Intertwinements in the determinations of PP and CNO neutrinos and the luminosity constraint

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The great observational progresses in the determination of solar neutrinos poses us new challenges, after the understanding of oscillations. For various of these current and urgent issues, the **luminosity constraint** plays a key role: we examine it critically improving the coefficients first obtained by Bahcall, we assess the importance of this constraint and we discuss various applications.

Interestingly, *the knowledge of PP and CNO neutrinos turns out to be intertwined:* An empirical determination of the PP neutrinos from the luminosity constraint is possible only if know the CNO neutrinos sufficiently well. Moreover, as discussed by Till Kirsten and Vladimir Gavrin, the interpretation of the Gallium results depends upon both fluxes; as shown by Daniele Guffanti at this workshop, a precise determination of the PEP neutrinos in Borexino is a prerequisite to extract the CNO neutrino signal; etc

The Standard Solar Model − see A Serenelli and FL Villante -- and current observational knowledge on the solar neutrino fluxes − see K Lande, H Robertson, Y Suzuki, T Kirsten, V Gavrin, M Wurms, D Guffanti

INTRODUCTION

Standard Solar Model Predictions

identification index i	pp	Be	pep	B	hep	N	O	F
exponent α_i	10	9	8	6	3	8	8	6
BU1988 [15]	6.0	4.7	1.4	5.8	7.6	6.1	5.2	5.2
errors	0.1	0.7	0.1	2.1	7.6	3.1	3.0	2.4
BP2000 [16]	5.95	4.77	1.40	5.05	9.3	5.48	4.80	5.63
errors	0.06	0.48	0.02	1.01	9.3	1.15	1.20	1.41
B16-GS98 [17]	5.98	4.93	1.44	5.46	7.98	2.78	2.05	5.29
errors	0.04	0.30	0.01	0.66	2.39	0.42	0.35	1.06
B16-AGSS09met [17]	6.03	4.50	1.46	4.50	8.25	2.04	1.44	3.26
errors	0.03	0.27	0.01	0.54	2.48	0.29	0.23	0.59

Table 1: *Theoretical predictions for the solar neutrino fluxes in a few SSM. In a few cases when they are not symmetric (of BP2000) we quote conservatively the maximum error.*

Standard Solar Model Predictions

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Table 1: *Theoretical p* … *v cases when they are*
not symmetric (of BP2 …

$$\Phi_i = \text{coeff} \times 10^{\alpha_i}$$

in $1/cm^2s$

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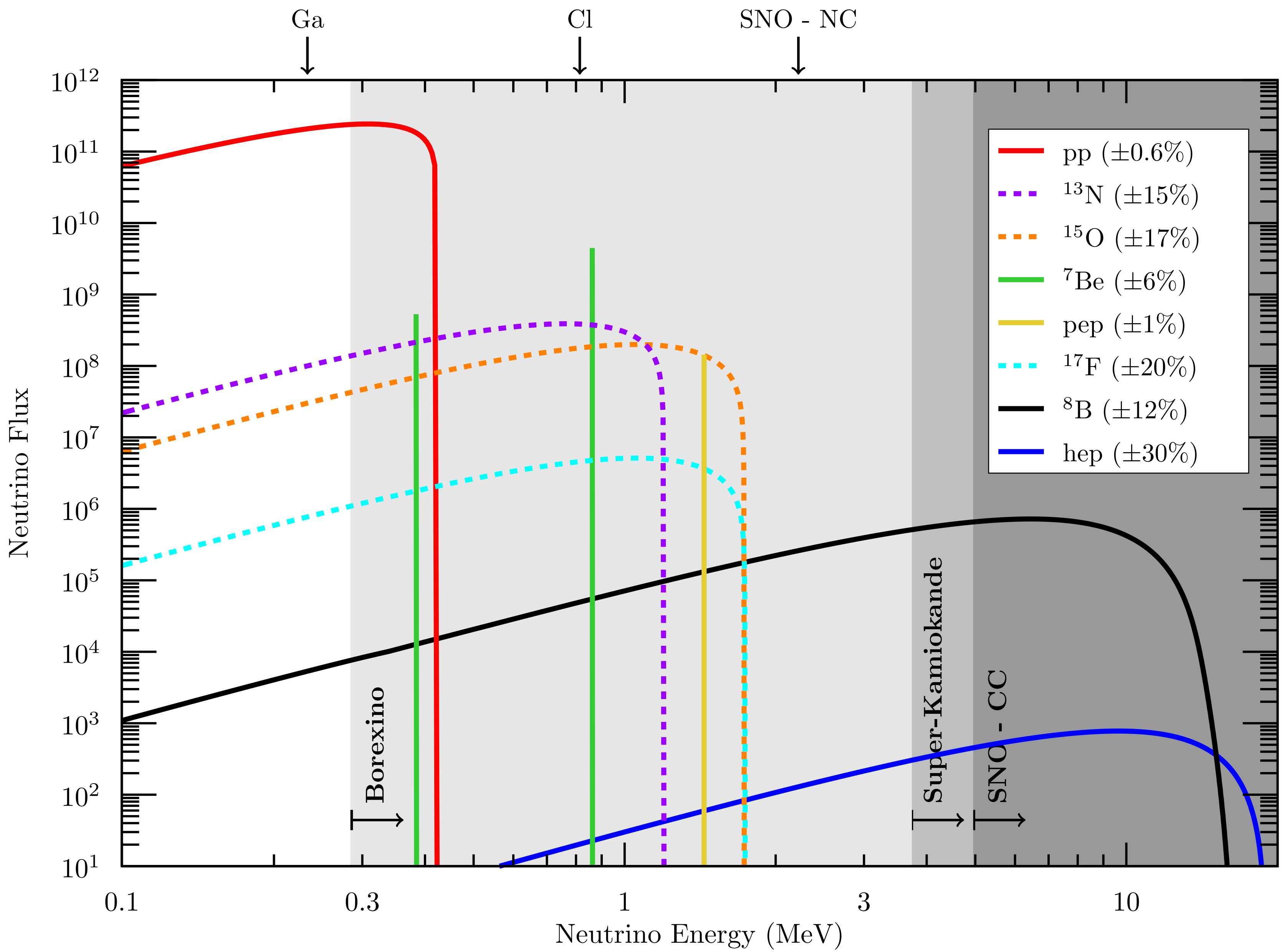

Gallo Rosso et al 2017 based on Vinyoles et al 2017

Fit results – Overview

JG|U

Results

arXiv : 1707.09279

- **Data-set:** Dec 14th 2011- May 21st 2016
- **Total exposure**: 1291.51 days x 71.3 tons
- **Fit range**: (0.19-2.93) MeV

Solar ν	Borexino experimental results		B16(GS98)-HZ		B16(AGSS09)-LZ	
	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	131.0 ± 2.4	$5.98\,(1 \pm 0.006) \times 10^{10}$	132.1 ± 2.3	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	47.8 ± 2.9	$4.93\,(1 \pm 0.06) \times 10^{9}$	43.7 ± 2.6	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^{8}$ (95% C.L.)	4.91 ± 0.56	$4.88\,(1 \pm 0.11) \times 10^{8}$	3.52 ± 0.37	$3.51\,(1 \pm 0.10) \times 10^{8}$

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remark on solar neutrino experiments

- The original goal of solar neutrino experiments was to measure neutrino fluxes – or to understand the Sun -- with the help of the SSM
- This was the concept of Homestake and it is the one of Borexino

- Strictly speaking, only SNO measured directly the SSM flux

  (note incidentally that H Chen refers to SSM)
- All other experiments (e.g. Borexino) can measure the fluxes, only relying on our understanding of oscillations

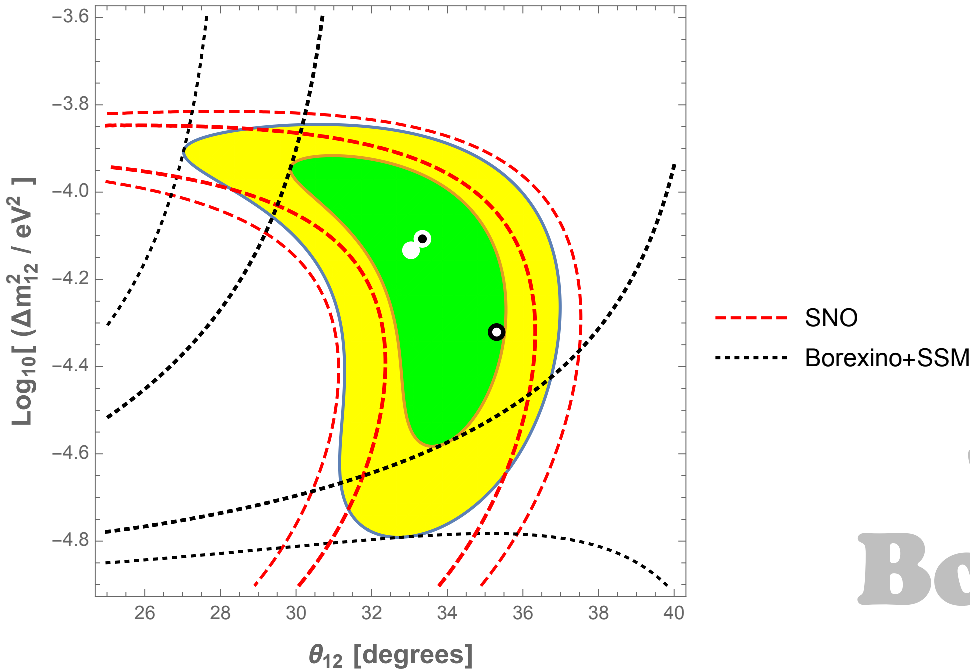
Current picture of neutrino oscillations − see Alexei Smirnov for the detailed explanation of how this works in practice, specially for the solar neutrinos

STATUS OF OSCILLATIONS

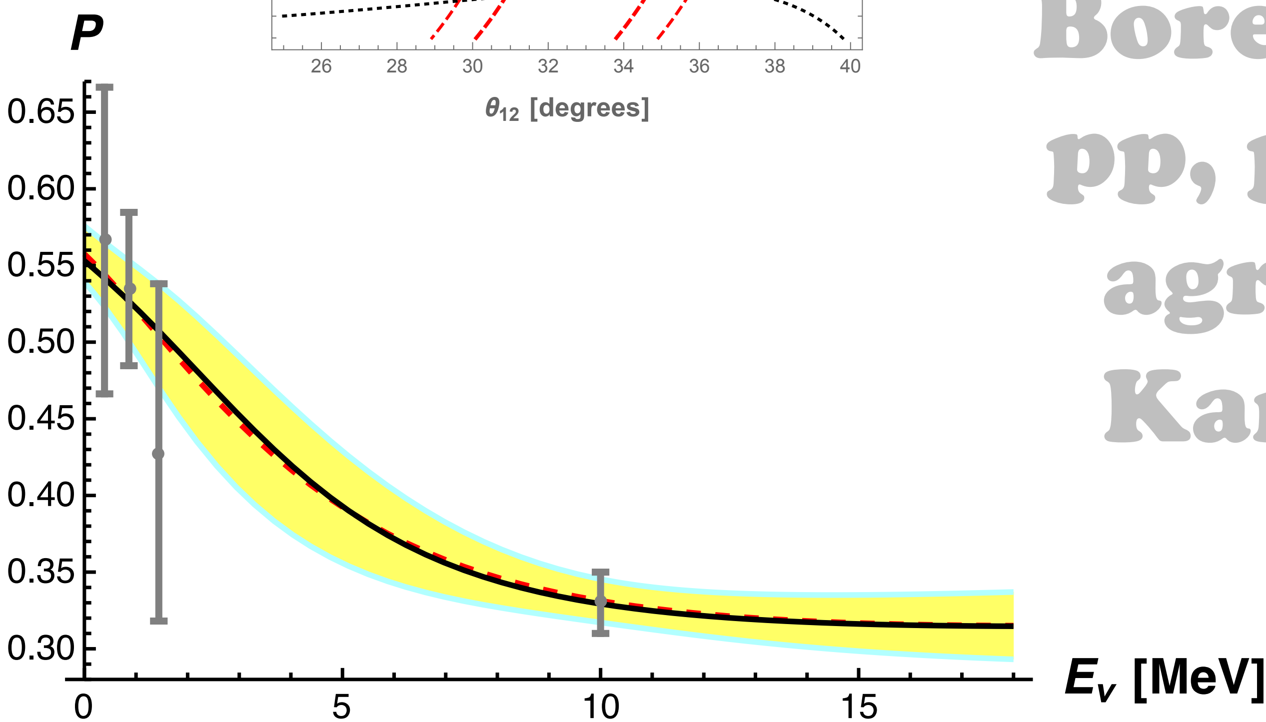
Current picture of oscillations

- there are three light weak-interacting neutrinos ν_e, ν_μ, ν_τ
- solar and atmospheric neutrinos proved oscillations - Nobel 2015
- tests and measurements at reactor & accelerator experiments
- consistent with observational cosmology (BBN and CMB)

solar neutrino anomaly? D/N and shape of ^{8}B in SK
(see next page for a new test)



SNO ^{8}B & Borexino ^{7}Be, pp, pep rates agree with KamLAND



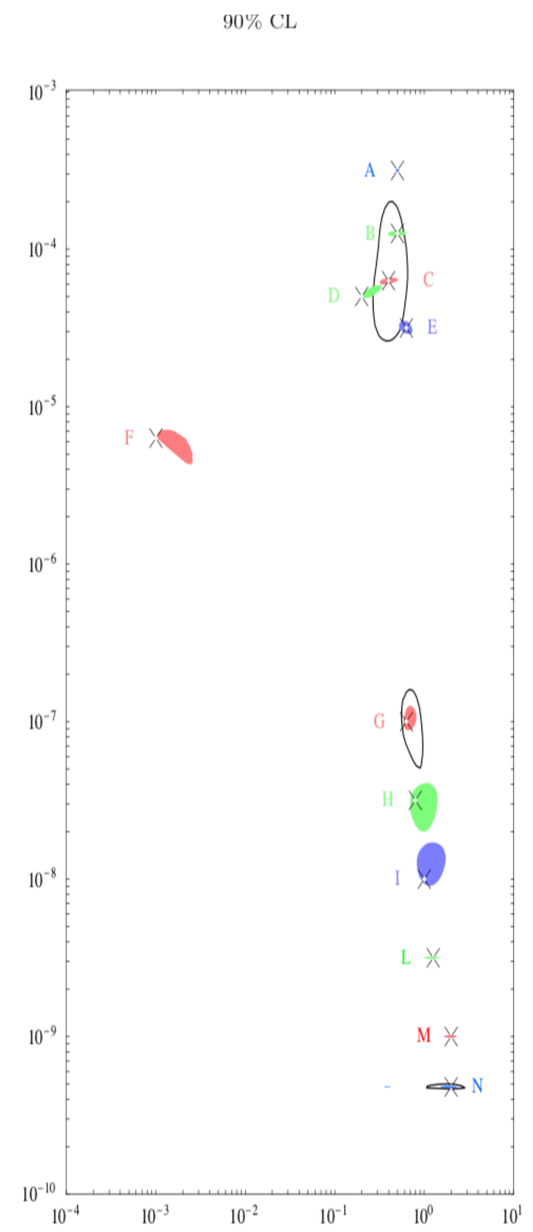
Which solar neutrino experiment after KamLAND & Borexino?

① In 2001 with A. Strumia we examined the prospects of measuring the parameters of oscillation: We found that KamLAND & Borexino were enough for this purpose.

② Indeed this happened; due to the specific parameters (LMA solution of solar anomaly) KamLAND succeeded.

③ This is not the same as testing *directly* solar neutrino oscillations; note, e.g., that KamLAND uses antineutrinos. Independent tests of solar neutrino are important.

④ The current discussion is even more interesting, for Super-Kamiokande best fit parameters (based on boron neutrinos) agree only at 2σ with KamLAND's.



STERILE NEUTRINOS?

◎LSND-MiniBooNe anomaly is with us since 1995; in latest data is mostly/only at lowest energies. Again with A Strumia, we have examined them in a global analysis

◎Ga- & reactor anomalies tested with movable detector close to reactors. Not supported by DANSS, Stereo, NEOS

◎Adding sterile neutrinos does not help: the ensuing theory is predictive, leading to inconsistencies between these and other data

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Nuclear Physics B 708 (2005) 215–267

NUCLEAR PHYSICS B

Probing oscillations into sterile neutrinos with cosmology, astrophysics and experiments

M. Cirelli [a], G. Marandella [b], A. Strumia [c], F. Vissani [d]

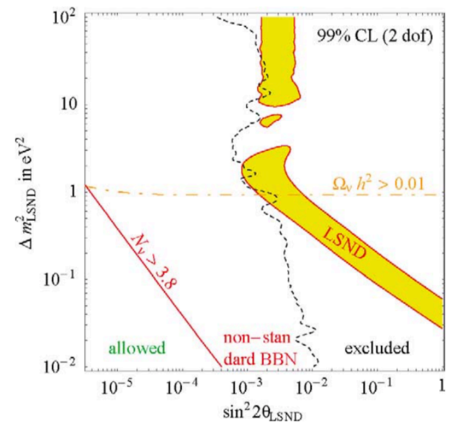
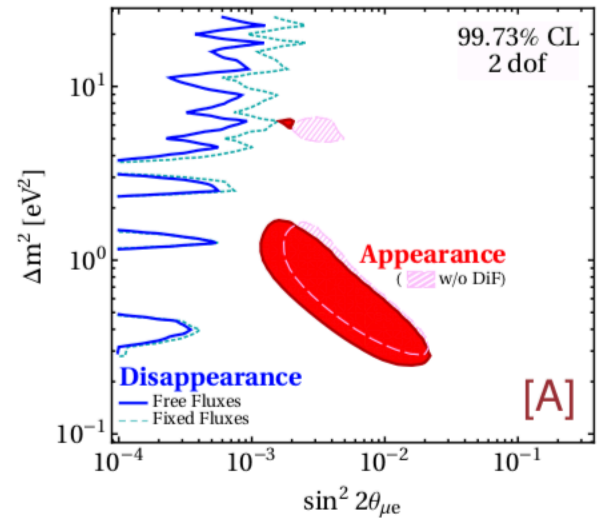
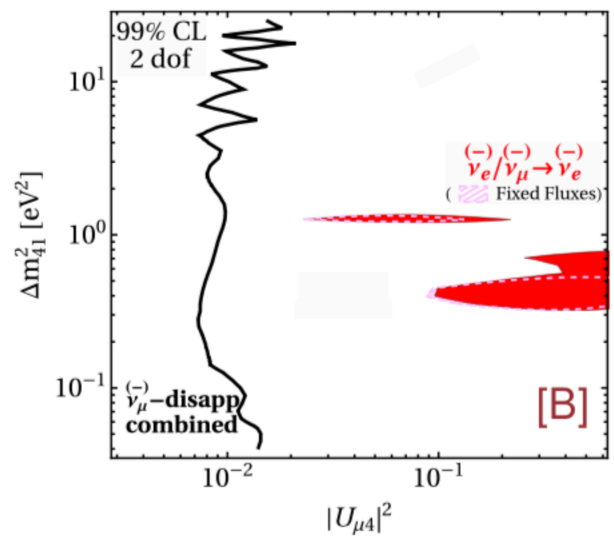


Fig. 13. The LSND anomaly interpreted as oscillations of 3 + 1 neutrinos. Shaded region: suggested at 99% C.L. by LSND. Black dotted line: 99% C.L. global constraint from other neutrino experiments (mainly Karmen, Bugey, SK, CDHS). Continuos red line: $N_\nu = 3.8$ thermalized neutrinos. Dot-dashed orange line: $\Omega_\nu h^2 = 0.01$.

(3+1): tension among data samples

- Limits on $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$ disappearance imply a bound on the $\nu_\mu \to \nu_e$ appearance probability;
- such bound is stronger than what is required to explain the LSND and MiniBooNe excesses [A];
- hence, severe tension arises between **APP** and **DIS** data: $\chi^2_{\text{PG}}/\text{dof} = 29.6/2 \Rightarrow \text{PG} = 3.7 \times 10^{-7}$ [17];
- a similar result is visible when comparing "ν_e-data" ($\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$) and "ν_μ-data" ($\nu_\mu \to \nu_\mu$) [B];
- note: tension between **APP** and **DIS** data first pointed out in 1999 [34]. Full global fit in 2001 [35] cornered (3+1) models. No conceptual change since then...





[17] M. Dentler *et al.*, arXiv:1803.10661.
[34] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454].
[35] MM, Schwetz, Valle, PLB **518** (2001) 252 [hep-ph/0107150].

Introduction to the relationship between the measured solar luminosity and the neutrino fluxes. A closer look at the PP chain

THE LUMINOSITY CONSTRAINT [1]

According to Perrin's rudimental ideas (1919)

$4\,H \rightarrow {}^4He$

$4\times M(H)-M({}^4He)=26.7$ MeV

According to most recent SSM (2017)

$4\,p \rightarrow \alpha + 2\,e^+ + 2\,\nu_e$

$4\,p + 4\,e^- \rightarrow \alpha + 4\,e^- + 2\,e^+ + 2\,\nu_e$

$4\,H \rightarrow {}^4He + Q + 2\,\nu_e$

Q=heat or kinetic energy=26.1 MeV

The naïve estimation

$$L_\odot \approx \dot{N}(^4\mathrm{He}) \times Q \approx \frac{1}{2}\dot{N}(\mathrm{pp}) \times Q$$

where $Q = 26.7$ MeV. Using

$$\Phi_{\mathrm{pp}} = \frac{\dot{N}(\mathrm{pp})}{4\pi \times \mathrm{au}^2}$$

we conclude

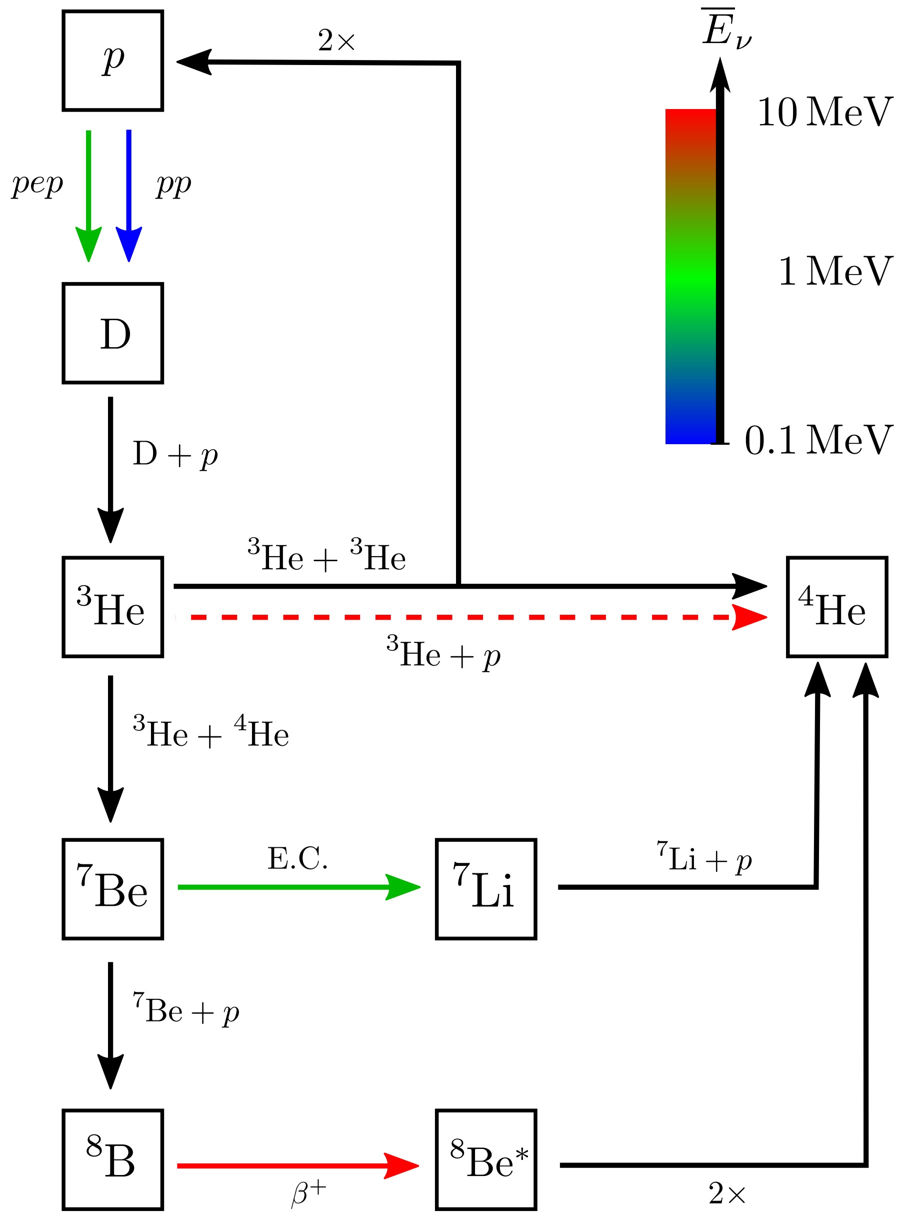
$$\Phi_{\mathrm{pp}} \approx \frac{2\ L_\odot}{4\pi \times \mathrm{au}^2 \times Q} = 6.4 \times 10^{10} \frac{\nu_e}{\mathrm{cm}^2\mathrm{s}}$$

The most accurate position of Bahcall, 2002

$$L_\odot = 4\pi \times \mathrm{au}^2 \times \sum_i \mathcal{Q}_i \times \Phi_i$$

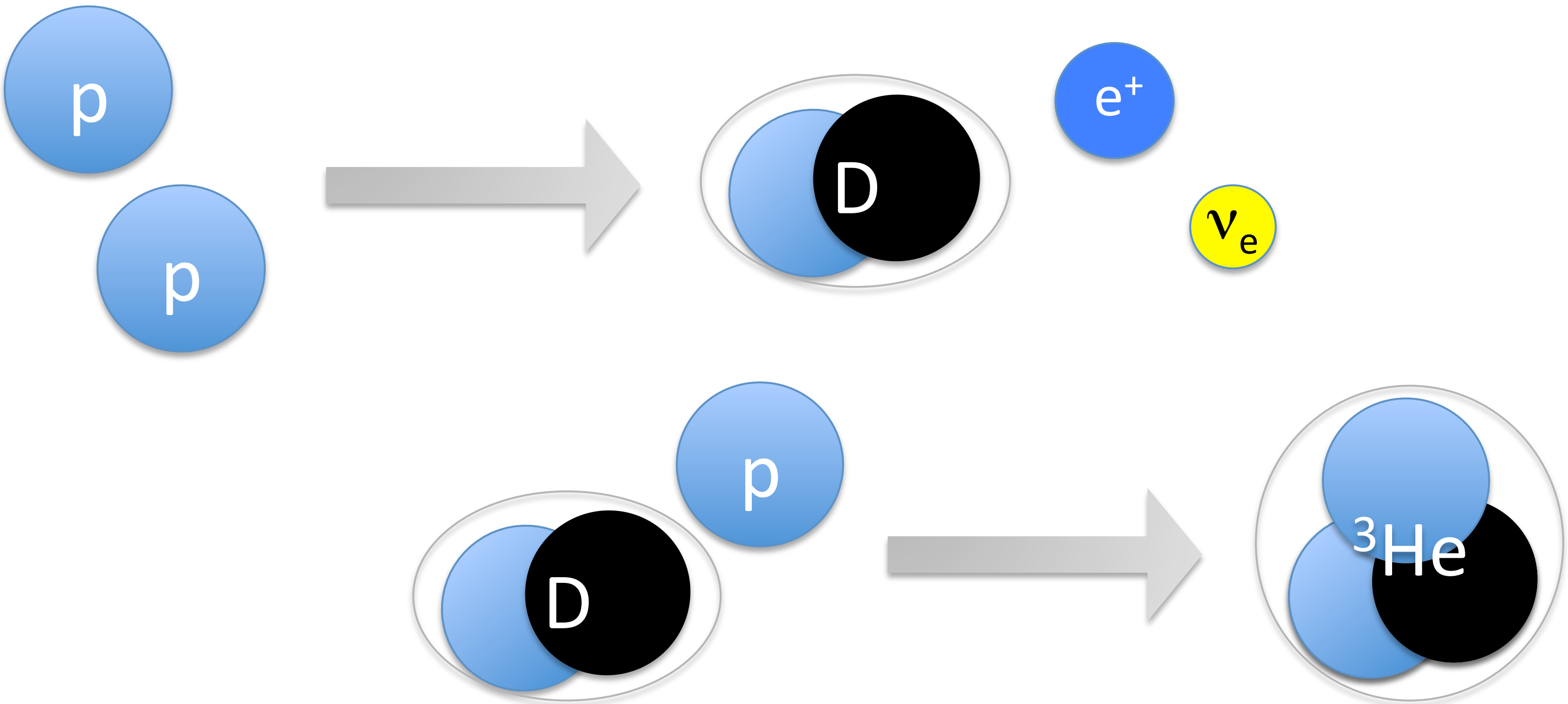
where

$$\begin{cases} 4\pi \times \mathrm{au}^2 = 4.50579 \times 10^{21} \ \dfrac{\mathrm{erg\ cm}^2}{\mathrm{MeV}} \\ i = \mathrm{pp}, \mathrm{Be}, \mathrm{pep}, \mathrm{B}, \mathrm{hep}, \mathrm{N}, \mathrm{O}, \mathrm{F} \\ \Phi_i = \text{solar neutrino fluxes } [\ 1/(\mathrm{cm}^2\mathrm{s})\ ] \\ \mathcal{Q}_i = \text{heat associated to the } i\text{-th flux } [\ \mathrm{MeV}\ ] \end{cases}$$

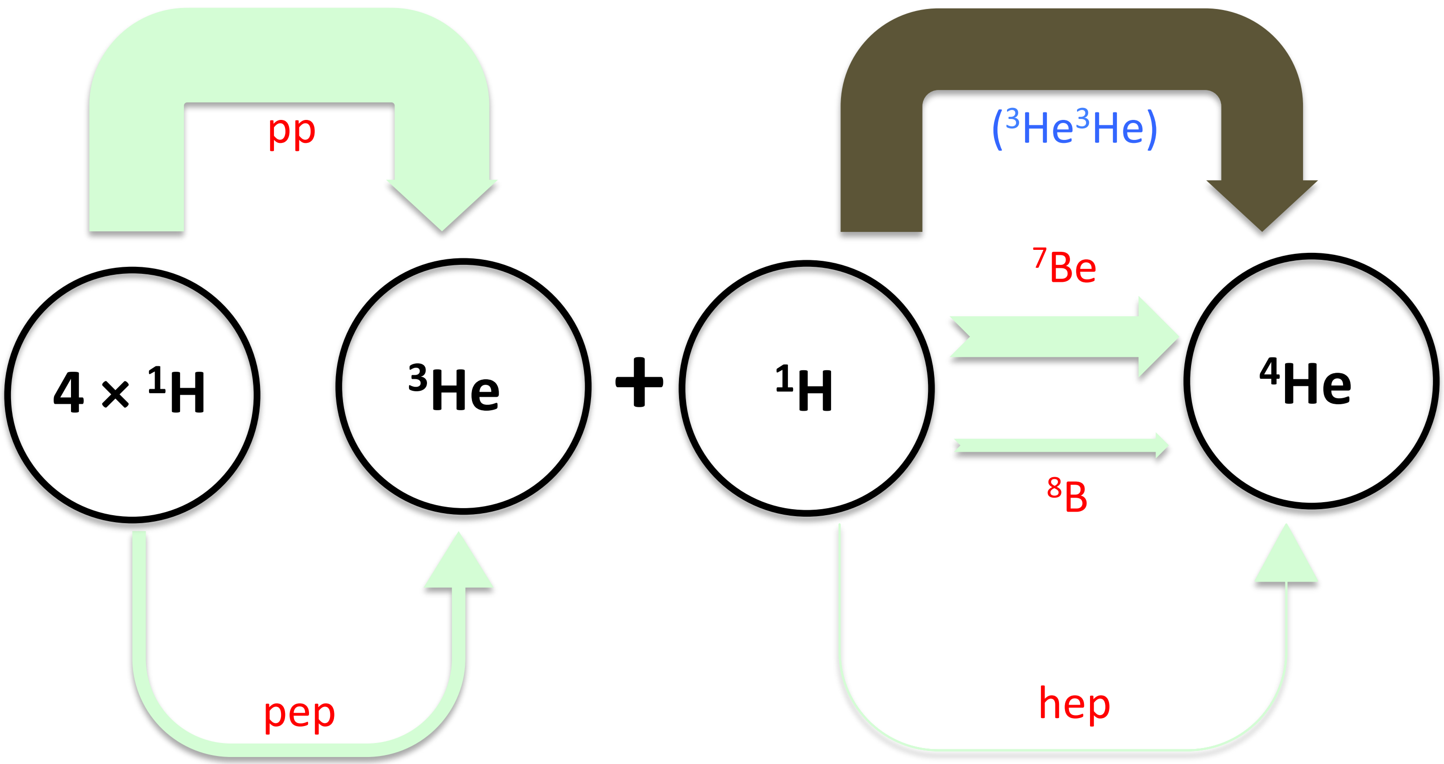


C Mascaretti et al 2018

pp-chain: the 1st steps



$$3\times M(^1H) - M(^3He) = E_{\gamma,i} + E_{\nu,i} = 6.936\ \text{MeV}$$



production of ^{3}H fully tagged by pp + pep neutrinos

consumption of ^{3}H = (^{3}H^{3}H) + ^{7}Be + ^{8}B + hep neutrinos

Improved coefficients and comparison with Bahcall's results

THE LUMINOSITY CONSTRAINT [2]

	pp	Be	pep	B	hep	N	O	F
$\mathcal{Q}_a^{\text{this work}}$[MeV]	13.0987	12.5525	11.9205	6.6305	3.7355	11.0075	14.0194	15.6800
$\mathcal{Q}_a^{\text{Bahcall}}$[MeV]	13.0987	12.6008	11.9193	6.6305	3.7370	3.4577	21.5706	–
$\Delta\mathcal{Q}_a$ in keV	0	48.3	−1.2	0	1.5	−7549.8	7551.2	−15680

Table 1: *Coefficients to express the solar luminosity as a function of the neutrino fluxes.*

Remarks:

1. Two contributions to luminosity in perfect agreement, those of pp- and B-fluxes
2. Two trivial differences, namely,
   - pep- and hep-contributions are small and within roundoff errors; note, $\mathcal{Q}_{\text{pep}} + \langle E_{\nu,\text{pep}} \rangle$ and $\mathcal{Q}_{\text{hep}} + \langle E_{\nu,\text{hep}} \rangle$ fixed by atomic mass differences.
   - F-flux contribution to luminosity not included by Bahcall; this contribution is not large, even if (expected to be) larger than B-flux one.
3. Three non-trivial differences: Be, N, O.

The beryllium lines

Two beryllium lines cause energy losses. The procedure advocated by Bahcall requires two steps:

“one must average over the two ^{7}Be neutrino lines with the appropriate weighting and include the γ-ray energy from the 10.3% of the decays that go to the first excited state of ^{7}Li.”

1) The energy loss of EC on ^{7}Be is due to the transition to the ground state in ~90% the cases and to 1st excited level in the rest; the average energy loss is 0.895 × 863.1 + 0.105 × 385.5 = 813.0 keV (we change 10.3 → 10.5%, using Tilley et al 2002).

2) The gain of energy due to the γ-ray of 477.61 keV, emitted in 10.5% of the cases by the first excited state of ^{7}Li, amounts to 50.1 keV; however, we do not include it as Bahcall for this amounts to double counting: in fact, 863.1 − 813.0 = 50.1.

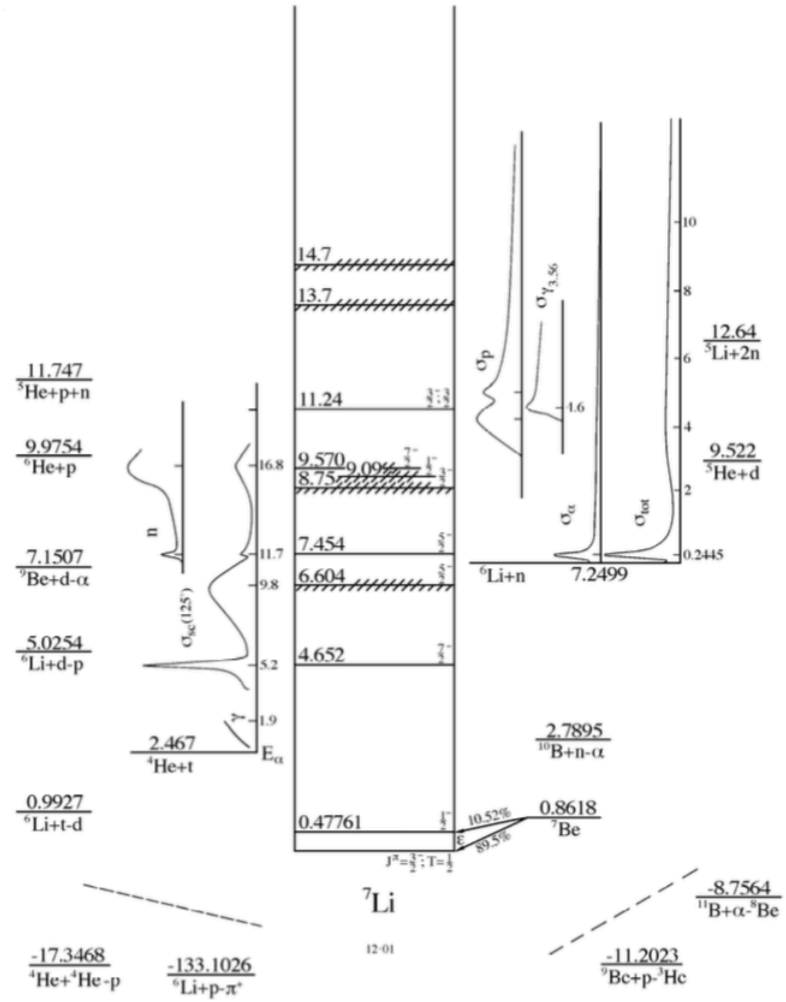
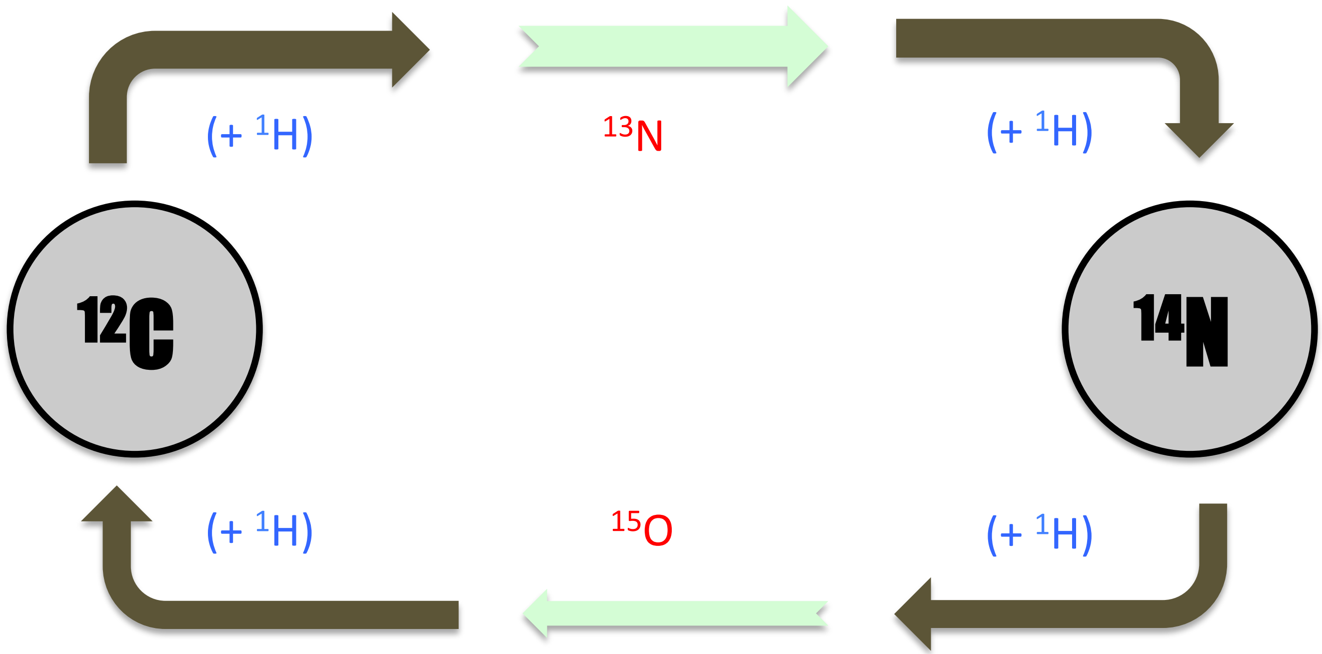


Figure 9: Energy levels of ^{7}Li. For notation see Fig. 5.



synthesis of ^{14}N = tagged by ^{13}N-neutrinos

conclusion of ^{4}He-catalysis = tagged by ^{15}O-neutrinos

Summary

- The luminosity $L_\odot$ is known with σ=0.4% accuracy (much better than neutrino's)

- The treatment of ^{7}Be decreases the luminosity; the different ascription to the N and O-neutrinos increases it, just as the inclusion of F-neutrinos.

	^{7}Be	N+O	F	total
AGSS	-0.64σ	+1.33σ	+0.15σ	+0.84σ
GS98	-0.70σ	+1.62σ	+0.24σ	+1.16σ

- The SSM roundoff errors on pp-neutrinos, unfortunately, are twice σ. Both the new and old coefficients agree with the tabulated SSM values

Another form of luminosity constraint

$$\Phi_a = \varphi_a \times 10^{\alpha_a} \ \frac{\nu_e}{\text{cm}^2\text{s}}$$

$$L_\odot^{\text{th.}} = \kappa_a \ \varphi_a \times 5.9020 \times 10^{32} \ \frac{\text{erg}}{\text{s}}$$

	pp	Be	pep	B	hep	O	N	F
α_a	10	9	8	6	3	8	8	6
κ_a	1.00000	0.09583	0.00910	0.00005	0.00000	0.01070	0.00840	0.00012

Table 1: Coefficients to express the solar luminosity as a function of the neutrino fluxes.

Link between pp and CNO flux from the luminosity; a quasi-empirical model for the flux of the chain; CNO neutrinos from radiochemical experiments; ditto from Borexino; a very weak hint for CNO neutrino; how to determine pep precisely to help future Borexino's search of CNO neutrinos

SOME APPLICATION

Luminosity and the pp-flux

- The luminosity constrain fixes precisely a combination of fluxes. Writing as usual $\Phi = \phi \times 10^{\alpha}/\text{cm}^2\text{s}$, we have

$$L_{\odot} \propto \phi_{pp} + 9.6\%\ \phi_{Be} + 1.9\%\ \phi_{CN} + 0.9\%\ \phi_{pep} + \text{small}$$

- The Be-contribution is measured by Borexino
- The pep is directly related to pp-one
- Thus, changing the central value of CNO changes the pp-value. Let us begin the discussion setting it to zero.

a quasi-empirical model for the pp-chain

Measurements

1. pp neutrinos constrained by **Gallium exps** & seen by **Borexino**
2. beryllium and pep neutrinos as measured by **Borexino**
3. boron neutrinos as measured by **SNO**
4. hep neutrinos as bound by **SNO** & **SK**

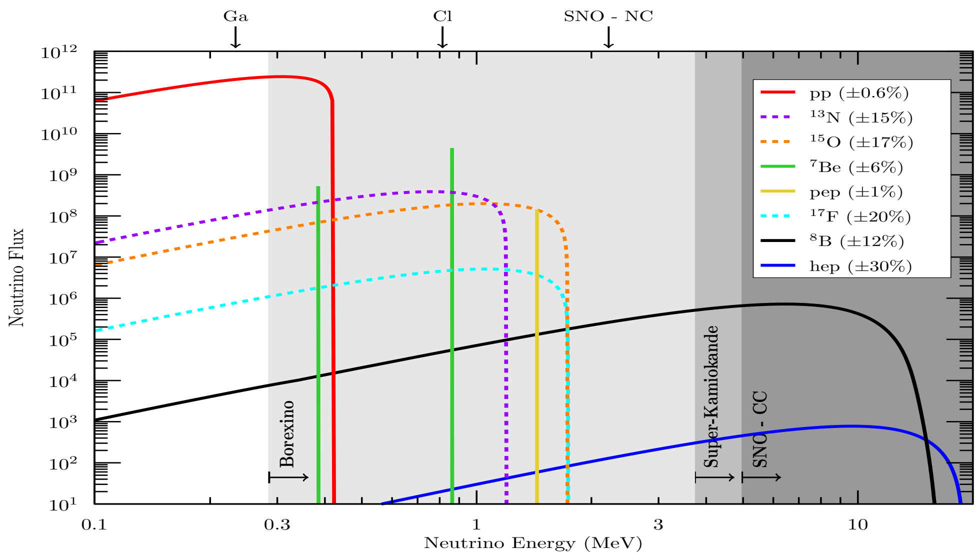
ident. index i	pp	Be	pep	B	hep
observations	6.04	4.99	1.33	5.25	< 23
errors	0.53	0.13	0.29	0.20	90%
quasi-empirical	6.02	4.99	1.45	5.25	8
errors	0.03	0.13	0.03	0.20	9
exponent α_i	10	9	8	6	3

Quasi Empirical Model

precise value of pp-neutrinos follows from luminosity constraint (χ^2 analysis)

ratio pep/pp is free from nuclear physics uncertainties

hep set to the theoretical value



Mascaretti et al, 2017

CNO from radiochemical experiments?

- based on SAGE 2009 -

Chlorine The measured rate is

$$R_{\rm exp}({\rm Cl}) = 2.56 \pm 0.23 \text{ SNU}$$

The contributions from the neutrinos pp-chain, in order of importance, are,

$$\{{\rm B}, {\rm Be}, pep, hep\} = \{1.86, 0.64, 0.12, 0.01\} \text{ SNU}$$

Including the error on the cross section,

$$R_{\rm th}^{pp}({\rm Cl}) = 2.63 \pm 0.08 \text{ SNU}$$

Therefore the rate of CNO neutrinos, extracted from these data, is,

$$R_{\rm th}^{CNO}({\rm Cl}) = -0.07 \pm 0.24$$

Gallium The measured rate from SAGE and Gallex/GNO is

$$R_{\rm exp}({\rm Ga}) = 66.1 \pm 3.1 \text{ SNU}$$

Expectations based on *quasi-empirical model* (Borexino, luminosity and SNO) are

$$\{pp, {\rm Be}, {\rm B}, pep\} = \{39.1, 18.1, 3.9, 1.4\} \text{ SNU}$$

The error on the cross section implies,

$$R_{\rm th}^{pp}({\rm Ga}) = 62.6^{+3.7}_{-1.9} \text{ SNU}$$

errors of pp, Be, B are almost equal and are summed linearly (not quadratically). Assuming, $R_{\rm exp}({\rm Ga}) = R_{\rm th}({\rm Ga}) = R_{\rm th}^{pp}({\rm Ga}) + R_{\rm th}^{CNO}({\rm Ga})$ we find

$$R_{\rm th}^{CNO}({\rm Ga}) = 3.5^{+3.6}_{-4.8} \text{ SNU}$$

Impact of current Borexino's bound/result

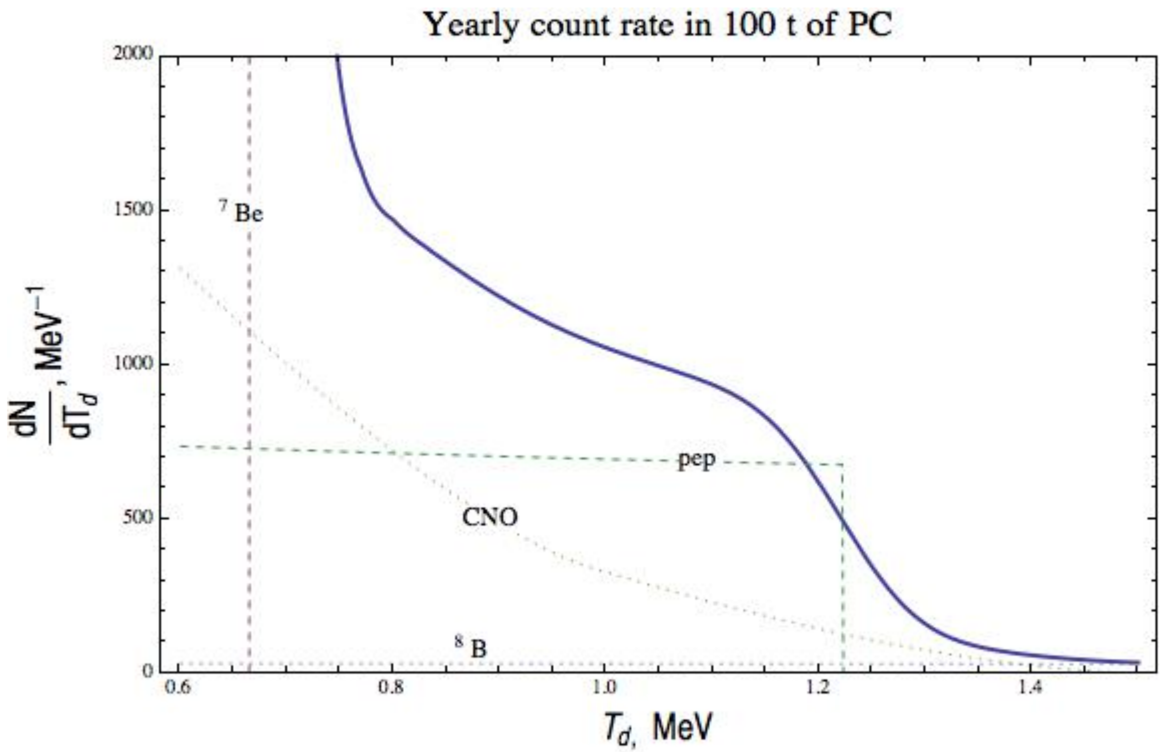
- Φ_{cno}=4.88 and 3.51 in units $10^8/cm^2s$ for GS98 and AGSS
- Φ_{cno}=2.34±2.85 reproduces best fit (fig.6 of Borexino) and 2σ bound

at 1σ compatible with expectations-and with zero-a bit smaller

By combining this hint with those from gallium, we have

$$\Phi_{cno} = (2.69 \pm 2.77) \times 10^8/cm^2s$$

same conclusion as above



Minimizing the impact of pep as (beam related) background to CNO search in Borexino

We can use the luminosity constraint to determine the pp neutrino flux accurately, then employing the known ratio between pep and pp: 2.35×10^{-3} (possibly including also a % error, to be estimated precisely).

Summary

- After the discovery of oscillations, we had great observational results on solar neutrinos and more to come
- The luminosity constraint, based on the hypotheses that we understand nuclear physics and the Sun is in equilibrium, is a precious tool to proceed
- We have examined it accurately and proposed slight revisions
- This constraints and various other facts show that the PP and CNO neutrinos, that are two independent astrophysical mechanisms, are intertwined by the need to extract them from observations.

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Francesco Vissani
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Borexino Collaboration
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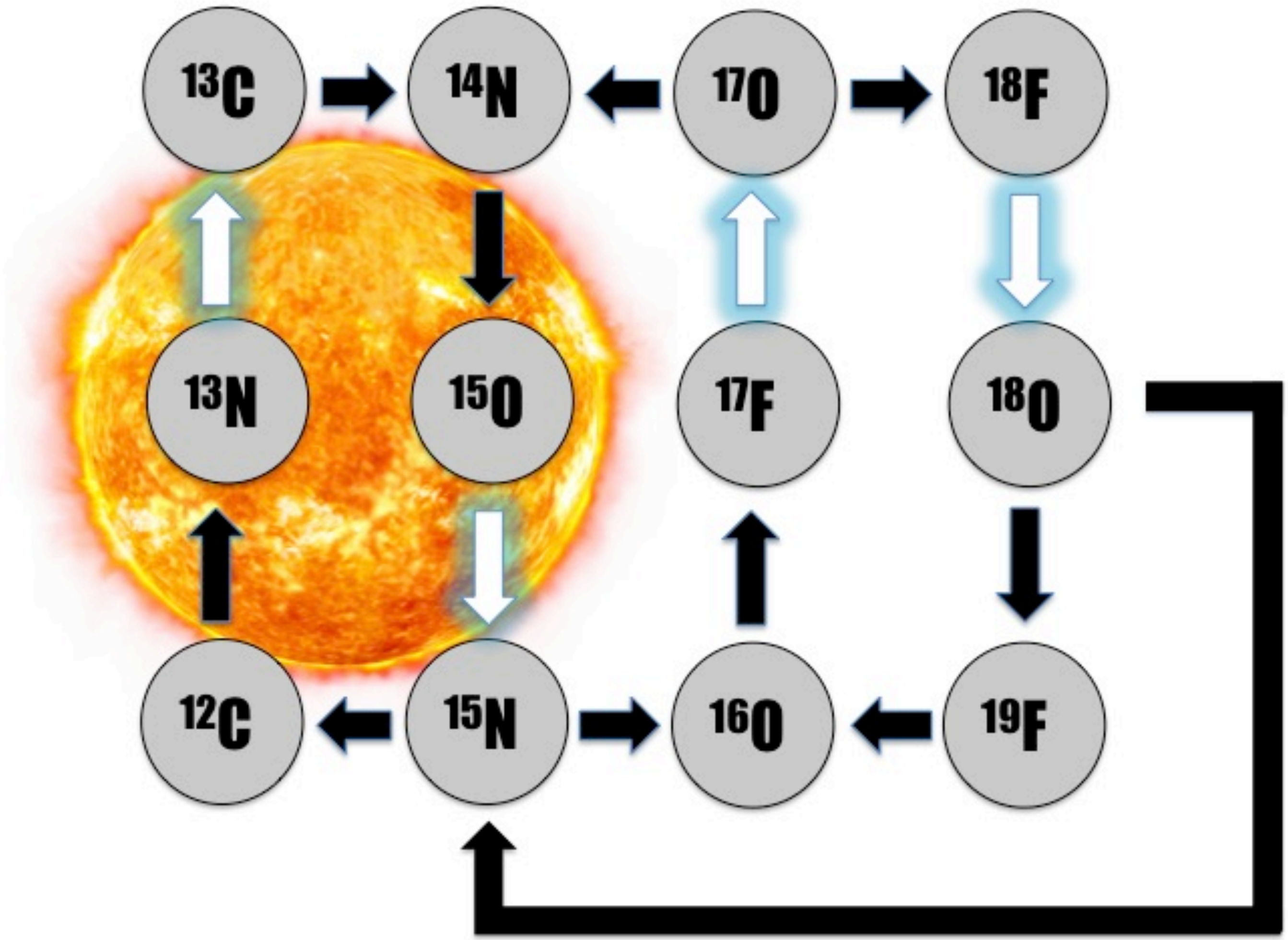
Andrea Gallo Rosso, Carlo Mascaretti, Andrea Palladino, Francesco Vissani
presented at the Azarquiel school, proceedings submitted at the EPJ

MORE ON THE CNO CYCLES


13C
14N
17O
18F
13N
15O
17F
18O
12C
15N
16O
19F

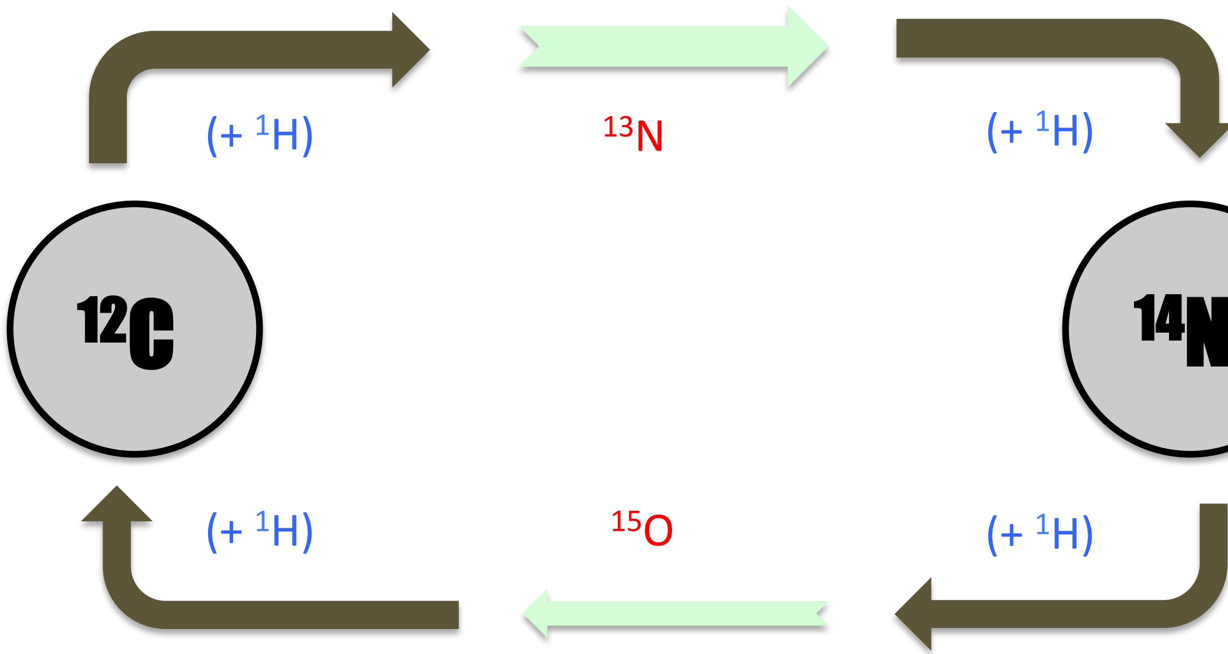
CNO neutrinos expectations [1/2]

- A set of four catalytic cycles.

- CNO-II neutrinos are rare: $p^{15}N$ prefers to end α than γ. So CNO-III and –IV are not active.

- ^{17}F and ^{15}O neutrinos are experimentally indistinguishable from each other, due to almost identical shape.

- The key part for the Sun is the CNO-I (or CN) cycle: let us examine it closely, noting that <u>it is composed by 2 semi-cycles</u>



synthesis of ^{14}N = tagged by ^{13}N-neutrinos

conclusion of ^{4}He-catalysis = tagged by ^{15}O-neutrinos

CNO neutrinos expectations [2/2]

When we focus o CNO-I, the most important remark is simply that:
the slowest node is $p^{14}N$

(In fact, the S-factor is similar for $p^{14}N$ and $p^{12}C$, but Z=7 has more Coulomb repulsion)

In the Sun, there are two populations of CNO-I neutrinos:

1. *In $R<0.1R_\odot$, CNO-I does cycle: As many neutrinos from ^{13}N decays as from ^{15}O*
2. *In $R>0.1R_\odot$, reactions stop at ^{14}N: neutrinos only from ^{13}N decays*

NUCLEAR SPECIES, INTERACTION RATES AND NEUTRINO FLUXES

VARIATION OF SPECIES AND REACTION RATES

$$[\dot{\mathrm{D}}] = \langle p, p\rangle + \langle p, e, p\rangle - \langle p, \mathrm{D}\rangle$$

$$[{}^3\dot{\mathrm{He}}] = \langle p, \mathrm{D}\rangle - 2\langle {}^3\mathrm{He}, {}^3\mathrm{He}\rangle - \langle p, {}^3\mathrm{He}\rangle - \langle {}^3\mathrm{He}, {}^4\mathrm{He}\rangle$$

$$[{}^7\dot{\mathrm{Be}}] = \langle {}^3\mathrm{He}, {}^4\mathrm{He}\rangle - \langle e, {}^7\mathrm{Be}\rangle - \langle p, {}^7\mathrm{Be}\rangle$$

$$[{}^7\dot{\mathrm{Li}}] = \langle e, {}^7\mathrm{Be}\rangle - \langle p, {}^7\mathrm{Li}\rangle$$

$$[{}^8\dot{\mathrm{B}}] = \langle p, {}^7\mathrm{Be}\rangle - \langle {}^8\mathrm{B}\rangle$$

$$[{}^8\dot{\mathrm{Be}}^*] = \langle {}^8\mathrm{B}\rangle - \langle {}^8\mathrm{Be}^*\rangle$$

$$[{}^4\dot{\mathrm{He}}] = \langle p, {}^3\mathrm{He}\rangle + \langle {}^3\mathrm{He}, {}^3\mathrm{He}\rangle + \langle p, {}^7\mathrm{Li}\rangle + \langle {}^8\mathrm{Be}^*\rangle$$

VARIATION OF SPECIES AND REACTION RATES

$$[\dot{\mathrm{D}}] = \langle p, p\rangle + \langle p, e, p\rangle - \langle p, \mathrm{D}\rangle$$

$$[{}^3\dot{\mathrm{He}}] = \langle p, \mathrm{D}\rangle - 2\langle {}^3\mathrm{He}, {}^3\mathrm{H} \ldots$$

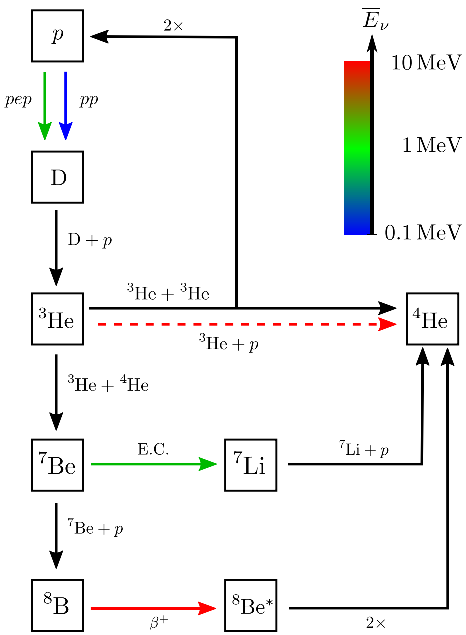
All these species are in local kinetic equilibrium in excellent approximation, their time derivative is ZERO.

We obtain a condition on the rates.

$$\ldots \mathrm{Be}\rangle - \langle {}^8\mathrm{B}\rangle$$

$$[{}^8\dot{\mathrm{Be}}^*] = \langle {}^8\mathrm{B}\rangle - \langle {}^8\mathrm{Be}^*\rangle$$

$$[{}^4\dot{\mathrm{He}}] = \langle p, {}^3\mathrm{He}\rangle + \langle {}^3\mathrm{He}, {}^3\mathrm{He}\rangle + \langle p, {}^7\mathrm{Li}\rangle + \langle {}^8\mathrm{Be}^*\rangle$$



$$[\dot{\mathrm{D}}] = \langle p,p\rangle + \langle p,e,p\rangle - \langle p,\mathrm{D}\rangle = 0$$

$$[{}^3\dot{\mathrm{He}}] = \langle p,\mathrm{D}\rangle - 2\langle {}^3\mathrm{He},{}^3\mathrm{He}\rangle - \langle p,{}^3\mathrm{He}\rangle - \langle {}^3\mathrm{He},{}^4\mathrm{He}\rangle = 0$$

$$[{}^7\dot{\mathrm{Be}}] = \langle {}^3\mathrm{He},{}^4\mathrm{He}\rangle - \langle e,{}^7\mathrm{Be}\rangle - \langle p,{}^7\mathrm{Be}\rangle = 0$$

$$[{}^7\dot{\mathrm{Li}}] = \langle e,{}^7\mathrm{Be}\rangle - \langle p,{}^7\mathrm{Li}\rangle = 0$$

$$[{}^8\dot{\mathrm{B}}] = \langle p,{}^7\mathrm{Be}\rangle - \langle {}^8\mathrm{B}\rangle = 0$$

$$[{}^8\dot{\mathrm{Be}}^*] = \langle {}^8\mathrm{B}\rangle - \langle {}^8\mathrm{Be}^*\rangle = 0$$

$$[{}^4\dot{\mathrm{He}}] = \langle p,{}^3\mathrm{He}\rangle + \langle {}^3\mathrm{He},{}^3\mathrm{He}\rangle + \langle e,{}^7\mathrm{Be}\rangle + \langle {}^8\mathrm{B}\rangle > 0$$

$$\langle p,\mathrm{D}\rangle = \Gamma(p) + \Gamma(pep)$$

$$\langle {}^3\mathrm{He},{}^3\mathrm{He}\rangle = \frac{1}{2}\left(\Gamma(p) + \Gamma(pep) - \Gamma(hep) - \Gamma({}^7\mathrm{Be}) - \Gamma({}^8\mathrm{B})\right)$$

$$\langle p,{}^7\mathrm{Li}\rangle = \Gamma({}^7\mathrm{Be})$$

$$\langle p,{}^7\mathrm{Be}\rangle = \Gamma({}^8\mathrm{B})$$

$$\langle {}^8\mathrm{Be}^*\rangle = \Gamma({}^8\mathrm{B})$$

$$\langle {}^3\mathrm{He},{}^4\mathrm{He}\rangle = \Gamma({}^7\mathrm{Be}) + \Gamma({}^8\mathrm{B})$$

ν-emission measures reaction rates

$$\langle p, \mathrm{D} \rangle = \Gamma(p) + \Gamma(pep)$$

$$\langle ^3\mathrm{He}, ^3\mathrm{He} \rangle = \frac{1}{2} \left(\Gamma(p) + \Gamma(pep) - \Gamma(hep) - \Gamma(^7\mathrm{Be}) - \Gamma(^8\mathrm{B}) \right)$$

$$\langle p, ^7\mathrm{Li} \rangle = \Gamma(^7\mathrm{Be})$$

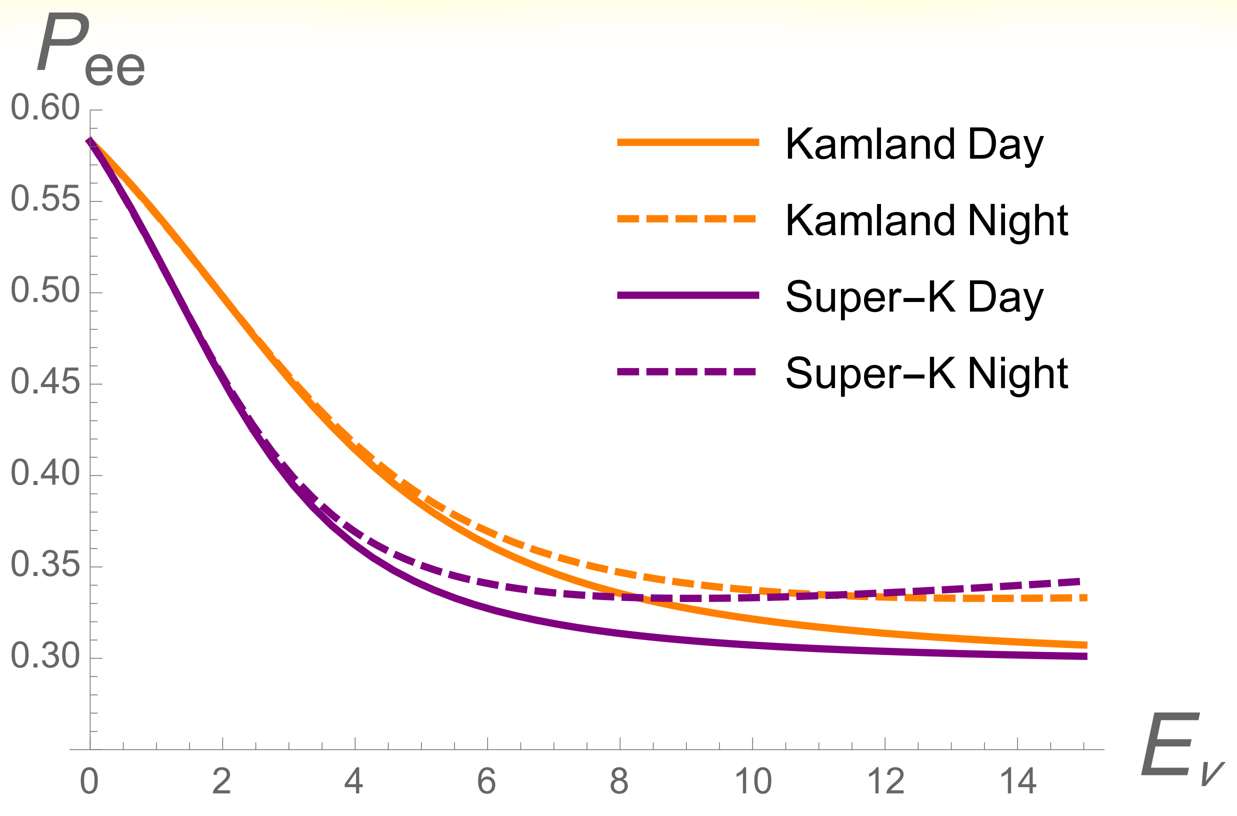
$$\langle p, ^7\mathrm{Be} \rangle = \Gamma(^8\mathrm{B})$$

$$\langle ^8\mathrm{Be}^* \rangle = \Gamma(^8\mathrm{B})$$

$$\langle ^3\mathrm{He}, ^4\mathrm{He} \rangle = \Gamma(^7\mathrm{Be}) + \Gamma(^8\mathrm{B})$$

$$\int \Gamma_i(x)\, d^3x = 4\, \pi\, \mathrm{au}^2 \times \Phi_i$$

issues with spectral shape and D/N



Ultrapure scintillators Borexino has searched for the CNO neutrino $\varphi_{\rm CNO}$, defined as the adimensional coefficient $\Phi_{\rm CNO} = \varphi_{\rm CNO} \times 10^8/{\rm cm}^2{\rm s}$. The currently expected value is $\varphi_{\rm CNO} = 4.88$ and 3.51 in the GS98 and AGSS09 models. The 95% bound that was obtained scaling the fluxes predicted in either models - all three fluxes together - is $\varphi_{\rm CNO} < 7.9$ for both models [21]. From their fig. 6 one reads that the best fit value is non-zero. The $\chi^2_{\rm Borexino}(n)$ as a function of the counting rate $n_{\rm CNO}$, there shown - obtained assuming the GS98 model - is well described by a parabolic shape, which implies that the likelihood is almost Gaussian. The minimum is at $n_{\rm CNO} = 2.4$ cdp/100t, that corresponds to a flux $\varphi_{\rm CNO} = 2.34$ [21]. Therefore, we can quote the $\chi^2_{\rm Borexino}(\varphi_{\rm CNO}) = (\varphi_{\rm CNO} - 2.34)^2/\delta\varphi^2$, where $\delta\varphi = 2.85$ reproduces the quoted 95% bound and where we assume that the best fit value does not change drastically assuming the AGSS09 model instead. Summarizing, the results of Borexino allow us to derive a few important conclusions concerning the experimental knowledge on the CNO flux:

1. its value is lower than the one indicated by the GS98 and AGSS09 models;
2. within the upper 1σ range, it is compatible with both of them;
3. within the lower 1σ range, it is also compatible with no CNO flux at all,

Combined result By combining the results of gallium experiments and Borexino, we find (for both models) $\varphi_{\rm CNO} = 2.69 \pm 2.77$, that we can quote as a flux reinserting the units:

$$\Phi_{\rm CNO} = (2.69 \pm 2.77) \times \frac{10^8}{{\rm cm}^2{\rm s}} \tag{16}$$

This result shows that the inclusions of the results of the gallium experiments in the analysis do not change strongly the result of Borexino alone and the three conclusions outlined just above remain valid.