Solar models and solar neutrinos

F. L. Villante – University of L'Aquila and LNGS-INFN

Outline

- The present situation
- The solar composition problem
- The role of CNO neutrinos
- Summary and conclusions

Hydrogen Burning: PP chain and CNO cycle

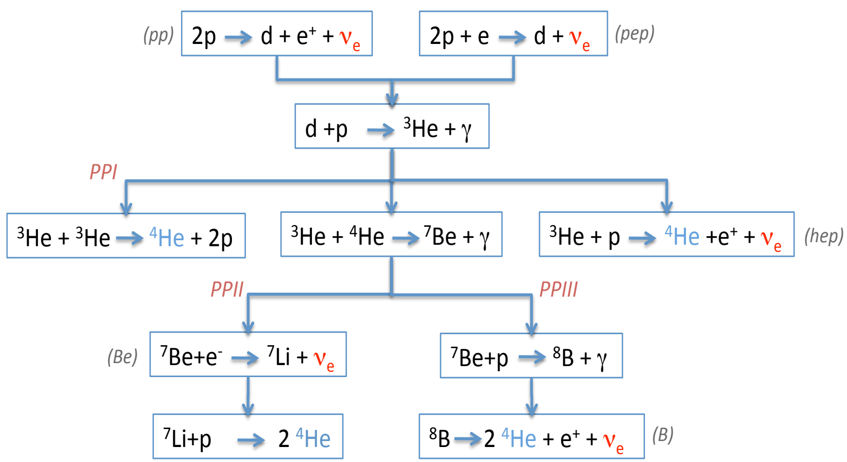
The Sun is powered by nuclear reactions that transform H into ^{4}He:

$$4H + 2e^- \rightarrow {}^4He + 2\nu_e + \text{energy}$$

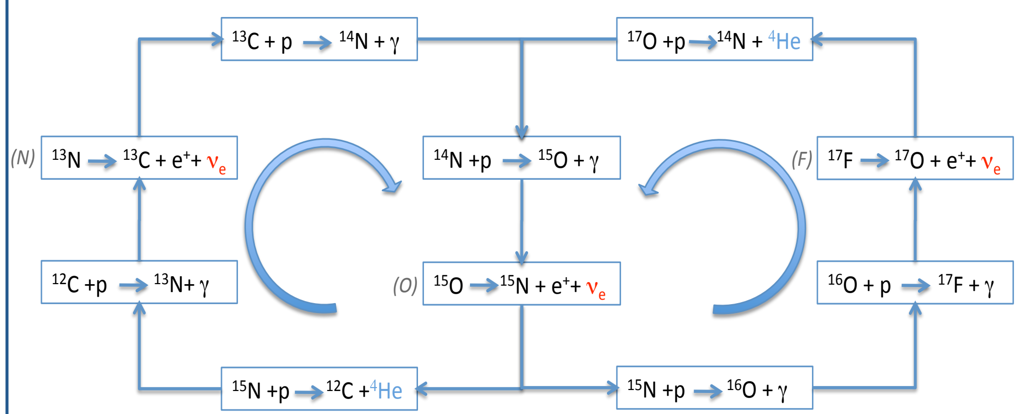
Q = 26,7 MeV (globally)

Free stream – 8 minutes to reach the earth
Direct information on the energy producing region.

The PP-chain



The CN-NO bi-cycle

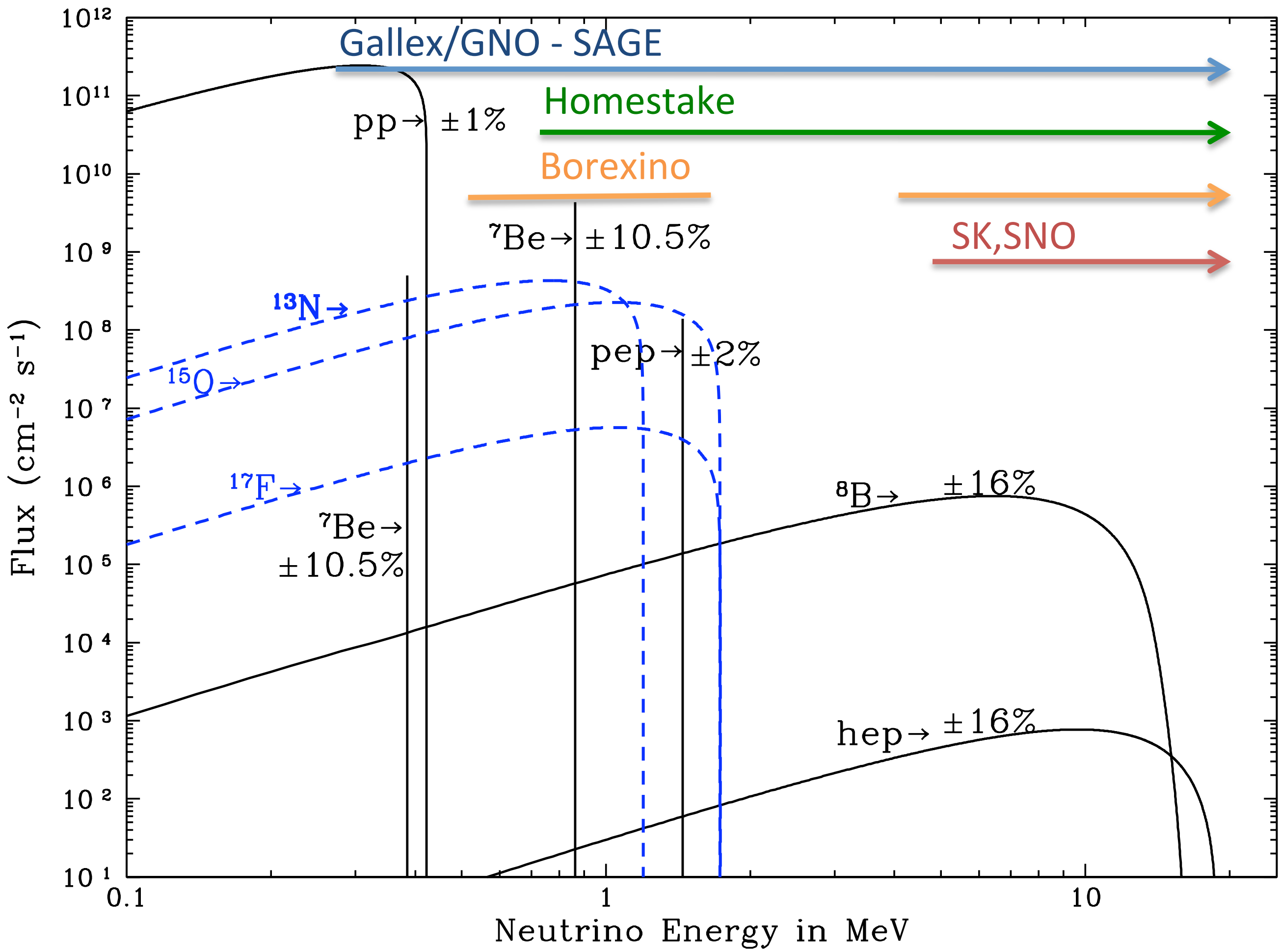


The pp chain is responsible for about 99% of the total energy (and neutrino) production.

C, N and O nuclei are used as catalysts for hydrogen fusion.

CNO cycle is responsible for about 1% of the total neutrino (and energy) budget. Important for more advanced evolutionary stages

The solar neutrino spectrum



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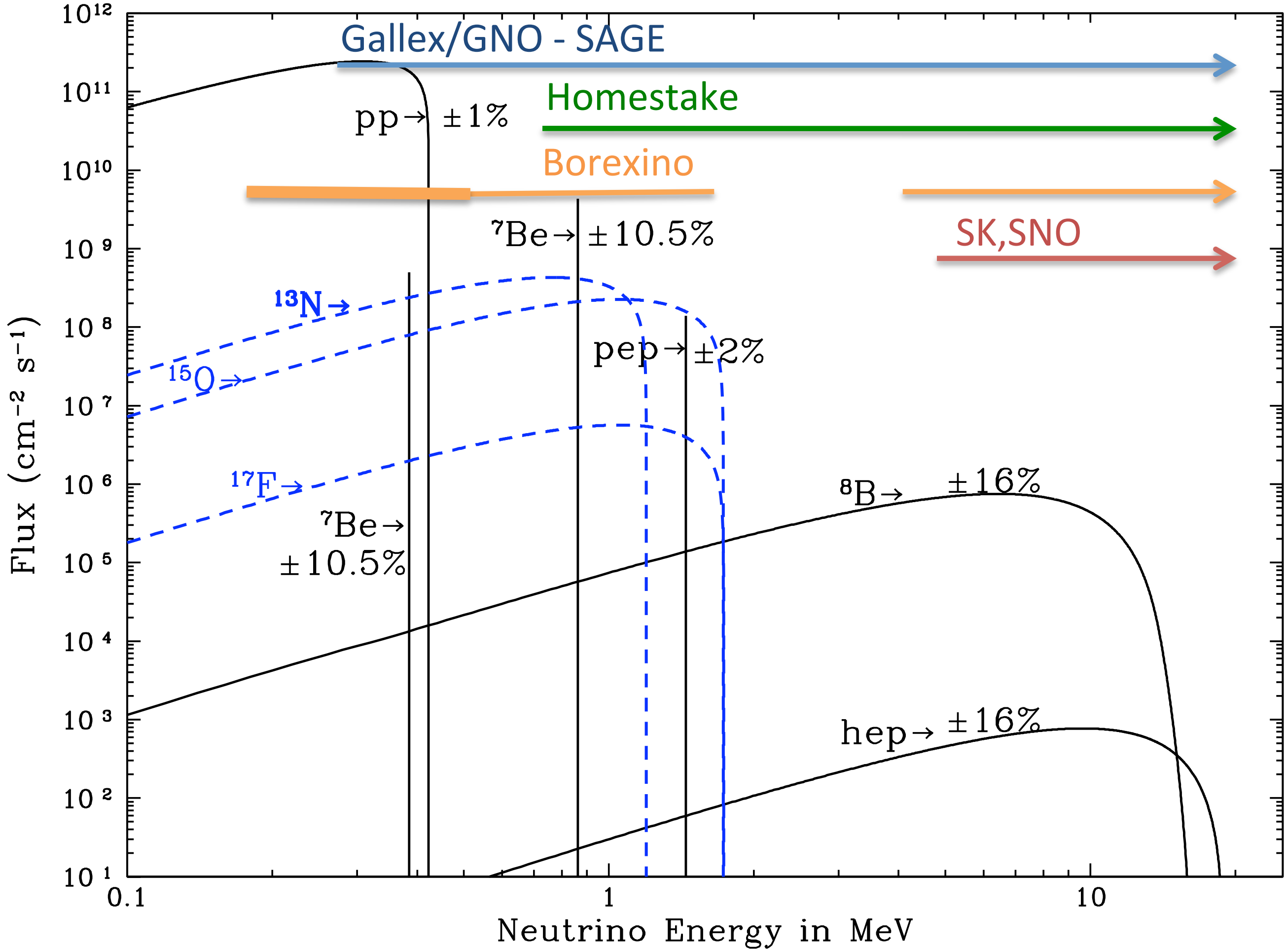

$$\Phi_{pp} = (6.6 \pm 0.7) \times 10^{10}\ cm^{-2}\ s^{-1}$$

Borexino 2014 - Nature 512 (2014) 383

First direct measurement of the solar pp-component

The present situation

Experimental results agree with Standard Solar Models (SSM) + flavor oscillations:

Serenelli, Haxton, Pena-Garay, ApJ 2011

ν flux	AGSS09	GS98	Solar
$\Phi_{\rm pp}$	$6.03\,(1 \pm 0.006)$	$5.98\,(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$
$\Phi_{\rm pep}$	$1.47\,(1 \pm 0.012)$	$1.44\,(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$
$\Phi_{\rm Be}$	$4.56\,(1 \pm 0.07)$	$5.00\,(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$
$\Phi_{\rm B}$	$4.59\,(1 \pm 0.14)$	$5.58\,(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
$\Phi_{\rm hep}$	$8.31\,(1 \pm 0.30)$	$8.04\,(1 \pm 0.30)$	$18(1^{+0.4}_{-0.5})$
$\Phi_{\rm N}$	$2.17\,(1 \pm 0.14)$	$2.96\,(1 \pm 0.14)$	≤ 6.7
$\Phi_{\rm O}$	$1.56\,(1 \pm 0.15)$	$2.23\,(1 \pm 0.15)$	≤ 3.2
$\Phi_{\rm F}$	$3.40\,(1 \pm 0.16)$	$5.52\,(1 \pm 0.16)$	≤ 59

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^{8}B @ 3% (SNO & SK) and now ^{7}Be @ 4.5% (Borexino)

Note that:

$$\delta\Phi_{\rm B} \simeq 20\ \delta T_{\rm c}$$

Solar thermometer!

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pp and pep are strongly bound by the "luminosity constraint"

otherwise solar luminosity matched @ 15% (Maltoni et al. 2010)

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$\Phi_{pp} = 6.6\ (1 \pm 0.11)$

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Direct measurement of pp now to 11% Borexino

L_ν(8 minutes) ≈ L_γ (10^5 year) – test of solar stability

Still not accurate enough to test SSMs (≈ few % accuracy required)

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CNO neutrinos

- No direct detection
- Loose upper bounds obtained by combining the different expt results

The electron neutrino survival probability

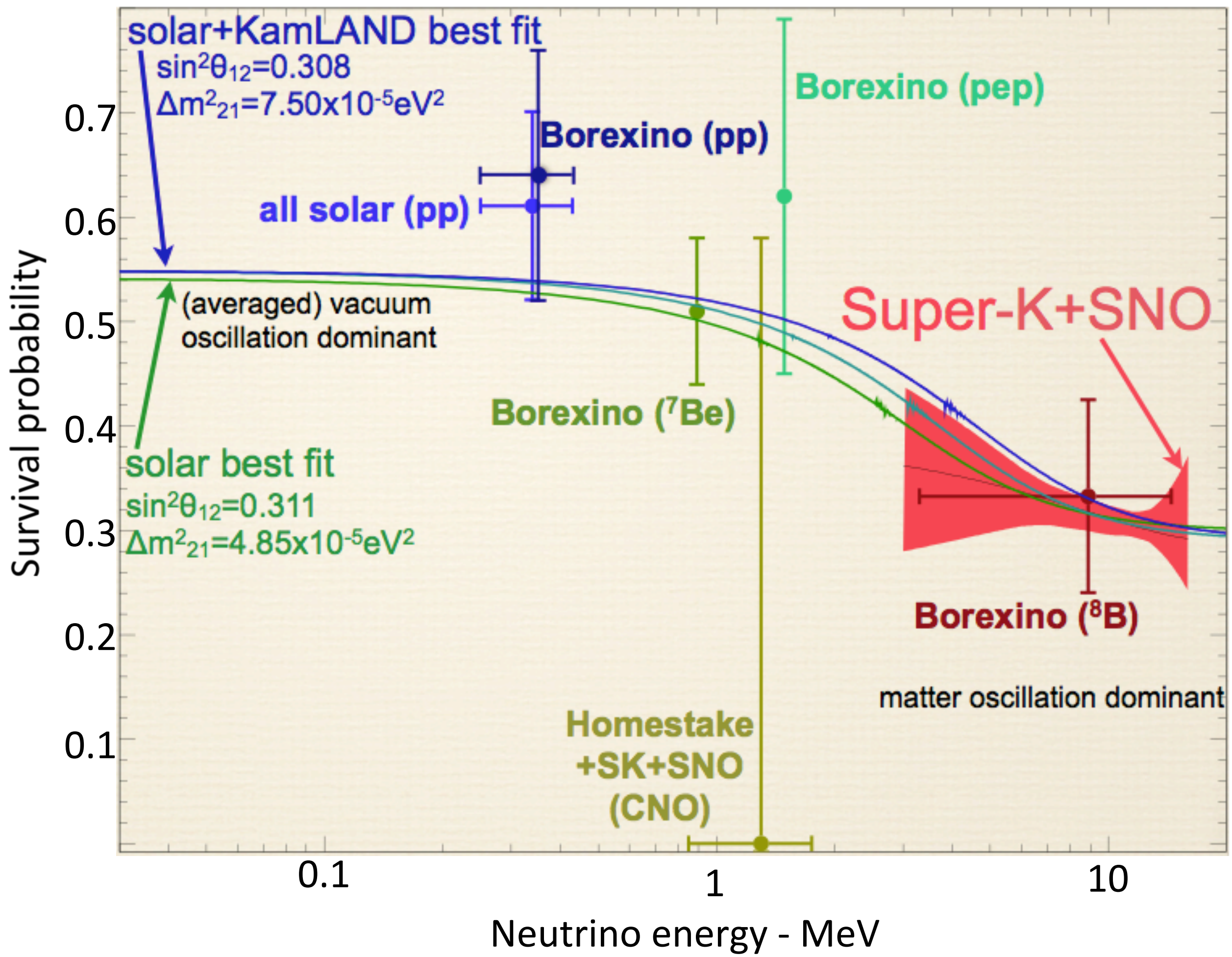
- Searching for the final confirmation of MSW transition (or looking for new physics):

The ν_e survival probability at E_ν = 1-3 MeV probes transition between vacuum and matter dominated regimes

Sensitive to new physics effects (mass varying neutrinos, sterile neutrinos, NSI, etc.)

Combined analysis of SK I-IV PRL 112 (2014) 091805 Provide a 2.7σ observation of day-night effect;

From Michael Smy talk @ WINP 15



Helioseismology

The Sun is a non radial oscillator. The observed oscillation frequencies can be used to determine the properties of the Sun. Linearizing around a known solar model:

$$\frac{\delta\nu_{nl}}{\nu_{nl}} = \int_0^R dr\ K^{nl}_{u,Y}(r)\,\frac{\delta u}{u}(r) + \int_0^R dr\ K^{nl}_{Y,u}(r)\,\delta Y + \frac{F(\nu_{nl})}{\nu_{nl}}$$

surface helium abundance

squared isothermal sound speed

See Basu & Antia 07 for a review

Impressive agreement with SSM predictions …

Surface helium abundance

$$Y_{\rm b} = 0.2485 \pm 0.0035$$

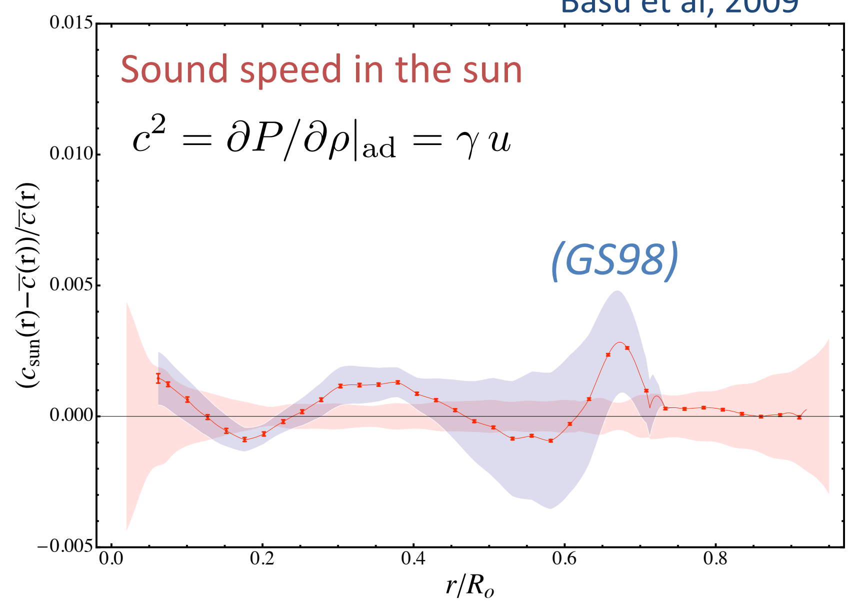
$Y_{\rm b} = 0.243$ *(GS98)*

Inner radius of the solar convective envelope

$$R_{\rm b}/R_\odot = 0.713 \pm 0.001$$

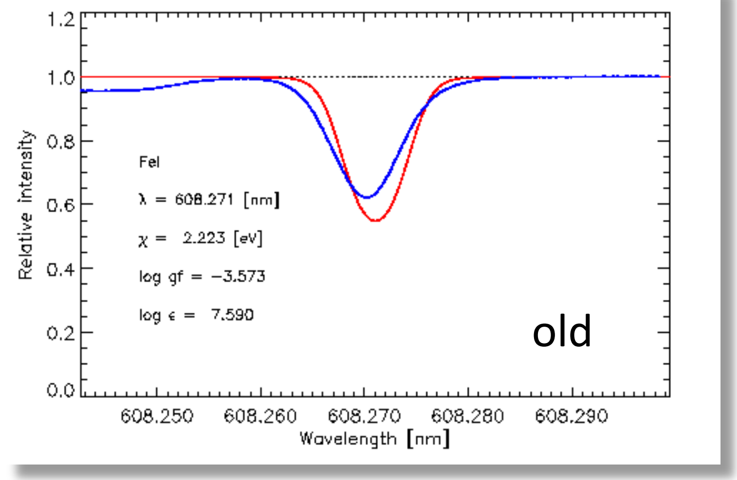
$R_{\rm b}/R_\odot = 0.712$ *(GS98)*

Basu et al, 2009



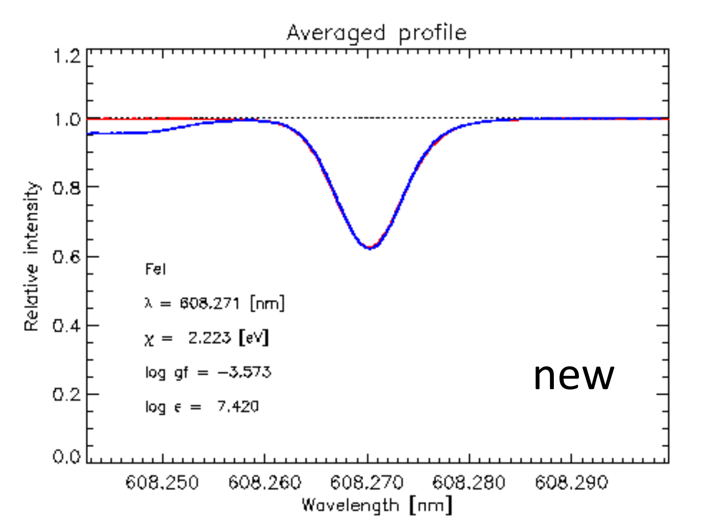
… till few years ago

Asplund et al. 05 (AGS05); Asplund et al. 09 (AGSS09)
Re-determination of the photospheric abundances of nearly all available elements **(inputs for SSM calculations)**



Improvements with respect to previous analysis[*]:

- 3D model instead of the classical 1D model of the lower solar atmosphere
- Careful and very demanding selection of the spectral lines… AVOID blends!!! NOT TRIVIAL!!!
- Careful choice of the atomic and molecular data NOT TRIVIAL!!!!
- NLTE instead of the classical LTE hypothesis… WHEN POSSIBLE !!!
- Use of ALL indicators (atoms as well as molecules,CNO)



[*]N. Grevesse talk at PHYSUN10

The solar composition problem

AGS05 and AGSS09

Downward revision of heavy elements photospheric abundances …

Element	GS98	AGSS09	δz_i
C	8.52 ± 0.06	8.43 ± 0.05	0.23
N	7.92 ± 0.06	7.83 ± 0.05	0.23
O	8.83 ± 0.06	8.69 ± 0.05	0.38
Ne	8.08 ± 0.06	7.93 ± 0.10	0.41
Mg	7.58 ± 0.01	7.53 ± 0.01	0.12
Si	7.56 ± 0.01	7.51 ± 0.01	0.12
S	7.20 ± 0.06	7.15 ± 0.02	0.12
Fe	7.50 ± 0.01	7.45 ± 0.01	0.12
Z/X	0.0229	0.0178	0.29

$$[I/H] \equiv \log\left(N_I/N_H\right) + 12$$

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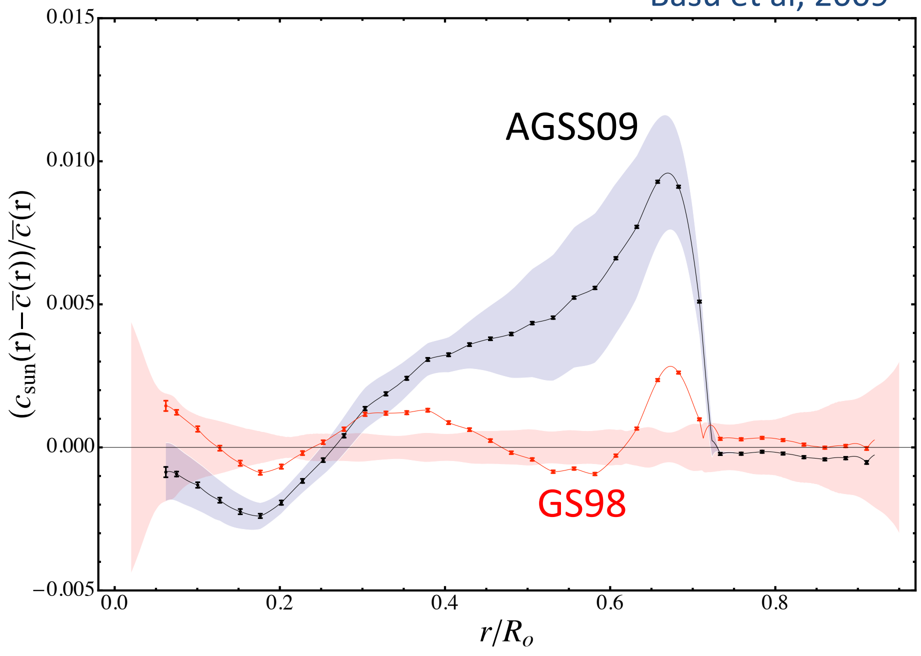
Basu et al, 2009



... leads to SSMs which do not correctly reproduce helioseismic observables

	AGSS09	GS98	Obs.
$Y_{\rm b}$	$0.2319\,(1 \pm 0.013)$	$0.2429\,(1 \pm 0.013)$	0.2485 ± 0.0035
$R_{\rm b}/R_\odot$	$0.7231\,(1 \pm 0.0033)$	$0.7124\,(1 \pm 0.0033)$	0.713 ± 0.001
$\Phi_{\rm pp}$	$6.03\,(1 \pm 0.005)$	$5.98\,(1 \pm 0.005)$	$6.05(1^{+0.003}_{-0.011})$
$\Phi_{\rm Be}$	$4.56\,(1 \pm 0.06)$	$5.00\,(1 \pm 0.06)$	$4.82(1^{+0.05}_{-0.04})$
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$\Phi_{\rm N}$	$2.17\,(1 \pm 0.08)$	$2.96\,(1 \pm 0.08)$	≤ 6.7
$\Phi_{\rm O}$	$1.56\,(1 \pm 0.10)$	$2.23\,(1 \pm 0.10)$	≤ 3.2

(≈ 4σ discrepancies)

A quantitative analysis of the solar composition problem

To combine observational infos, we need an estimator that is **non-biased** and that can be used as a **figure-of-merit** for solar models with different composition:

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right] .$$

$$\delta Q = \frac{Q_{\rm obs} - Q}{Q}$$

Fogli et al. 2002

where:

$$\{\delta Q\} = \{\delta \Phi_{\rm B},\ \delta \Phi_{\rm Be};\ \delta Y_{\rm b},\ \delta R_{\rm b};\ \delta c_1,\ \delta c_2, \ldots,\ \delta c_{30}\}$$

^{7}Be and ^{8}B neutrino fluxes

Surface helium and convective radius

Sound speed data points (from Basu et al, 2009)

and:

- U_Q — Uncorrelated (observational) errors
- $C_{Q,I}$ — Correlated (systematical) uncertainties

We consider 18 input parameters:

$$\{I\} = \{\text{opa, age, diffu, lum,}$$
$$S_{11},\ S_{33},\ S_{34},\ S_{17},\ S_{e7},\ S_{1,14},\ S_{\rm hep},$$
$$\text{C, N, O, Ne, Mg, Si, S, Fe}\}$$

Enviromental

Nuclear

Composition

The status of the AGSS09 standard solar model

The SSM implementing the AGSS09 composition provides a poor fit of the observational data (**χ^2/ d.o.f. = 72.5/34**; χ^2_{obs}= 42.9 ; χ^2_{syst}= 29.6)

$$\chi^2 \equiv \chi^2_{\rm obs} + \chi^2_{\rm syst} = \sum_Q \tilde{X}_Q^2 + \sum_I \tilde{\xi}_I^2$$

$\bar{\xi}_I \equiv$ *Pulls of systematic*

$$\tilde{X}_Q \equiv \frac{\delta Q_{\rm obs} - \sum_I \tilde{\xi}_I \, C_{Q,I}}{U_Q}$$

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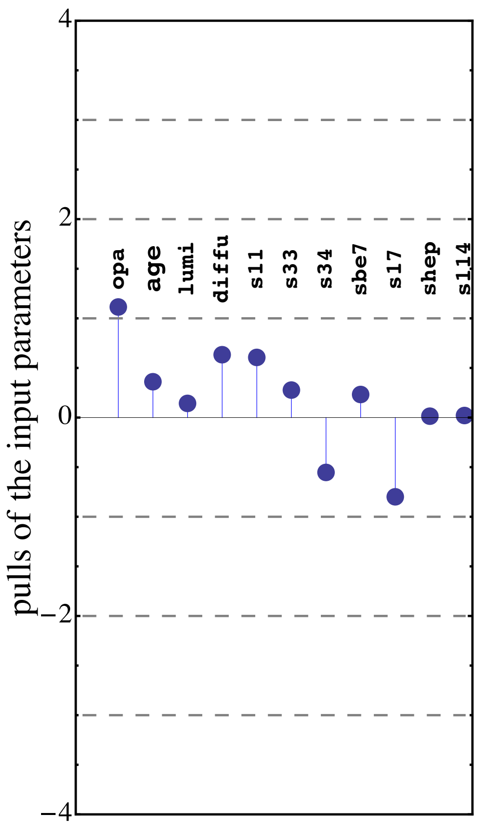
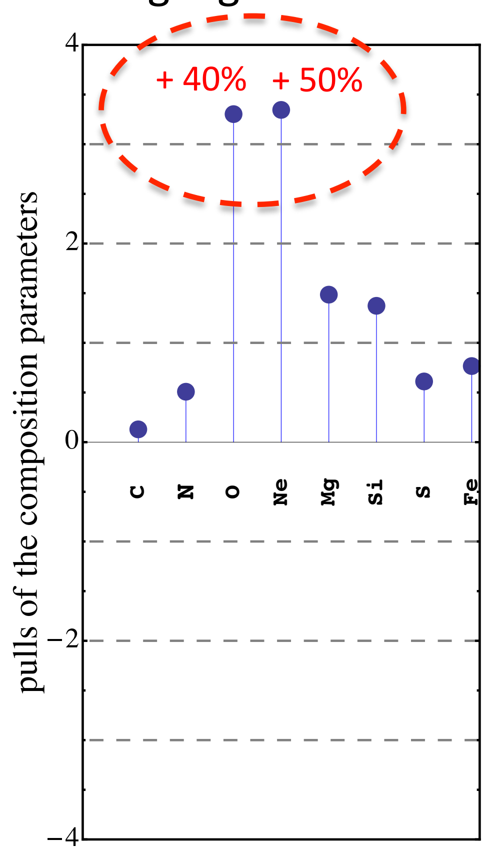
$$\bar{\xi}_I \equiv \quad \textit{Pulls of systematic}$$

$$\tilde{X}_Q \equiv \frac{\delta Q_{\rm obs} - \sum_I \tilde{\xi}_I \, C_{Q,I}}{U_Q}$$

The distribution of the pulls of systematics highlight tensions in the model:





Obs. data requires an increase of the metal abundance of the sun, in particular for light elements (O, Ne).

The solar composition problem

Is there something **wrong** or **unaccounted** in solar models?

- Are properties of the solar matter (e.g. **opacity**) correctly described?
- Are the new abundances (i.e. the atmospheric model) **wrong**?
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

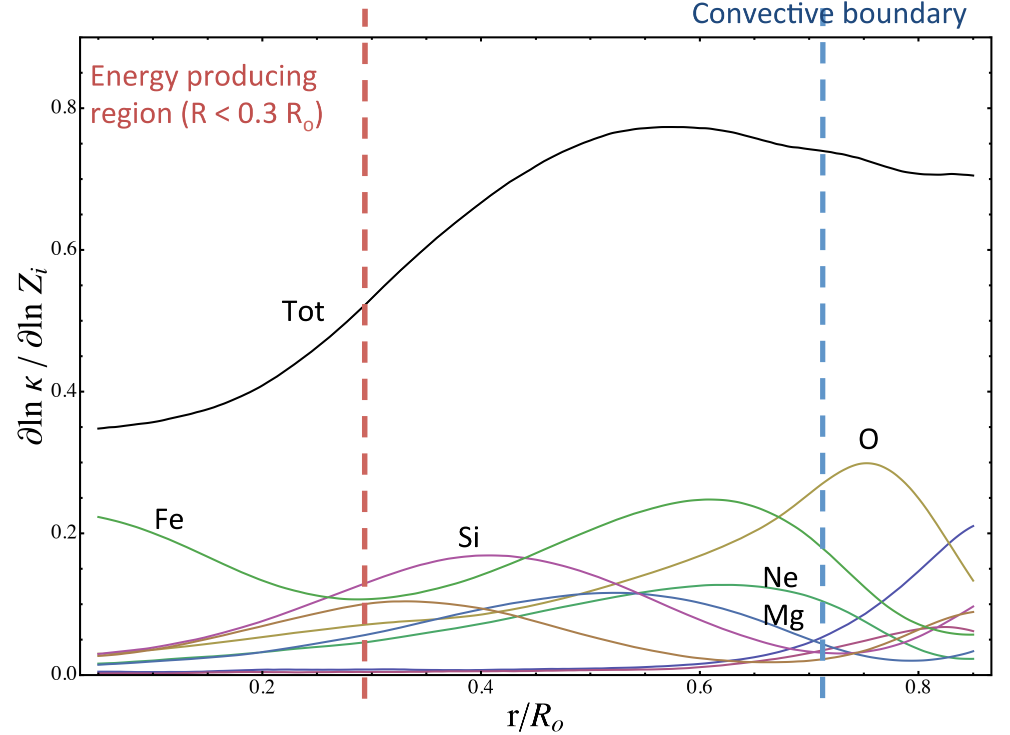
Note that:

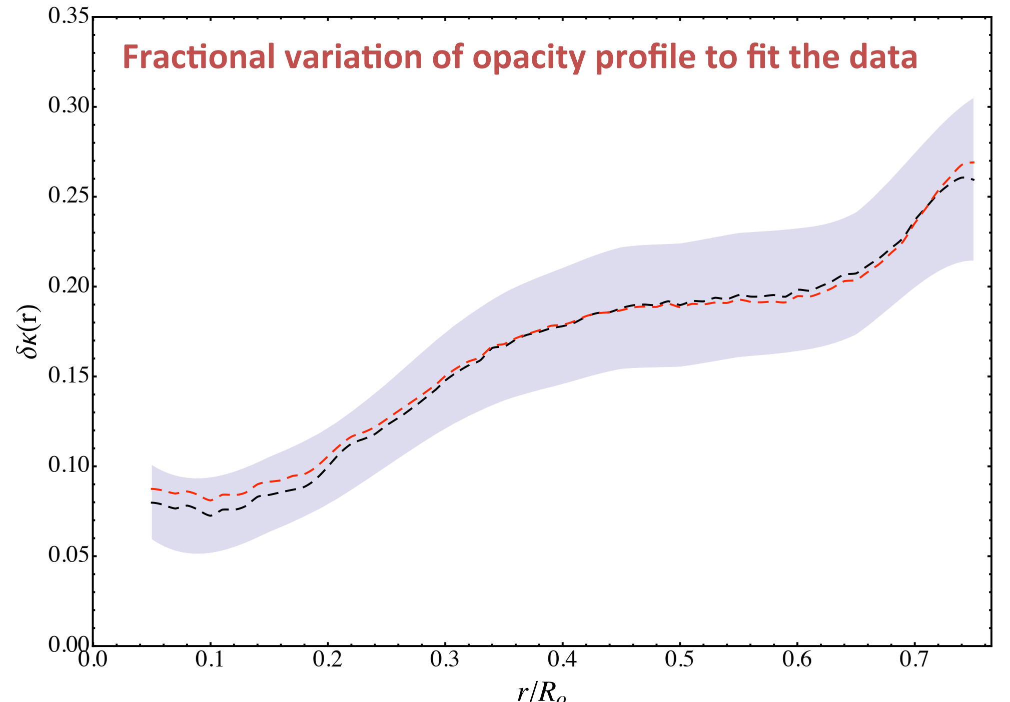
It is not just the problem of deciding between AGSS09 (new) and GS98 (old and presumably wrong) abundances

*The Sun provide the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

Wrong opacity?

A change of the solar composition produces the same effects on the helioseismic observables and on ^8B and ^7Be neutrinos of a **suitable change of the solar opacity profile δκ(r).**





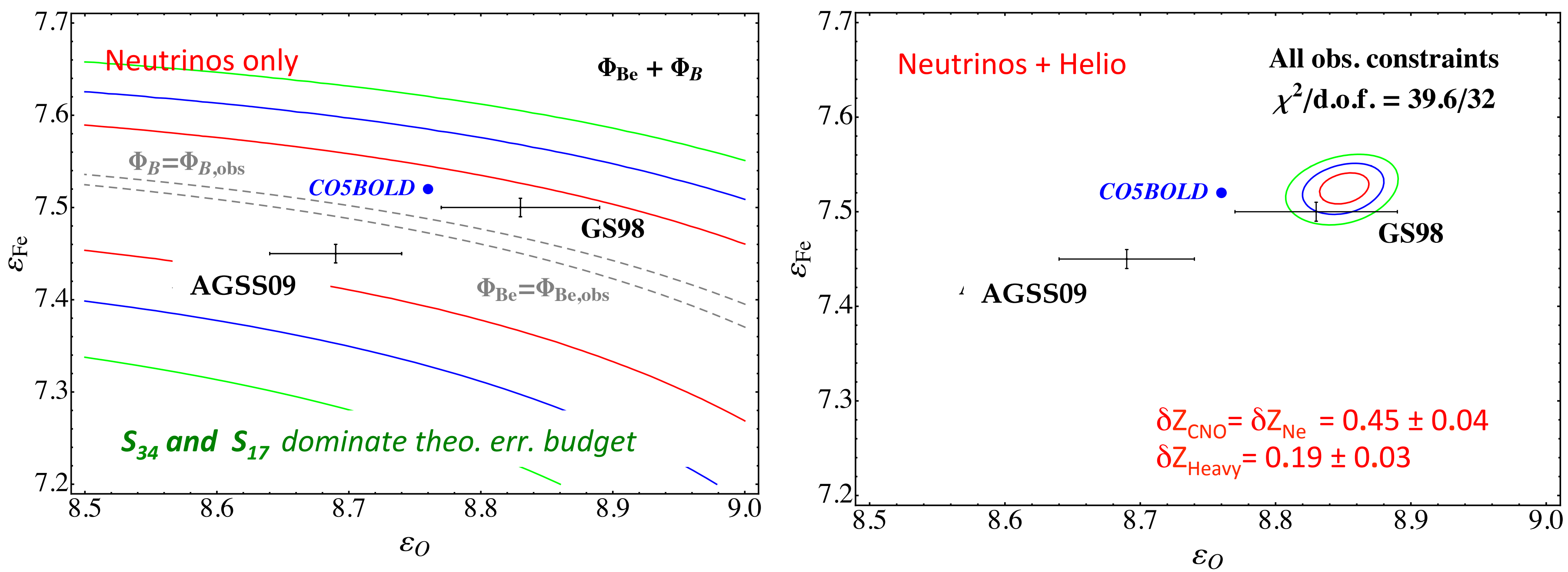
- The required variations are too large wrt uncertainties (≈ few %)
- Non standard effects (e.g. WIMPs accumulation in the solar core) do not provide the correct profile.

*F.L. Villante and B. Ricci - **Astrophys.J.714:944-959,2010***
*F.L. Villante – **Astrophys.J.724:98-110,2010***

Wrong composition?

We can use the data (helioseismology + neutrinos) determine the optimal composition:

Two parameter analysis (δZ_{CNONe} ; δZ_{Heavy})



F.L. Villante et al. – ApJ 2014

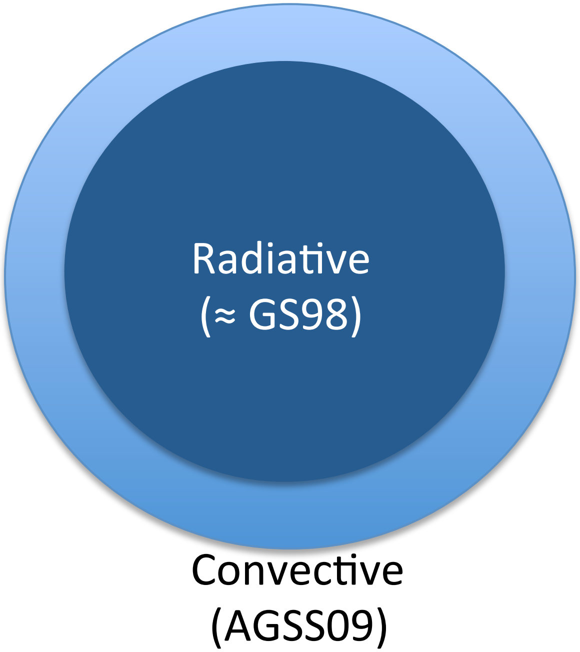
However, data not so effective in constraining composition in more realistic scenarios:

- degeneracies among the various δZ_i ;
- no real constraints on the Ne/O ratio

Wrong chemical evolution?

Helioseismic observables and neutrino fluxes are sensitive to **the metallicity of the radiative core of the Sun.**

The observations determine **the chemical composition of the convective envelope** (2-3% of the solar mass).



Difference between AGSS09 and GS98 correspond to $\approx 40 M_{\oplus}$ of metal, when integrated over the Sun's convective zone.

Could this difference be accounted in non standard chemical evolution scenarios (e.g. by accretion of material with non standard composition)?

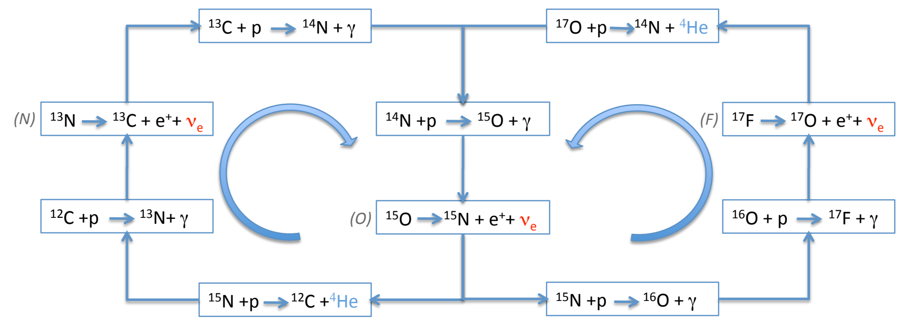
See A. Serenelli et al. – ApJ 2011

This is a well posed and extremely important question but …

… no satisfactory solutions have been proposed up to now, in my opinion

CNO neutrinos

CNO neutrinos allows to determine directly the C+N abundance in the solar core:



$$1+\delta\Phi_\nu = (1+\delta X_{\rm CN})\left[1+\int dr\; K_\nu(r)\;\delta\kappa(r)\right]$$

Determines the central temperature

$$X_{\rm CN} \equiv X_{\rm C}/12 + X_{\rm N}/14$$

Total number of catalysts for CN-cycle

At present, we only have a loose upper limit on CNO neutrino fluxes:

ν flux	GS98	AGSS09	Solar
^{13}N $(10^8\,{\rm cm^{-2}\,s^{-1}})$	$2.96(1\pm0.14)$	$2.17(1\pm0.14)$	≤ 6.7
^{15}O $(10^8\,{\rm cm^{-2}\,s^{-1}})$	$2.23(1\pm0.15)$	$1.56(1\pm0.15)$	≤ 3.3
^{17}F $(10^6\,{\rm cm^{-2}\,s^{-1}})$	$5.52(1\pm0.17)$	$3.04(1\pm0.16)$	≤ 59

Will it be possible to detect CNO neutrino?

Very difficult, in practice. Not impossible, in principle .....

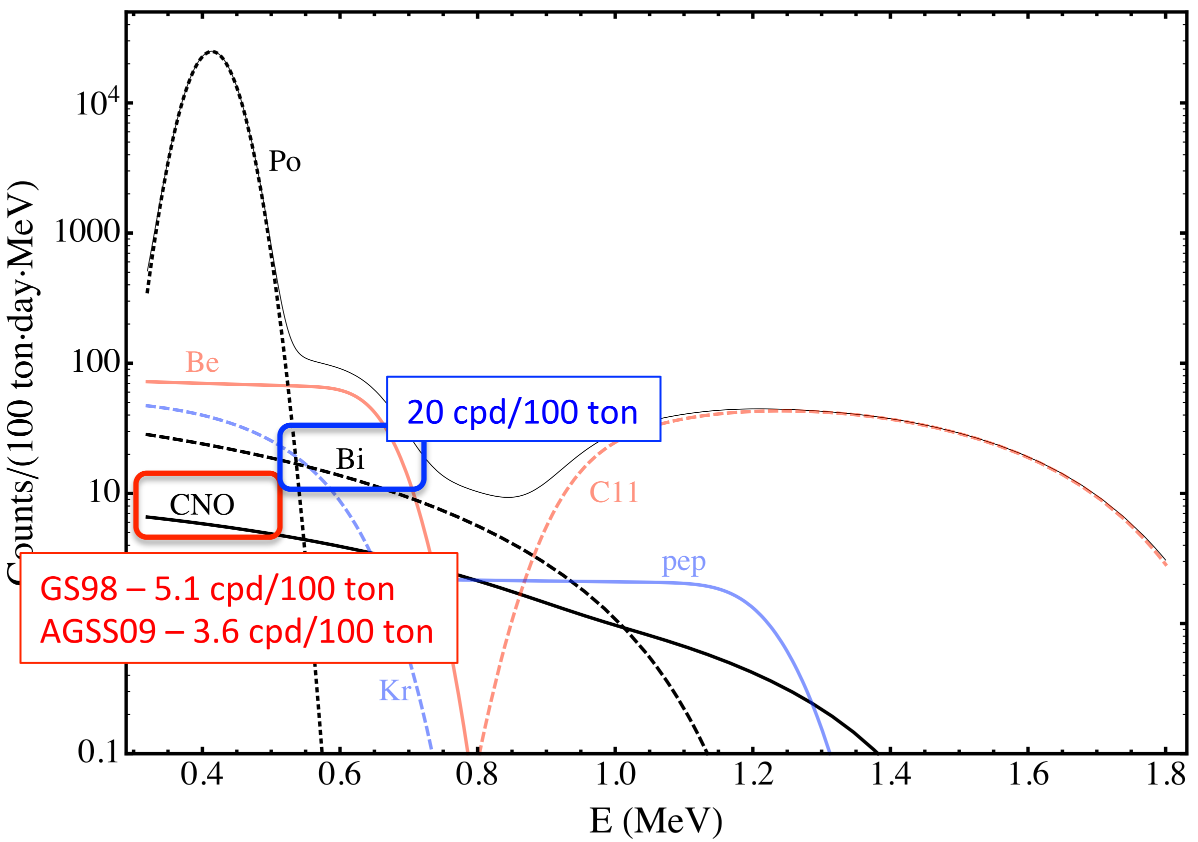
F.L. Villante et al. – Phys.Lett. B701 (2011) 336

Is it possible to observe CNO neutrinos in LS?

The detection of CNO neutrinos is very difficult:

- Low energy neutrinos → endpoint at about 1.5 MeV
- Continuos spectra → do not produce recognizable features in the data.
- Limited by the background produced by beta decay of ^{210}Bi.

Event spectrum in ultrapure liquid scintillators (Borexino-like)



Determining ^{210}Bi with the help of ^{210}Po?

$$^{210}\mathrm{Bi} \rightarrow ^{210}\mathrm{Po} + e^- + \overline{\nu}_e$$

$$^{210}\mathrm{Po} \rightarrow ^{206}\mathrm{Pb} + \alpha$$

τ_{Bi} = 7.232 d

τ_{Po} = 199.634 d

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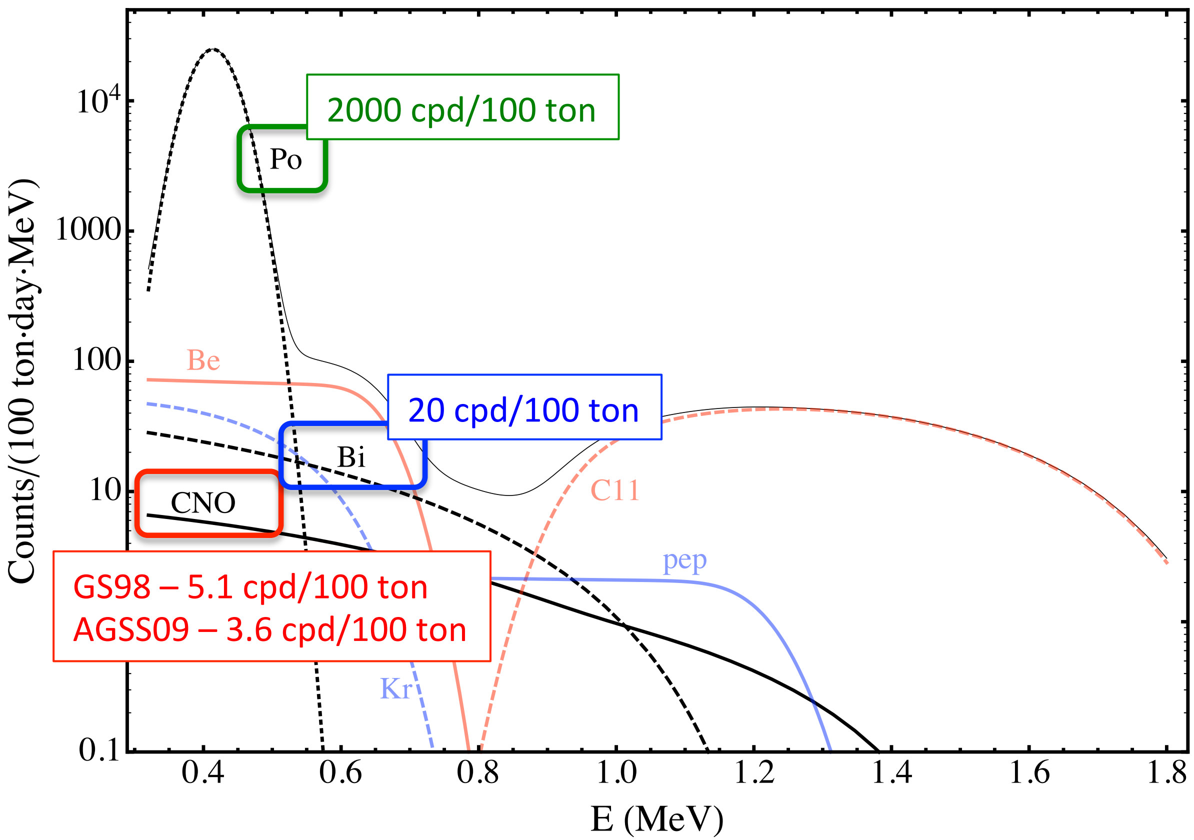

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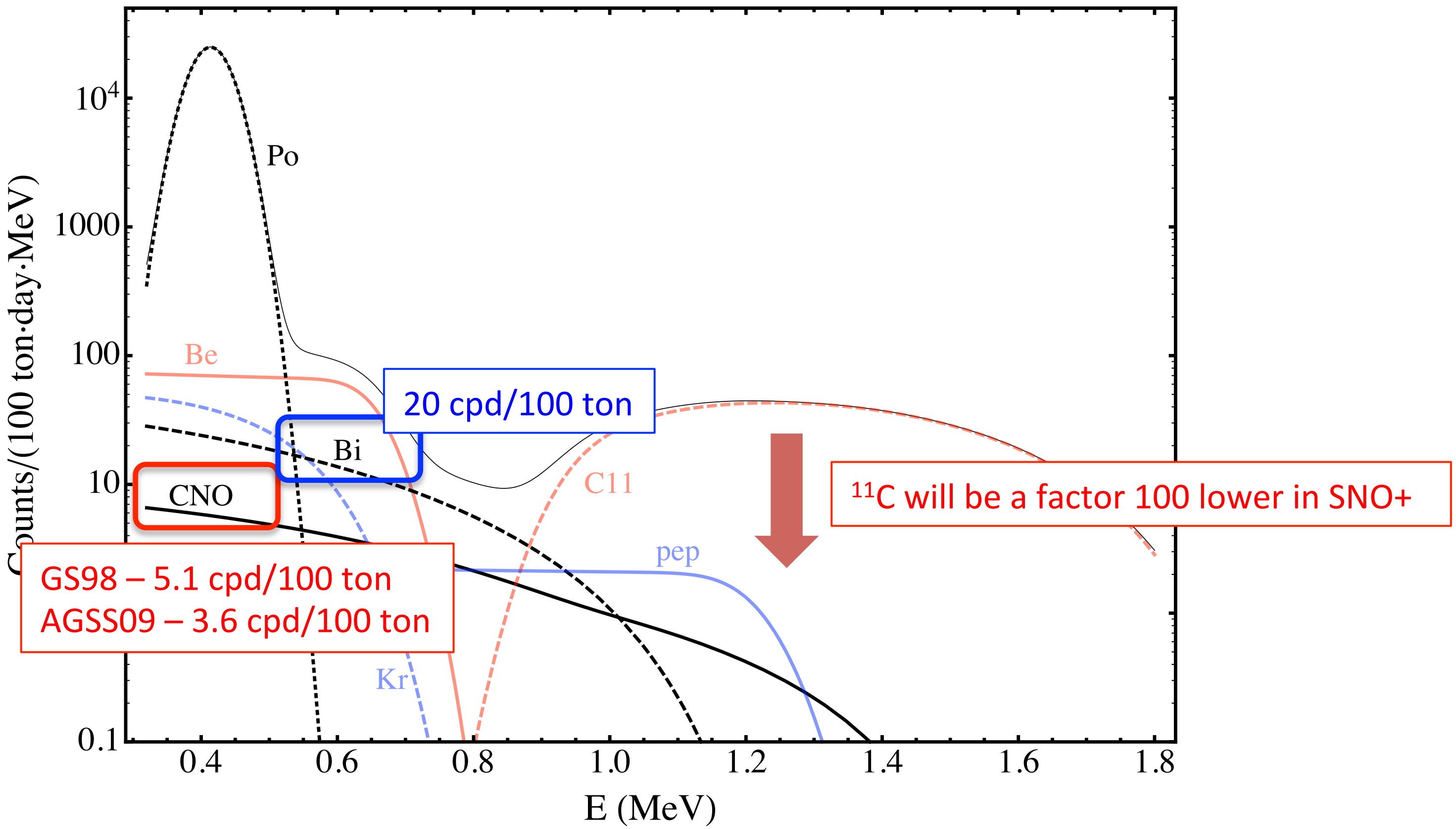
- Deviations from the exponential decay law of ^{210}Po can be used to determine ^{210}Bi
- Borexino already have the potential to probe the CNO neutrino flux … but the detector should be stable (no convective motions) over long time scales.

How to improve?

Increase the detector depth → reduction of cosmogenic ^{11}C background
Consider larger detectors → Stat. uncertainties scales as $1/M^{1/2}$
SNO+ (1 kton), LENA (50 kton)

Event spectrum in ultrapure liquid scintillators (Borexino-like)



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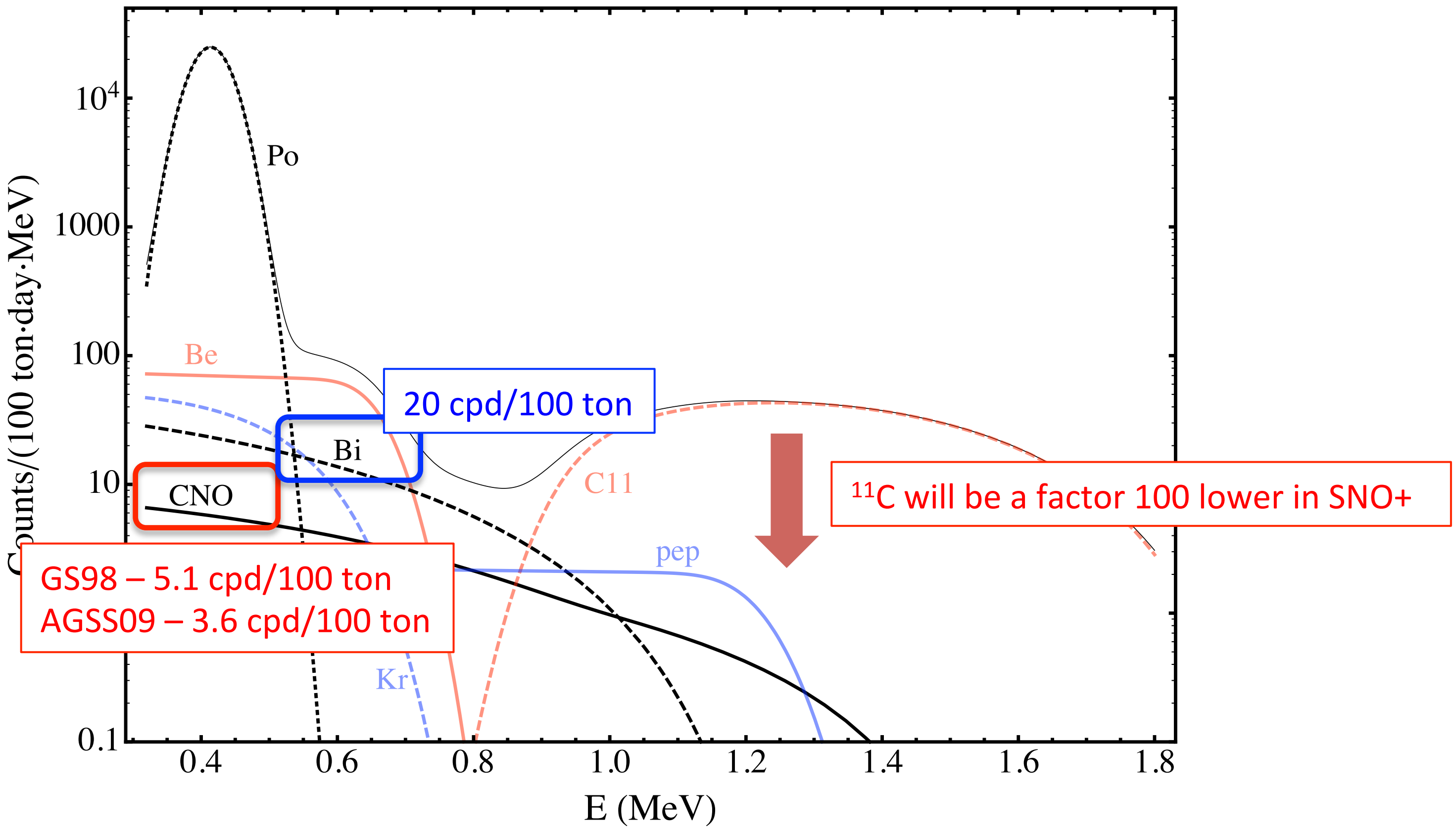


The final accuracy depends, however, on the internal background (^{210}Bi)

Borexino: 20cpd/100 ton → 150 nuclei / 100 ton

Significance of CNO measurement in LENA

From Michael Wurm talk @ NNN14

Assuming constraints of ^{210}Bi rate at the 1% level:

Time	CNO prec (stat.)	PEP prec. (stat.)	CNO significance
1 y	10.7 %	2.5 %	4.2 σ (avg)
2 y	9.2 %	1.9 %	5.5 σ (avg)
3 y	8.2 %	1.7 %	6.5 σ (avg)
4 y	7.5 %	1.6 %	$> 5\sigma$ (99% prob.)
5 y	7.0 %	1.4 %	$> 5\sigma$ (99% prob.)
10 y	5.6 %	1.1 %	$> 5\sigma$ (99% prob.)

Assuming no constraints of ^{210}Bi rate:

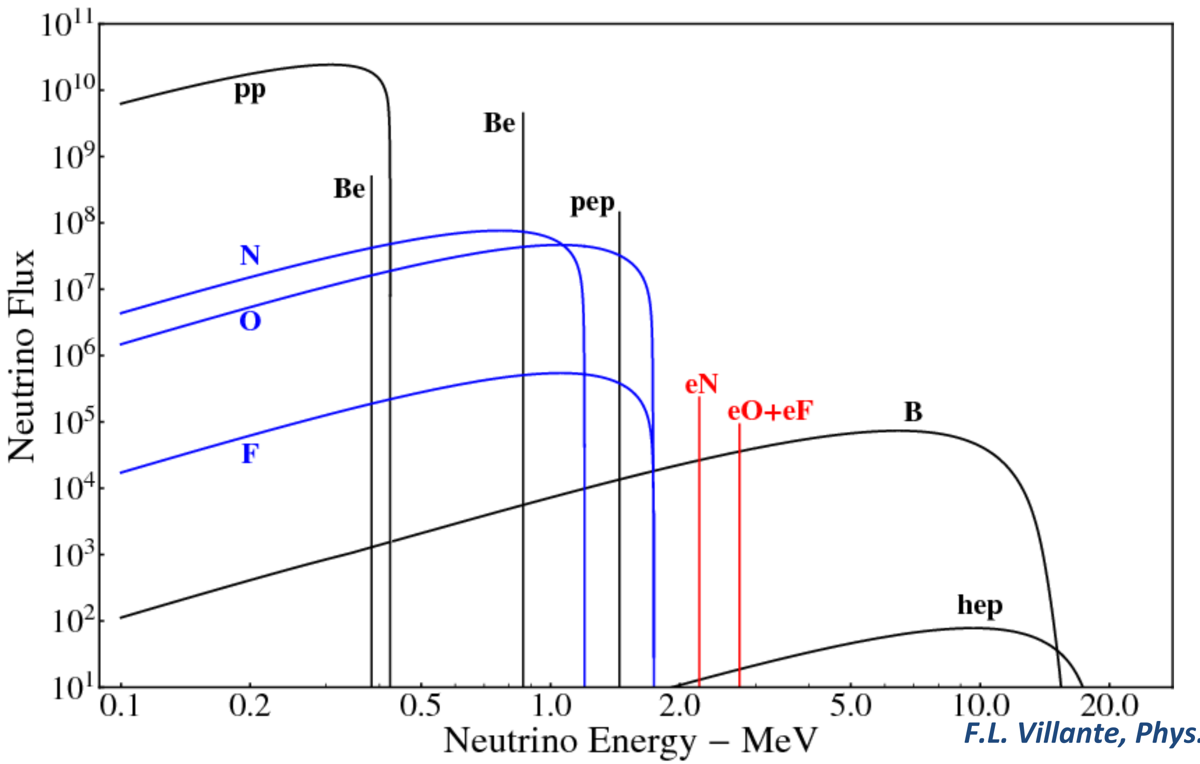
Time	CNO prec (stat.)	PEP prec. (stat.)	CNO significance
1 y	22.7 %	4.3 %	0.7 σ (avg)
2 y	16.0 %	3.0 %	1.8 σ (avg)
3 y	13.1 %	2.5 %	2.8 σ (avg)
4 y	11.3 %	2.2 %	3.7 σ (avg)
5 y	10.1 %	1.9 %	4.5 σ (avg)
10 y	7.2 %	1.4 %	8.1 σ (avg)

ecCNO neutrinos: a challenge for gigantic ultrapure LS

In the CNO cycle, (monochromatic) neutrinos are also produced by electron capture reactions:

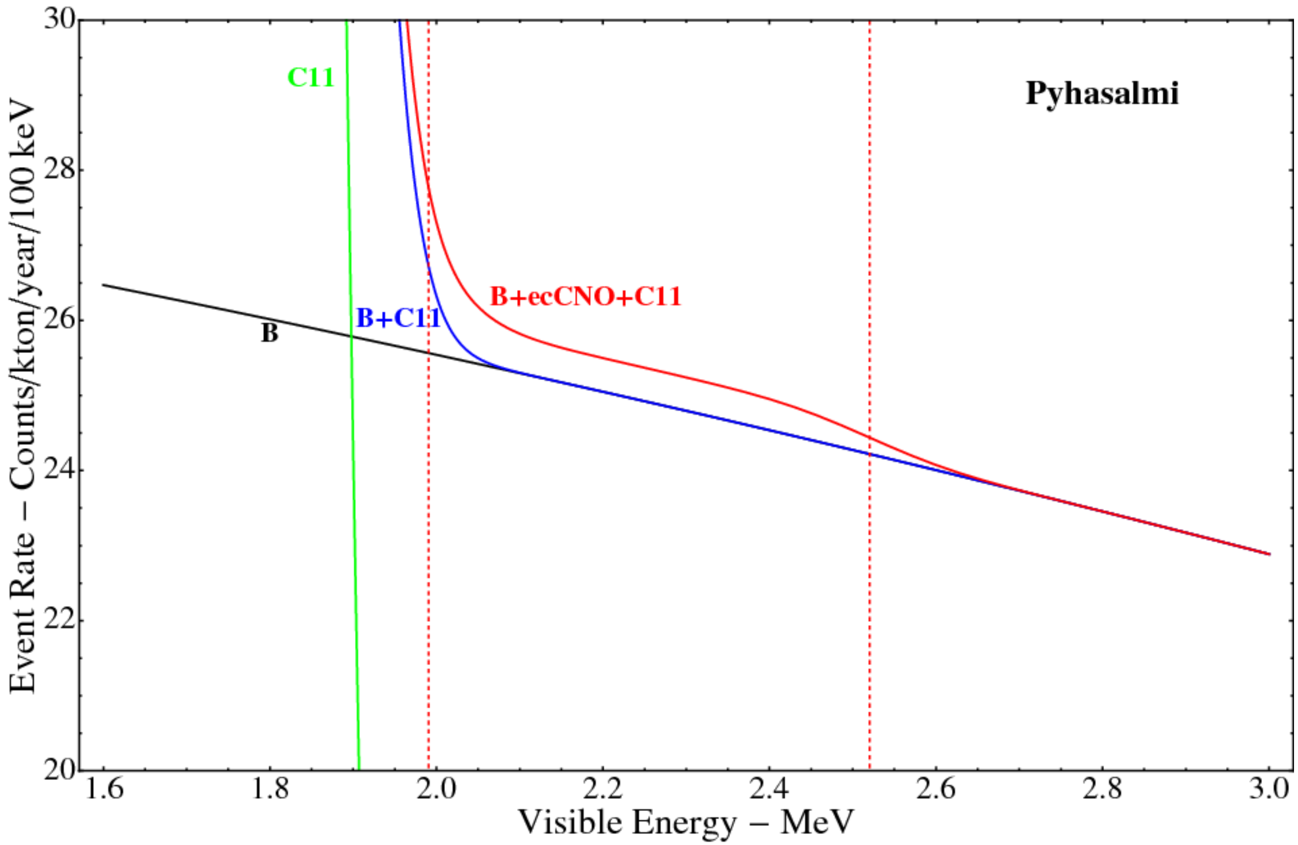
$$^{13}\mathrm{N} + e^- \quad \rightarrow \quad ^{13}\mathrm{C} + \nu_e \qquad\qquad E_\nu = 2.220 \text{ MeV}$$
$$^{15}\mathrm{O} + e^- \quad \rightarrow \quad ^{15}\mathrm{N} + \nu_e \qquad\qquad E_\nu = 2.754 \text{ MeV}$$
$$^{17}\mathrm{F} + e^- \quad \rightarrow \quad ^{17}\mathrm{O} + \nu_e \qquad\qquad E_\nu = 2.761 \text{ MeV}$$

- ecCNO neutrinos probe the **core metallicity** and **Pee in the transition region**.
- fluxes are extremely low: $\Phi_{ecCNO} \approx (1/20)\ \Phi_B$



F.L. Villante, Phys.Lett. B742 (2015) 279-284

ecCNO neutrinos: expected event rate in LENA



Below 2.5 MeV, the ecCNO neutrino signal is comparable to stat. fluctuations for a detector with an exposure ε = 10 kton × year or larger.

100 counts / year above 1.8 MeV in 20 kton detector → 3σ detection in 5 year in LENA

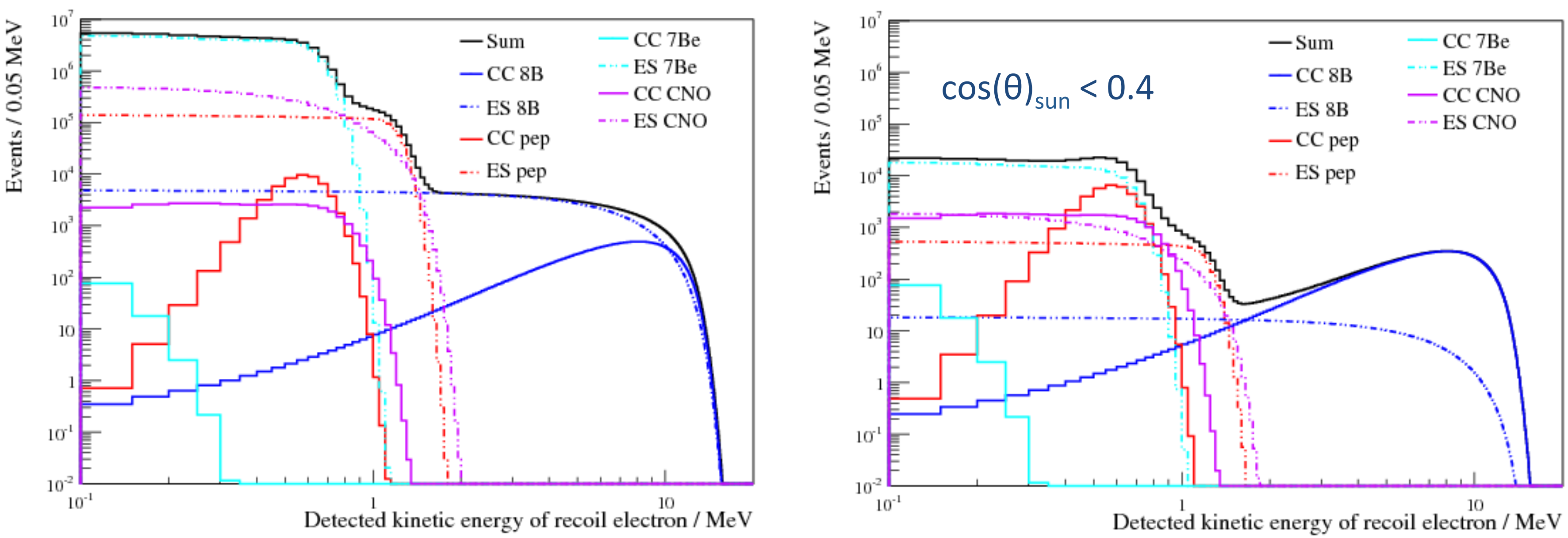
F.L. Villante, Phys.Lett. B742 (2015) 279-284

In the future … Advanced Scintillator Detector Concept (ASDC)

It combines:
- Water based Liquid Scintillators (WbLS)
- High efficiency and ultra fast photosensor
- Deep underground location

30-100 kton scale detector
Cherenkov + Scintillation
100pe/MeV

"Salty" WbLS → doped (1% by mass) with ^{7}Li
CC detection of ν_e on ^{7}Li enhances spectral separation



From arXiv:1409.5864

Summary and conclusions

✦ Solar neutrino physics in still interesting

✦The solar composition problem is open and is potentially pointing at inadequacy in standard solar model paradigm.

✦Borexino opened the way to pp-neutrino flux determinations and tested the solar stability. We look forward for future measurements.

✦CNO neutrino detection requires careful bkgd evaluation in existing or next future LS detectors and/or new experimental approaches.

Thank you for your attention

Standard Solar Models

Stellar structure equations are solved, starting from a ZAMS model to present solar age (we neglect rotation, magnetic fields, etc.):

$$
\begin{aligned}
\frac{\partial m}{\partial r} &= 4\pi r^2 \rho \\
\frac{\partial P}{\partial r} &= -\frac{G_{\rm N} m}{r^2}\rho \\
P &= P(\rho, T, X_i) \\
\frac{\partial l}{\partial r} &= 4\pi r^2 \rho\, \epsilon(\rho, T, X_i) \\
\frac{\partial T}{\partial r} &= -\frac{G_{\rm N} m T \rho}{r^2 P}\nabla
\end{aligned}
$$

$$
\nabla = {\rm Min}(\nabla_{\rm rad}, \nabla_{\rm ad}) \rightarrow
\begin{cases}
\nabla_{\rm rad} = \dfrac{3}{16\pi a c\, G_{\rm N}} \dfrac{\kappa(\rho, T, X_i)\, l\, P}{m\, T^4} \\
\nabla_{\rm ad} = (d \ln T / d \ln P)_{\rm s} \simeq 0.4
\end{cases}
$$

Chemical evolution driven by nuclear reaction, diffusion and gravitational settling, convection

Standard input physics for equation of states, nuclear reaction rates, opacity, etc.

Free-parameters (mixing length, Y_{ini}, Z_{ini}) adjusted to match the observed properties of the Sun (radius, luminosity, Z/X).

Note that equations are non-linear → Iterative method to determine mixing length, Y_{ini}, Z_{ini}

The ingredients of the SSM

Stellar structure equations:

continuity eq., hydrostatic eq., energy cons., energy trans.
+ EOS, nuclear cross section, opacity

+

Chemical evolution paradigm

The Sun was born chemically homogenous
Chemical evolution driven by nuclear reactions (do not change metal abundances and diffusion (10% effect)

+

Obs constraints:

Radius, Luminosity, Surface composition

Metals in the Sun

• Metals give a negligible contribution to EOS and energy generation

• Metals give a **substantial** contribution to **opacity**:

Energy producing region ($R < 0.3\ R_o$)

$$\kappa_Z \approx \frac{1}{2}\kappa_{tot}$$

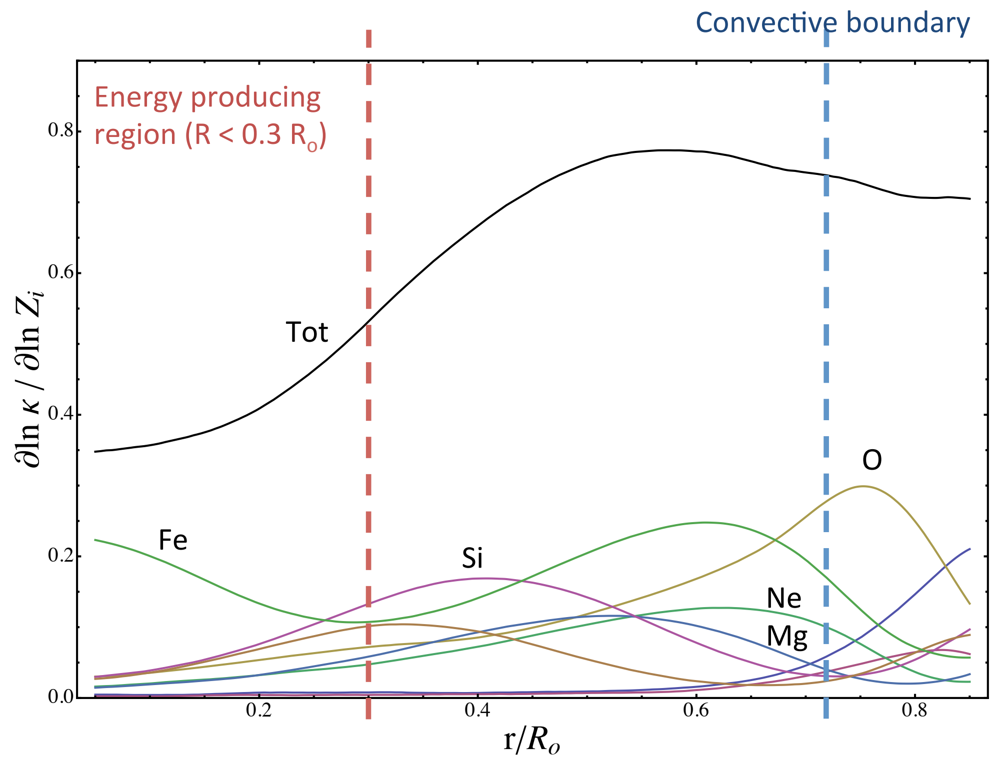
Fe gives the largest contribution.

Outer radiative region ($0.3 < R < 0.73\ R_o$)

$$\kappa_Z \sim 0.8\ \kappa_{tot}$$

Relevant contributions from several diff. elements (O,Fe,Si,Ne,…)

• Z_{CNO} control the efficiency of CNO cycle

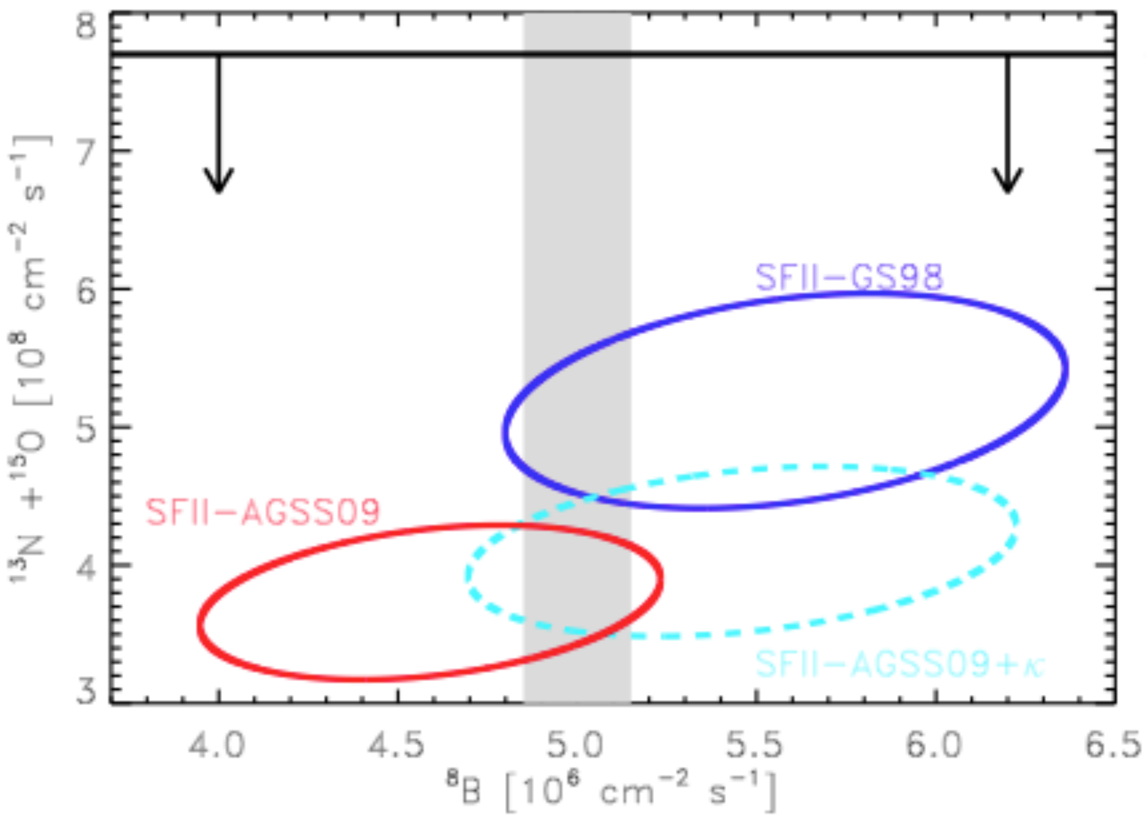


Solar composition problem?

What we know about the opacity profile of the present sun?

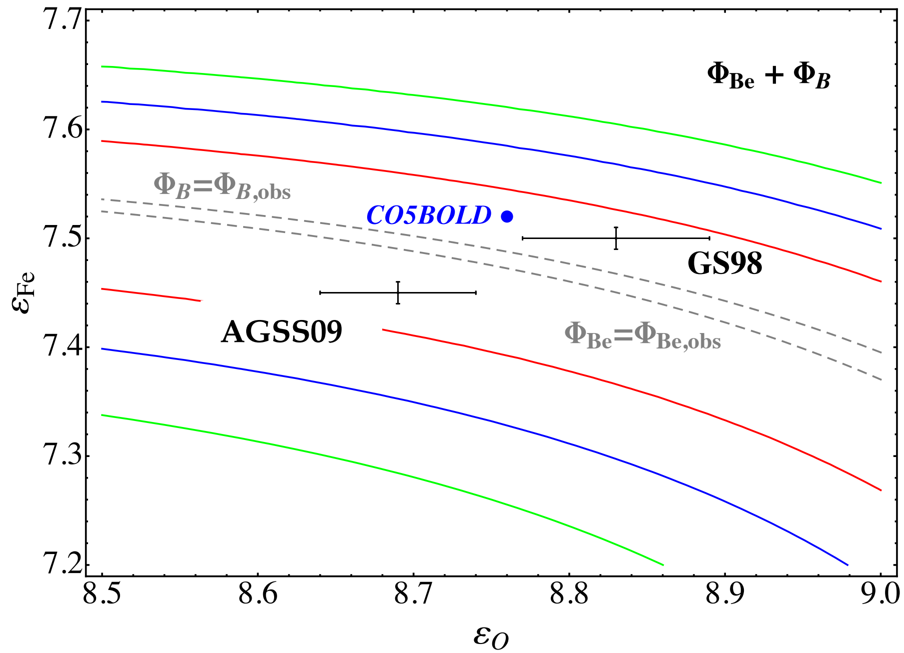
CN fluxes break the degeneracy because they carry extra (i.e. not associated with temperature) linear dependence on C+N abundance

From Aldo Serenelli, see e.g. talk@KITP



The role of ^{7}Be and ^{8}B neutrinos …

F.L. Villante et al. – ApJ 2014



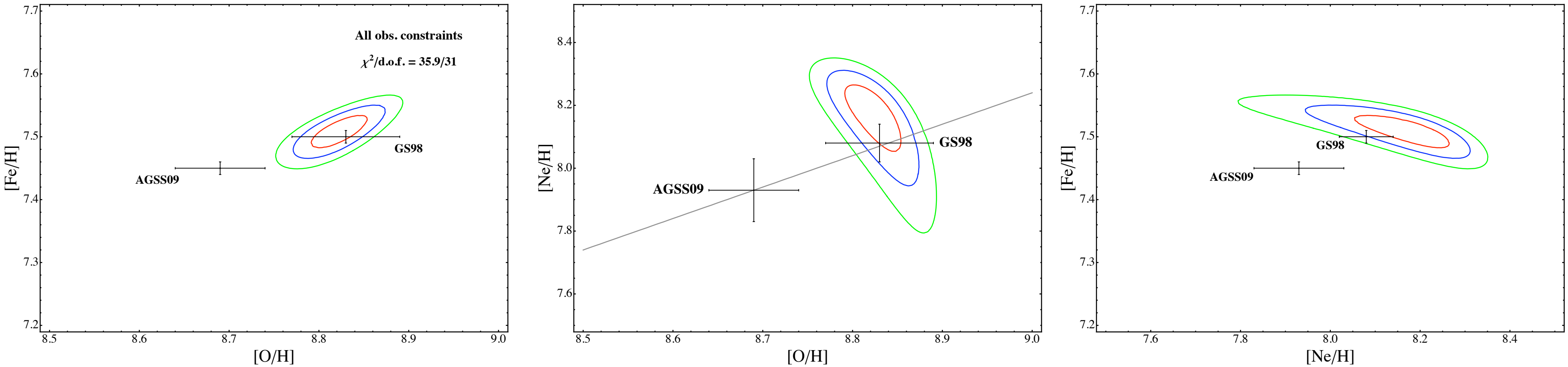
Note that: the error budget for ^{8}B and ^{7}Be neutrinos is dominated by systematical uncertainties

	Age	Diffu	Lum	S_{11}	S_{33}	S_{34}	S_{17}	S_{e7}	$S_{1,14}$	Opa
Y_b	-0.001	-0.012	0.002	0.001	0	0.001	0	0	0.	0.0036
R_b	-0.0004	-0.0029	-0.0001	-0.0006	0.0001	-0.0002	0	0	0	0.0014
Φ_{pp}	0	-0.002	0.003	0.001	0.002	-0.003	0	0	0	-0.0008
Φ_{Be}	0.003	0.022	0.014	-0.010	-0.023	0.047	0	0	0	0.009
Φ_B	0.006	0.044	0.029	-0.025	-0.022	0.046	0.075	-0.02	0	0.020
Φ_N	0.004	0.054	0.018	-0.019	0.001	-0.003	0	0	0.051	0.013
Φ_O	0.006	0.062	0.024	-0.027	0.001	-0.002	0	0	0.072	0.018

Table 1: *The contributions $C_{Q,I}$ to uncertainties in theoretical predictions for helioseismic observables and solar neutrino fluxes.*

Three parameter analysis (δZ_{CNO}; δZ_{Ne} ; δZ_{Heavy})

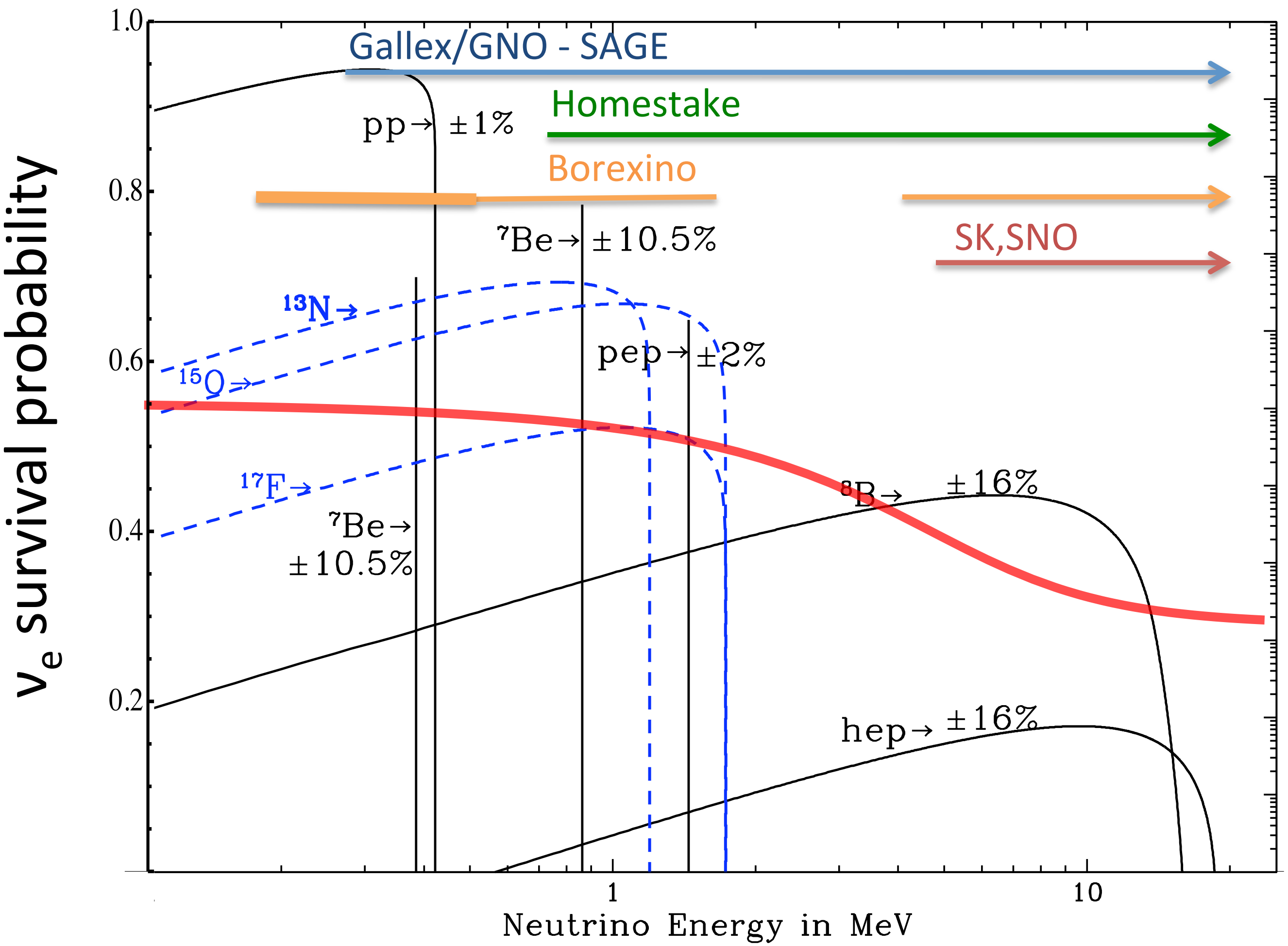
Prior: Neon-to-oxygen ratio forced at the AGSS09 value with 30% accuracy



GS98 still favored by observational data but:

- errors in the inferred abundances larger than before;
- degeneracies appear among the various δZ_i ;
- obs.data do not effectively constrain the Ne/O ratio (we recover the prior).

The solar neutrino spectrum

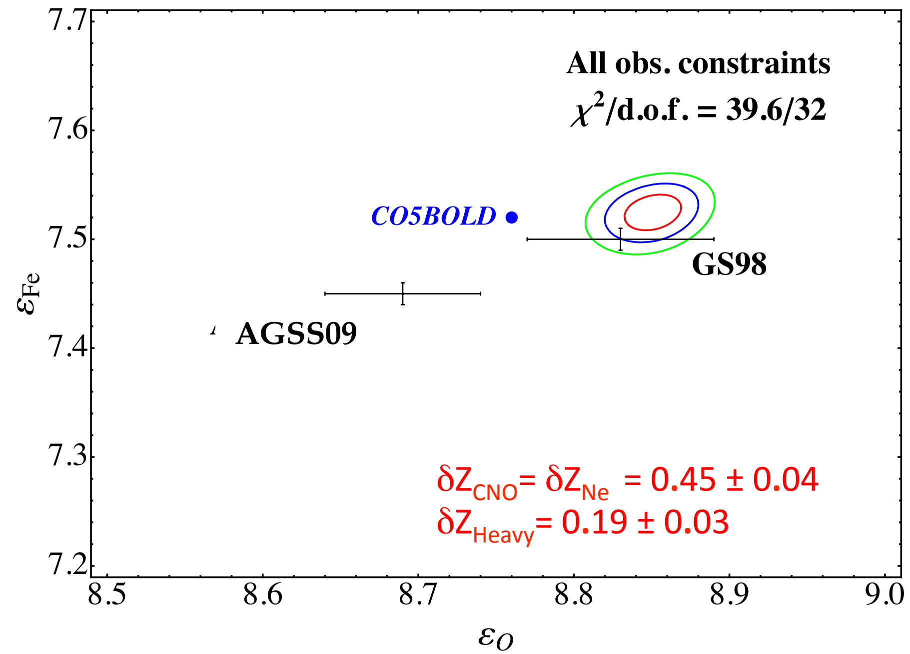


Wrong composition?

We can use the data (helioseismology + neutrinos) determine the optimal composition:

- Substantial agreement between the infos provided by the various obs. constraints. The quality of the fit is quite good being **χ^2/ d.o.f. = 39.6/32**.
- The best-fit abundances are **consistent** at 1 sigma with **GS98**. The **errors** on the inferred abundances **are smaller** than what is obtained by observational determinations.

Two parameter analysis (δZ_{CNONe} ; δZ_{Heavy})



F.L. Villante et al. – ApJ 2014

However, data not so effective in constraining composition in more realistic scenarios:

- degeneracies among the various δZ_i ;
- no real constraints on the Ne/O ratio

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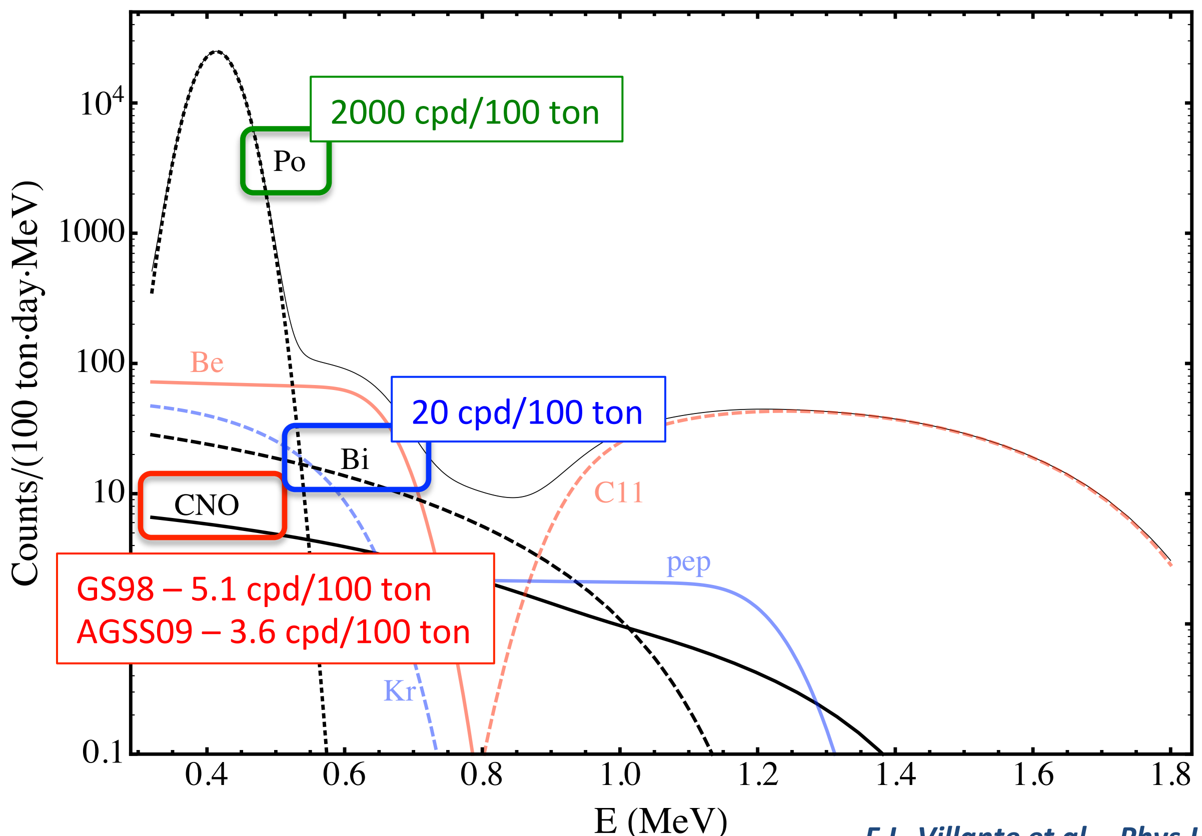

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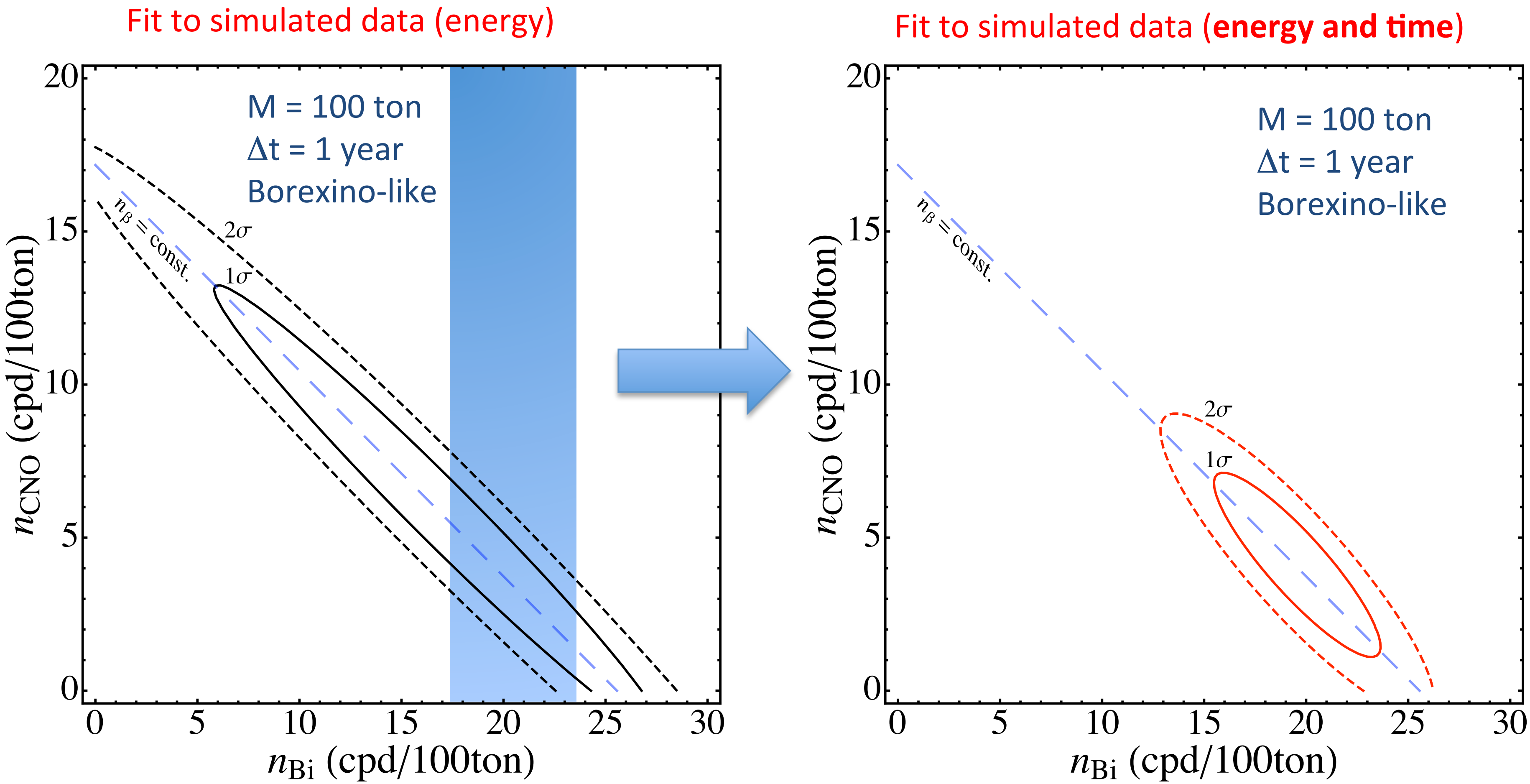
Deviations from the exponential decay law of Po210 can be used to determine Bi210:

$$n_{\rm Po}(t) = [n_{\rm Po,0} - n_{\rm Bi}]\ \exp(-t/\tau_{\rm Po}) + n_{\rm Bi}$$



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