Review of solar physics and solar neutrinos

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

Hydrogen Burning: PP chain and CNO cycle

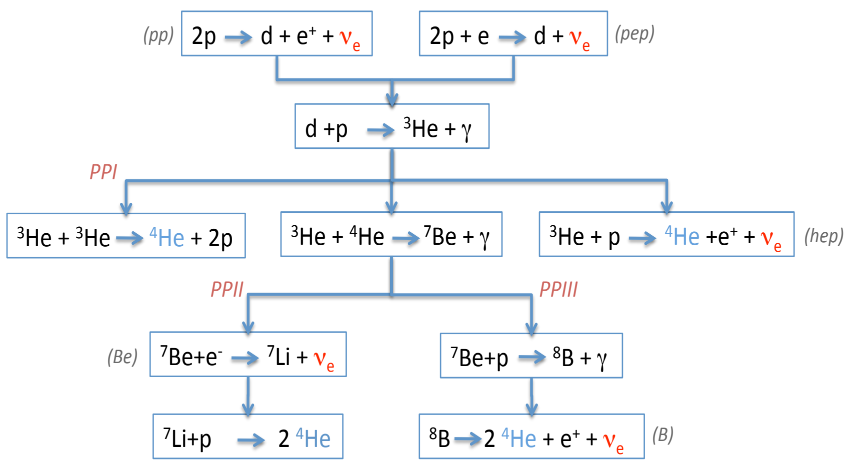
The Sun is powered by nuclear reactions that transform H into ^4He:

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

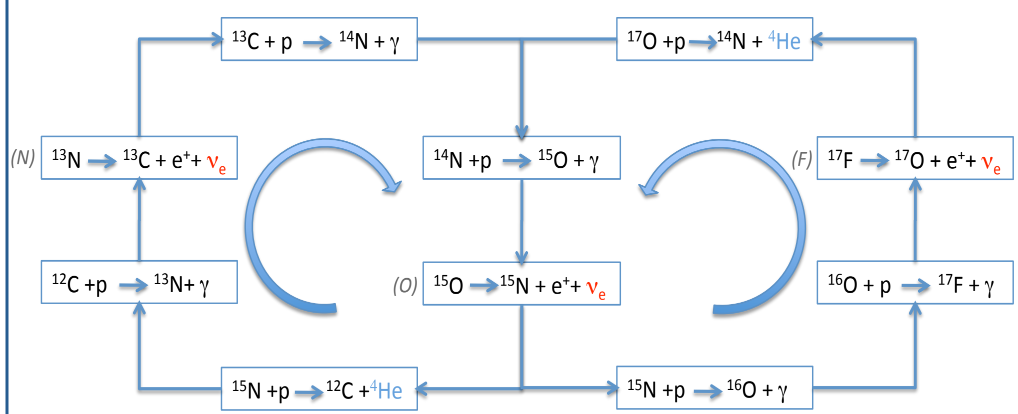
→ Q = 26,7 MeV (globally)

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

The PP-chain



The CN-NO bi-cycle

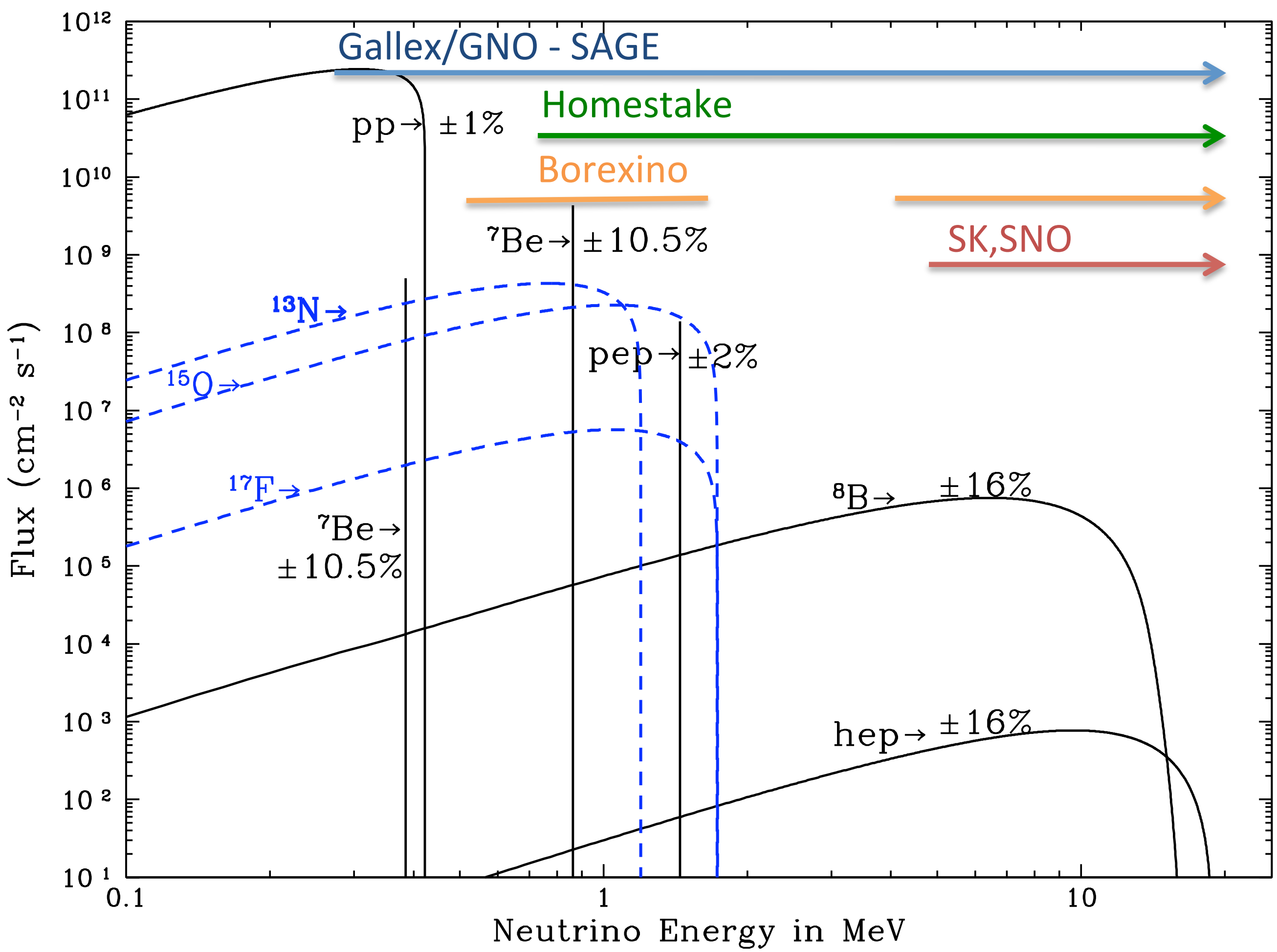


The pp chain is responsible for about 99% of the total energy (and neutrino) production.

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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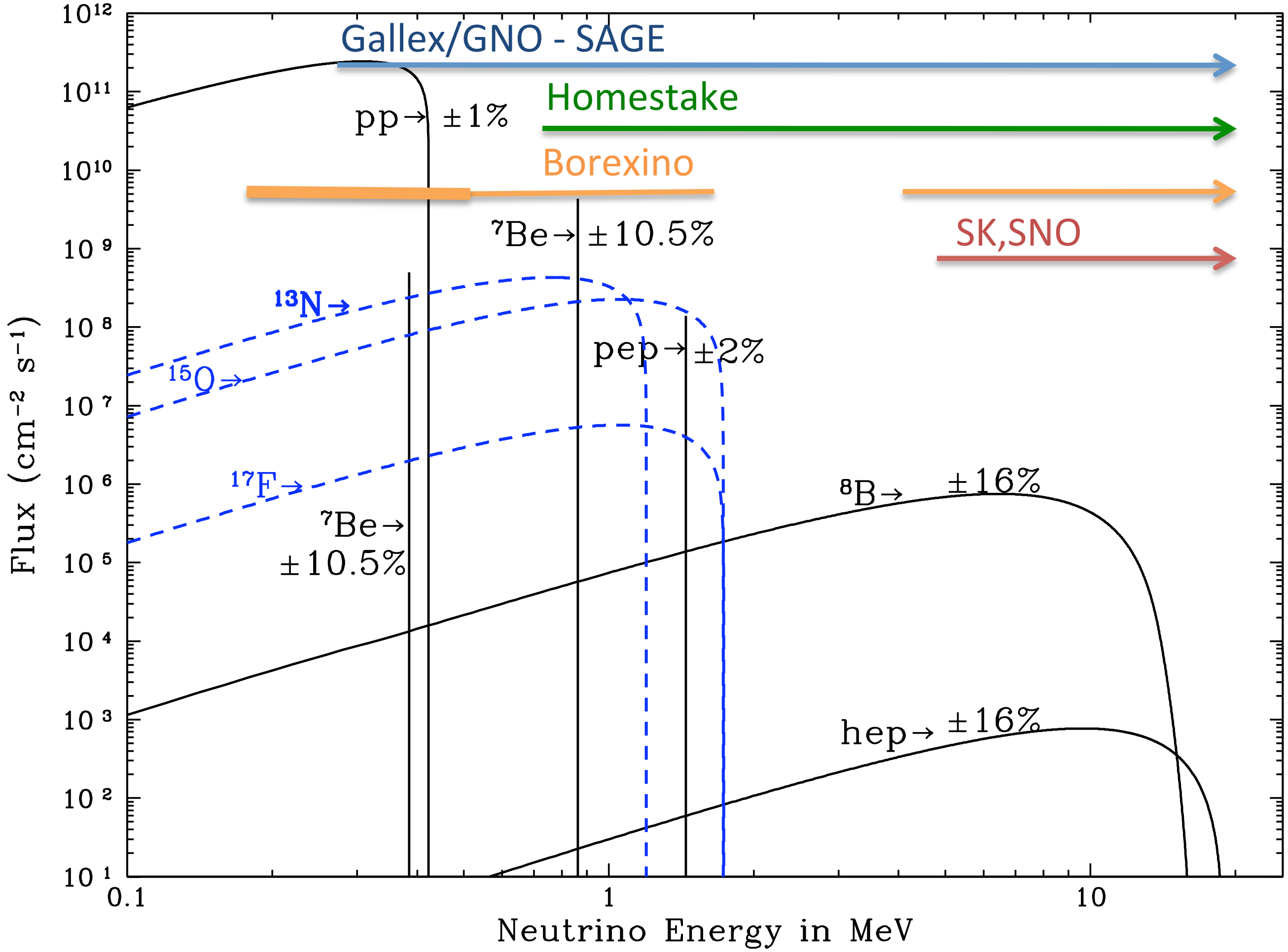
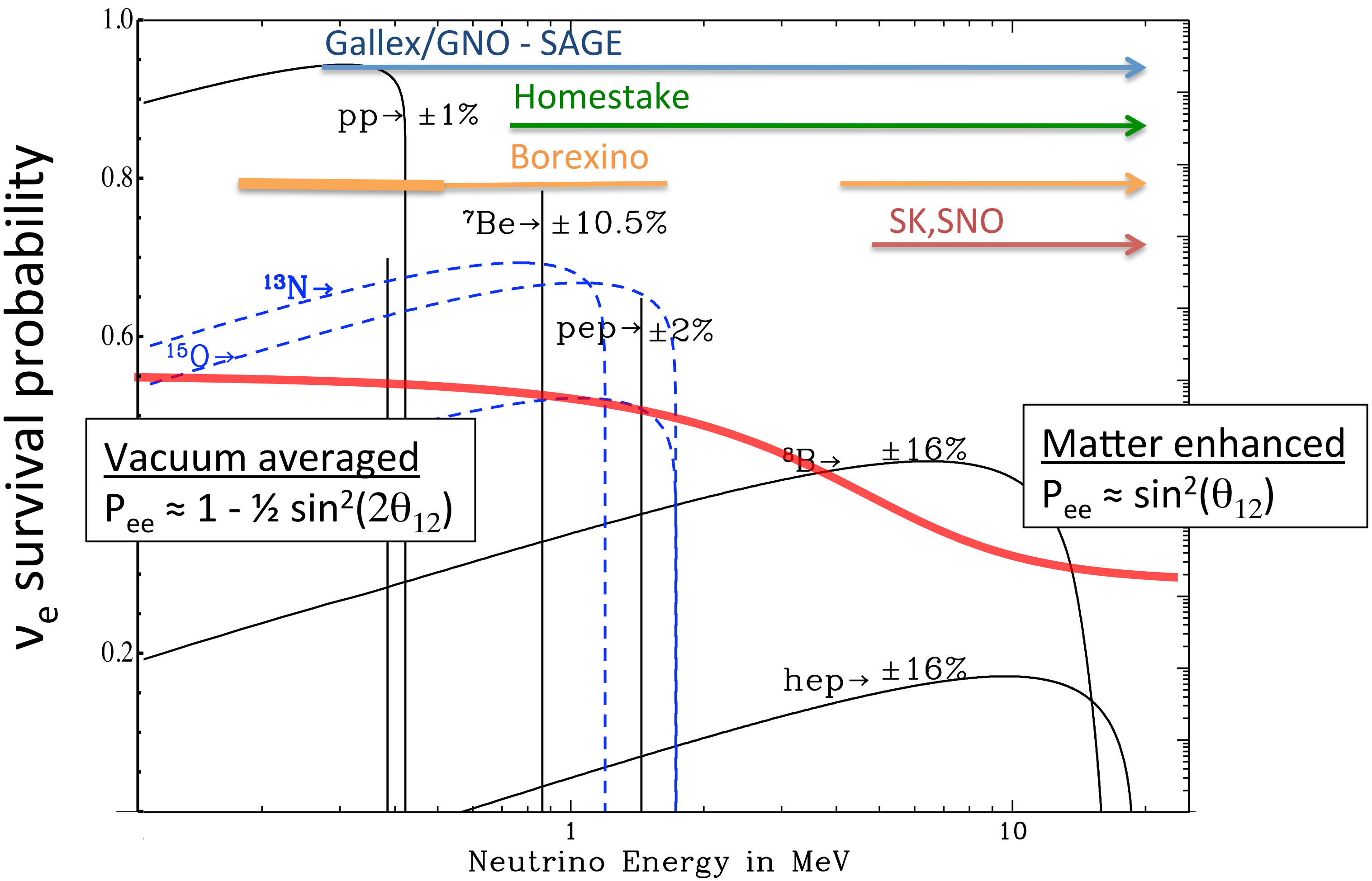


$$\Phi_{pp} = (6.6 \pm 0.7) \times 10^{10}\ cm^{-2}\ s^{-1}$$

Borexino, Nature 2014

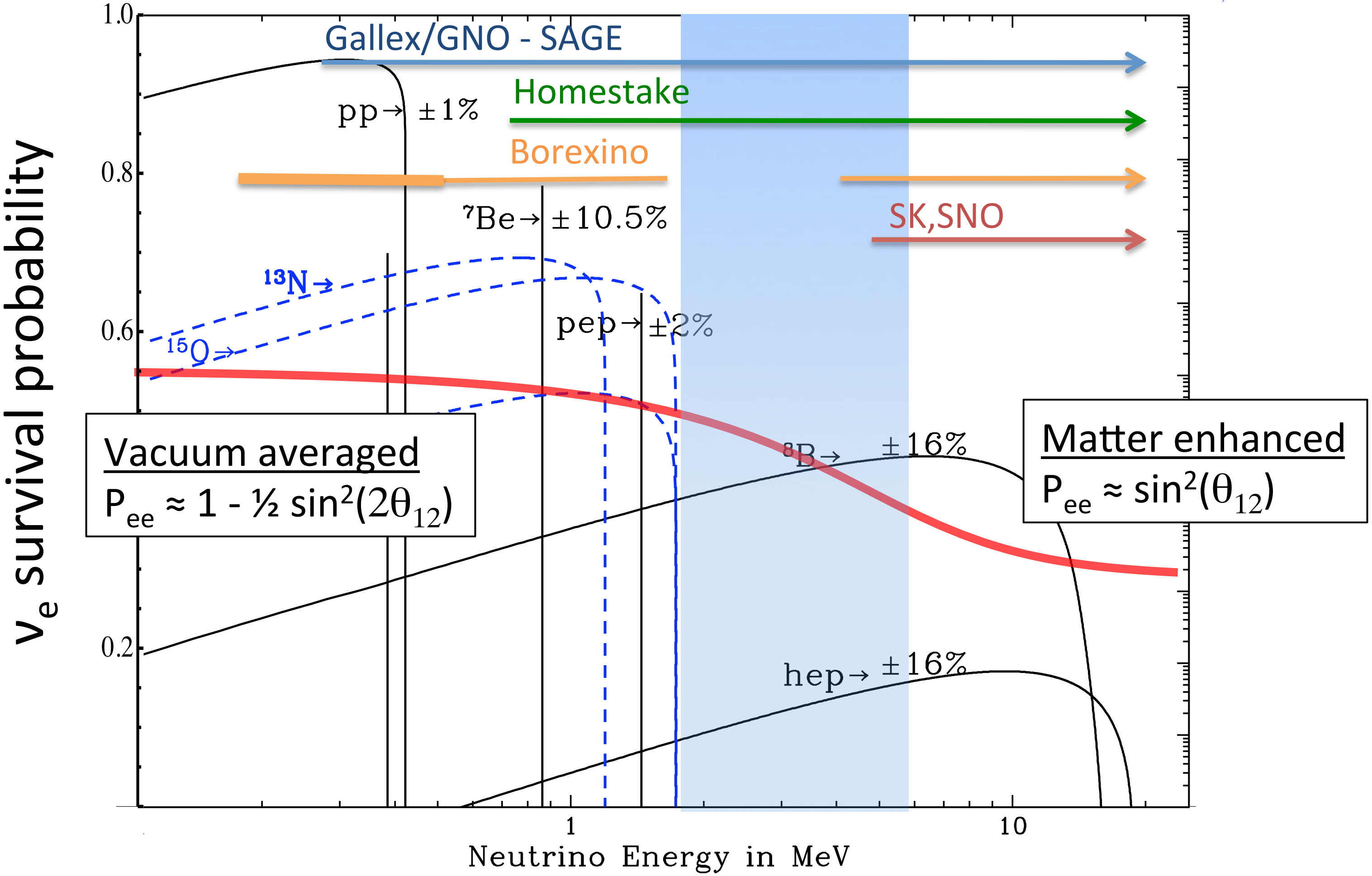
First direct measurement of the solar pp-component

The solar neutrino survival probability



The solar neutrino survival probability

"Transition" at: $E^* = \frac{\Delta m^2_{21} \cos(2\theta_{12})}{2\sqrt{2}\, G_F\, n_{e,\odot}}$



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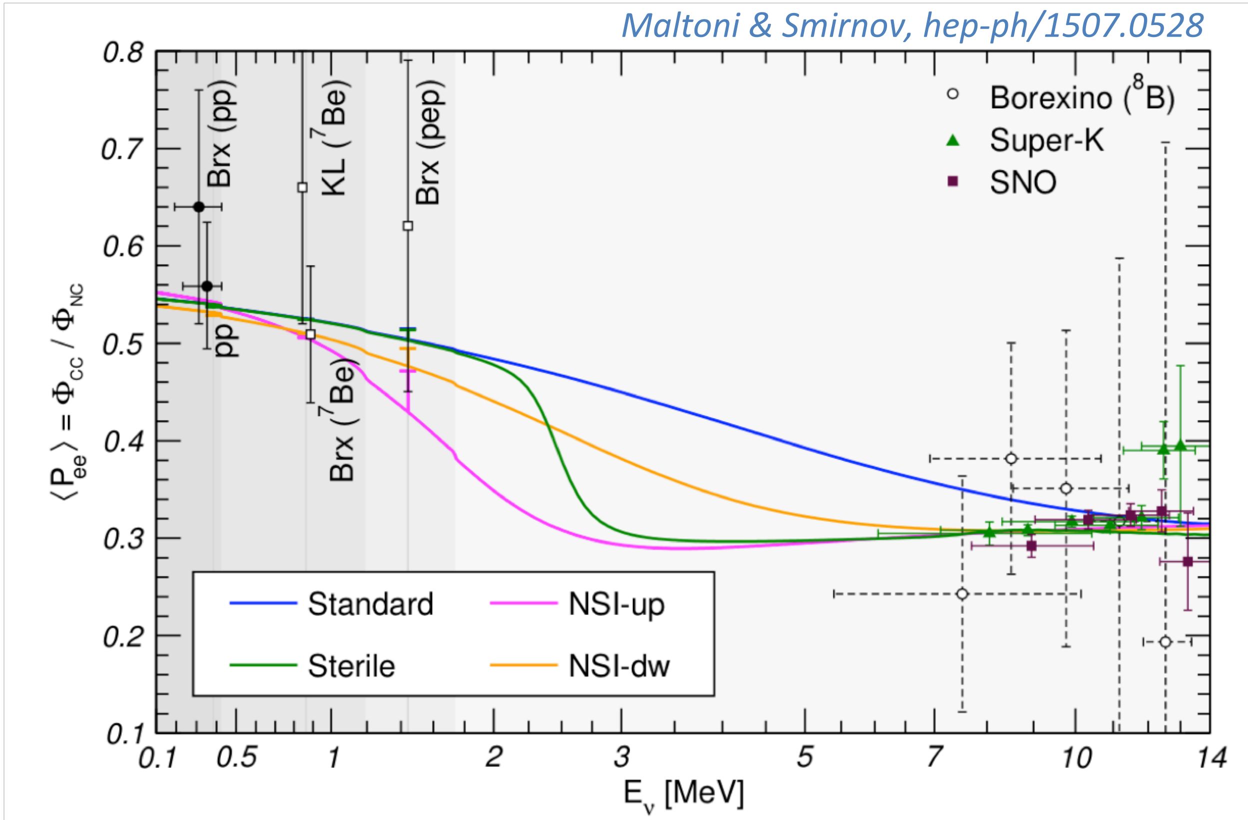

Combined analysis of SK I-IV (PRL 2014) also provided 2.7σ evidence for D/N effect;

The transition region:

- Final confirmation of LMA-MSW paradigm
- Constraints on new physics beyond the standard 3ν paradigm: see e.g. *Maltoni & Smirnov, hep-ph/1507.0528*

“Observing” the Sun with neutrinos: 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

Units:
pp: 10^{10} cm ^{2} s^{-1};
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Φ_{pp} = 6.6 (1 ± 0.11) Borex. only
[Φ_{pp} = 6.4 (1 ± 0.08)] combined

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Direct measurement of pp now to 11% Borexino (90% CL)

L_ν(8 minutes) ≈ L_γ (10^5 year) – test of solar stability
Still not accurate enough to test SSMs (≈ few % accuracy required)

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:

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

squared isothermal sound speed

Related to temperature stratification in the sun

surface helium abundance

See Basu & Antia 07 for a review

Impressive agreement with SSM predictions …

Surface helium abundance

$$Y_b = 0.2485 \pm 0.0035$$

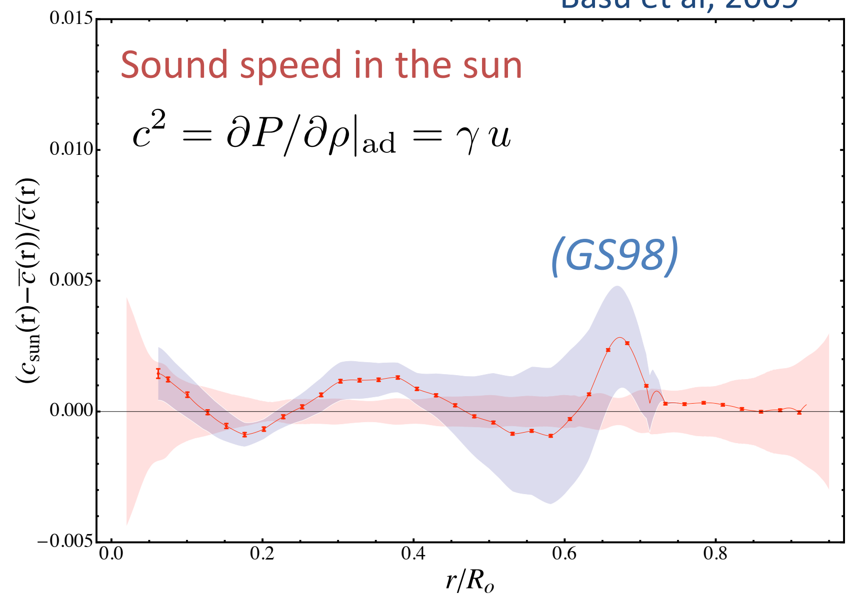
$Y_b = 0.243$ *(GS98)*

Inner radius of the solar convective envelope

$$R_b/R_\odot = 0.713 \pm 0.001$$

$R_b/R_\odot = 0.712$ *(GS98)*

Basu et al, 2009

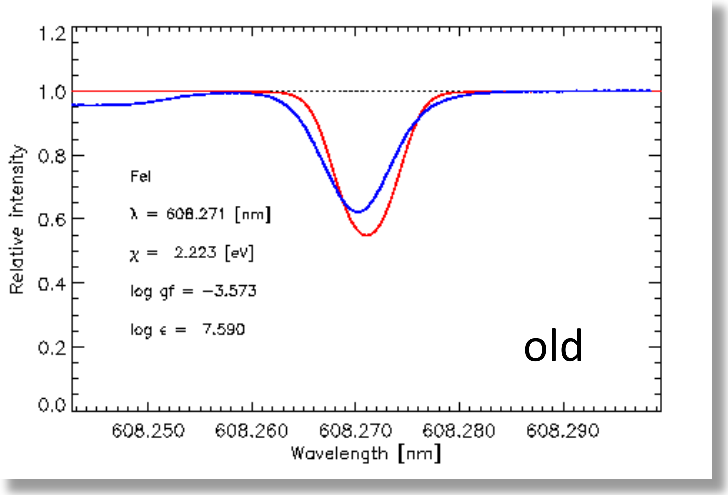


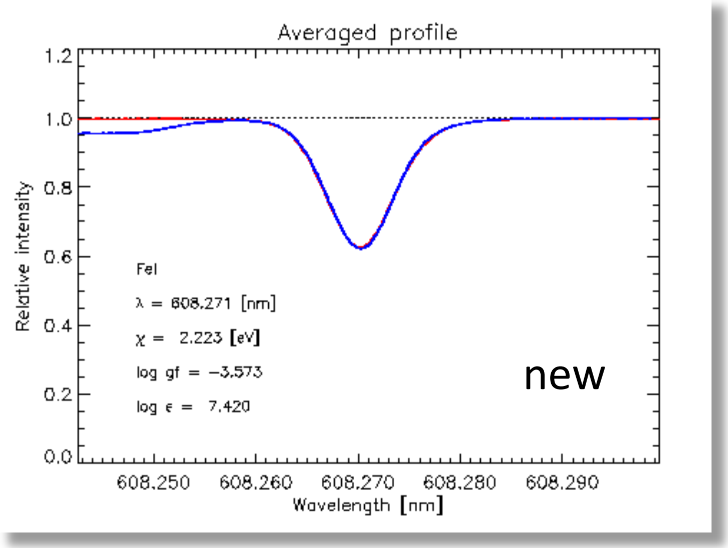
… till few years ago

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

Less metallic sun …

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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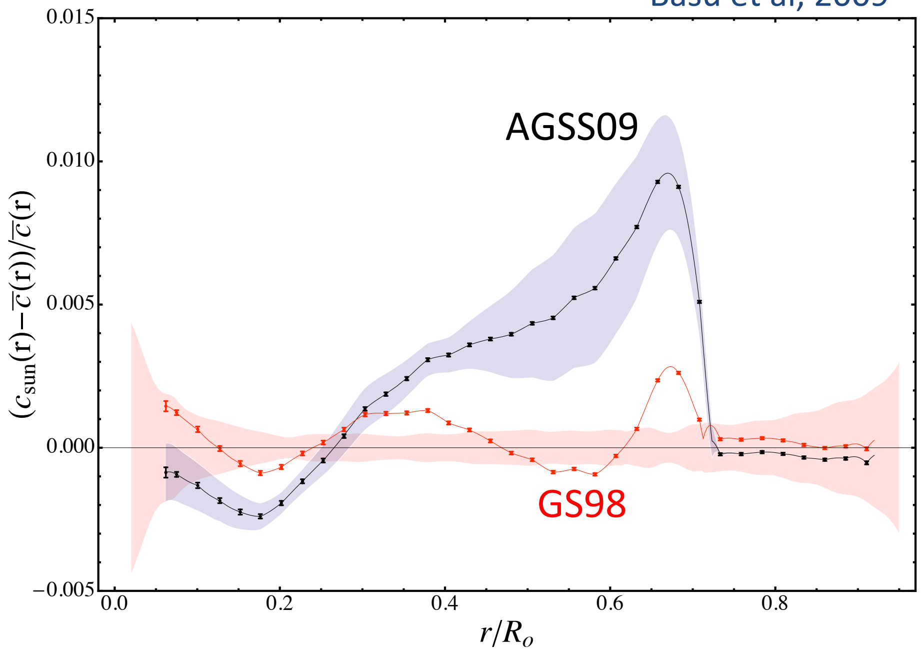

… leads to SSMs which do not correctly reproduce helioseismic observables

	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

($\approx 4\sigma$ discrepancies)

The solar composition problem

There is 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**?
- Non standard effects (e.g. DM accumulation in the solar core)?

  see e.g. Vincent et al. – arxiv:1411.6626 / 1504.04378
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

  see A. Serenelli et al. – ApJ 2011

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 ...*

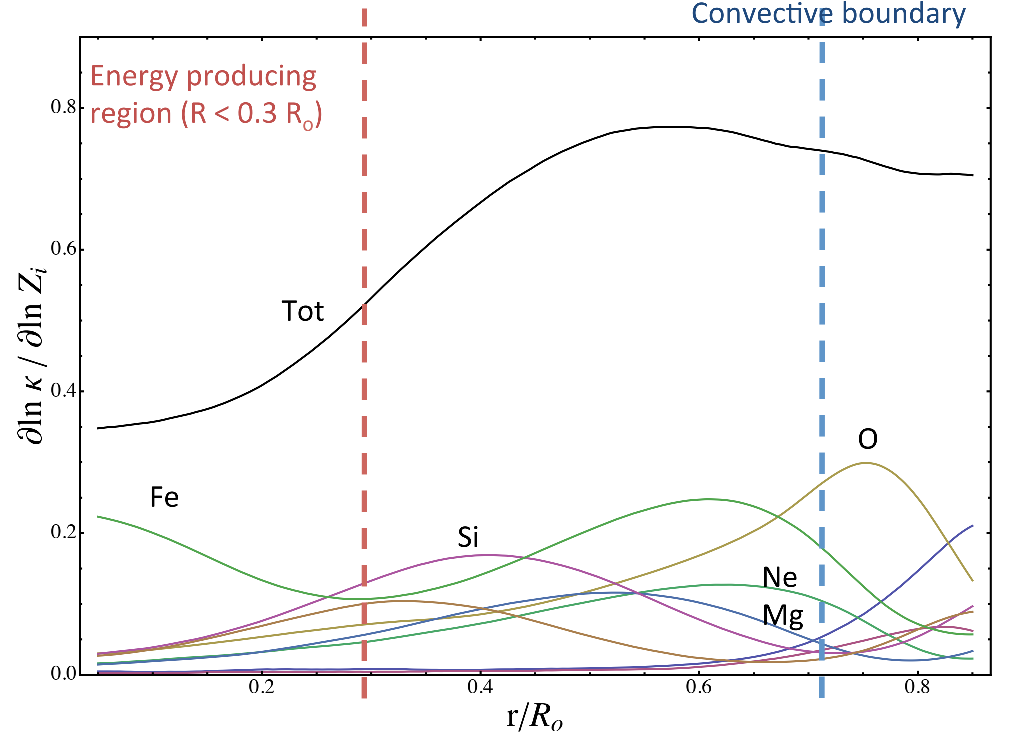
The role of metals

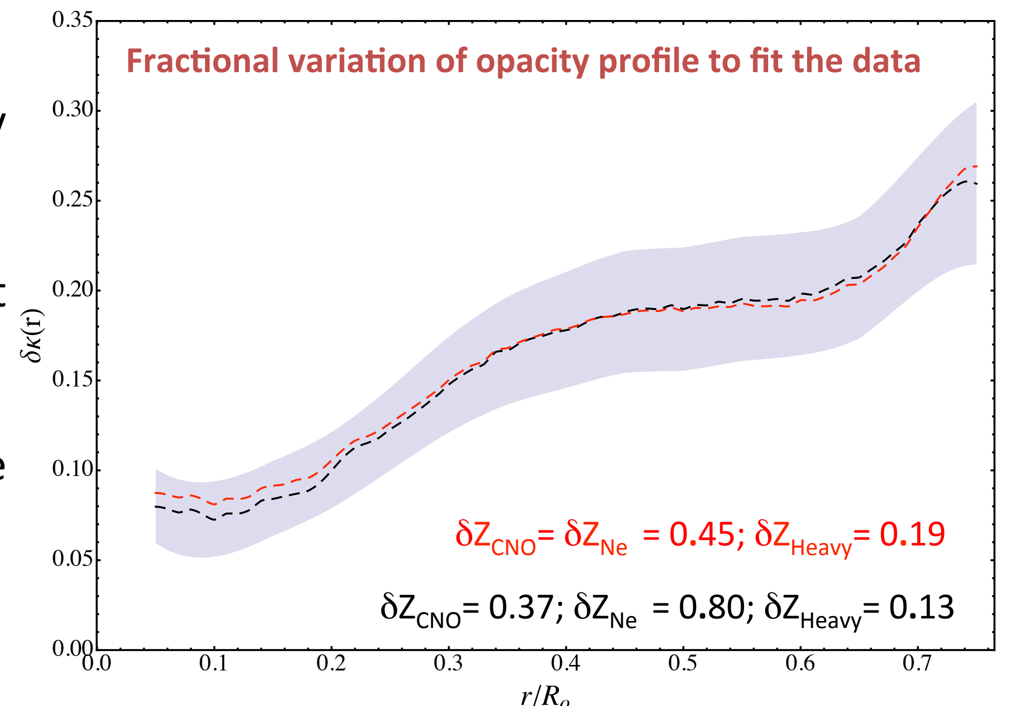
A change of the solar composition produces the same effects on the helioseismic observables and on neutrino fluxes (except CNO neutrinos) of a **suitable change of the solar opacity profile δκ(r).**

$$\delta\kappa(r) = \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j}\, \delta z_j$$

- ✓ Opacity (not composition) is directly constrained by present obs. data.
- ✓ The required variations are too large wrt uncertainties (≈ few %)
- ✓ Different admixtures $\{\delta z_i\}$ can reproduce (equally well) the required δk(r);

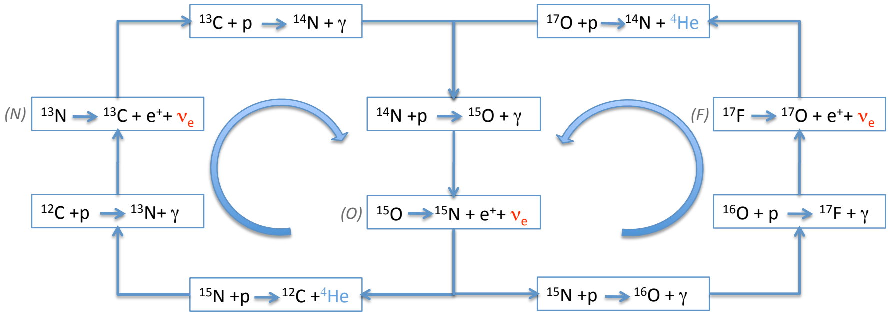
F.L. Villante and B. Ricci - ***Astrophys.J.714:944-959,2010***
F.L. Villante – ***Astrophys.J.724:98-110,2010***





CNO neutrinos

CNO neutrinos allow us 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

Constrained by Φ_B and Φ_{Be}

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

Total number of catalysts for CN-cycle

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

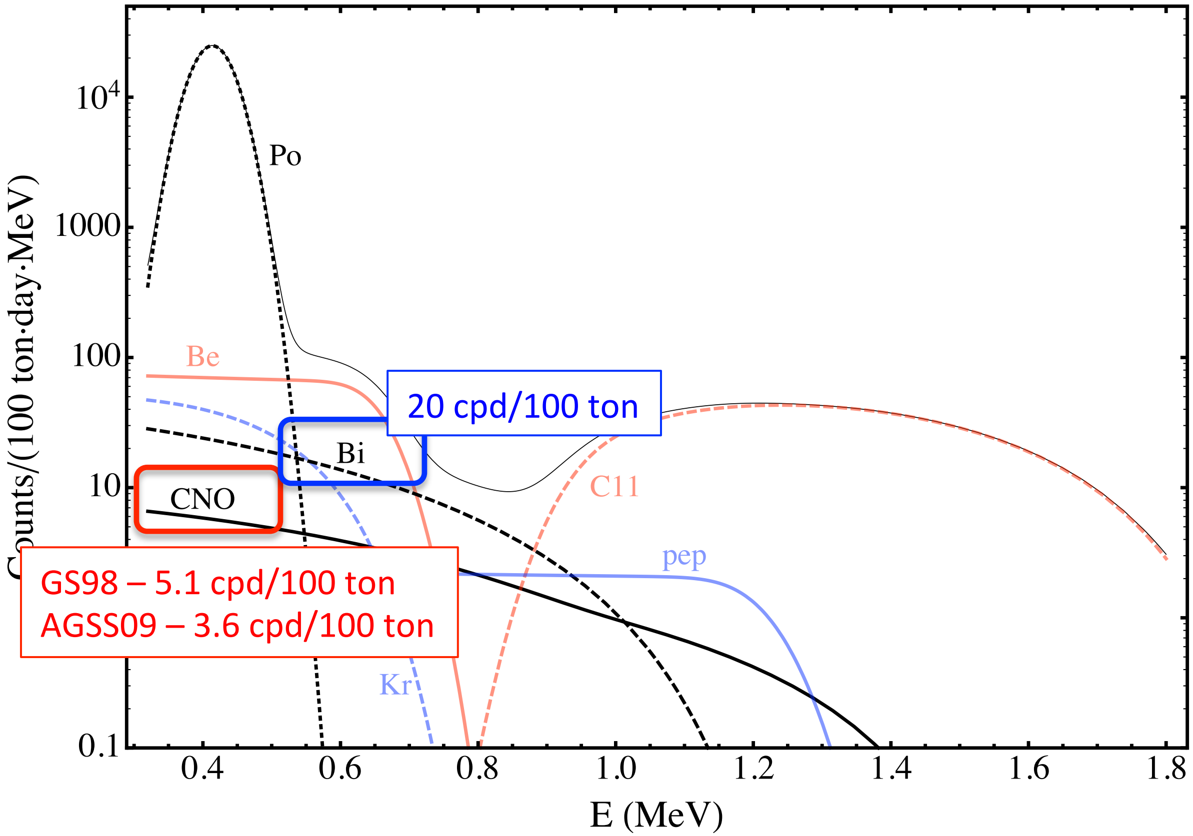
ν flux	GS98	AGSS09	Solar
$^{13}{\rm N}\ (10^8\,{\rm cm}^{-2}\,{\rm s}^{-1})$	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
$^{15}{\rm O}\ (10^8\,{\rm cm}^{-2}\,{\rm s}^{-1})$	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.3
$^{17}{\rm F}\ (10^6\,{\rm cm}^{-2}\,{\rm s}^{-1})$	$5.52(1 \pm 0.17)$	$3.04(1 \pm 0.16)$	≤ 59

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)



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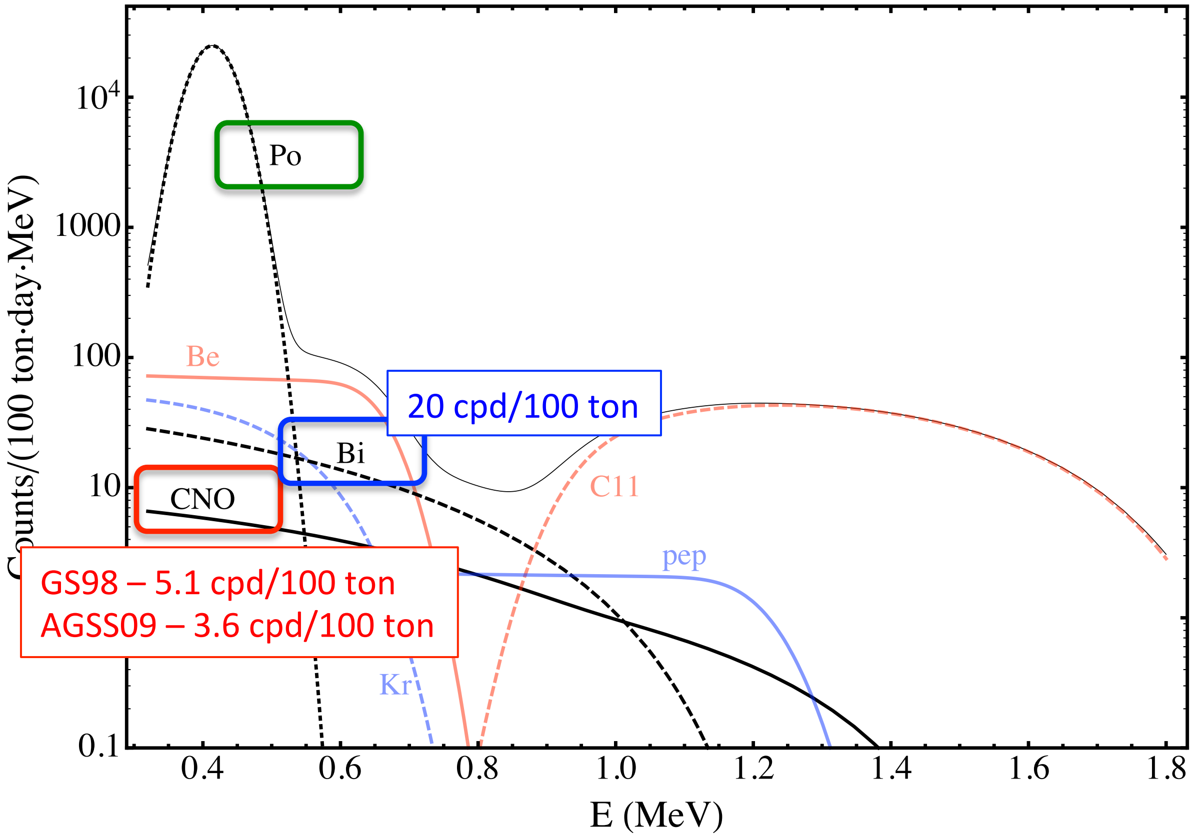

Determining ^{210}Bi from ^{210}Po time evolution?

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

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

How to improve?

Increase the detector depth → reduction of cosmogenic ^{11}C background

SNO+: factor 100 lower than BX

Consider larger detectors → Stat. uncertainties scales as $1/M^{1/2}$

SNO+ (1 kton), LENA (50 kton)

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

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Future Proposals

- Water based Liquid Scintillators (WbLS)
- "Salty" WbLS → doped (1% by mass) with ^{7}Li (CC detection of ν_e on ^{7}Li)
- Advanced Scintillator Detector Concept discussed in arXiv:1409.5864 (assuming 30-100 kton detector)

See J.Klein talk at this conference

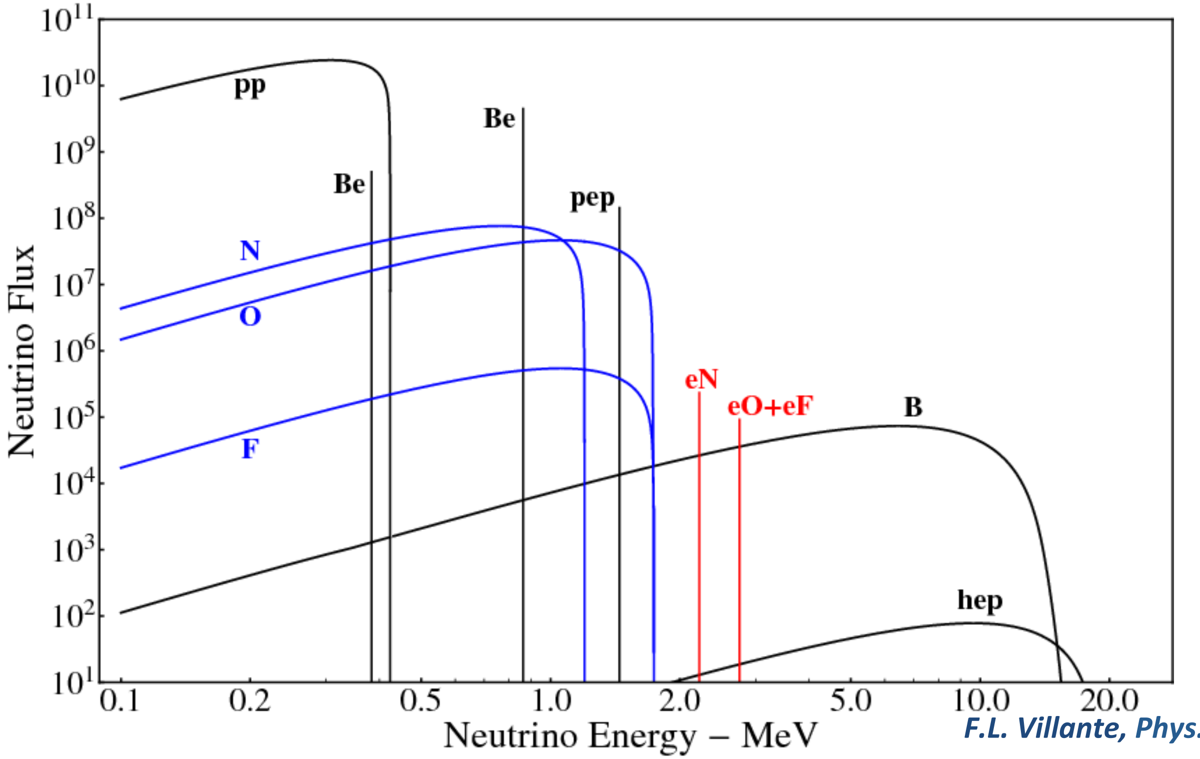
- Liquid argon: the potential of 300 ton detector@LNGS for solar neutrino studies is discussed in D.Franco et al. arXiV:1510.04196

ecCNO neutrinos: a challenge for gigantic ultrapure LS

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

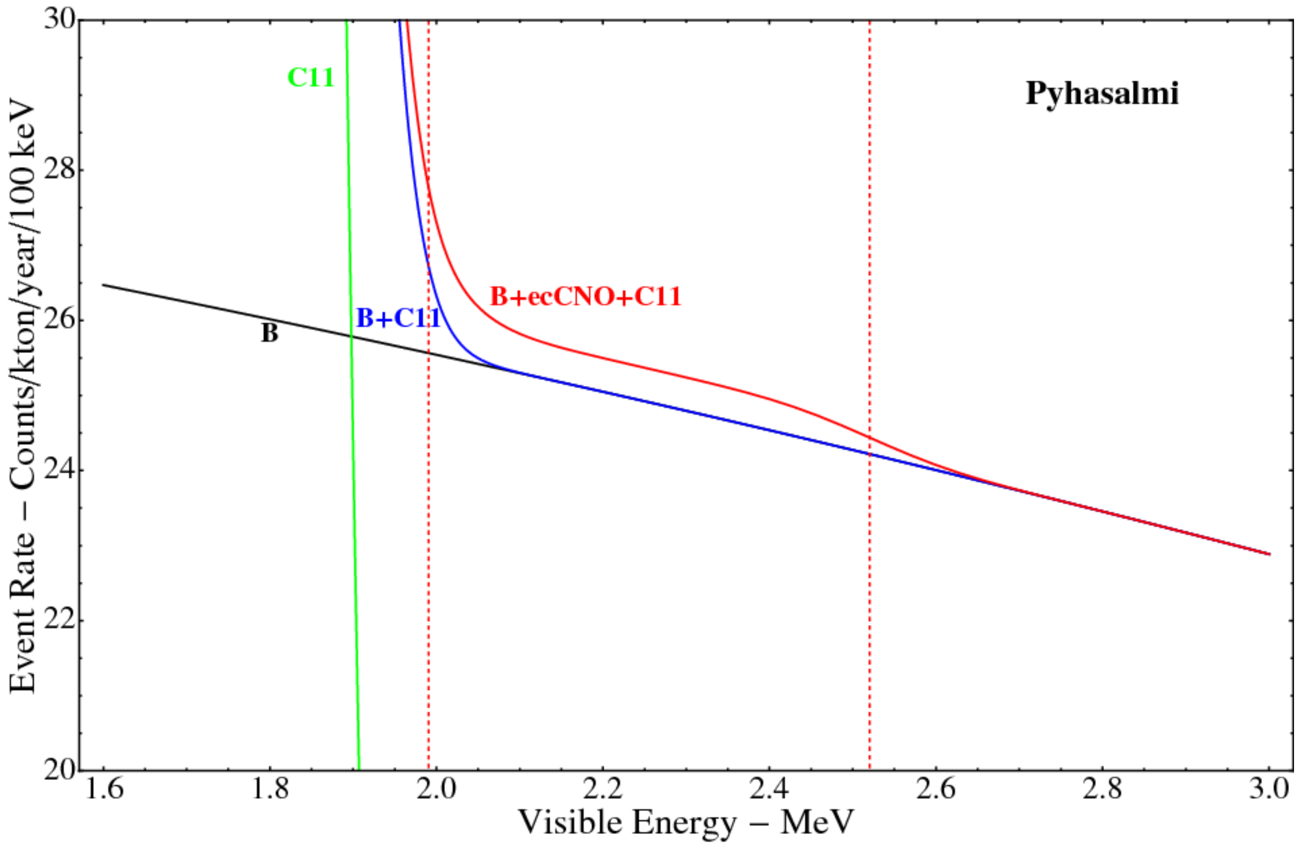
$$^{13}\mathrm{N} + e^- \rightarrow {}^{13}\mathrm{C} + \nu_e \qquad E_\nu = 2.220\ \mathrm{MeV}$$
$$^{15}\mathrm{O} + e^- \rightarrow {}^{15}\mathrm{N} + \nu_e \qquad E_\nu = 2.754\ \mathrm{MeV}$$
$$^{17}\mathrm{F} + e^- \rightarrow {}^{17}\mathrm{O} + \nu_e \qquad E_\nu = 2.761\ \mathrm{MeV}$$

- 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

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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

A quantitative analysis of the solar composition problem

Villante et al. 2014

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:

$$\begin{aligned} \{I\} \;=\; & \{\text{opa},\ \text{age},\ \text{diffu},\ \text{lum}, && \text{Enviromental} \\ & S_{11},\ S_{33},\ S_{34},\ S_{17},\ S_{e7},\ S_{1,14},\ S_{\rm hep}, && \text{Nuclear} \\ & \text{C},\ \text{N},\ \text{O},\ \text{Ne},\ \text{Mg},\ \text{Si},\ \text{S},\ \text{Fe}\} && \textbf{Composition} \end{aligned}$$

The status of the AGSS09 standard solar model

The SSM implementing the AGSS09 composition provides a poor fit of the observational data. By considering (R_b, Y_b; Φ_B, Φ_{Be}; c_1, ..., c_{30}), we obtain **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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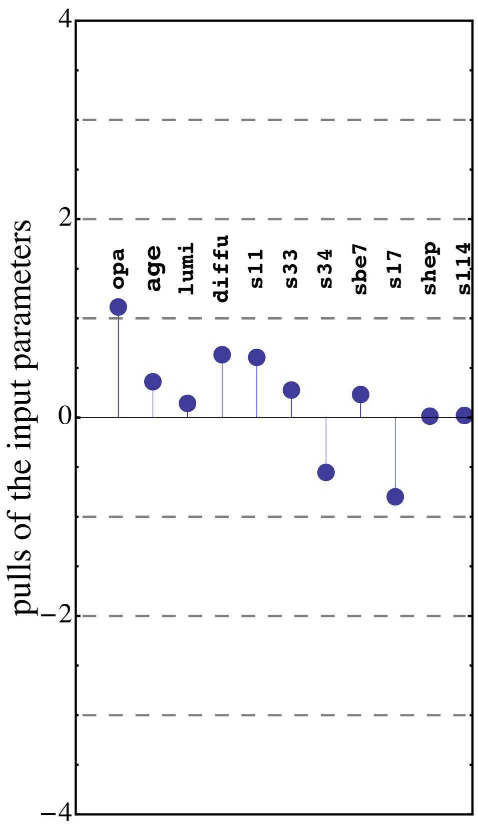
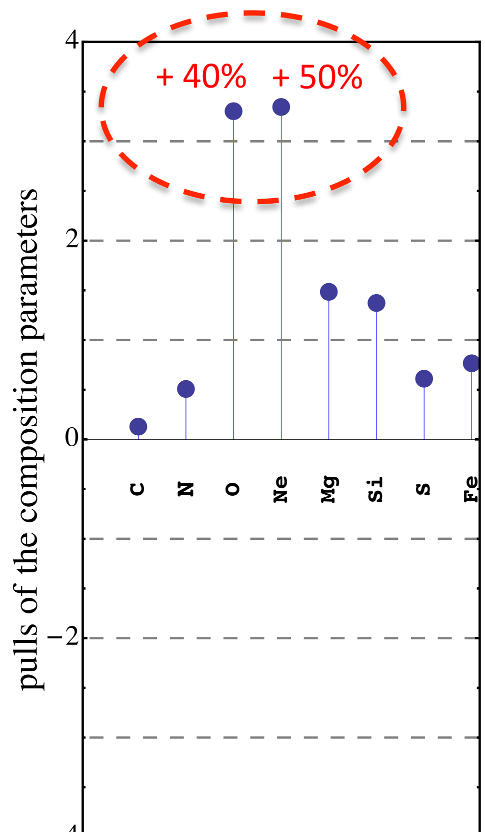
The distribution of the pulls of systematics (input for SSM) highlight tensions in the model:





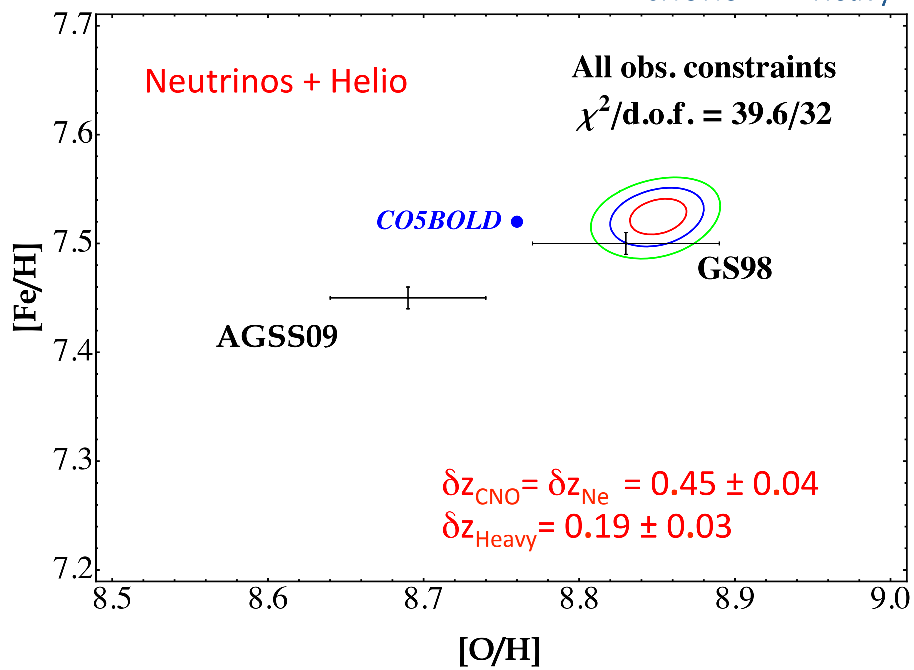
Obs. data requires an increase of the metal abundance of the sun, in particular for light elements (O, Ne).

Wrong surface composition?

We can use helioseismology + neutrinos (R_b,Y_b; Φ_B, Φ_{Be}; c_1, ..., c_{30}) to determine the optimal composition (F.L. Villante et al. – ApJ 2014):

- The best-fit abundances are **consistent** at 1σ with **GS98**. The **errors** on the inferred abundances **are smaller** than what is obtained by observational determinations.
- 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**.

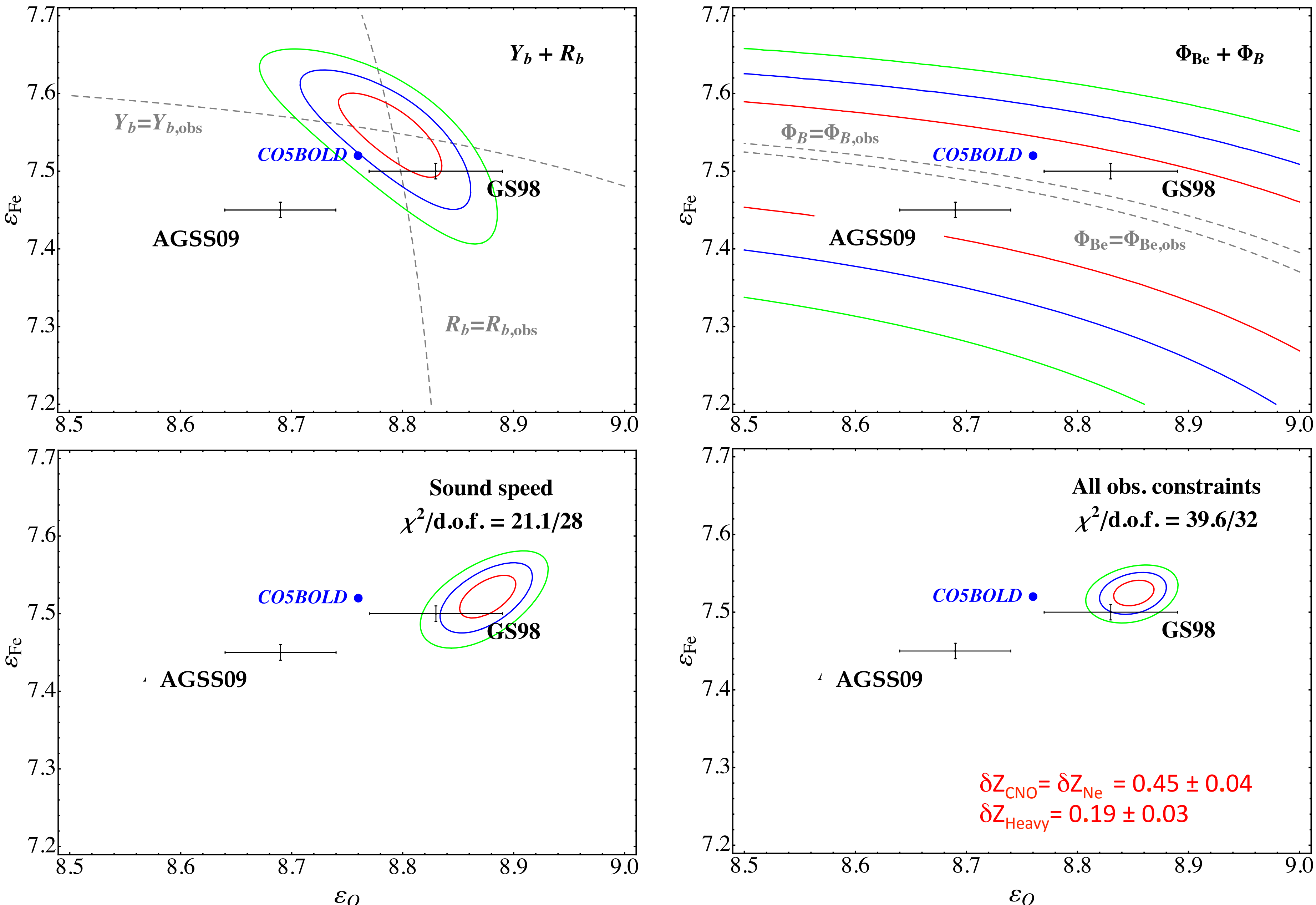
Two parameter analysis (δz_{CNONe} ; δz_{Heavy})



$$[\mathrm{O/H}] = \overline{[\mathrm{O/H}]} + \log(1+\delta z_{\mathrm{CNO}})$$
$$[\mathrm{Fe/H}] = \overline{[\mathrm{Fe/H}]} + \log(1+\delta z_{\mathrm{Heavy}})$$

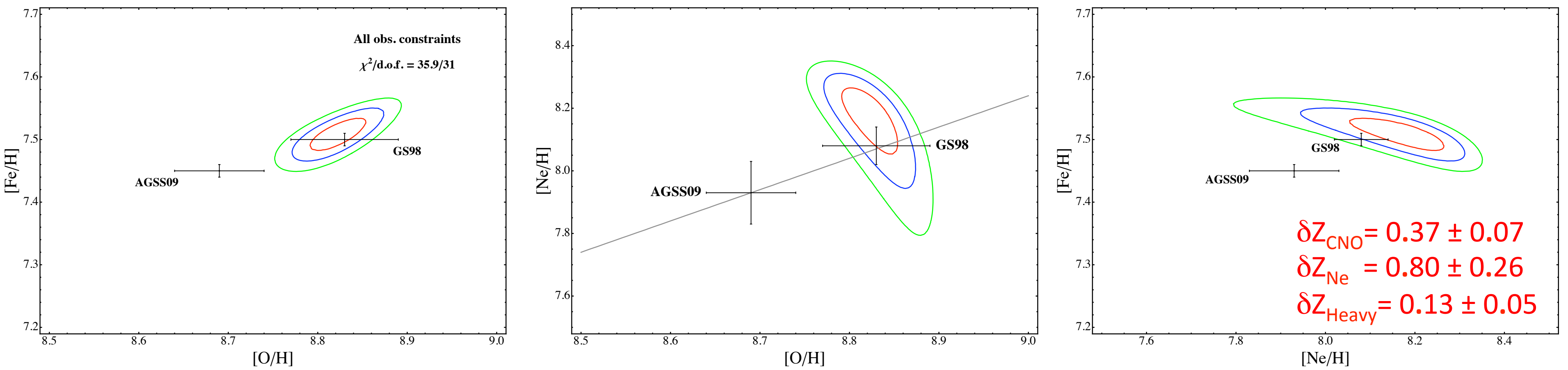
However, data are not effective in constraining composition **in more realistic scenarios**:
- different admixtures $\{\delta z_i\}$ can reproduce (equally well) the required $\delta k(r)$;
- no real constraints on the Ne/O ratio

Two parameter analysis ($\delta Z_{CNO} = \delta Z_{Ne}$; δZ_{Heavy})



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 opacity profile

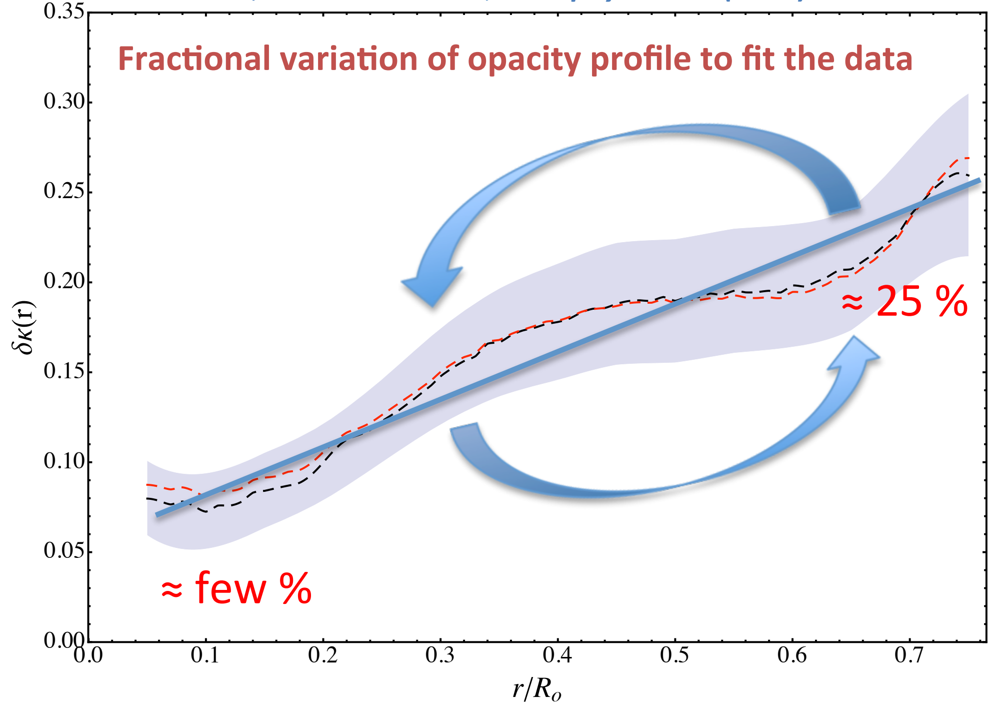
The "optimal" opacity profile **(i.e. the temperature stratification)** of the Sun is **well determined** by observational data

Note that:

- The sound speed and the convective radius determine the tilt of δk(r) (but not the scale)

- The surface helium and the neutrino fluxes determine the scale for δk(r)

*F.L. Villante and B. Ricci - **Astrophys.J.714:944-959,2010***
*F.L. Villante – **Astrophys.J.724:98-110,2010***
*F.L. Villante, A. Serenelli et al., **Astrophys.J. 787 (2014) 13***

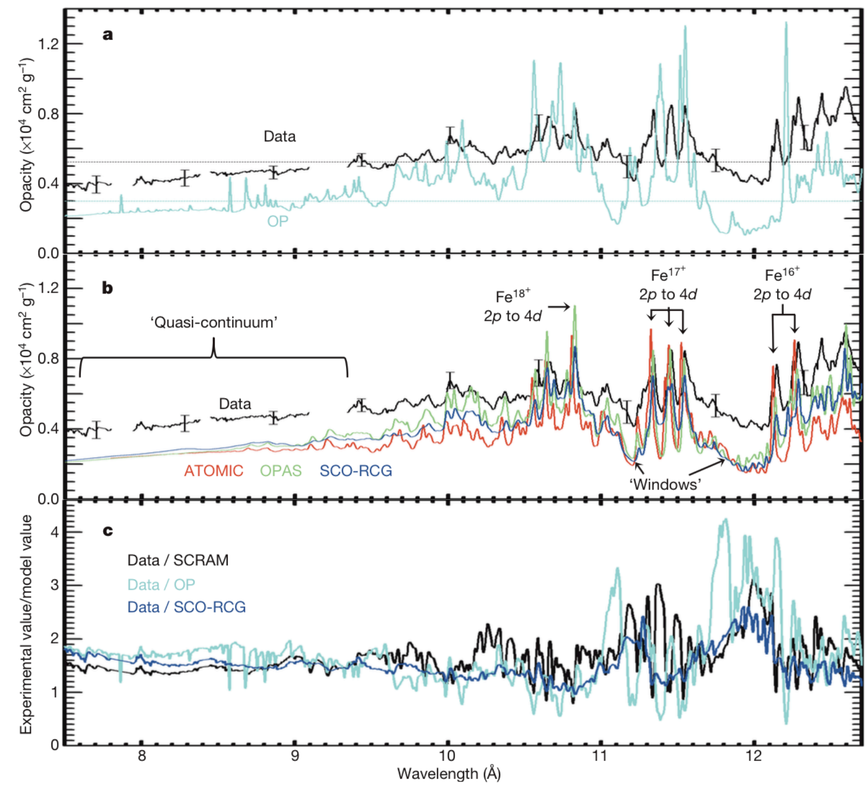


Wrong opacity?

(Very) recent progress:

- Opacity is being measured at stellar interiors conditions (see Bailey et al., Nature 2015);
- Monochromatic opacity is higher than expected for iron (up to a factor 2);
- Total opacity of solar plasma (integrated over the wavelength and summed over the composition), is increased by about 7%

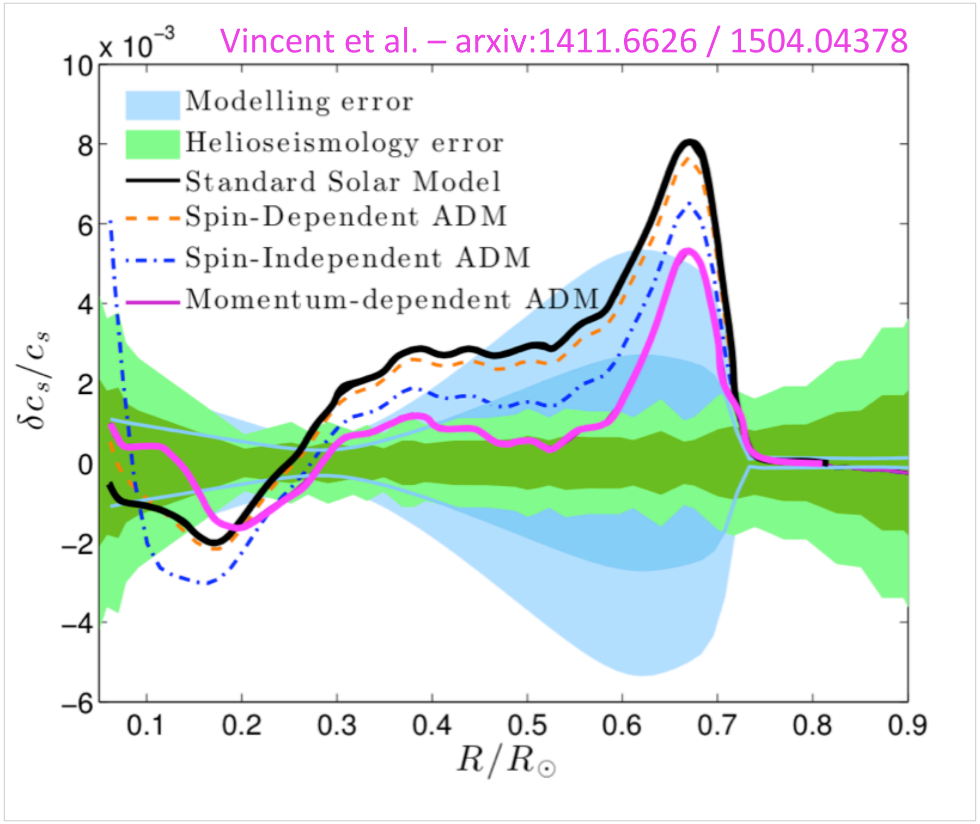
Bailey et al., Nature 2015



Asymmetric DM

DM accumulation in the solar core:

→ Additional energy transport;
→ **Reduction** of the "effective opacity";
→ Modification of temperature profile;



Agreement with helioseismic data can be improved. However:

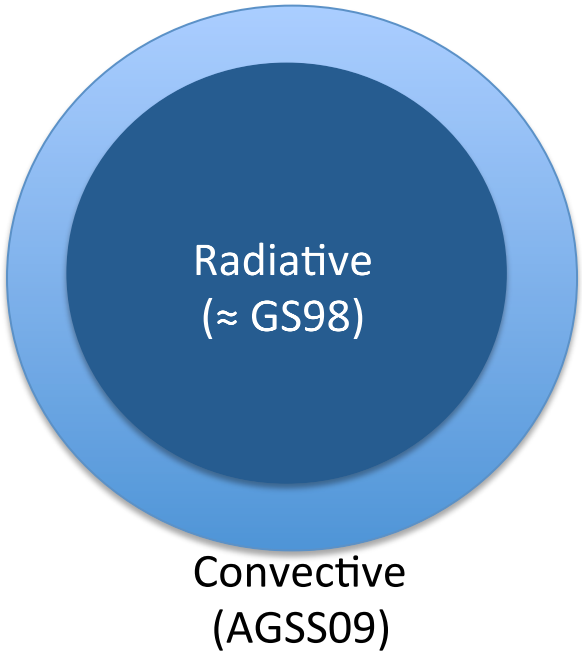
→ DM accumulation do not provide the optimal opacity profile;
→ Potential tension with neutrino fluxes and surface helium;
→ Caveat: DM evaporation not accounted for (relevant for few GeV masses)

$$\sigma = \sigma_0 \left(\frac{q}{q_0}\right)^2 \quad \begin{cases} m_\chi = 3\ \mathrm{GeV} \\ \sigma_0 = 10^{-37}\ \mathrm{cm}^2 \\ q_0 = 40\ \mathrm{MeV} \end{cases}$$

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

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

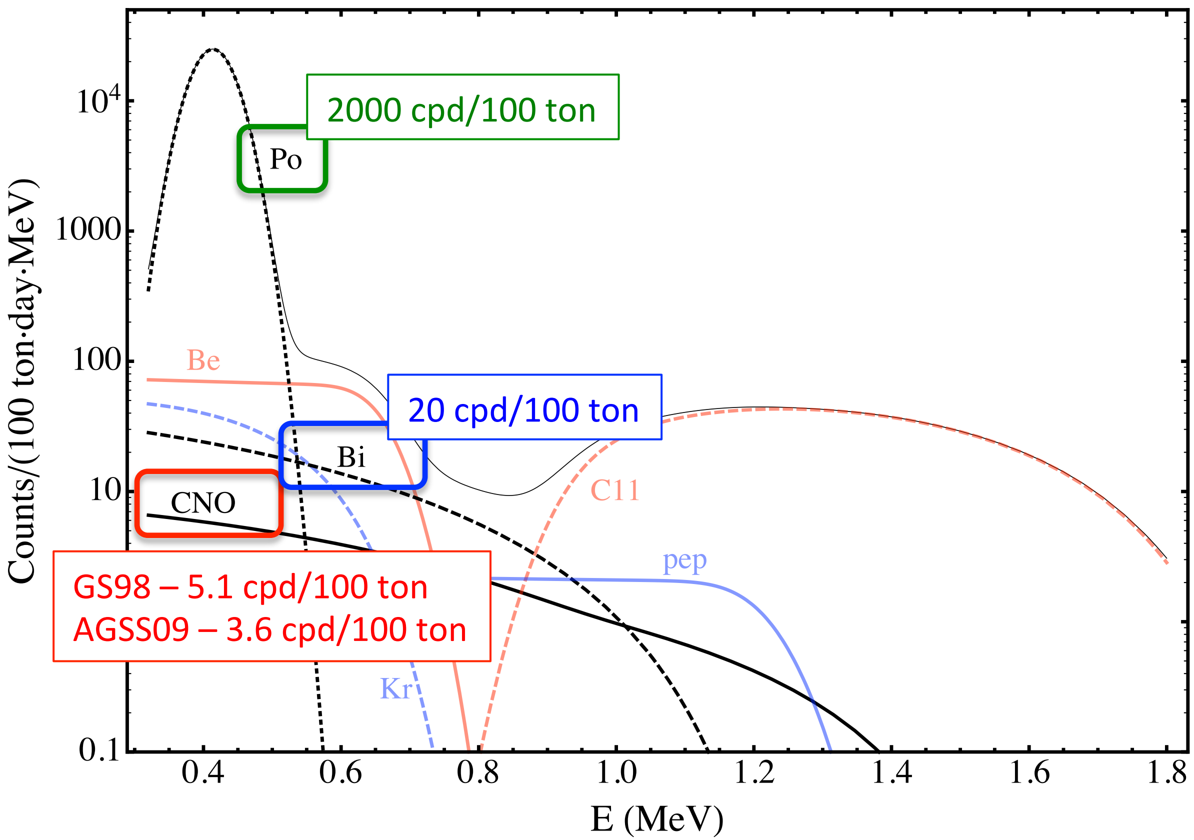
$$^{210}\mathrm{Bi} \rightarrow ^{210}\mathrm{Po} + e^- + \overline{\nu}_e$$

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

τ_{Bi} = 7.232 d

τ_{Po} = 199.634 d

Event spectrum in ultrapure liquid scintillators



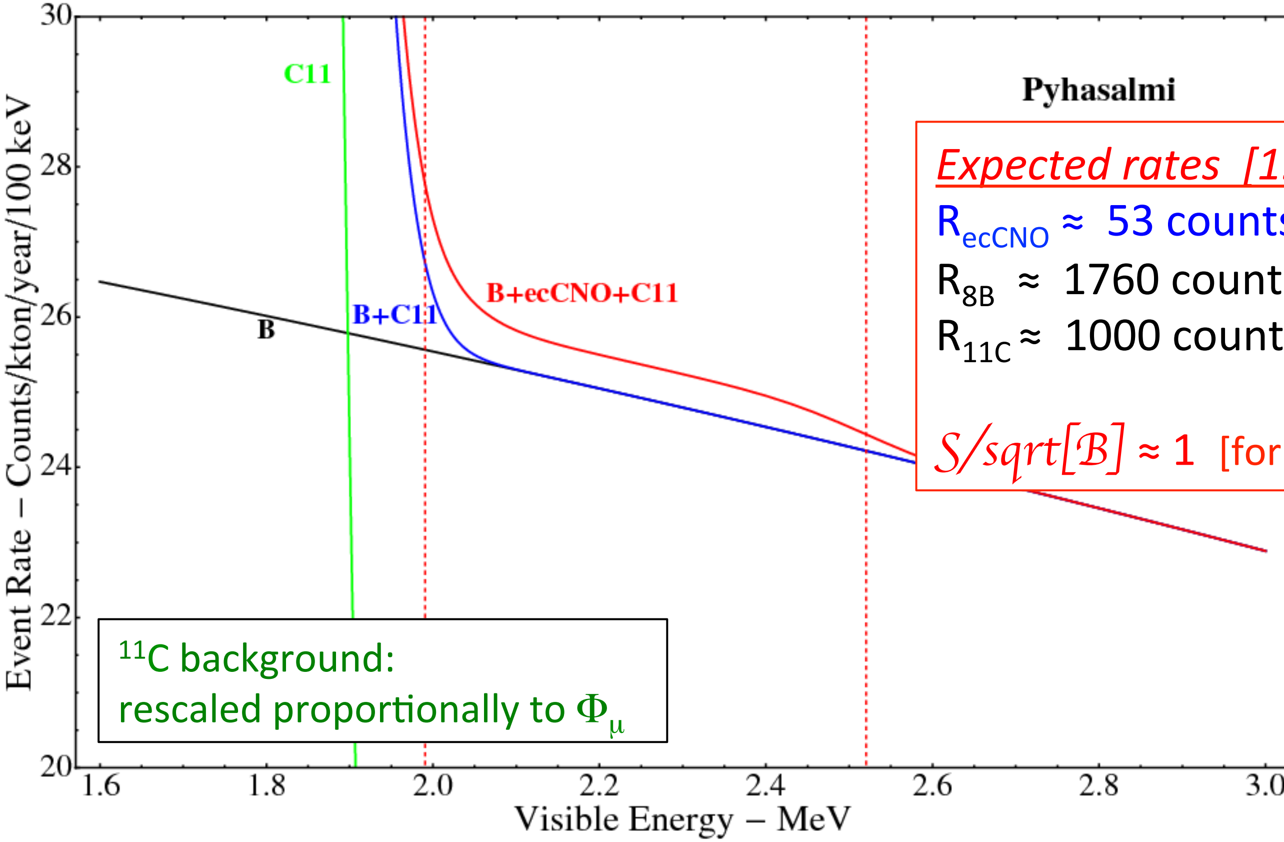
F.L. Villante et al. - Phys.Lett. B701 (2011) 336-341

- 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.

Expected rates in Liquid Scintillators

Additional background sources:

- **Intrinsic:** negligible/tagged (with Borexino Phase-I radio-purity levels);
- **External:** reduced by self-shielding (Fid. mass reduced from 50 to ≈20 kton in LENA);
- **Cosmogenic:** ^{11}C overlap with the observation window.



Expected rates [1.8 MeV, 2.5 MeV]

R_{ecCNO} ≈ 53 counts/10 kton/year

R_{8B} ≈ 1760 counts/10kton/year

R_{11C} ≈ 1000 counts/10kton/year

$S/sqrt[B]$ ≈ 1 [for 10kton × year exposure]

Signal comparable to stat. fluctuations for exposures 10 kton × year or larger.

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

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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:

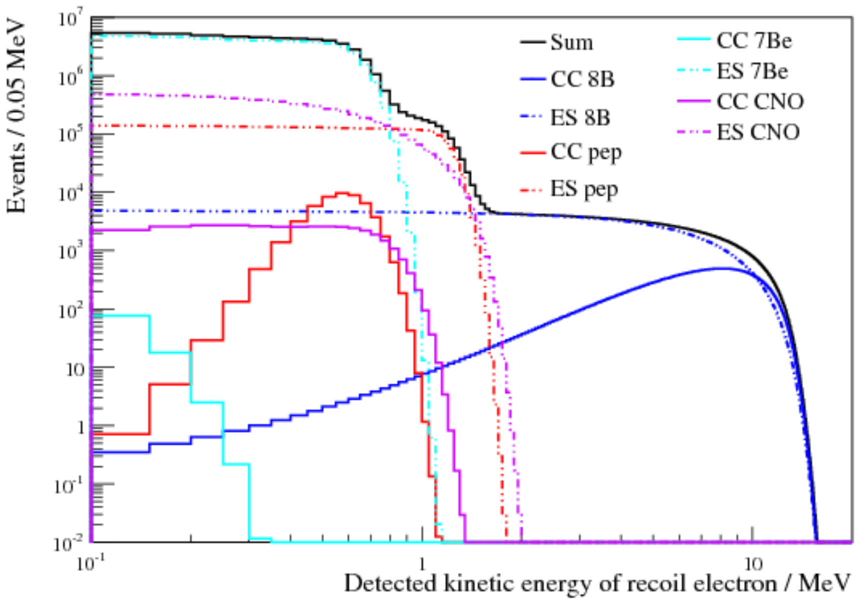
Time	CNO prec (stat.)	PEP prec. (stat.)	CNO significance
1 y	22.7 %	4.3 %	0.7 σ (avg)
2 y	16.0 %	3.0 %	1.8 σ (avg)
3 y	13.1 %	2.5 %	2.8 σ (avg)
4 y	11.3 %	2.2 %	3.7 σ (avg)
5 y	10.1 %	1.9 %	4.5 σ (avg)
10 y	7.2 %	1.4 %	8.1 σ (avg)

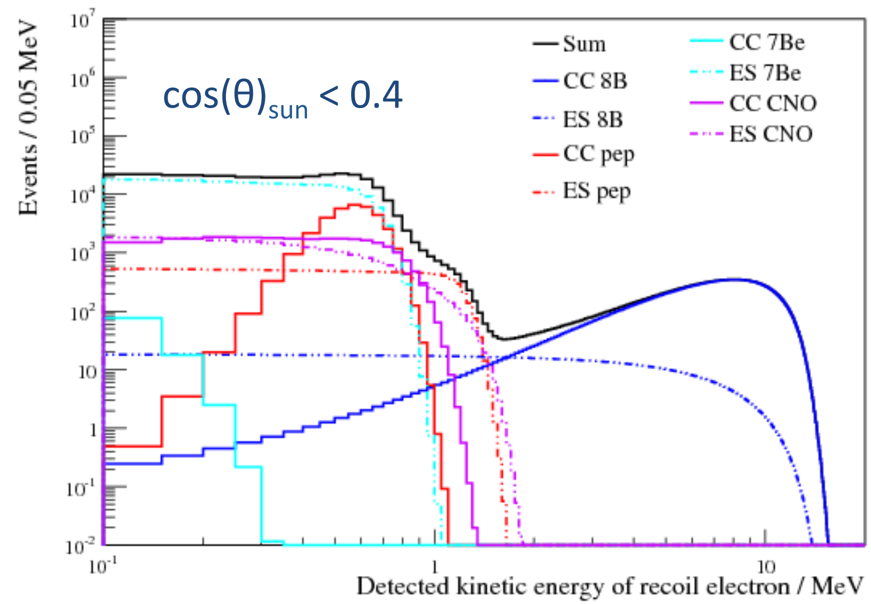
In the future … Advanced Scintillator Detector Concept (ASDC)

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

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

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





From arXiv:1409.5864