On the detection of neutrinos (Chapter 3.4):

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.)

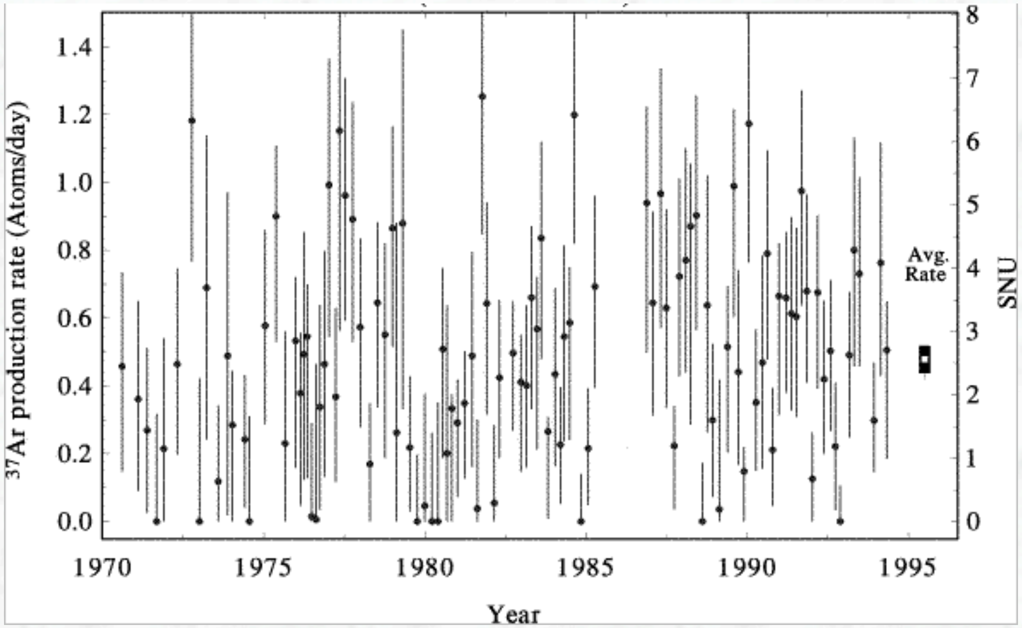
Erwartete Produktionsrate von Ar^{37} Atomen ≈ **1.5 pro Tag**

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

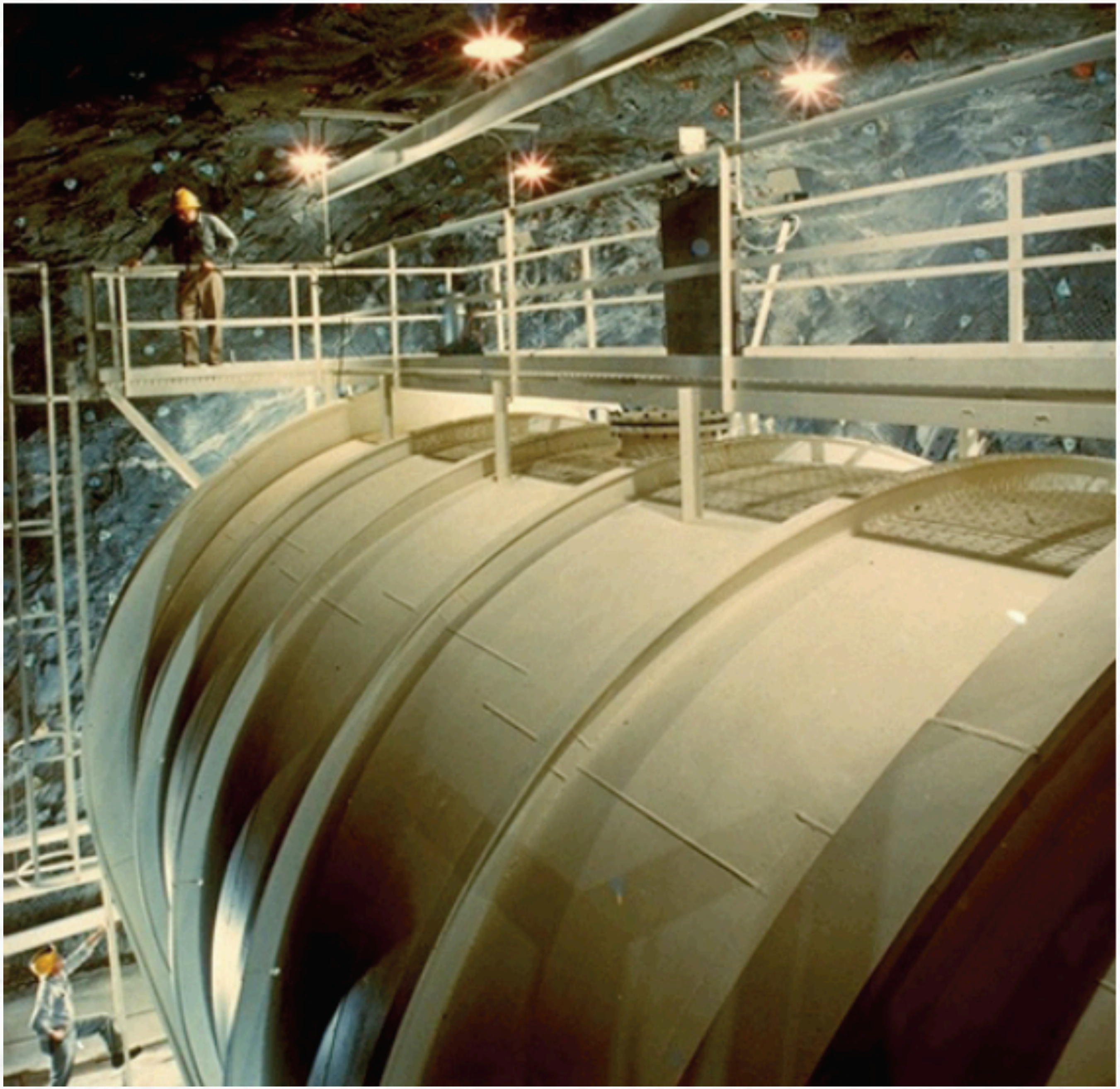
<u>Mittelwert aller Messungen:</u>

$R(Cl^{37}) = 2.56 \pm 0.16 \pm 0.16$ 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: $\sigma(\nu_e) \approx 6\,\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)$

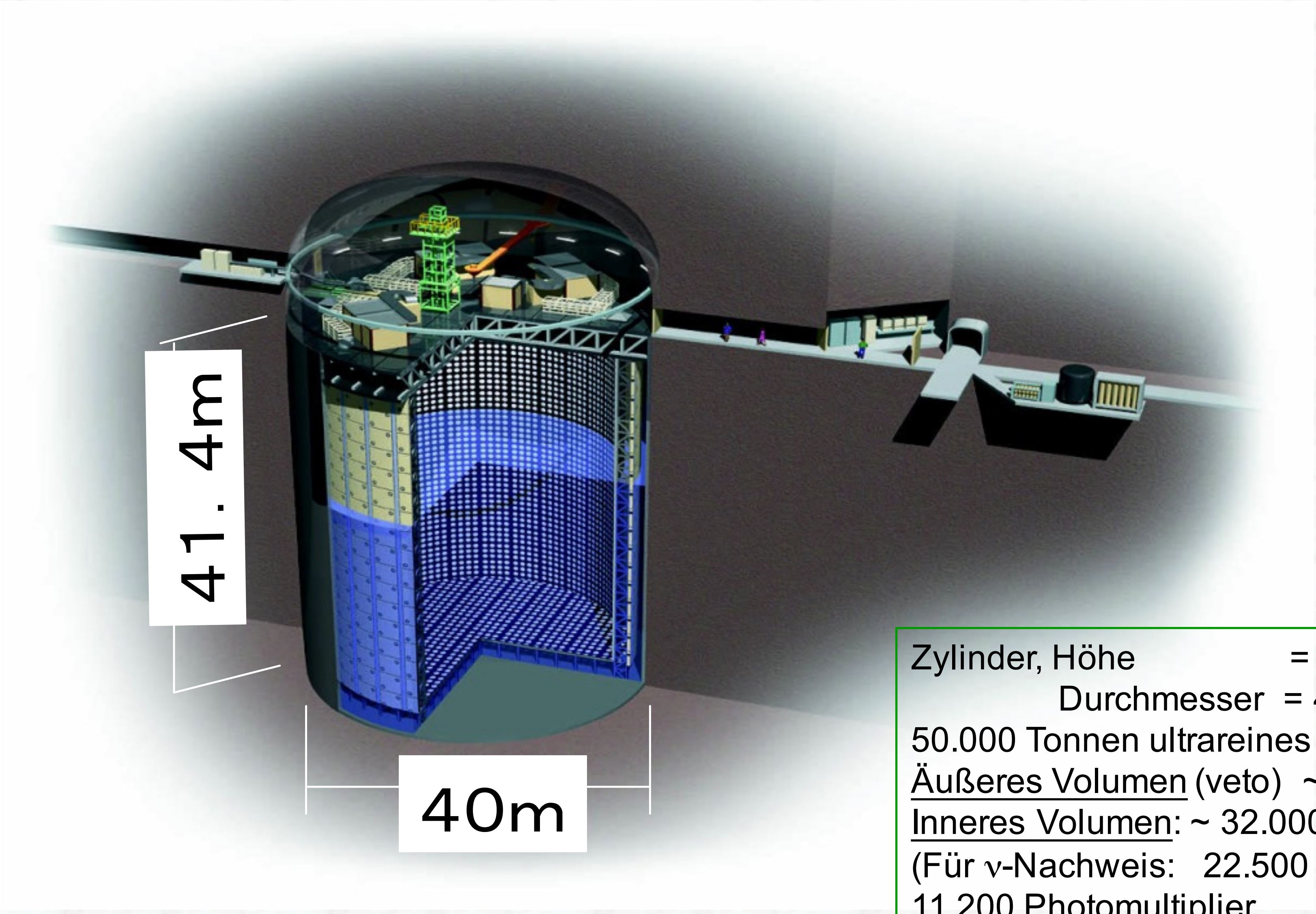
W and Z Austausch | Nur Z Austausch

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

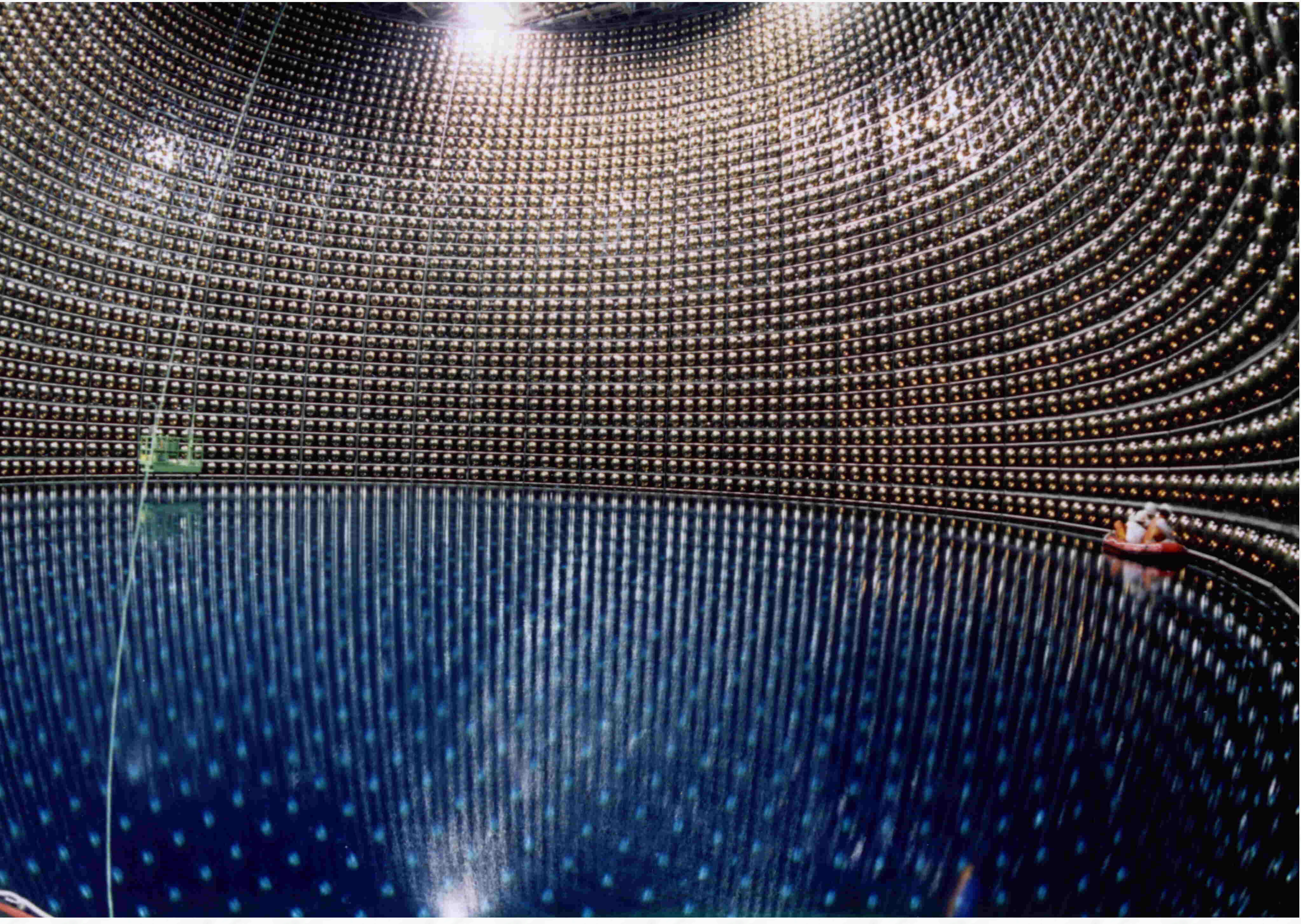
Super-Kamiokande (1996 – 2001) Volumen: 22.500 m^3

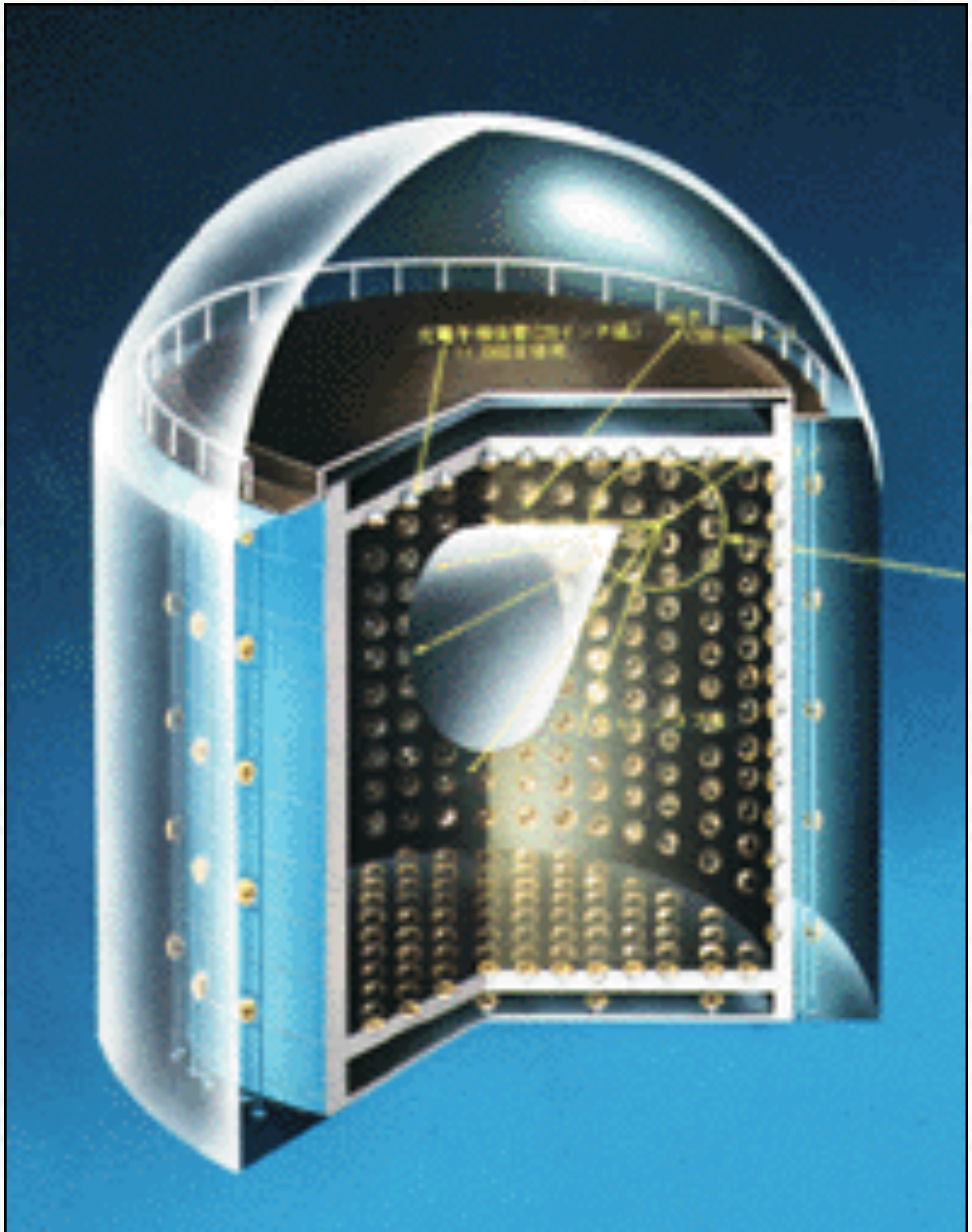
Installiert in der Kamioka-Mine (Japan)
bei einer Tiefe entsprechend 2670 m w.e.

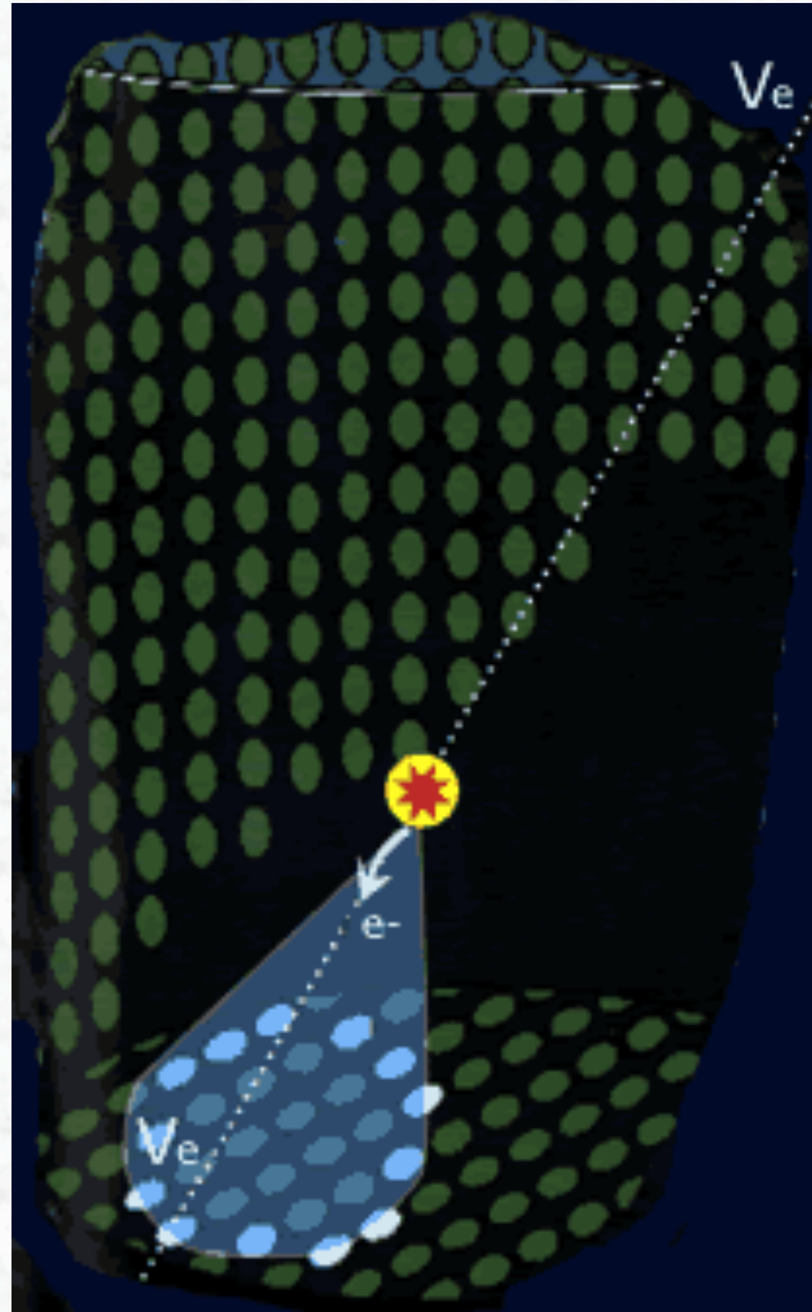
Superkamiokande-Detektor (Japan)

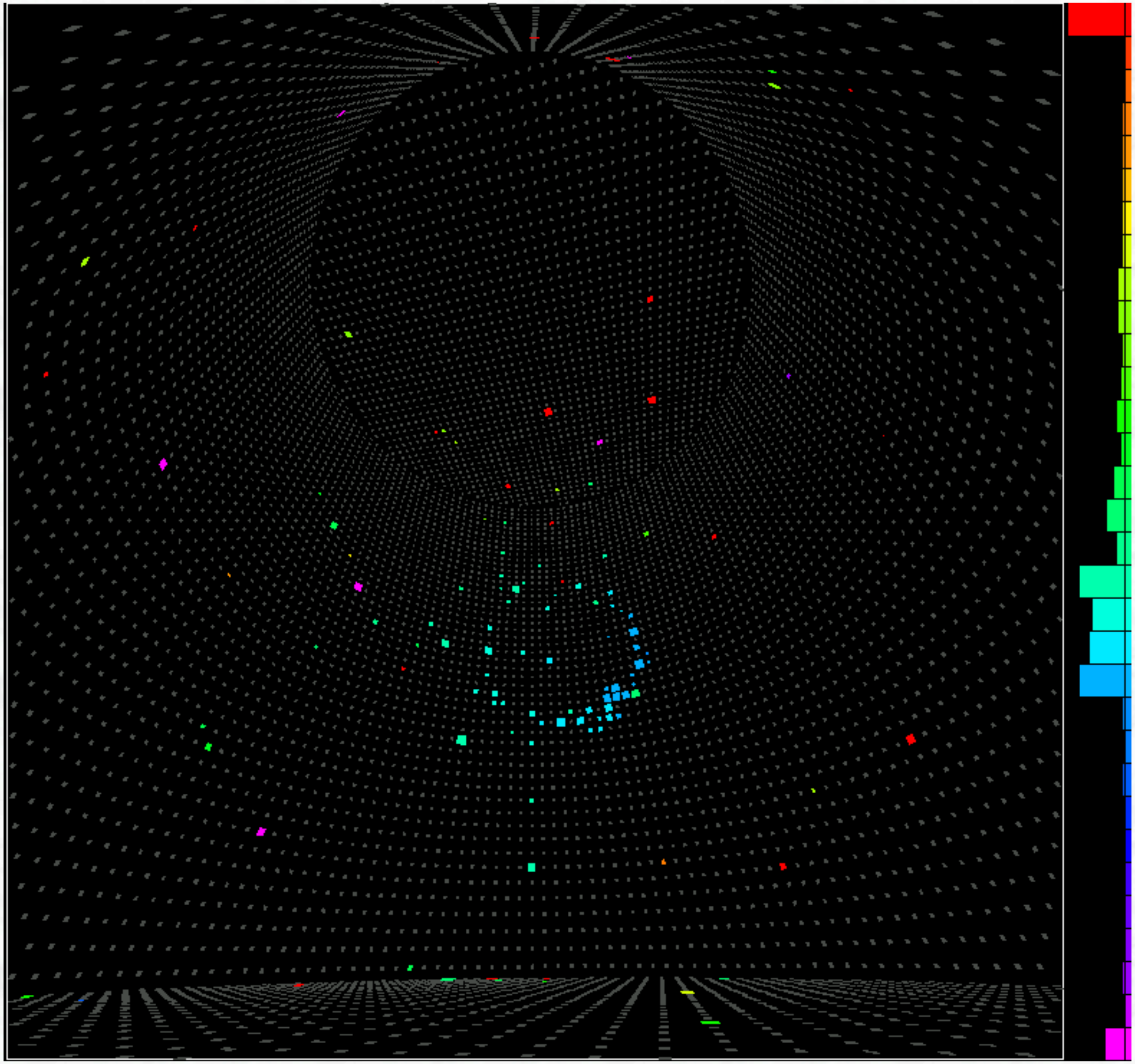


Zylinder, Höhe = 41.4 m
Durchmesser = 40 m
50.000 Tonnen ultrareines Wasser
Äußeres Volumen (veto) ~2.7 m dick
Inneres Volumen: ~ 32.000 Tonnen
(Für ν-Nachweis: 22.500 Tonnen)
11.200 Photomultiplier
Durchmesser = 50 cm






νe
e-
νe

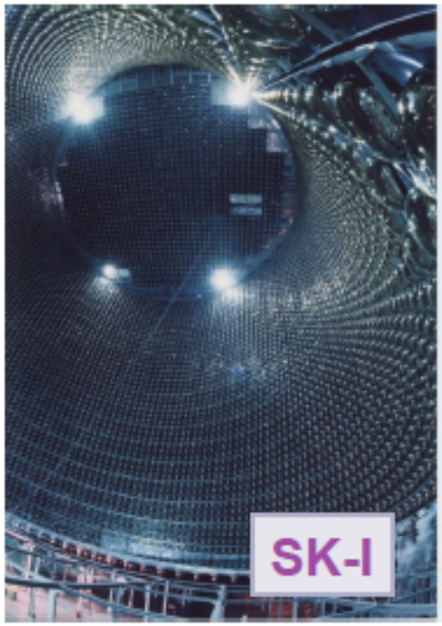


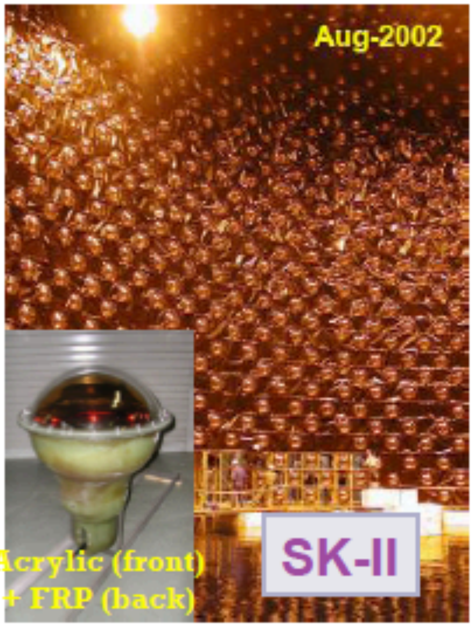
12 MeV
Neutrino
von der Sonne
im SK-Detektor

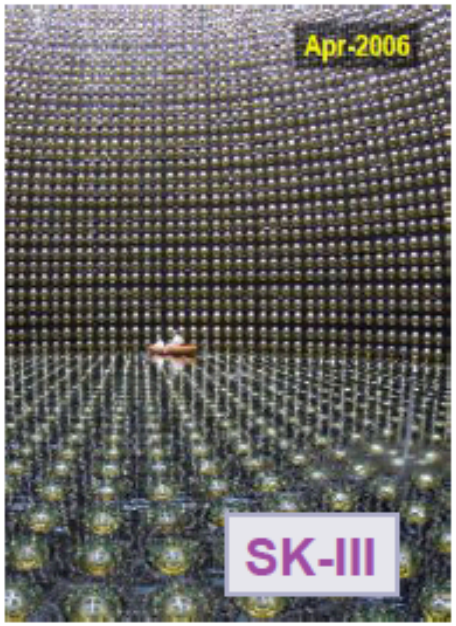
History of Super-Kamiokande

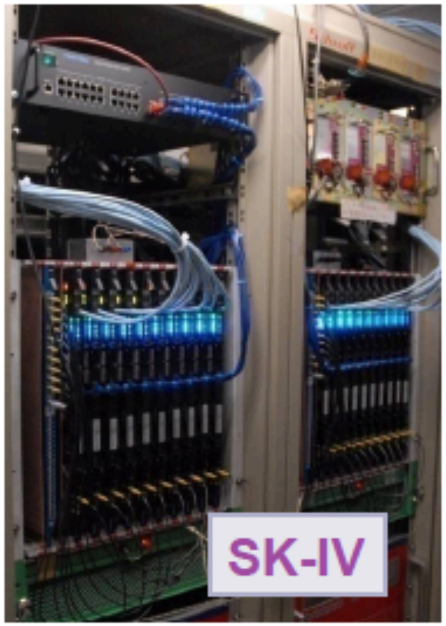
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

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

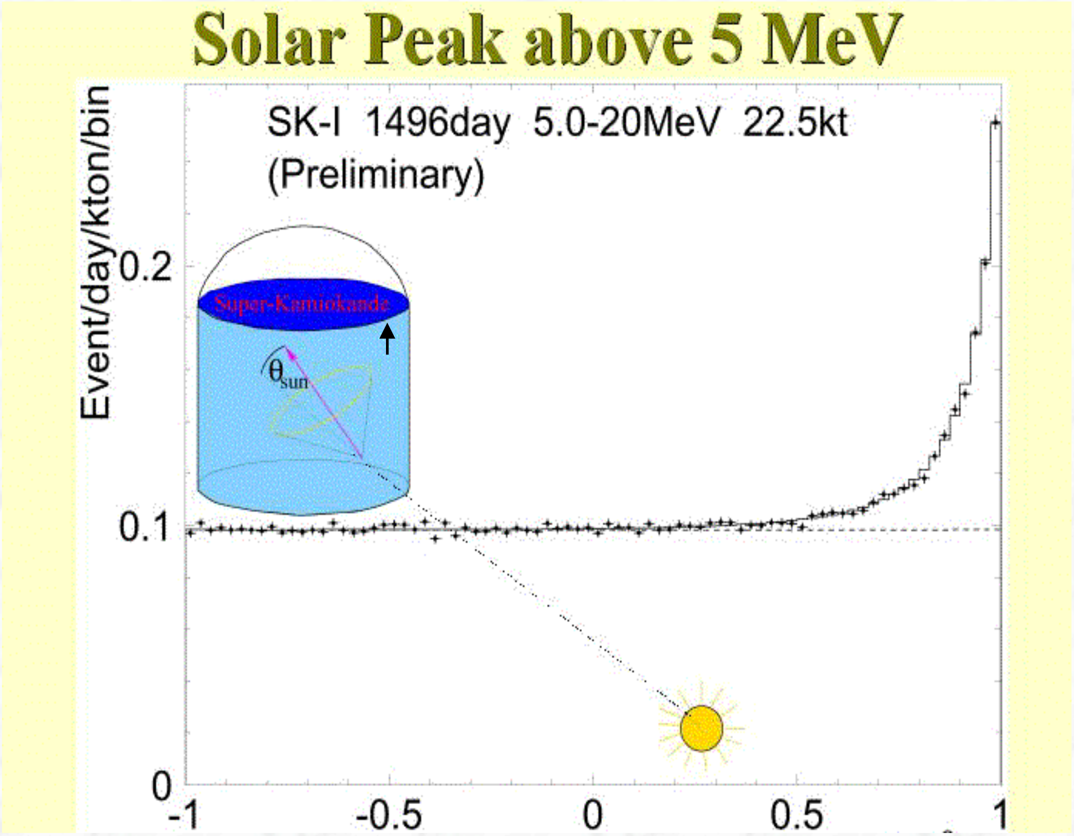








	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
Threshold: (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				now	goal



cosθ$_{Sonne}$

Bestätigung des solaren Ursprungs der nachgewiesenen Neutrinos:

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

The GALLEX-Experiment in Gran Sasso

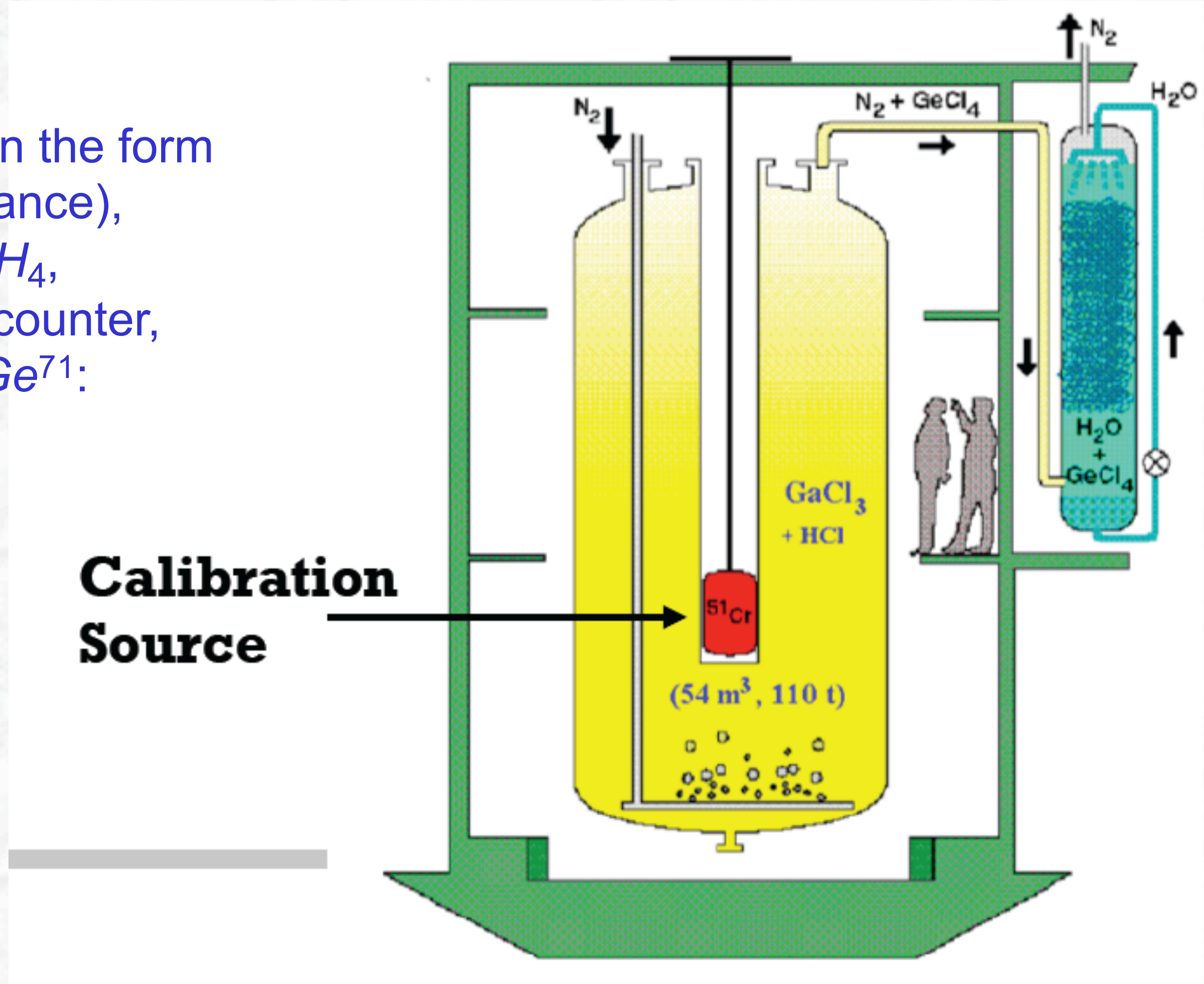
Experimental method:

•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}:

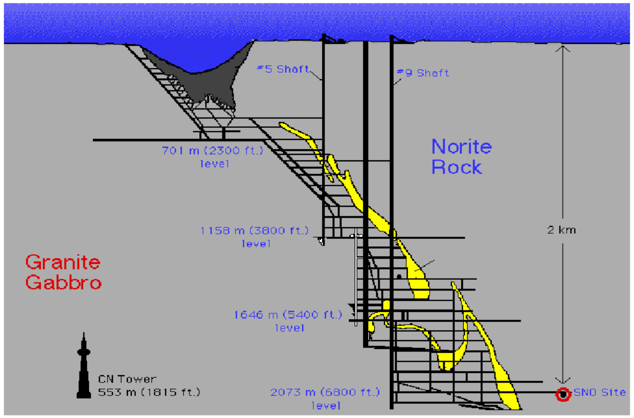
$$e^- + Ge^{71} \rightarrow \nu_e + Ga^{71}$$

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

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



The SNO Experiment



Sudbury Neutrino Observatory

1000 tonnes D_2O

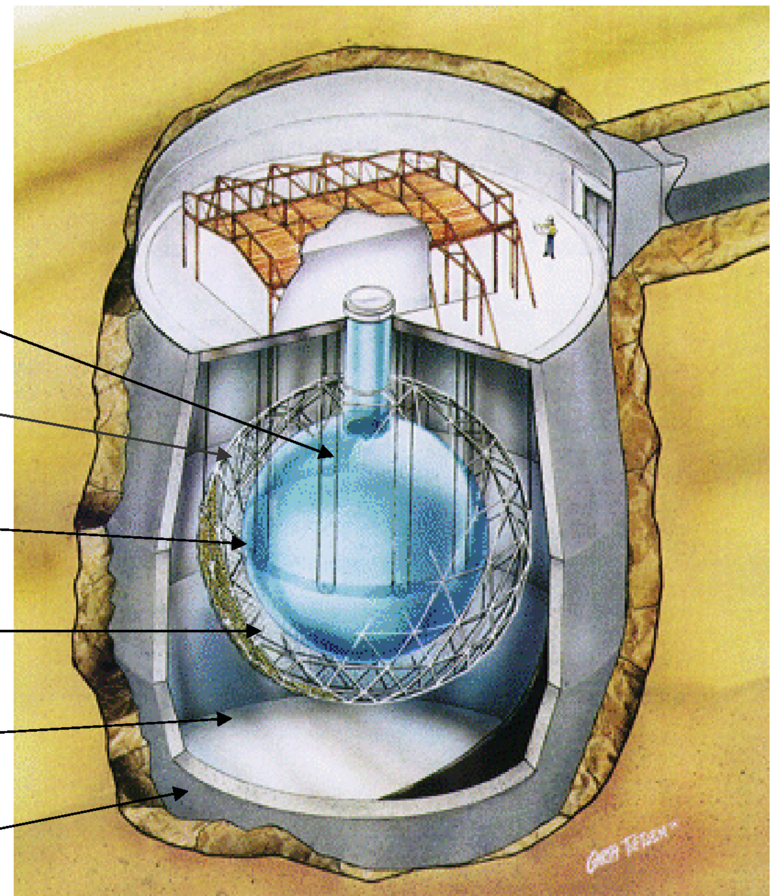
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

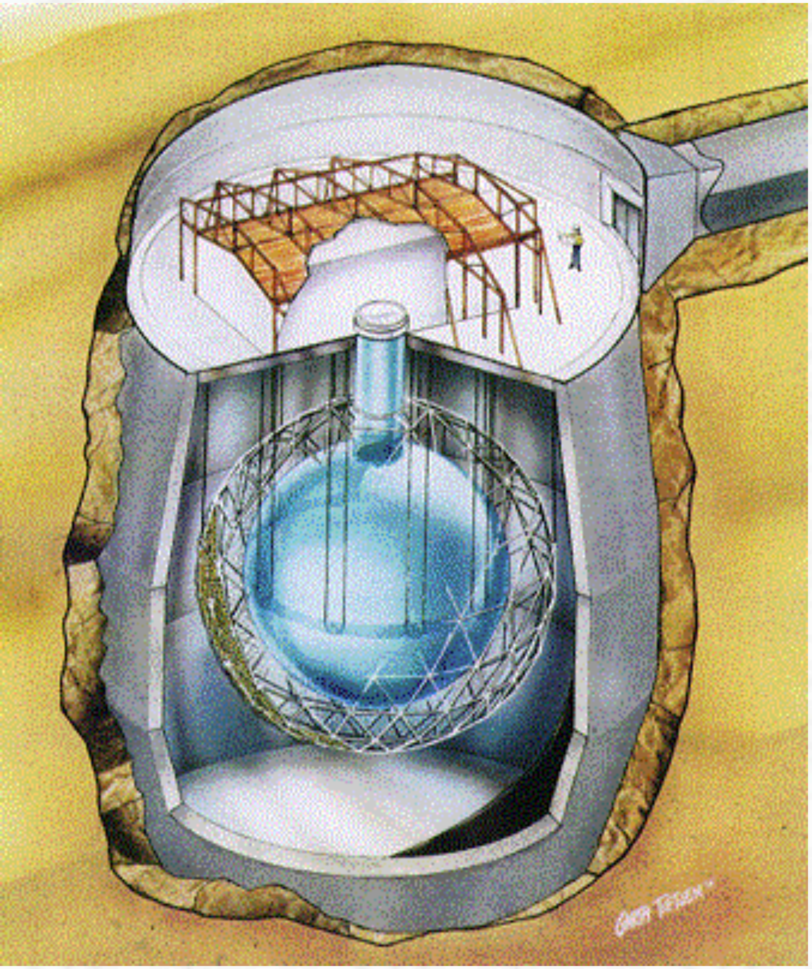
1700 tonnes Inner Shielding H_2O

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

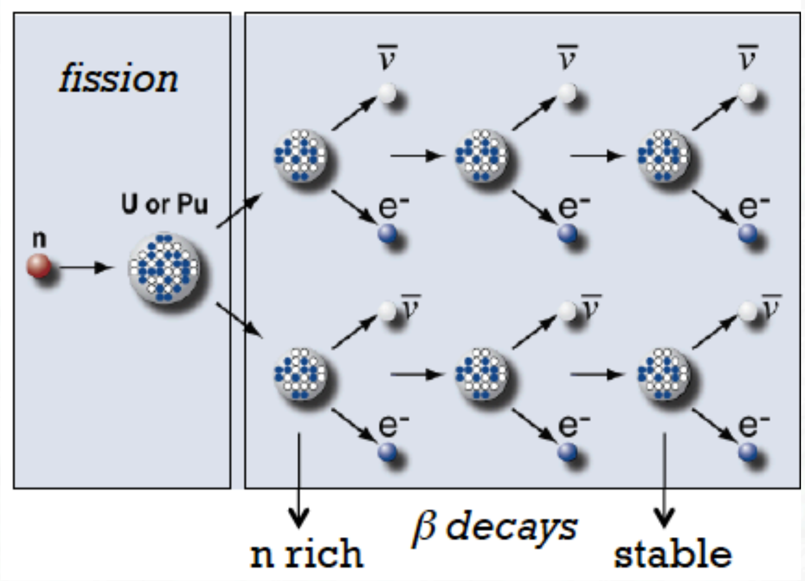
Weakly directional: recoil electron angular distribution $\propto 1 - (1/3)\cos(\theta_{sun})$
Good measurement of the ν_e energy spectrum (because the electron takes most of the ν_e energy)

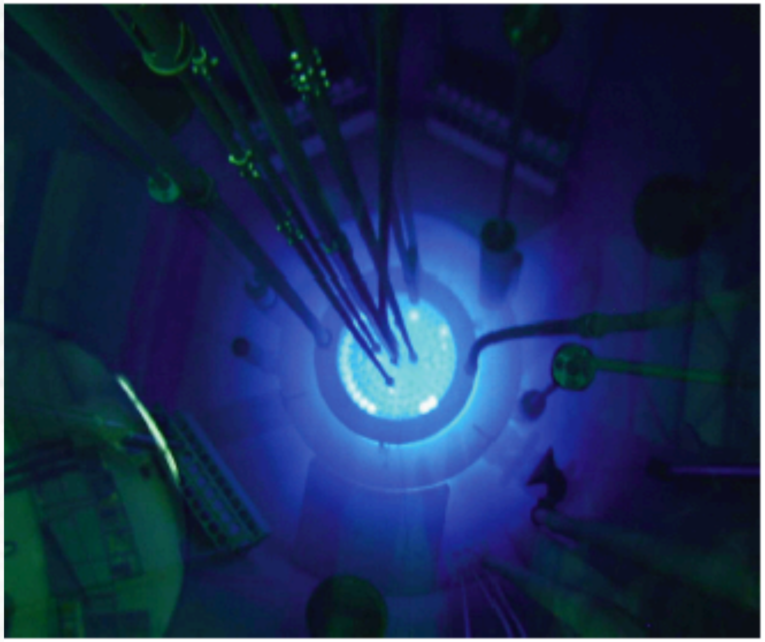
3. Neutral Current Reaction (NC): $\nu + d \rightarrow \nu + p + n$

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

Reactor experiments

- Nuclear reactors are very intense, pure and isotropic sources of anti-electron neutrinos from the neutron-rich fission products
  $\sim 2\ 10^{20}\ \nu_e\ s^{-1}\ GW_{th}^{-1}$

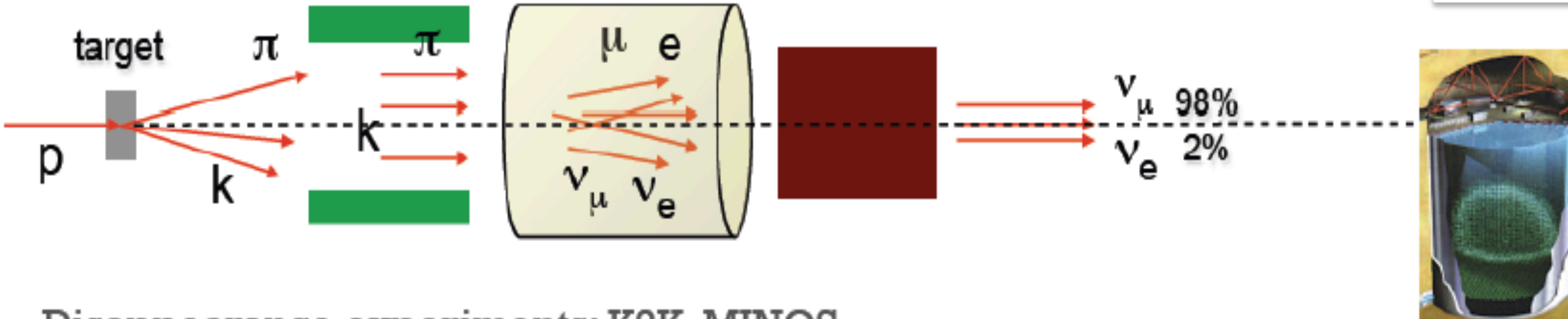




Neutrinos from accelerators

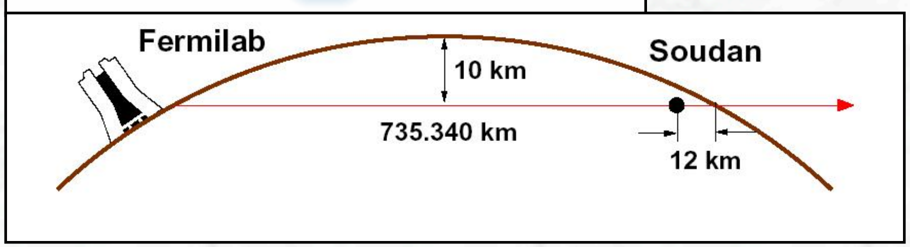
- *K2K* in Japan
- T2K in Japan
- MINOS / USA (Fermilab)
- Gran Sasso / Italy (CERN)

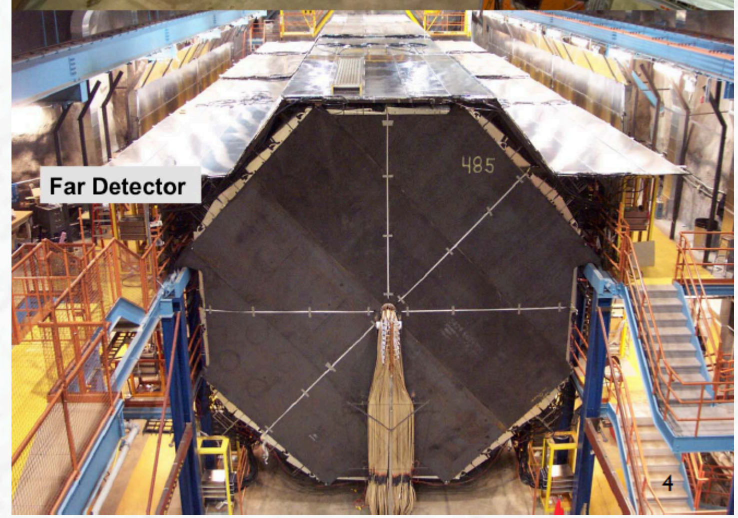
- Conventional neutrino beam:



- 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

Fermilab – MINOS Experiment



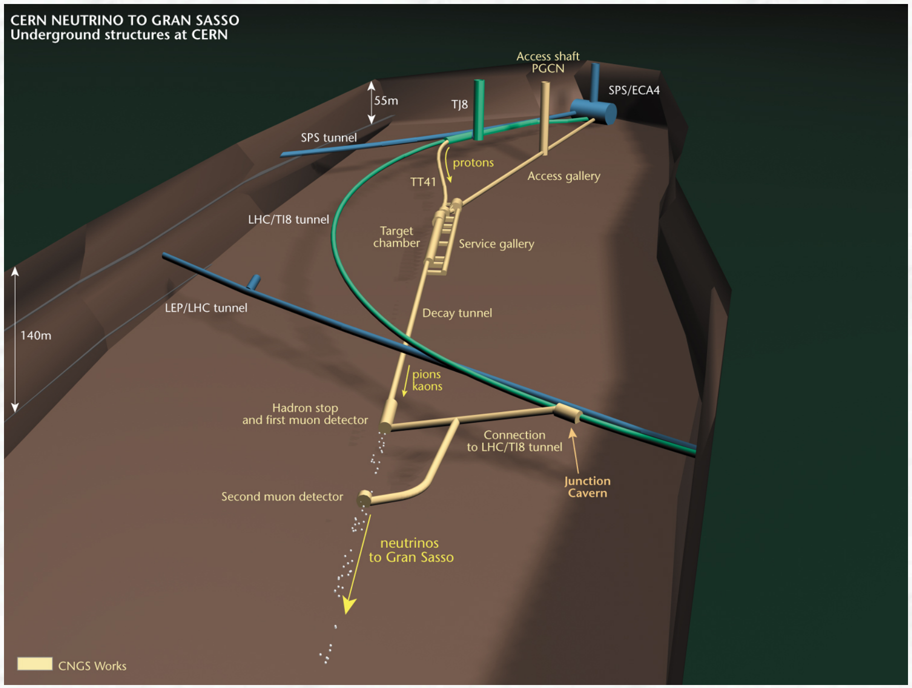


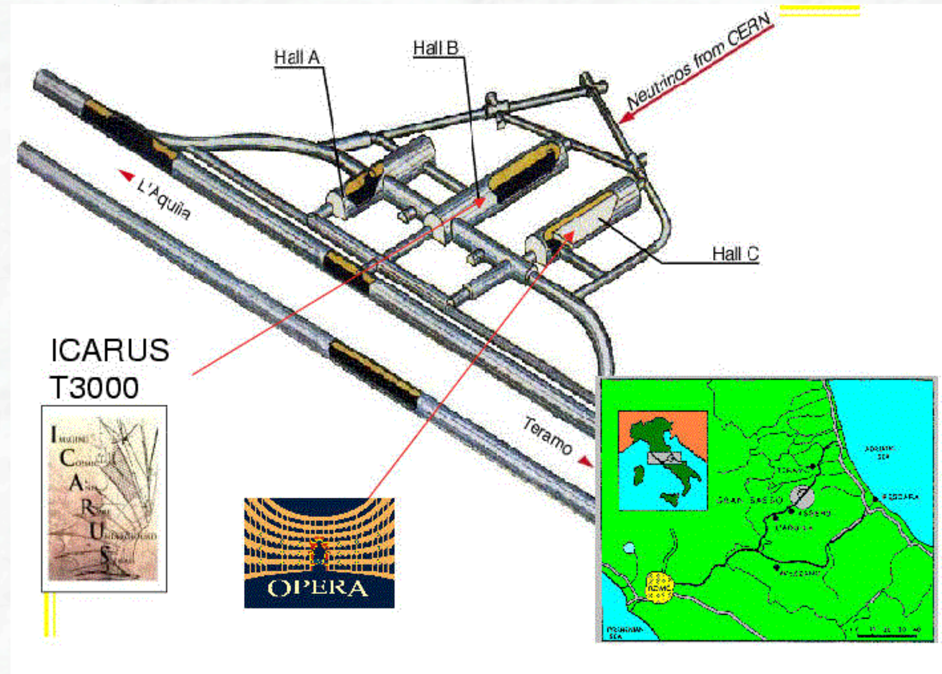
Fermilab Main Injector (MI): 120 GeV proton synchrotron

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

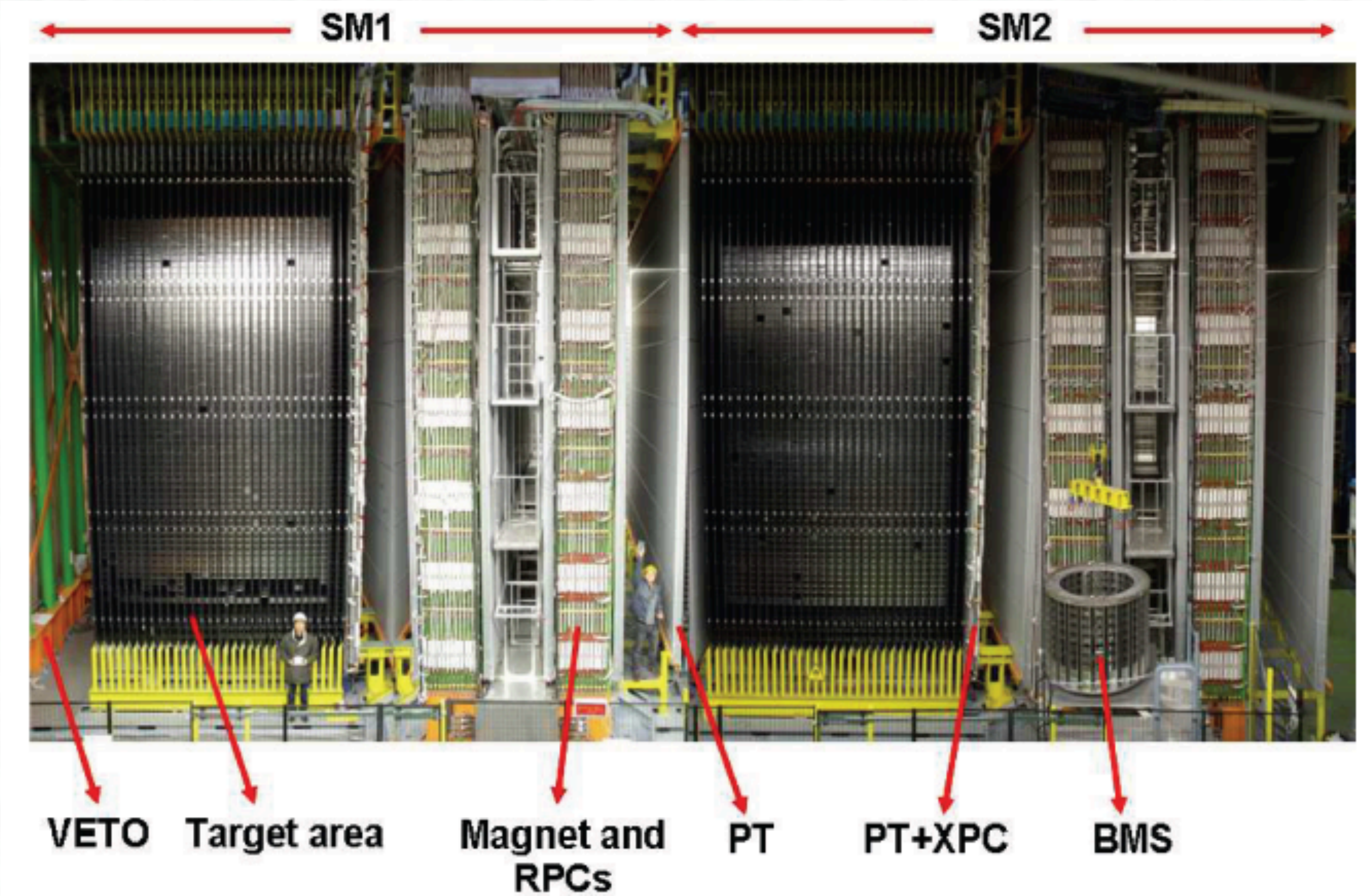
CNGS (CERN Neutrinos to Gran Sasso)





Main goal: Detection of ν_τ appearance after 732 km

OPERA Experiment in Gran Sasso



Candidate event for ν_τ appearance in OPERA