SOLAR NEUTRINOS

(experiments)

- Introductory remarks
- Running experiments

  SNO
  Superkamiokande

  Specific talks

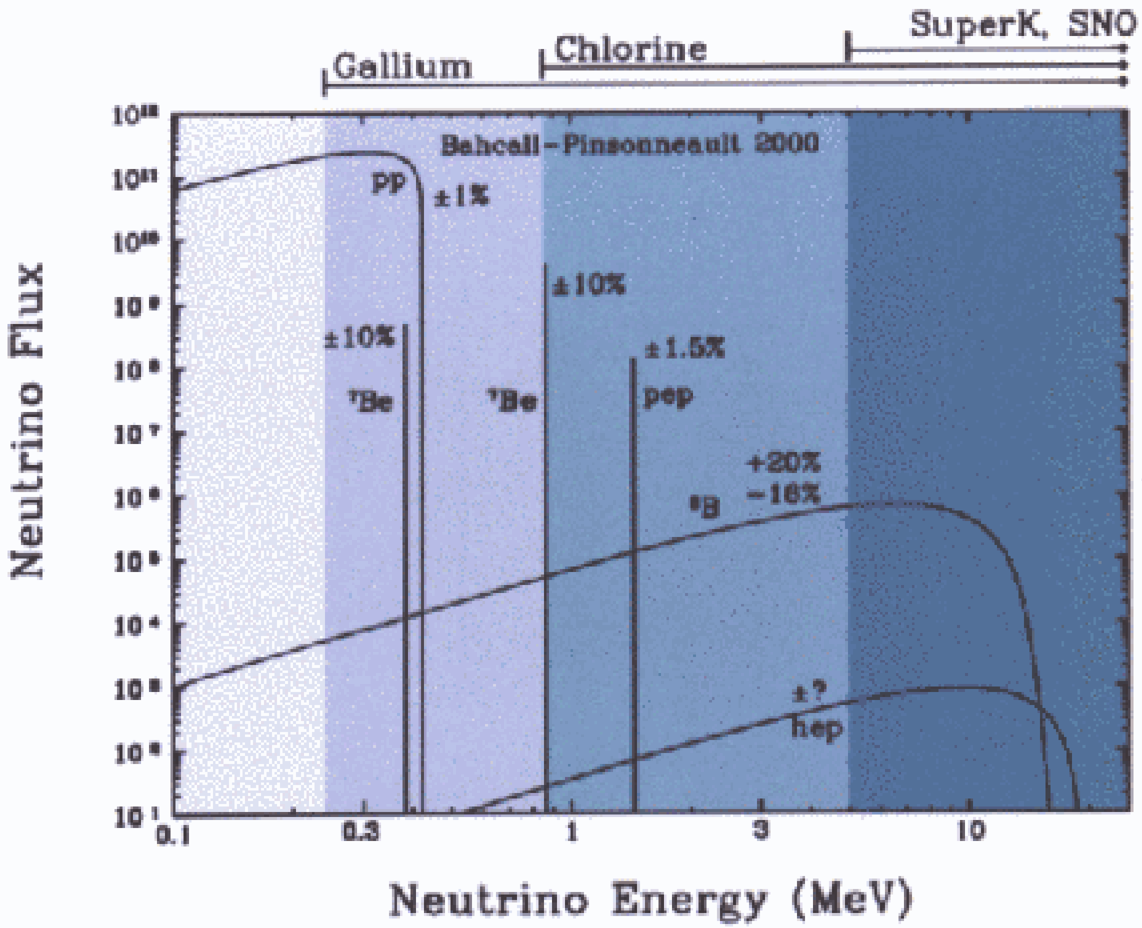
  Gallium experiments

- Future experiments

  BOREXINO and KAMLAND (close to start)

  ICARUS

- Other future experiments in R&D stage
- Antineutrinos from the SUN
- Conclusions



Source	Flux (10^{10} cm^{-2}s^{-1})	Cl (SNU)	Ga (SNU)	Li (SNU)
pp	$5.96\,(1.00^{+0.01}_{-0.01})$	0.0	69.9	0.0
pep	$1.40 \times 10^{-2}\,(1.00^{+0.015}_{-0.015})$	0.22	2.9	9.2
hep	9.3×10^{-7}	0.04	0.1	0.1
^{7}Be	$4.82 \times 10^{-1}\,(1.00^{+0.10}_{-0.10})$	1.16	34.5	9.2
^{8}B	$5.15 \times 10^{-4}\,(1.00^{+0.20}_{-0.16})$	5.87	12.3	20.1
^{13}N	$5.56 \times 10^{-2}\,(1.00^{+0.21}_{-0.17})$	0.09	3.4	2.4
^{15}O	$4.88 \times 10^{-2}\,(1.00^{+0.25}_{-0.19})$	0.33	5.5	12.0
^{17}F	$5.73 \times 10^{-4}\,(1.00^{+0.25}_{-0.25})$	0.0	0.1	0.1
Total		$7.7^{+1.3}_{-1.1}$	129^{+9}_{-7}	$53.0^{+6.6}_{-6.1}$

How far are S.S.M. predictions from experimental data?

	pp	pep	^{7}Be	^{8}B	CNO	Total	Exp.
GALLEX-GNO (*)	70.	2.9	34.5	12.3	9.	129^{+9}_{-7}	74.1 ± 6.8
SAGE (*)							75 ± 7
Cl (*) Homestake	0	0.22	1.16	5.87	.4	$7.7^{+1.3}_{-1.1}$	$2.55 \pm .25$
Super Kamiokande	0	0	0	$5.15\ 10^{6}$ ($9.3\ 10^{3}$)	0	$5.15\ 10^{6}$ ($9.3\ 10^{3}$)	$2.4 \pm 0.095\ 10^{6}$

(*) units are SNU's - 1SNU = 1 capture/(second x 10^{36} target atoms)

Is it possible to cure this large discrepancy?

lowering the ^{7}Be contribution

^{3}He-^{3}He	increase, but LUNA results
^{3}He-^{4}He	decrease (new measurement planned)

and, if needed, increasing the p-^{7}Be interaction rate

Therefore

neutrino oscillations

supported by large discrepancy in the rates,
mainly by the apparent lack of ^{7}Be neutrinos in gallium experiments

but not by other effects like
^{8}B energy spectrum distortions; $\langle T_e \rangle$
time variation (day-night; seasonal)

Other solutions ?

SNO results are crucial

- comparison of the SK data in different background (muon flux) conditions
- detection of semileptonic charge currents : comparison with elastic scattering off electrons in the same experiment and with SK measurement
- detection of semileptonic neutral currents (no " superposition" with charge electron neutrino reactions like in elastic scattering off electrons)
- first measurement of the total neutrino flux (^8B)
- check of the solar model

$$1<\Phi_{\nu e}/\Phi_{tot}<2.75$$

input parameters of S.M. inaccurate
or
oscillation to sterile neutrinos
(contradiction with other experiments)

solar model perfect

oscillation to active neutrinos

GALLIUM

GALLEX-GNO and SAGE

Radiochemical experiments

$$^{71}Ga\,(\nu_{e},\,e)\,^{71}Ge$$

distinctive feature: low energy threshold (233keV)
pp spectrum 0-420 keV

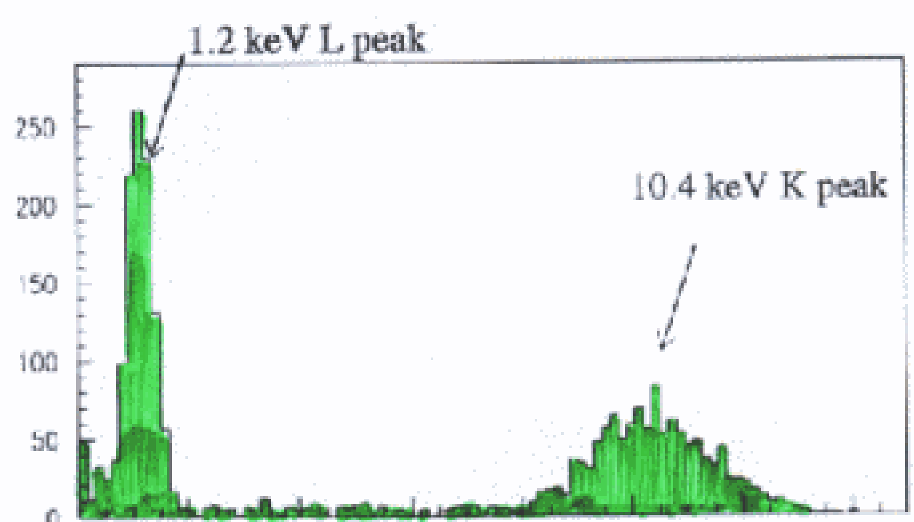
expected rates 0.3 ^{71}Ge atom / (day x ton ^{nat}Ga x 100 SNU's)

GNO (Gran Sasso)
30 tons of ^{nat} Ga
in hydrochloric solution

SAGE (Baksan)
55 tons of ^{nat} Ga
in metallic form

Different background
Different extraction technique

^{71}Ge E.C. $T_{1/2} = 11.4$ days
Auger electrons and X rays detected in proportional counters



Results

GALLEX – GNO

2168 days (live time) **74.1± 6.8 SNU**
(+ 350 days)

SAGE

1990 –1997 **$67.2^{+7.2+3.5}_{-7.0-3.0}$ SNU**
(pub.ed in 1999)

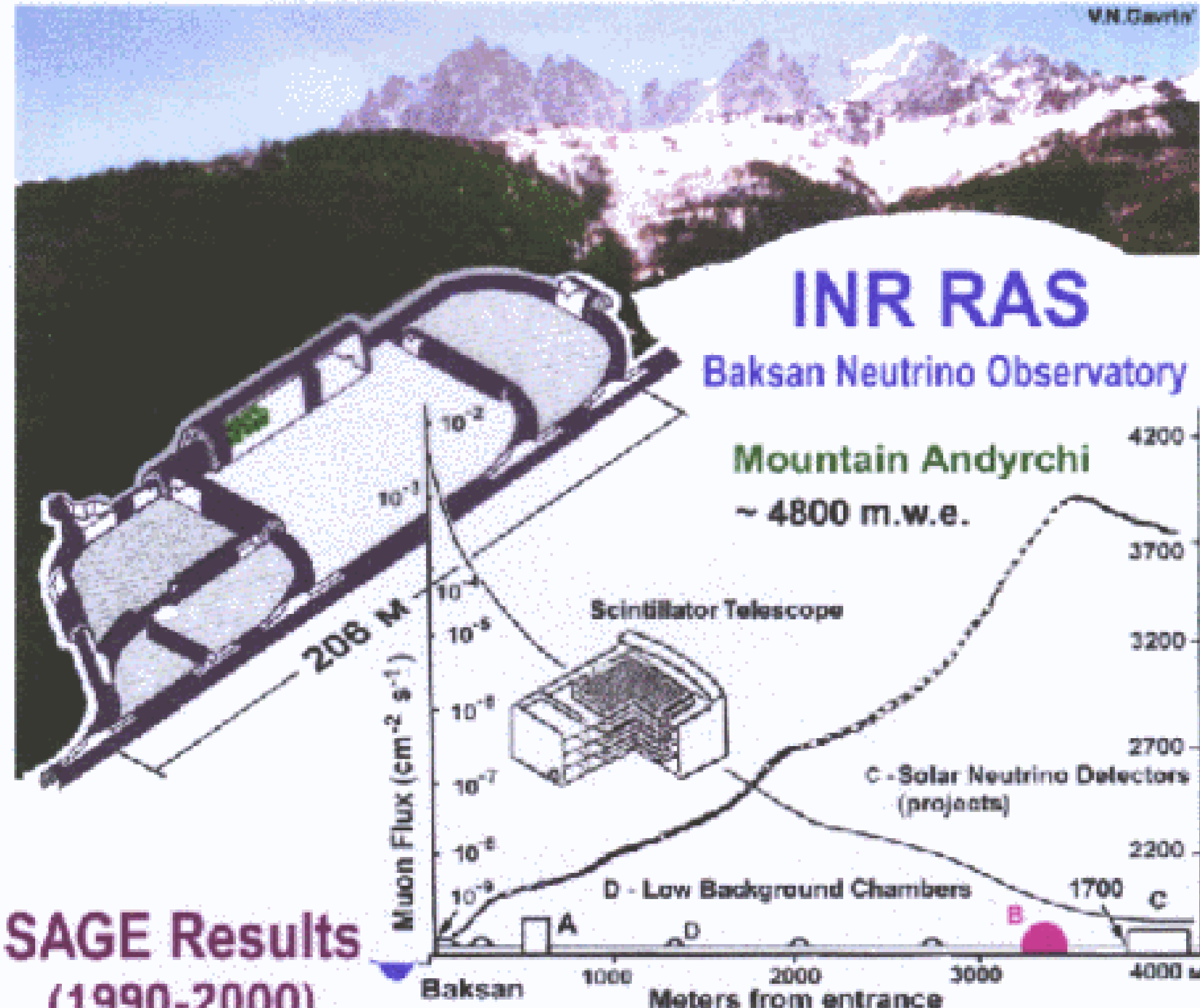
1990-1999 **75^{+7}_{-6} SNU** 77
efficiency reevaluated (neutrino 2000 Conf.)

Mean

To be compared with

129^{+9}_{-7} SNU

pp and pep contribution = **73 SNU**

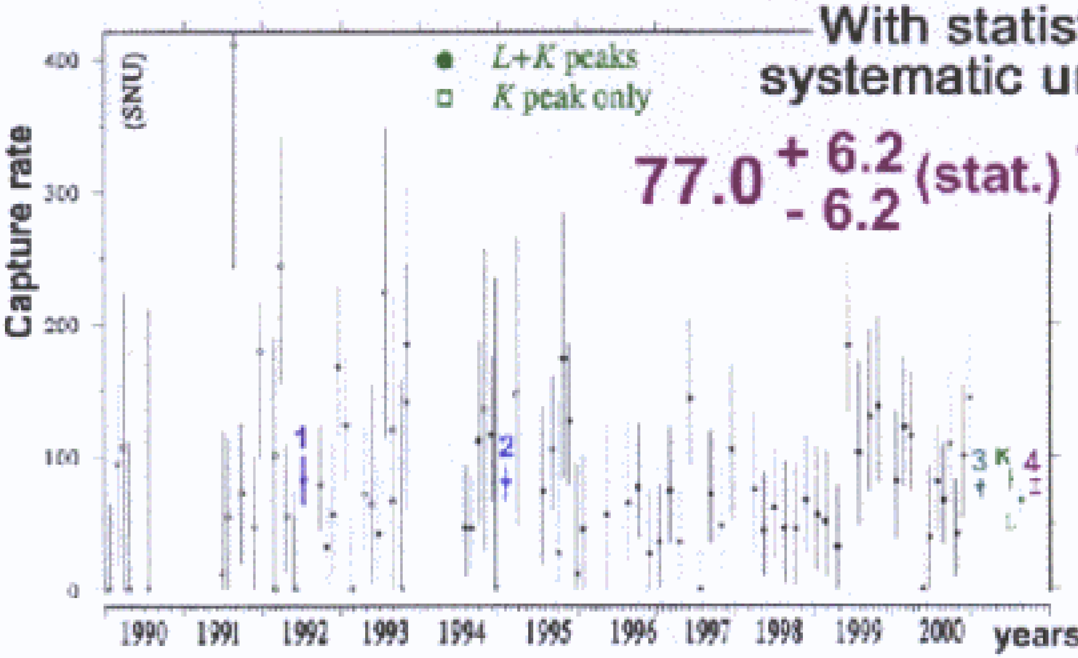


SAGE Results (1990-2000)

With statistical and systematic uncertainties

$$77.0 \,^{+6.2}_{-6.2}\,(\text{stat.})\,^{+3.5}_{-3.0}\,(\text{syst.})$$

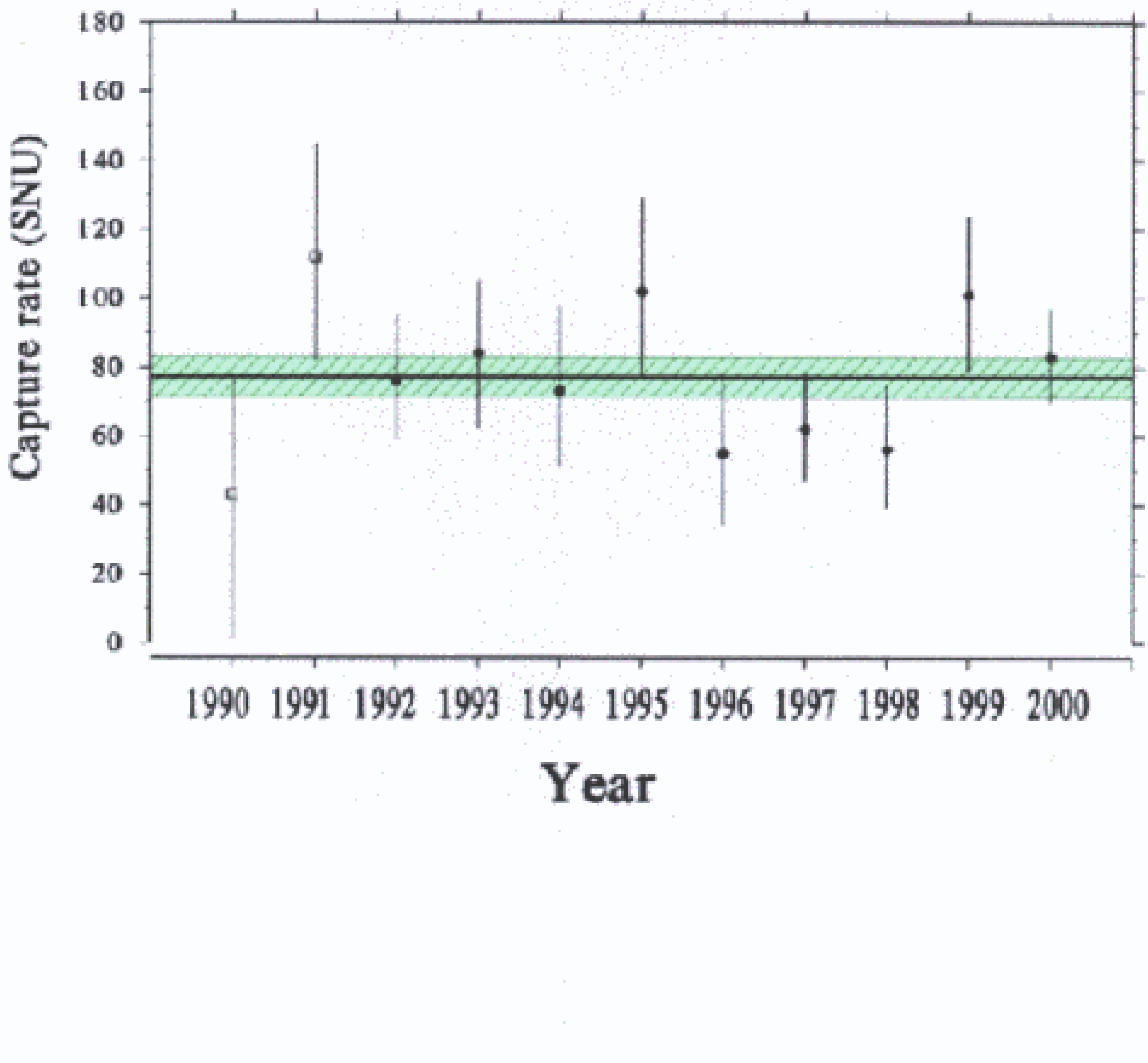
SNU



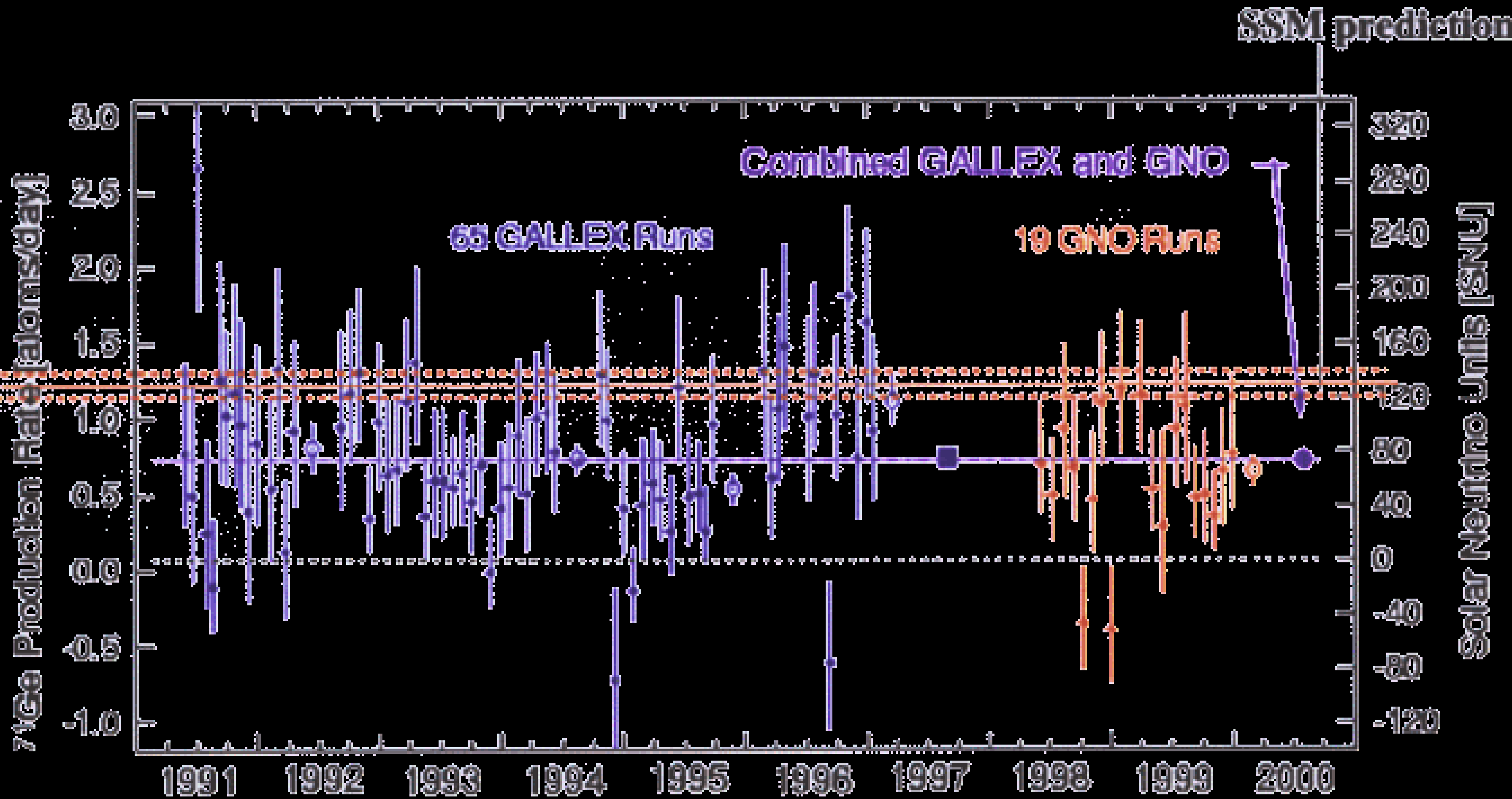
SAGE 1: 81^{+20}_{-18} SAGE 2: 79^{+13}_{-13} SAGE 3: 76^{+7}_{-8} SAGE: $77.0^{+7.1}_{-6.9}$ SNU

Gavrin' 2001

SAGE Results (1990-2000)



GNO+GALLEX RESULTS



Comb. Result (SR1-SR84): 74.1 +- 5.4 (stat) $^{+4.0}_{-4.2}$ (sys)

Submitted to Phys.Lett. B

Solar Models predictions : 120 - 140 SNU

REDUCTION OF THE SYSTEMATIC ERROR IN GNO

Item	GALLEX (%) 1997	GNOI 2000	GNO 2002 (2001)	GNO > 2002
Background from side reactions	1.6	1.6	1.6	1.6
Background from ^{68}Ge	1.8	1.4	~0.5	~0
Radon cut inefficiency	1.6	1.1	~0.5 (new measurement)	~0.5
Counting efficiency (including energy and pulse shape cuts)	4.5	4.5	3–4	2–3
Chemical yield and target size	2.2	2.2	2.2	2.2
TOTAL	**5.8**	**5.5**	**4–5**	**3.5–4**

% of 74 SNU's

- (yellow) Results from ongoing Rn test
- (blue) Measurement of counting efficiency for all used counters
- (red) Standardization of the proportional counters

Some detail on GNO activity

Data taking in progress (+ 17% of the statistics)
Blank (1 day exposure) 5 runs o.k.

Background due to Radon decays

Radon decays can mimic genuine Ge decays

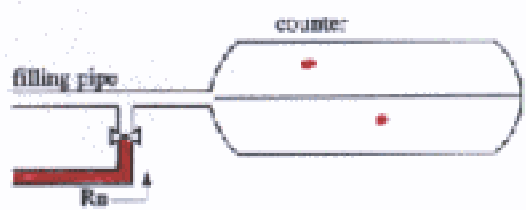
A few atoms of Rn are present in the gas mixture
A very few atoms are released from the counters

Radon events are rejected:
Alfa's give a high signal (saturation)
Bismuth-Polonium chain $T_{1/2}$ 163 μs

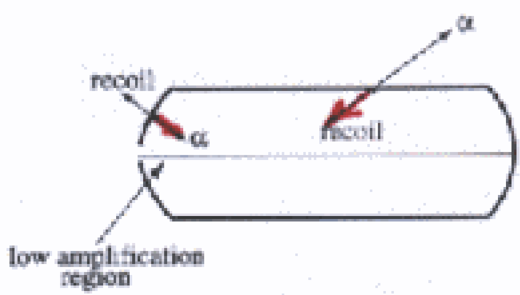
Rejection efficiency (91±5) %

New measurement

A dedicated counter
2-3 Rn atoms/ day injected in the counter
➢ 500 days of live time
data analysis in progress
rejection efficiency (94± 3 ± 2) %
expected final result ± 3%

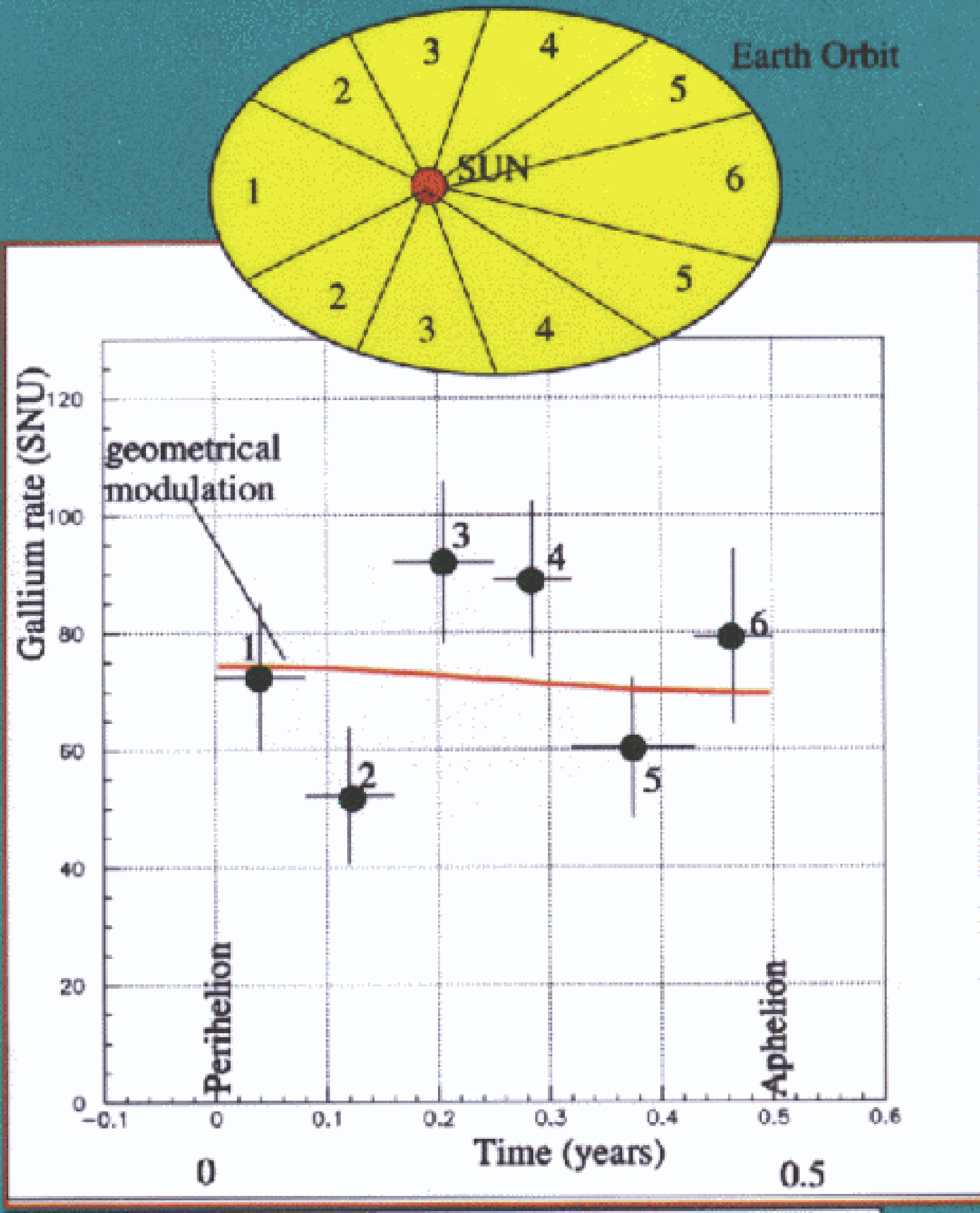


A remark

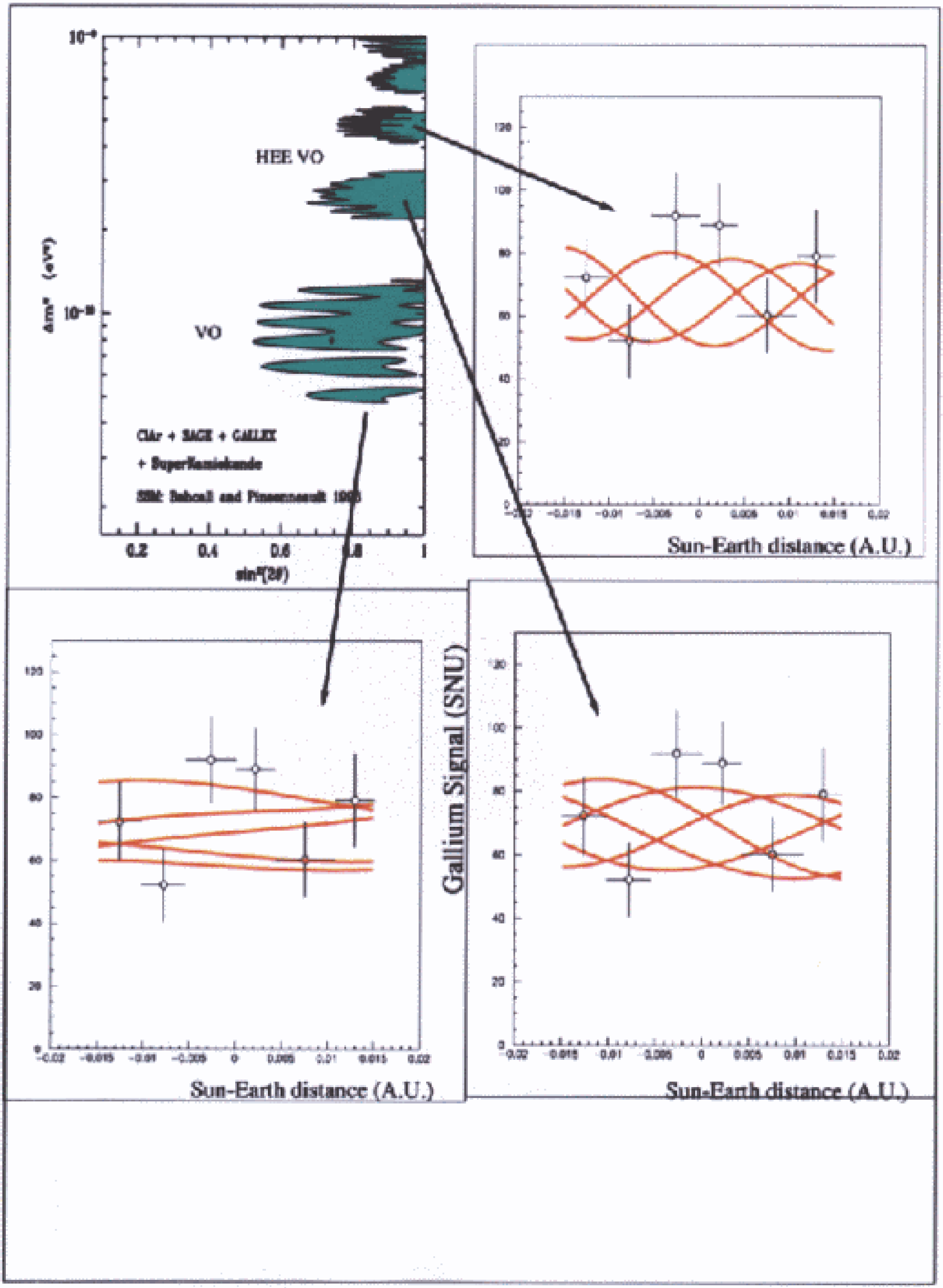


Interpretation confirmed by Bi-Po chain data

GALLEX/GNO data binned with distance from the Sun



chi2 = 8.3 / 5 DOF   C.L. = 14%


HEE VO
VO
ClAr + SAGE + GALLEX
+ SuperKamiokande
SSM: Bahcall and Pinsonneault 1998
$\sin^2(2\theta)$
Δm^2 (eV^2)
Sun-Earth distance (A.U.)
Gallium Signal (SNU)
Sun-Earth distance (A.U.)
Sun-Earth distance (A.U.)

Neutrino artificial source

51Cr	**Berillium lines**
751 keV (9 %)	
746 keV (81%)	**860 keV (90 %)**
431 keV (1 %)	
426 keV (9 %)	**380 keV (10%)**

Three exposures

R= measured/ expected

SAGE

19. ±0.2 PBq	**13.1 metallic**	**.95±.12 (exp)**

GALLEX

63.4 ± 0.5 PBq	**30 tons solution**	**$1.01^{+.12}_{-.11}$**
69.1 ± 0.6 PBq	**"**	**$.84^{+.12}_{-.11}$**

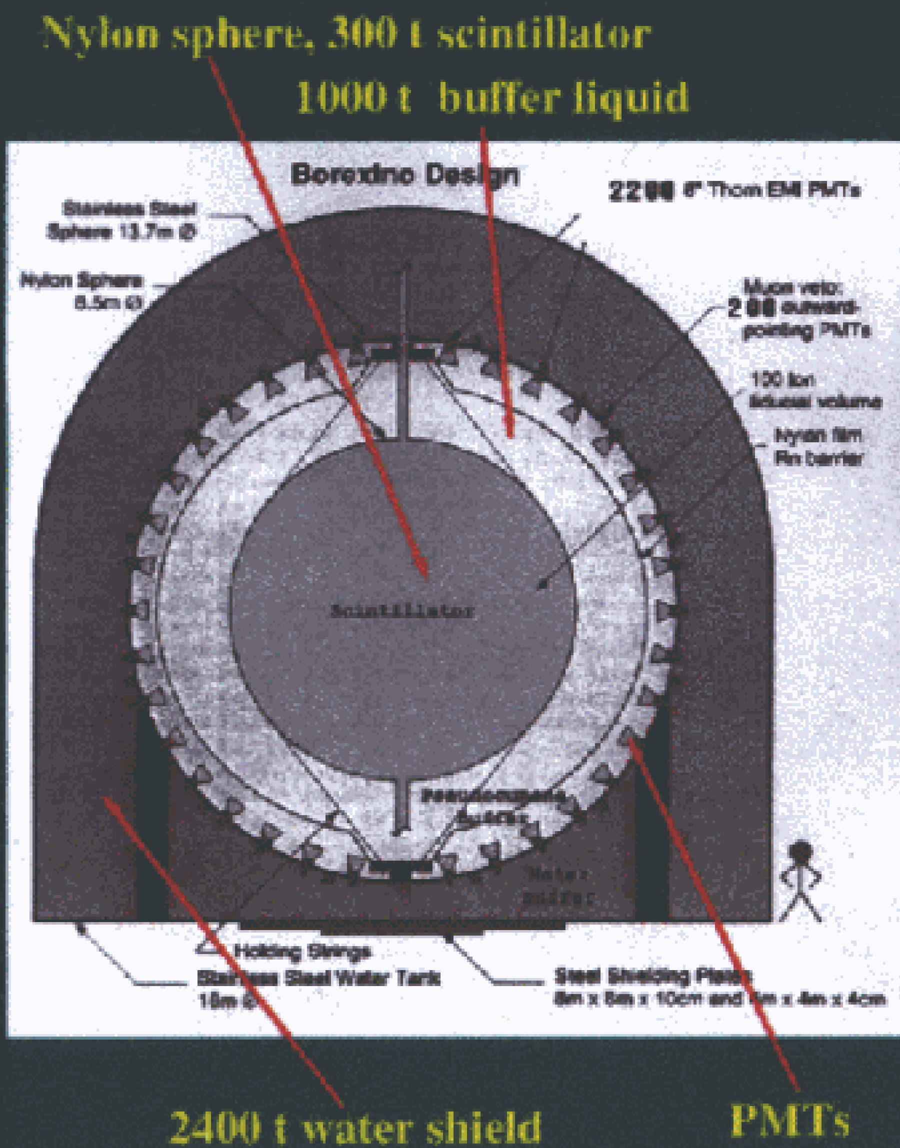
A new exposure for a better determination of cross sections

(a problem with excited states?)

Technically 2.5 MCi source is feasible

Final error (adding the four exposures) 5-6 %

BOREXINO



Location Laboratori Naz. del Gran Sasso (Italy)

Target 300 t liquid scintillator

Technique detection of scintillation light by pmts

Neutrino interactions:

e scattering e (ν_x ν_x) e E_{thr} ~ 250 keV

Observables integral ν capture rate
energy of scattered e

Expected signal (SSM)
~ 50 events/day

Sensitivity ^{7}Be ν

Data taking ~ 2002

BOREXINO AT LNGS

MAIN GOAL: MEASURE OF THE ^{7}Be N INTERACTION RATE

(SIGNIFICANTLY LOWER THAN SSM PREDICTIONS)

Past years:

- Understanding and reduction of background
- Prototype (Counting Test Facility installed at Gran Sasso)
- Design of the detector
- Installation

Structure	*installed*
Cables, electronics	*installed*
Piping, purification	*close to be completed*
Inner vessel	*end 2001*
Filling	*[with H2O for testing? fall 2001]* *PC beginning 2002*

KamLAND

Main goal:

Detection of antineutrinos from distant reactors to investigate f.i.

the region of the LMA solution (Δm^2 10^{-5} eV^2) !

(for a detailed discussion H.Murayama, A.Pierce - hep-ph/0012075 v3 Dec. 2000
V. Barger et al. Hep-ph/0011251 v3 Feb 2001)

Detector structure quite similar to BOREXINO

But:

Fiducial mass 600 tons
Scintillator mineral oil based (20 % PC)

Expected rate:

450 antineutrino ev.t's/ year

If the background level will be low enough,
Solar neutrinos !

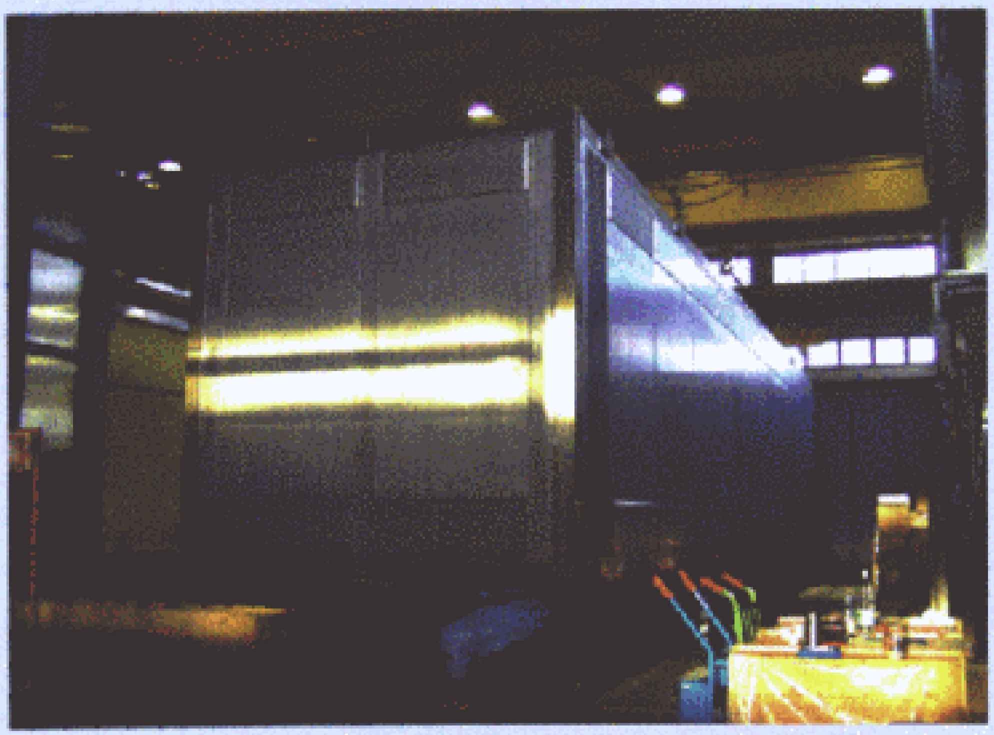
Data taking 2001

ICARUS

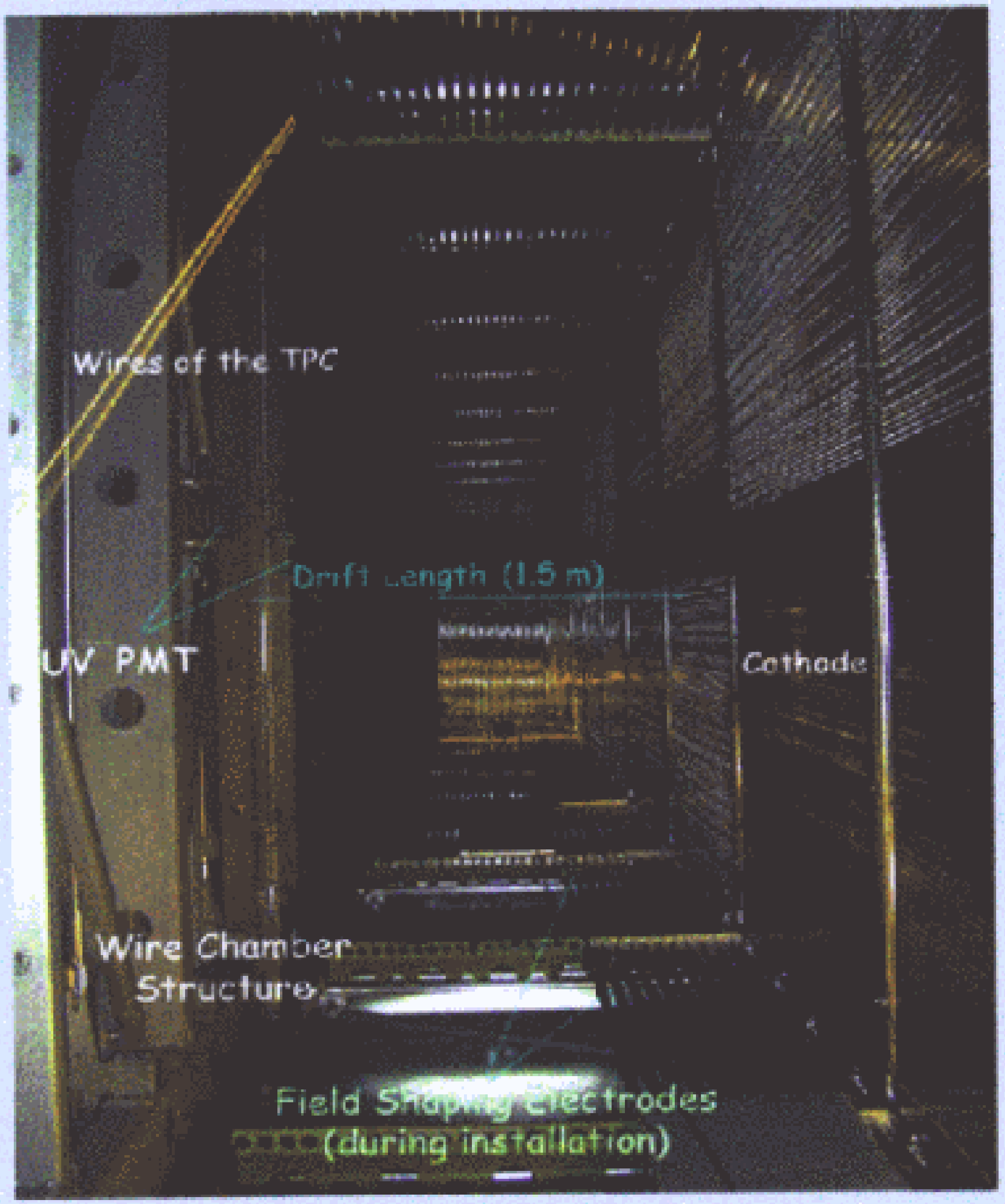
The ICARUS genealogy:

- 3 ton prototype, CERN 1990 - 1994
- 50 l chamber, CERN (ν beam & other tests)
- $10m^3$ module, PV & Gran Sasso, 1998 - 2000

- T600 module: ready to operate in Pavia NOW

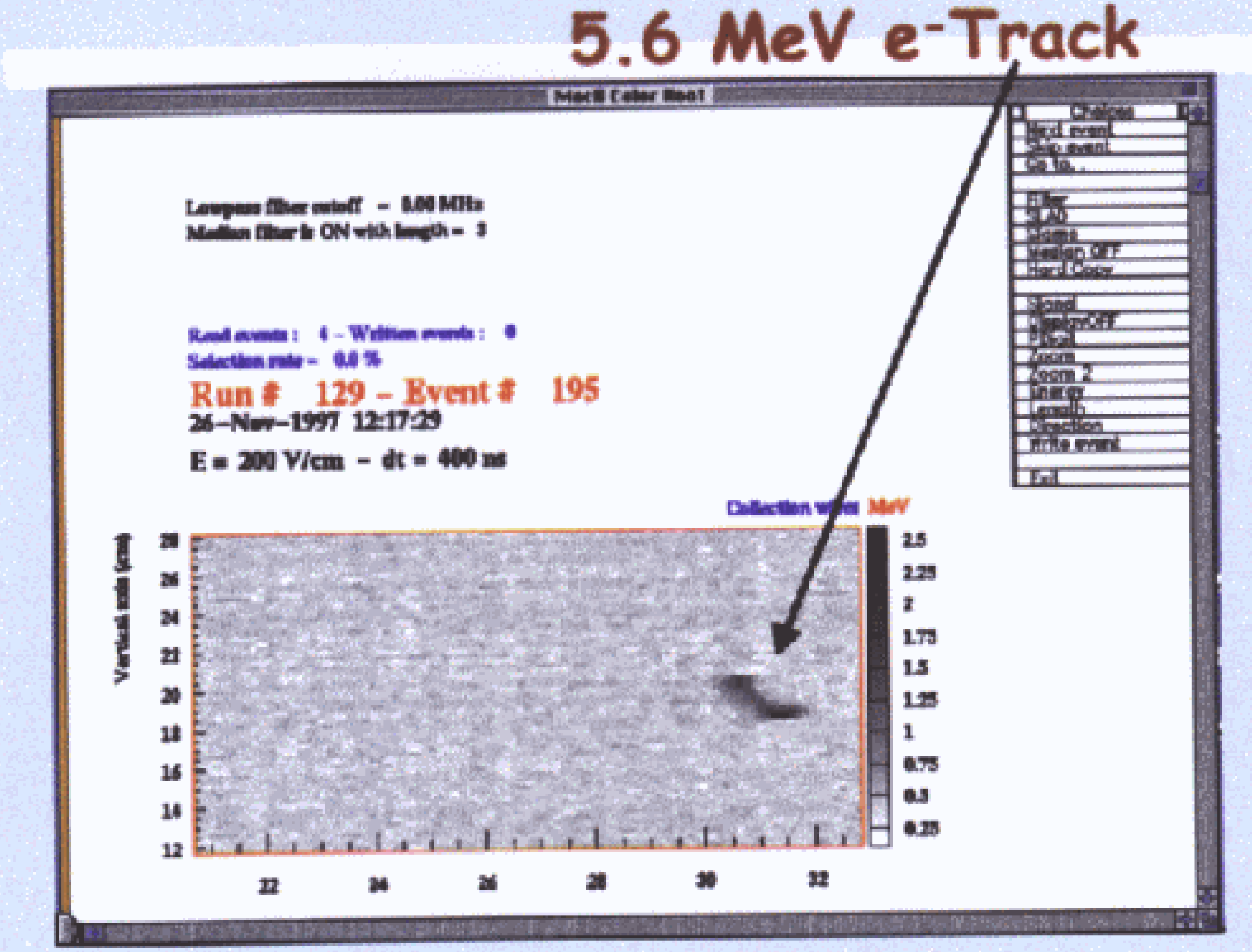


Interior of one T600 half-module



The ICARUS Technology for solar ν

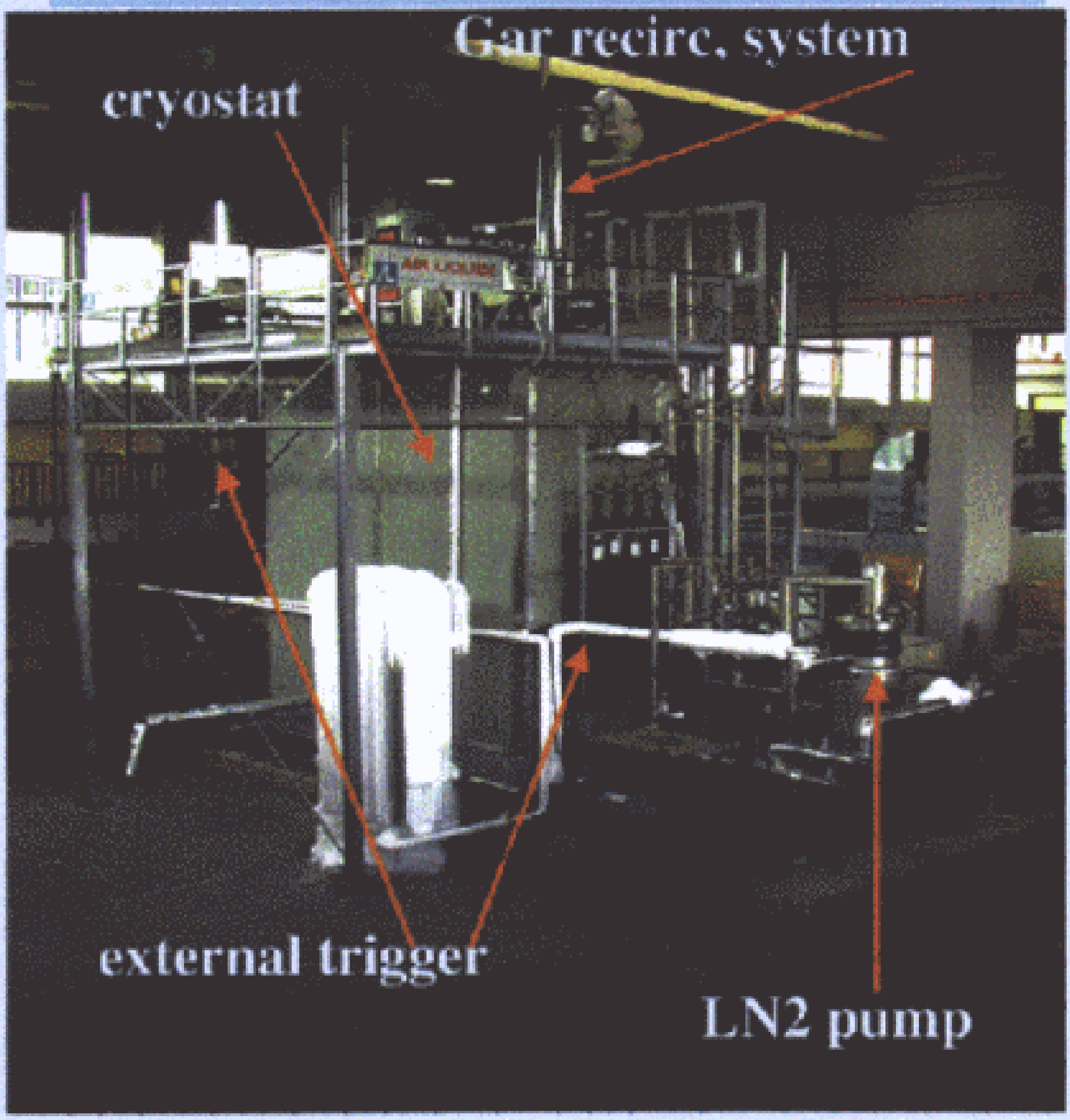
Real Event recorded with 50lt
ICARUS Prototype



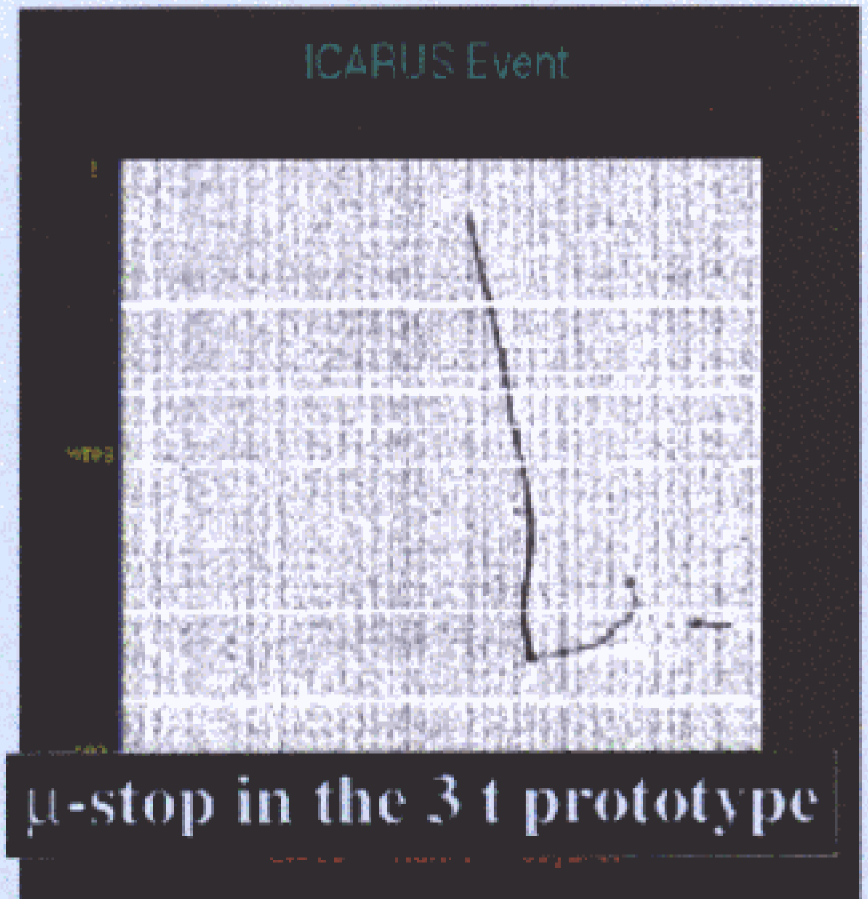
The ICARUS Technology for solar ν

The 10m³ module in *Gran Sasso*:

- a full scale "slice" of T600
- Continuous run Jan - May 2000
- Excellent cryogenic stability
- e- lifetime up to ~ 2 ms
- Thousands of events recorded



The ICARUS Technology for solar ν



$\nu_x + e \dashrightarrow \nu_x + e$

$\nu + Ar \dashrightarrow K^* + e$

(Fermi trans. + Gamow Teller)

$E_{thr}(e) = 5$ MeV

(limited by background)

EVENT Rates, from MC simulation

(E_{thr}=5 MeV, 1 Kton/year)

elastic: 792

Fermi: 730

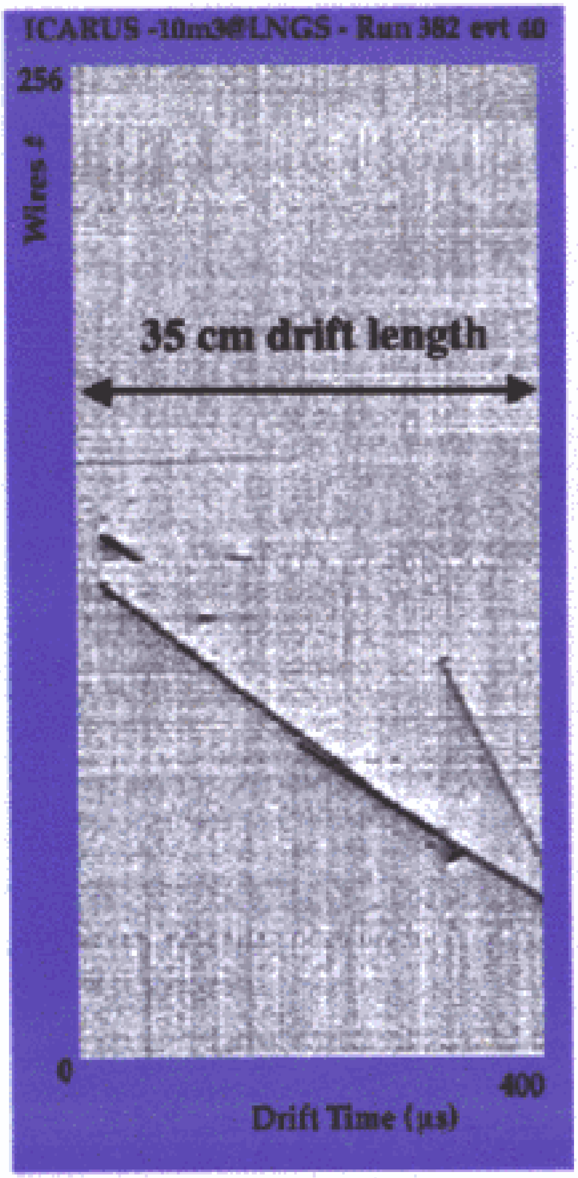
G-T: 1453

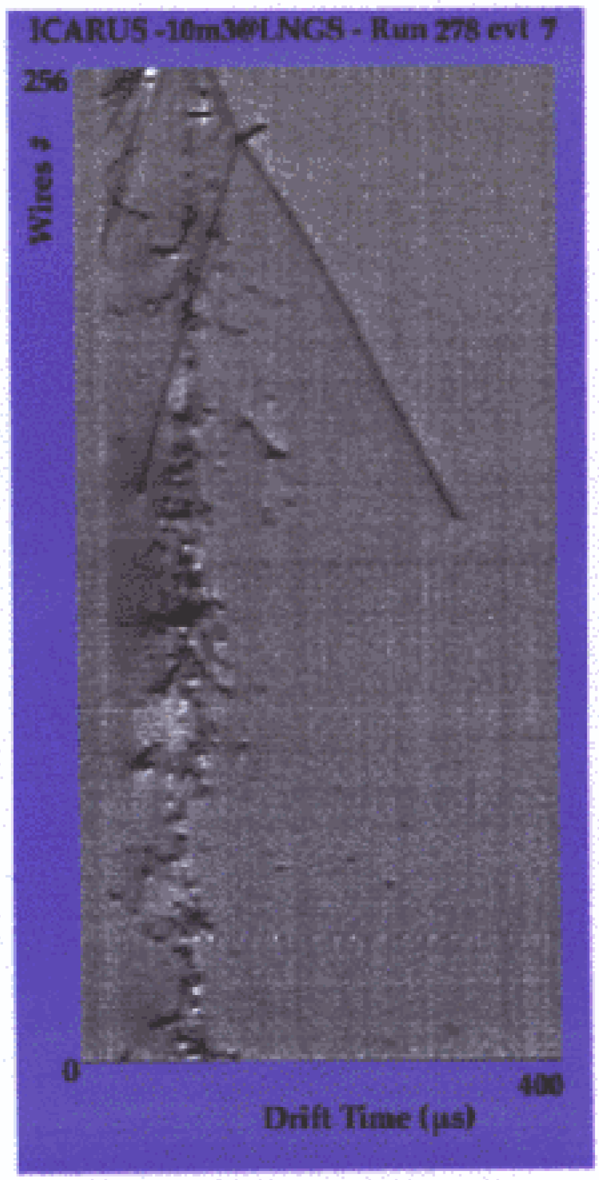
Energy res.

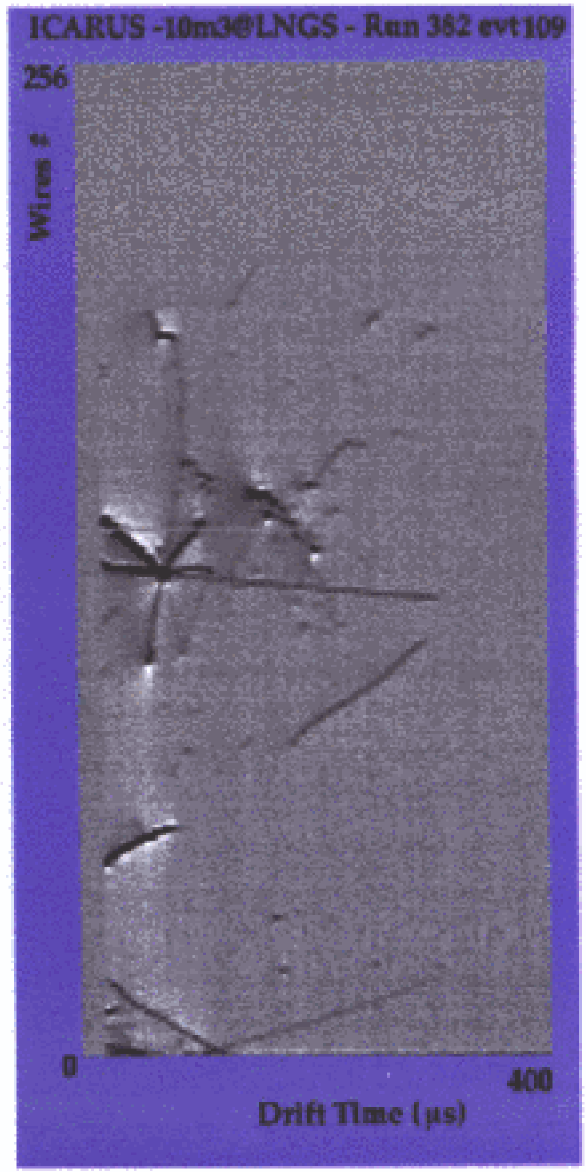
σE (5 MeV) ~ 7%

Angular Eff.: 65% for a 25° cone

Events from $10m^3$ ICARUS module at Gran Sasso







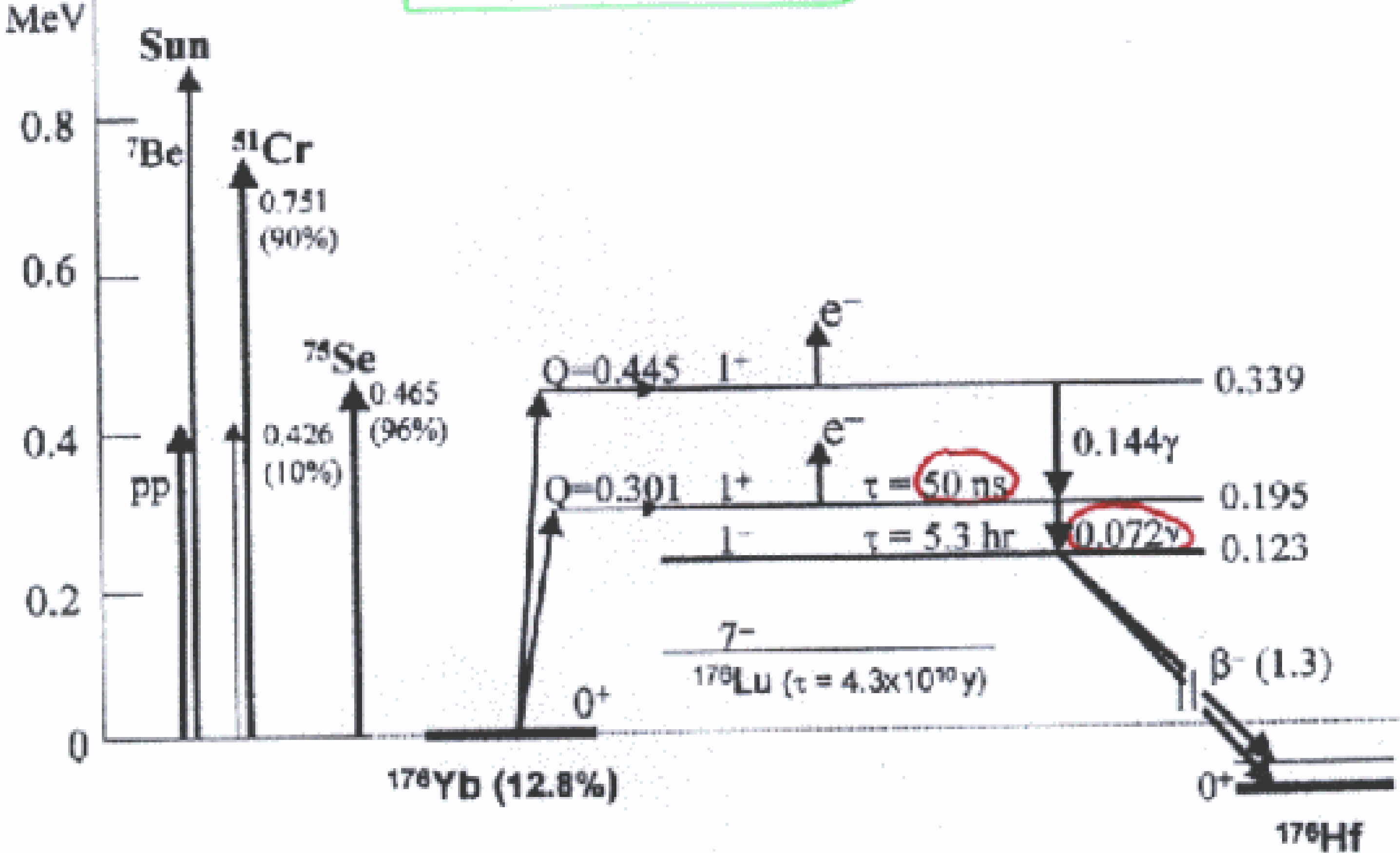
LENS

Low Energy Neutrino Spectroscopy

Aim: direct observation of solar neutrinos with E < 2 MeV

Basic interaction:

$$^{176}Yb\,(\nu\ ,e)\ ^{176}Lu$$

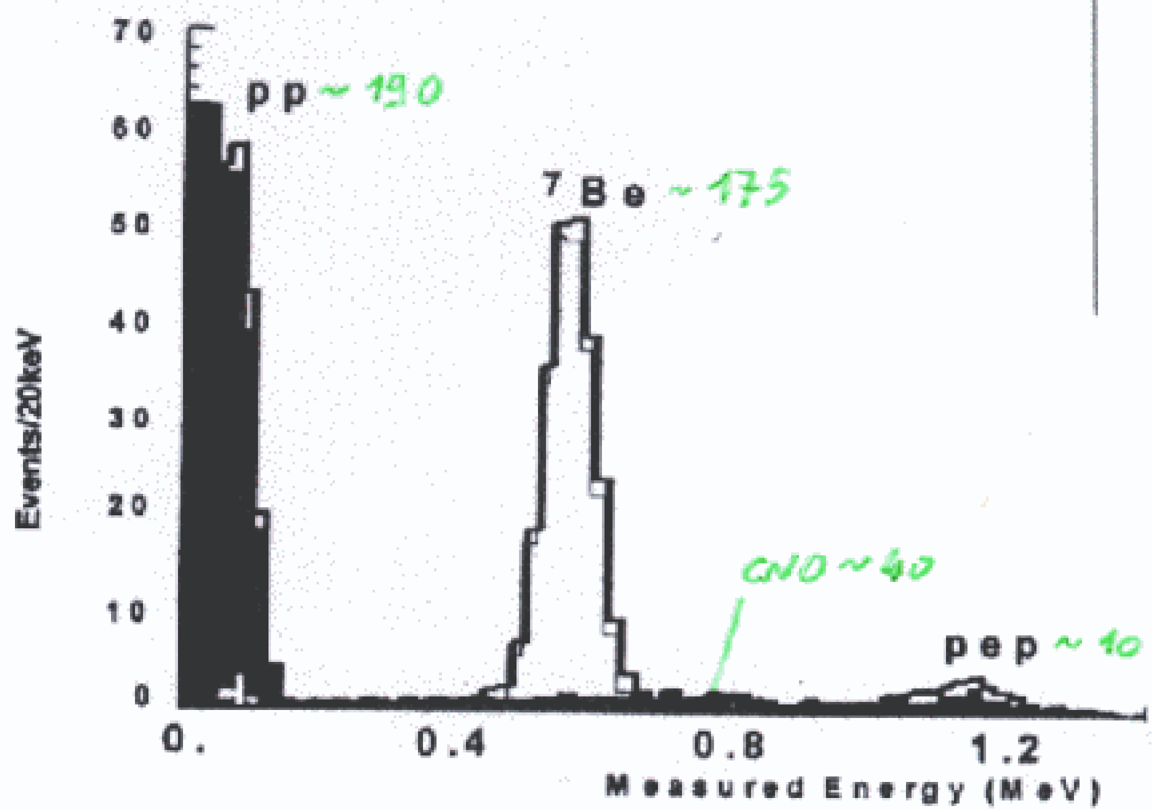


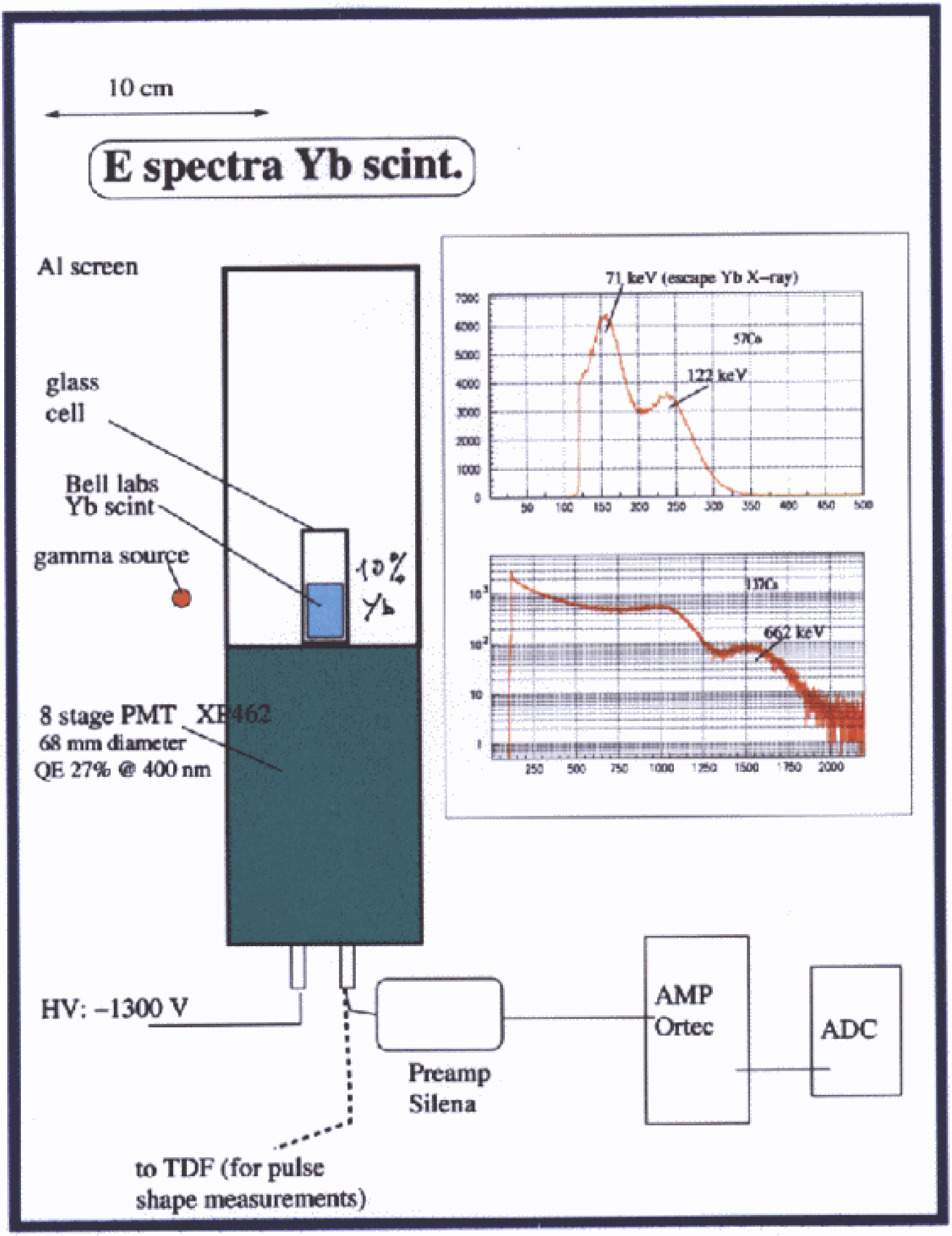
Target: ~ 20 t liquid scintillator Yb loaded detector with modular structure

LENS
The neutrino signal

Neutrino tag: 2 time-coincident signals (tau = 50 ns)
(prompt signal + delayed 72 keV gamma)
within the same fractional volume

Expected signal (20 tons , 1 year)





10 cm
E spectra Yb scint.
Al screen
glass
cell
Bell labs
Yb scint
gamma source
10%
Yb
8 stage PMT XP462
68 mm diameter
QE 27% @ 400 nm
71 keV (escape Yb X-ray)
57Co
122 keV
137Cs
662 keV
HV: -1300 V
Preamp
Silena
AMP
Ortec
ADC
to TDF (for pulse
shape measurements)

OTHER EXPERIMENT
R&D Stage

Helium pp neutrinos energy spectrum

Hellaz (TPC)

Heron (superfluid)

Lithum ^{8}B (threshold 861 keV)

Argon TPC pp neutrinos energy spectrum

NaI crystals spectroscopy

^{100}Mo (9.6% i.a) very low energy threshold (168 keV)
delayed coicidence with Tc decay ($\tau = 16$ s)
965 SNU !

^{125}In low threshold, but radioactive

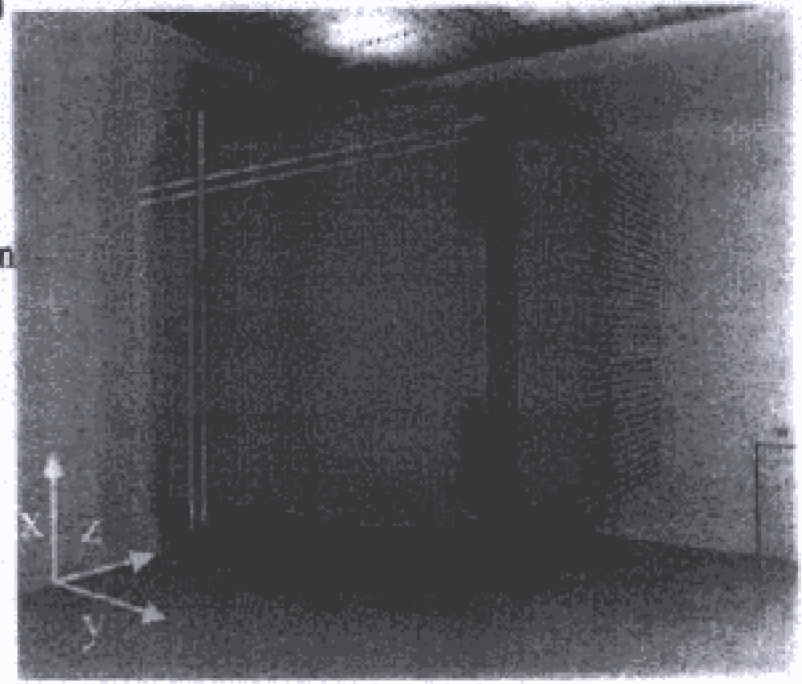
^{127}I ^{7}Be and ^{8}B (threshold ≈ 500 keV)

Possible MOON Detector

Requirements

Plastic/WLS Mo-foil ensemble

- ^{100}Mo 3.3 tons ; ^{nat}Mo 34 tons(9.6% ^{100}Mo)
- Energy resolution ➡ 15% for 7Be-ν (7% for 0νββ)
- position resolution ➡ 1/K~10^{-9}
- purity of Mo foil etc. ➡ b < 10^{-2}Bq/ton (~ppt)



- Mo foil ;thickness = 0.05gr/cm^2
  (x,y)=(5.9m,5.9m) × 1950 sheet
- PL (x,y)=(6m,6m=30×0.2m,0.25cm)
  ; 30 extruded flat-bars
- WLS-fiber light collection
  222(x) & 222(y)(# 8.66×10^5);each with 1.2mmφ×6m & 2.7cm interval
- PMT; Hamamatsu multi-anode(4×4) with 8 multiplexing(# 6800)
  each accept 128 WLS-fiber through clear fiber

Speculative explanation (still not excluded)
is based on the existence of neutrino transition magnetic moment ($\mu_\nu \sim 10^{-11}\,\mu_B$) and is due to resonant spin-flavor precession (RSFP)

Pulido (2001)
Derkaoui & Tayalati (2001)
Akhmedov (2000)
Guzzo & Nunokawa (1999)
.

Combination of spin-flavor precession in solar magnetic field
(convective zone, B ~ 30 T)
resonantly enhanced by matter effects
(resulting in an energy dependent neutrino deficit)
Possible transitions depends on neutrino nature:
Dirac ν: $\nu_e^L \rightarrow \nu_\mu^R$ (sterile)
Majorana ν: $\nu_e^L \rightarrow \overline{\nu}_\mu^R$ (active)

Possible time dependence of solar neutrino signal due to solar magnetic field variability (11-year periodicity)

If neutrino=Majorana particle and if both RSFP and flavor mixing (MSW or vacuum) operate (hybrid solution)
$\nu_e^L \rightarrow \text{RSFP} \rightarrow \overline{\nu}_\mu^R \rightarrow \text{flavor mix} \rightarrow \overline{\nu}_e^R$
$\nu_e^L \rightarrow \text{flavor mix} \rightarrow \nu_\mu^L \rightarrow \text{RSFP} \rightarrow \overline{\nu}_e^R$
i.e. an observable flux of solar antineutrinos would be expected
(for a not too small mixing angle, $\sin^2 2\theta \geq 0.1$, and $\Delta m^2 \sim 10^{-8}$ eV^2)

For a hybrid solution: smoking gun signature = antineutrinos from the Sun.
Proof of Majorana nature of ν

On the other side: bounds on antineutrino flux can be translated into constraints on the mixing parameters.

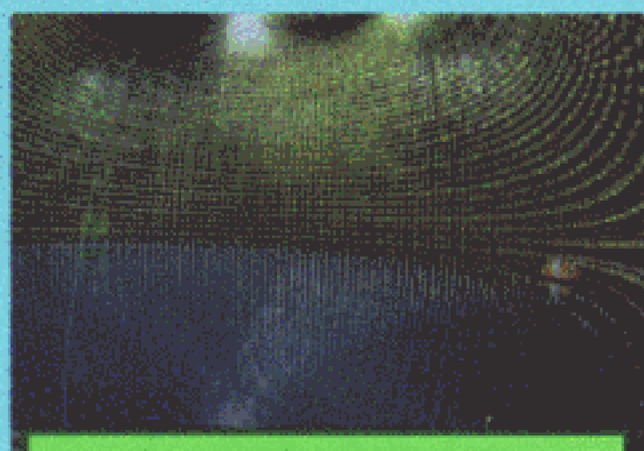
Experimentally:

signature of $\bar{\nu}_e$ through the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$

LSD (Mont Blanc) (liquid scintillator detector, 90 ton)
@ $9 < E_\nu < 20$ MeV
$\Phi_{\bar{\nu}_e}/\Phi_{\nu_e}^{SSM} < 6.3\%$ (90 c.l.)

Kamiokande (water Cherenkov detector, 2000 ton):
@ $E_\nu > 10.6$ MeV
$\Phi_{\bar{\nu}_e}/\Phi_{\nu_e}^{SSM} < 6\%$ (99 c.l.)

LVD (Gran Sasso) (liquid scintillator detector, 1000 ton)
@ $13 < E_\nu < 15$ MeV
$\Phi_{\bar{\nu}_e}/\Phi_{\nu_e}^{SSM} < 5.8\%$ (90 c.l.)
(100 ton/year)



SuperKamiokande (water Cherenkov detector, 50000 ton):
@ $E_\nu > 6.5$ MeV
$\Phi_{\bar{\nu}_e}/\Phi_{\nu_e}^{SSM} < 3.5\%$ (95 c.l.)

Further results will come from:
LVD (full dataset/full volume)
SNO
Borexino
KamLand