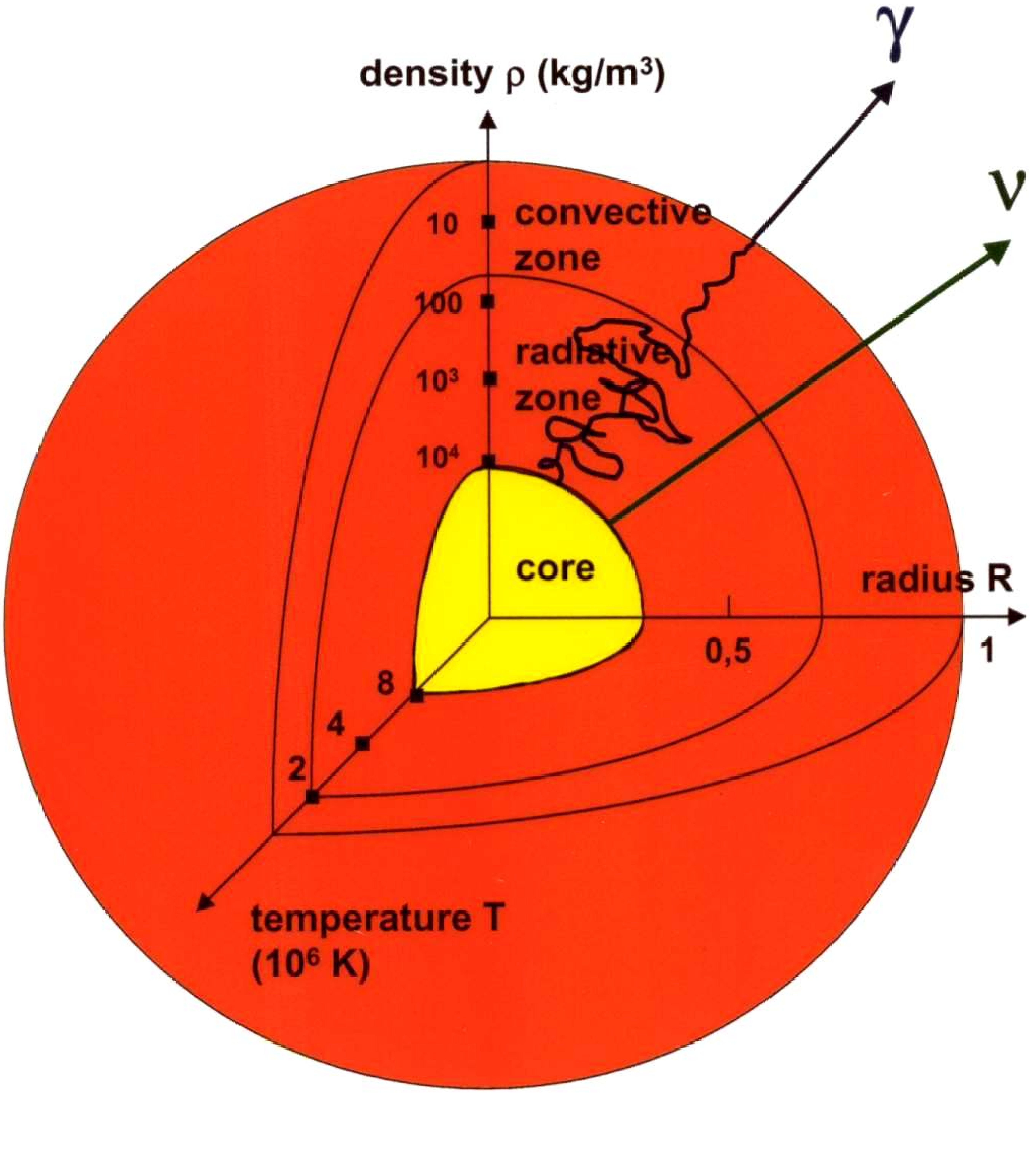
Les Houches
June 19, 2001
D.Vignaud

Solar neutrinos : past, present and future

1. The Sun … and the neutrinos
2. Solar neutrino results
   - Chlorine
   - Gallium
   - SuperKamiokande
   - SNO !
3. The solar neutrino problem : towards the neutrino mass ?
4. New experiments
   - Short term (Borexino)
   - Long term : R&D(s) in progress
5. (Tentative) Conclusion

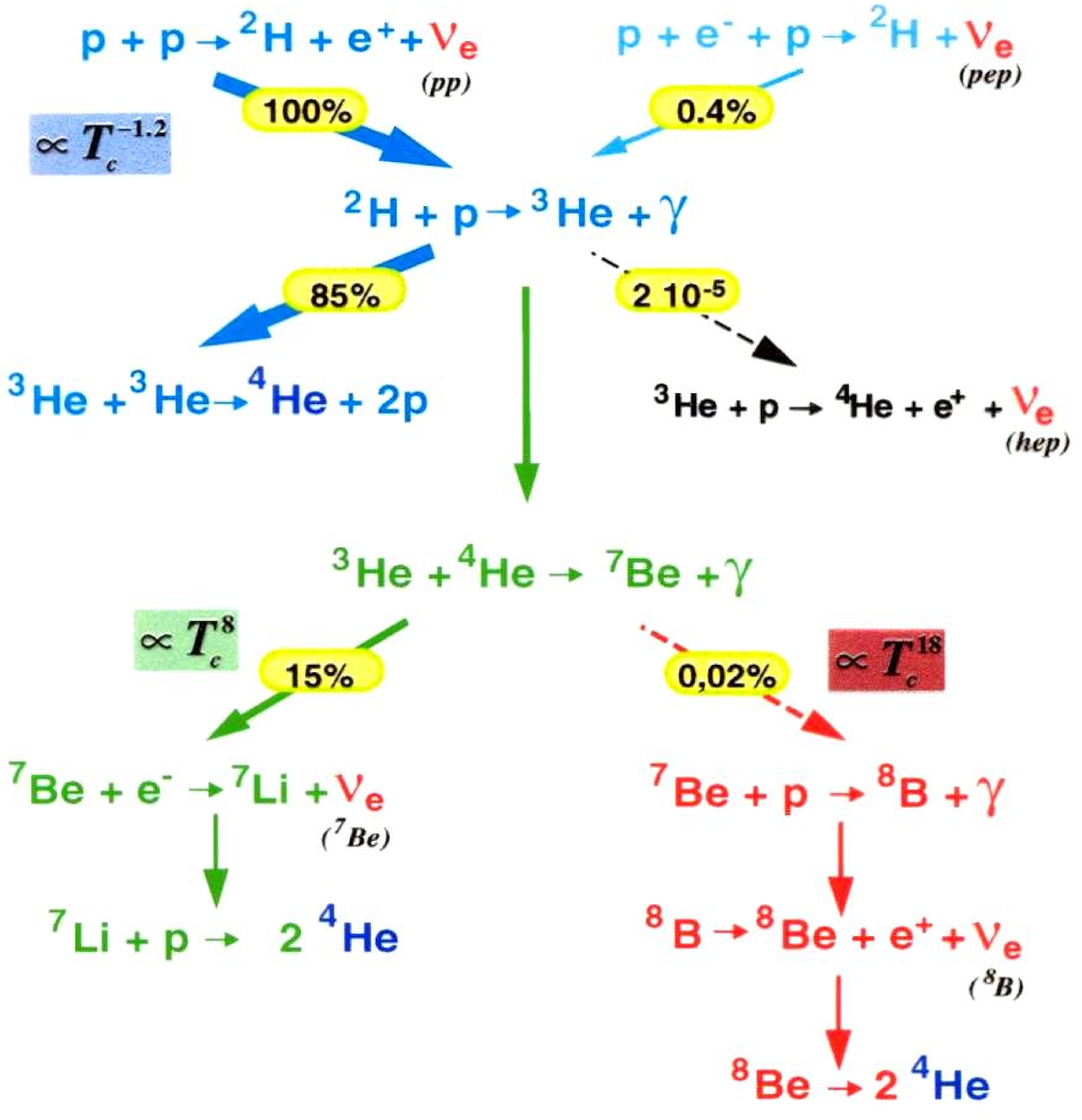
The Sun

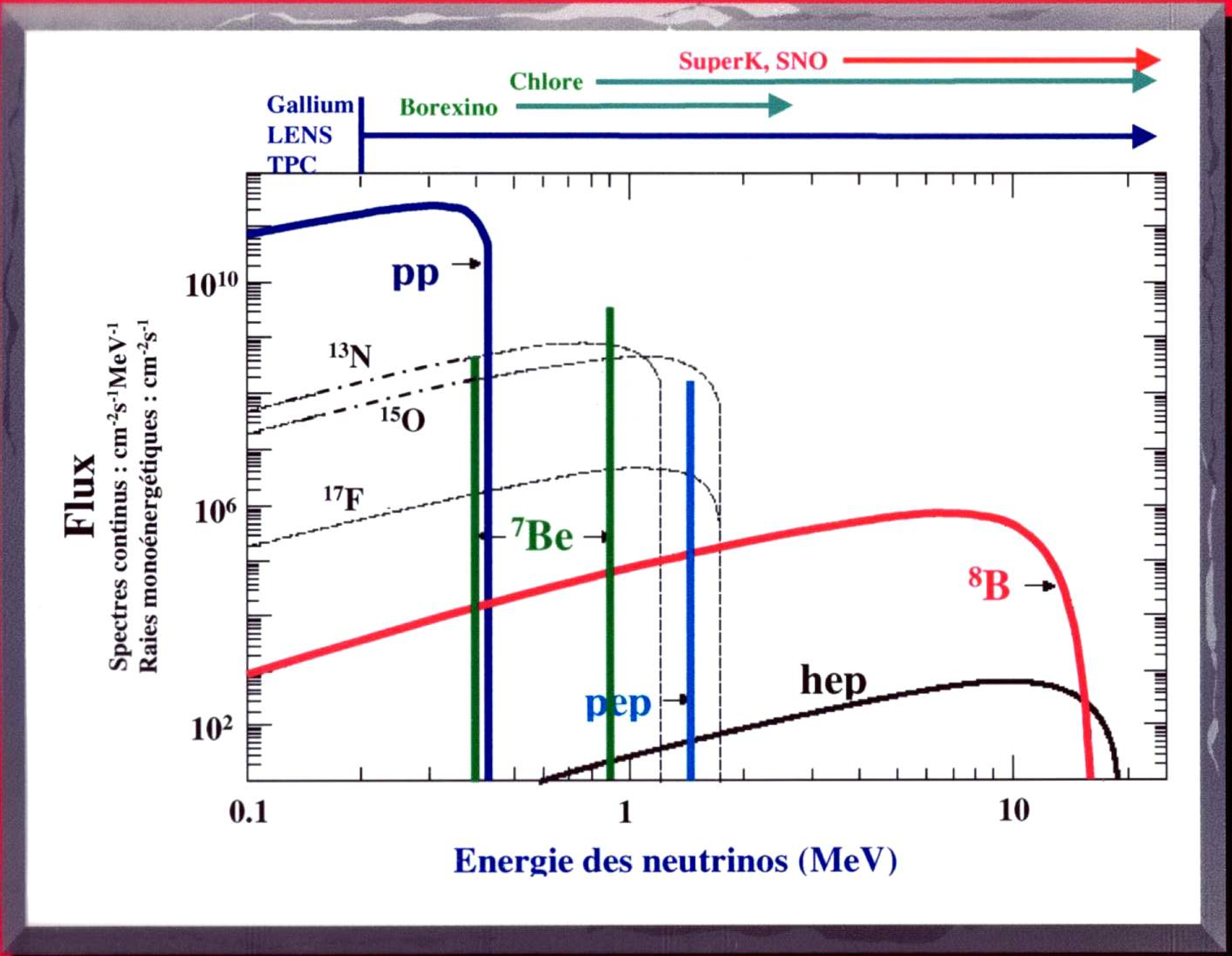


Energy in the Sun due to nuclear reactions

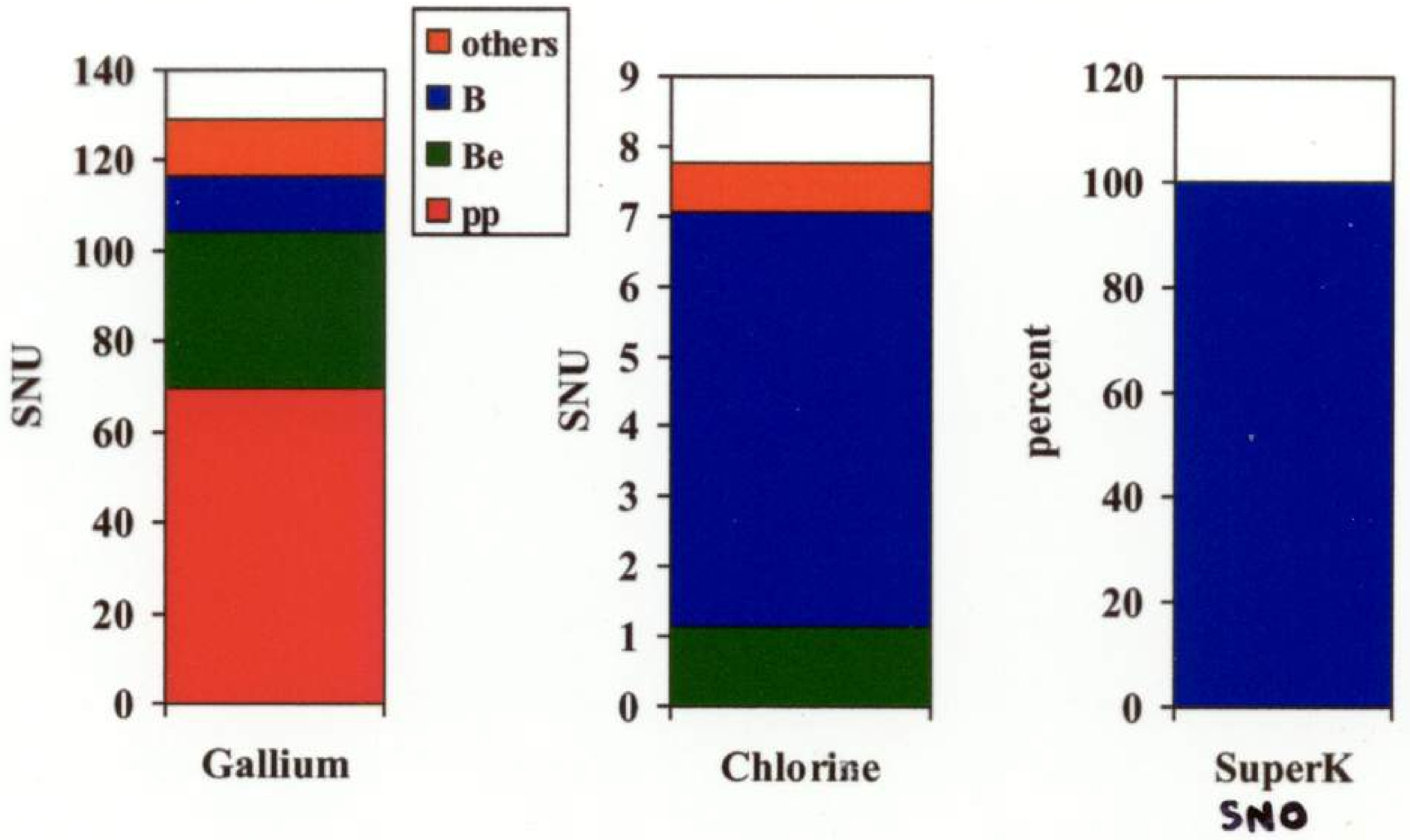
→ neutrino emission

Nuclear reactions in the Sun




SuperK, SNO
Chlore
Borexino
Gallium
LENS
TPC
pp
^{13}N
^{15}O
^{17}F
^{7}Be
^{8}B
hep
pep
10^{10}
10^{6}
10^{2}
0.1
1
10
Flux
Spectres continus : $cm^{-2}s^{-1}MeV^{-1}$
Raies monoénergétiques : $cm^{-2}s^{-1}$
Energie des neutrinos (MeV)

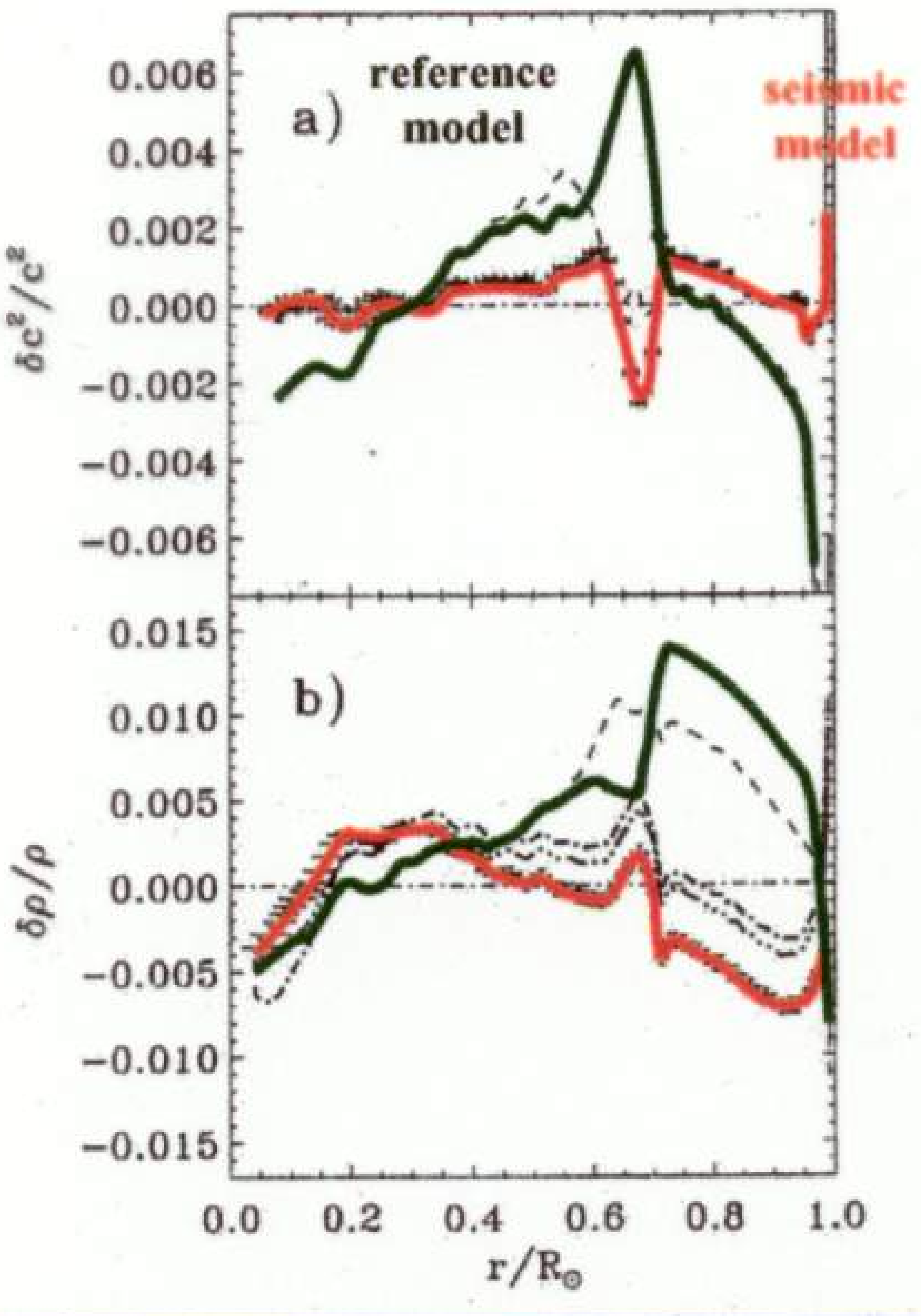
Standard Model(s) Predictions

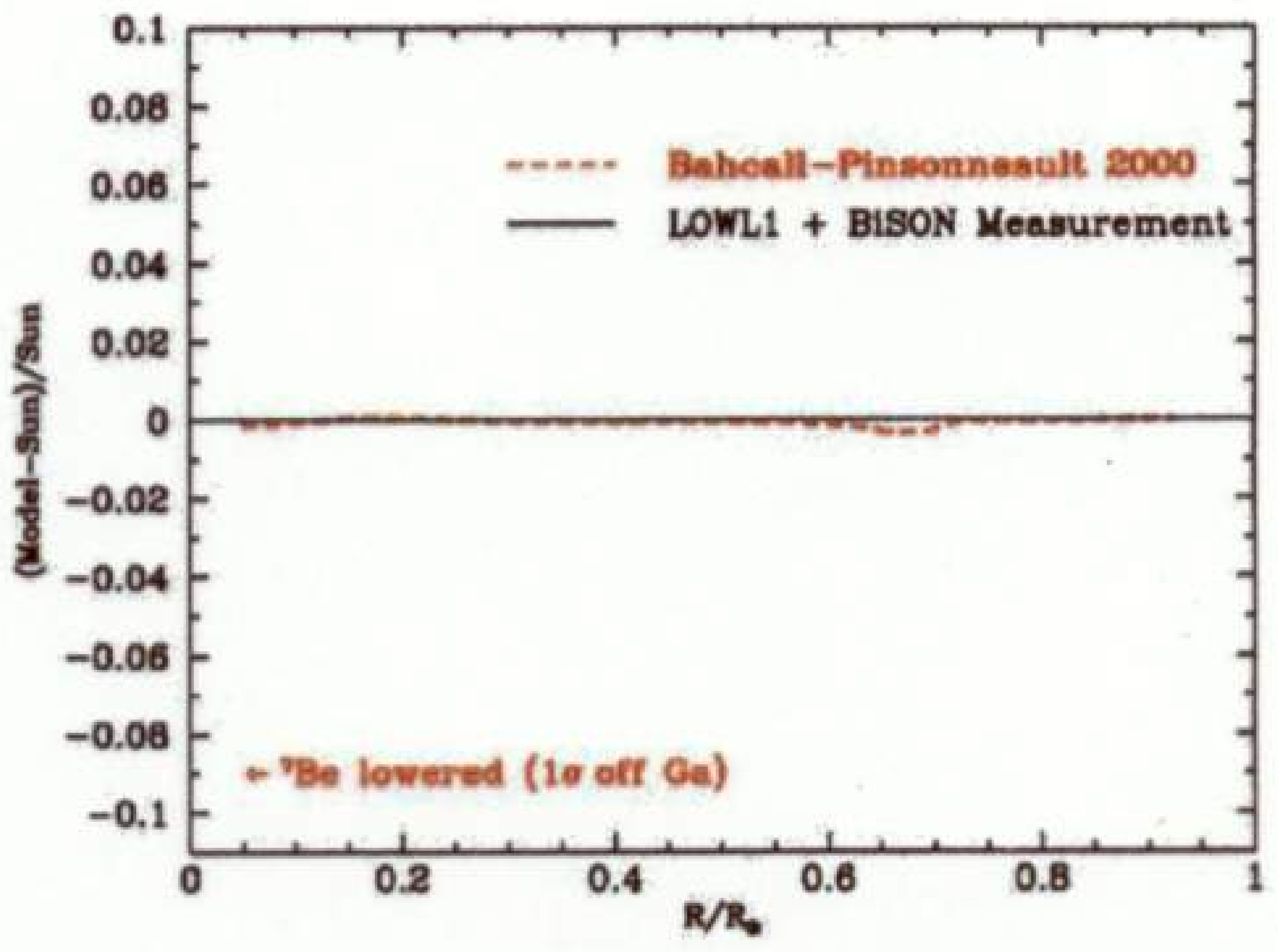


- J.N.Bahcall, M.Pinsonneault, S.Basu, astro-ph/0010346 (Mar 2001)
- S.Turck-Chièze et al., Ap. J. Lett., to appear,

1 SNU = 10^{-36} capture/atom/s	BP01	Saclay01
Gallium (SNU)	128 ± 8	128 ± 9
Chlorine (SNU)	7.7 ± 1.2	7.45 ± 1.0
SuperK, SNO (10^6 cm^{-2} s^{-1})	5.05 ± 1.0	4.95 ± 0.7

Helioseismology constraints





S.Turck-Chièze et al., Ap. J. Lett. 2001
(GOLF-MDI data)

Seismic model = Reference model +
a) Diffusive treatment of the tachocline
b) pp reaction rate : +1%
c) heavy elements : +3.5%

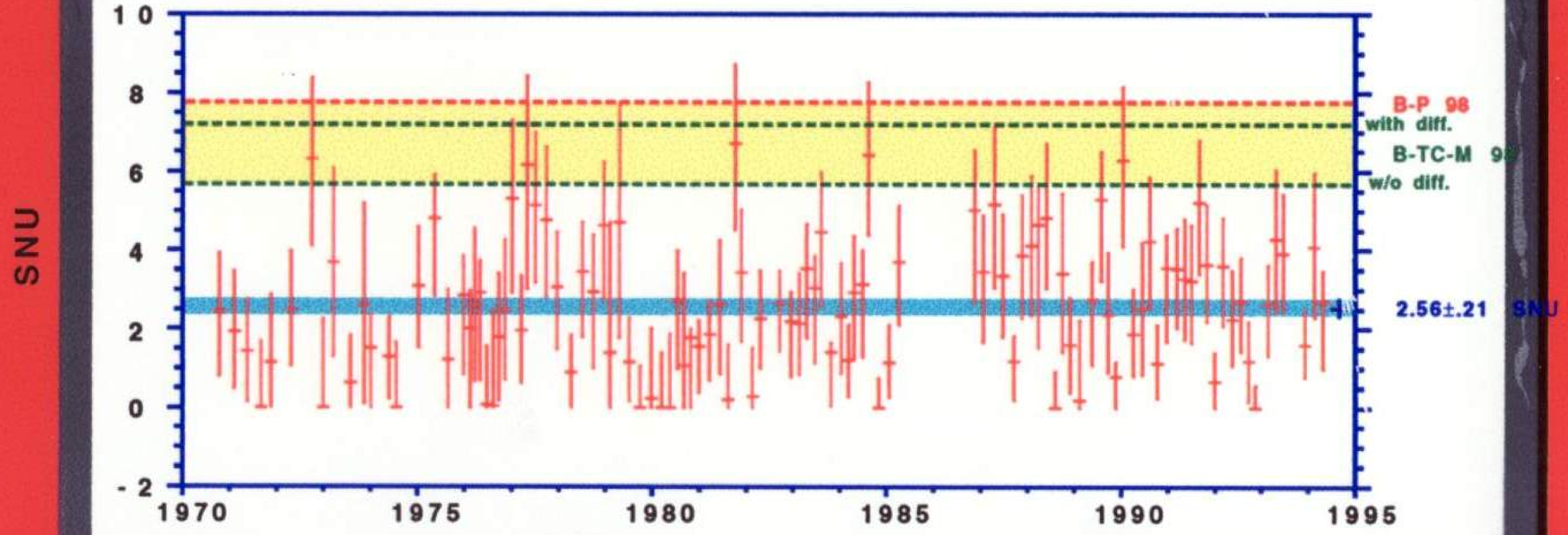
J.N.Bahcall et al., Ap. J., July 2001

Experimental results

Chlorine experiment

- radiochemical
- sensitive to ν_{Be} & ν_B
- 25 years of data (more than 100 runs)
- 2.56 ± 0.20 SNU *(ApJ 496(1998)505)*
- **27 - 38 % of the SSM predictions**

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$



GALLEX :

radiochemical detection of (pp) neutrinos

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

threshold = 233 keV

τ = 16.49 days

$\rightarrow$ ${}^{71}Ga$

decay by electron capture

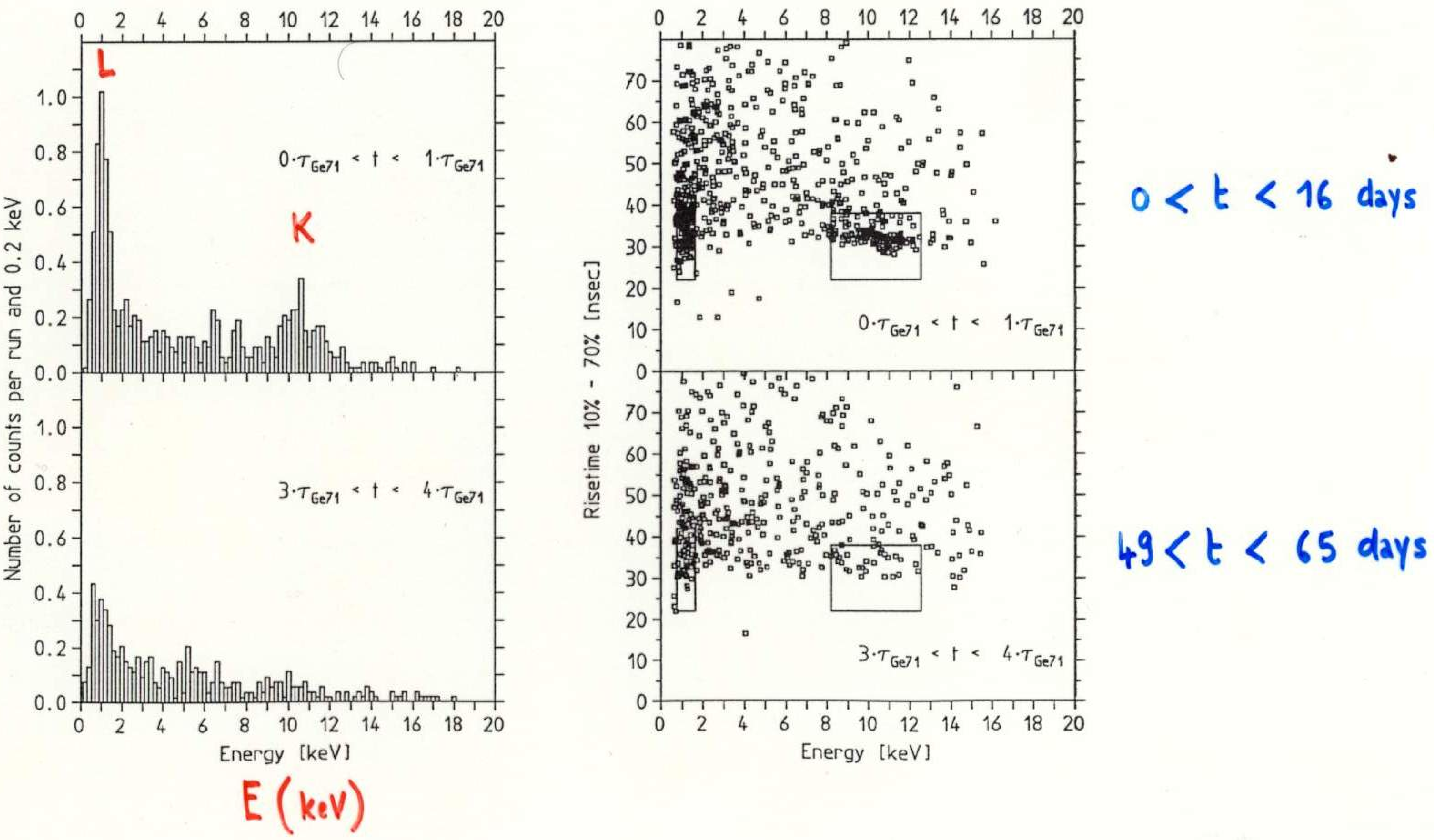
* L capture : 1.17 keV

* K capture : 10.37 keV

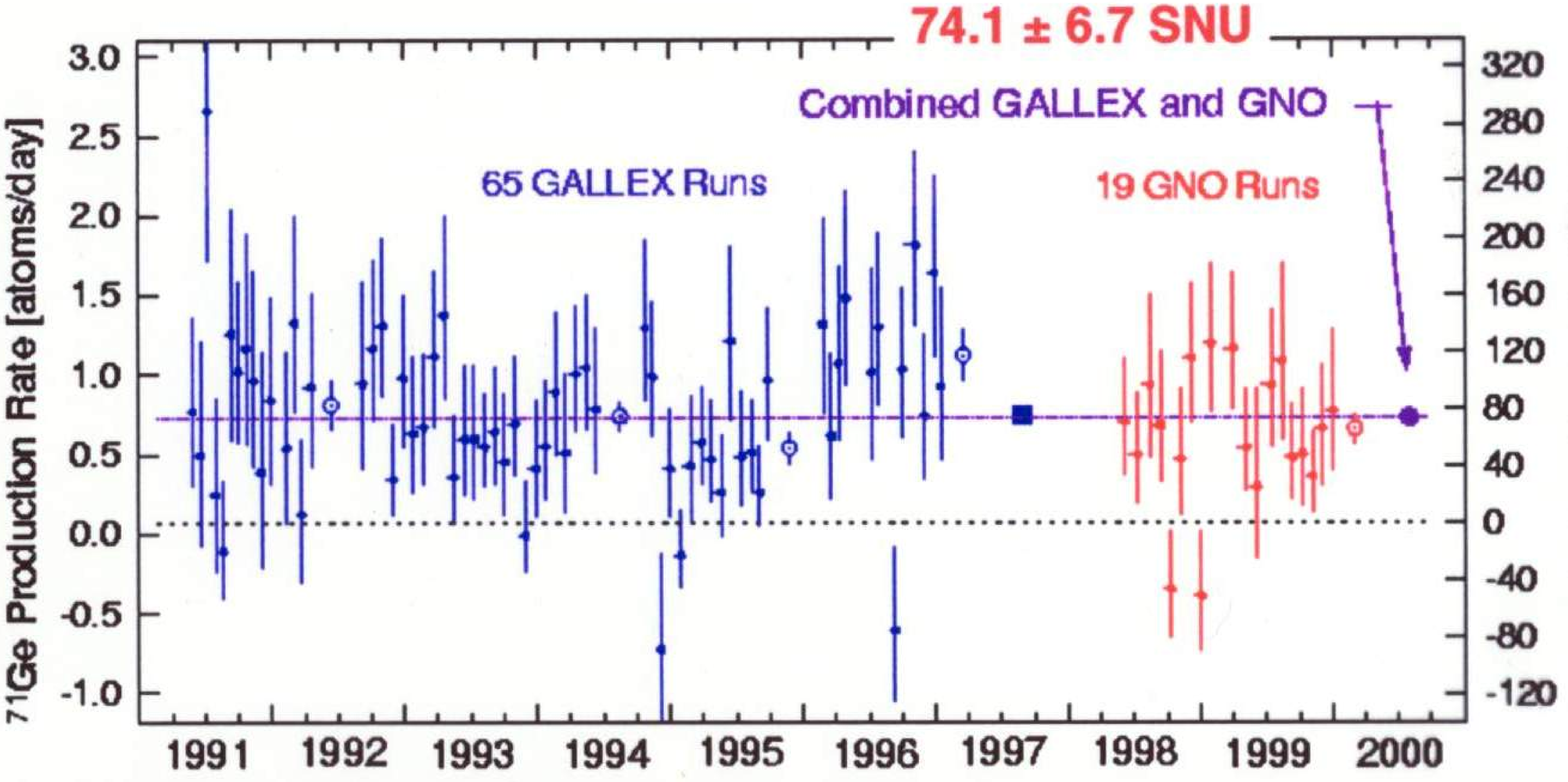
65 10^9 solar neutrinos/cm^2/s

$\Longrightarrow$ 1.2 ${}^{71}Ge$ atom per day in 30 tons of gallium

5 years of data taking for GALLEX



GALLEX & GNO


74.1 ± 6.7 SNU
Combined GALLEX and GNO
65 GALLEX Runs
19 GNO Runs
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
1998
1999
2000

Performance checks of the GALLEX detector

✸ Ge carrier

- In each run recovery (yield ≈95%) of 1 mg Ge carrier (more than 100 runs)
- $O(10^{19})$ atoms Ge in 10^{30} target atoms

☺ ≈ 1% experiment

✸ Chromium neutrino sources
(Phys. Lett. B420 (1998) 114)

- Overall check of the whole detector with in-situ ν-induced ^{71}Ge production
- $O(10^{2})$ ^{71}Ge atoms in 10^{30} target atoms

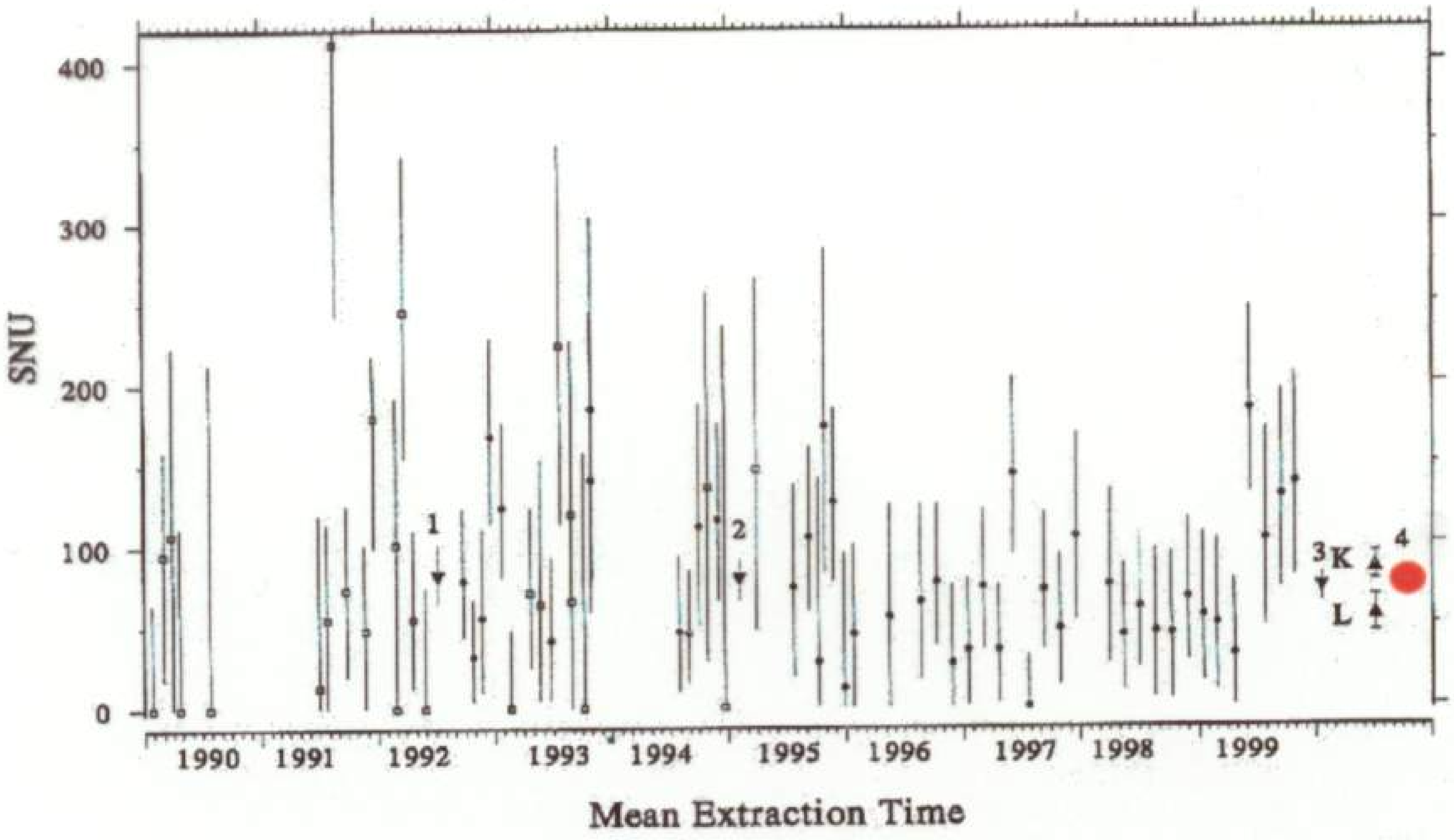
☺ ≈ 10% experiment

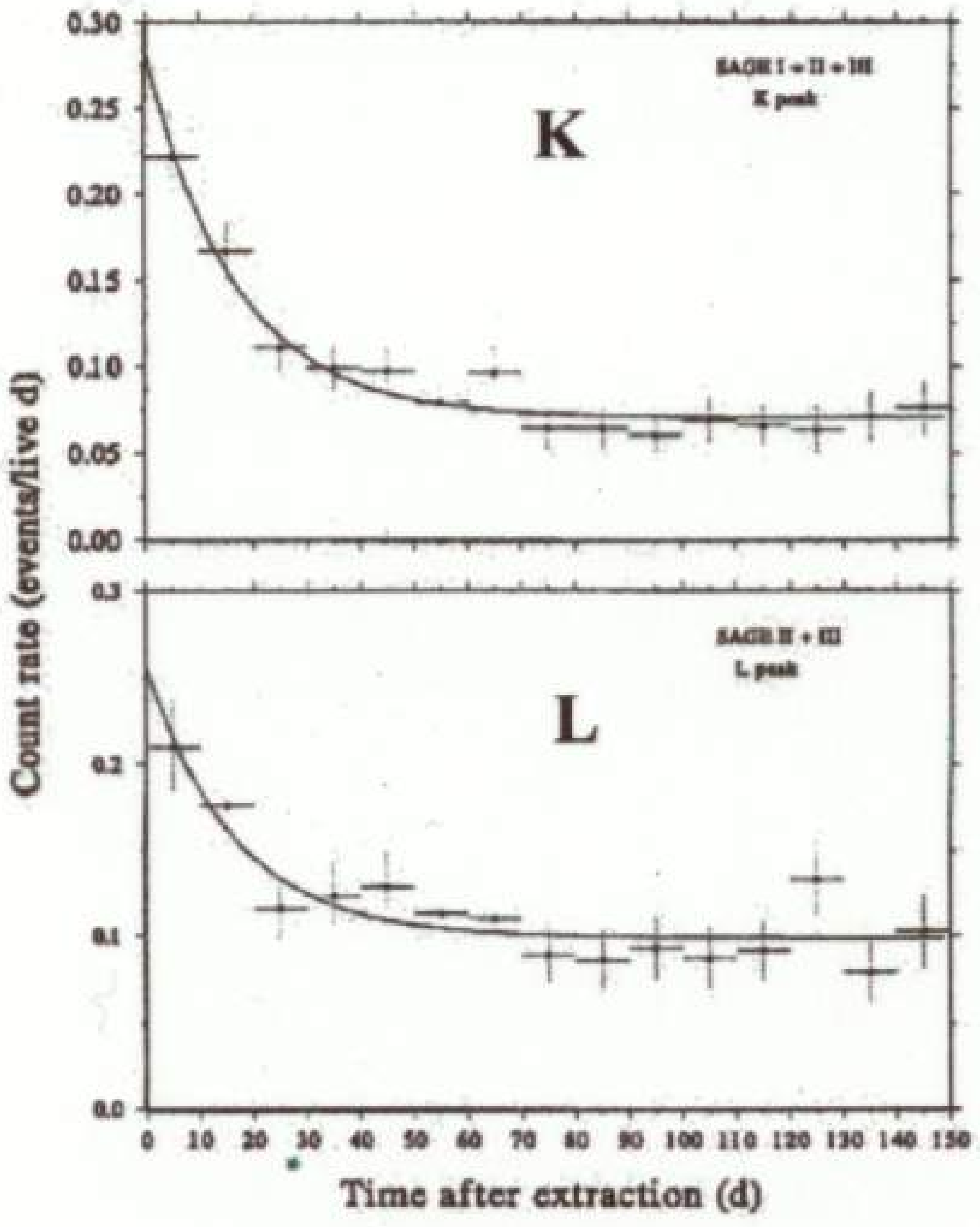
✸ Arsenic-spiking experiments
(Phys. Lett. B436 (1998) 158)

- In situ production of ^{71}Ge via β decay of ^{71}As added to the target tank
- $O(10^{4})$ ^{71}Ge atoms in 10^{30} target atoms

☺ ≈ 1% experiment

SAGE





About 50 tons of Ga metal

70 runs

75.4 ± 7. (stat.) ± 3.5 SNU (syst.)

Check with a ^{51}Cr source :

0.95 ± 0.12

Count rates for L and K peak

Nucl. Phys. B (Proc. Suppl.) 91 (2001) 36

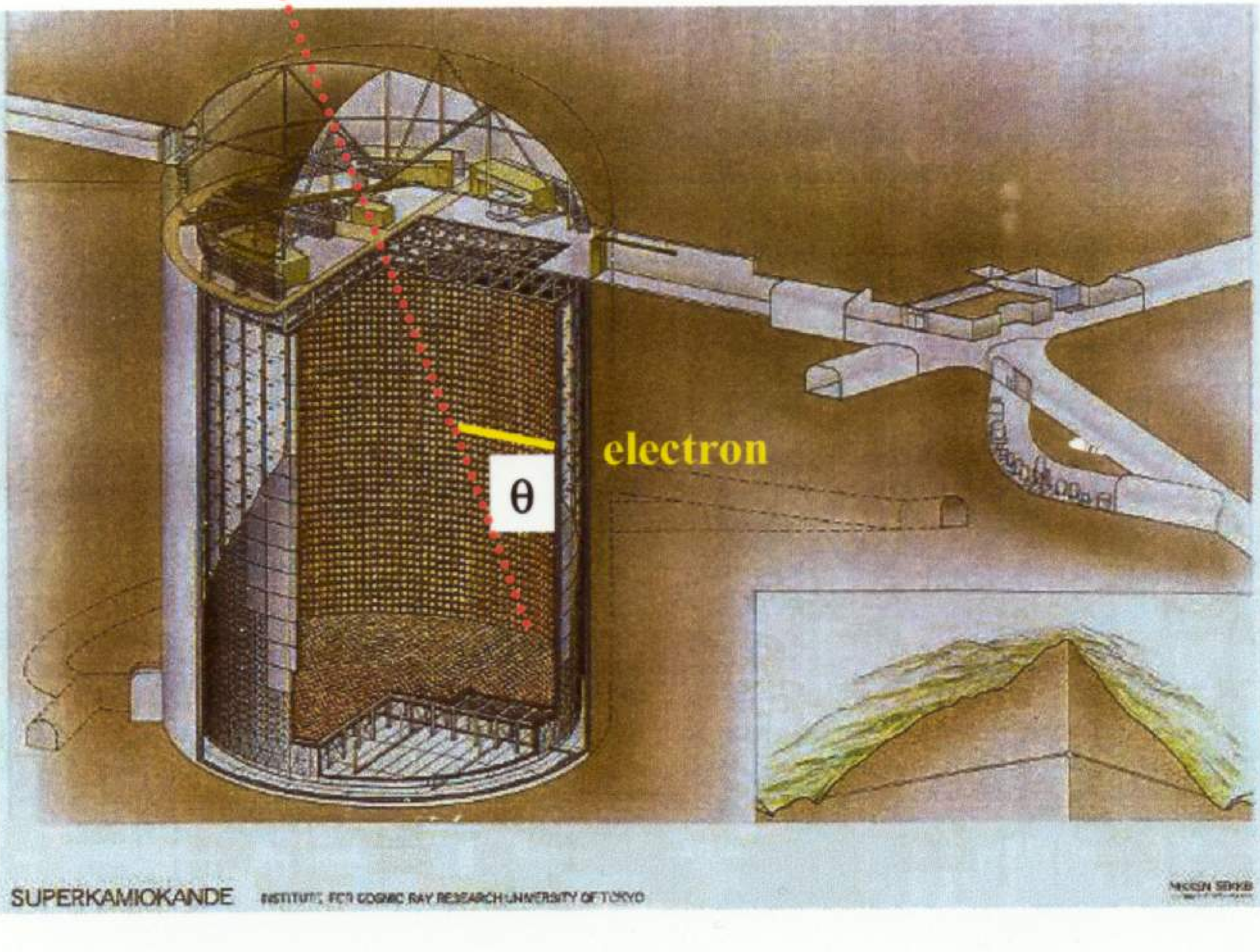
SuperKamiokande

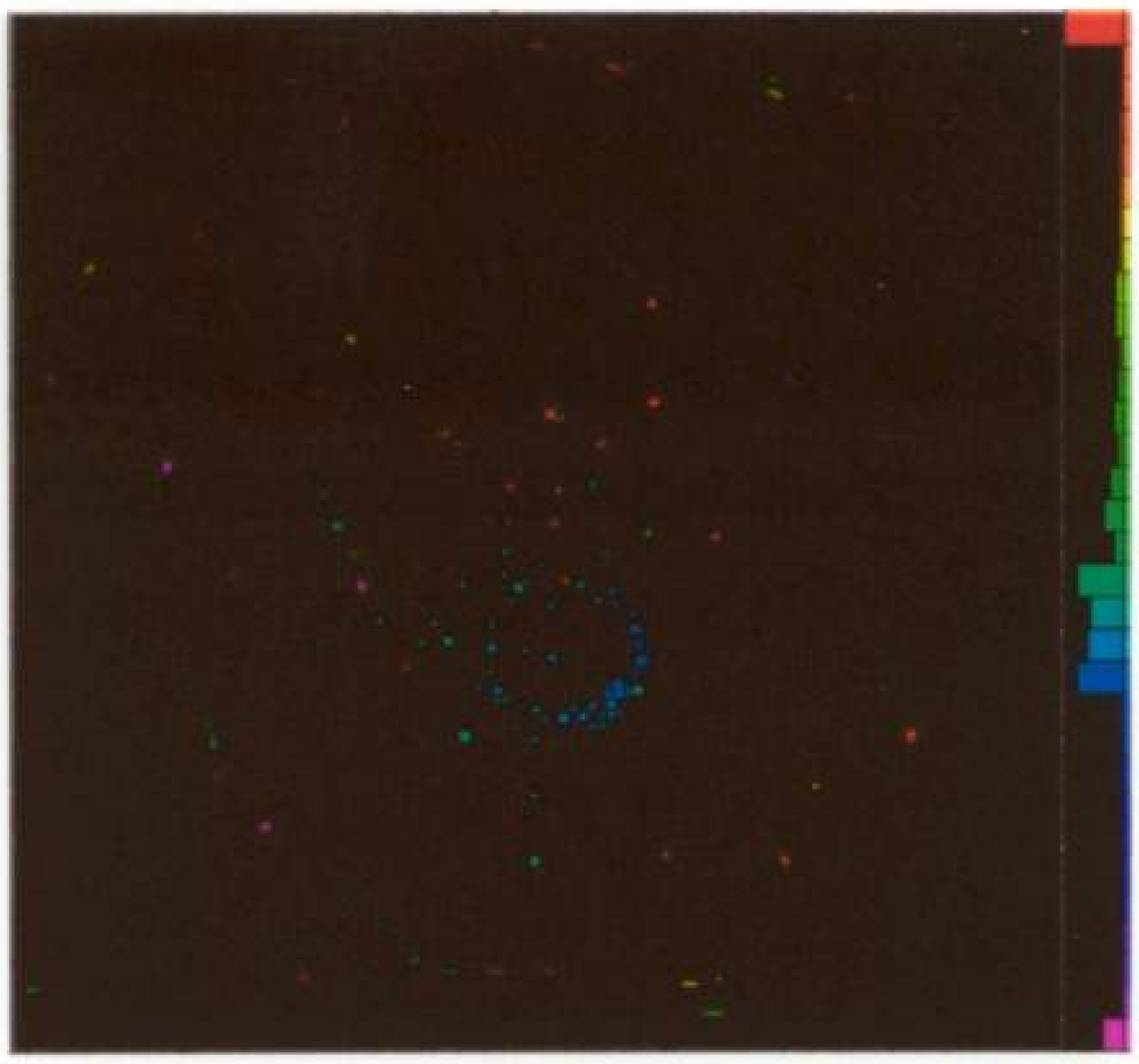
$\nu + e \rightarrow \nu + e$

22.5 kton fiducial volume

1258 days data taking

neutrino





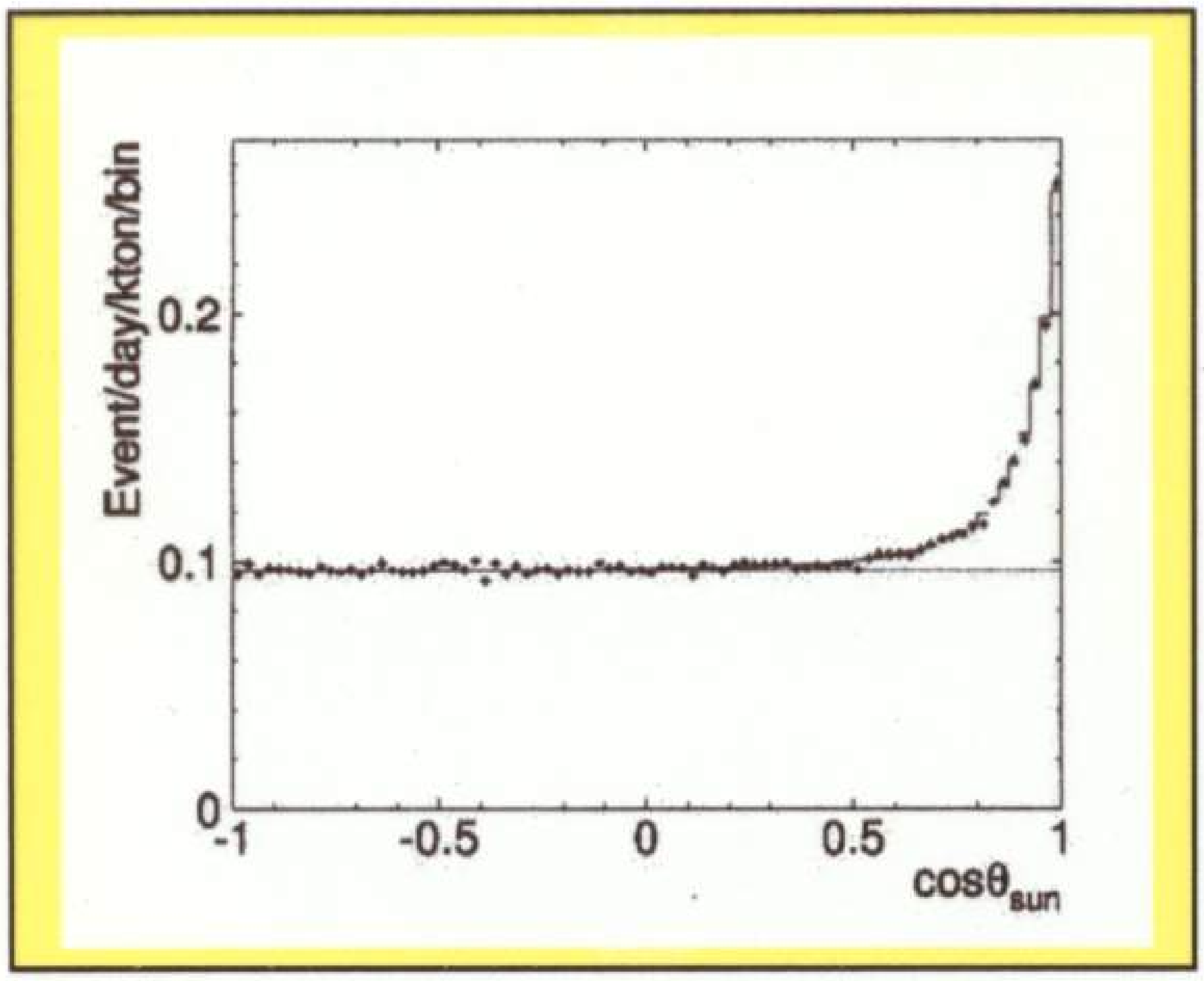
Typical solar neutrino event

E > 5 MeV (6.5 MeV for the first 280 days)

$2\ 10^9$ events

Data reduction :
Cosmic ray muons
Spallation cut
External γ-ray cut
Vertex quality

236 140 events



Signal :
18 464 ± 204 ± 600 events
(15 / day)

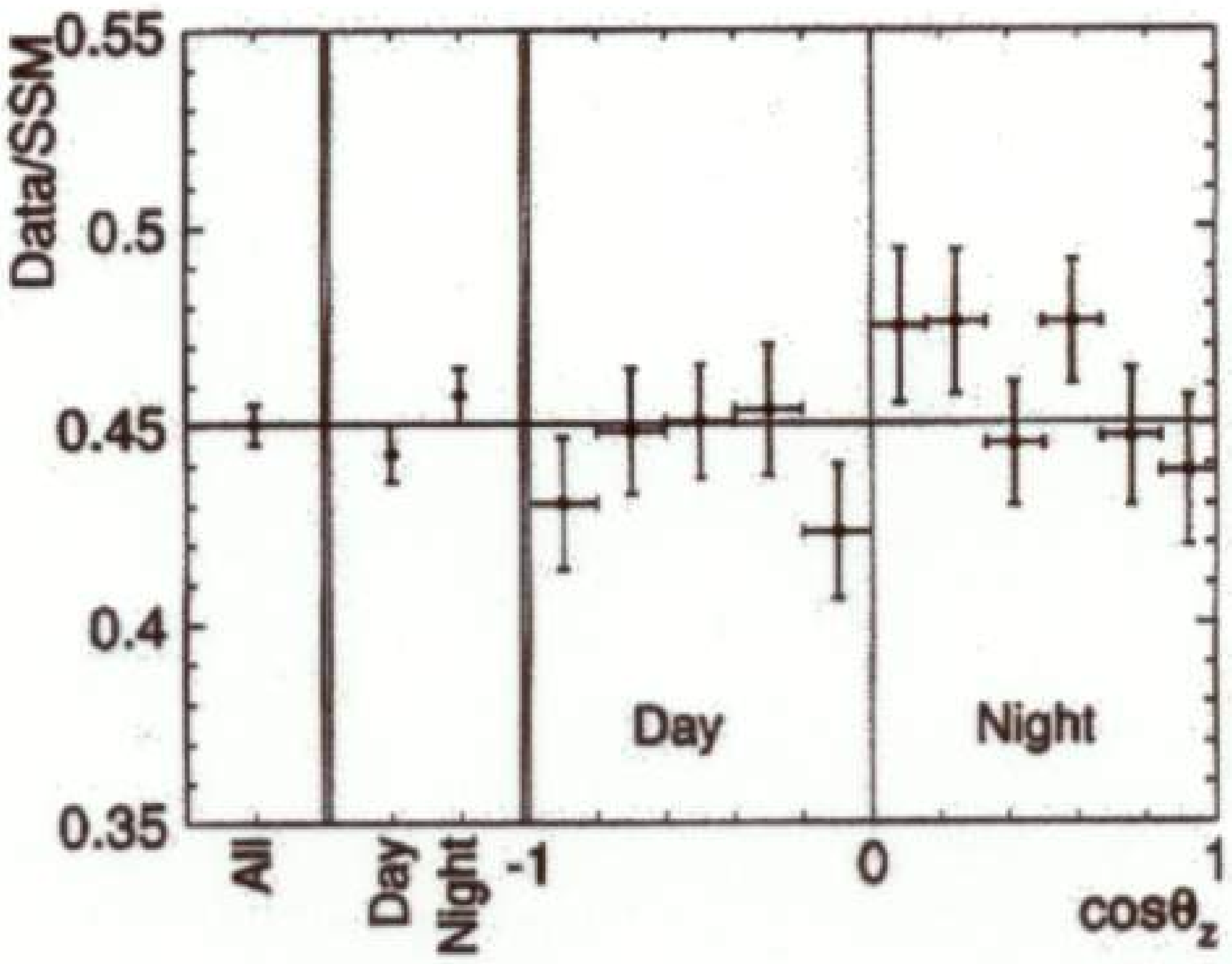
hep-ex/0103032

Flux measured for $^8B\ \nu$:

$(2.32 \pm 0.03$ (stat.) ± 0.08 (syst.)$)\ 10^6\ cm^{-2}\ s^{-1}$

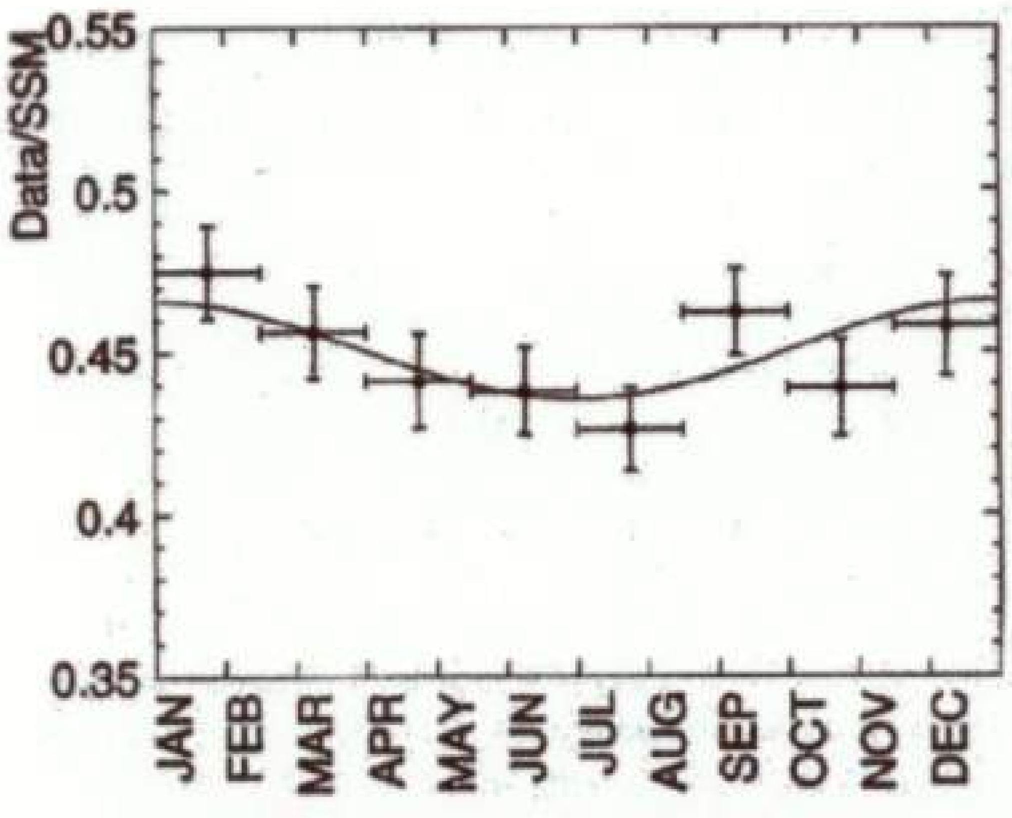
About 45% of solar models

Day/Night variation ?



Day : $(2.28 \pm 0.04$ (stat.) ± 0.08 (syst.)$)\ 10^6\ cm^{-2}\ s^{-1}$
Night : $(2.36 \pm 0.04$ (stat.) ± 0.08 (syst.)$)\ 10^6\ cm^{-2}\ s^{-1}$

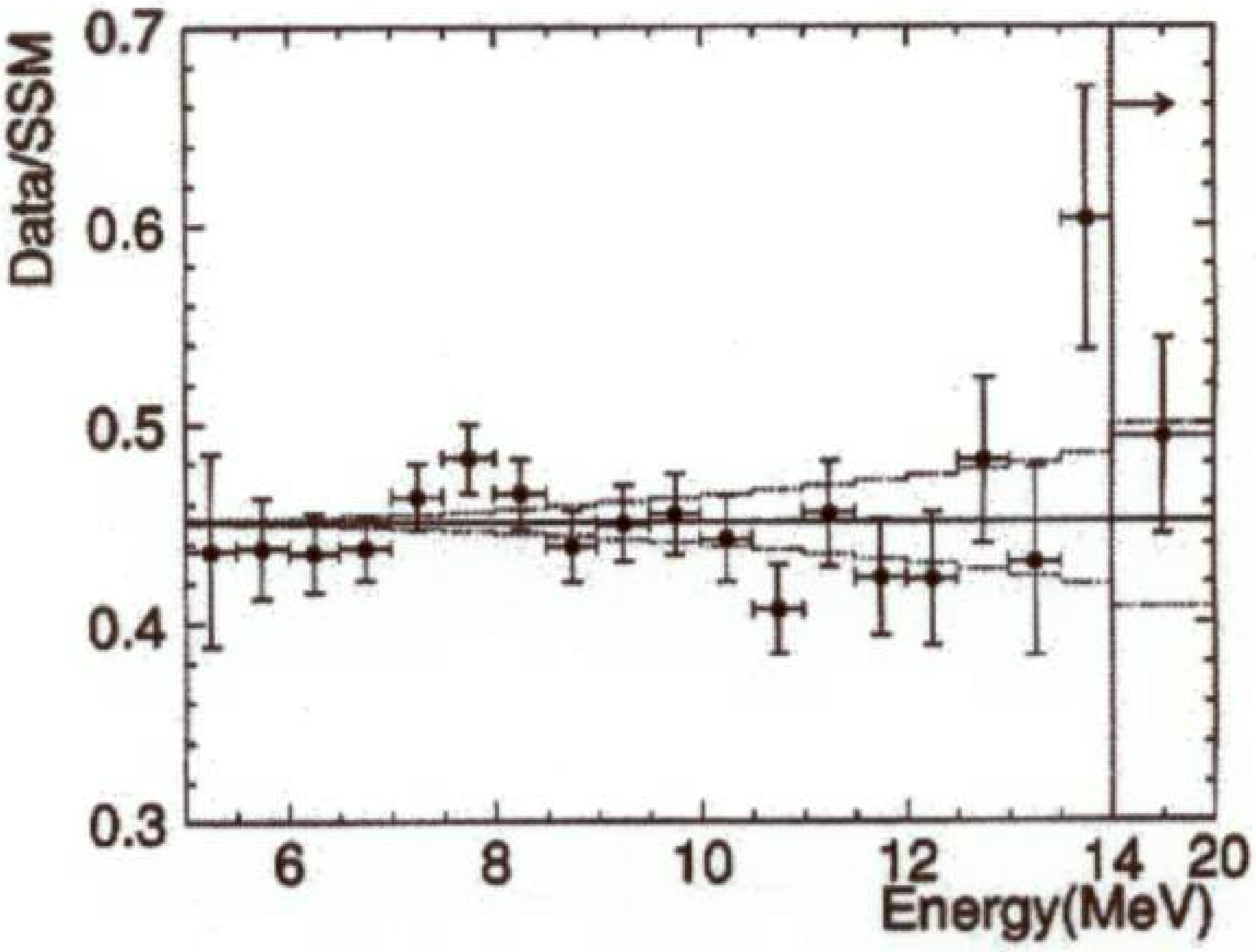
Asymmetry = (N-D) / 0.5 (N+D) = 0.033 ± 0.022 (stat.) ± 0.013 (syst.))
[1.3 σ from 0]



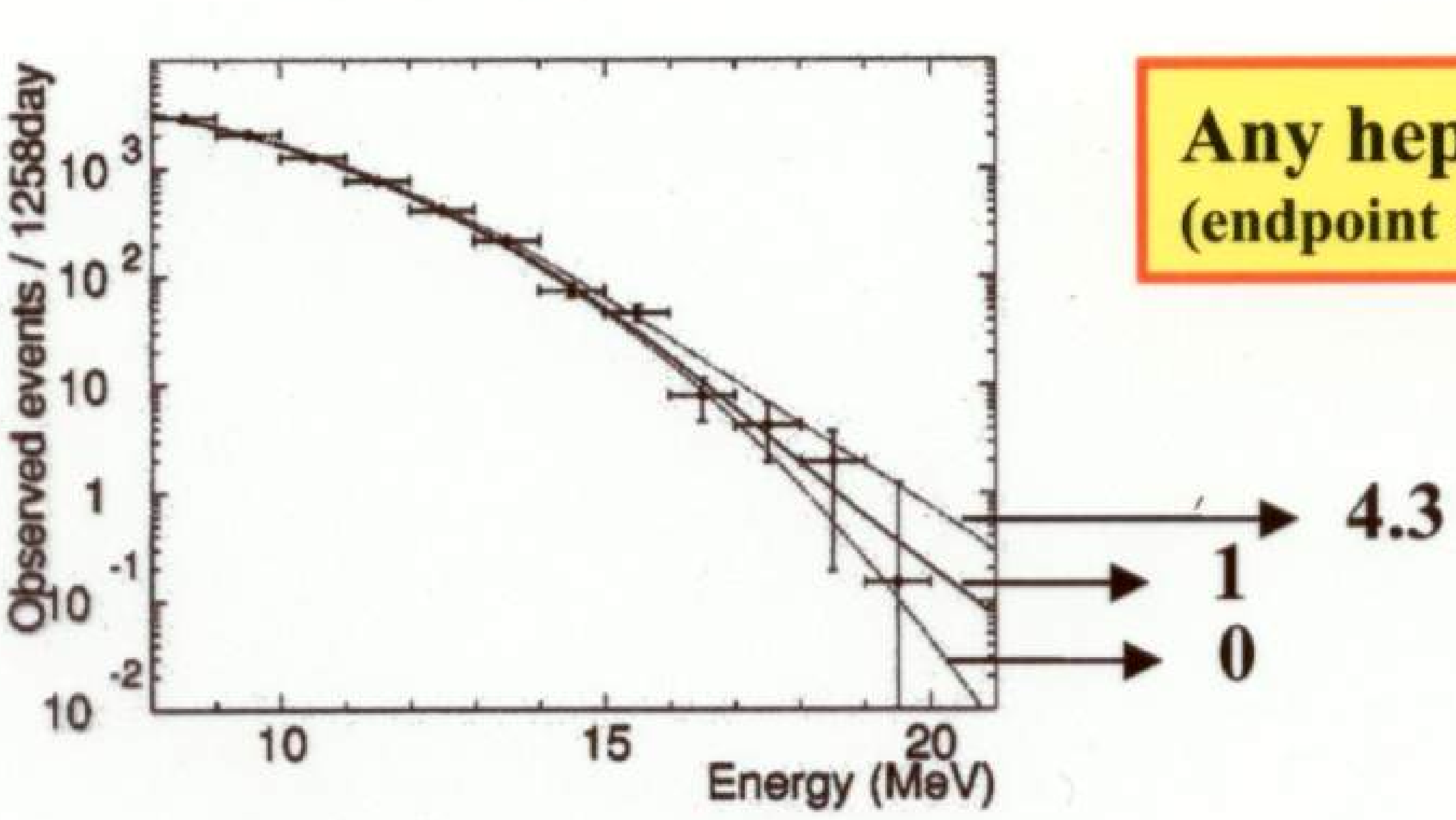
Seasonal variation

hep-ex/0103032

Electron spectrum



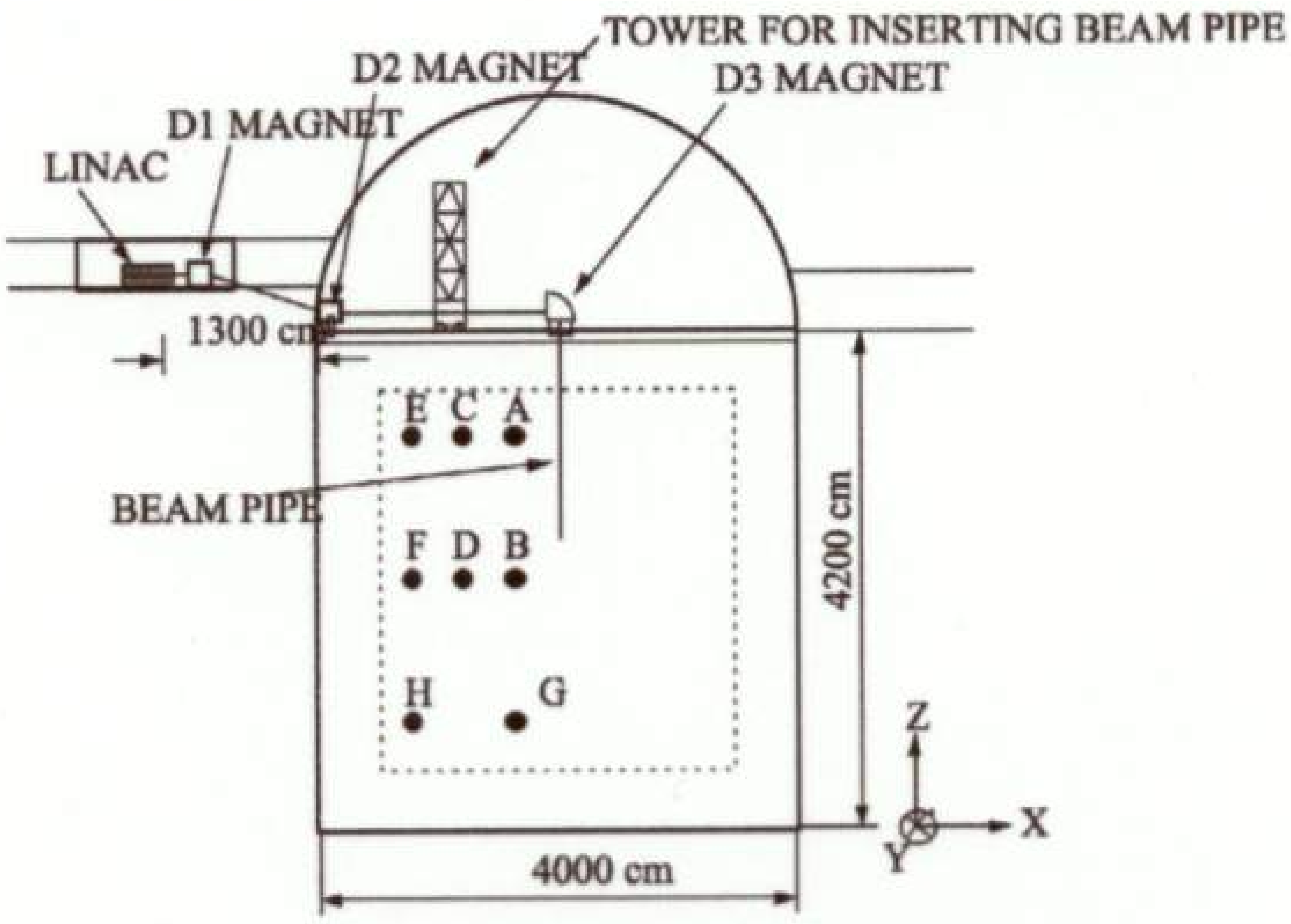
χ^2 for a flat spectrum : 19.0 for 18 d.o.f.



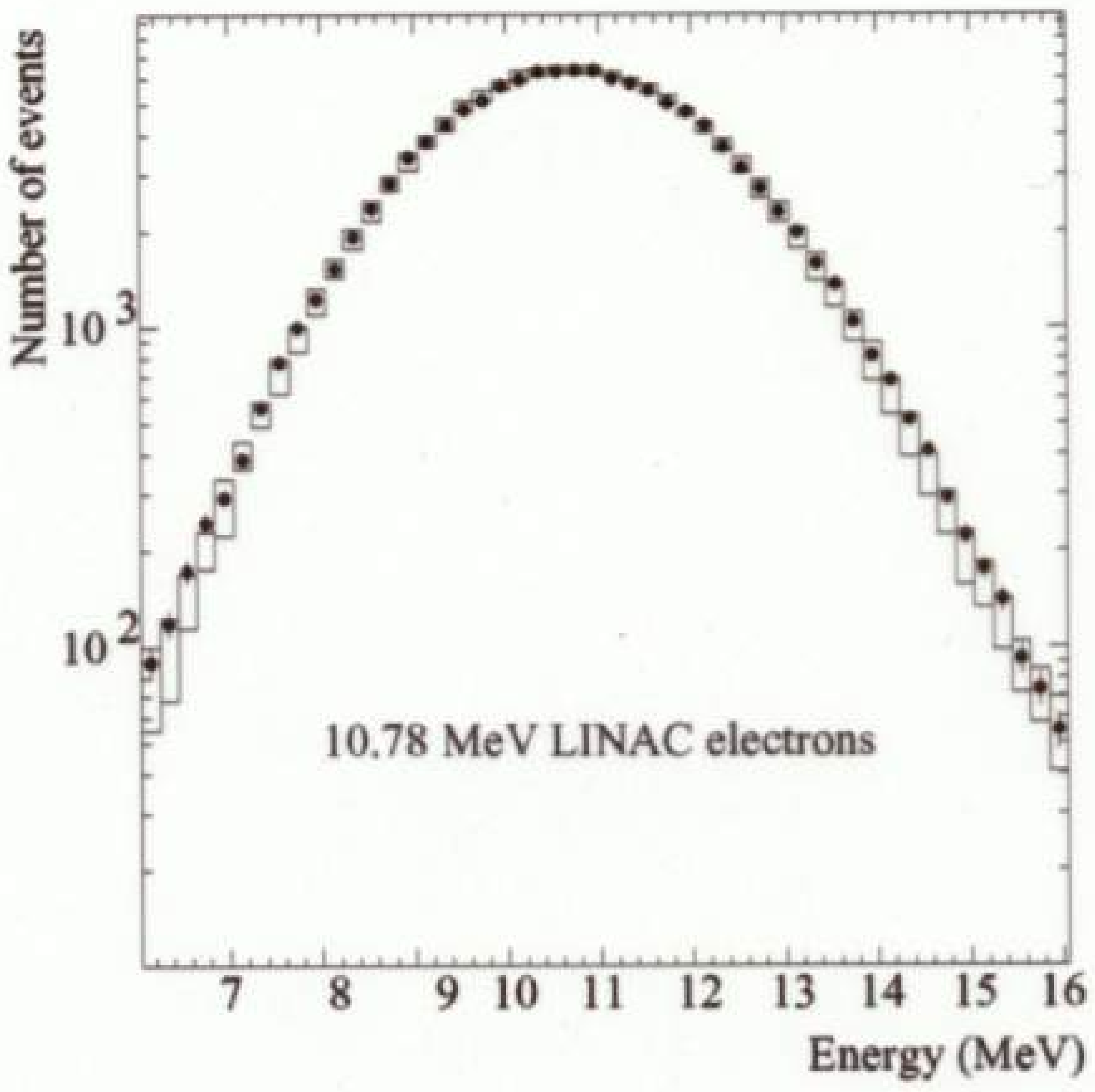
Any hep contribution ?
(endpoint : 18.7 MeV)

hep-ex/0103032

Calibration with a LINAC

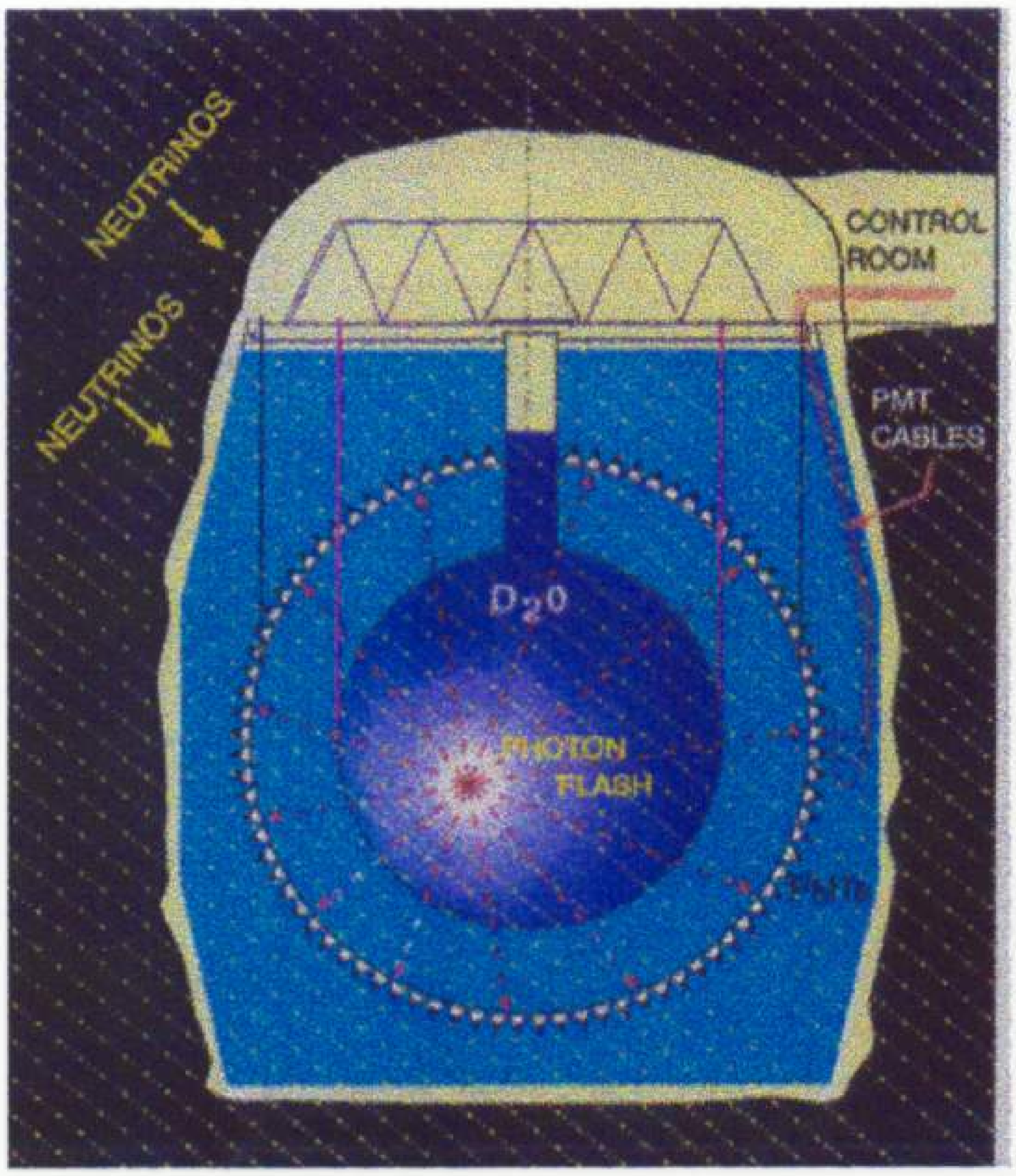


7 measurements with 4.89 < electron momentum < 16.09 MeV



Sudbury Neutrino Observatory

- **Heavy water Cerenkov detector**
  - **➤1000 tons D_2O**
  - **➤7500 tons H_2O**



- **Sensitive to all ν flavors (> 7 MeV)**

$\nu_X + D \rightarrow p + n + \nu_X$	2600 *evts / y*
$\nu_X + e^- \rightarrow \nu_X + e^-$	1200 *evts / y*
$\nu_e + D \rightarrow p + p + e^-$	8800 *evts / y*

- **Start : January 1999 (?)**
- **in Canada : nickel mine**

SNO [units $10^{6}\ cm^{-2} s^{-1}$]

$$\phi_{cc} = 1.75 \pm 0.13$$

$$\phi_{ES} = 2.39 \pm 0.34 \pm 0.15$$

$$\phi_{ES}^{SK} = 2.32 \pm 0.03 \pm 0.08$$

$$\phi_{ES}^{SK} - \phi_{cc} = 0.57 \pm 0.17$$

3.3 σ

$$\phi_{tot} = 5.44 \pm 0.99$$

BPB : 5.05 ± 1.0

Tc : 4.95 ± 0.7

$$\phi_{\mu\tau} = 3.69 \pm 1.13$$

$$\frac{NC}{CC} \approx 3$$

Summary of the solar neutrino problem

	Experiment	**Theory** **BPB 01** *Saclay 01*	**Exp/Th** **BPB** *Saclay*
Chlorine (SNU)	**2.56 ± 0.23**	**7.7 ± 1.2** *7.45 ± 1.0*	**0.33 ± 0.06** *0.34*
SuperKamiokande (10^6 cm^{-2} s^{-1})	**2.32 ± 0.09**	**5.05 ± 1.0** *4.95 ± 0.7*	**0.46 ± 0.09** *0.47*
SNO (10^6 cm^{-2} s^{-1})	1.75 ± 0.13	**5.05 ± 1.0** *4.95 ± 0.7*	0.35 ± 0.03 *?*
GALLEX/GNO (SNU)	74.1 ± 6.8		0.58 ± 0.07 *0.58*
SAGE (SNU)	75.4 ± 7.8	**128 ± 8** *128 ± 9*	0.59 ± 0.07 *0.59*
Gallium (SNU)	**74.7 ± 5.0**		**0.58 ± 0.06** *0.58*

BPB01 : J.N.Bahcall, M.H.Pinsonneault and S.Basu - astro-ph/0010346 v2 (13 Mar 2001), Ap. J., July 2001.

Saclay 01 : S.Turck-Chièze et al. - accepted by Ap. J. Lett. (19 Apr 2001)

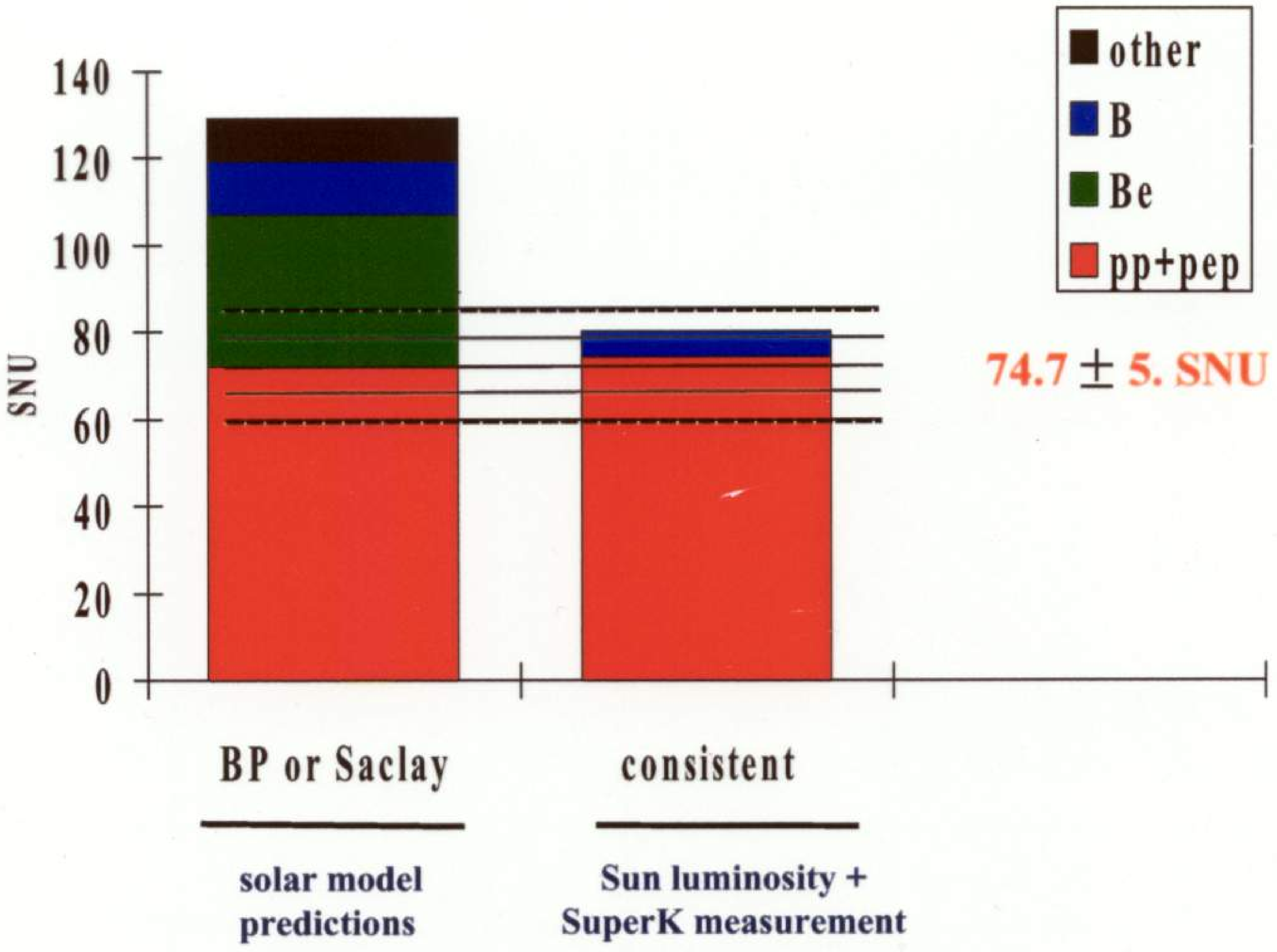
Summary of the experimental results for solar neutrinos

	Experiment / Predictions	Predictions for the different solar neutrino sources		
		ν_{pp}	ν_{Be}	ν_B
Gallium	~ 60%	60%	30%	10%
Chlorine	~ 30%		20%	80%
SuperK	~ 45%			100%

All experiments observe less neutrinos than what is predicted by astrophysicists !

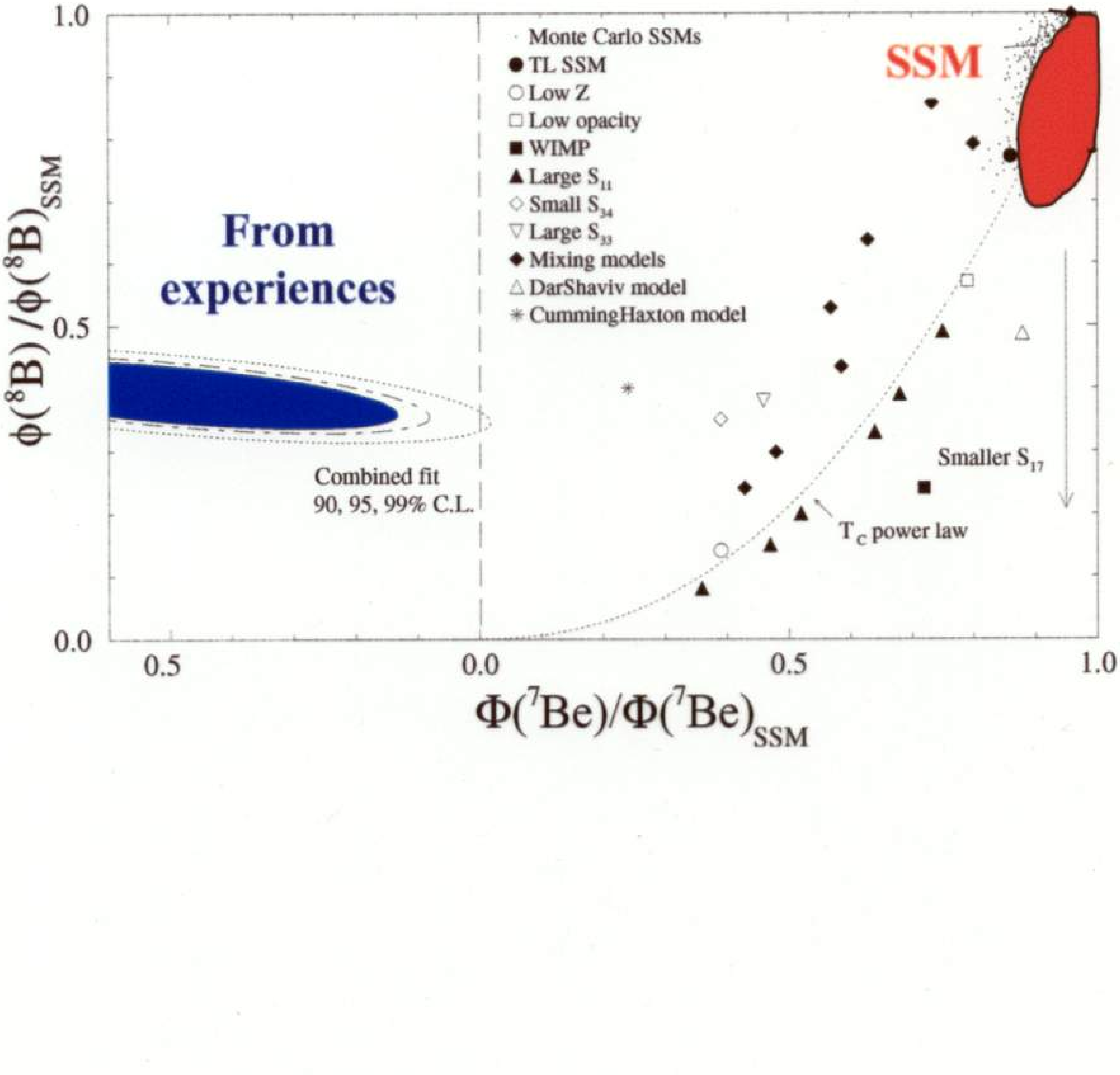
Where are the missing solar neutrinos ?

First level interpretation of the gallium results



⟹ **No room for ^{7}Be neutrinos**

Difficulties for astrophysical solutions to interpret the experimental results



N.Hata and P.Langacker, hep-ph/9811460

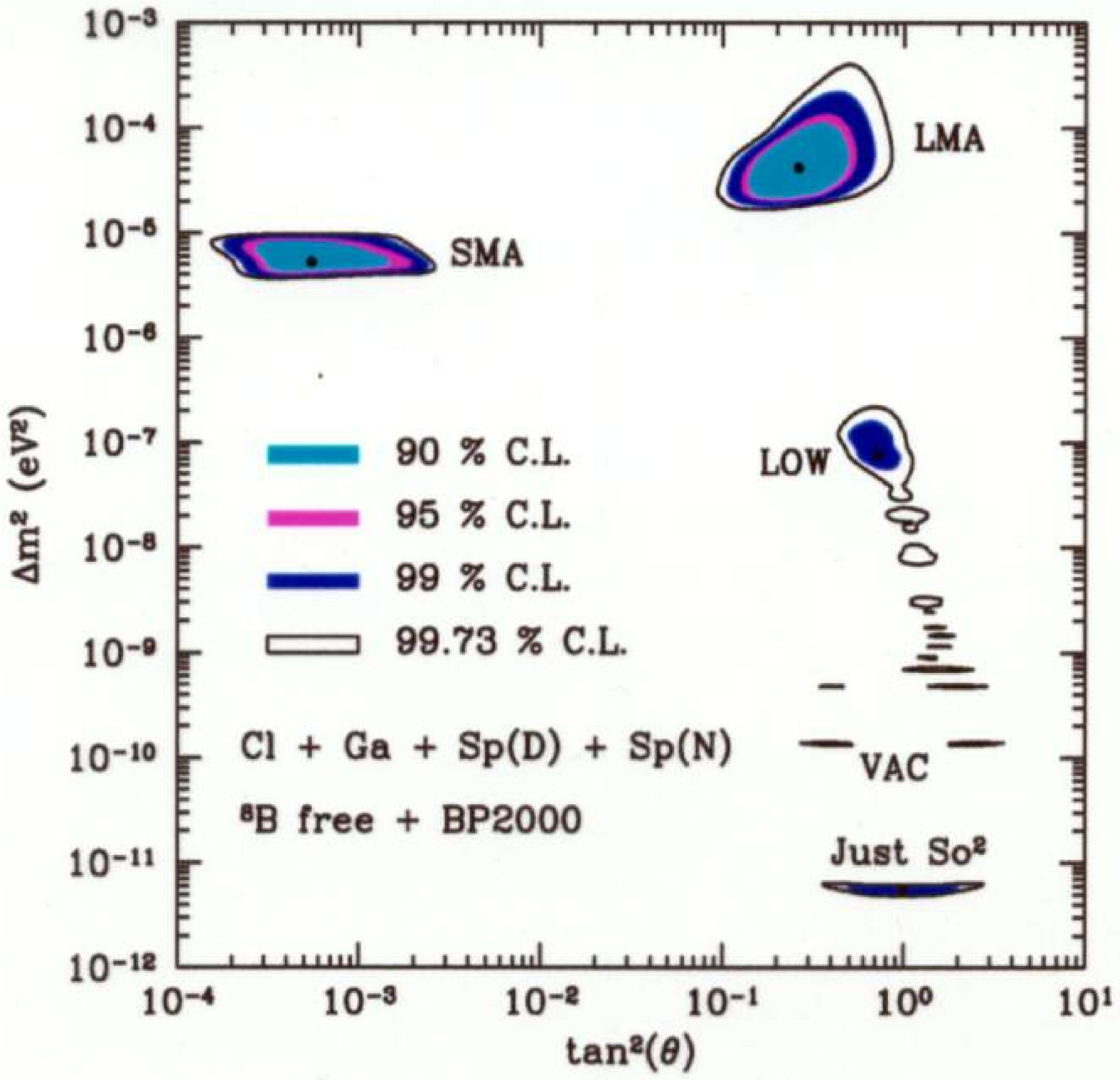
❶ **Nuclear reactions in the Sun produce only ν_e**

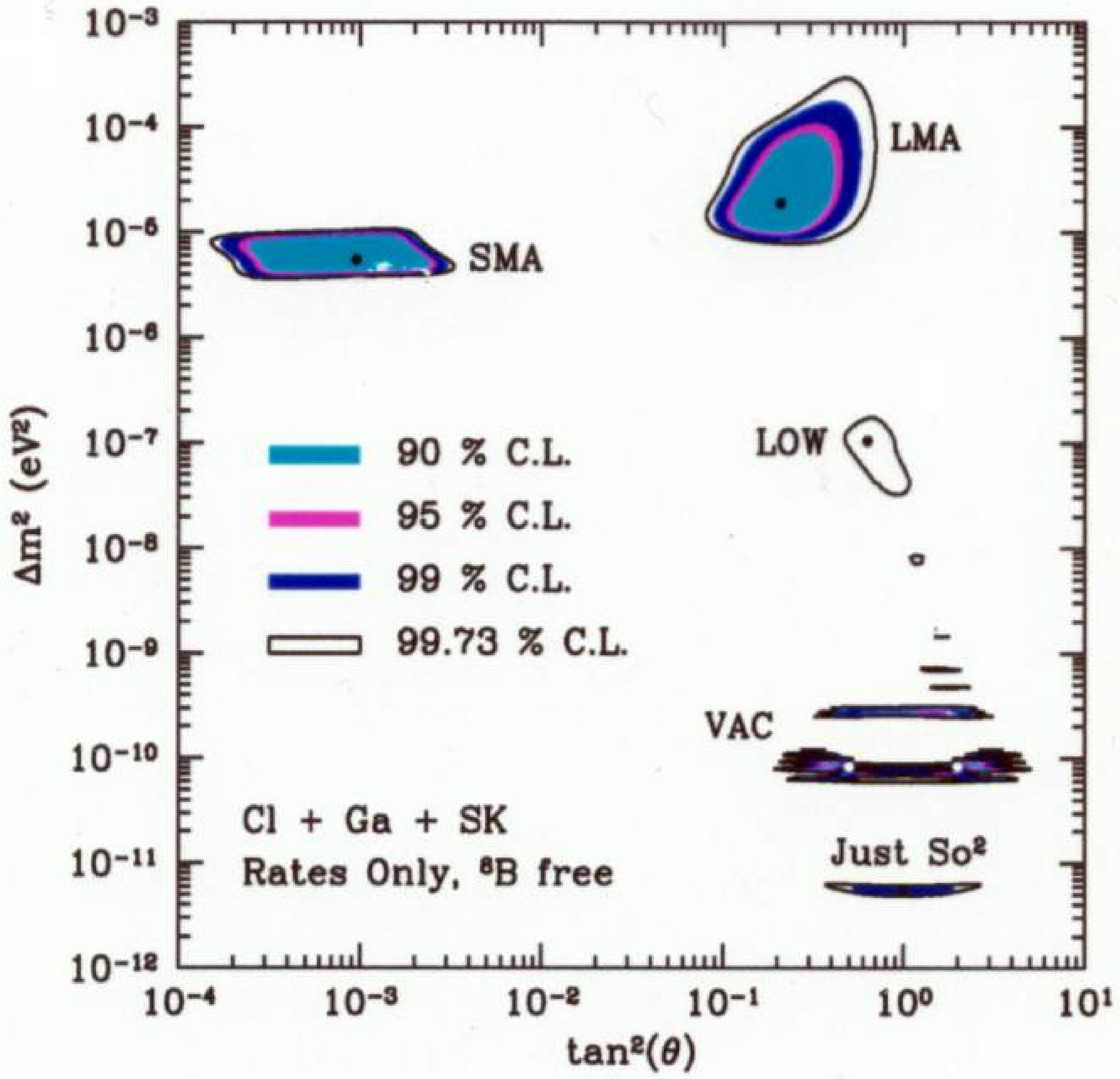
❷ **Solar neutrino detectors are sensitive only (or mostly) to ν_e**

→ **If ν_e have been partially transformed into ν_μ or ν_τ we have a possible explanation to the deficit**

☸ **We fit simultaneously the reductions observed by the four experiments**

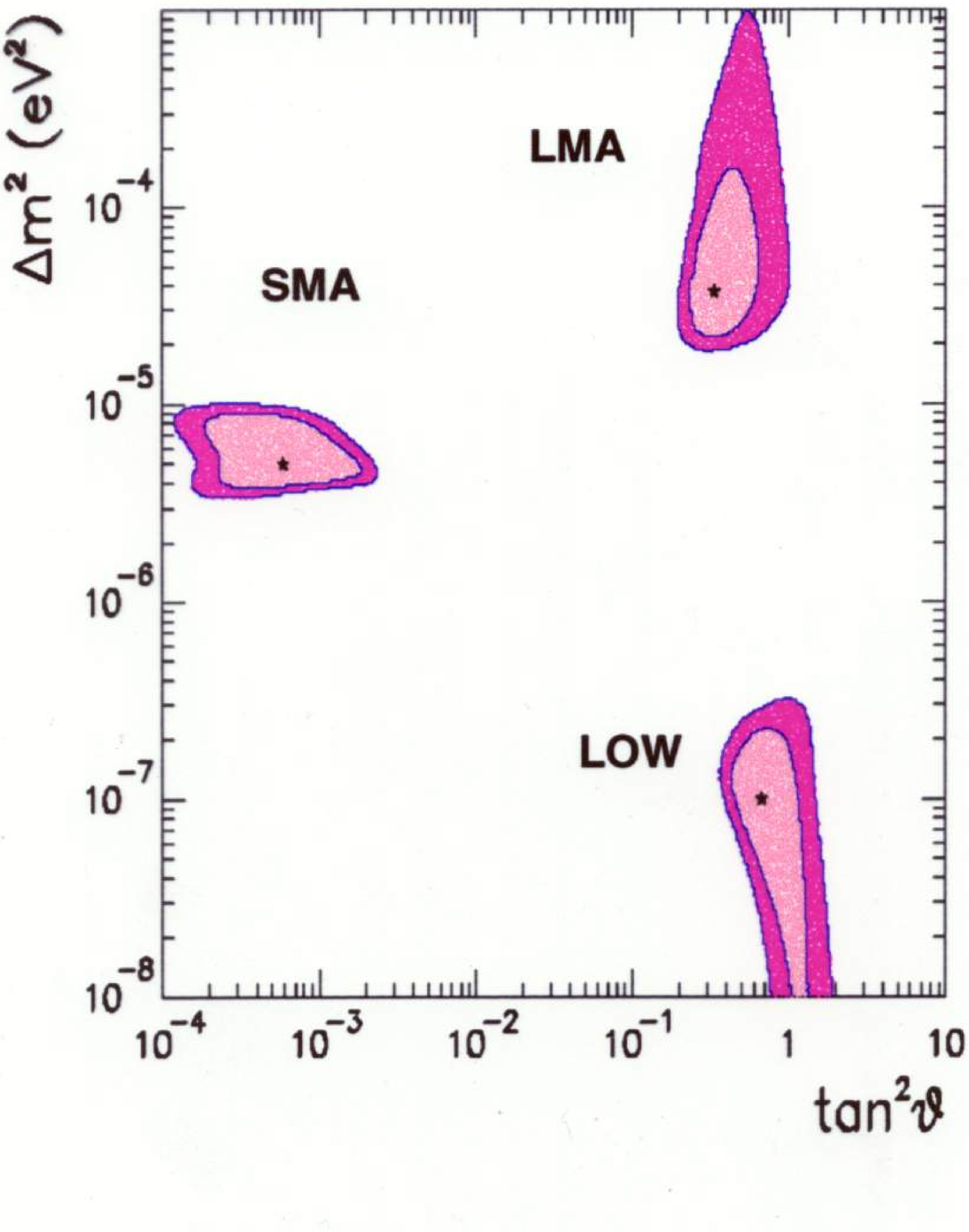
MSW solutions





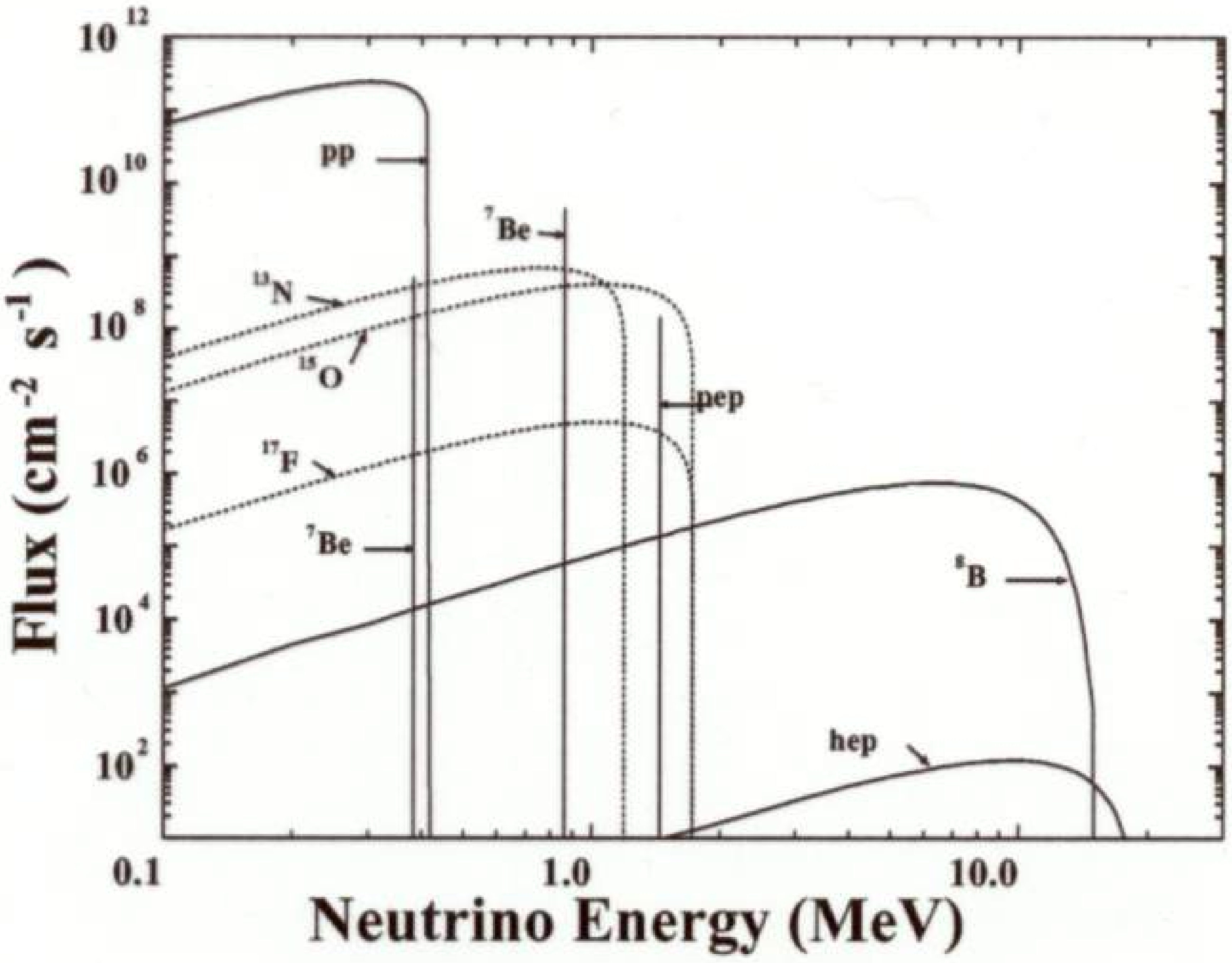
Bahcall, Krastev, Smirnov, hep-ph/0103179

M.C. Gonzalez-Garcia et al. hep-ph/0012313

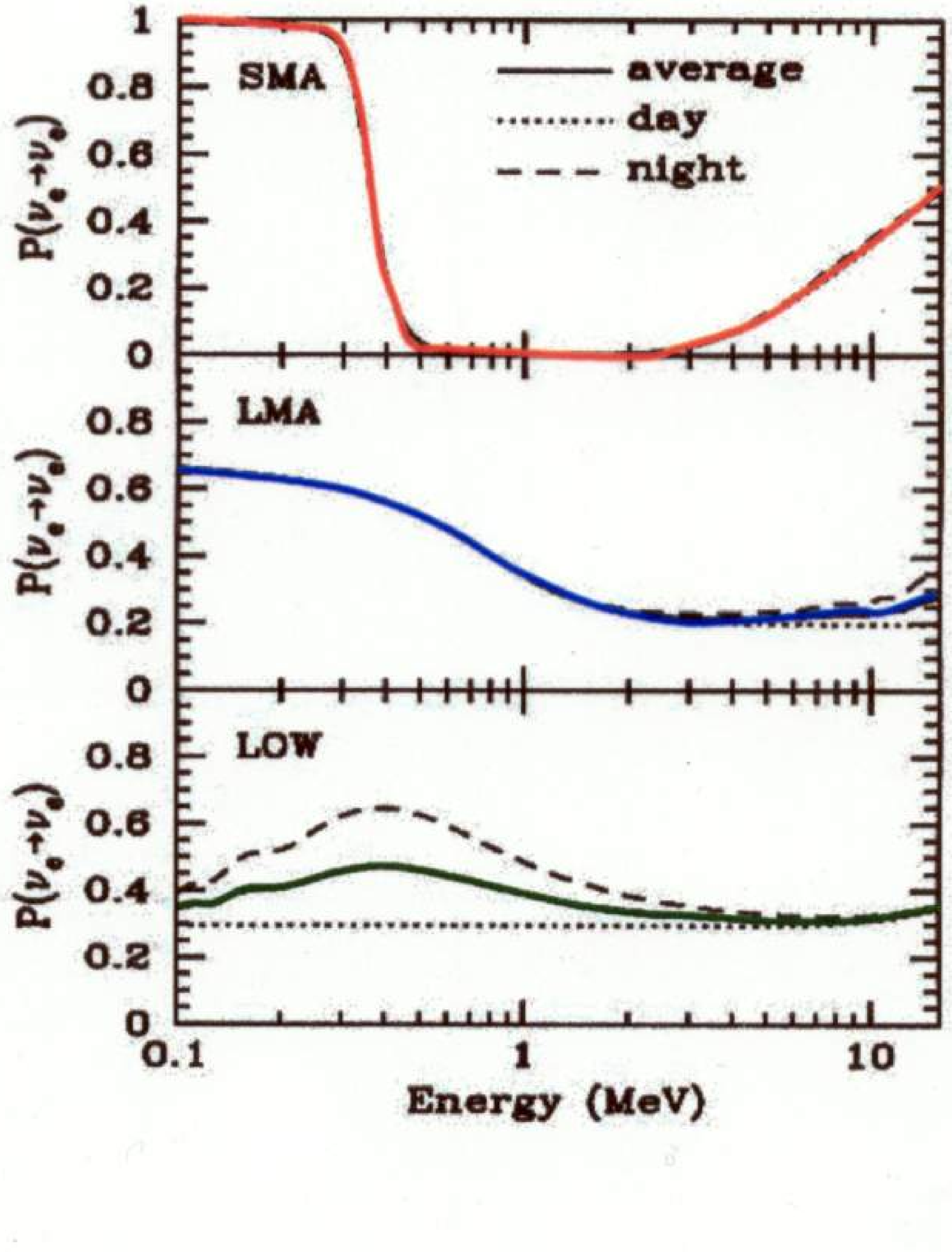


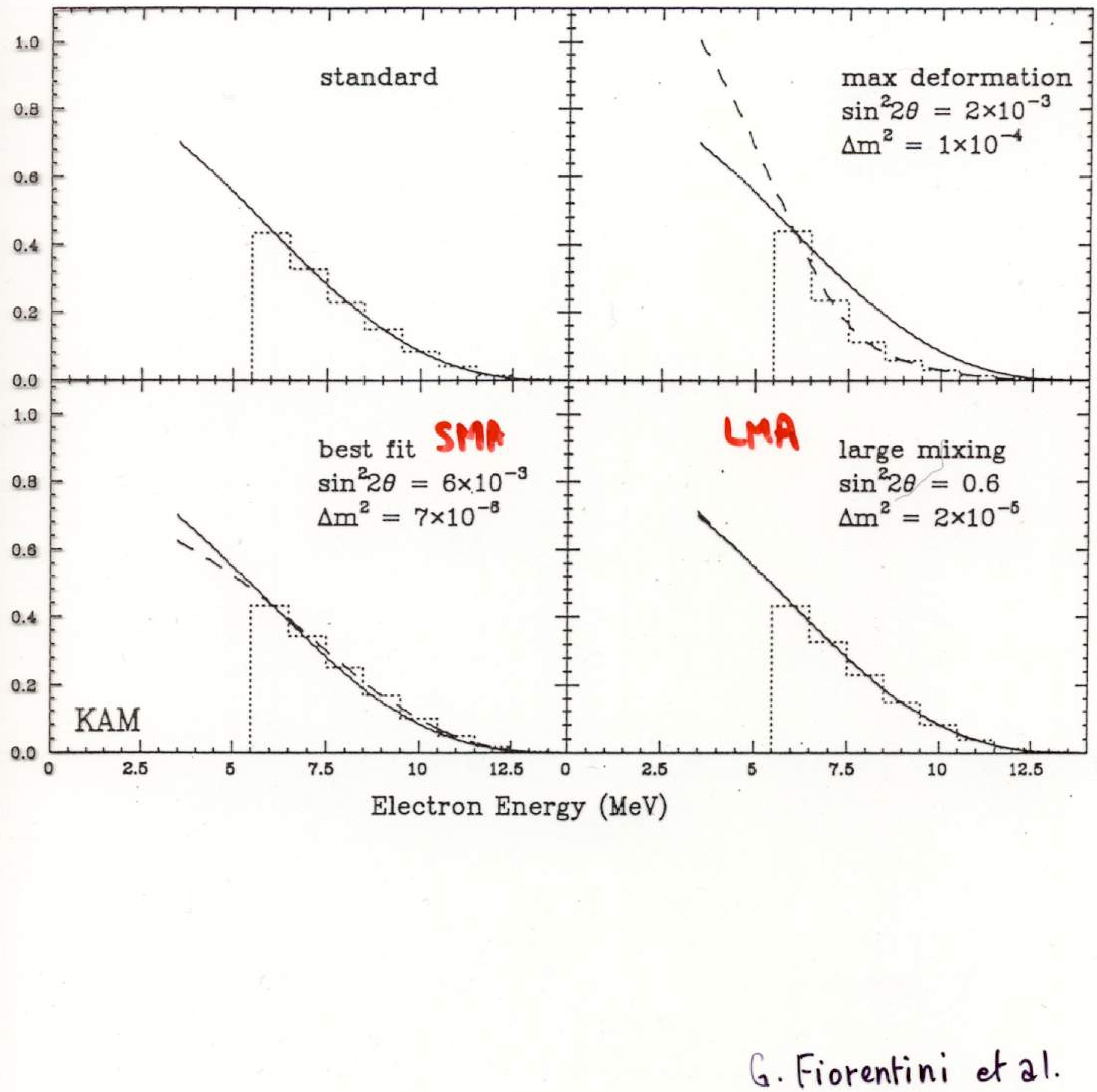
90% & 99% Confidence level

How solar neutrino spectrum is modified by the MSW effect



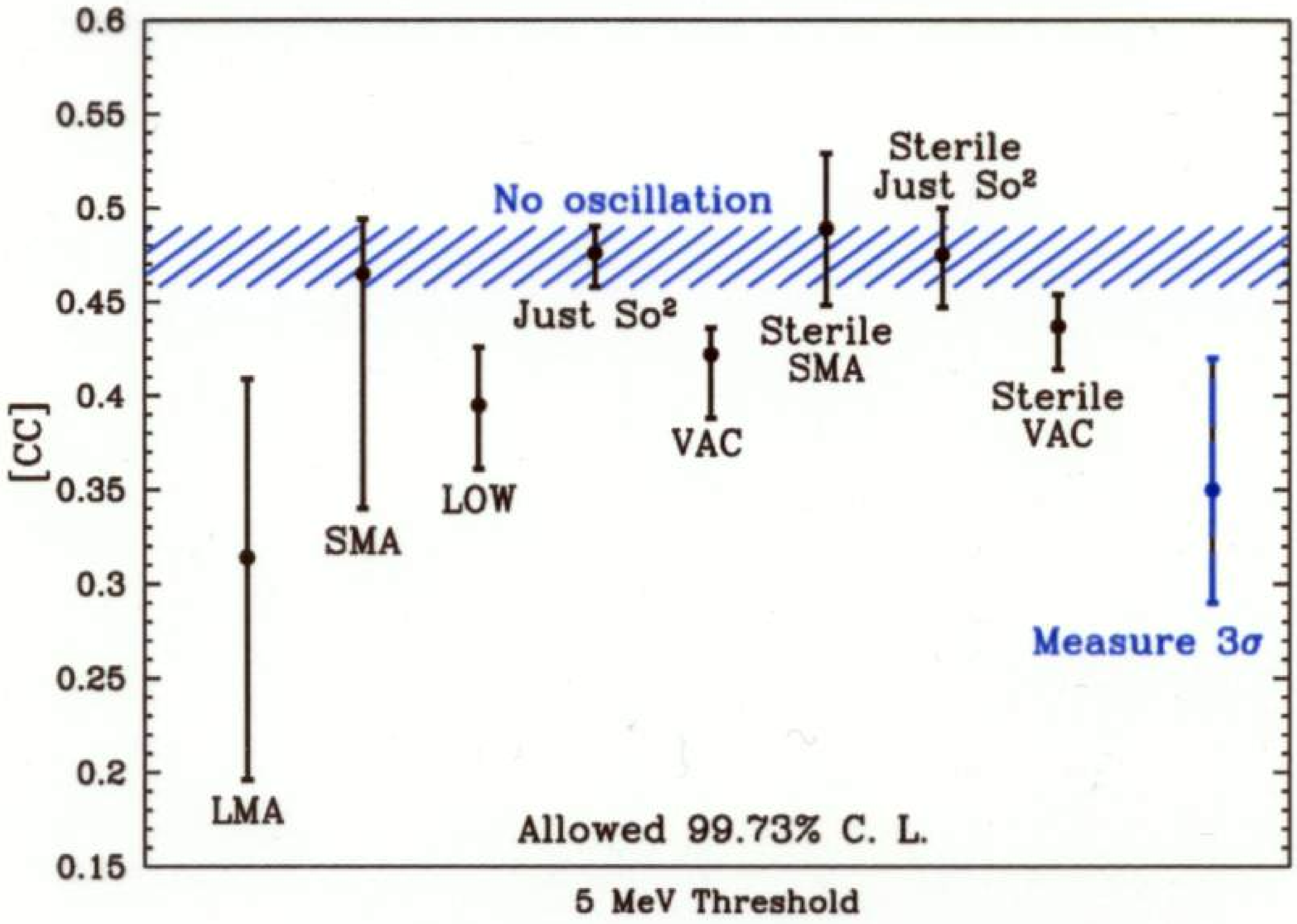
Survival probabilities with MSW effect

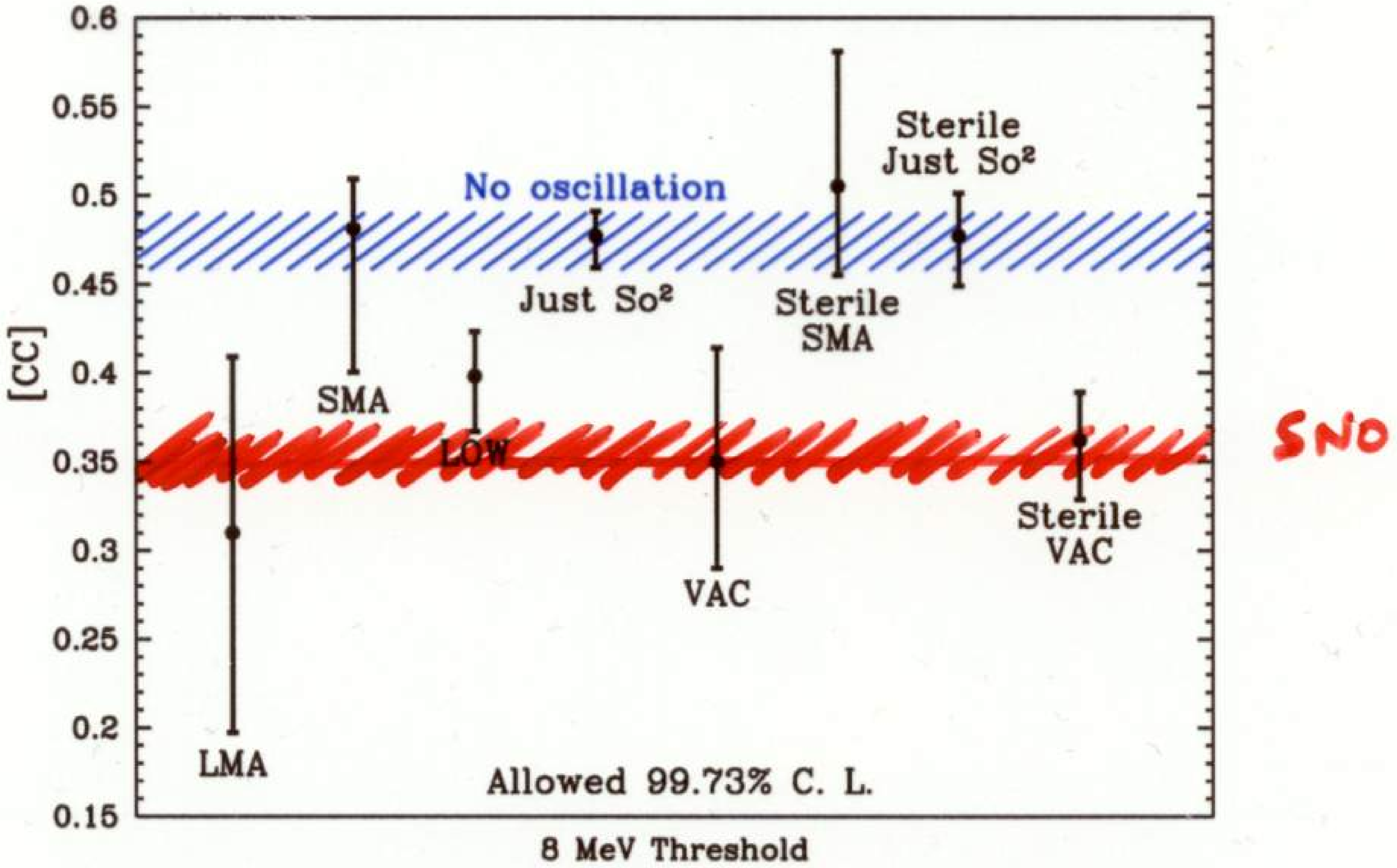




G. Fiorentini et al.
Phys. Rev. D49 (1994) 6298

MSW solutions





Bahcall, Krastev, Smirnov, hep-ph/0103179

* SK : LMA (and LOW) favoured
SMA disfavoured using D/N spectrum

* SNO : evidence for $\nu_e \to \nu_{\mu,\tau}$ osc.

. not yet a fit of the spectrum

. not yet a day-night analysis

↓

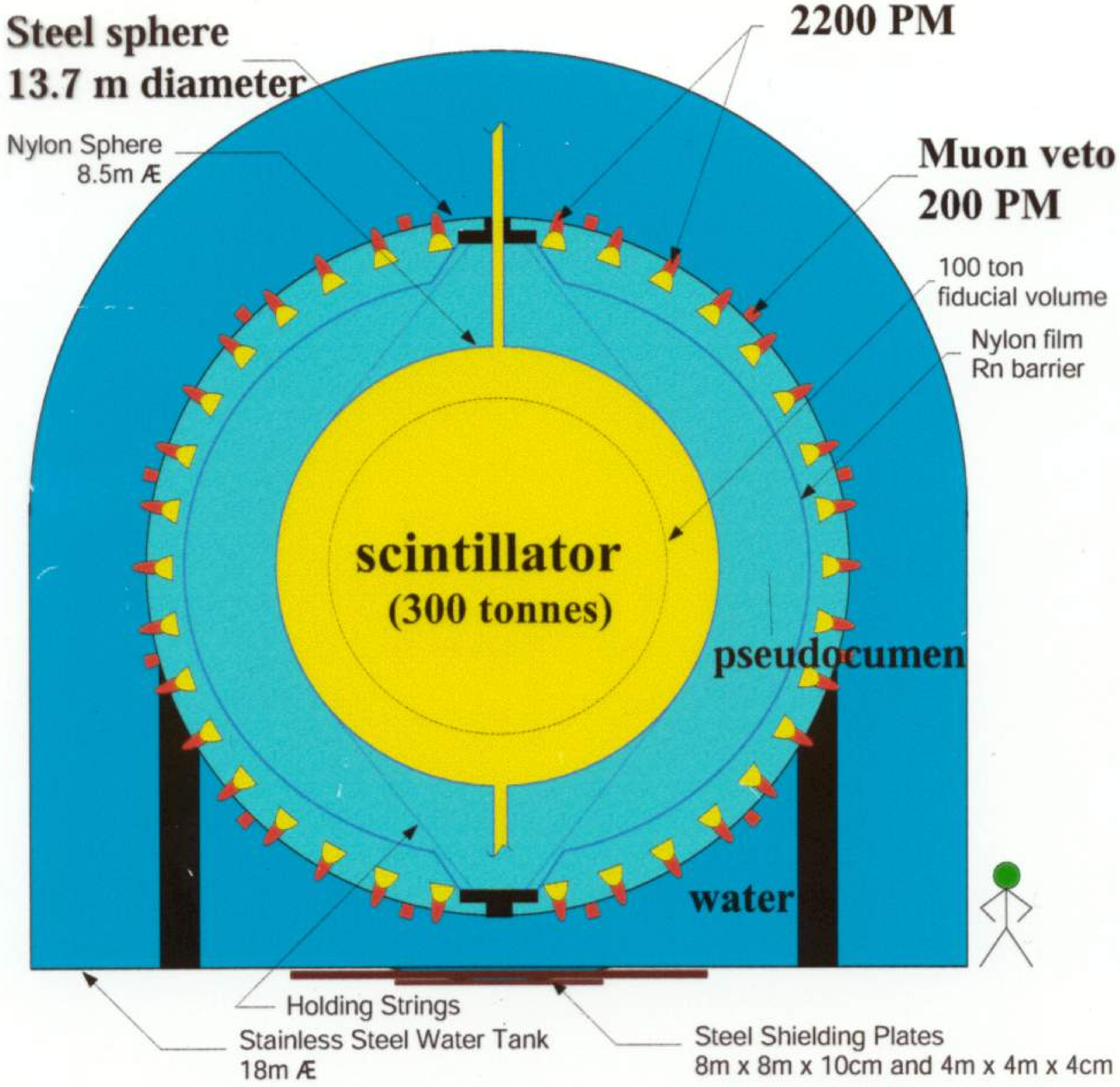
New experiments to disentangle the solutions

↓

Forthcoming years

- KAMLAND
- Borexino

Borexino experiment



elastic diffusion

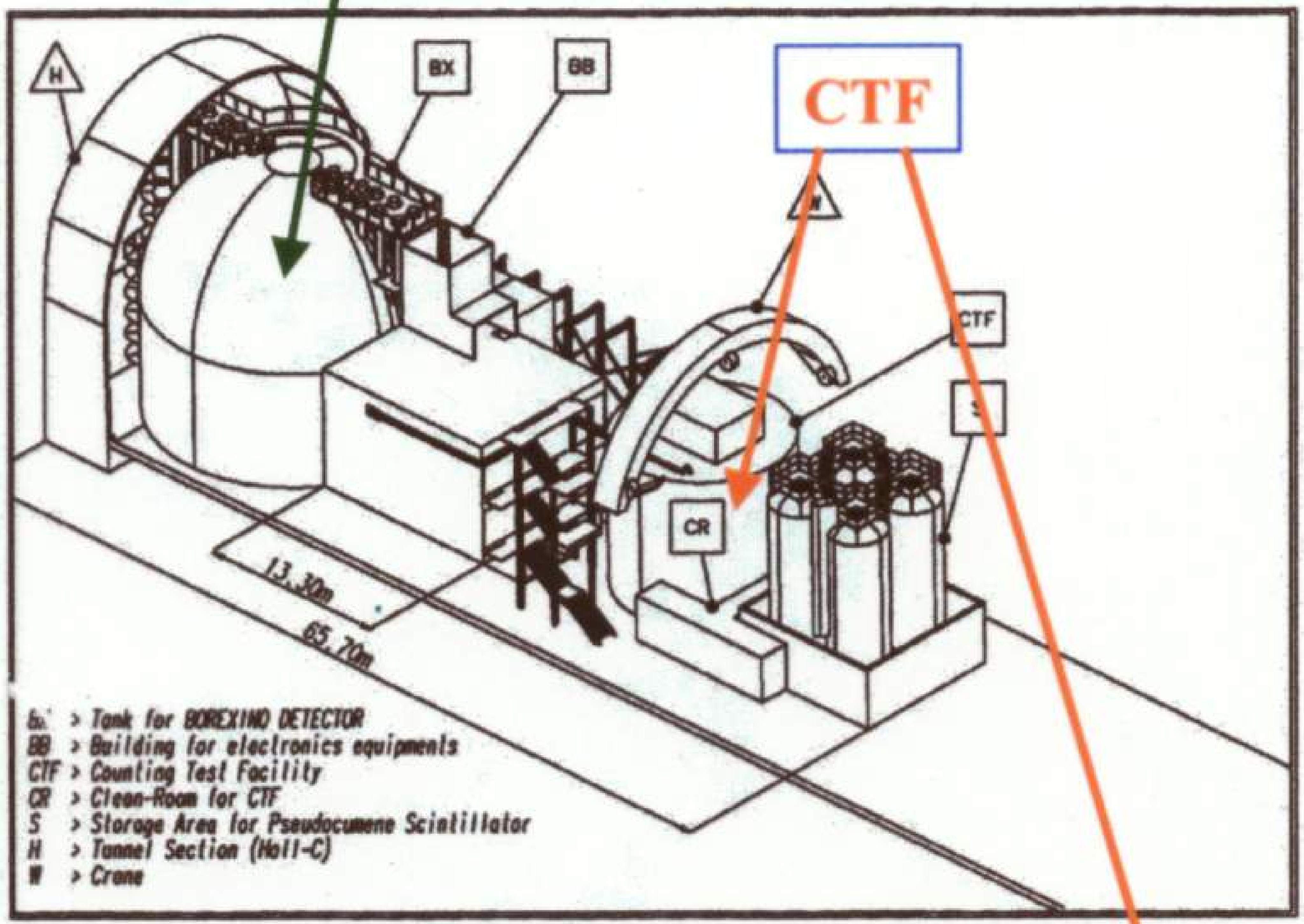
$\nu e \rightarrow \nu e$

50 events / day (without oscillation)

10 - 30 events / day (if oscillation)

Gran Sasso (Italy)

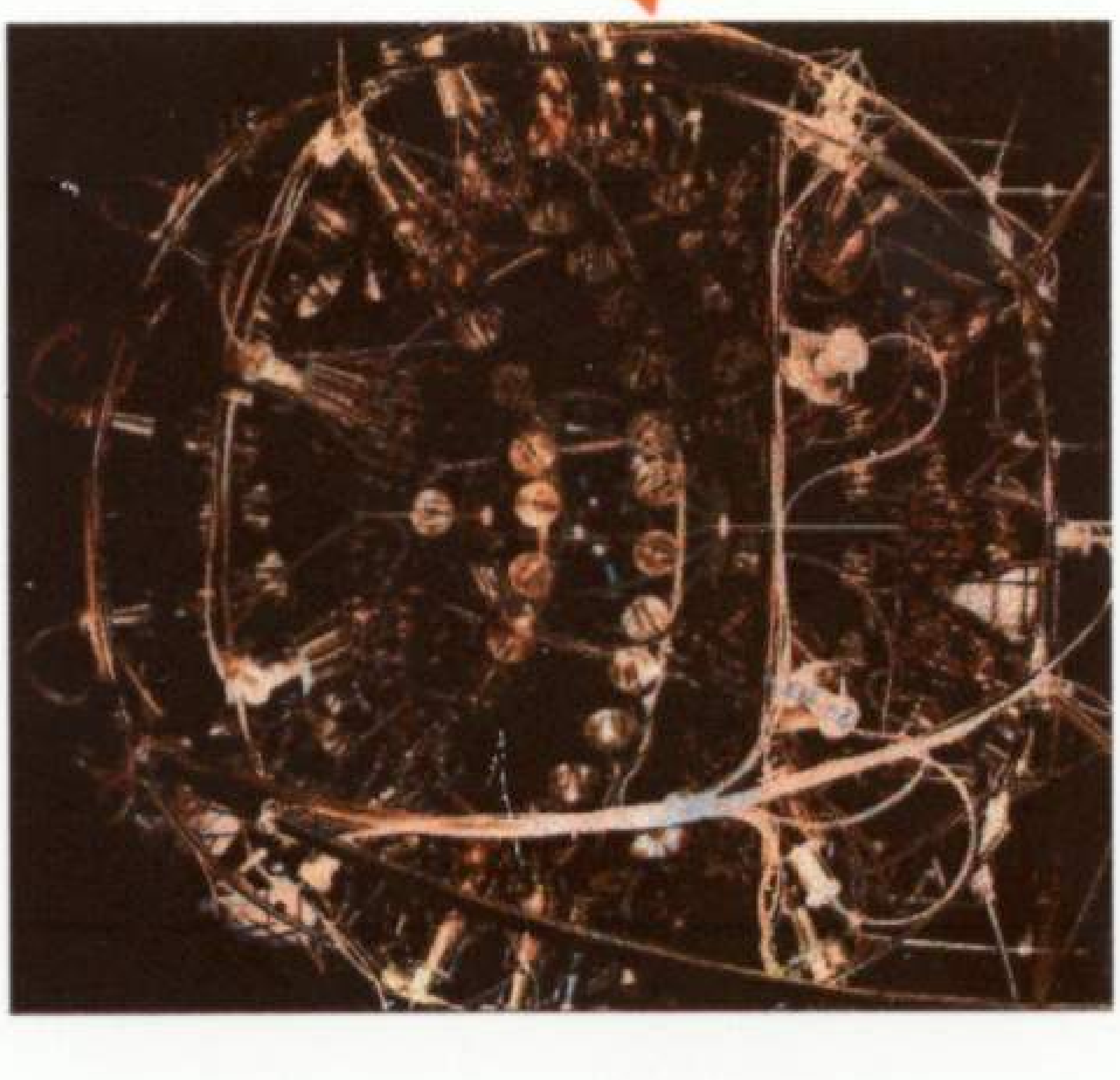
Borexino



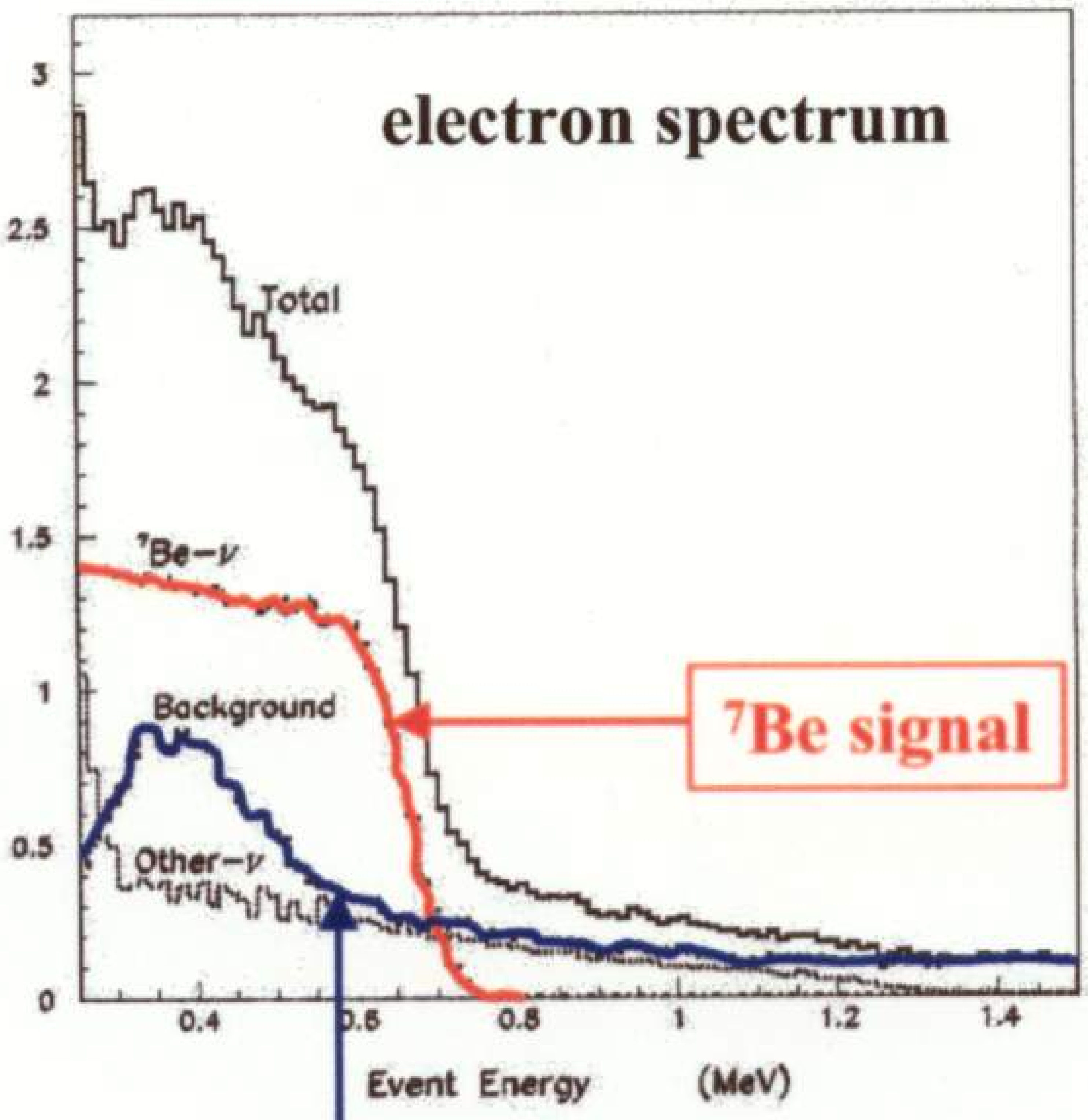
Gran Sasso

3500 mwe

1.1 μ / m^2 / h



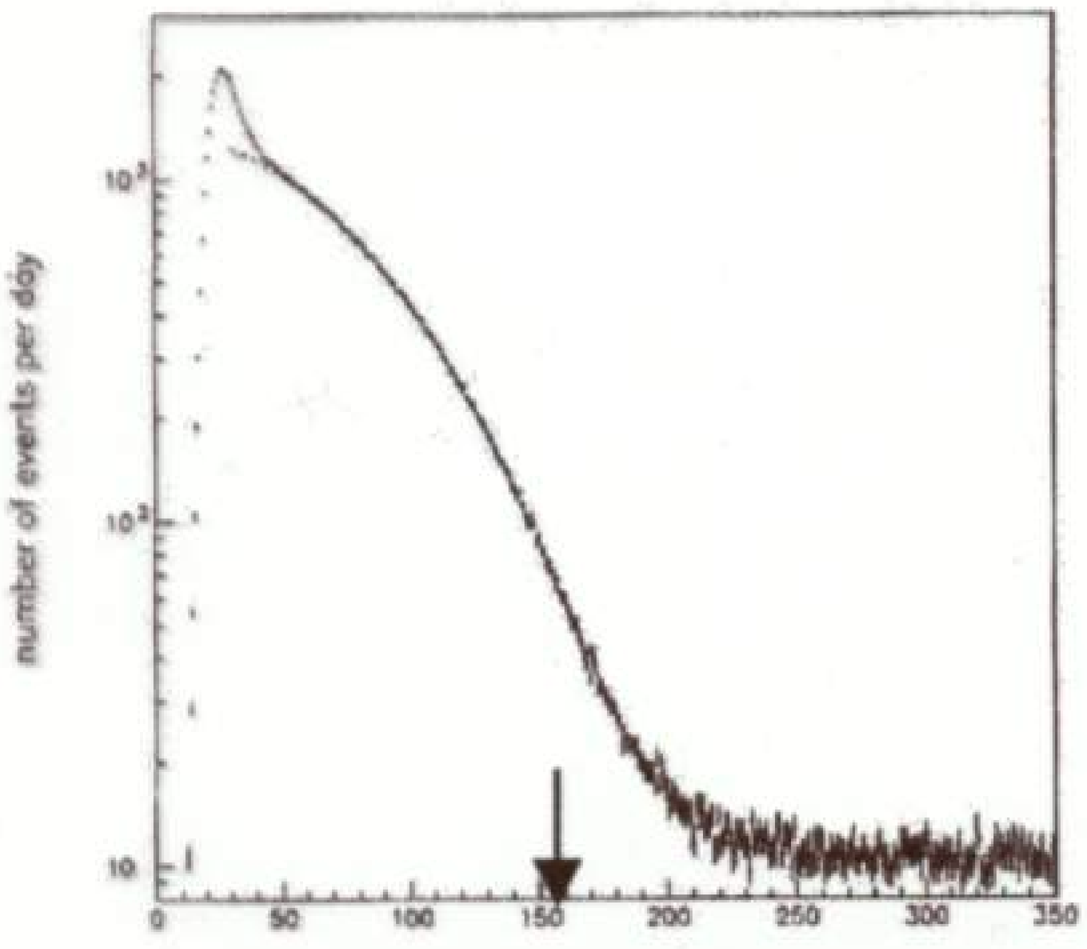
Borexino



Background estimated for :
- 10^{-16} g/g U
- α/β discrimination of 90%

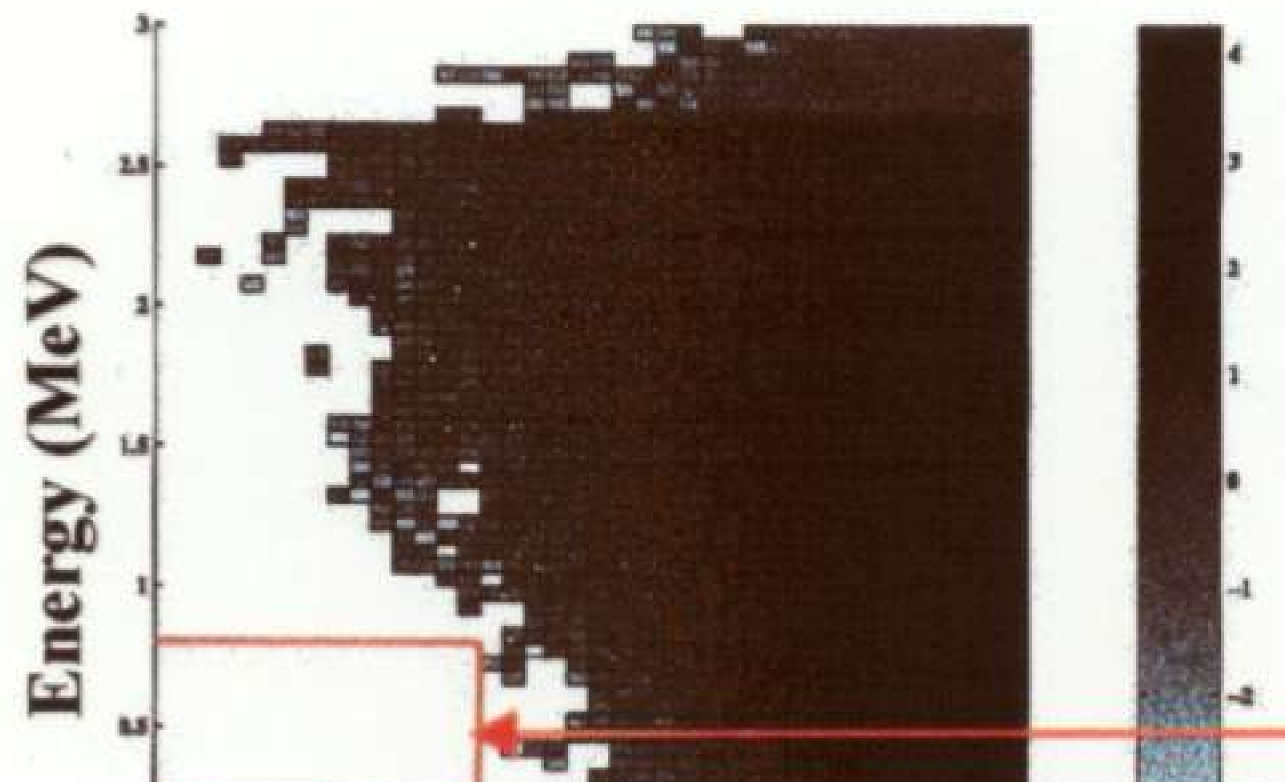
Signal : 55 events / day (SSM)
31 events / day (LMA solution)
12 events / day (SMA solution)
29 events / day (LOW solution)

Borexino



^{14}C β spectrum measured in the CTF (endpoint : 156 keV)

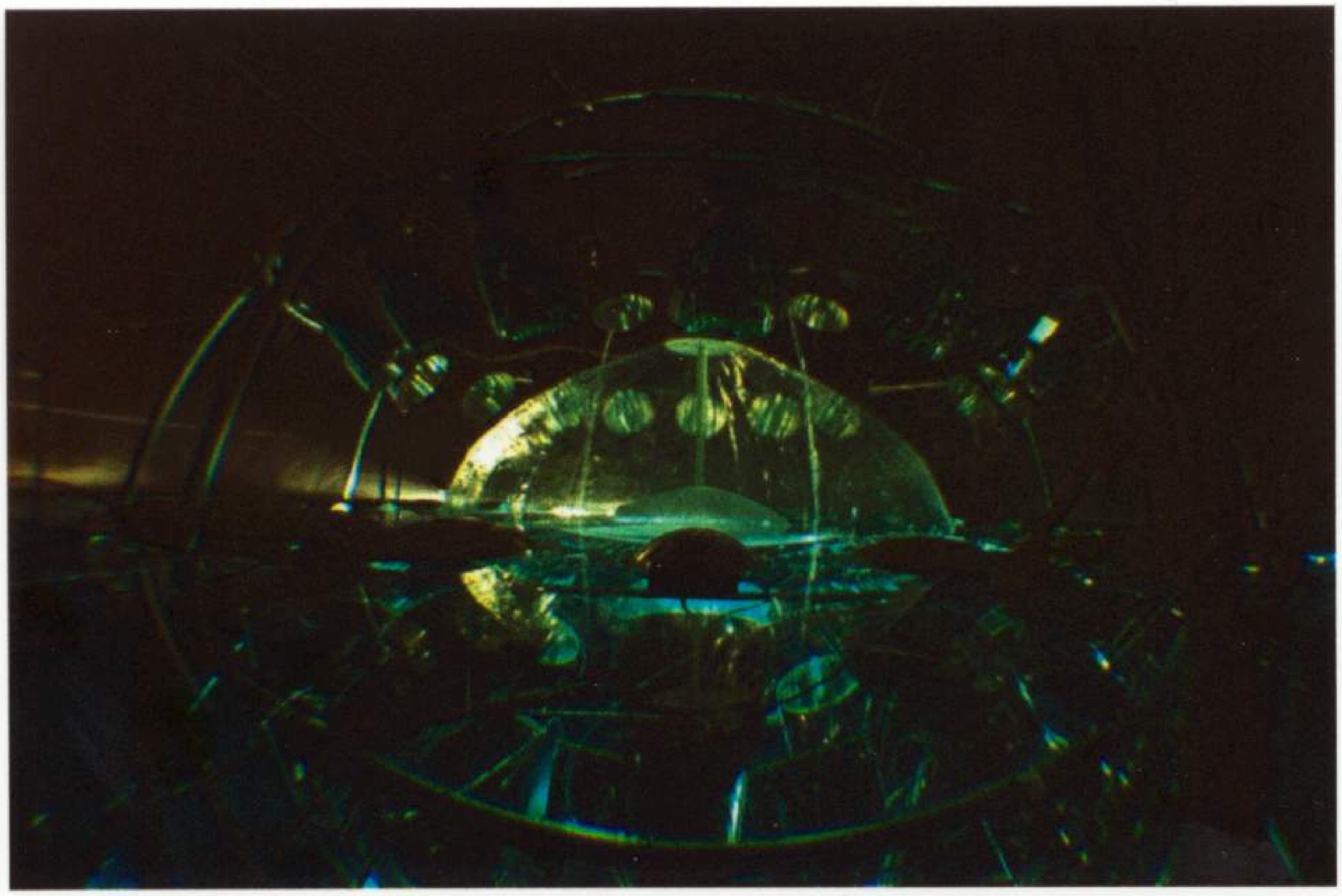
<u>Radiopurity requirements for Borexino</u>
(values achieved in CTF)
- **Stainless steel : 10^{-9} g/g of Th, U equiv.**
- **External water : 10^{-10} g/g of Th, U equiv.**
- **PM : 10^{-8} g/g of Th, U equiv.**
- **Scintillator : 10^{-16} g/g of Th, U equiv.**
- **Scintillator : 10^{-18} $^{14}C/^{12}C$**



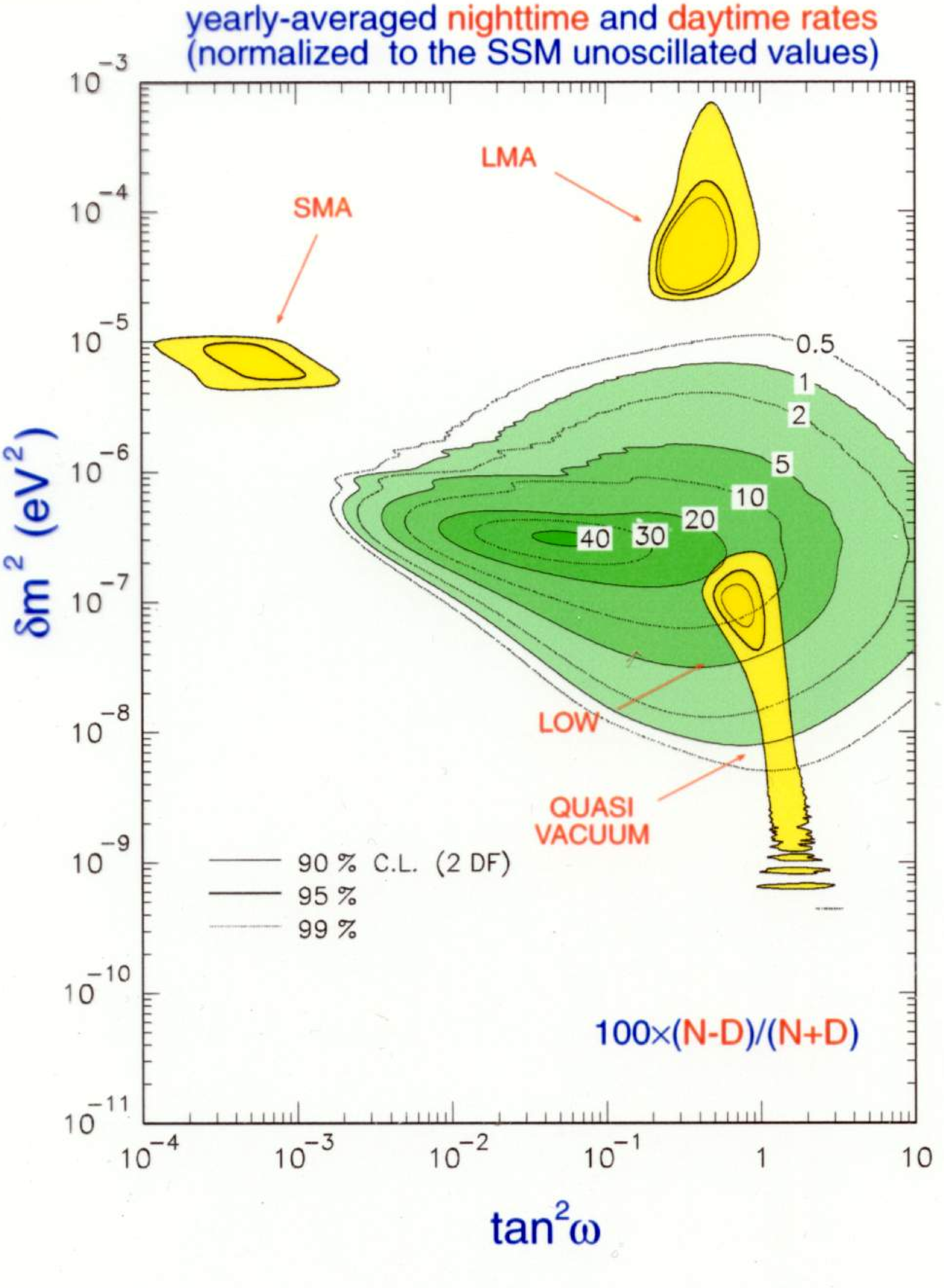
MC simulation of external background

Borexino

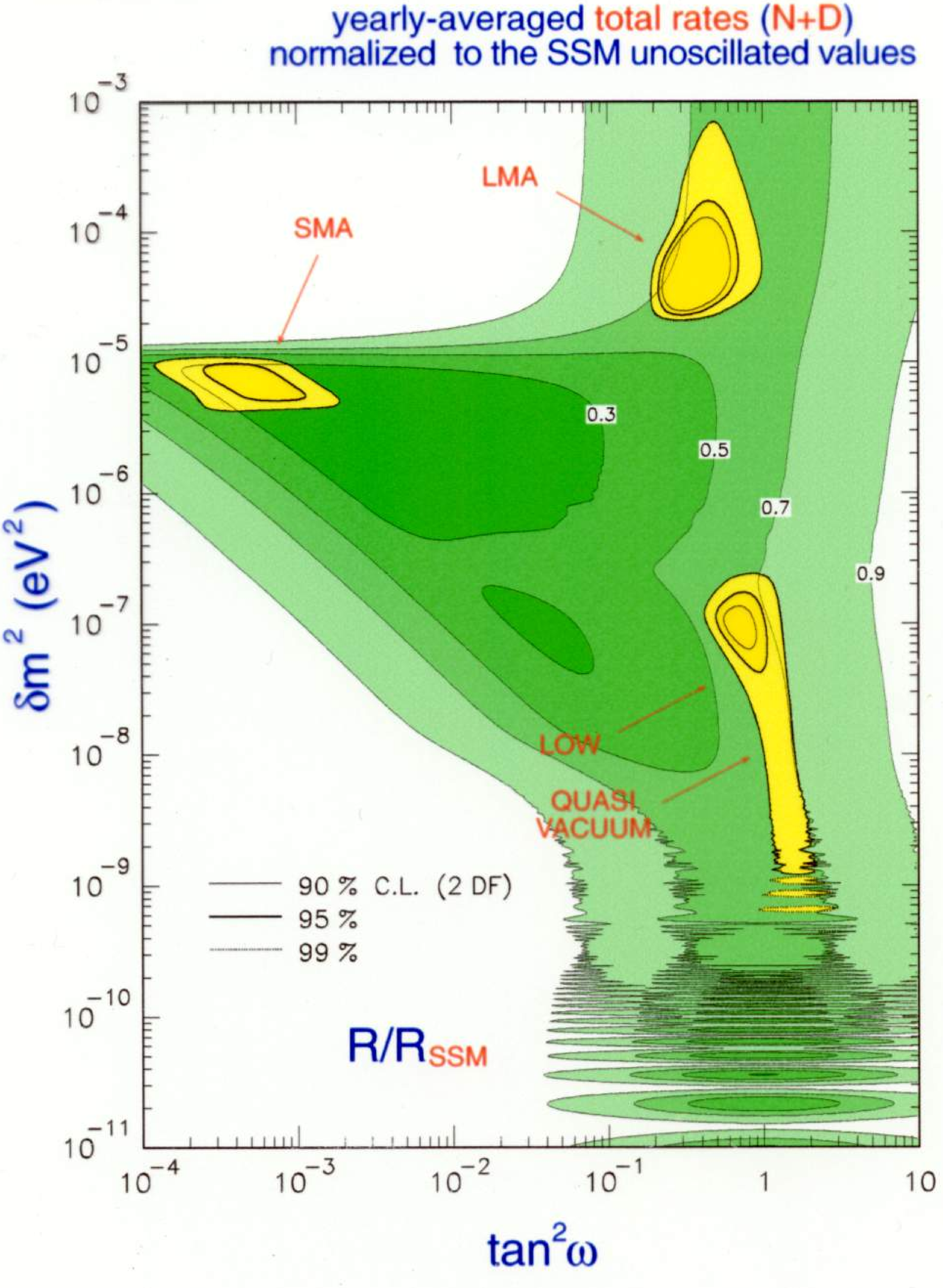
Filling of the CTF with water (June 10, 2001)



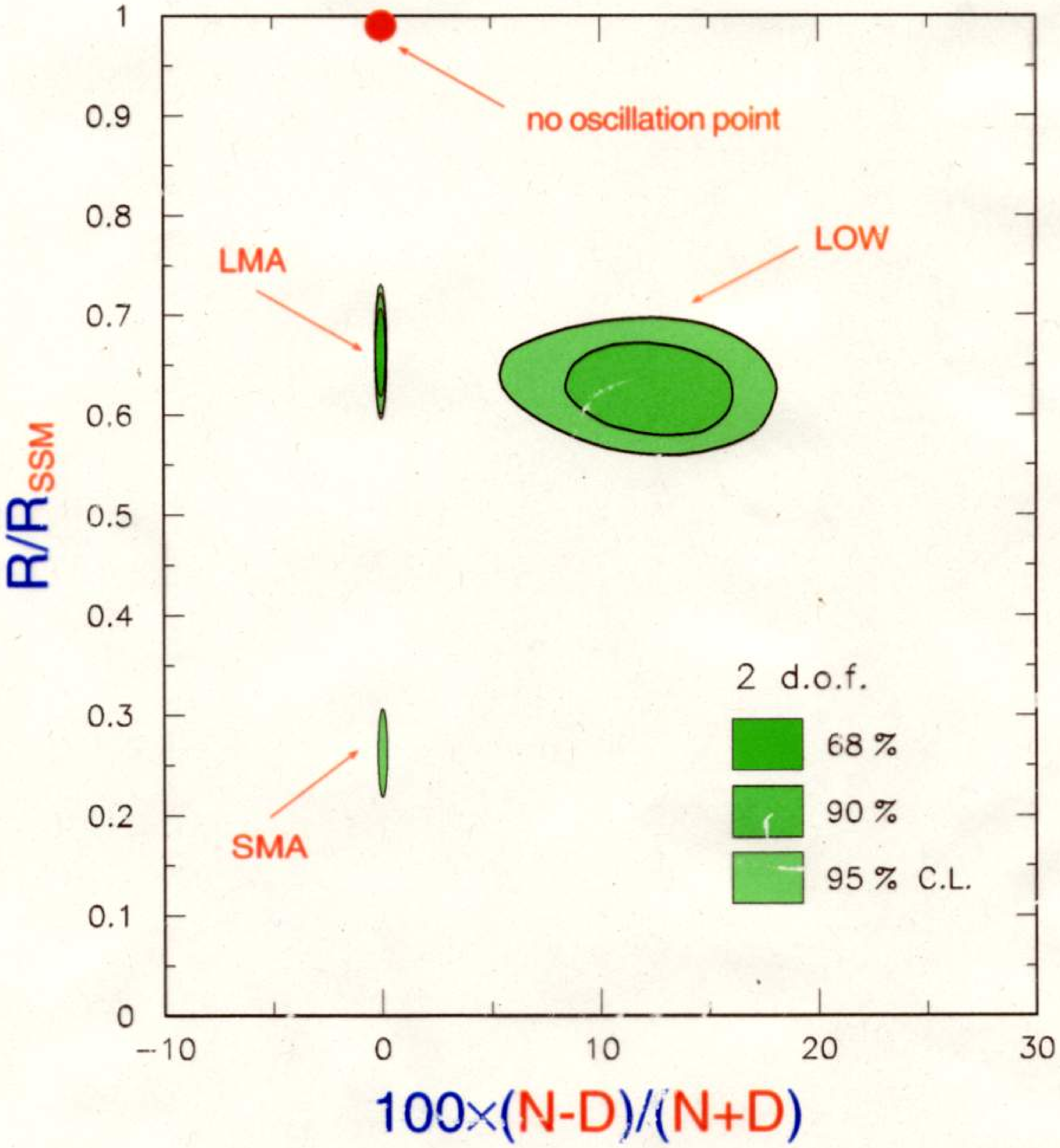
Borexino N-D asymmetry compared with the SMA, LMA and LOW solutions



Borexino total rates compared with the SMA, LMA and LOW solutions



Borexino discovery potential compared with the SMA, LMA and LOW solutions



er Borexino (start in 2002), we need :
precise determinations of pp and Be (CC)
precise measurement of pp spectrum

⇒ **More low energy projects (now R&D phase)**

- ⌘ **LENS**
- ⌘ **HELLAZ**
- ⌘ **HERON (R.E.Lanou)**
- ⌘ **Xenon (Y.Suzuki)**
- ⌘ **Indium ???**

Also (but only « mean energy » experiments) :

Iodine (Radiochemical exp. @Homestake - 100 tons) : $\nu_e + {}^{127}I \rightarrow {}^{127}Xe + e^-$ (threshold = 0.79 MeV)

Lithium (Russia) : $\nu_e + {}^{7}Li \rightarrow {}^{7}Be + e^-$ (threshold : 0.86 MeV) - cryogenic detection of ${}^{7}Be$.

Low Energy Neutrino Spectroscopy (LENS)

$E_e = E_\nu - E_{th}$

$$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)^*$$

$$(A,Z+1)^* \rightarrow (A,Z+1) + \gamma$$

☺ (A,Z) = rare earths ytterbium or gadolinium with a low threshold to be sensitive to pp ν

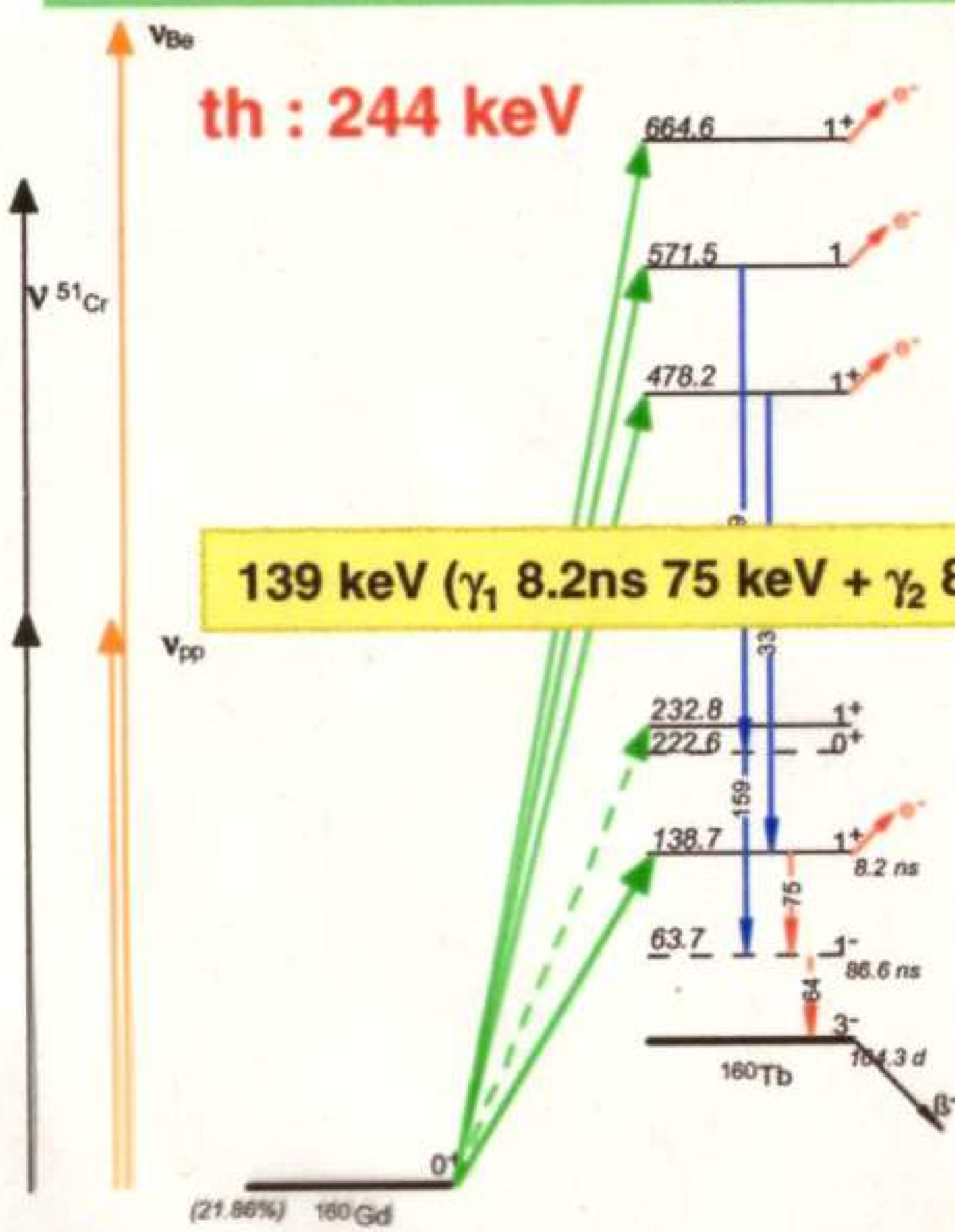
- **direct measurement of pp and Be neutrinos**
- **CC reaction (complementary to Borexino)**
- **real time**
- **specific signature (e + delayed coincidence for γ)**

Detection scheme

$\nu_e + {}^{160}Gd \longrightarrow {}^{160}Tb^* + e^-$

$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow {}^{160}Tb + \gamma_1 + \gamma_2$

th : 244 keV



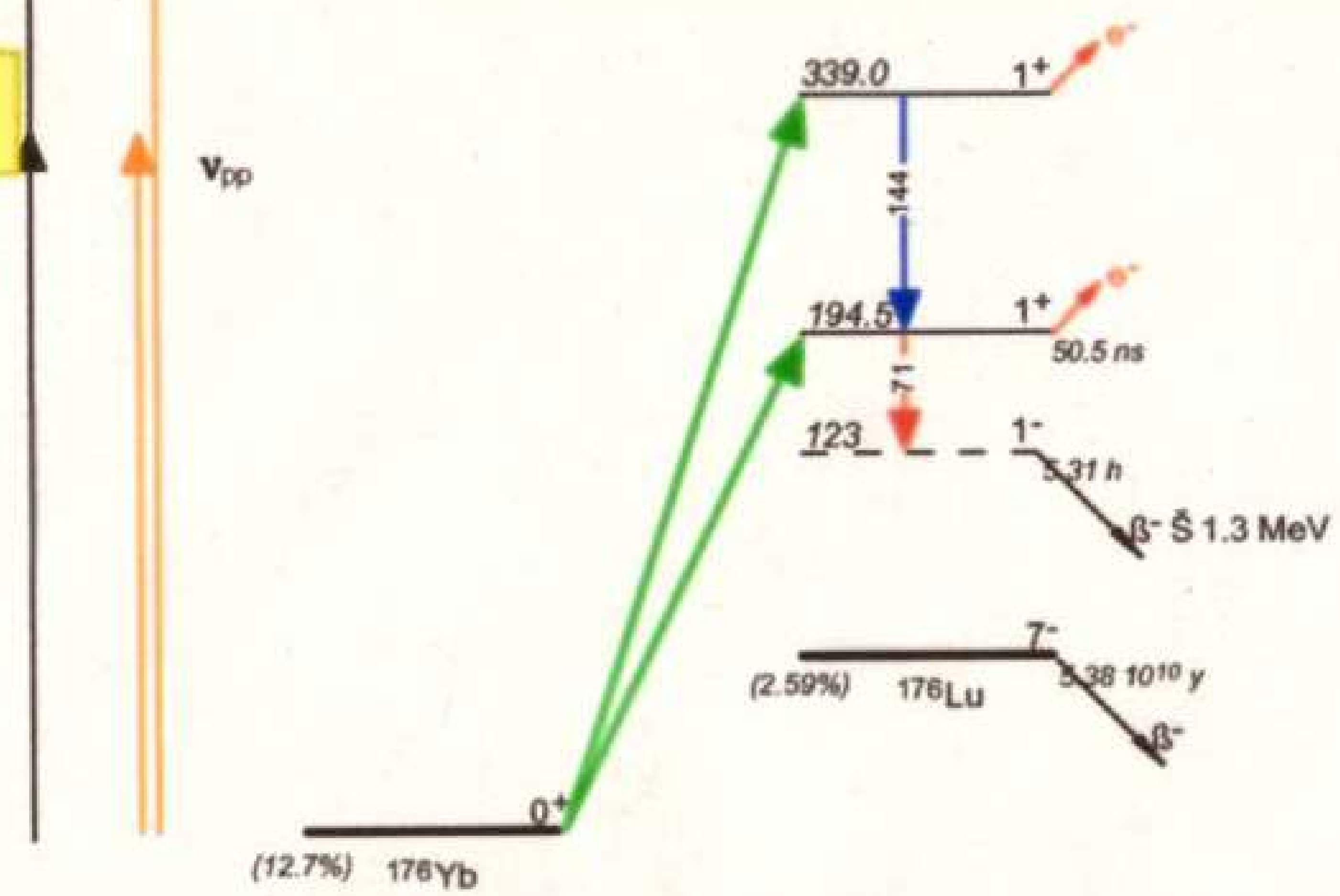
139 keV (γ_1 8.2ns 75 keV + γ_2 86.6ns 64 keV)

$\nu_e + {}^{176}Yb \longrightarrow {}^{176}Lu^* + e^-$

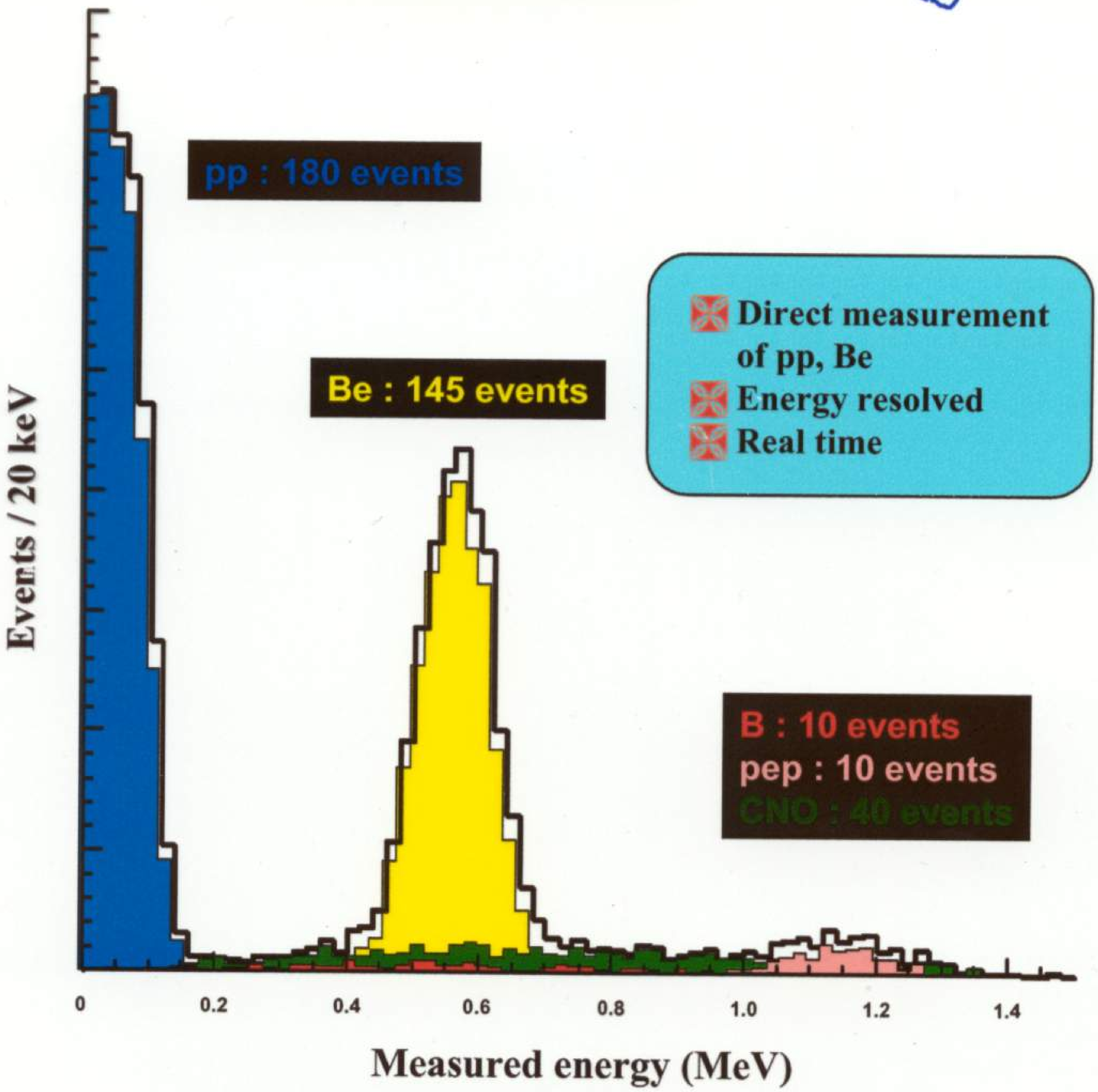
$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow {}^{160}Lu + \gamma_1$

th : 301 keV

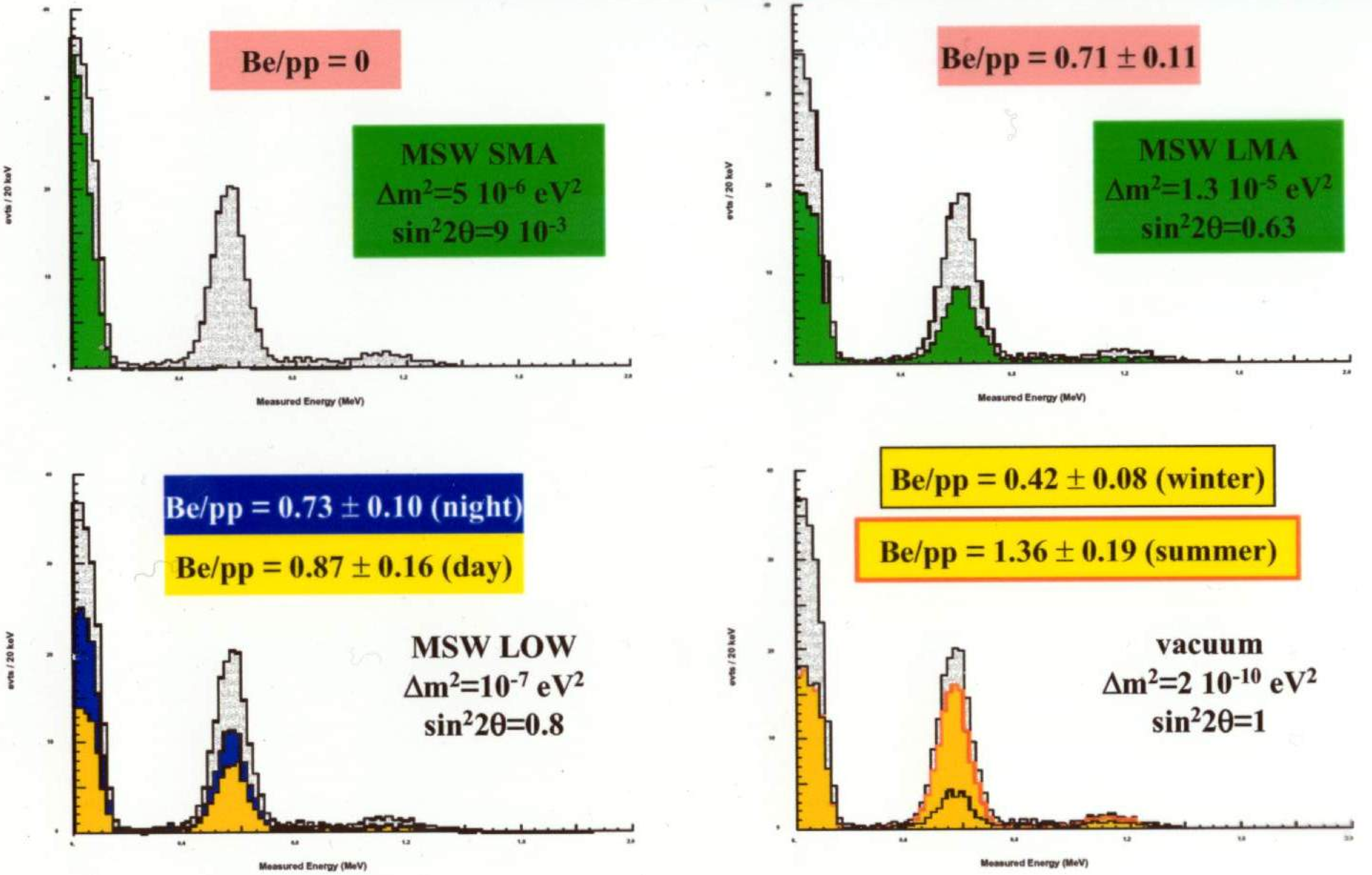
a) 194 keV ($t_{1/2}$=50.5ns + 71 keV)
b) 339 keV (through 194 keV + 144 keV γ)



20 tons of Ytterbium
1 year



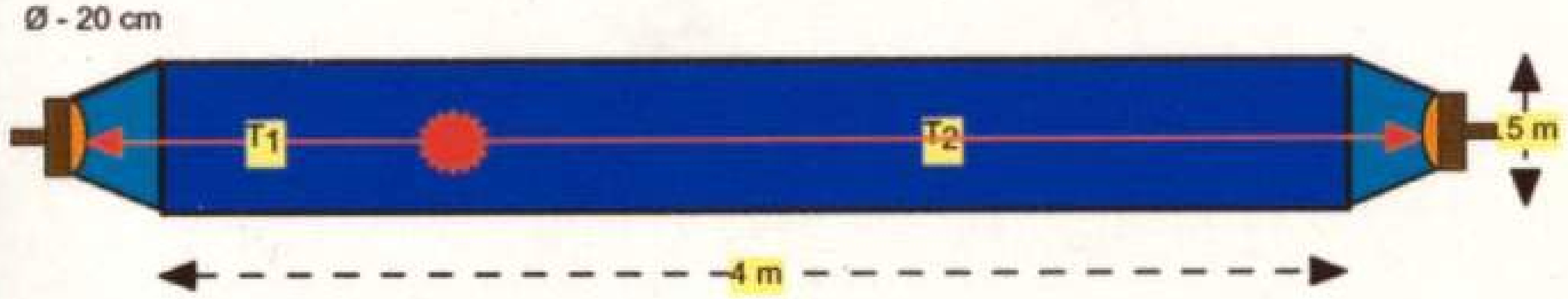
Disentangle the puzzle : 20 tons Yb in one year



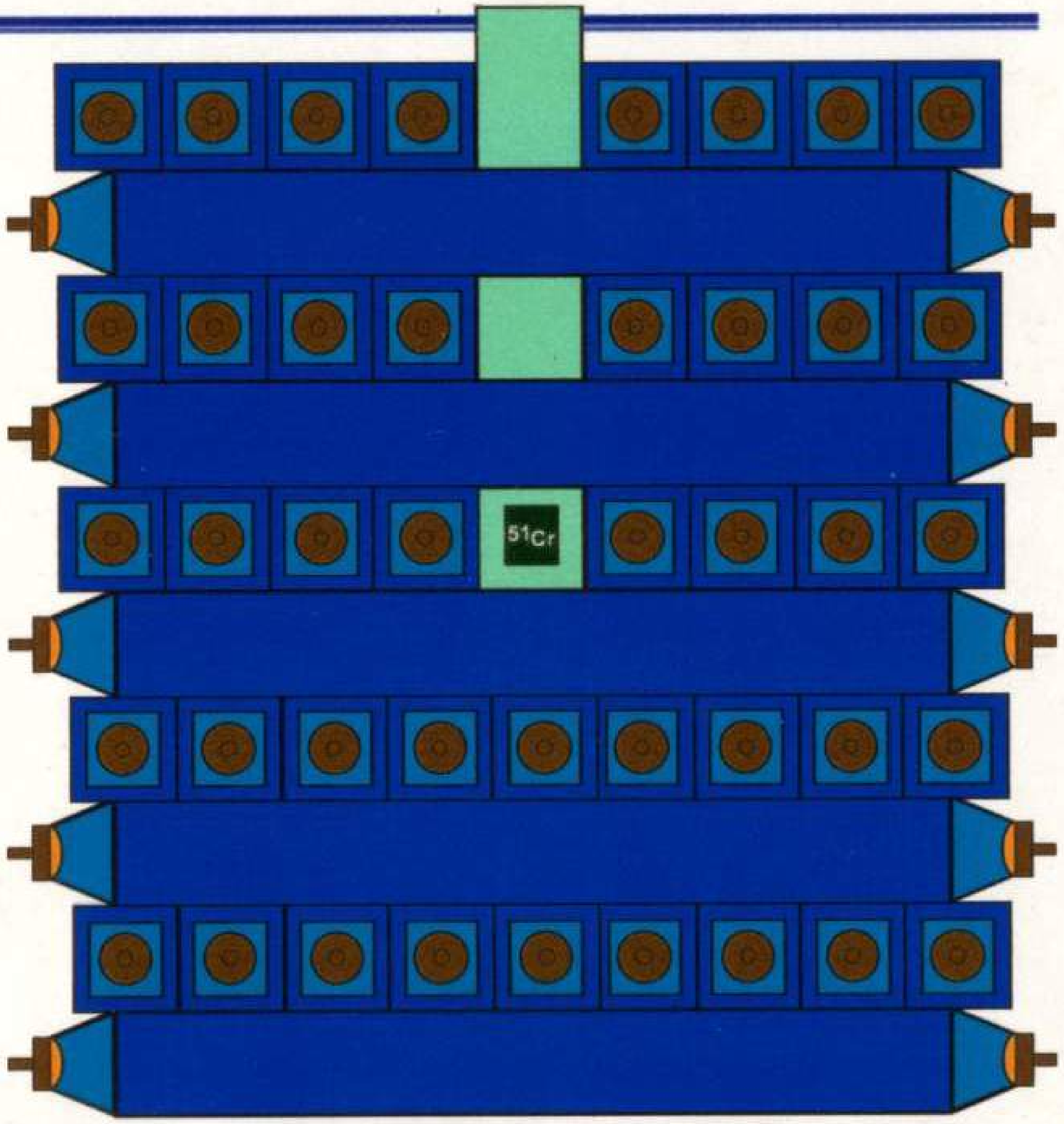
A possible detector

❑ A unit module...

- 100 kg Yb
- technique :
  - → liquid scintillator

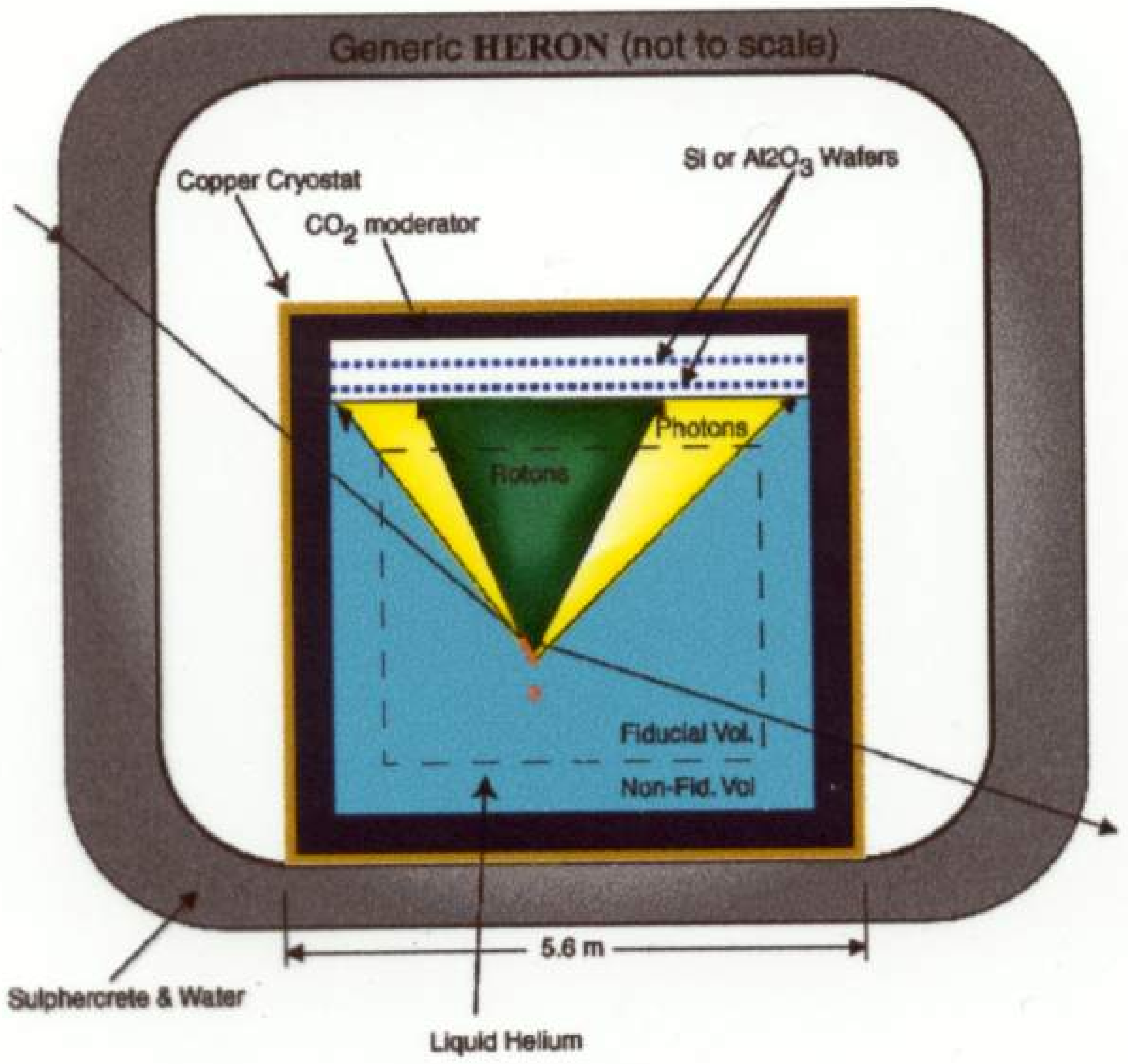


- 1 m^3
- localisation $\Delta V/V \approx 15\%$
- energy $\Delta E/E < 20\%$



...repeated 100 times

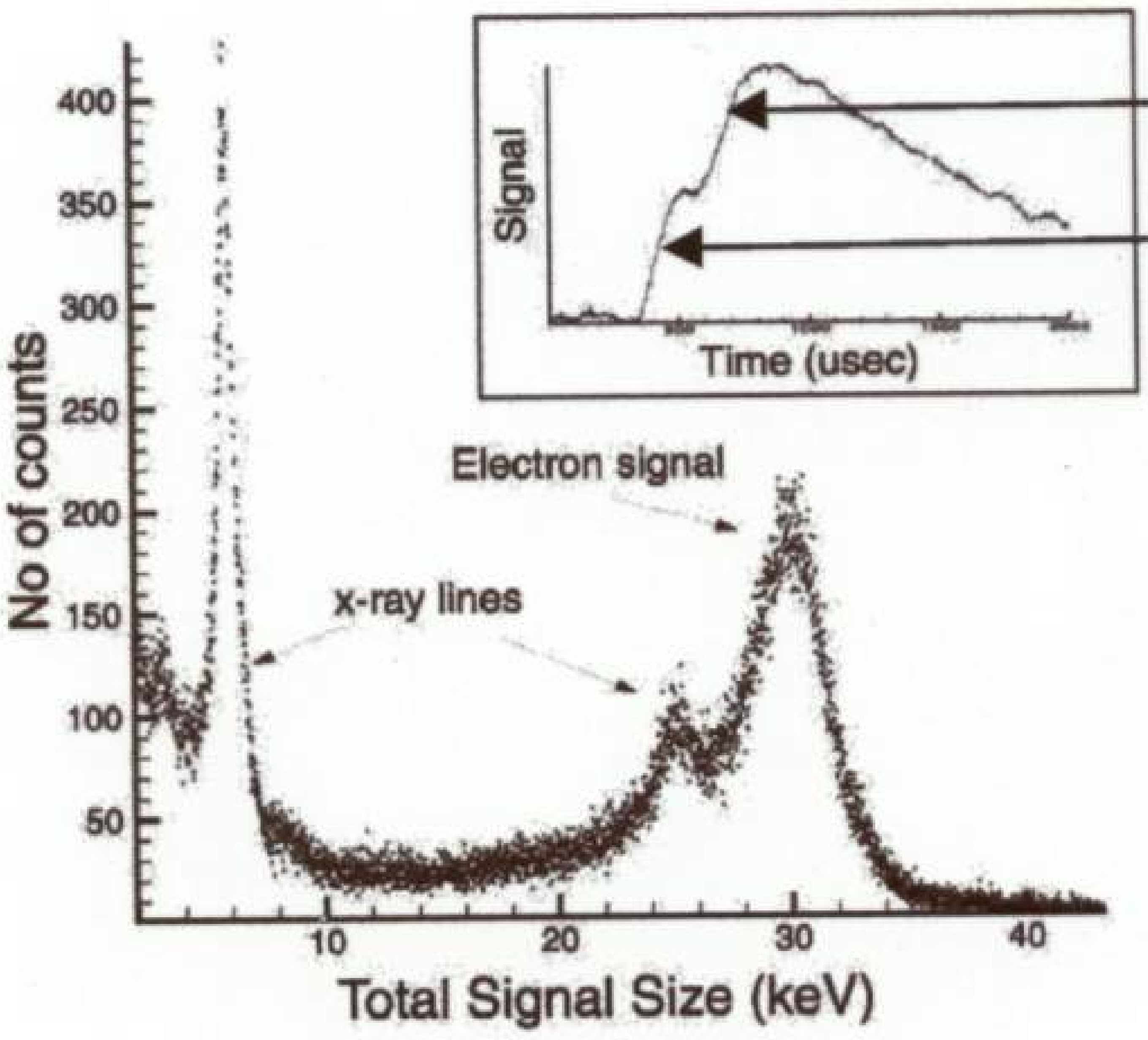
HERON



Elastic diffusion νe ⟶ νe

Target : superfluid helium (2 ev. / ton / day)

Detection : UV scintillation + delayed roton/phonon signal detected on thin wafer calorimeters (coded aperture method for position and energy).



Phonons/Rotons

Photons

Typical pulse

Energy spectrum for 364 keV electrons in superfluid helium

http://www.physics.brown.edu/research/heron/index.html

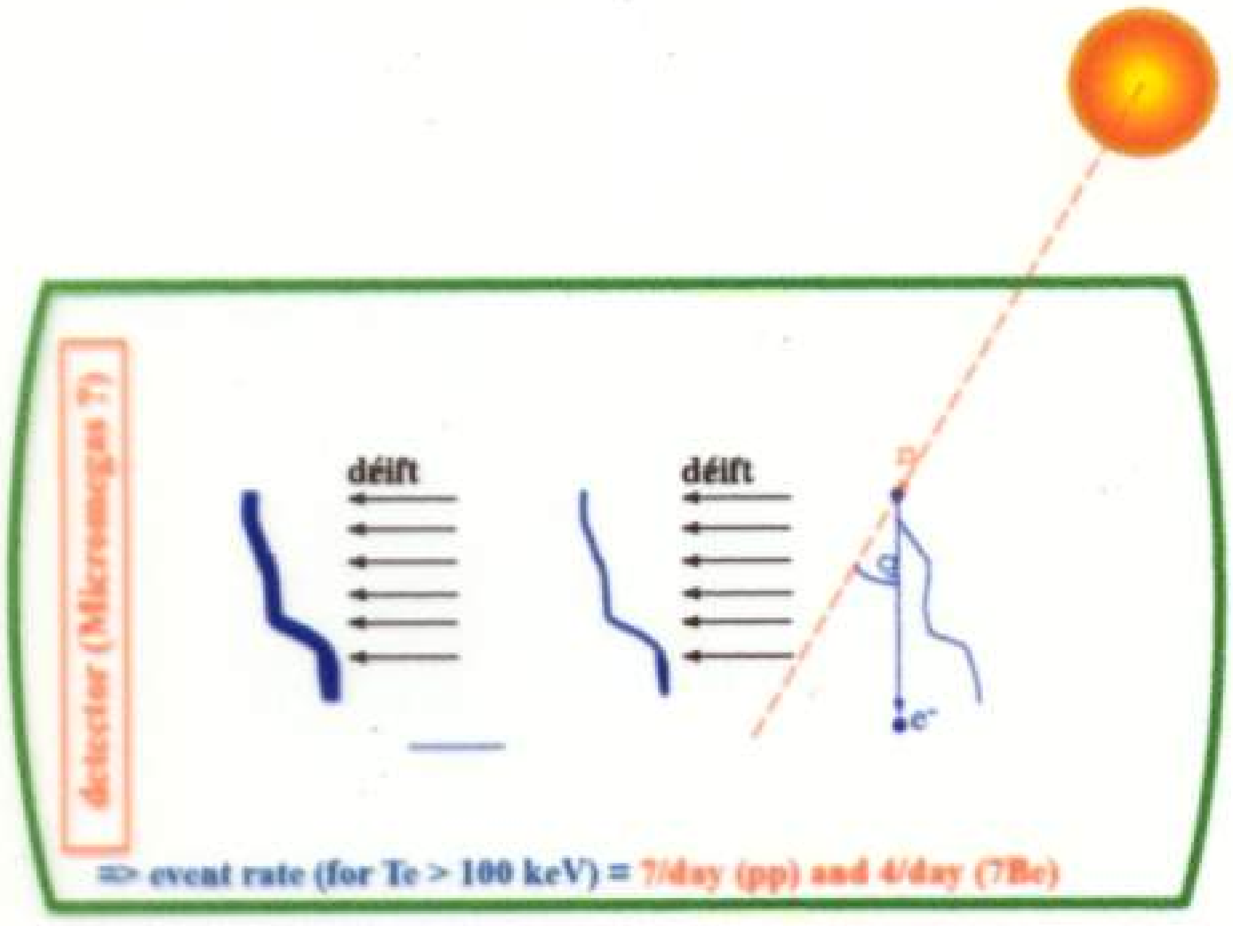
HELLAZ

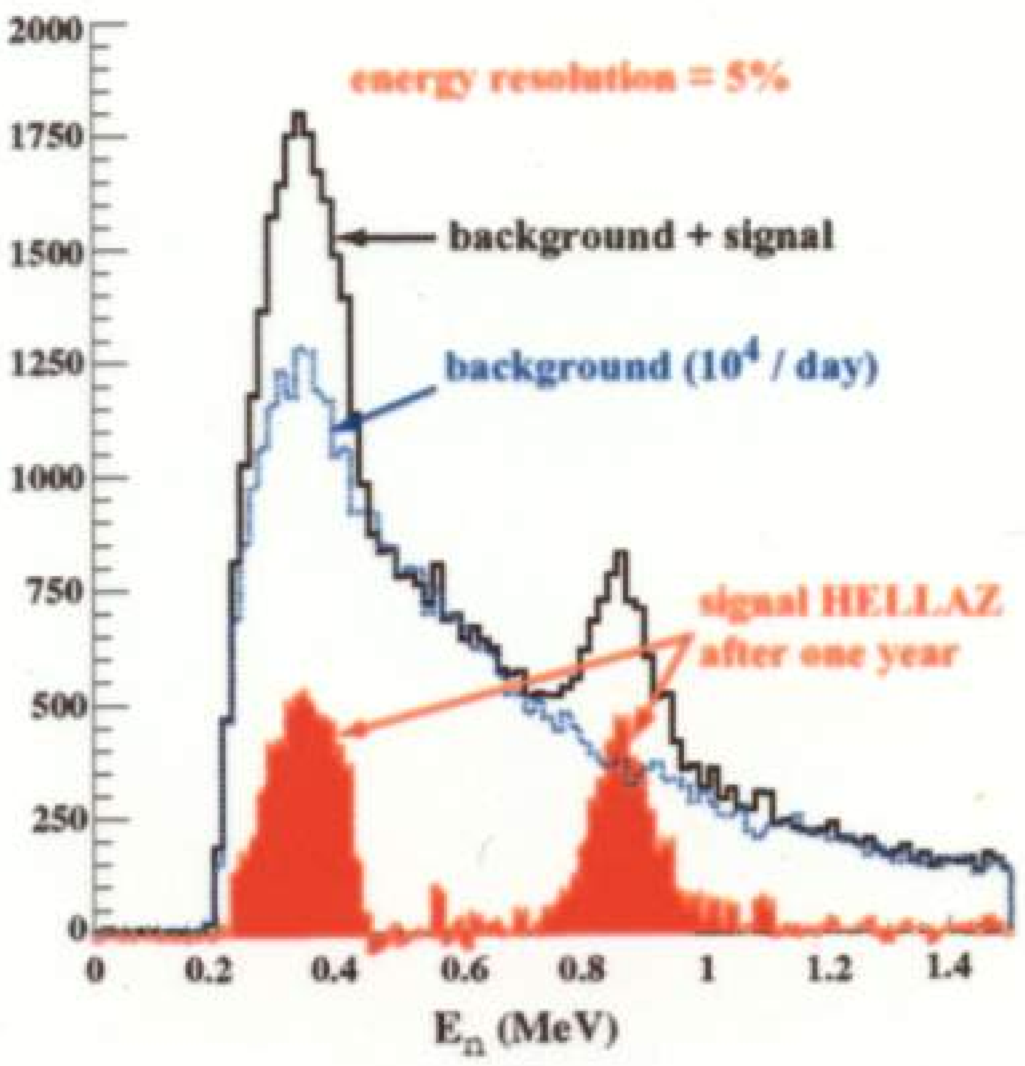
➢ Measurement of the « pp » spectrum

elastic diffusion neutrino - electron in a TPC filled with He

$\rho_{He} = 3.124 \times 10^{-3}$ g/cm^3, 6 tons He $\Rightarrow N_e = 2\ 10^{30}$

- **Measurement of T_e (σ_T/T @ 3%) and θ (σ_θ/θ @ 35 mrad)**
- **Neutrino energy :** $E_\nu = \dfrac{m_e}{\sqrt{1 + \dfrac{2m_e}{T_e}\cos\theta}}$





HELLAZ

Elastic diffusion νe ⟶ νe (CC+NC)

2000 m³ helium (≈10 ev. / day above 100 keV electrons)

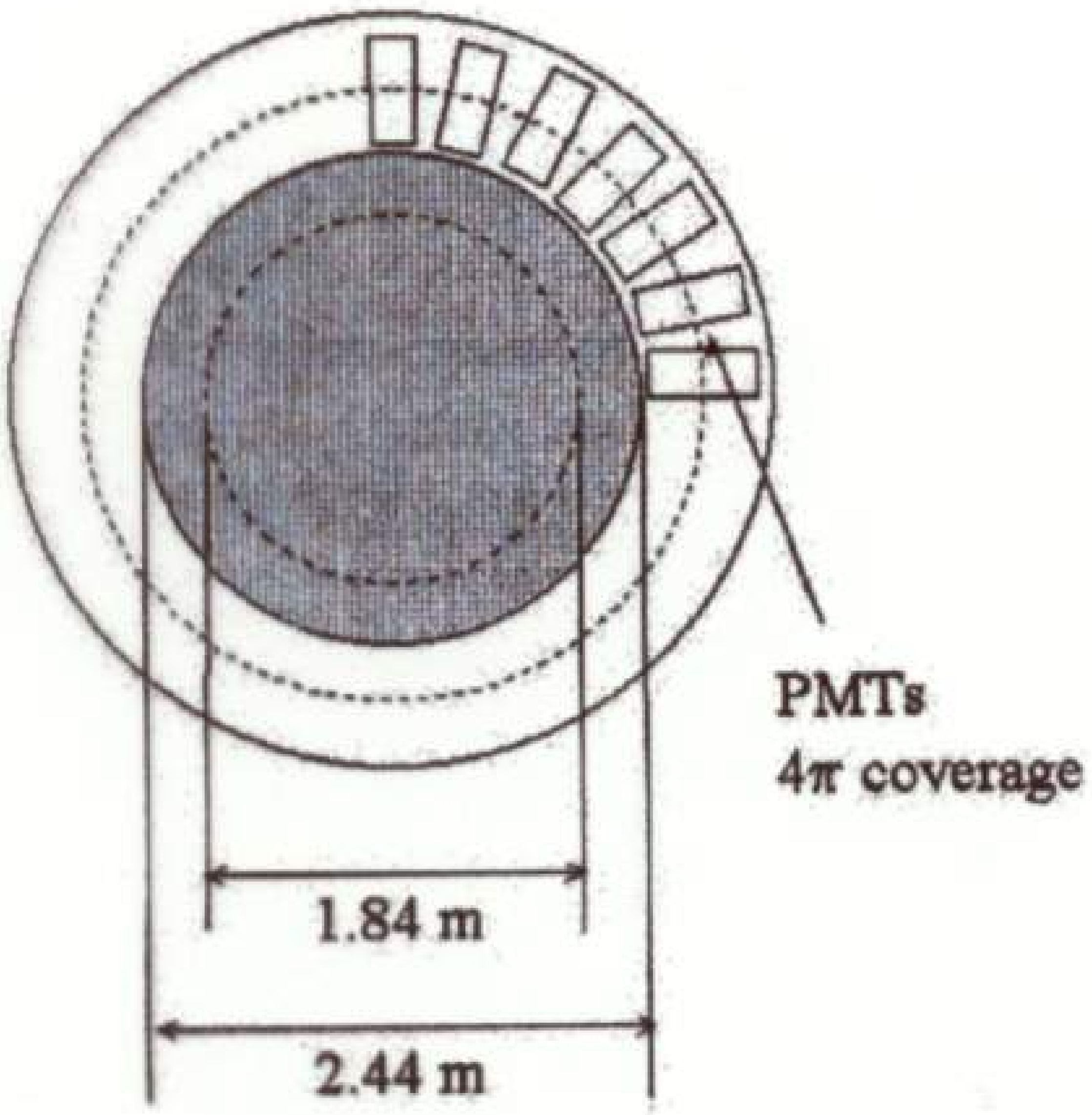
Detection : Micromegas detector after drift on several meters

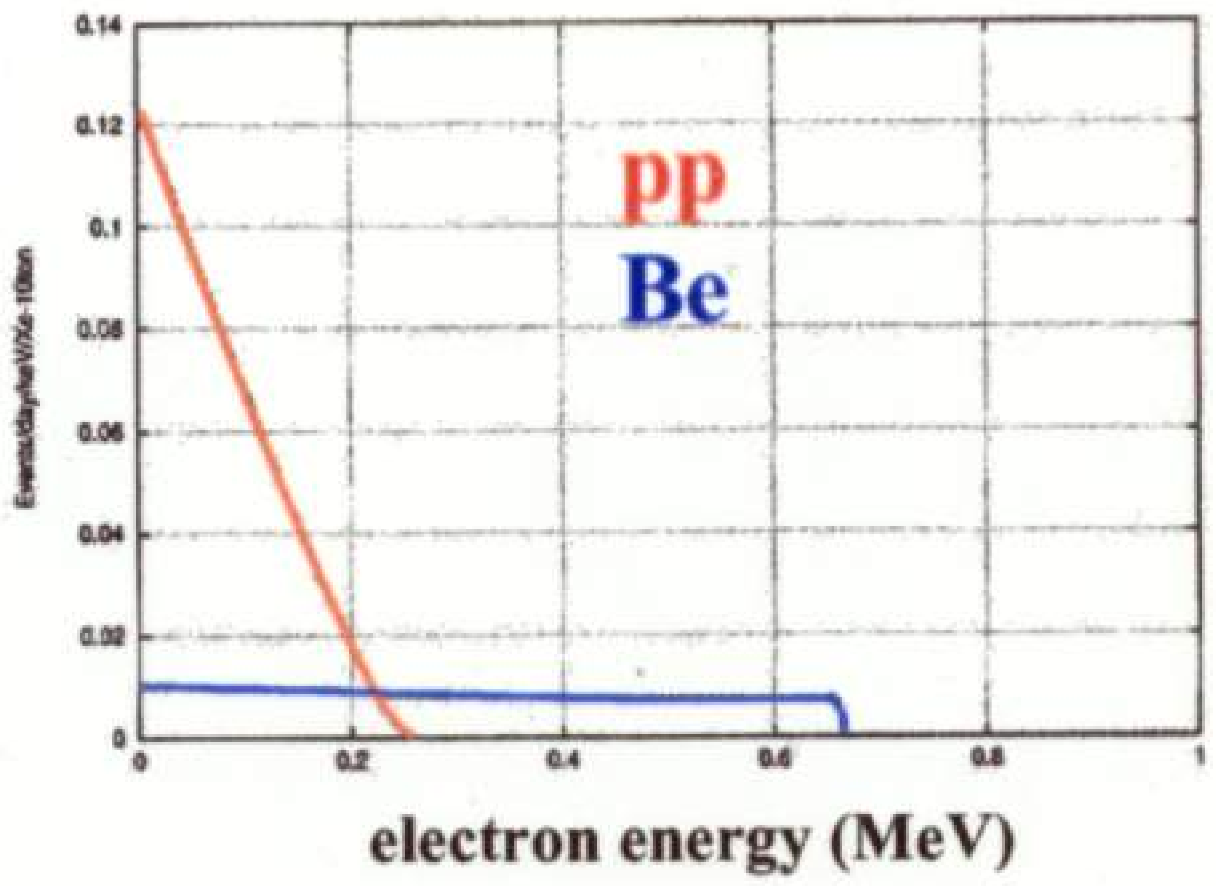
Status :
- R&D stopped at Collège de France
- LOI in preparation in USA (WIPP ?) [G.Bonvicini et al.)]

P.Gorodetzky et al., Nucl. Phys. B (Proc. Suppl.) 87 (2000) 506

Xenon

« pp » spectrum + Be line





Elastic diffusion νe ⟶ νe (CC+NC)

10 tons liquid xenon (≈20 ev. / day)

Detection : 43000 photoelectrons/MeV (≈3000 PM)

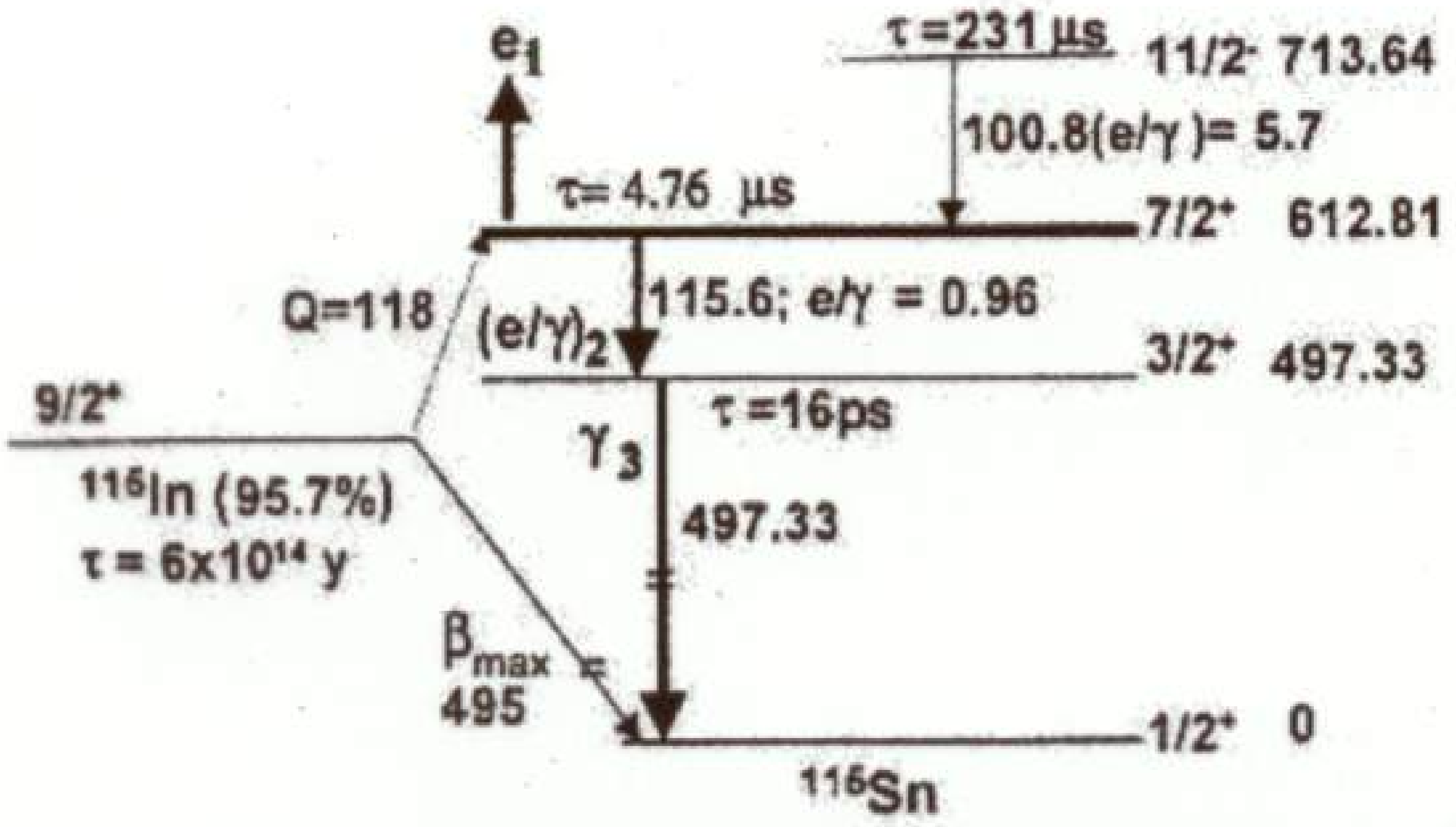
Backgrounds : radioactivity of Xe, ββ decay of ^{136}Xe, ...

Status : R&D at ICRR Tokyo

Y.Suzuki, hep-ph/0008296

Indium (« le retour »)

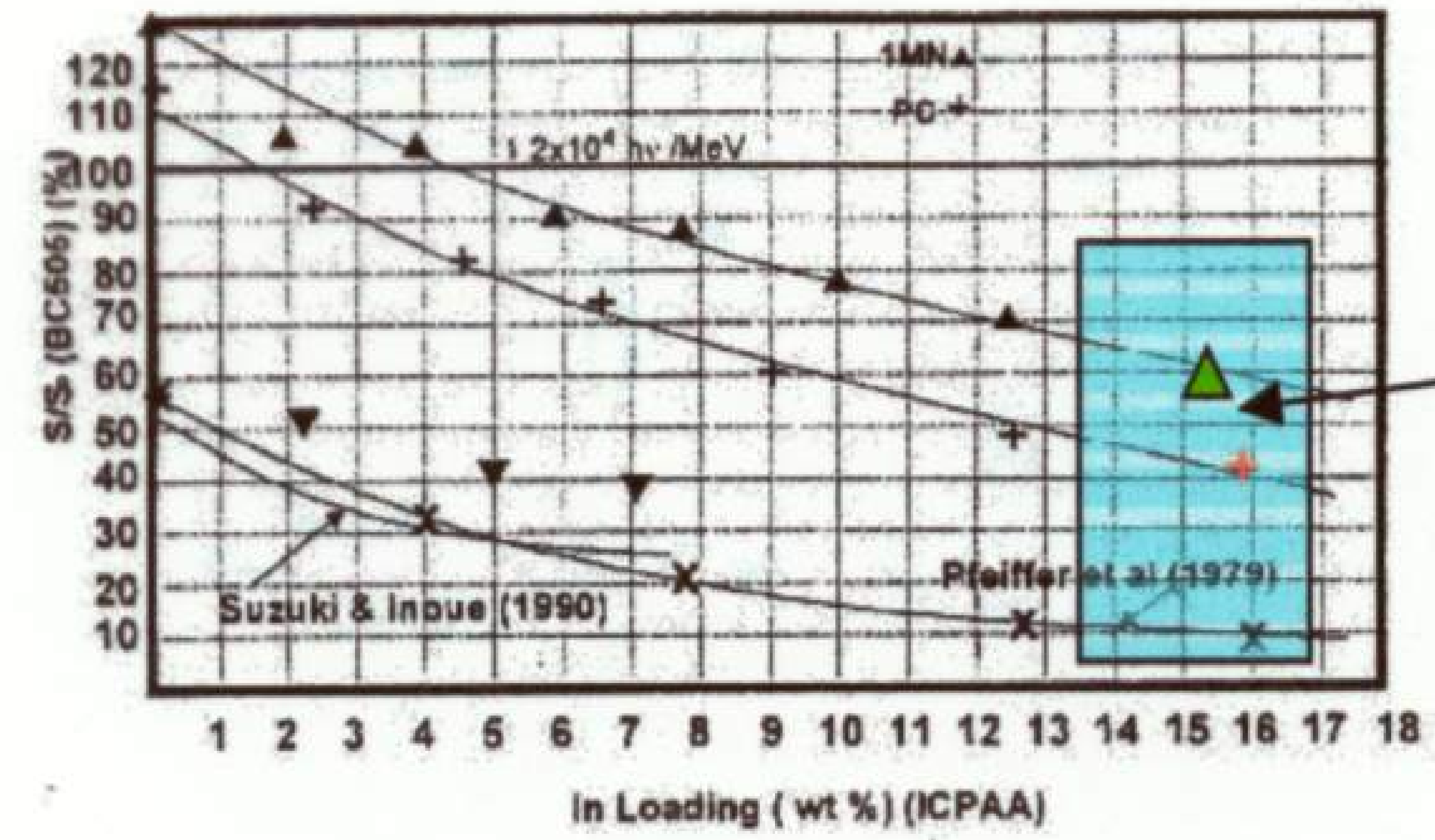
➢ « pp » spectrum + Be line



$\nu_e + {}^{115}In \rightarrow e^-_1 + {}^{115}Sn^*$

$\tau = 4.76\ \mu s$

$\rightarrow (e/\gamma)_2 + \gamma_3 + {}^{115}Sn$



New high quality indium loaded scintillator (pseudocumene PC + or methylnaphtalene MN ▲)

CC reaction

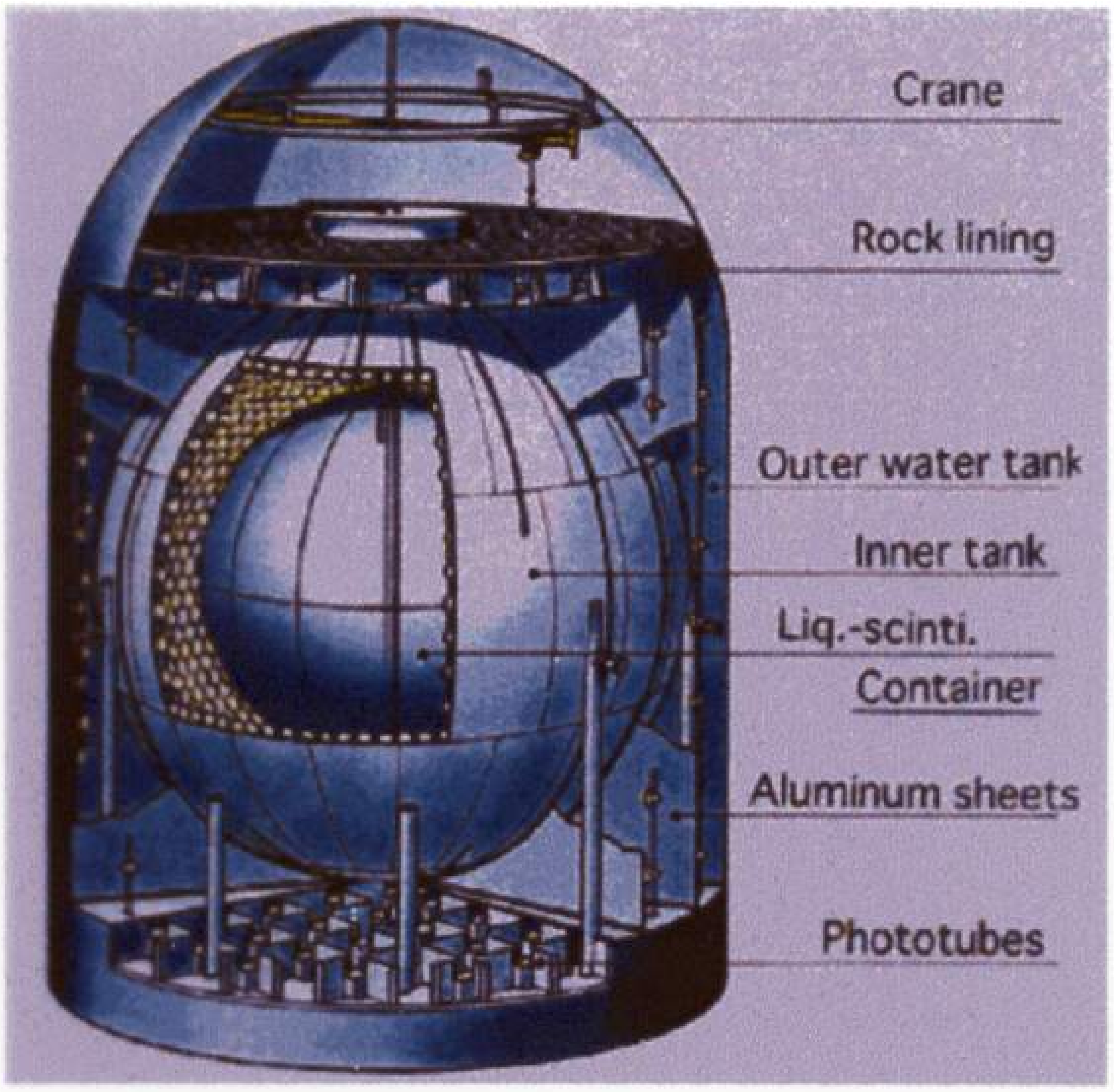
8 tons indium in liquid scintillator (≈400 ev. / year)

☺ Neutrino tag with a good space-time coincidence

☹ Backgrounds : radioactivity of In, correlated and uncorrelated coincidences, ...

R.Raghavan, hep-ex/0106054

Kamland

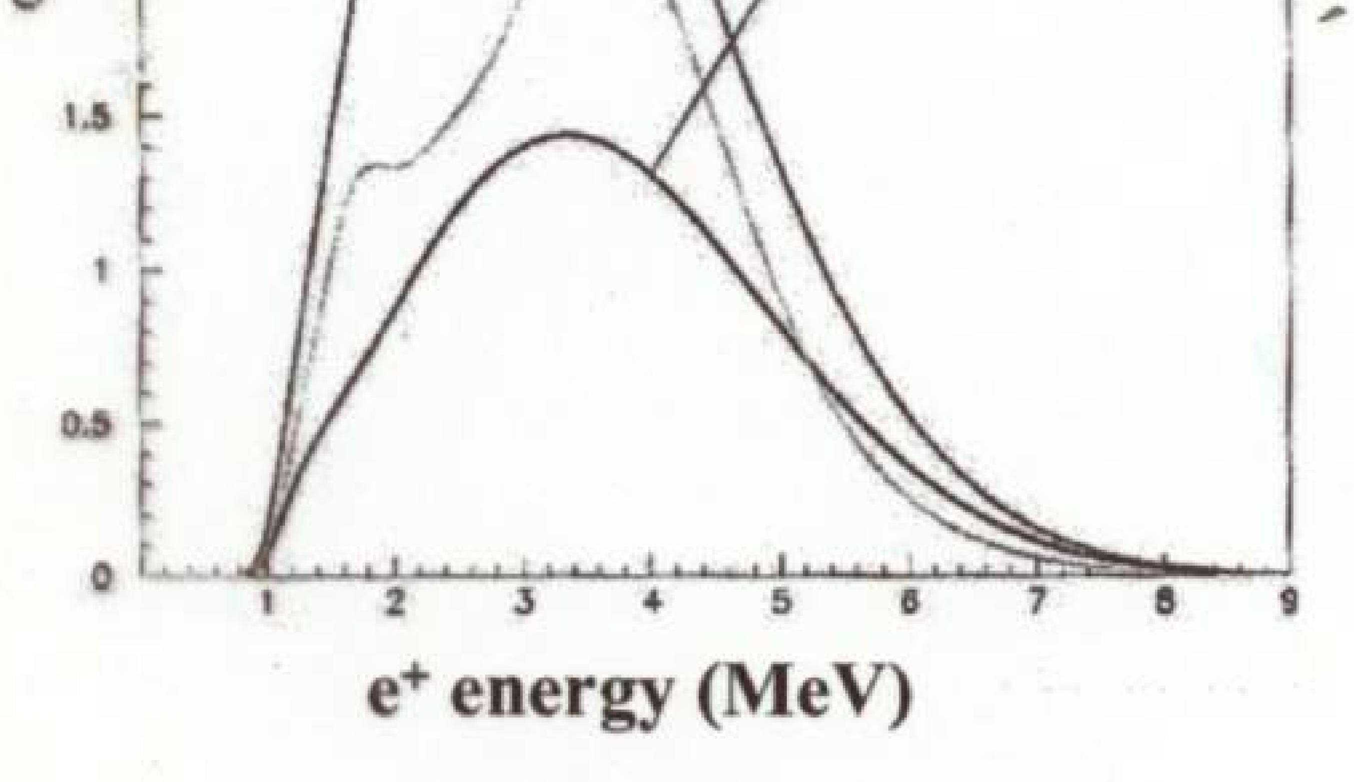


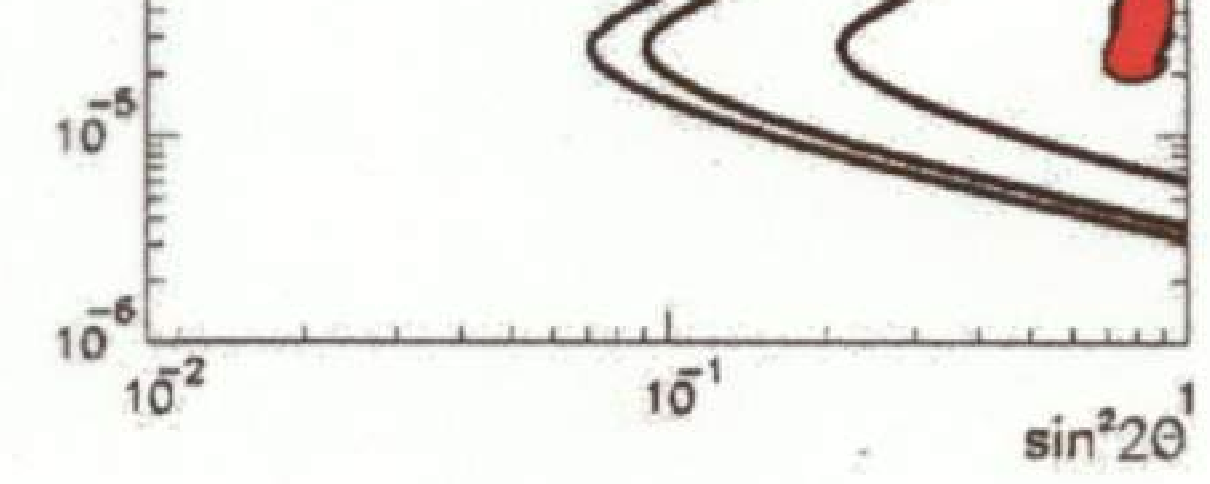
Neutrinos from (Japanese) reactors to prove or disprove the LMA solution!

[<d> $\approx$ 200 km]

1000 tons of liquid scintillator

Data taking start in 2001 ?





Tentative conclusion

- Beautiful SNO results today
- Strong evidence for a solar neutrino deficit.
- Astrophysics cannot explain.
- Most attractive solution : oscillation between ν_e and ν_μ (after the probable $\nu_\mu \leftrightarrow \nu_\tau$ oscillation in atmospheric neutrinos). LMA solution favoured ?
- How to proove it ? How to disentangle the different solutions ?
  - At high energy : spectrum distortion (SK and SNO), NC/CC (SNO)
  - KAMLAND (reactor-ν) for LMA solution
  - Below 1 MeV : Borexino
- Next : measurement of the pp and Be contributions and of the pp spectrum

Difficult but beautiful R&D(s) !

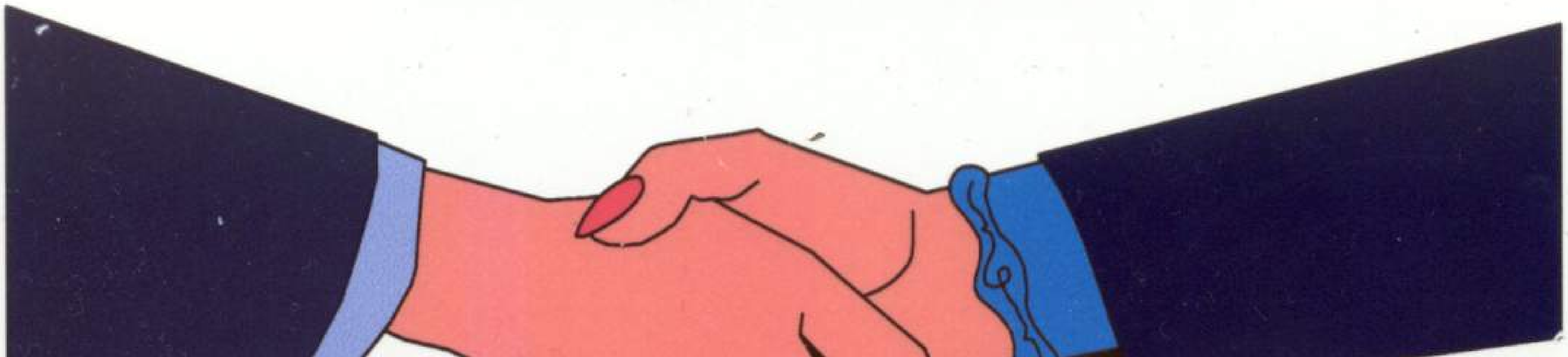
Congratulations to our

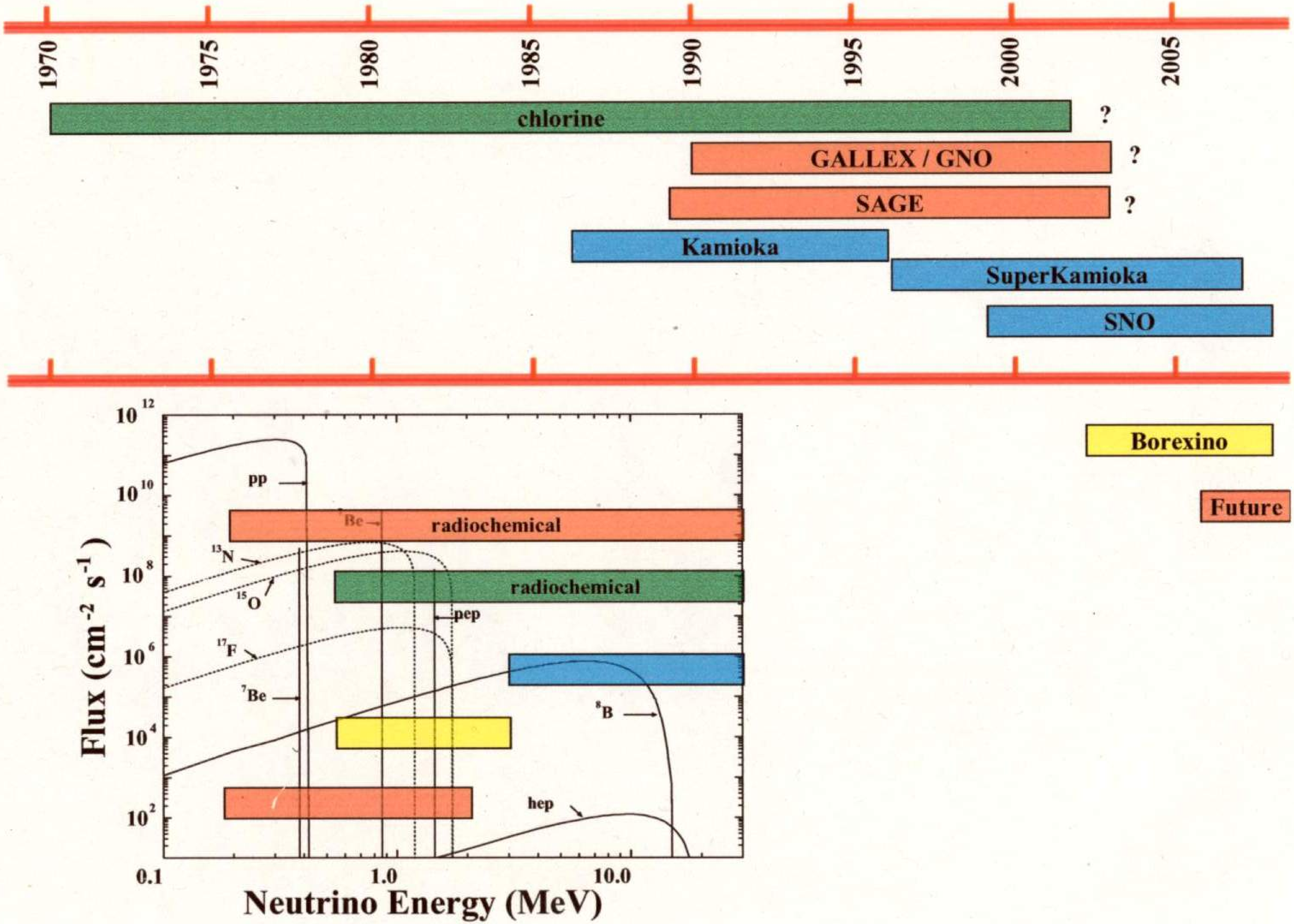
SNO

Colleagues

for their

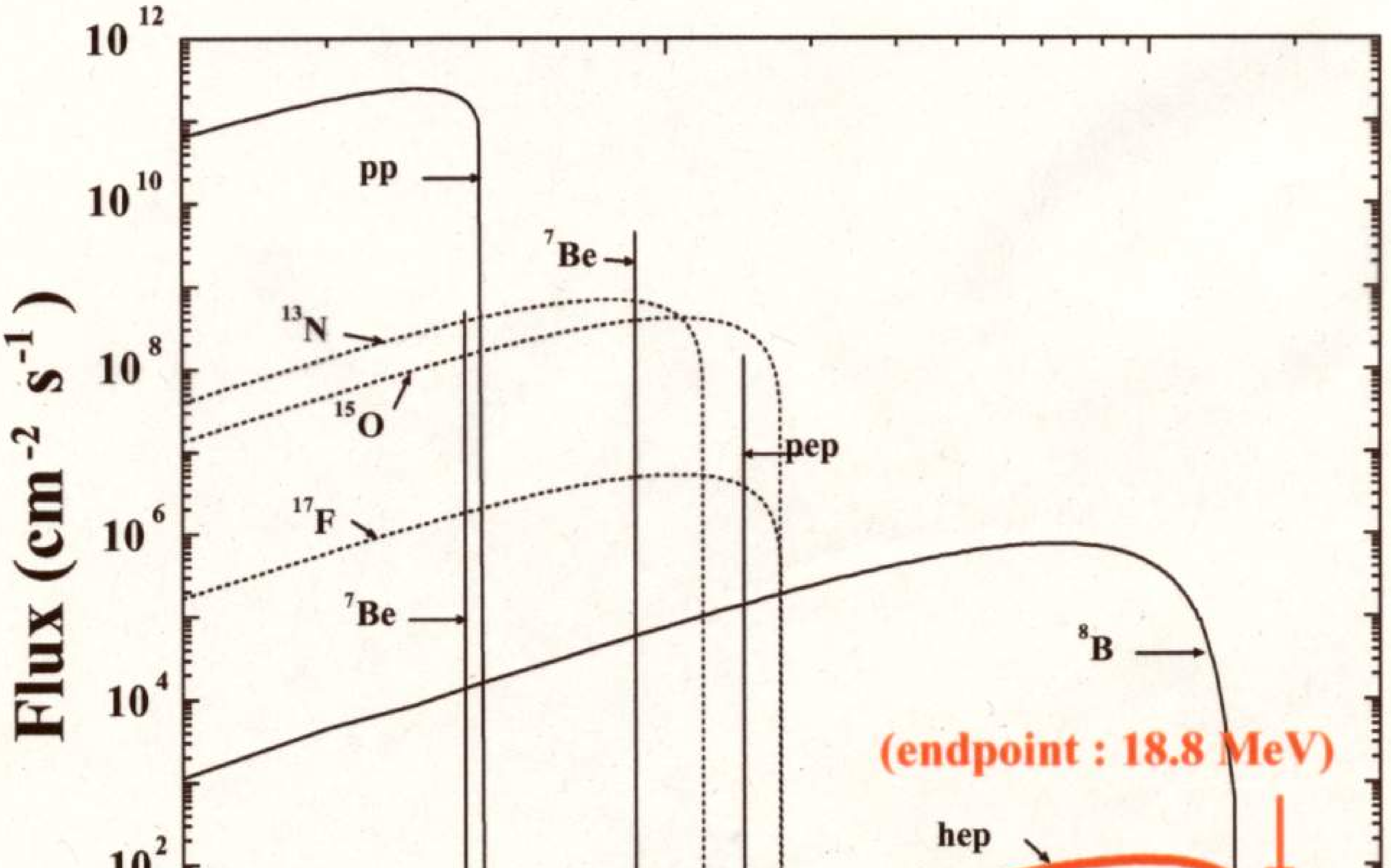
Beautiful Results !!!




1970
1975
1980
1985
1990
1995
2000
2005
chlorine
?
GALLEX / GNO
?
SAGE
?
Kamioka
SuperKamioka
SNO
Borexino
Future
radiochemical
radiochemical
Flux (cm⁻² s⁻¹)
Neutrino Energy (MeV)
0.1
1.0
10.0
pp
13N
15O
17F
7Be
pep
8B
hep

Do hep neutrinos affect the solar neutrino energy spectrum ?

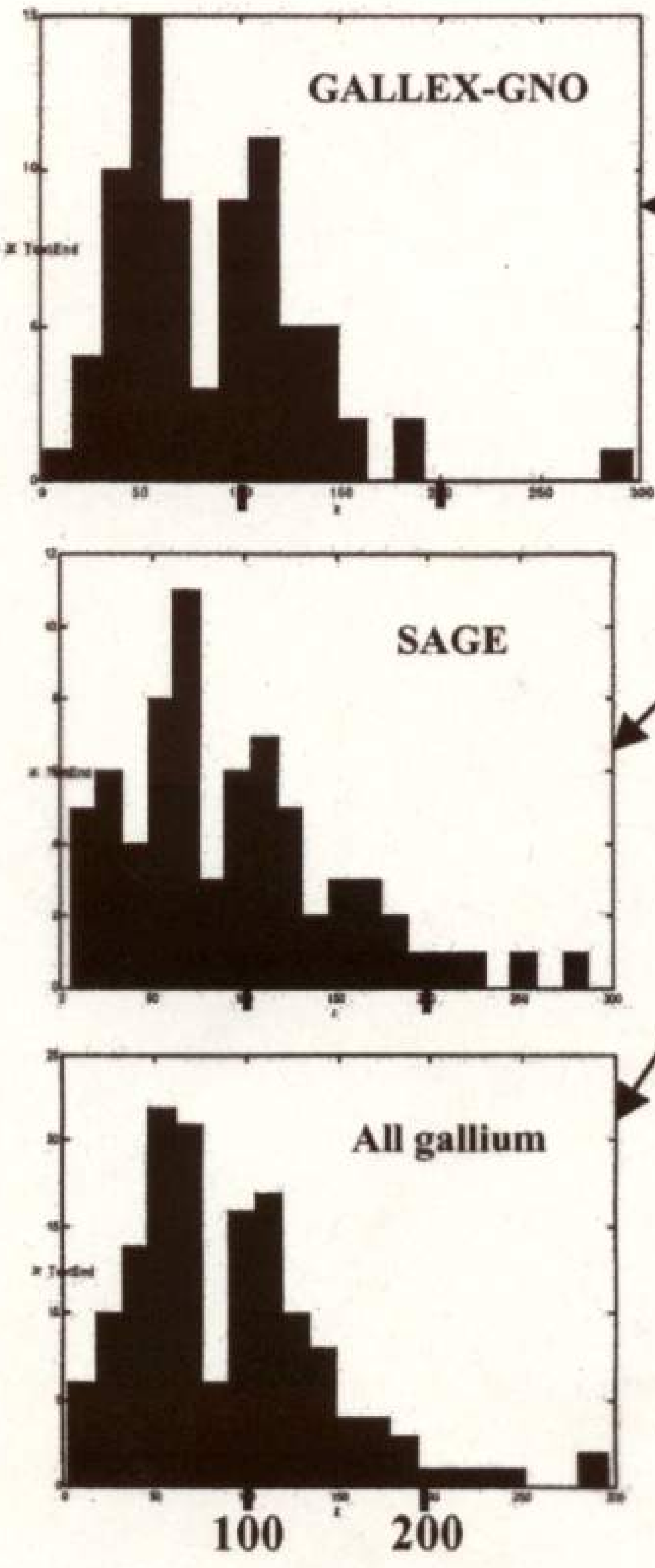
$$^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$$



Large uncertainty on its cross section

J.Bahcall and P.Krastev, Phys. Lett. B436 (1998) 243

Any variability of the solar neutrino flux ?



Analysis of gallium data : is there any evidence for a bimodal flux ?

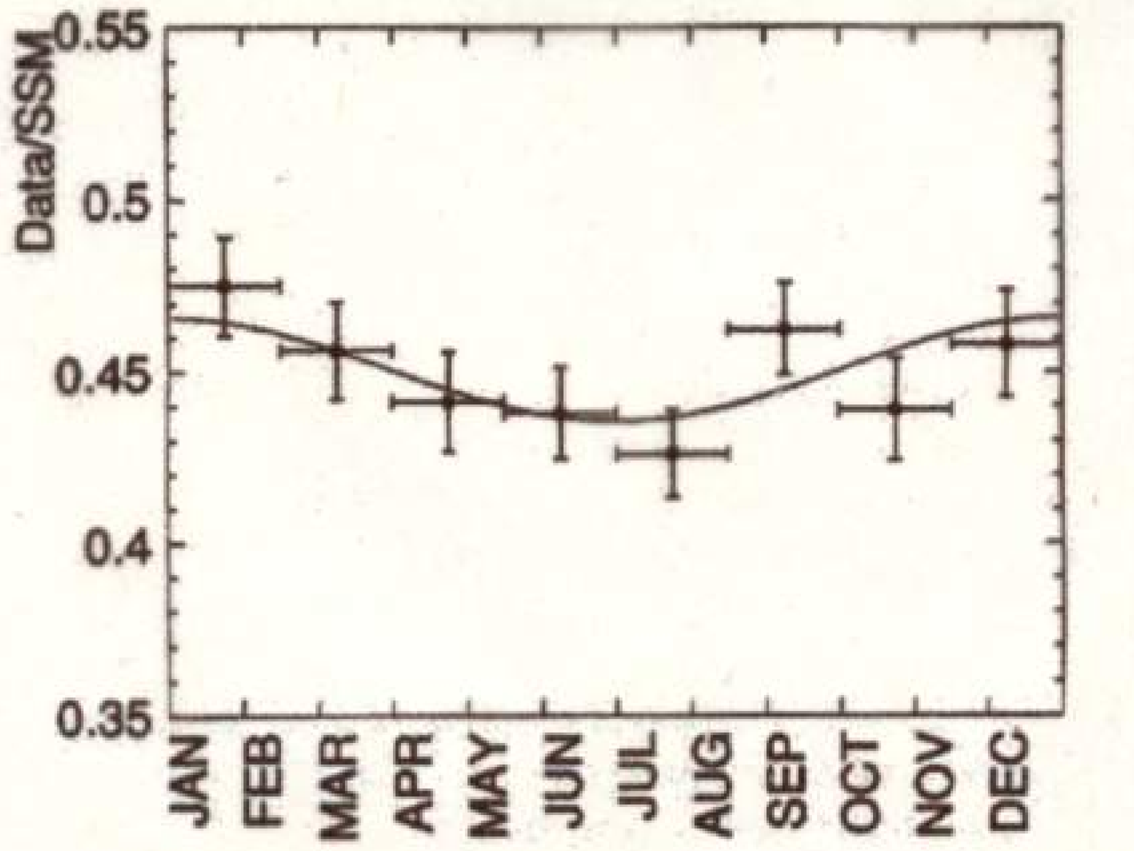
P.A.Sturrock and J.D.Scargle (Nov. 2000)

Chlorine :

- **Absence of correlation with the sunspot number (G.Walther - astro-ph/9710031)**
- **J.Boger et al., Ap. J. 537 (2000) 1080**

SuperK :

Data consistent with the expected annual variation (hep-ph/0103032)



Nothing convincing until now !