SOLAR NEUTRINOS: THE PIONEERING EXPERIMENTS

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1. **Solar Model + Neutrino Fluxes**
2. **The Radiochemical Method**
3. **HOMESTAKE Chlorine Experiment**
4. **KAMIOKANDE (+SK) *real-time* Experiment**
5. **GALLEX (+GNO) Gallium Experiment**
6. **SAGE Gallium Experiment**
7. **SYNOPSIS (as of the end of the past millenium)**

1. Solar Model + Neutrino Fluxes

A.S. Eddington

John Bahcall

Standard Solar Model

* hydrostatic equilibrium: stationary
* equation of state: ideal gas
* thermal equilibrium: radiation-dominated
* energy production: hydrogen fusion ⇓ neutrino emission

Major Input Data

solar mass, radius, luminosity, age
chemical composition (Z)
nuclear cross sections (S-factors)
opacities

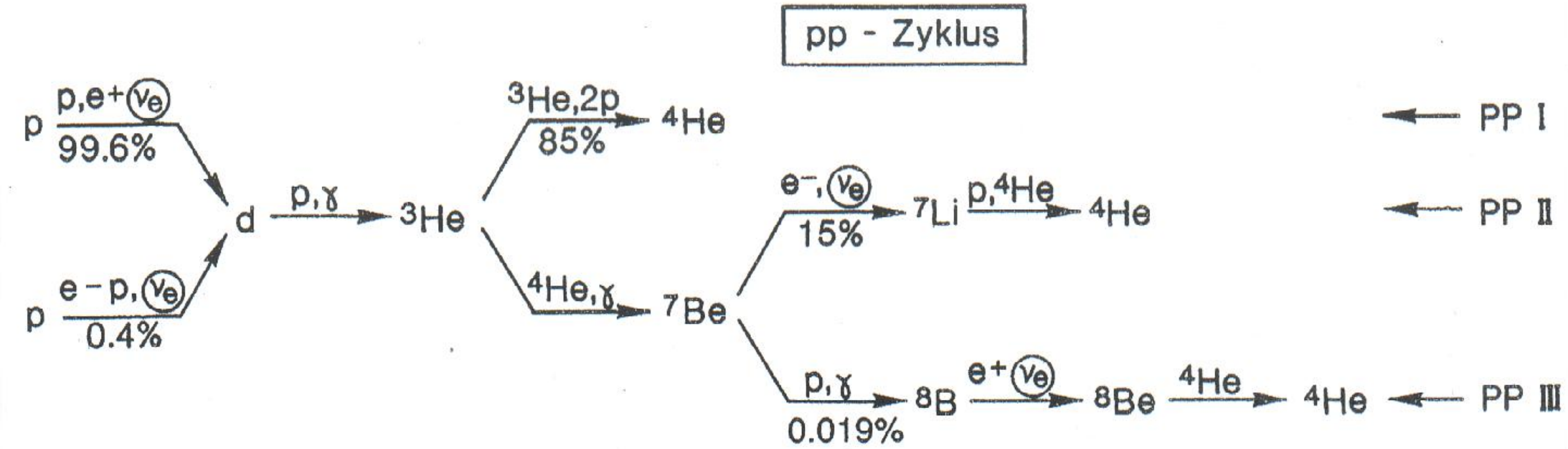
Observable random conditions through HELIO-SEISMOLOGIE

see sect. 7

For the SUN, the pp-cycle dominates

$$4\,H^{+} + 2e^{-} \rightarrow {}^{4}He^{++} + 2\,\nu_e + 26.73\ MeV$$

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

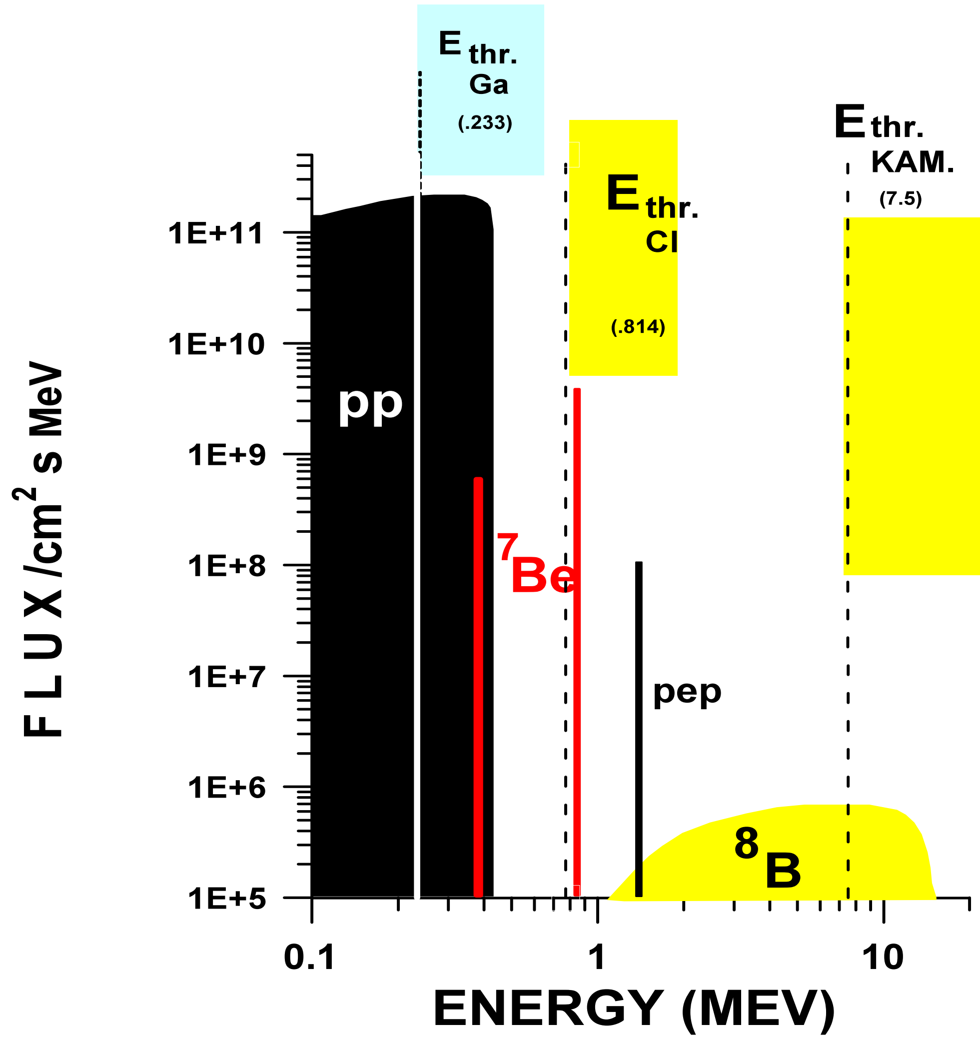


EXPECTED NEUTRINO FLUXES

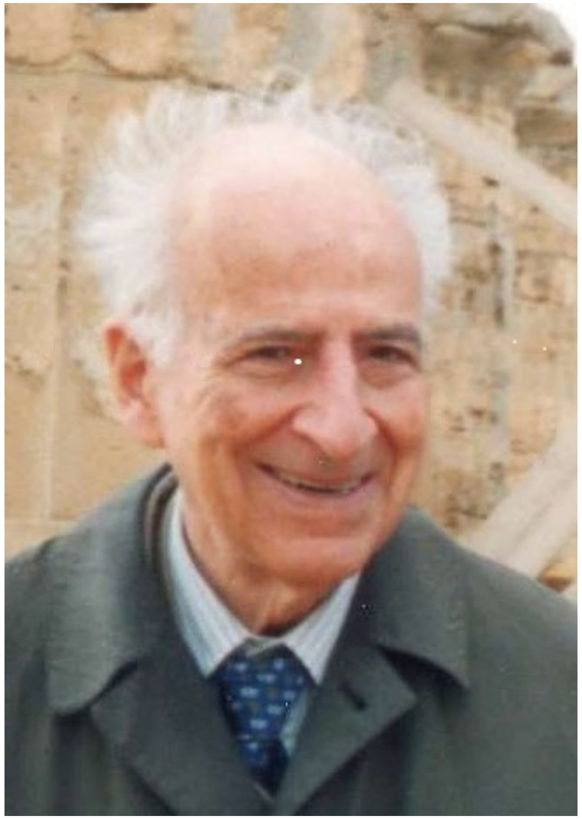
predicted by the Standard Solar Model to arrive at the Earth:

pp - ν :	**60 billions /cm², s**	$\sim T_c^{-1}$
^{7}Be - ν :	**~ 5 billions /cm², s**	$\sim T_c^{8}$
^{8}B - ν :	**~ 5 millions /cm², s**	$\sim T_c^{18}$

SOLAR NEUTRINO SPECTRUM



2. The Radiochemical Method



Bruno Pontecorvo

The *radiochemical* detection technique approached the problem of the incredibly low interaction cross sections of low energy neutrinos by using *very large target masses* and by collecting the reaction products over *extended time periods*. After the conceptional impetus by *Bruno Pontecorvo,* It was first applied by *Ray Davis* for his Chlorine detector, in which, however, *pp-neutrinos were not accessible* because their energy is below the threshold of the Cl^{37}-Ar^{37} reaction.

NEUTRINO DETECTION

'Inverse Beta Decay'

ν_e + A(Z) $\Rightarrow$ A(Z +1) + e-

$\Uparrow$ SUN — $\Uparrow$ TARGET — $\Uparrow$ PRODUCT (radioactive)

$\nu_e + {}^{37}Cl \Rightarrow {}^{37}Ar + e^-$ [$T_{1/2}$ = 34 d]

$\nu_e + {}^{71}Ga \Rightarrow {}^{71}Ge + e^-$ [$T_{1/2}$ =11.4 d]

Radiochemical Method

* Large Target Quantities (many tons)
* Underground Lab to shield from Cosmic Radiation
* Radiochemical Purity (Side Reactions)
* Extraction of Product Nuclides (separation factor $\approx 10^{30}$)
* Individual Atom Detection (‘free’ of Background)

TYPICAL RATES:

Only of order 1ν-capture per day in 10 - 1000 tons, depending on the target element

Davis Homestake chlorine experiment, *first* detection of solar neutrinos (^{8}B-neutrinos), 1970

Threshold 814 keV, hence not sensitive to main neutrino branches (pp, ^{7}Be-neutrinos)

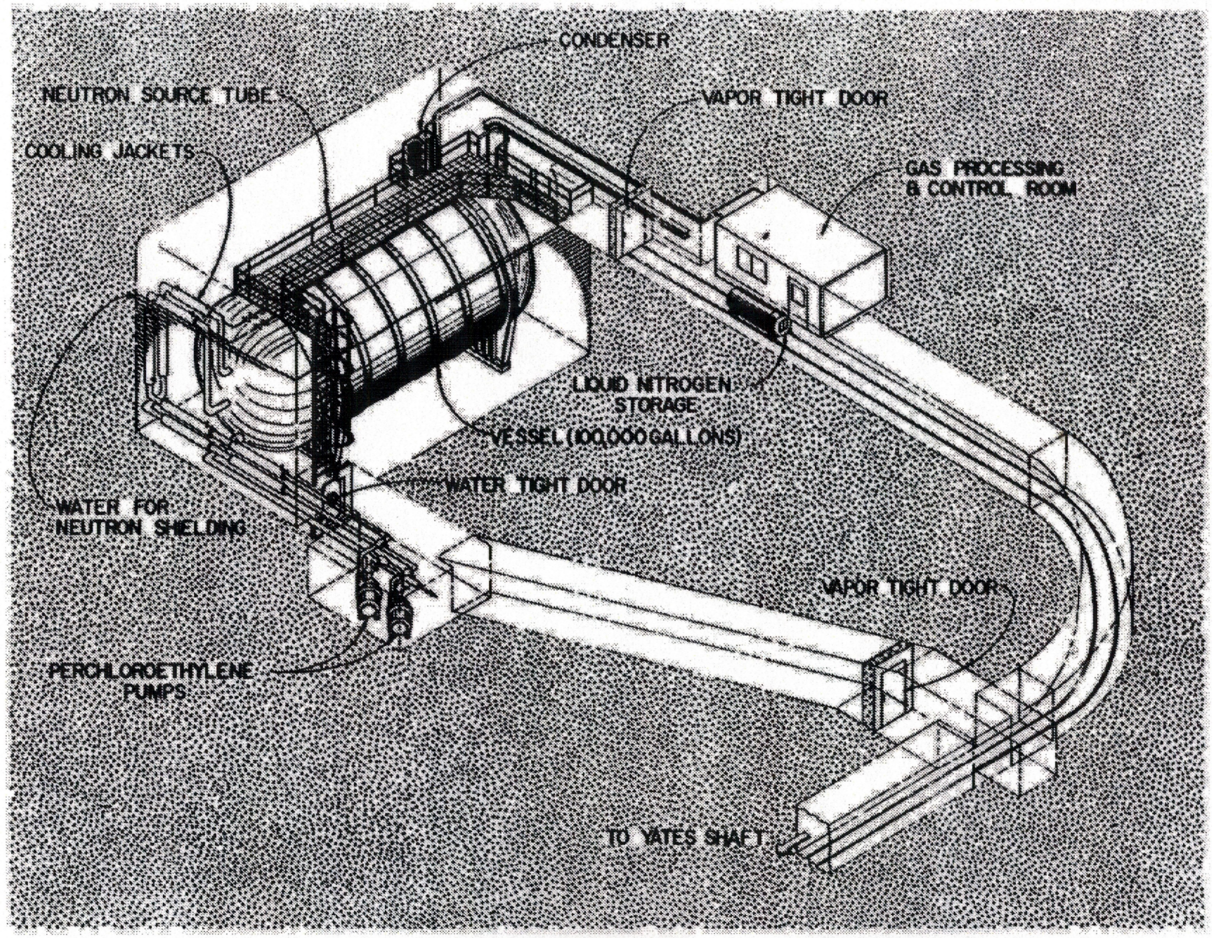
GALLEX experiment at Gran Sasso.

Threshold 233 keV, main signal from pp- and ^{7}Be neutrinos

3. HOMESTAKE Chlorine Experiment

Raymond Davis jr.

Homestake Setup



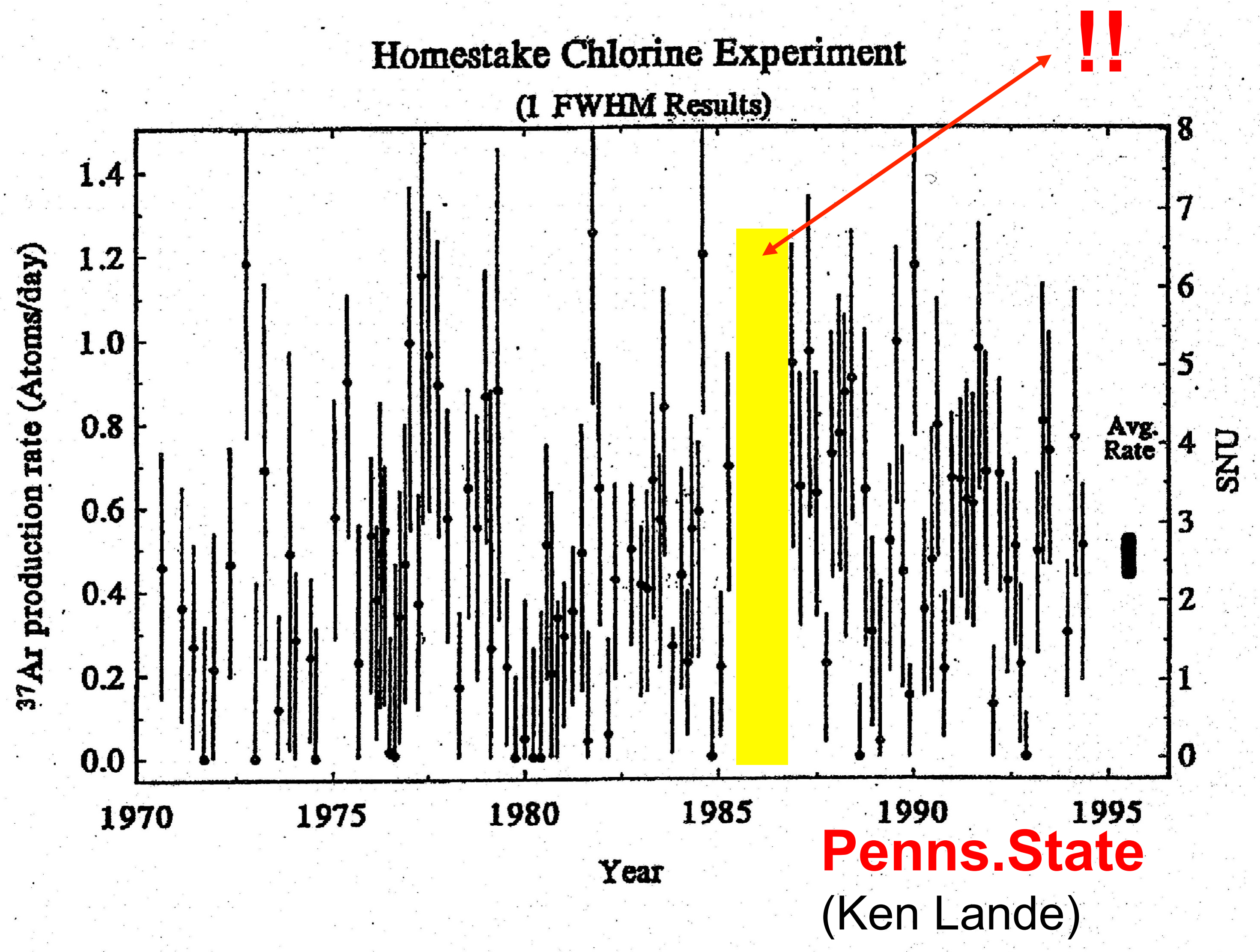


Fig. 2. Results from 108 individual solar neutrino observations made with the Homestake Chlorine detector. The individual error bars are statistical only.

Results of The Homestake Experiment

^{37}Cl (ν_e, e^-) ^{37}Ar (E_{thr} = 814 keV)
K_{shell} EC → ^{37}Cl + 2.82 keV (*Auger* e^-, *X*) τ = 50.5 d

615 tons of liquid Perchlorethylene (C_2Cl_4)
Homestake Mine; South Dakota USA; 4200mwe; 1964-1994
- First measurement of solar neutrino interaction rate
- Raised the problem of missing neutrinos ("SNP")
- Opened a new field of research. Davis was awarded the Nobel prize in 2002 *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"*

Rate = 2.56 ± 0.23 SNU ; SSM expectation was = 8 ± 3 SNU (3σ)
(SNU = Solar Neutrino Unit = 10^{-36} events/target atom/s)
[Summary, Cleveland et al., Nucl.Phys.B (Proc.Suppl.) 38,47,1995]
Constancy of the solar neutrino flux (over 23 years): no correlation has been found between the production rate and the solar cycle, inspite of many speculation on this item in the '90th .

4. Kamiokande Experiment

KAMIOKA**NDE** 1983-1996

this real-time water Cerenkov detector aimed primarily for proton decay and atmospheric neutrinos.

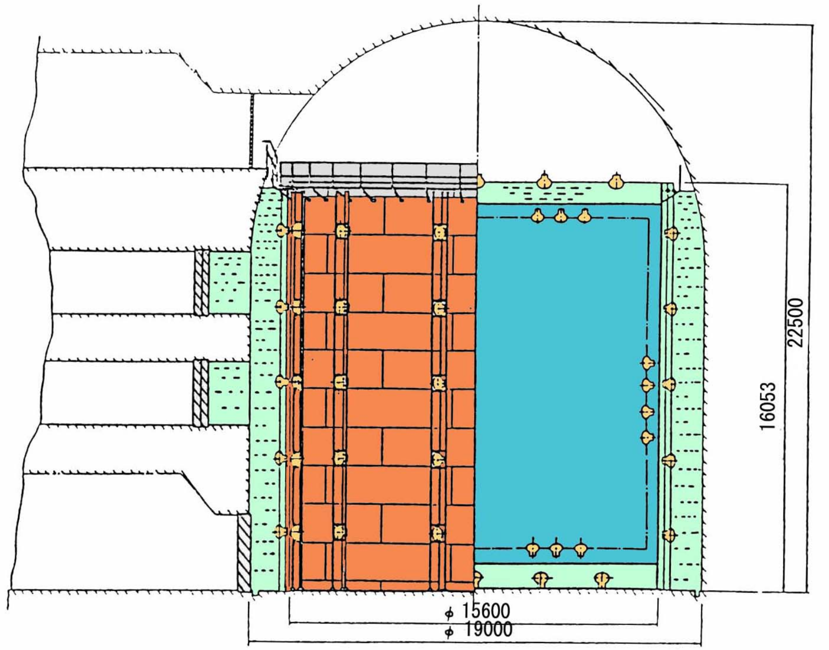
Initially, Solar neutrinos (and the surprising Supernova 1987a) have been more or less subordinated step-childs because of their lower Energy

Kamiokande

1982: Kamioka**NDE** was **funded**

Nucleon decay experiment

operation:1983-1996



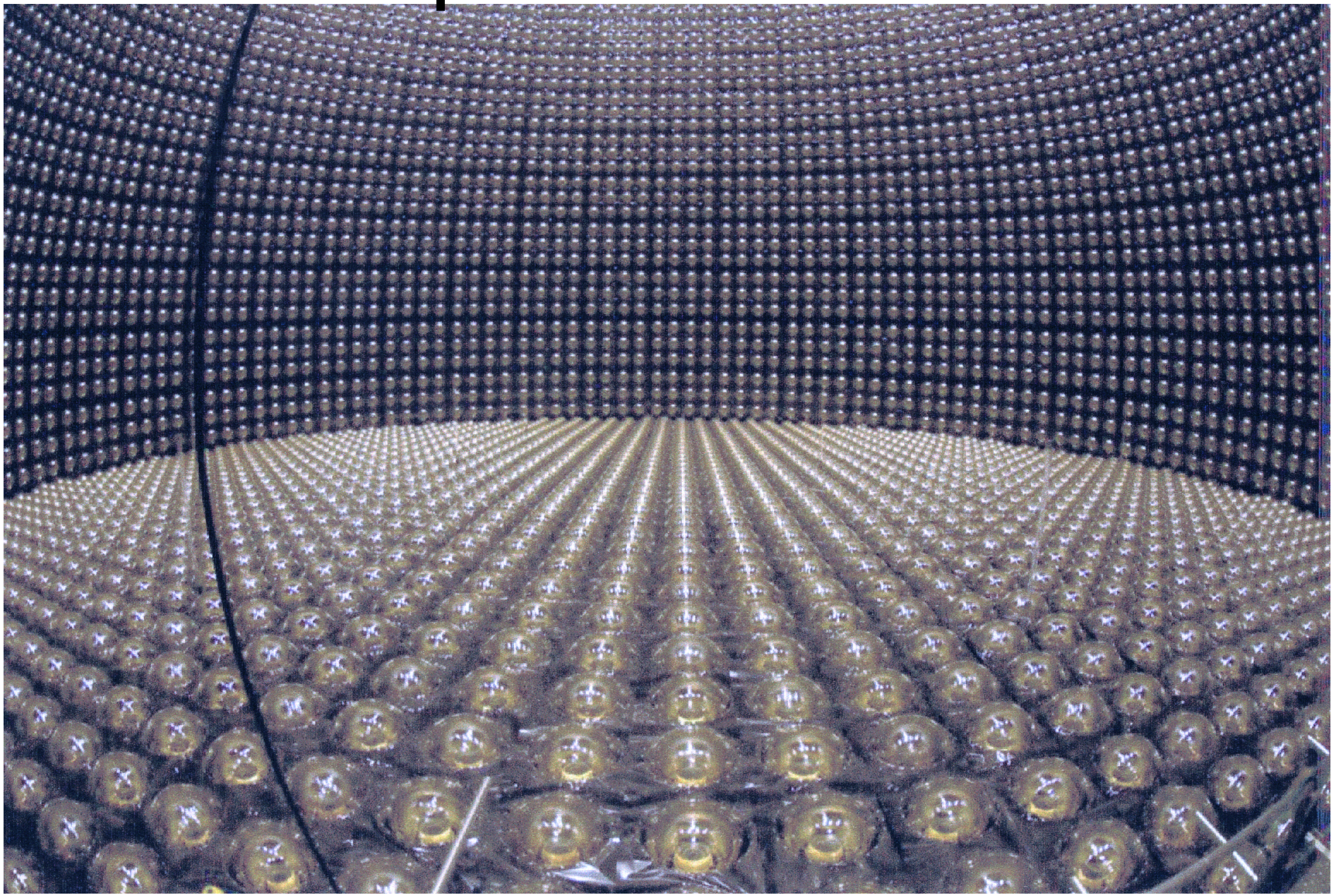
- **Total mass: 3000 tons [15.6mϕ x 16m in height]**
- **Inner mass: 2140 tons [fid. 680 tons for solar ν]**
- **948 20-in PMTs (cov. 20%)**

K + SK Phases

Experi-ment-phase	PMT-cover-age	Time period	days	Fid. mass [tons]	E_e-thresh. [MeV]	observed $\nu_\odot$ events	^{8}B-ν Flux [10^6/cm^2/s]
KAMIO-KANDE		1/1987 – 2/1995	2079	680	7.5	830	2.82 ± 0.38
SUPER-KAM-I	40%	5/1996 – 7/2001	1496	22500	5.0	22400 ± 230	2.35 ± 0.08
Accident		Nov. 2001					
SUPER-KAM-II	19%	12/2002 – 10/2005	791	22500	7.0	7213 ± 152	2.38 ± 0.17
SUPER-KAM-III	40%	just started			5.0 or less		

^{8}B-ν flux is only ***about half*** of what is predicted from the Standard Solar Model (SSM)

Super-Kamiokande



5. GALLEX (+GNO)

Why sub-MeV Neutrinos?

98 % of all solar neutrinos are sub-MeV
($\Phi_7 \sim 7$ % , $\Phi_{pp} \sim 91$ %).
The pp- neutrino flux is coupled to the solar luminosity. It is a fundamental astrophysical parameter that should definitely be measured, as precisely as possible. Stringent limitations (or observation) of departures from the standard solar model are obtained if the flux of pp neutrinos could be deduced.

Pre - Gran Sasso Time

Brookhaven, March 1979

Preparing for the Experiment at Gran Sasso (1979) 1983 - 1985

1979 Underground laboratory proposed by Antonio Zichichi, President of INFN

1982 Start of excavations at Gran Sasso

1984 First meeting of TK with Nicola Cabibbo, INFN- President

1984 N. Cabibbo strongly supports solar neutrino research as a major topic at LNGS

Formation of the GALLEX Collaboration

3 / 1984	KFK Karlsruhe joins MPIK
9 / 1984	TUM München joins
10 / 1984	Meeting at CdF in Paris: Frejus?
11 / 1984	N. Cabibbo favourable for space at LNGS. INFN Roma and Milano join
11 / 1984	Saclay joins for Gran Sasso
11 / 1984	WI Rehovot joins
2 / 1985	Constituting GALLEX meeting
7 / 1985	Approval of GALLEX at LNGS by the GS Scientific Committee

At Hall A excavation site, 1987

GALLEX / GNO

Radiochemical Method (product accumulation)

Gallium Experiment at Gran Sasso

GALLEX

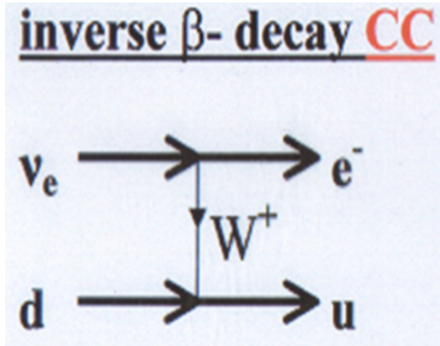
INTERNATIONAL SOLAR NEUTRINO RESEARCH COLLABORATION

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

(Ge^{71}: $T_{1/2} = 11.4$ d)

Low threshold! (0.233 MeV)

Implies a serious challenge concerning backgrounds



Conception of the Gallium Experiment (GALLEX / GNO)

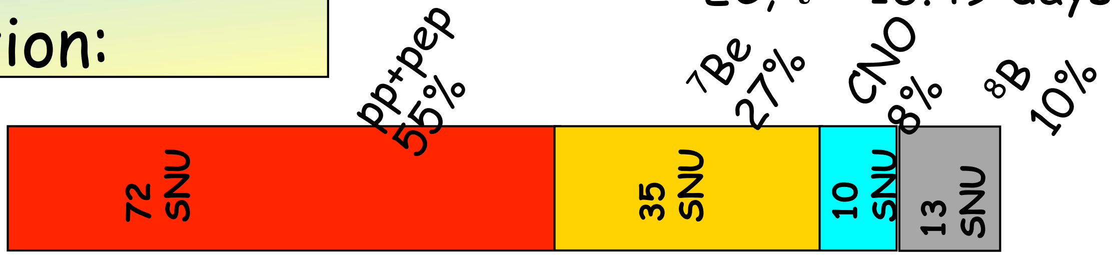
Purpose: detection of low energy solar neutrinos

Basic interaction: $^{71}Ga(\nu_e,e)^{71}Ge$ (E_{thr} = 233 keV)

→ EC, τ = 16.49 days

ν signal composition:

Tot: 128^{+9}_{-7} SNU



Technique: Radiochemical

Target: 103 tons of $GaCl_3$ acidic solution containing 30 t of natural gallium

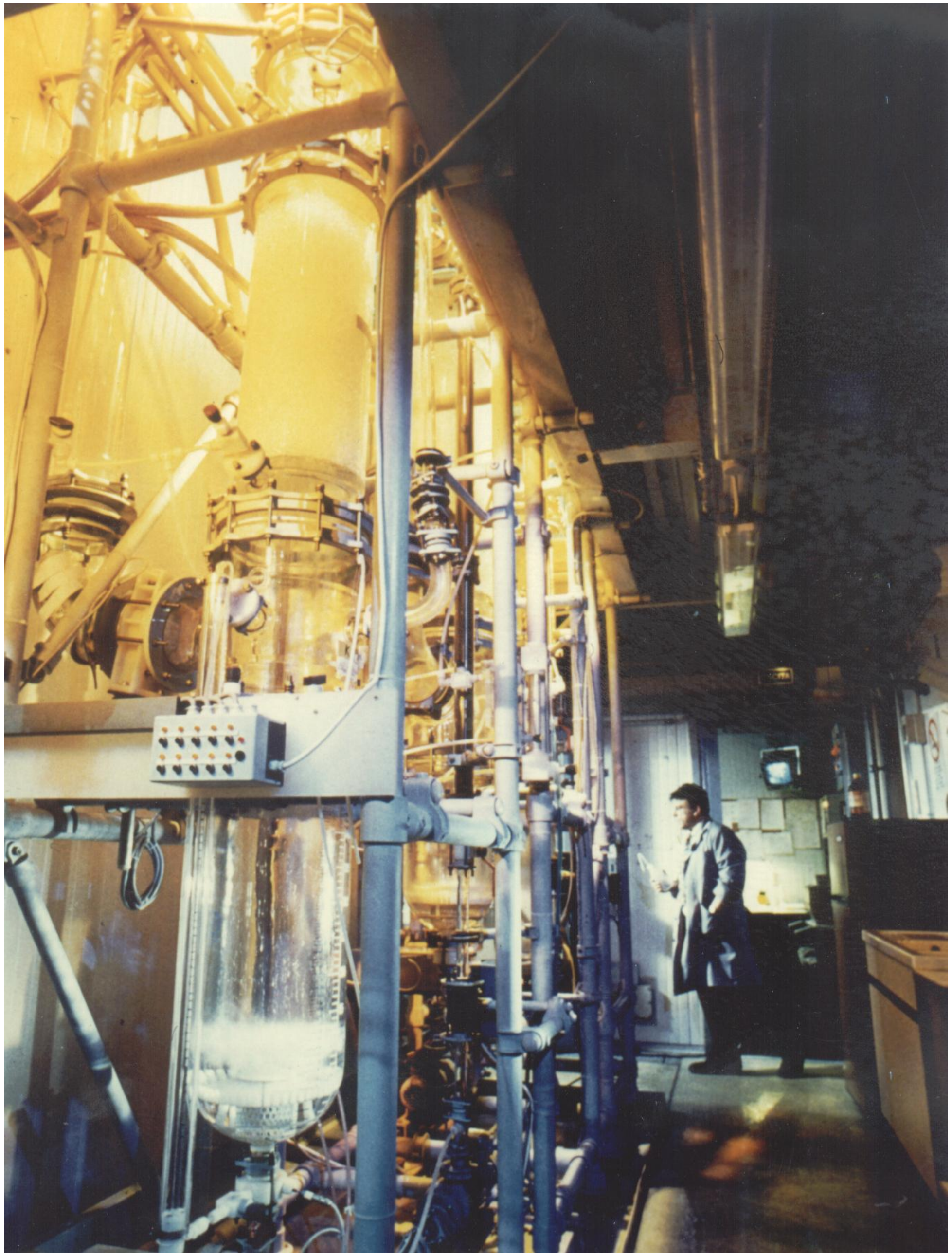
Chemical extraction of ^{71}Ge every 3-4 weeks (nitrogen purging of $GeCl_4$)

Detection of ^{71}Ge decay with gas proportional counters

Expected signal (SSM): ≈ 9 ^{71}Ge counts detected per extraction

GALLEX@LNGS (GRAN SASSO)

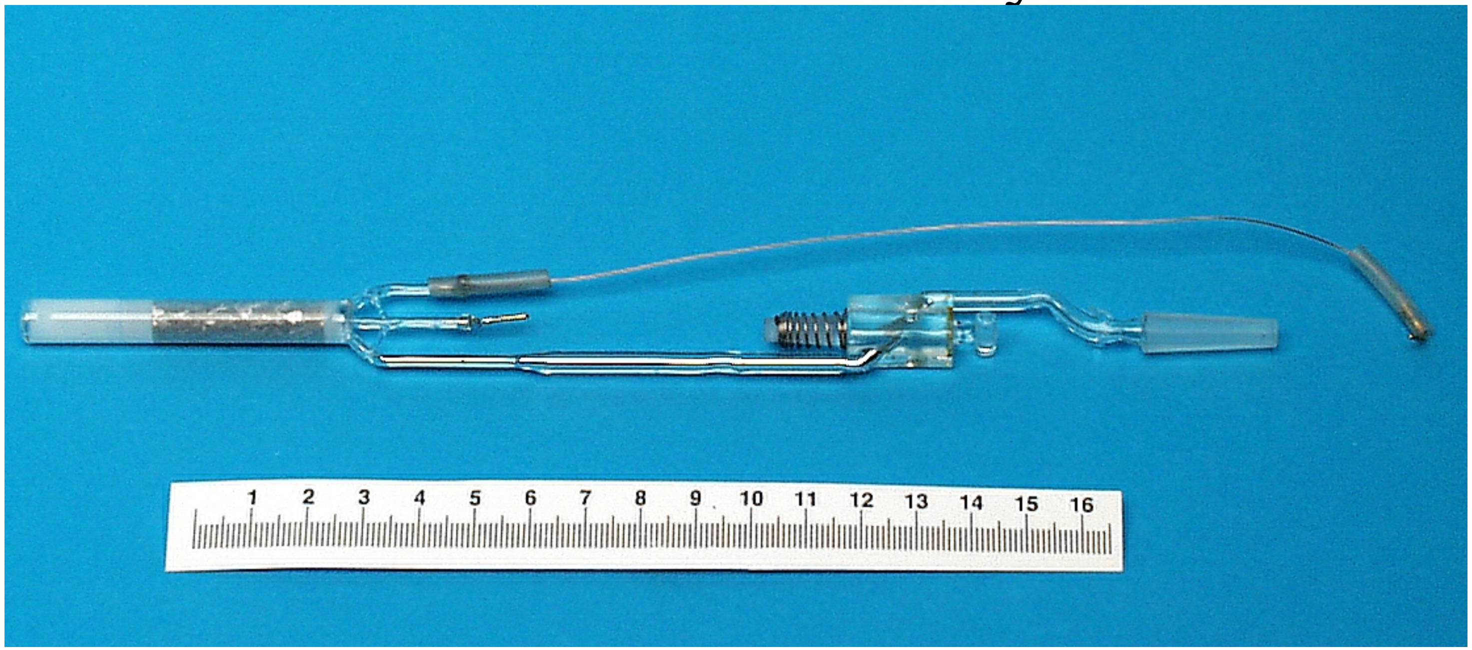
Tanks installed, September 1989



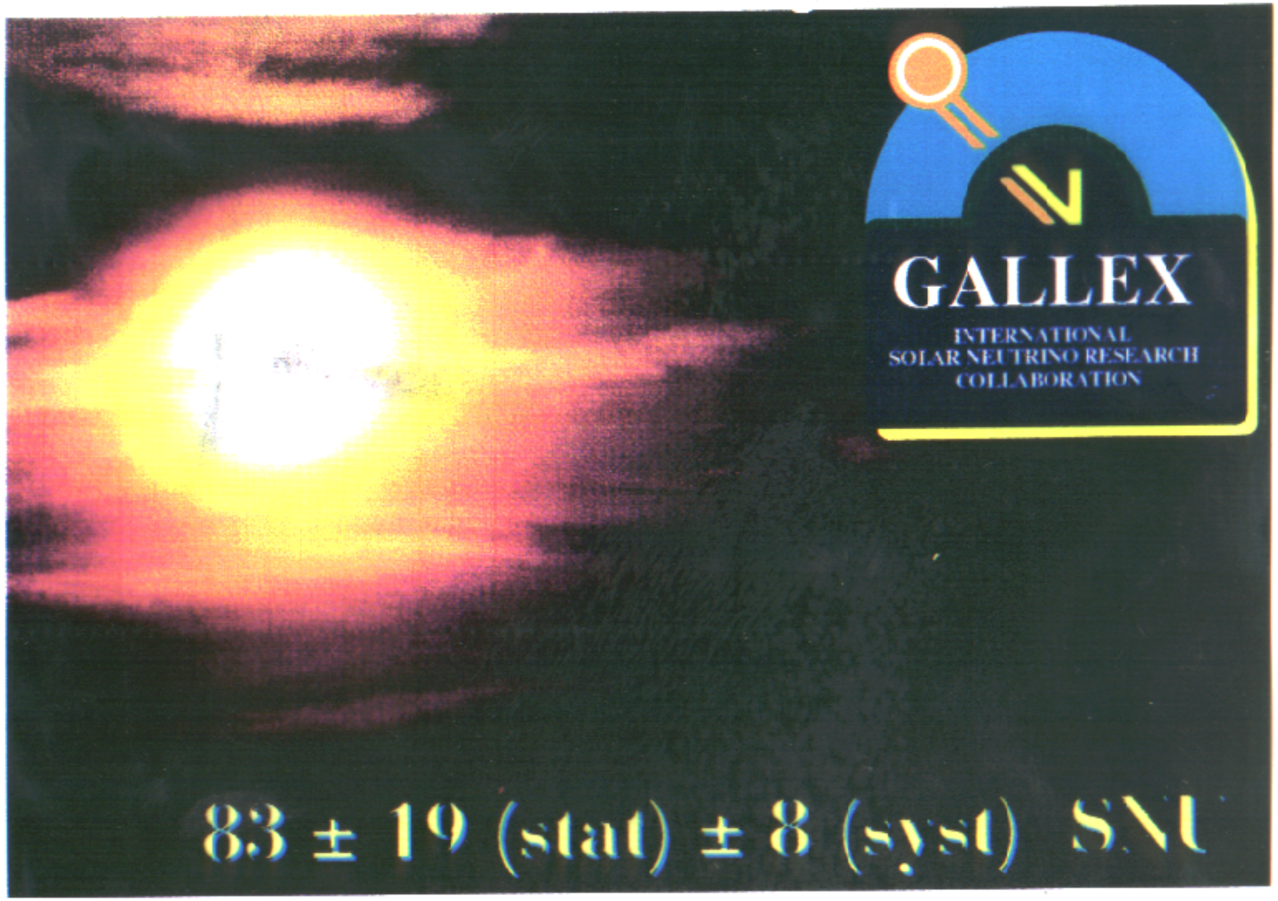
Germanium-Extraction System

Low Level Gas Proportional Counter

- Miniaturized Counters made from Suprasil ultrapure synthetical quartz
- Fe oder Si- Cathodes
- Counting gas: GeH4 + Xe
- Active Volume 0.6 – 0.9 cm³ only



Granada, June 8th, 1992
GALLEX announces first observation of solar pp-neutrinos at „Neutrino 92“



GALLEX RESULT IMPLICATIONS (1992)

Physics Letters B285 (1992) 376 *Citation index 31.5.92:* # 5 + # 11

Physics Letters B285 (1992) 390 14 RUNS

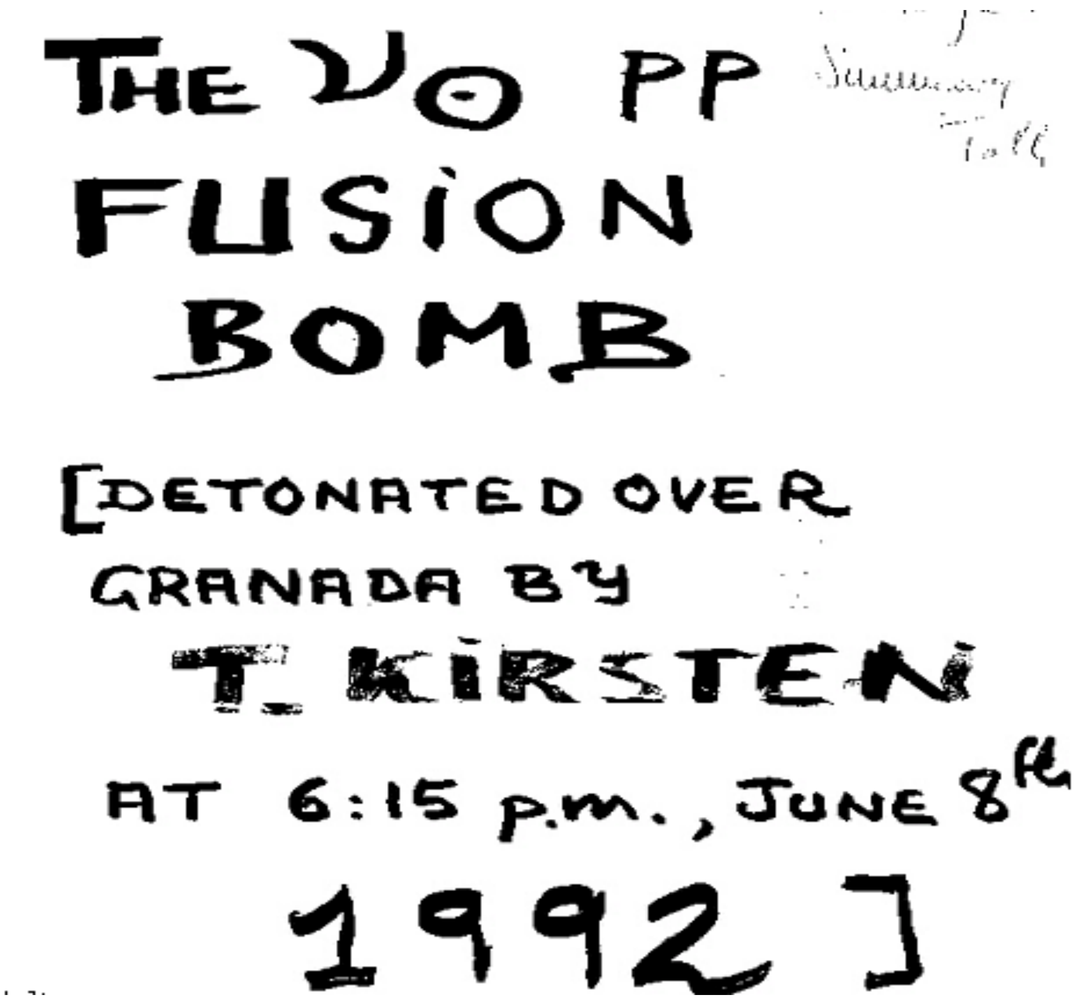
≈ 105 % of the pp- expectation

⇒ Hydrogen fusion in the solar interior experimentally observed

≈ 60 % of the total SSM- expectation

⇒ Definite deficit of pp- and/or ^{7}Be- neutrinos observed

NEUTRINO 92, Granada 7-12 June 1992

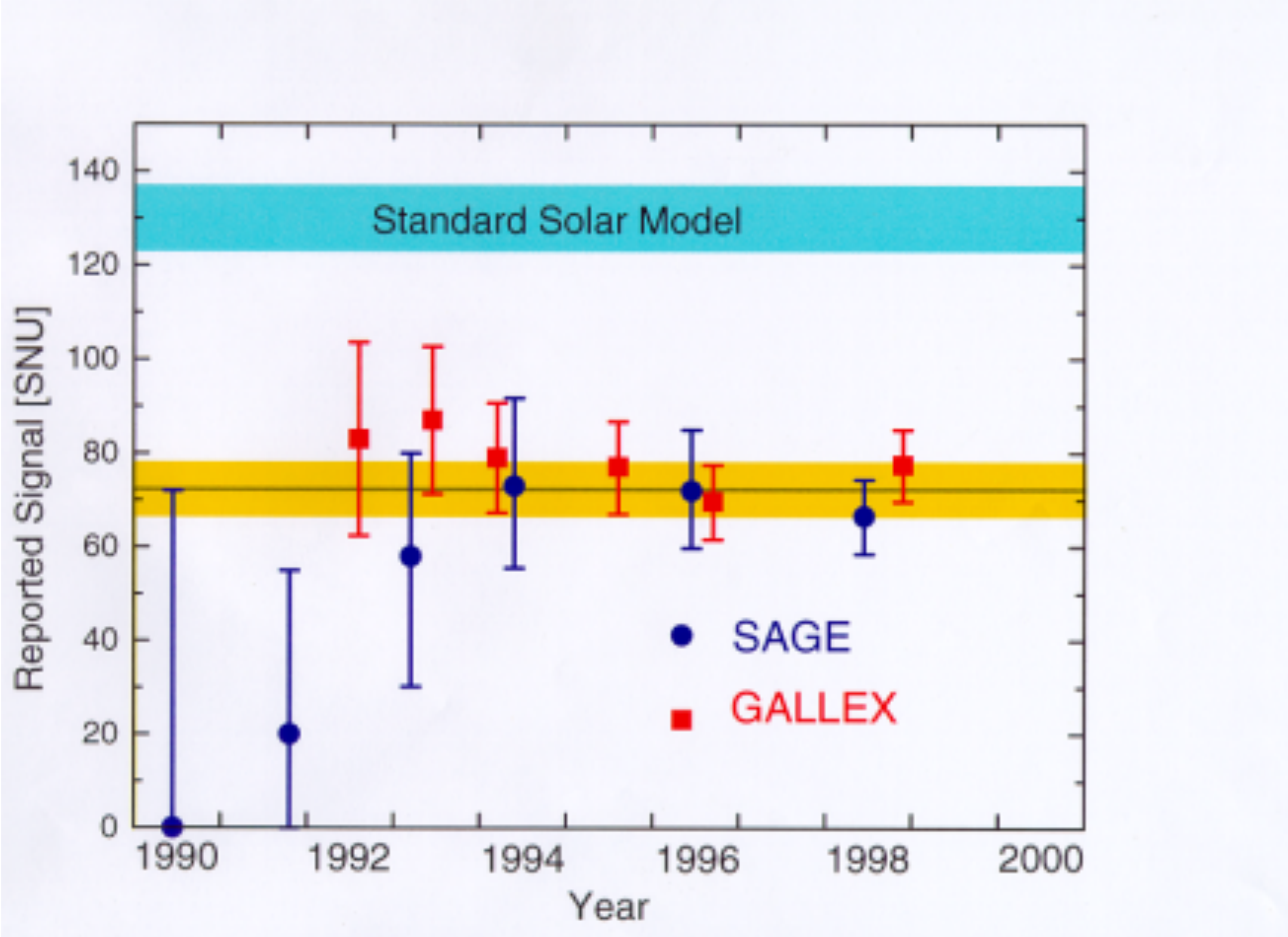


THE $\nu_{\odot}$ PP
FUSION
BOMB

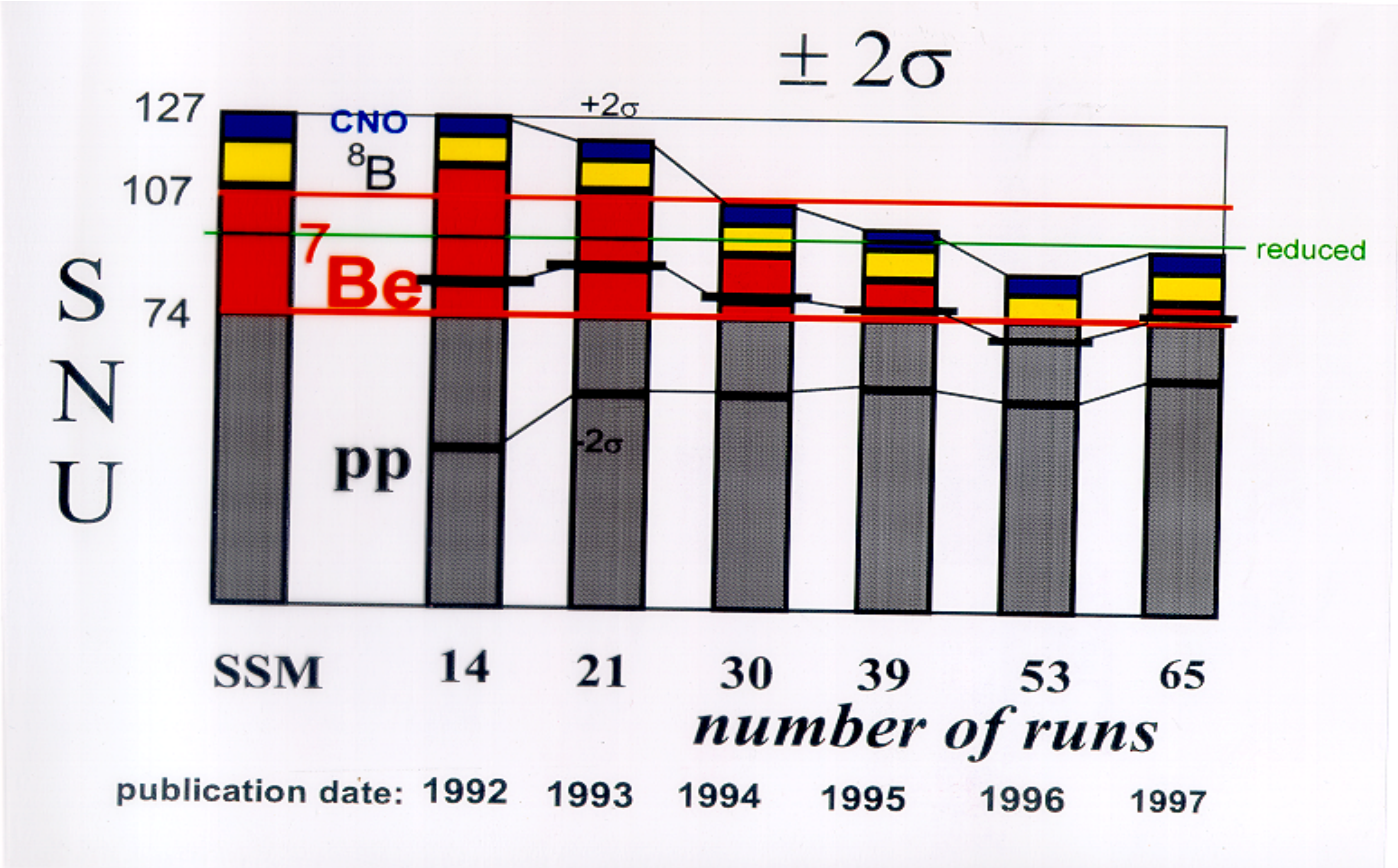
[DETONATED OVER
GRANADA BY
T. KIRSTEN
AT 6:15 p.m., JUNE 8th
1992]

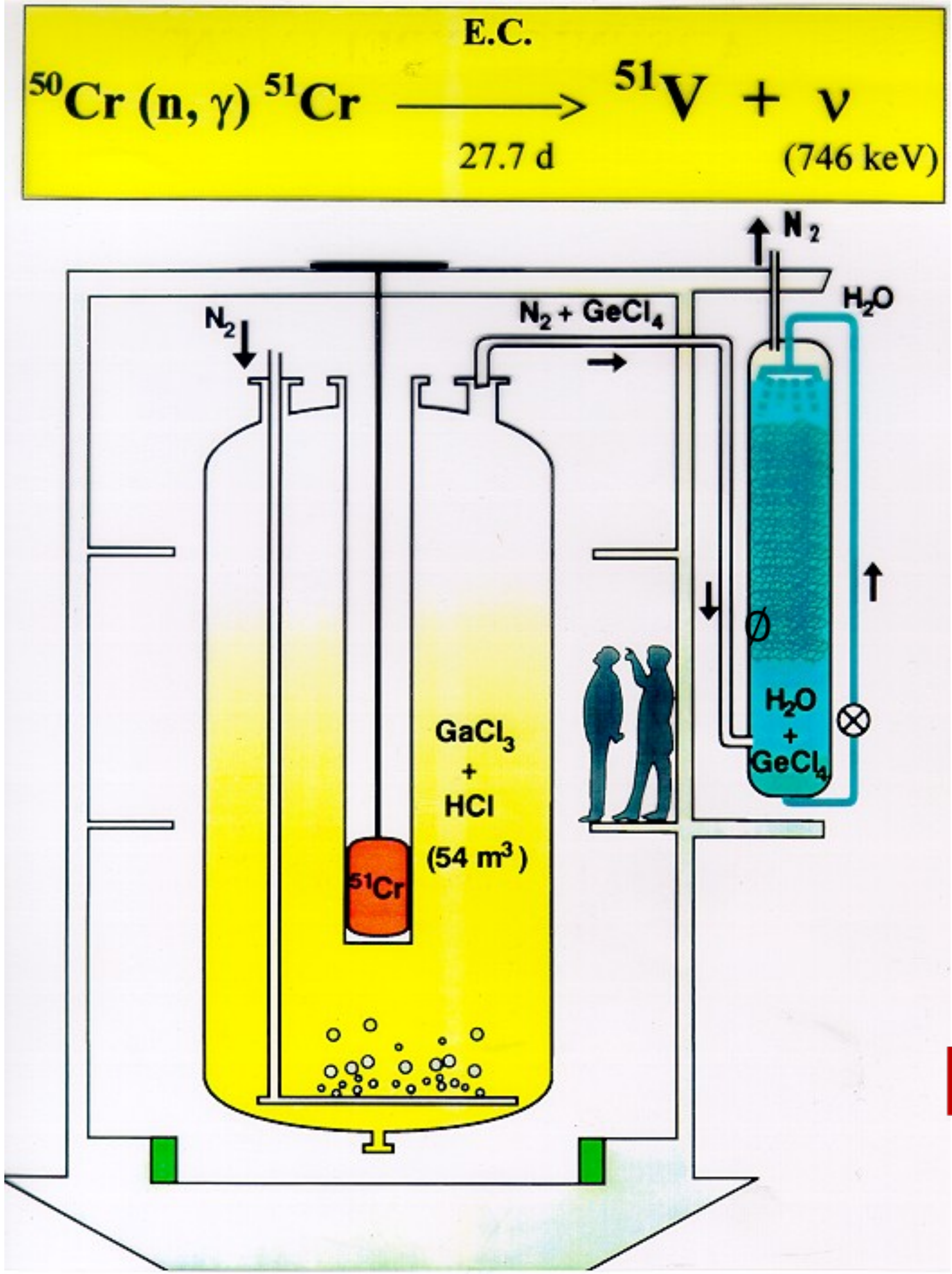
de Rujula
Conference
Summary Talk

Published data 1990-1998



Significance of Deficit in Time





Cr-source experiment

1: 1995 (PLB342) [1994]
2: 1998 (PLB420) [1996]
1+2 PS: 2010 (PLB685)

A(Cr1) = 1.714 ± 0.036 MCI
A(Cr2) = 1.868 ± 0.073 MCI

R(Cr1) = 0.953 ± 0.11
R(Cr2) = 0.812 ± 0.10

$$R_{\emptyset ps} = 0.93 \pm 0.08$$

Arsenic Tests

Repeated tests under variable and purposely unfavorable conditions respective to the:

- **standing time**
- **mixing- and extraction conditions**
- **method and magnitude of carrier addition**

to exclude witholdings (classical or 'hot-atom'-effects)

Method: **Triple-batch comparison,**

≈ 30 000 ^{71}As atoms (half-life 2.72 d)

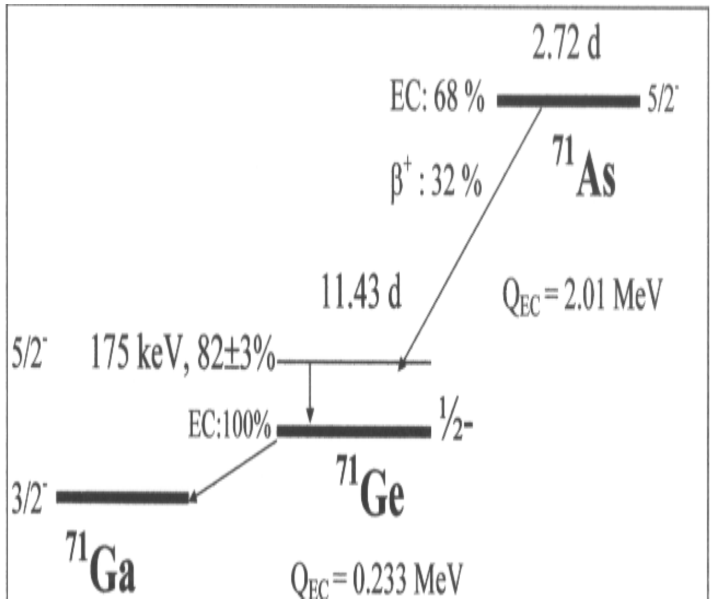
added to:

Tank sample, full GX procedure!

External sample

Calibration sample (γ-spectrom.)

Decay into ^{71}Ge



Result: Recovery **99+ %**

GALLEX final Results 1991-1997

Phys. Letters B 685 (2010) 47-54

GALLEX (65 runs)	**$73.4 \pm^{7.1}_{7.3}$ SNU**

yet, not the end! → GNO =

GALLIUM NEUTRINO OBSERVATORY

START of GNO

After a **complete overhaul** and modernization of the GALLEX detector in 1997/98, the **reshaped collaboration** resumed

pp-neutrino recording in 1998

(after the $^{71}As/^{71}Ge$ activity from the As-Test was completely gone).

GALLEX

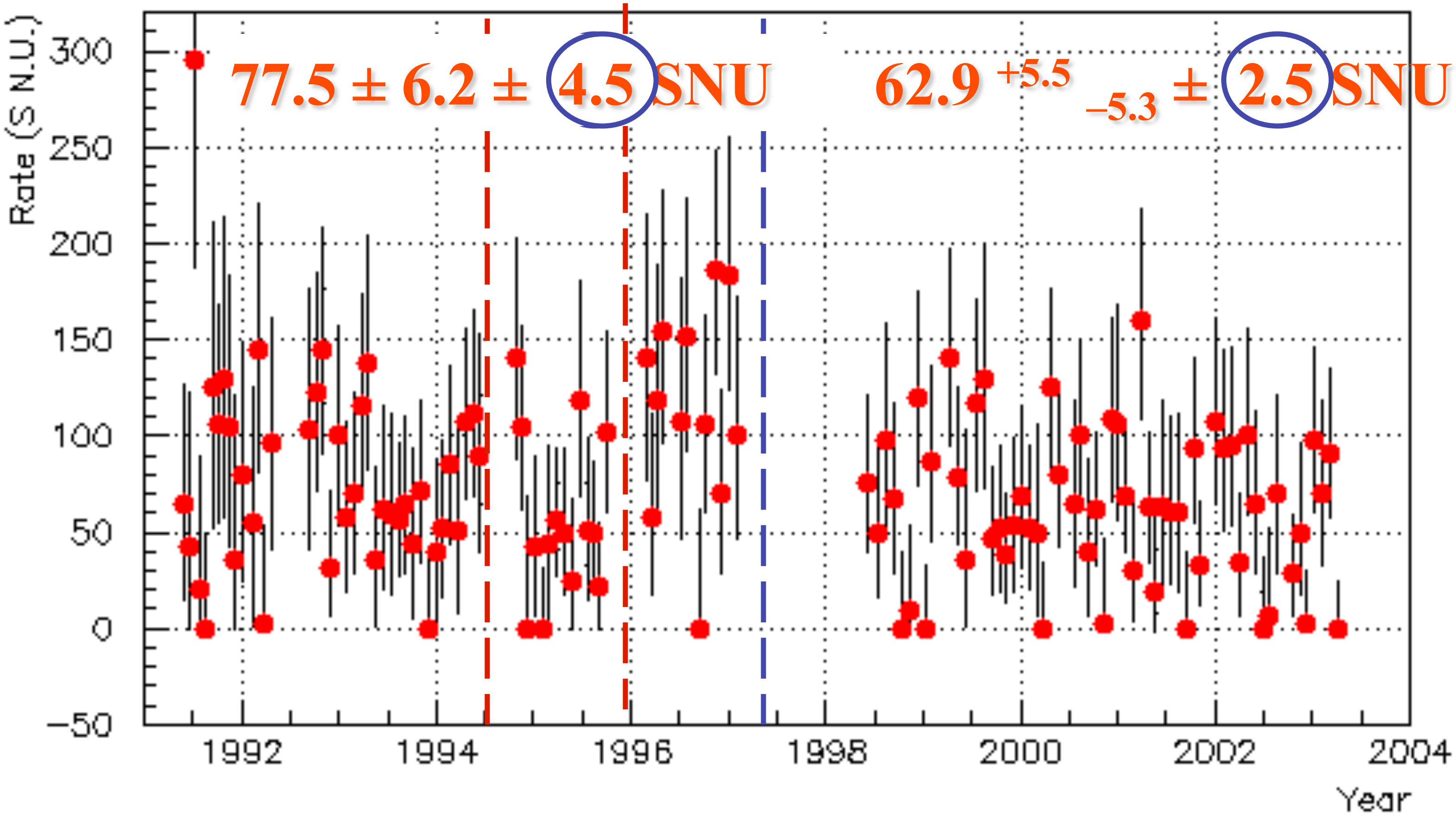
65 Solar runs = 1594 d

23 Blank runs

GNO

58 Solar runs = 1713 d

12 Blank runs



In addition: ^{51}Cr sources, ^{71}As experiments

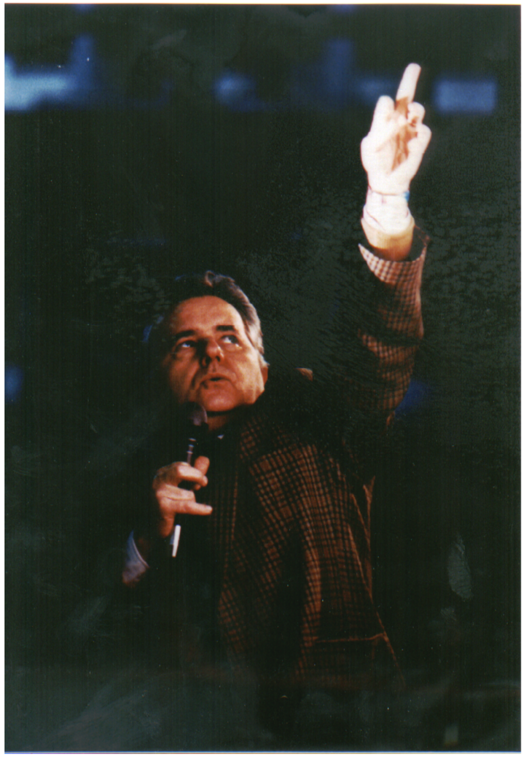
Gallium Result Summary
123 runs

GALLEX + GNO 69.3 ± 5.5 (incl. syst.) 1σ

May 1991 – April 2003

Compare with Solar Model prediction:

128 ± 9 SNU



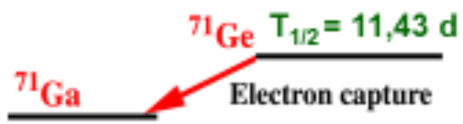
LUCIANO MAIANI **NICOLA CABIBBO** **ENRICO BELLOTTI**

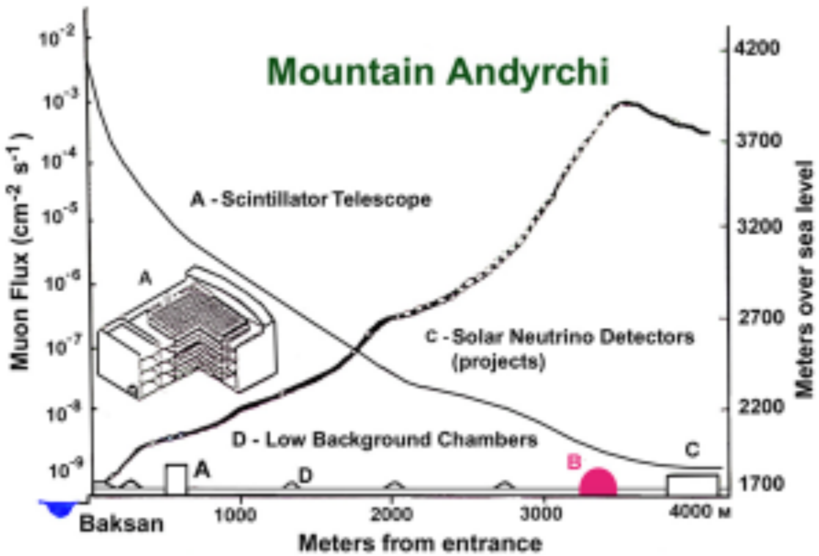
6. SAGE

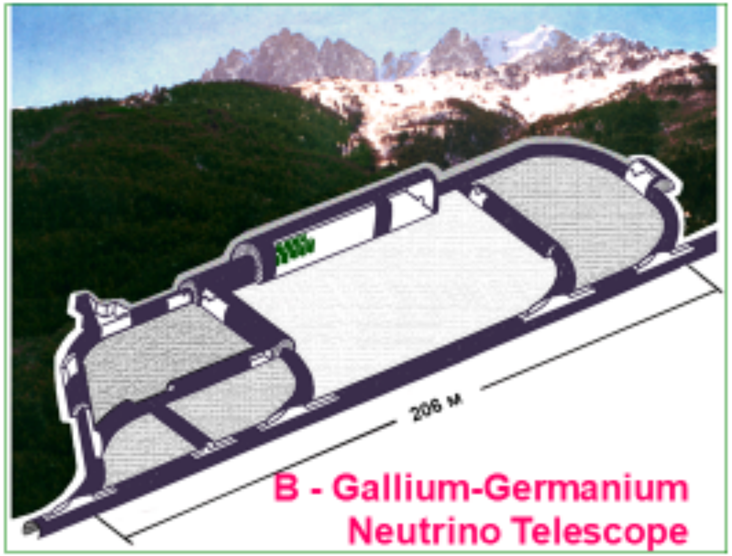
(Soviet American Gallium Experiment)
Baksan Neutrino Observatory, Northern Caucasus,
3.5 km from entrance of horizontal adit,
2100 m depth (4700 m.w.e.)
Data taking: Jan 1990 - till present (2018),
≈50 tons of *metallic* Ga (in multiple reactors).
^{71}Ge atoms are chemically extracted and their decay is counted.
Sensitivity: One ^{71}Ge atom from $5 \cdot 10^{29}$ atoms Ga with efficiency ~90%

From V.Gavrin, adapted by T.K. for: History of the Neutrino, September 5, 2018 Paris

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





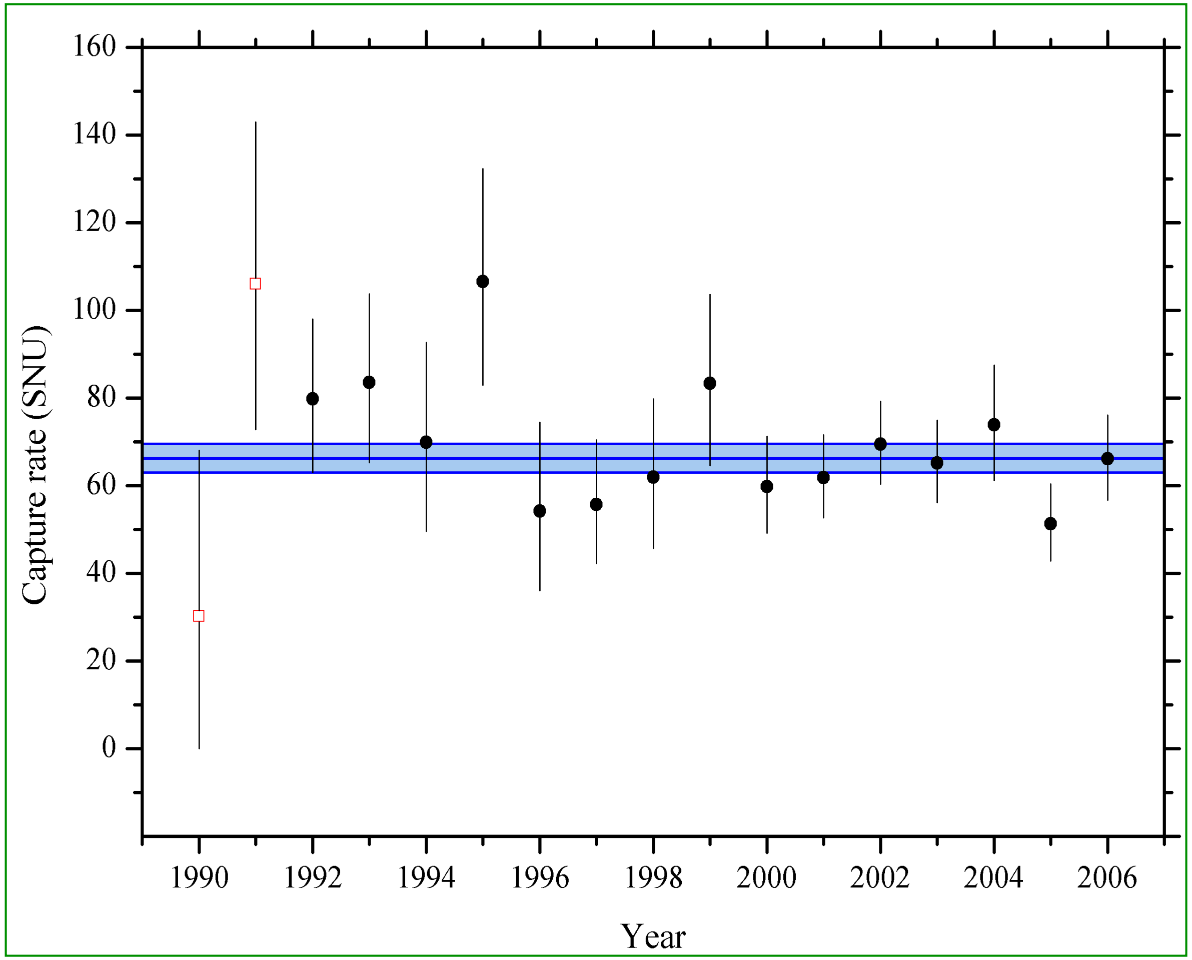


SAGE

Measurement of the solar neutrino capture rate with gallium metal. $^{71}Ga(\nu, e^-)^{71}Ge$, E_{th} = 0.233 keV

17 year period (1990 – 2006): 157 runs

Overall result
64 $^{+24}_{-22}$ SNU

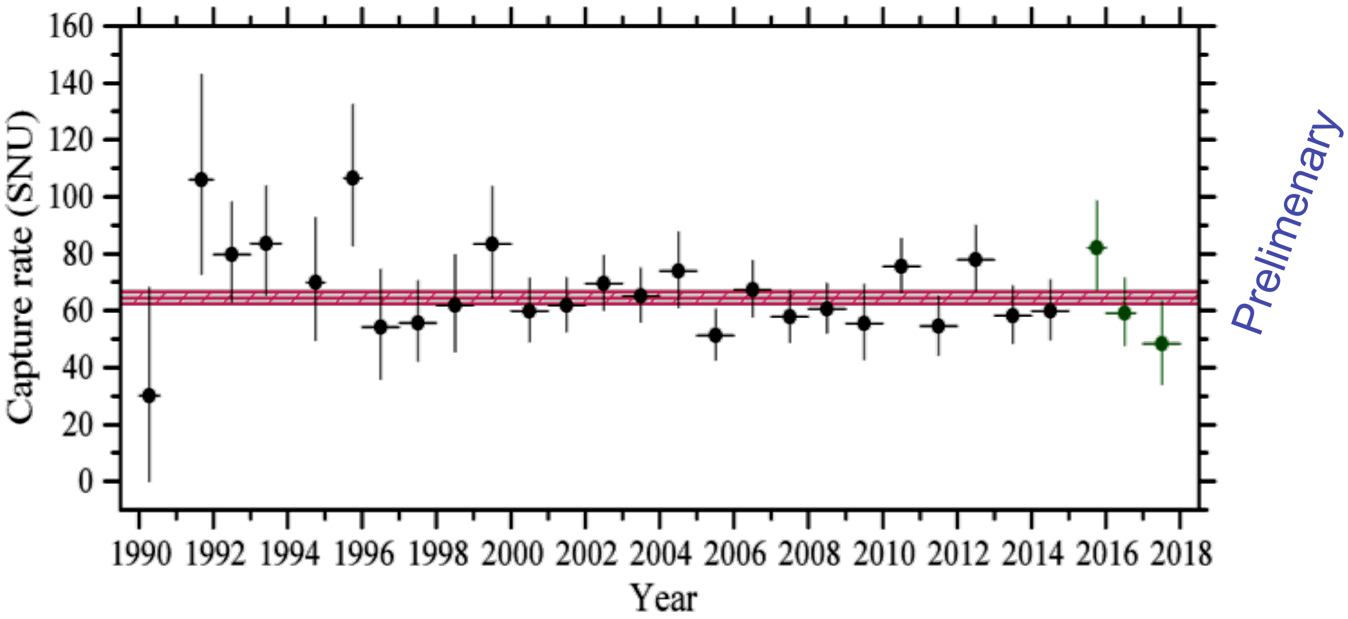


Combined results for each year

SAGE continues regular solar neutrino extractions every four weeks with ~50 t of Ga

1990 – Oct. 2017: 266 runs

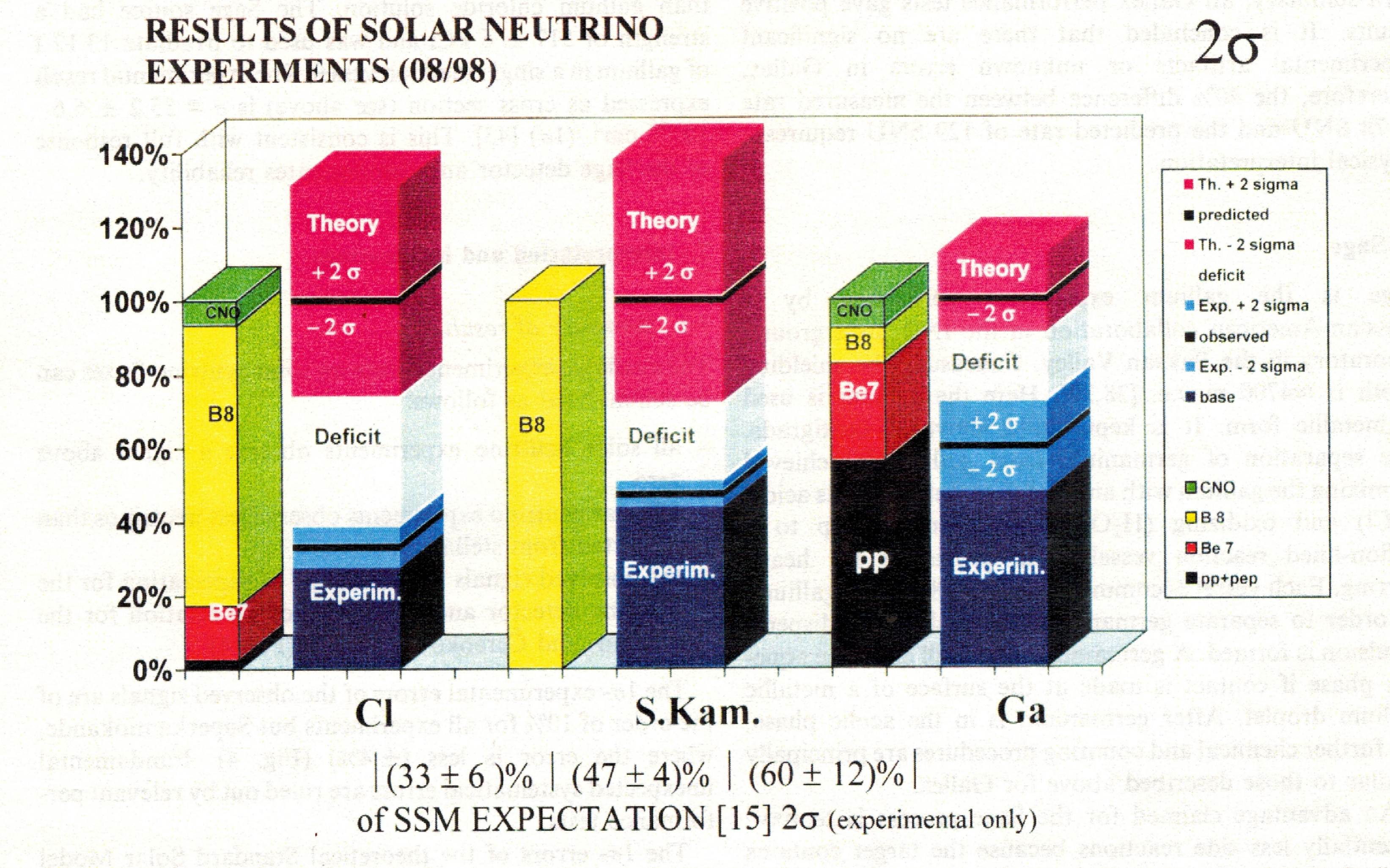
$$64.5\ ^{+2.4}_{-2.3}\,(\mathrm{stat})\ ^{+2.6}_{-2.8}\,(\mathrm{syst})\ \mathrm{SNU}$$



Combined results for each year

7. SYNOPSIS

(as of the end of the former millenium)



Can the astrophysical solution be a viable explanation of the observed ν- flux deficits?

- ► Helioseismology confirms the Standard Solar Model with a high degree of accuracy

► For the same input data, ν-flux predictions of different authors are consistent

► the impact of fine tuning for:

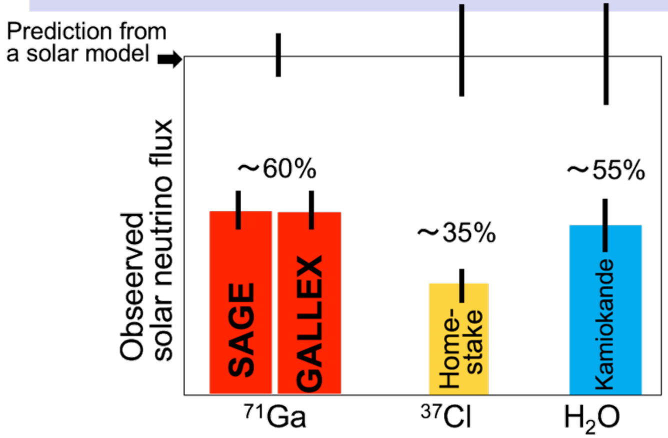
He-diffusion; Z-diffusion, rotational mixing, opacity codes (Z/X, partial ionization, screening-modifications,…) is generally of order ≤ 10% (especially also for ^{7}Be-ν)

► just to lower the central temperature is not sufficient to explain the data

NO ! particle physics solution is required!

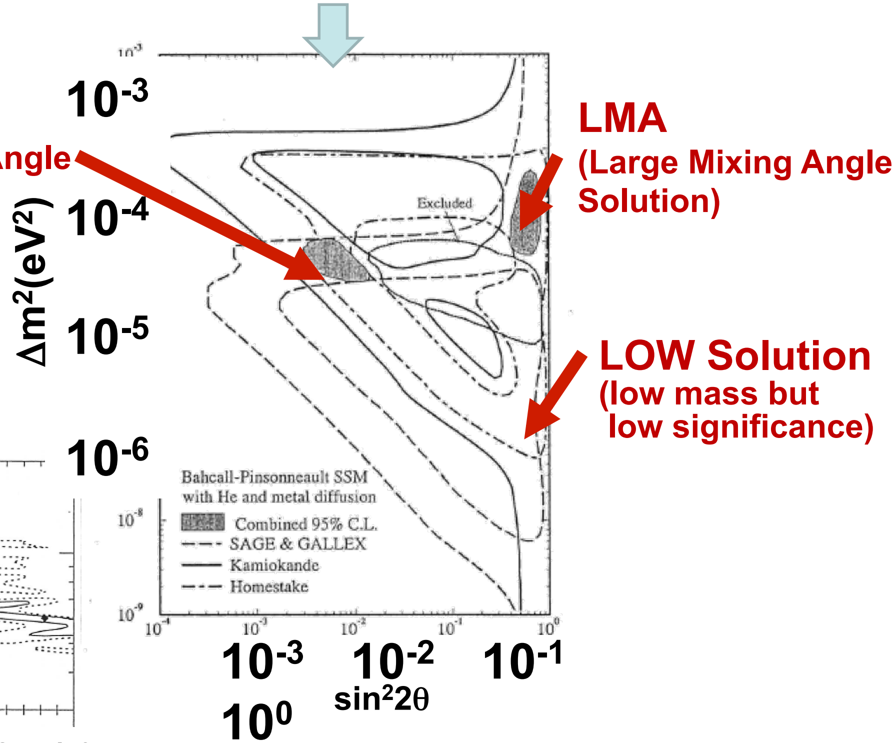
Situation of Solar ν when Super-K started:

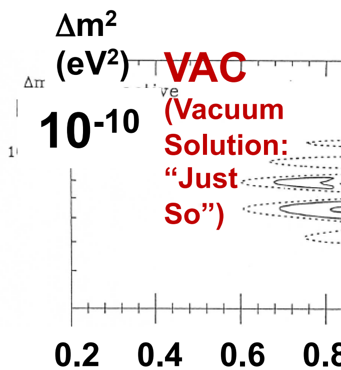
4 solar ν experiments and 4 solutions



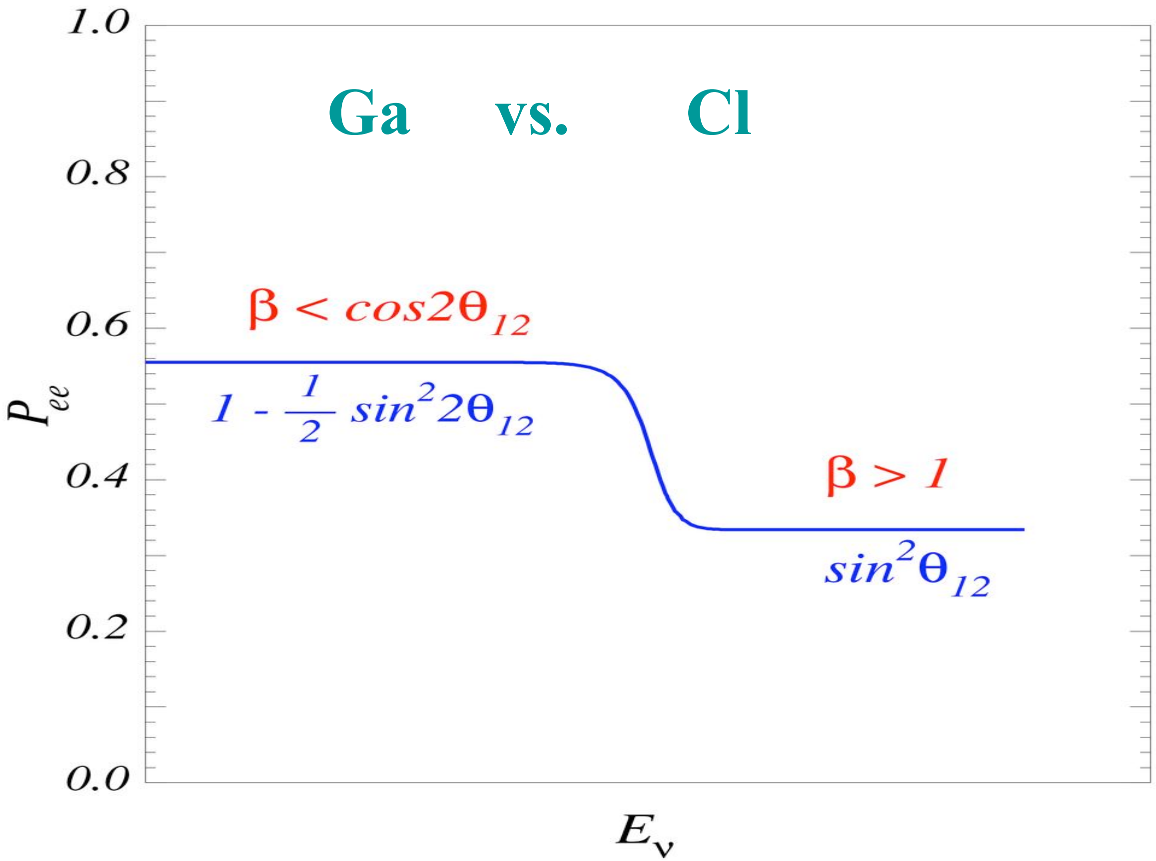
- **4 experiments: HomestakGallium experiments (SAGE and e, Kamiokande and GALLEX) in early '90**
- **All showed deficits of solar neutrinos**

4 solutions based on oscillation hypothesis (using a flux prediction from standard solar models)





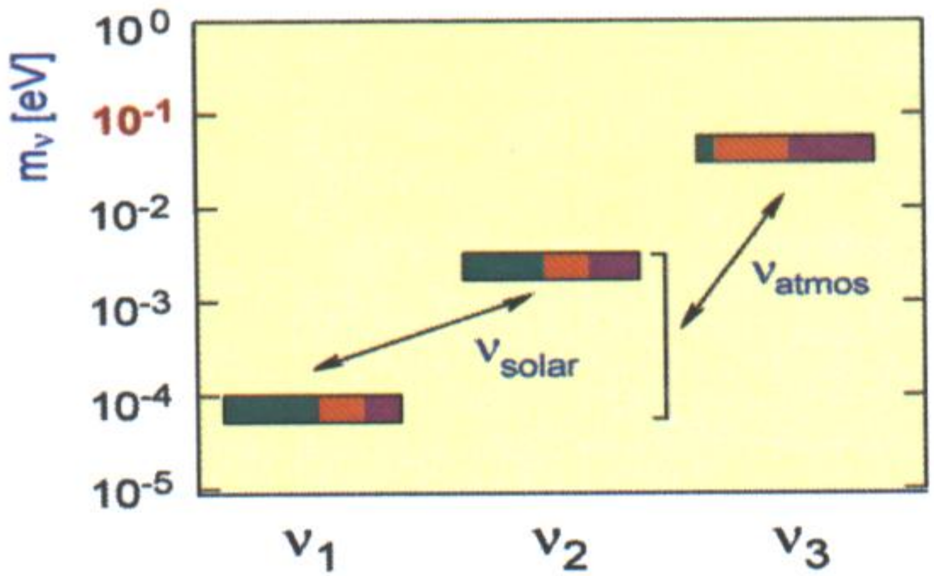
Below ~1-2 MeV, the vacuum oscillation domain takes over from the matter oscillation domain at > 2 MeV



from C. Pena-Garay

CONSEQUENCES

Neutrino-Masses



Solar Neutrinos $\nu_e \leftrightarrow \nu_\mu$
(Gallex, SuperKamiokande, SNO)
Atmospheric Neutrinos
(SuperKamiokande) $\nu_\mu \leftrightarrow \nu_\tau$

- The positively detected pp-neutrinos confirm the fundamentals of stellar structure
- Neutrino-oscillations are responsible for the reduced flux also for the more energetic neutrinos (^{7}Be-, ^{8}B- ν)
- Neutrino masses are $\neq 0$, yet too small to account for the cosmologically „missing mass“

πάντα ῥεῖ

Radiochemical experiments led to

great pathmaking discoveries,

till the turn of the last millenium.

This phase ceased with the advent of

real-time experiments (SK,SNO,Borexino,Kamland...)

that now allowed to observe

multiple parameters synchroneously,

not just reaction rates only.

merci!

SPARES

1. Solar Model + Neutrino Fluxes

☉ SUN:

REAL TIME LOOK INTO THE INTERIOR →

TEST OF STELLAR STRUCTURE AND EVOLUTION

$N_\nu(E)dE = f\,(T(r);\ (\rho);\ composit.)$

ν NEUTRINO:

***IN VACUO:* 150 Mio km (8 min)**

***IN MATTER:*: 700 000 km**

Test of NEUTRINO PROPERTIES (especially : rest mass)

ν_e- DISAPPEARANCE through: flavor changes !?

decay ? …..?

BASIC SOLAR MODEL

(Eddington, Bethe, Vogt, Bahcall, Turck-Chieze, …)

Mass and chemical composition determine unequivocally the structure and evolution of main sequence stars (Vogt‘s law)

	H	**He**	**‚metals’**
initial	**71 %**	**27 %**	**2 %**
now	**34 %**	**64 %**	**2 %**

AGE of the SUN 4.6×10^9 yrs

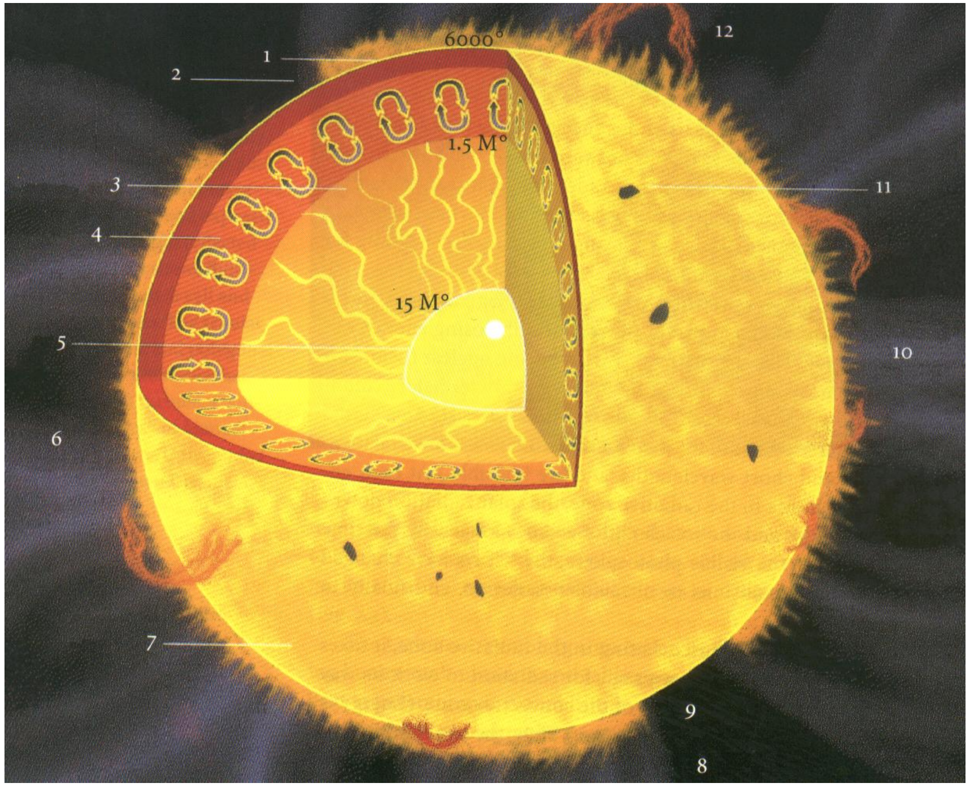
CENTRAL TEMPERATURE 15.6×10^6 °C
CENTRAL DENSITY 148 g/cm^3
CENTRAL PRESSURE 2.3×10^{11} Bar
LUMINOSITY 3.9×10^{23} kW

The solar core, the strongest accessible low energy neutrino source

$$N_\nu(E)dE = f[T(r);\rho(r),composition]$$

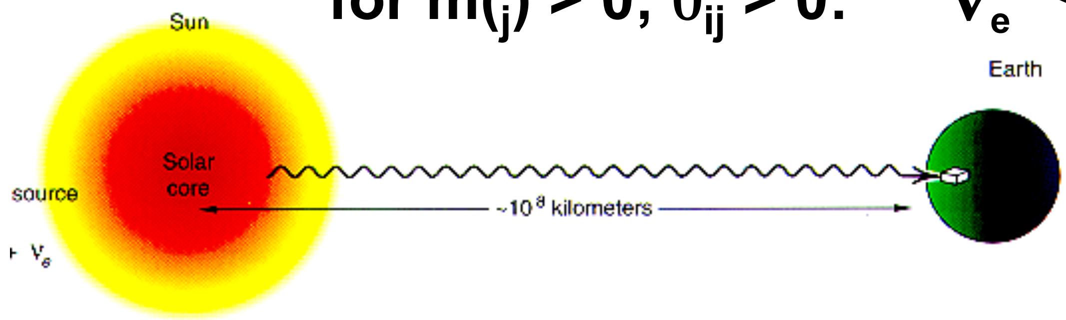
Test of stellar structure and evolution

Real time look into the stellar interior!



Neutrino Flavour Oscillations

for m(j) > 0; θ_{ij} > 0: $\nu_e \leftrightarrow \nu_{\mu(\tau)}$



$$In\quad vacuo:\quad \begin{aligned} \nu_e &= \nu_1 \cos\theta_\nu + \nu_2 \sin\theta_\nu \\ \nu_\mu &= -\nu_1 \sin\theta_\nu + \nu_2 \cos\theta_\nu \end{aligned}$$

$$\Delta m_{12}^2 = \left| m_{\nu_1}^2 - m_{\nu_2}^2 \right|$$

$$Oscillation \quad length \quad L \propto E / \Delta m^2$$

for the distance Sun-Earth, this is sensitive to masses as small as $\Delta m^2 \approx 10^{-11}$ $(eV/c^2)^2$

pp - Neutrinos as Standard Candle to deduce Neutrino Oscillations and Neutrino Mass

Neutrino propagation

– *in vacuo:* 150 Mio km (8 min)

– *in matter:* 700 000 km

ν_e - disappearance due to flavour changes (neutrino oscillations) ? To claim this,

– ***the flux at origin (the solar core) must be well known***

Inverse ß Process

B.Pontecorvo 1946 (Chalk River Report PD-205)

- **"the experimental observation of an inverse beta process produced by neutrinos is not out of the question with the modern experimental facilities"**
- **"The radioactivity of the produced nucleus (in: ν_e+ Z → (Z+1) + $ß^-$) may be looked for as proof of the inverse process"**
- **"The essential point, in this method, is that radioactive atoms produced by an inverse ß-ray process have different chemical properties from the irradiated atoms. Consequently, it may be possible to concentrate the radioactive atoms of known period from a very large irradiated volume"**

B. Pontecorvo 1946 on pre-requisites:

The nucleus produced in inverse ß-transformations must be radioactive with a *period* of at least one day, because of the long time involved in the separation.
The *separation* of the radioactive atoms from the irradiated material must be relatively simple.
The *background* (i.e., the production of element Z+1 by other causes than the inverse ß process) must be as small as possible. The material to be irradiated must not be too *expensive*.

Related road-making of Pontecorvos universal ideas and anticipations

Inverse ß-decay	Chalk River Report PD-205, 1946
Leptonic charge	JINR P-95, Dubna 1957
ν - Oscillations (also ν⇔ν)	Usp.Fiz.Nauk 79,3-21,1963
Double Beta Decay (also $^{130}Te/^{128}Te$)	Phys.Lett. 26B, 630, 1968
Proportional Counting	Helv.Phys.Acta 23, Suppl.3, 97-118, 1950
(also pulse shape analysis)	1968

Conceptional Conditions for Radiochemical Solar Neutrino Experiments

Inverse ß-decay - sensitive only to ν_e - not to $\nu_{\mu,\tau}$

Extremely small production rates →
huge target size (multi tons)
Side reactions (Cosmic radiation, radioactivity) →
underground laboratories, passive and active shielding, ultrapurity of target and auxiliary components
Extreme separation factors, $O(1:10^{30})$ →
purging techniques
Very low background detection of single radioactive atoms
→ proportional counting with pulse shape analysis

3. Homestake Chlorine Experiment

Strictly following Pontecorvos receipt

"The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra Chloride, for a time of the order of one month, and extracting the radioactive Ar^{37} from such volume by boiling. The radioactive argon would be introduced inside a small counter, the counting efficiency is close to 100%, because of the high Auger electron yield".

Early milestones towards Homestake

- 1949 **L.W.Alvarez** describes Cl-detector details and backgrounds (for use near a nuclear reactor!) (UCRL-328
- 1953 **Davis** detects ^{37}Ar in perchlorethylen (C_2Cl_4)
- What is the expected rate from ^{8}B?(Detector size?)
- 1959 **Holmgreen**+Johnston: $\sigma(^{3}He,^{4}He)^{7}Be+\gamma$ is large

  PR113,1556

- 1963 **Mottelson** $^{8}B\text{-}\nu+^{37}Cl \rightarrow ^{37}Ar+e^{-}$ super-allowed analogue state of ^{37}Cl at 5.1 MeV contributes a lot
- 1968 **J.Bahcall** updates rate to 7.5 ± SNU
- Davis measures ≈ **1/3**
- 1969 Gribov+ **Pontecorvo** (PL**B**28,493) : ν_e-ν_μ oscillation

  (τ still unknown) → **1/2**

The Pioneering Davis Chlorine Experiment

WITH REACTOR ANTINEUTRINOS
Savannah River,
4 tons, 1958

^{37}Cl (? ν_e, e^-)^{37}Ar (E_{thr} = 813 keV)

K_{shell} EC τ = 50.5 d

→ ^{37}Cl + 2.82 keV (*Auger* e^-, *X*)

no signal above muonic background!

WITH SOLAR NEUTRINOS
Homestake mine

^{37}Cl (ν_e, e^-)^{37}Ar (E_{thr} = 813 keV)

K_{shell} EC τ = 50.5 d

→ ^{37}Cl + 2.82 keV (*Auger* e^-, *X*)

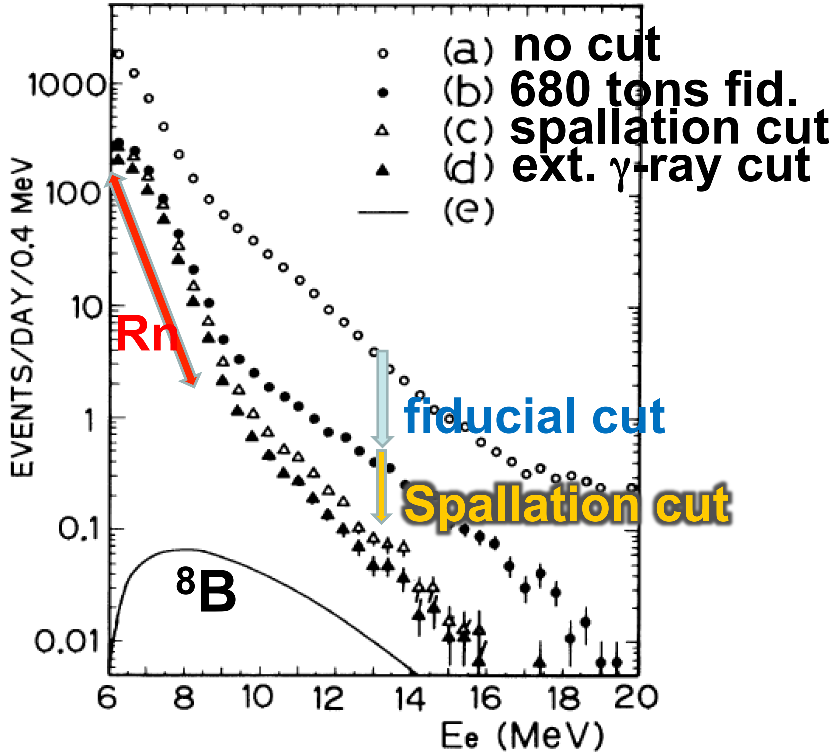
signal ! (even though less than expected, ~1/3)

1983: KM started

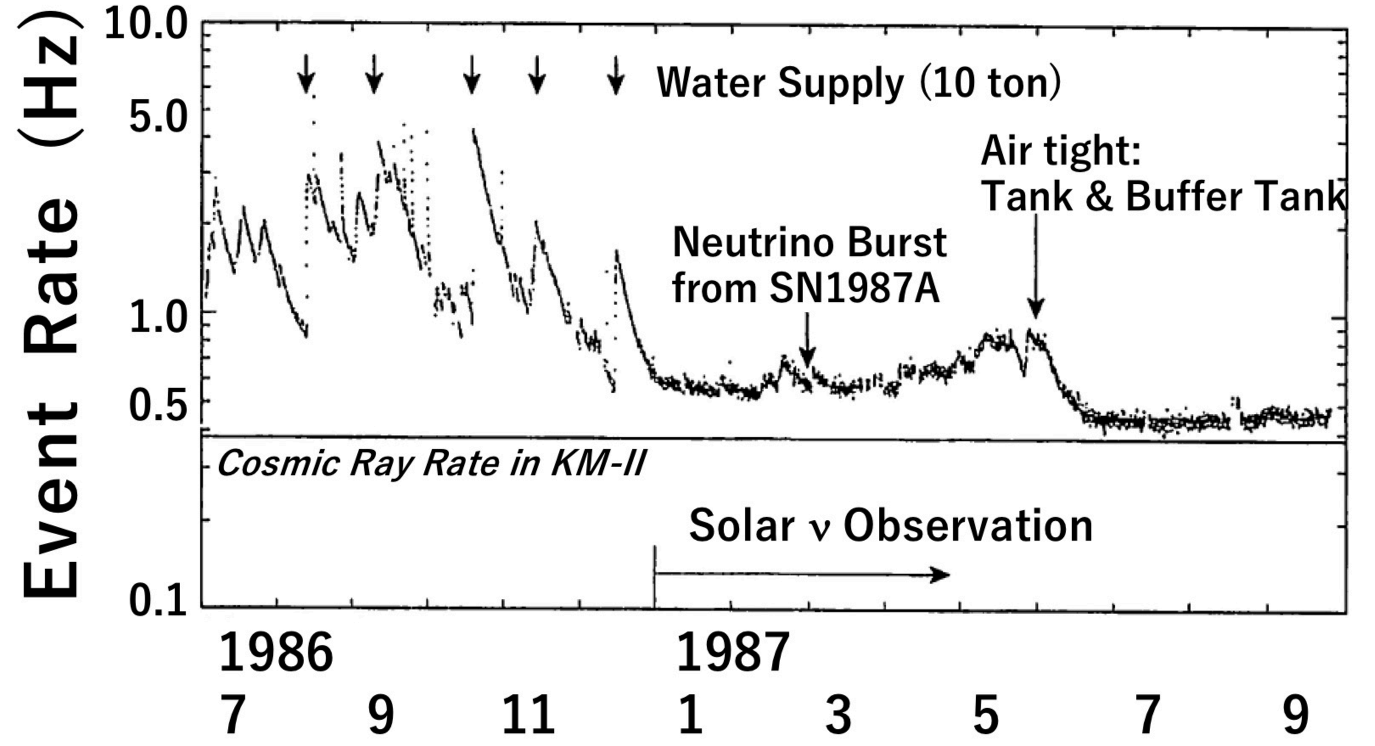
- Immediately after the start, KM observed μ decay electrons down to 15 MeV
- Realized a possibility to lower the threshold down to 10 MeV
- Solar neutrino measurement becomes possible
  - Background must be reduced
    - Spallation, external-γ, Rn
  - Most problem in low energy is Rn:

$^{214}Bi \rightarrow {}^{214}Po + e^- + \bar{\nu}$ $(E^e_{max} = 3.26$ MeV$)$

PRL.1989



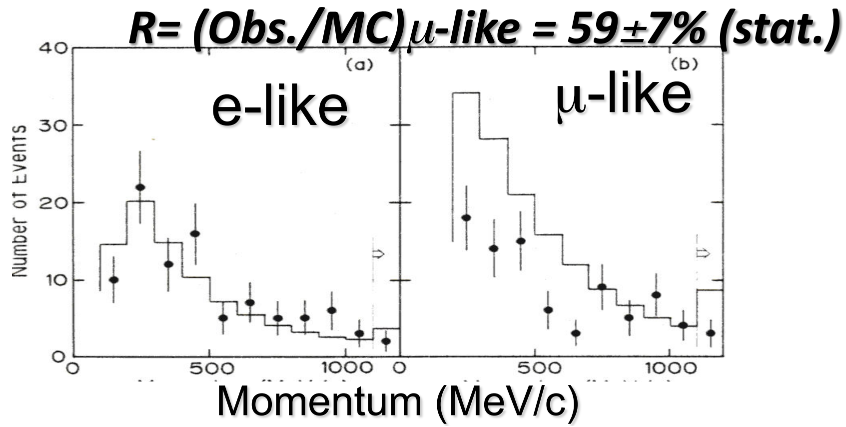
Kamiokande-II

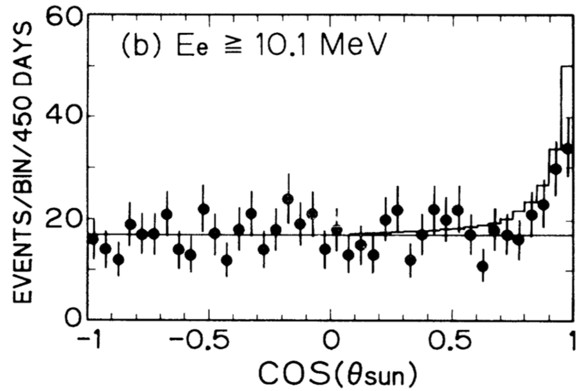


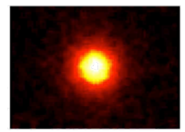
- For the upgrade of Kamiokande detector, Penn Group (Al Mann and his colleagues) joined KM w/timing electronics. KM-II formed
- 1987.1: KM-II started w/ outer layer, new timing elec.
- 1987.2: detection of SN1987A

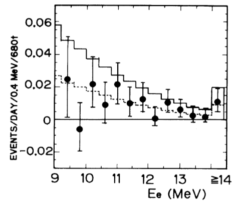
Two Early Hints from KM-II

- **1988: atmospheric neutrino anomaly**
  - Kamiokande Observed fewer μ-like events in atmospheric ν interactions than expected
  - Phys. Lett. B205, 416(1988).
- **1989: solar neutrino detection**
  - KM-II: a second solar neutrino experiment, confirmed the solar neutrino deficits of the Davis's experiment
  - 21years after his first indication
  - Real time measurement w/ energy and direction measurement
  - Phys. Rev. Lett. 63, 16(1989).

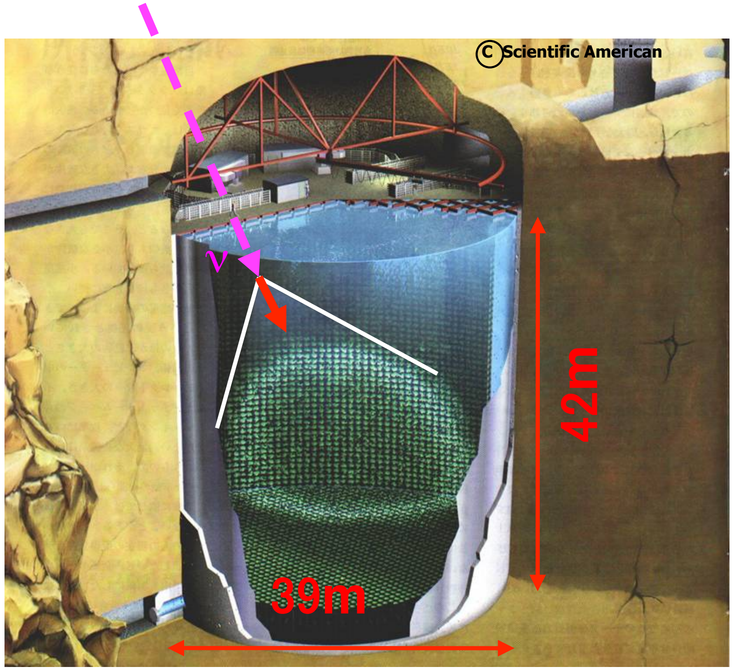








Super-Kamiokande



- **50,000 tons (22,500 ton fid.) Ring Imaging Water Cherenkov Detector**
- **1,000m underground**
- **Inner-Detector (ID)**
  - **11,146 50cmϕ PMTs (40%)**

  Outer-Detector (OD)
  - **1,885 20cmϕ PMTs**

- ~ 130 collaborators from 36 institutions (10 countries) as of 2017
  Japan, US, Poland, Spain, China, Korea, Canada, UK, France, Italy

GALLEX Collaboration

ACTIVE DATA TAKING

- Start of Solar Neutrino Recordings 14.5.1991
- First Data Release (GALLEX I): 8.6.1992
- GALLEX II Recordings: 8/1992 - 6/1994
- 1st ^{51}Cr Source Experiment 6/1994 - 10/1994
- GALLEX III Recordings: 10/1994 - 9/1995
  - CLAIM FOR MASSIVE NEUTRINOS
- 2nd ^{51}Cr Source Experiment 10/1995 - 2/1996
- GALLEX IV Recordings: 2/1996 – 23.1.1997
- ^{71}As-Test of the Detector: 2/1997 - 4/1997
- GNO Data Taking: 5/1998 – 9.4.2003

GALLEX

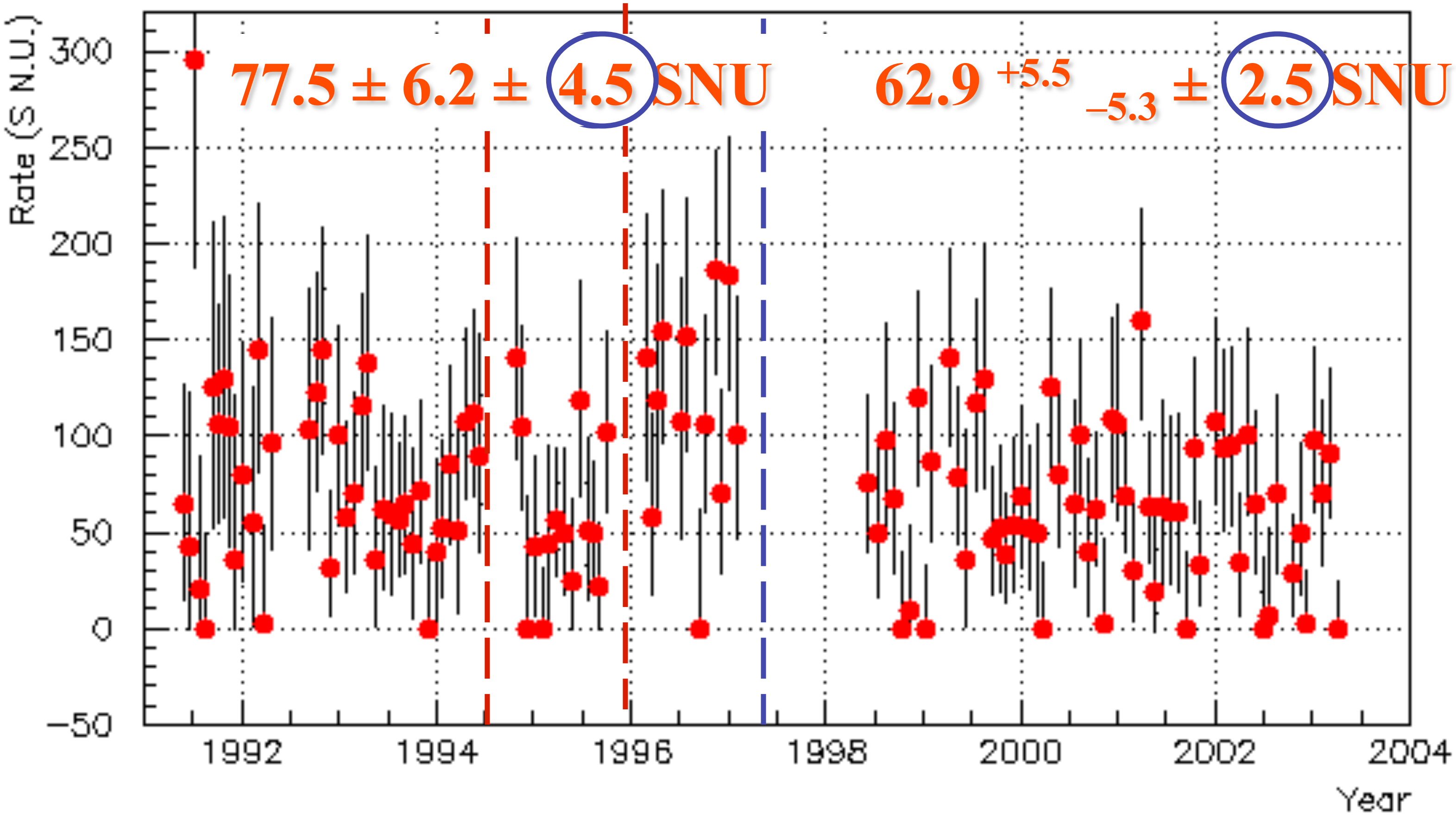
65 Solar runs = 1594 d

23 Blank runs

GNO

58 Solar runs = 1713 d

12 Blank runs



In addition: ^{51}Cr sources, ^{71}As experiments

3 / 1996 GNO Proposal submitted to INFN

Motivations

- **continuous monitoring of the Sun after completion of GALLEX in 1997**
- **maintain possibility for a 100 ton experiment** (Ga from GNO and SAGE combined) **for statistical error reduction**
- **option of additional neutrino source calibrations for systematical error reduction**
- **20.12.1996**

INFN - approval by providing the $$$

required to keep the Ga beyond 1997

- Dip. Di Fisica dell'Università di Milano "La Bicocca" e INFN sez. **Milano**
- INFN Laboratori Nazionali del **Gran Sasso**
- Dip. Di Fisica dell'Università di Roma "Tor Vergata" e INFN sez. **Roma II**
- Dip. Di Ingegneria Chimica e dei Materiali Università dell'**Aquila**
- Max Planck Institut fur Kernphysik – **Heidelberg**
- Physik Dep. E15 – Technische Universitaet – **Muenchen**

Latest Update

F.Kaether, W.Hampel, G.Heusser, J.Kiko, T.Kirsten, PLB 685(2010) 47-50

Results of a recent complete re-analysis of the Gallex+GNO data

(using ~10^5 Ge-decays per counter) not allowed before completion of the low rate measurment phase (solar runs)

- Improved Rn-cut efficiency (multi-year low-rate
- Counter efficiency error reduction after full calibration experiment)
- full PSA instead of RTA

Also for Cr-source data

-Counter efficiency error reduction after full calibration (as above)

- solar subtraction to include also GNO data

GALLEX	$77.5 \pm ^{7.5}_{7.8}$ SNU
re-evaluated	$73.4 \pm ^{7.1}_{7.3}$ SNU
GNO (unchanged)	$62.9 \pm ^{6.0}_{5.9}$ SNU
GALLEX+GNO	69.3 ± 5.5 SNU
re-evaluated	67.6 ± 5.1 SNU

The End

(Gallium was sold in April 2007 to
Recapture Metals Inc., Ontario, Canada)

April 6, 2005 : *GNO17*, the last regular (semi-annual) GNO meeting was held in Assergi

Febr 28, 2006: *Final Celebration Ceremony* for GALLEX/GNO at Gran Sasso, ending a successful fifteen year period that started with the Inauguration Ceremony on November 30, 1990

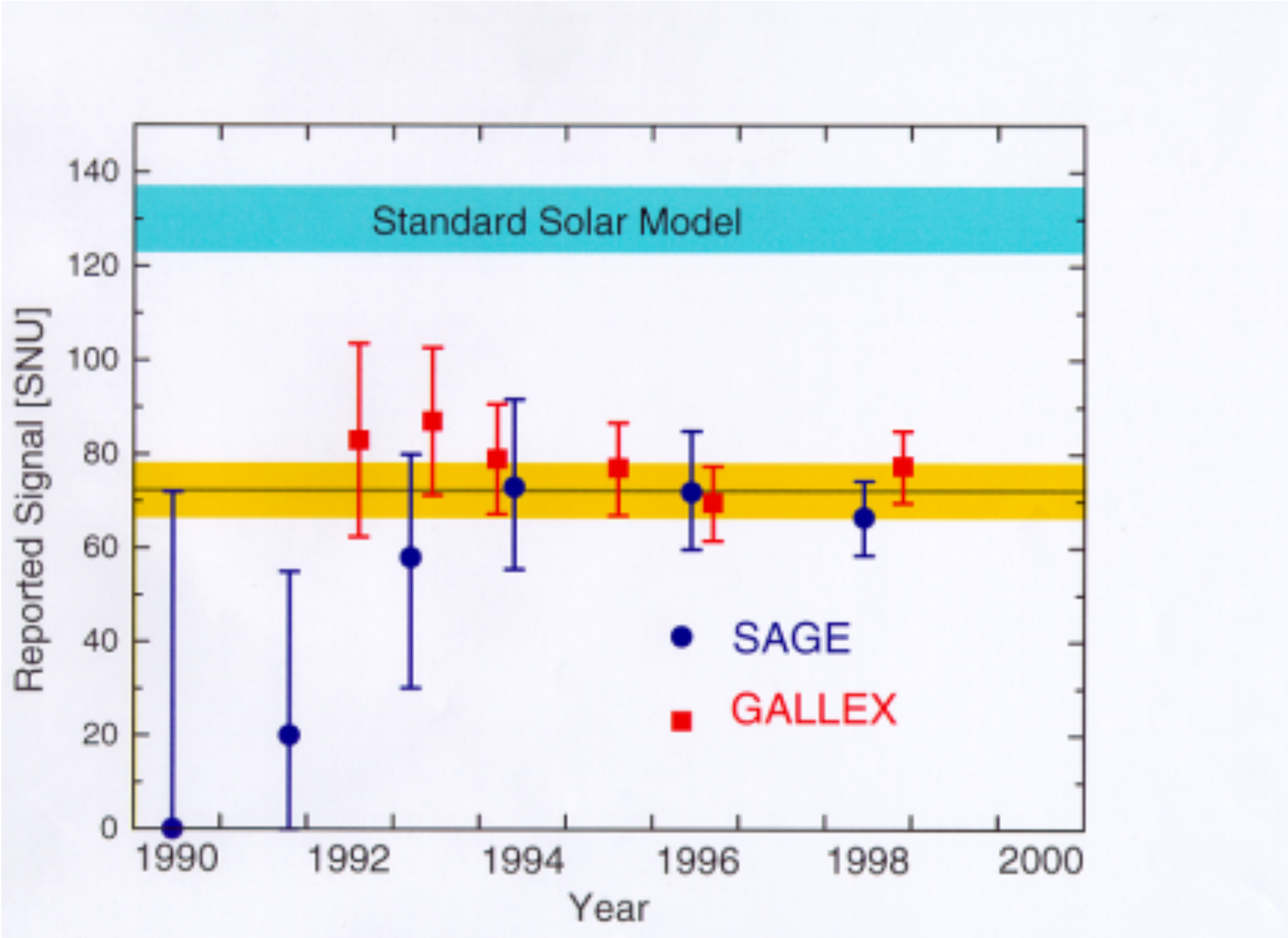
CREDITS

- **INFN** *Nicola Cabibbo, Luciano Maiani,…*
- **LNGS** **still unique facility worldwide**
  Enrico Bellotti,…
- **MPG**
- **KRUPP Foundation**
- **CNRS**
- **Smoothly functioning international collaboration with wonderful colleagues**

Reference for more internal details:

- Radiochemical Solar Neutrino Experiments:
  Door opener for modern Astroparticle Physics
  Il Nuovo Saggiatore, Percorsi, Vol.31/ No1-2/ p.46-58/ anno2015

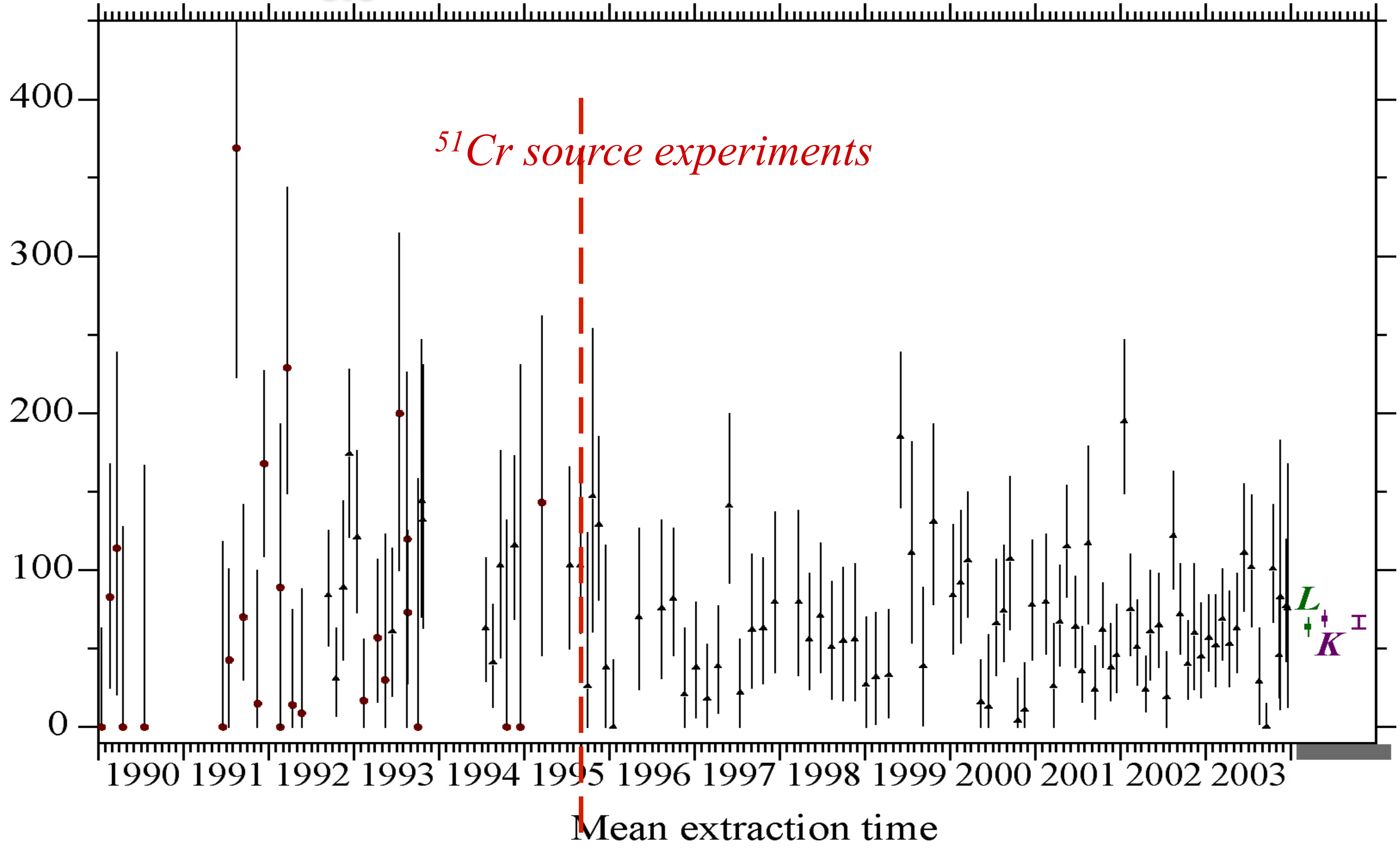
Published data 1990-1998



SAGE January 1990 – December 2003

14 years – 121 runs

66.9 $^{+5.3}_{-5.0}$ SNU



From V.N.Gavrin, adapted by T.K. for: History of the Neutrino,September 5, 2018 Paris

SAGE & GALLEX neutrino source experiments

Neutrino sources:

^{51}Cr: 747 keV (81.6%), 427 keV (9.0%), 752 keV (8.5%), 432 keV (0.9%)

^{37}Ar: 811 keV (90.2%), 813 keV (9.8%)

GALLEX (6/1994+9/1995)

$A(Cr_1) = 1.714 \pm 0.036$ MCI

$A(Cr_2) = 1.868 \pm 0.073$ MCI

SAGE (1996+2004)

$A(Cr) = 0.517 \pm 0.006$ MCI

$A(Ar) = 0.409 \pm 0.002$ MCI

Results vs. Expectation (based on Bahcall 1997)

$R(Cr_1) = 0.953 \pm 0.11$

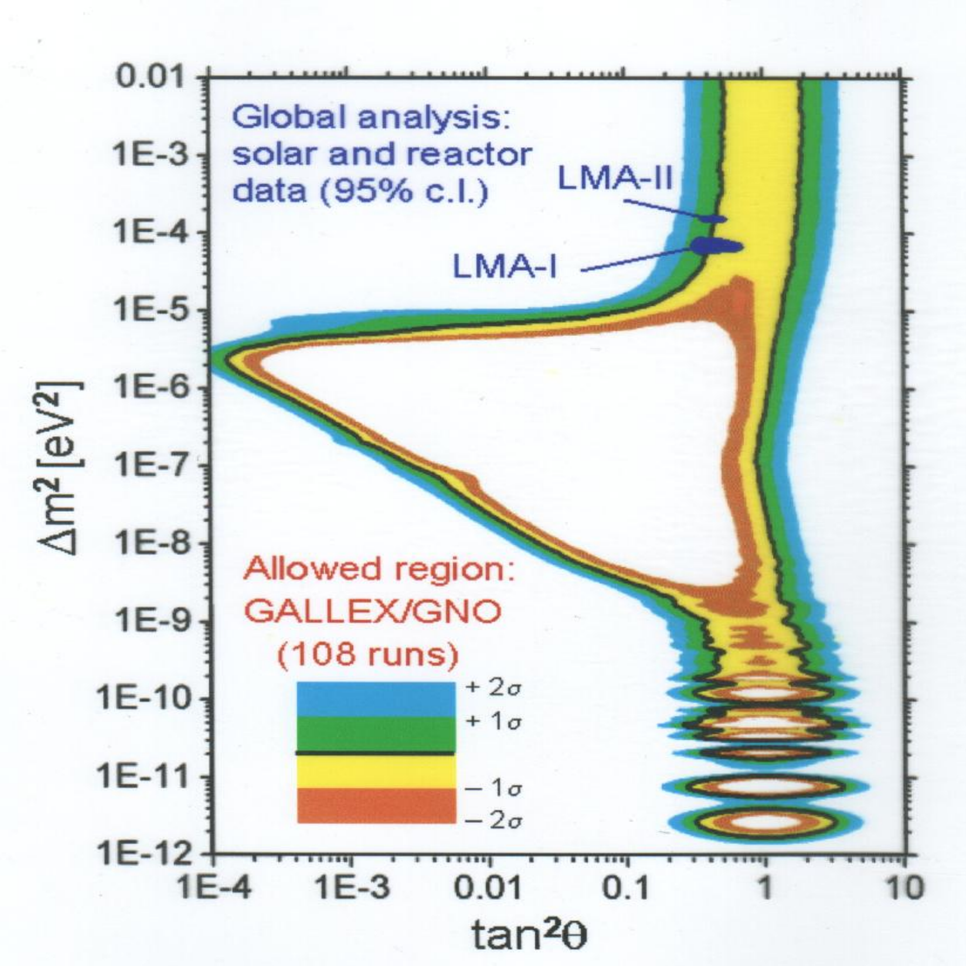
$R(Cr_2) = 0.812 \pm 0.10$

$R(Cr_s) = 0.95 + 0.12$

$R(Ar) = 0.791 \pm 0.084$

Till Kirsten, MPIK Heidelberg, History of the Neutrino, September 5, 2018 Paris
(Sage data from V.N.Gavrin, as quoted on top)

Mass mixing plot for Gallex/GNO



Oscillation parameters

If the LMA(MSW) solution is the correct explanation of the SNO/SK data, then vacuum oscillations must dominate below 1 MeV and the mixing angle is estimated as

$\theta = 32 \pm 1.6$ degrees (B-PG04)

From our data we extract the suppression factor P for sub-MeV pp- and ^{7}Be neutrinos (after a small correction for the minor ^{8}B contribution from the known ^{8}B-flux data of SNO/SK) as

$$P = 1 - 0.5 \sin^2(2\theta) = 0.556 \pm 0.071$$

Hence, $\theta = 35.2^{+9.8}_{-5.4}$ **degrees**

THIS AGREEMENT IMPLIES THE EXPERIMENTAL VERIFICATION OF THE SOLAR MODEL AND OF THE NEUTRINO OSCILLATION MECHANISMNS at *ENERGIES THAT ARE OTHERWISE INACCESSIBLE*