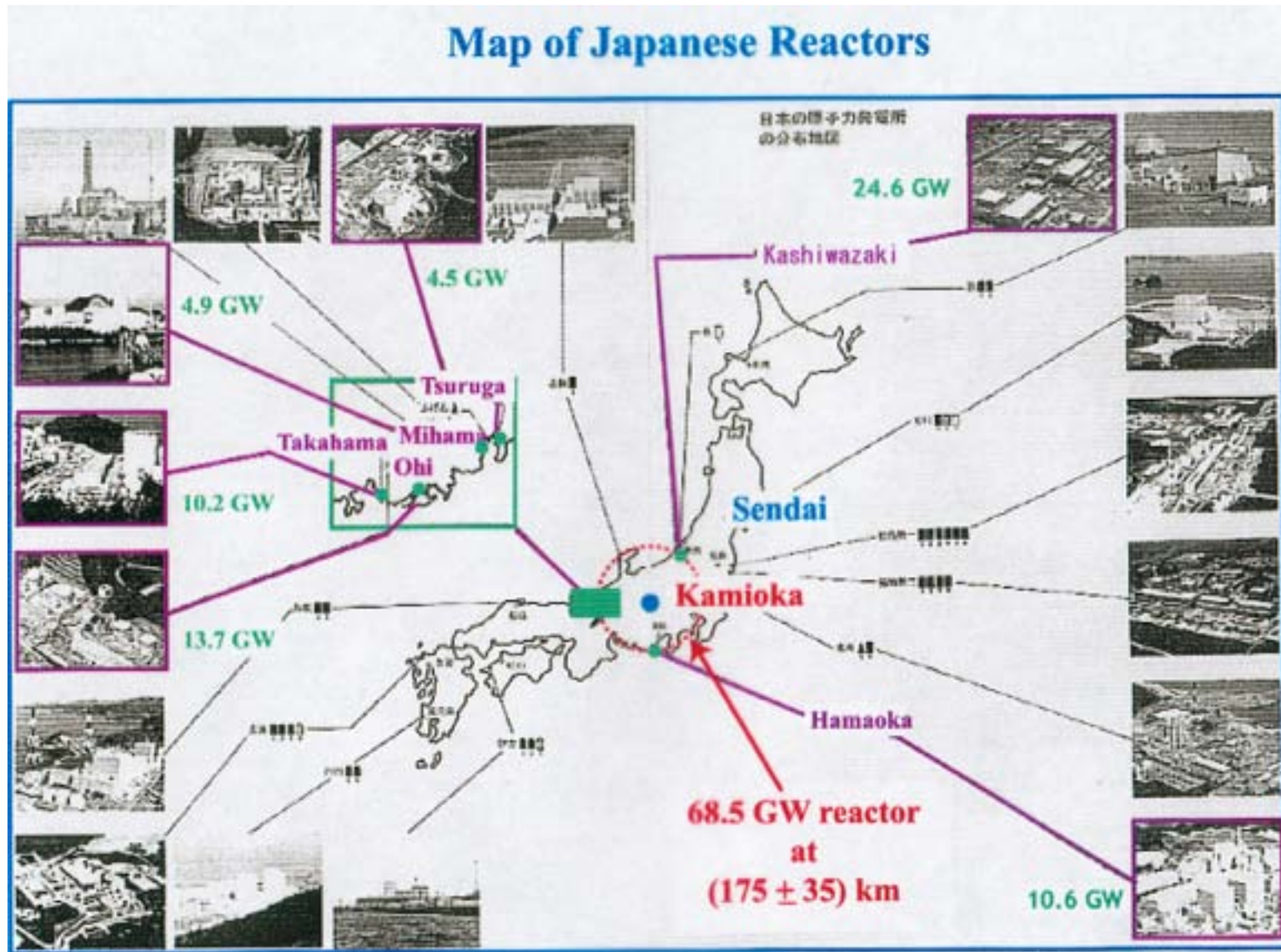
- Kann man Neutrino Oszillationen mit man-made Neutrinos sehen?

$$P_{surv} = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 c^4 \text{ GeV } L}{eV^2 E_\nu \text{ km}} \right)$$

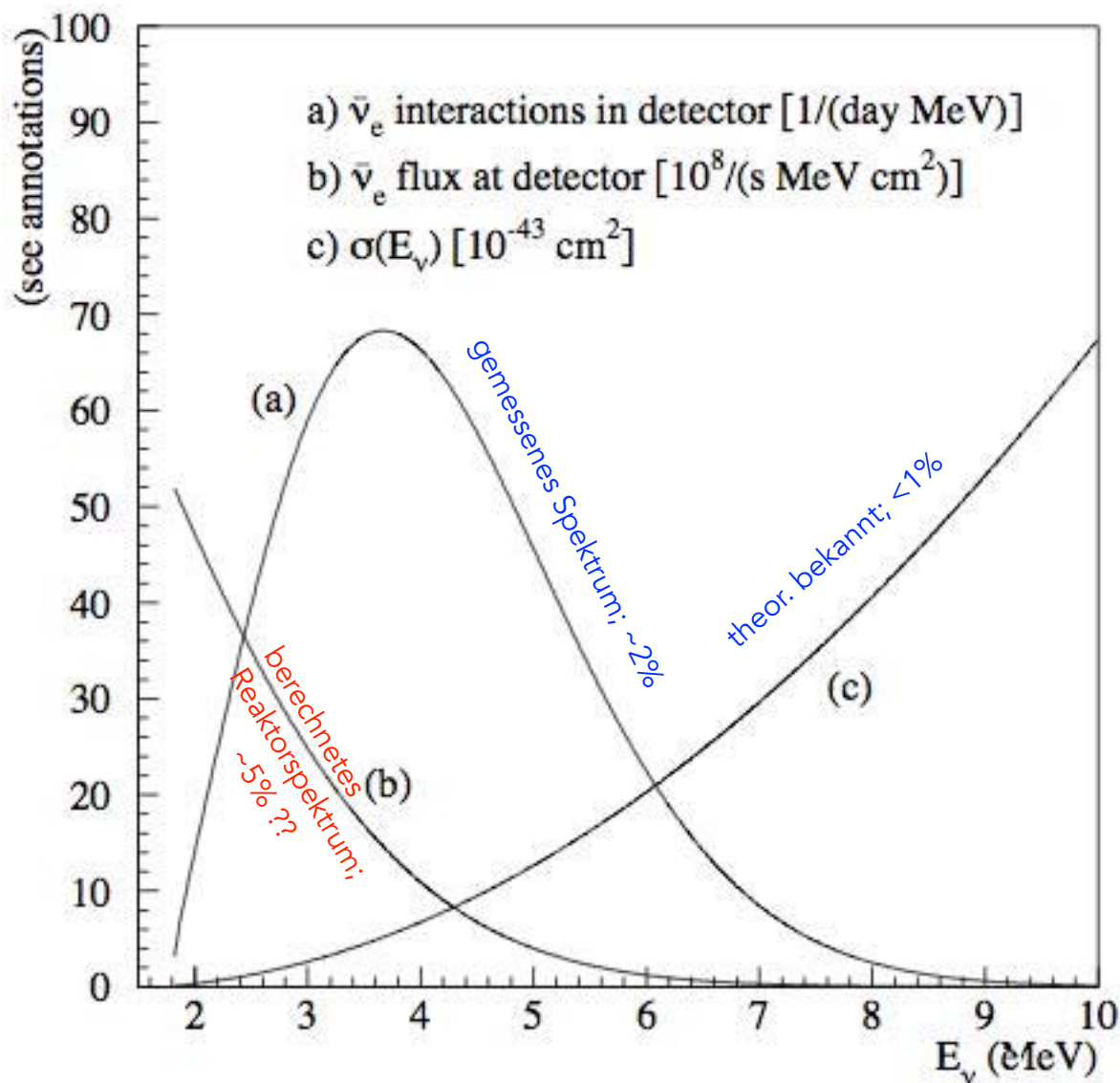
- schwierig für kleine Δm^2
- Um LMA zu testen, braucht man $L \sim 100\text{km}$, 1kt
- niedrige E_ν , hohe Φ_ν
- Reaktor: $n \rightarrow p e^- \bar{\nu}_e$
- Nachweis: $\bar{\nu}_e p \rightarrow n e^+$
- e^+ : $e^+ e^- \rightarrow 2\gamma$; n Einfang



Kamland ist umgeben von vielen Hochleistungsreaktoren
(L ~ 180 km)

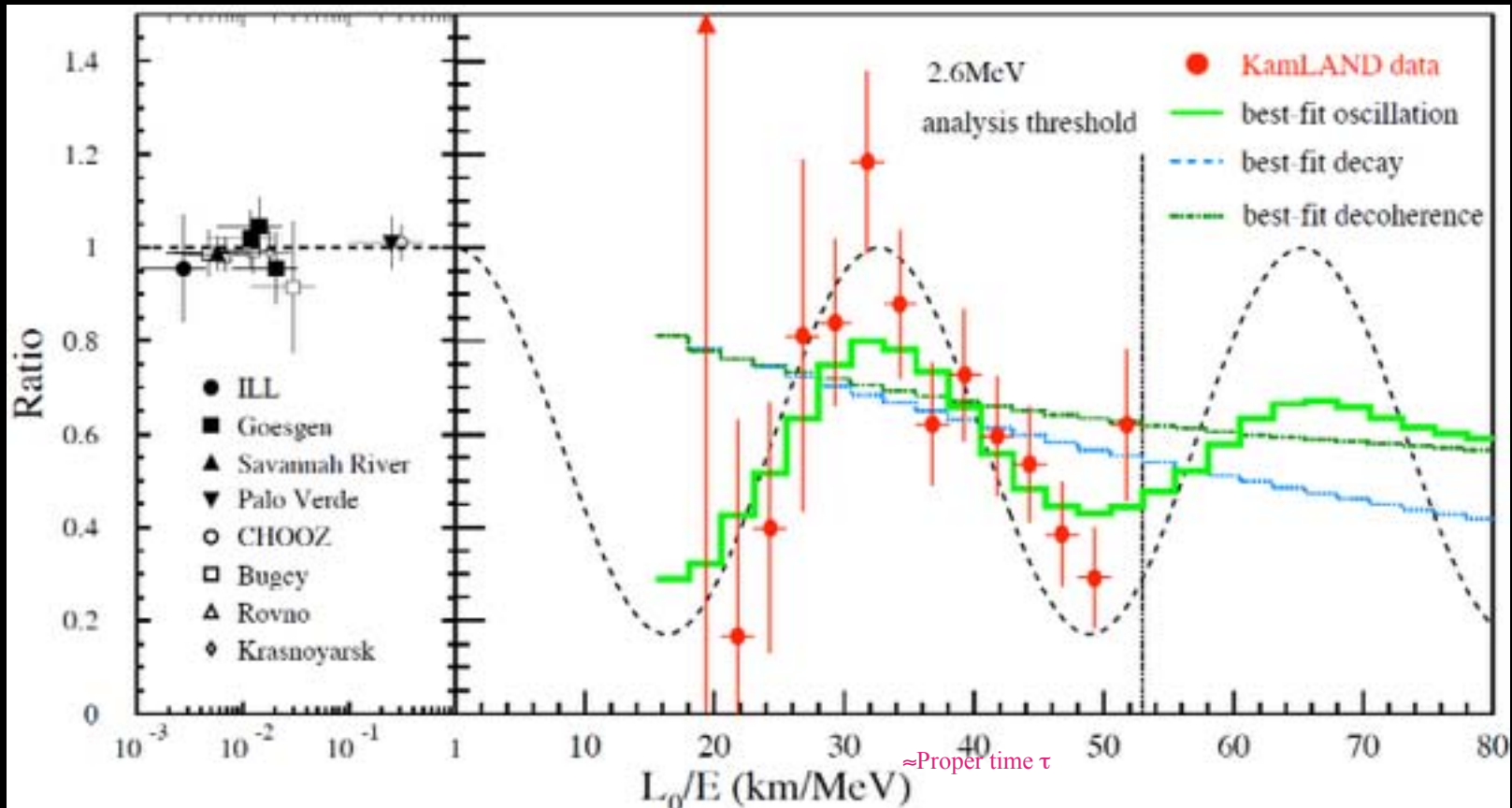


Energiespektren



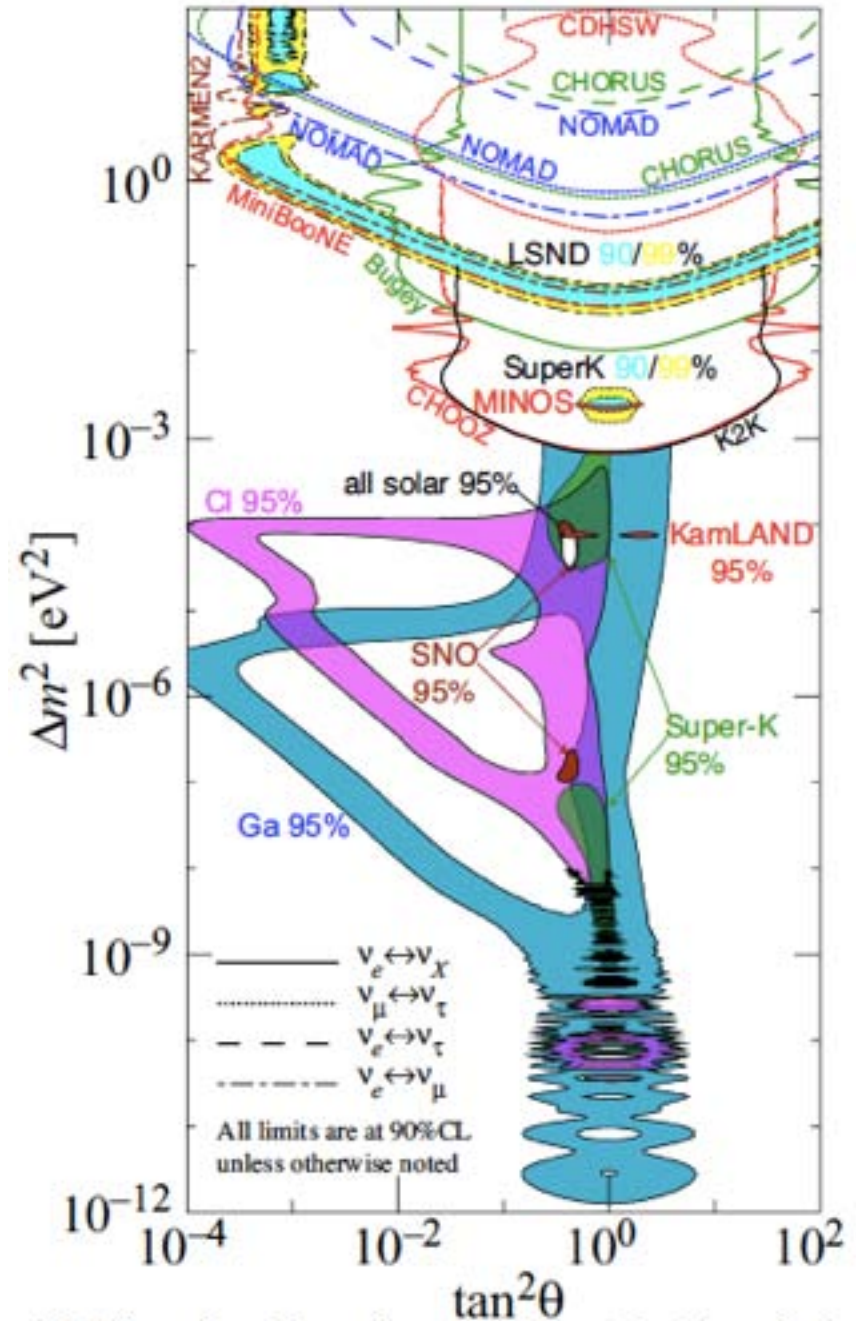
KamLAND

Reaktor Neutrinos oszillieren!

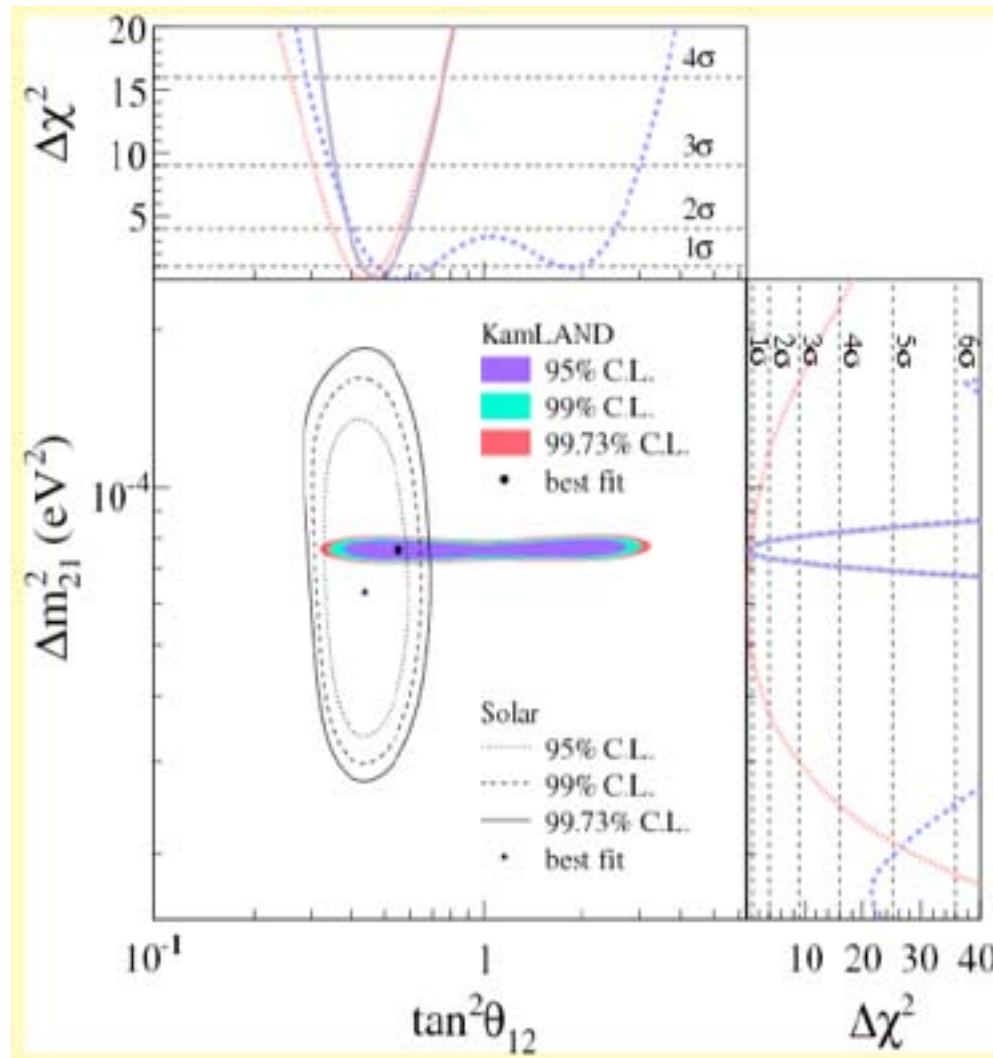


$L_0 = 180$ km

Zusammenfassung aller
 Oszillations-Messungen
 (farbige Flächen) und
 Ausschlussmessungen
 (Linien):
 [Annahme: 2- ν -mixing]



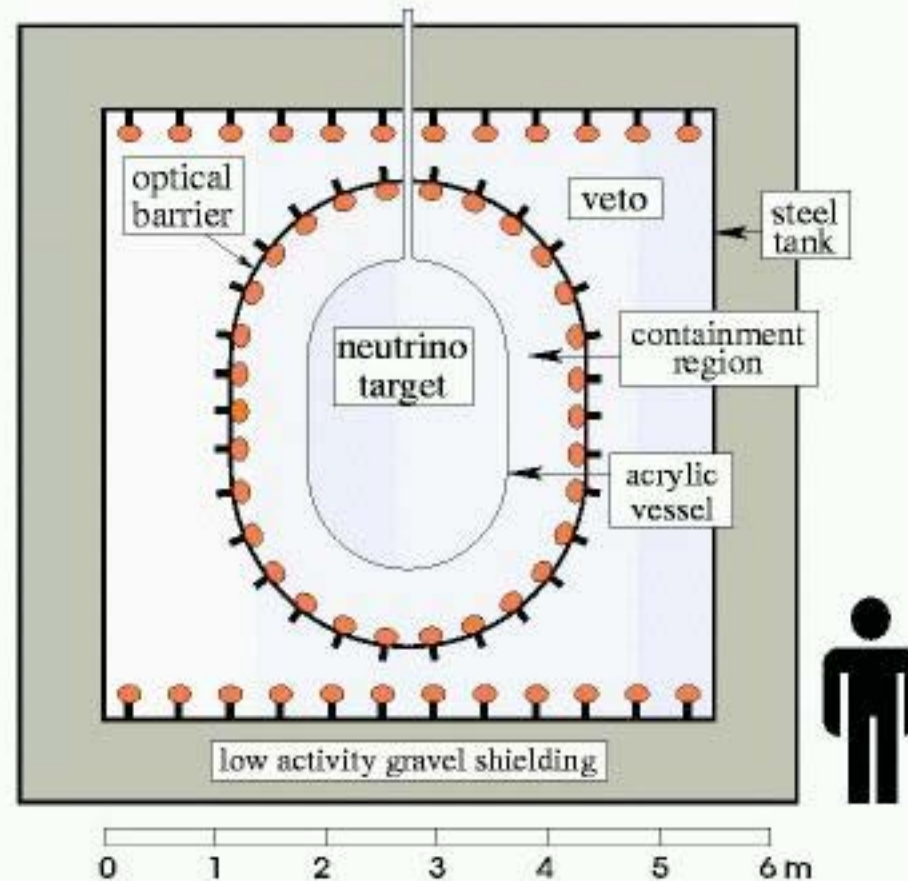
Kombination aller solaren Neutrino Daten mit KamLAND Reaktor Daten:



$$\Delta m^2 = 8.0_{-0.4}^{+0.6} \times 10^{-5} \text{ eV}^2 \quad \theta = 33.9_{-2.2}^{+2.4} \text{ deg}$$

θ_{13} ?

Chooz



- target: 5 t flüssig-Szintillator, dotiert mit Gadolinium
- containment region: 17 t Szintillator (undotiert)
- veto region: 80 t Szintillator (undotiert)

$$\sin^2\theta_{13} < 0.17 \quad (\theta_{13} < 24^\circ) \quad \text{bei} \quad \Delta m_{13}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$$

Double-Chooz



Near ()
<L> 400m
~300v/day
120mwe
Target: 8.2t
2014



Far
<L> 1050m
~40v/day
300mwe
Target: 8.2t
April 2011



Two Reactors

Power: 8.5GW_{th}

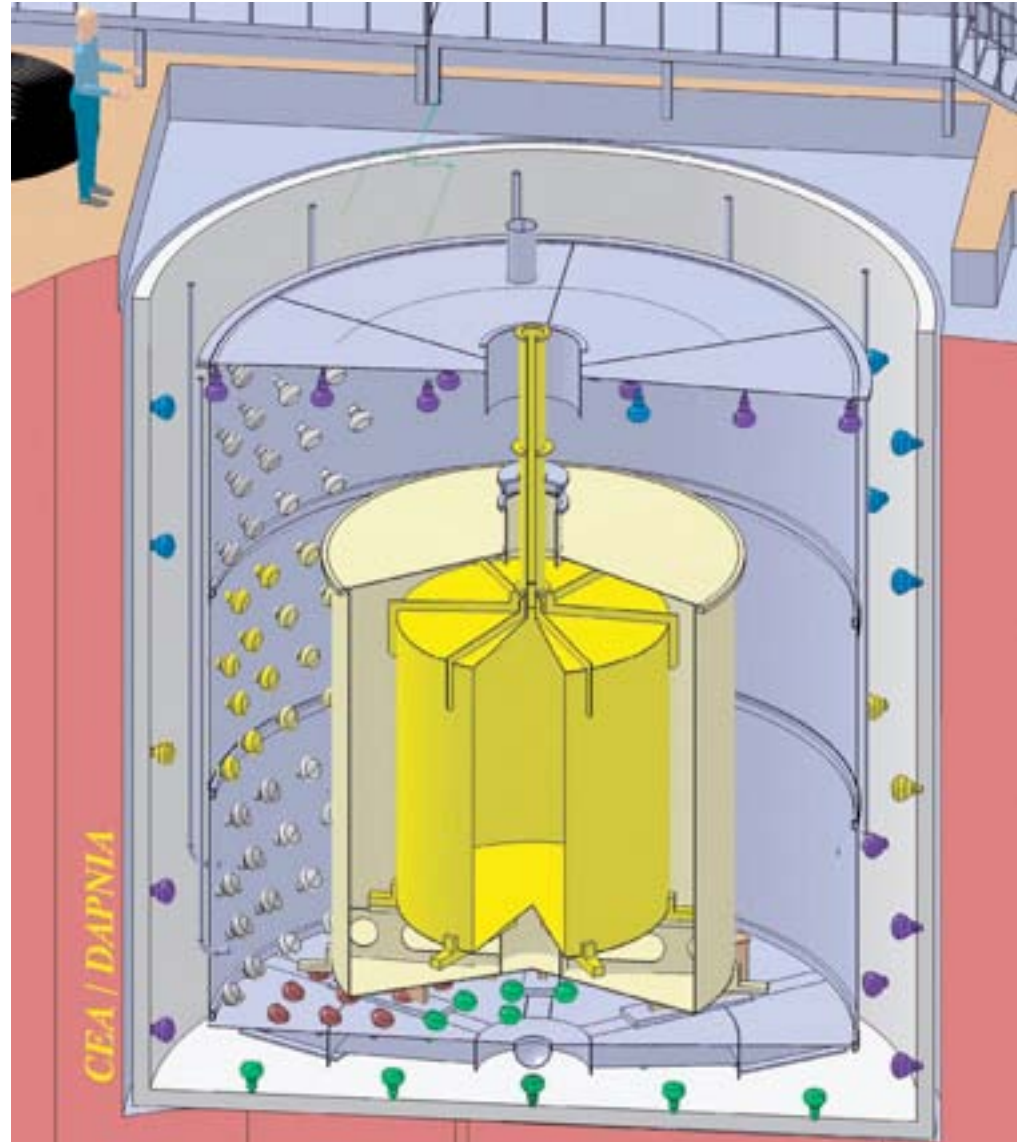
$\Rightarrow \sim 10^{21}\text{v/s}$

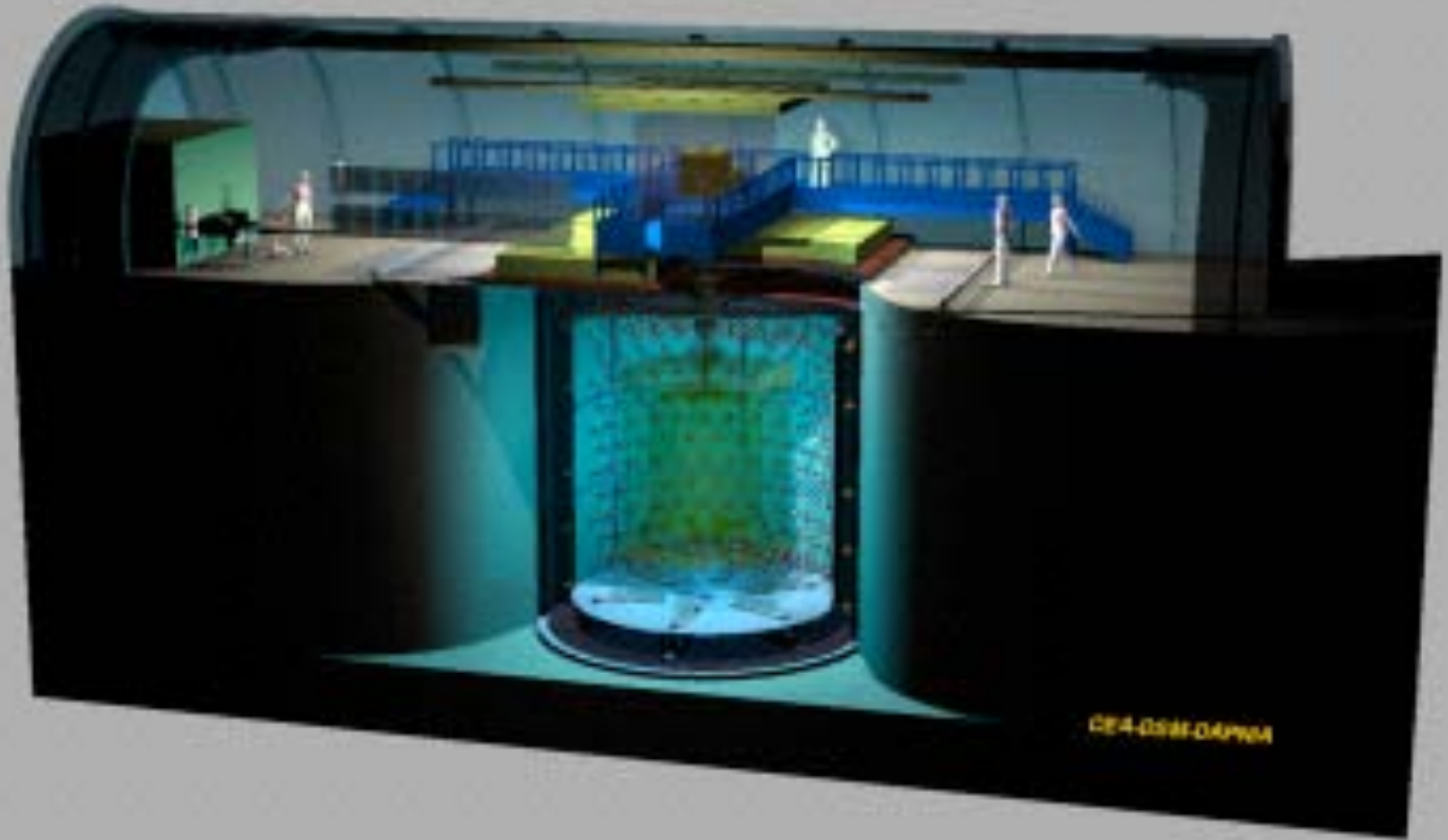
Double-Chooz

- 10 t Flüssigszintillator (Gadolinium-dotiert)
- 500 Photomultiplier
- Untersuchung von $\sin^2\theta_{13}$ im Bereich ~ 0.03 bis 0.20
- Sensitivität: 0.03 nach 3 Jahren Betrieb

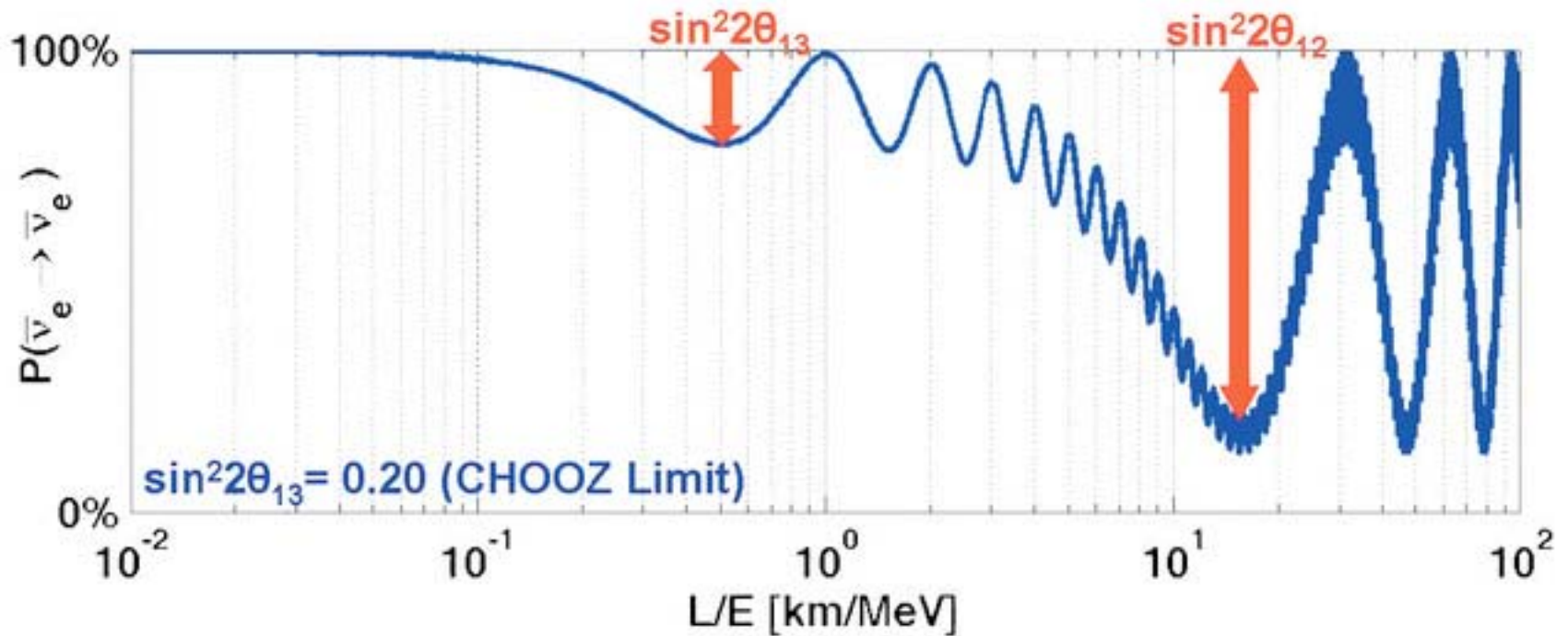
Messung:

- inverser β -Zerfall $\nu_e \bar{p} \rightarrow n e^+$
- $e^+ e^-$ Vernichtung $\rightarrow 2\gamma$
- n-Einfang Gadolinium $\rightarrow \gamma$ (30 ms)





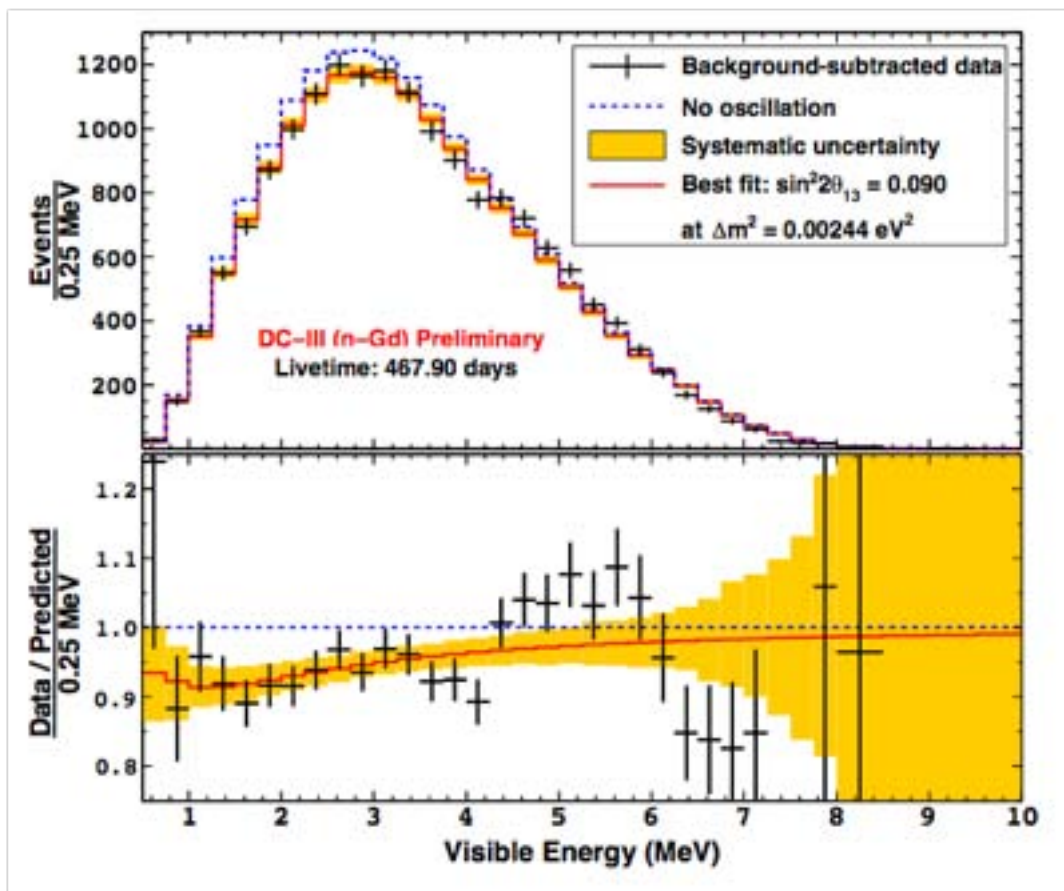
Double-Chooz



after ~ 3 years with both detectors: $\Delta \sin^2 2\theta_{13} \sim 0.03$

Double-Chooz (2013; far detector)

Rate+Shape results



$$\sin^2(2\theta_{13}) = (0.09 \pm 0.03)$$

$$(\chi^2/\text{n.d.f.} = 51.4/40)$$

The Daya Bay Experiment



Far Hall

1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden

Ling Ao Near Hall

481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden

3 Underground
Experimental Halls

Entrance

Daya Bay Near Hall

363 m from Daya Bay
98 m overburden

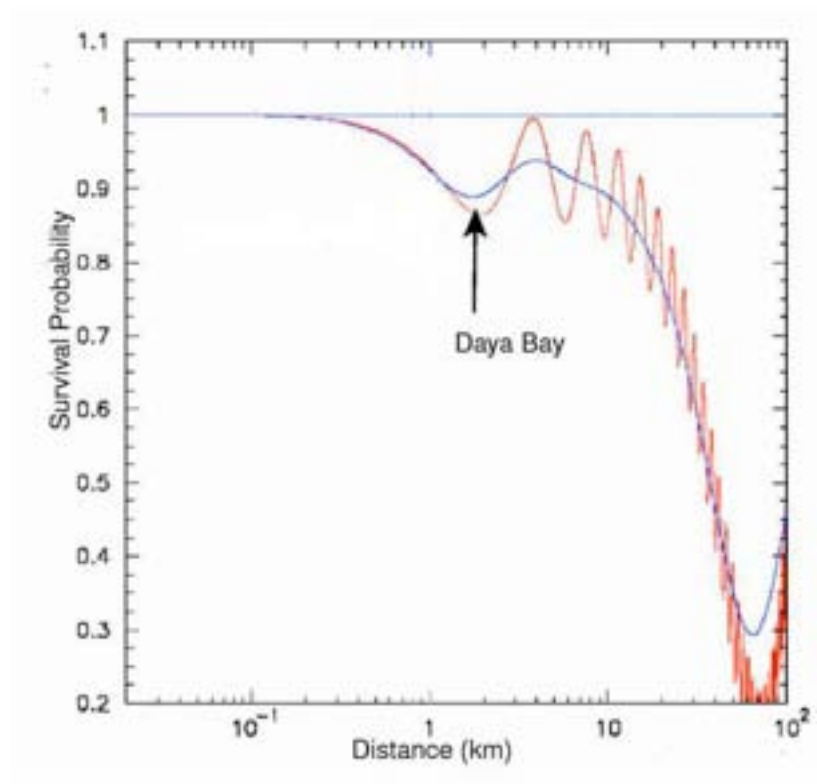
Ling Ao II Cores

Ling Ao I Cores

Daya Bay Cores

- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

Daya Bay

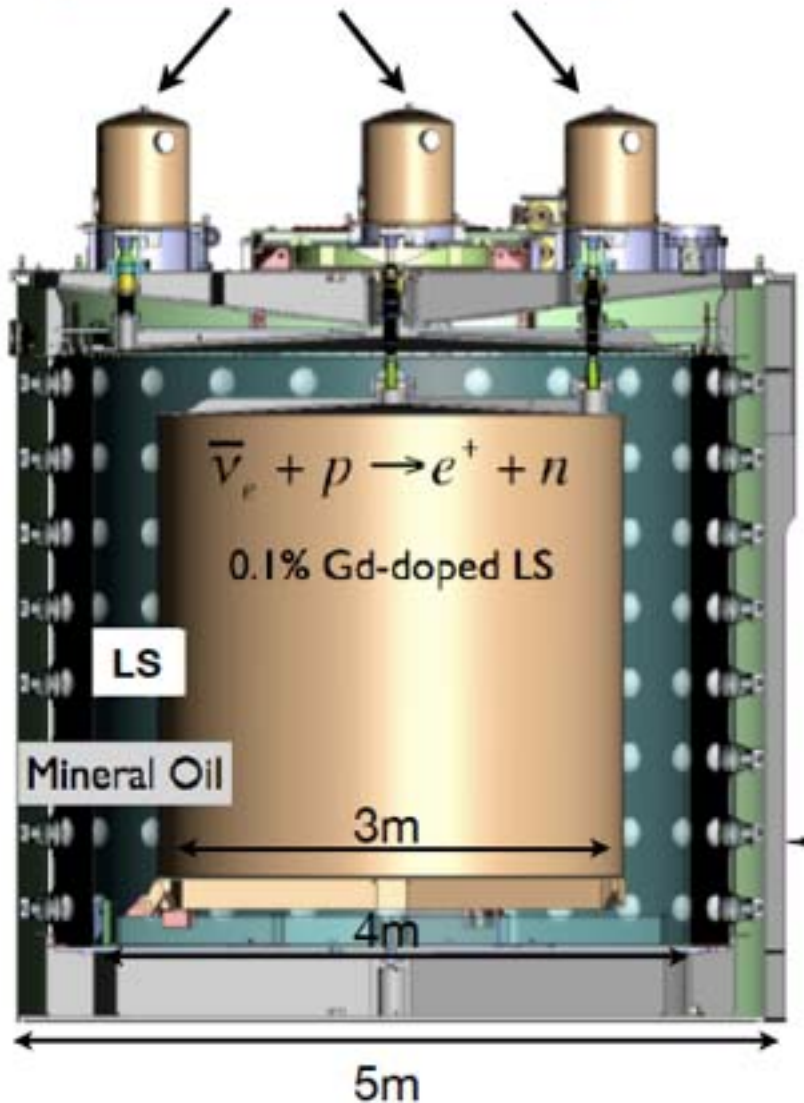


— mono-energetische ν
— Daya Bay E-Verteilung

- Sensitivität: bis 0.01 in $\sin^2\theta_{13}$

Daya Bay Antineutrino Detector

Automated Calibration Units



8 functionally identical detectors

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}} \right) \left(\frac{L_n}{L_f} \right)^2 \left(\frac{\epsilon_f}{\epsilon_n} \right) \left[\frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

Each detector has 3 nested cylindrical zones separated by Acrylic Vessels:

Inner: 20 tons Gd-doped LS (target volume)

Mid: 20 tons LS (gamma catcher)

Outer: 40 tons mineral oil (buffer)

Each detector has:

192 8-inch Photomultipliers (PMTs)

Optical reflectors at top/bottom of cylinder

- effectively 12% photocoverage

~ 160 photoelectrons / MeV

~ 8%/√E (MeV) energy resolution

The Timeline of Detector Installation

EH1



EH3



EH3



Aug. 2011

Dec. 2011

Aug. 2012

6-AD Data Taking

8-AD Data Taking

Nov. 2011

2011/12 - 2012/07

Aug. 2012

2012/10 - now



EH2



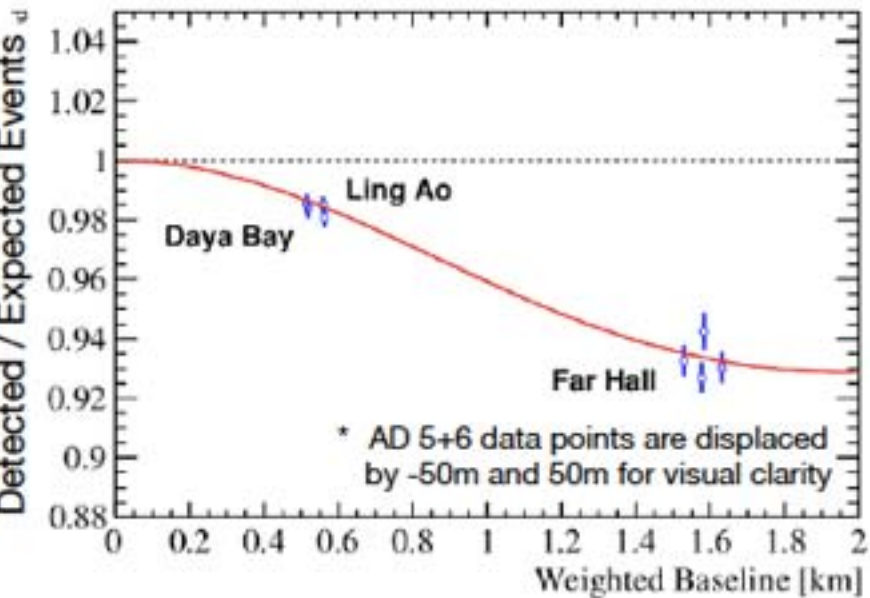
EH2



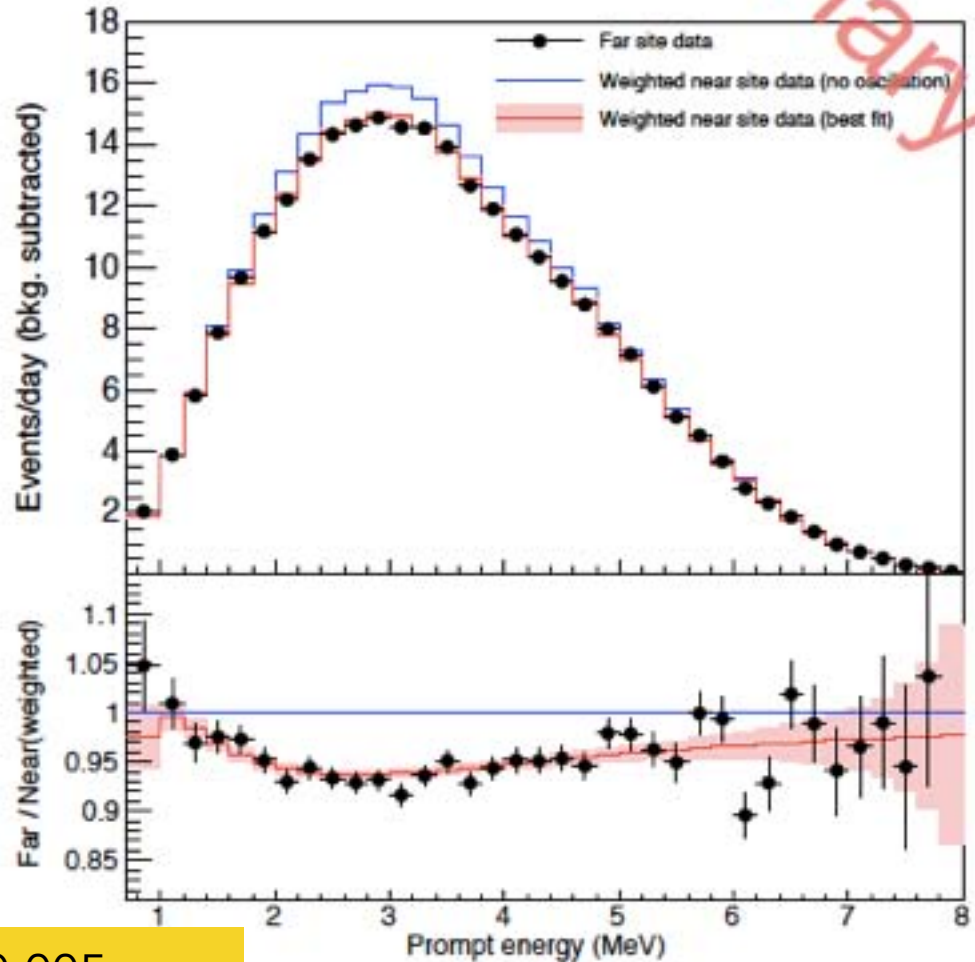
Far v.s. Near Comparison

Preliminary

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\Delta m_{ee}^2 \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left(\Delta m_{21}^2 \frac{L}{4E} \right)$$



The observed **relative rate deficit** and **relative spectrum distortion** are highly consistent with oscillation interpretation

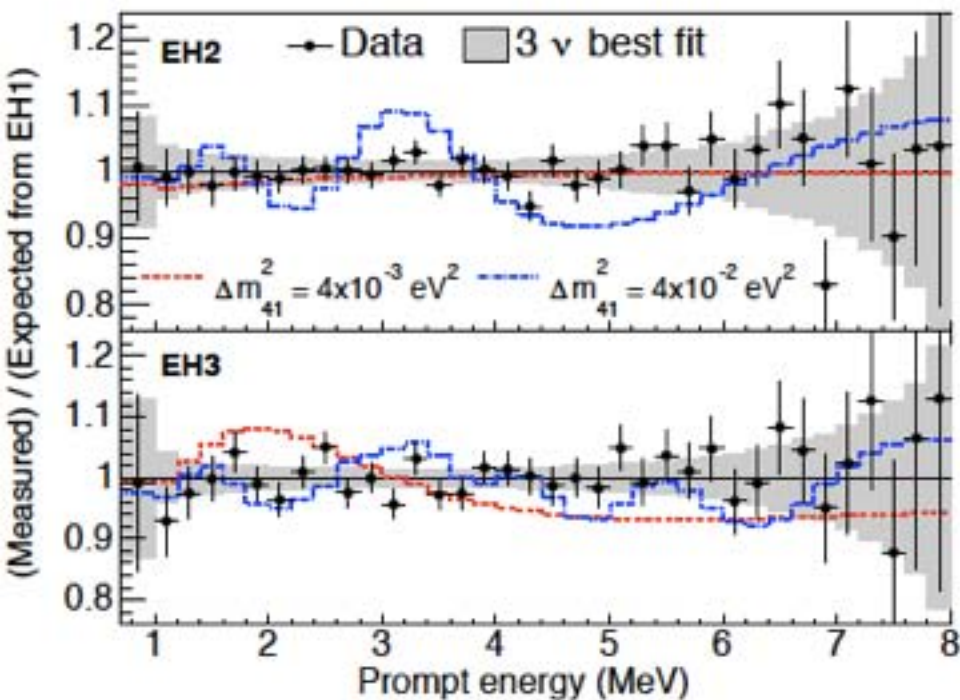


$$\sin^2 2\theta_{13} = 0.08 \pm 0.005$$

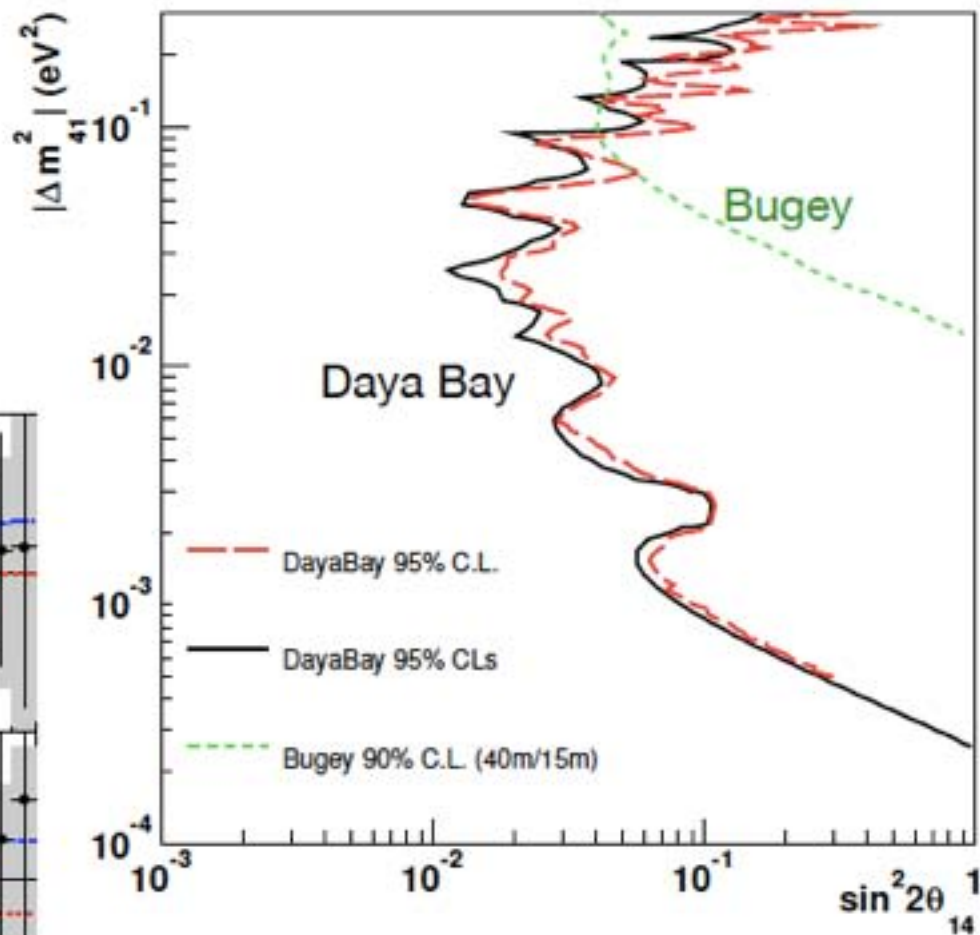
$$|\Delta m_{ee}^2| = 2.44 \pm 0.10 \cdot 10^{-3} \text{eV}^2$$

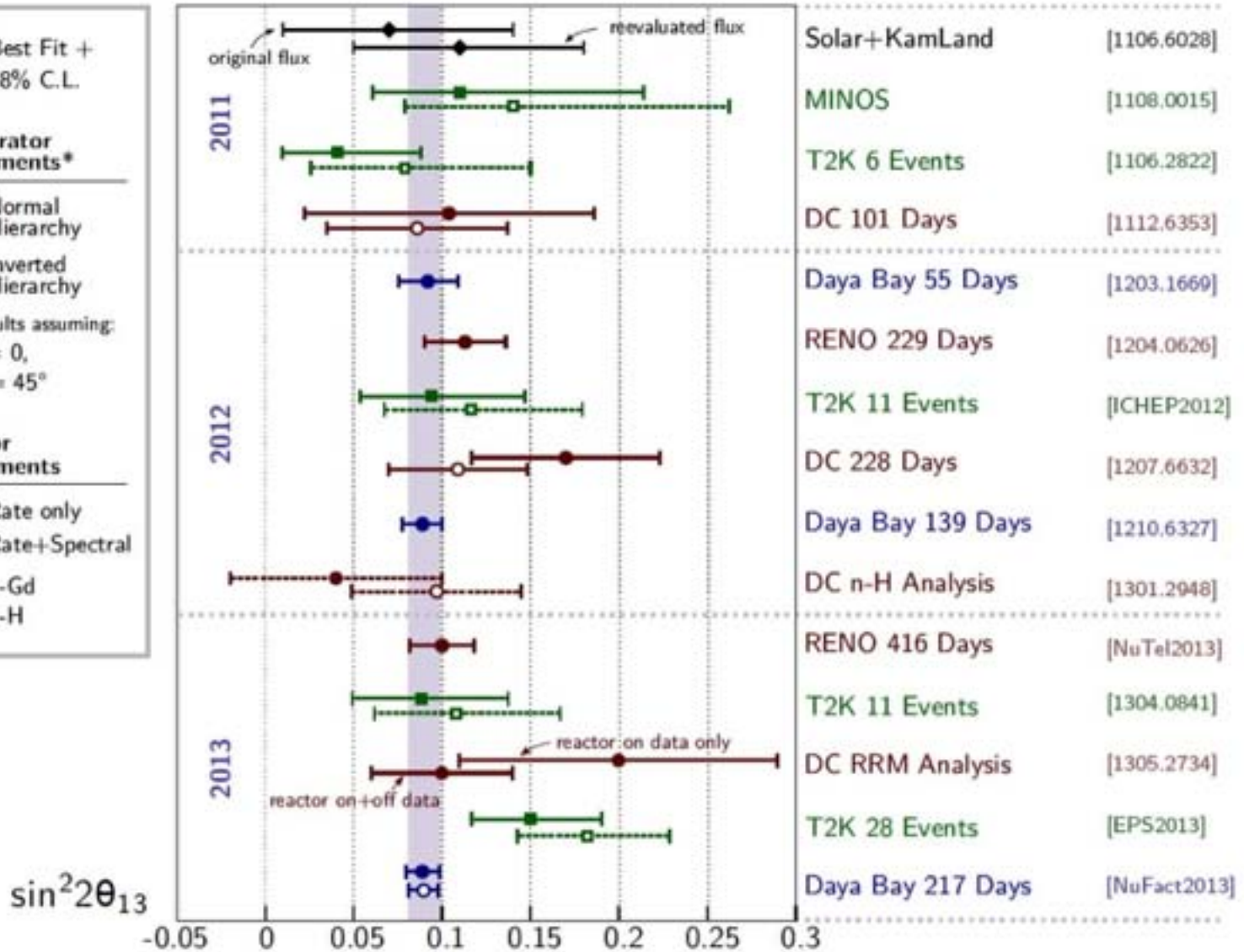
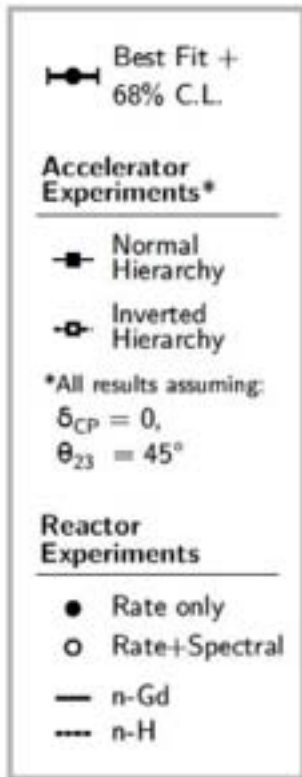
Light Sterile Neutrino Search Results

- All 217 days of 6-AD period
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region $10^{-3} \text{ eV}^2 < \Delta m_{41}^2 < 0.1 \text{ eV}^2$



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$





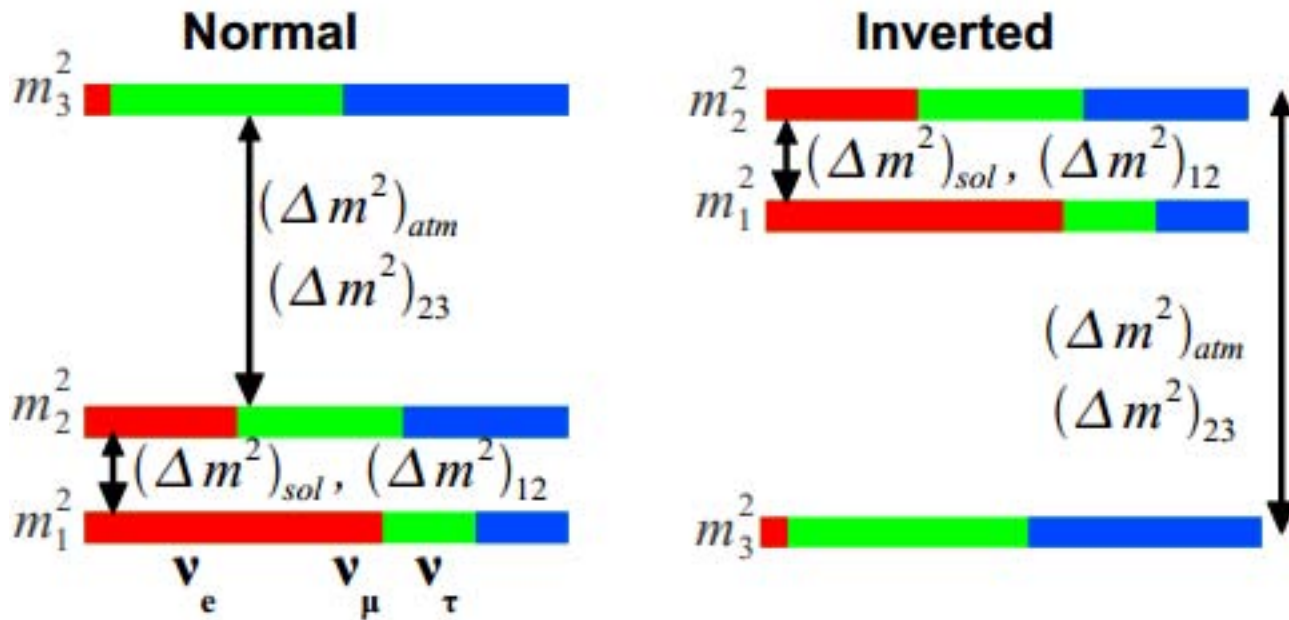
Zusammenfassung:

- Neutrino-Oszillationen erklären solares Neutrino-Defizit!
- Neutrinos haben Masse!
- Reaktorneutrinos bestätigen Oszillation der atmosph. und solaren Neutrinos
- $\sin^2 2\theta_{13} = 0.080 \pm 0.005 > 0$ (-> CP Verletzung messbar)

weitere offene Fragen:

- Majorana oder Dirac Neutrinos?
- Massen-Hierarchie?
- CP-Verletzung im Neutrino-Sektor

Massenhierarchie:



3-Neutrino global fit (2012):

Table 13.7: The best-fit values and 3σ allowed ranges of the 3-neutrino oscillation parameters, derived from a global fit of the current neutrino oscillation data (from [173]). The results shown are obtained with the “old” reactor $\bar{\nu}_e$ fluxes [159]. The values (values in brackets) correspond to $m_1 < m_2 < m_3$ ($m_3 < m_1 < m_2$). The definition of Δm^2 used is: $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m_{31}^2 - \Delta m_{21}^2/2$, if $m_1 < m_2 < m_3$, and $\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2/2$ for $m_3 < m_1 < m_2$.

Parameter	best-fit ($\pm 1\sigma$)	3σ	
Δm_{21}^2 [10^{-5} eV ²]	$7.54^{+0.26}_{-0.22}$	6.99 – 8.18	
$ \Delta m^2 $ [10^{-3} eV ²]	$2.43^{+0.06}_{-0.10}$ ($2.42^{+0.07}_{-0.11}$)	2.19(2.17) – 2.62(2.61)	
$\sin^2 \theta_{12}$	$0.307^{+0.018}_{-0.016}$	0.259 – 0.359	(33.7 ± 1.0) ^o
$\sin^2 \theta_{23}$	$0.386^{+0.024}_{-0.021}$ ($0.392^{+0.039}_{-0.022}$)	0.331(0.335) – 0.637(0.663)	(38.5 ± 1.4) ^o
$\sin^2 \theta_{13}$ [173]	0.0241 ± 0.0025 ($0.0244^{+0.0023}_{-0.0025}$)	0.0169(0.0171) – 0.0313(0.0315)	(8.9 ± 1.5) ^o

(G.L. Fogli, 2012)

Literatur:

- B. Kayser, „**Neutrino Mass, Mixing, and Flavor Change**“: **arXiv:0804.1497** [hep-ph]
- K. Nakaruma, S. Petcov „**Neutrino Mass, Mixing, and Oscillations**“: auf: pdg.lbl.gov
- Th. Schwetz et al., „**Three-flavour neutrino oscillation update**“; **arXiv:0808.2016v2**
- G.L. Fogli et al., „**Global analysis of neutrino masses, mixings and phases**“; **arXiv:1205.5254, Phys.Rev: D86, 013012.**
- neueste Resultate von der Boston Neutrino Conference 2014: <http://neutrino2014.bu.edu>