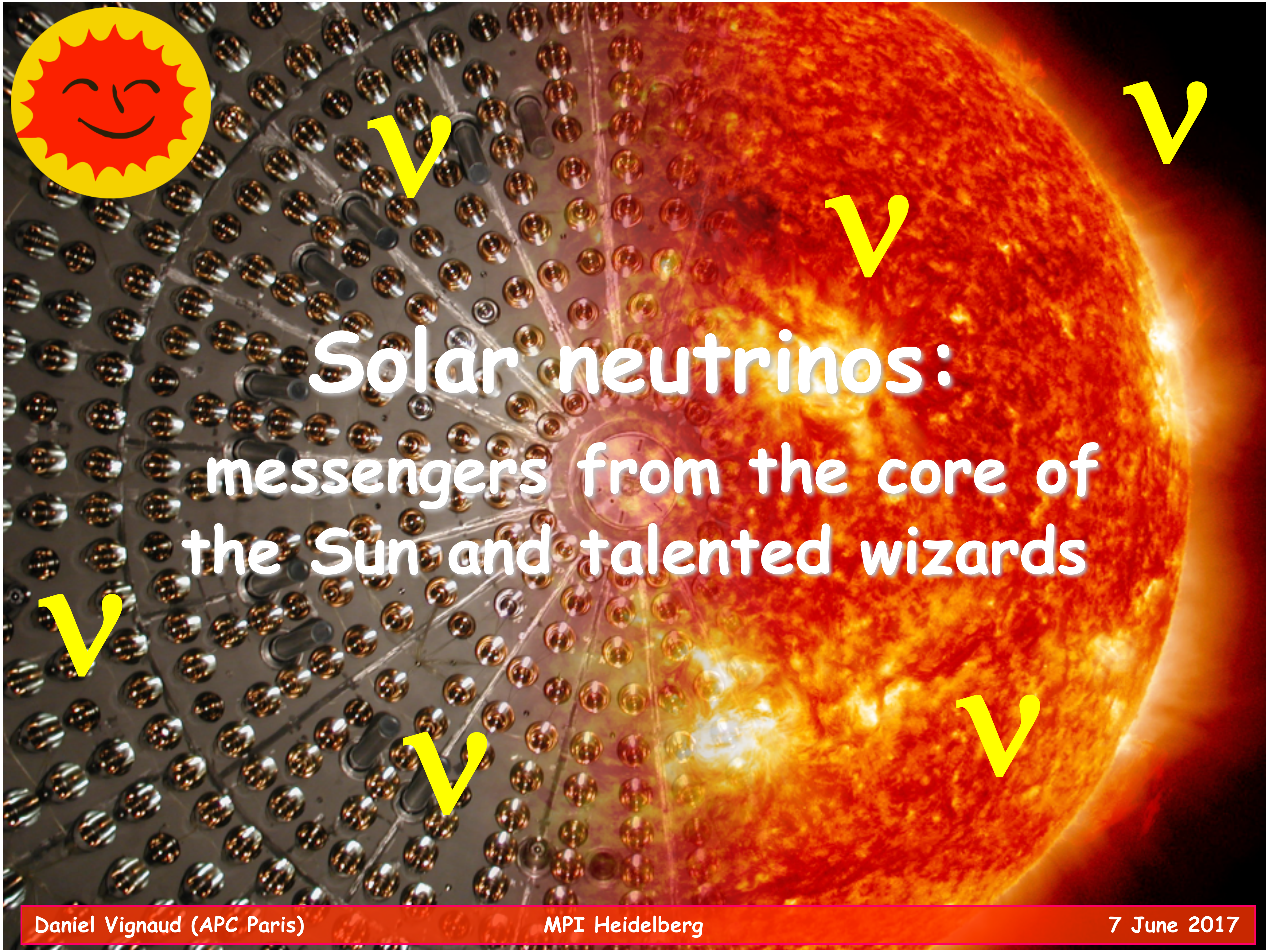

Solar neutrinos:

messengers from the core of the Sun and talented wizards

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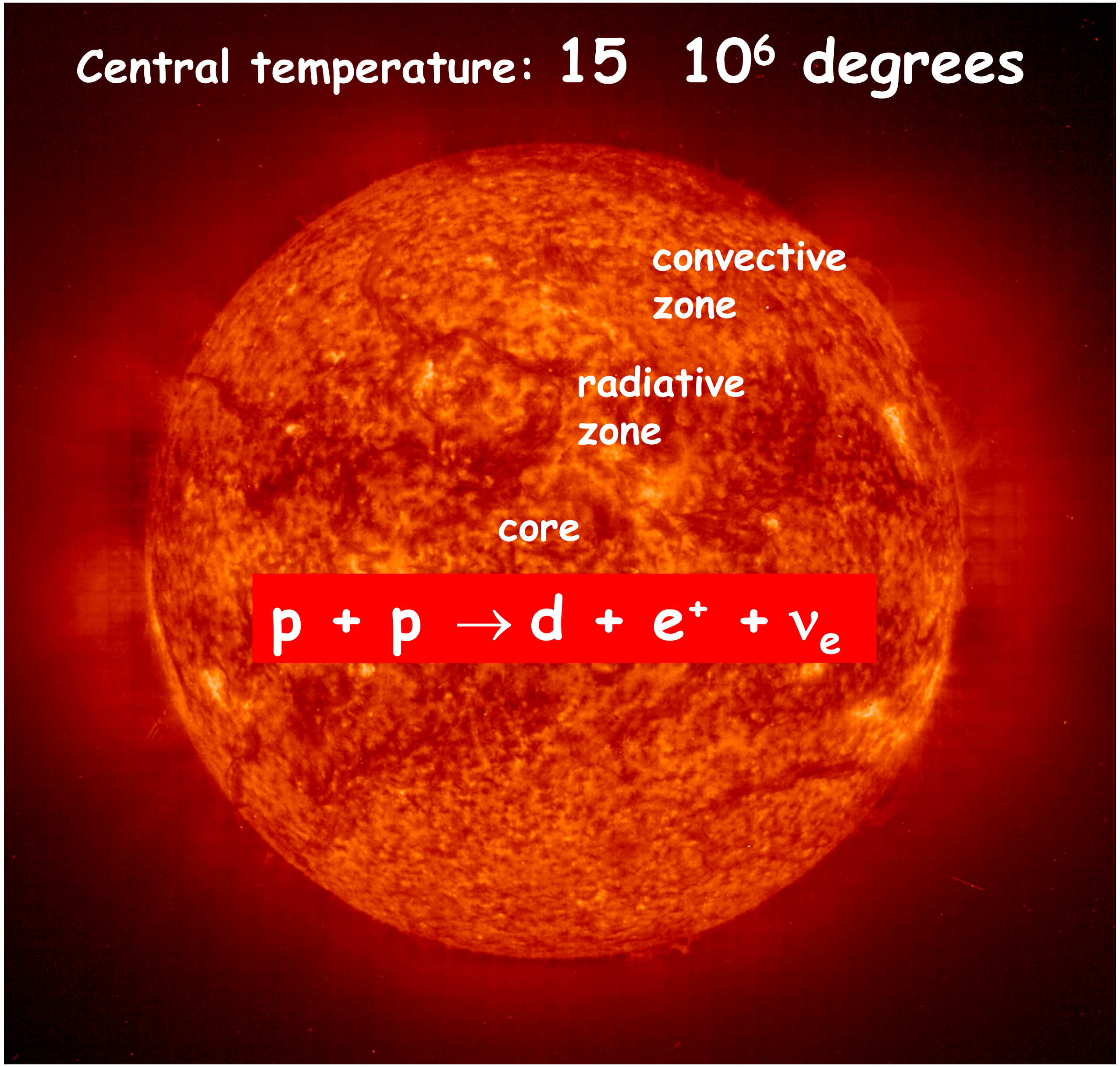
The Sun

- Composition :

73% hydrogen (H)
25% helium (He)
2% other elements

H. Bethe
& C. von Weiszacker
1938



Central temperature: $15\ \ 10^6$ degrees

$$p + p \rightarrow d + e^+ + \nu_e$$

Energy production in the Sun: cycles of nuclear reactions

Energy balance : 4 protons + 2 electrons → helium-4 + 2 neutrinos + $4\ 10^{-12}$ W

The Sun

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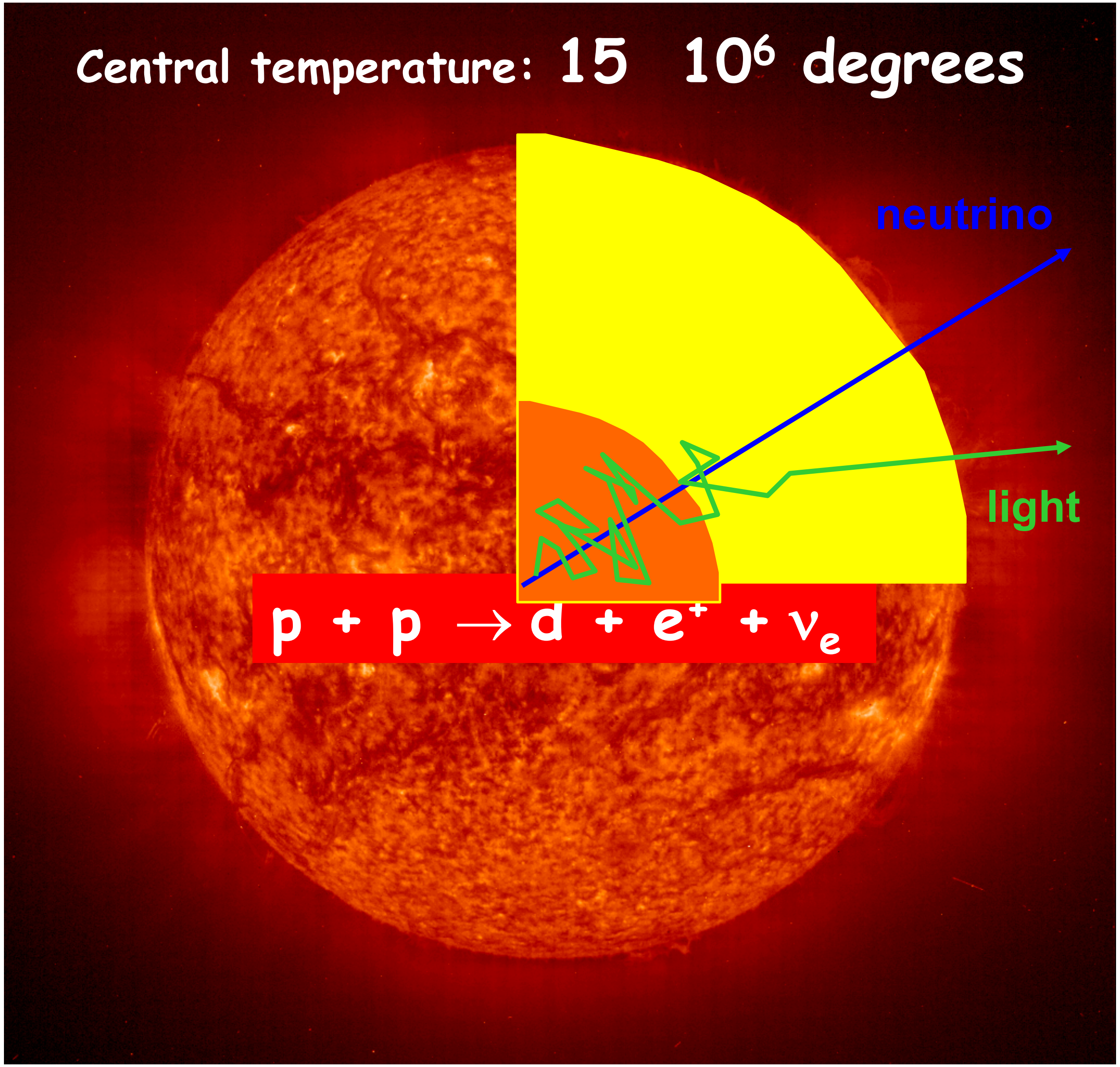


Central temperature: 15 10^6 degrees

$p + p \rightarrow d + e^+ + \nu_e$

Energy production in the Sun: cycles of nuclear reactions

Energy balance : 4 protons + 2 electrons → helium-4 + 2 neutrinos + 4 10^{-12} W

The standard solar model (SSM)

Basic hypotheses

- **hydrostatic equilibrium (radiative pressure vs. gravity)**
- **spherical symmetry, no rotation, no magnetic field**
- **energy transport by photons (radiative zone) or by convective currents (convective zone) - No wimps**
- **energy generation by nuclear reactions**
- **primordial solar interior chemically homogeneous**

Observational Constraints

- **Mass : 2 10^{33} g**
- **Luminosity : 3.84 10^{26} W**
- **Radius : 7 10^{8} m**
- **Age : 4.57 10^{9} years**
- **T (5800 K) and composition of the surface**
- **Helioseismology**
- **Neutrinos**

Ingredients and Uncertainties

- **Opacity tables**
- **Microscopic diffusion of He and heavy elements**
- **Z/X (heavy elements / hydrogen) : 0.0245 (1 ± 0.01) (photospheric and meteoritic determination) – presently controversial**
- **Y/X (helium / hydrogen) : 0.25 ± 0.01**
- **Nuclear reaction rates**

Basic equations of stellar evolution

pressure

gravitational cst

$$\frac{dP}{dr} = - \frac{M(r)\ G}{r^2}\ \rho$$

radius

density

hydrostatic equilibrium : each gas shell dr is balanced by the competition between downward gravitational force and outward pressure force.

M(r) : mass enclosed within a sphere of radius r :

$$\frac{dM}{dr} = 4\pi r^2\ \rho$$

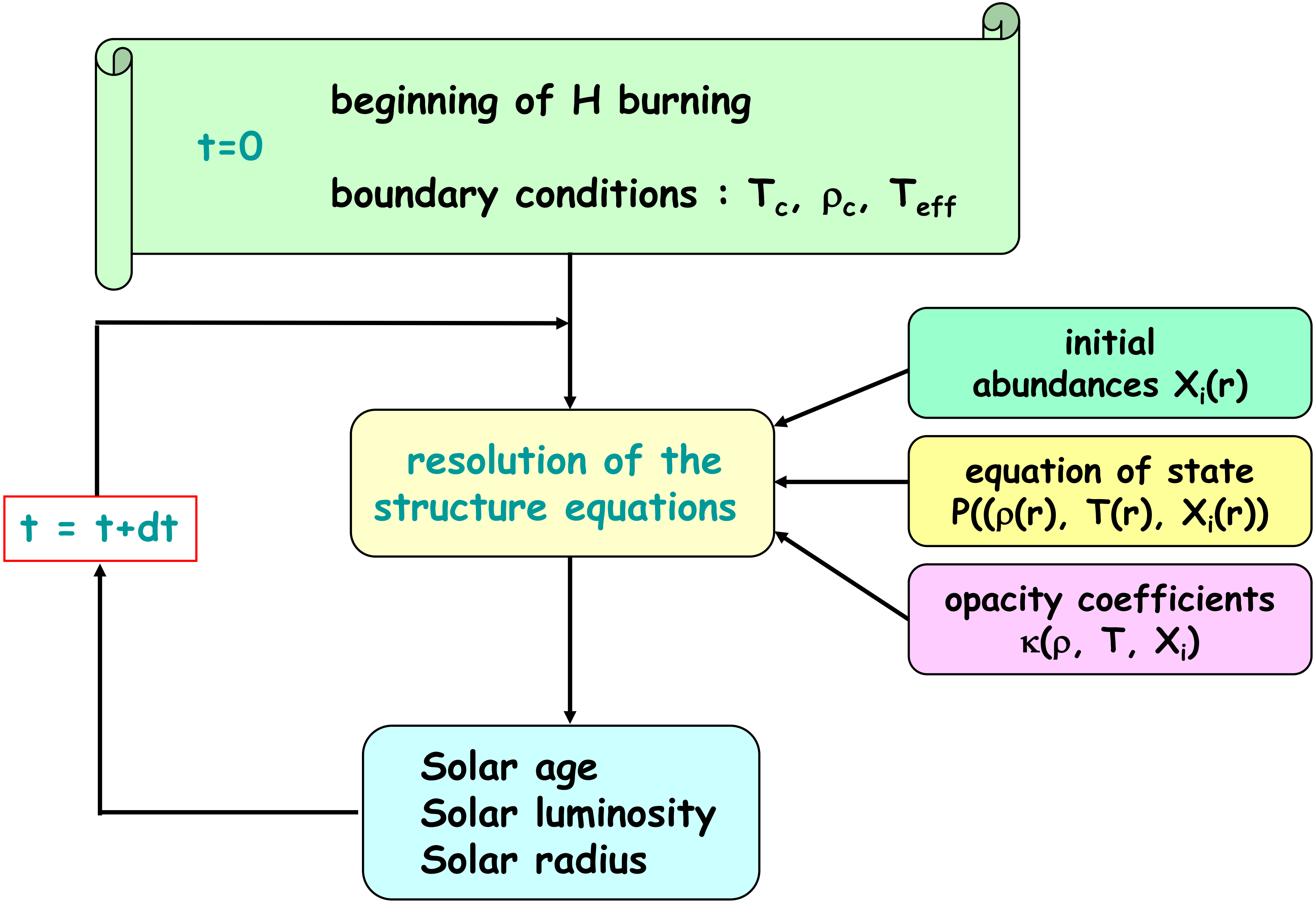
thermal equilibrium : energy ε produced by nuclear reactions balances the energy flux L(r) emerging from the sphere of radius r :

$$\frac{dL}{dr} = 4\pi r^2\ \rho\,(\varepsilon_{nucl} - T\,\frac{dS}{dT})$$

correction (heat transfer)
(S is entropy)

A third equation governs the temperature gradient dT/dr, which depends on the luminosity and the physical process of the energy transport.

How to build a solar model ?



t=0

beginning of H burning

boundary conditions : T_c, ρ_c, T_{eff}

resolution of the structure equations

initial abundances $X_i(r)$

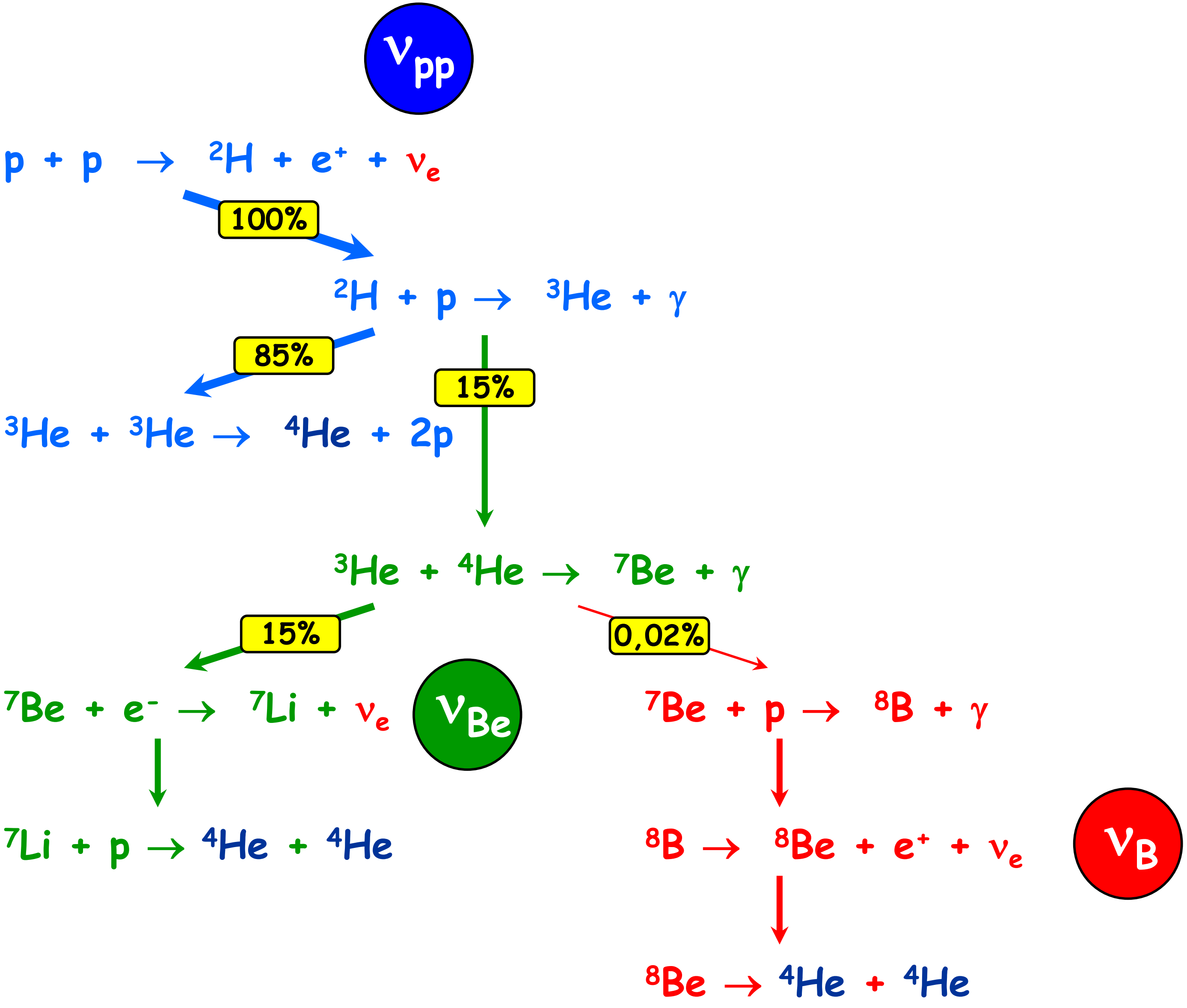
equation of state $P((\rho(r), T(r), X_i(r))$

opacity coefficients $\kappa(\rho, T, X_i)$

Solar age
Solar luminosity
Solar radius

t = t+dt

Nuclear reactions in the Sun



ν_{pp}

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

100%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

85%

15%

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

15%

0,02%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

ν_{Be}

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

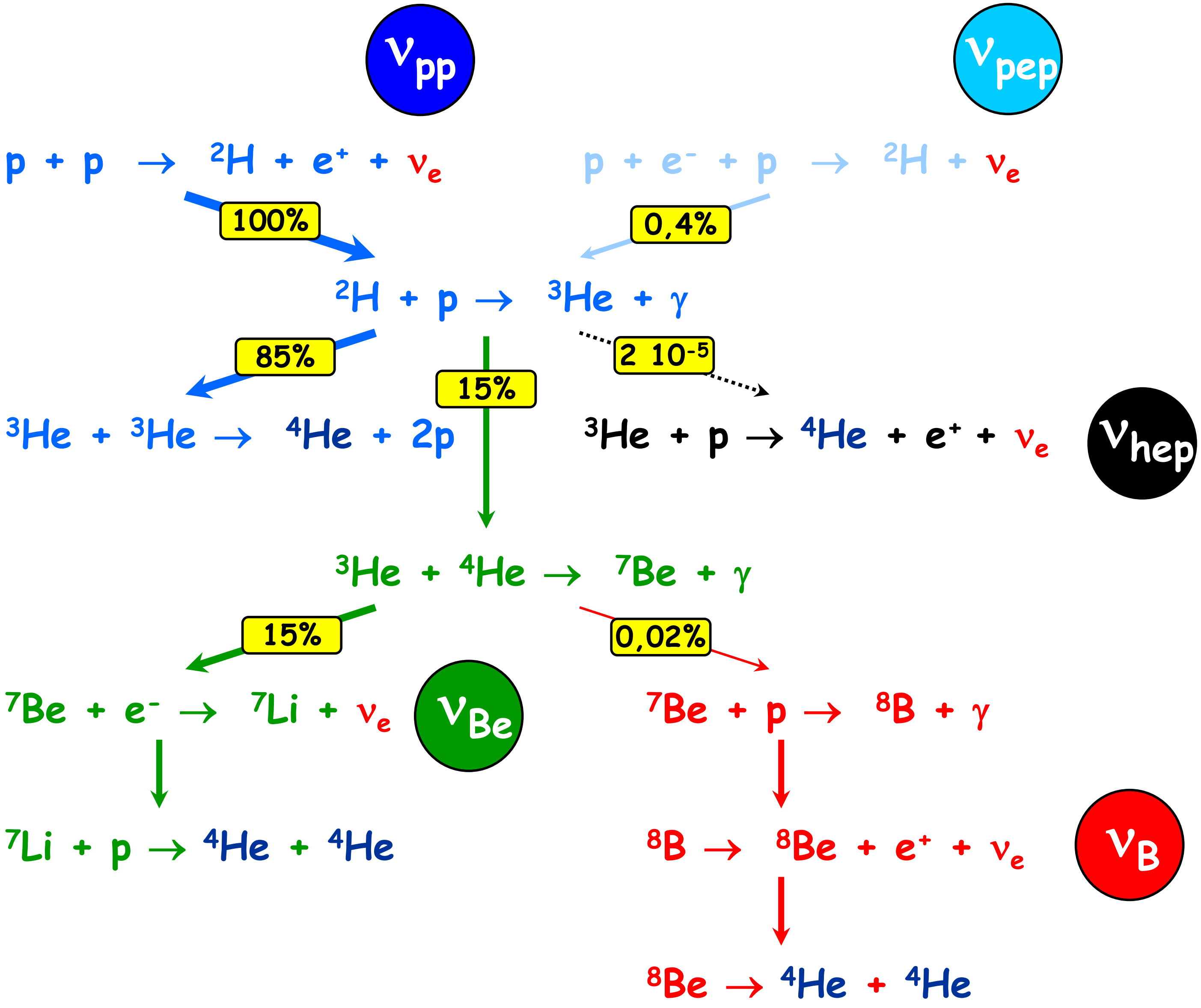
${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$

ν_{B}

${}^{8}Be \rightarrow {}^{4}He + {}^{4}He$

Nuclear reactions in the Sun



ν_{pp}

$p + p \rightarrow {}^2H + e^+ + \nu_e$

ν_{pep}

$p + e^- + p \rightarrow {}^2H + \nu_e$

100%

0,4%

${}^2H + p \rightarrow {}^3He + \gamma$

85%

15%

2 10-5

${}^3He + {}^3He \rightarrow {}^4He + 2p$

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

ν_{hep}

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

15%

0,02%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

ν_{Be}

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow {}^4He + {}^4He$

${}^8B \rightarrow {}^8Be + e^+ + \nu_e$

ν_B

${}^8Be \rightarrow {}^4He + {}^4He$

Nuclear reactions in the Sun

CNO cycle

$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$ ν_N

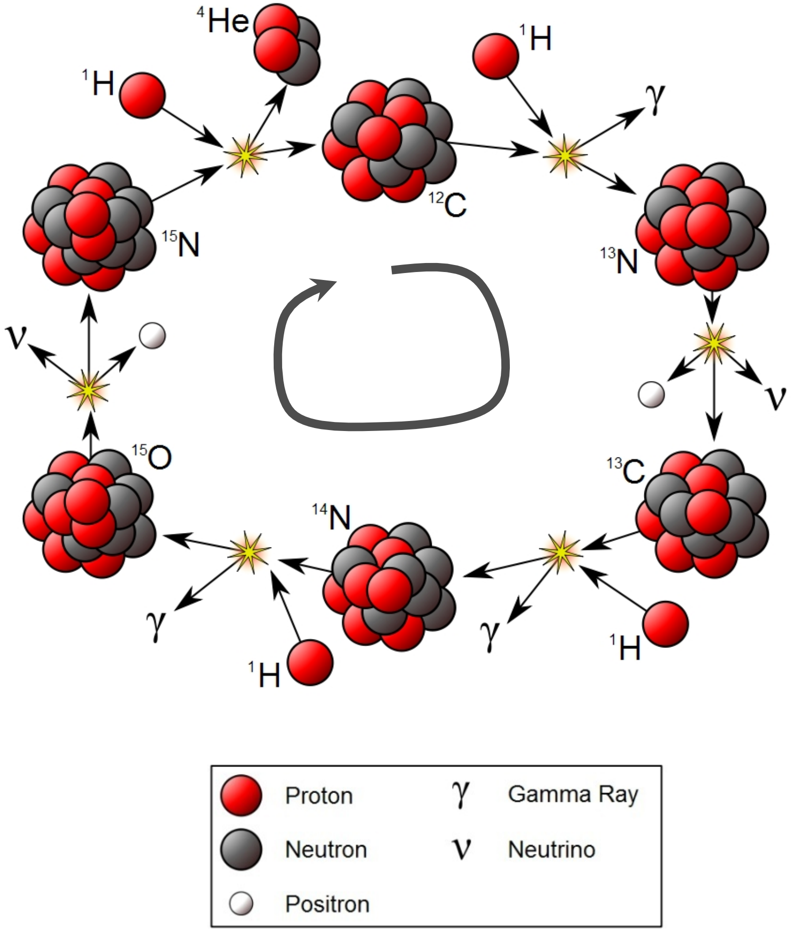
$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

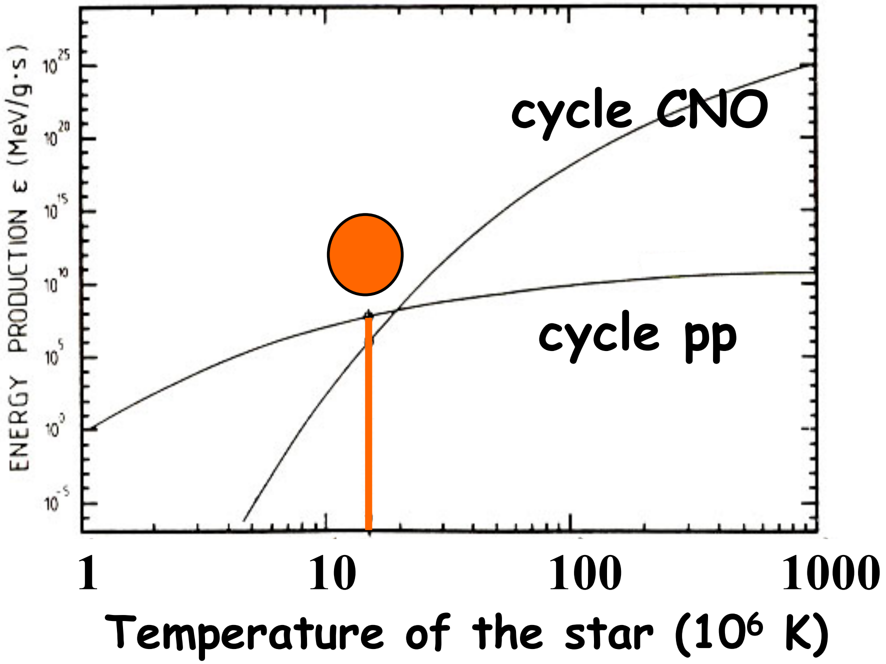
$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$ ν_O

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

^{12}C : catalyst

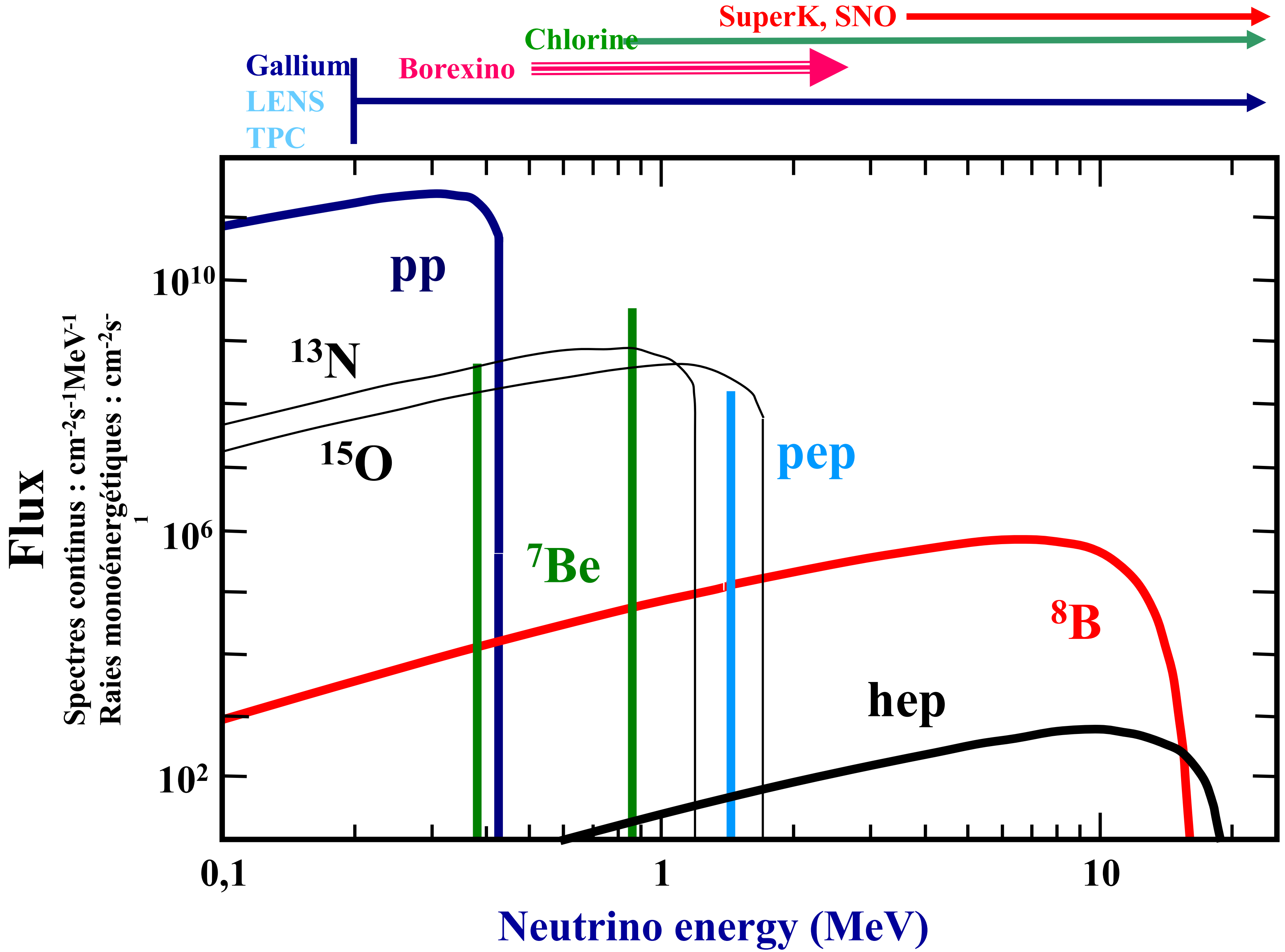


Energy production in stars

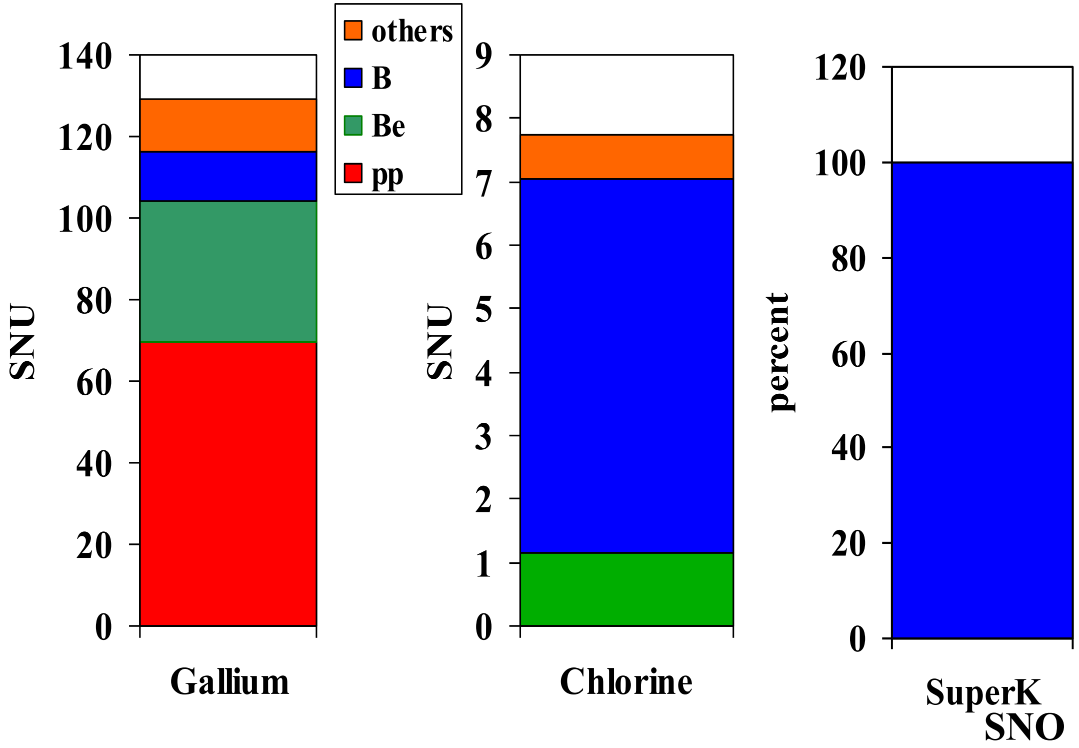


Competition between the pp chain and the CNO cycle as a function of the stellar temperature. For the Sun, the pp chain is still dominant.

Energy spectrum of solar neutrinos



Predictions of the solar models



Flux (cm^{-2} s^{-1})	GS98 (High met.)	AGS09 (Low met.)	Seismic (AGS09)	Error (~)
pp (10^{10})	5.98	6.03		0.6%
pep (10^{8})	1.44	1.47	1.4	1.2%
^{7}Be (10^{9})	5.00	4.56	4.72	7%
^{8}B (10^{6})	5.58	4.59	5.31	14%
^{13}N (10^{8})	2.96	2.17	4	14%
^{15}O (10^{8})	2.23	1.56	3.5	15%
Radioch. (SNU)				
Chlorine	8.5	6.9	7.67	10%
Gallium	128	121	123.4	6%

Z/X 0.0229 0.0178

50 years of solar modeling

Updated determination of the Sun metallicity (should be the best), but disagreement with helioseismology

☸ J.N.Bahcall, M.Pinsonneault, S.Basu, astro-ph/0010346, Ap. J. 555 (2001) 990

A.M. Serenelli, W.C. Haxton, C. Pena-Garay, arXiv:1104.1639

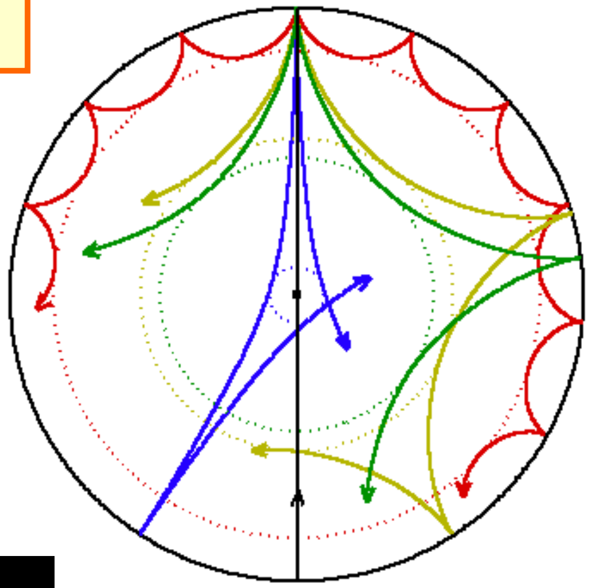
N. Vinyoles et al., arXiv:1611.09867 (updates in some nuclear reaction rates and, a new treatment of uncertainties due to radiative opacities)

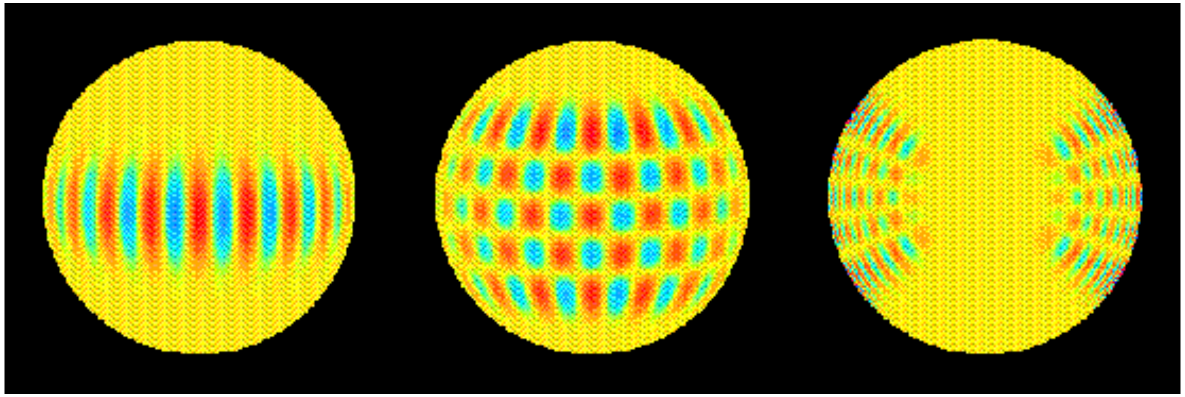
☸S.Turck-Chièze et al., Ap. J. Lett. 555 (2001) L69

S. Turck-Chièze and S. Couvidat, Rep. Prog. Phys. 74 (2011) 086901
SSM and Seismic model

Helioseismology

The Sun acts as a resonating cavity, exhibiting millions of oscillation modes (described by spherical harmonics)

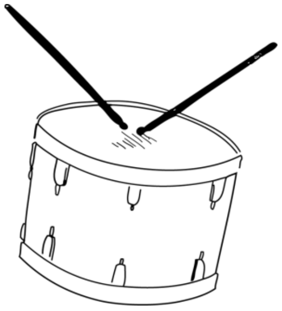




l=19
m=19

l=19
m=15

n=11
l=19
m=15



The Sun as a drum

Observation of acoustic waves at the surface of the Sun : tool to explore the interior (SOHO satellite and others)

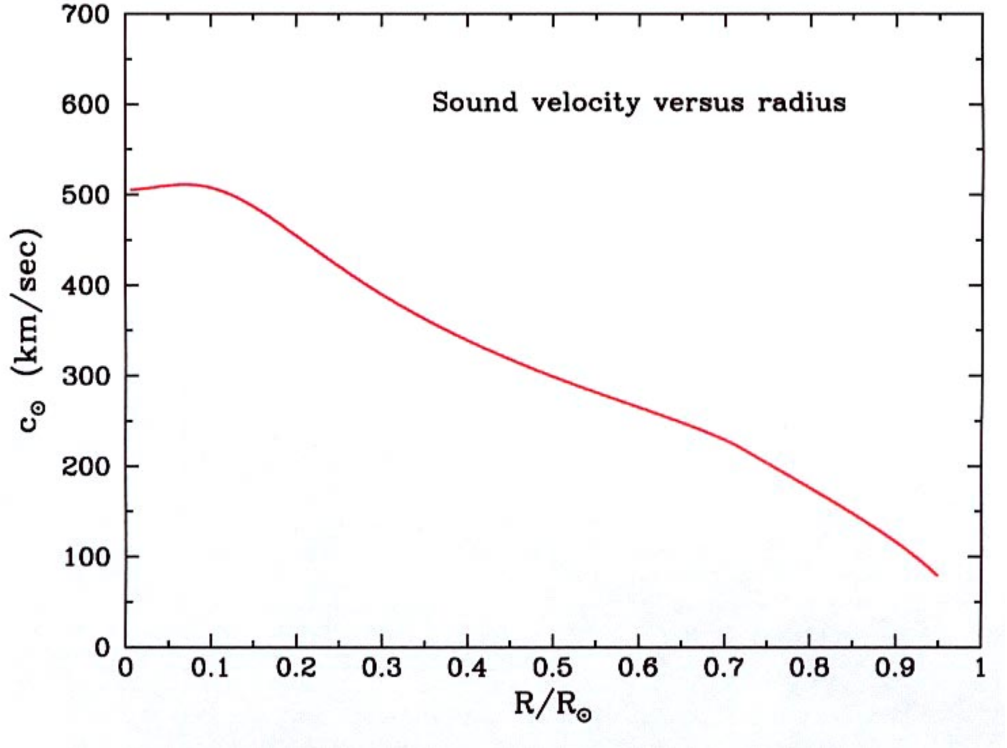
Helioseismology constraint : the sound speed

sound speed

temperature

$\boxed{c^2 = T/\mu}$

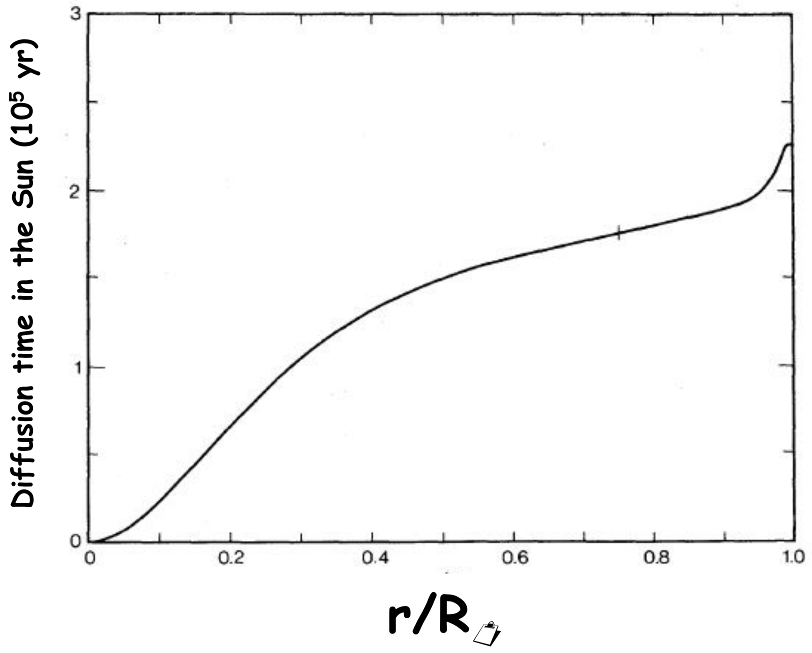
mean molecular weight



J.N.Bahcall et al., Ap. J. 555 (2001) 990

How long it takes to energy (« the light ») to escape the Sun ?

Photons are faced to an « infinite » succession of collisions (emission, reabsorption). Their mean free path is : $l = 1/(\kappa\rho)$
κ is opacity and ρ density (determined by solar models)



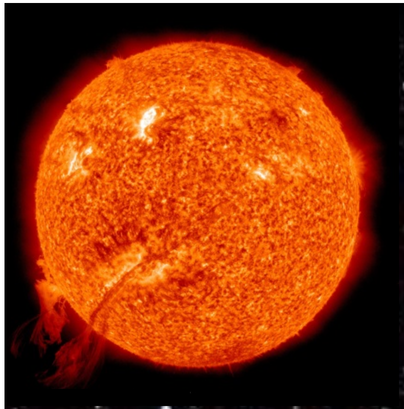
10^{25} collisions
l = 0,09 cm

t = 170 000 yr !

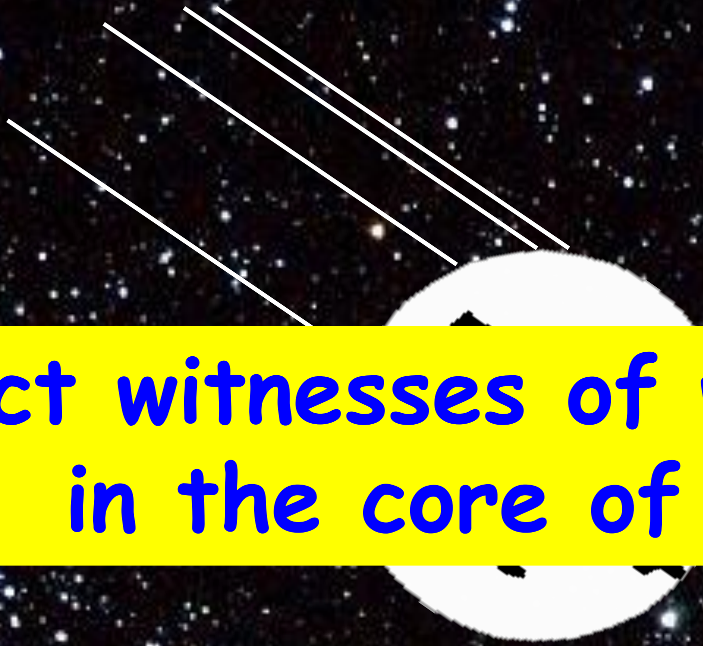
[Be careful, it is a mean estimate]

Photon energy in the core of the Sun : ~100 keV. At the surface they are visible (eV)!
Opacity sources are electron diffusion, photoionization, inverse bremsstrahlung,…
A lot of atomic physics to create opacity tables.

Mitalas & Sills (Ap. J. 401 (1992) 759)



For the neutrinos : 2 seconds
to cross the Sun !!!



Direct witnesses of what happens in the core of the Sun

… and 8 minutes to reach the
Earth (quasi at the light speed)!

Solar neutrinos :

messengers from the core of the Sun and talented wizards

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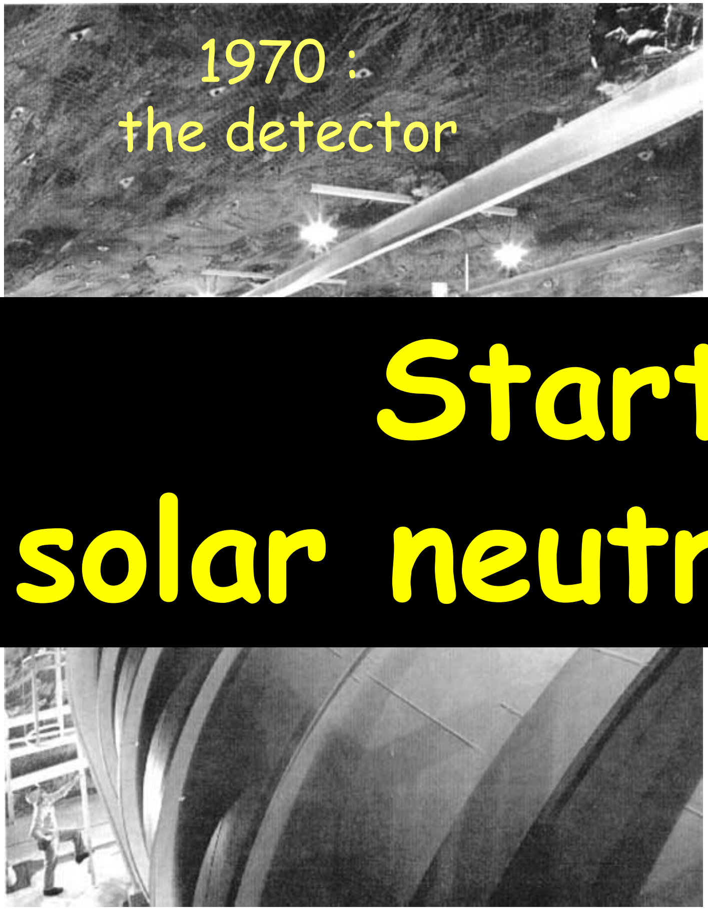
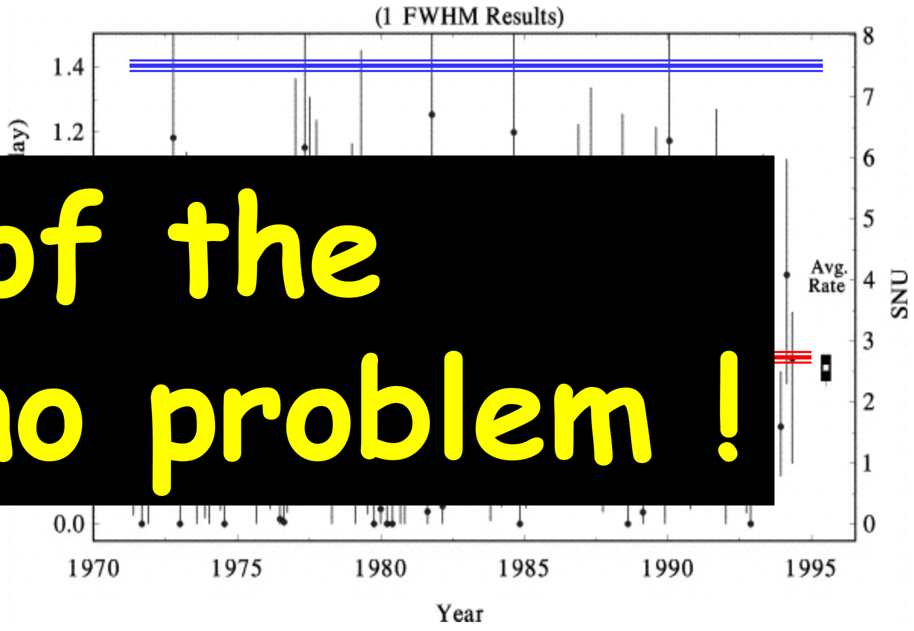
The « pioneering » chlorine experiment



- Radiochemical
- Sensitive to ^{7}Be and ^{8}B



**Start of the
solar neutrino problem !**

Result :
2.56 ± 0.20 SNU

1/3 of solar models
(6.9-7.5 SNU)

Homestake mine (South Dakota)

600 tons of C_2Cl_4

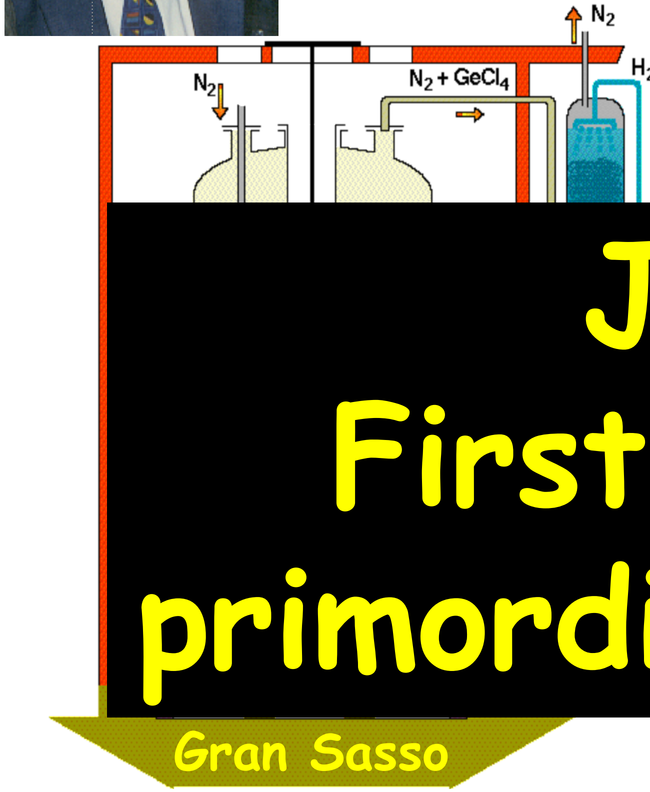
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

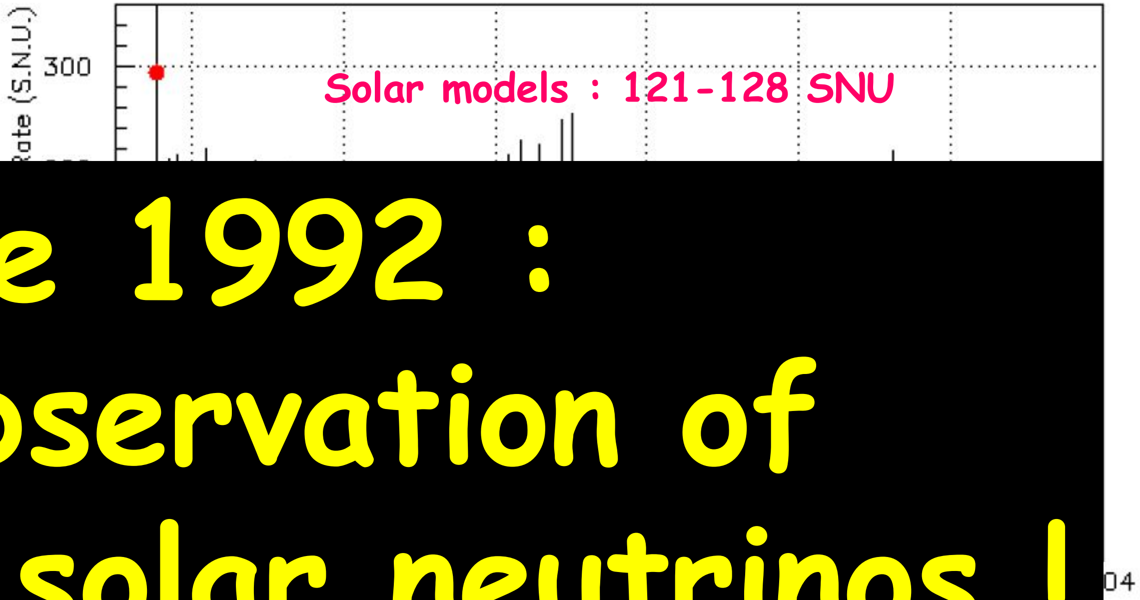
$$\hookrightarrow {}^{37}Cl \quad (T_{1/2}=35\ d)$$

B.T.Cleveland et al., Ap. J. 496 (1998) 505

GALLEX / GNO :

radiochemical detection of primordial solar ν





June 1992 :
First observation of primordial solar neutrinos !

30.3 tons of gallium
in aqueous solution ($GaCl_3$ + HCl)

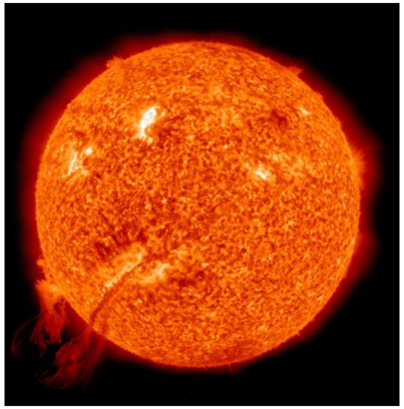
$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

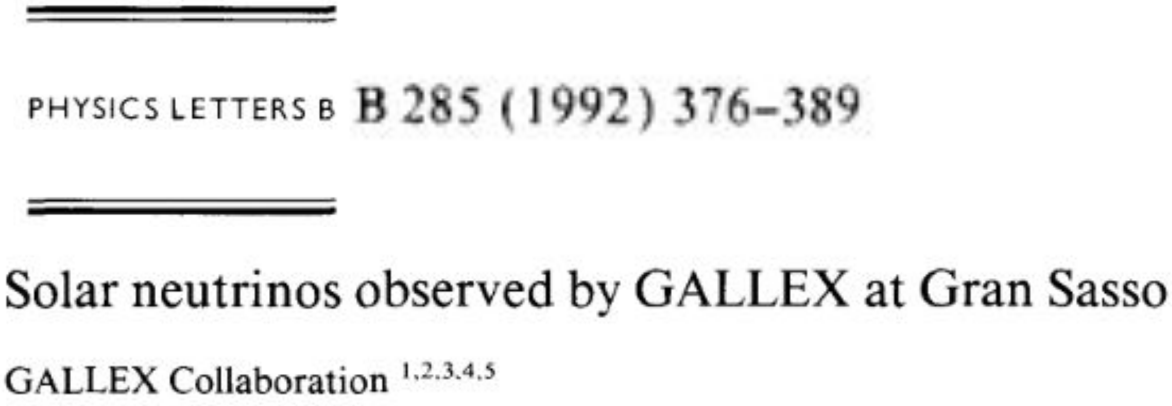
threshold = 233 keV
sensitive to all ν
(including pp)

GALLEX : 77.5 ± 7.8 SNU (73.4 ± 7.2 SNU)
GNO : 62.9 ± 6.0 SNU
GALLEX/GNO : 69.3 ± 5.5 SNU (67.6 ± 5.1 SNU)

~60% of solar models

W.Hampel et al., Phys. Lett. B447 (1999) 127
M.Altmann et al., Phys. Lett. B616 (2005) 174
F.Kaether et al., Phys. Lett. B685 (2010) 47





PHYSICS LETTERS B B 285 (1992) 376–389

Solar neutrinos observed by GALLEX at Gran Sasso

GALLEX Collaboration [1,2,3,4,5]

Gallium Experiment at Gran Sasso

GALLEX

> The GALLEX experiment can truly claim to have observed, for the first time, the primary pp neutrinos.

Libération

MERCREDI 10 JUIN 1992

LES PARTICULES VENUES DU SOLEIL SE LAISSENT UN PEU PLUS ATTRAPER, MAIS PAS ASSEZ

Les neutrinos, lutins du cosmos

On n'en trouvait qu'un tiers de ce qui était prévu par les modèles théoriques. Maintenant, on en piège les deux tiers. Les neutrinos, témoins privilégiés de l'activité solaire, conservent leur mystère.

LE FIGARO VENDREDI 5 JUIN 1992

SCIENCES Une découverte au laboratoire de Gran Sasso, en Italie

Des neutrinos qui éclairent l'enfer du Soleil

Un détecteur installé sous 1 000 m de rocher a pour la première fois piégé de ces particules dites « primordiales », de faible énergie, émises au cœur de notre étoile lors de réactions thermonucléaires. L'inventaire de ces fantômes et de leurs avatars reste encore à faire.

DER SPIEGEL

218 DER SPIEGEL 26/1992

Neutrinos

Flitzer zu Gott

Auf einer Forschertagung in Granada gab es Streit um die Frage: Haben Neutrinos, die flüchtigsten unter den Atomteilchen, eine Masse oder nicht?

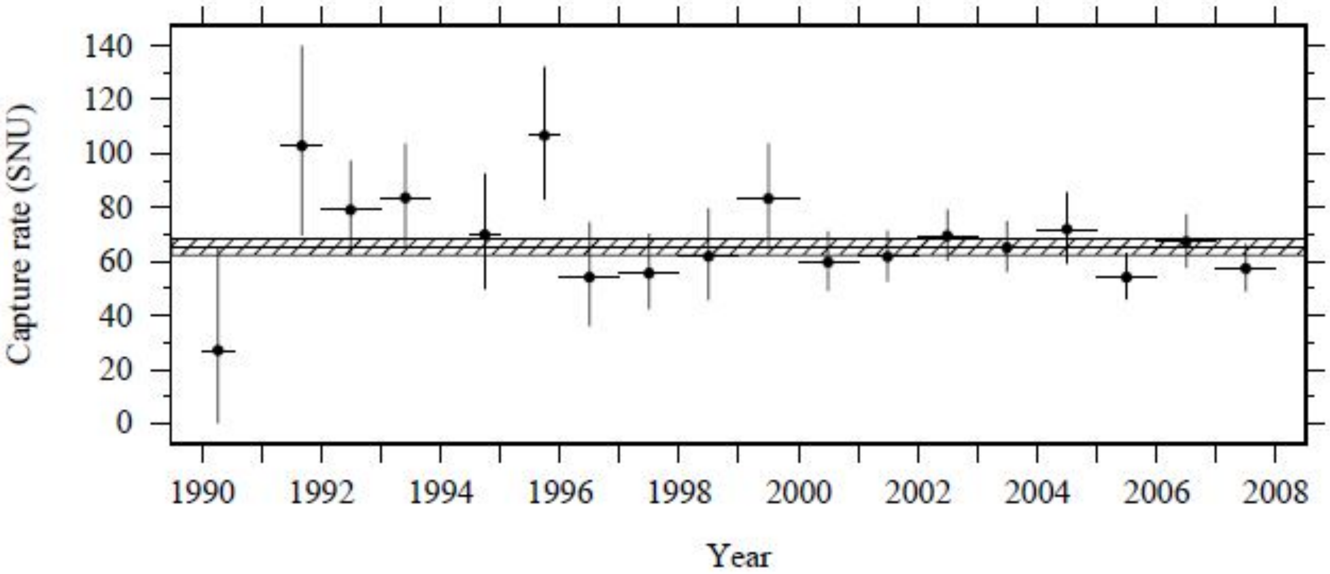
Le Monde Mercredi 10 juin 1992

Casse-tête solaire

On croyait connaître le Soleil. Mais des particules manquent à l'appel qui pourraient bouleverser la théorie

SAGE :

radiochemical detection of primordial solar ν



SAGE : 65.4 ± 3.1 ± 2.7 SNU

Similar result

J.N. Abdurashitov et al., arXiv:0901.2200

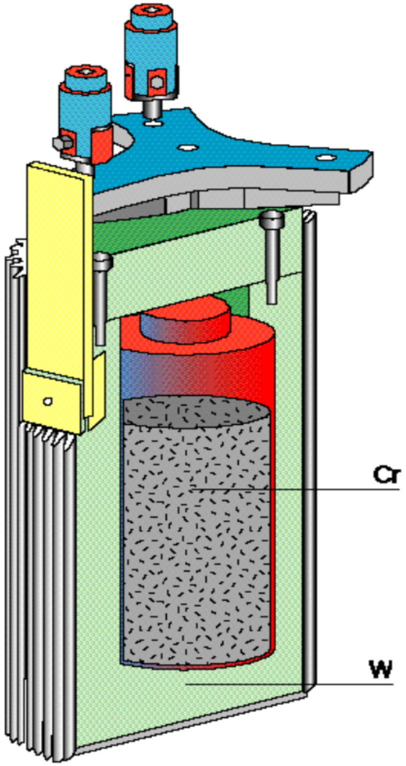
Baksan (Russia)
50 tons of liquid metallic gallium

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

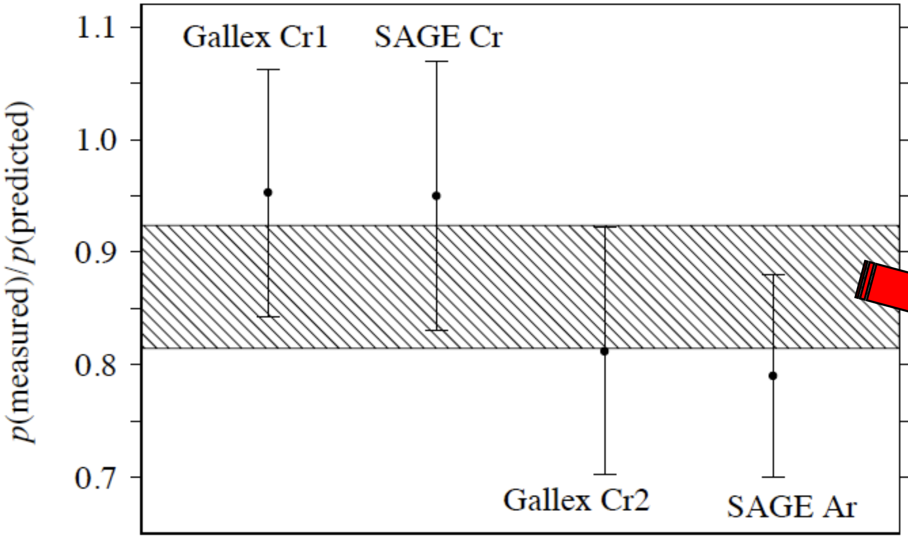
threshold = 233 keV
sensitive to all ν
(including pp)

~60% of solar models

Validation with a ^{51}Cr neutrino source



- 40 kg of Cr enriched in ^{50}Cr
- 2 sources prepared at Grenoble (Siloé reactor)
  $n + {}^{50}\mathrm{Cr} \rightarrow {}^{51}\mathrm{Cr} + \gamma$
  followed by $^{51}\mathrm{Cr} + e^- \rightarrow {}^{51}\mathrm{V} + \nu_e$ (751 keV)
- Source activity : ~65 PBq



R = 0.93 ± 0.08

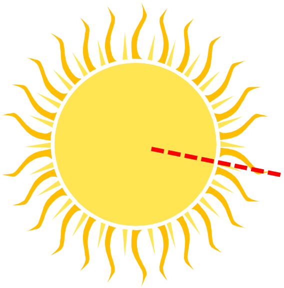
R = 0.88 ± 0.08

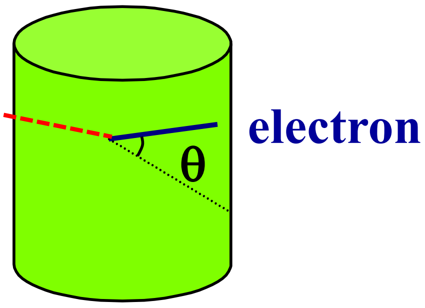
Experimental proof of the radiochemical method

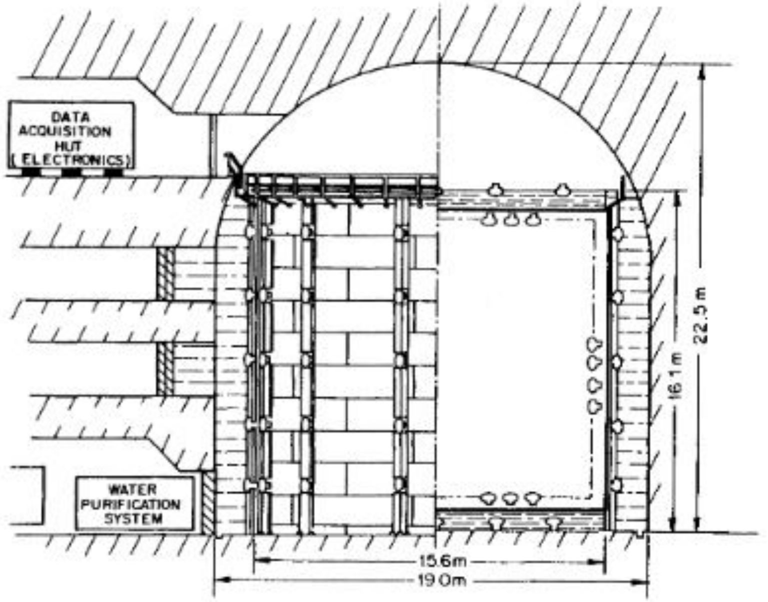
☹ **Is the cross section on Ga overestimated ? Sterile ν's ???**

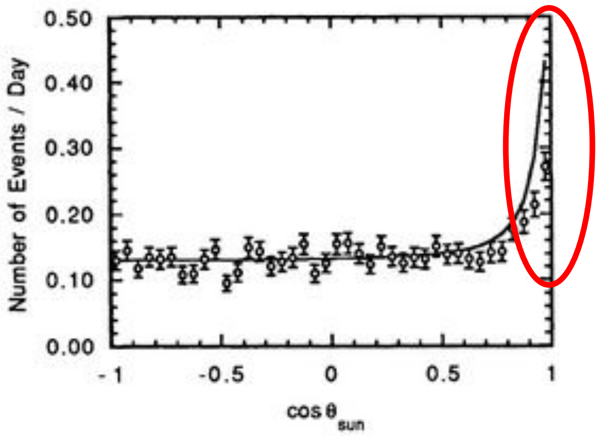
W.Hampel et al., Phys. Lett. B420 (1998) 114
F.Kaether et al., Phys. Lett. B685 (2010) 47

Kamiokande
1987-1990









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

sensitive to ^8B ν

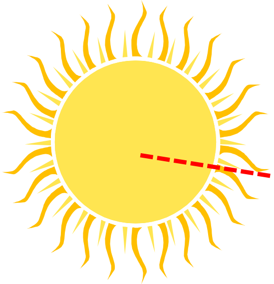
Kamiokande
E > 7.5 MeV

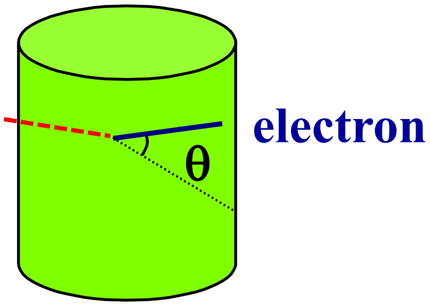
Flux measured for ^8B ν / Flux SSM:
(0.46 ± 0.05 (stat.) ± 0.06 (syst.))

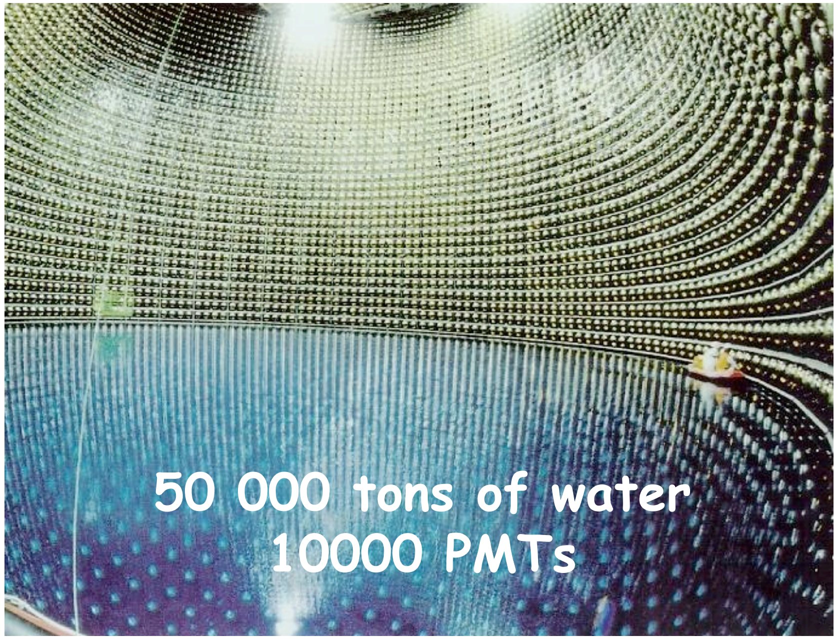
~45% of solar models
$(5 \pm 1)\ 10^6\ cm^{-2}\ s^{-1}$

K.S.Hirata et al. : Phys. Rev. D44 (1991) 2241

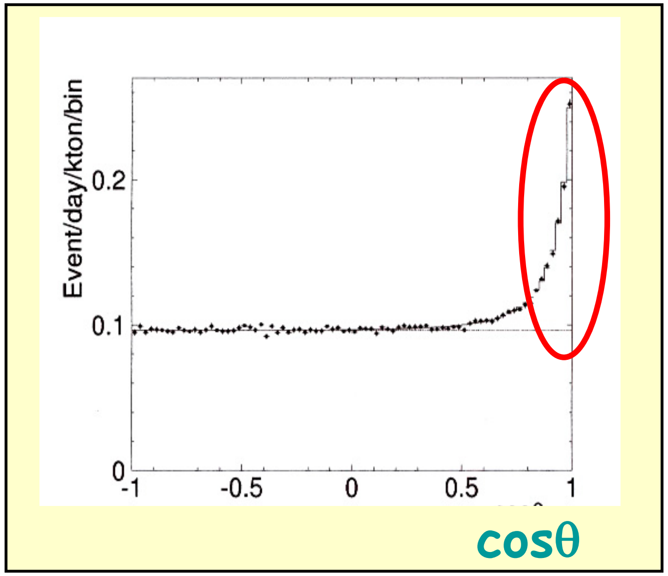
SuperKamiokande
(from 1996)







50 000 tons of water
10000 PMTs



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

sensitive to ^8B ν

SuperKamiokande I
(1996-2001)
E > 5 MeV

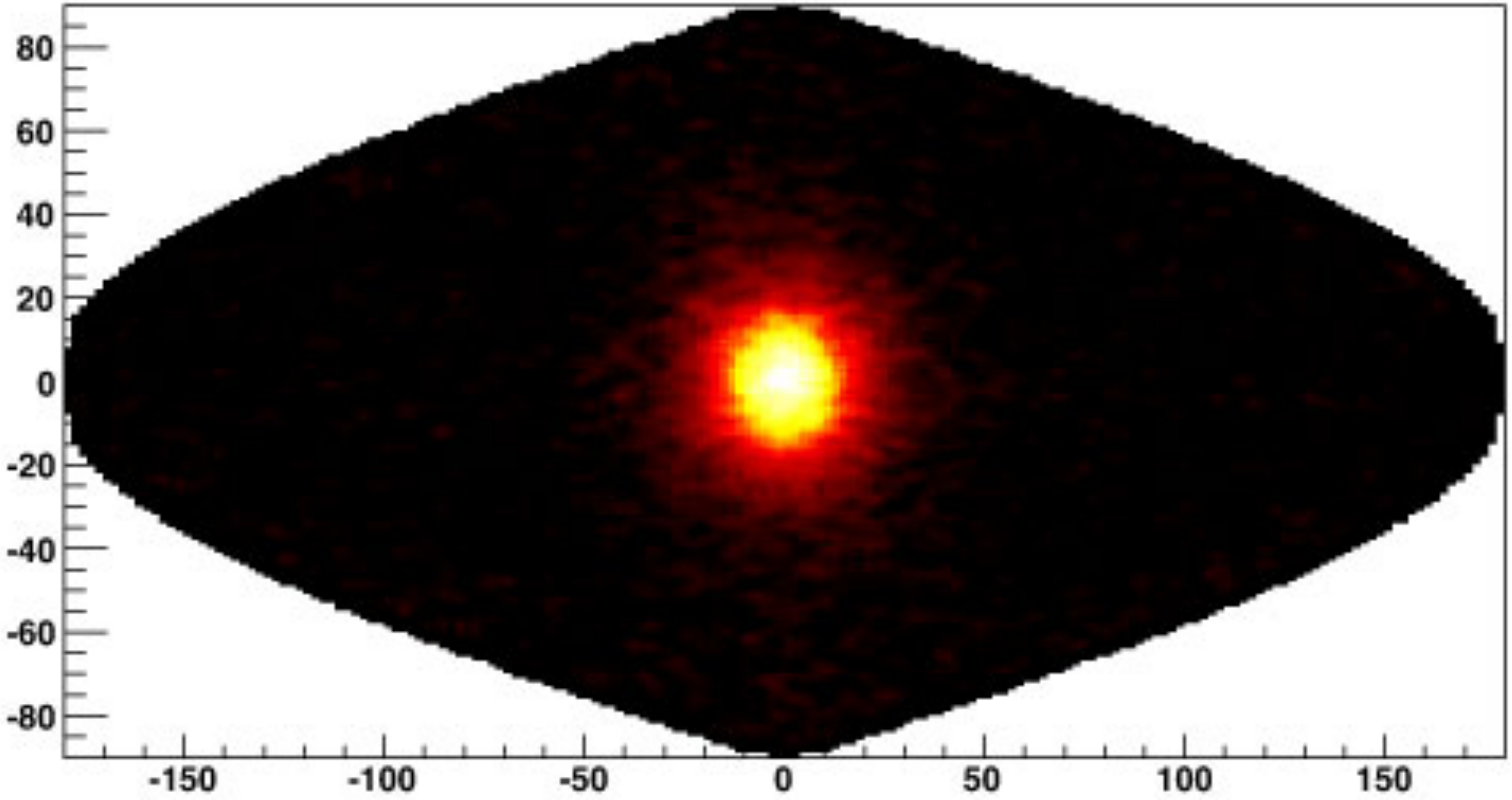
Flux measured for ^8B ν :
(2.35 ± 0.02 (stat.) ± 0.08 (syst.)) 10^6 cm^{-2} s^{-1}

45% of solar models
(5 ±1) 10^6 cm^{-2} s^{-1}

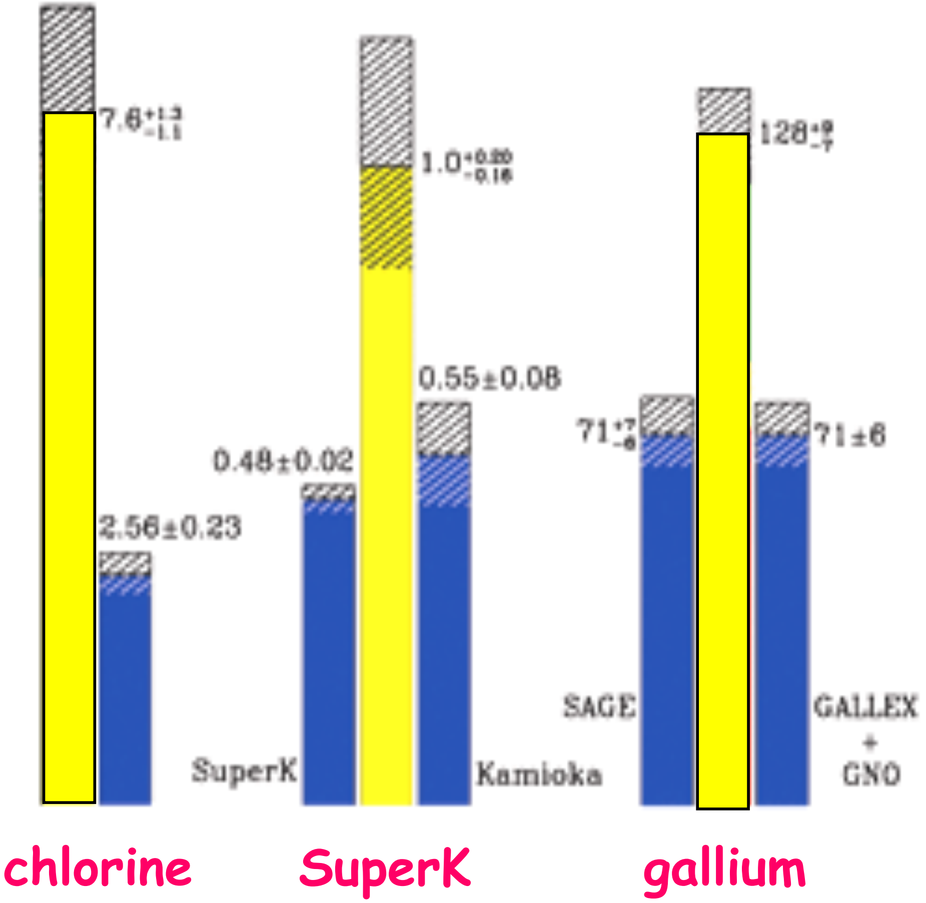
J. Hosaka et al. : hep-ex/0508053

SuperKamiokande

The Sun seen with neutrinos !



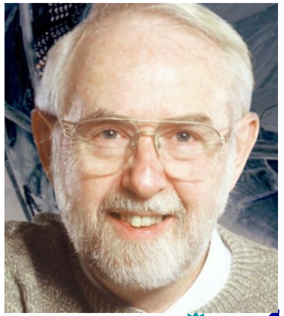
Solar neutrinos:
results 🟦 and predictions 🟨



Spring 2001

Solar neutrino problem
(since 1970) !

1. The solar models are wrong ?
2. The experiments are wrong ?
3. Solar neutrinos « oscillate » ?



Sudbury Neutrino Observatory (SNO)

- 1000 tons D_2O (target)
- 7000 tons H_20 (shield)
- 9600 8" PM for Cerenkov light
- Canada-USA-GB Collaboration

- Start data taking : nov. 1999

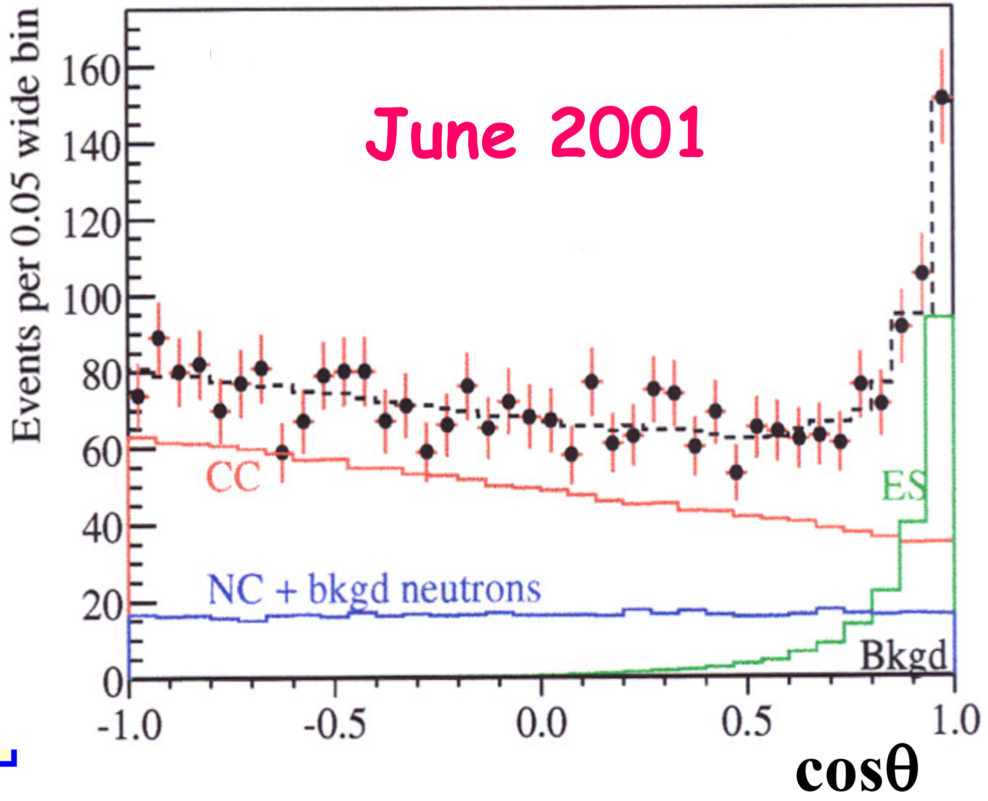
$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(CC)}$$

$$\nu_x + d \rightarrow p + n + \nu_x \qquad \text{(NC)}$$

n detection
$$\begin{cases} n + d \rightarrow t + \gamma \\ n + Cl \rightarrow Cl + \gamma \\ n + {}^3He \rightarrow t + p \end{cases}$$

$$\nu_e + e^- \rightarrow \nu_e + e^- \qquad \text{(elastic sc.)}$$

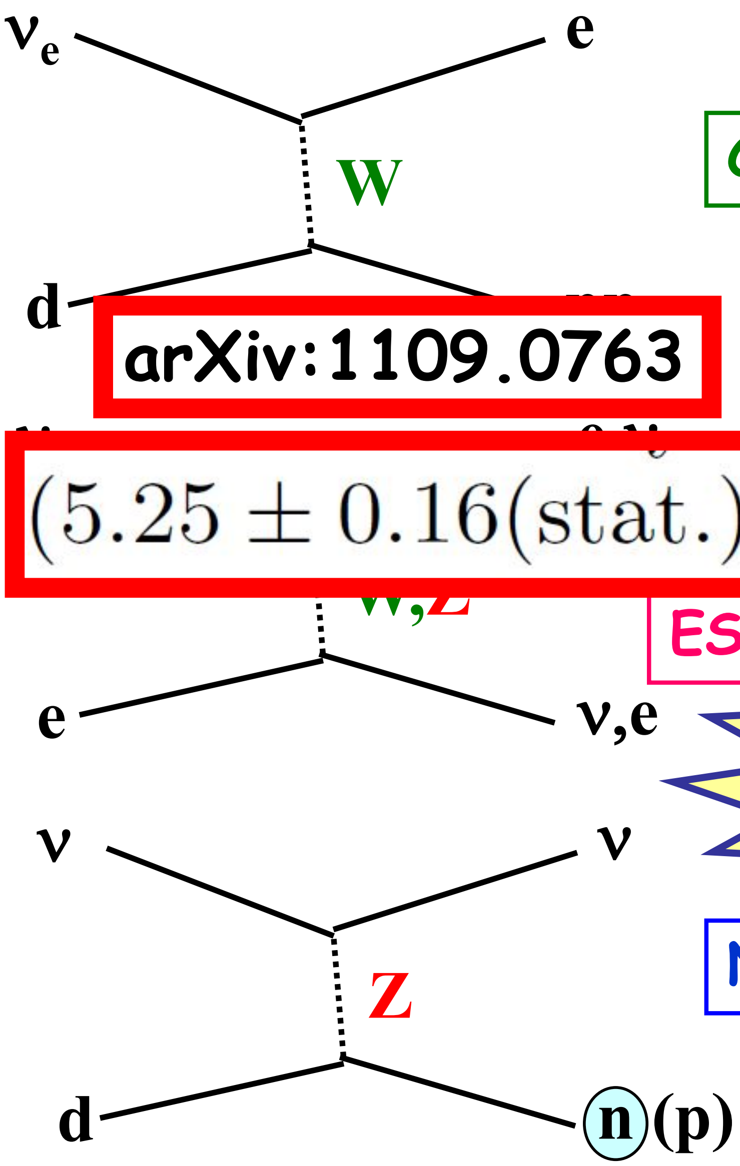
E > 4-5 MeV
sensitive to ^8B ν



June 2001

Summary of SNO results

(2006) [units : 10^6 cm^{-2} s^{-1}]



arXiv:1109.0763

$$(5.25 \pm 0.16(\text{stat.})^{+0.11}_{-0.13}(\text{syst.})) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

CC : 1.76 ± 0.11

CC : 1.68 ± 0.10

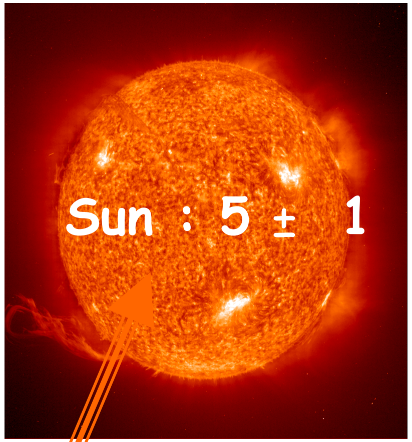
ES : 2.35 ± 0.27

ES(SK) : 2.32 0.08

Salt phase

NC : 5.09 ± 0.63

NC : 4.94 ± 0.43

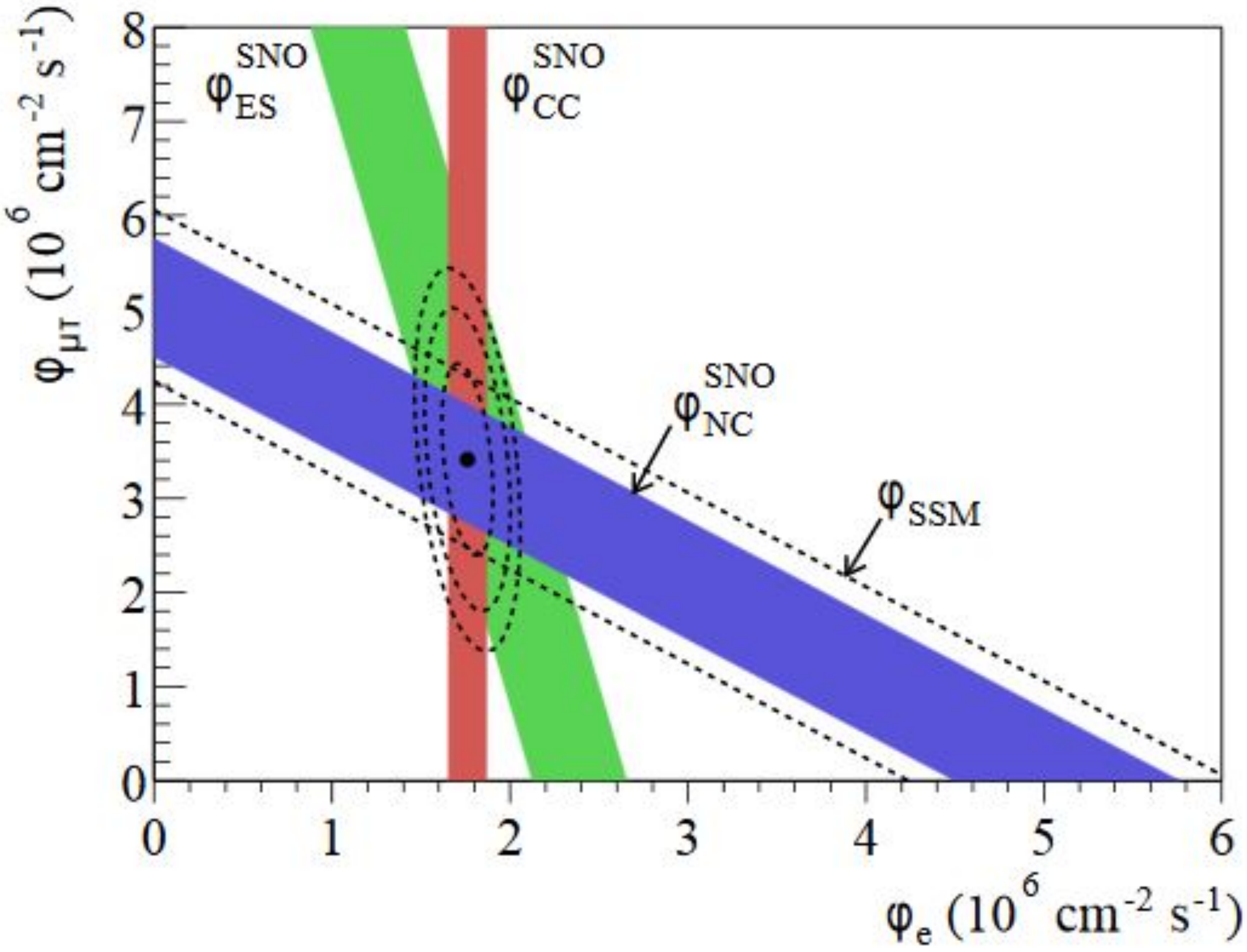


Total flux =
ES = CC = NC

Oscillation
Total flux =
CC + (ES-CC)*6
= NC

Summary of SNO results

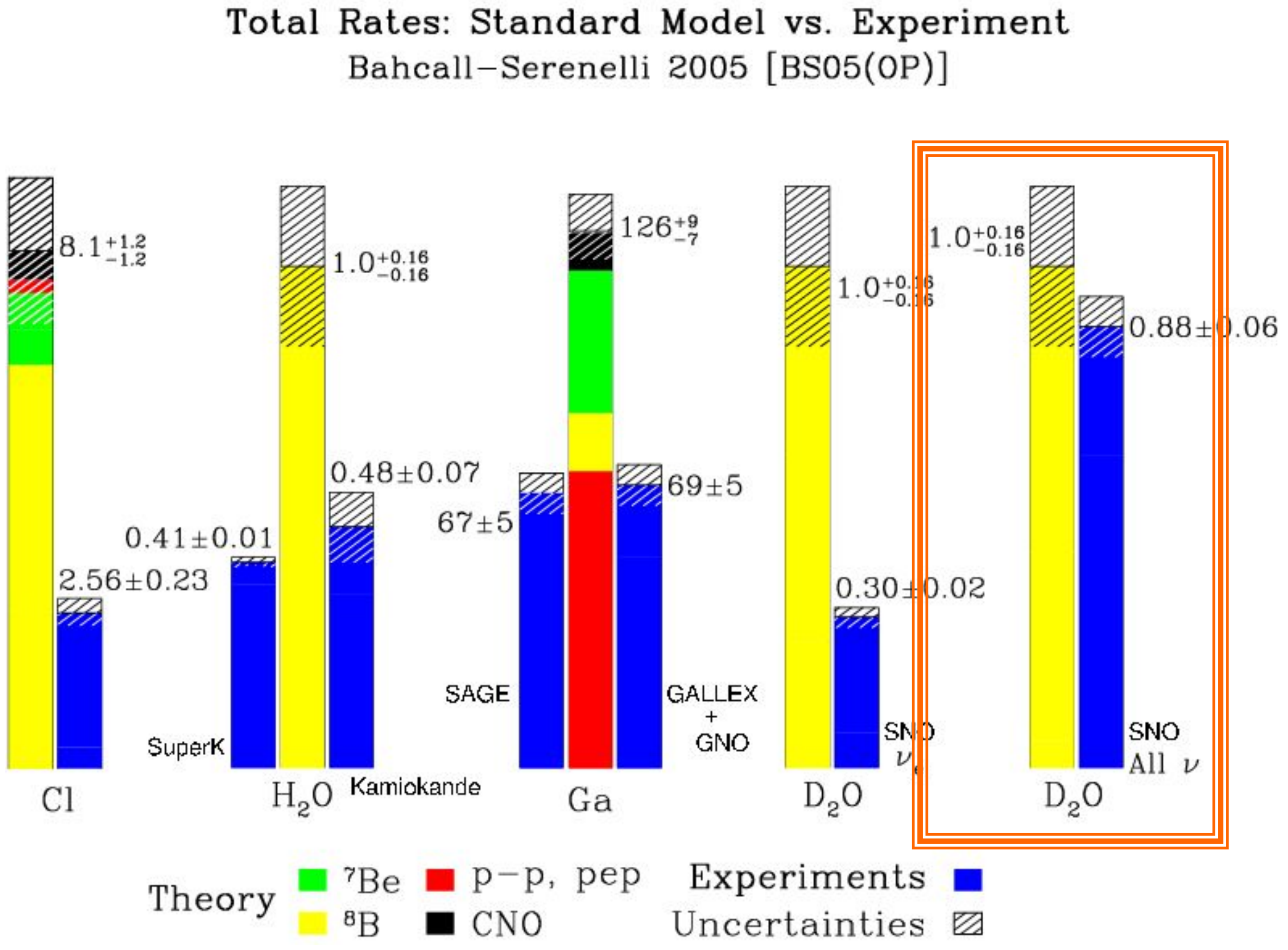
(2006) [units : 10^6 cm^{-2} s^{-1}]



No oscillation :
Total flux =
ES = CC = NC

Oscillation
Total flux =
CC + (ES-CC)*6
= NC

Experimental results after SNO

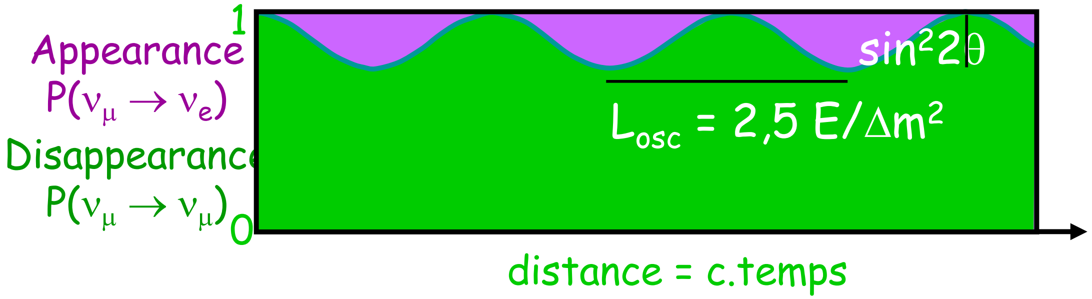


How to interpret all this ?

❶ Nuclear reactions in the Sun produce only ν_e

❷ Solar neutrino detectors were (until SNO) sensitive only (or mainly) to ν_e

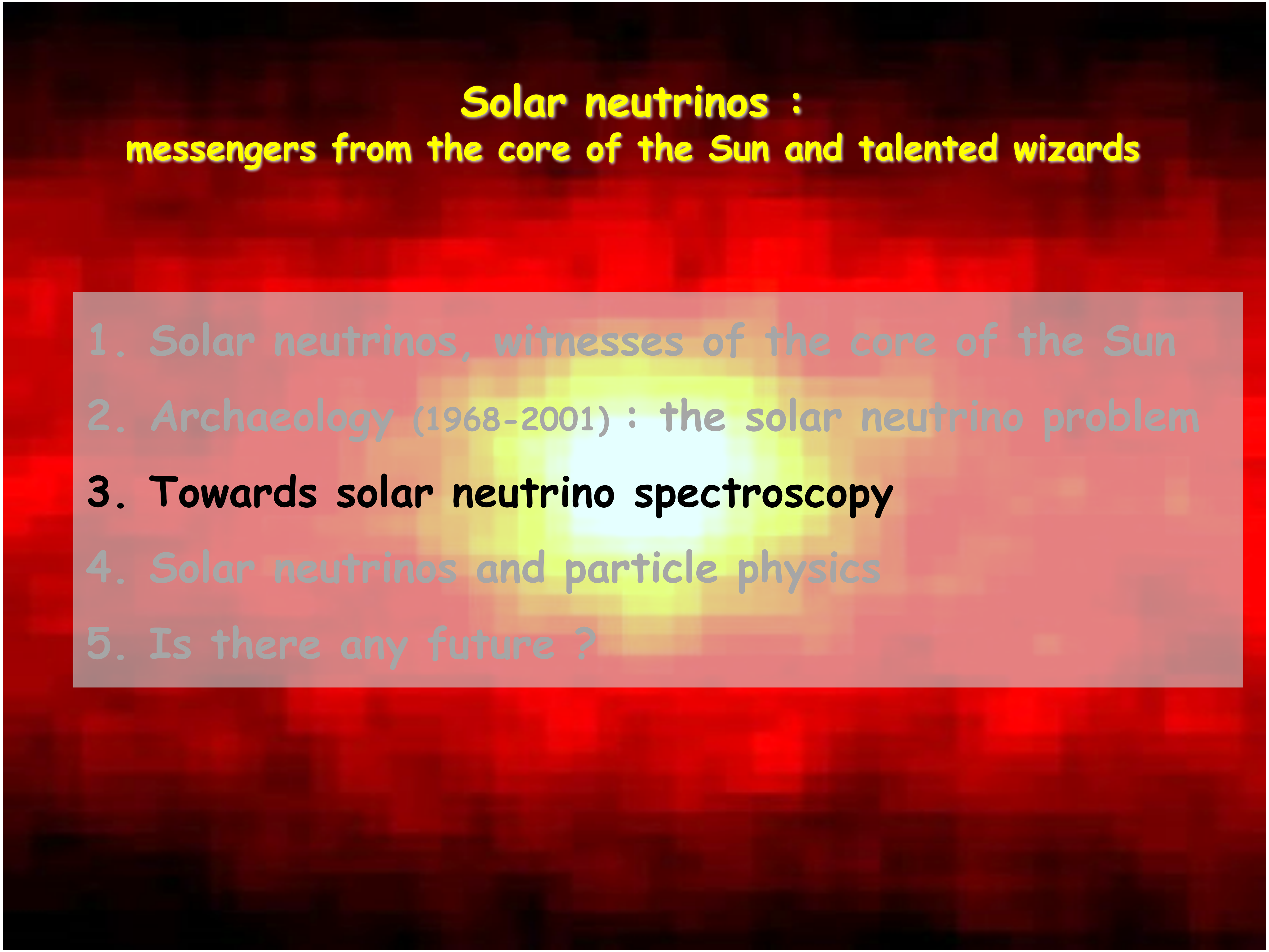
SNO has shown that ν_e have been (partially) transformed into ν_μ or ν_τ and the « oscillation mechanism » explains the deficit observed.



☸ To obtain the oscillation parameters (θ et Δm^2), the ν_e flux reductions observed in the experiments and energy spectra are fitted simultaneously.

☺ The problem is solved

… and the SSM is (at first order) right !



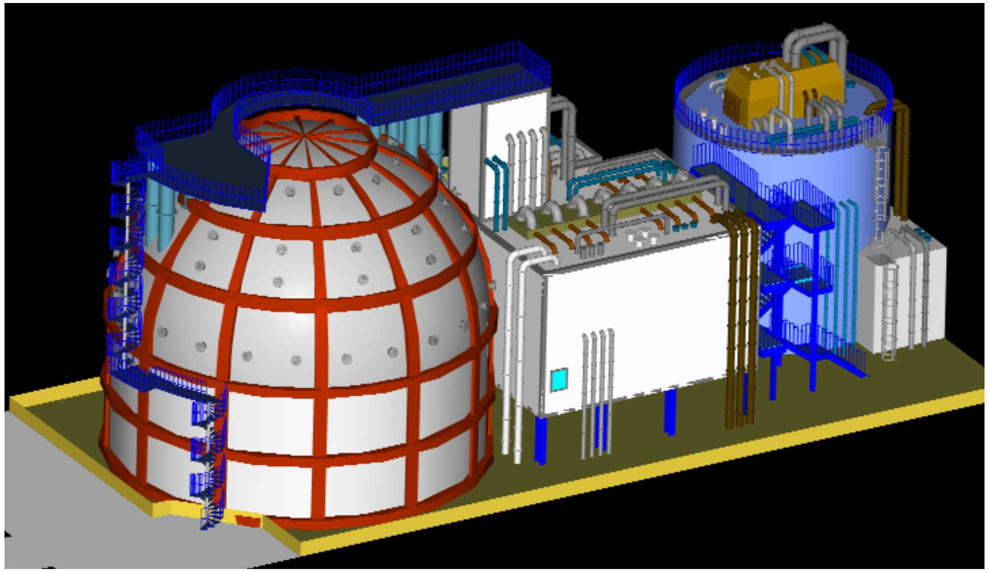
Solar neutrinos :

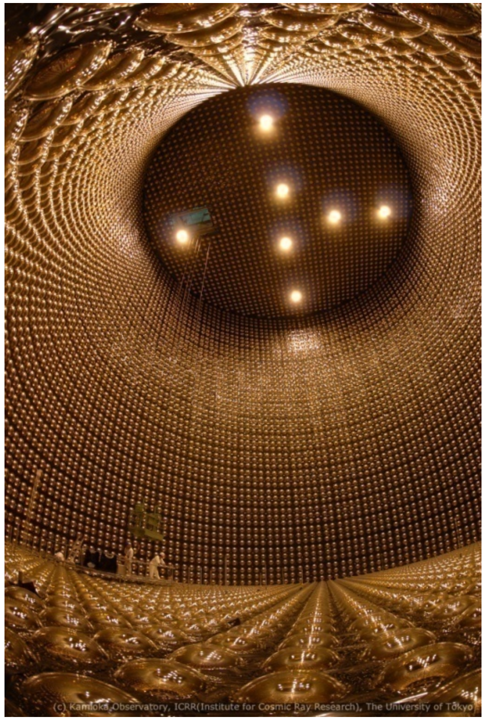
messengers from the core of the Sun and talented wizards

1. Solar neutrinos, witnesses of the core of the Sun
2. Archaeology (1968-2001) : the solar neutrino problem
3. **Towards solar neutrino spectroscopy**
4. Solar neutrinos and particle physics
5. Is there any future ?

Towards solar neutrino spectroscopy

1. Borexino :
pp, ^{7}Be, pep, CNO, ^{8}B

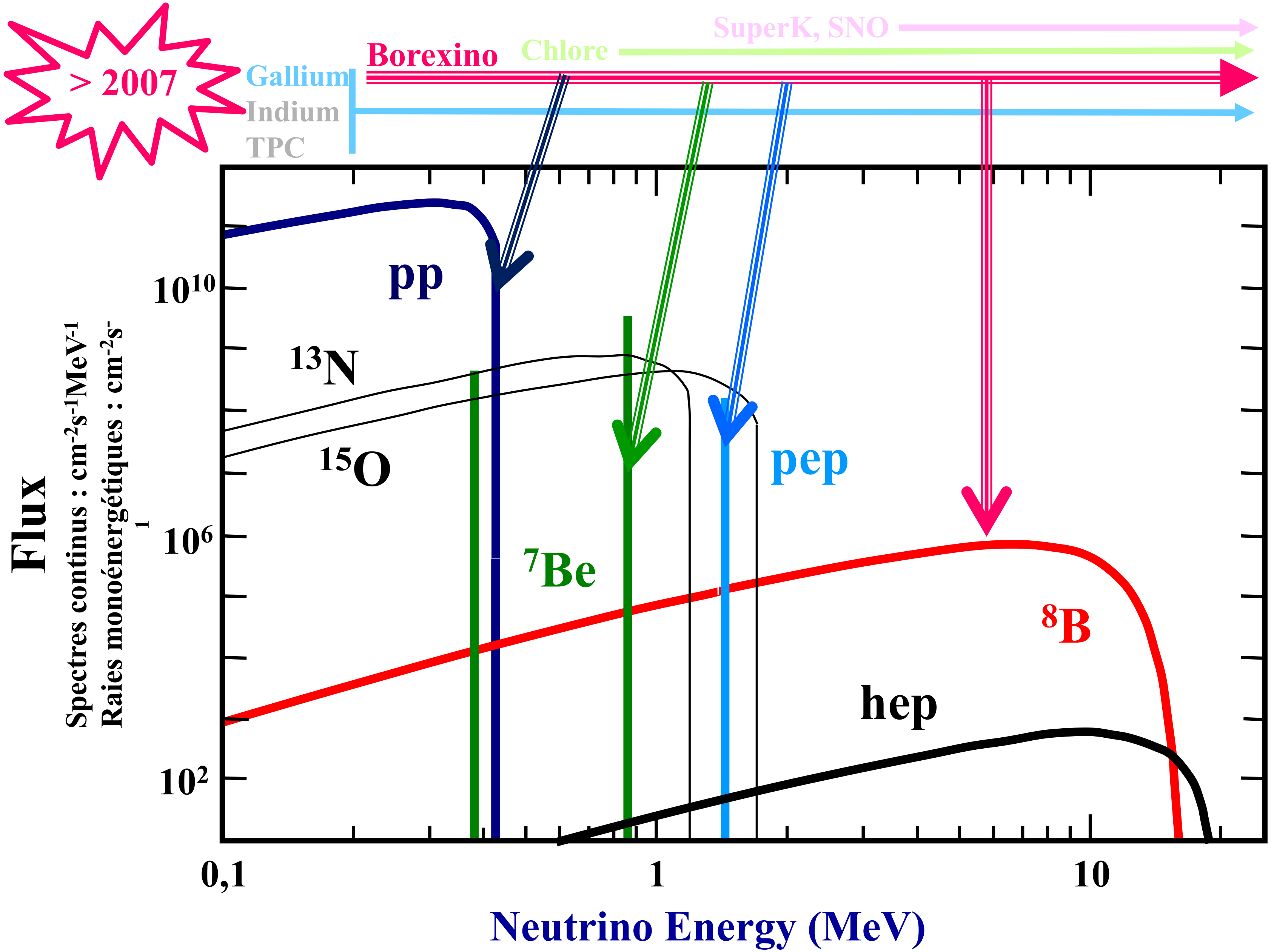




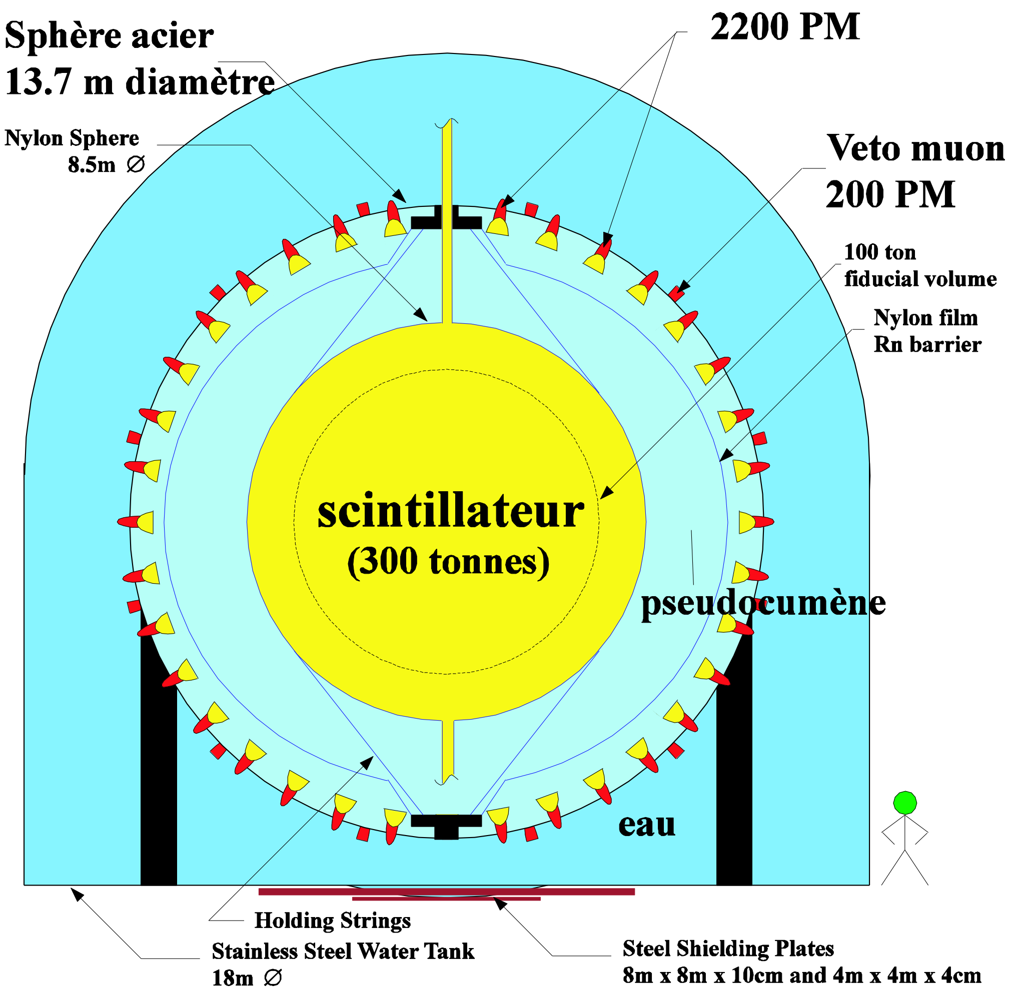
2. SuperK, new results on ^{8}B

3. SNO : results on hep

Energy spectrum of solar neutrinos



Borexino (2007-…)



Elastic diffusion

$$\nu\, e \rightarrow \nu\, \textcircled{e}$$

Target n° 1 : ^{7}Be neutrinos

Proposal :
60 events / day (no oscillation)
10-40 (oscillation)

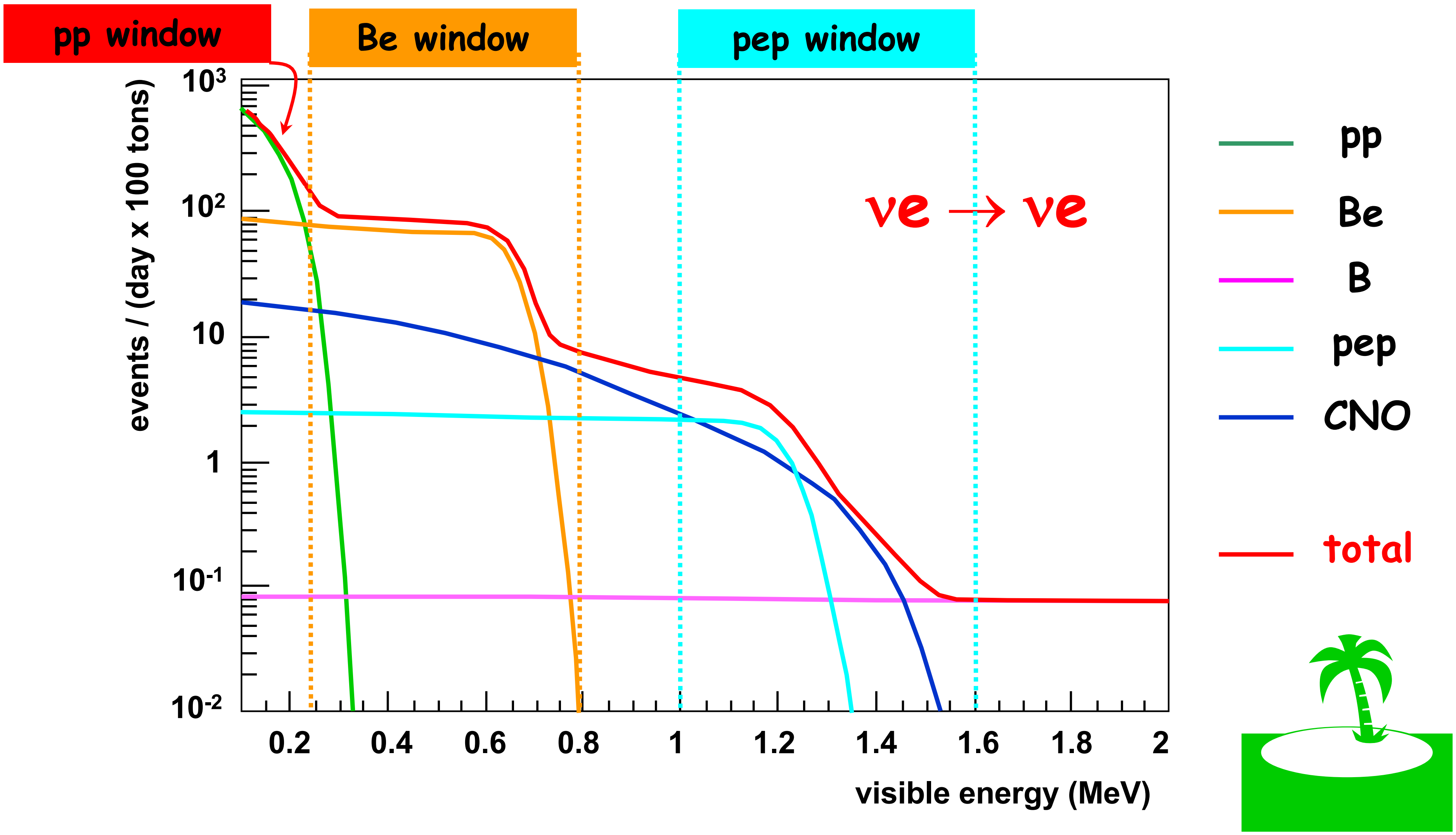
Gran Sasso (Italy)

3800 m.w.e.

Scintillator

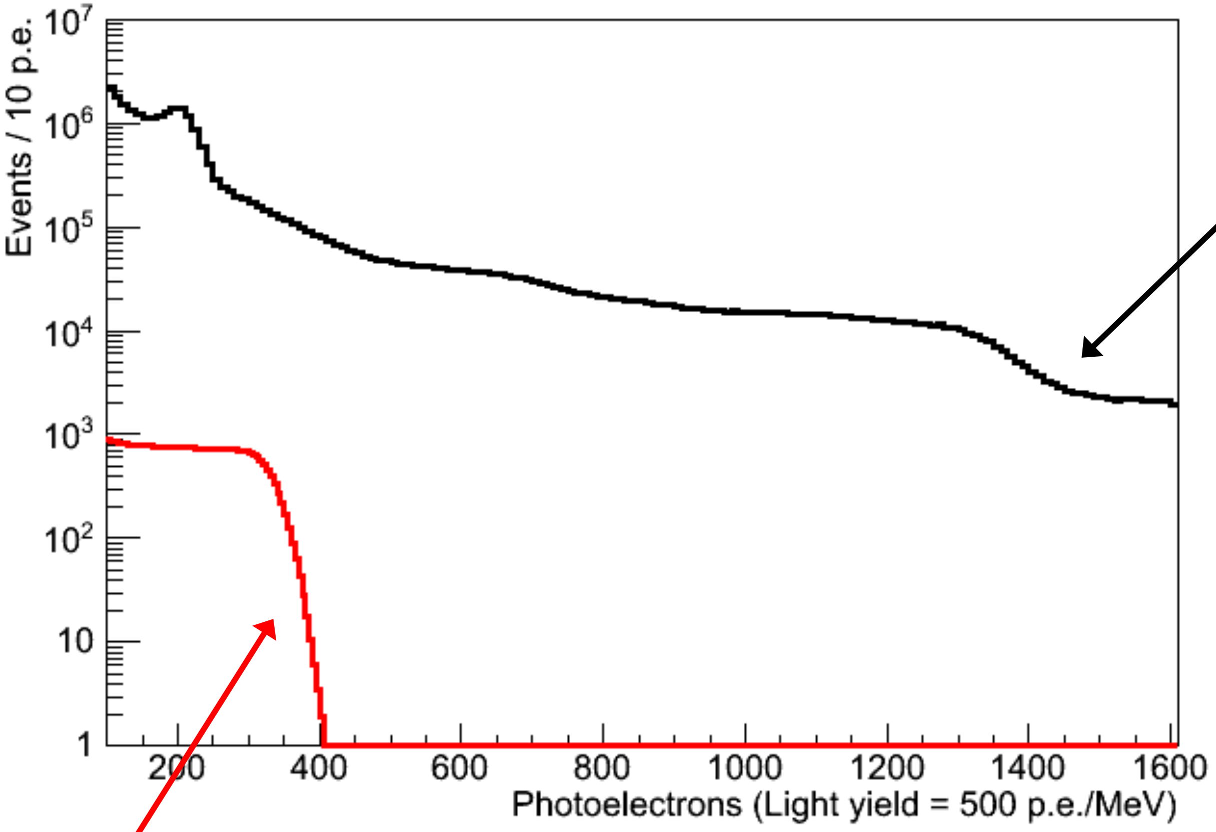
- ☺ 50 times more light than Cherenkov
- ☹ No directionality
- ★ No discrimination e^- Sun and e^- radioactivity

Expected signal in Borexino (SSM+ oscillation [LMA])



Towards ^{7}Be solar ν

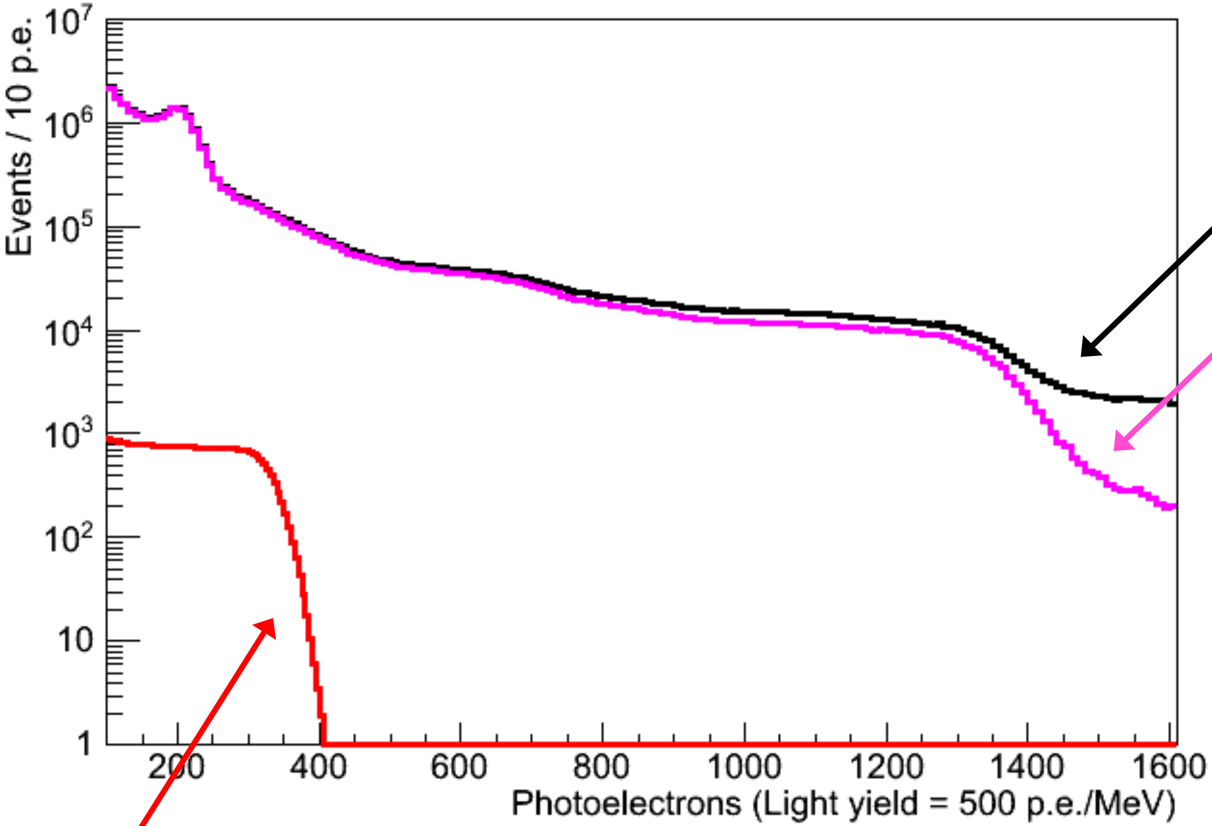
Historically, Borexino designed to measure ^{7}Be ν's



All data: 740 live days

Expected ^{7}Be signal

Towards ^{7}Be solar ν

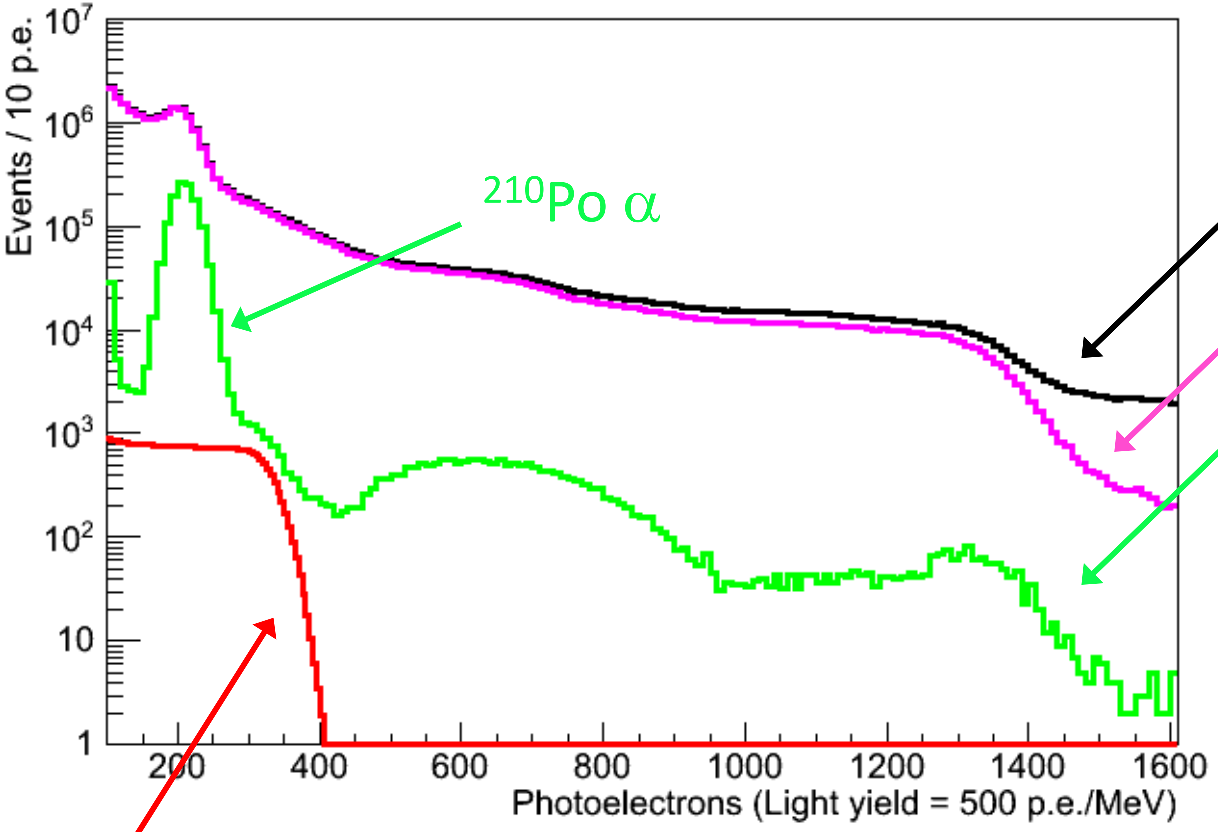


All data: 740 live days

Remove μ + μ followers (2 ms)

Expected ^{7}Be signal

Towards ^{7}Be solar ν



^{210}Po α

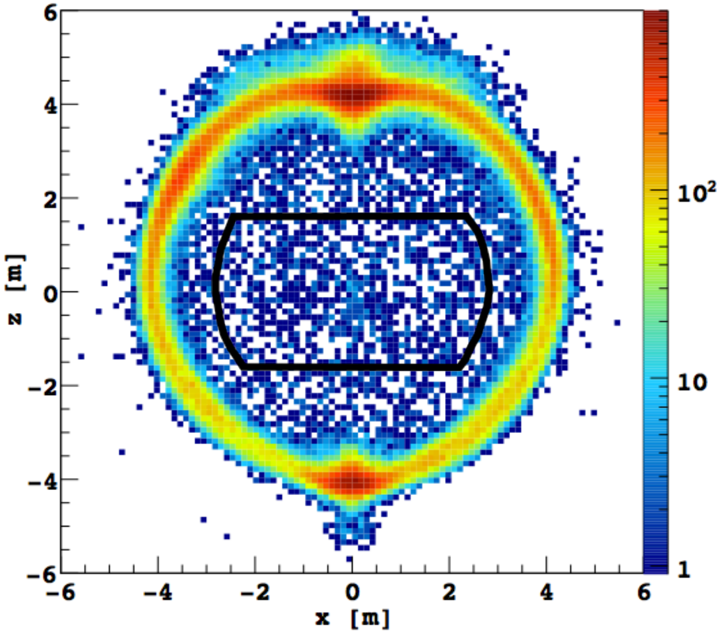
All data: 740 live days

Remove μ + μ followers (2 ms)

Fiducial Volume

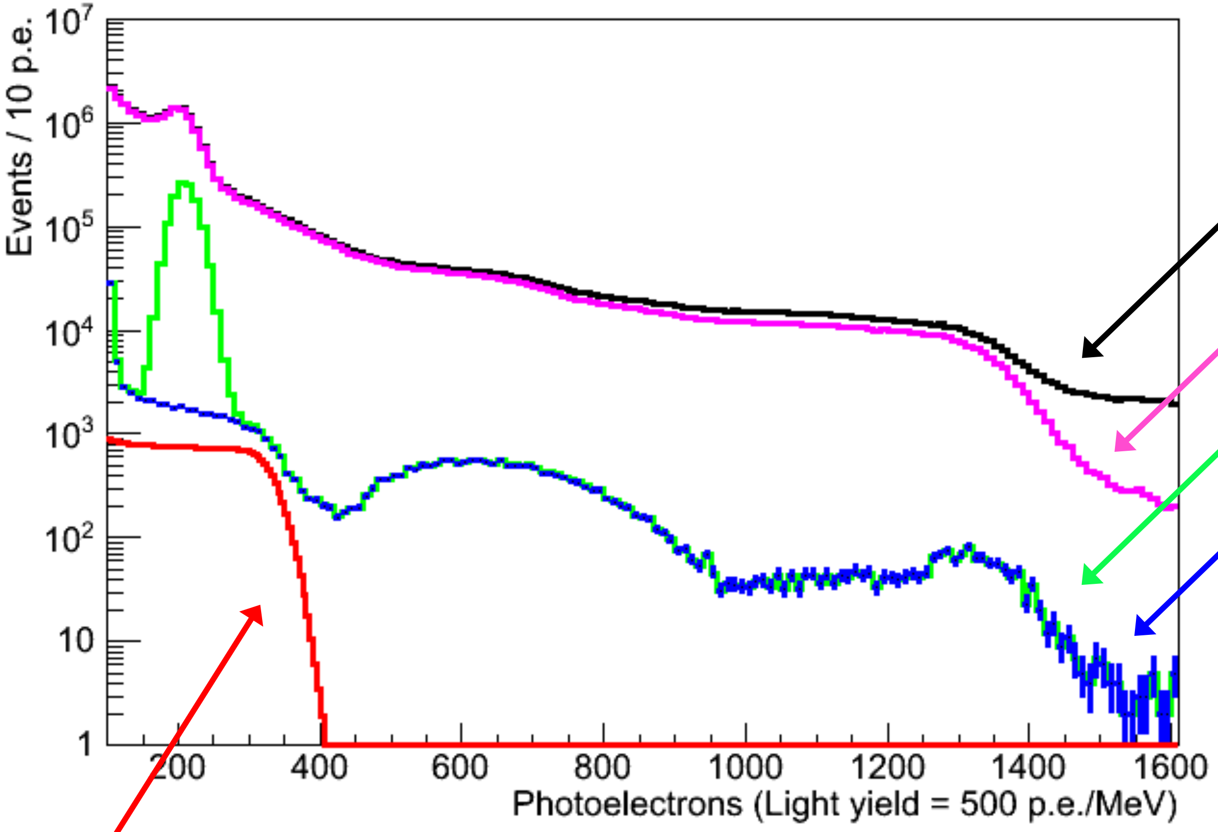
Expected ^{7}Be signal

R < 3.02m
|z| < 1.67m



Fiducial mass = 75.6 tonnes

Towards ^{7}Be solar ν



All data: 740 live days

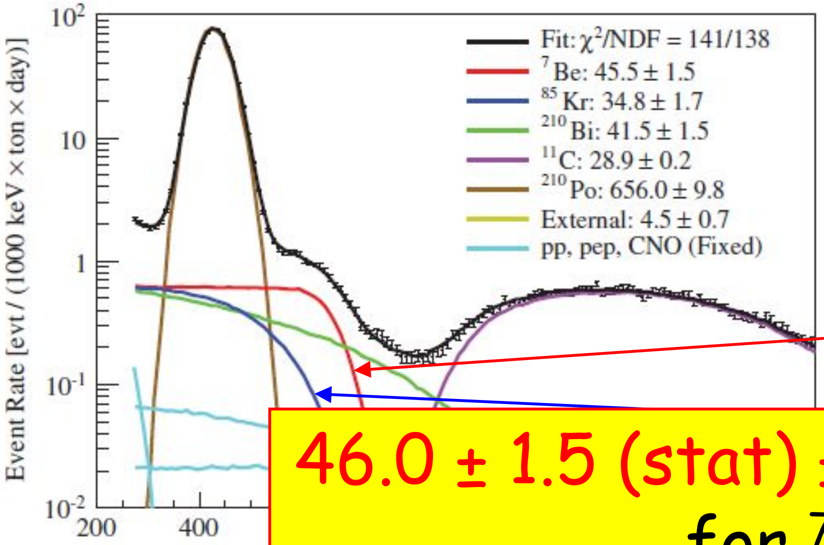
Remove μ + μ followers (2 ms)

Fiducial Volume

Statistically subtract α's [α/β discrimination by pulse shape analysis using the Gatti parameter]

Expected ^{7}Be signal

Towards ^{7}Be solar ν



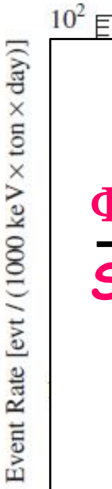
Events / day / 100 tons :

^{7}Be: 46.0 ± 1.5 ± 1.5

± 4.7

± 2.3

46.0 ± 1.5 (stat) ± 1.5 (syst) ev./day /100 tons
for ^{7}Be (862 keV) $\nu_\odot$



$$\frac{\Phi(^7\text{Be-862 keV}) = (2.78 \pm 0.13)\ 10^9\ \text{cm}^{-2}\ \text{s}^{-1}}{\text{SSM-High Met} = (4.48 \pm 0.31)\ 10^9\ \text{cm}^{-2}\ \text{s}^{-1}}$$

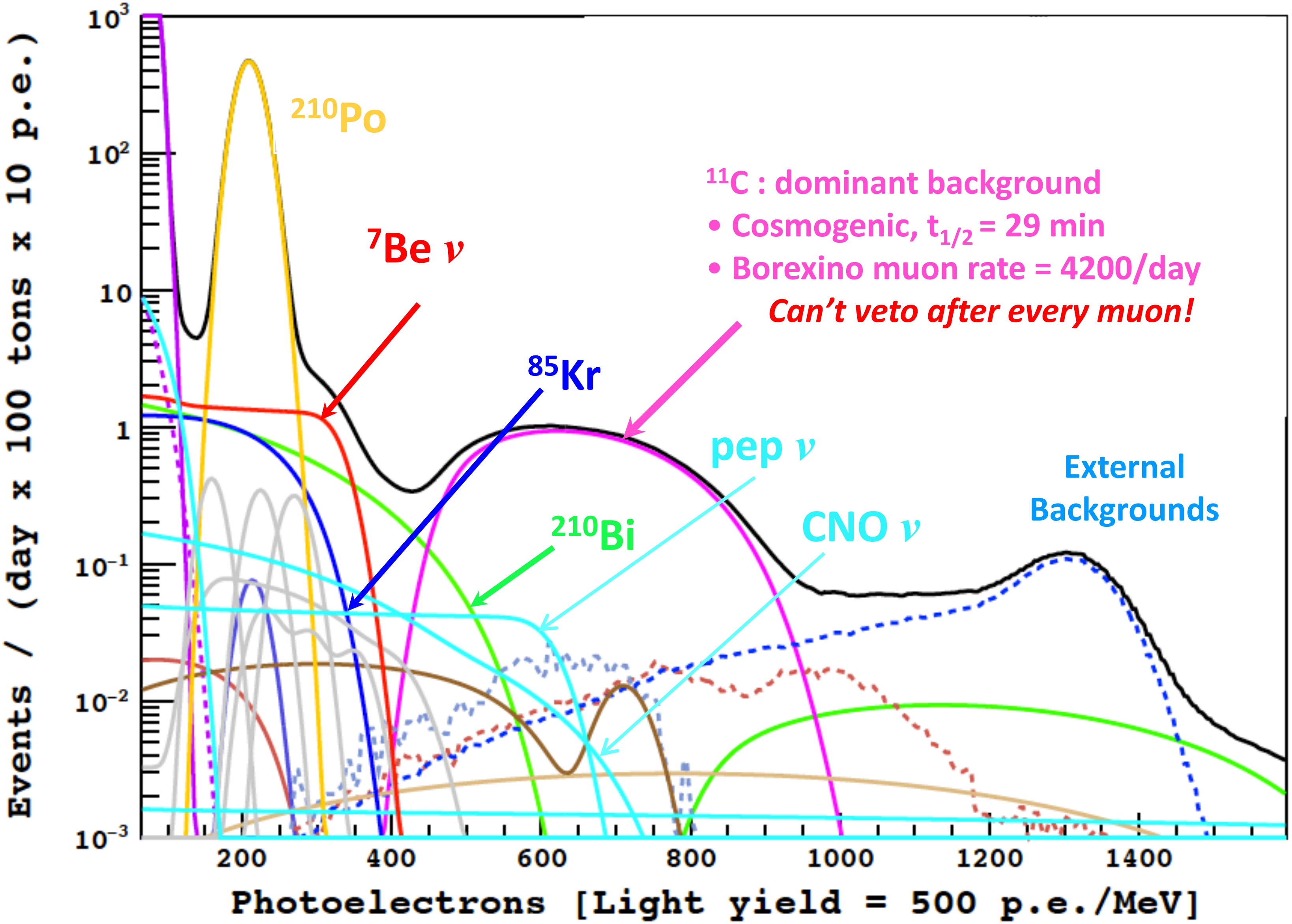
Ratio = 0.62 ± 0.05

P_{ee} = 0.51 ± 0.07

$[\sigma(\nu_e)=4.5\ \sigma(\nu_\mu,\nu_\tau)]$

arXiv:1104.1816
Phys. Rev. Lett. 107, 141302 (2011)

Towards pep and CNO ν

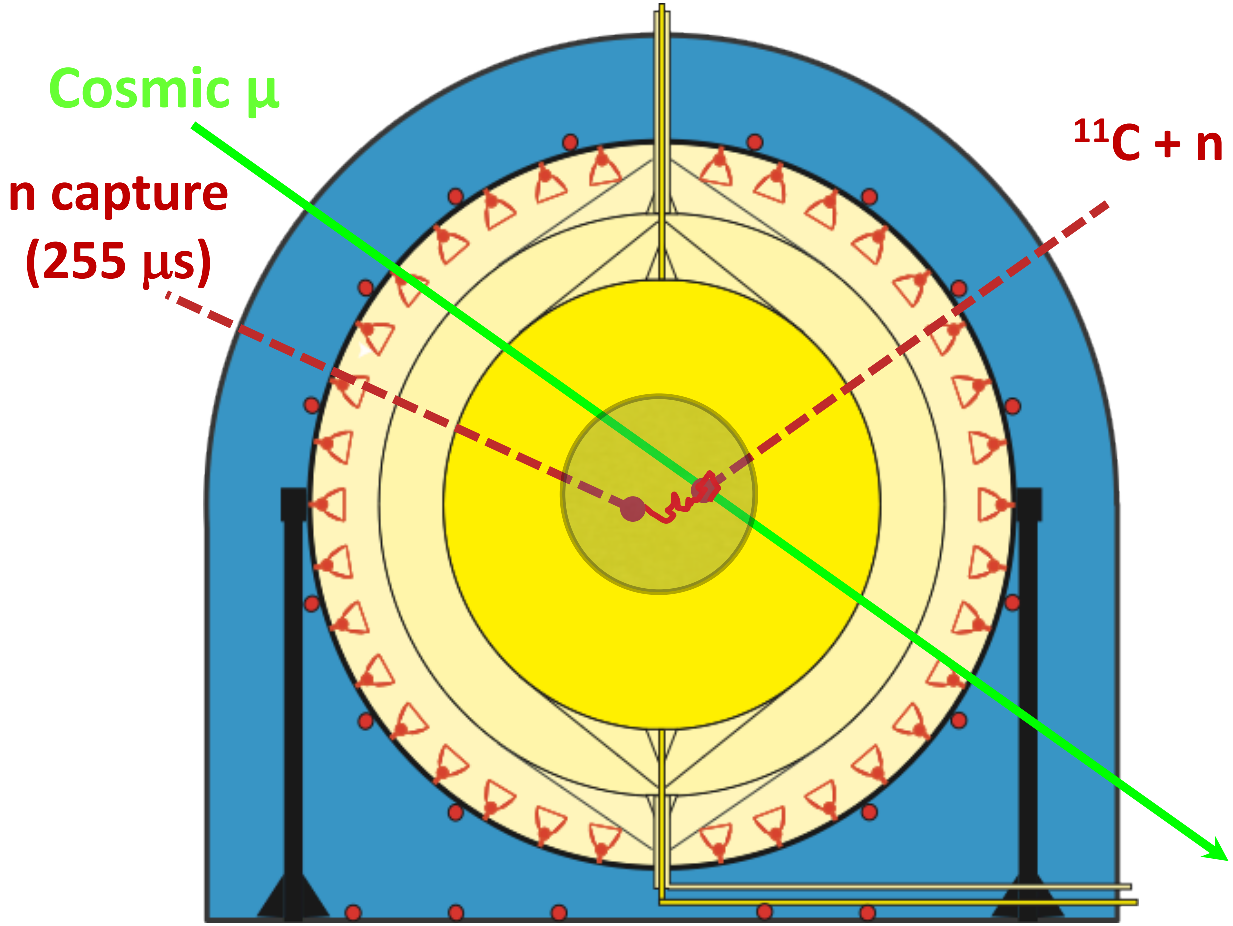


^{11}C : dominant background

- Cosmogenic, $t_{1/2}$ = 29 min
- Borexino muon rate = 4200/day

Can't veto after every muon!

Towards pep and CNO ν



- Most ^{11}C ($t_{1/2}$=29 min) produced via

  $\mu + {}^{12}C \rightarrow {}^{11}C + n$

  ${}^{11}C \rightarrow {}^{11}Be + e^+ + \nu_e$

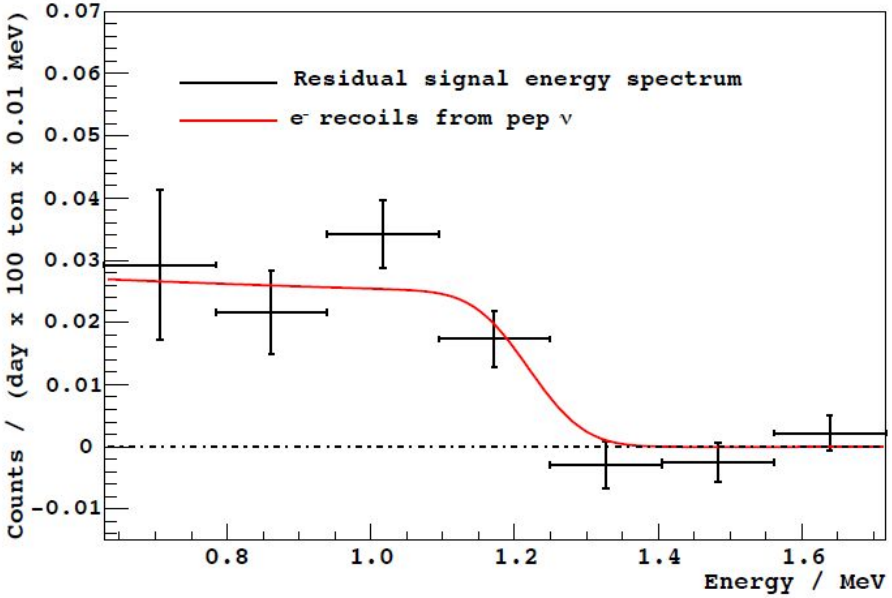
- Delayed neutron capture (2.2 MeV γ signal) identifies when and where ^{11}C was produced

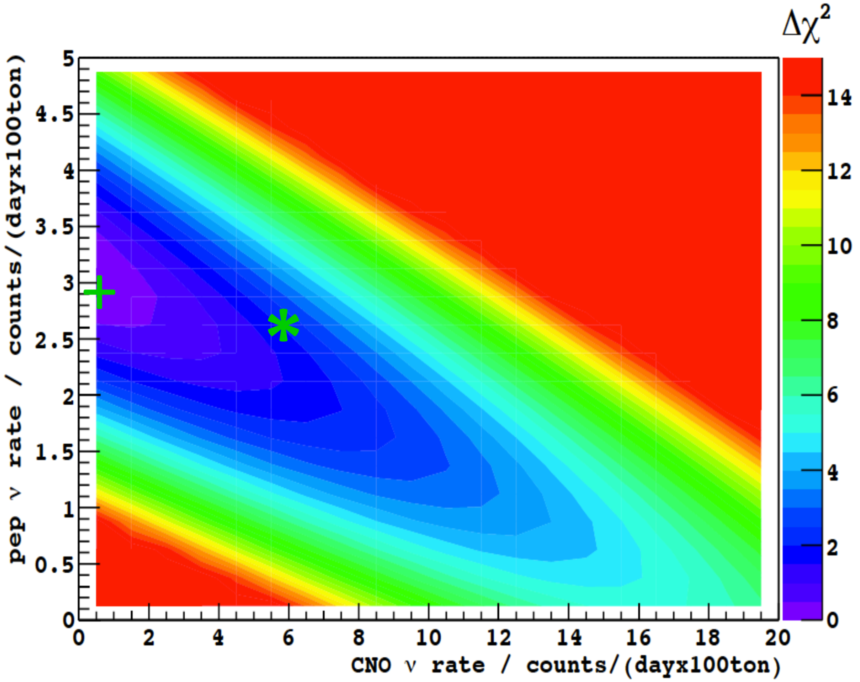
  ➔ geometrical cut

The 125 muon-neutron coincidences/day can be vetoed without excessive loss of live time.

Towards pep and CNO ν

Multidimensional fit with all the ingredients





pep flux

3.1 ± 0.6 ± 0.3 counts/(day.100 ton)

$\Phi(pep) = 1.6 \pm 0.3\ 10^8\ cm^{-2}s^{-1}$

$\Phi(SSM) = 1.45 \pm 0.1\ 10^8\ cm^{-2}s^{-1}$

CNO flux

< 7.9 counts/(day.100 ton)

$\Phi(CNO) < 7.7\ 10^8\ cm^{-2}s^{-1}$

$\Phi(SSM) = 5.2\ (3.7)\ 10^8\ cm^{-2}s^{-1}$

arXiv:1110.3230
Phys. Rev. Lett. 108 (2012) 051302

Why pp-neutrinos ?

J.N. Bahcall
(2001)

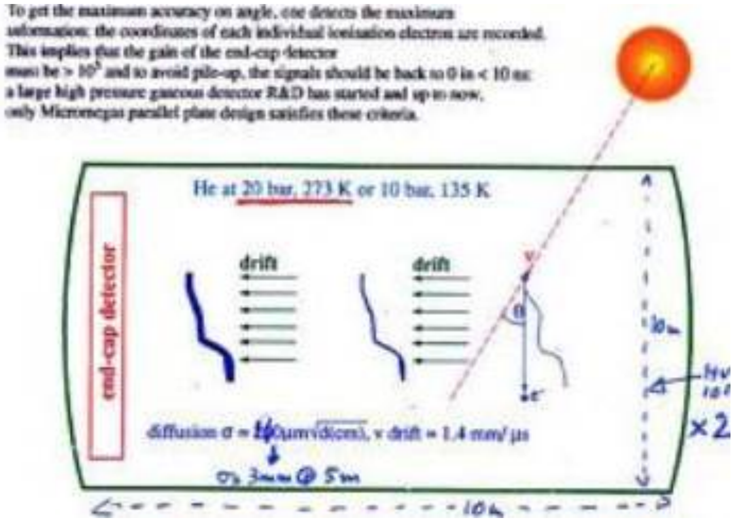
pp neutrinos are the gold ring of solar neutrino physics and astronomy. Their measurement will constitute a simultaneous and critical test of stellar evolution theory and of neutrino oscillation solutions.

…

pp neutrinos are a fundamental product of the solar energy generation process who flux is precisely predicted but not yet measured separately.

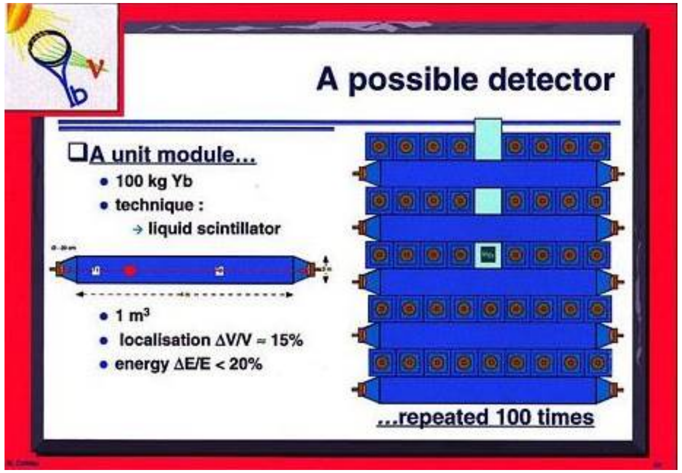
Some desperate attempts

HELLAZ (TPC hélium 20 bars)



To get the maximum accuracy on angle, one detects the maximum information: the coordinates of each individual ionisation electron are recorded. This implies that the gain of the end-cap detecter must be > 10^5 and to avoid pile-up, the signals should be back to 0 in < 10 ns: a large high pressure gaseous detector R&D has started and up to now, only Micromegas parallel plate design satisfies these criteria.

Indium (R&D + LENS)



A possible detector

☐ A unit module…

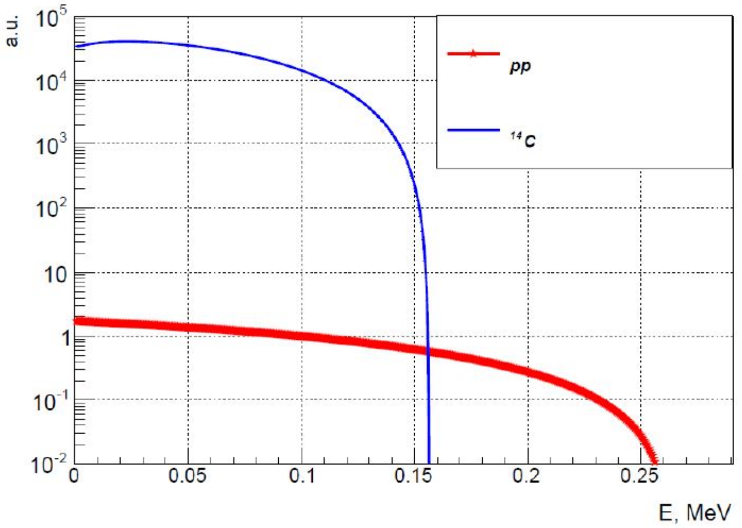
- 100 kg Yb
- technique :
  - → liquid scintillator
- 1 m^3
- localisation ΔV/V ≈ 15%
- energy ΔE/E < 20%

…repeated 100 times

Super Munu,…

Towards pp neutrinos

Zoom (theoretical) at low energy

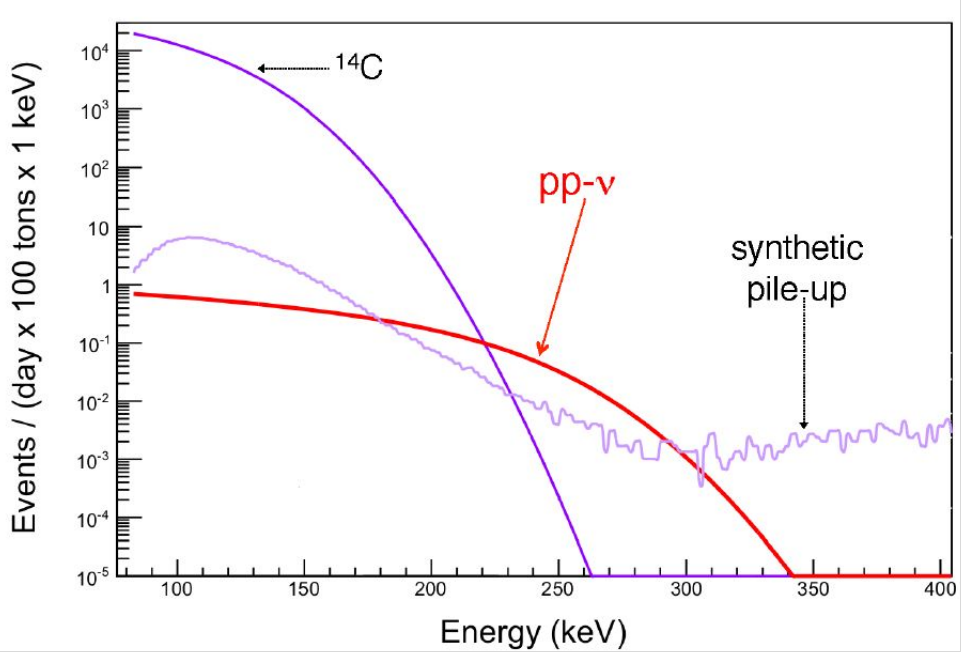


156 keV (^{14}C)

264 keV ν-pp

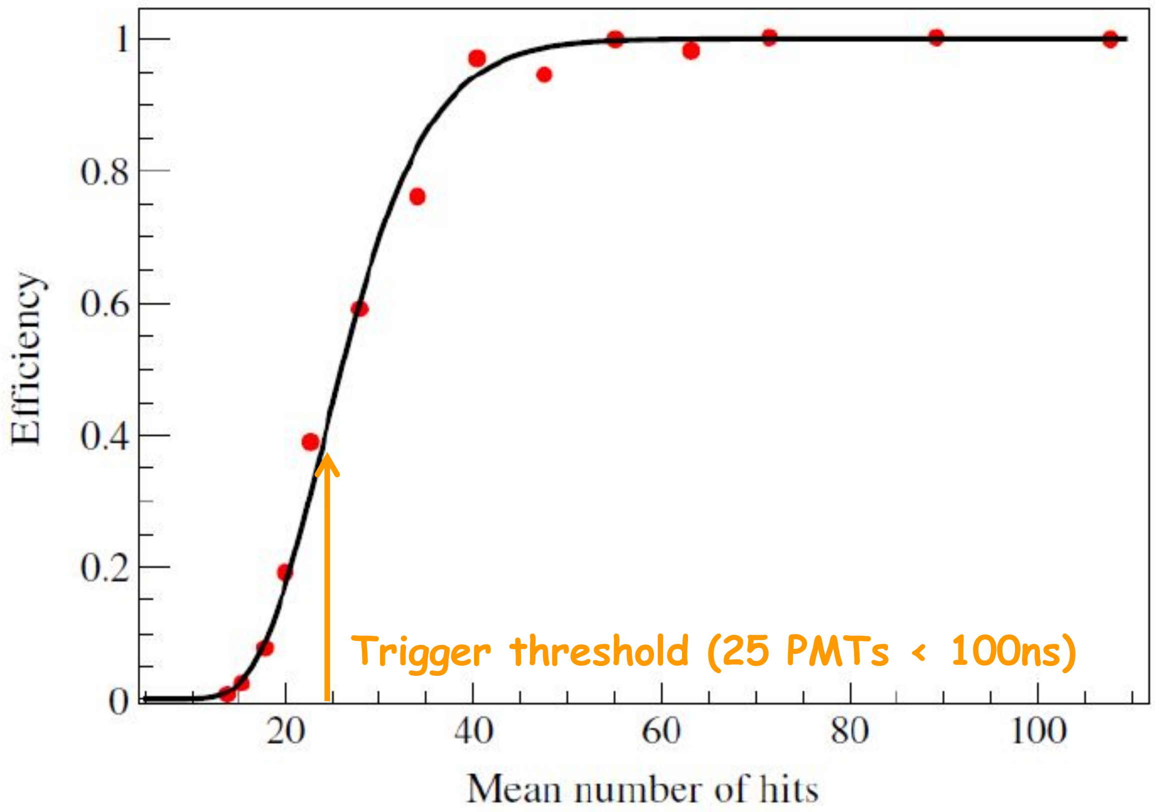
To measure ν-pp, we need:
- Low energy threshold
- Good energy resolution (10% @ 200 keV)
- Low radioactivity
- Low ^{14}C rate (tail and pile-up)

Hard reality !



Towards pp neutrinos

Energy threshold



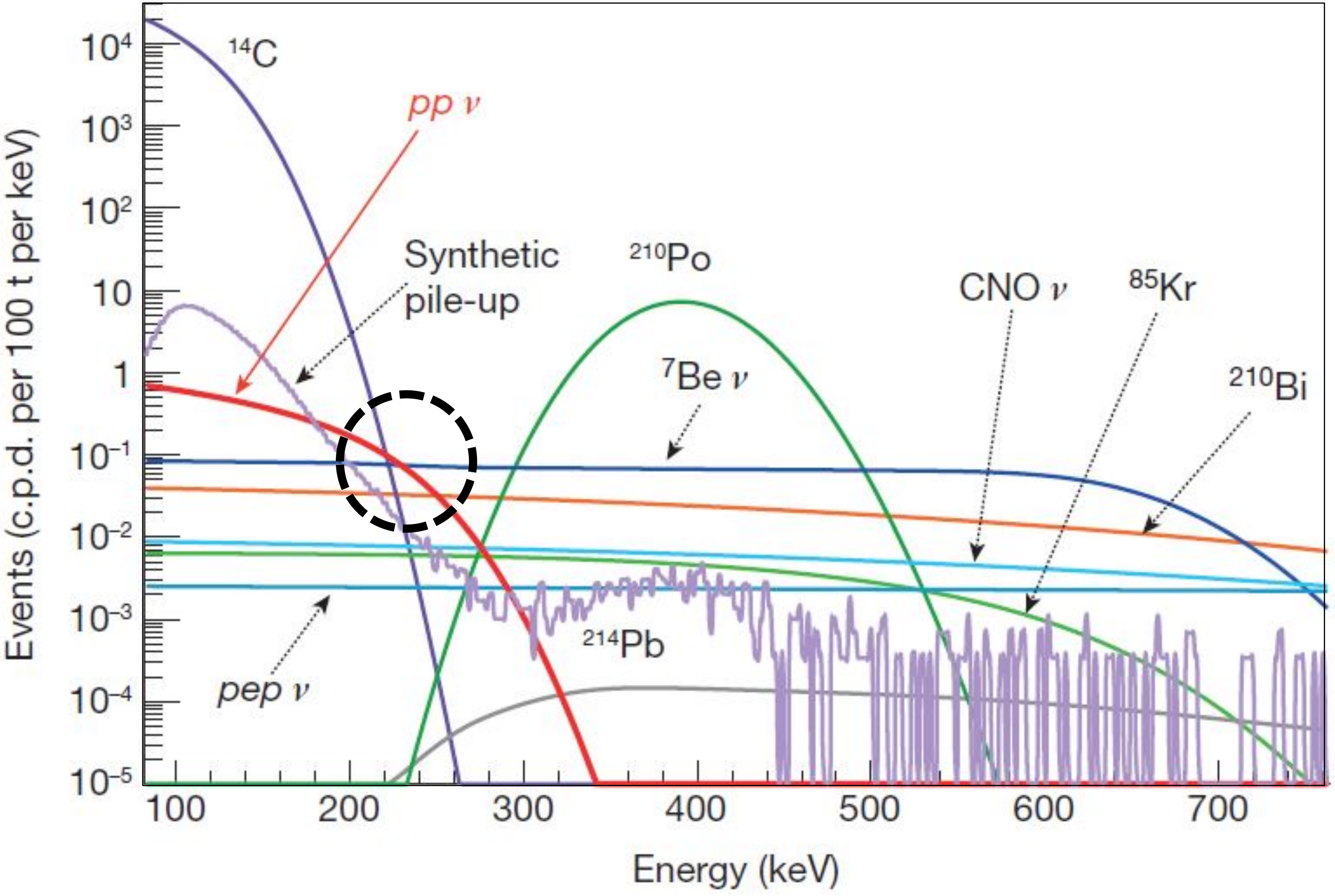
Trigger threshold (25 PMTs < 100ns)

Energy ~proportional to
number of photoelectrons :
60 PMTs
~120 keV

ð No problem to
measure ^{14}C…
and to fit ν-pp!

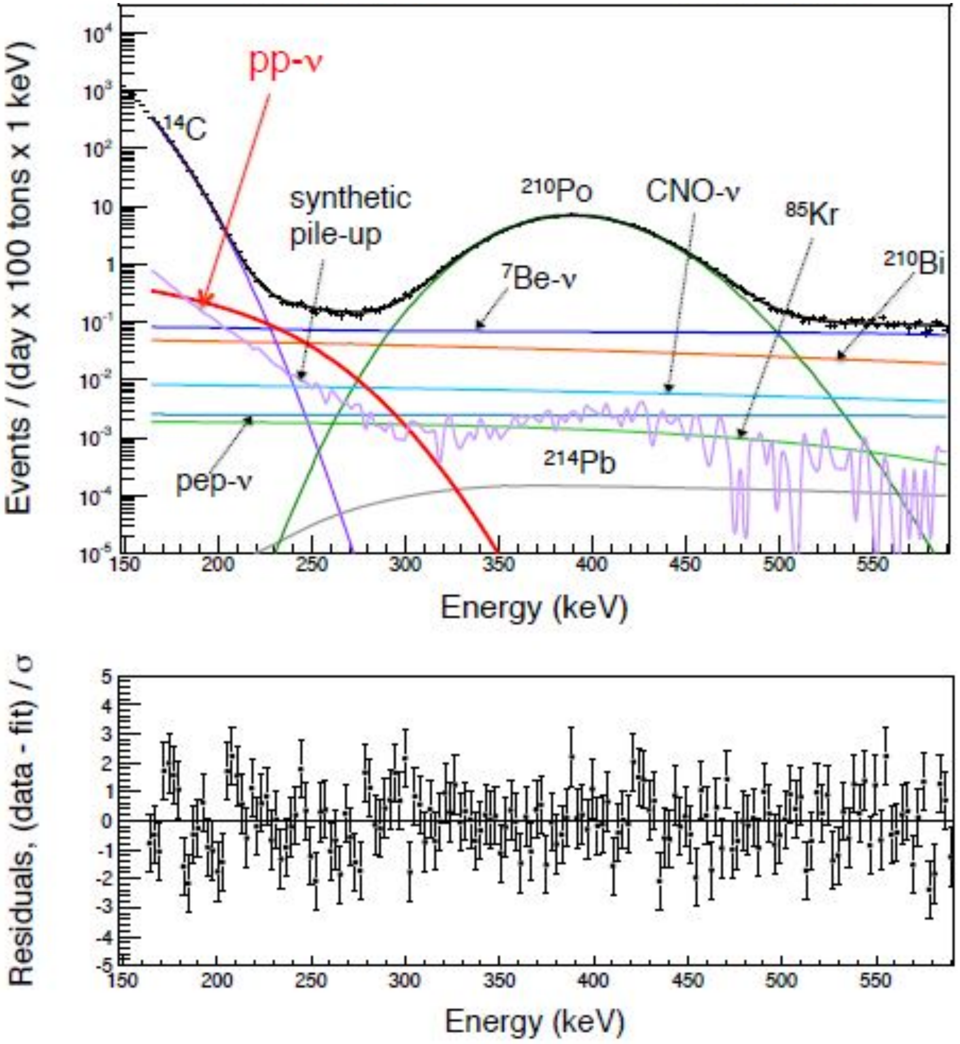
Towards pp neutrinos

Expected energy spectrum



Towards pp neutrinos

Result



- ○ ^{7}Be constrained (measured value with σ)
- ○ pep, CNO fixed (SSM)
- ○ ^{214}Pb fixed at the measured rate (BiPo)
- ○ ^{14}C and pile-up constrained (measured value with σ)
- ○ pp, ^{210}Po, ^{210}Bi, ^{85}Kr : free

χ^2/d.o.f. = 172.3/147

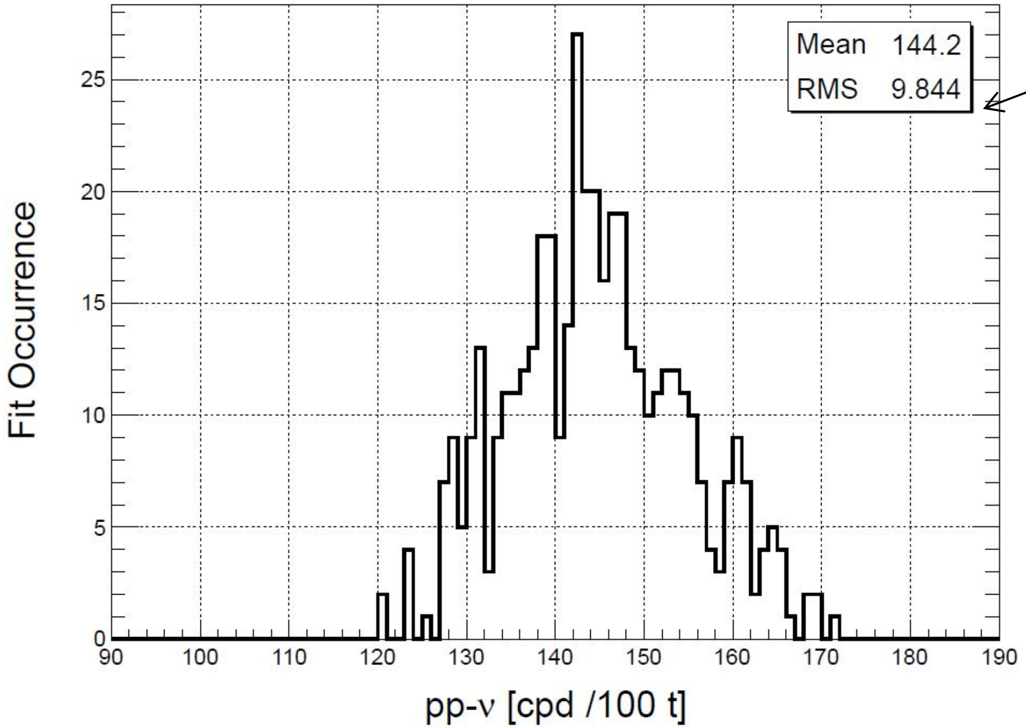
— *pp ν*: 144 ± 13 (free)
— ^{7}Be ν: 46.2 ± 2.1 (constrained)
— *pep* ν: 2.8 (fixed)
— CNO ν: 5.36 (fixed)
— ^{214}Pb: 0.06 (fixed)
— ^{210}Po: 583 ± 2 (free)
— ^{14}C: 39.8 ± 0.9 (constrained)
— Pile-up: 321 ± 7 (constrained)
— ^{210}Bi: 27 ± 8 (free)
— ^{85}Kr: 1 ± 9 (free)

Towards pp neutrinos

Result

ν-pp : 144 ± 13 (stat) ± 10 (syst) cpd / 100 t

Total systematic error
- 7% (see figure)
- 2% (nominal fiducial mass)

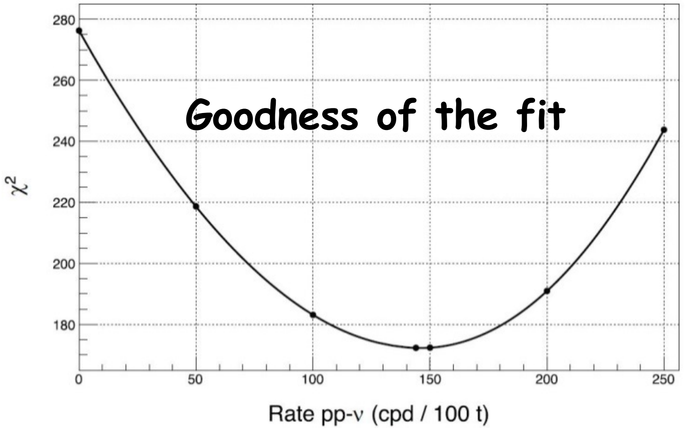


Many fits varying initial conditions (energy window, data selection criteria, other method for pile-up, energy estimator, …) ≤ 7% systematic error

Towards pp neutrinos

Result

ν-pp : 144 ± 13 (stat) ± 10 (syst) cpd / 100 t



Absence of a ν-pp
signal excluded at 10σ.

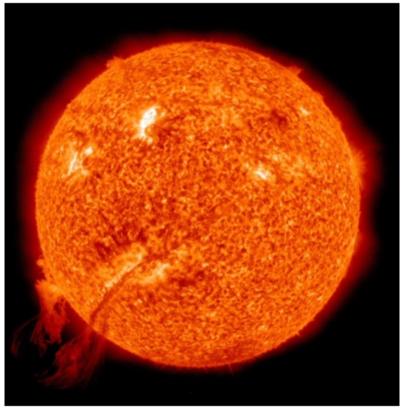
$\Phi(\nu\text{-pp})$: $6.6 \pm 0.7\ 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

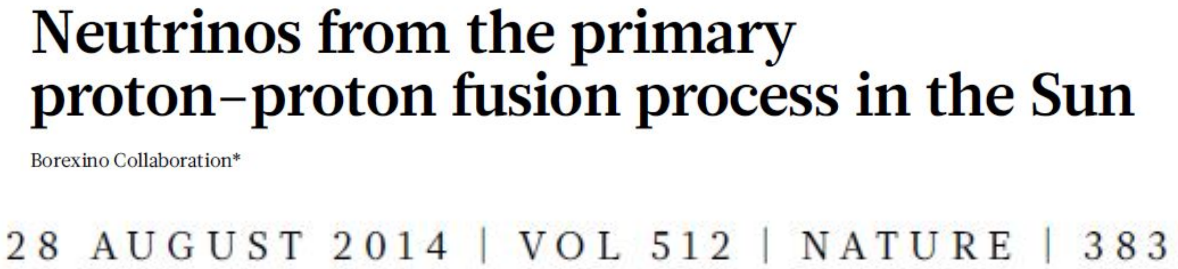
SSM
High met. : $5.98\ (1 \pm 0.06)\ 10^{10}$
(131±2 cpd / 100 t)
Low met. : $6.03\ (1 \pm 0.06)\ 10^{10}$

nb e$^-$

$$P(\nu_e \rightarrow \nu_e) = \frac{R_{exp} - \Phi^{SSM}\ n_e\ \sigma_\mu}{\Phi^{SSM}\ n_e\ (\sigma_e - \sigma_\mu)} = 0.64 \pm 0.12$$

Cross sections ν_e et ν_μ





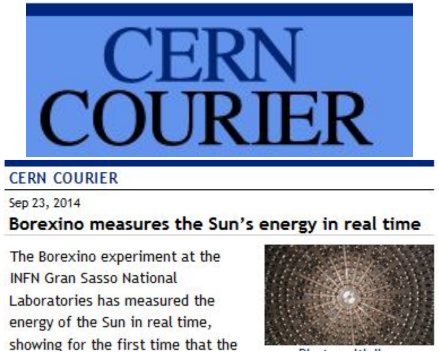
Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

28 AUGUST 2014 | VOL 512 | NATURE | 383

Plongée dans le cœur thermonucléaire du Soleil

ACTUALITE > SCIENCES & ENVIRONNNEMENT Par Tristan Vey | Publié le 29/08/2014 à 17:41



CERN COURIER

CERN COURIER

Sep 23, 2014

Borexino measures the Sun's energy in real time

The Borexino experiment at the INFN Gran Sasso National Laboratories has measured the energy of the Sun in real time, showing for the first time that the

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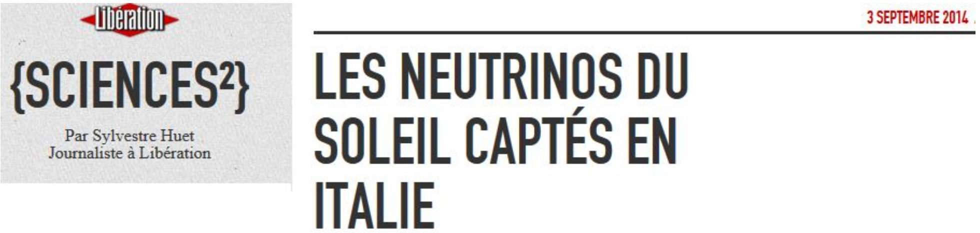
LA TÊTE AU CARRÉ

par **Mathieu Vidard**
du lundi au vendredi de 14h à 15h

l'émission du **jeudi 18 septembre 2014**

Soleil et neutrinos



{SCIENCES²}

Par Sylvestre Huet
Journaliste à Libération

3 SEPTEMBRE 2014

LES NEUTRINOS DU SOLEIL CAPTÉS EN ITALIE

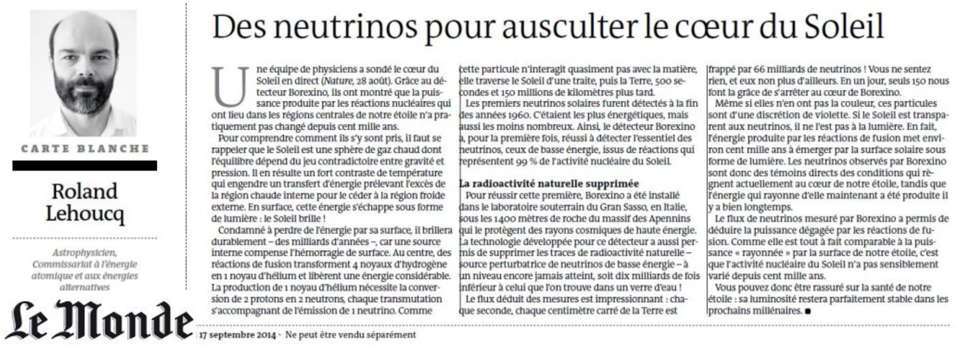
POUR LA SCIENCE

ACTUALITÉS | 03/09/2014 10:30 | Réagir à cet article | < Précédent - Suivant >

ASTROPHYSIQUE

Neutrinos : le Soleil à cœur ouvert

Les physiciens de l'expérience *Borexino* ont mesuré pour la première fois le flux des neutrinos produits par la fusion de protons au centre du Soleil, les témoins directs de la production d'énergie de notre étoile.



CARTE BLANCHE

Roland Lehoucq

Astrophysicien, Commissariat à l'énergie atomique et aux énergies alternatives

Des neutrinos pour ausculter le cœur du Soleil

Une équipe de physiciens a sondé le cœur du Soleil en direct (*Nature*, 28 août). Grâce au détecteur Borexino, ils ont montré que la puissance produite par les réactions nucléaires qui ont lieu dans les régions centrales de notre étoile n'a pratiquement pas changé depuis cent mille ans.

Pour comprendre comment ils s'y sont pris, il faut se rappeler que le Soleil est une sphère de gaz chaud dont l'équilibre dépend du jeu contradictoire entre gravité et pression. Il en résulte un fort contraste de température qui engendre un transfert d'énergie prélevant l'excès de la région chaude interne pour le céder à la région froide externe. En surface, cette énergie s'échappe sous forme de lumière : le Soleil brille !

Condamné à perdre de l'énergie par sa surface, il brillera durablement – des milliards d'années –, car une source interne compense l'hémorragie de surface. Au centre, des réactions de fusion transforment 4 noyaux d'hydrogène en 1 noyau d'hélium et libèrent une énergie considérable. La production de 1 noyau d'hélium nécessite la conversion de 2 protons en 2 neutrons, chaque transmutation s'accompagnant de l'émission de 1 neutrino. Comme cette particule n'interagit quasiment pas avec la matière, elle traverse le Soleil d'une traite, puis la Terre, 500 secondes et 150 millions de kilomètres plus tard.

Les premiers neutrinos solaires furent détectés à la fin des années 1960. C'étaient les plus énergétiques, mais aussi les moins nombreux. Ainsi, le détecteur Borexino a, pour la première fois, réussi à détecter l'essentiel des neutrinos, ceux de basse énergie, issus de réactions qui représentent 99 % de l'activité nucléaire du Soleil.

La radioactivité naturelle supprimée

Pour réussir cette première, Borexino a été installé dans le laboratoire souterrain du Gran Sasso, en Italie, sous les 1400 mètres de roche du massif des Apennins qui le protègent des rayons cosmiques de haute énergie. La technologie développée pour ce détecteur a aussi permis de supprimer les traces de radioactivité naturelle – source perturbatrice de neutrinos de basse énergie – à un niveau encore jamais atteint, soit dix milliards de fois inférieur à celui que l'on trouve dans un verre d'eau !

Le flux déduit des mesures est impressionnant : chaque seconde, chaque centimètre carré de la Terre est frappé par 66 milliards de neutrinos ! Vous ne sentez rien, et eux non plus d'ailleurs. En un jour, seuls 150 nous font la grâce de s'arrêter au cœur de Borexino.

Même si elles n'en ont pas la couleur, ces particules sont d'une discrétion de violette. Si le Soleil est transparent aux neutrinos, il ne l'est pas à la lumière. En fait, l'énergie produite par les réactions de fusion met environ cent mille ans à émerger par la surface solaire sous forme de lumière. Les neutrinos observés par Borexino sont donc des témoins directs des conditions qui règnent actuellement au cœur de notre étoile, tandis que l'énergie qui rayonne d'elle maintenant a été produite il y a bien longtemps.

Le flux de neutrinos mesuré par Borexino a permis de déduire la puissance dégagée par les réactions de fusion. Comme elle est tout à fait comparable à la puissance « rayonnée » par la surface de notre étoile, c'est que l'activité nucléaire du Soleil n'a pas sensiblement varié depuis cent mille ans.

Vous pouvez donc être rassuré sur la santé de notre étoile : sa luminosité restera parfaitement stable dans les prochains millénaires. ■

Le Monde

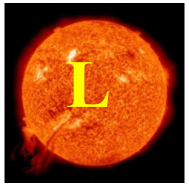
17 septembre 2014 - Ne peut être vendu séparément

Play with numbers

In the core of the Sun:

~10^{38} pp interactions / second (and as many ν's)

[3,84 10^{26} W / 4,28 10^{-12} J]

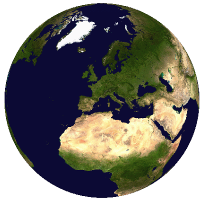


$m_{4p} - m_{He}$

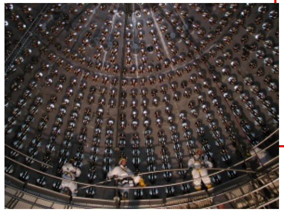
1 ν ~2 10^{-12} W

~600 millions tons of hydrogen burnt per second

On Earth:

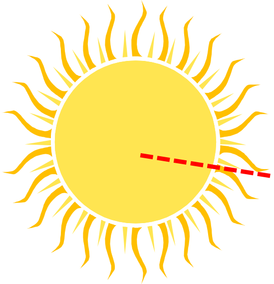


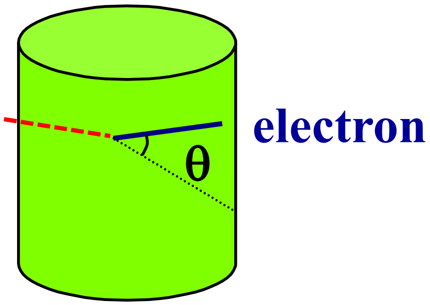
65 10^{13} ν / m^2 / s 1360 W/m^2

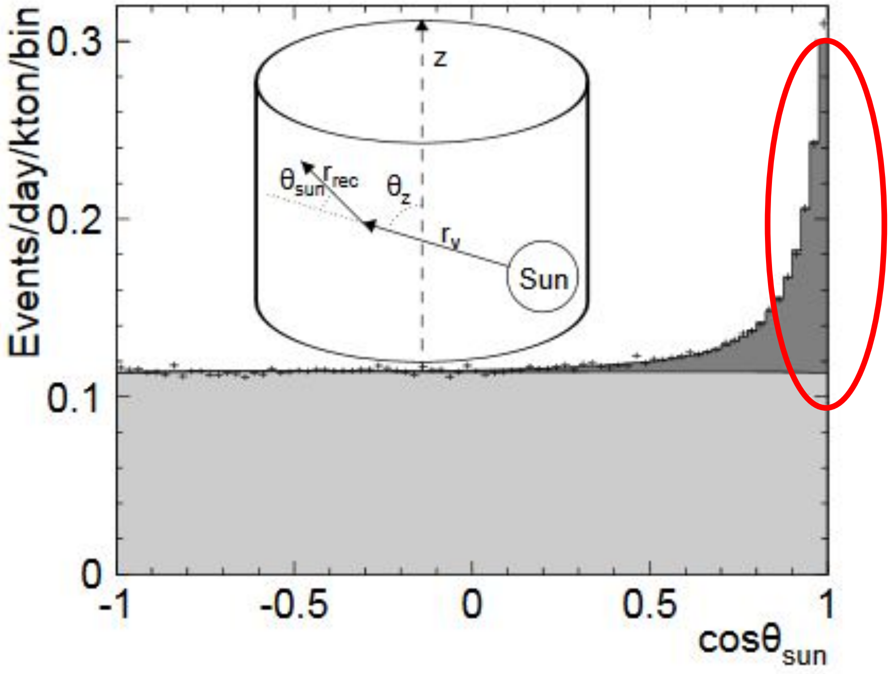


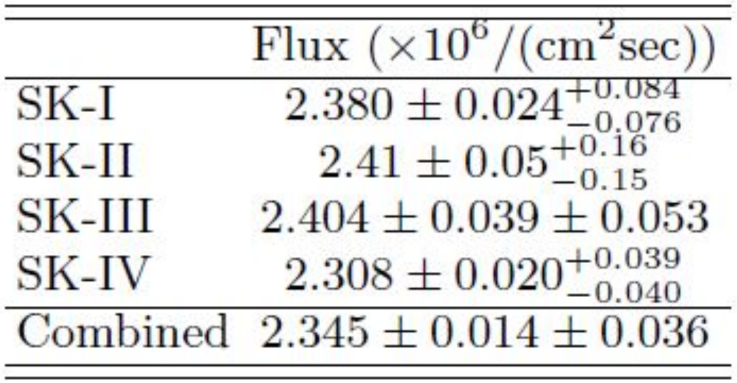
1,5 10^{21} ν crossed the target each day ~150 trapped !

SuperKamiokande









	Flux $(\times 10^6/(\mathrm{cm}^2\mathrm{sec}))$
SK-I	$2.380 \pm 0.024^{+0.084}_{-0.076}$
SK-II	$2.41 \pm 0.05^{+0.16}_{-0.15}$
SK-III	$2.404 \pm 0.039 \pm 0.053$
SK-IV	$2.308 \pm 0.020^{+0.039}_{-0.040}$
Combined	$2.345 \pm 0.014 \pm 0.036$

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

sensitive to ^{8}B ν

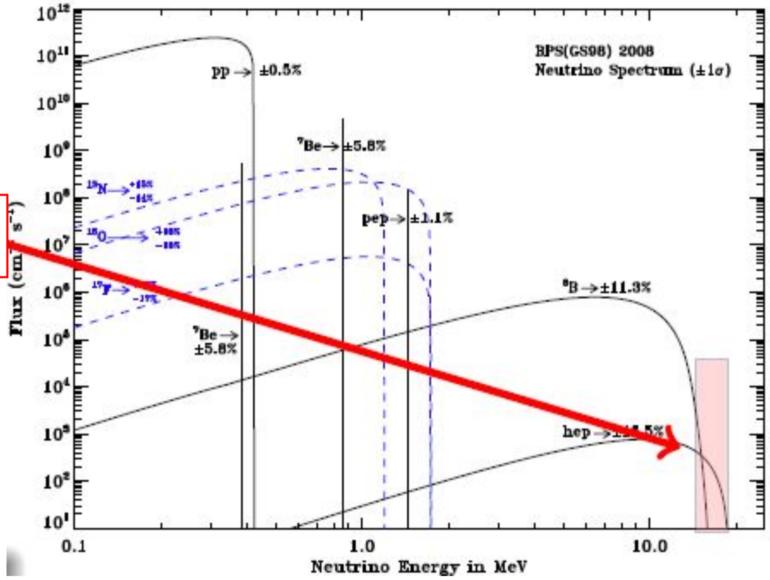
Flux measured for ^{8}B ν :
(2.31 ± 0.02 (stat.) ± 0.04 (syst.)) 10^6 cm^{-2} s^{-1}

SuperKamiokande IV
(2008-2014)
E > 3.5 MeV

45% of solar models
(5 ±1) 10^6 cm^{-2} s^{-1}

K. Abe et al. : arXiv:1606.07538

SNO : what's new ?
hep neutrinos



hep solar neutrinos

1000 times less than 8B !

$\Phi(\mathrm{hep})_{SSM} = (8.0 \pm 1.2)\ 10^3\ \mathrm{cm^{-2}s^{-1}}$

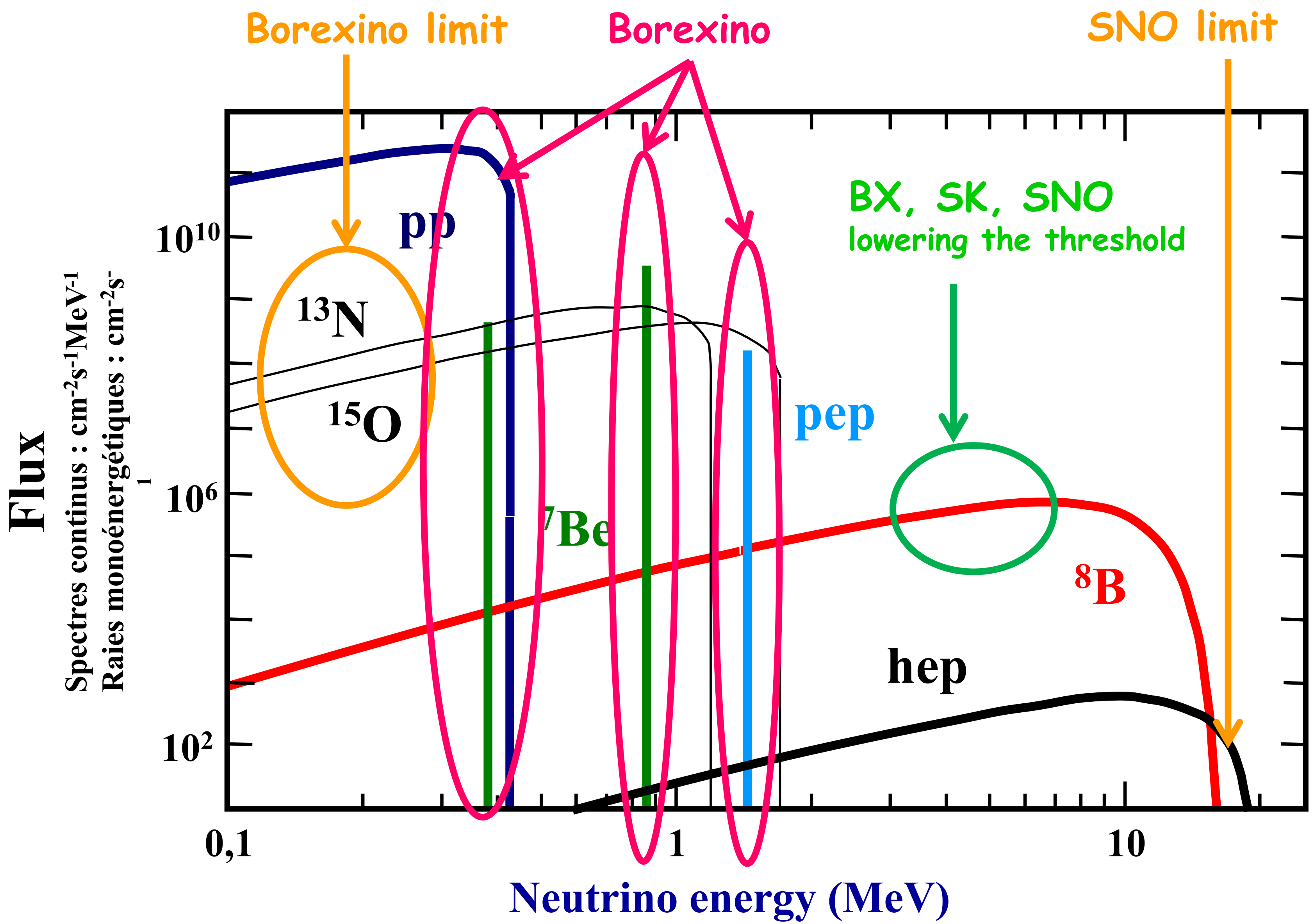
1054 days of SNO data

$\Phi(\mathrm{hep}) < 21\ 10^3\ \mathrm{cm^{-2}s^{-1}}$ [preliminary]

$[\Phi(\mathrm{hep})_{SK} < 1.5\ 10^5\ \mathrm{cm^{-2}s^{-1}}]$

N. Fiuza de Barros, NOW 2012

Towards spectroscopy of solar neutrinos

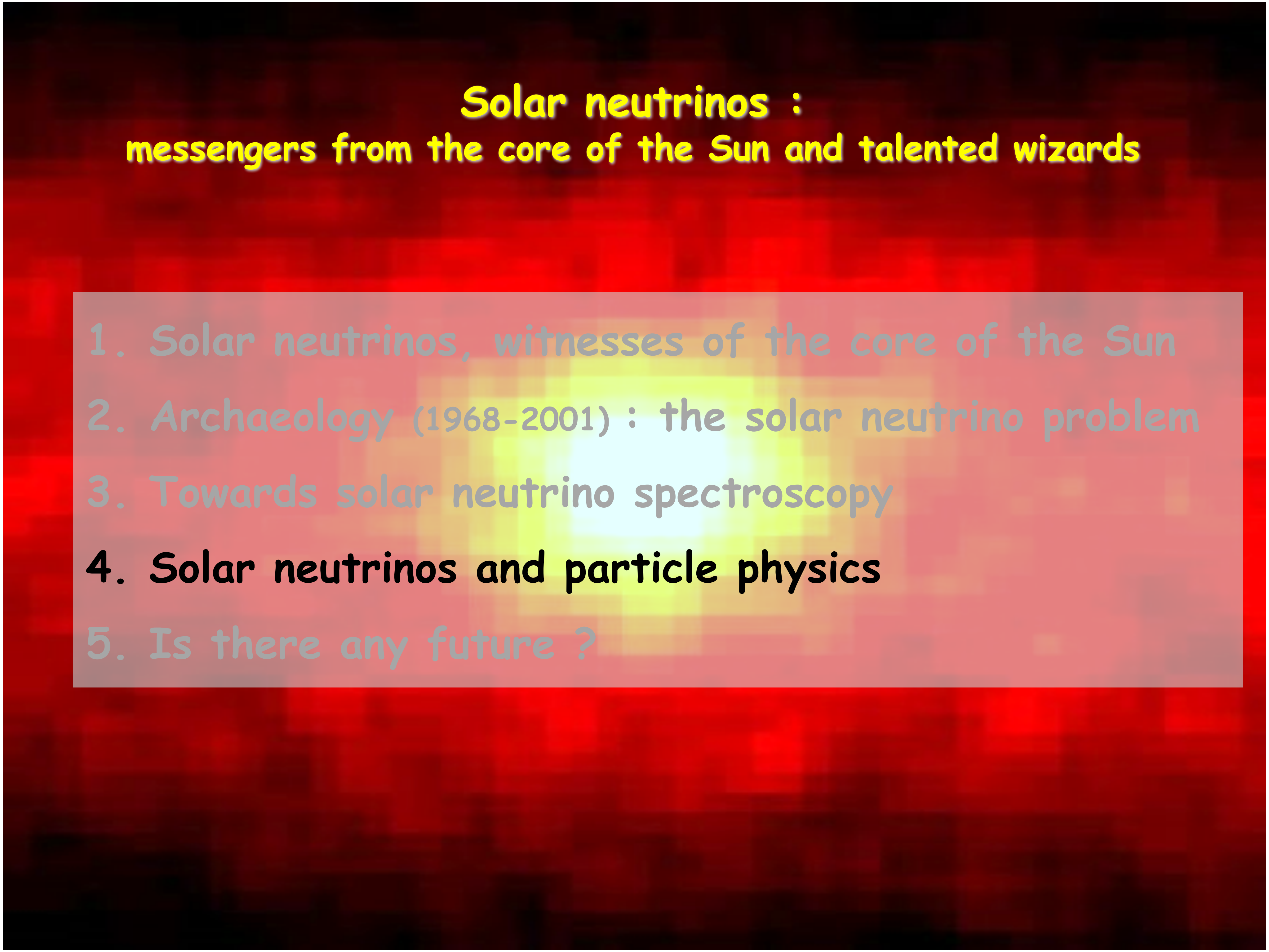


Borexino limit

Borexino

SNO limit

BX, SK, SNO
lowering the threshold

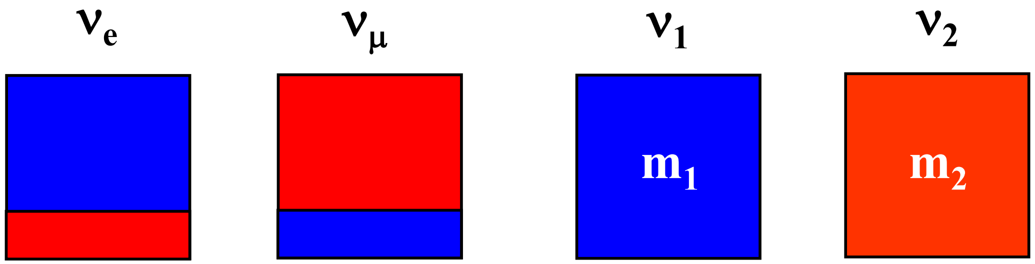


Solar neutrinos :

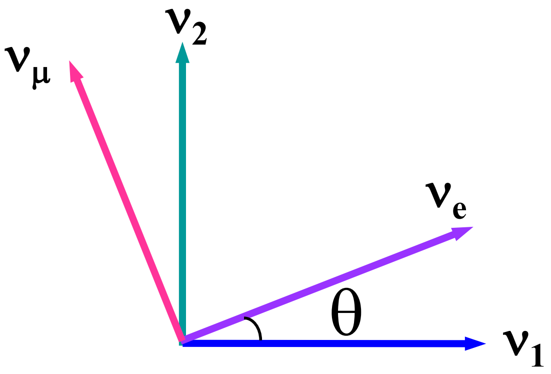
messengers from the core of the Sun and talented wizards

1. Solar neutrinos, witnesses of the core of the Sun
2. Archaeology (1968-2001) : the solar neutrino problem
3. Towards solar neutrino spectroscopy
4. **Solar neutrinos and particle physics**
5. Is there any future ?

Vacuum oscillations



Flavour eigenstates **Mass eigenstates**



$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

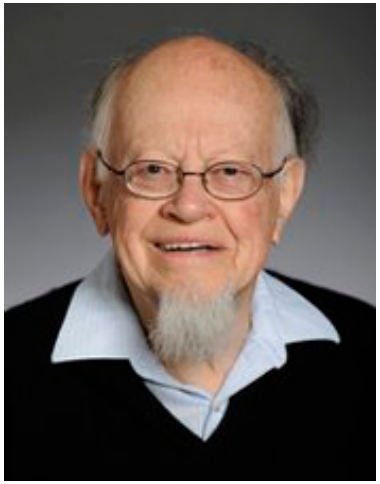
Evolution equation :

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\frac{\Delta m^2}{4p}\cos 2\theta & -\frac{\Delta m^2}{4p}\sin 2\theta\\ -\frac{\Delta m^2}{4p}\sin 2\theta & -\frac{\Delta m^2}{4p}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$\boxed{P(\nu_e \rightarrow \nu_e) = f(E, \Delta m^2, \theta)}$$

Thanks to three musketeers ! The oscillation mechanism is not as simple as that imagined by Pontecorvo !

M	S	W



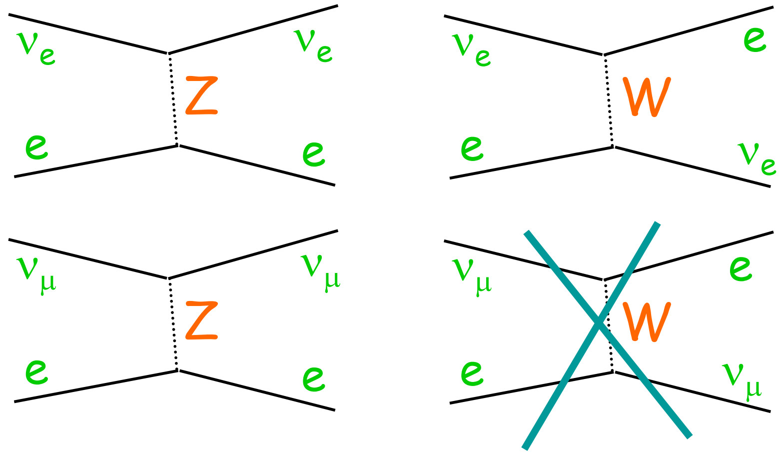
S.P. Mikheyev & A.Yu. Smirnov
June 1985

L. Wolfenstein
1978

MSW effect

Evolution equation in matter (Wolfenstein) :

Dissymetric behaviour of ν_e and ν_μ in matter

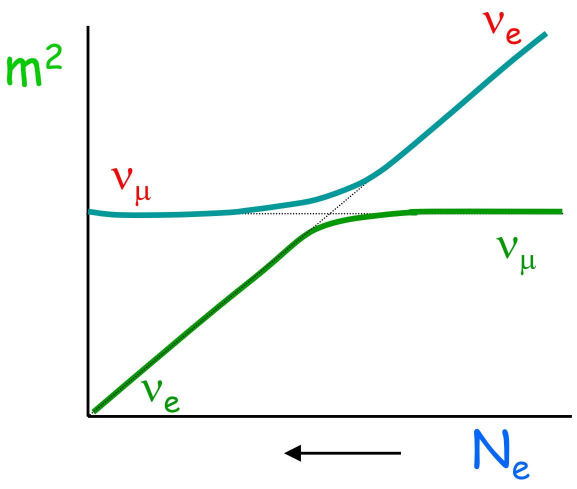


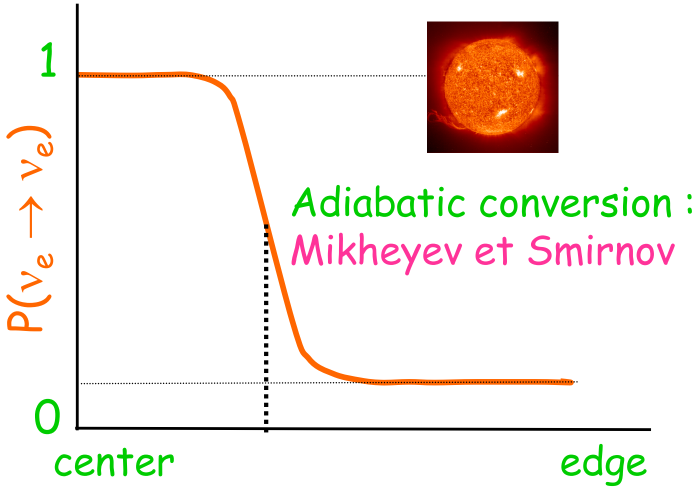
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} \frac{\Delta m^2}{4p}\cos2\theta+\frac{GN}{\sqrt{2}} & -\frac{\Delta m^2}{4p}\sin2\theta \\ -\frac{\Delta m^2}{4p}\sin2\theta & -\frac{\Delta m^2}{4p}\cos2\theta-\frac{GN}{\sqrt{2}}\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

N_e : electronic density

$P(\nu_e \rightarrow \nu_e) = f(E, \Delta m^2, \theta, N_e)$

$\Delta f(0)=f_e(0)-f_\mu(0) \propto GN_e$





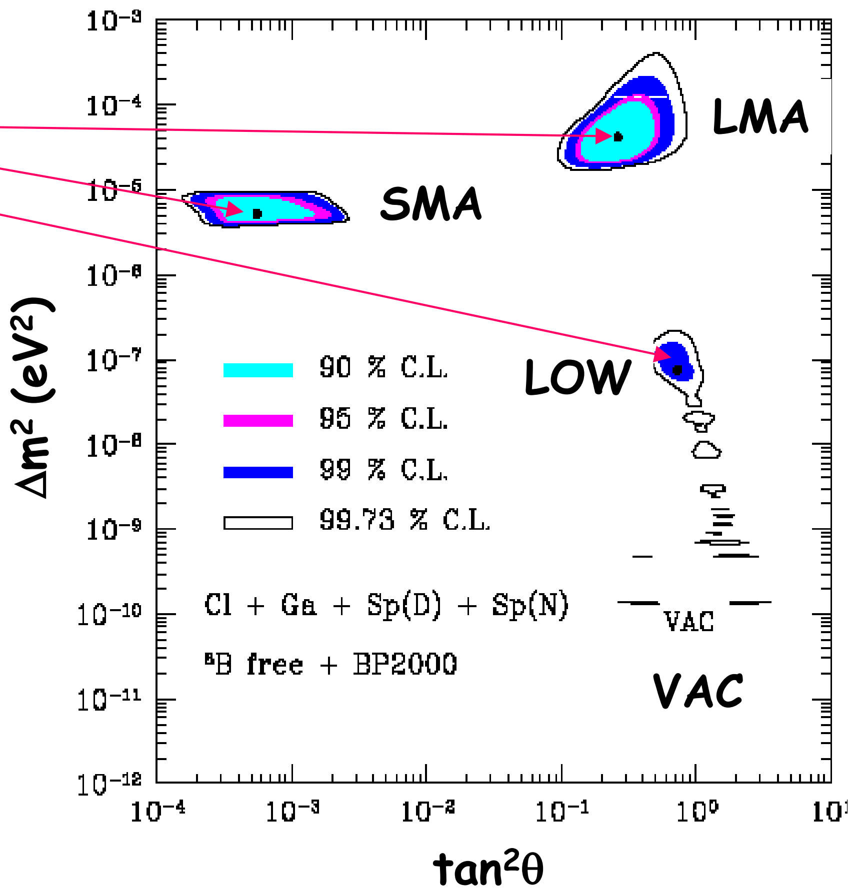
Adiabatic conversion : Mikheyev et Smirnov

Solar neutrinos and oscillation parameters

- To obtain the oscillation parameters (θ et Δm^2), the ν_e flux reductions observed in the experiments and energy spectra are fitted simultaneously.

Solar neutrinos and oscillation parameters (spring 2001)

Thanks to MSW effect



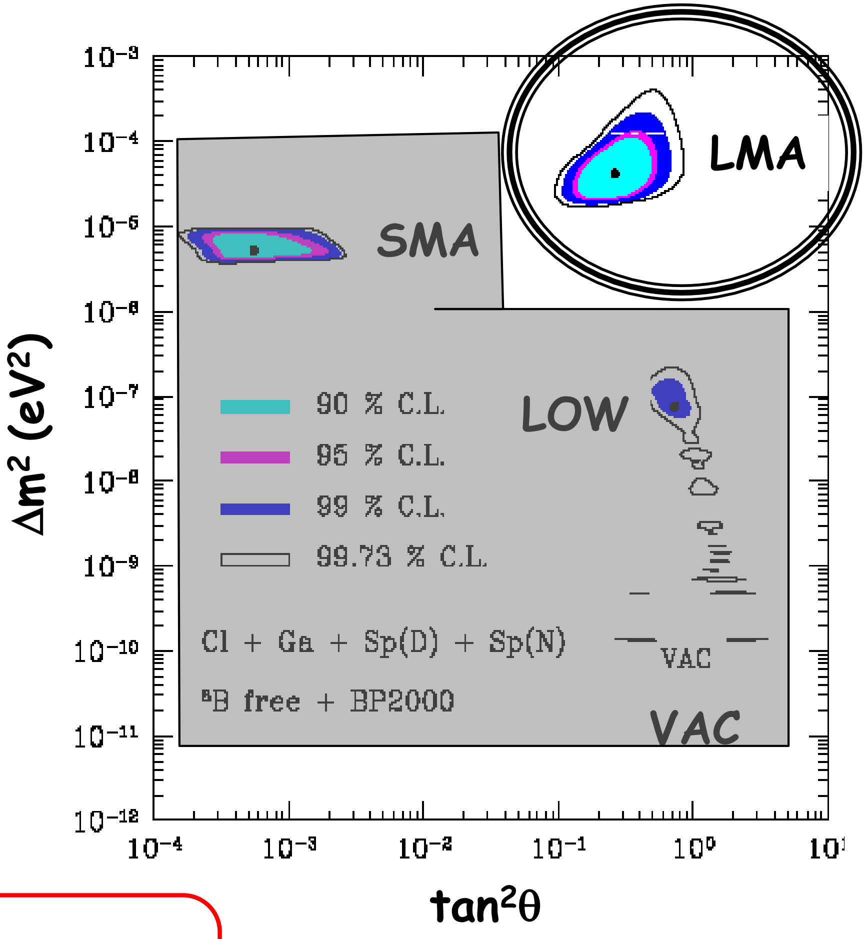
Δm^2_{12}

θ_{12}

Bahcall, Krastev, Smirnov, hep-ph/0103179

Solar neutrinos and oscillation parameters (June 2001)

Δm^2_{12}

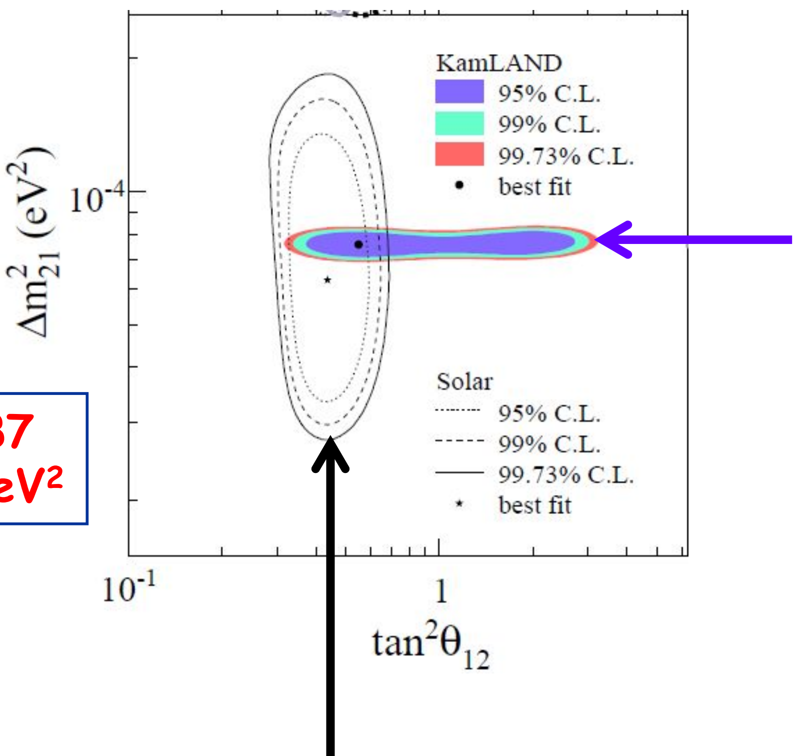


θ_{12}

2 phenomena :
- Vacuum oscillation
- ν_e transformation in the Sun (MSW effect)

Bahcall, Krastev, Smirnov, hep-ph/0103179

Solar neutrinos and oscillation parameters (precision)

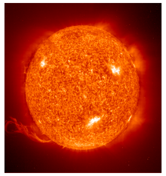


$\sin^2(2\theta_{12})$ = 0.87
Δm^2 = 7.6 10^{-5} eV^2

KamLAND

(2008)

precision on Δm^2_{12}

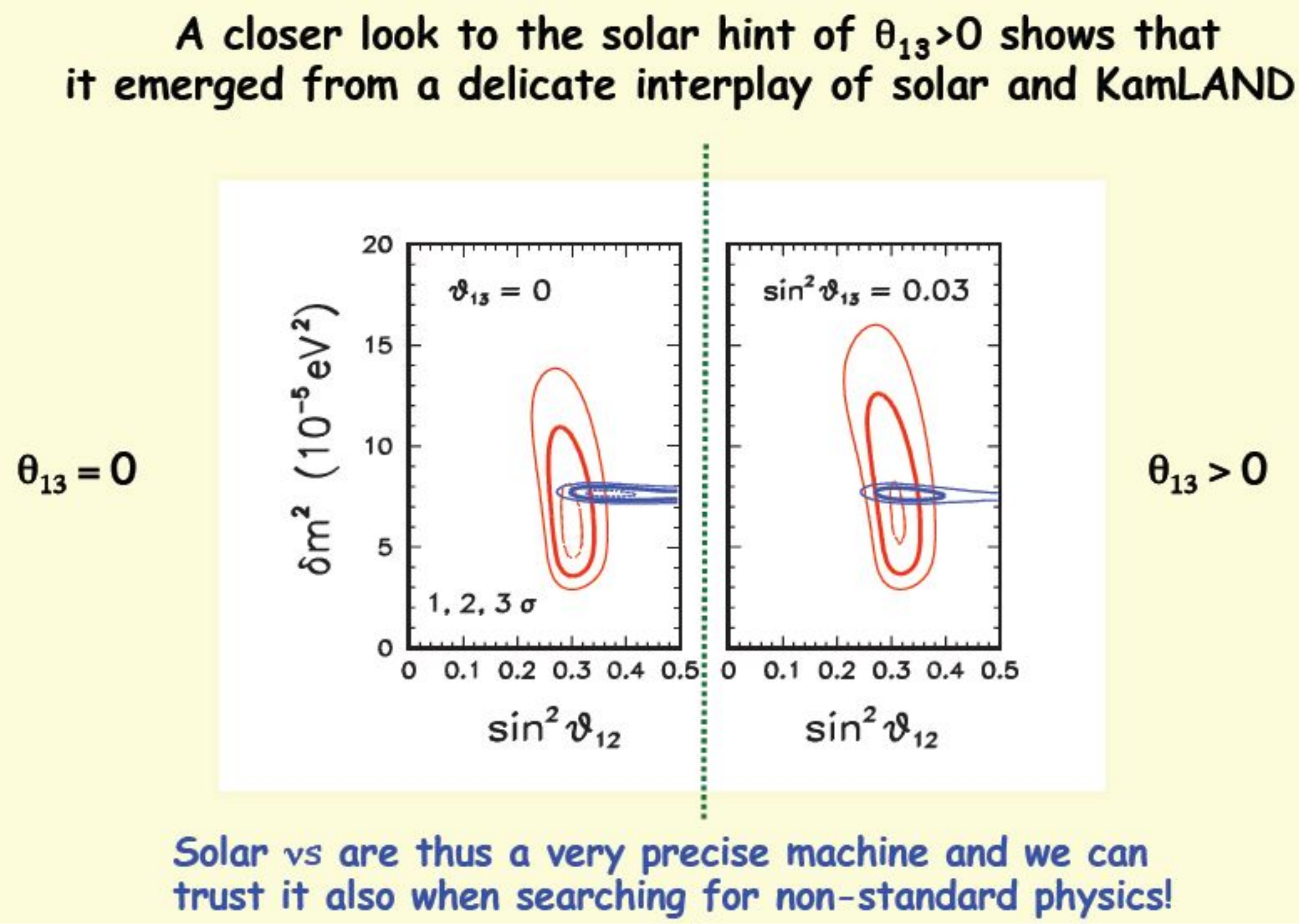


Sun

precision on θ_{12} angle

Phys. Rev. Lett. 100 (2008) 221803

Solar neutrinos and oscillation parameters (precision)



A closer look to the solar hint of $\theta_{13}>0$ shows that it emerged from a delicate interplay of solar and KamLAND

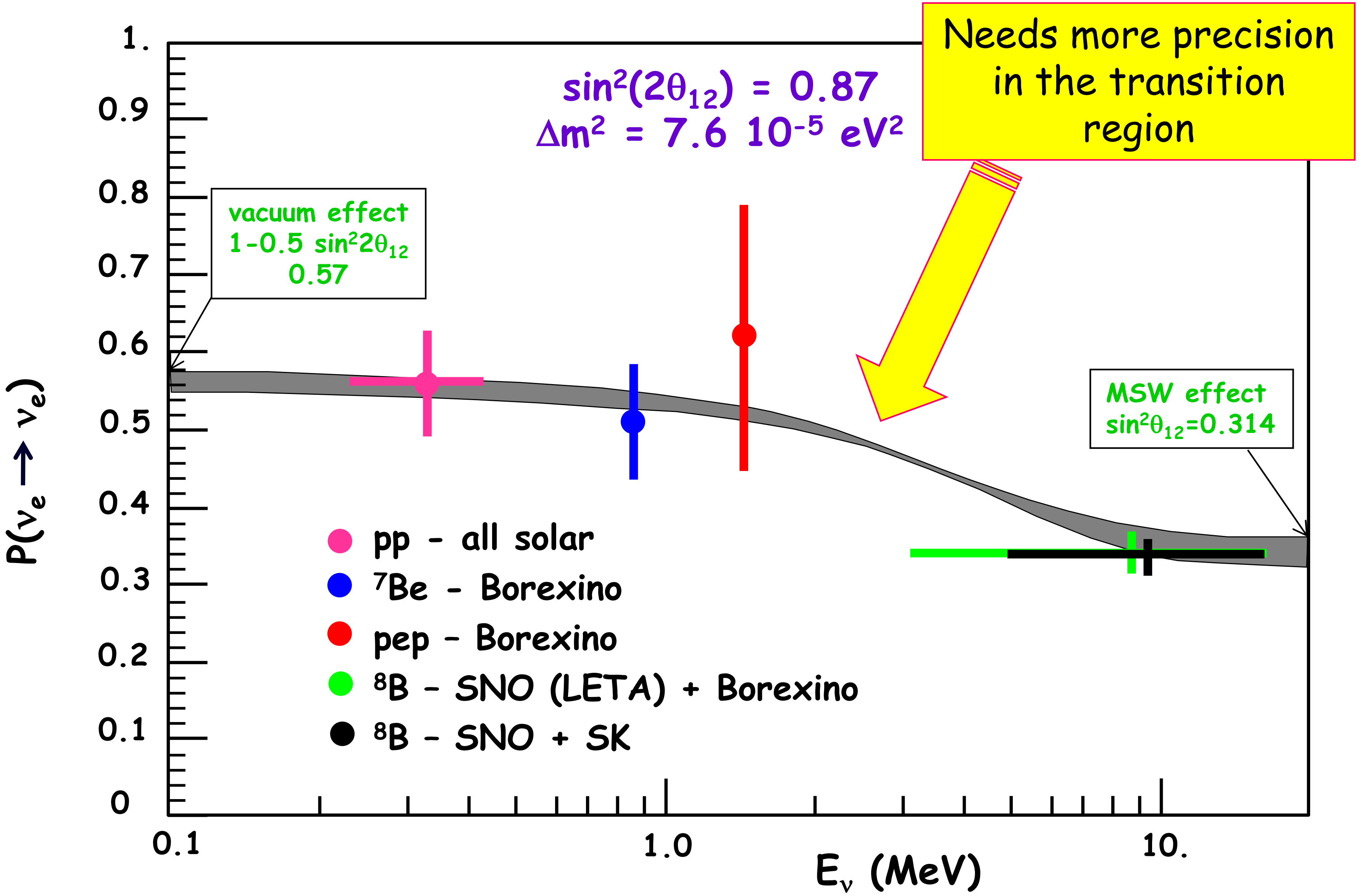
$\theta_{13} = 0$

$\theta_{13} > 0$

Solar νs are thus a very precise machine and we can trust it also when searching for non-standard physics!

A. Palazzo, Physun 2012

MSW effect : the Sun and LMA



$\sin^2(2\theta_{12}) = 0.87$
$\Delta m^2 = 7.6\ 10^{-5}\ eV^2$

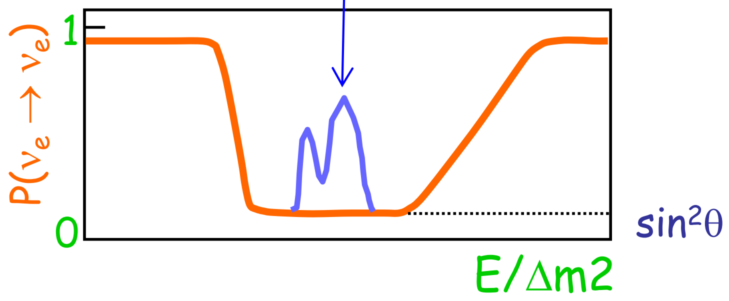
Needs more precision in the transition region

vacuum effect
$1-0.5\ \sin^2 2\theta_{12}$
0.57

MSW effect
$\sin^2\theta_{12}=0.314$

Day-night asymmetry of ^7Be ν_e

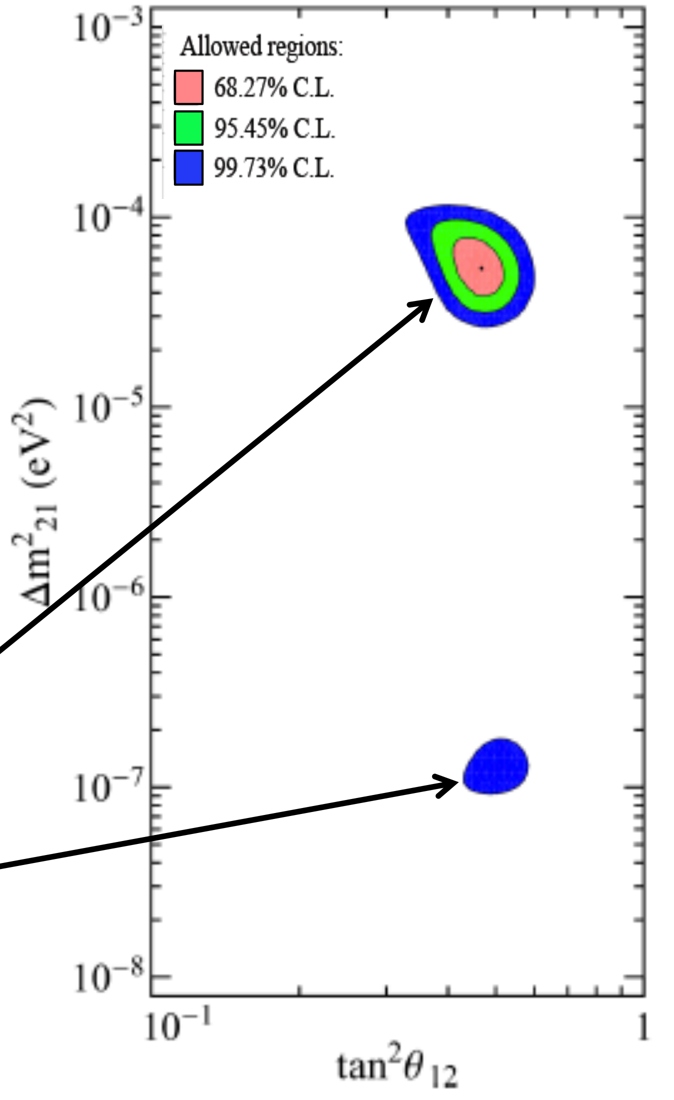
- Possible regeneration of solar ν_e if they cross the Earth before interacting (Cribier et al., 1986).



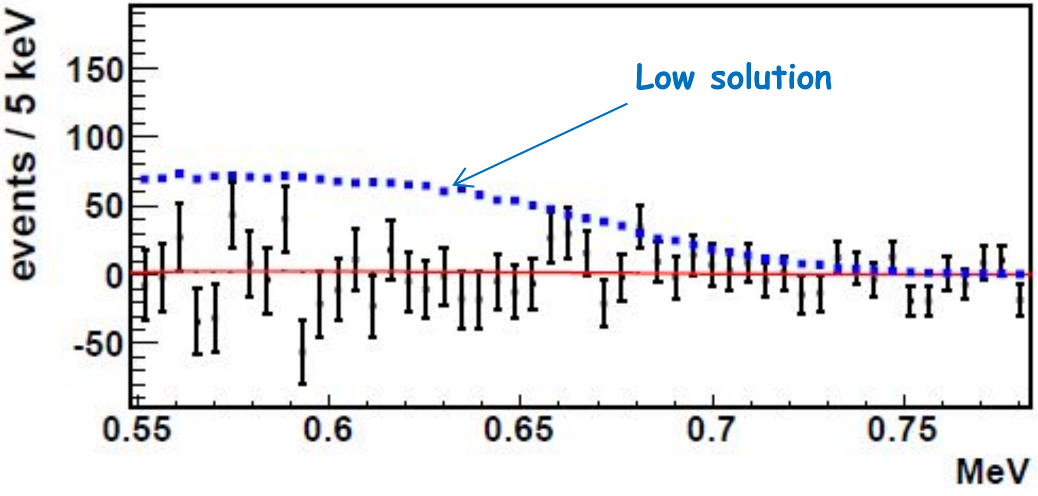
$$A_{dn} = 2\frac{R_n^{^7Be} - R_d^{^7Be}}{R_n^{^7Be} + R_d^{^7Be}} = \frac{R_{diff}}{R}$$

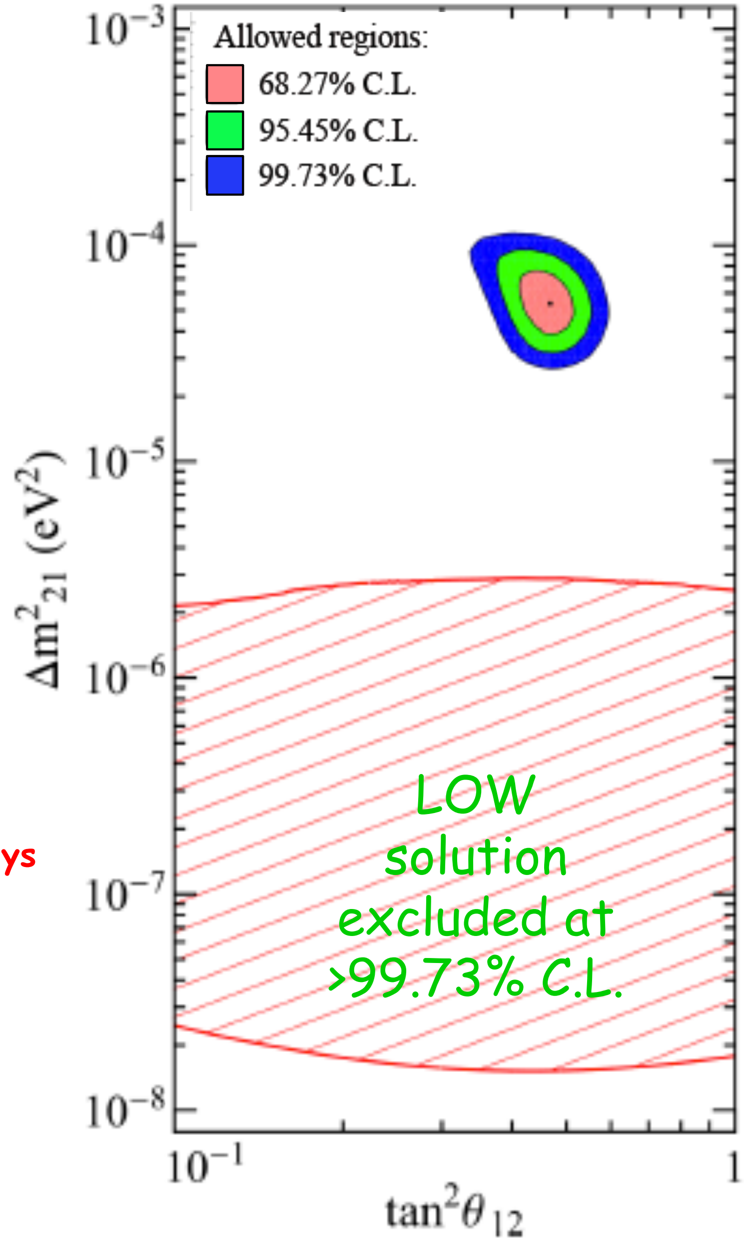
Model	Predicted A_{nd} (862 keV)
LMA	<0.001
LOW	0.11 - 0.80
MaVaN	~0.20

Solar before Borexino



Day-night asymmetry of ^{7}Be ν_e





LOW solution excluded at >99.73% C.L.

A_{dn}(862 keV): $0.001 \pm 0.012_{stat} \pm 0.007_{sys}$

Solar WITH Borexino

arXiv:1104.2150
Phys. Lett. B707 (2012) 22

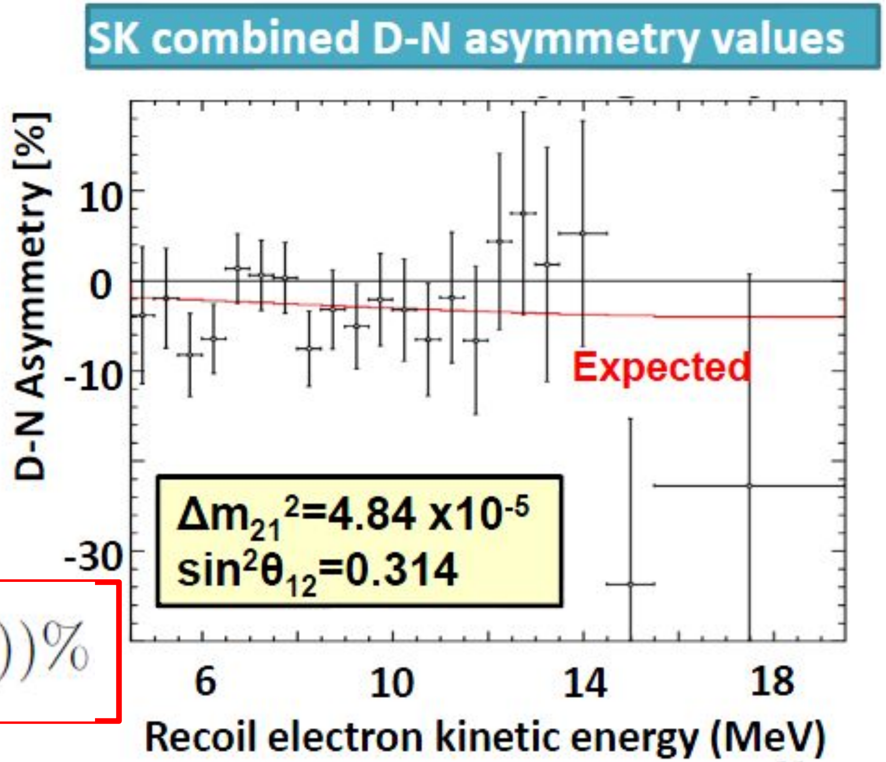
Day-night in SuperKamiokande

- Un-binned Day-Night analysis (PRD69, 011104) is applied in each SK phase, then obtained **Day-Night asymmetry values ($=A_{DN}$)** from fitted Day-Night amplitude parameter.
  - Consider energy and zenith angle dependence of event rate variation.

$$A_{DN} = \frac{\text{Day flux} - \text{Night flux}}{0.5\,(\text{Day flux} + \text{Night flux})}$$

	A_{DN} (±stat.±sys.)
SK-I	-2.0±1.7±1.0 %
SK-II	-4.3±3.8±1.0 %
SK-III	-4.3±2.7±0.7 %
SK-IV	-2.8±1.9±0.7 %

$$A_{\rm DN}^{\rm fit,\,SK} = (-3.3 \pm 1.0({\rm stat.}) \pm 0.5({\rm syst.}))\%$$

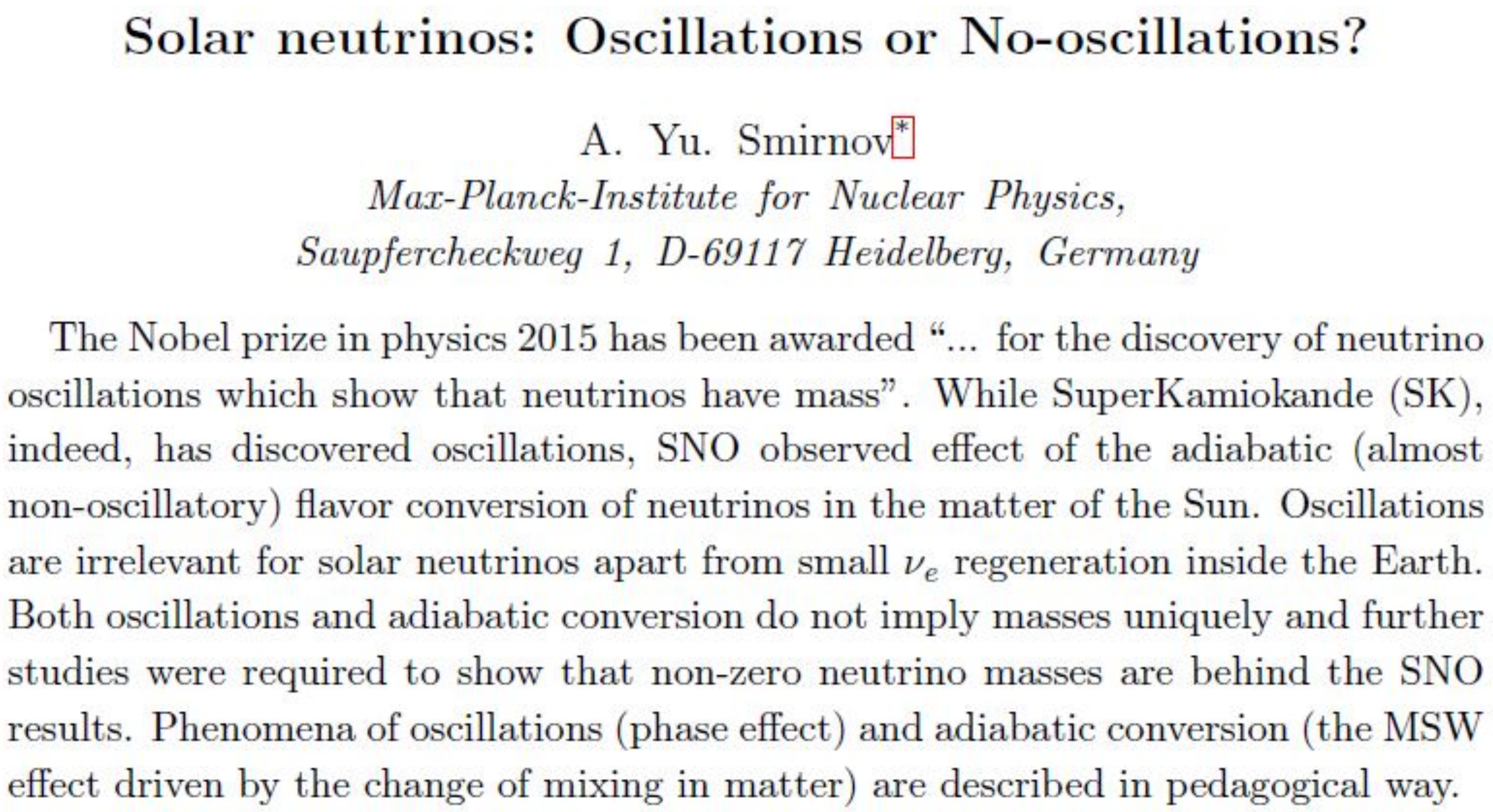

SK combined D-N asymmetry values

first significant indication for matter-enhanced ν oscillation ?

arXiv:1606.07538

Physun 2012

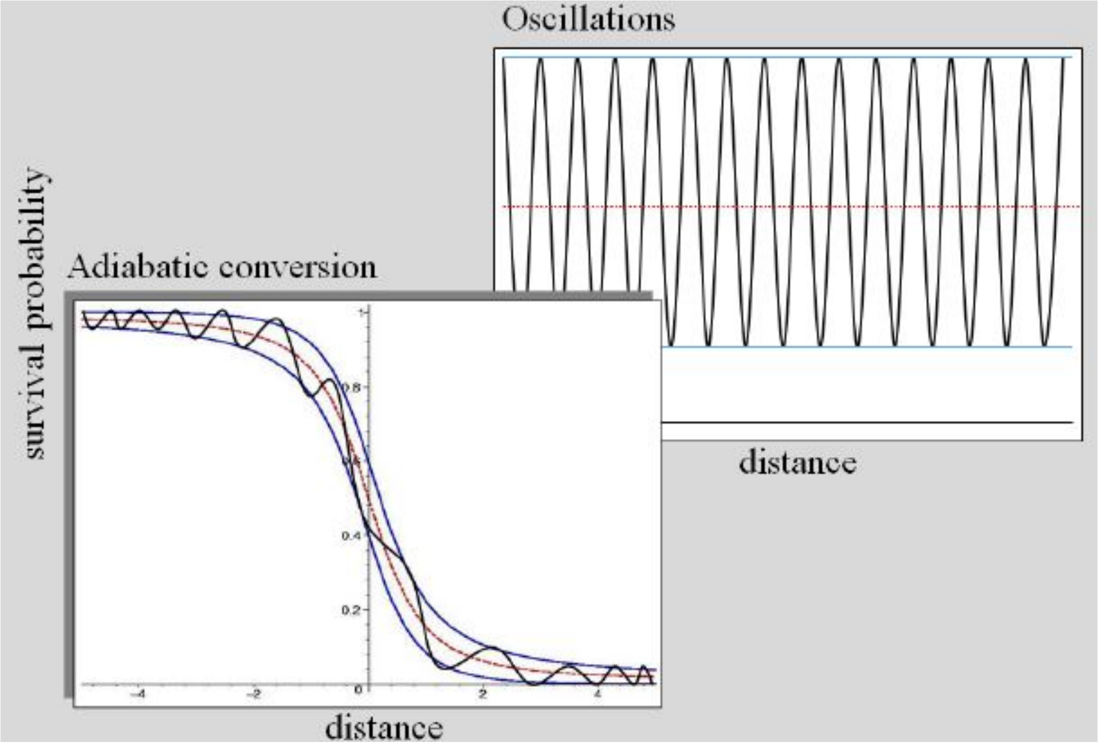
Smirnov paper arXiv:1609.02386



Solar neutrinos: Oscillations or No-oscillations?

A. Yu. Smirnov*
Max-Planck-Institute for Nuclear Physics,
Saupfercheckweg 1, D-69117 Heidelberg, Germany

The Nobel prize in physics 2015 has been awarded "... for the discovery of neutrino oscillations which show that neutrinos have mass". While SuperKamiokande (SK), indeed, has discovered oscillations, SNO observed effect of the adiabatic (almost non-oscillatory) flavor conversion of neutrinos in the matter of the Sun. Oscillations are irrelevant for solar neutrinos apart from small ν_e regeneration inside the Earth. Both oscillations and adiabatic conversion do not imply masses uniquely and further studies were required to show that non-zero neutrino masses are behind the SNO results. Phenomena of oscillations (phase effect) and adiabatic conversion (the MSW effect driven by the change of mixing in matter) are described in pedagogical way.



In conclusion, the answer to the question in the title of the paper is

“Solar neutrinos: Almost No-oscillations”.

The SNO experiment has discovered effect of *the adiabatic flavor conversion* (the MSW

high energies (SNO) the adiabatic conversion is close to the non-oscillatory transition which corresponds to production of single eigenstate. Oscillations with small depth occur in the matter of the Earth.

We are sure that at least the authors of the paper have well understood the MSW mechanism !

Back on solar models

What is the best solar metallicity ?

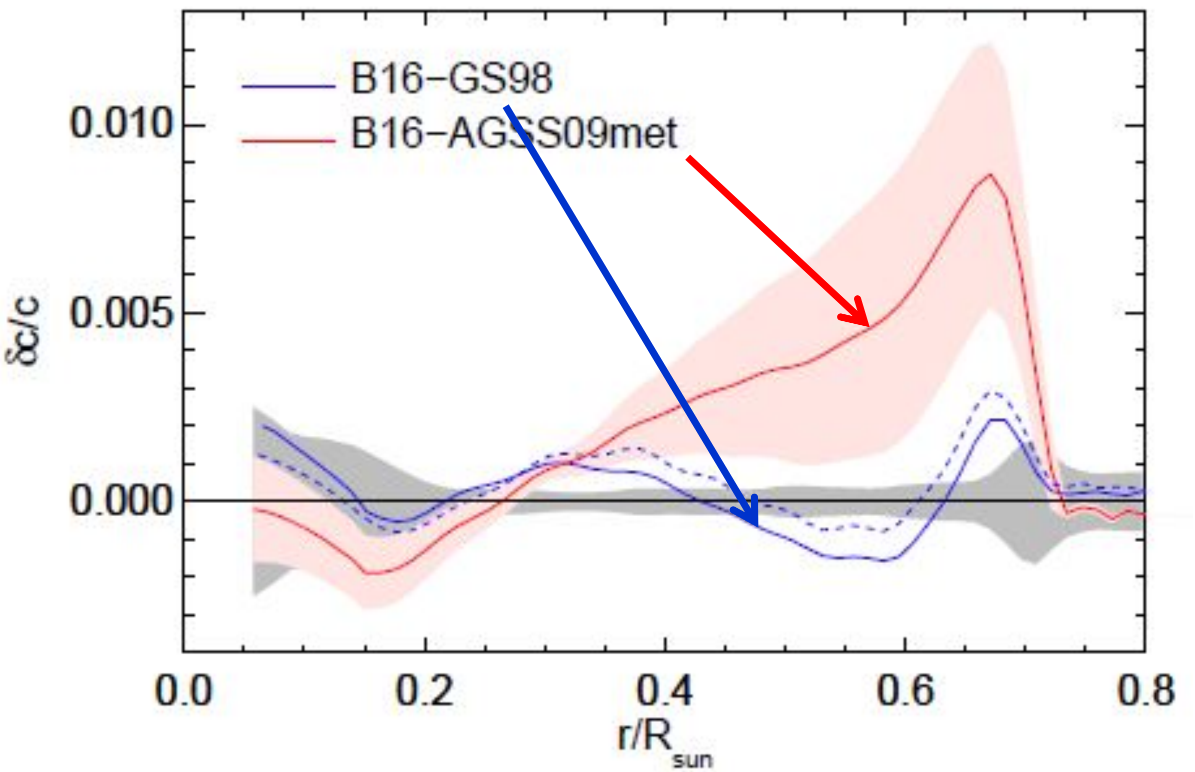
Why the best solar metallicity does not satisfies helioseismology ?

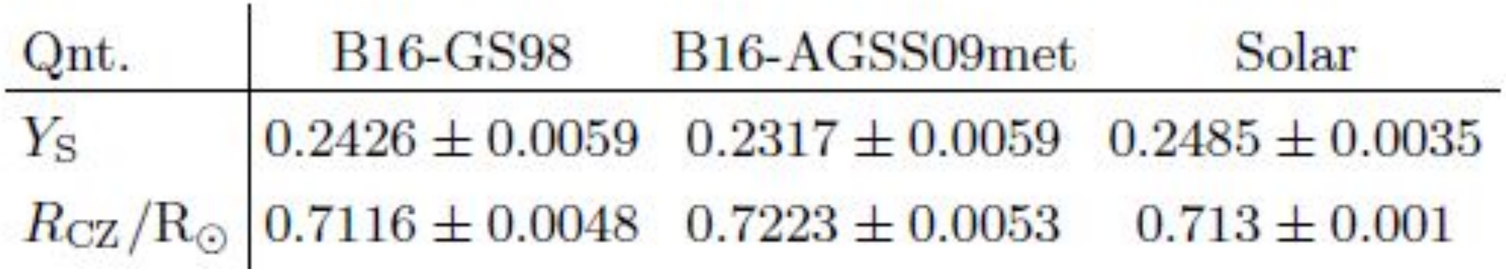
Grevesse & Sauval 1998 (GS98)
old (high) solar metallicity $Z/X = 0.0229$

Asplund, Grevesse, Sauval, Scott 2009 (AGS09)
new (low) solar metallicity $Z/X = 0.0178$

N. Vinyoles et al., arXiv:1611.09867

sound speed

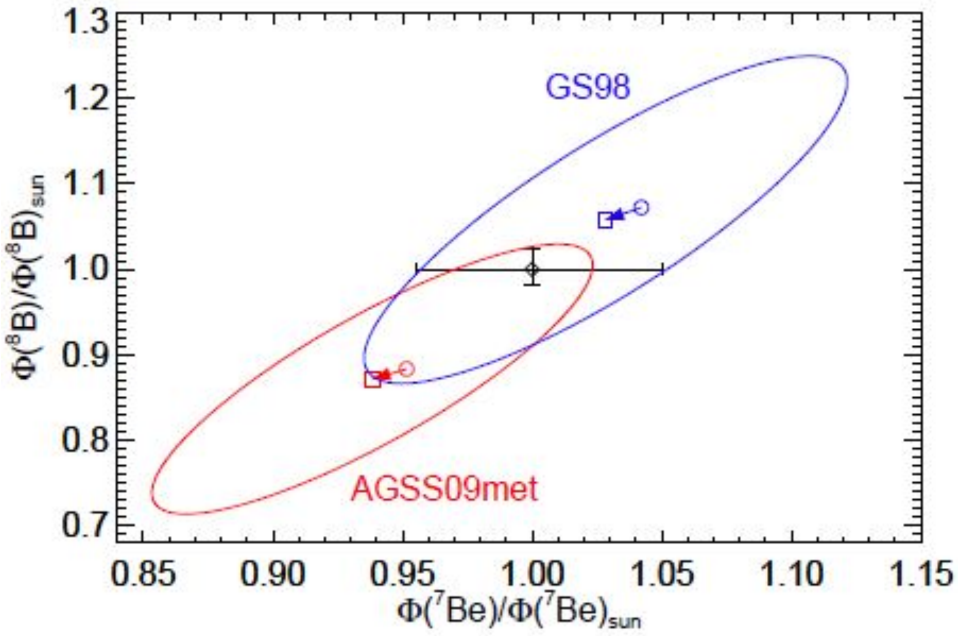




Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001

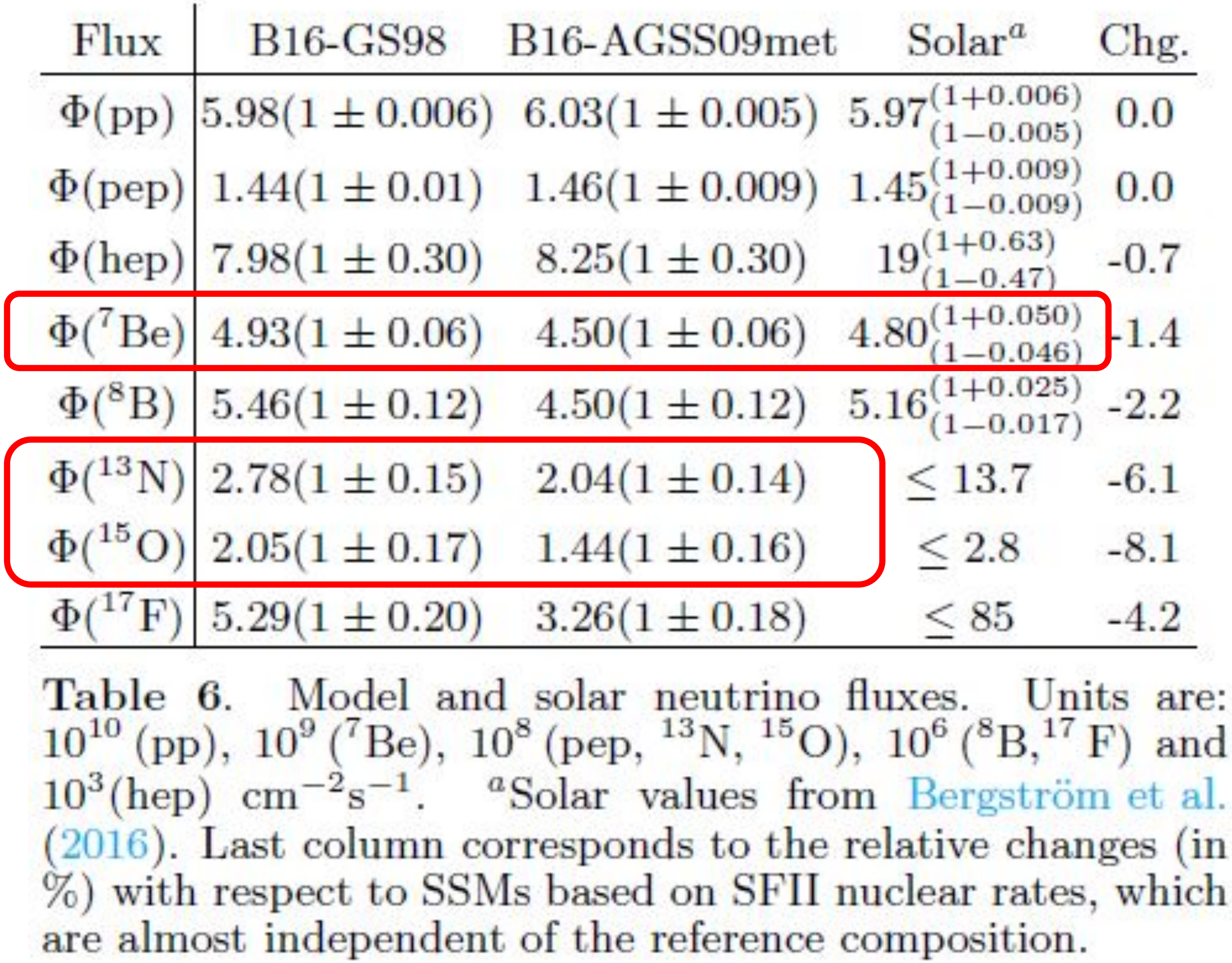
Very good agreement for B16-GS98 (0.5σ)
and a poor one (2.1σ) for B16-AGSS09met.

N. Vinyoles et al., arXiv:1611.09867



^{8}B and ^{7}Be fluxes normalized to solar values (Bergstrom et al. 2016). 1σ solar models.

N. Vinyoles et al., arXiv:1611.09867



Flux	B16-GS98	B16-AGSS09met	Solar^a	Chg.
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$	0.0
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$	0.0
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$	-0.7
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$	-1.4
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$	-2.2
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7	-6.1
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8	-8.1
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85	-4.2

Table 6. Model and solar neutrino fluxes. Units are: 10^{10} (pp), 10^9 (^{7}Be), 10^8 (pep, ^{13}N, ^{15}O), 10^6 (^{8}B,^{17}F) and 10^3(hep) cm^{-2}s^{-1}. ^{a}Solar values from Bergström et al. (2016). Last column corresponds to the relative changes (in %) with respect to SSMs based on SFII nuclear rates, which are almost independent of the reference composition.

Is CNO ν's measurement will allow to solve the metallicity ?

Solar neutrinos :

messengers from the core of the Sun and talented wizards

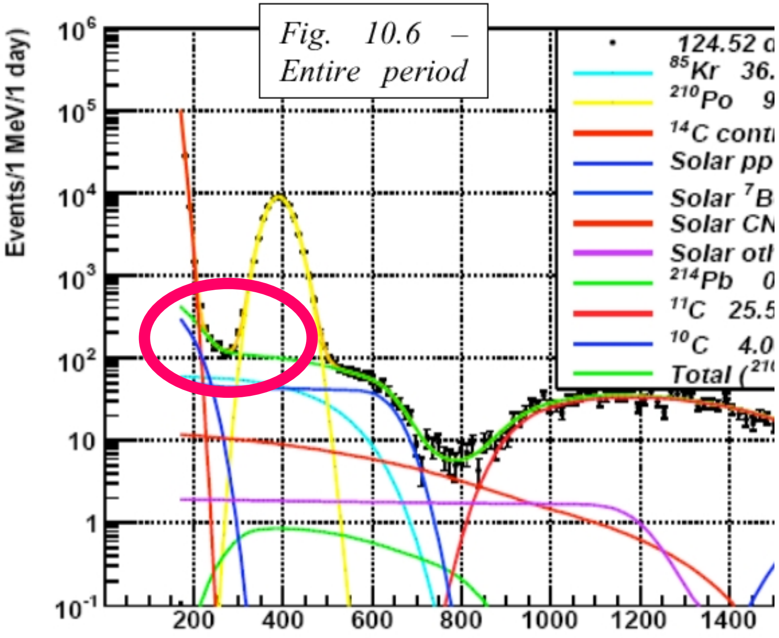
1. Solar neutrinos, witnesses of the core of the Sun
2. Archaeology (1968-2001) : the solar neutrino problem
3. Towards solar neutrino spectroscopy
4. S particle physics
5.

?

Future for solar ν in Borexino

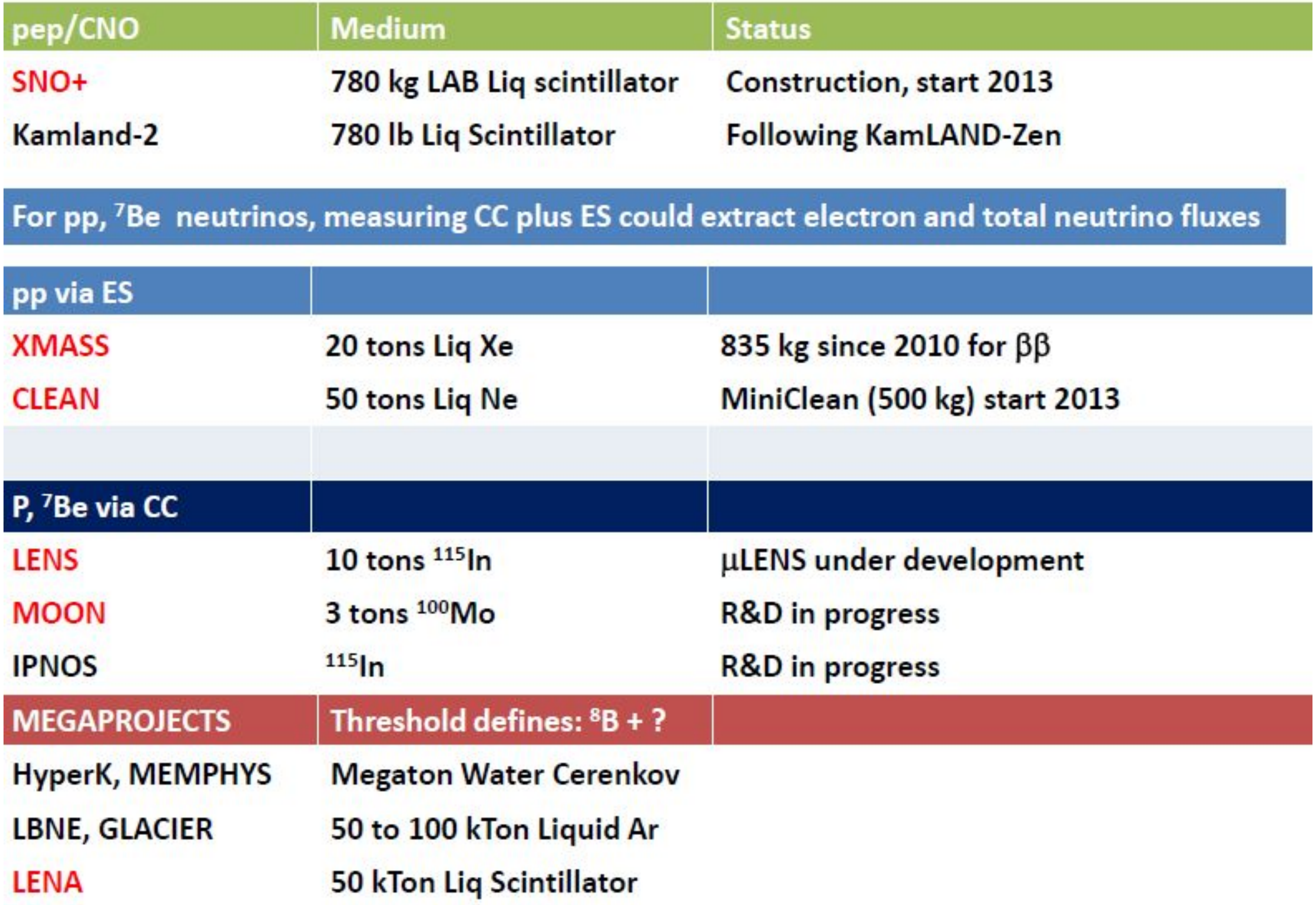
❶ measure **CNO** ν (if suppression of ^{210}Bi) ?

❷ improve pp, ^{7}Be, ^{8}B



Many astrophysical implications :
- Help to solve the metallicity problem
- Check homogeneous young Sun (e.g. accretion during formation of planetary system) ,…

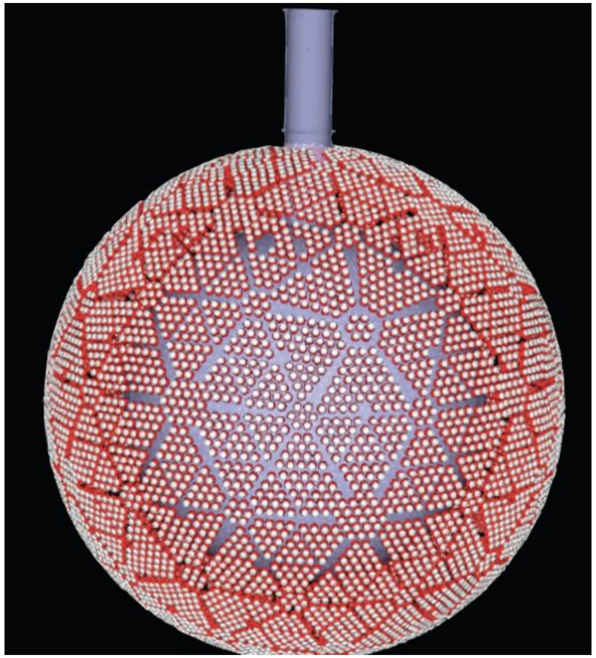
Future Solar ν experiments (beyond Borexino)



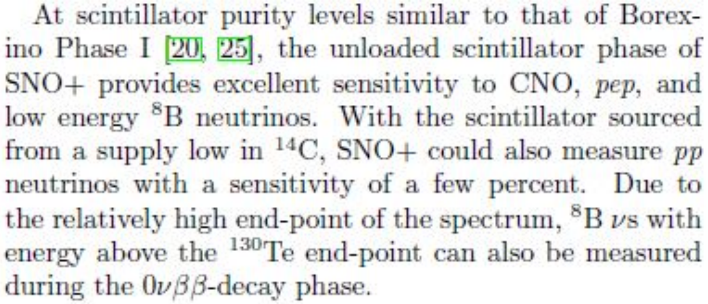
pep/CNO	Medium	Status
SNO+	780 kg LAB Liq scintillator	Construction, start 2013
Kamland-2	780 lb Liq Scintillator	Following KamLAND-Zen
For pp, ^{7}Be neutrinos, measuring CC plus ES could extract electron and total neutrino fluxes		
pp via ES		
XMASS	20 tons Liq Xe	835 kg since 2010 for ββ
CLEAN	50 tons Liq Ne	MiniClean (500 kg) start 2013
P, ^{7}Be via CC		
LENS	10 tons ^{115}In	μLENS under development
MOON	3 tons ^{100}Mo	R&D in progress
IPNOS	^{115}In	R&D in progress
MEGAPROJECTS	Threshold defines: ^{8}B + ?	
HyperK, MEMPHYS	Megaton Water Cerenkov	
LBNE, GLACIER	50 to 100 kTon Liquid Ar	
LENA	50 kTon Liq Scintillator	

A. Mc Donald, Neutrino 2012

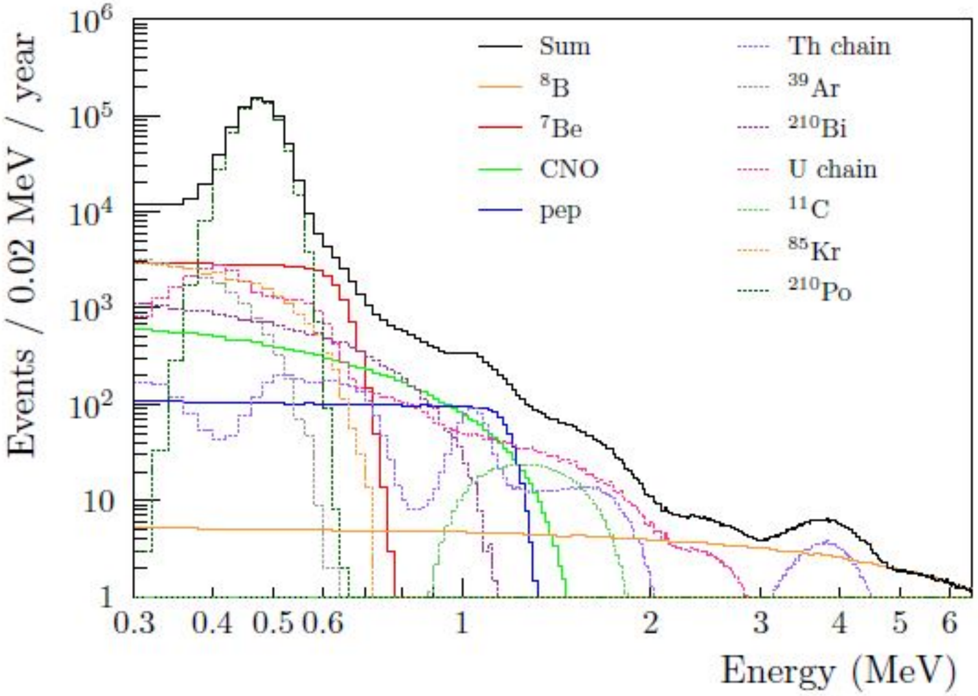
SNO+

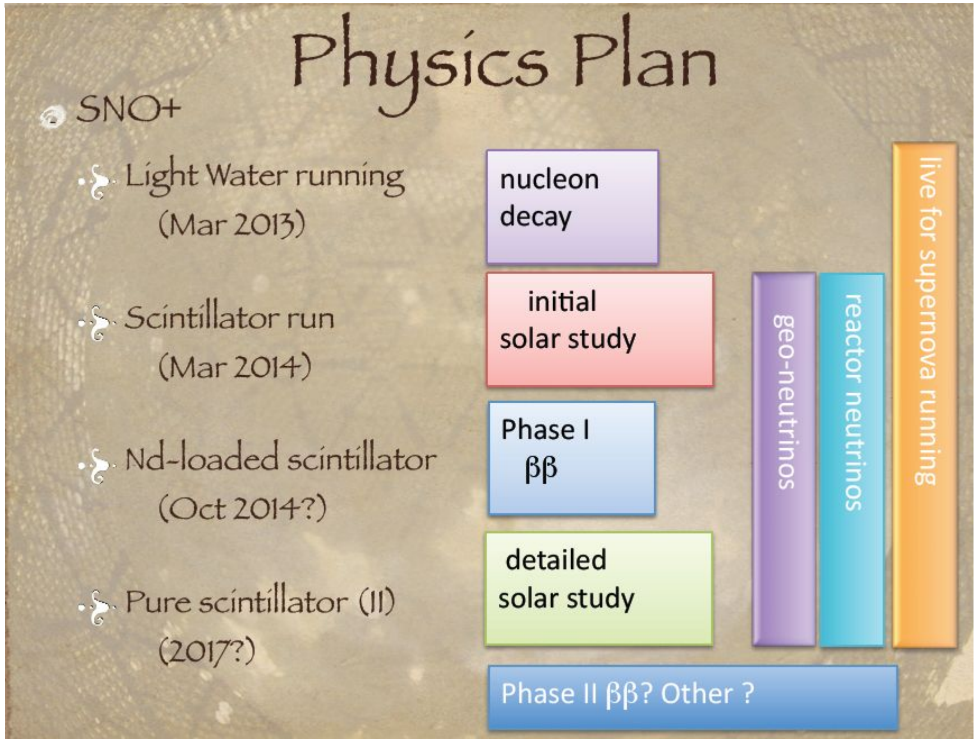


Liquid scintillator (Linear Alkyl Benzene LAB) in the old SNO sphere



At scintillator purity levels similar to that of Borexino Phase I [20, 25], the unloaded scintillator phase of SNO+ provides excellent sensitivity to CNO, *pep*, and low energy ^{8}B neutrinos. With the scintillator sourced from a supply low in ^{14}C, SNO+ could also measure *pp* neutrinos with a sensitivity of a few percent. Due to the relatively high end-point of the spectrum, ^{8}B νs with energy above the ^{130}Te end-point can also be measured during the $0\nu\beta\beta$-decay phase.





Physics Plan

- SNO+
  - Light Water running (Mar 2013)
  - Scintillator run (Mar 2014)
  - Nd-loaded scintillator (Oct 2014?)
  - Pure scintillator (II) (2017?)

nucleon decay

initial solar study

Phase I ββ

detailed solar study

Phase II ββ? Other ?

geo-neutrinos

reactor neutrinos

live for supernova running

☹ **Schedule delayed**

arXiv:1508.05759

Conclusion

- Since 50 years, solar neutrinos have been a major and exciting topic at the crossroad of particle physics, astrophysics and astroparticle physics
- Two Nobel prizes have rewarded the main successes
- We know « how the Sun shines » and solar neutrino spectroscopy is now impressive
- The experiments fix fluxes for solar models
- The elegant (and now precise) “oscillation” solution LMA-MSW has convinced the more sceptical physicists
- Future : CNO ? Precision measurements ?


Talented wizards ?
ν_e
ν_τ
ν_μ


ν_e
ν_τ
ν_μ


ν_e
ν_τ
ν_μ


ν_τ
ν_e
ν_μ


ν_e
ν_τ
ν_μ


ν_e
ν_τ
ν_μ


ν_e
ν_μ
ν_τ

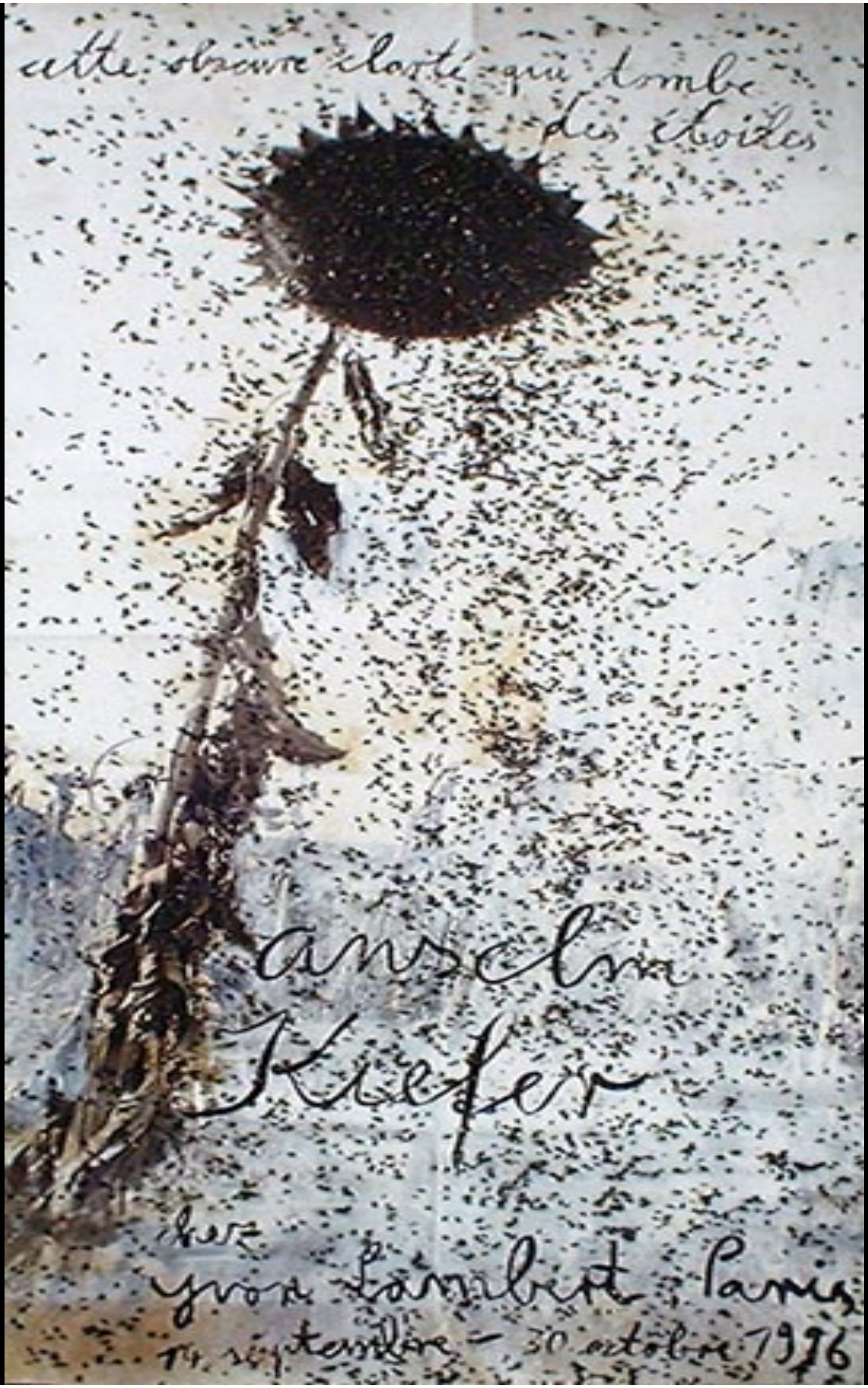

ν_e
ν_τ
ν_μ

Thanks to Symmetry magazine

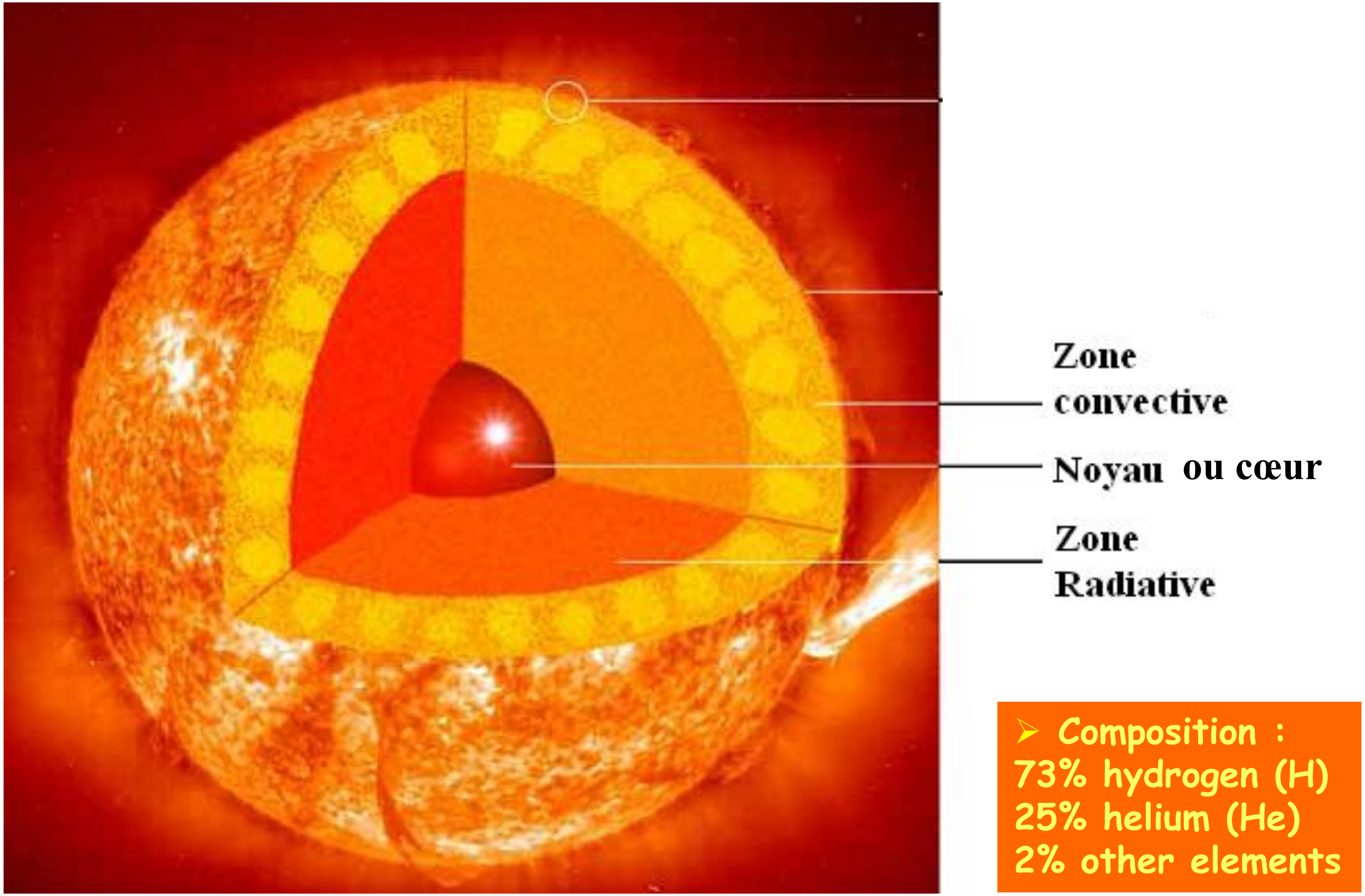
④ This obscure clarity falling from the stars !

Pierre Corneille (Le Cid) & Anselm Kiefer

E N D

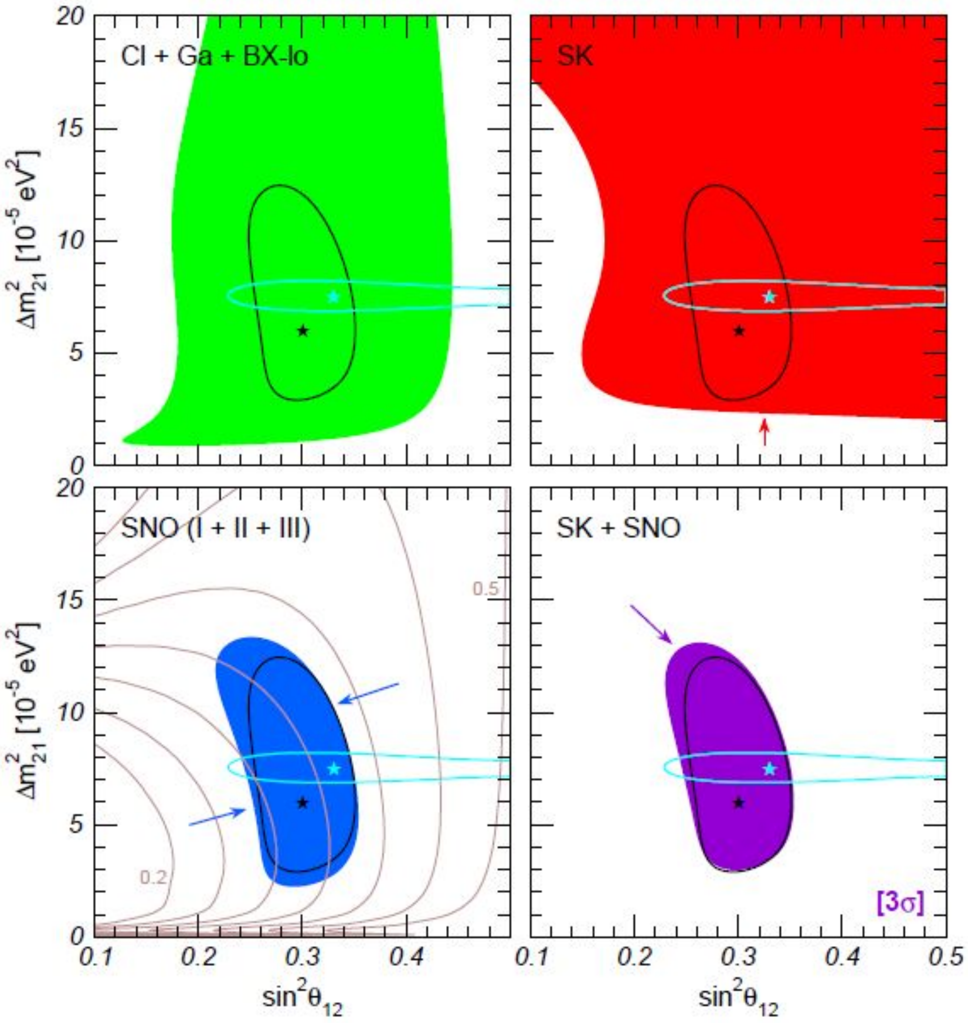


HAVE A LOOK INSIDE THE SUN



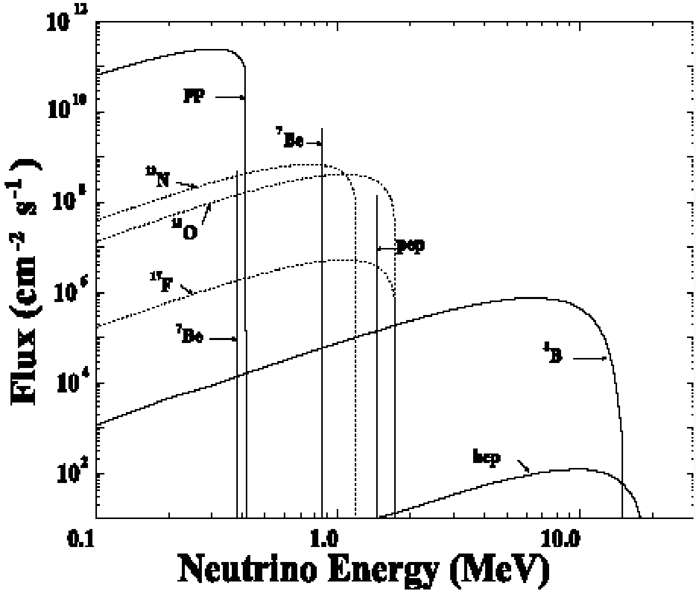
- **Composition :**
73% hydrogen (H)
25% helium (He)
2% other elements

Solar neutrinos and oscillation parameters (precision)

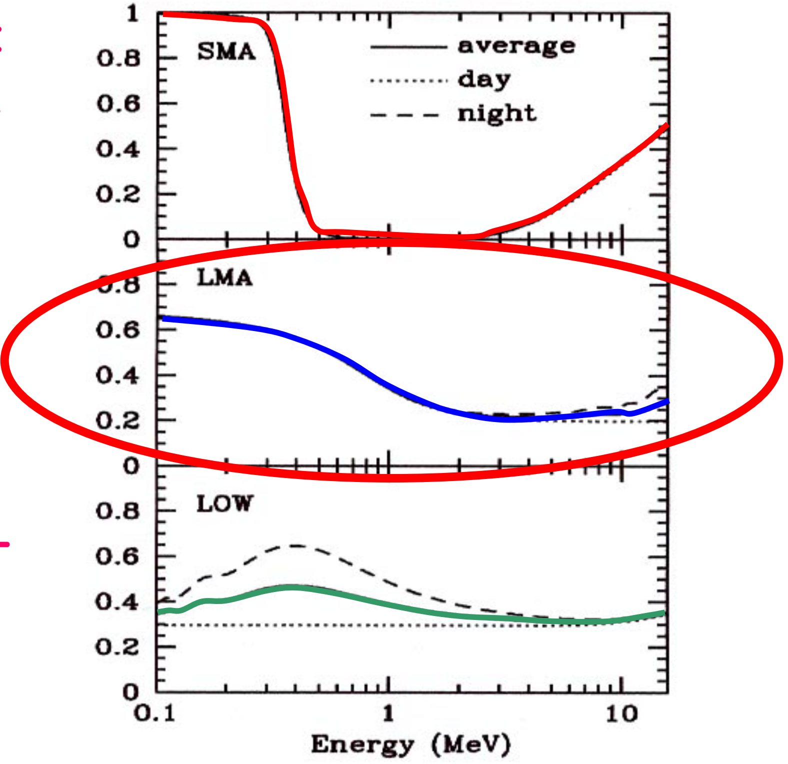


M. Maltoni, Physun 2012

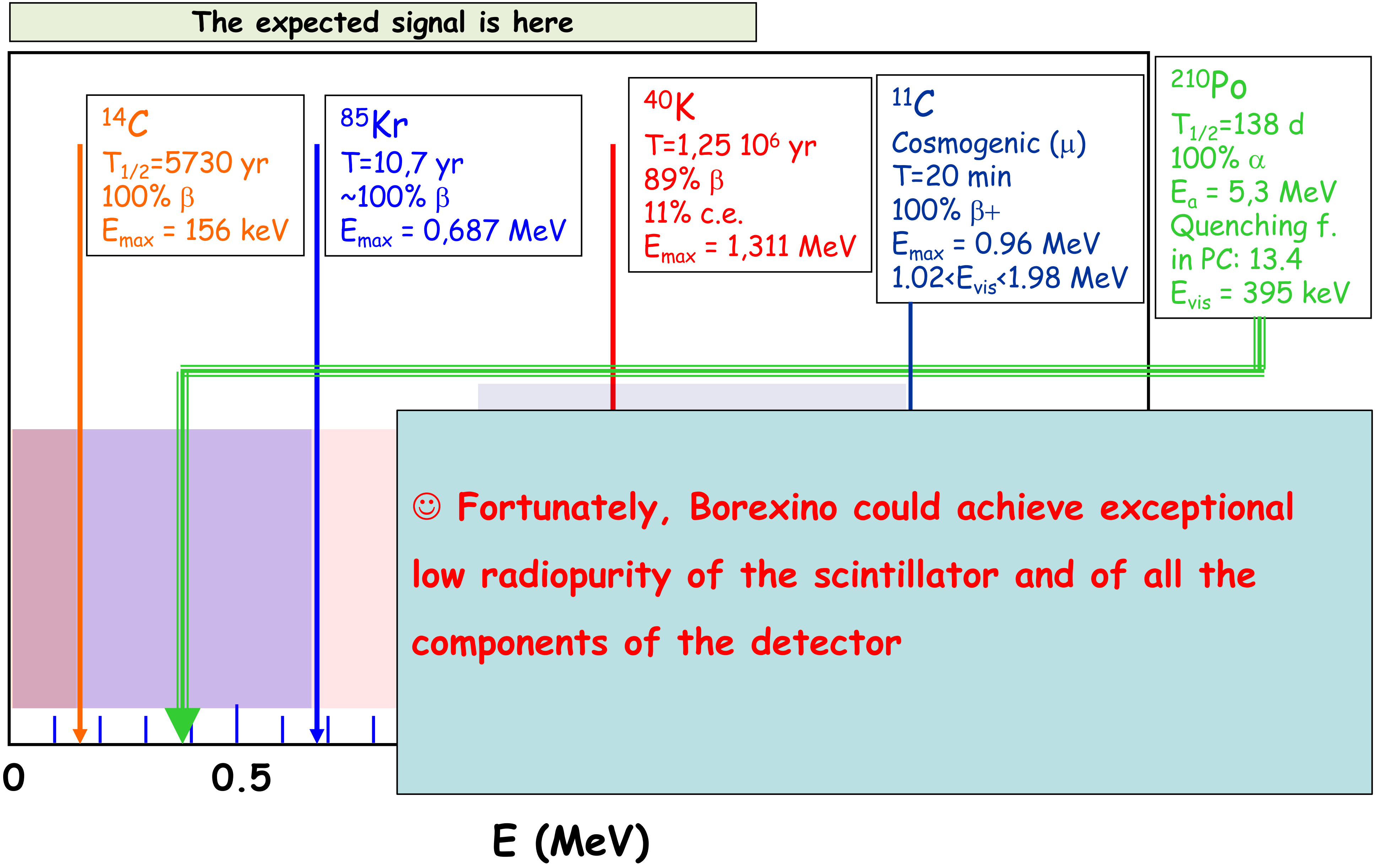
How the solar neutrino spectrum is modified by the MSW effect ?



Survival probabilities with MSW effect



Many radioactive enemies !



The expected signal is here

^{14}C
$T_{1/2}$=5730 yr
100% β
E_{max} = 156 keV

^{85}Kr
T=10,7 yr
~100% β
E_{max} = 0,687 MeV

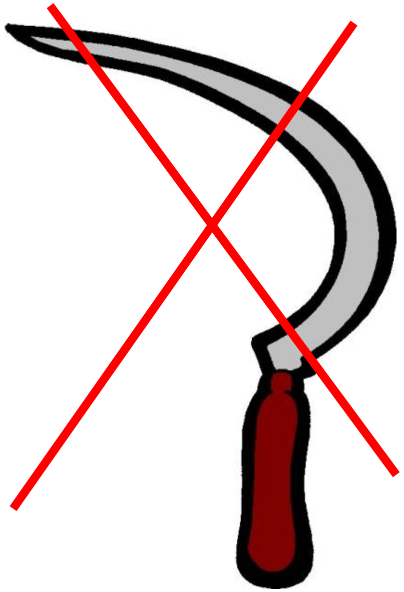
^{40}K
T=1,25 10^6 yr
89% β
11% c.e.
E_{max} = 1,311 MeV

^{11}C
Cosmogenic (μ)
T=20 min
100% β+
E_{max} = 0.96 MeV
1.02<E_{vis}<1.98 MeV

^{210}Po
$T_{1/2}$=138 d
100% α
E_{α} = 5,3 MeV
Quenching f. in PC: 13.4
E_{vis} = 395 keV

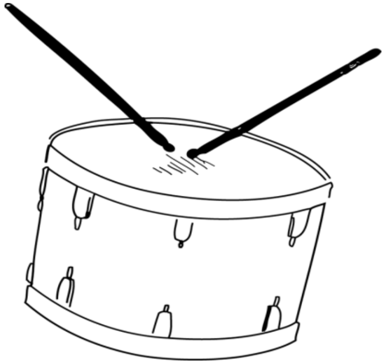
☺ **Fortunately, Borexino could achieve exceptional low radiopurity of the scintillator and of all the components of the detector**

How ? 2 tools

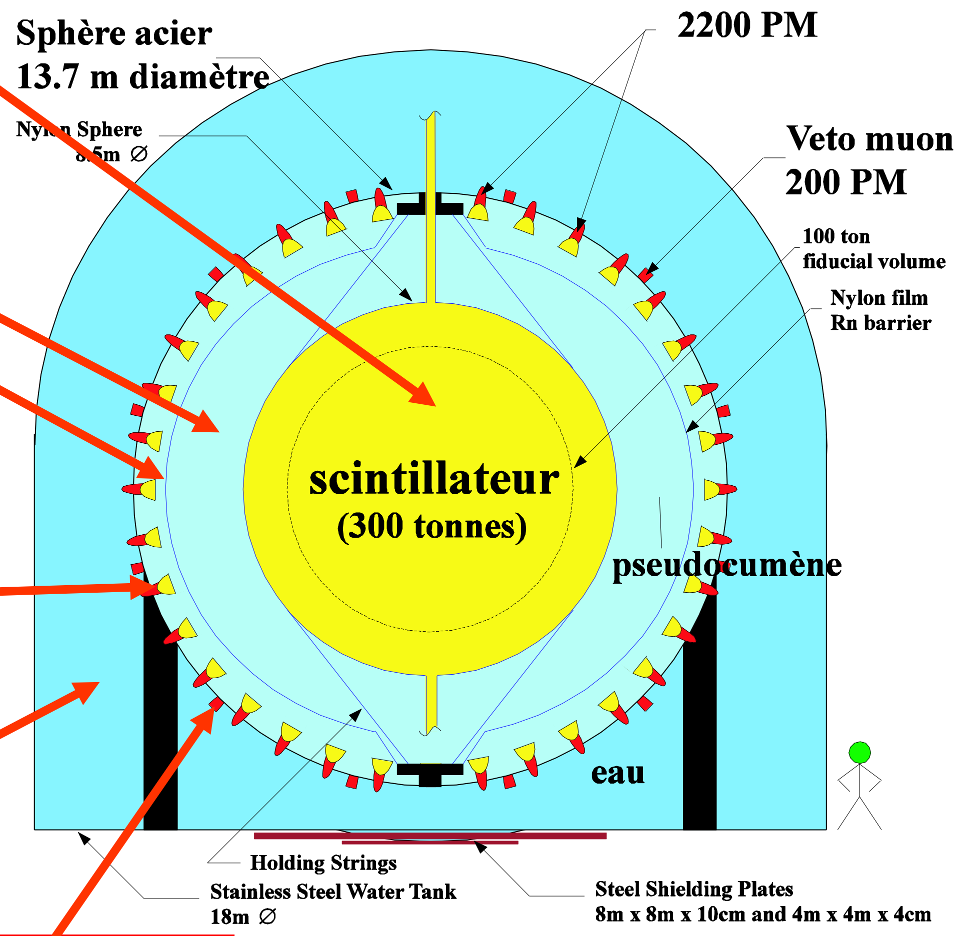


Neutrinos ν

Helioseismology



➢ Borexino is underground the Gran Sasso mountain (3800 m.w.e.)



Target: 300 tons of liquid scintillator in a nylon vessel (4,25 m radius)

1er shielding: 900 tons of liquid scintillator

2nd nylon vessel (against radon)

2200 photomultipliers looking at the center

2nd shielding: 2100 tons of water

208 PMTs to sign muons (veto)

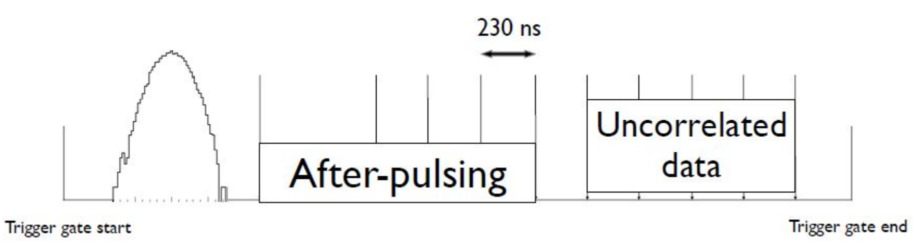
Towards pp neutrinos

Le « pile-up » et comment s’en débarrasser

Pile-up : deux événements si proches en temps qu’on ne peut les séparer (le second profite de la porte ouverte pour s’engouffrer)

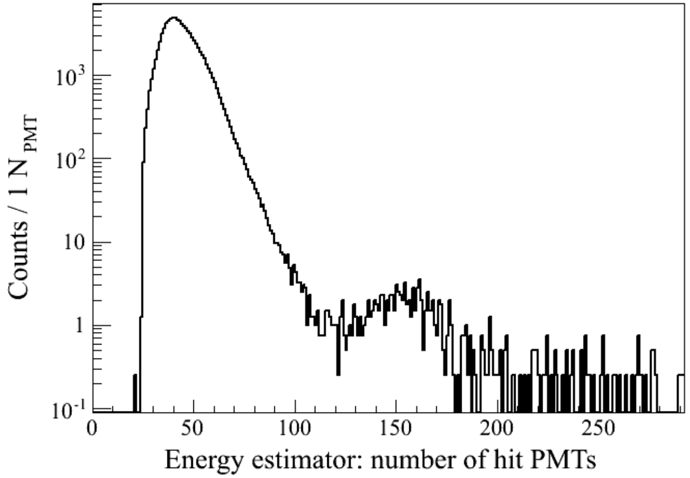
L’essentiel est dû au ^{14}C (mais aussi bruit de fond externe, PMT dark noise ou 210Po).
Estimation du taux :
(300 tonnes x 40 Bq/100 t) x 40 Bq/100 t x 230 ns = 100 cpd / 100 t

A comparer avec le taux attendu de ν-pp : 130 cpd / 100 t



Synthetic pile-up : on « overlappe » des données non corrélées avec les événements réguliers.

Fit du pile-up ^{14}C-^{14}C : 154±10 cpd / 100 t



Spectre en énergie des données pile-up

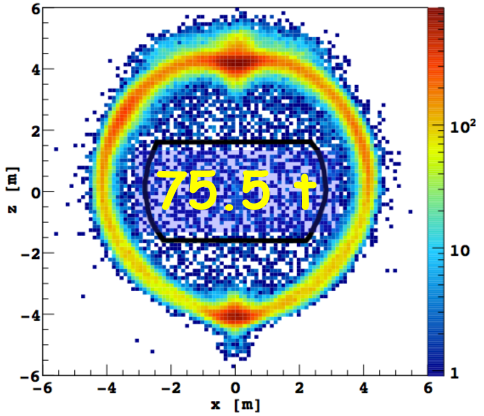
Towards pp neutrinos

Towards the fit !

1. Sélection des données (Janvier 2012 – Mai 2013 : 408 jours).

2. Calcul de l'énergie (passer du nombre de PMTs en keV [calibration + Monte Carlo]), de la position pour tous les événements,….

3. Coupures :
   a) Pas de coïncidence avec un μ (veto de 300 ms)
   b) Reconstruction dans le volume fiduciel :
   $R < 3.021$ m et $|z| > 1.67$ m.
   c) …



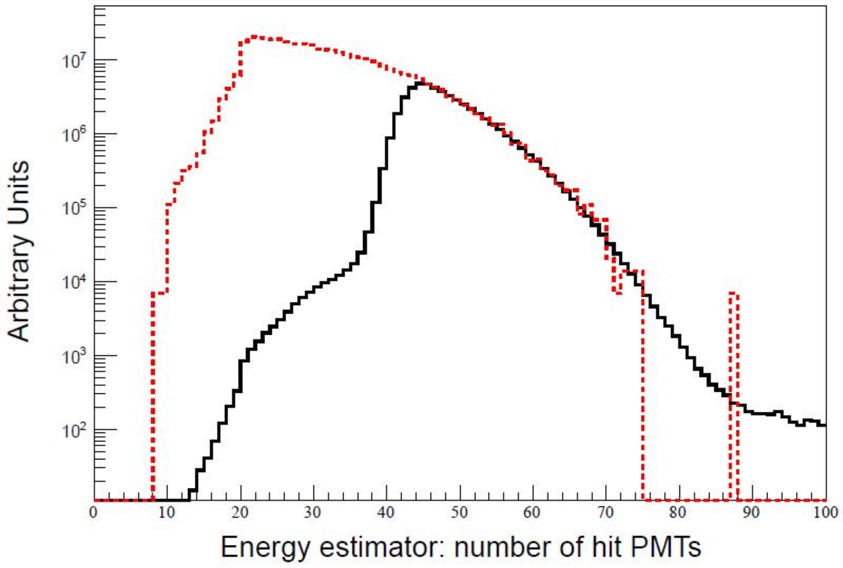
4. Contraindre le ^{14}C.

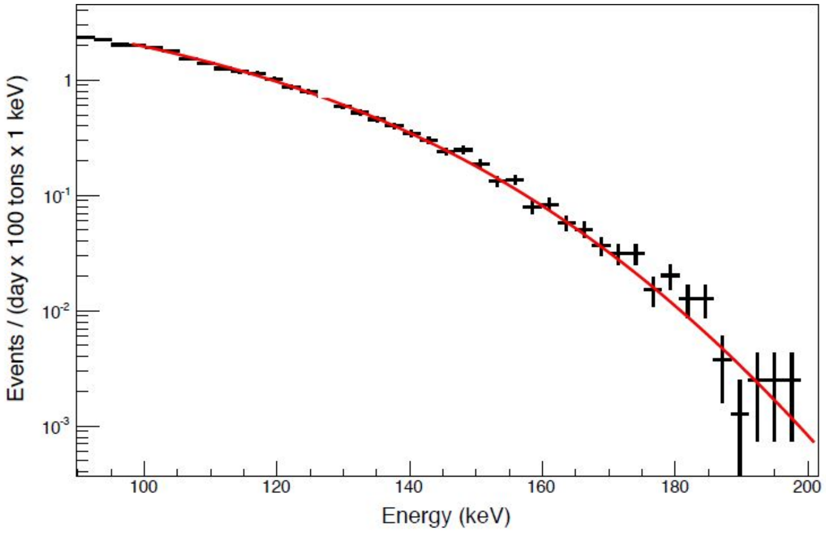
5. Contraindre le pile-up.

6. Effectuer le « fit spectral » entre 165 et 590 keV. Utilise un outil software développé précédemment.

Towards pp neutrinos

Estimation of ^{14}C (public enemy n°1)





^{14}C determined from a sample where the event provoking the trigger is followed by a second event (in red) in a 16 ms window (in black: spectrum of the triggered events)

^{14}C fit

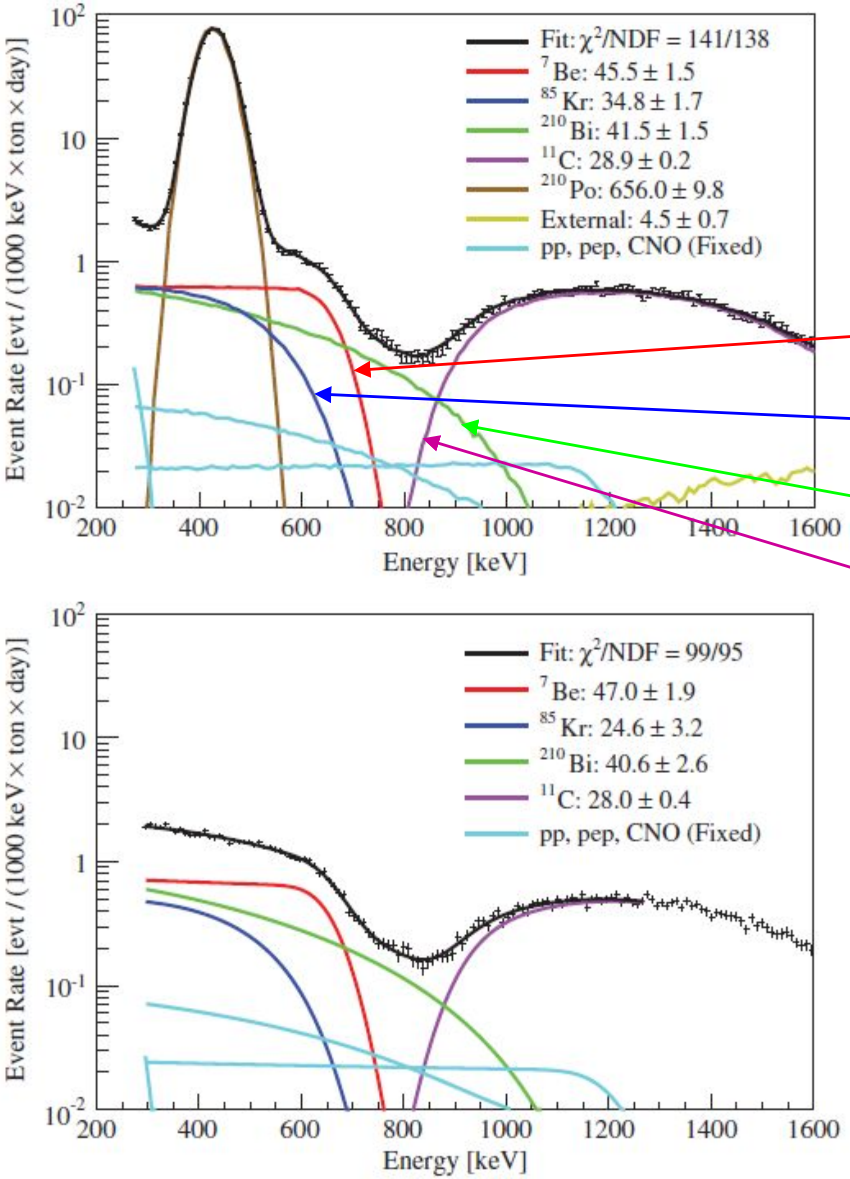
40±1 Bq/100 t

corresponds to

$2.7\pm0.1\ 10^{-18}$ g/g of $^{14}C/^{12}C$

(origin « oil » du scintillator)

Towards ^{7}Be solar ν



Events / day / 100 tons :

^{7}Be: 46.0 ± 1.5 ± 1.5

^{85}Kr: 31.2 ± 1.7 ± 4.7

^{210}Bi: 41 ± 1.5 ± 2.3

^{11}C : 28.5 ± 0.2 ± 0.7

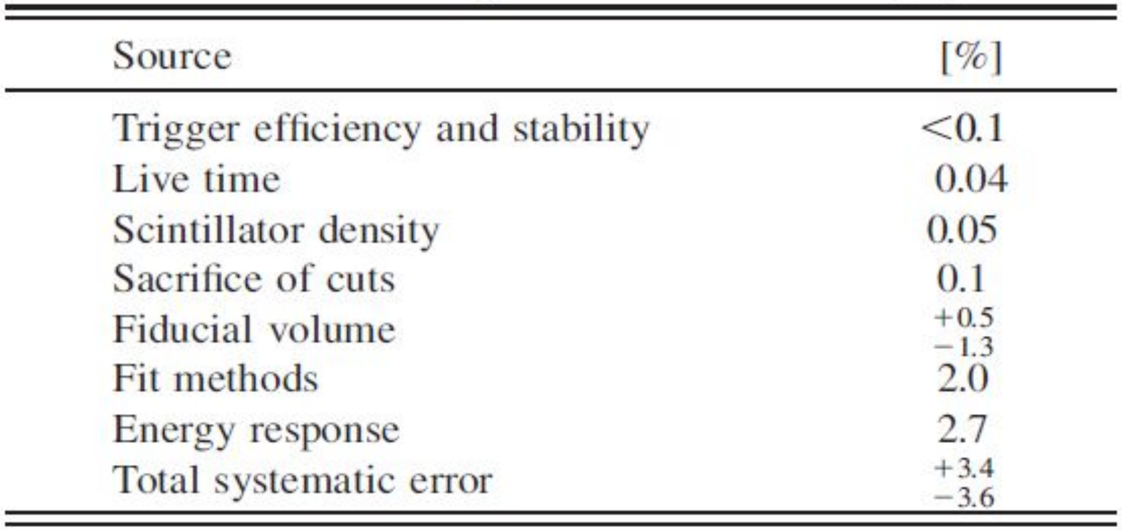
2 types of fit :

1) No subtraction of α from ^{210}Po - Energy from number of photons
2) Subtraction of α (pulse shape method by Gatti) - Energy from total charge

Towards ^{7}Be solar ν

46.0 ± 1.5 (stat) ± 1.5 (syst) ev./day /100 tons
for ^{7}Be (862 keV) $\nu_\odot$

Systematic errors



Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Fiducial volume	$^{+0.5}_{-1.3}$
Fit methods	2.0
Energy response	2.7
Total systematic error	$^{+3.4}_{-3.6}$

$$\frac{\Phi(^7\text{Be-862 keV}) = (2.78 \pm 0.13)\ 10^9\ \text{cm}^{-2}\ \text{s}^{-1}}{\text{SSM-High Met} = (4.48 \pm 0.31)\ 10^9\ \text{cm}^{-2}\ \text{s}^{-1}}$$

Ratio = 0.62 ± 0.05

$P_{ee} = 0.51 \pm 0.07$

$[\sigma(\nu_e)=4.5\ \sigma(\nu_\mu,\nu_\tau)]$

arXiv:1104.1816
Phys. Rev. Lett. 107, 141302 (2011)

$$\frac{\Phi(^{7}\mathrm{Be}\text{-}862\ \mathrm{keV}) = (2.78 \pm 0.13)\ 10^{9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}{\text{SSM-High Met} = (4.48 \pm 0.31)\ 10^{9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$$

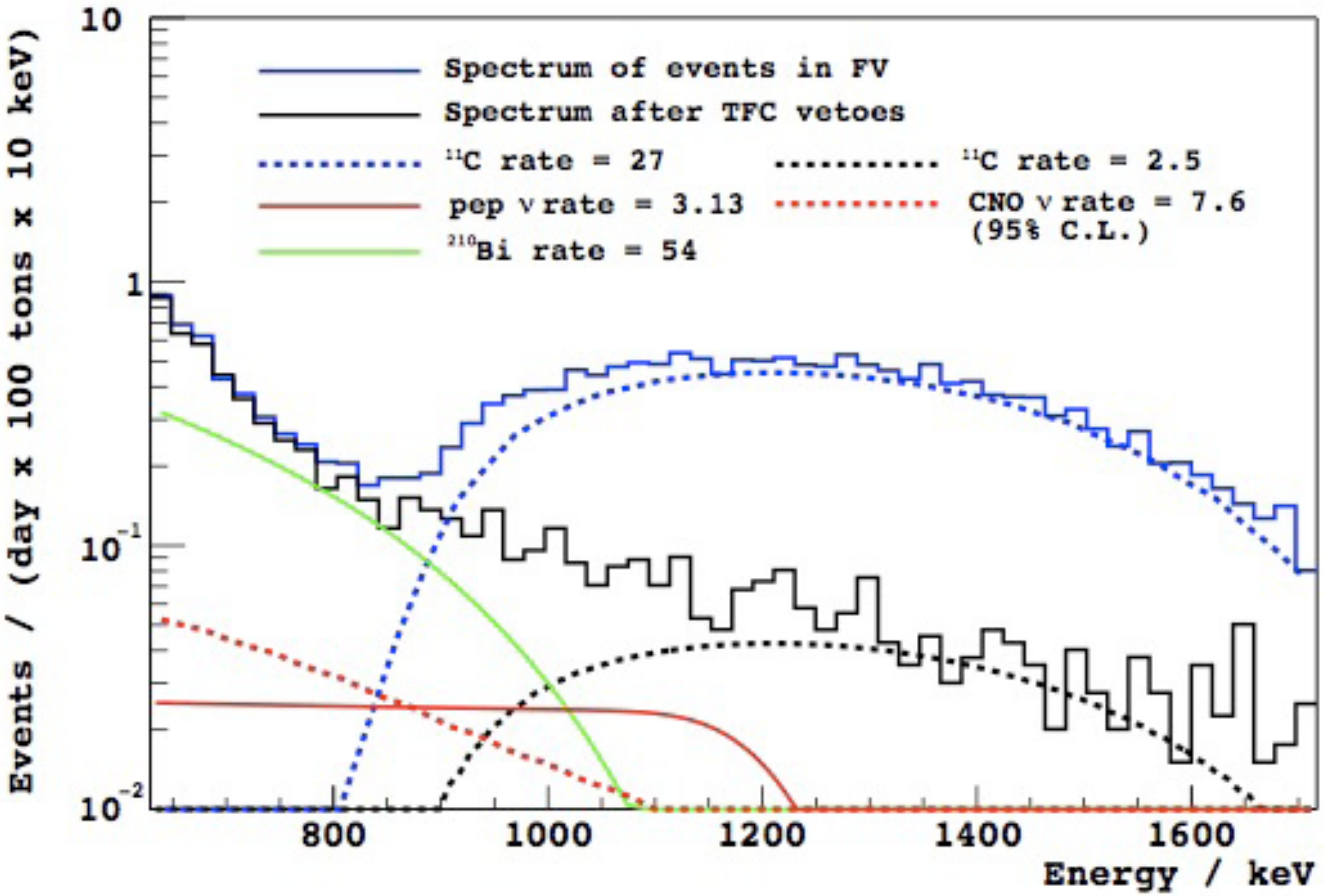
$\mathrm{Ratio} = 0.62 \pm 0.05$

$P_{ee} = 0.51 \pm 0.07$

$[\sigma(\nu_e)=4.5\ \sigma(\nu_\mu,\nu_\tau)]$

Towards pep and CNO ν

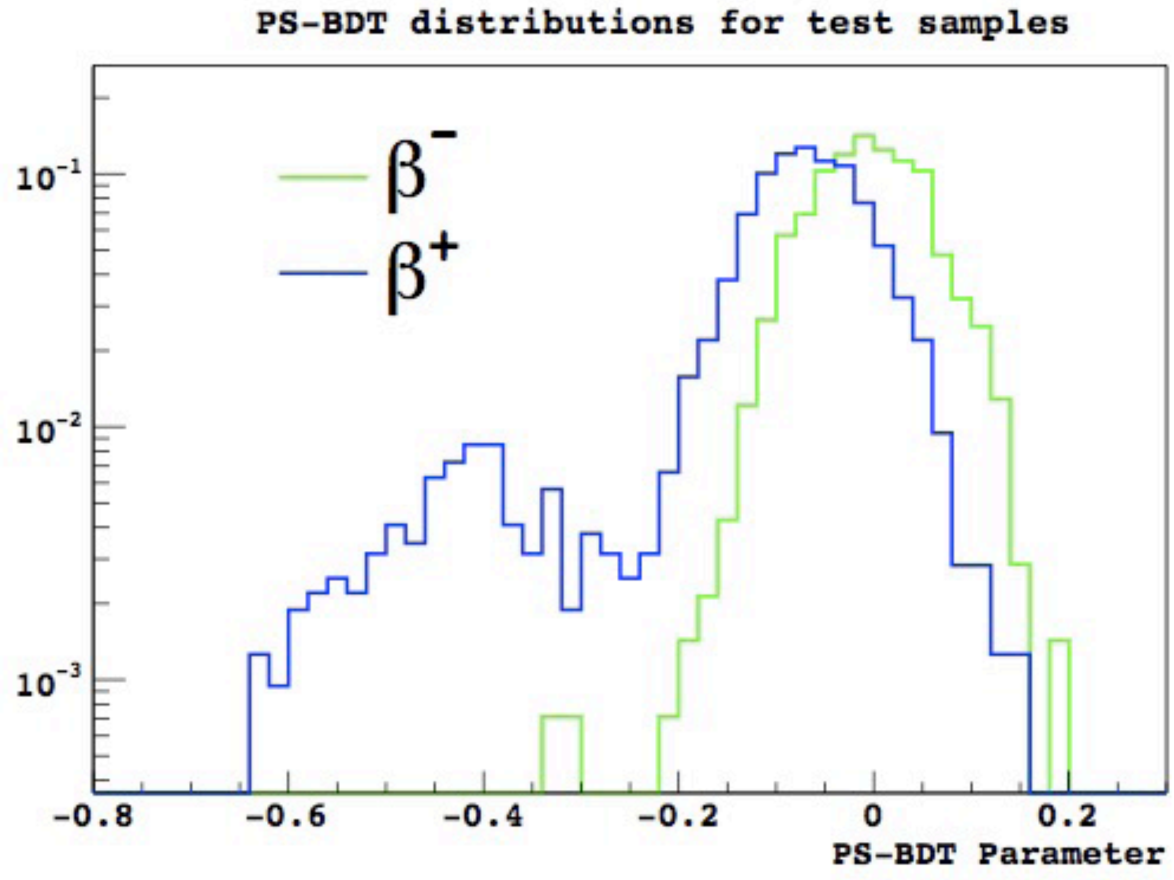
I. Three-fold coincidence : space and time veto after coinc. between μ and cosmogenic n



Remove 91% of ^{11}C with a livetime sacrifice of 51.5%.

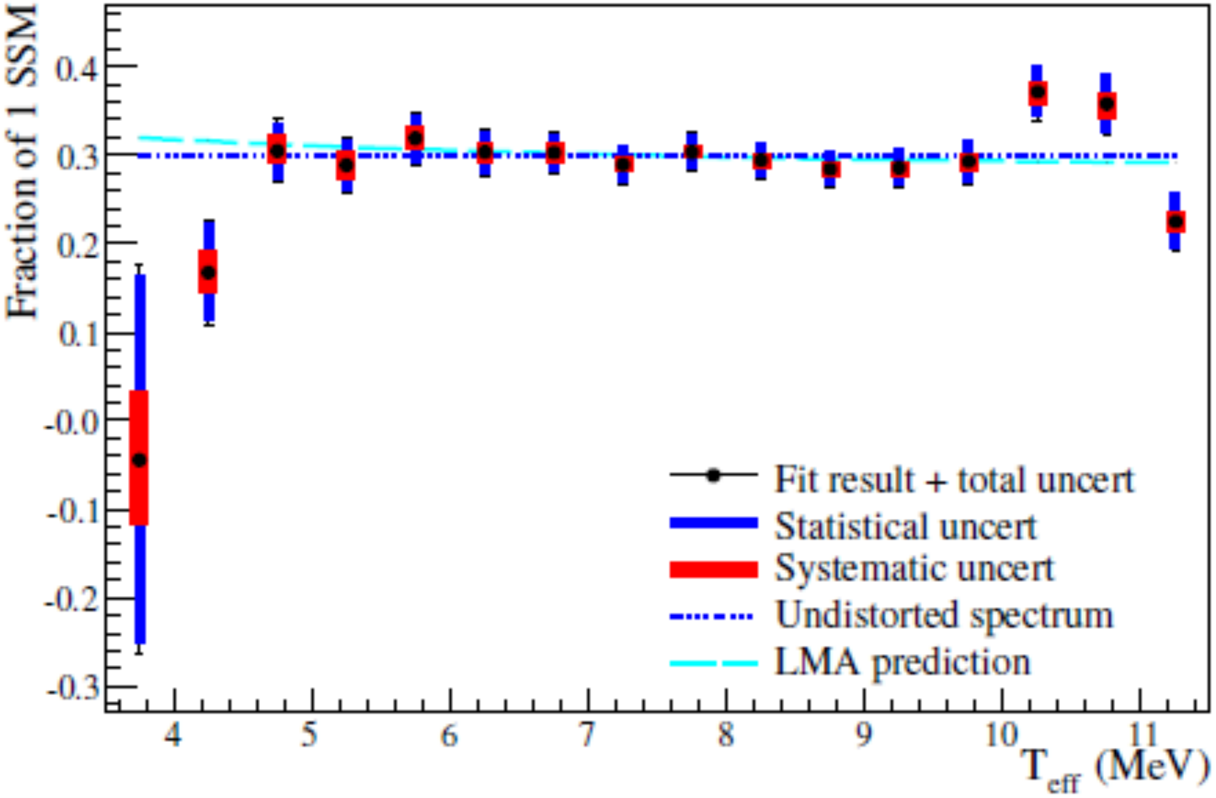
Towards pep and CNO ν

II. Pulse shape discrimination between e^+ and e^- (50% of e^+ give orthopositronium ($t_{1/2}$=3 ns))



SNO : what's new ?
I- Low Energy Threshold

I- LETA (Low Energy Threshold Analysis) : T_{eff} > 3.5 MeV

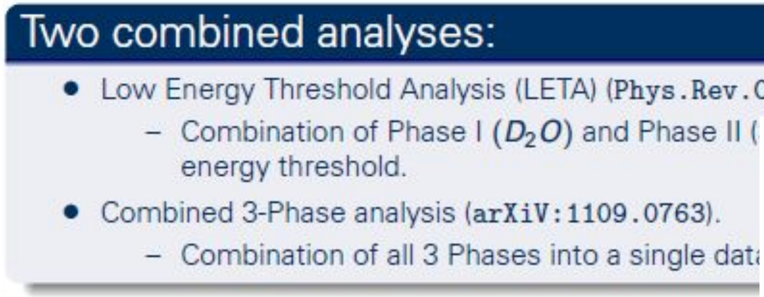


Low energy spectrum still consistent with no distortion

Phys. Rev. C81 (2010) 055504

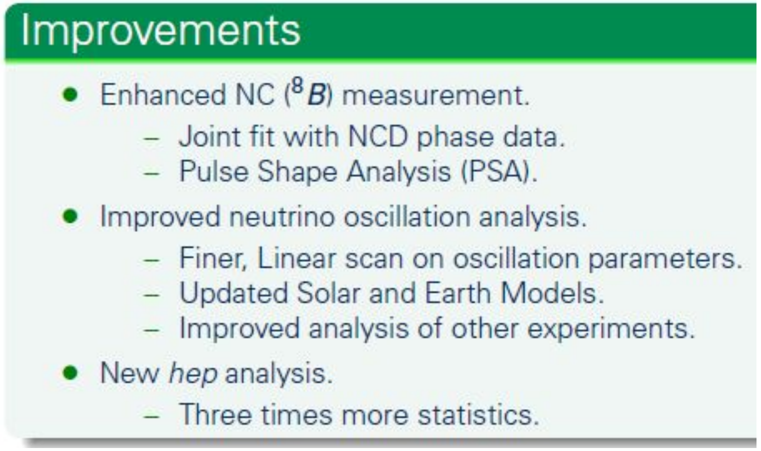
SNO : what's new ?
II- 3 phase analysis

Combine data taking phases into a single analysis (to avoid double counting of common systematics)



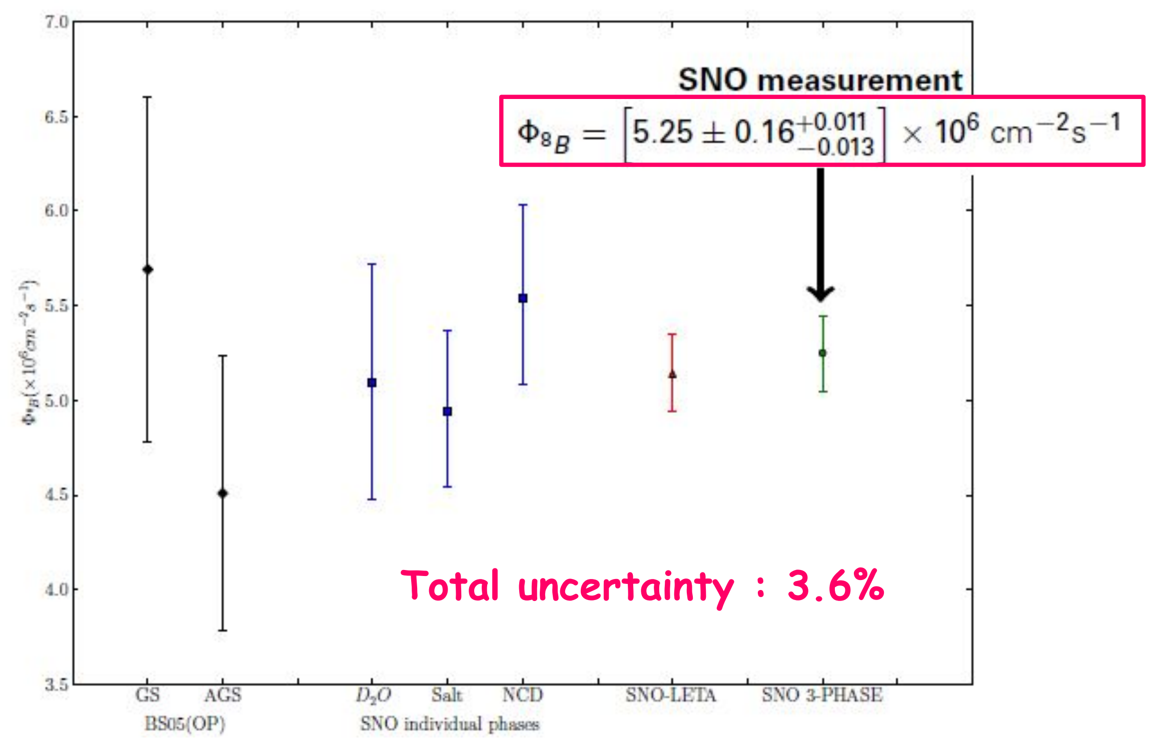
Two combined analyses:

- Low Energy Threshold Analysis (LETA) (`Phys.Rev.C81:055504,2010`).
  - Combination of Phase I (D_2O) and Phase II (
    energy threshold.
- Combined 3-Phase analysis (`arXiV:1109.0763`).
  - Combination of all 3 Phases into a single dat



Improvements

- Enhanced NC (^8B) measurement.
  - Joint fit with NCD phase data.
  - Pulse Shape Analysis (PSA).
- Improved neutrino oscillation analysis.
  - Finer, Linear scan on oscillation parameters.
  - Updated Solar and Earth Models.
  - Improved analysis of other experiments.
- New *hep* analysis.
  - Three times more statistics.



SNO measurement

$$\Phi_{^8B} = \left[5.25 \pm 0.16^{+0.011}_{-0.013}\right] \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Total uncertainty : 3.6%

N. Fiuza de Barros, NOW 2012