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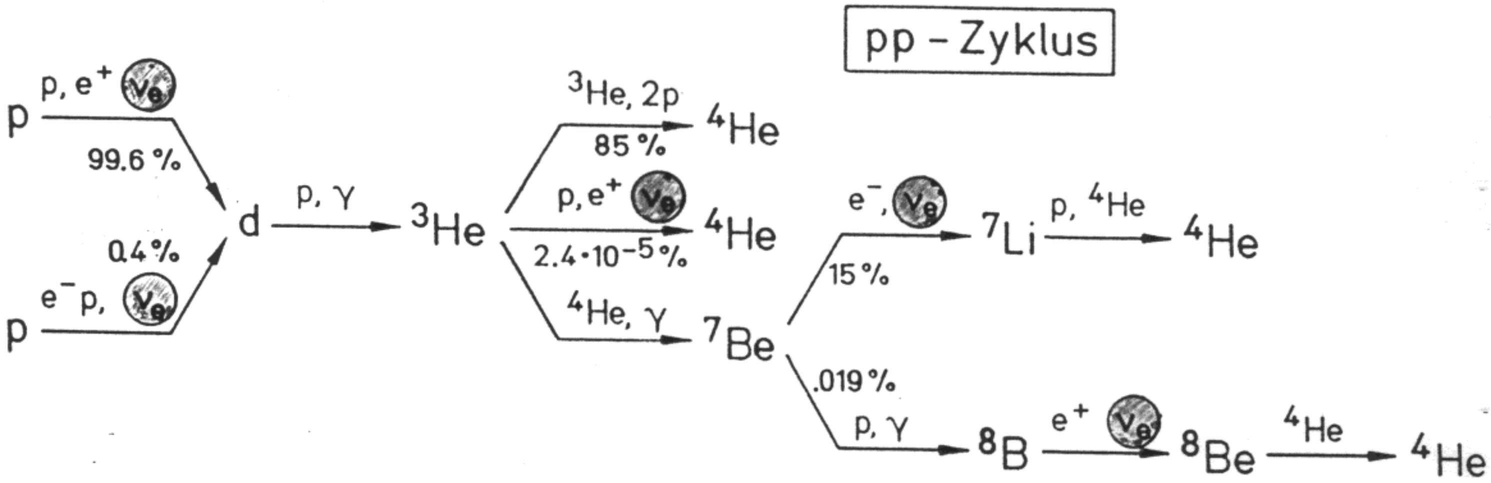
VENICE / 2 / 1999

EXPECTED NEUTRINO FLUXES

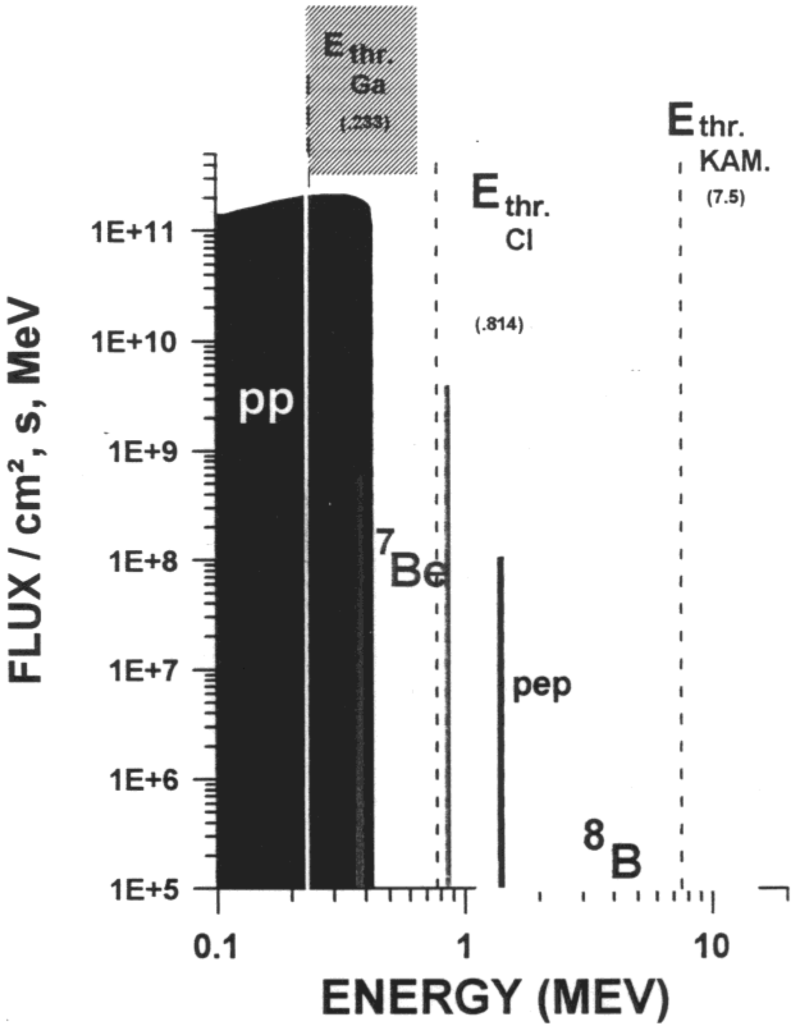
FOR THE SUN, THE PP-CYCLE DOMINATES

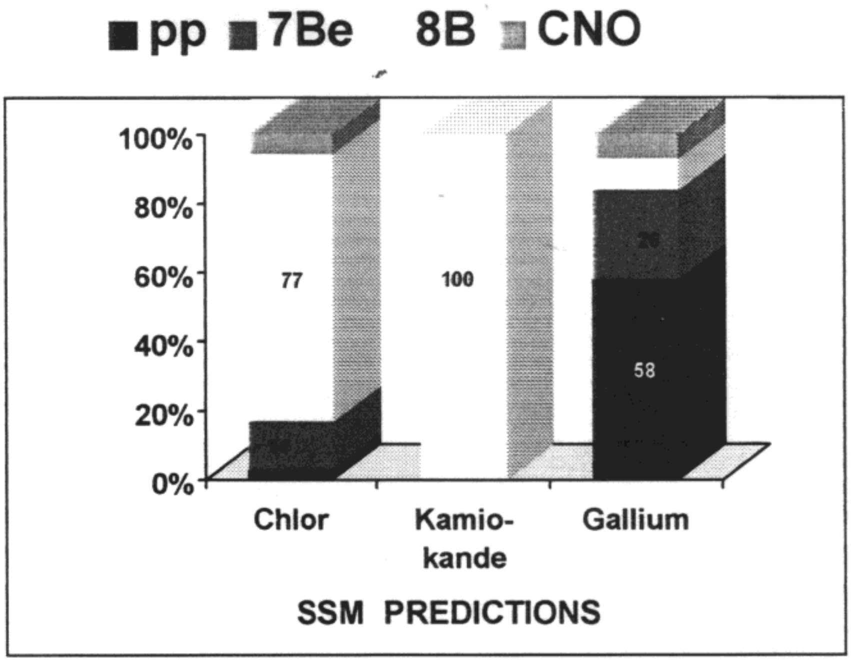
$$4H \longrightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$
$$\langle E(2\nu_e)\rangle = .59\ MeV$$



arriving on Earth:

pp - ν :		60 Billions /cm^2,s	$\sim T_c^{-1}$
^{7}Be - ν :	~	5 Billions /cm^2,s	$\sim T_c^{8}$
^{8}B - ν :	~	5 Millions /cm^2,s	$\sim T_c^{18}$


E thr. Ga
(.233)
E thr. Cl
(.814)
E thr. KAM.
(7.5)
1E+11
1E+10
1E+9
1E+8
1E+7
1E+6
1E+5
FLUX / cm², s, MeV
pp
7Be
pep
8B
0.1
1
10
ENERGY (MEV)


pp
7Be
8B
CNO
100%
80%
60%
40%
20%
0%
77
100
58
Chlor
Kamio-
kande
Gallium
SSM PREDICTIONS

NEUTRINO DETECTION

'Inverse Beta Decay'

$$\nu_e + A(Z) \Rightarrow A(Z+1) + e^-$$

⇑ SUN ⇑ TARGET ⇑ PRODUCT (radioactive)

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

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

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**

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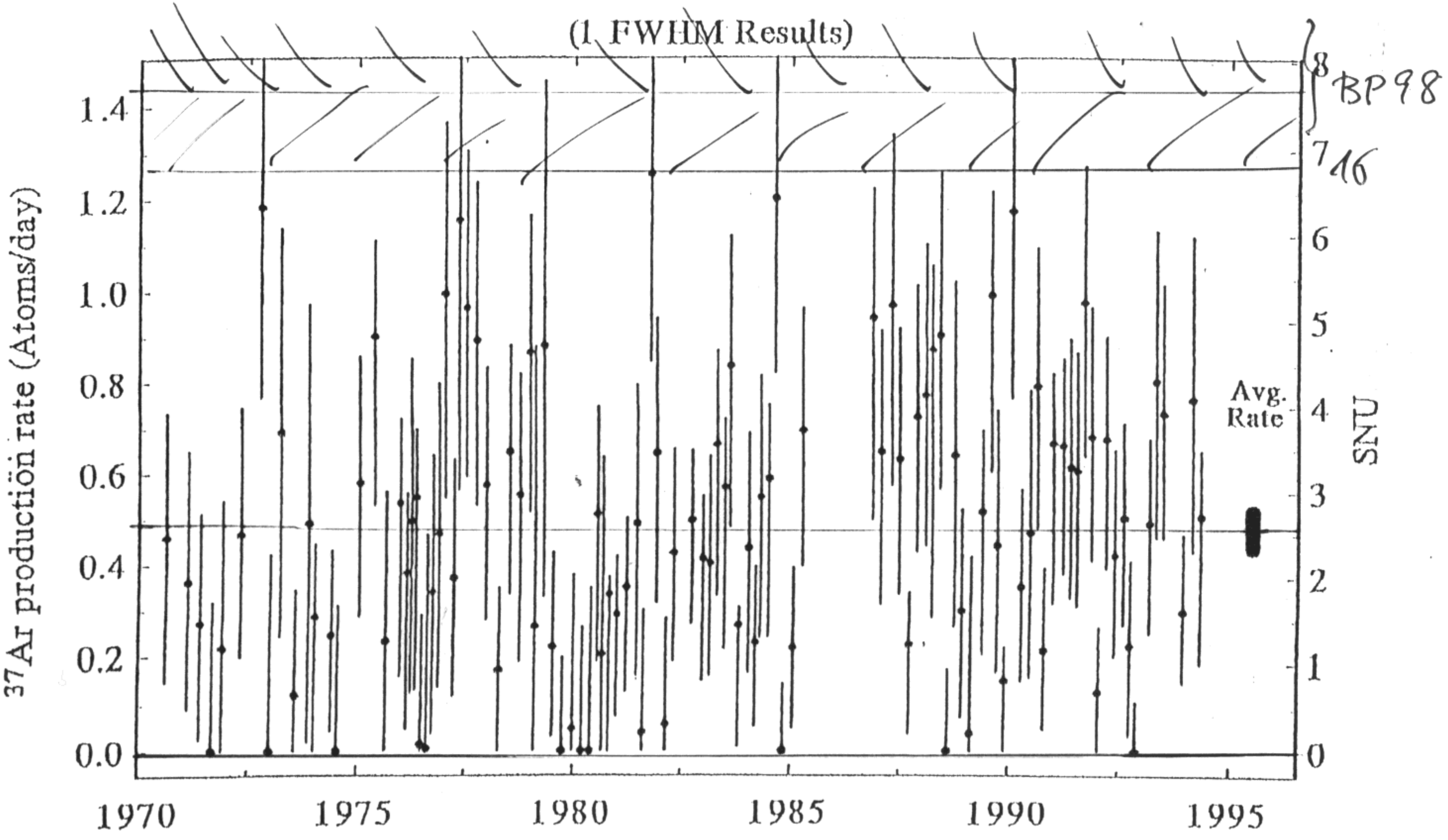
Homestake Chlorine Experiment



Result: 2.56 ± 0.23 SNU

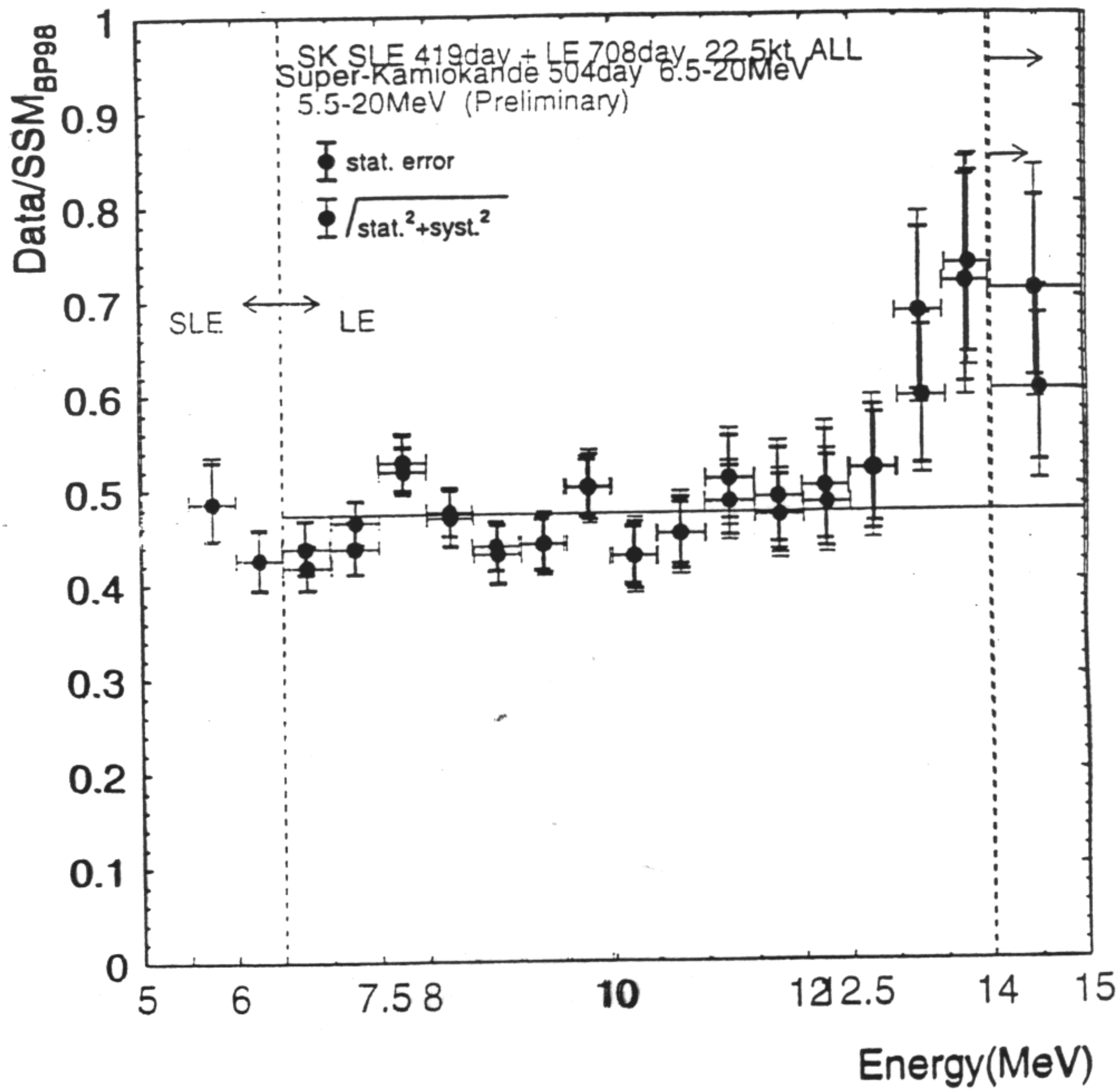
Predicted: BP98: $7.7 \pm^{1.2}_{1.0}$ SNU

$\frac{exp}{th} = \frac{1}{.3}$

check

+ : 504 days (@ ν98) (> 6.5 MeV)

+ : 708 days (> 6.5 MeV)
419 days (5.5 – 6.5 MeV)



GALLIUM-EXPERIMENT

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

i = 39.6 % ; $T_{1/2}$ = 11.43 days
threshold energy: 233 keV

SSM-Expectation:

$129 \pm ^{8}_{6}$ SNU (1σ) ∅ **[B.P.98]with diff.**

[1 SNU = solar neutrino unit = 10^{-36} captures per target nucleus per second]

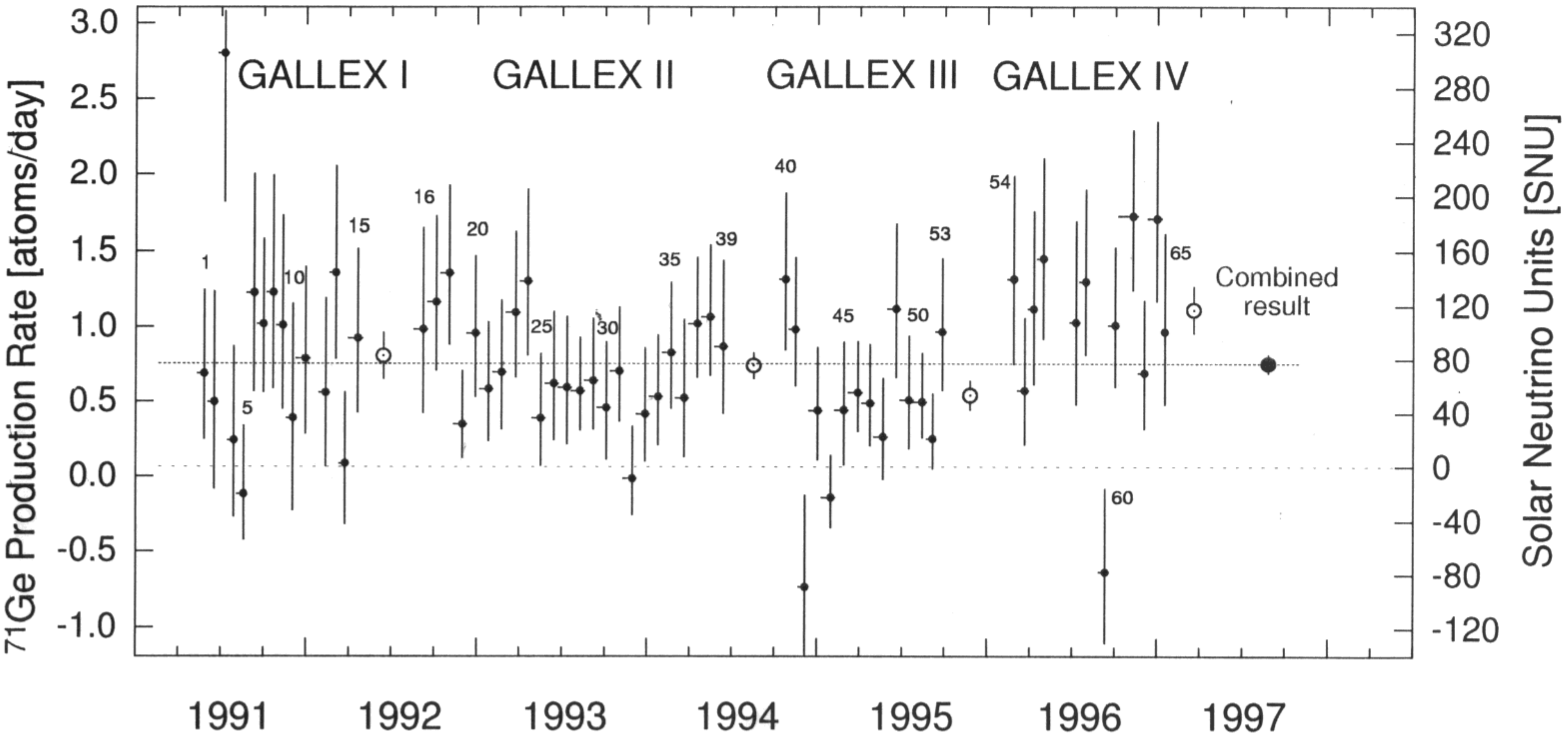
56.5 % from pp - ν (incl.pep) (73 SNU)

34 % from ^{7}Be and CNO - ν (44 SNU)

only 9 % from ^{8}B (12 SNU)

100 tons of aqueous Gallium chloride solution
(= 30.3 t Gallium);
correspond to a SSM-production rate of
1.18 atoms of ^{71}Ge per day or
≈14 atoms at the end of a 3-week exposure

Extraction every 3 - 4 weeks , ε ≅ 99 %



GALLEX I
GALLEX II
GALLEX III
GALLEX IV
Combined
result
71Ge Production Rate [atoms/day]
Solar Neutrino Units [SNU]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
320
280
240
200
160
120
80
40
0
-40
-80
-120
1991
1992
1993
1994
1995
1996
1997
1
5
10
15
16
20
25
30
35
39
40
45
50
53
54
60
65

Result for GALLEX I - IV

77.5 ± 6.2 (stat) $\pm^{4.3}_{4.7}$ (syst) SNU

value rounded, errors combined (1σ): 78 ± 8 SNU

GALLEX I: 83.4 ± 17.2 (stat) $\pm^{6.8}_{9.0}$ (syst) SNU
GALLEX II: 75.~~6~~9 ± 9.7 (stat) $\pm^{4.2}_{4.6}$ (syst) SNU
GALLEX III: 53.~~8~~9 ± 10.6 (stat) ± 3.1 (syst) SNU
GALLEX IV: 118.4 ± 17.8 (stat) ± 6.6 (syst) SNU

χ^2 for the data taking periods to be compatible with the mean of GX I-IV:

periods	SNU	runs contained		χ^2, d.o.f.	confi-dence limit
GX I - IV	**77.5 ± 6.2**				
Gallex 1	83.4 ± 17.2	**15**	(#01 - #15)	**10.43 / 3**	**1.5 %**
Gallex 2	75.6 ± 9.7	**24**	(#16 - #39)		
Gallex 3	53.8 ± 10.6	**14**	(#40 - #53)		
Gallex 4	118.4± 17.8	**12**	(#54 - #65)		
but, rearranged:					
1.quarter of runs	88.3 ± 16.0	**17**	(#01 - #17)	**3.91 / 3**	**26.7 %**
2.quarter of runs	67.6 ± 11.4	**16**	(#18 - #33)		
3.quarter of runs	66.0 ± 10.8	**16**	(#34 - #49)		
4.quarter of runs	95.2 ± 14.2	**16**	(#50 - #65)		

Check of the distribution of single run results using the MAXIMUM LIKELIHOOD RATIO TEST

all runs	χ^2 = 71.6 ; 64 d.o.f.	**24.2 %**

Gallex 3 (8000 MC simulations)	261 cases < 53.8 SNU	**3.3 %**
Gallex 4 (8000 MC simulations)	30 cases > 118.4 SNU	**0.4 %**

PERFORMANCE CHECKS OF THE GALLEX DETECTOR

already existing tests:

Ge - Carrier

In *each* run the recovery of ≈ 1 mg initially added stable Ge-carrier-isotope is routinely measured.
Yields are > 97 % (more than 100 runs!)

$O(10^{19})$ atoms Ge in 10^{30} target atoms

≈ 1% - experiment

^{51}Cr - Neutrino Source

in situ neutrino-induced ^{71}Ge-production, direct verification

$O(10^{2})$ atoms ^{71}Ge in 10^{30} target atoms;

≈ 10 % -experiment

New: ARSENIC - SPIKING EXPERIMENTS

^{71}As - Beta-decay

in-situ production of ^{71}Ge via beta-decay of ^{71}As added to the target tank

$O(10^{4})$ atoms ^{71}Ge in 10^{30} target atoms

≈ 1 % - experiment

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GALLEX ^{51}Cr ν- SOURCES

Source strengths:

1: $1.71 \pm ^{.03}_{.04}$ MCi; 2: $1.87 \pm ^{.09}_{.06}$ MCi

Measured rate:

$$R = \frac{\text{OBSERVED}}{\text{EXPECTED}} = \mathbf{0.93 \pm 0.08}$$

[1.01 ± 0.10 and 0.84 ± 0.11]

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with new value for solar "background" after GALLEX IV (=77.5 SNU):

$$R = \mathbf{0.91 \pm 0.08}$$

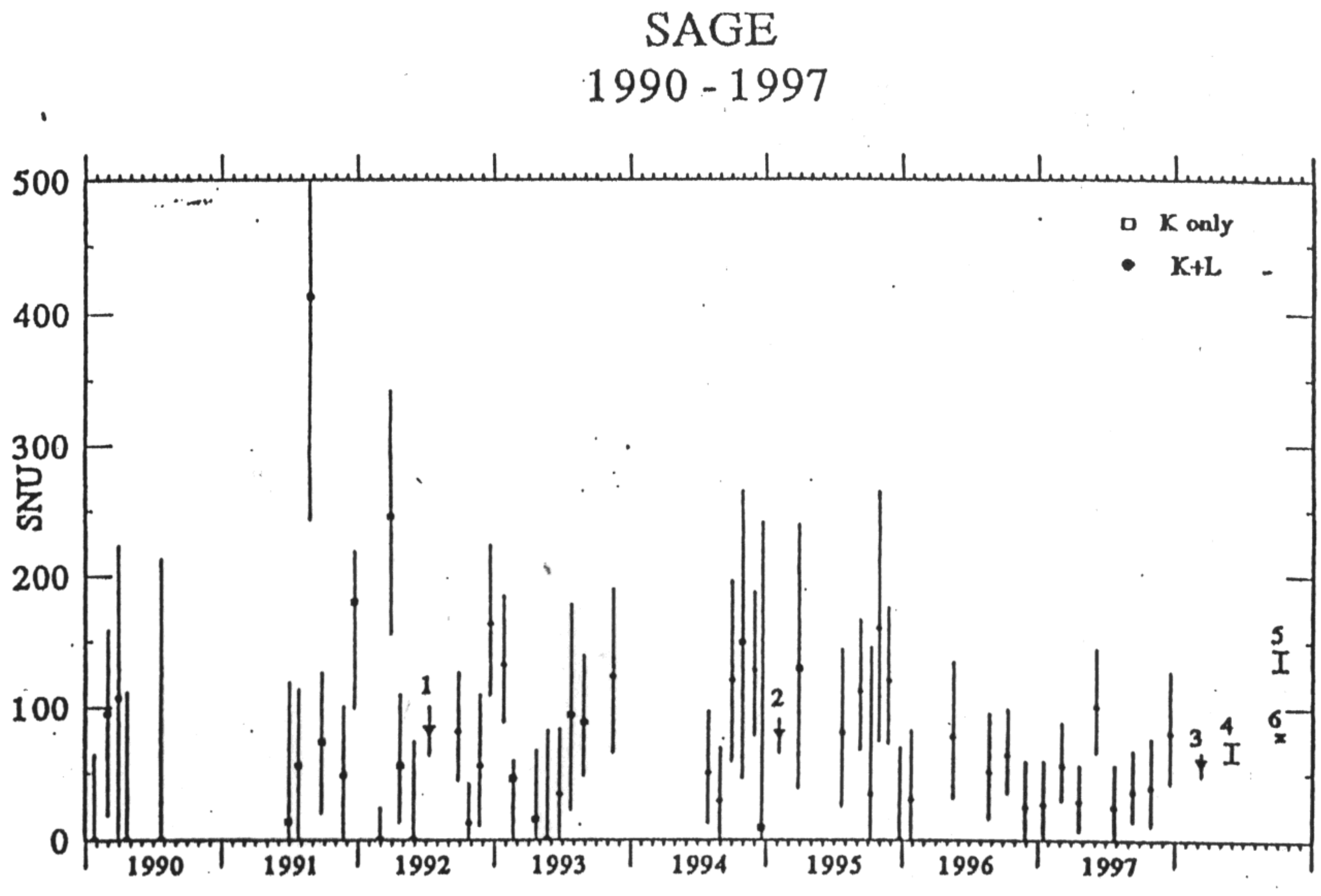
EXPERIMENTAL PROOF OF THE RADIOCHEMICAL METHOD

As - major results (subm. to Phys.Lett.B , May 1998)

As preparation	A		B	
As experiment #	1	2	3	
tank residence time	long	long	short	long
name of experiment	A1t	A2t	B3tS	B3tL
description of the experiment	heavy mixing	carrier free no mixing	short exposure (3d)	long exposure (22d)
result (recovery in %)	100.7 ± 1.6 %	99.6 ± 1.4 %	99.7 ± 1.4 %	99.4 ± 1.8 %

GALLEX overall recovery factor: $R_{experim.}$ = 99.9 ± 0.8 % (1σ)

Blanks : theoretical yields confirmed
unknown memory < per mil !

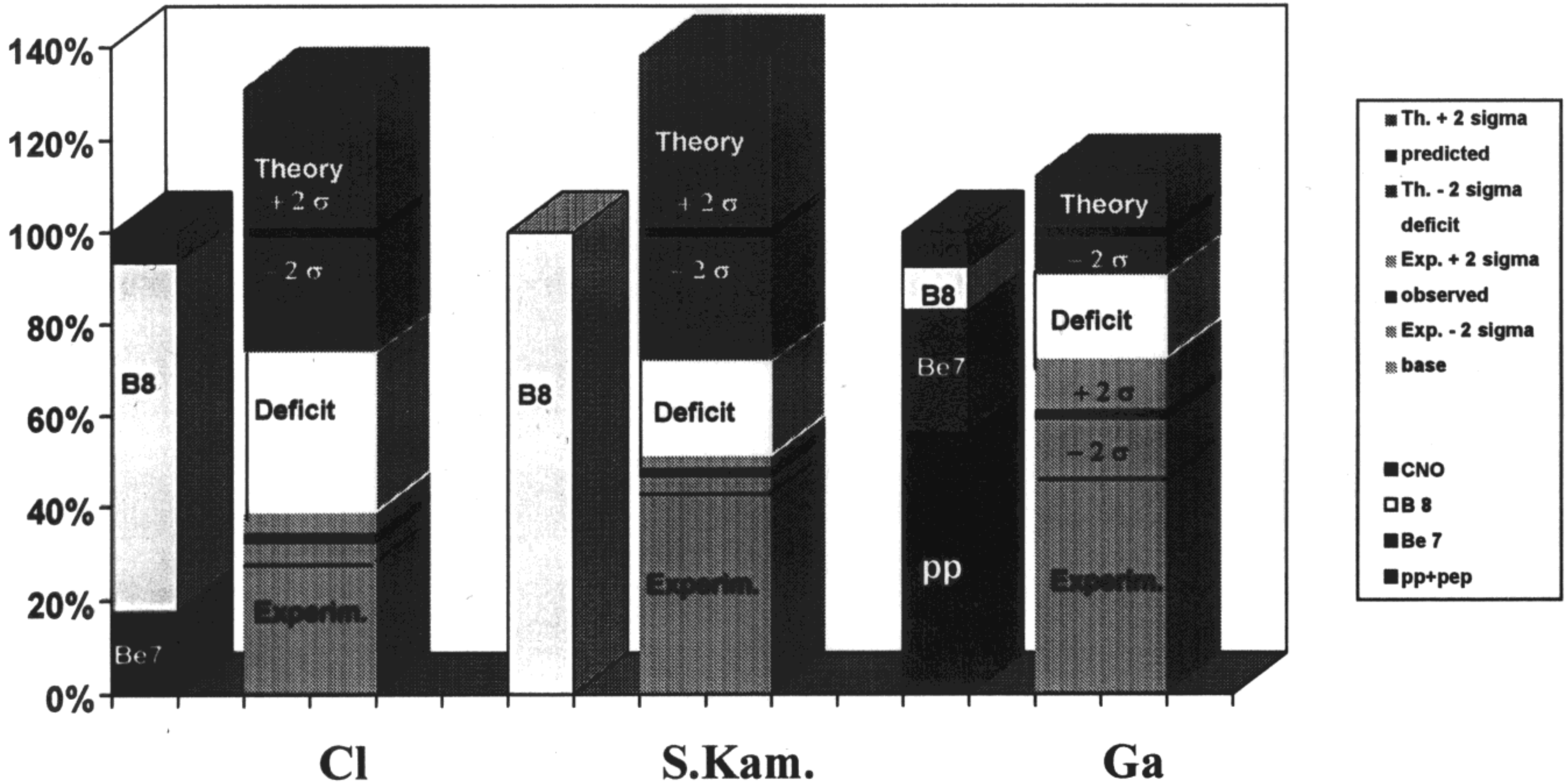


SAGE
1990 - 1997
K only
K+L
SNU
500
400
300
200
100
0
1990
1991
1992
1993
1994
1995
1996
1997
1
2
3
4
5
6

	HOME-STAKE	GALLEX	SAGE	KAMIO-KANDE	SUPERKA-MIOKANDE
Energy threshold	0.814 MeV	0.233 MeV	0.233 MeV	7.5 MeV	5.5 MeV
Sample	108 runs	1593 d/ 65 r.	52 runs	2079 days	708 days
Period	1970 - 1994	1991 - 1997	1990 - 1997	1987 - 1995	5/96 – 11/ 98
Reference	Cleveland *et al.*, (1997)	T. Kirsten (1998)	Sage Collab. (1998)	Fukuda *et al.*, (1996)	Y. Suzuki, (1999)WIN 99
Prediction, S_{th} (Bahcall and Pin-sonneault, 1998)	$7.7 \pm ^{1.2}_{1.0}$ [SNU]	$129 \pm ^{8}_{6}$ [SNU]	$129 \pm ^{8}_{6}$ [SNU]	$5.15 \pm ^{0.98}_{0.72}$ [10^6 ^{8}B-ν / cm^2 s]	$5.15 \pm ^{0.98}_{0.72}$ [10^6 ^{8}B-ν / cm^2 s]
EXPERIMENTAL RESULT, S_{exp}	**2.56 ± 0.22** [SNU]	**77.5 ± 8** [SNU]	**66.6 ± 8** [SNU]	**2.82 ± 0.38** [10^6 ^{8}B-ν / cm^2 s]	**2.42 ± 0.08** [10^6 ^{8}B-ν / cm^2 s]
Observed ratio $R = S_{exp} / S_{th}$	(33 ± 6) %	(60 ± 7) %	(52 ± 7) %	$(55 \pm ^{13}_{11})$ %	$(47 \pm ^{9}_{7})$ %
Reduction factor $R^{-1} = S_{th} / S_{exp}$	3.0	1.7	1.9	1.8	2.1
Deficit (absolute) $\Delta = S_{th} - S_{exp}$	$5.14 \pm ^{1.22}_{1.02}$ [SNU]	$51.5 \pm ^{11.2}_{9.8}$ [SNU]	$62.4 \pm ^{11.2}_{10.1}$ [SNU]	$2.33 \pm ^{1.05}_{0.81}$ [10^6 ^{8}B-ν / cm^2 s]	$2.73 \pm ^{0.99}_{0.73}$ [10^6 ^{8}B-ν / cm^2 s]
Signif.of minimal deficit $\lvert \Delta / -\delta\Delta \rvert$	**5.0 σ**	**5.3 σ**	**6.2 σ**	**2.9 σ**	**3.7 σ**

RESULTS OF SOLAR NEUTRINO EXPERIMENTS (08/98)

2σ



| (33 ± 6)% | (47 ± 4)% | (60 ± 12)% | [T.K.]

of SSM EXPECTATION [(BP98) 2σ-experim.only]

SNTR808d.DOC

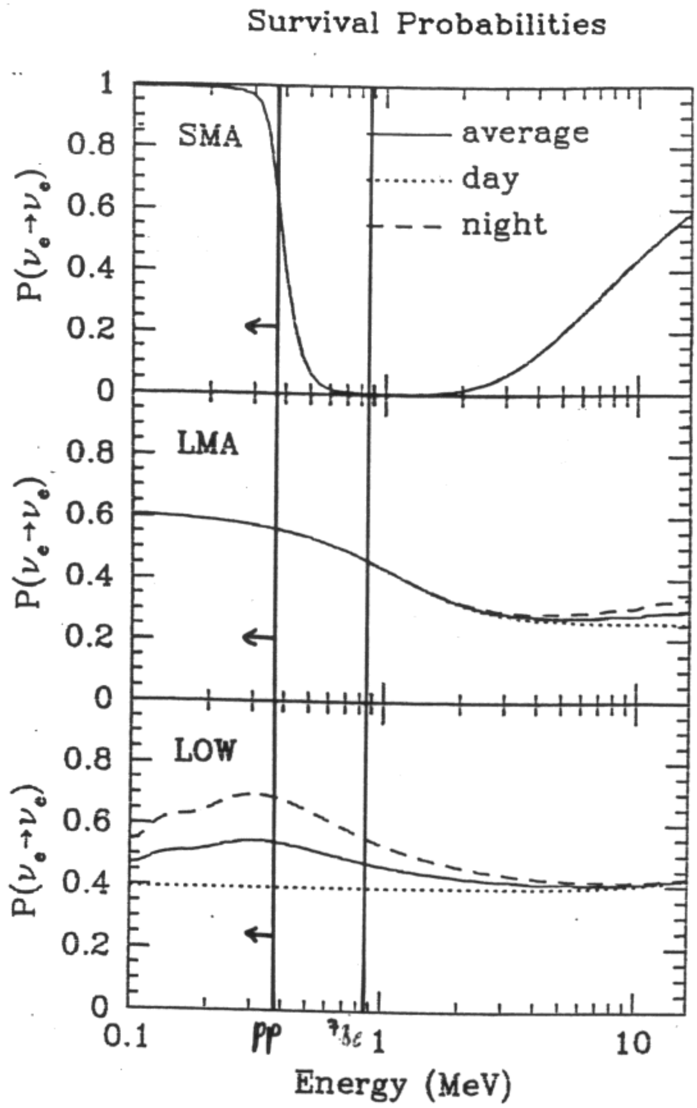
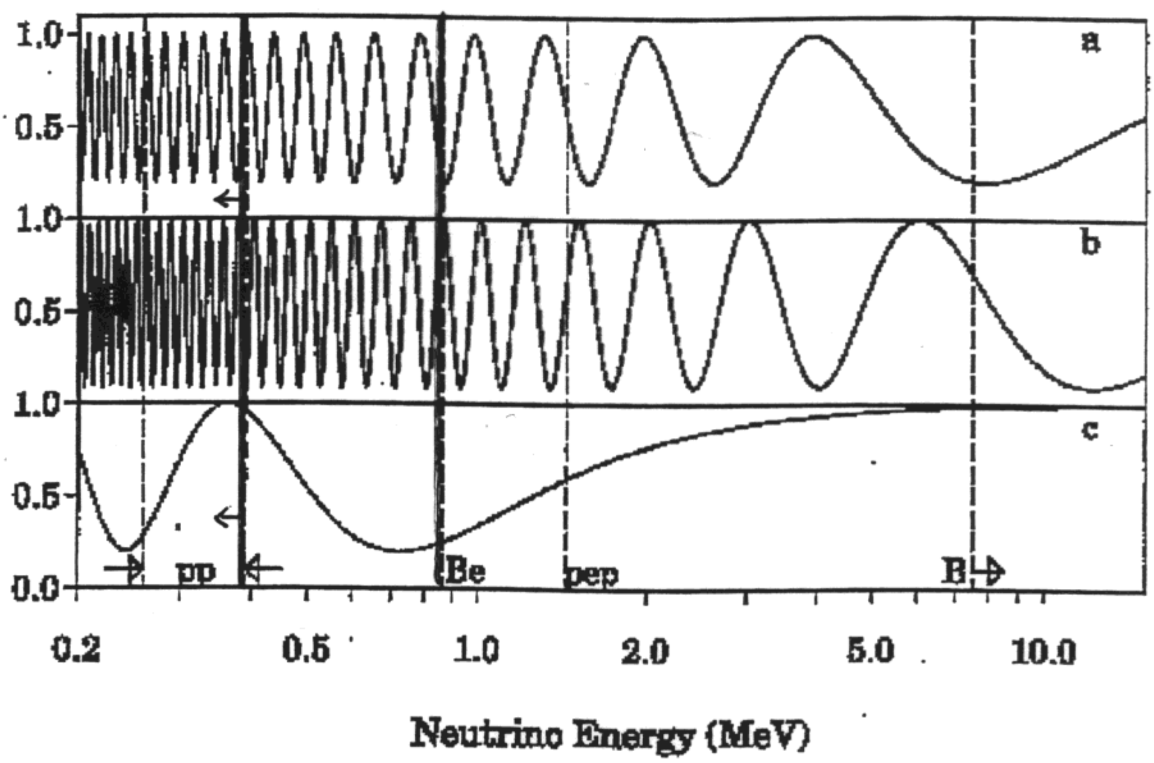


Fig. 1 Survival probabilities of ν_e *on Earth shown for the various MSW solution.*



2 Survival probabilities of ν_e *on Earth shown for the various vacuum solution.*

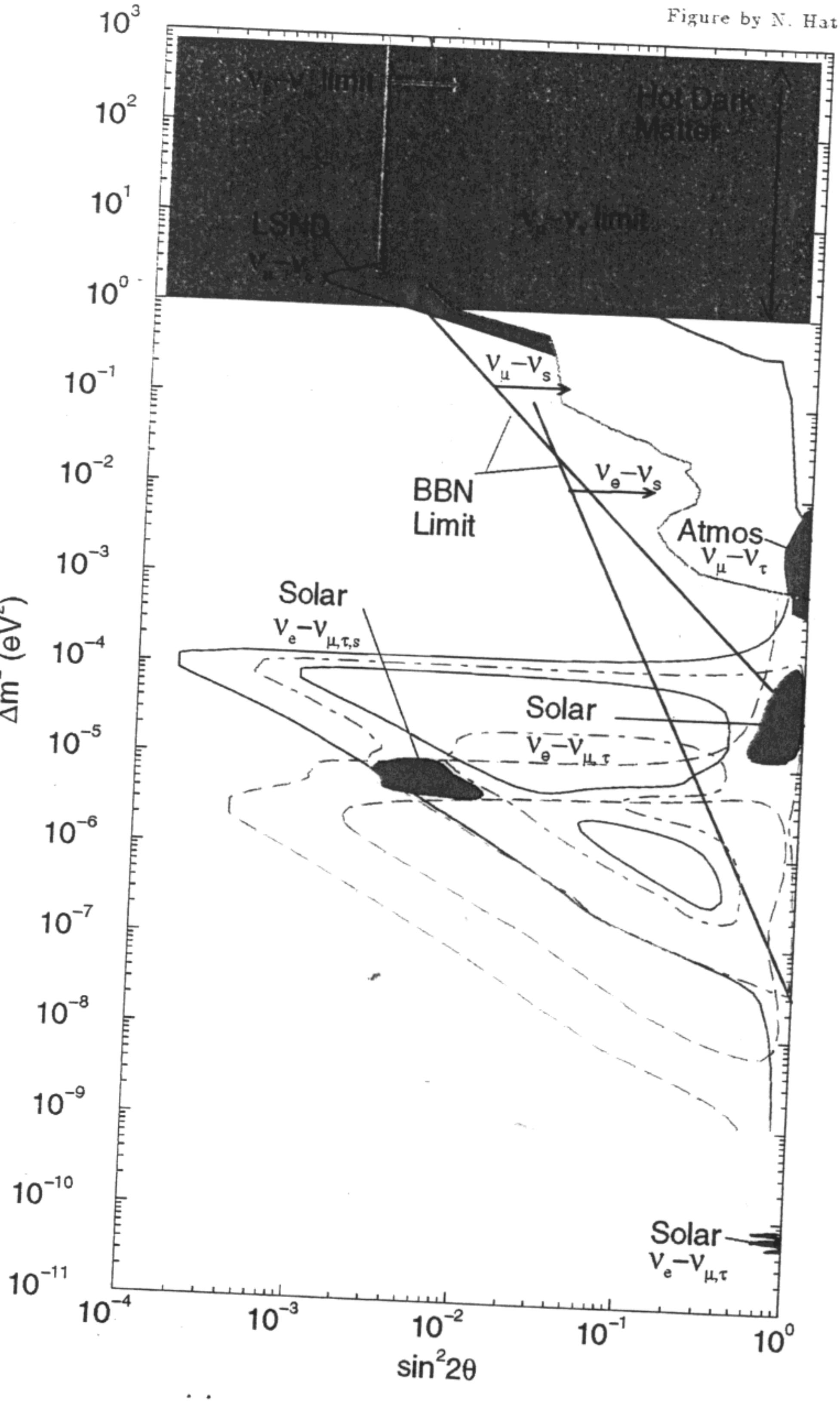


Figure by N. Hata.

→ The experimental results from five solar neutrino experiments and their error estimates are reliable

→ Helioseismological observations confirm that the Standard Solar Model is a very good model

→ Fine tuning of solar models or change of the input data has no principal influence on the persistence of the 2nd and 3rd solar neutrino problem

→ Just to lower ad-hoc the central temperature of the Sun is not sufficient to explain the data

→ Neutrino flavor conversion can consistently account for all solar neutrino data

→ No plausible alternatives have yet been suggested

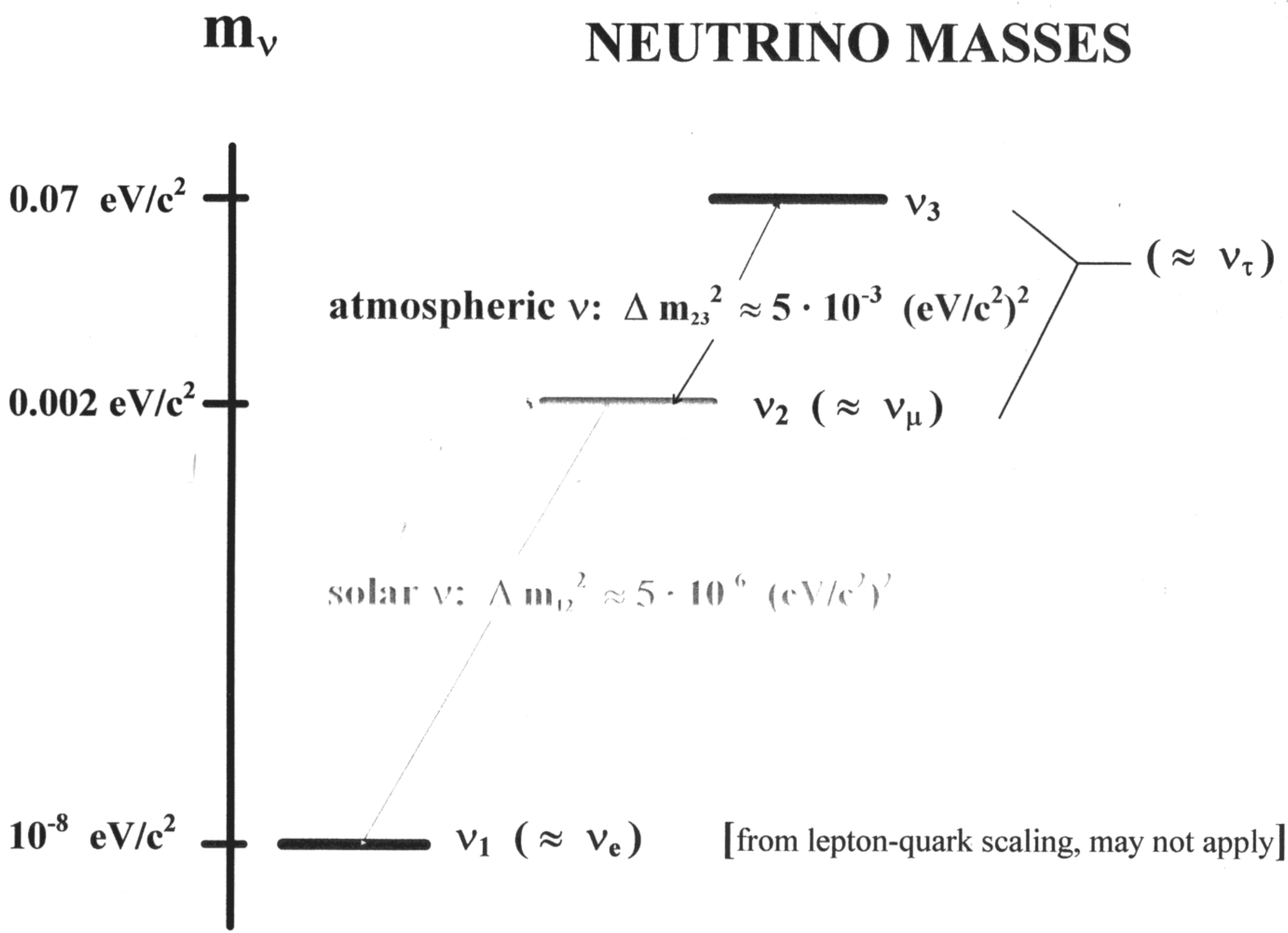
The evidence is between convincing and overwhelming, however, there is no 'smoking gun'. Being based on disappearance, it is indirect.
The situation for the Superkamiokande ν_μ / ν_e anomaly for atmospheric neutrinos is similar: convincing, yet indirect.

Solar MSW solution: $\delta m^2 \approx 5 \cdot 10^{-6}\ (eV/c^2)^2$ $\nu_e \leftrightarrow \nu_\mu$

Athmospheric MSW solution: $\delta m^2 \approx 5 \cdot 10^{-3}\ (eV/c^2)^2$ $\nu_\mu \leftrightarrow \nu_\tau$

Fitting the same scheme (MSW), the 'solar' evidence and the 'atmospheric' evidence tend to support each other and increase the probability that their interpretation reflects the truth.

NEUTRINO MASSES



Reaction	$E_{thr.}$ MeV	domin. ν-type	Target form	Detection method	Fidu. tons	Events / day	Project	Year (?!)
$e^-(\nu_x, \nu_x)e^-$	0.3 (e^-)	^{7}Be-ν	Pseudo-cumene	liquid scintillator	100	43 (SSM)	BOREXINO	2001
$e^-(\nu_x, \nu_x)e^-$	0.3 (e^-)	^{7}Be-ν	open	liquid scintillator	100	40 (SSM)	KAMLAND	2001?
$e^-(\nu_x, \nu_x)e^-$	0.2 (e^-)	pp-ν	He gas 5 atm,77K	TPC	8^α	7 (SSM)	HELLAZ	>>2002
$e^-(\nu_x, \nu_x)e^-$	0.2 (e^-)	pp-ν	CF_4 gas (1 atm)	TPC	7^α	10 (SSM)	SUPER-MuNu	>>2002
$e^-(\nu_x, \nu_x)e^-$	0.2 (e^-)	pp-ν	liquid He	cryogenic roton detect.	10^α	20 (SSM)	HERON	>2000
$^2H(\nu_x, e^-)$ pp $^2H(\nu_x, \nu_x)$ pn	6.5 2.2	^{8}B-ν	heavy water	Cerenkov + n-detector (^{3}He; or ^{35}Cl)	1000	25 5 (SSM)	SNO	1999 -

Future ***Radiochemical*** *Experiments*

$^7Li(\nu_e, e^-)\,^7Be$ (53.3 d)	862	^{8}B-ν	Li-metal	Low-T calori-meter	≈10 t	≈ 60 ± 10	Moscow/ Genova	pilot phase
$^{127}I(\nu_e, e^-)\,^{127}Xe^*$ (36. d)	789	^{7}Be-ν (?)	aqu. NaI solution	P.C. + NaI γ - coincidence	100 t iodine	≈ 50 (?)	U. of Penn-sylvania	started modul
$^{131}Xe(\nu_e, e^-)\,^{131}Cs$ (9.7 d)	352	^{7}Be- + ^{8}B-ν	liquid Xe	Si – ionization semiconductor	1000 t	$45 \pm ^{12}_{6}$	Kiev	very early ideas

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REACTION	$E_{thr.}$ MeV	domin ν-type	Target form	Detection method	Fidu. tons	Events / day	Project	Year (?!)
^{7}Li (ν_e , e^-) ^{7}Be no coinc.	≈ 0.5	pep-ν	LiF cryst. LiI(Eu)cr.	cryog. thermal bolometer crystal scint.	4^{α}	0.1 (SSM)	AT&T ,Bell Univ. of Maryland	>>2000 just ideas
^{19}F (ν_e , e^-) $^{9}Ne^*$	≈ 5	^{8}B-ν	hexafluoro benzene	liquid scintillator	600^{α}	10 (SSM)	INR	just ideas
^{40}Ar (ν_e , e^-)$^{40}K^*$	≈ 5	^{8}B-ν	liquid Ar	time projection chamber	$600 \cdot x^{\alpha}$	1· x (x = 1...10)	ICARUS	1999 -
^{71}Ga(ν_e , e^-)^{71}Ge no coinc.	0.23	pp-ν	GaAs crys.	ioniz. semic. (20 °C)	125^{α}	2	INR + LANL	just ideas
			Ga single crystals	cryog. therm. detector	60^{α}	2	Oxford, others	just ideas
^{81}Br (ν_e , e^-)$^{81}Kr^*$	0.47	^{7}Be-ν	NaBr or CsBr cr.	cryogenic therm. bolom.	100^{α}	0.7	Milano University	>>2002
^{115}In(ν_e,e^-) $^{115}Sn^*$	0.12	pp-ν	InSb crystals	supercond tunnel junct.	4^{α}	1 (SSM)	Oxford	>>2002
^{176}Yb(ν_e ,e^-) $^{176}Lu^*$ ^{160}Gd(ν_e ,e^-) $^{160}Tb^*$	0.3 0.24	pp + ^{7}Be-ν	dissolved in scintill.	liquid scintillator	10^{α}	0.5 (SSM)	LENS	LOI

<u>all these reactions can in principle exploit:</u> $e^-(\nu_x,\nu_x)e^-$ and neutral current excitations of type $T(\nu_x,\nu_x)T^* \rightarrow T + \gamma$ (T=target nuclide) as well.

GNO STATUS (2/99)

GNO
is a
RUNNING EXPERIMENT

- extraction run GNO 1 was done on 22 April 1998 (~1 year exposure!)
- since then, regular run schedule
- extraction run GNO 11 was done on 9 February 1999
- counting already completed for runs GNO I – GNO 6
- the first GNO data release is planned after completion of counting of ≈15 runs. This is anticipated for end of this year (≈12/99)

DETECTION REACTIONS

1) Inverse beta decay (Charged Current)

$\nu_e + d \rightarrow p + p + e^-$ 11* events/day

2) Deuteron disintegration (Neutral Current)

$\nu_x + d \rightarrow p + n + \nu_x$ 3 to 9* events/day

releases neutron into D2O

Neutron Observation:

a) $n + d \rightarrow t + \gamma$

b) $n + Cl \rightarrow Cl + \gamma$

c) $n + {}^3He \rightarrow t + p$

3) Electron Scattering (ES)

$\nu_{\underset{(x)}{e}} + e^- \rightarrow \nu_{\underset{(x)}{e}} + e^-$ 1* event/day

same as in H_2O

* assumes a 5 MeV detection threshold

BOREXINO

REAL TIME LOW-ENERGY NEUTRINO DETECTOR AT GRAN SASSO

Objective: measure ^{7}Be- ν flux (Compton-edge at 600 keV)
EXPECTED SIGNAL [d^{-1}]: SSM 53 ± 7; MSW,SA $12 \pm^{13}_{0.5}$;
MSW,LA $31 \pm^{8}_{10}$; V.O. $24 \pm^{24}_{10}$
EXPECTED BACKGROUND [d^{-1}]: ≈ 12 (BASED ON CTF-RESULTS)

$\nu_e\,(e^-, e^-)\,\nu_e$; Threshold $E_\nu > 400$ keV ($E_e > 150$ keV)

300 t liquid Scintillator (fid.:100 t). Pseudocumene + PPO
linear Dimensions: height: 17 m ; diameter: 18 m

Onion shell: INNER NYLON VESSEL / NYLON SHROUD / STAINLESS STEEL SPHERE / WATER TANK / ROCK
SCINTILLATOR / ORGANIC BUFFER / WATER (2.5 KILOTONS)

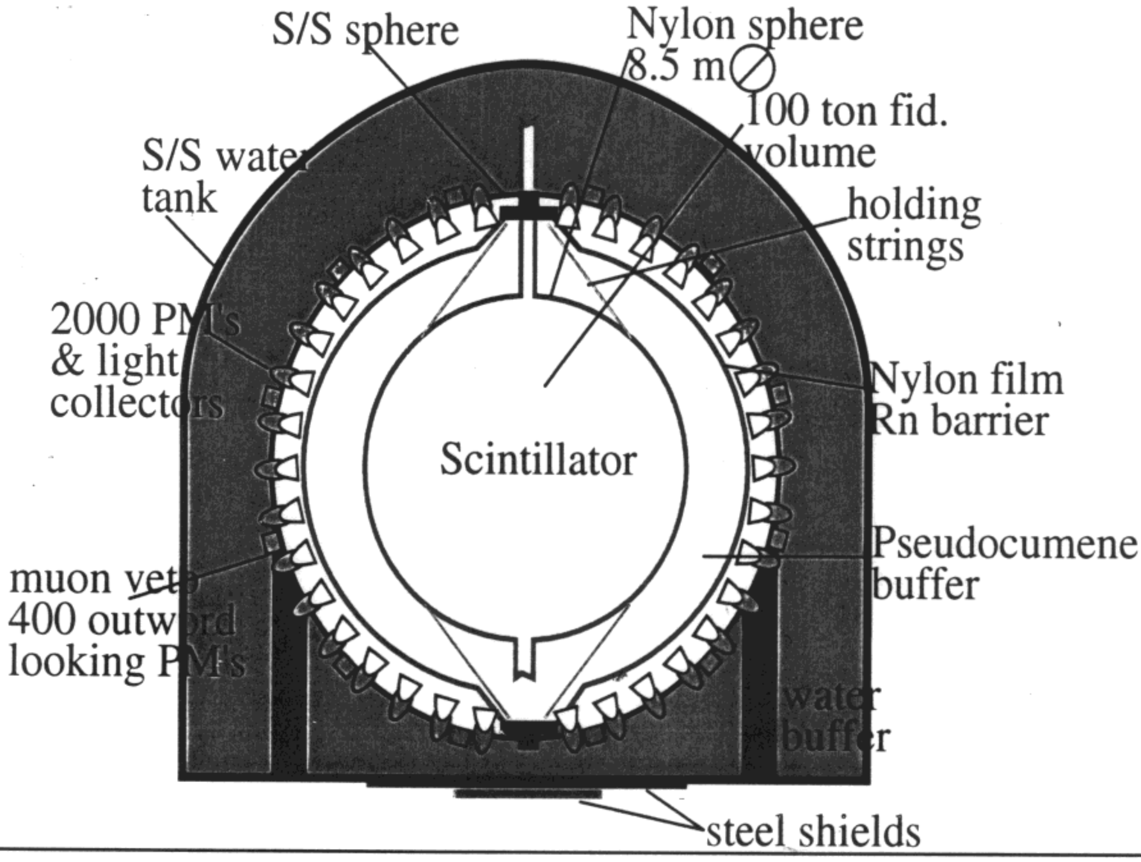
PMT coverage: 30 %
2000 PMT + 400 for muon veto (outwards)
energy resolution (at .2 - .8 keV): 8 %
spatial resolution ≈ 10 cm

BOREXINO

STATUS = UNDER CONSTRUCTION

Real time detector for low energy (>0.4 MeV) solar neutrinos

Physics.
Measure the monoenergetic (0.86 MeV) electron neutrinos from ^7Be
Solar Standard Model → 18.000 events/year (2 ev./h)
Possible interpretation of existing experiments ⇒ ≤0



300 tons liquid scintillator (Pseudocumene + PPO)
surrounded by a S/S sphere, 13.7 m diameter, supporting 2200 PMT's & optical concentrators.
space between nylon vessel and sphere is filled with pure Pseudocumene
second nylon balloon, 11m diameter: barrier against Rn diffusion
the S/S sphere is immersed in 2500 t of purified water contained in a tank (18m diam., 16.9m height)

PM coverage	**30%**
en resol (200-800 keV)	**8%**
spatial resolution	**10-15 cm**

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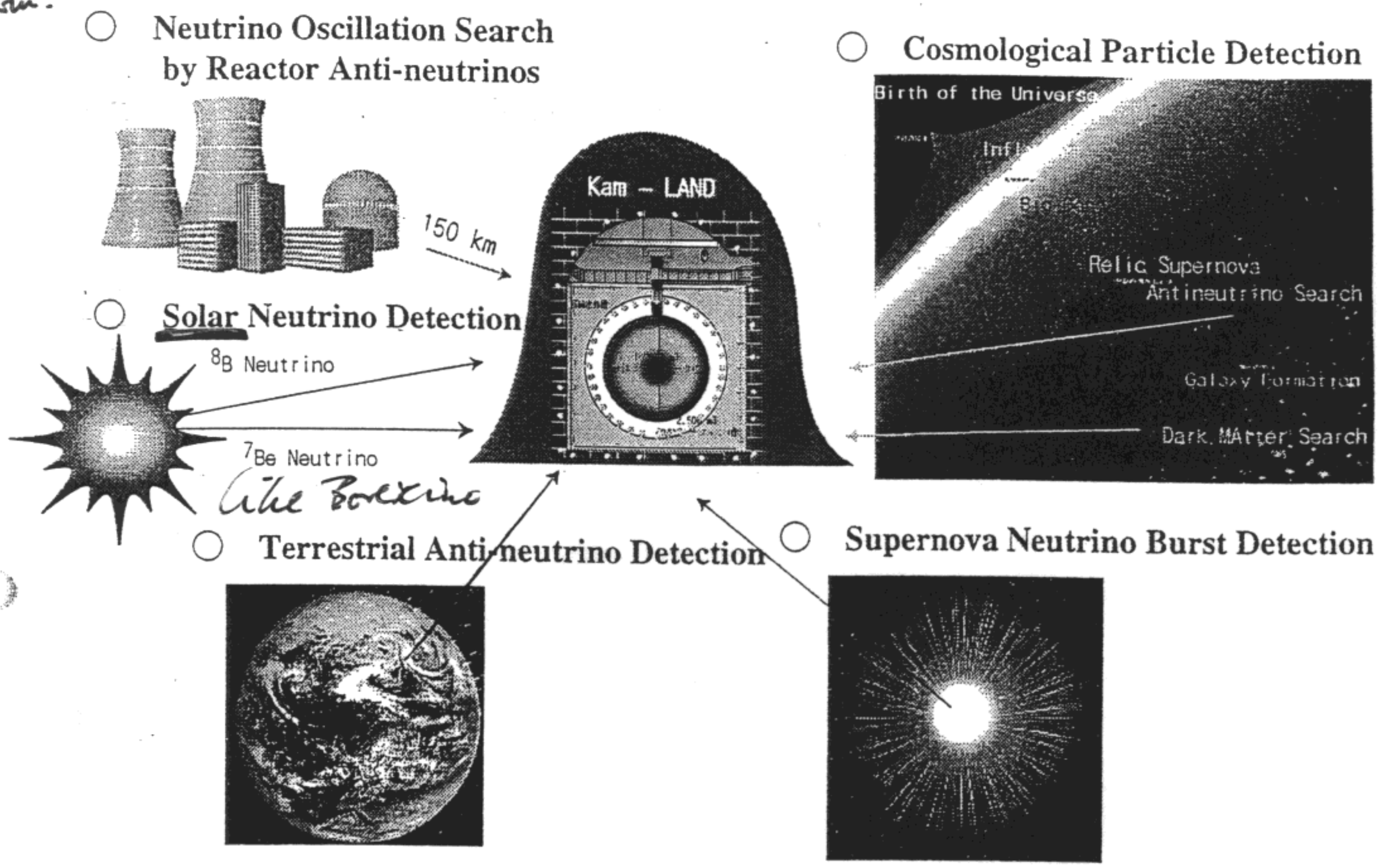
BOREXINO STATUS DETAILs (2/99)

Water tank	completed, hydrostatic test done
Stainless steel sphere	panels with flanges ready, presently surface treatment
Scintillator and buffer	Enichem in Sarroch, shipping vessels: tender
PMT	glass problems at ETL (EMI) 4/98 – 10/00
Electronics	in production
Purification and fluid handling:	parts prepared, assembly in 6/99 in hall C
External clean room	(for PMT assemblage) ready
Radon monitoring	ready (Morex)
Nitrogen plant	90% ready
Cr-neutrino source	feasibility study at RIAR: > 2.5 MCi source feasible

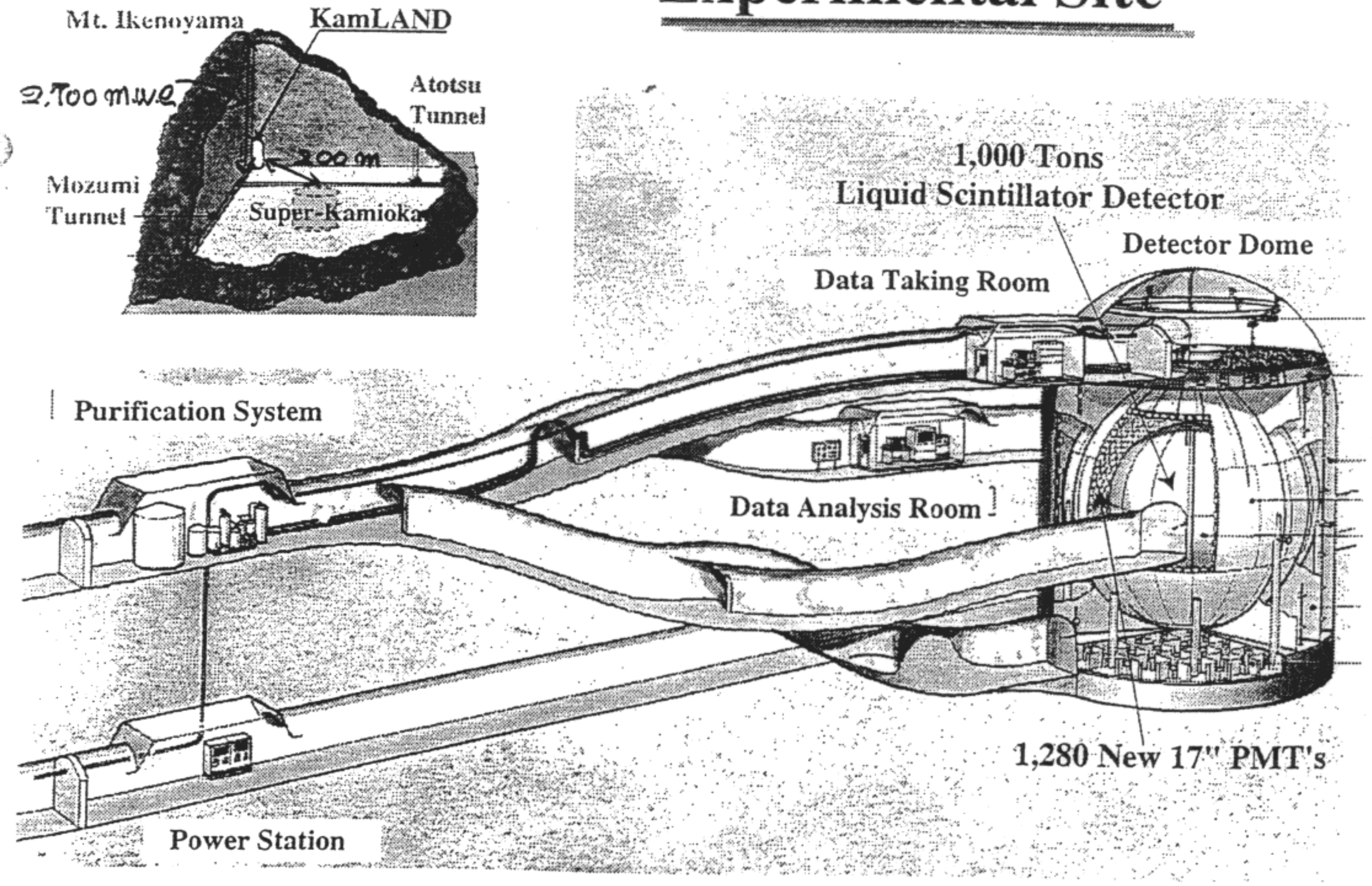
$\bar{\nu} + p \rightarrow e^+ + n$

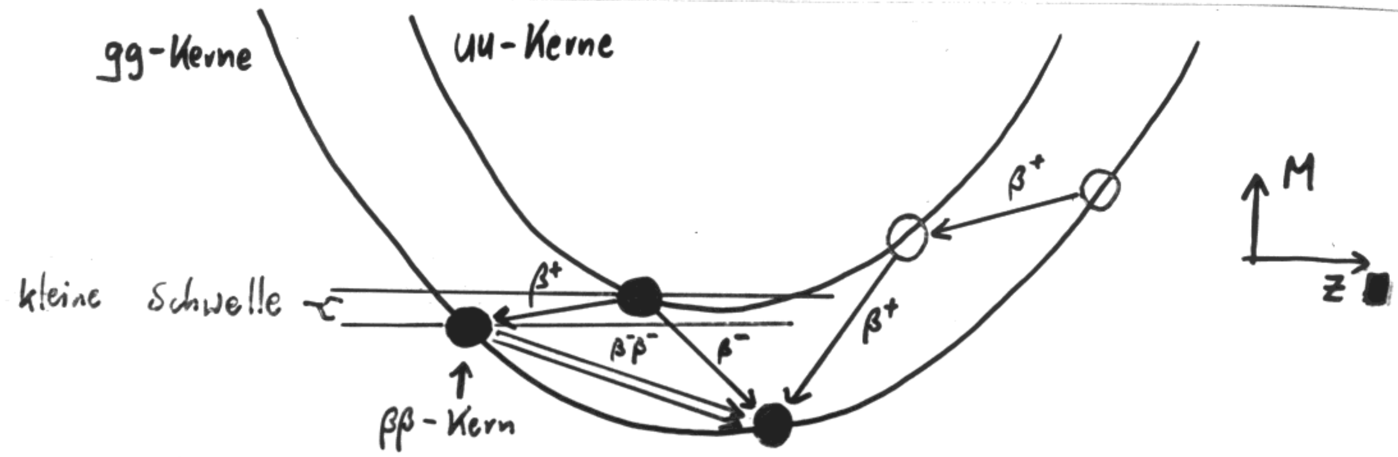
$n + p \rightarrow d + \gamma$ del-coinc.

KamLAND Physics

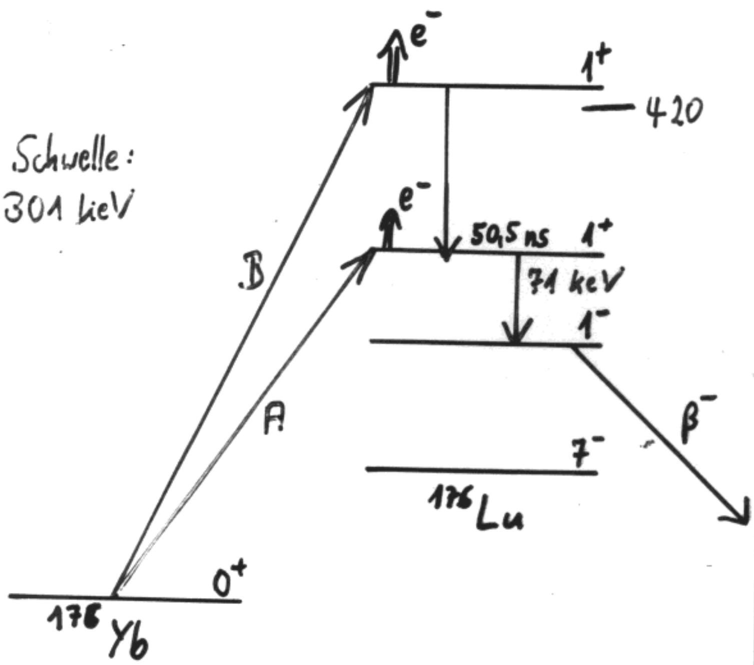


Experimental Site

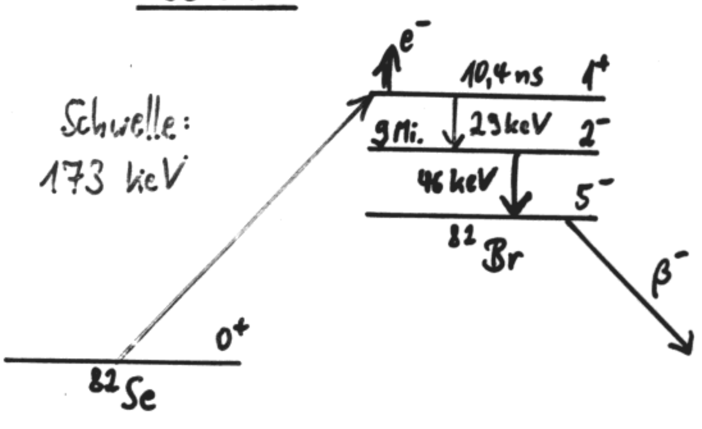




Ytterbium:



Selen:



Gadolinium: