

# Neutrino Physics

part II:

Solar- and Reactor-Neutrinos

# Eigenschaften der Neutrinos

	Familien			elektr. Ladung	Kräfte			
					st	em	schw	grav
Quarks	<b>u</b>	<b>c</b>	<b>t</b>	2/3	x	x	x	x
	<b>d</b>	<b>s</b>	<b>b</b>	-1/3	x	x	x	x
Leptonen	$\nu_e$	$\nu_\mu$	$\nu_\tau$	0	-	-	x	x
	<b>e</b>	<b><math>\mu</math></b>	<b><math>\tau</math></b>	-1	-	x	x	x

- im Standardmodell:  $\nu$  sind masselos
- $\nu$  ( $\bar{\nu}$ ) 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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Leptonen	$\nu_e$	$\nu_\mu$	$\nu_\tau$	0	-	-	x	x
	<b>e</b>	<b><math>\mu</math></b>	<b><math>\tau</math></b>	-1	-	x	x	x

- $\nu$  könnten ihre eigenen Antiteilchen sein (Majorana Teilchen)
- mögliche Konsequenzen von  $\nu$ -Massen:
  - flavour-Eigenzustände  $\nu_e$   $\nu_\mu$   $\nu_\tau$  können **Mischung** der Massen-Eigenzustände  $\nu_1$   $\nu_2$   $\nu_3$  sein
  - $\rightarrow$  Oszillationen zwischen flavour-Eigenzuständen
  - $\nu$  könnten ein (kleines) magnetisches Moment haben  
 $\rightarrow$  wechselwirken auch elektromagnetisch?

## 2-Flavour Neutrino Oszillationen:

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

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

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

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

(L in km,  
E in GeV, m in eV)

## 3-Flavour Neutrino Oszillationen:

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

$$c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}$$

$\delta$ : CP verletzende Phase

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

n.b.: CP Verletzung wird immer mit  $s_{13}$  verknüpft!

# Neutrino-Quellen:

## • **Solare Neutrinos**

(Entstehen bei den Fusionsreaktionen in der Sonne), ca  $2 \times 10^{38}$  /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**

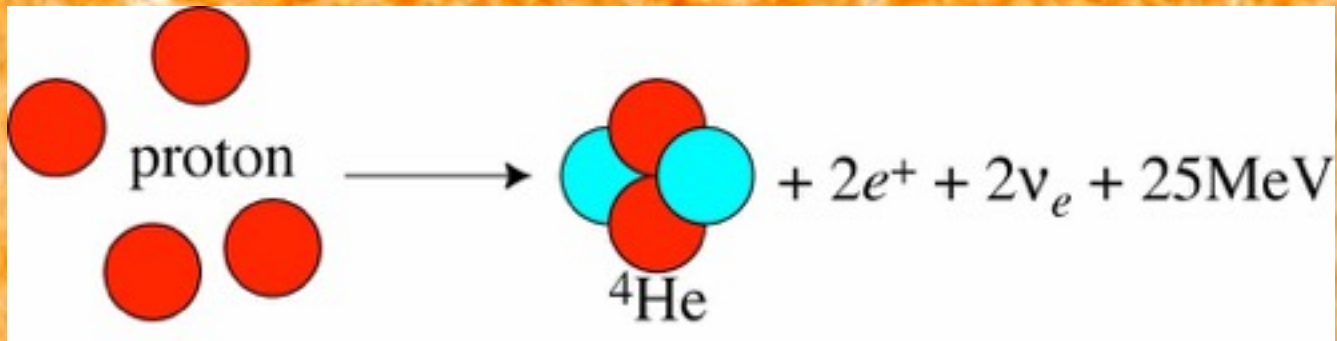
Reaktor-Neutrinos (MeV-Bereich), ca  $10^{20}$  /s;  
Beschleuniger (MeV  $\rightarrow$  GeV),

# Sensitivität verschiedener Oszillationsexperimente

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

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

# Energieerzeugung in der Sonne



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

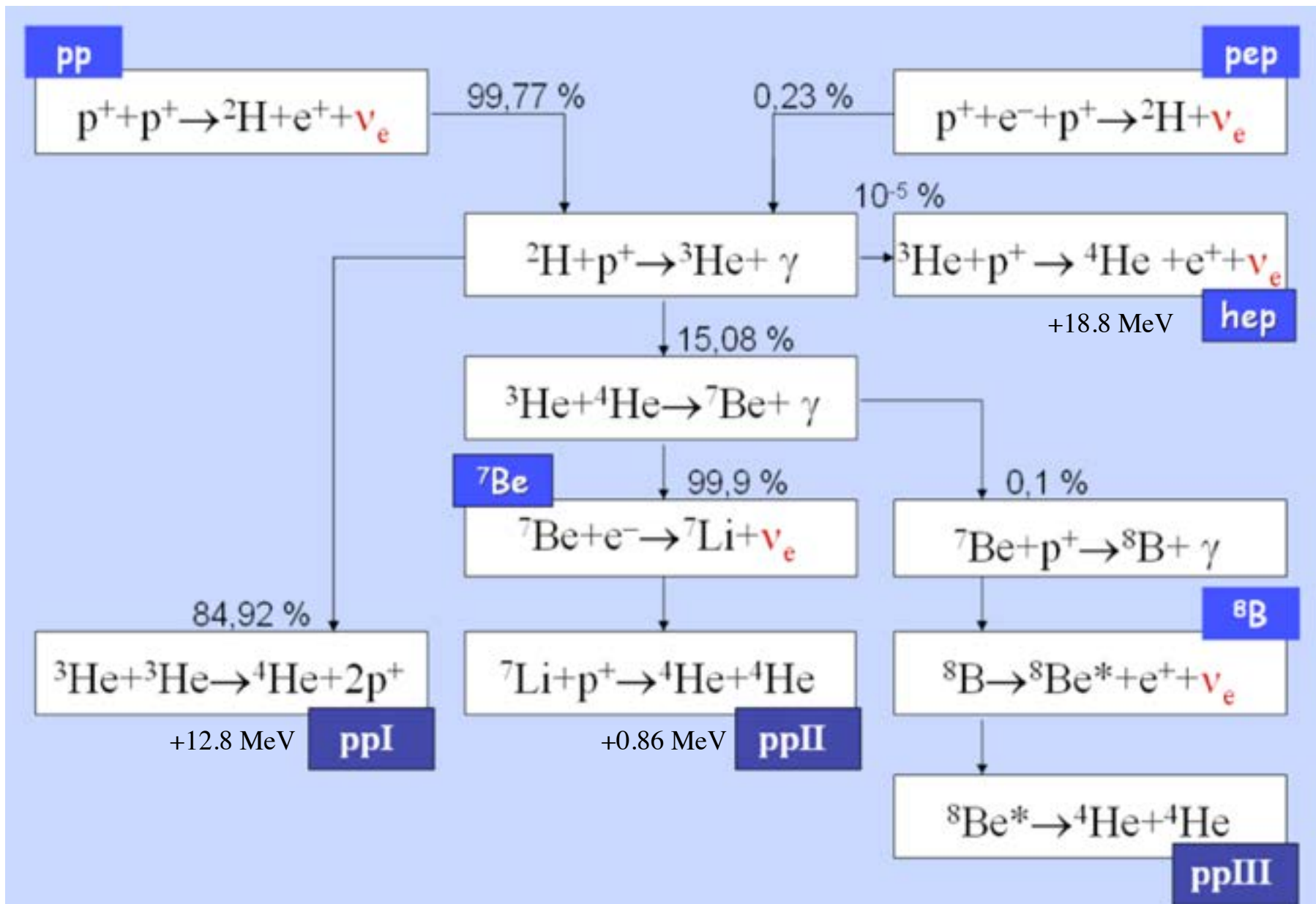


**FACT:** about 65 billion neutrinos pass through your thumbnail every second.

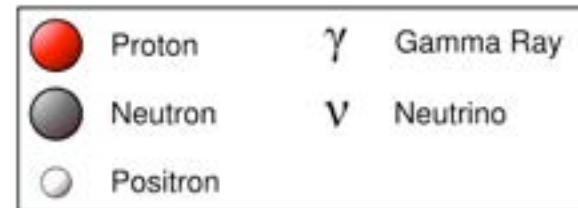
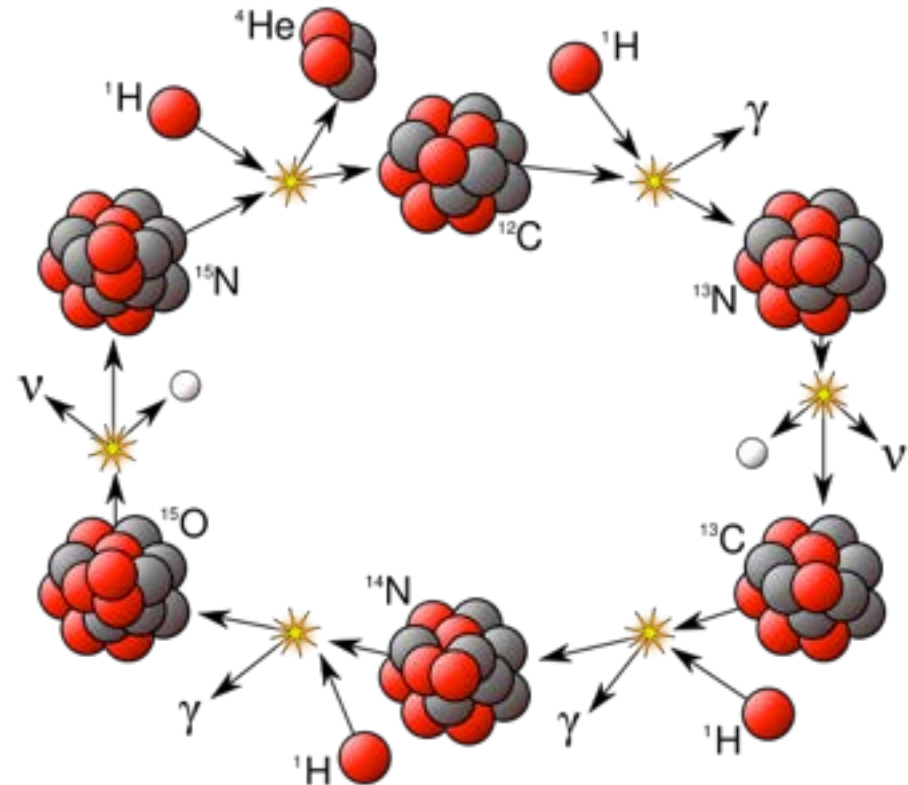
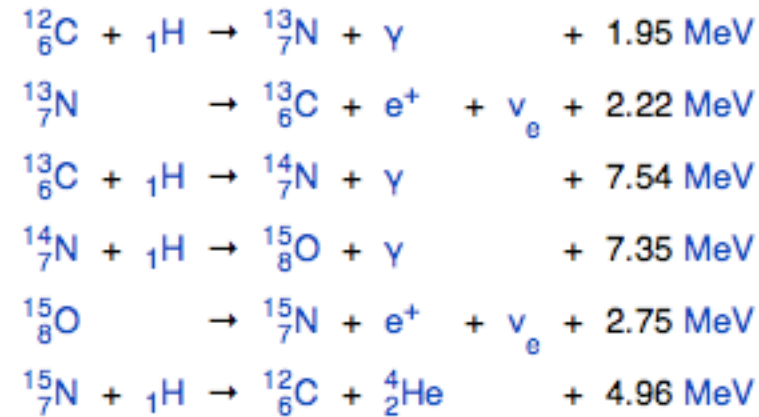
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# Das solare Standardmodell: Proton-Proton-Kette

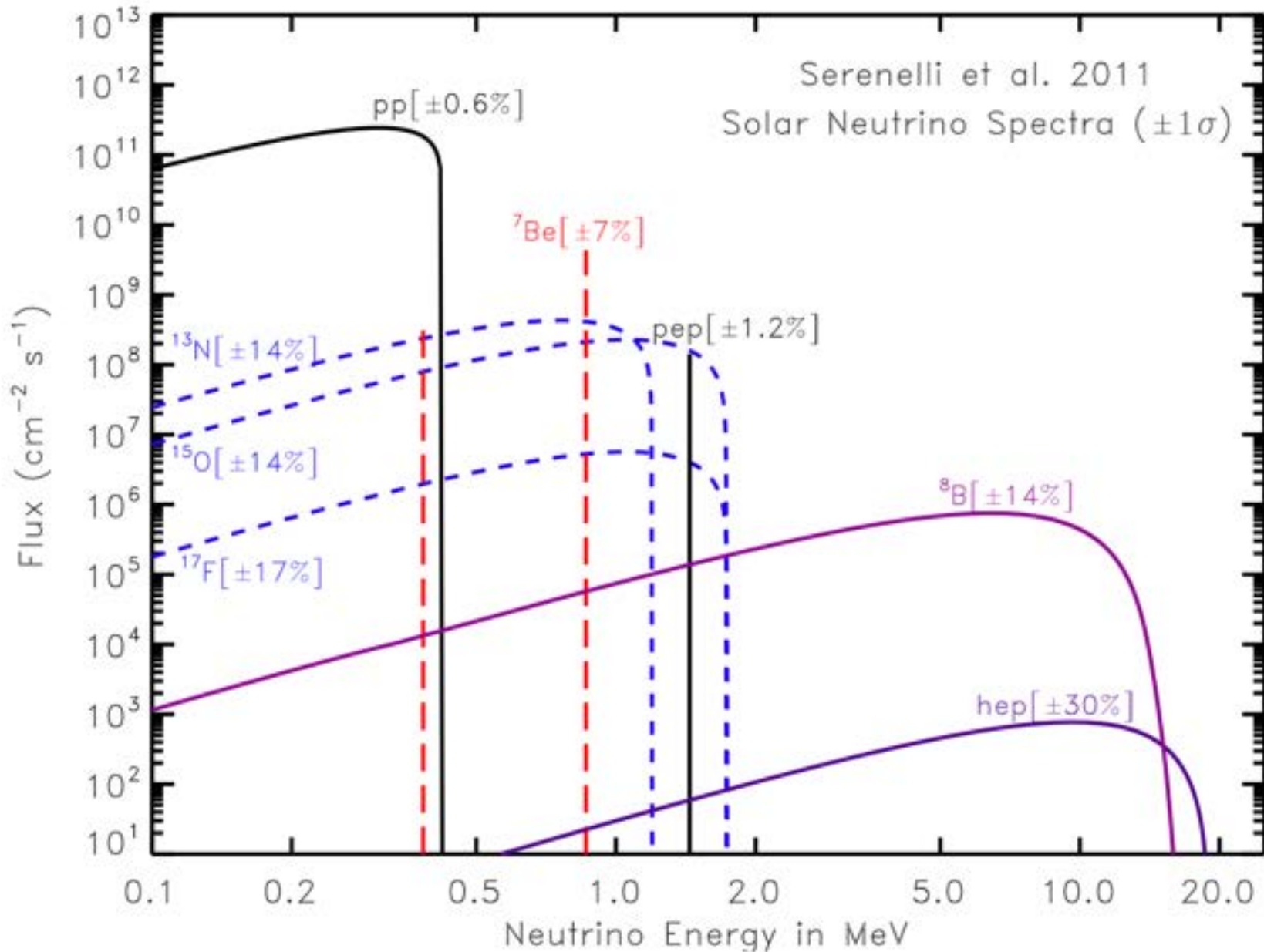


# der CNO Kreislauf (Bethe-Weiszäcker)

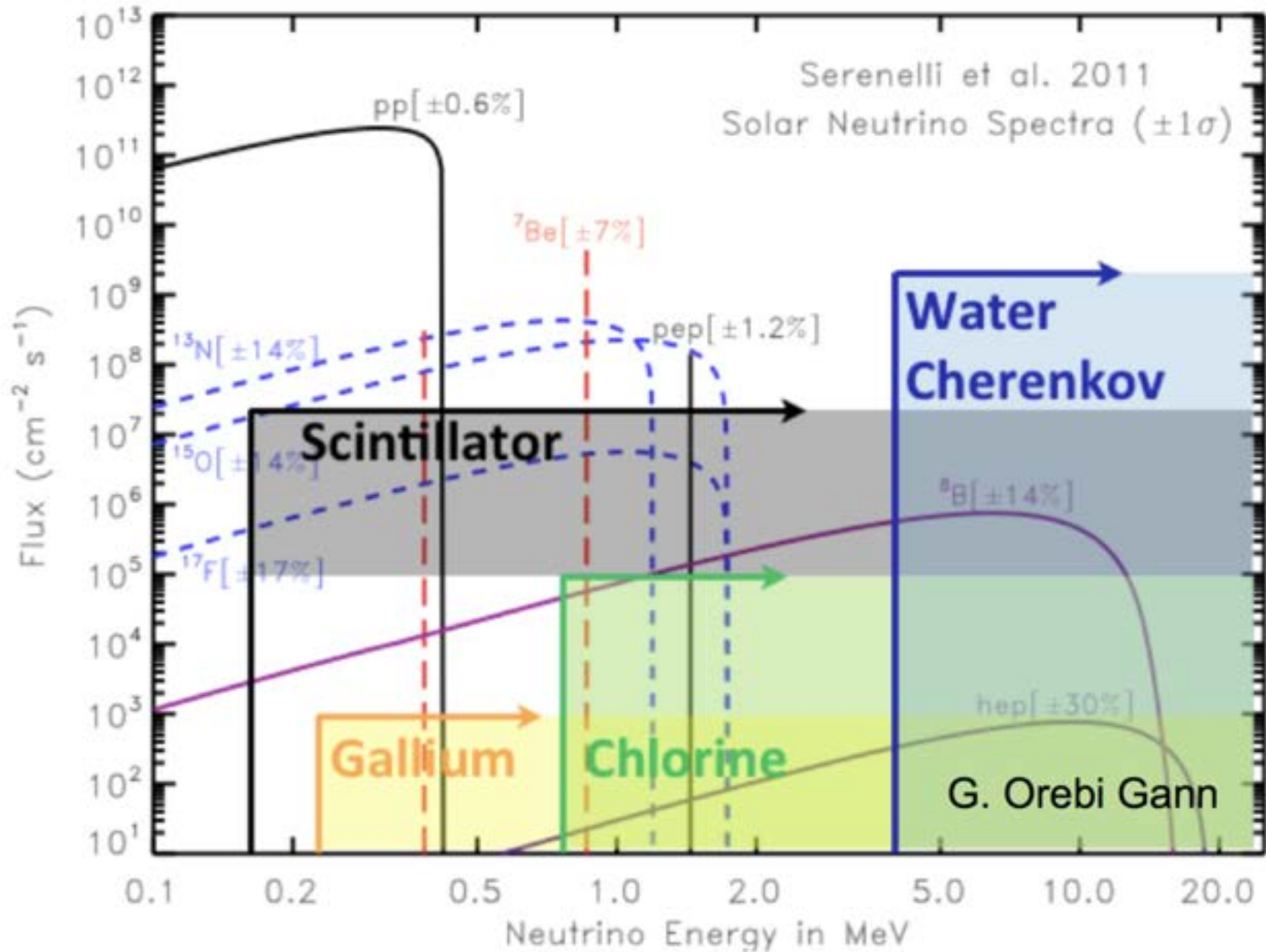


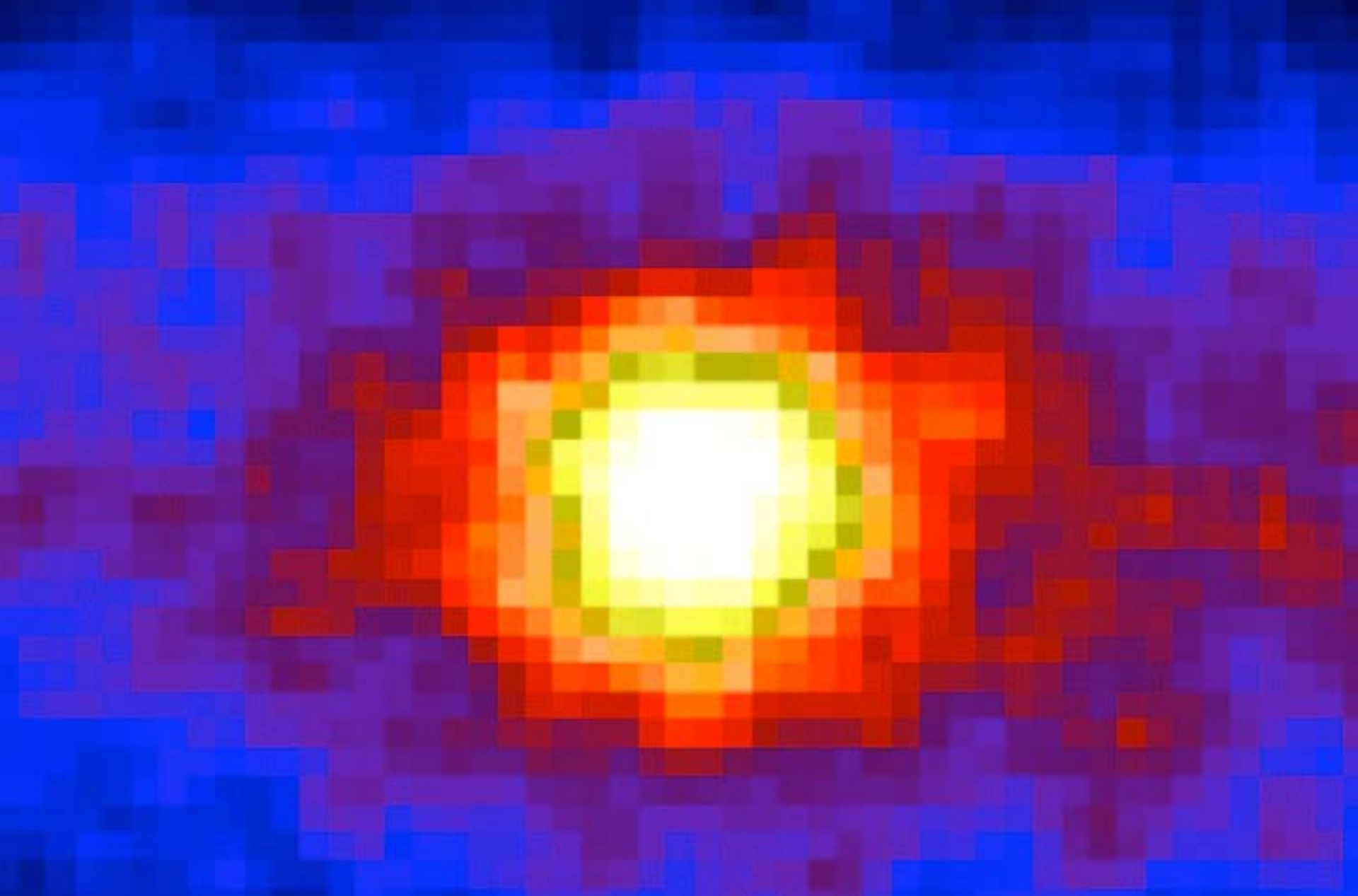
- CNO dominiert in schweren Sternen
- Sonne: ca. 1.7% des  ${}^4\text{He}$  durch CNO, sonst p-p.

# Solar Neutrino Spectrum (prediction)



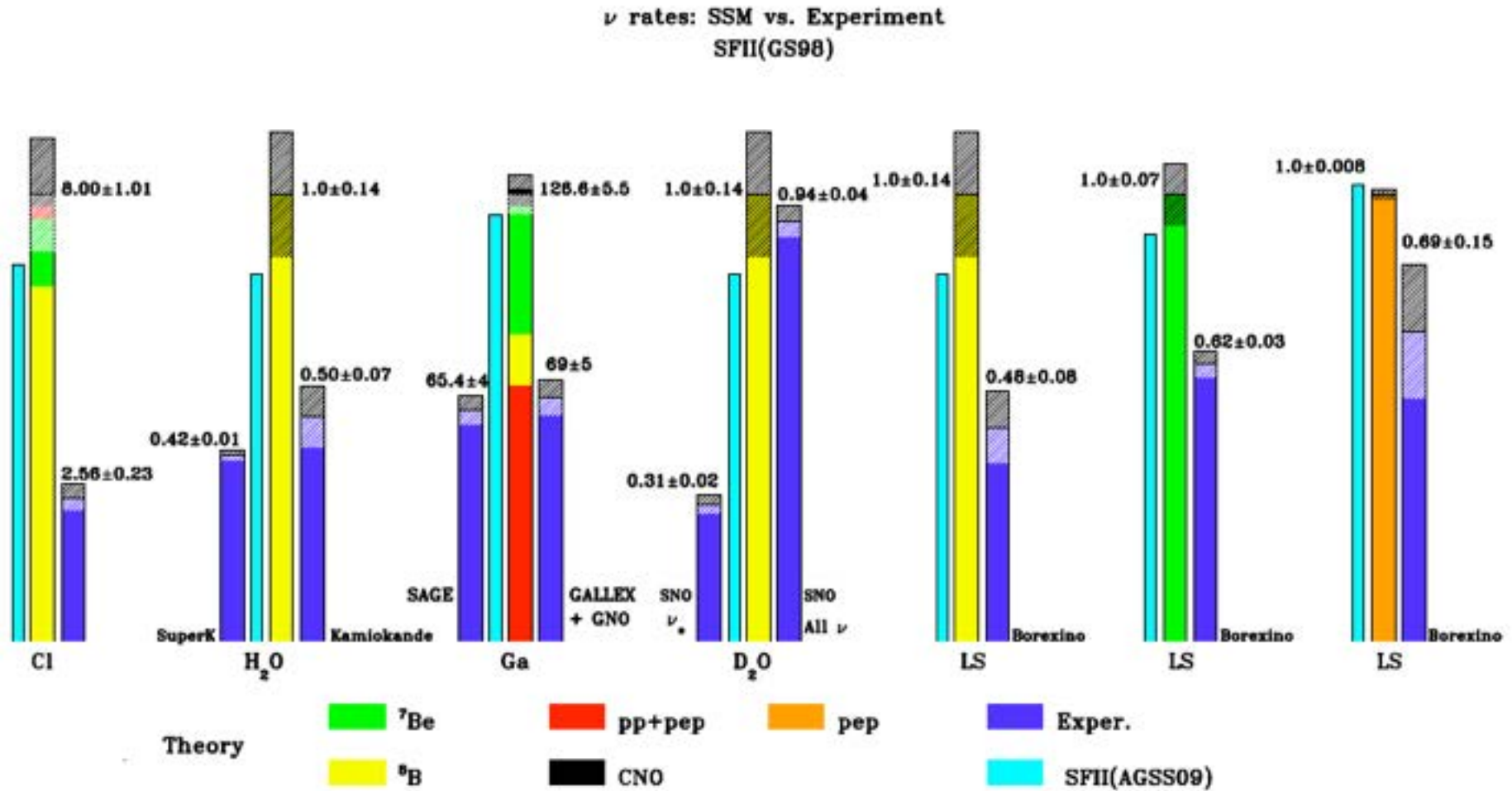
# Solar Neutrino Spectrum (prediction)





Die Sonne „gesehen“ mit Neutrinos (SuperK)

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

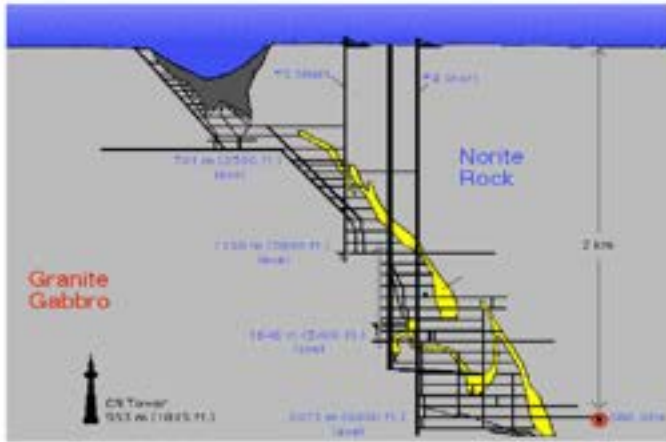


Quelle: Serenelli, Neutrino 2012, Kyoto

Experimente messen i.w.  $^8\text{B}$  Neutrinos

# Sudbury Neutrino Observatory (SNO)

(1999-2006, near Ontario, Canada)



1000 tonnes  $D_2O$

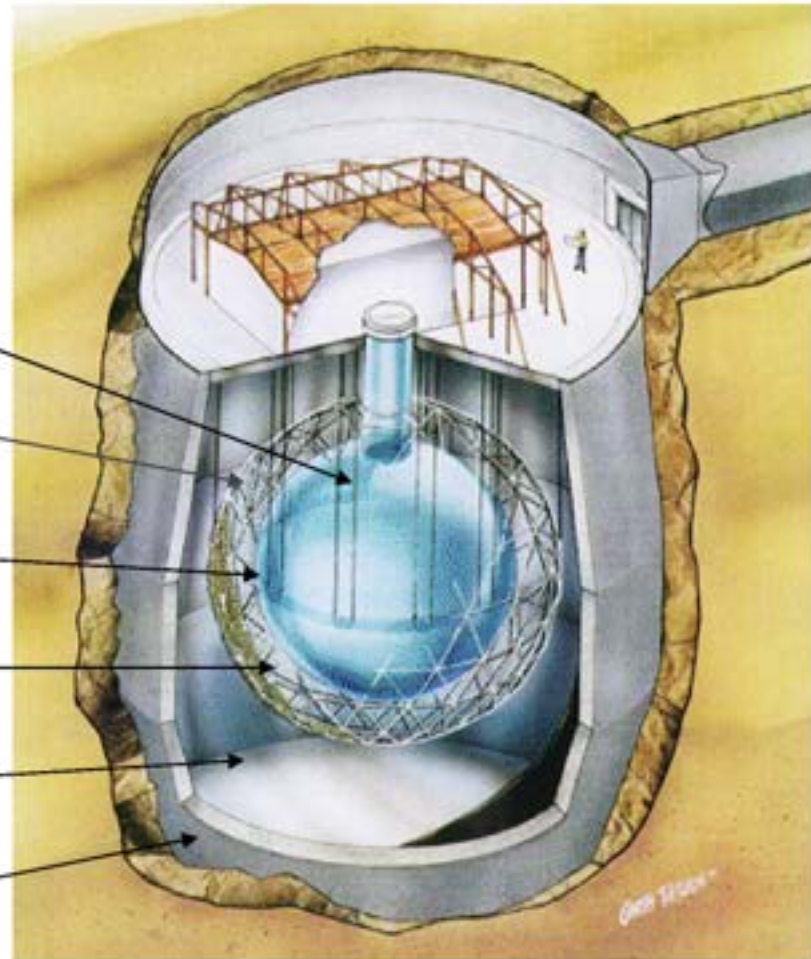
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding  $H_2O$

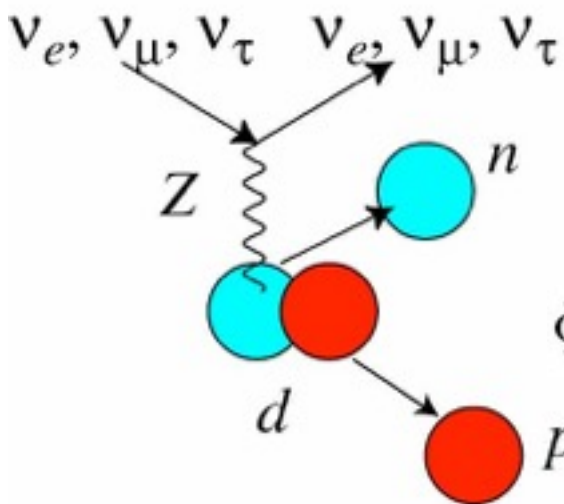
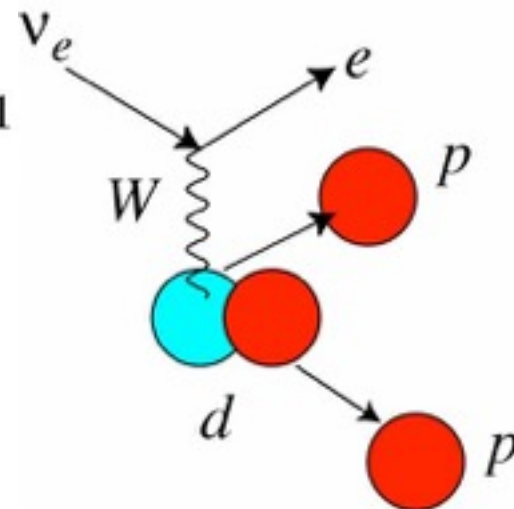
5300 tonnes Outer Shield  $H_2O$

Urylon Liner and Radon Seal



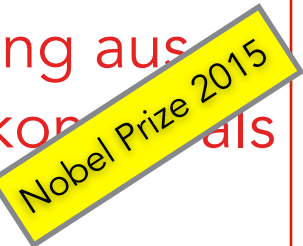
SNO misst Elektron-Neutrino-Raten (cc)  
und Summe aller Neutrinos (nc):

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



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

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



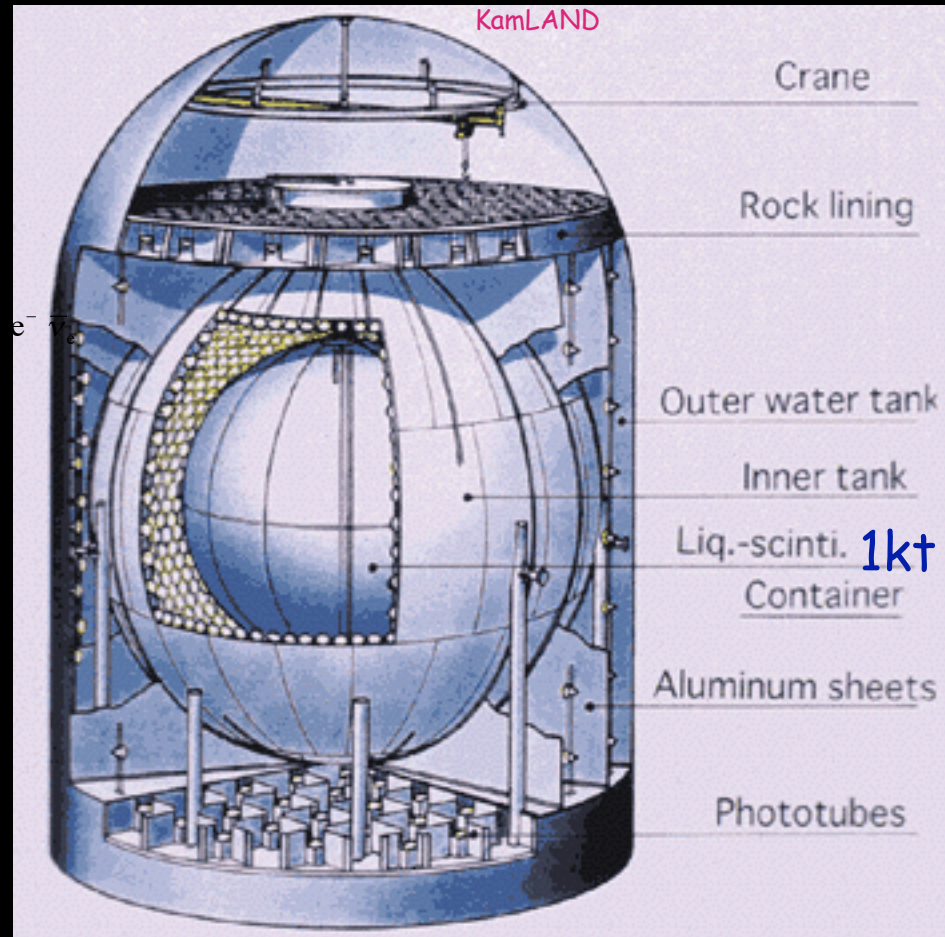


# Terrestrische “Solare Neutrinos”: Neutrinos von Kernreaktoren

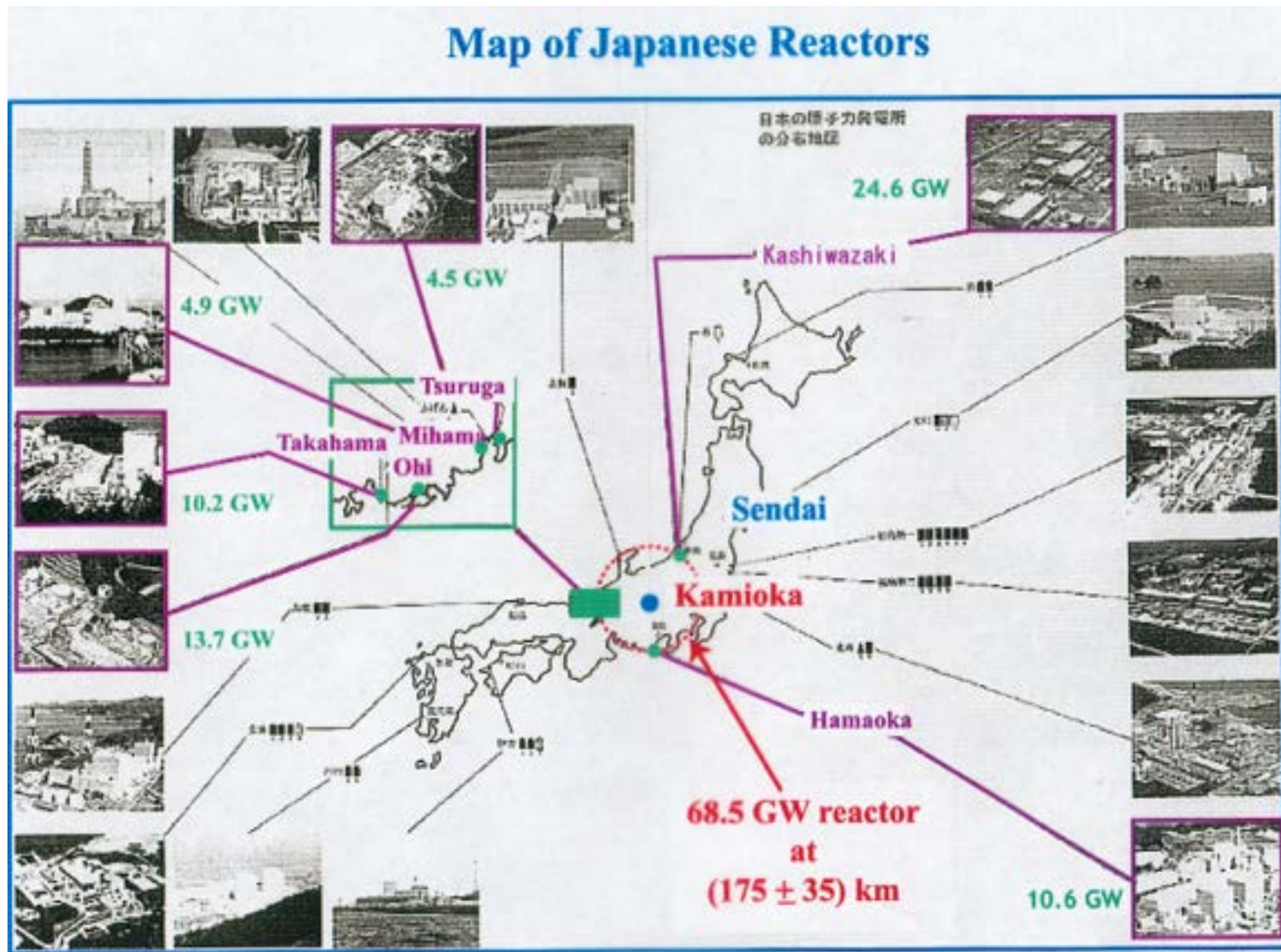
- Kann man Neutrino Oszillationen mit man-made Neutrinos sehen?

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

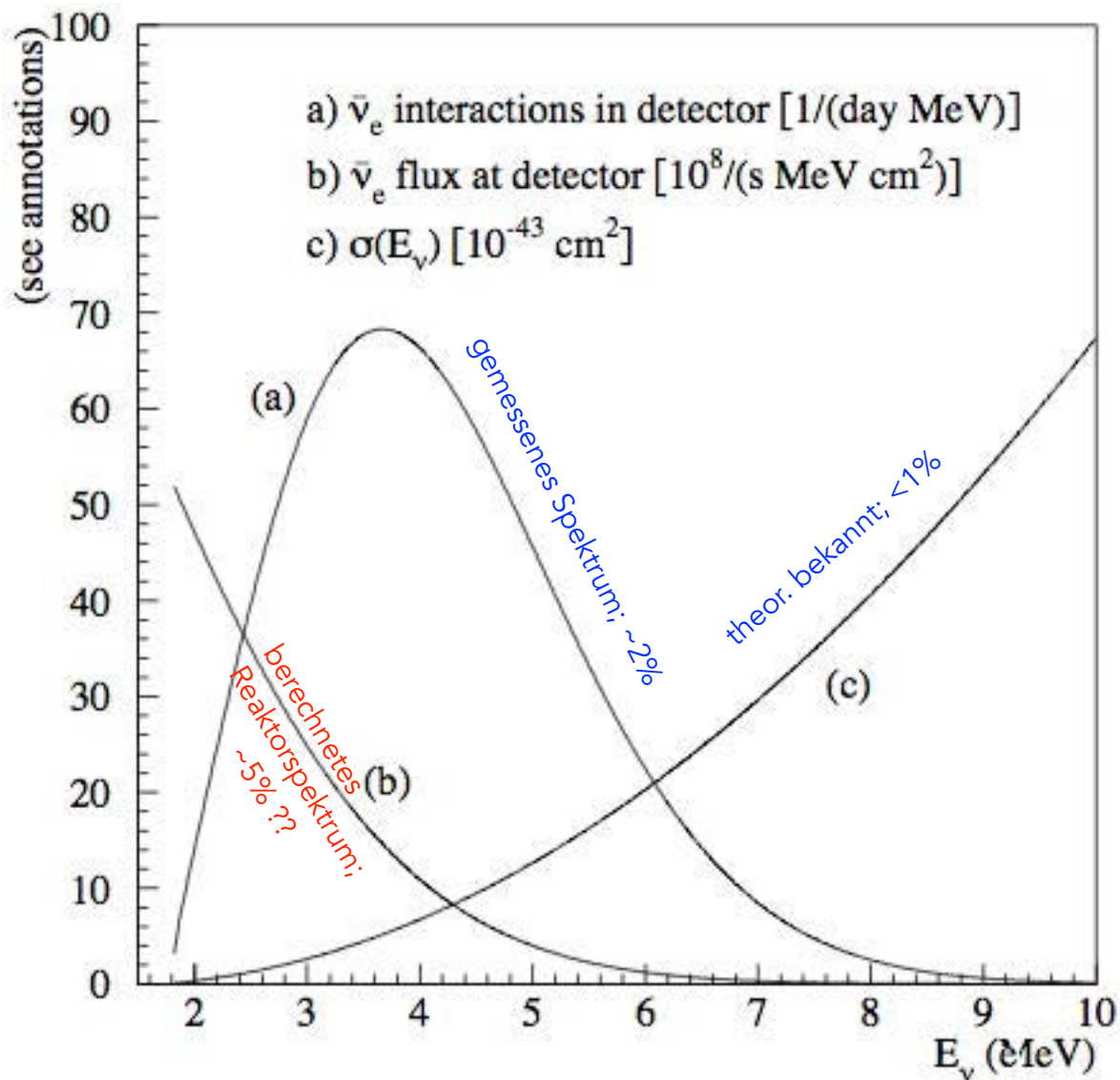
- schwierig für kleine  $\Delta m^2$
- Um LMA zu testen, braucht man  $L \sim 100\text{km}$ ,  $1\text{kt}$
- niedrige  $E_\nu$ , hohe  $\Phi_\nu$
- Reaktor:  $n \rightarrow p e^- \bar{\nu}_e$
- Nachweis:  $\bar{\nu}_e p \rightarrow n e^+$
- $e^+$  :  $e^+ e^- \rightarrow 2\gamma$ ; n Einfang



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

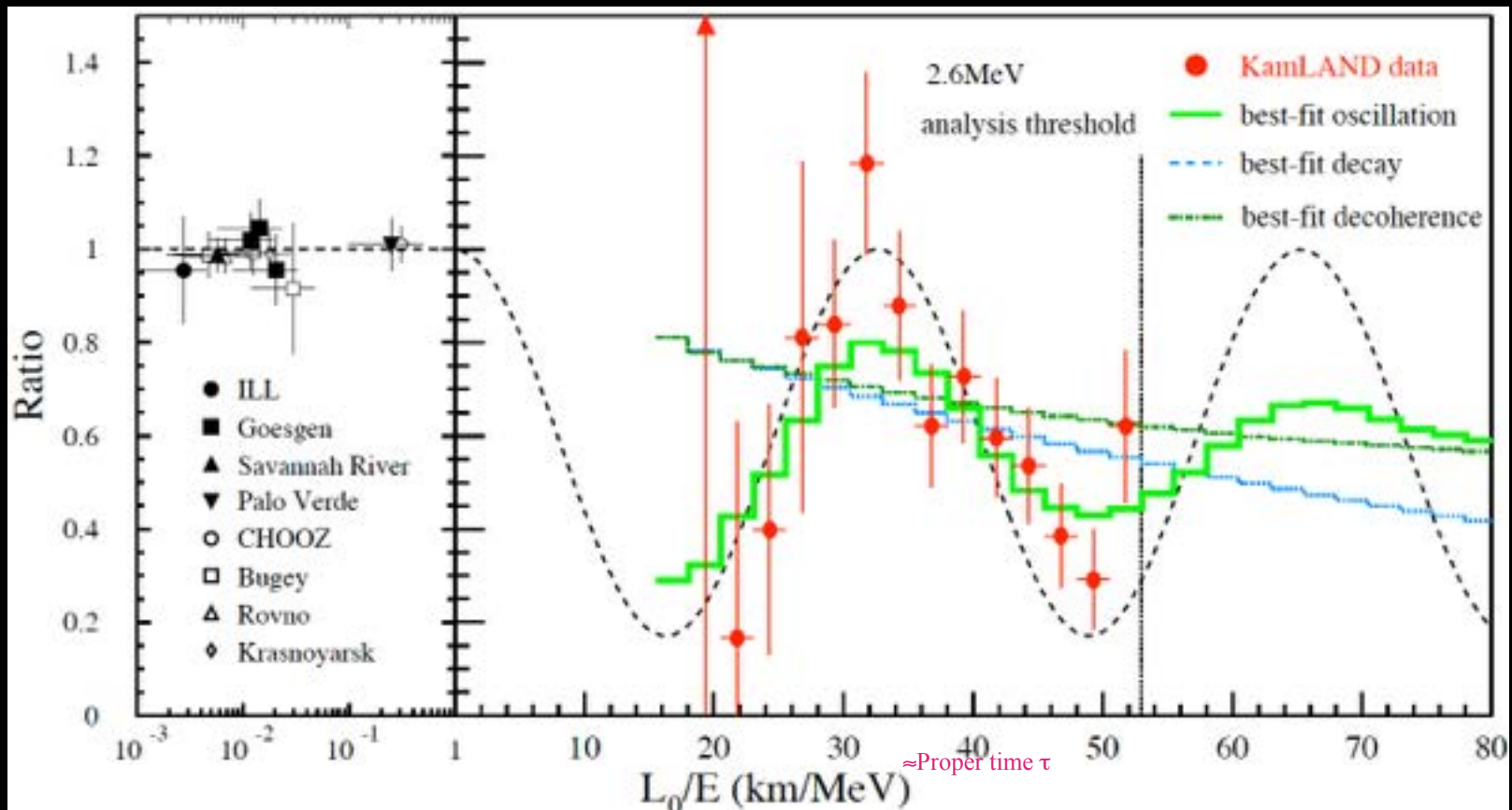


# Energiespektren



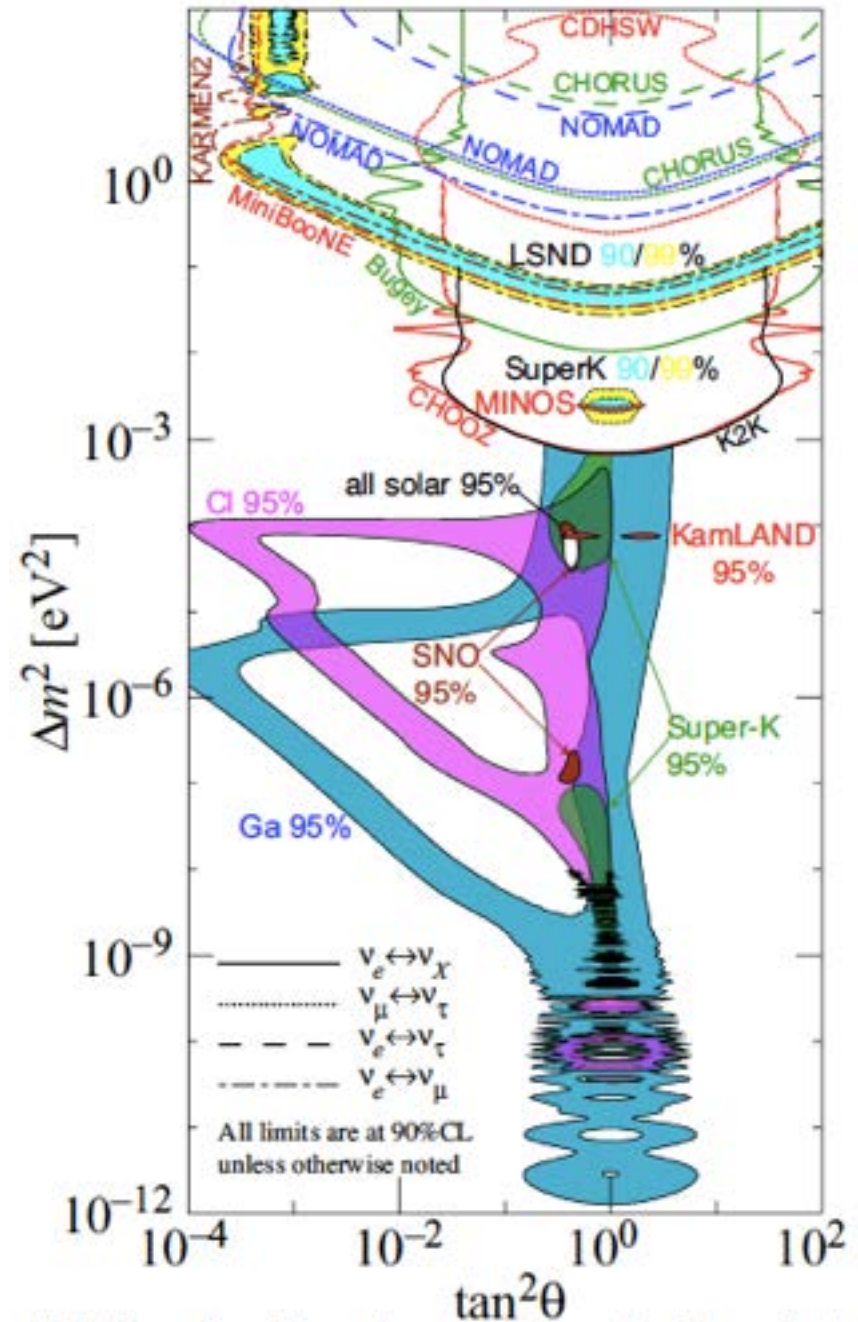
# KamLAND

## Reaktor Neutrinos oszillieren!

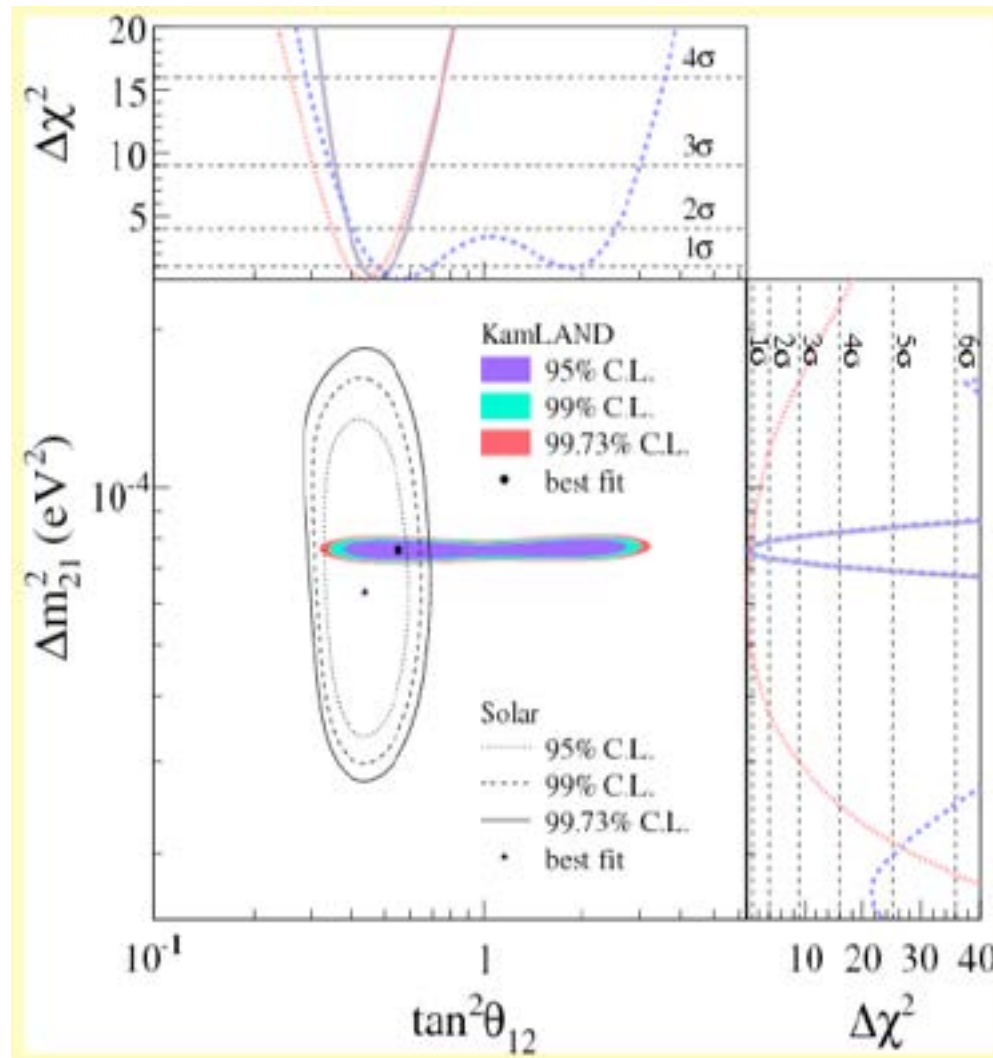


$L_0 = 180$  km

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



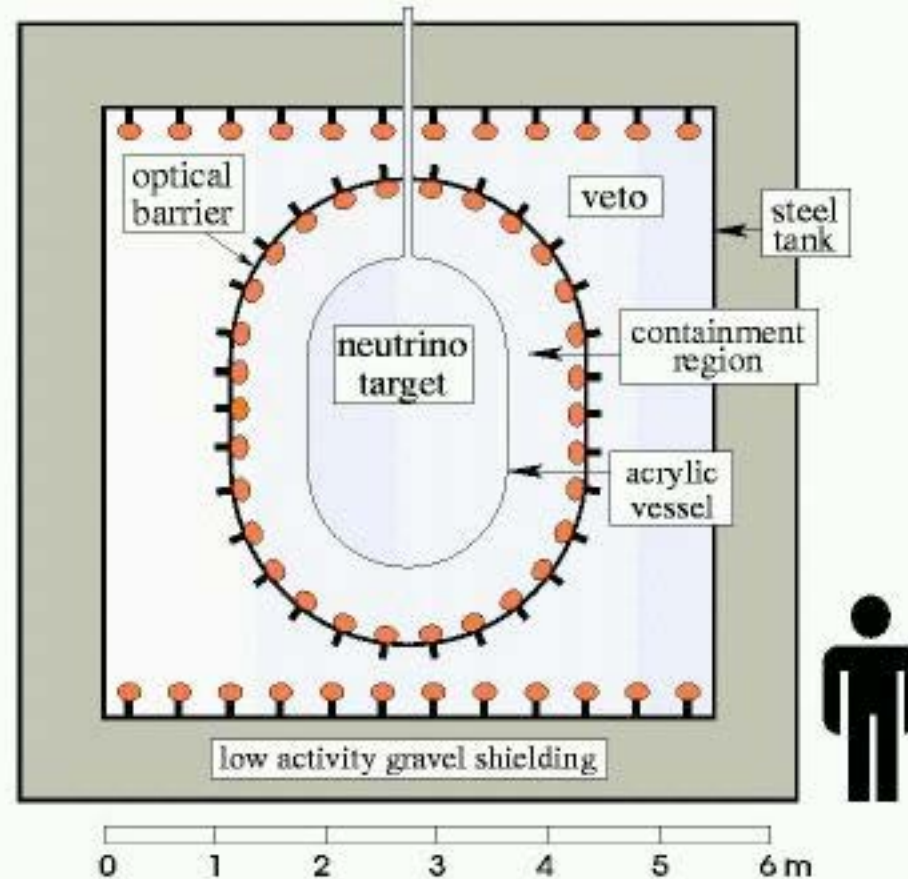
# Kombination aller solaren Neutrino Daten mit KamLAND Reaktor Daten:



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

$\theta_{13}$  ?

# Chooz



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

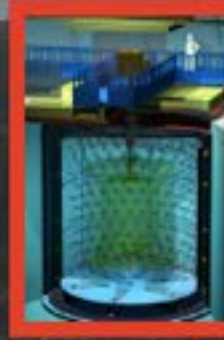
$$\sin^2\theta_{13} < 0.17 \quad (\theta_{13} < 24^\circ) \quad \text{bei} \quad \Delta m_{13}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$$



# 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<sub>th</sub>

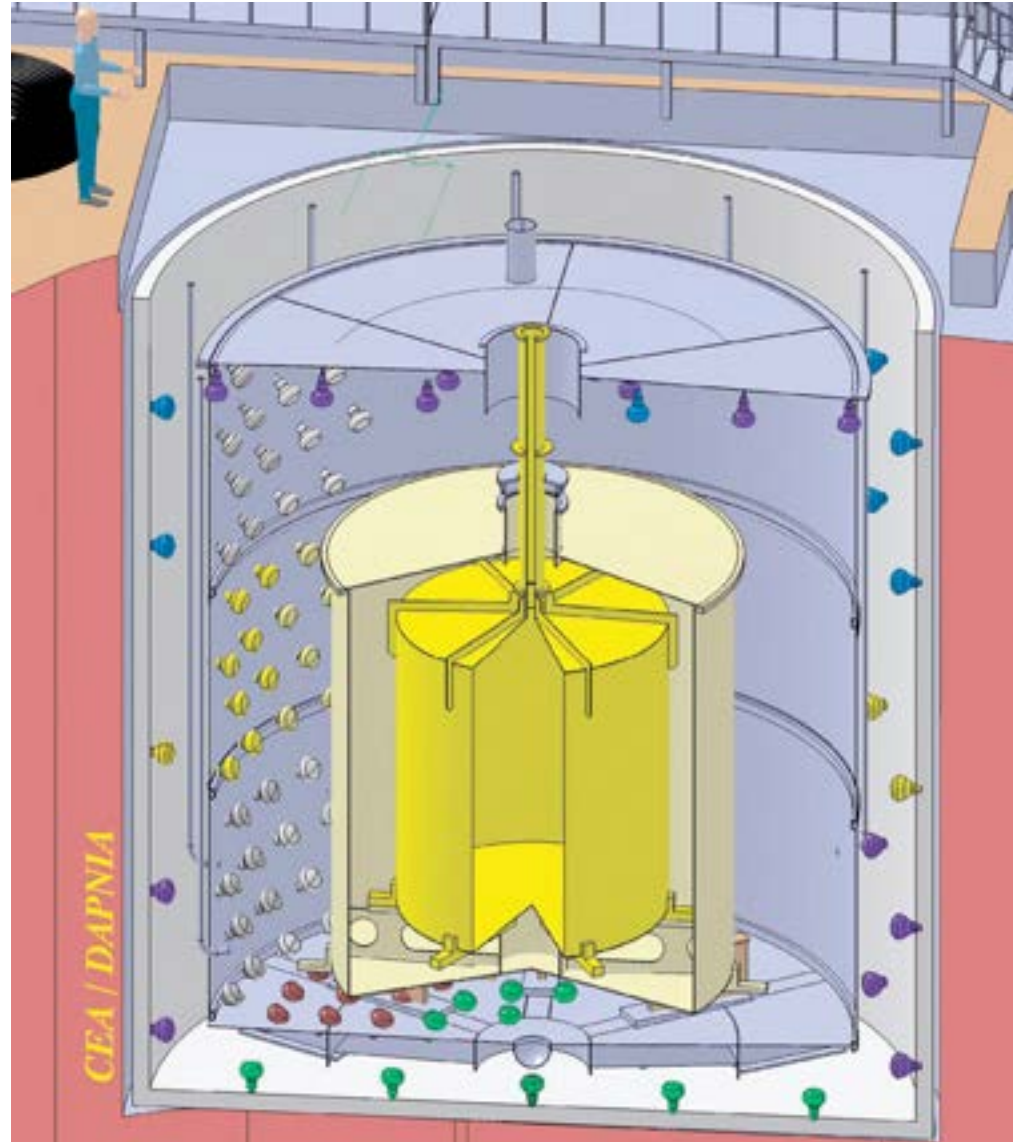
⇒ ~10<sup>21</sup>v/s

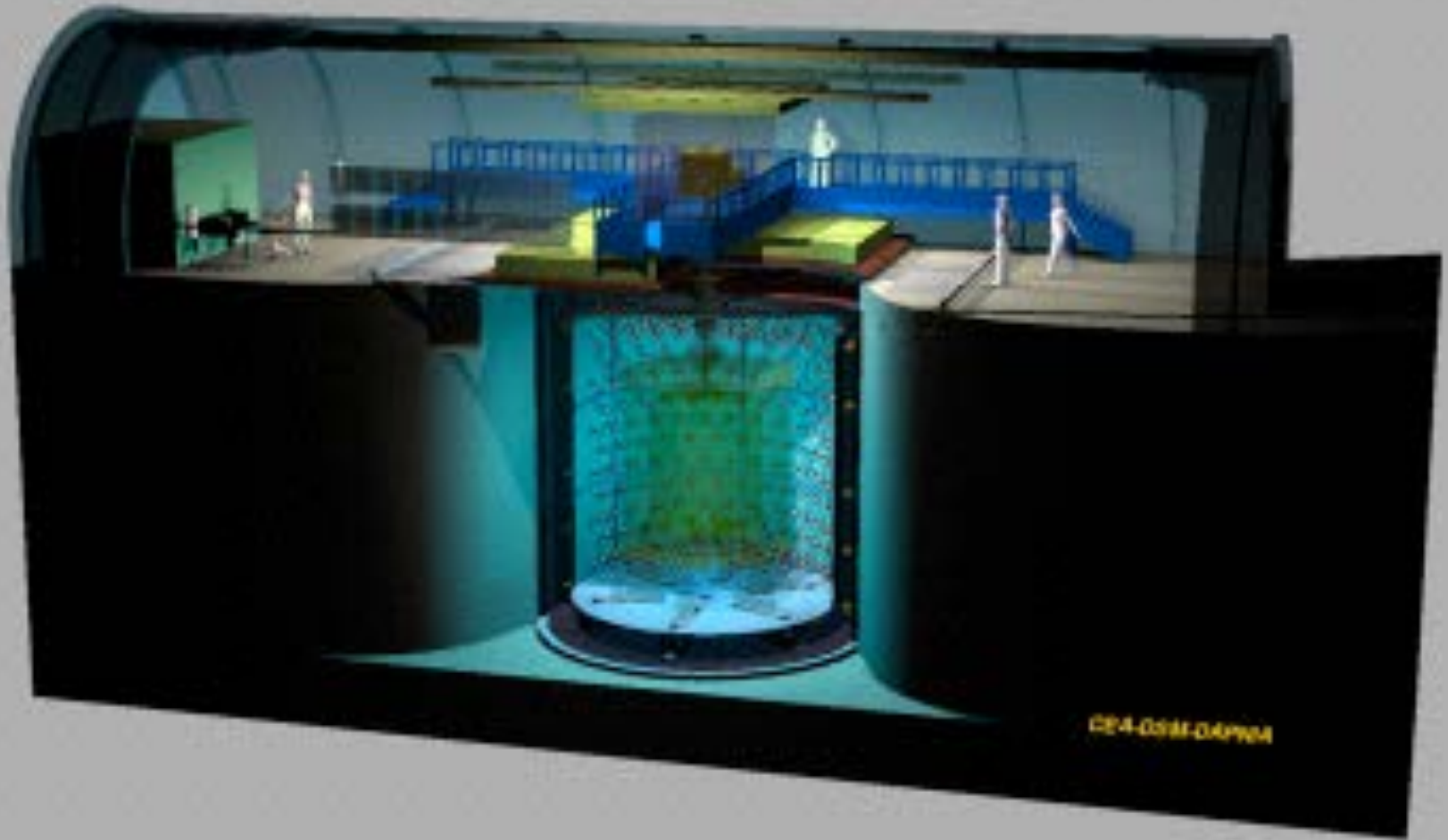
# Double-Chooz

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

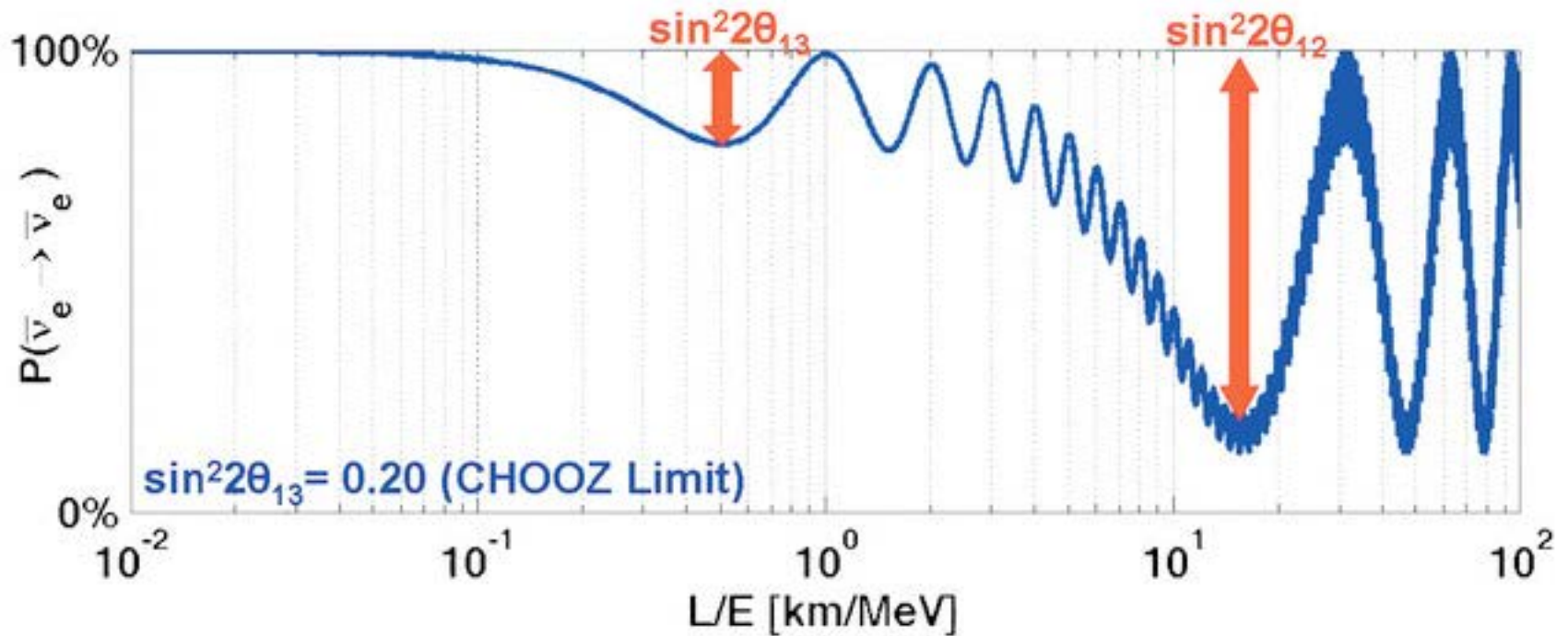
Messung:

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





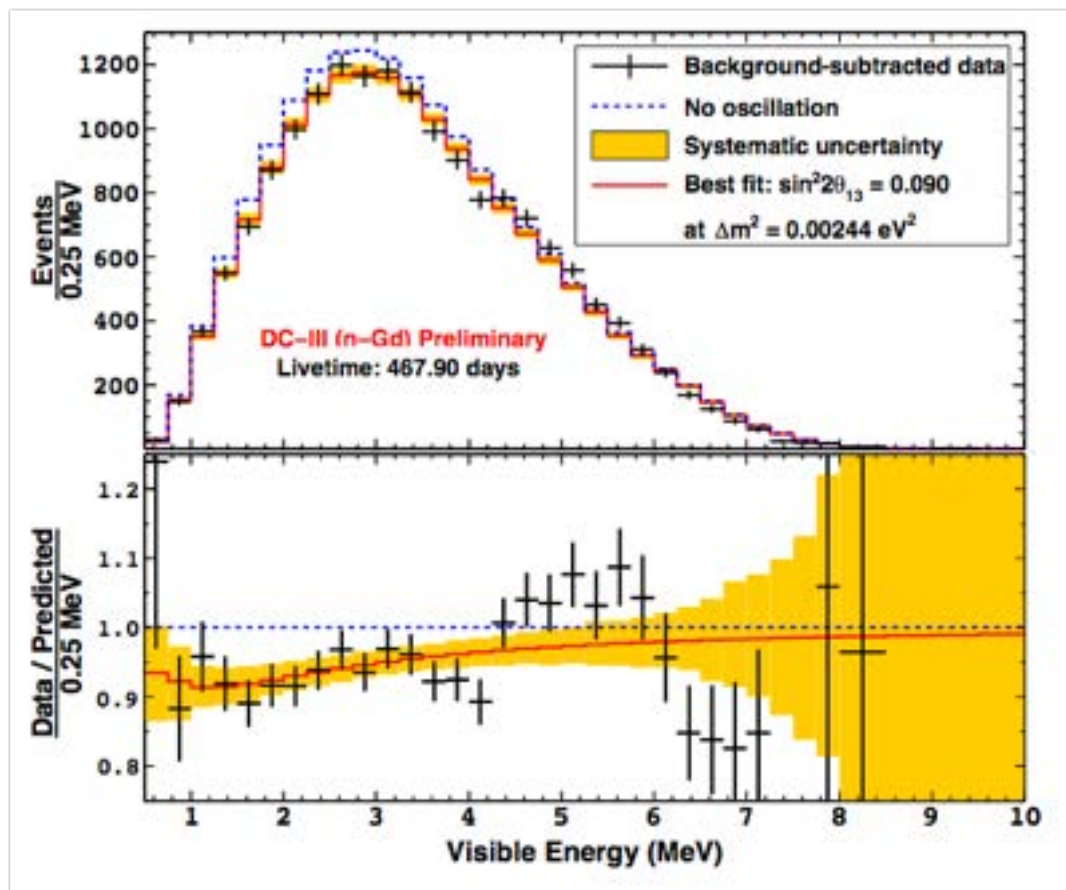
# Double-Chooz



after  $\sim 3$  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

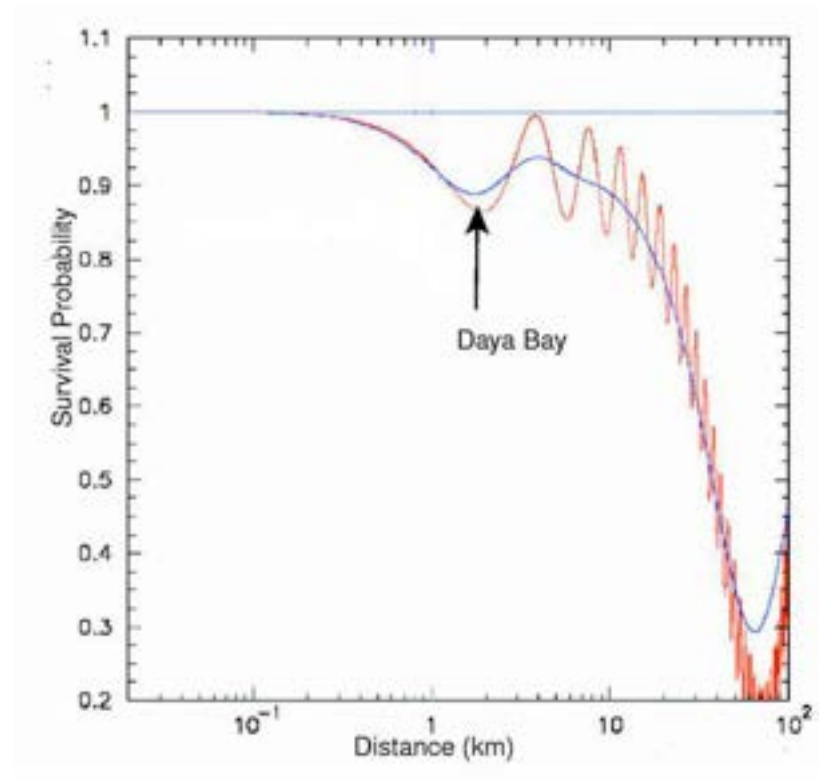
Ling Ao II Cores  
Ling Ao I Cores

Daya Bay Cores

- 17.4 GW<sub>th</sub> power
- 8 operating detectors
- 160 t total target mass

Shenzhen 45 km  
Hongkong 65 km

# Daya Bay

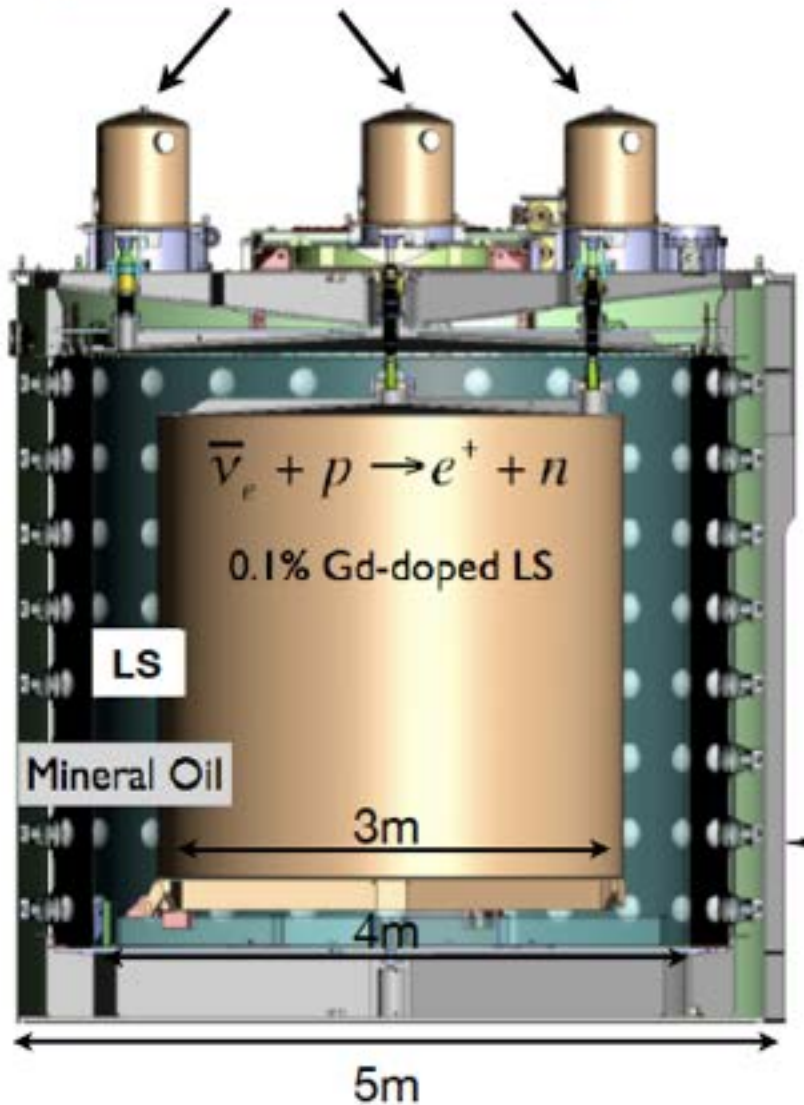


— mono-energetische  $\nu$   
— Daya Bay E-Verteilung

- 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

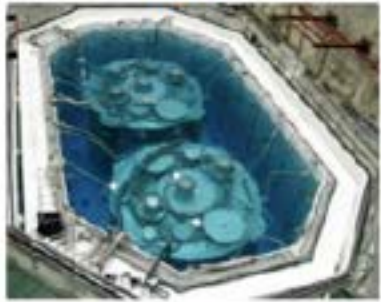
~ 160 photoelectrons / MeV

~ 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



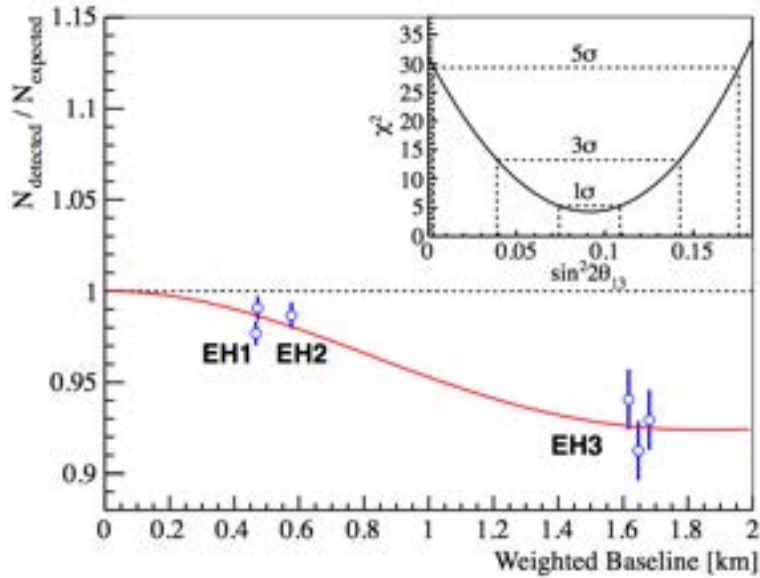
EH2



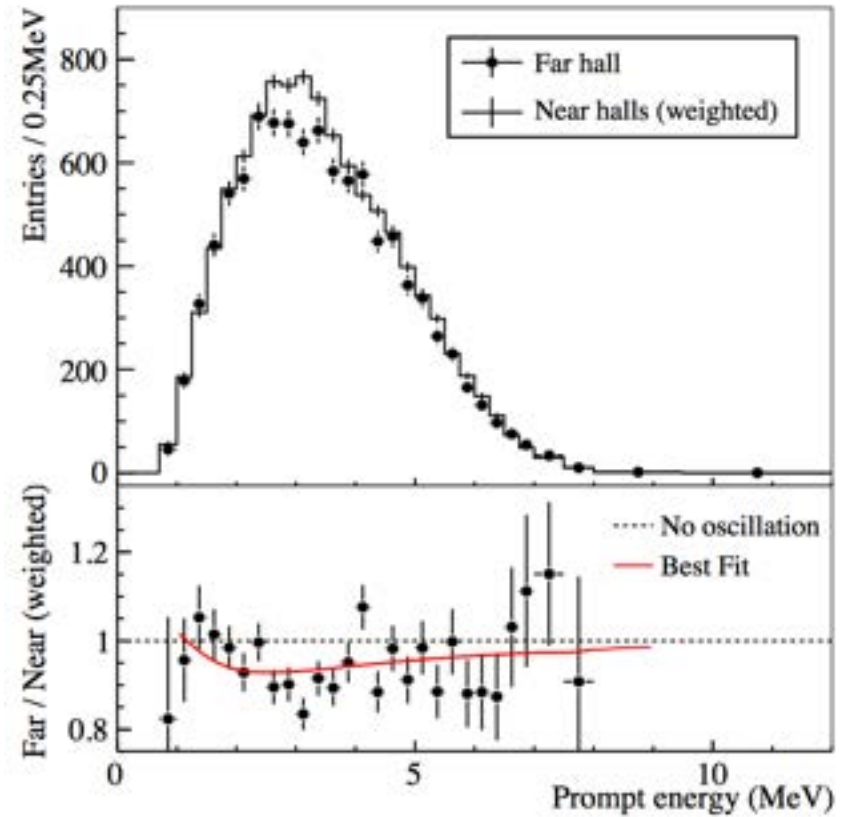
# Far vs Near Comparison (2012)

arXiv:1203.1669 [hep-ex]

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



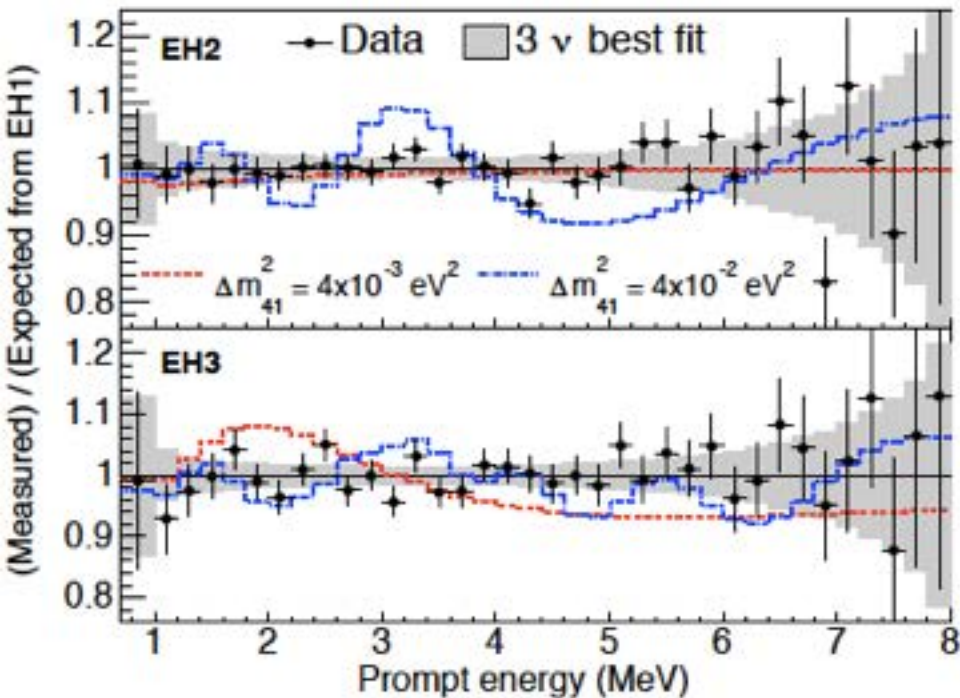
The observed **relative rate deficit** and **relative spectrum distortion** are highly consistent with oscillation interpretation



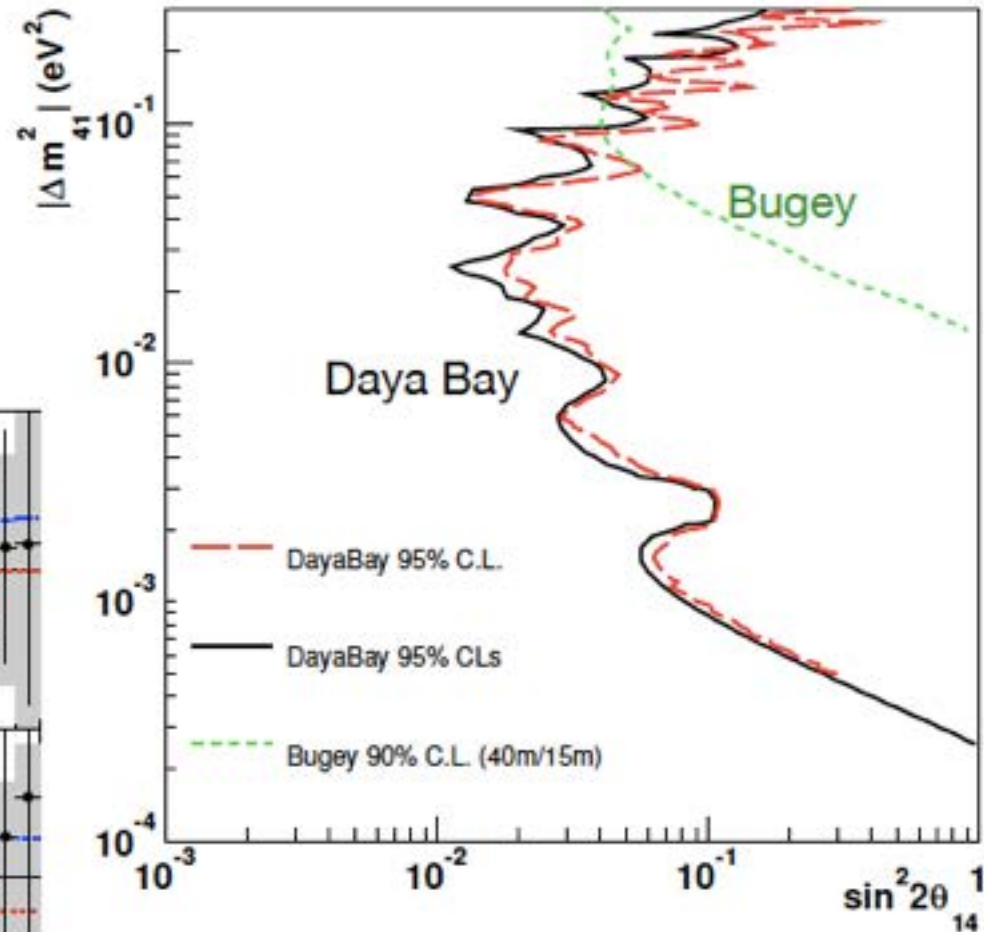
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

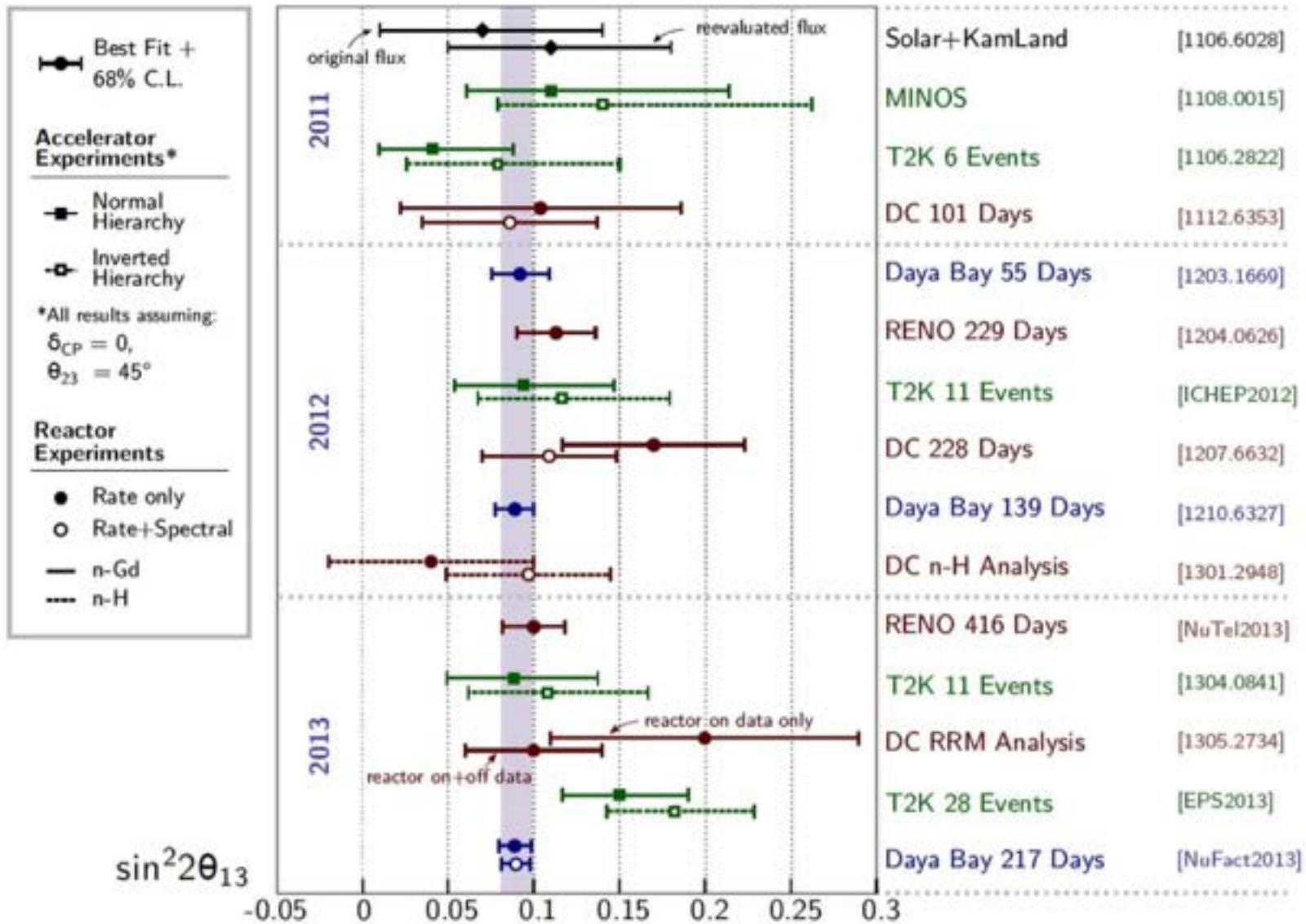
# Light Sterile Neutrino Search Results

- 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  $\sin^2 2\theta_{14} = 0.1$





## 3-Neutrino global fit (PDG 2014):

- $\sin^2(2\theta_{13}) = 0.093 \pm 0.008$ .<sup>[20]</sup> PDG combination of Daya Bay, RENO, and Chooz results.
- $\sin^2(2\theta_{12}) = 0.846^{+0.021}_{-0.021}$ .<sup>[20]</sup> corresponds to  $\theta_{\text{sol}}$  (solar), from KamLand, solar, reactor and accelerator data.
- $\sin^2(2\theta_{23}) > 0.92$  at 90% confidence level, corresponding to  $\theta_{23} \equiv \theta_{\text{atm}} = 45 \pm 7.1^\circ$  (atmospheric)<sup>[21]</sup>
- $\Delta m^2_{21} \equiv \Delta m^2_{\text{sol}} = 7.53^{+0.18}_{-0.18} \times 10^{-5} \text{ eV}^2$ <sup>[20]</sup>
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\text{atm}} = 2.44^{+0.06}_{-0.06} \times 10^{-3} \text{ eV}^2$  (normal mass hierarchy)<sup>[20]</sup>

## Zusammenfassung:

- Neutrino-Oszillationen erklären solares Neutrino-Defizit!
- Neutrinos haben Masse!
- Reaktorneutrinos bestätigen Oszillation der atmosph. und solaren Neutrinos
- $\sin^2 2\theta_{13} = 0.093 \pm 0.008 > 0$  (-> CP Verletzung messbar)

## weitere offene Fragen:

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

# 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](http://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.**
- newest results from London Neutrino Conference 2016:  
<http://neutrino2016.iopconfs.org/programme>