BRUNO PONTECORVO´S LEGACY:
RADIOCHEMICAL SOLAR NEUTRINO DETECTION AND NEUTRINO OSCILLATIONS

I. INVERSE BETA DECAY

II. SOLAR NEUTRINOS

III. ν-OSCILLATIONS

Selinunte, 11/1989

Recollections, ≈ 1968 - 2005

I. INVERSE BETA DECAY

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: $\nu_e + Z \rightarrow (Z+1) + \beta^-$) 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 prerequisites:

"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."

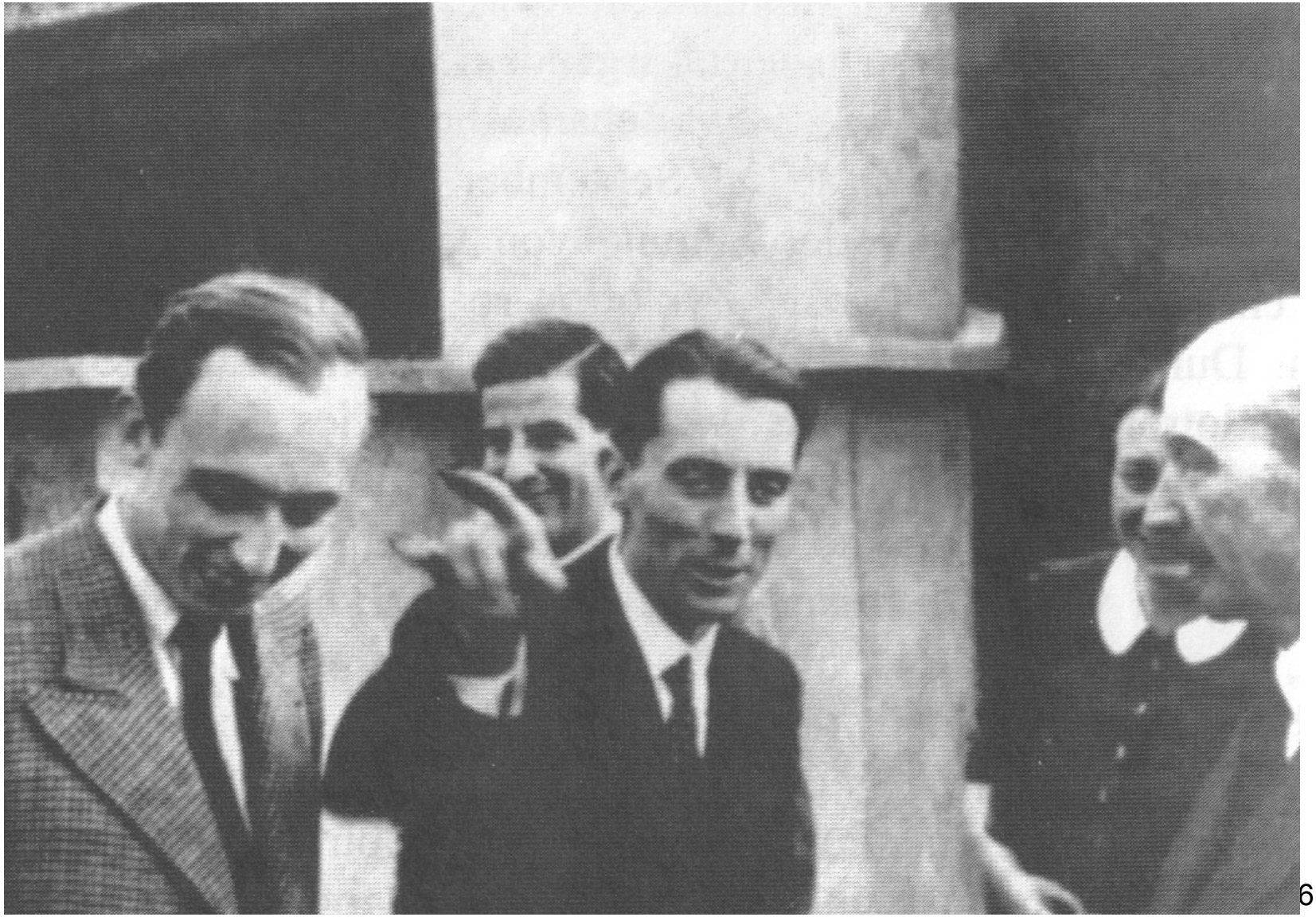
"The material to be irradiated must not be too expensive."

Chlorine

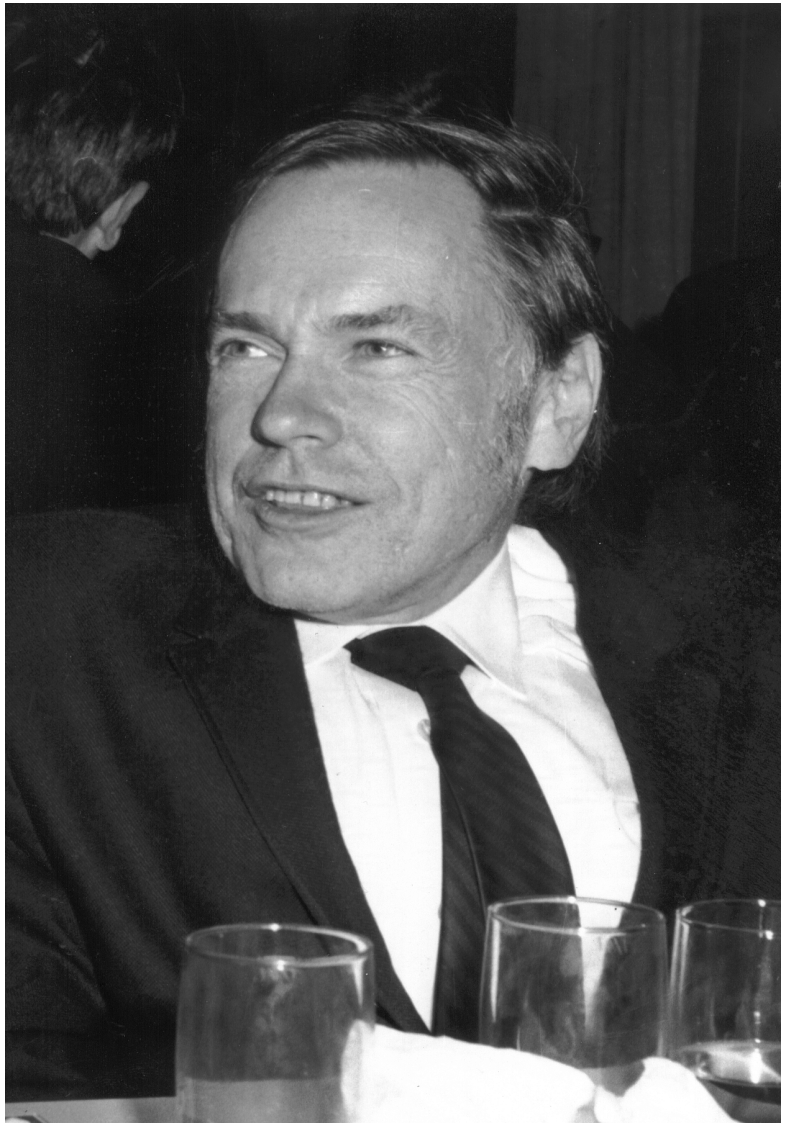
"The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra Chloride , for a time of the order of one month, and extracting the radioactive Ar^{37} from such volume by boiling. The radioactive argon would be introduced inside a small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

Wolfgang Gentner

Gentner, Pontecorvo, Joliot, Bothe



Oliver Schaeffer



(from 1966) learning at Brookhaven:

LOW-LEVEL-COUNTING:

^{3}H, ^{22}Na, ^{26}Al, ^{36}Cl, ^{37}Ar,^{39}Ar, ^{53}Mn…

II. SOLAR NEUTRINOS

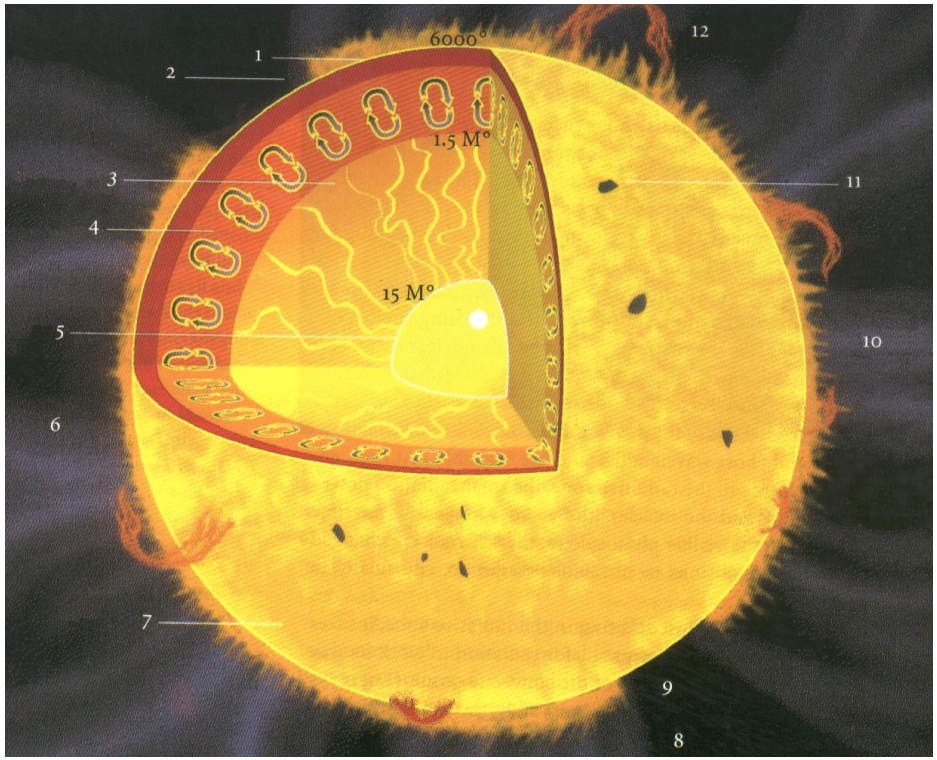
Ray Davis

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!



SOLAR MODEL (Bahcall, others..)

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

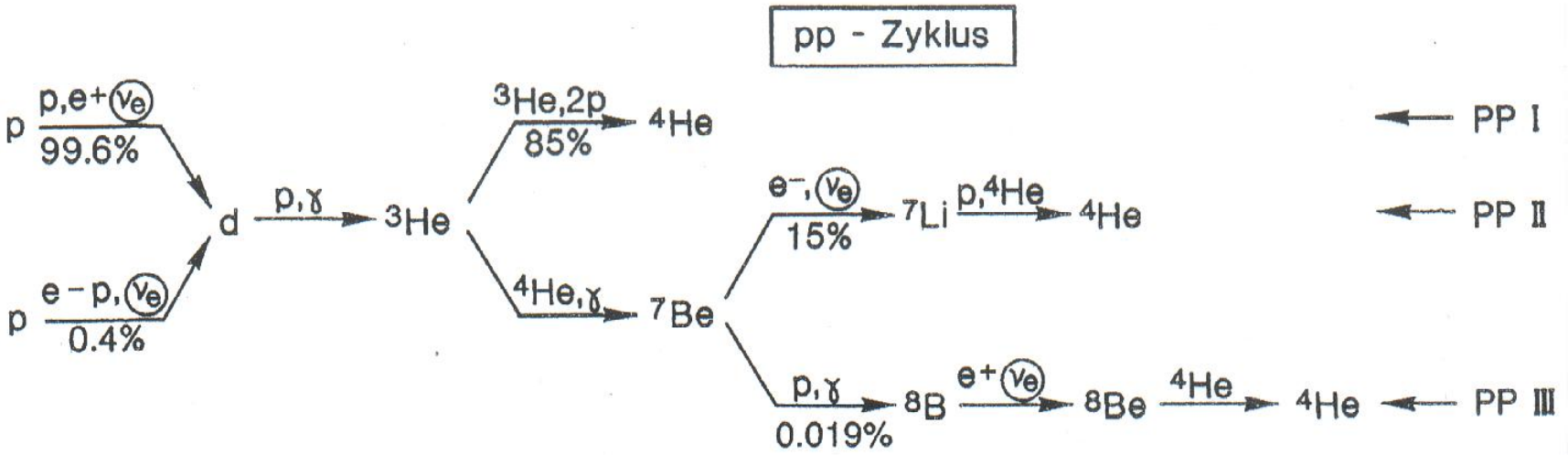
CENTRAL DENSITY 148 g/cm^3

CENTRAL PRESSURE 2.3×10^{11} Bar

LUMINOSITY 3.9×10^{23} kW

For the SUN, the pp-cycle dominates

$$4\,H^{+} + 2e^{-} \rightarrow {}^{4}He^{++} + 2\,\nu_e + 26.73\ MeV$$
$$< E(2\nu_e) > = 0.59\ MeV$$

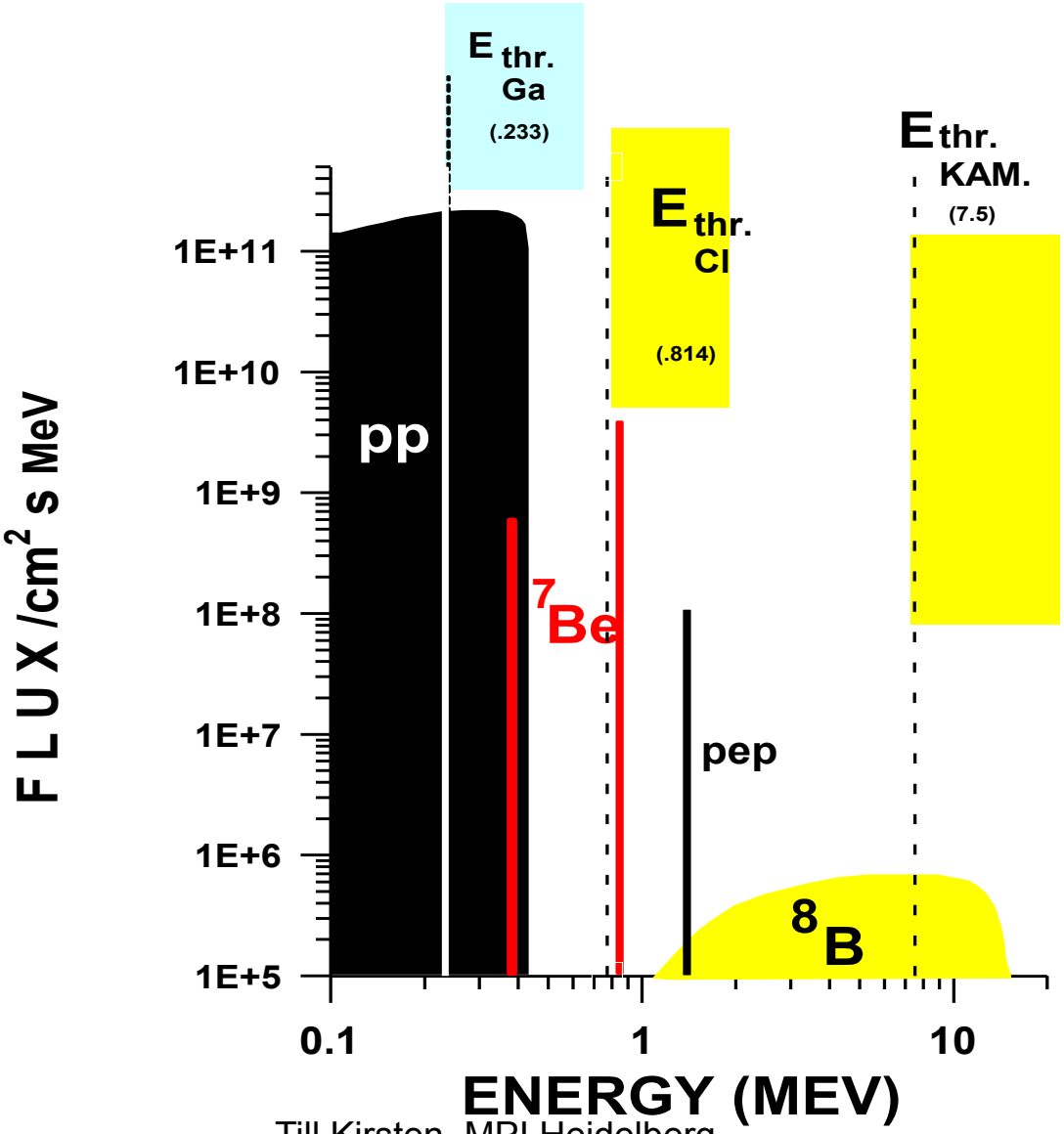


EXPECTED NEUTRINO FLUXES

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

pp - ν :		60 billions /cm^2,s	~ T_c^{-1}
^{7}Be - ν :	~	5 billions /cm^2,s	~ T_c^{8}
^{8}B - ν :	~	5 millions /cm^2,s	~ T_c^{18}

SOLAR NEUTRINO SPECTRUM



The Pioneering Davis Chlorine Experiment

WITH REACTOR ANTINEUTRINOS
Savannah River, 4 tons, 1958

$^{37}Cl\ (\bar{\nu}_e, e^-)^{37}Ar$ $(E_{thr} = 813\ keV)$

K_{shell} **EC** $\tau = 50.5$ d

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

no signal above muonic background!

WITH SOLAR NEUTRINOS
Homestake mine

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

K_{shell} **EC** $\tau = 50.5$ d

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

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

Results of The Homestake Experiment

^{37}Cl (ν_e, e^-) ^{37}Ar (E_{thr} = 814 keV)

K_{shell} EC τ = **50.5** d

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

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 .

What caused the "Solar Neutrino Problem" ?

Astrophysical Solution: **SOLAR MODEL**
Particle Physics Solution: **ν - OSCILLATIONS**
Decision: measure **sub-MeV Neutrinos!**

The pp-neutrino flux is directly coupled to the solar luminosity. It is a fundamental astrophysical parameter.

98 % of all solar neutrinos are sub-MeV
($\Phi_{^7Be} \sim 7$ % , $\Phi_{pp} \sim 91$ %).

GALLEX / GNO

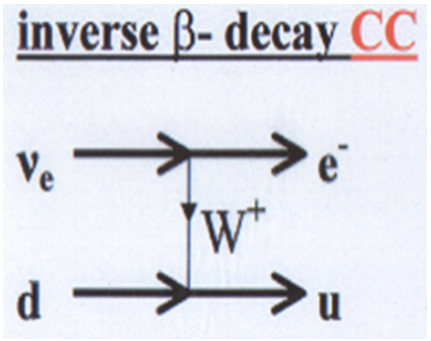
Radiochemical Method (product accumulation)

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

$T_{1/2} = 11.4$ d

Low threshold! (0.233 MeV)

Implies a serious challenge concerning backgrounds



Nicola Cabibbo

Enrico Bellotti

Rudolf Mößbauer

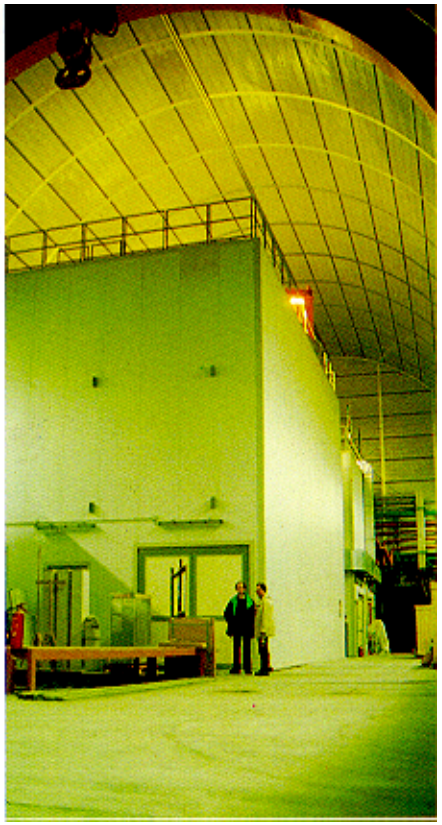
The GALLEX Collaboration

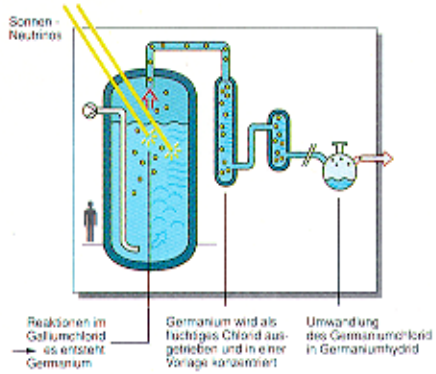
GALLEX COMPONENTS

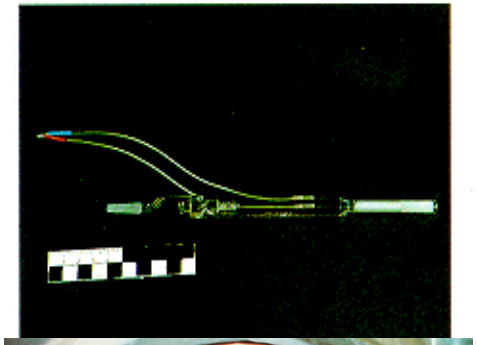
Gallium Experiment at Gran Sasso

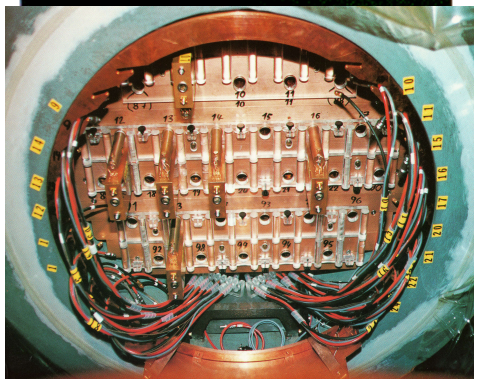
GALLEX

INTERNATIONAL
SOLAR NEUTRINO RESEARCH
COLLABORATION



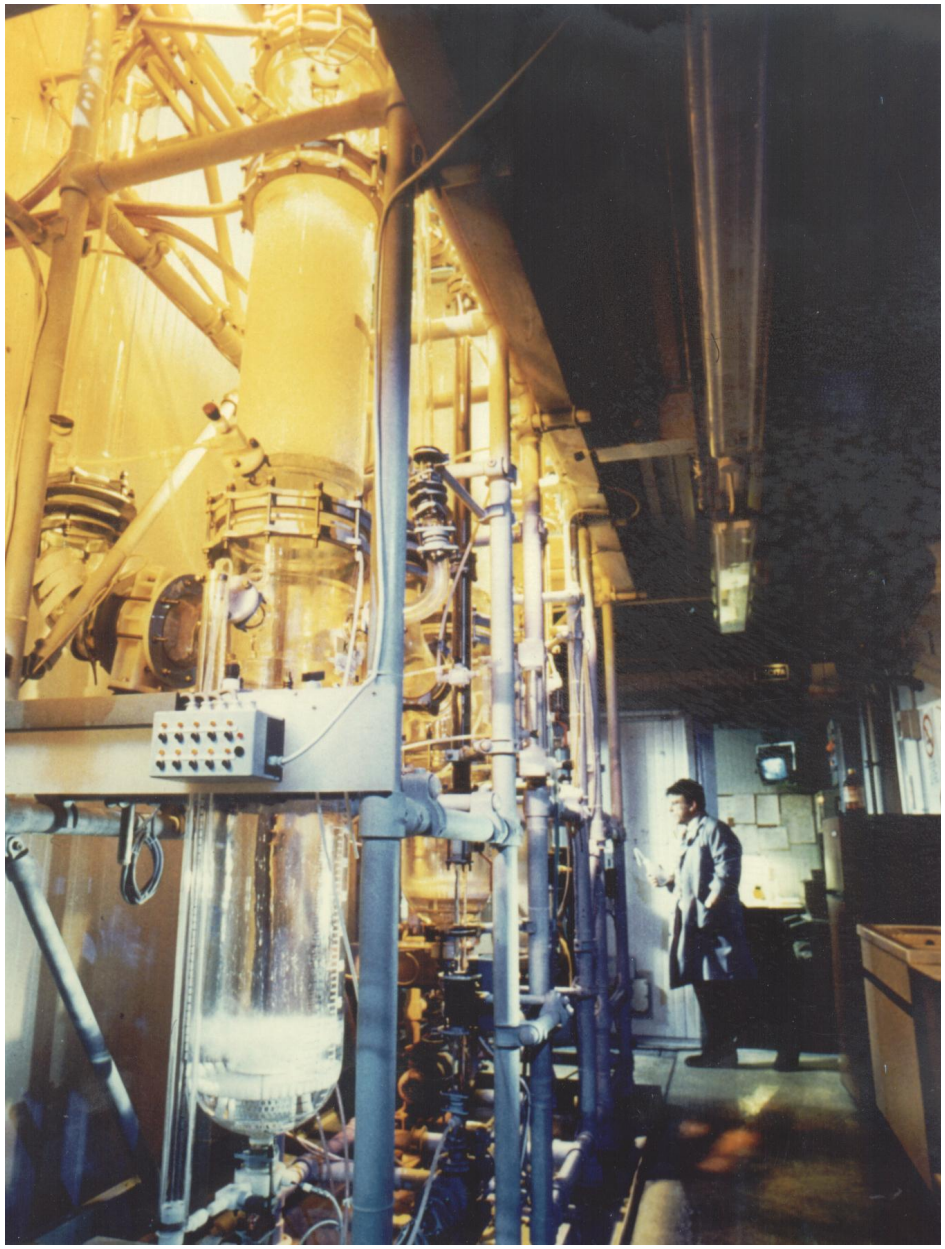






Tanks installed, September 1989

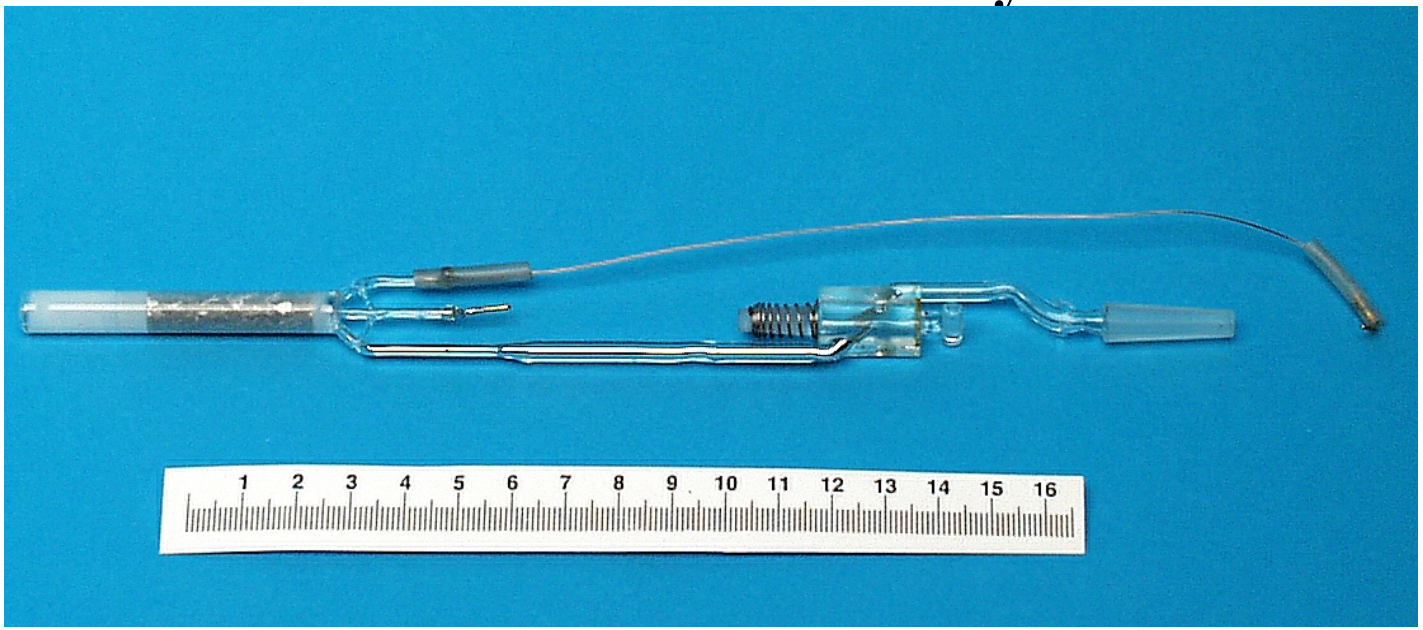
Percolation in action



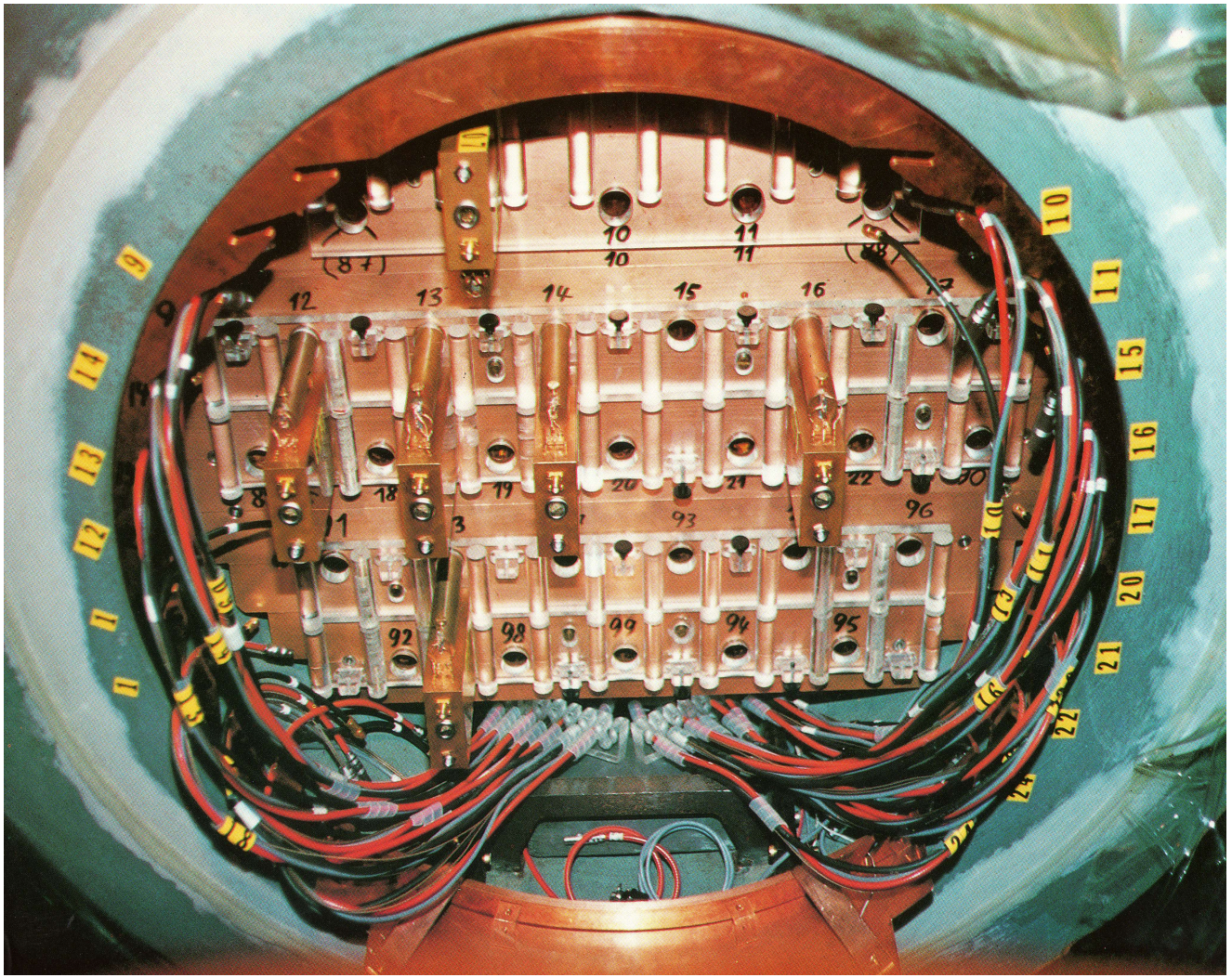
Germanium-Extraction System

Low Level Gas Proportional Counter

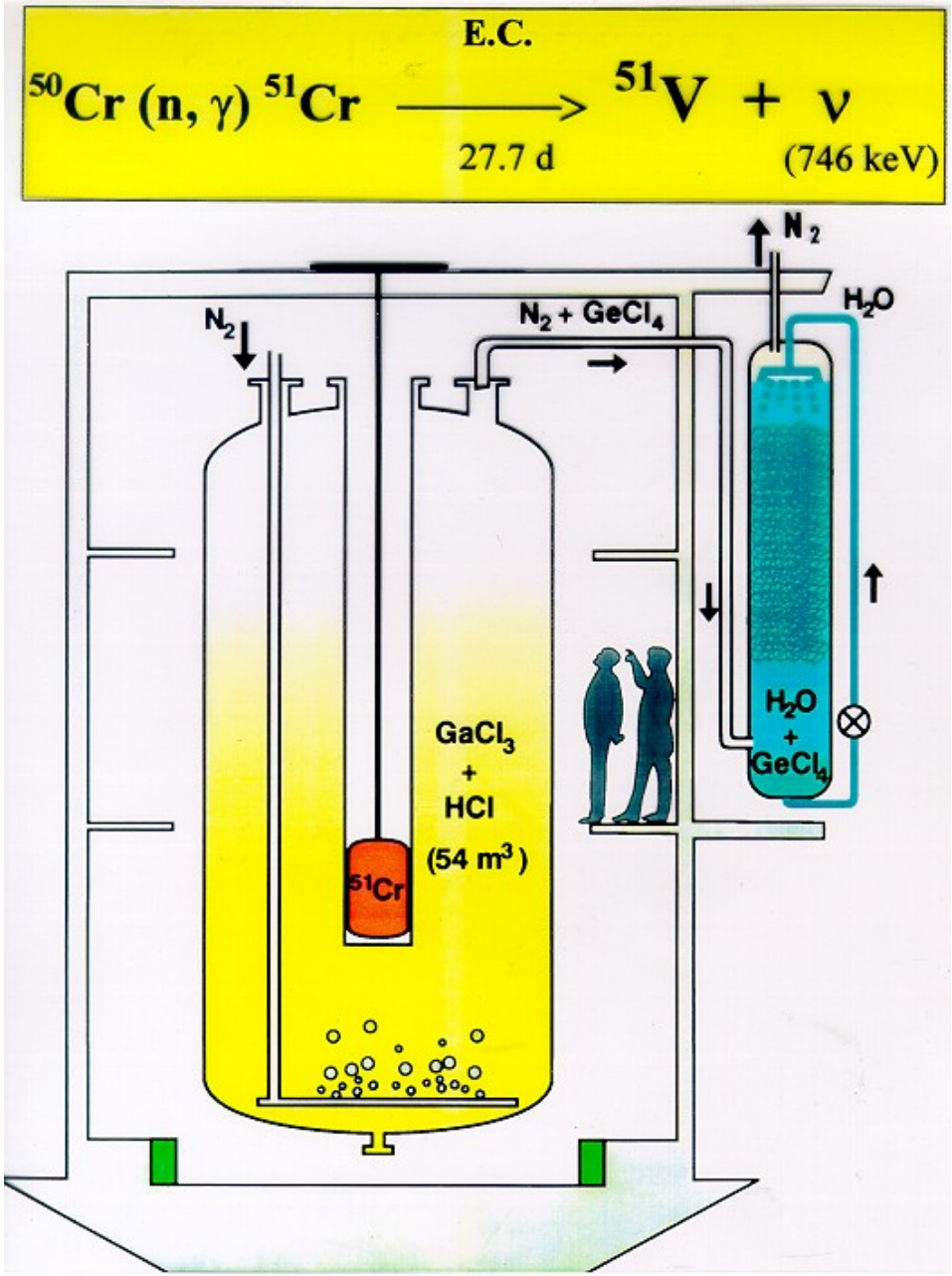
- **Miniaturized Counters made from Suprasil ultrapure synthetical quartz**
- **Fe oder Si- Cathodes**
- **Counting gas: GeH_4 + Xe**
- **Active Volume 0.6 – 0.9 cm^3 only**



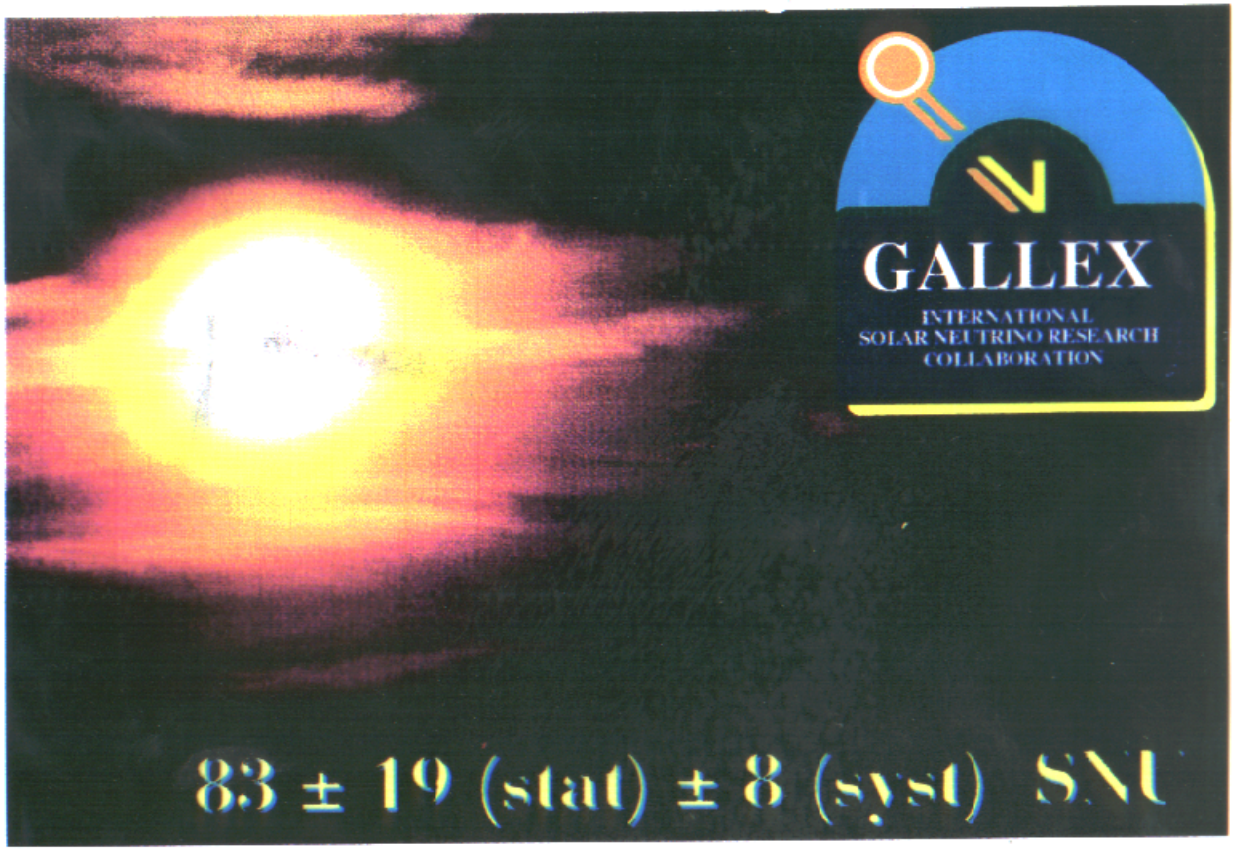
Shielded Counting Setup



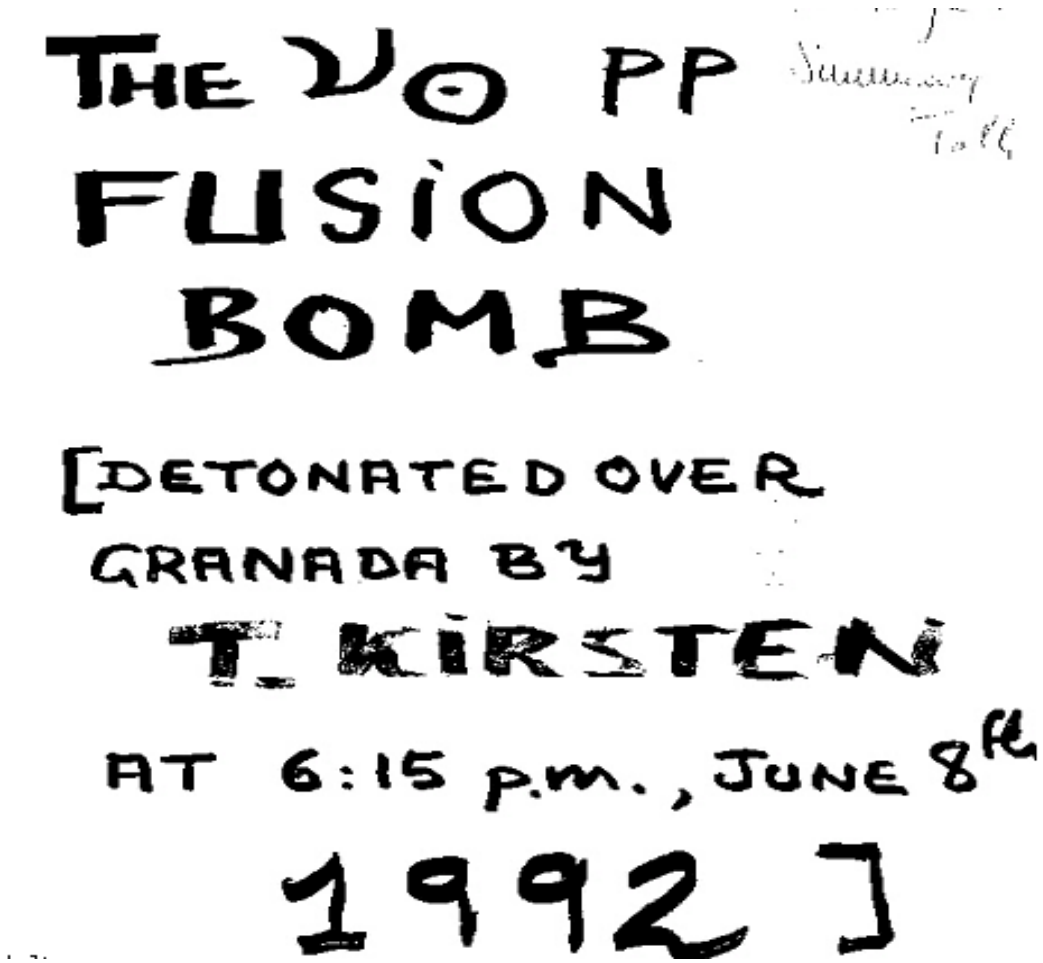
Cr-source experiment



GALLEX announces first observation of solar pp-neutrinos at „Neutrino 92“



NEUTRINO 92, Granada 7-12 June 1992



de Rujula
Conference
Summary Talk

Fred Reines

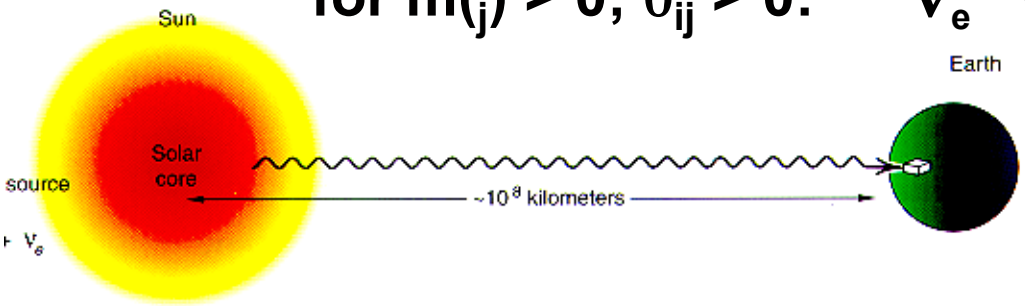
Granada 1992

A. Morales

Bruno Pontecorvo

III. ν- FLAVOUR OSCILLATIONS

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



$$In \quad vacuo: \quad \nu_e = \nu_1 \cos\theta_\nu + \nu_2 \sin\theta_\nu$$
$$\nu_\mu = -\nu_1 \sin\theta_\nu + \nu_2 \cos\theta_\nu$$

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

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

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

NEUTRINO PROPAGATION

- *in vacuo:* 150 Mio km (8 min)
- *in matter:* 700 000 km

ν_e - disappearance due to flavour changes (neutrino oscillations) ?

- to deduce neutrino properties, the Flux at origin (the solar core) must be *well known*

Sub-MeV Solar Neutrinos

Astrophysics

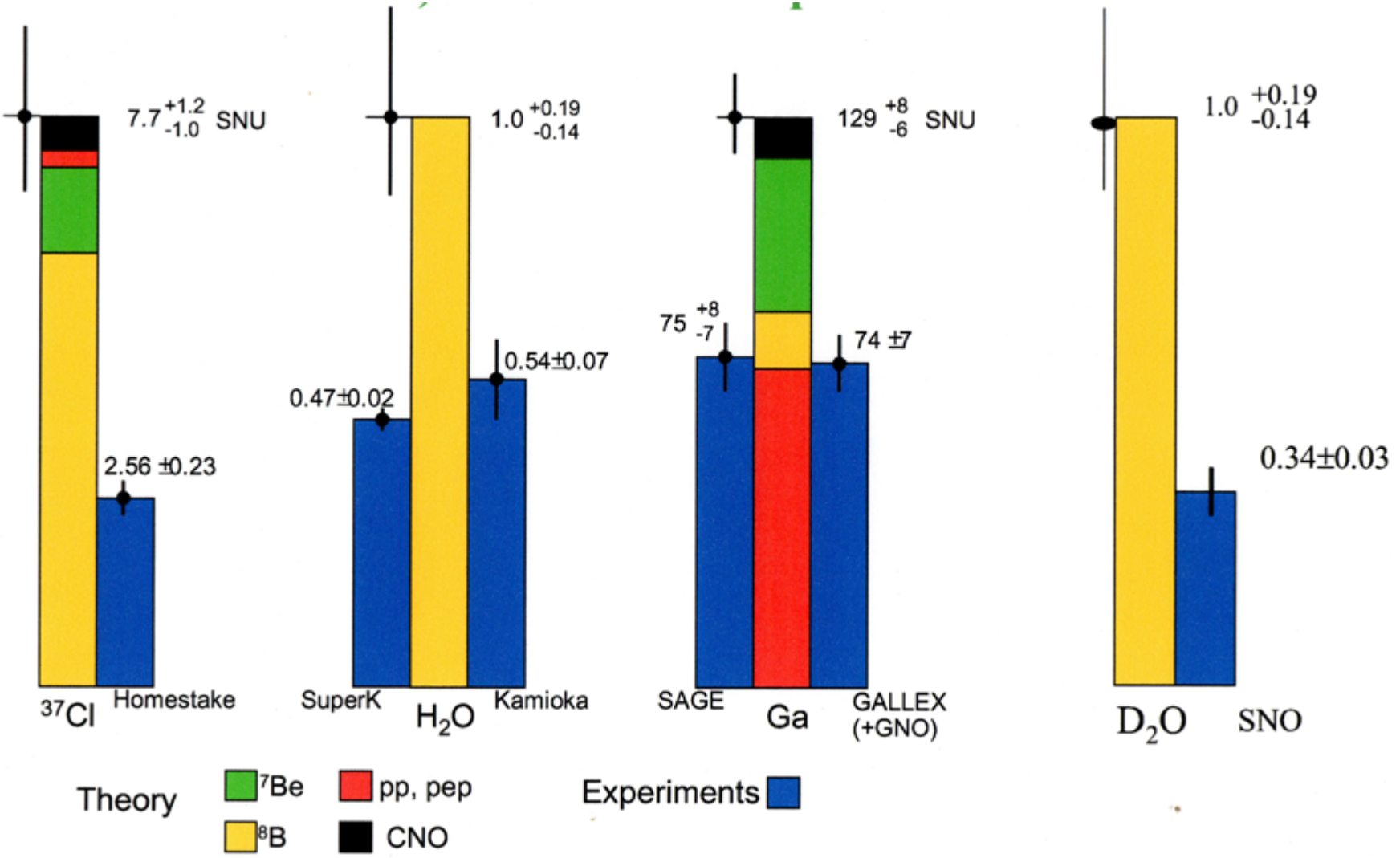
- Verification of Standard Solar Model

Particle Physics

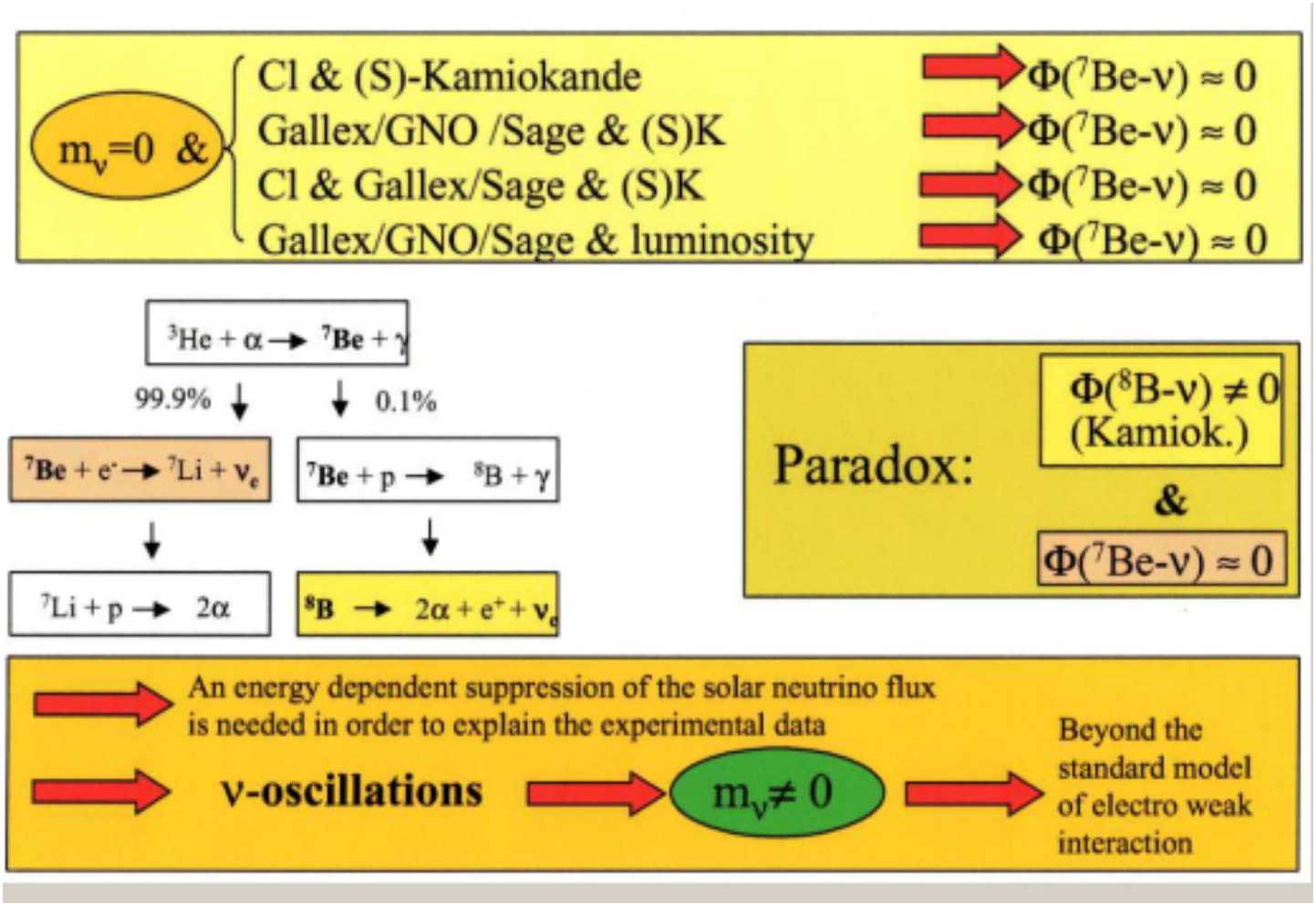
- pp-Neutrinos as Standard Candle to deduce Neutrino Oscillations, hence: Neutrino Mass

Evidence for Oscillations of Solar Neutrinos

(not enough ^{7}Be-ν to account for the observed ^{8}B-ν)



^{7}Be ν - Paradox



Neutrino Mixing and Oscillations

$m_\nu \neq 0 \Rightarrow$ neutrino mixing expected: $\nu_\alpha = U_{\alpha i}\, \nu_i$ $(\alpha = e,\mu,\tau;\ i = 1,2,3)$

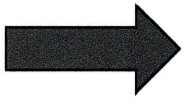
2–Flavour: $U = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix}$

flavour eigenst. — mixing matrix. — mass eigenst.

Vacuum oscillations (2-flavour): $P(\nu_e,t) = 1 - 1/2\, \sin^2 2\Theta\, [1 - \cos \frac{1}{2} \frac{\Delta m^2}{E_\nu} t]$

Oscillation length: $\lambda = 4\pi \frac{E_\nu}{\Delta m^2}$; $\Delta m^2 = |m_i^2 - m_j^2|$

Interaction in matter (e^-) is different for ν_e and ν_μ, ν_τ ,
ν_e: Z^0 and W (NC+CC)
ν_μ, ν_τ: Z^0 (NC)



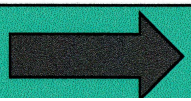
Effective masses in matter

$\nu_i \rightarrow \nu_{i\text{-matter}}$

$\Theta_{vac} \rightarrow \Theta_{matter}$

$\Rightarrow$ Matter Oscillations: Mixing becomes maximal ($\sin^2 2\Theta = 1$) for a distinct combination of E_ν, Δm^2, Θ_{vac}, N_e (electron density)

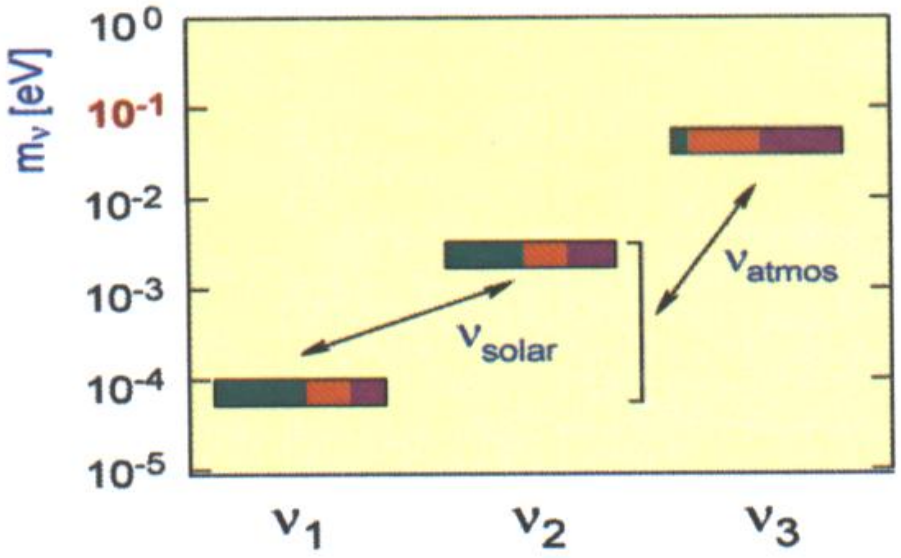
Sun: N_e varies with radius: $\rho \approx 150 \rightarrow 0$ g/cm^3



MSW-effect (resonant conversion in matter)

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 ≠ 0 , yet too small to account for the cosmologically „missing mass“**

GEOCHEMICAL DOUBLE BETA DECAY (DBD) - DETECTION

B.Pontecorvo, 1968

"The attention should be seriously turned to the possibility that the transition ^{128}Te→^{128}Xe entirely and the transition ^{130}Te-^{130}Xe partally are due to neutrinoless double beta decay"

Phys.Lett. 26B, 630-632, 1968

Xe from 1.31 b.y. old native tellurium ore, Goodhope mine, Colorado

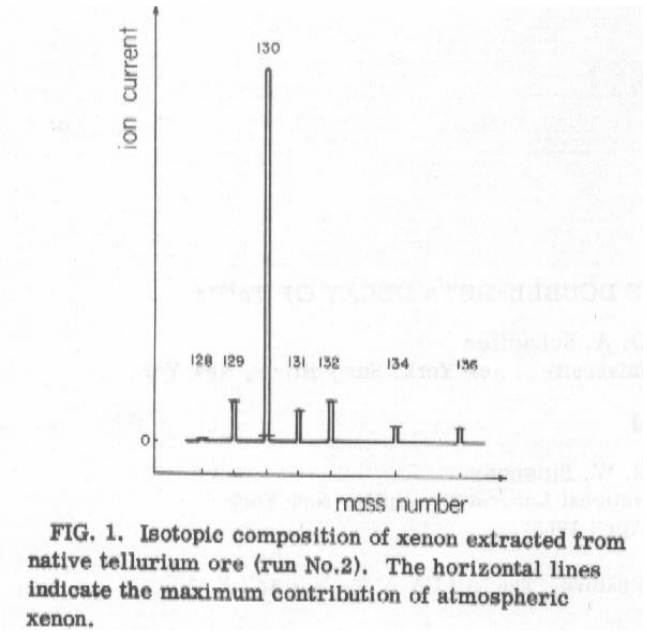
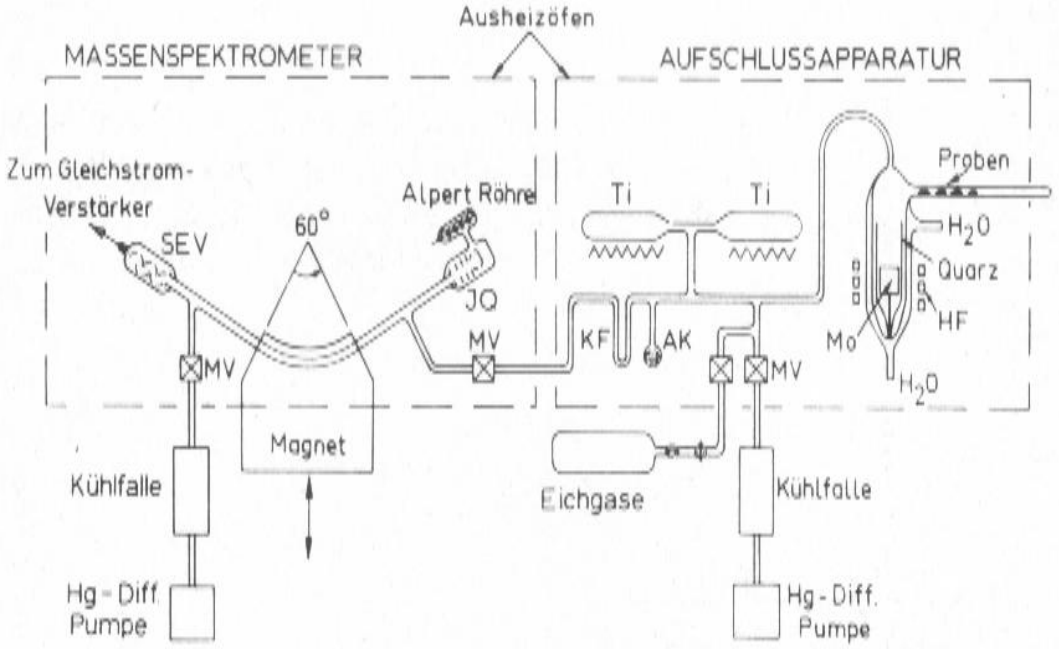
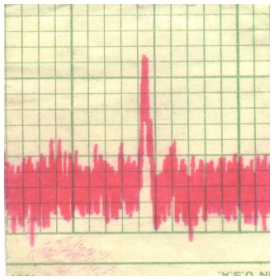


FIG. 1. Isotopic composition of xenon extracted from native tellurium ore (run No.2). The horizontal lines indicate the maximum contribution of atmospheric xenon.



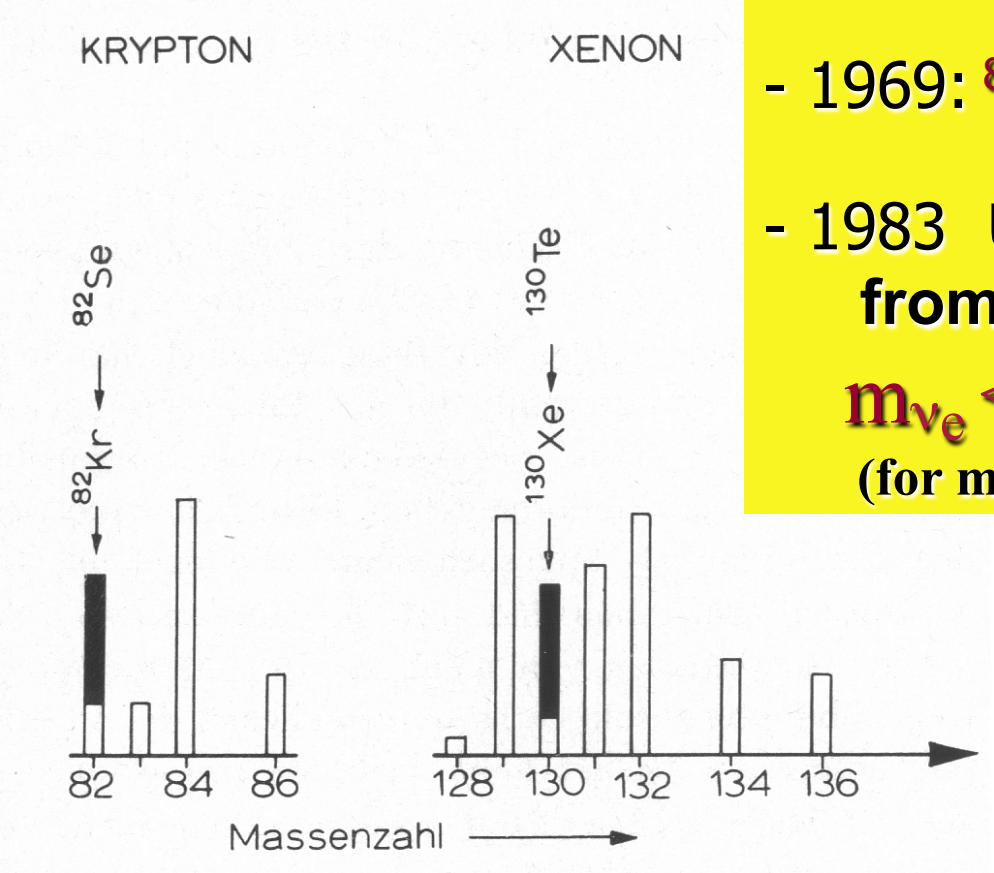
$T_{1/2} = (2.2 \pm 0.6)\ 10^{21}$ yrs



EURECA!

DBD decay in old tellurium- and selenium ores

Accumulation principle, like for K-Ar



The classic 2ν-DBD was detected for the first time in

- 1968: $^{130}Te \rightarrow ^{130}Xe$ $T_{1/2} = (2.2 \pm 0.6)\ 10^{21}$ a
  Phys.Rev.Lett. 20,1300,1968
- 1969: $^{82}Se \rightarrow ^{82}Kr$ $T_{1/2} = (1.4 \pm 0.3)\ 10^{20}$ a
  Earth Planet. Sci. Lett. 6,271,1969
- 1983 **Upper neutrino mass limit from** $(^{130}Te/^{128}Te) / (^{130}Xe/^{128}Xe)$:

$m_{\nu_e} < 5.6$ eV **Z.Phys.C 16,189,1983**

(for many years the best limit)