The Sun and solar neutrinos

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

Hydrogen Burning: PP chain and CNO cycle

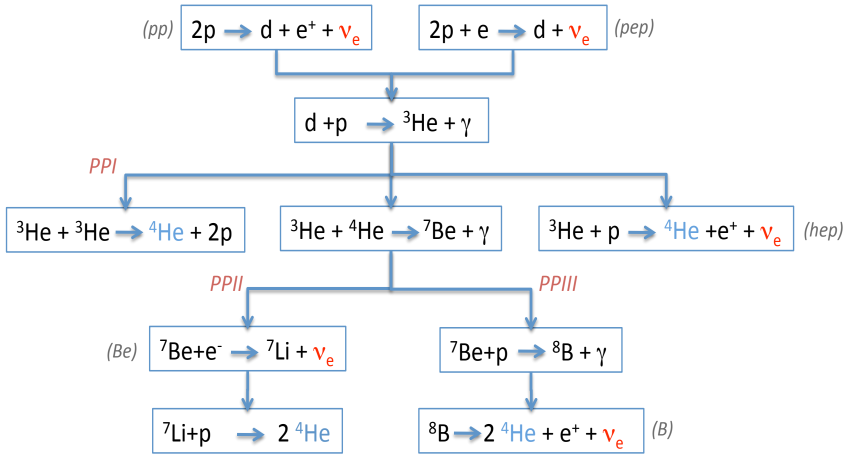
The Sun is powered by nuclear reactions that transform H into ^{4}He:

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

Q = 26,7 MeV (globally)

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

The PP-chain


(pp) $2p \rightarrow d + e^+ + \nu_e$

$2p + e \rightarrow d + \nu_e$ (pep)

$d + p \rightarrow {}^3He + \gamma$

PPI

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

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

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

PPII

PPIII

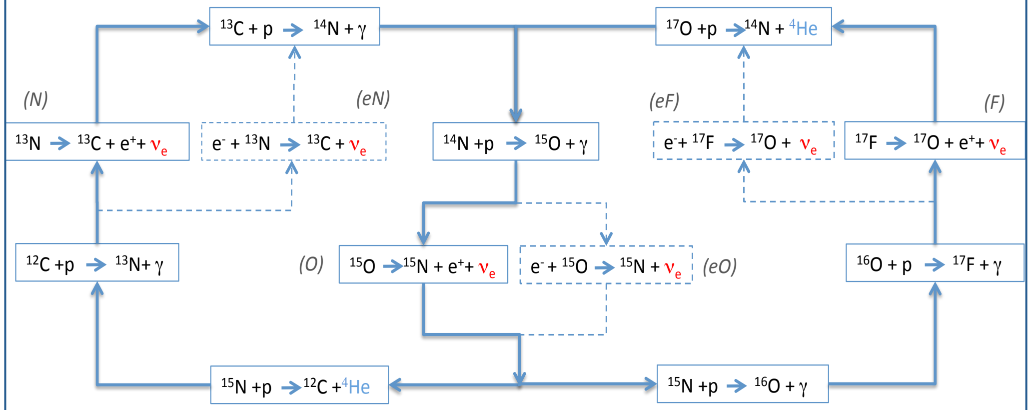
(Be) $^7Be + e^- \rightarrow {}^7Li + \nu_e$

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

$^7Li + p \rightarrow 2\,{}^4He$

$^8B \rightarrow 2\,{}^4He + e^+ + \nu_e$ (B)

The CN-NO (bi-)cycle


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

$^{17}O + p \rightarrow {}^{14}N + {}^4He$

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

(eN) $e^- + {}^{13}N \rightarrow {}^{13}C + \nu_e$

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

(eF) $e^- + {}^{17}F \rightarrow {}^{17}O + \nu_e$

(F) $^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$

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

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

$e^- + {}^{15}O \rightarrow {}^{15}N + \nu_e$ (eO)

$^{16}O + p \rightarrow {}^{17}F + \gamma$

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

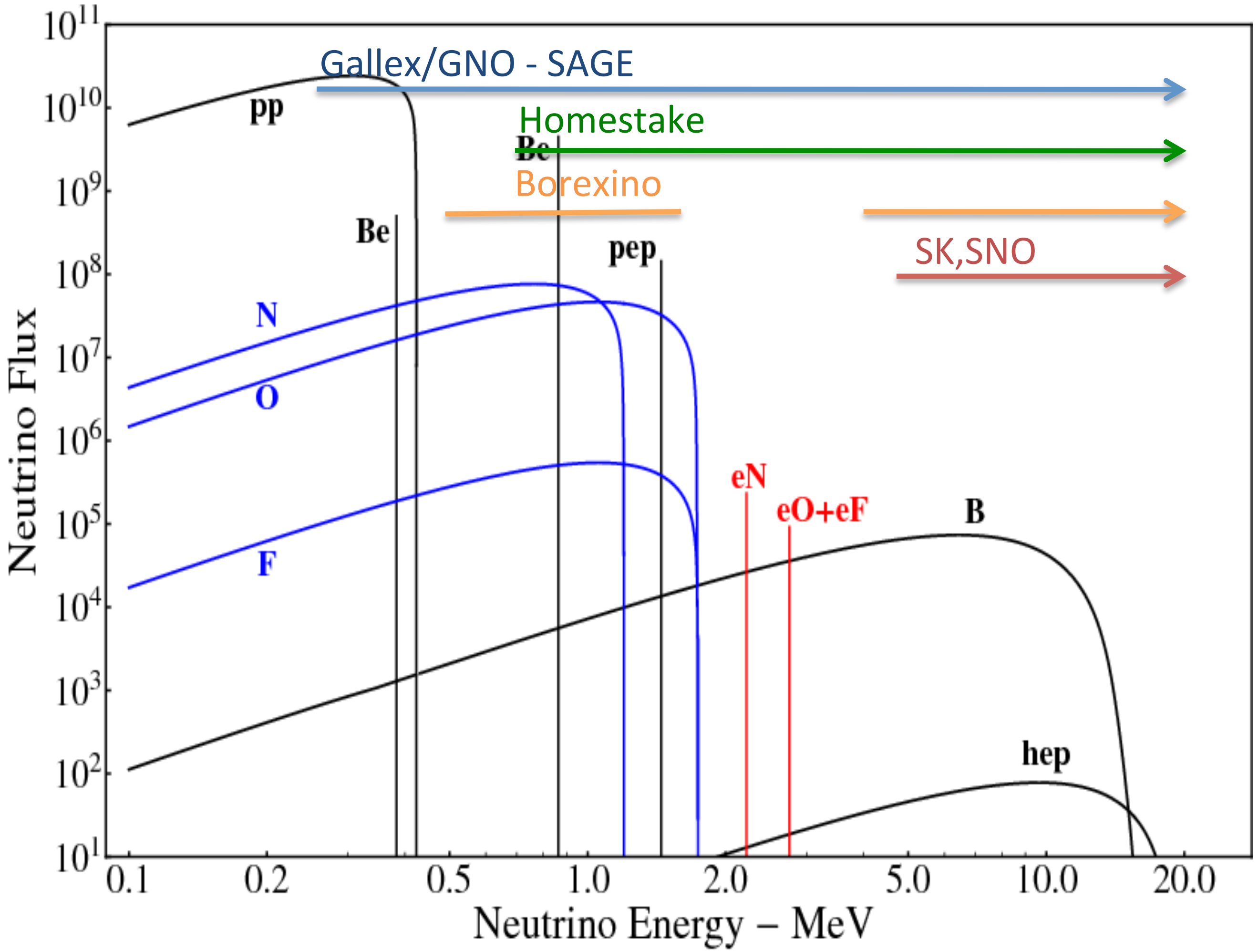
$^{15}N + p \rightarrow {}^{16}O + \gamma$

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 (bi-)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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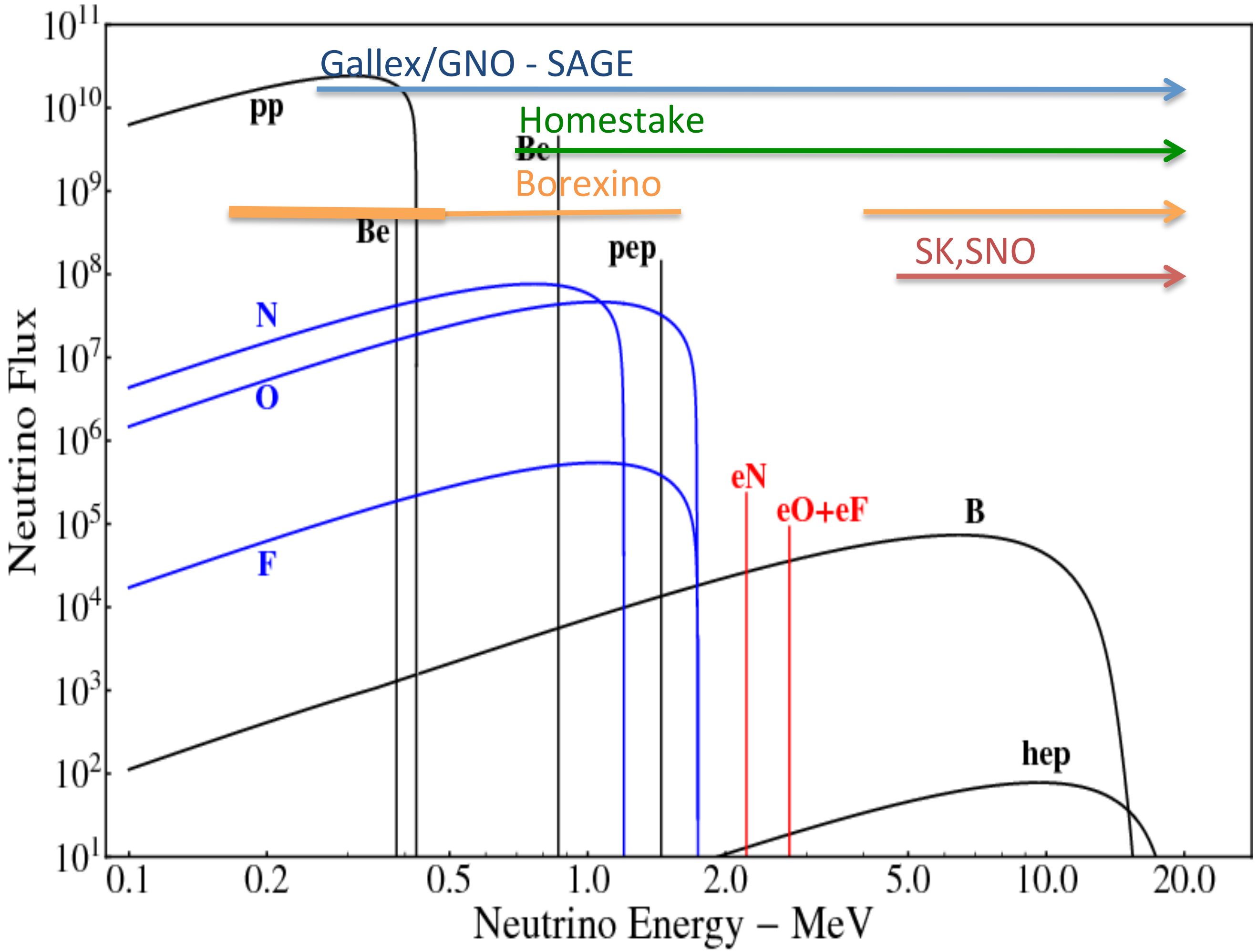

$\Phi_{pp} = (6.6 \pm 0.7) \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Borexino, Nature 2014

First direct measurement of the solar pp-component

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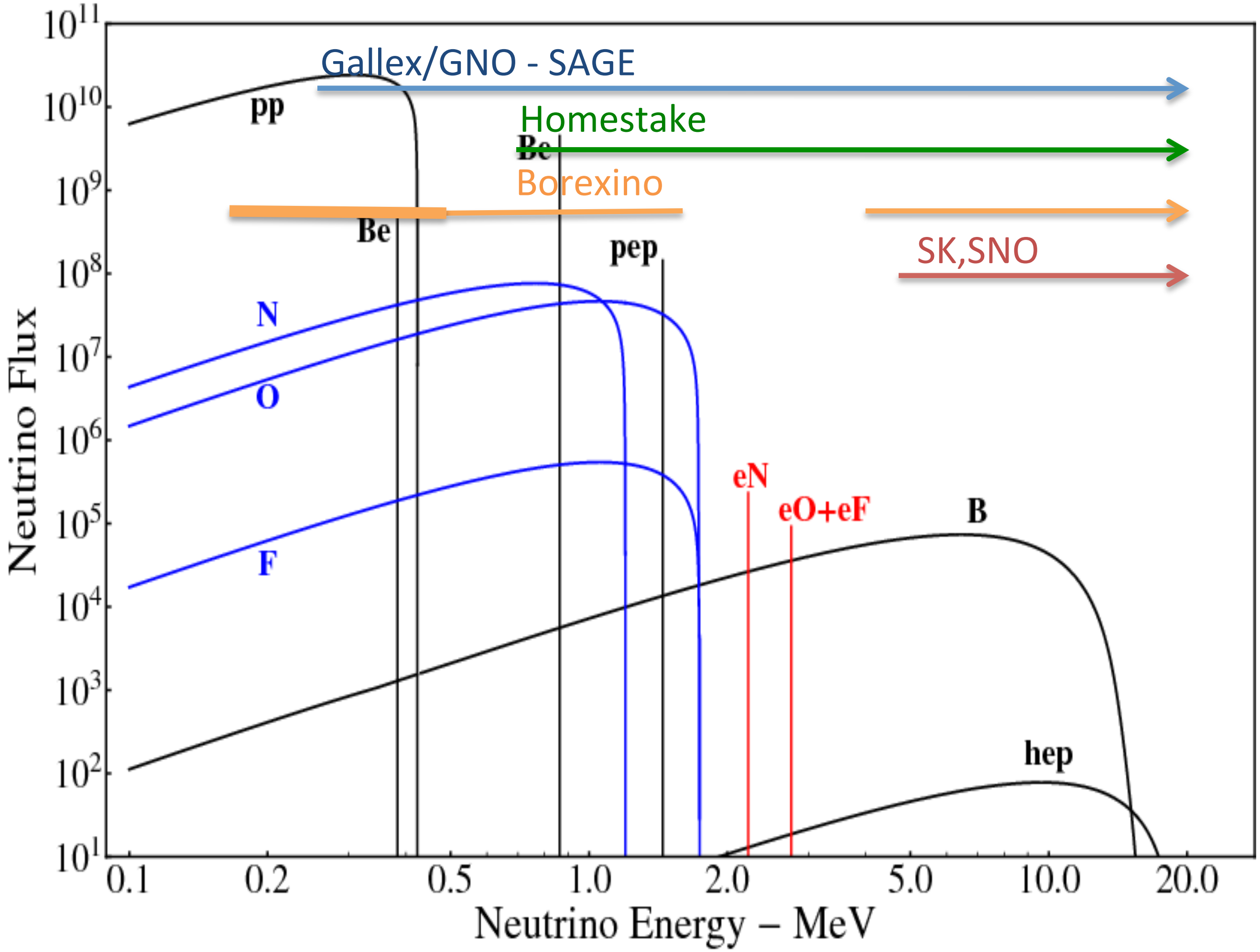

Bergstrom et al, JHEP 2016

	Obs
$\Phi(pp)$	$5.971^{+0.037}_{-0.033}$
$\Phi(pep)$	1.448 ± 0.013
$\Phi(hep)$	$\lesssim 19^{+12}_{-9}$
$\Phi(^7Be)$	$4.80^{+0.24}_{-0.22}$
$\Phi(^8B)$	$5.16^{+0.13}_{-0.09}$
$\Phi(^{13}N)$	$\lesssim 13.7$
$\Phi(^{15}O)$	$\lesssim 2.8$
$\Phi(^{17}F)$	$\lesssim 85$

Units:
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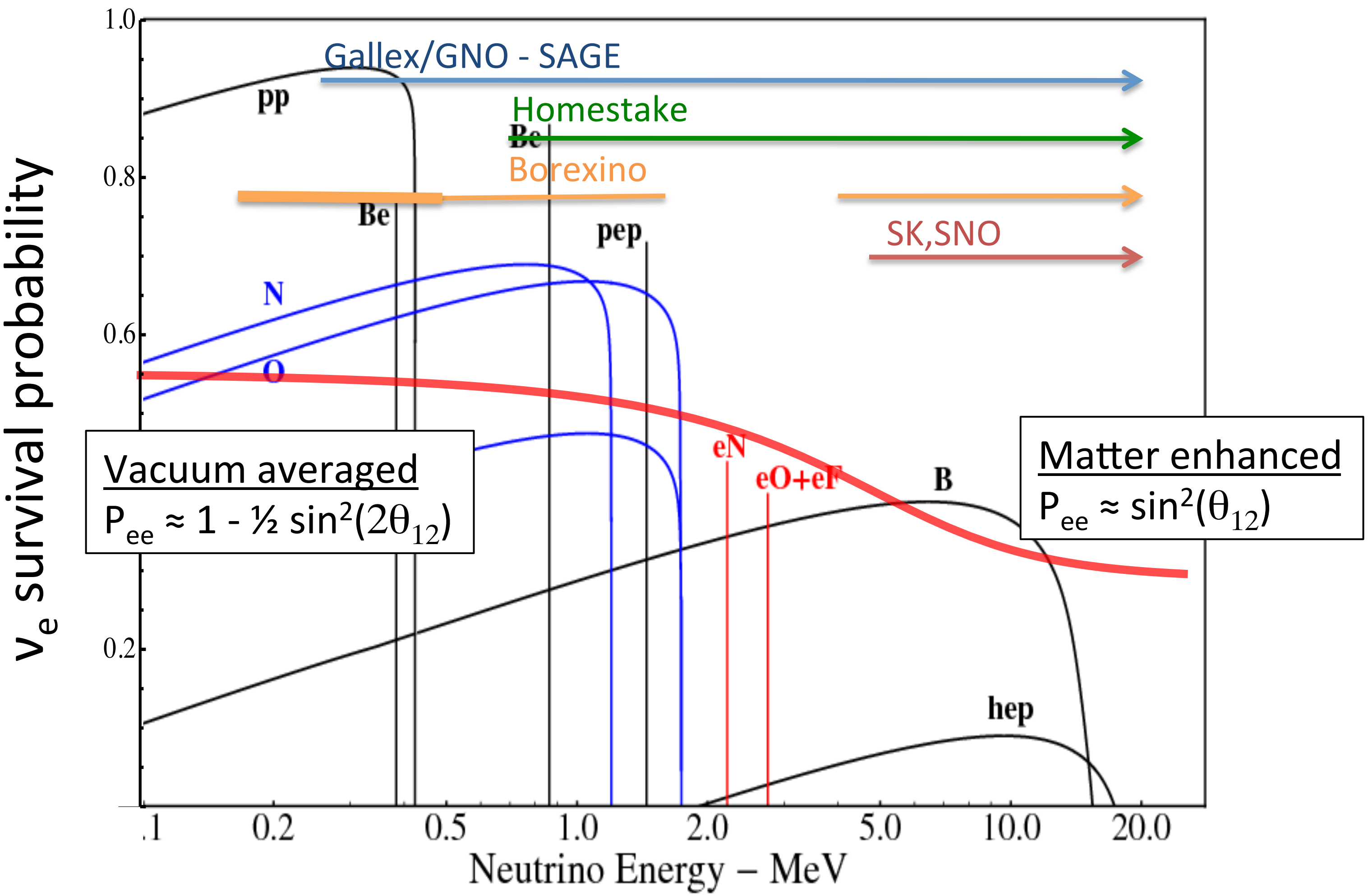
The solar neutrino survival probability



Vacuum averaged

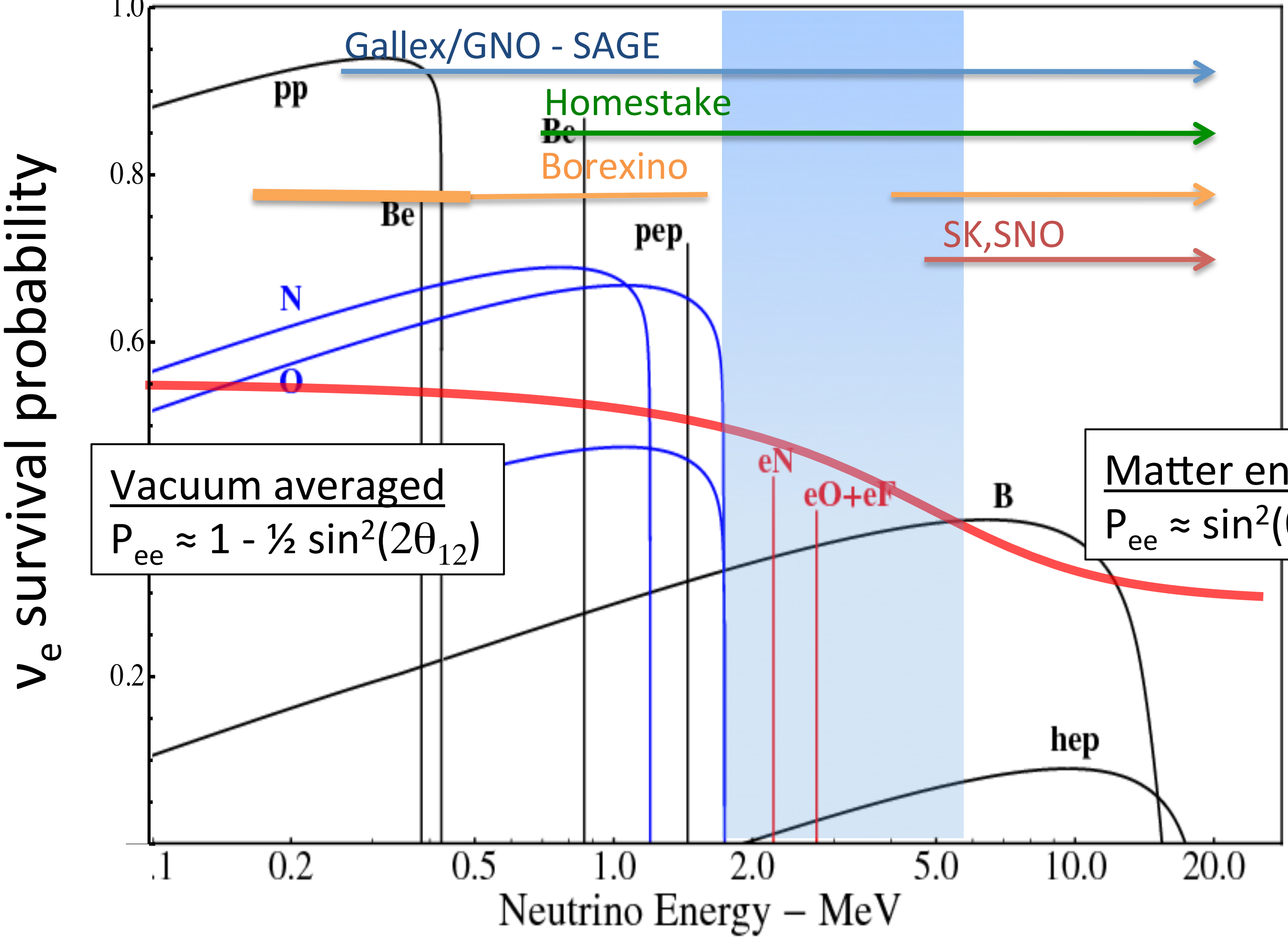
$P_{ee} \approx 1 - \frac{1}{2} \sin^2(2\theta_{12})$

Matter enhanced

$P_{ee} \approx \sin^2(\theta_{12})$

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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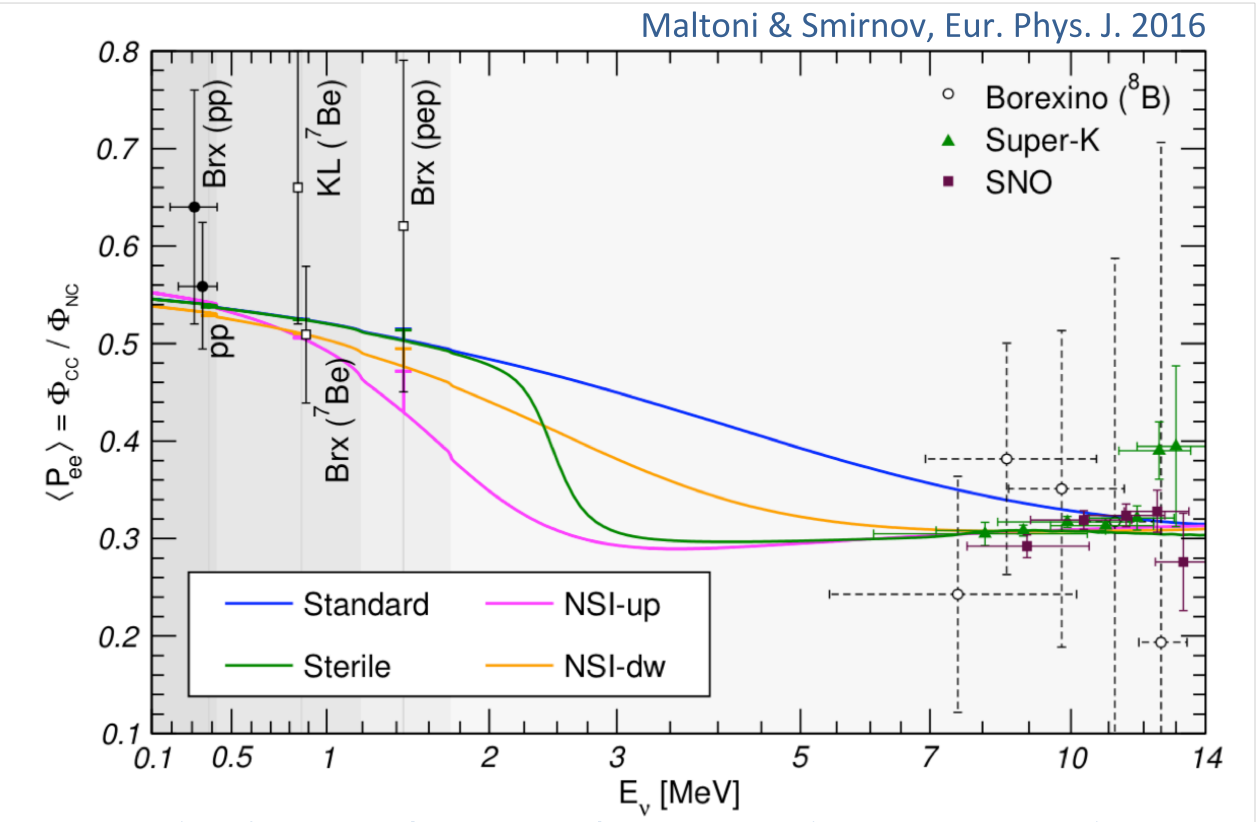

Combined analysis of SK I-IV (PRL 2014) also provided 2.7 σ evidence for D/N effec.

The transition region:

- Final confirmation of LMA-MSW paradigm
- Constraints on new physics beyond the standard 3ν paradigm:
  see e.g. Maltoni & Smirnov, Eur. Phys. J. 2016

"Advertising" electron-capture CNO neutrinos …

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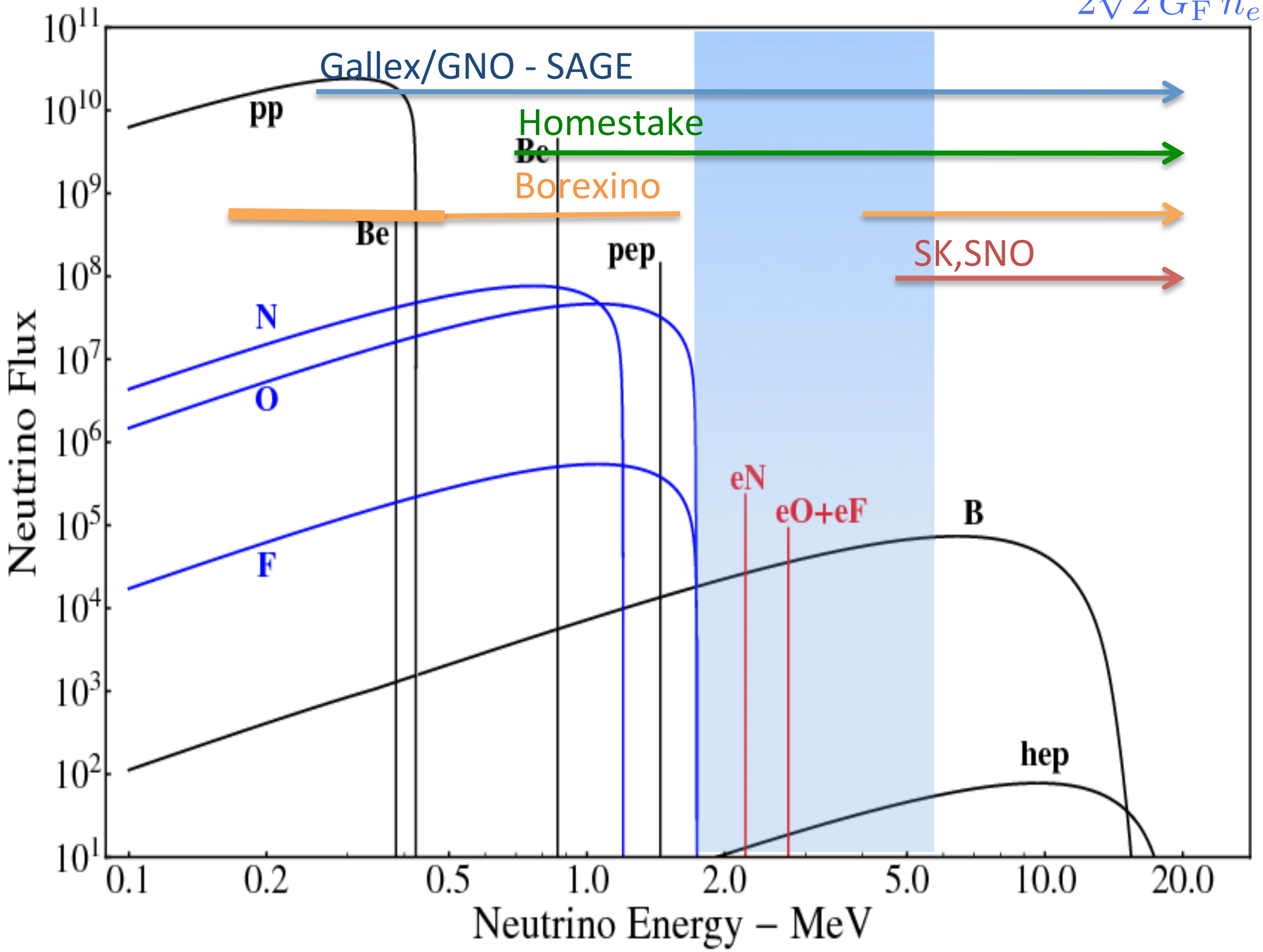

J.N. Bahcall, PRD 1990
L.C. Stonehill et al., PRC 2004
F.L. Villante, PLB 2015

ecCNO neutrinos:

- produced by e.c. reactions within the CN0 cycle $\Phi_{ecCNO} \approx 1/20\ \Phi_B$
- monochromatic (and located in the transition region)

The Standard Solar Model (SSM)

Our comprehension of the Sun is based on the **Standard Solar Model (SSM).**
This implies:

✓ Stellar structure equations;
(α = mixing length)

✓ Chemical evolution paradigm:
ZAMS homogenous model (Y_{ini}, Z_{ini})
Nuclear reactions + elemental diffusion

✓ Knowledge of the properties of solar plasma
(i.e. opacity, equation of state, nuc. cross sections);

No free parameters
The unknown quantities
- α, Y_{ini}, Z_{ini},

are fixed by requiring that the present Sun (t_{sun}=4.57 Gyr) reproduces its observational properties
- R_{sun}, L_{sun}, $(Z/X)_{Surf}$

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

Latest (improved) SSM calculations

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]

Flux	B16-GS98	B16-AGSS09met
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
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$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
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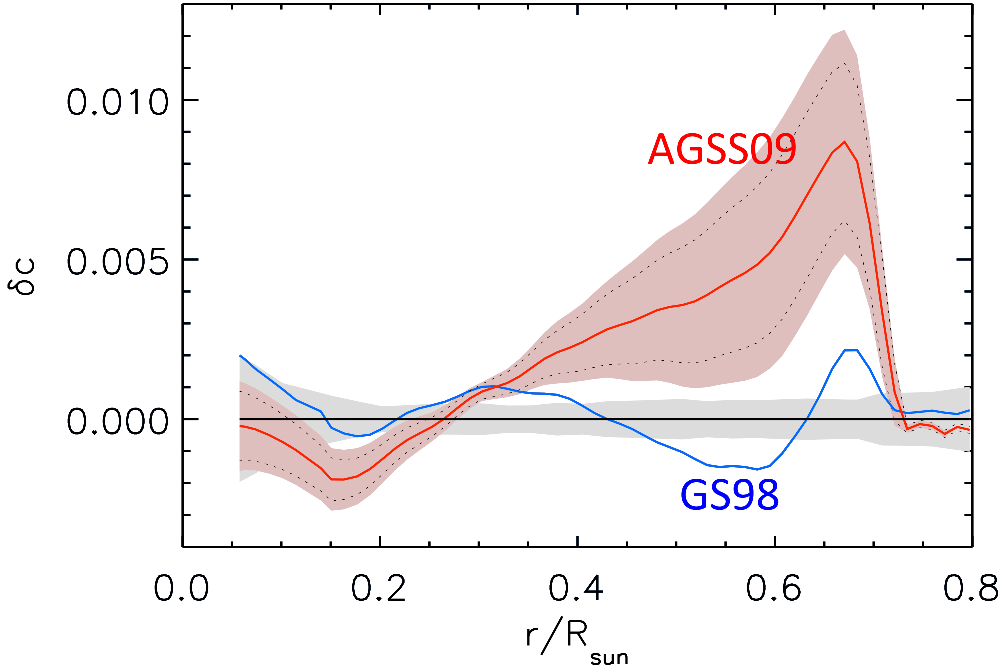
- Improved EOS;
- Updated astrophysical factors (S_{11}, S_{17}, S_{114});
- Different treatment of opacity uncertainties.

Heavy elements photospheric abundances → **inputs for SSM calculations**
Grevesse et al. 98 (**GS98**): 1D atm. model (old) – High metallicity
Asplund et al. 09 (**AGSS09**): 3D + NLT model (new) – Low metallicity
(20% for C,N; 40% for O,Ne; 12% Fe,Si, S,Mg)

Note: GS98 and AGSS09 are used as references but do not exhaust the list of possible values.
See e.g.: CO^{5}BOLD (Caffau et al, 2011)
Solar wind abundances (von Steiger & Zurbuchen, 2016) and rel. criticisms (Serenelli et al., 2016).

SSM and Helioseismology

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]



$$\delta c \equiv (c_{\rm obs} - c_{\rm mod})/c_{\rm mod}$$

High-Z models are preferred by helioseismology.

	GS98	AGSS09	Obs
$< \delta c/c >$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	-
$R_{\rm cz}/R_\odot$	0.7117 ± 0.0048	0.7224 ± 0.0053	0.713 ± 0.001
$Y_{\rm S}$	0.2426 ± 0.0059	0.2316 ± 0.0059	0.2485 ± 0.0035
$Z_{\rm S}$	0.0170 ± 0.0012	0.0134 ± 0.0008	-
$Y_{\rm C}$	0.6320 ± 0.0053	0.6209 ± 0.0062	-
$Z_{\rm C}$	0.0200 ± 0.0014	0.0159 ± 0.0010	-

The solar composition problem

There is something **wrong** or **unaccounted** in solar models

- Are the new abundances (i.e. the atmospheric model) **wrong**?

  see e.g. Villante et al., ApJ 2014
  Song et al., arXiv:1710.02147

- Are properties of the solar matter (e.g. **opacity**) correctly described?

  see e.g. Song et al., arXiv:1710.02147
  Villante, ApJ 2011
  Christensen-Dalsgaard et al, A&A 2009
  Bailey et al, Nature 2015; Krief et al, arXiv:1603.01153

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

  see e.g. Vincent et al. – arxiv:1411.6626 / 1504.04378 / 1605.06502

- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

  see e.g. Serenelli et al. – ApJ 2011

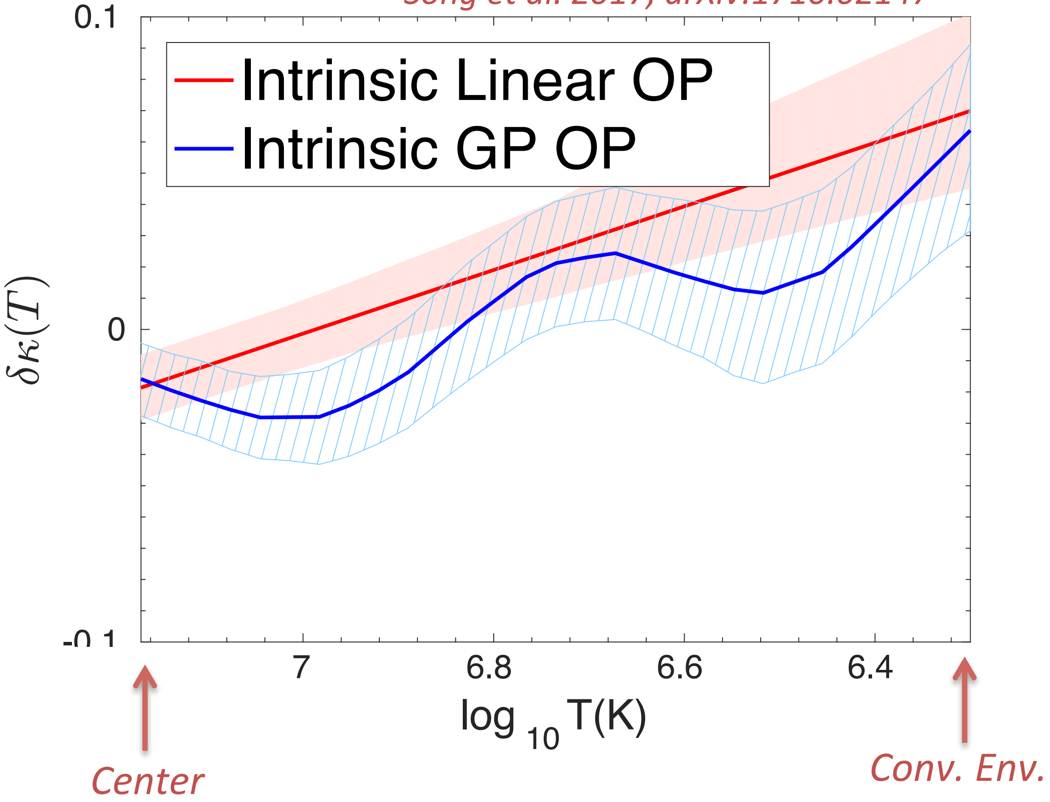
Note that:

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

Wrong opacity?

We can use helioseismology + neutrinos (R_b,Y_b; c(r) ; Φ_ν) to determine the optimal opacity profile of the Sun

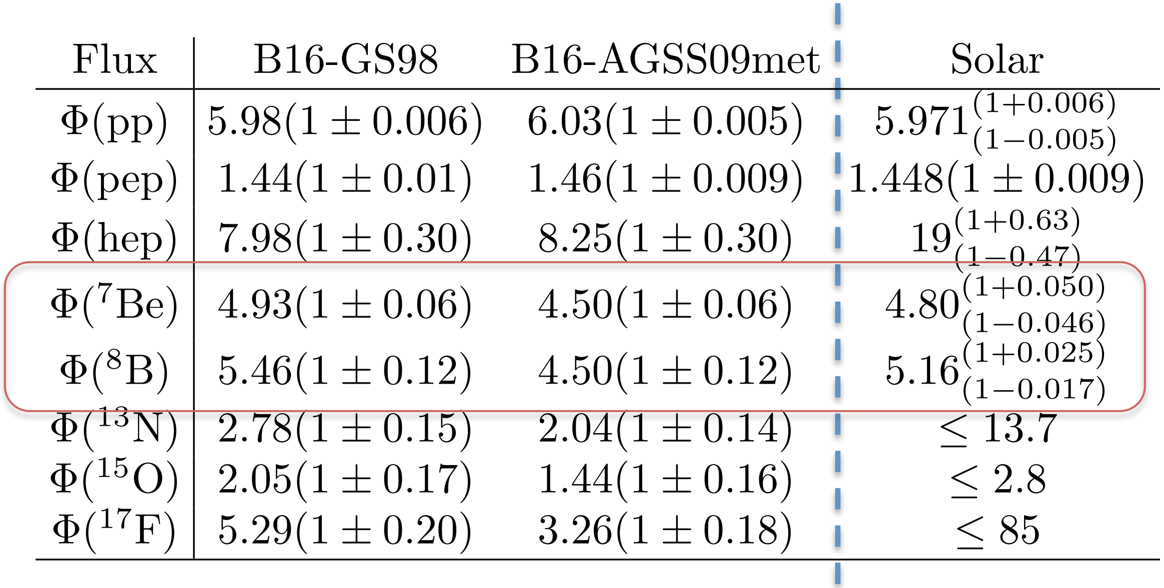
Song et al. 2017, arXiv:1710.02147



- NB: The final results depends on the assumed composition (opacity-composition degeneracy)
- The above profile is obtained by assuming a flat prior [AGSS09-3σ,GS98+3σ] for abundances

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

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]



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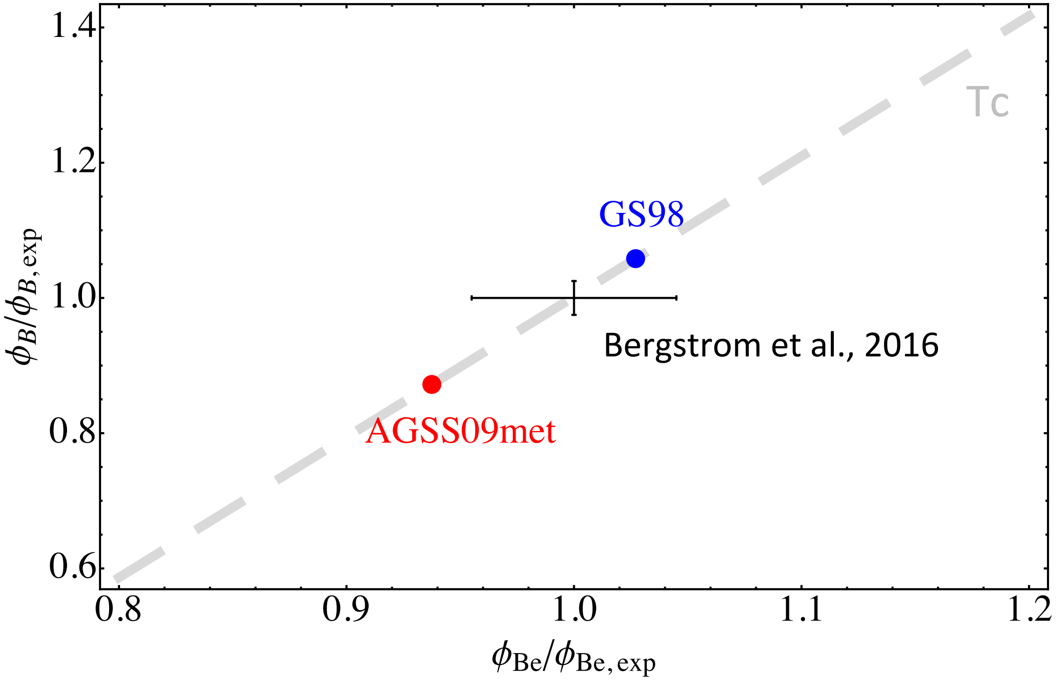

$$\phi_{\mathrm{B}} \propto T_{\mathrm{c}}^{20} \quad \rightarrow \quad (\delta T_{\mathrm{c}})^{\mathrm{GS98}}_{\mathrm{AGSS09}} \leq 1\%$$

Exp. data are sufficiently accurate to discriminate GS98-AGSS09met central values.

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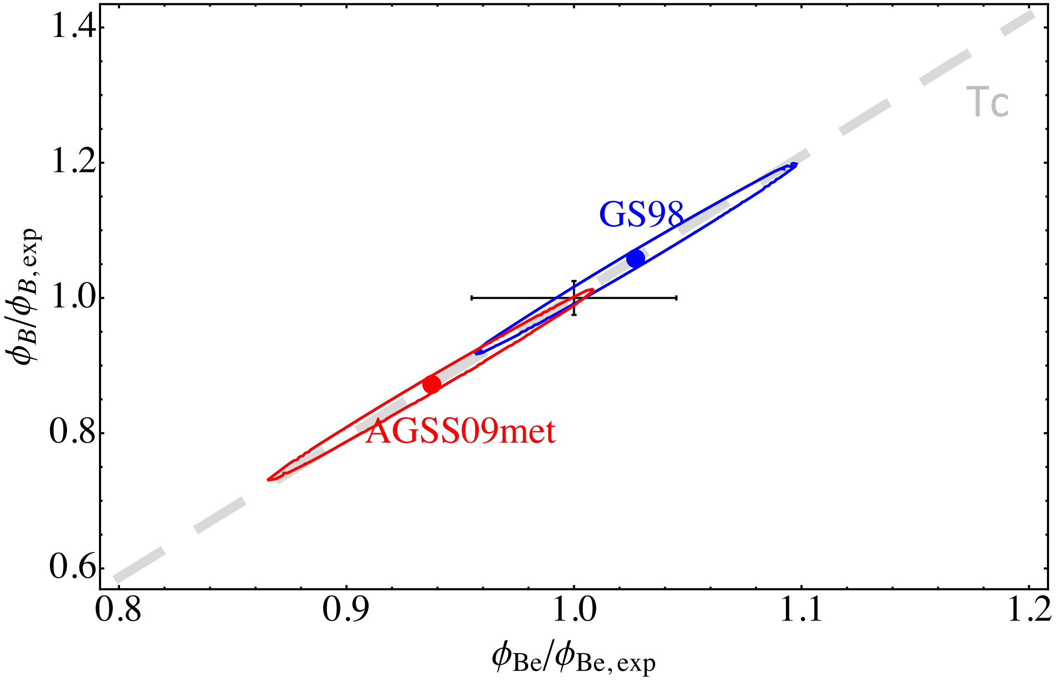

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- Surface composition
- Environmental parameters: opacity (few %), diffusion coeff. (15%), etc
- Nuclear cross section: S_{17}(4.7%), S_{33}(5.2%), S_{34}(5.4%) dominant error sources

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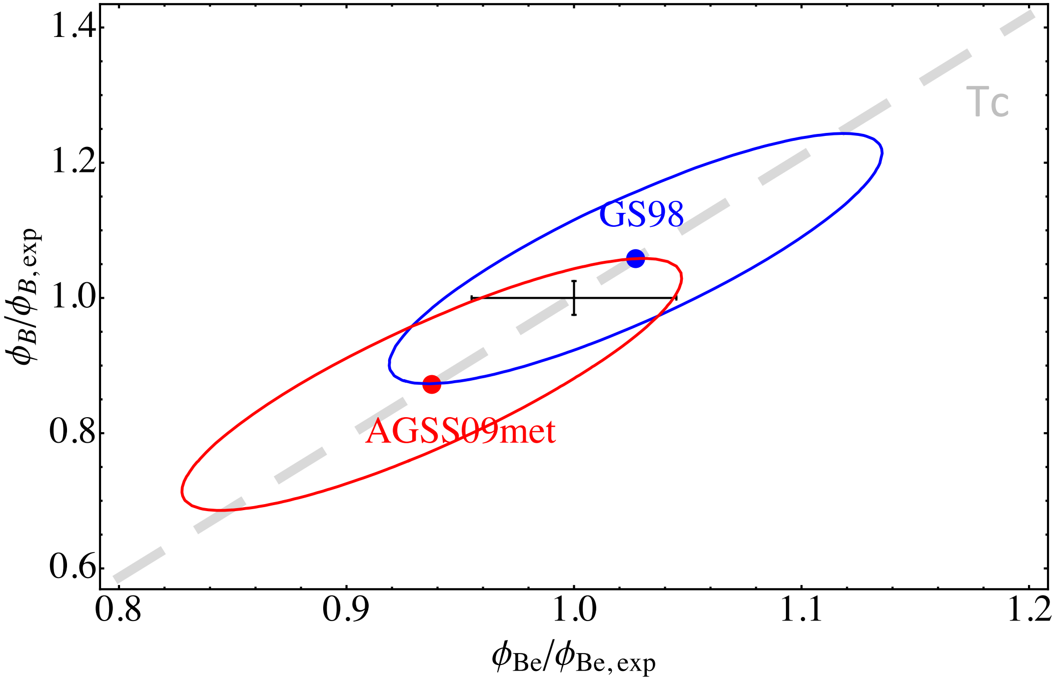

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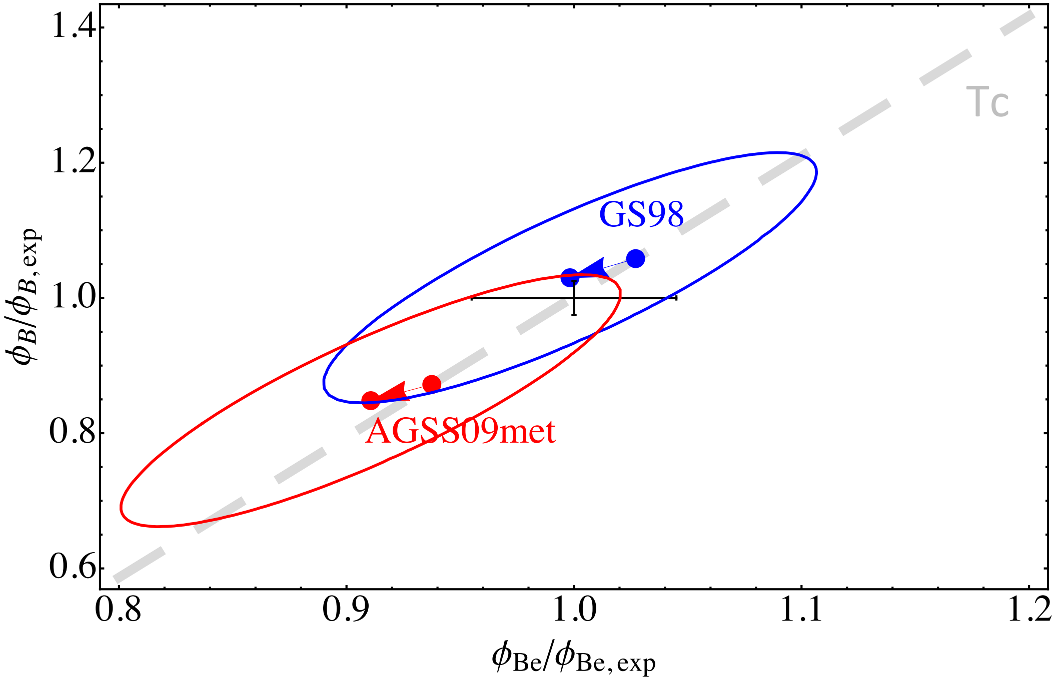
The role of ^{3}He(α,γ)^{7}Be cross section



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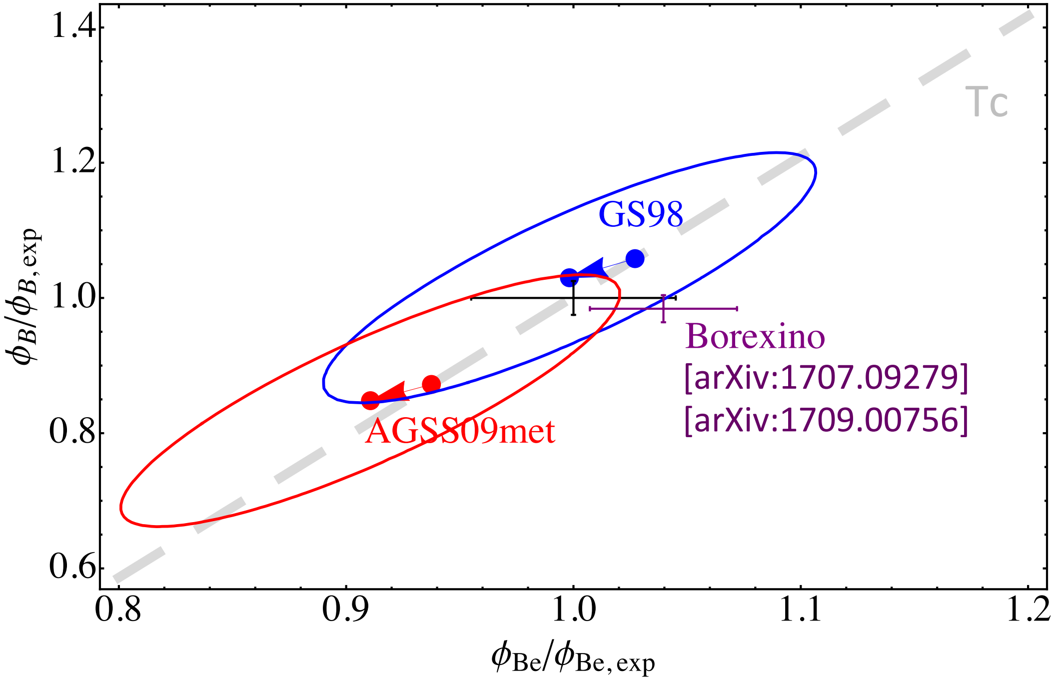
- B16-SSMs adopt Adelberger et al 2011 recommended value (with 5.4% uncertainty)
- deBoer et al. 2014 provided a new determination of **S_{34}** (not a new measure) based on R-matrix fit of the data → **≈ 3% lower** than Adelberger et al 2011;
- Slight preference for GS98 → not statistically significant

The new Borexino results



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The CNO cycle uses C, N and O nuclei are used as catalysts for hydrogen fusion.

$$\frac{\phi(^{15}O)}{\phi^{\mathrm{SSM}}(^{15}O)} \simeq \left[\frac{C+N}{C^{\mathrm{SSM}}+N^{\mathrm{SSM}}}\right]\left(\frac{T_{\mathrm{c}}}{T_{\mathrm{c}}^{\mathrm{SSM}}}\right)^{20}$$

CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars

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- Provide a direct determination of the C+N abundance in the **solar core**:

$$\frac{\Phi(^{15}O)}{\Phi(^{15}O)^{\rm SSM}} / \left[\frac{\Phi(^{8}B)}{\Phi(^{8}B)^{\rm SSM}}\right]^{0.785} = \left[\frac{C+N}{C^{\rm SSM}+N^{\rm SSM}}\right] (1 \pm 0.4\%({\rm env}) \pm 2.6\%({\rm diff}) \pm 10\%({\rm nucl}))$$

Serenelli et al., PRD 2013

- ^{8}B neutrinos are used as a solar thermometer;
- ^{15}O/^{8}B → breaks the (otherwise complete) **degeneracy** between **temperature stratification** (i.e. opacity, DM accumulation, etc.) and **chemical composition** effects (accretion, diffusion, atmospheric models, etc.)

High-Z .vs. Low-Z:

$$\frac{\Phi_{\rm GS98}(^{15}O)}{\Phi_{\rm AGSS09}(^{15}O)} - 1 \simeq 40\%$$

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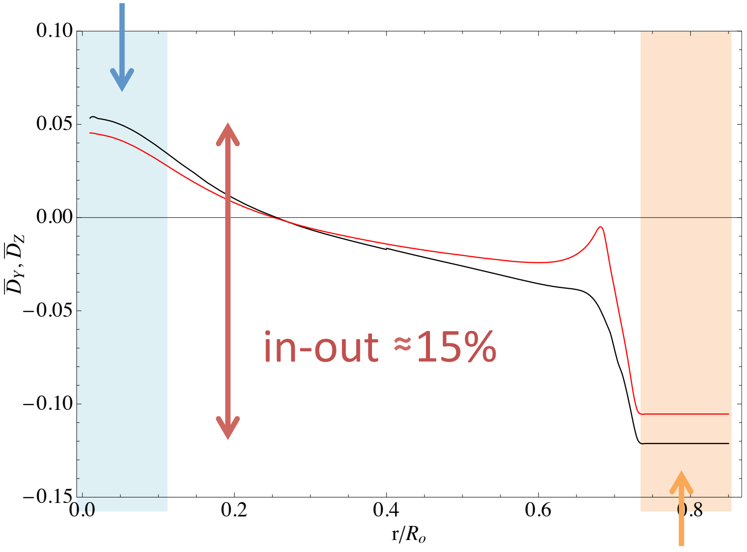
Beyond solar composition problem (10%):

CNO neutrinos allow us to test for mixing processes in the Sun (and other stars)

$$\begin{aligned} Y(r) &= Y_{\rm ini}\,[1 + D_Y(r)] + Y_{\rm nuc}(r) \\ Z(r) &= Z_{\rm ini}\,[1 + D_Z(r)] \end{aligned}$$

ν production region



in-out ≈15%

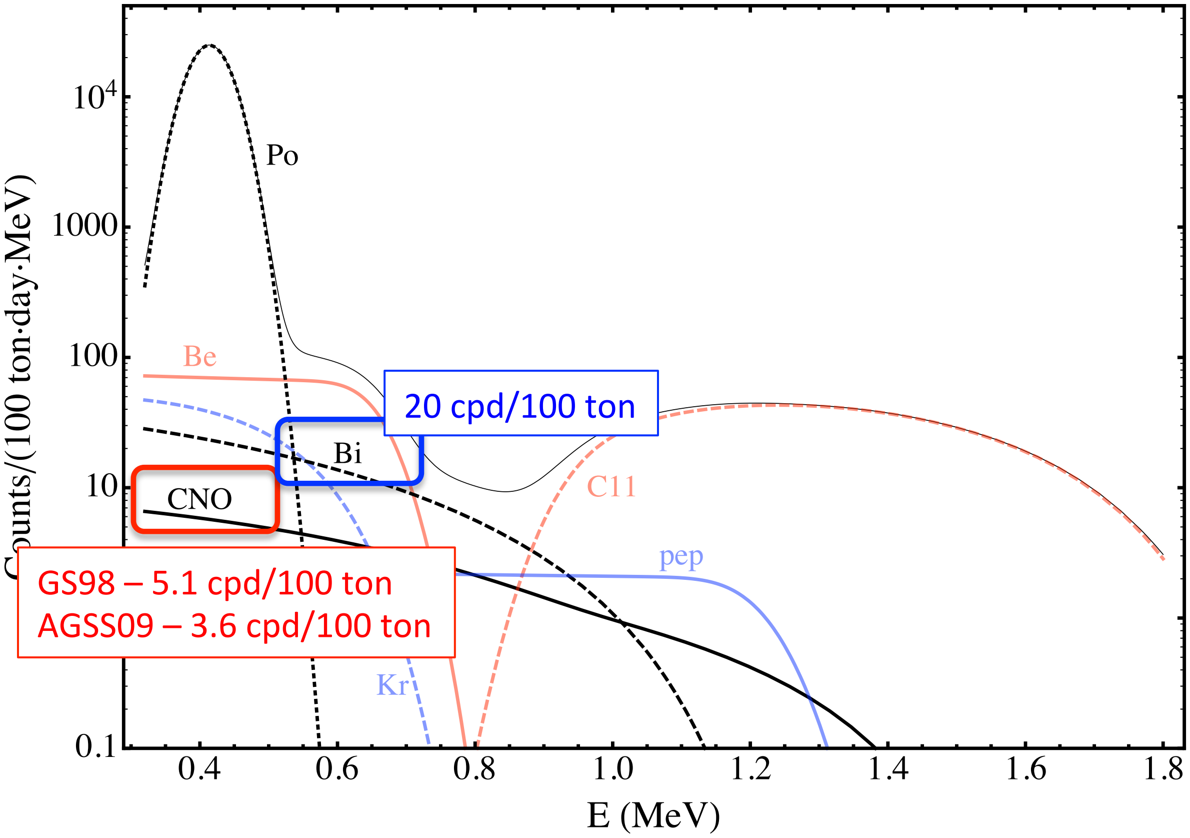
Surface abundances

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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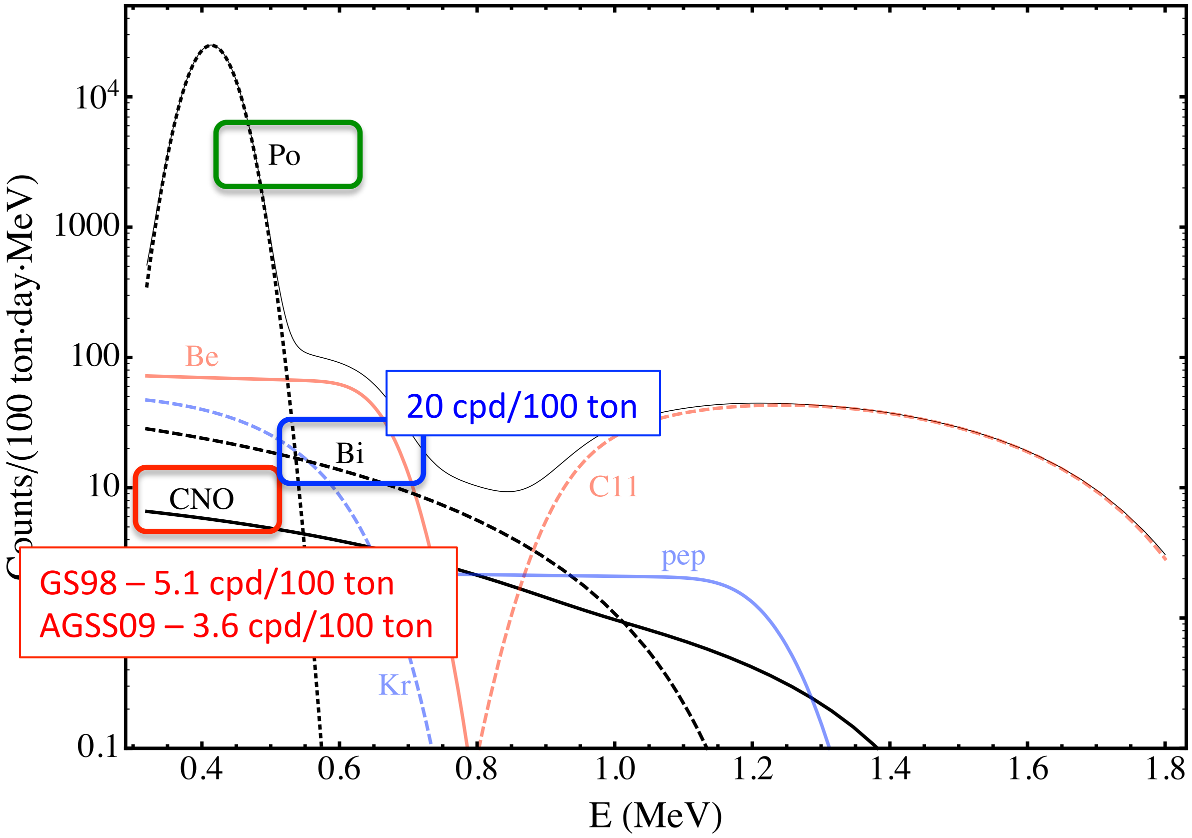

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Determining ^{210}Bi from ^{210}Po time evolution?

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

Villante et al., PLB 2011

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

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- 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 also G. Orebi-Gann talk@Neutrino2014

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Franco et al. arXiV:1510.04196 (300 ton Lar-detector@LNGS for solar-ν).

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- ecCNO neutrinos: A challenge for gigantic ultra-pure LS detectors (Villante, PLB 2015)
  Expt. requirements: *as clean (and deep) as Borexino;*
  as large as JUNO;

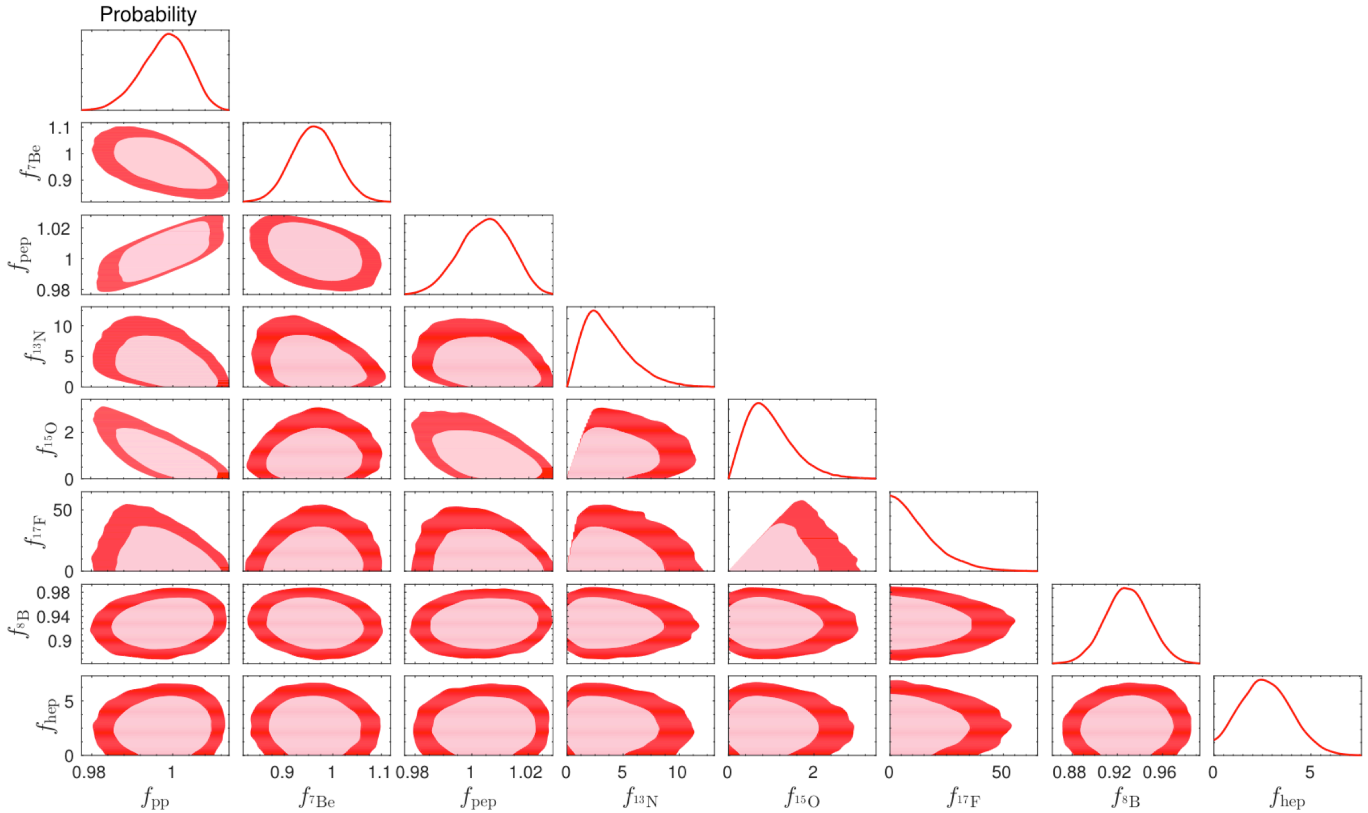
Summary and conclusions

- ✓ Helioseismology shows that a solar composition problem exists. This could potentially indicate inadequacies in the standard solar model paradigm.
- ✓ Borexino opened the way to pp-neutrino detection and tested the dominant hydrogen burning mechanism in the Sun.
- ✓ CNO neutrinos would allow us to see the dominant hydrogen burning mechanism in more massive and/or evolved stars and to test for mixing processes in the Sun.
- ✓ CNO neutrino detection requires careful bkgd evaluation in existing or next future LS detectors and/or new experimental approaches.

Thank you

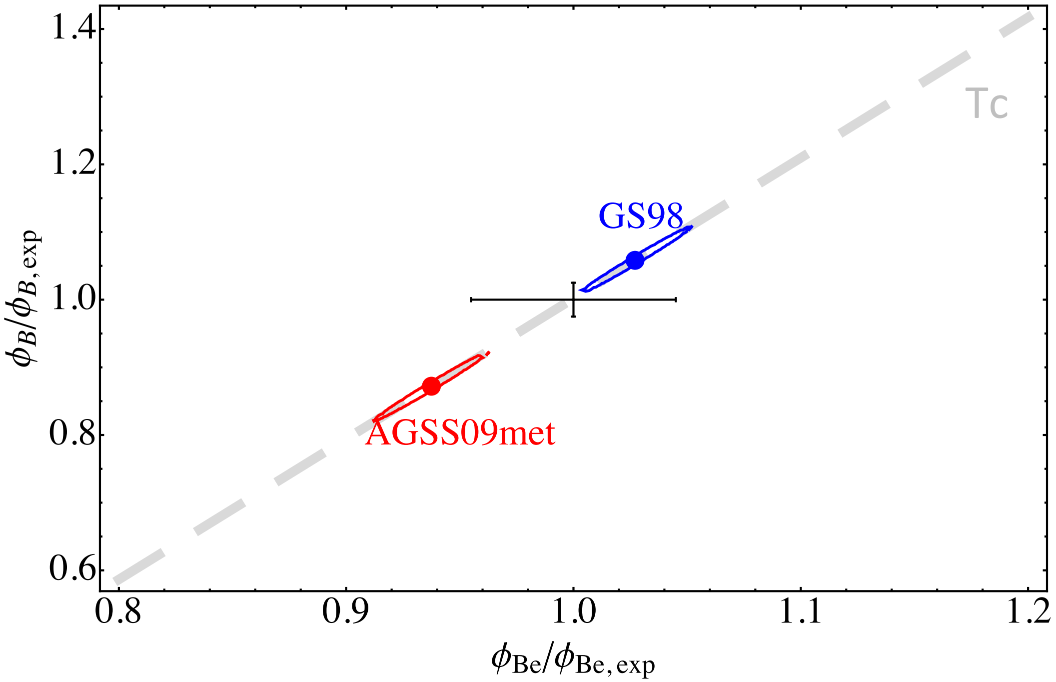
Additional slides

Observational costraints on n fluxes – Bergstrom et al, JHEP 2016



SSM and neutrinos

N.Vinyoles et al., 2016 – arXiv:1611.09867v1



$$\phi_{\mathrm{B}} \propto T_{\mathrm{c}}^{20} \quad \rightarrow \quad (\delta T_{\mathrm{c}})^{\mathrm{GS98}}_{\mathrm{AGSS09}} \leq 1\%$$

Exp. data are sufficiently accurate to discriminate GS98-AGSS09met central values. Unfortunately, **theoretical uncertainties dominate the error budget**. These are due to:

- Surface composition
- Environmental parameters: opacity (few %), diffusion coeff. (15%), etc
- Nuclear cross section: S_{17}(4.7%), S_{33}(5.2%), S_{34}(5.4%) dominant error sources

At the moment, ^{7}Be and ^{8}B neutrinos do not determine composition with suff. accuracy

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

Asplund et al. 05 (AGS05); Asplund et al. 09 (AGSS09)

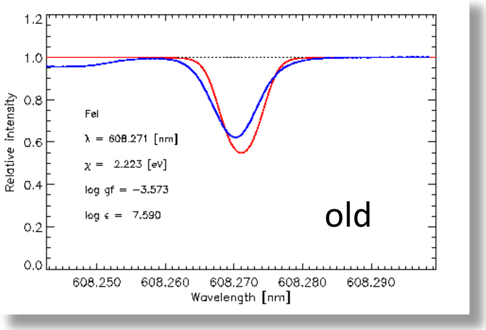
(*)*N. Grevesse talk at PHYSUN10*

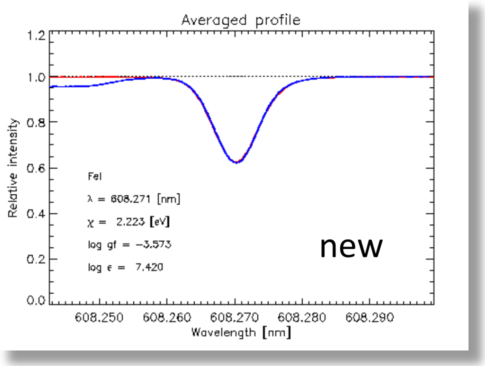
Re-determination of the photospheric abundances of nearly all available elements **(inputs for SSM calculations)**

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)
- **Downward revision of heavy elements photospheric abundances …**

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





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

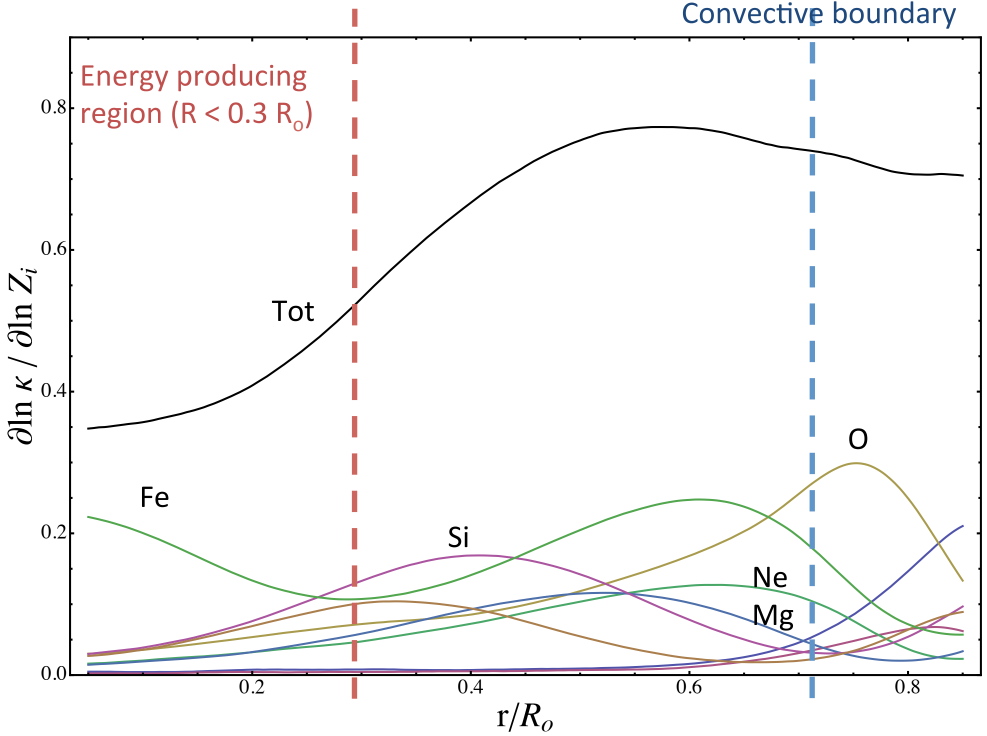
The role of metals

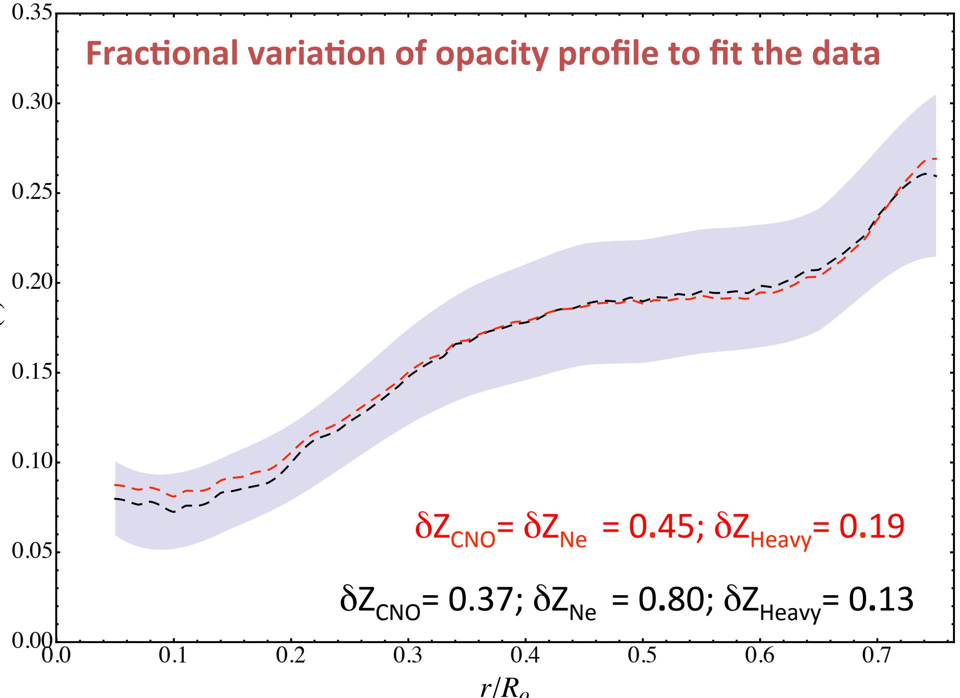
A change of the solar composition produces the same effects on the helioseismic observables and on neutrino fluxes (except CNO neutrinos) of a **suitable change of the solar opacity profile δκ(r).**

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

- ✓ 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***



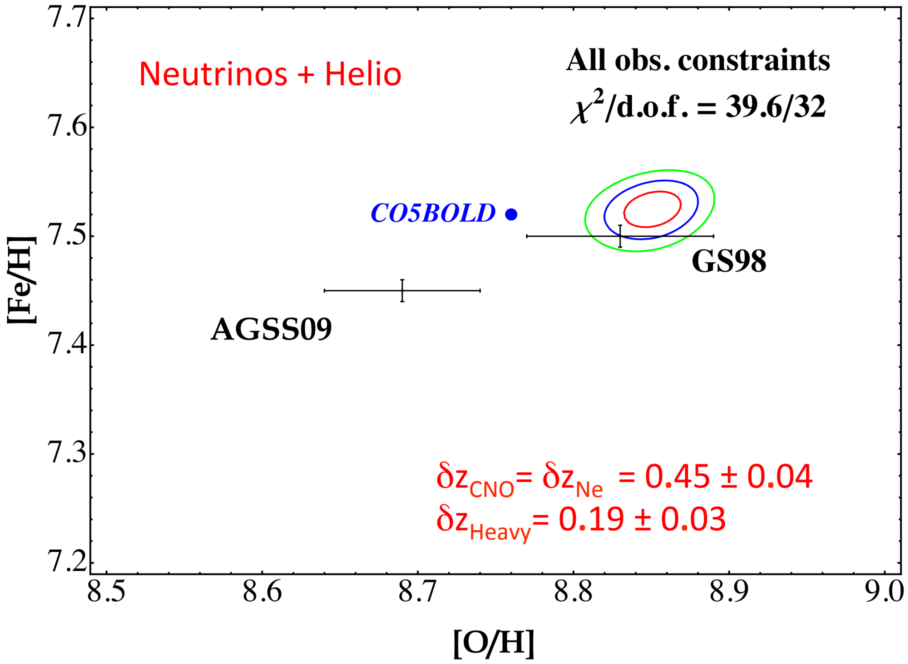


Wrong surface composition?

We can use helioseismology + neutrinos (R_b,Y_b; Φ_B, Φ_{Be}; c_1, …, c_{30}) to determine the optimal composition (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})



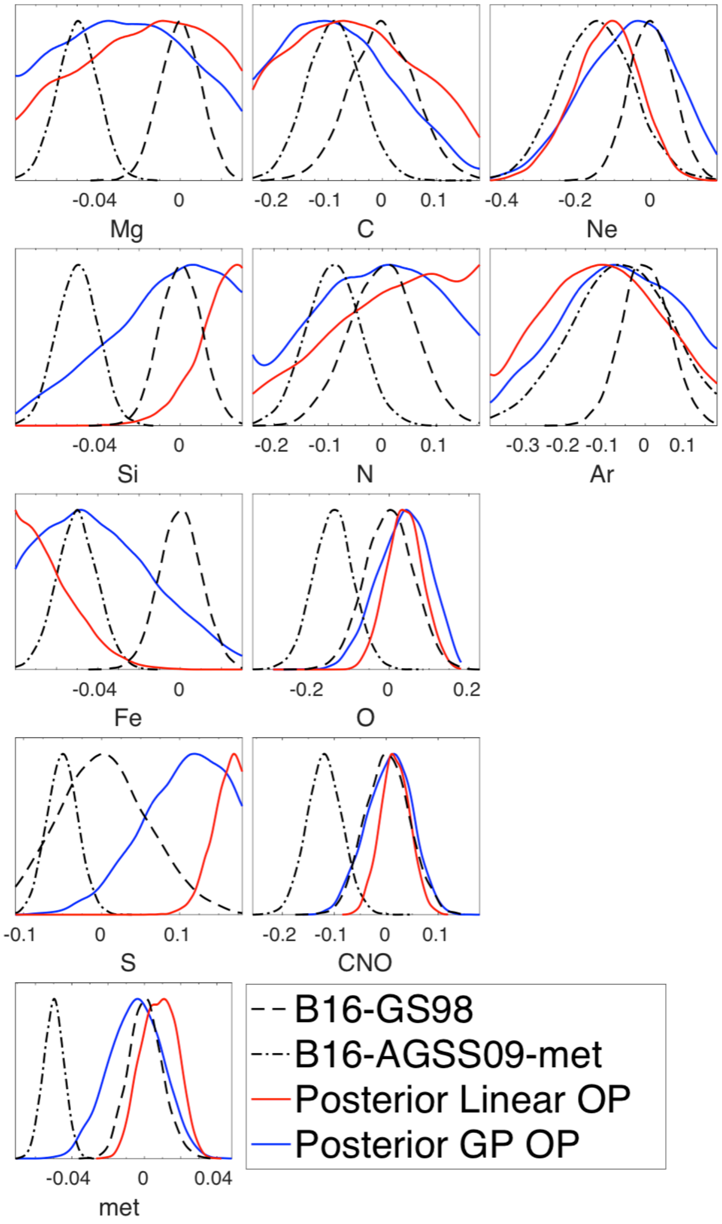
$$\begin{aligned}[\mathrm{O/H}] &= \overline{[\mathrm{O/H}]} + \log\left(1 + \delta z_{\mathrm{CNO}}\right)\\ [\mathrm{Fe/H}] &= \overline{[\mathrm{Fe/H}]} + \log\left(1 + \delta z_{\mathrm{Heavy}}\right)\end{aligned}$$

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

Wrong surface composition?

We can use helioseismology + neutrinos (R_b,Y_b; c(r) ; Φ_ν) to determine the optimal composition (Song et al. 2017):

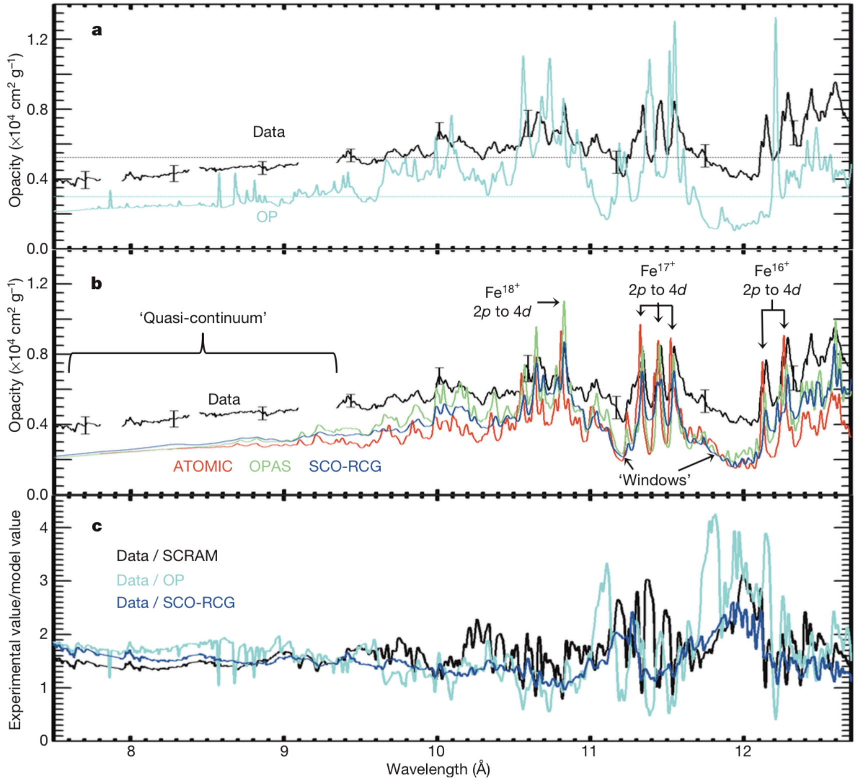


Wrong opacity?

(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%

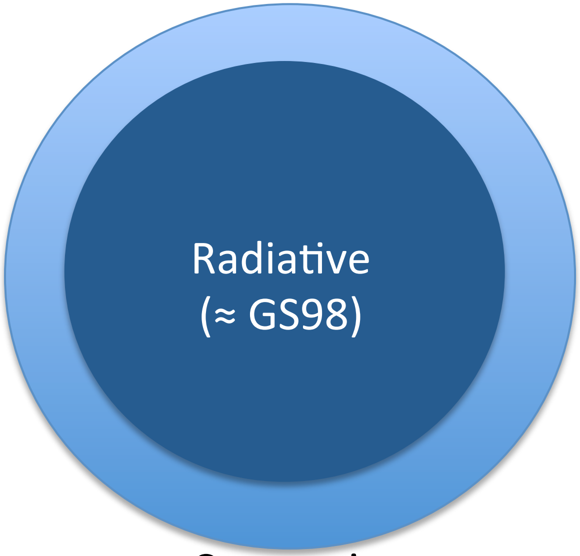
Bailey et al., Nature 2015



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).



Radiative
(≈ GS98)

Convective
(AGSS09)

Difference between AGSS09 and GS98 correspond to $\approx 40M_{\oplus}$ 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

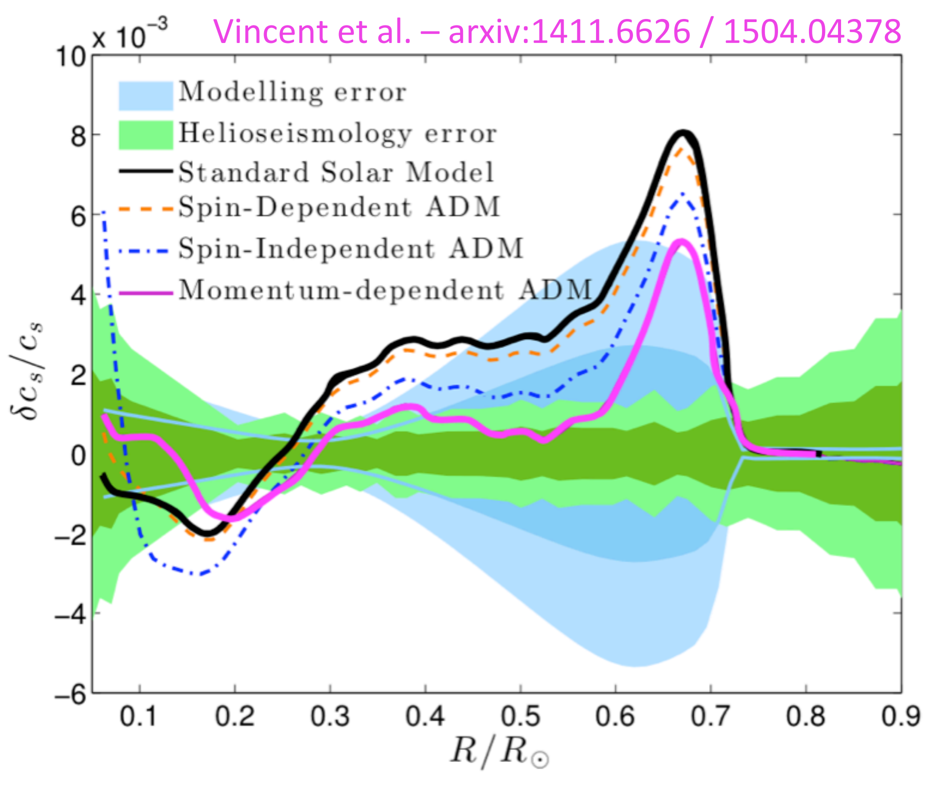
This is a well posed and extremely important question but …

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

Asymmetric DM

DM accumulation in the solar core:

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



Vincent et al. – arxiv:1411.6626 / 1504.04378

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)

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

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

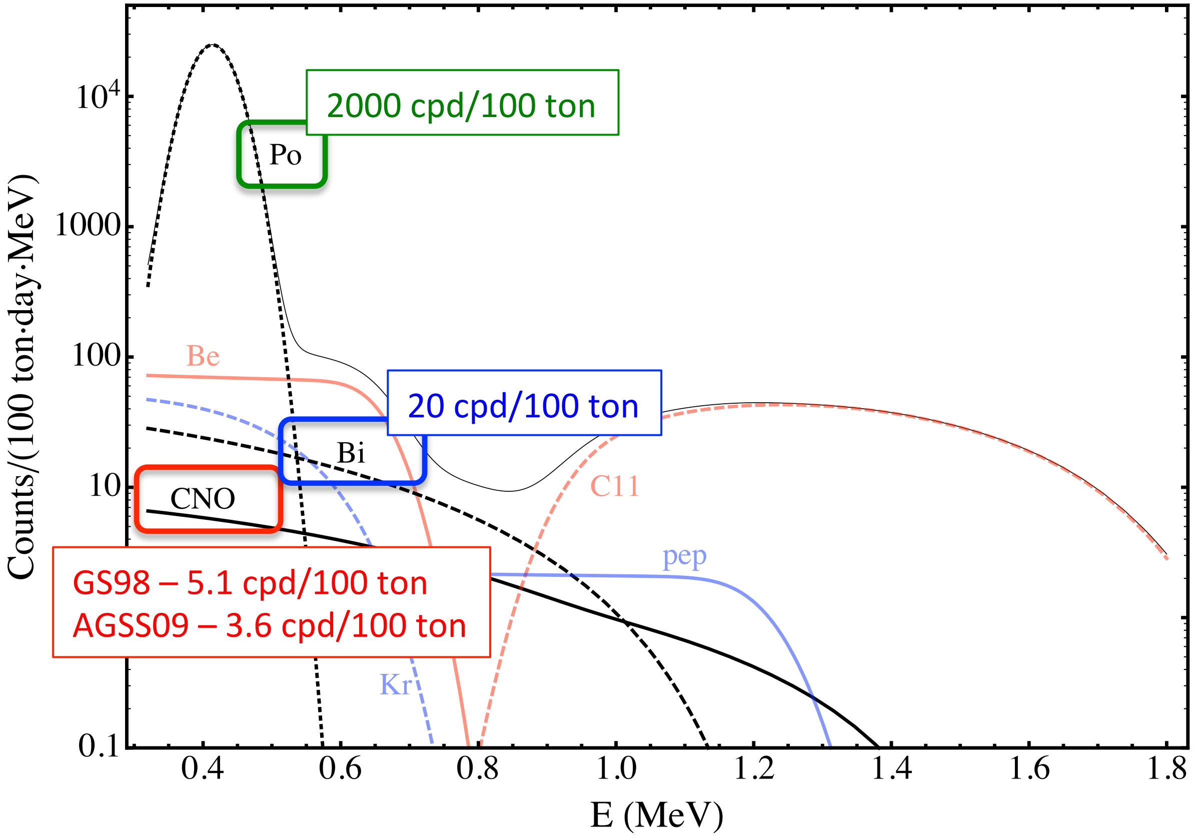
$$^{210}\mathrm{Bi} \rightarrow ^{210}\mathrm{Po} + e^- + \overline{\nu}_e$$

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

τ_{Bi} = 7.232 d

τ_{Po} = 199.634 d

Event spectrum in ultrapure liquid scintillators



2000 cpd/100 ton

20 cpd/100 ton

GS98 – 5.1 cpd/100 ton
AGSS09 – 3.6 cpd/100 ton

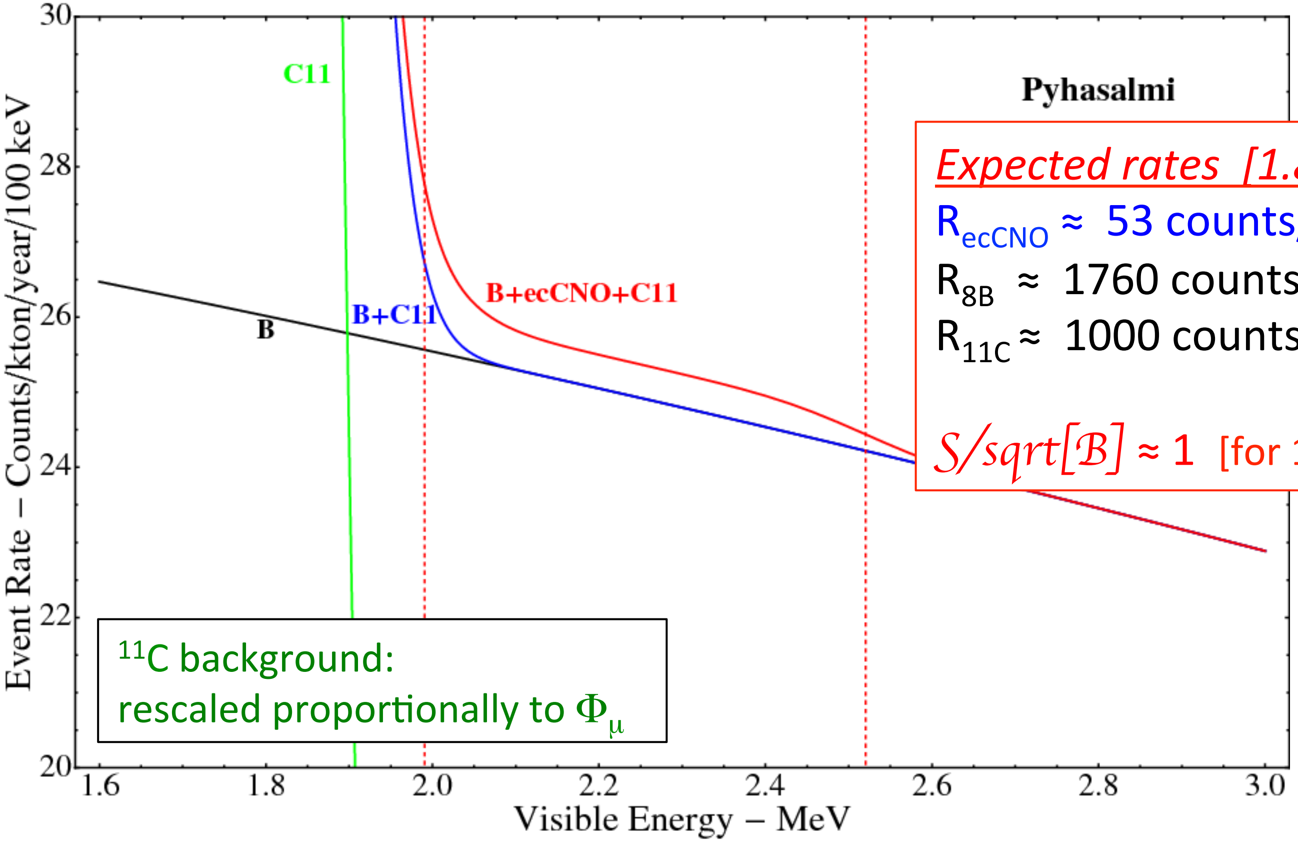
F.L. Villante et al. - Phys.Lett. B701 (2011) 336-341

- 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.

ecCNO - 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.



^{11}C background:
rescaled proportionally to Φ_μ

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

$S/\mathrm{sqrt}[B] \approx 1$ [for 10kton × year exposure]

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

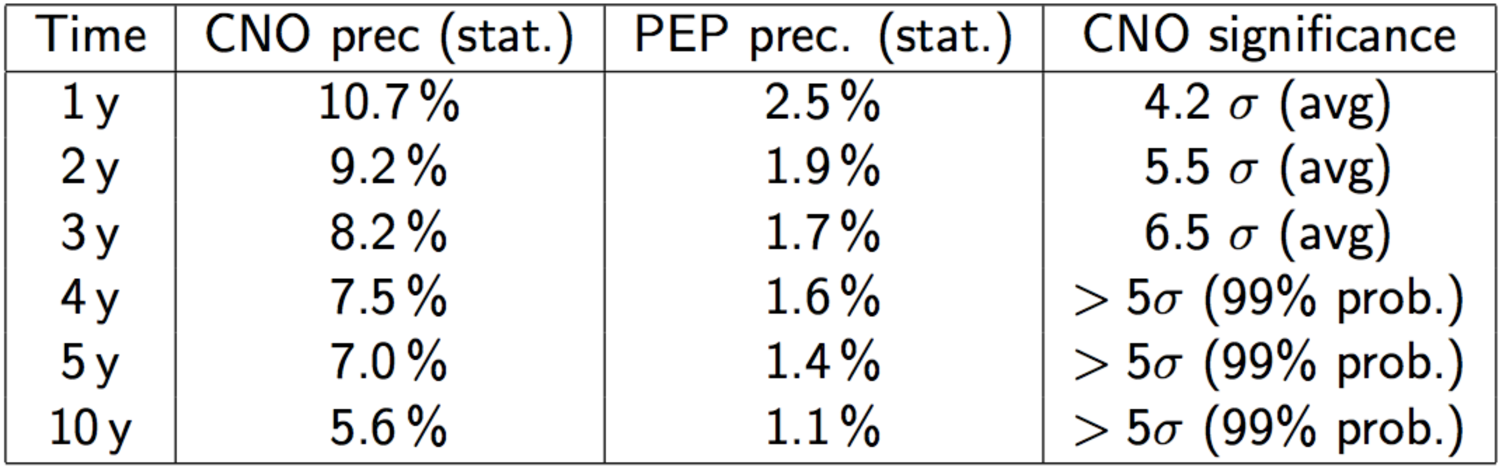
100 counts / year above 1.8 MeV in 20 kton detector → 3σ detection in 5 year in LENA

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

Significance of CNO measurement in LENA

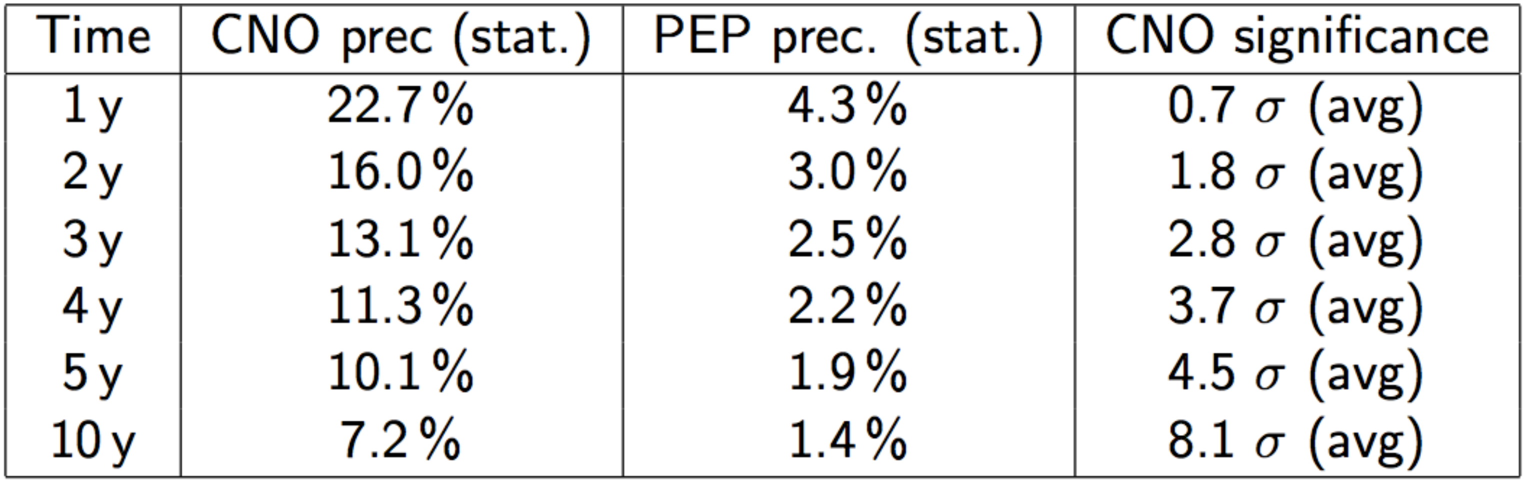
From Michael Wurm talk @ NNN14

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:



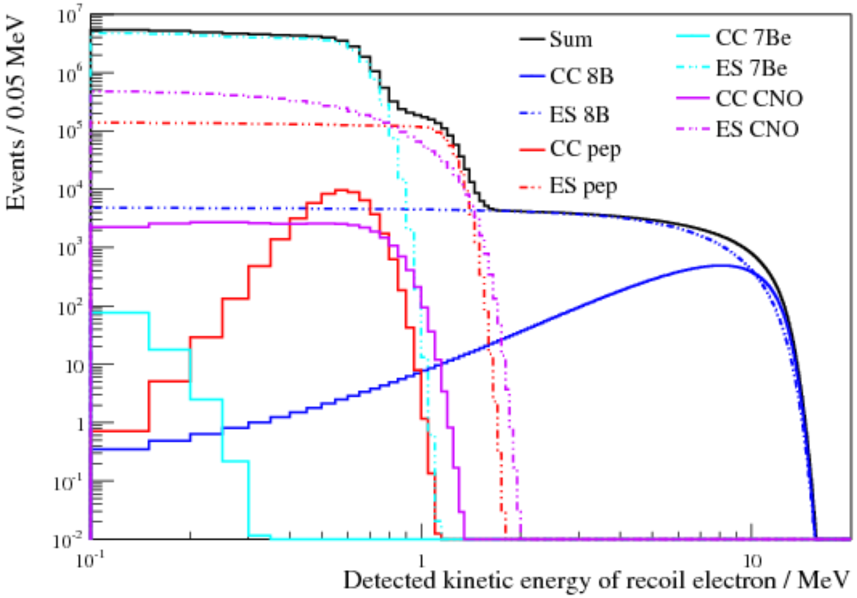
Time	CNO prec (stat.)	PEP prec. (stat.)	CNO significance
1 y	22.7 %	4.3 %	0.7 σ (avg)
2 y	16.0 %	3.0 %	1.8 σ (avg)
3 y	13.1 %	2.5 %	2.8 σ (avg)
4 y	11.3 %	2.2 %	3.7 σ (avg)
5 y	10.1 %	1.9 %	4.5 σ (avg)
10 y	7.2 %	1.4 %	8.1 σ (avg)

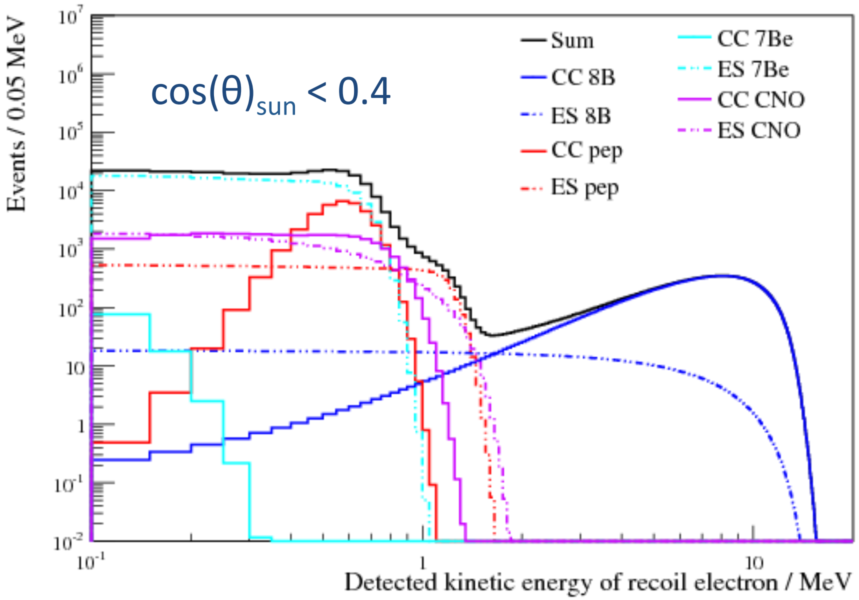
In the future … Advanced Scintillator Detector Concept (ASDC)

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




$\cos(\theta)_{sun} < 0.4$

From arXiv:1409.5864