Gallex & GNO:
the pioneering era of solar neutrino searches at LNGS

Neutrini e massimi sistemi - LNGS 22nd Febbraio 2023

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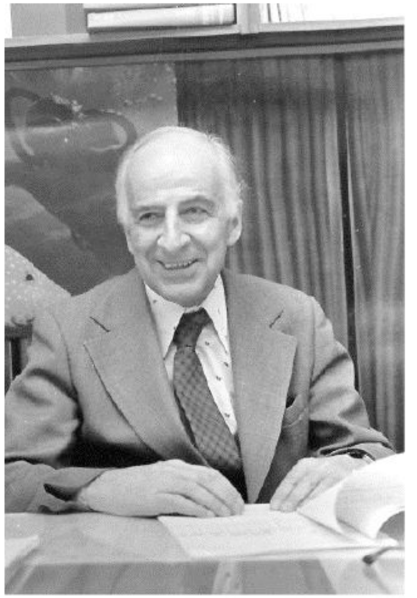
The prologue

- B.M. Pontecorvo - Chalk River Laboratories (1946)
  - Neutrino detection by CC interaction with ^{37}Cl and other nuclei by *Inverse β process*
- F. Reines (1956)
  - Discovery of ν_e *by Inverse β process*



(1918-1998)
1995 Nobel Prize for the discovery in 1956 of ν_e by Inverse β process

(1914-2006)
2002 co-Nobel Prize (M. Koshiba and R.Giacconi) for the first detection of solar neutrino

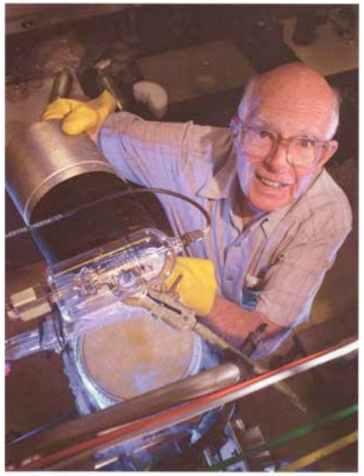
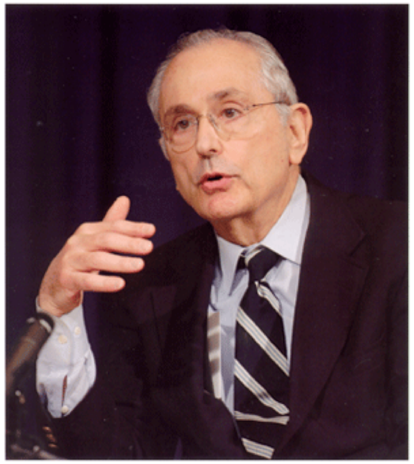
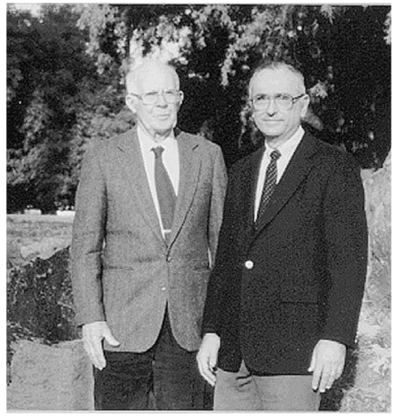


Photo courtesy of Brookhaven National Laboratory





- R. Davis e J. Bahcall publish (Phys. Rev. Lett. – 1964) the feasibility study of a Cl exp.: E_{thr}= 833 keV - no access at the pp neutrinos.
- The BNL Department of Chemistry supports the project that get funded
- First solar run: 22 June - 14 October 1967
- **Measured Int.rate** (23 years): **2.56 (0.23) SNU** (8.2 SNU expected from SSM no oscillation). **?????**

Birth of the Solar Neutrino Problem

What to do next?

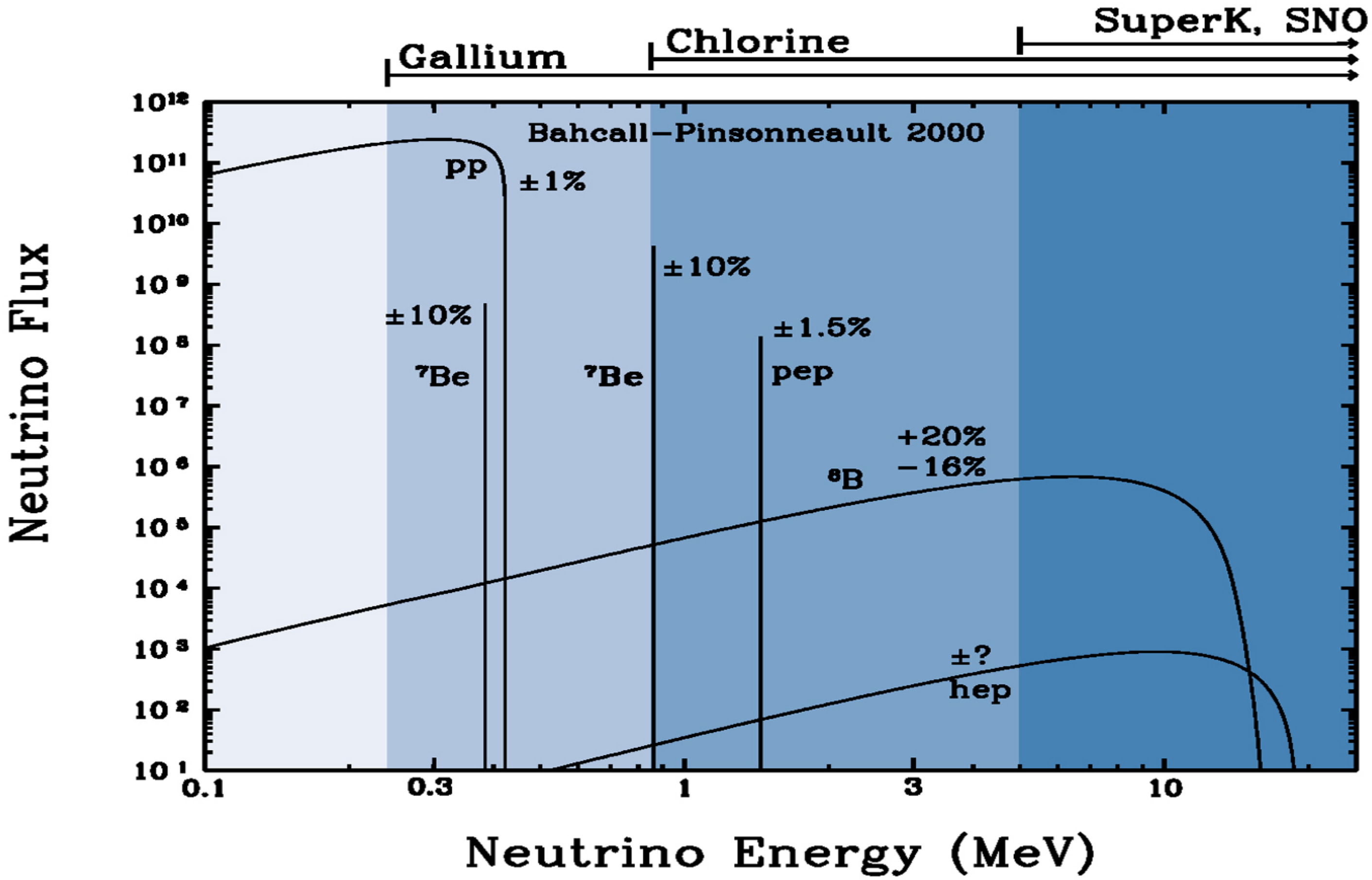
- Is the lack of ν related to the Standard Solar Model (SSM) and/or its input parameters?
  - Measure the p-p ν flux, by far the more abundant, strictly related to L_{Sun} and almost model independent

Gallium → GALLEX e SAGE

- Is the lack of ν related to intrinsic ν properties (oscillation)?
  - Design an experiment to detect both the ν_e and other ν flavor

Deuterium → SNO

The SSM expectations



Chain	Flux [cm^{-2} s^{-1}]	Flux Uncertainty	T dependence
pp	60 Billion	1%	T_c^{-1}
^{7}Be	5 Billion	10%	T_c^8
^{8}B	5 Million	~20%	T_c^{18}

1960-1980: The proposed radiochemical experiments

- In the URSS Markov e Zatzepin (e anche O. Ryashskaya)
  Proposal to repeat the Cl experiment

- **V. Kuzmin (1965) (URSS) proposes the Gallium**
  60 ton of metallic Ga will be installed at the Baksan Underground site
  The experiment give the first results in 1990

- Negli USA, **Bahcall, Cleveland, Davis….**
  50 ton of Ga in solution or in metallic form
  Phys. Rev. Lett. 40(1978) 1351

Generalities on radiochemical experiments

- CC experiments sensitive only to ν_e. Proposed by Pontecorvo in 1946.

$$\nu_e + N \rightarrow N' + e^-$$

N' (unstable) is then separated from the target with physical-chemical techniques and then quantitatively measured observing its decay back in N.

$$Interaction\ Rate\,(R) = N_{\mathrm{target}} \cdot \sum_{\mathrm{i}} \int \sigma_i(E) \cdot \frac{d\Phi_i(E)}{dE} P(\nu_e \rightarrow \nu_e) dE$$

as

$$\sigma_{\mathrm{i}} \sim 10^{-46}\ cm^2; \Phi_{\mathrm{i}} \sim 6 \times 10^{10}\ [s\ cm^2]^{-1}$$

1 *Solar Neutrino Unit* [SNU] = 1 ν interaction/sec each 10^{36} target atoms.

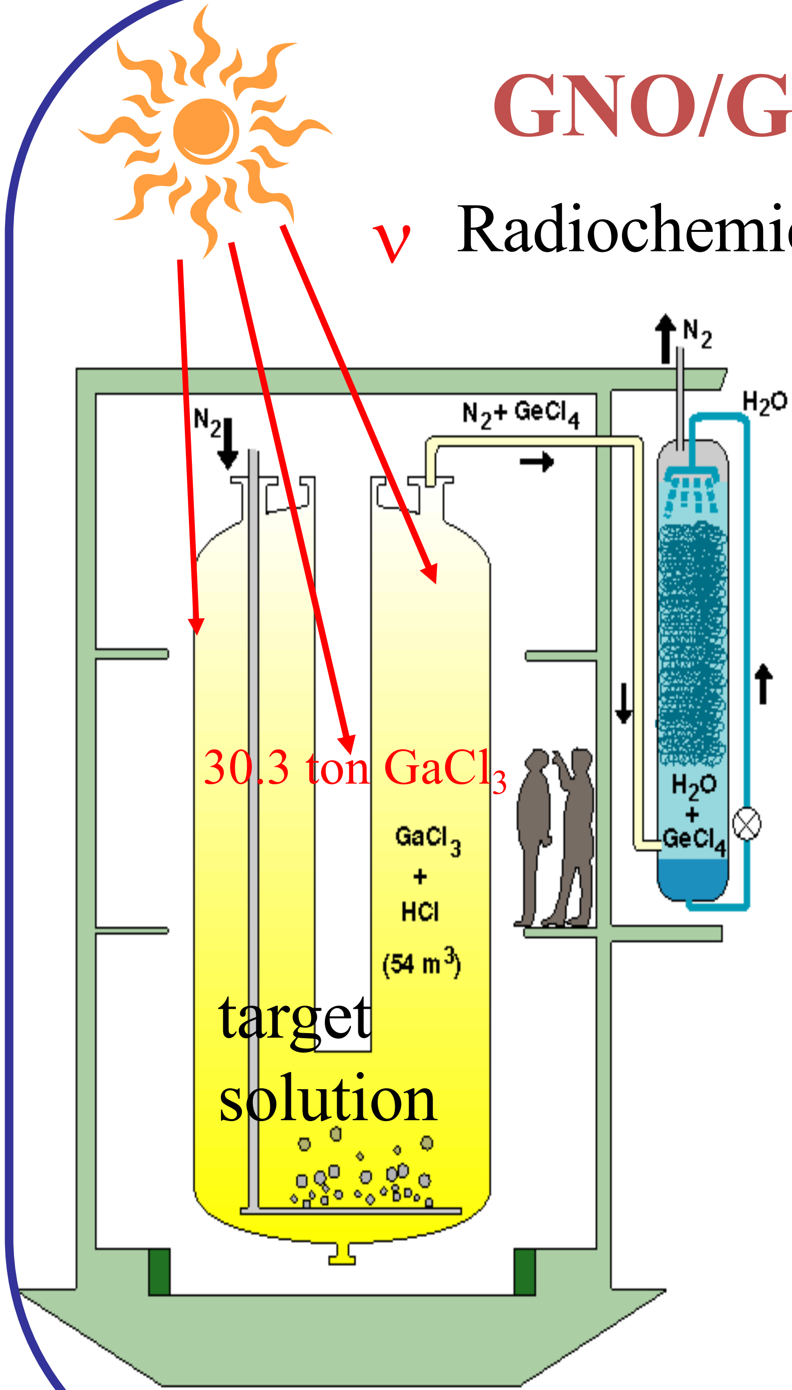
$N_{target} = 10^{29}$-10^{30} nuclei, namely O(10-100) tons of target to have O(1) ν interaction/day

The GALLEX Collaboration

- Max Planck Institute – Heidelberg
- ZFK – Karlsruhe
- TUM Monaco
- LNGS
- Milano /Milano Bicocca
- Roma Tor Vergata
- Nice
- Saclay
- Weizmann Institute
- Brookhaven
- Kurciatov e CEA – Grenoble for the Cr source

Till Kirsten the GALLEX spokeperson

GNO/Gallex experiments



- ν Radiochemical detector

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

EC (L/K)

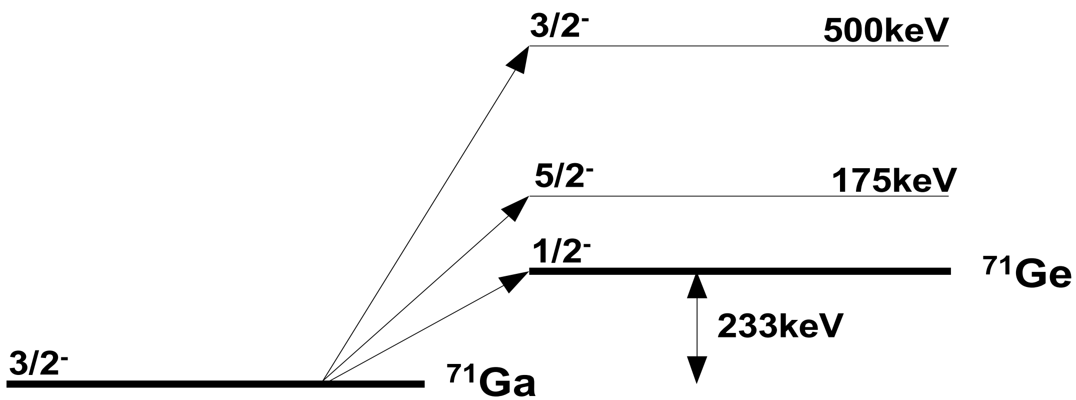
τ = **16.5** d

$^{71}Ga^*$

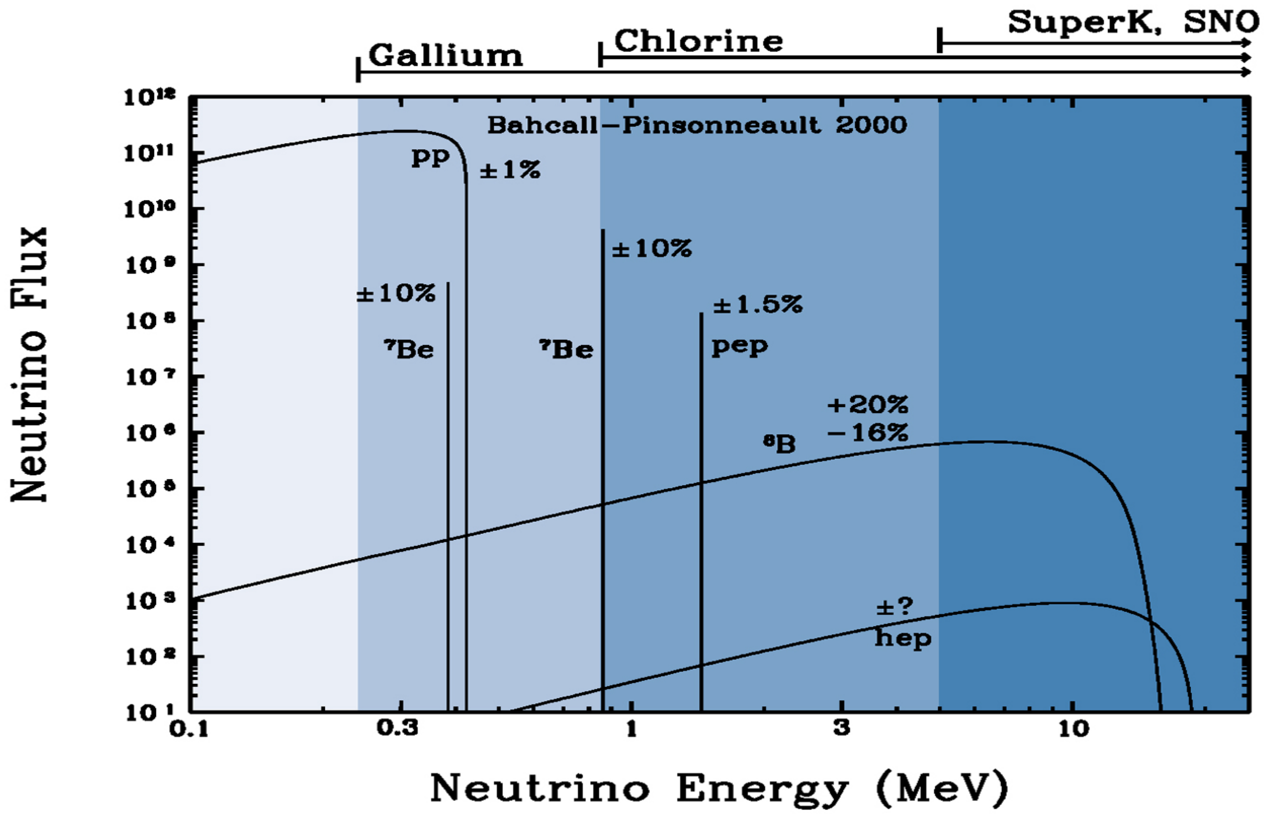
detected: X rays, Auger electrons

Threshold energy: 233 keV

Only sensitive to CC (ν_e)



GALLEX:Solar neutrinos sensitivity



SSM signal [SNU]:

pp+pep	73 (55 %)
hep	0.1
^{7}Be	35 (27 %)
CNO	8 (8 %)
^{8}B	13 (10 %)

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

J. Bahcall *et al*, BP2000

(≈1.2 captures/day)

1 *Solar Neutrino Unit* [SNU] = 1 ν int./sec each 10^{36} target atoms.

Expected signal: 1.2 ν captures per day, but due to decay during exposure + ineff., **9 ^{71}Ge decay detected per extraction** (28 days exposure)

C. Cattadori for the GNO collaboration, TAUP 2001

The experiment

The ν_e interaction

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

EC τ = 16.5 d $\rightarrow$ ^{71}Ga

The signal composition: (BP00 SSM)

pp + pep	73 SNU	(55 %)
^{7}Be	35 SNU	(27 %)
CNO	8 SNU	(8 %)
^{8}B	13 SNU	(10 %)
Tot	129 SNU $^{+9}_{-7}$ 1σ	

The expected int.rate (SSM)

1.2 ν int. per day, but due to decay during exposure + ineff., 9 ^{71}Ge decay detected per extraction

(28 days exposure)

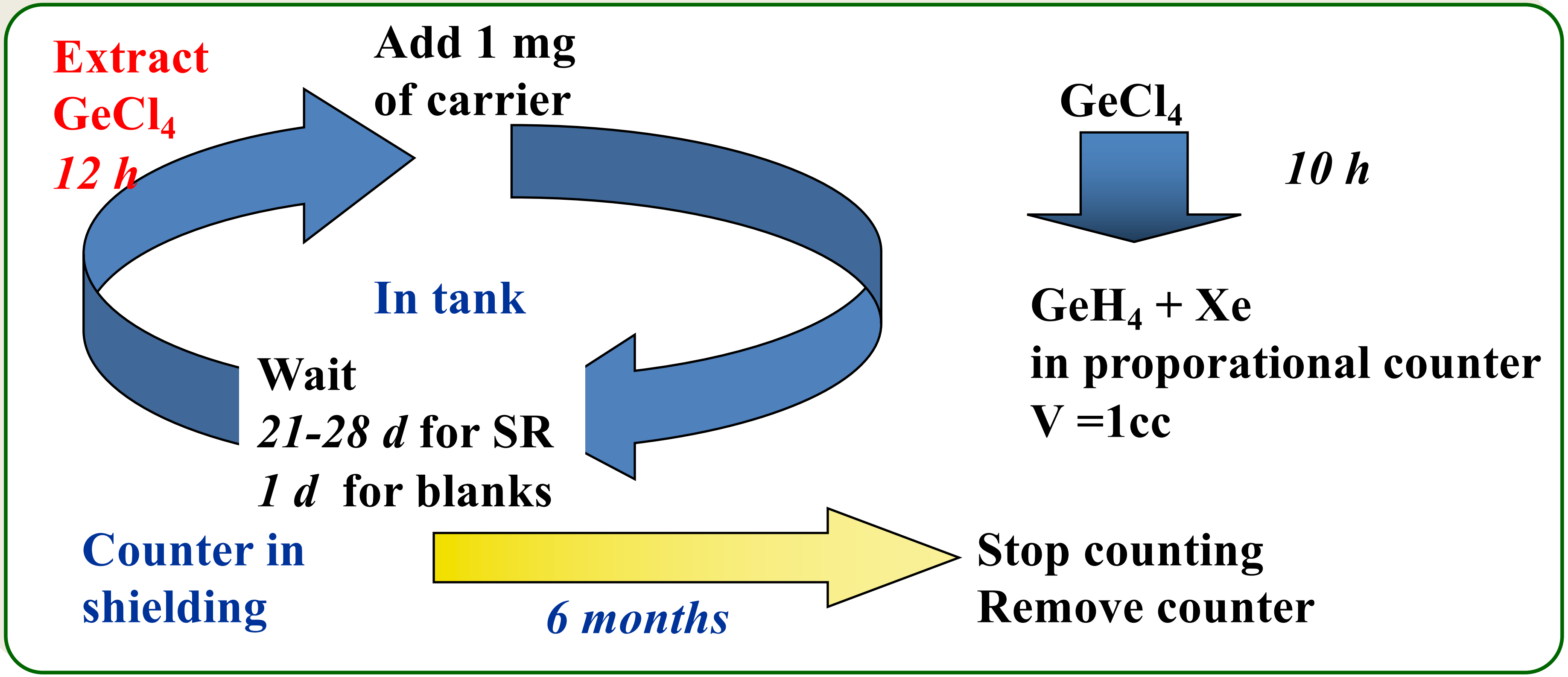
Extraction

N_2 Gas stripping of $GeCl_4$ (gas phase in acid environment) from 30.3 t of Ga_3Cl +HCl.

$N = N_0 \exp(-f\, Vgas/Vsol)$

The apparatus

See f.i. PL B490(2000)16
PL B314(1993)445

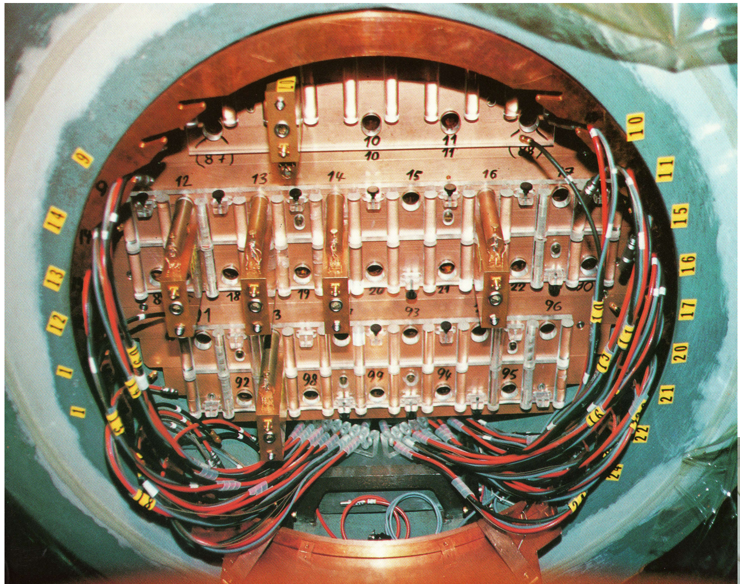


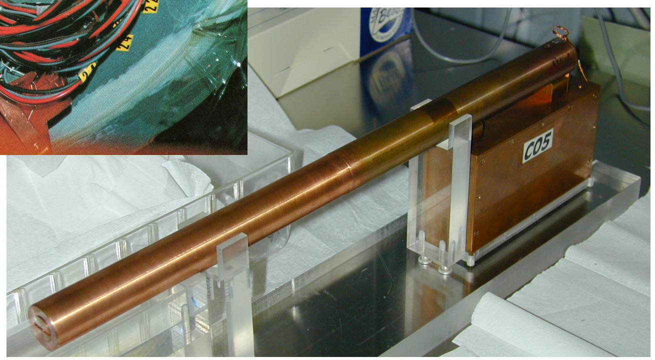
The preparation of the experimental site

- Digging of the containment pit (to prevent environment &recover in case of leak from the Ga tank)
- Building construction (TOF outside) and Hall A
- Two tanks (one spare) for GaCl3
- The extraction system
- The counting system (shielding tank+ cali system)
- The readout electronics

The $GeCl_4$ extraction columns

The GeH_4 synthesis and counter filling





The counter shileded box, the counting shield hosting counters

The proportional counter,


KWH
PIPE


WE ARE
PREPARING
FOR GNO

Relevant costs

•Gallium	•22M SF (7 M SF)
•Buildings	•1 M Euro
•Tanks & Chemistry	•1 M Euro
•Counter tanks& elect.	•0.5 M Euro
• Electronics 2	•0.4 M Euro
• Cr source	•2.5 M Euro
• Running costs	•~ 0.15 M Euro/anno

GALLEX Start-up & Commissioning

- GaCl3 received, weighted at TOF and then carried underground
- 1990: The first «cleaning» extraction
- Huge amount of Ge released daily:

  ca. 100 atoms/day

- ^{68}Ge (cosmogenico) trapped in the solution
- Decision: warm up the tank
- Huge release of ^{68}Ge
- Back at room T the Ge daily release is greatly reduced
- 14/05/1991→ First solar neutrino run

NEUTRINO 92, Granada 7-12 June 1992

THE $\nu_\odot$ PP
FUSION
BOMB

Summary Talk

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

de Rujula
Conference
Summary Talk

Courtesy: Till Kirtsen

The first GALLEX result @ Neutrino '92

- Interaction rate
  - Measured: **83.4 ± 19 SNU (stat) ± 8 SNU (syst)**
  - Expected from SSM: 129^{+9}_{-7} SNU

➢ Meas/SSM > 100 % of the pp- expectation

⇒ Hydrogen fusion in the Sun observed

➢ Meas/SSM ~ 60 % of the total SSM-expectation

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

- Result marginally compatible with a SSM
- No claim of neutrino oscillations

The GALLEX chrono-history

1986 - 1990	Construction of the detector	
May 1991 – May 1992	GALLEX I data taking 15 Solar runs, 5 Blanks 83.4 ± 19 SNU	PL B285 (1992) 376 PL B285 (1992) 390
Jun 1994 – Oct 1994	1st ^{51}Cr source experiment	PL B342 (1995) 440
Oct 1995 – Feb 1996	2nd source ^{51}Cr experiment	PL B420 (1998) 114
Feb. 1997	End of Solar Data Taking	PL B447 (1999) 127

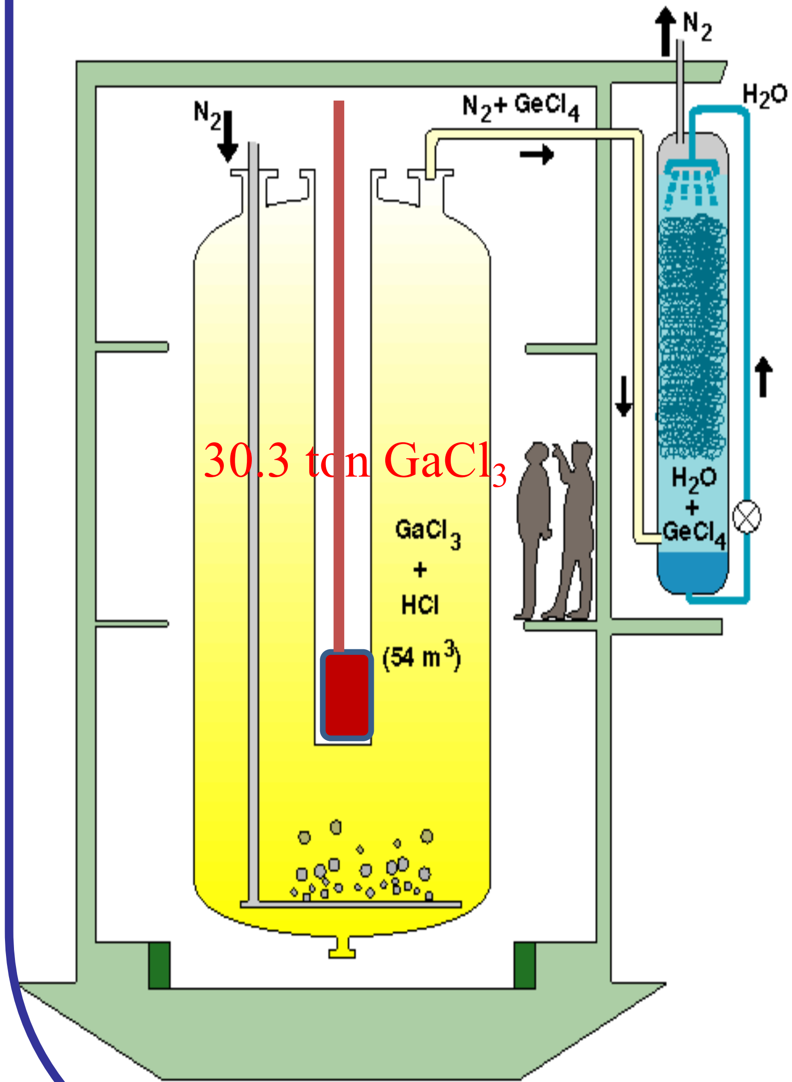
GALLEX Final Result

1594 days – 65 runs: **77.5 ± 7.7 SNU**

Feb 1997 – Apr 1997	Test of the detector with ^{71}As Extraction efficiency 100%	PL B436 (1998) 158

The ^{51}Cr experiment

- Artificial source

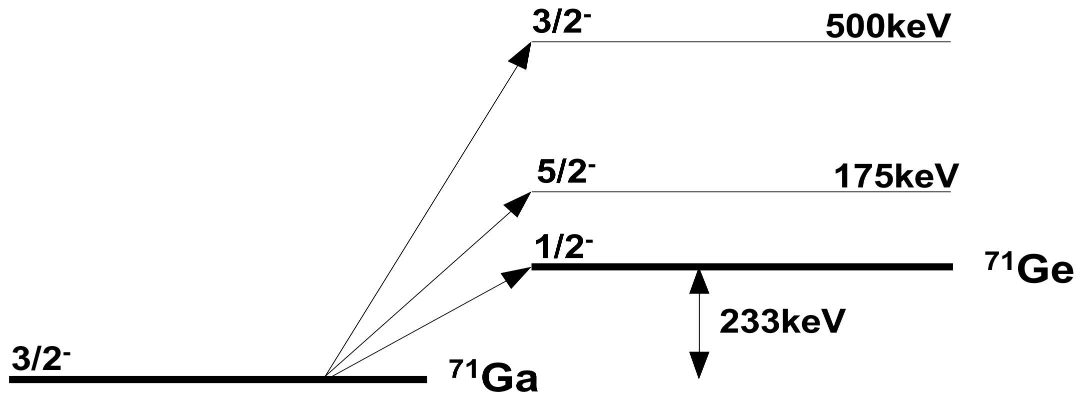


$$^{50}Cr + n \rightarrow \; ^{51}Cr + \gamma \; (320 \text{ keV})$$

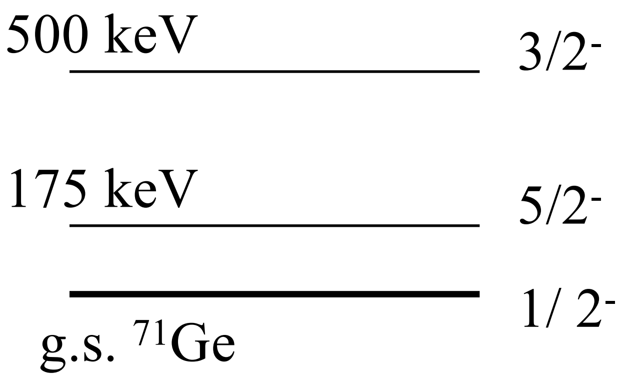
$\tau = 27.7$ d

$$^{51}V + \nu_e$$

^{51}Cr - ν_e : 751 keV (80%), 437 (9%) keV → Access the ^{71}Ge exc. States.



^{51}Cr Source results



Strength	63.4 PBq	69.1 PBq
R (meas/expt)	1.01 ±11.5%	0.84 ±11.5%
Average	0.93± 0.08	
New c.ter eff.	0.91±0.08	

Energy (keV)	^{51}Cr	^{7}Be
862	-	90%
751	80.6%	-
746	9.5%	-
431	8.8%	-
426	1.1%	-
384	-	10%

Arsenic test

Hot chemistry?

$GaCl_3 \longrightarrow$? $\longrightarrow GeCl_4$

Study Ge chemistry in $GaCl_{3\ env}$: standing time, conc., extraction parameters etc.

$^{71}As \rightarrow (\beta^+$ or EC$) \rightarrow {}^{71}Ge \rightarrow {}^{71}Ga$ ($Q_{EC} \approx 4$ MeV)

≈ 10 000 ^{71}As atoms added to three batches :

- Tank sample

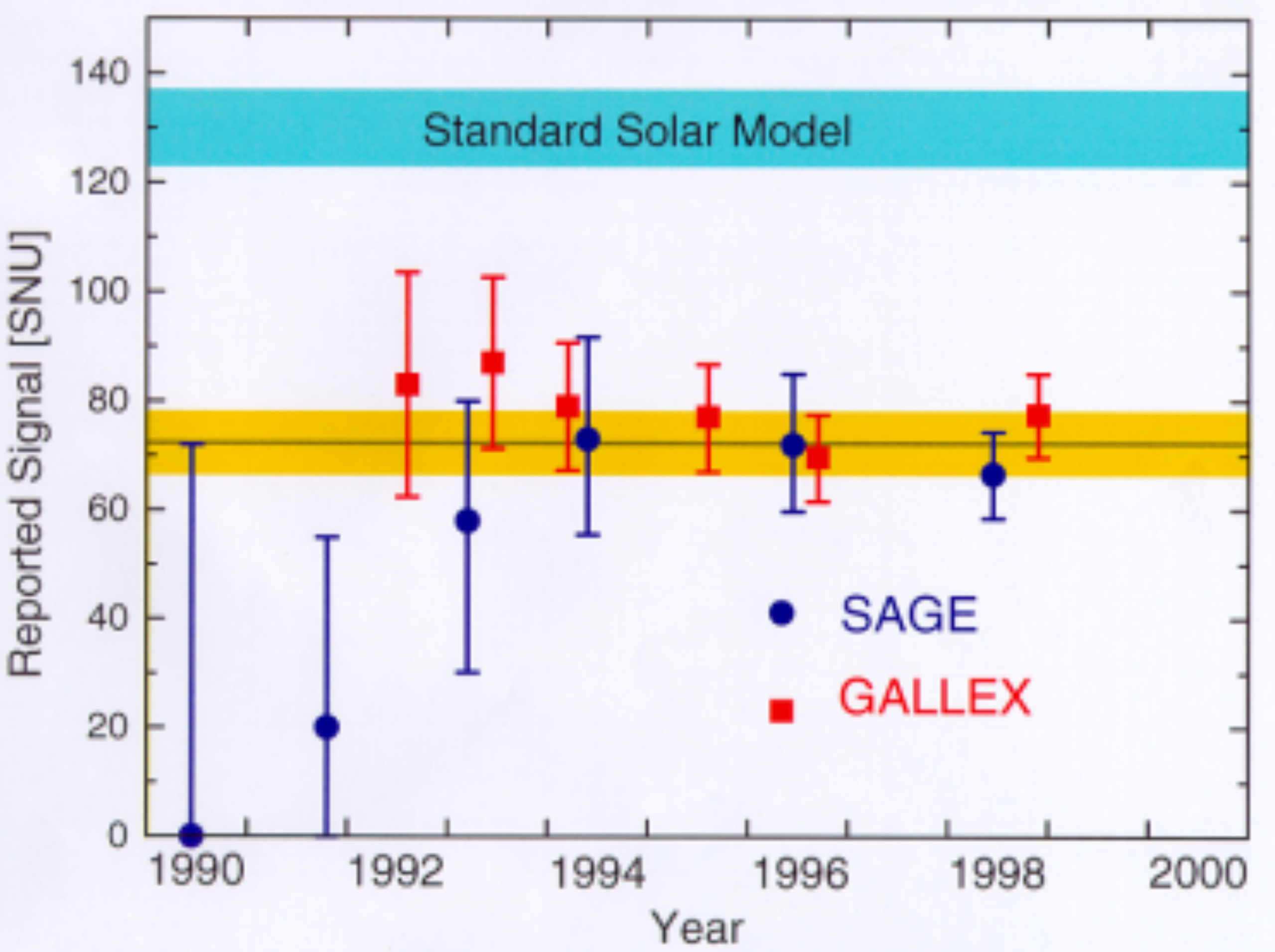
- External sample

- Calibration sample (γ-spectrom.)

Result: Ge Extraction/recovery eff. ~ 99% (small error)

GALLEX Final Result

1594 days – 65 runs: **77.5 ± 7.7 SNU**



GNO

Start of solar runs: **20 May 1998**

Three data releases
For a total of 1687 days

Rate 62.9 $\pm$ 6 SNU

Improvements

Many improvements resulting in a reduction of a factor of ≈ 2 in the systematic error

Item	Gallex	GNO
Target size	0.8%	0.8%
Chemical yield	2.0%	2.0%
Counting efficiency (active vol determination)	4.0%	**2.2%**
Pulse shape cuts	2.0%	**1.3%***
Event sel. (others)	0.3%	0.6%
Side reactions	1.2 SNU	1.2 SNU
Rn-cut inefficiency	1.2 SNU	**0.5 SNU**
^{68}Ge contamination	$^{+1.8\ SNU}_{-2.6\ SNU}$	-

* Neural network analysis

GALLEX

65 Solar runs = 1594 d

23 Blank runs

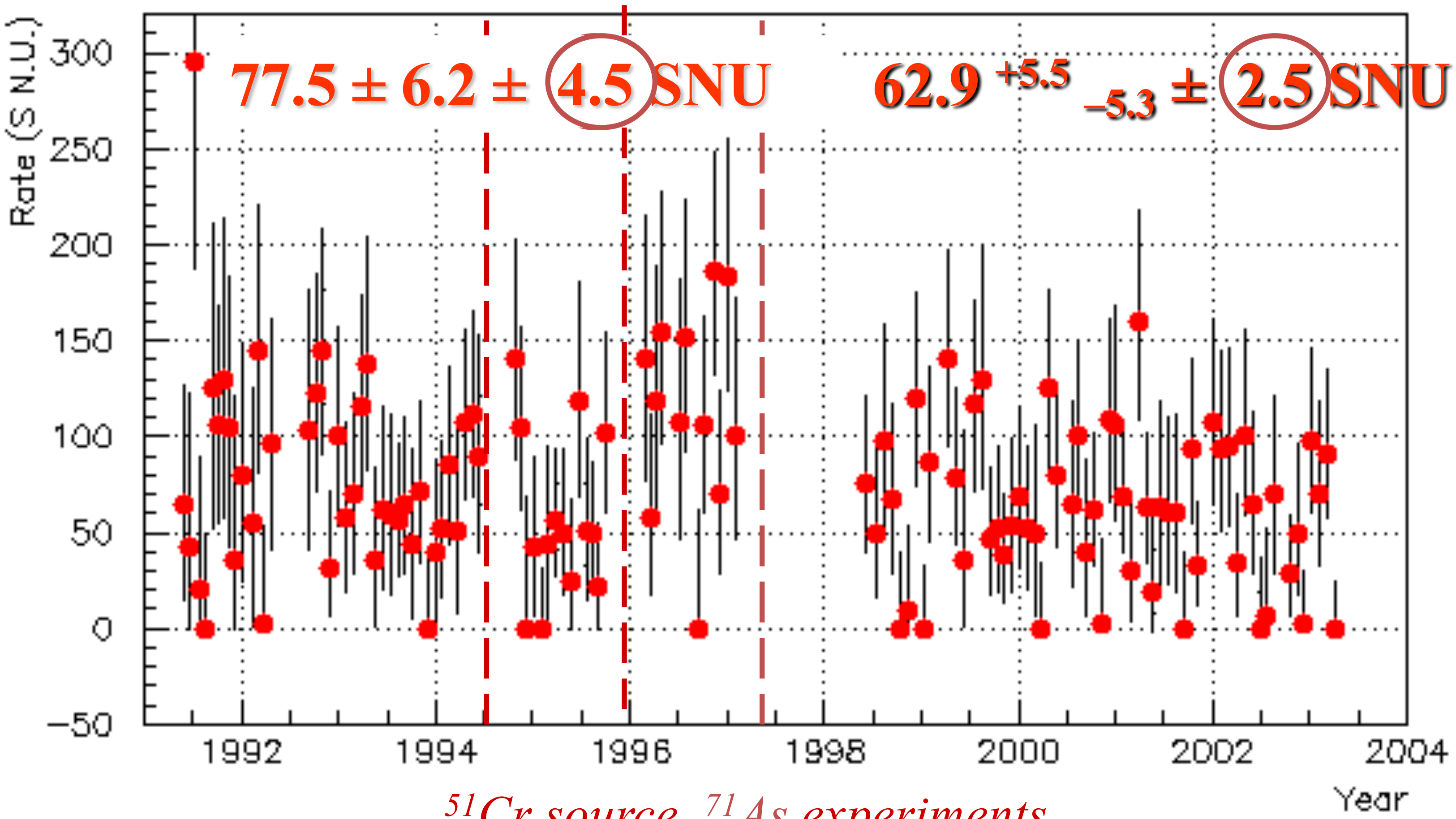
PL B447 (1999) 127

GNO

58 Solar runs = 1713 d

12 Blank runs

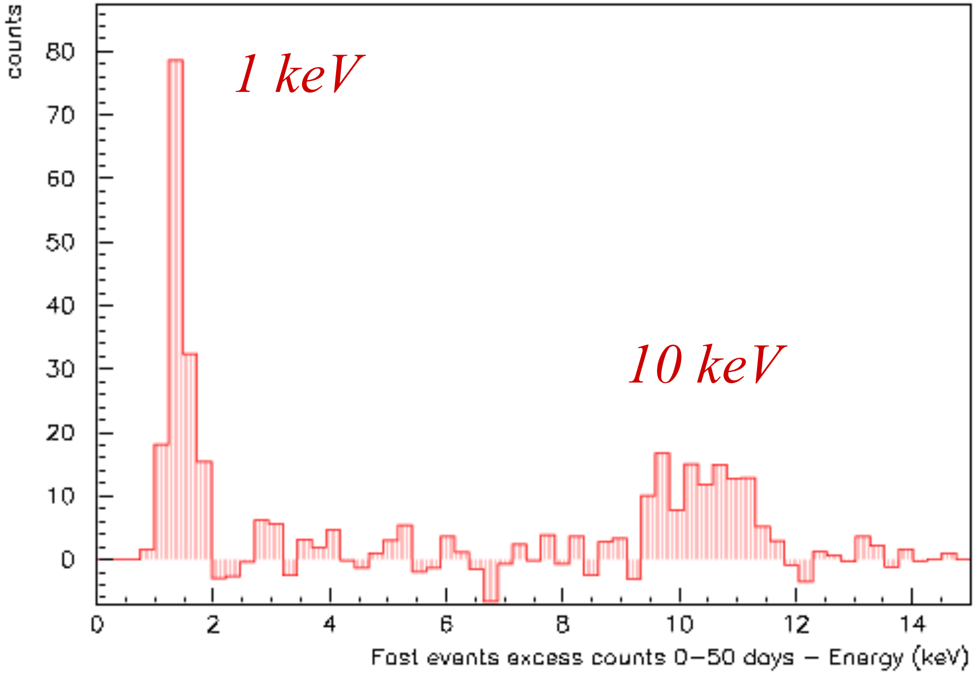
PL B 616 (2005) 174-190



^{51}Cr source, ^{71}As experiments

Rate 69.3 ± 4.1 (stat.) ± 3.6 (syst.) SNU

The observed signal is validated by



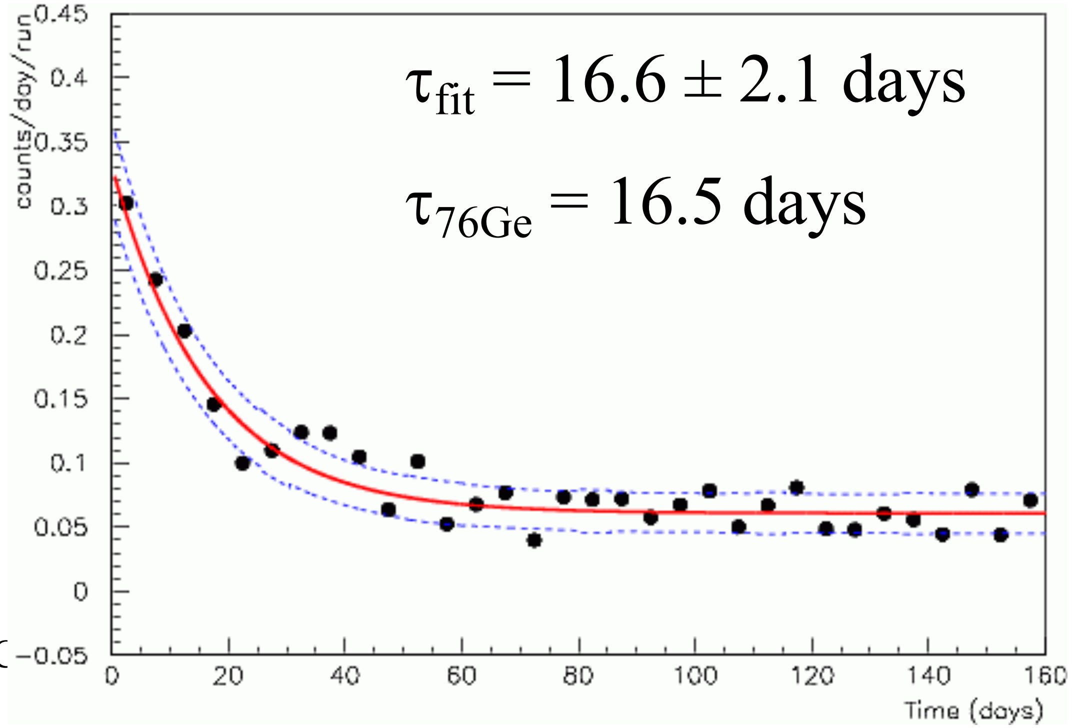
Event energy distribution

Important! No other peaks appear in the spectrum

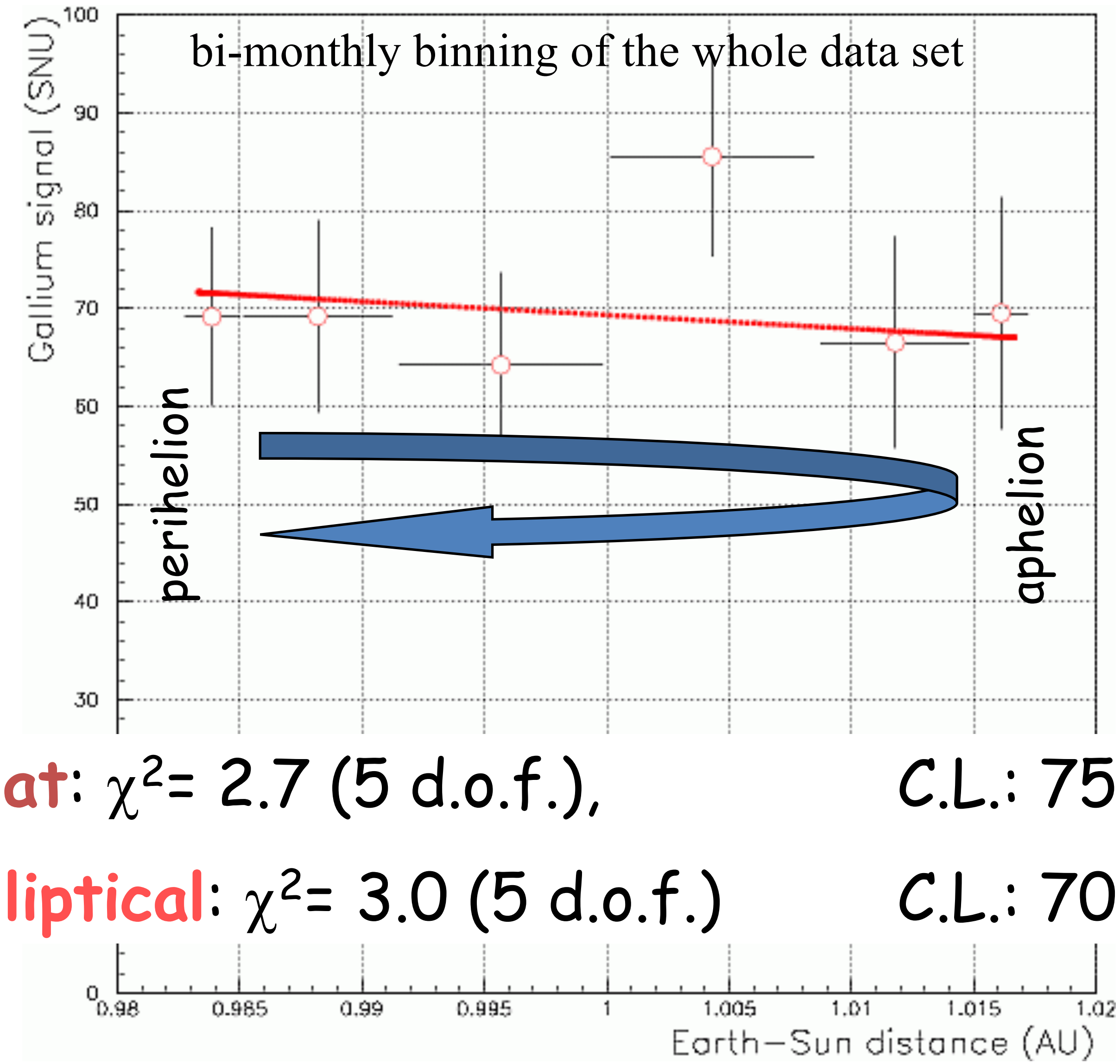
Event time distribution.

Analysis: M.L. analysis.

Null hypothesys: 1 decaying isotope + flat backgrd (independent /each run)



GALLEX/GNO searches of seasonal variation



Flat: χ^2= 2.7 (5 d.o.f.), C.L.: 75%

Elliptical: χ^2= 3.0 (5 d.o.f.) C.L.: 70%

Gallium Experiments

	Data taking	N runs	Average Efficieny *Tank to counter*	Hot chem check	Source calib	R_{ex} [SNU]
GALLEX /GNO LNGS Italy	1991-2003 stopped	123	97 %	^{71}*As*	***Yes twice*** ^{51}***Cr source***	**69.3 ± 4.1 ± 3.6** *5.9% 5.2%* ***69.3 ± 5.5***
SAGE Baksan Kabardino Balkaria	1990-ongoing	121	90 %	*No*	***Yes*** ^{51}***Cr*** ^{37}***Ar***	**66.9 ± 3.9 ± 3.6** *5.8% 5.2%* $66.9^{+5.3}_{-5.0}$

Combined value ***68.1 ± 3.75 (5.5%)***

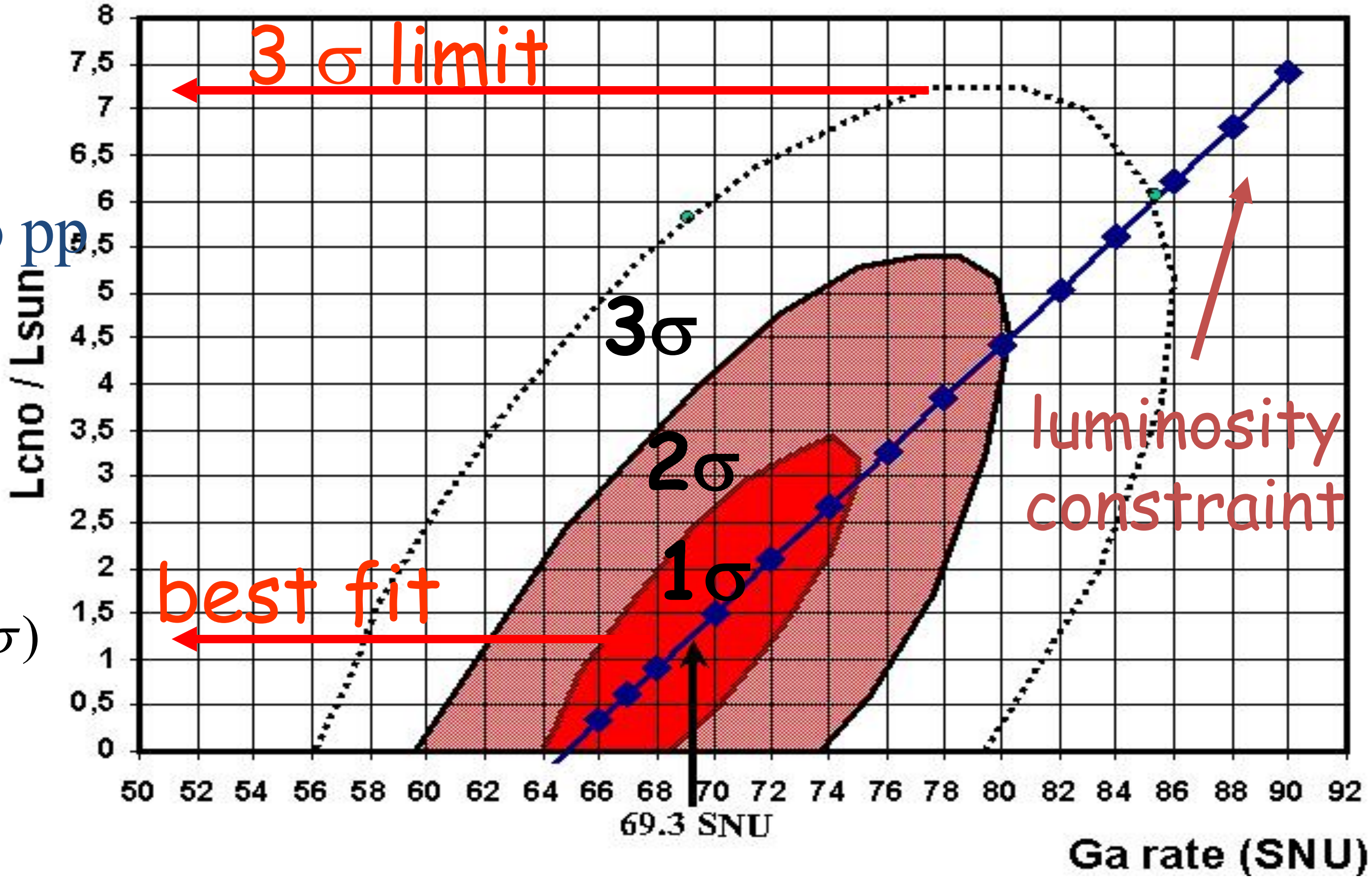
Constraining the CNO ν flux with Gallium data

- ^{8}B from SNO+SK
- ^{7}Be take from BP04
- pep strictly related to pp

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{G+G} \leq 7\% \, (3\sigma)$$

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{SAGE+G+G} \leq 5-6\,\% \, (3\sigma)$$

Phys.Let. B 616 (2005) 174-190



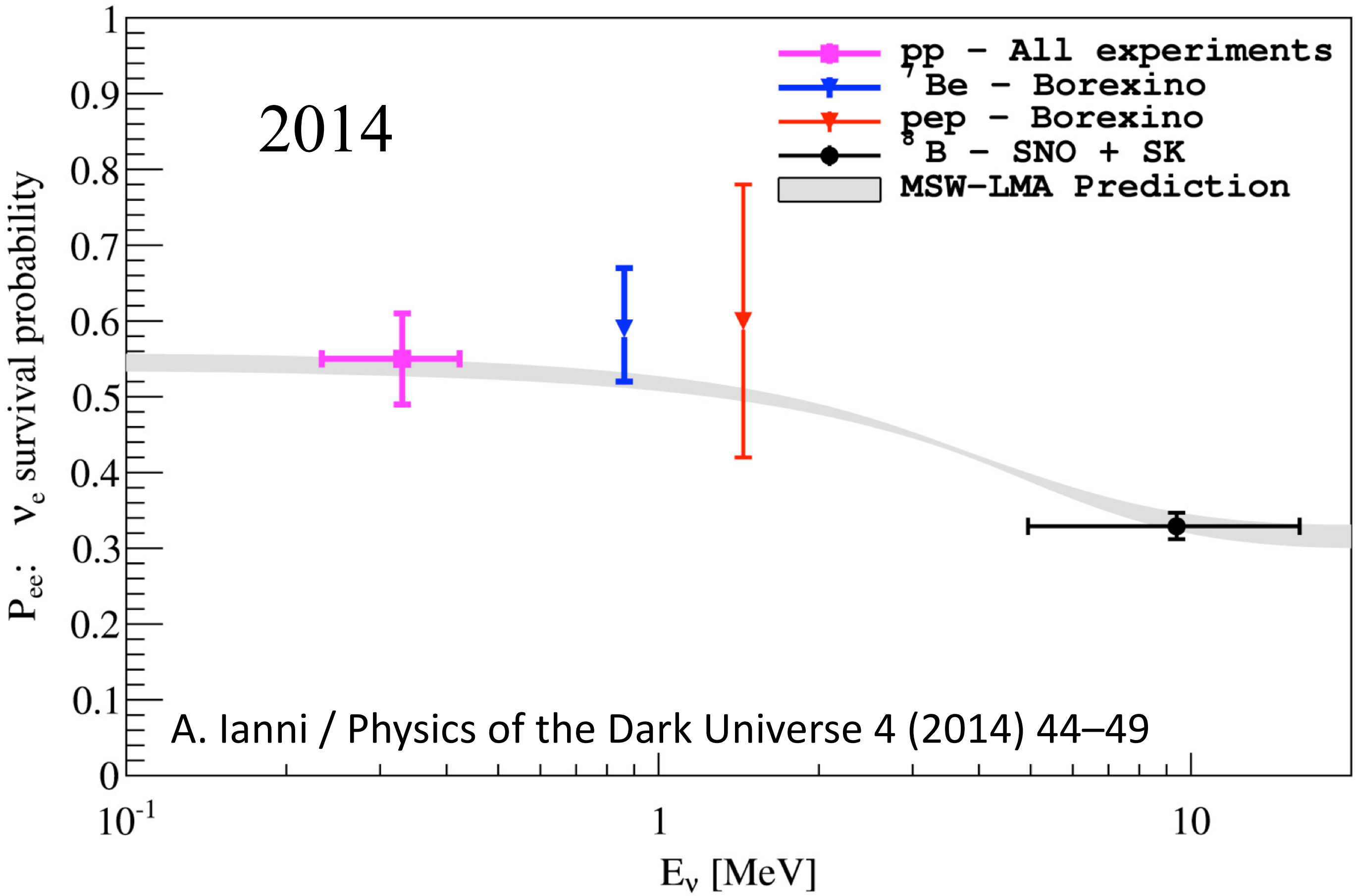
Important! The solar model N14 (Bahcall nomenclature) is used as reference, i.e. the CNO expectations take into account the reduced flux due to new $S_0(^{14}N(p,\gamma)^{15}O)$ measurement

.....with the listed assumptions and from the Ga capture rate the pp ν_e flux is determined

R_{Ga}	Φ_{pp} $[10^9\ cm^{-2}\ s^{-1}]$	Φ_{pp} / $\Phi_{pp}^{(BP04+N14)}$
69.3 *(G+G)*	59.9 $(1\pm 0.02 \pm 0.01_{theo})$	1.00(2)
68.1 *(G+G+S)*	58.8 (1 ± 0.02)	0.98(4)

Fantastic agreement !!

Ga results confirm/constrain the ν_e survival probability at low energies



Survival probability for solar ν_e using the low-Z SSM. The LMA-MSW prediction corresponds to 1σ band

Conclusions

• Gallium experiments confirmed the thermonuclear origin of the solar energy

• The dominant cycle is the pp

• The CNO and the Be contribution are properly described by the SSM

• ν oscillation are confirmed at sub-Mev energies (small matter effect at low energies) by solar models and neutrino oscillation mechanism

•No time modulations (seasonal, monthly, bimonthly, yearly) observed. No sensitivity

•Gallium experiments have been calibrated with high intensity neutrino sources. Hot chemistry effects have been excluded.

Technological results

•Few atoms chemistry

•Low level counting techniques

•Intense neutrino sources production (intensity calibration, know-how to produce and manipulate safely etc..)

•Radiochemistry techniques

•Radon counting and quantitative determination at level of few atoms.

•Ultra-low activity miniaturized proportional counters

In memoriam

- Luciano Paoluzi
  2002
- Burkhard Freudiger
  05.09.2005
- Dario Motta
  2005
- Michael Altmann
  31.07.2006
- Nicola Ferrari
  31.07.2006
- Keith Rowley
  29.10.2006
- Evry Schatzman
  25.04.2010
- Israel Dostrovsky
  28.09.2010
- Rudolf Mößbauer
  14.11.2011
- Silio d´Angelo
  02.02.2015

In memoriam

BACKUP

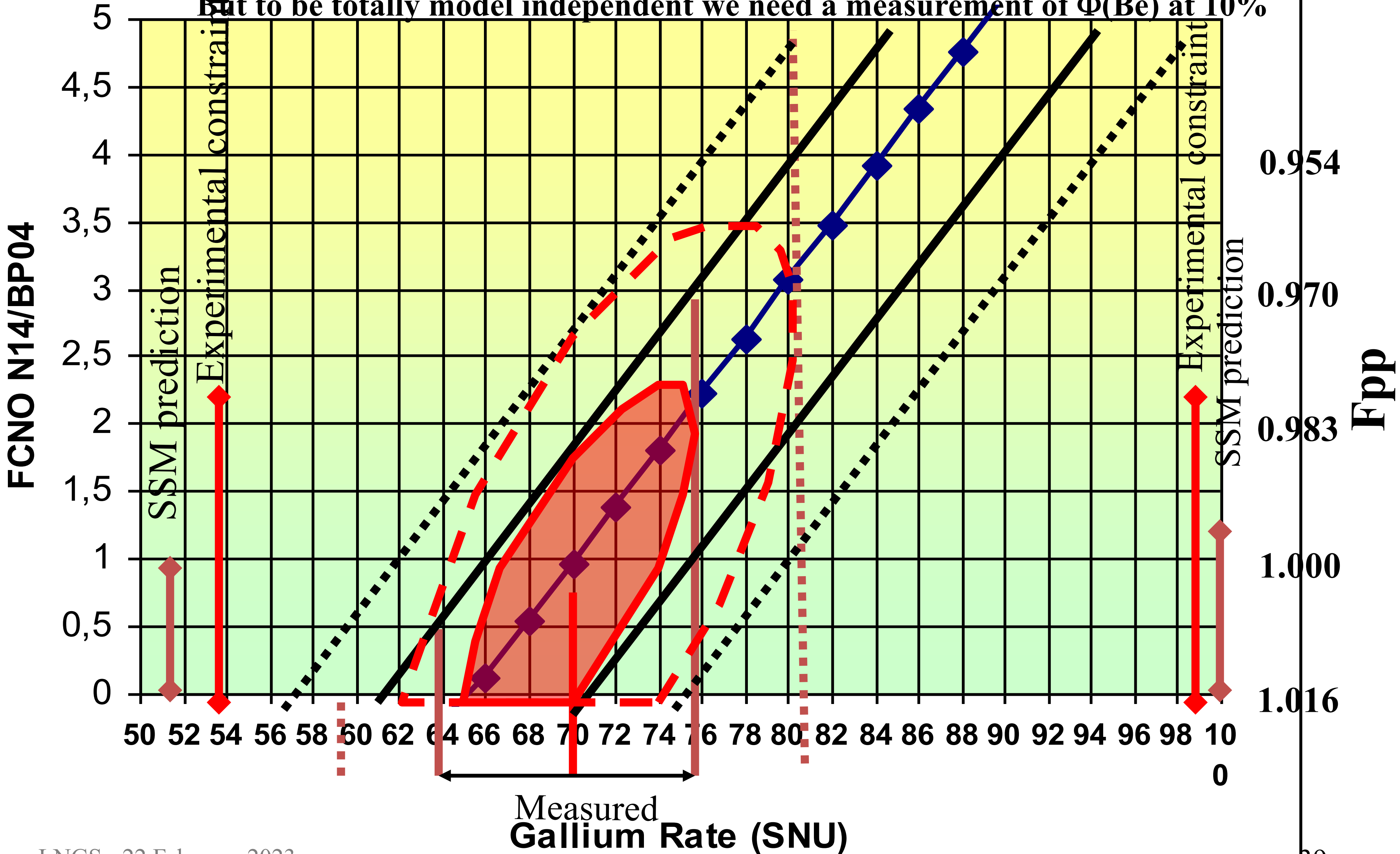
GALLEX/GNO - all uncertainties

Comments: perfect agreement of Ga rate with SSM + oscillation scenario

Φ(pp) probed at 2% level (1 sigma)

Φ(CNO) < 3.5 SSM (2 sigma)

But to be totally model independent we need a measurement of Φ(Be) at 10%



The Pioneer: Chlorine Experiment

The interaction

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

K_{shell} **EC** τ = **50.5** d

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

ν Signal Composition:
(BP04+N14 SSM+ ν osc)

pep+hep	0.15 SNU	(4.6%)
^{7}Be	0.65 SNU	(20.0%)
^{8}B	2.30 SNU	(71.0%)
CNO	0.13 SNU	(4.0%)
Tot	3.23 SNU ± 0.68 1σ	

Expected Signal
(BP04 + N14)

$8.2 \text{ SNU } ^{+1.8}_{-1.8}\ 1\sigma$

Results of Chlorine experiment

1. First measurement of solar neutrino interaction rate
2. Raised the problem of missing neutrinos
3. Opened a field of research that is not yet closed. Davis awarded in 2002, with the Nobel prize together with Koshiba and R. Giacconi

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

R = 2.56 ± 0.16 ± 0.16 SNU
= 2.56 ± 0.23

Constancy of the solar neutrino flux (over 23 years): no correlation has been found between R_{ν}^{Sun} and the solar cycle (many speculation on this item in the '90)

Generalities on radiochemical experiments

Nowadays, in the neutrino community, radiochemical experiment are considered like *turtles* ("protected" ancient animals):

- they are slow, low statistic experiment
- they are sensitive only to ν_e
- they measure only one quantity (the integral solar neutrino interaction rate).
- they do not measure neither the spectrum nor the incoming direction of solar neutrinos.

It is common opinion that having reached a statistical accuracy almost equal to the systematic accuracy they have almost accomplished their role.

	Collaboration	ν_e interaction reaction Lab overburden	Target comp. and mass	Exp. Time [d]	Data taking
GALLEX/ GNO LNGS Italy	D (MPIK,TUM), I (INFN), F (CEA), USA (BNL), Israel	$\nu_e(^{71}Ga,^{71}Ge)e^-$ 3500 mwe 0.6 μ [h m^2]$^{-1}$	GaCl3• HCl in H_2O 103 t (30 t Ga)	21-28 28	1991-2003
SAGE Baksan Kabardino Balkaria	RU (INR, RAS) USA (LNL,BNL)	$\nu_e(^{71}Ga,^{71}Ge)e^-$ 4800 mwe 0.1 μ [h m^2]$^{-1}$	Metallic Ga 50 tons	28	1990-ongoing

GALLIUM Experiments

The interaction
(proposed by Kuzmin in 1966)

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

K,L shell **EC** **τ = 16.5** d

^{71}Ga + 10 keV, 1 keV

(Auger e^-, X)

ν Signal Composition:
(BP04 +N14 SSM+ ν osc)

pp + pep	41.7 SNU	(62 %)
^7Be	19.0 SNU	(28 %)
CNO	2.6 SNU	(3.9 %)
^8B	4.1 SNU	(6.1 %)
Tot	67.4 SNU $^{+2.6}_{-2.3}$ 1σ	
No osc	127 SNU $^{+12}_{-10}$	

Expected Signal
(SSM + ν osc)

0.6 ν int. per day in GNO (1 in SAGE), but due to decay during exposure + ineff., 4.7 ^{71}Ge decay detected per extraction (28 days exposure).

Determination of Gallium-ν_e capture cross section

Ga-ν_e capture cross sections are needed to compute fluxes from rate

At low energy (< 410 keV, namely for pp ν_s) only g.s.-g.s.transitions are present;for this transition cross sections are evaluated from ^{71}Ge E.C.

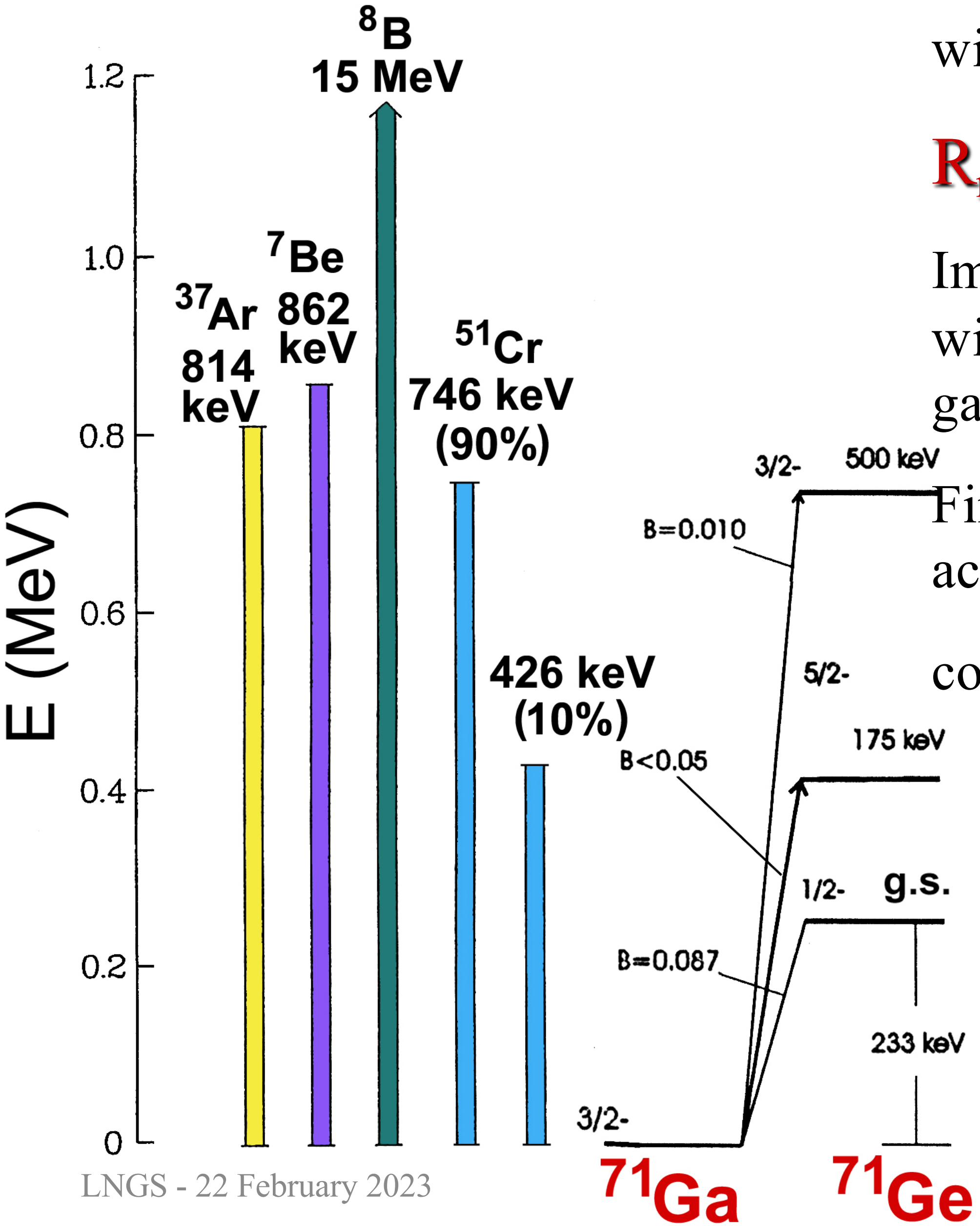
good accuracy (2.3% at 1σ)

At the ^{7}Be energies, the first two excited state (at 175 and 500 keV) must be considered; BGT estimated from (p,n) reactions;

estimated accuracy –3% +5%

Direct measurement desirable

Experimental situation



Two GALLEX and one SAGE calibrations,

with strong ^{51}Cr sources

$R_{meas} = 0.93 \pm 0.07\, R_{theo}$

Improvements are well possible irradiating with a 2MCi source f.i. 20 tons of metallic gallium

Final accuracy 5% or better = theoretical accuracy to addrees the question:

corrections to

g.s.-e.s. only

or to g.s.-g.s. also?

GALLEX sources: 1.71 MCi
1.87 MCi

SAGE source 0.52 MCi

Gas processing efficiencies evaluation

Data from neutrino source experiments can be used to infer on the cross section only once the extraction + gas processing efficiencies are exactly determined, and "hot chemistry" effect are excluded.

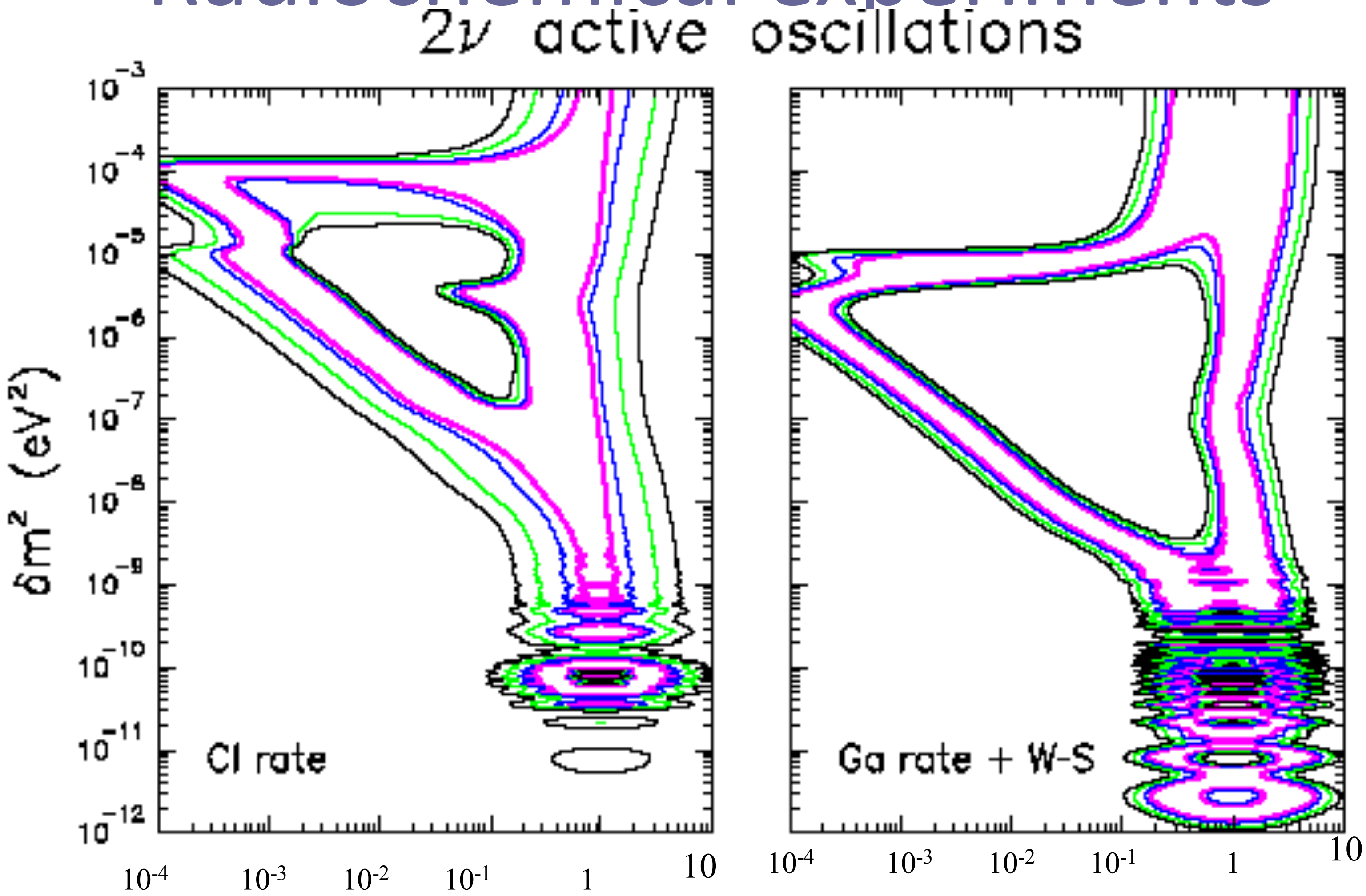
This has been done by the GALLEX collaboration, spiking the target with O(10000) atoms of ^{37}As, that beta decay to ^{76}Ge, kinematically mimicking the ν interaction.

The processing efficiency has been found to be correctly extimated (from the methods routinely adopted at each run) =100% with 1% error.

Impact of Gallium experimental results on neutrino oscillation parameters determination.

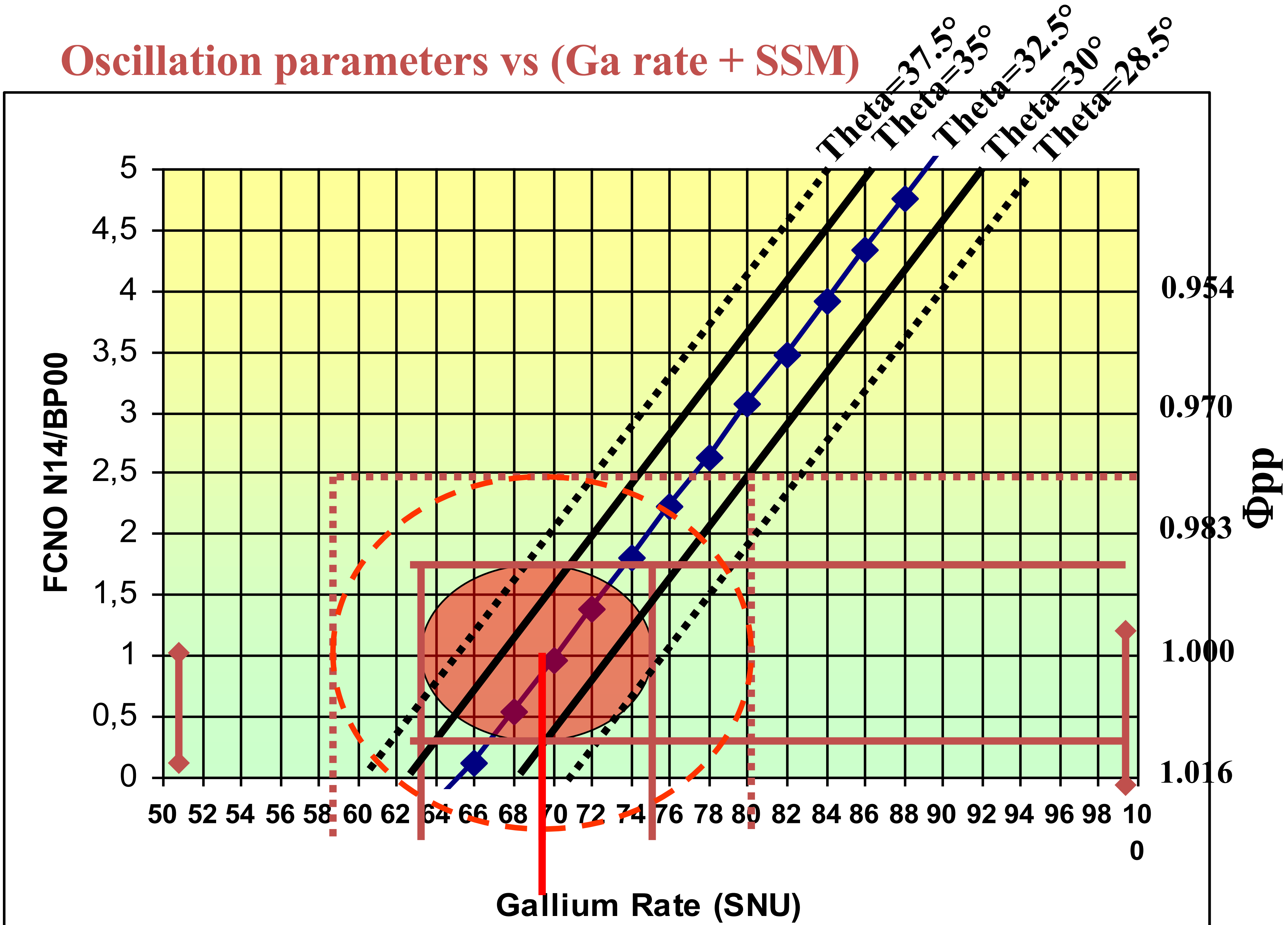
Almost irrelevant with the actual experimental accuracy
in the actual experimental scenario

Allowed $(\Delta m^2, tan^2\theta_{12})$ regions from Radiochemical experiments



Ga experiments are more sensitive to $tan^2\theta_{12}$ than to Δm^2

Oscillation parameters vs (Ga rate + SSM)



Comments: No sensitivity within the presently allowed oscillation parameter region

Impact of Gallium Results on Astrophysics

Solar Models *R* previsions for Radiochemical experiments

from LUNA experiment on $^{14}N(p,\gamma)^{15}O$
New $S_0(^{14}N+p) = 1.77$ keV ± 0.2

Flux ($cm^{-2}s^{-1}$)	BP00	BP04	BP04 + N14	BP04+ + N14	P_{ee} $\Delta m^2 = 7.1 \times 10^{-5}$ eV^2 $\theta_{12} = 32.5$
pp (10^9)	59.5 (± *1%*)	5.94 (± *1%*)	59.8	60.3	0.578 (vac)
pep (10^8)	1.40 (± *2%*)	1.40 (± *2%*)	1.42	1.44	0.531(vac)
hep (10^3)	9.24	7.88 (± *16%*)	7.93	8.09	~ 0.3 matter
^{7}Be (10^9)	4.77 (± *10%*)	4.86 (± *12%*)	4.86	4.65	0.557 vac
^{8}B (10^6)	$5.05^{+20\%}_{-16\%}$	5.79 (± *23%*)	5.77	5.24	0.324 matter
^{13}N (10^8)	$5.48^{+21\%}_{-17\%}$	5.71	$3.23^{+37\%}_{-35\%}$	2.30	0.557 vac
^{15}O (10^8)	$4.80^{+25\%}_{-19\%}$	5.03	$2.54^{+43\%}_{-39\%}$	1.79	0.541 vac
^{17}F (10^6)	$5.63^{+25\%}_{-25\%}$	5.91	$5.85^{+44\%}_{-44\%}$	3.93	

increased accuracy in $^7Be(p,\gamma)^8B$ measurement

Columns 2,3,4 from BP04

…… to summarize

BP00 with $Z/X_{old} = 0.0229$ ⟶ $R_{CZ} = 0.715\, R_{\Theta}$

BP04 = BP00 + New data on EOS, Nucl Phys.(Cross sections)

N14 = BP04 + $S_0(^{14}N+p) = 1.77\ keV \pm 0.2$

BP04+ = BP04 + $Z/X_{new}=0.0176$ ⟶ $R_{CZ} = 0.725\, R_{\Theta}$

to be compared with $R_{meas} = 0.713 \pm 0.001$

Solar Models *R* previsions for Radiochemical experiments

Experimental	Δm^2, $\tan^2\theta_{12}$	from experiments	BP00	BP04	BP04 + N14	$BP04^+$ + N14
SNO/ SK **5.21 ± 0.27** ($cm^{-2}s^{-1}$)	7.1, 0.45 † 7.3, 0.42 *	$1.00^{+6\%}_{-6\%}$ $1.01^{+6\%}_{-6\%}$				
	no osc		$5.05^{+20\%}_{-16\%}$	5.79 *(± 23%)*	5.77	5.24
Cl **2.56 ± 0.23** [SNU]	7.1, 0.45 † 7.3, 0.42 *	3.06 ± 0.04 2.79 ± 0.18		3.35 *(± 21%)*	3.23	2.95
	no osc		$7.6^{+1.3}_{-1.1}$	$8.5^{+1.8}_{-1.8}$	8.2	7.7
Ga **68.1 ± 3.75** [SNU]	7.1, 0.45 † 7.3, 0.42 *	69.4 ± 2.6 65.8 ± 4.5		67.7 ± 5.5	69.3 ± 5.3	67.7 ± 5.3

Comparison of solar model predictions with experimental results

- Neutrinos prefer a Sun having "low metallicity" solar interior, as the recent photospheric measurements indicate
- when this data are included in the SSM → tension with helioseismology as the depth of the convective zone goes to 0.726 R_{sun} (instead of 0.713 as measured i.e. 18% discrepancy).

L_{CNO} estimate from Gallium experimental results imposing the luminosity constraint

1. From R_{Ga} (which come frm the sum of all the neutrino components, weighted by the cross section and P_{ee}

$$R = N_{\text{target}} \cdot \sum_{\mathbf{i}} \int \sigma_i(E) \cdot \frac{d\Phi_i(E)}{dE} P(\nu_e \rightarrow \nu_e) dE$$

2. And the Luminosity constraint: nuclear fusion reactions are the only source of energy in the Sun→ relates the Sun energy release in photons to energy release in ν

$$L_{Sun} = \sum_i \Phi_i \cdot \alpha_i = 8.53 \cdot 10^{11} \, MeV cm^{-2} s^{-1}$$

$$\alpha_i = MeV \ in \ photons \ per \ emitted \ neutrino$$

Gallium
Uncertainties for evaluation of pp and CNO ν flux

Parameter	Parameter Uncertainty	Rga Uncertainty (SNU)
Theta	+/- 2.5° SNO+kam+SK	2.9
^{7}Be	10% SSM	1.9
Cross section GS -GS	2.3%	1.5
Cross section GS –ES(1,2)	50%	0.7
Cross section GS-ES>2	35%	1.5
8B	9 % SNO	0.4
pep	1.5 % SSM	0.1
		4.2

.....it is possible to estimate at the same time Φ_{pp} and Φ_{CNO} once we know the ^{8}B, ^{7}Be, pep fluxes

$$\frac{L_{CNO}}{L_{Sun}} = \frac{\Phi_O \cdot \alpha_O + \Phi_N \cdot \alpha_N}{\sum_i \Phi_i \cdot \alpha_i}$$

- ^{8}B take from experiments
- ^{7}Be take from SSM
- pep strictly related to pp

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{G+G}^{best\ fit} = 1.2_{-1.2}^{+2.3}\left[\frac{L_{CNO}}{L_{Sun}}\right]_{N14} \cong 0.6\left[\frac{L_{CNO}}{L_{Sun}}\right]_{BP04}$$

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{SAGE+G+G}^{best\ fit} = 1.0_{-??}^{+??}\left[\frac{L_{CNO}}{L_{Sun}}\right]_{N14} \cong 0.5\left[\frac{L_{CNO}}{L_{Sun}}\right]_{BP04}$$

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{BP04} = (1.6 \pm 0.6)\%$$

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{G+G} \leq 7\%\ (3\sigma)$$

$$\left[\frac{L_{CNO}}{L_{Sun}}\right]_{SAGE+G+G} \leq 5-6\ \%\ (3\sigma)$$

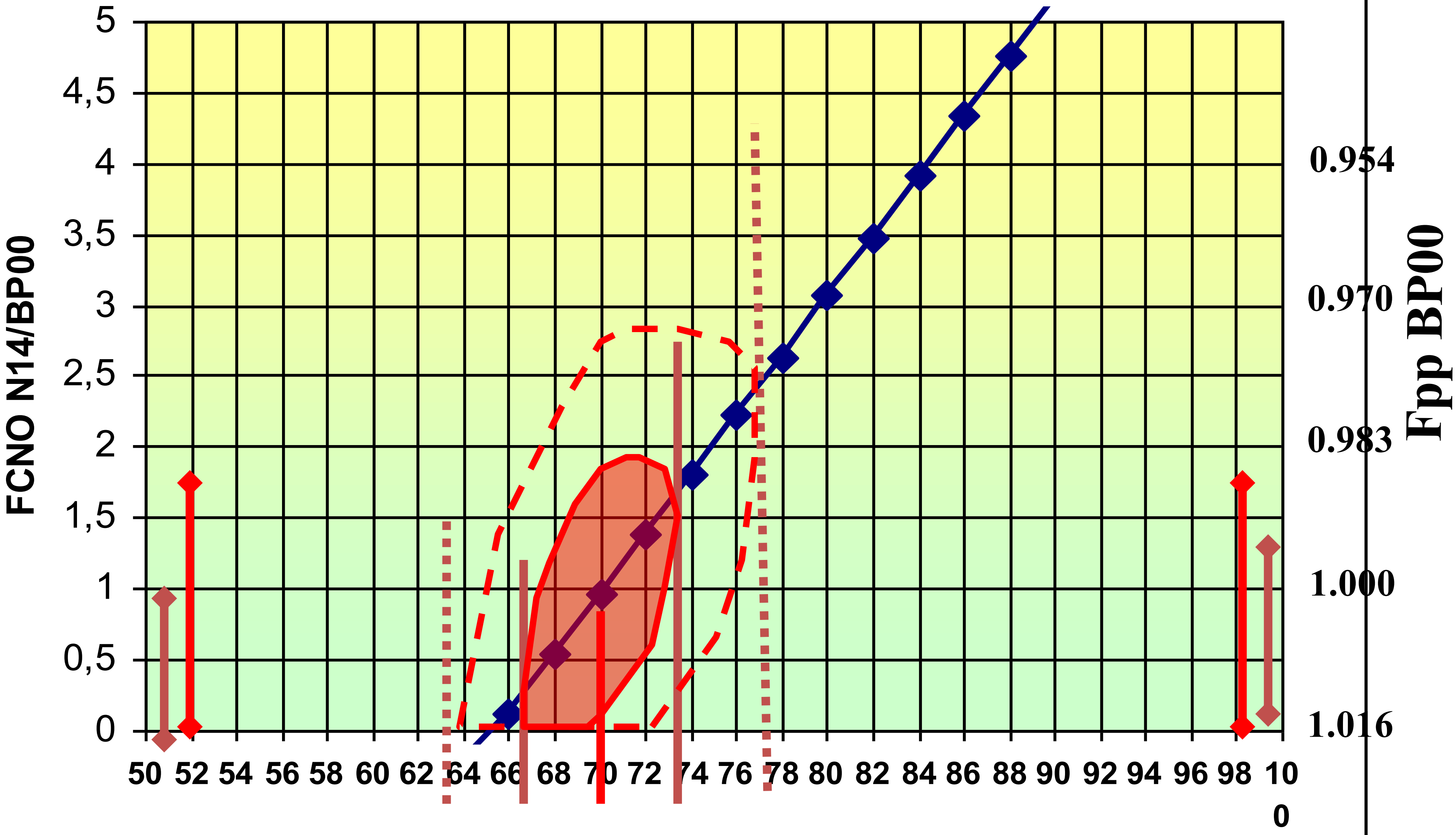
.... for ^{8}B and ^{7}Be

$$\Phi(^{8}B)_{meas} = (0.89 \pm 0.04_{ex} \pm 0.23_{theo})\ \Phi(^{8}B)_{BP04 + N14}$$

$$\Phi(^{7}Be)_{meas} = (0.91^{+0.24}_{-0.62\ ex} \pm 0.11_{theo})\ \Phi(^{7}Be)_{BP04+N14}$$

from BP04

Gallium- 5% error



R = 70.0 +- 3.5 SNU