A quantitative analysis of the solar composition problem

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

Based on work done in collaboration with:
A. Serenelli and N. Vinyoles

Outline

- The solar composition problem
- Metals .vs. opacity
- CNO and ecCNO neutrinos
- Summary and conclusions

The solar composition problem

The **downward revision** of heavy elements photospheric abundances …

Element	GS98	AGSS09met	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
$(\mathrm{Z/X})_\odot$	0.02292	0.01780	0.29

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

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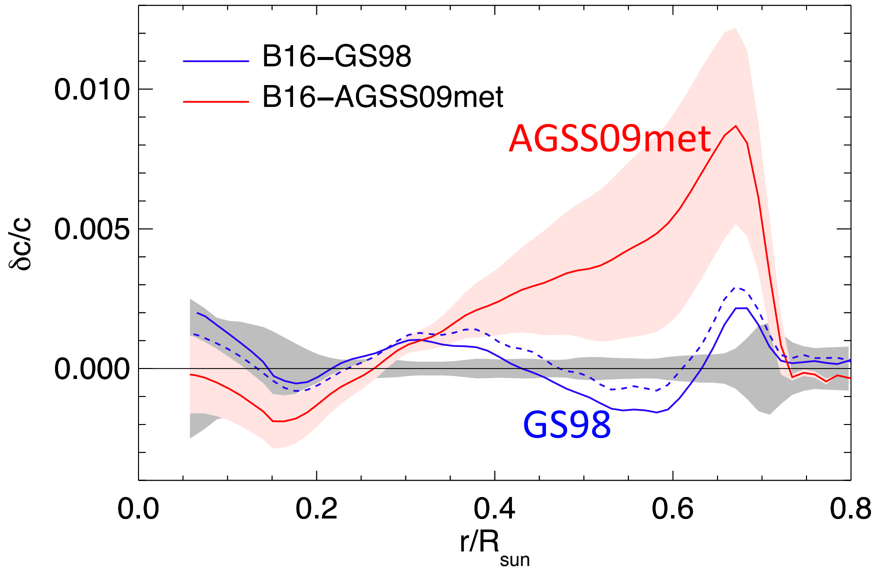
Vinyoles et al, ApJ 835 (2017) no.2, 202



… leads to SSMs which **do not correctly reproduce helioseismic observables**

Flux	B16-GS98	B16-AGSS09met	Solar
$Y_{\rm S}$	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{\rm cz}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\Phi_{\rm pp}$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
$\Phi_{\rm Be}$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi_{\rm B}$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi_{\rm N}$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi_{\rm O}$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8

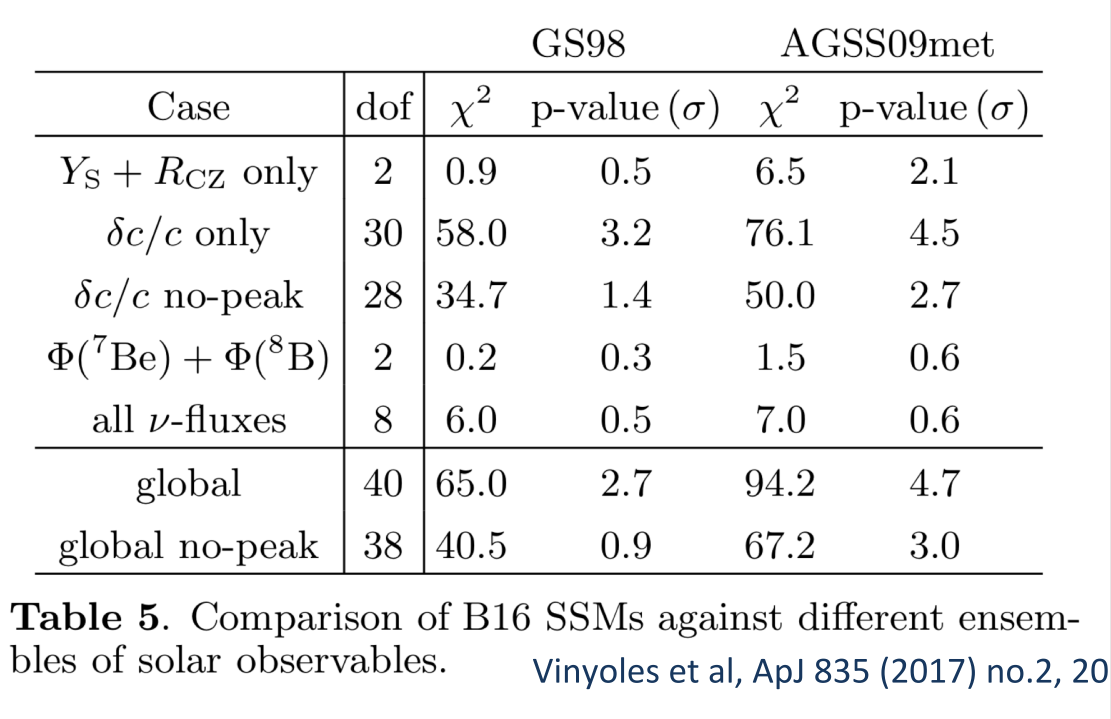
(≈ 2-3σ discrepancies)

Units:
pp: 10^{10} cm ^{2} s^{-1};
Be: 10^{9} cm ^{2} s^{-1};
pep, N, O: 10^{8} cm ^{2} s^{-1};
B, F: 10^{6} cm ^{2} s^{-1};
hep: 10^{3} cm ^{2} s^{-1}

How severe is the problem?

To combine observational infos, **we introduce a χ^2** that can be used as a **figure-of-merit** for solar models with different composition:

Villante et al. 2014, ApJ 787 (2014) 13



		GS98		AGSS09met	
Case	dof	χ^2	p-value (σ)	χ^2	p-value (σ)
$Y_S + R_{CZ}$ only	2	0.9	0.5	6.5	2.1
$\delta c/c$ only	30	58.0	3.2	76.1	4.5
$\delta c/c$ no-peak	28	34.7	1.4	50.0	2.7
$\Phi(^7\mathrm{Be}) + \Phi(^8\mathrm{B})$	2	0.2	0.3	1.5	0.6
all ν-fluxes	8	6.0	0.5	7.0	0.6
global	40	65.0	2.7	94.2	4.7
global no-peak	38	40.5	0.9	67.2	3.0

Table 5. Comparison of B16 SSMs against different ensembles of solar observables.

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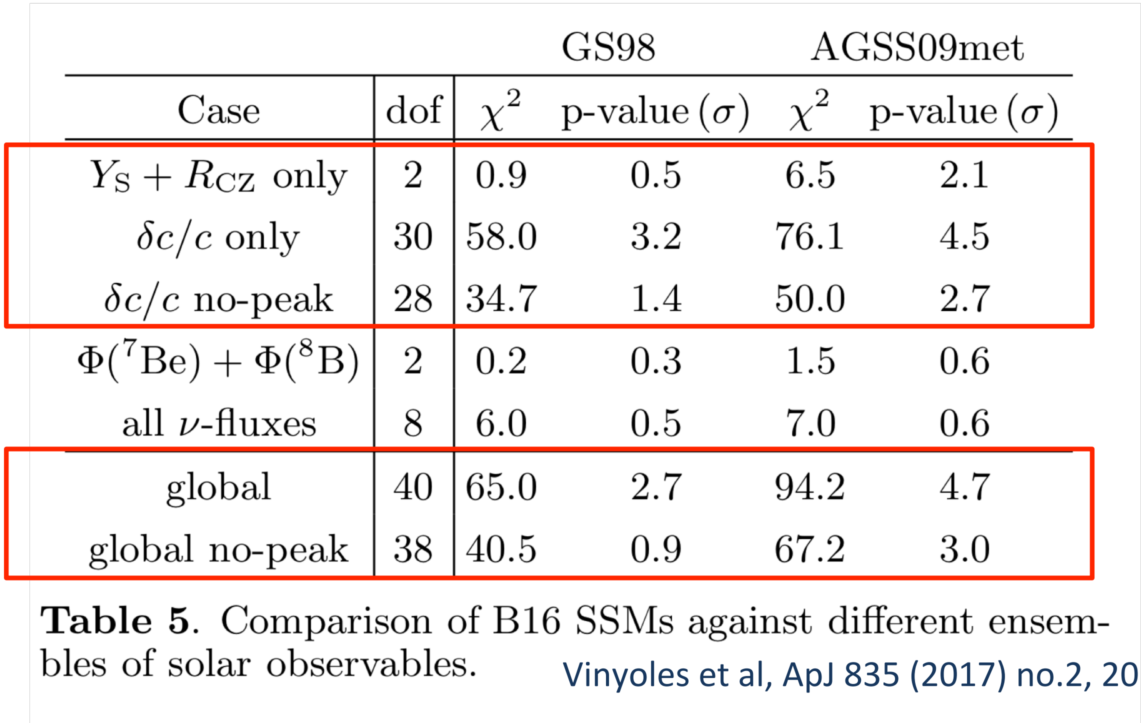

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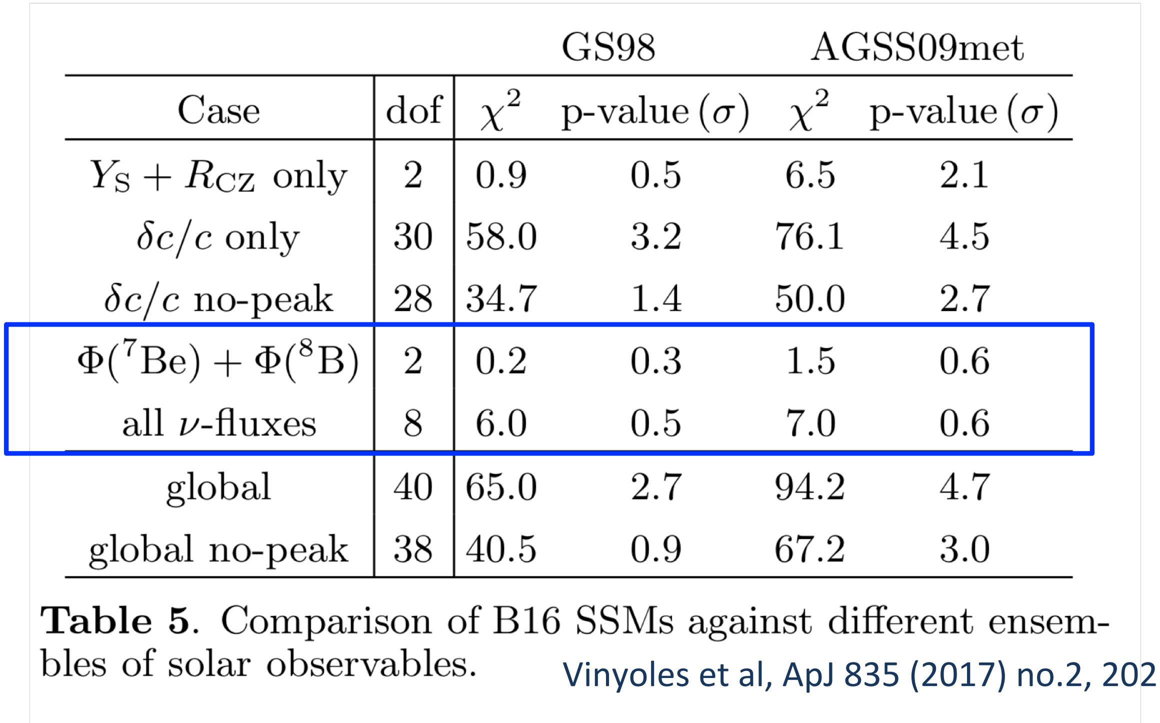

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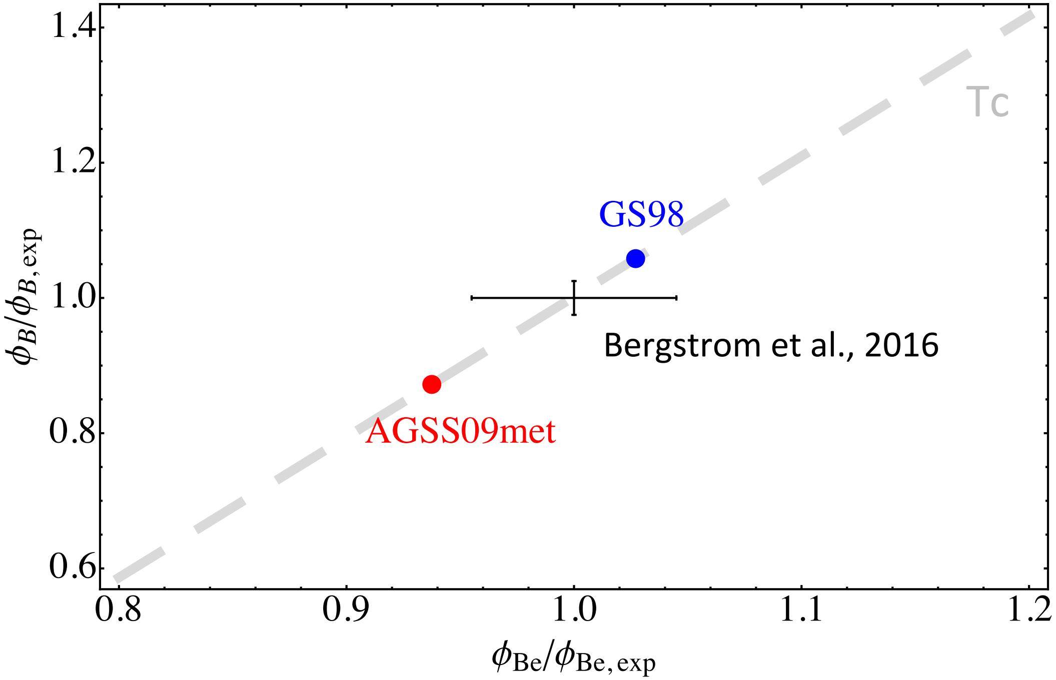

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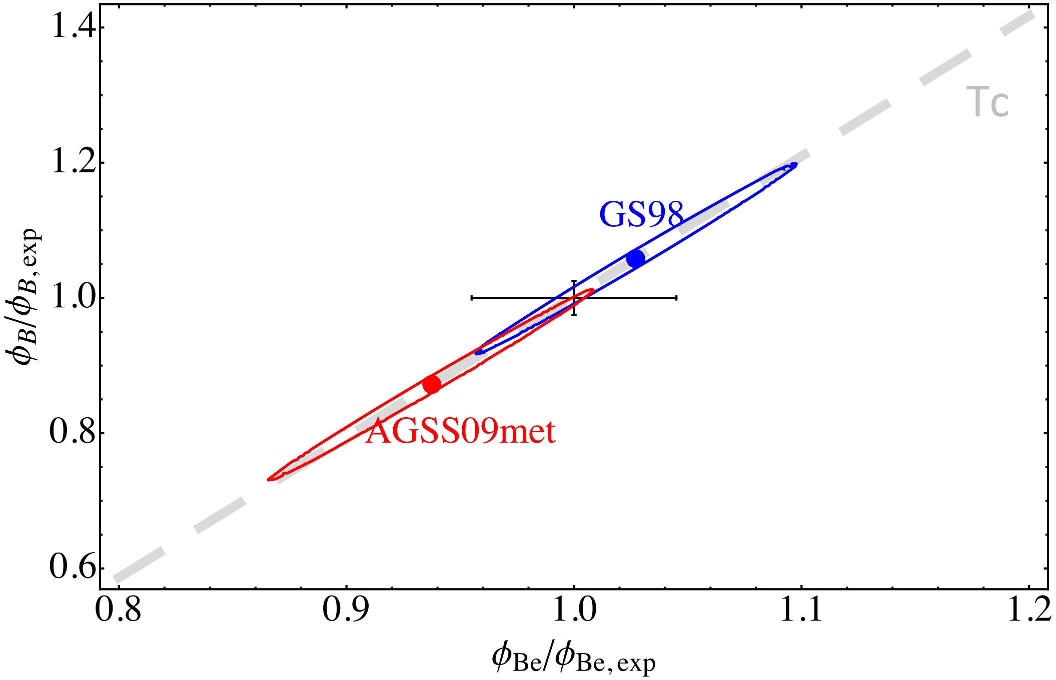

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- Surface composition
- Environmental parameters: opacity (few %), diffusion coeff. (15%), etc
- Nuclear cross section: S_{17}(4.7%), S_{33}(5.2%), S_{34}(5.4%) dominant error sources

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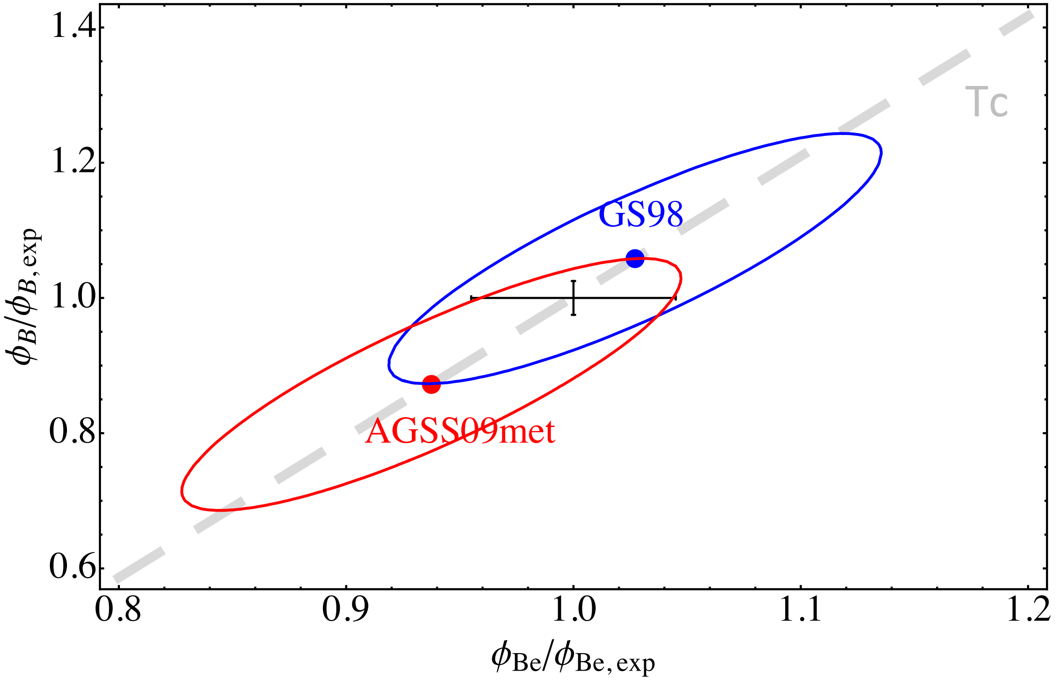

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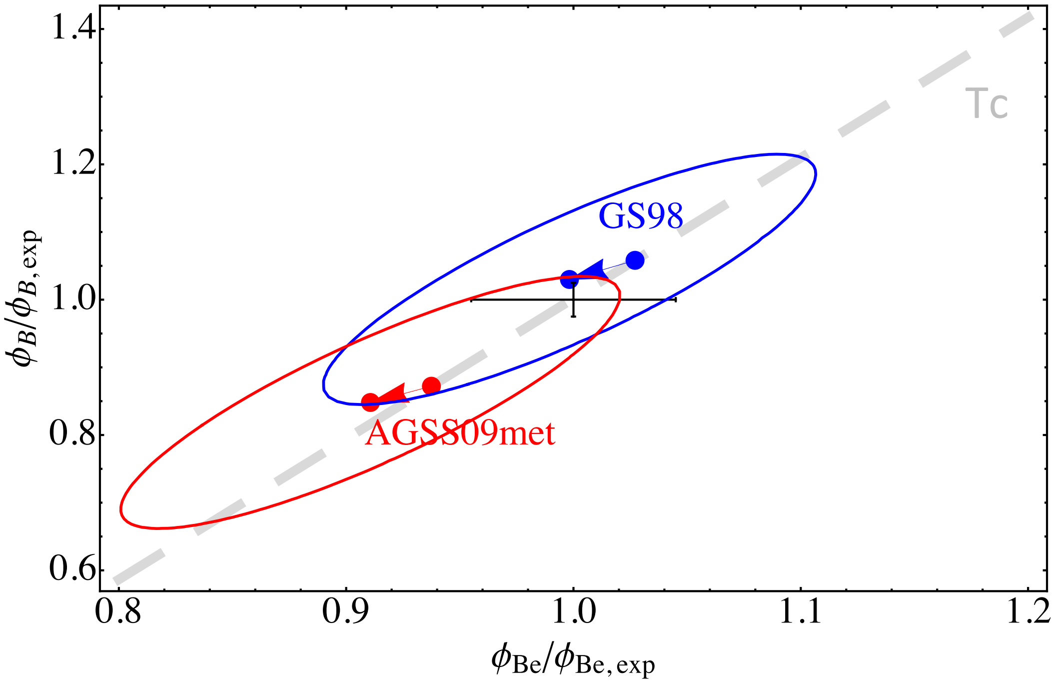
The role of ^{3}He(α,γ)^{7}Be cross section



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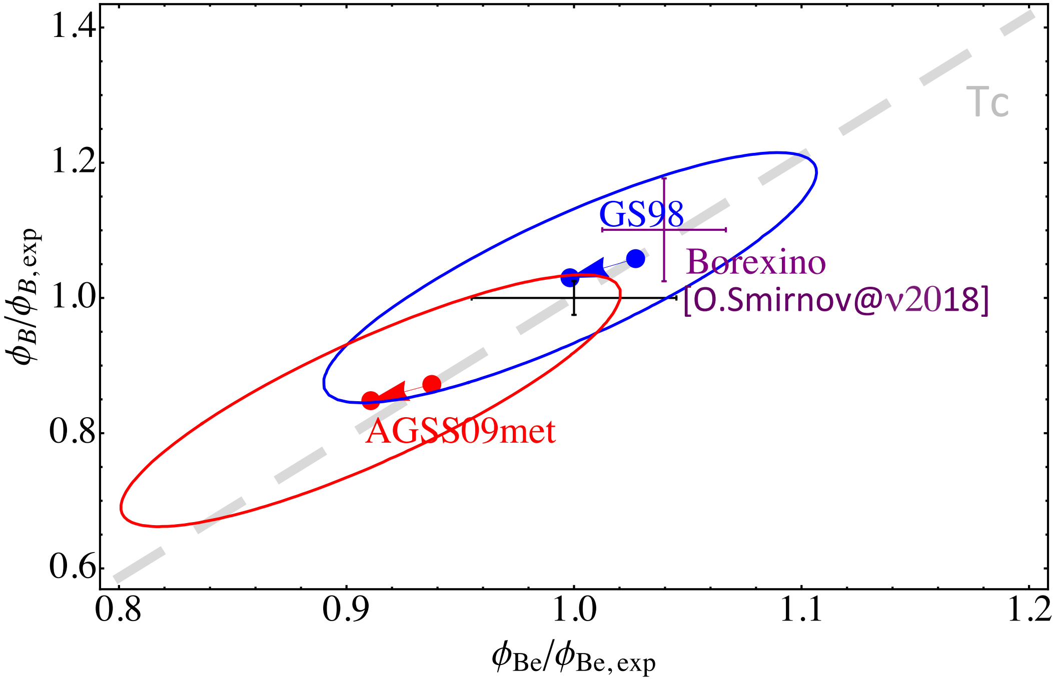
- **S_{34} astrophysical factor** determines the branching of different terminations in pp-chain
- B16-SSMs adopt Adelberger et al 2011 recommended value (with 5.4% uncertainty)
- deBoer et al. 2014 provided a new determination of **S_{34}** (not a new measure) based on R-matrix fit of the data → **≈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

The new Borexino results



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The role of metals in the Sun

- Metals give a negligible contribution to EOS

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

Energy producing region (R < 0.3 R_o)

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

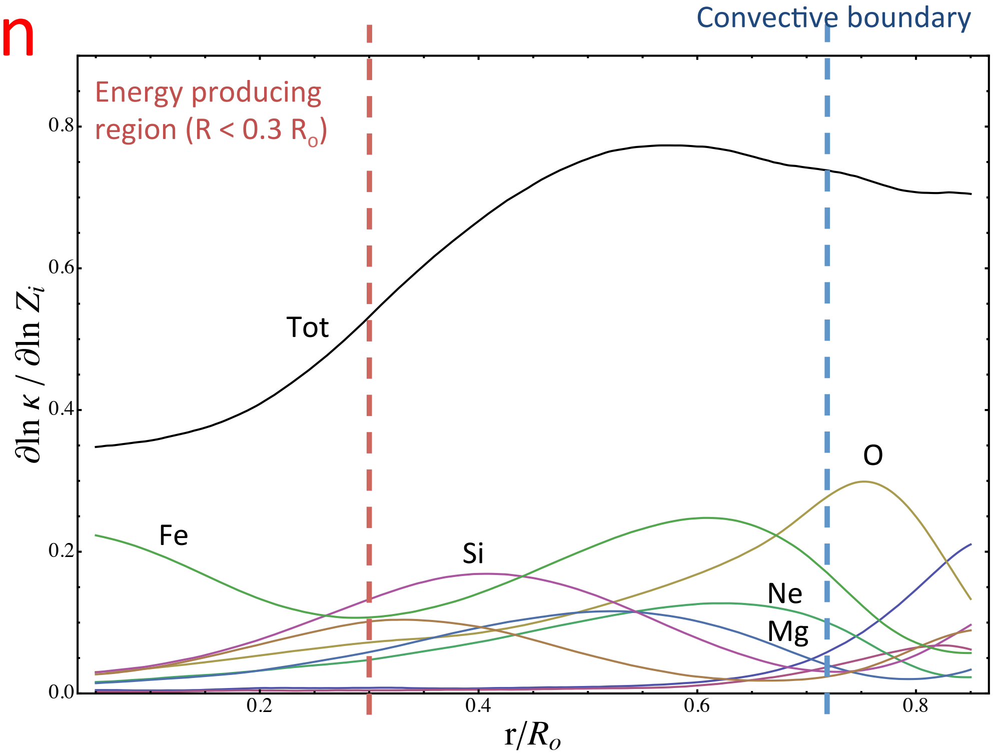
Fe gives the largest contribution.

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



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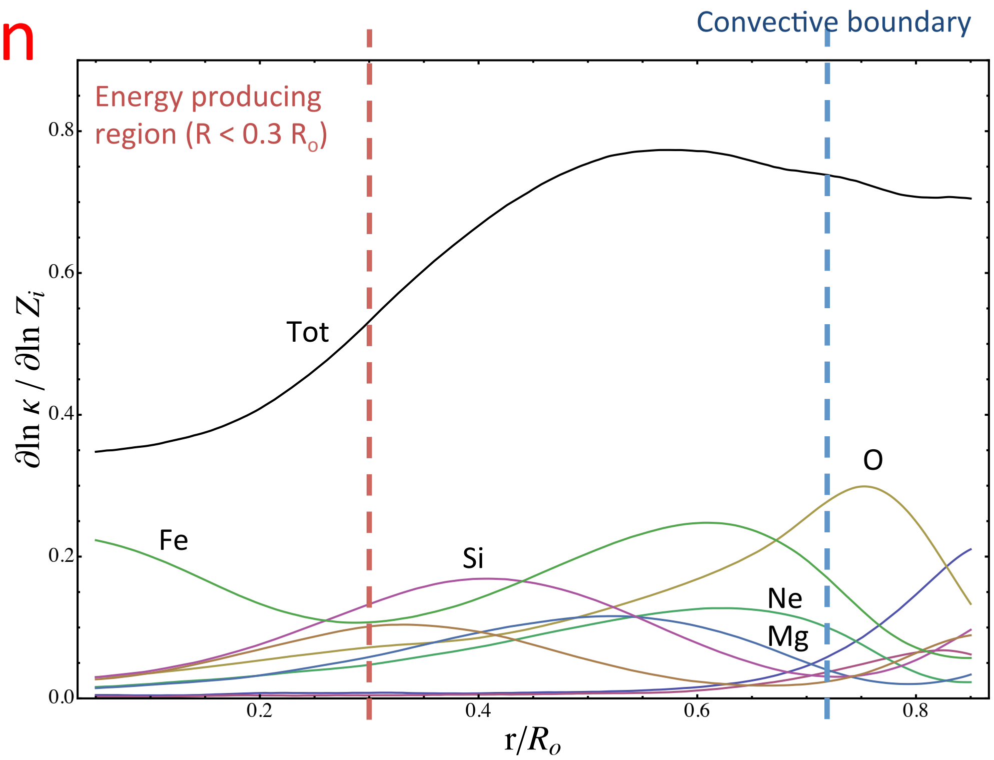

A change of the solar composition produces the same effects on the helioseismic observables and neutrino fluxes (except CNO) of a ***suitable change of the solar opacity profile δκ(r):***

$$\delta\kappa_{\rm Z}(r) \equiv \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j}\,\delta z_j$$

The solar opacity profile

F.L. Villante and B. Ricci - ***Astrophys.J.714:944-959,2010***
F.L. Villante – **Astrophys.J.724:98-110,2010**
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The **“optimal” opacity profile** of the Sun can be determined from obs. data

Note that:

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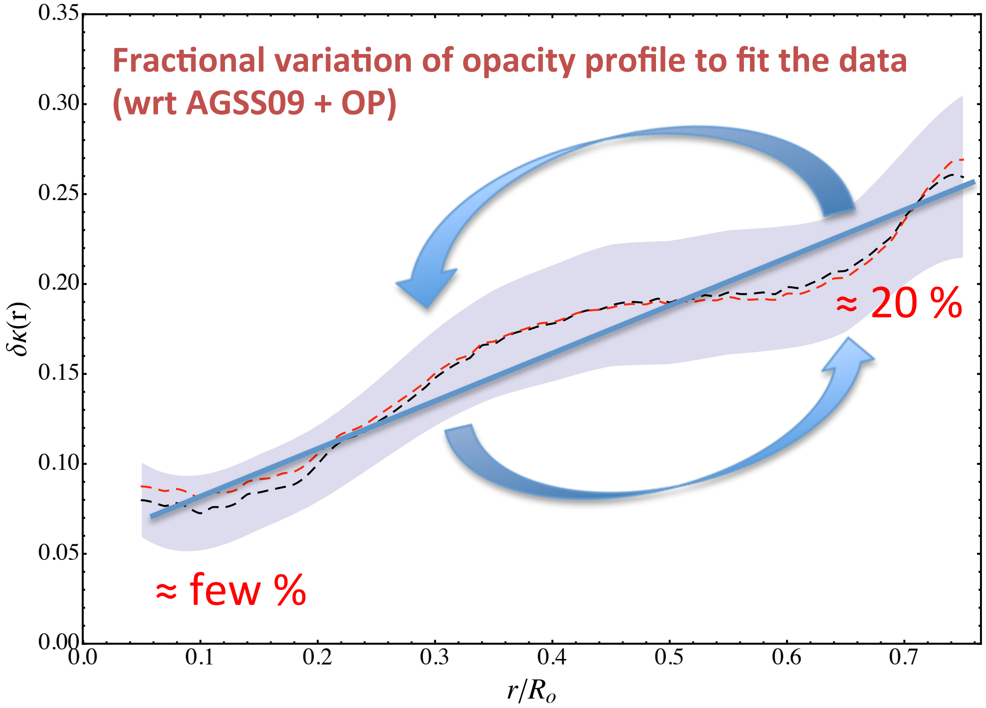

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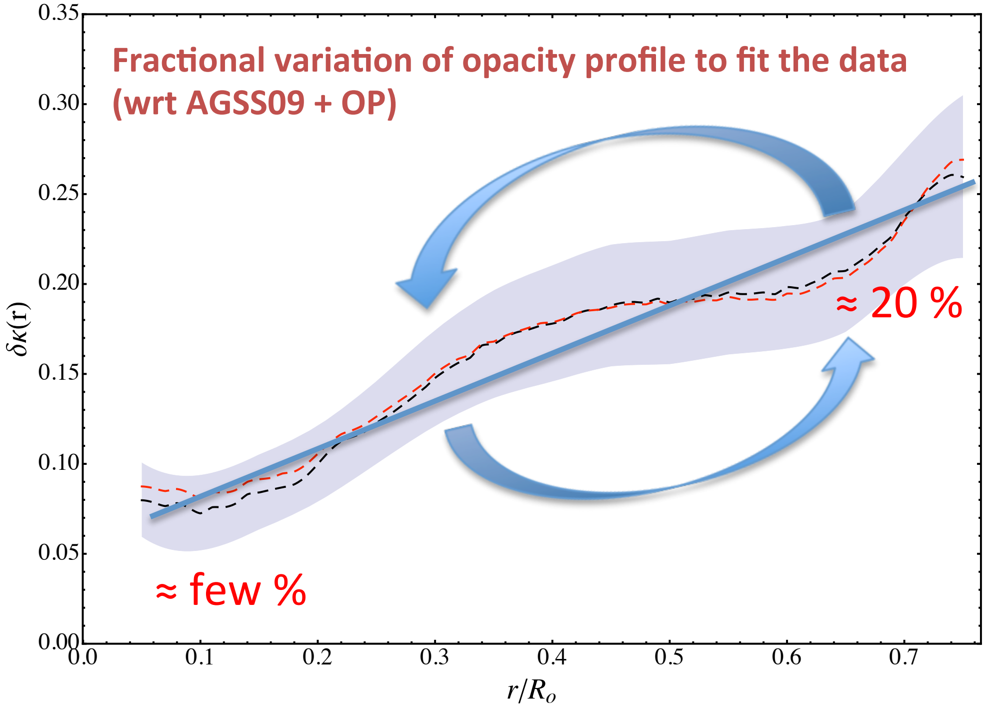

Fractional variation of opacity profile to fit the data (wrt AGSS09 + OP)

≈ 20 %

≈ few %

<u>*Caveat*</u>

- *Constraints are obtained by using parametrized δk(r)*
- *See (Song et al. 2017) for a "non-parametric" approach*
- *A direct determination of δκ(r) from heliosesmic observables is in preparation (Serenelli, Vinyoles and Villante, 2018)*

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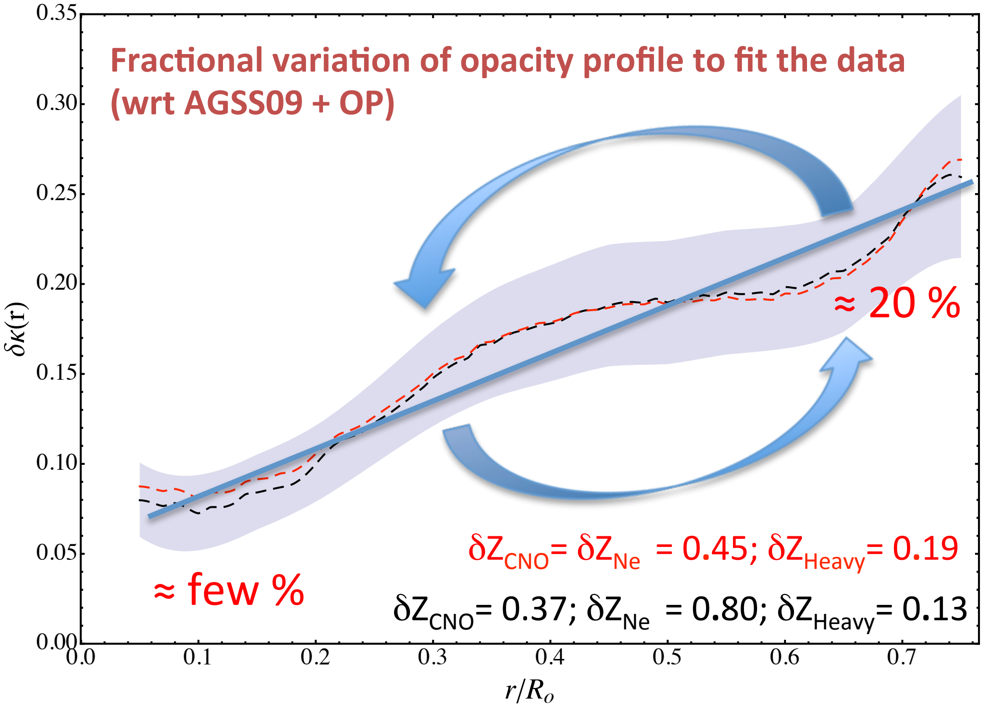

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$\delta Z_{CNO} = \delta Z_{Ne} = 0.45; \delta Z_{Heavy} = 0.19$

$\delta Z_{CNO} = 0.37; \delta Z_{Ne} = 0.80; \delta Z_{Heavy} = 0.13$

The interpretation is however complicated by the **opacity-composition degeneracy**. *Which fraction of the required δκ(r) has to be ascribed to intrinsic* (δκ$_I$(r)) *and/or composition opacity changes?*

$$\delta\kappa(r) = \delta\kappa_{\mathrm{I}}(r) + \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j}\delta z_j$$

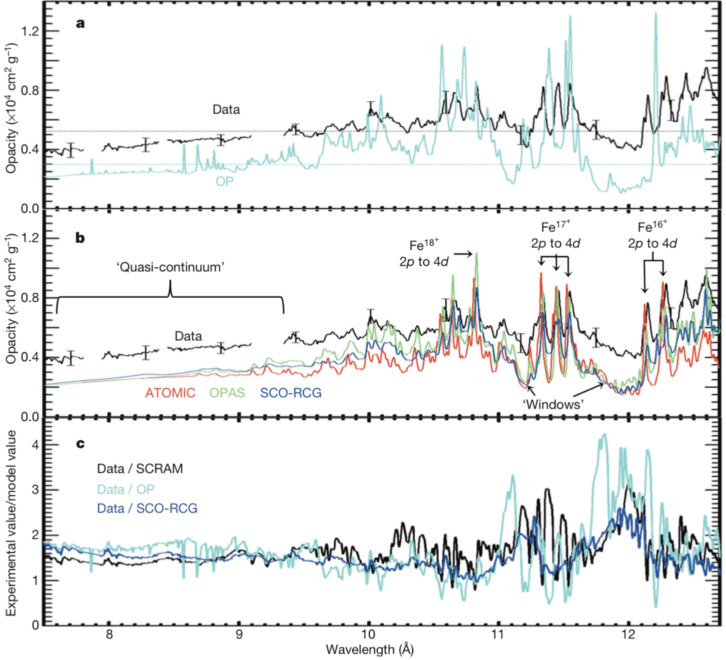
Opacity table “errors”
Non standard effects (WIMPs in solar core)
…

different admixtures {δz$_j$} can do equally well the job

Wrong opacity?

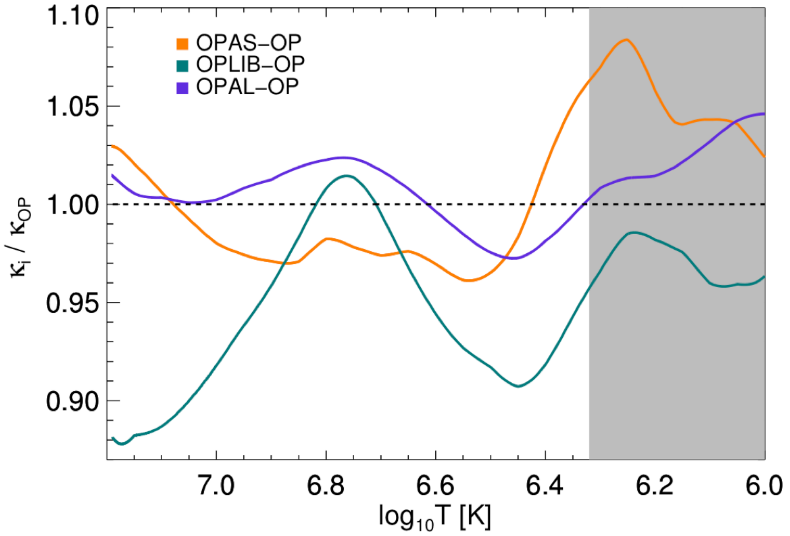
- Opacity is being measured at stellar interiors conditions (Bailey et al., Nature 2015);
- Monochromatic opacity is higher than expected for iron (up to a factor 2);
- Total opacity (integrated over the wavelength and summed over the composition) is increased by about 7%

Bailey et al., Nature 2015



- Different opacity tables may differ "locally" by a large amount (up to 10%) and with a complicated pattern

Vinyoles et al., 2017

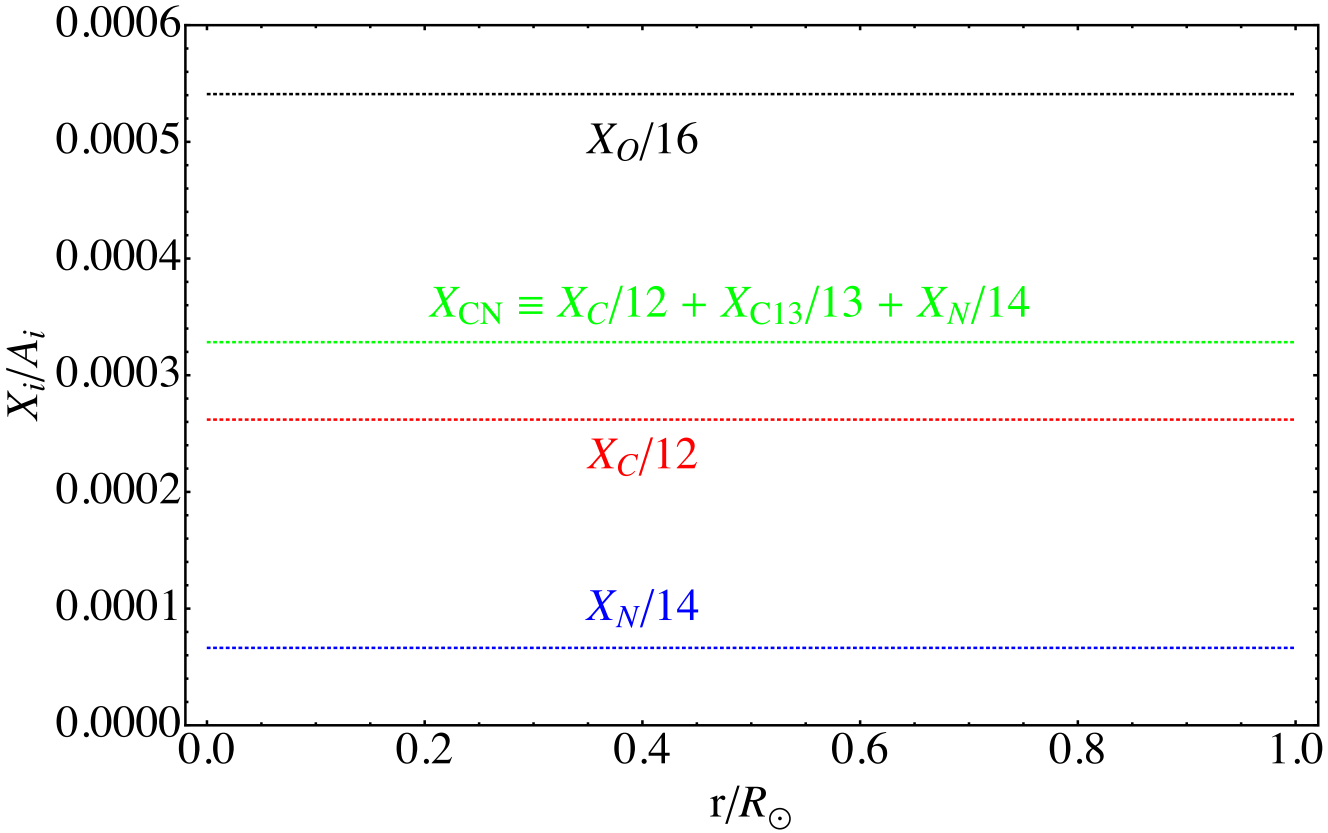


Wrong composition?

The Sun was born (at t=0) **chemical homogenous**.

The **present** chemical composition (t=4.57Gyr) differs from the **initial** composition due to:

- *Elemental diffusion*
- *Nuclear reactions*



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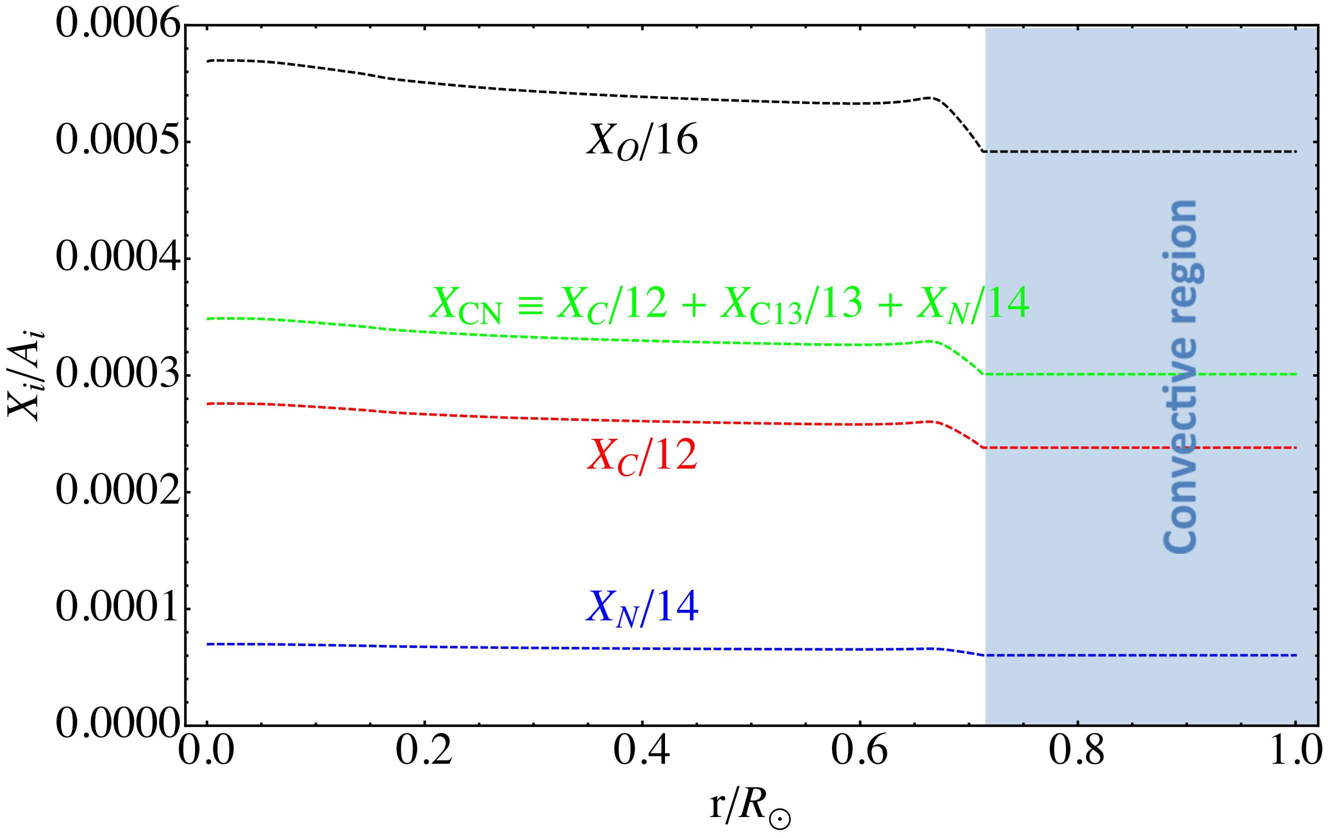

$$\frac{X_{\rm i,C} - X_{\rm i,S}}{X_{\rm i,ini}} \simeq 15\%$$

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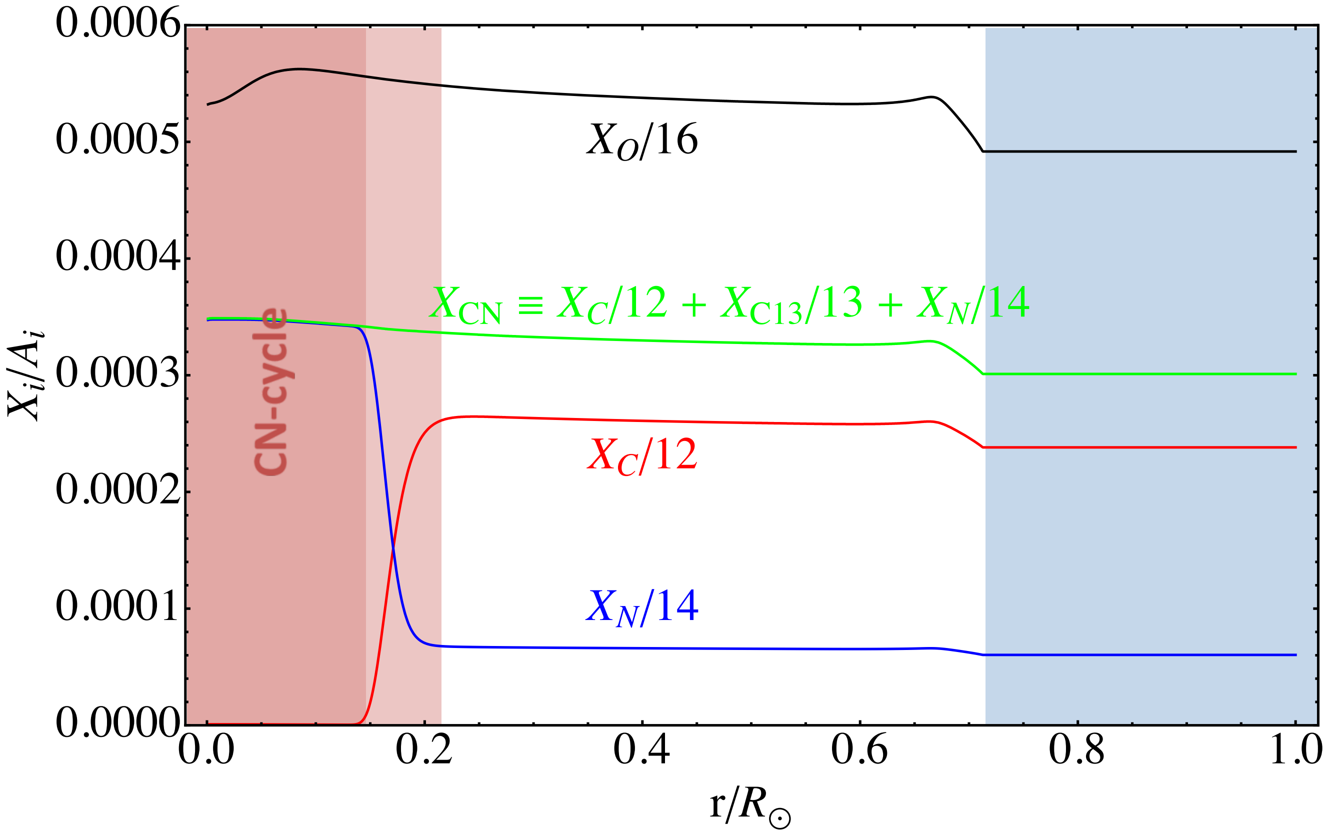

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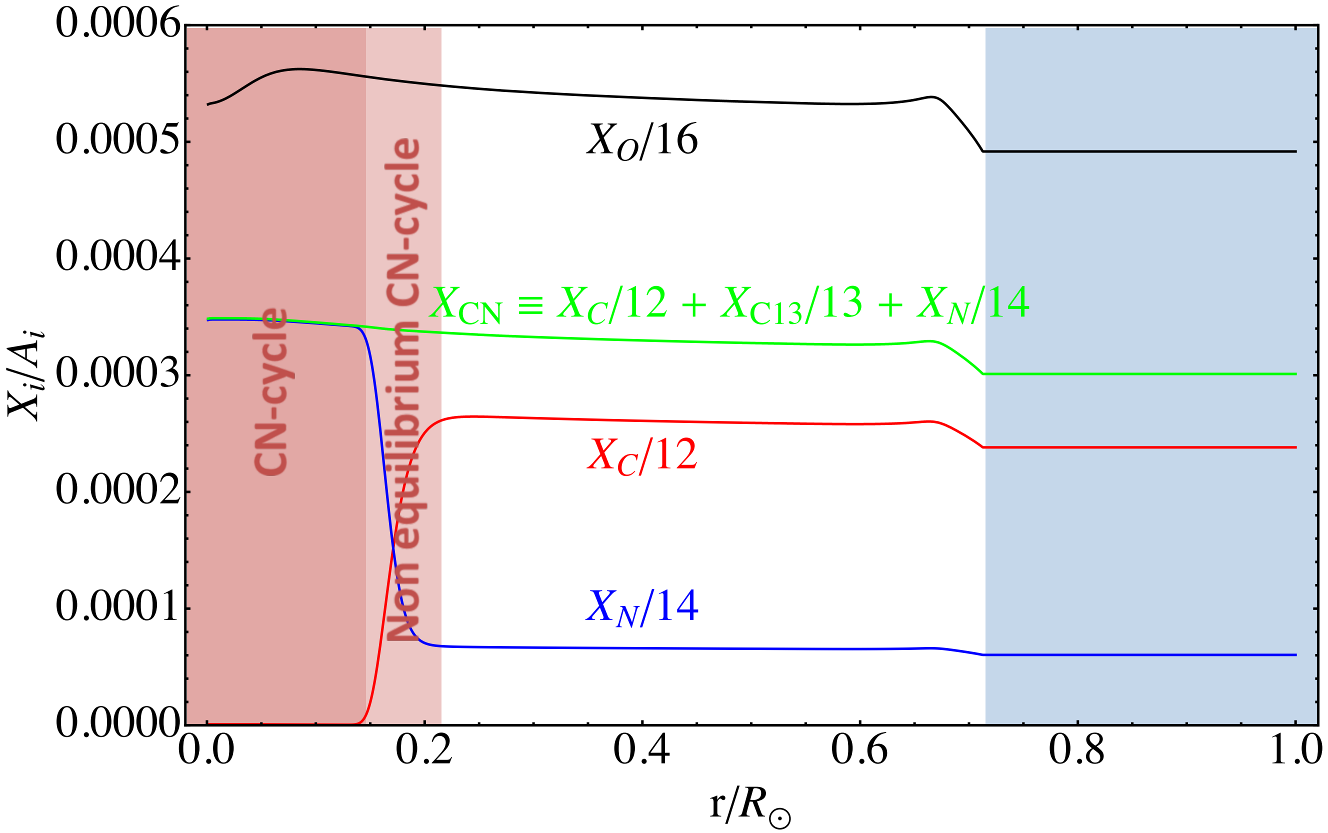
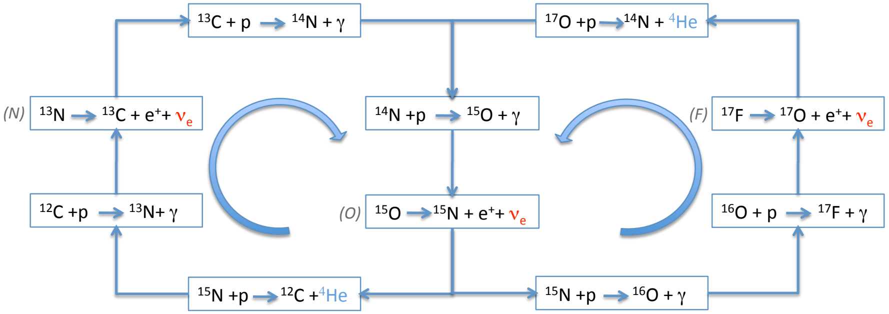


CN neutrino production

Neutrinos produced in the CN-cycle probe the abundance of carbon and nitrogen in the core of the Sun



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

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

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

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

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

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

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

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

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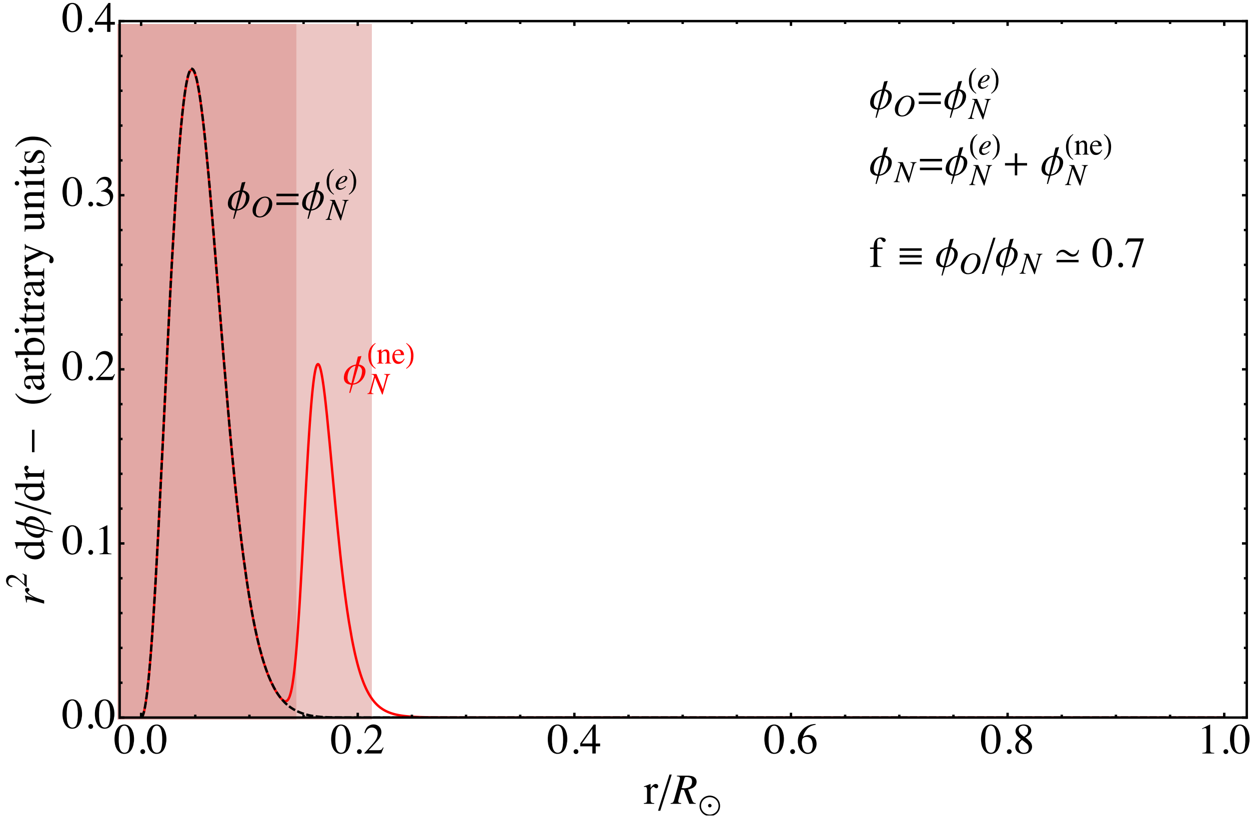

$$\phi_O = \phi_N^{(e)}$$

$$\phi_N = \phi_N^{(e)} + \phi_N^{(\mathrm{ne})}$$

$$\mathrm{f} \equiv \phi_O / \phi_N \simeq 0.7$$

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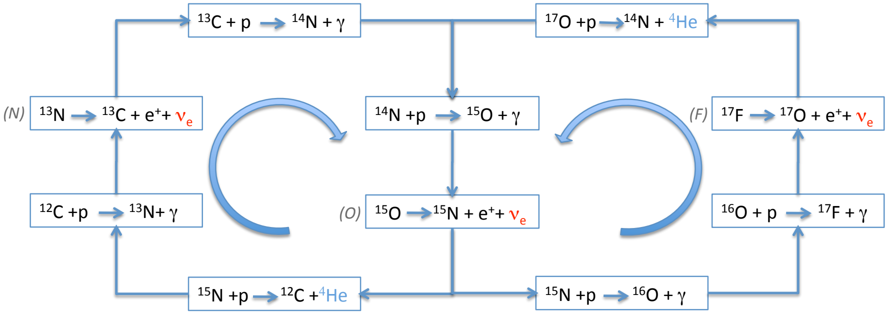

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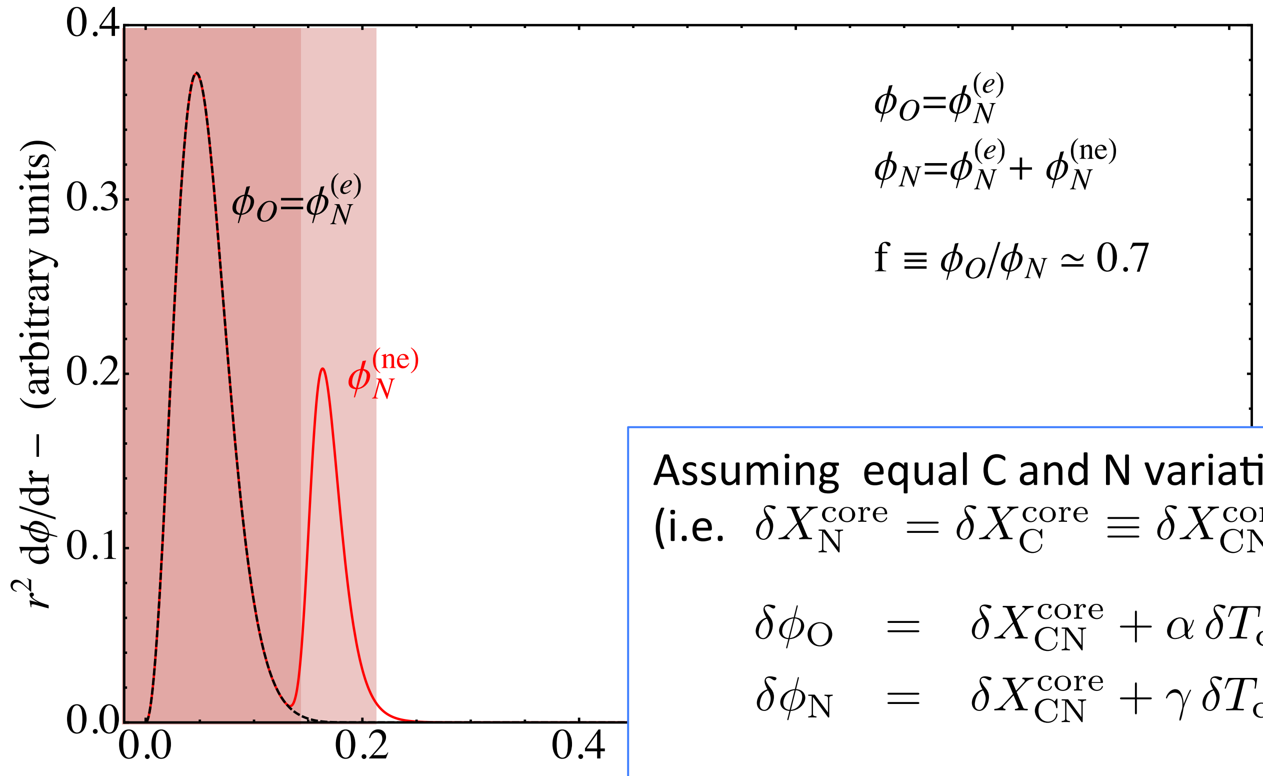


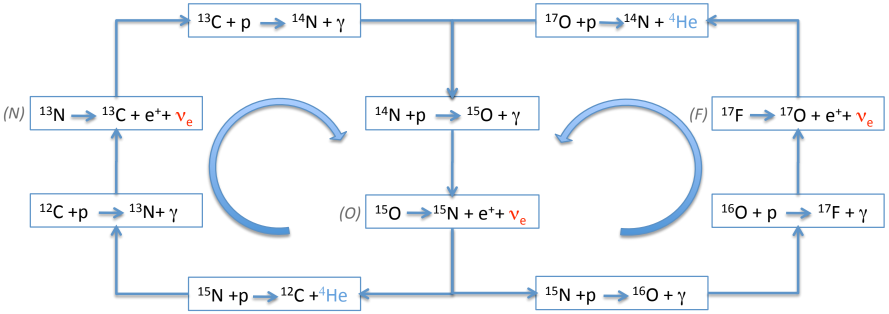
Assuming equal C and N variations
(i.e. $\delta X_{\mathrm{N}}^{\mathrm{core}} = \delta X_{\mathrm{C}}^{\mathrm{core}} \equiv \delta X_{\mathrm{CN}}^{\mathrm{core}}$):

$$\begin{aligned} \delta\phi_{\mathrm{O}} &= \delta X_{\mathrm{CN}}^{\mathrm{core}} + \alpha\, \delta T_{\mathrm{c}} + \delta S_{114} \\ \delta\phi_{\mathrm{N}} &= \delta X_{\mathrm{CN}}^{\mathrm{core}} + \gamma\, \delta T_{\mathrm{c}} + f\, \delta S_{114} \end{aligned}$$

where $\alpha \simeq \gamma \simeq 20$ and $f \simeq 0.7$

CN neutrino production

Neutrinos produced in the CN-cycle probe the abundance of carbon and nitrogen in the core of the Sun



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

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

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

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

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

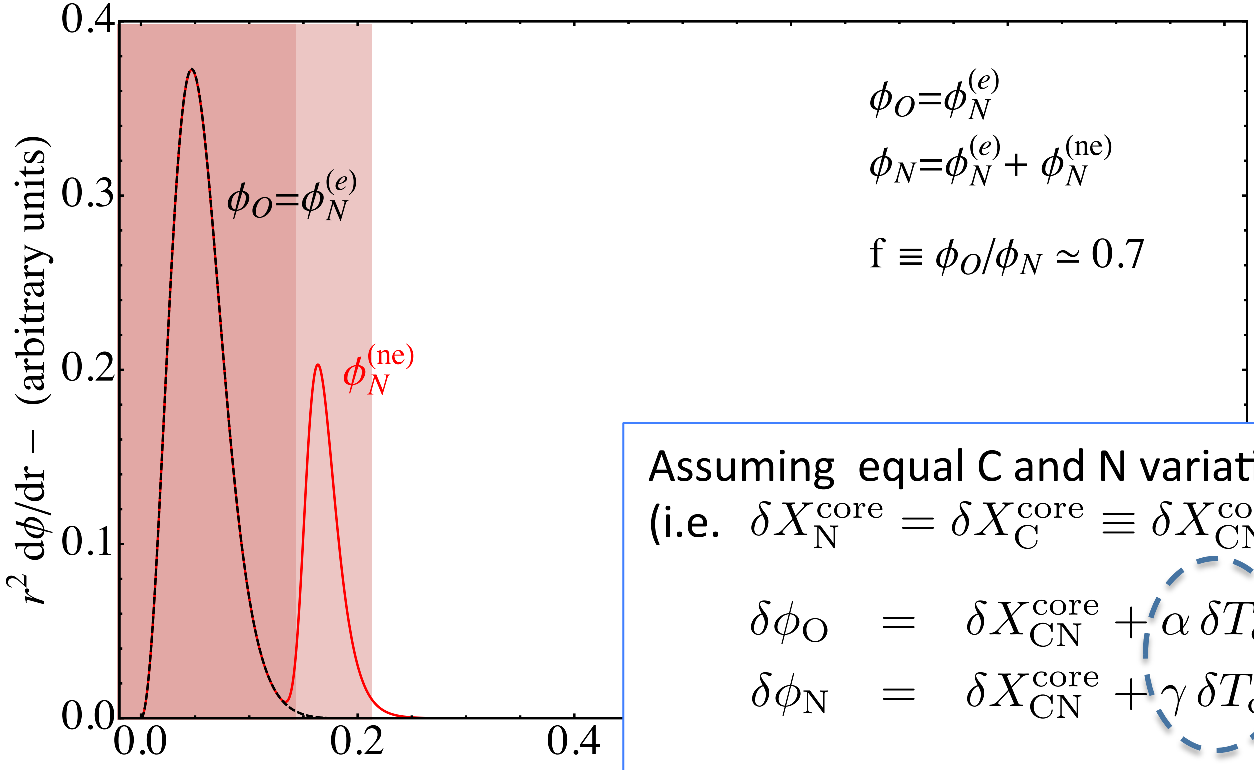
$^{12}C + p \rightarrow {}^{13}N + \gamma$

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

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

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

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



$$\phi_O = \phi_N^{(e)}$$

$$\phi_N = \phi_N^{(e)} + \phi_N^{(ne)}$$

$$f \equiv \phi_O/\phi_N \simeq 0.7$$

depends on $\delta\kappa(r)$

Assuming equal C and N variations

(i.e. $\delta X_{\rm N}^{\rm core} = \delta X_{\rm C}^{\rm core} \equiv \delta X_{\rm CN}^{\rm core}$):

$$\begin{aligned} \delta\phi_{\rm O} &= \delta X_{\rm CN}^{\rm core} + \alpha\, \delta T_{\rm c} + \delta S_{114} \\ \delta\phi_{\rm N} &= \delta X_{\rm CN}^{\rm core} + \gamma\, \delta T_{\rm c} + f\, \delta S_{114} \end{aligned}$$

where $\alpha \simeq \gamma \simeq 20$ and $f \simeq 0.7$

The importance of CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars
- Provide a direct determination of the C+N abundance in the **solar core**:

$$\begin{aligned}\delta\phi_{\rm O} &= \delta X_{\rm CN}^{\rm core} + \alpha\,\delta T_{\rm c} + \delta S_{114}\\ \delta\phi_{\rm N} &= \delta X_{\rm CN}^{\rm core} + \gamma\,\delta T_{\rm c} + f\,\delta S_{114}\end{aligned}$$

indeed, the (strong) dependence on T_c can be eliminated by using **B-neutrinos as solar thermometer**. E.g:

$$\delta\phi_{\rm O} - 0.785\,\delta\phi_{\rm B} = \delta X_{\rm CN}^{\rm core} \;\pm 0.4\%({\rm env})\;\pm 2.6\%({\rm diff})\;\pm 10\%({\rm nuc})$$

Serenelli et al., PRD 2013

The importance of CNO neutrinos

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Serenelli et al., PRD 2013

<u>High-Z .vs. Low-Z</u>

$$\delta\phi_{\rm O} = \frac{\phi_{\rm O}^{\rm HZ} - \phi_{\rm O}^{\rm LZ}}{\phi_{\rm O}^{\rm LZ}} \simeq 40\%$$

Beyond solar composition problem (10%):
Using CNO neutrinos to probe for mixing processes in the Sun (and other stars)

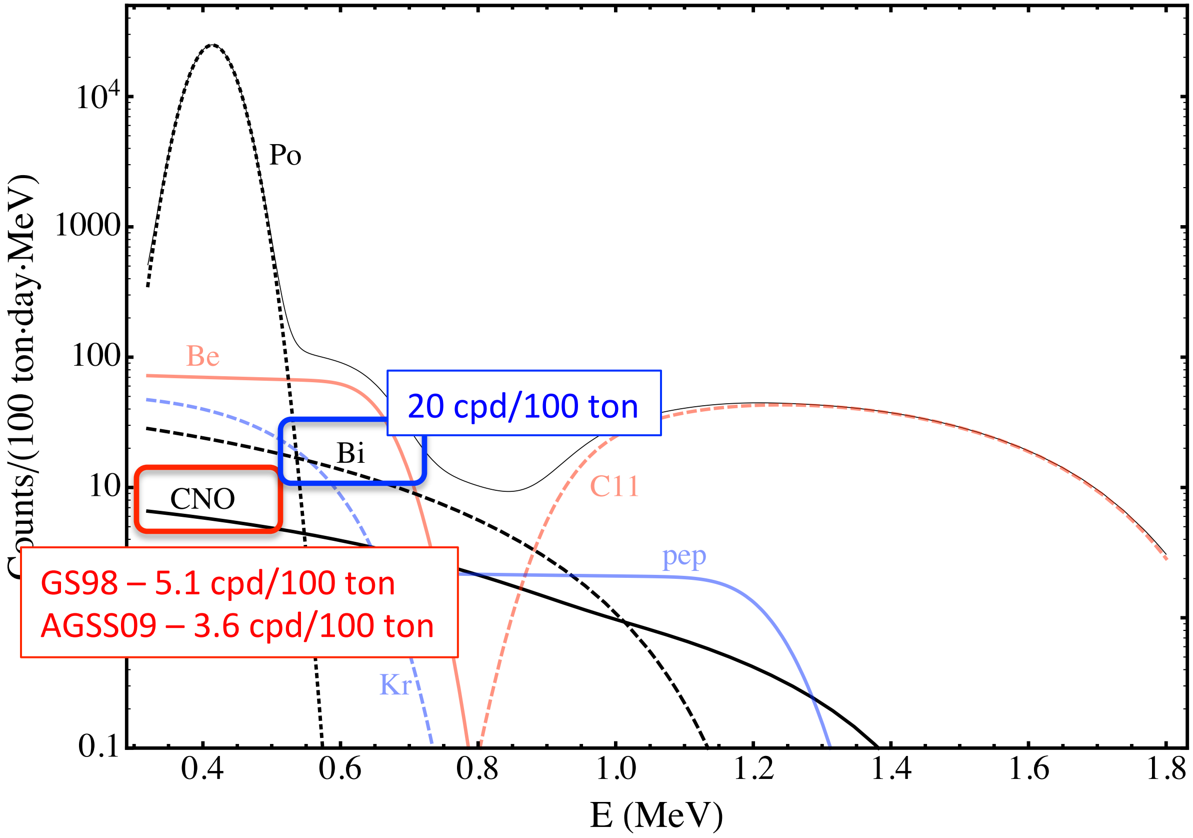
$$\delta X_{\rm CN} = \frac{X_{\rm CN}^{\rm core} - X_{\rm CN}^{\rm surf}}{X_{\rm CN,ini}} \simeq 15\%$$

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)



20 cpd/100 ton

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

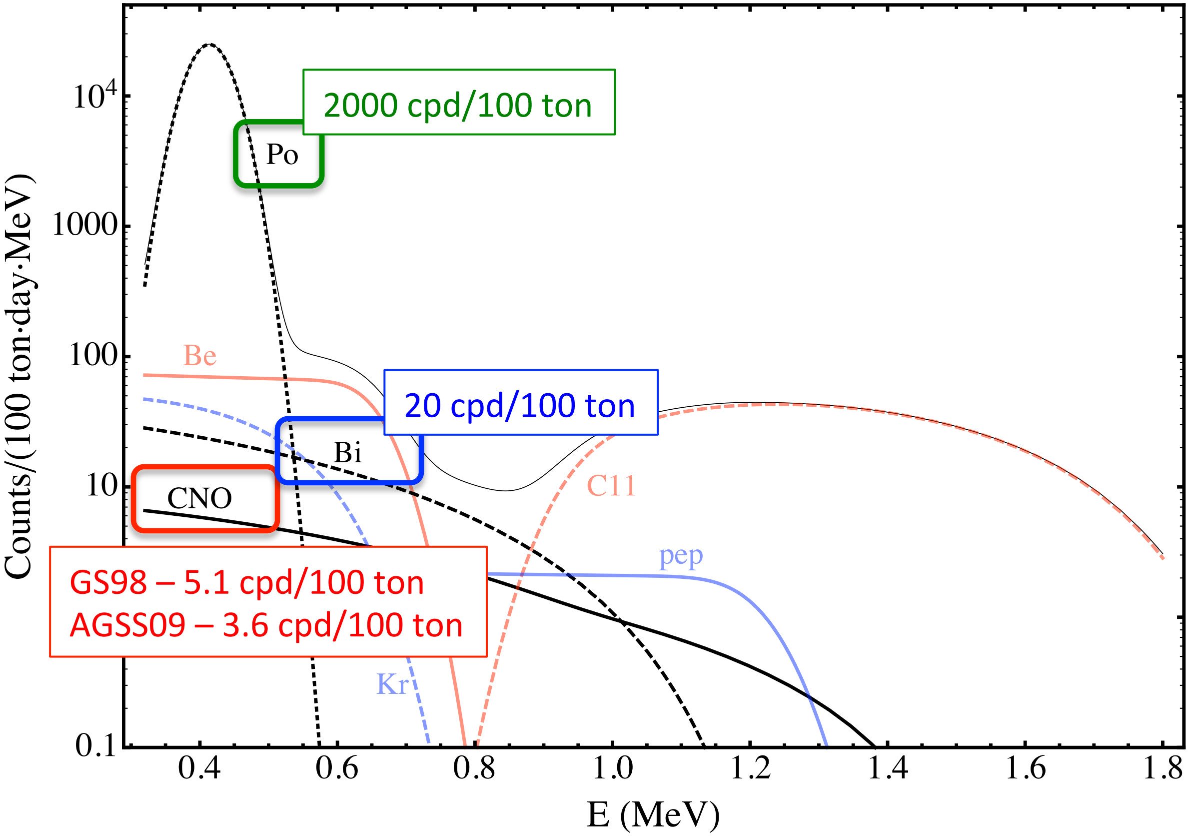
Determining ^{210}Bi with the help of ^{210}Po?

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

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

τ_{Bi} = 7.232 d

τ_{Po} = 199.634 d



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

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

- **Borexino already have the potential to probe the CNO neutrino flux** … but the detector should be stable (no convective motions) over long time scales.

See D. Guffanti's talk

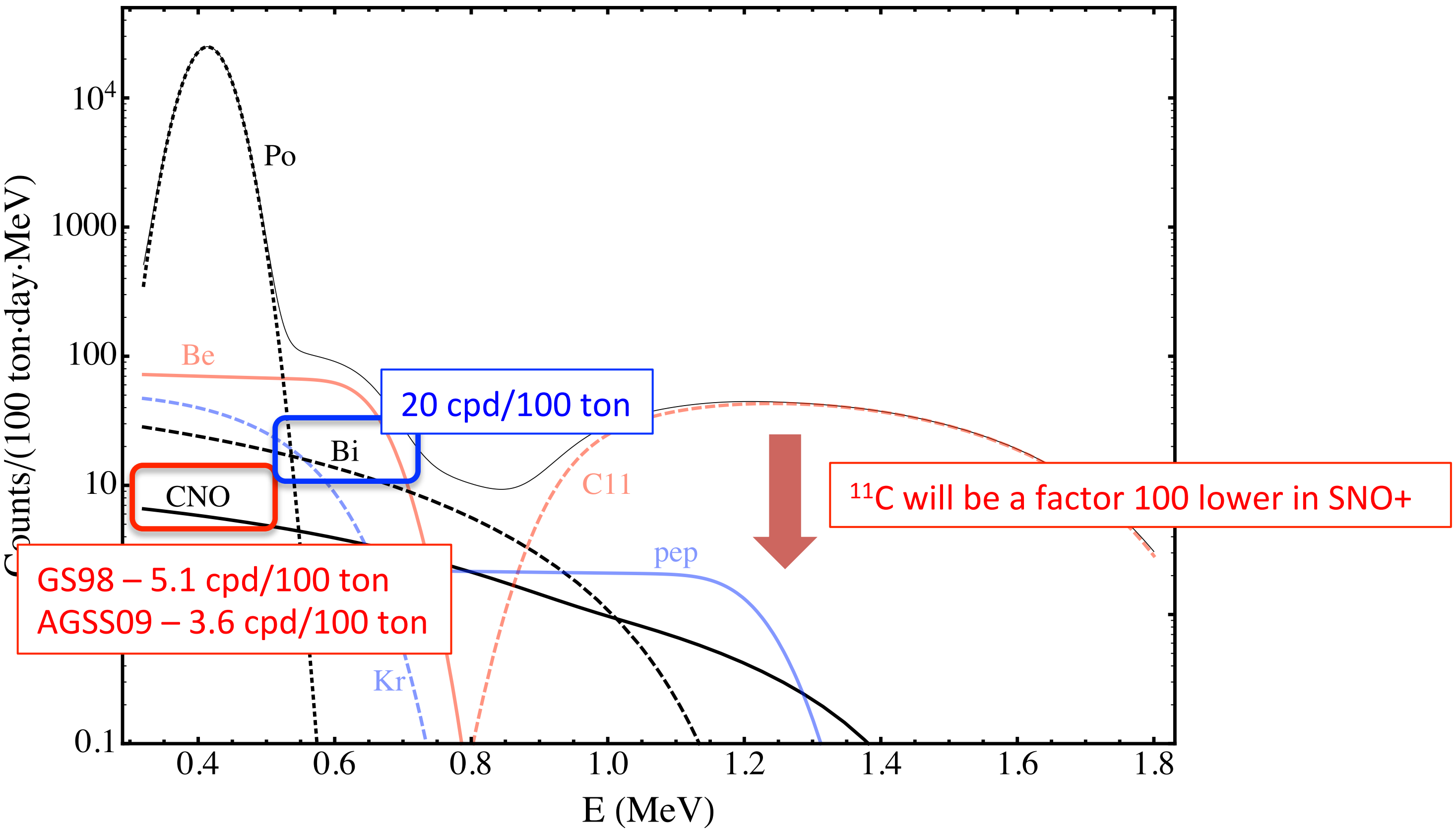
How to improve?

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)



20 cpd/100 ton

^{11}C will be a factor 100 lower in SNO+

GS98 – 5.1 cpd/100 ton

AGSS09 – 3.6 cpd/100 ton

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

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

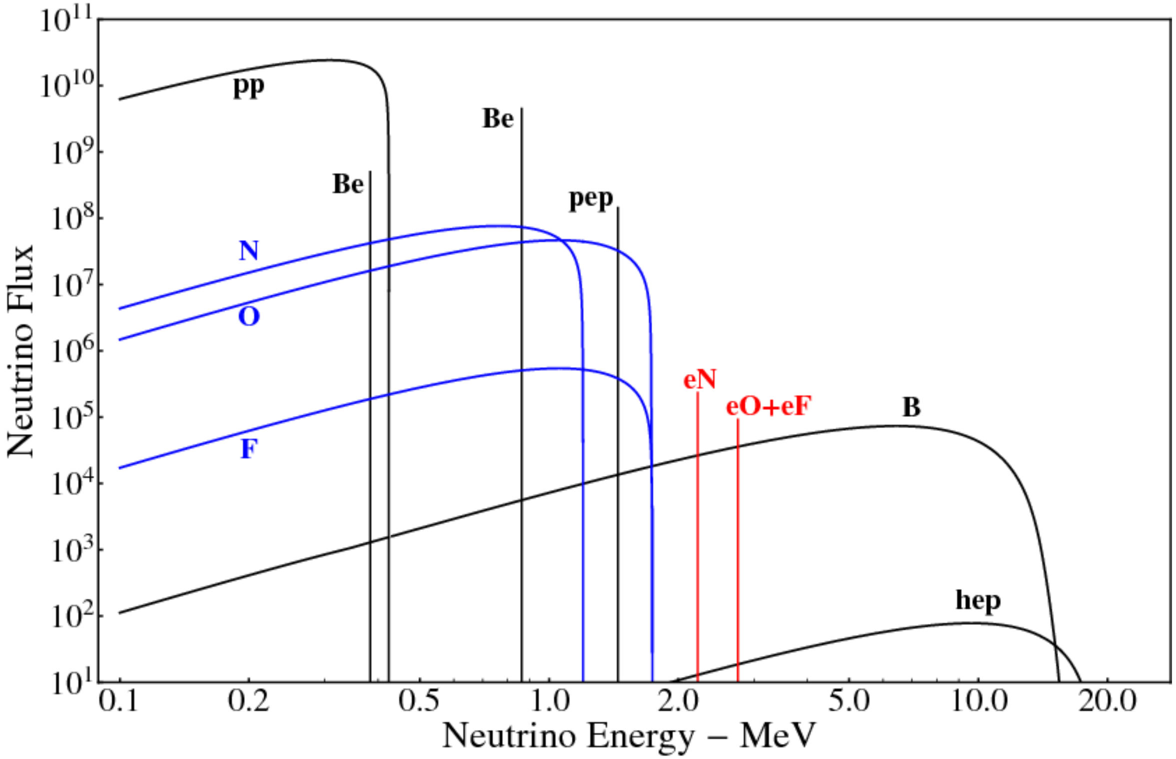
ecCNO neutrinos

In the CN-NO cycle, besides the conventional CNO neutrinos (blue lines), monochromatic ecCNO neutrinos (red lines) are also produced by **electron capture** reactions:

$$^{13}\mathrm{N} + e^- \rightarrow {}^{13}\mathrm{C} + \nu_e \qquad E_\nu = 2.220 \text{ MeV}$$

$$^{15}\mathrm{O} + e^- \rightarrow {}^{15}\mathrm{N} + \nu_e \qquad E_\nu = 2.754 \text{ MeV}$$

$$^{17}\mathrm{F} + e^- \rightarrow {}^{17}\mathrm{O} + \nu_e \qquad E_\nu = 2.761 \text{ MeV}$$



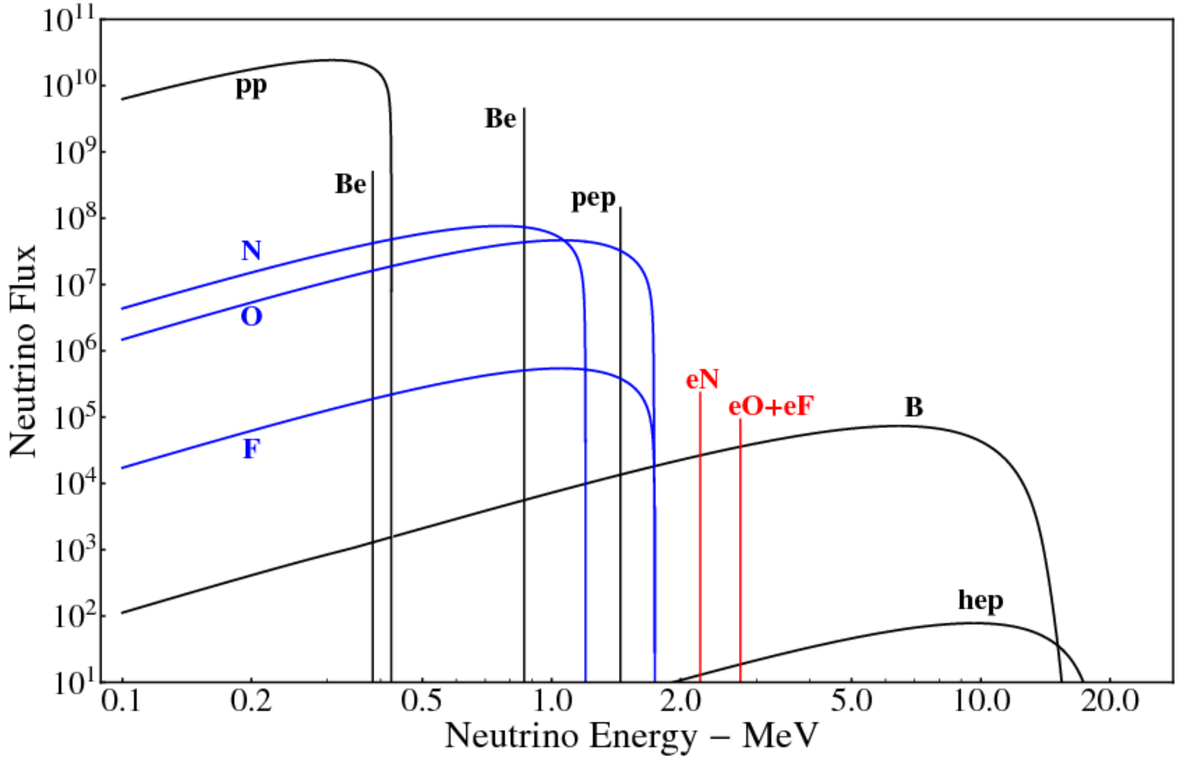
F.L. Villante, PLB 742 (2015) 279-284
L.C. Stonehill et al, PRC 69, 015801 (2004)
J.N. Bahcall, PRD 41, 2964 (1990).

ecCNO neutrinos

The ecCNO fluxes are extremely low: $\Phi_{ecCNO} \approx (1/20)\,\Phi_B$. Detection is extremely difficult but could be rewarding. Indeed:

- ecCNO neutrinos are sensitive to the **metallic content of the solar core** (same infos as CNO neutrinos);

- Being monochromatic, they probe the solar neutrino **survival probability** at specific energies ($E_\nu \cong 2.5$ MeV) exactly **in the transition region**.



F.L. Villante, PLB 742 (2015) 279-284
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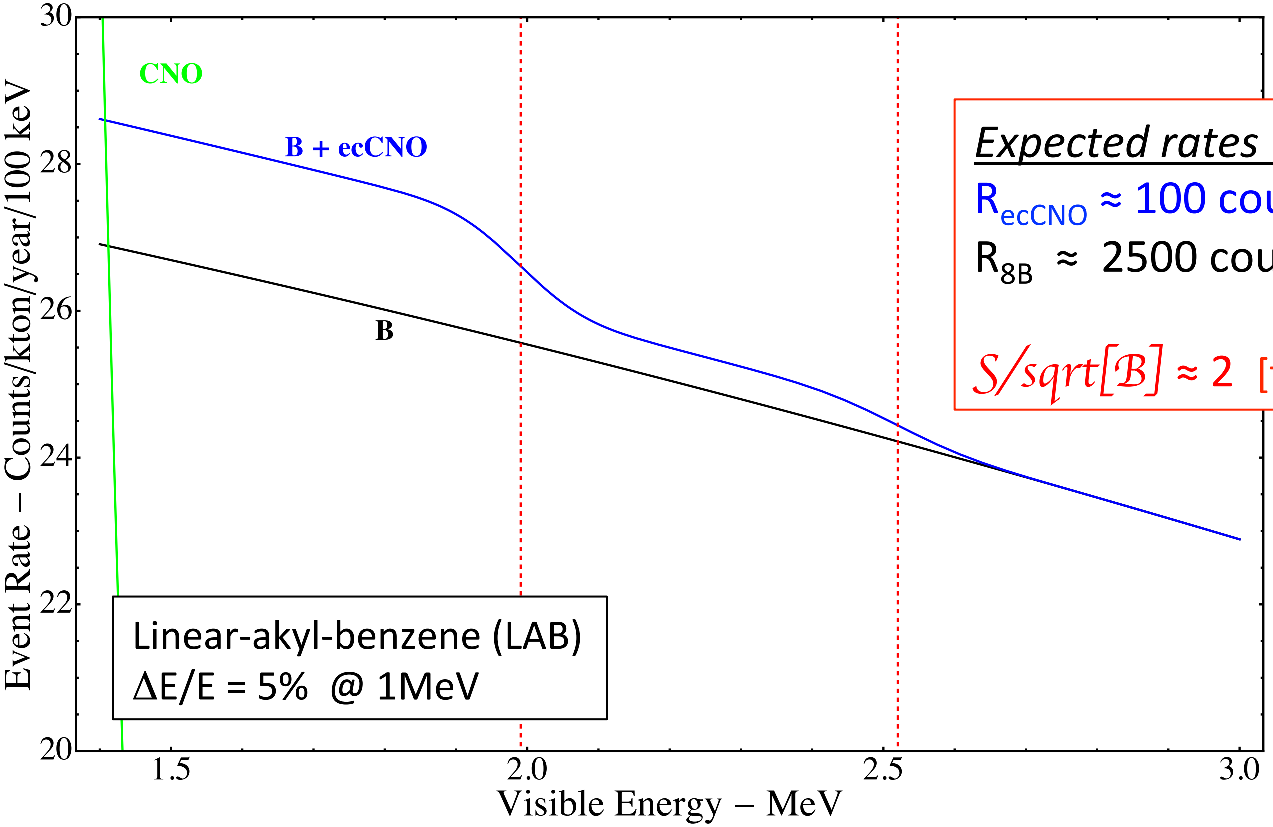
Expected rates in Liquid Scintillators

- $\nu - e$ elastic scattering of ecCNO neutrinos produces Compton shoulders (smeared by energy resolution) at 2.0 and 2.5 MeV;
- ecCNO neutrino signal has to be extracted statistically from the (irreducible) ^{8}B neutrino background.



Expected rates [1.5 MeV, 2.5 MeV]

R_{ecCNO} ≈ 100 counts/10 kton/year

R_{8B} ≈ 2500 counts/10kton/year

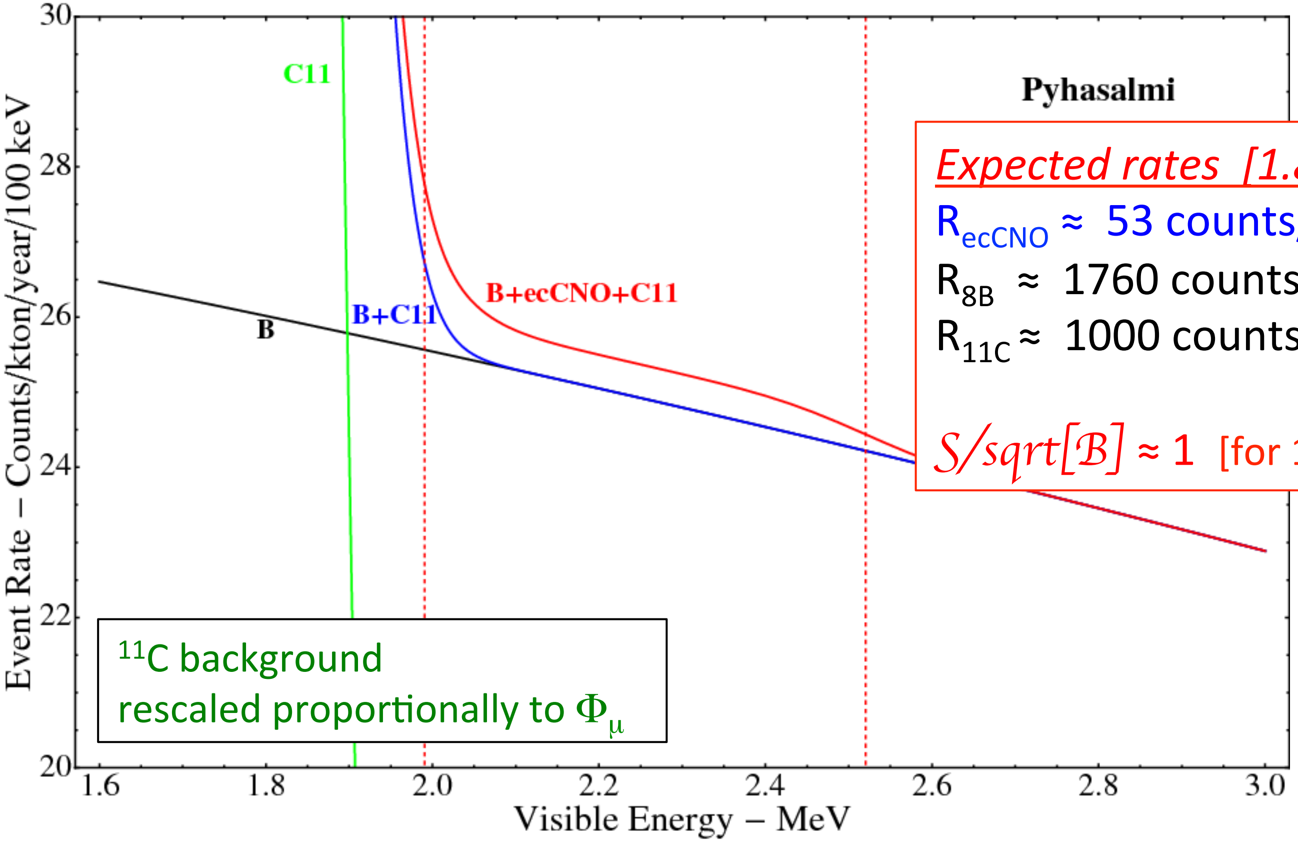
S/sqrt[B] ≈ 2 [for 10kton × year exposure]

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

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

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

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

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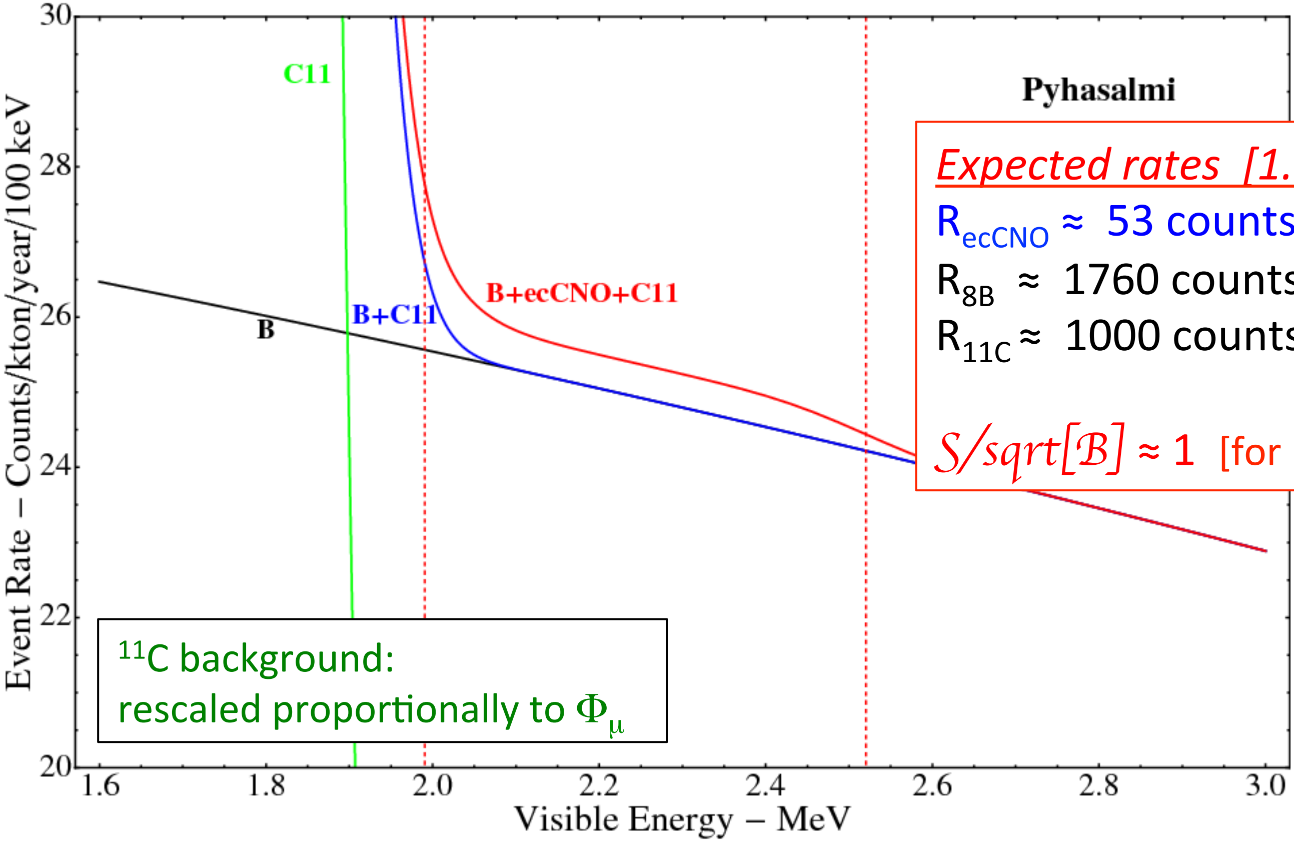

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^{11}C background:
rescaled proportionally to Φ_μ

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

Summary

The **solar composition problem** indicates that 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**?
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

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

CNO and ecCNO neutrinos, besides testing CN-NO cycle, could provide clues for the solution of the puzzle.

Thank you

How severe is 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:

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

F.L. Villante, A. Serenelli et al., 2014
Fogli et al. 2002

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

where:

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

^{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:

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

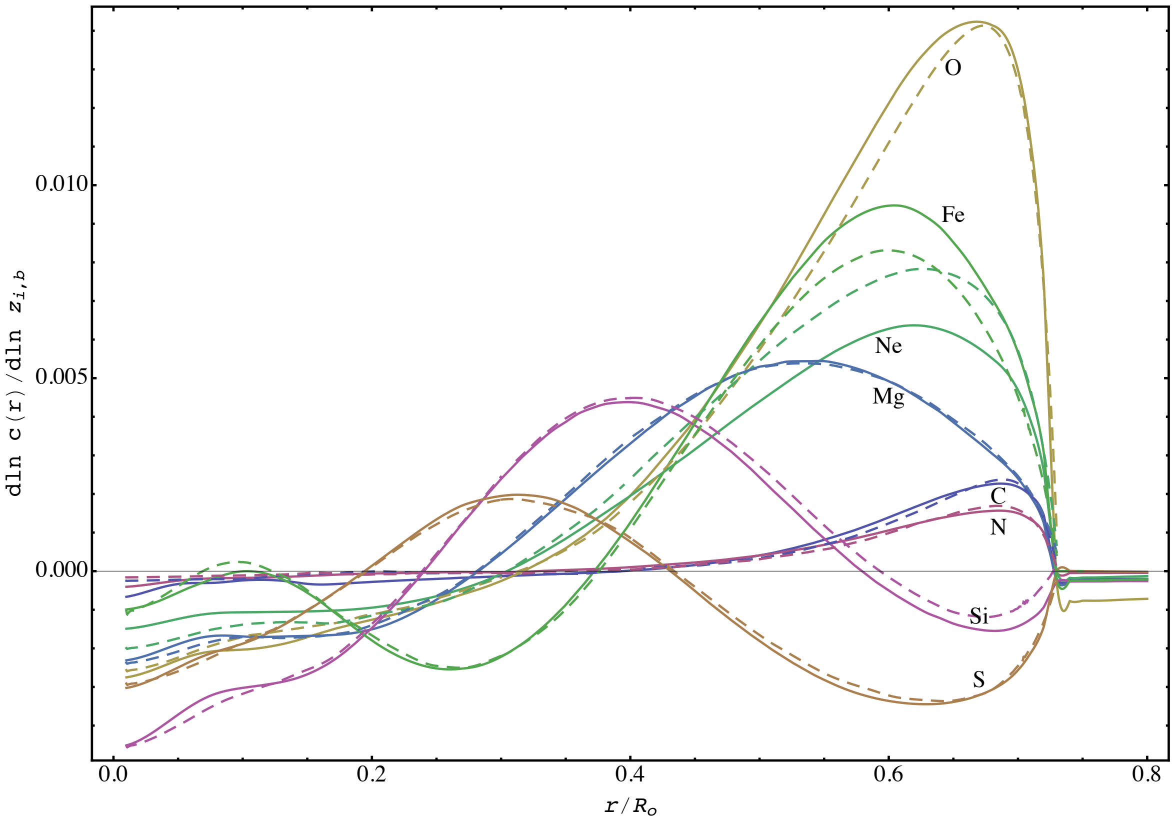
Enviromental

Nuclear

Composition

The degeneracy between opacity and metals

- The derivative of the sound speed with respect to the (surface) composition



Solid lines → **calculated** from SSMs with **different (surface) composition**
Dotted lines → **reconstructed** performing ad-hoc **opacity changes** (in LSMs)

Standard Solar Models

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

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

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

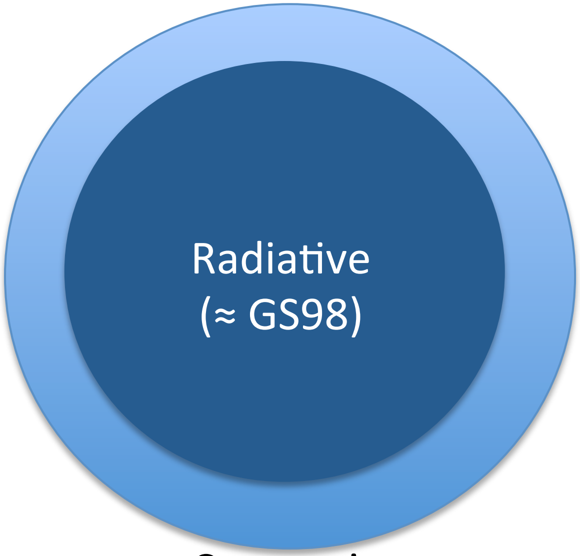
Chemical evolution driven by nuclear reaction, diffusion and gravitational settling, convection

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

Wrong chemical evolution?



Radiative
(≈ GS98)

Convective
(AGSS09)

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 $\approx 40M_{\oplus}$ 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 …

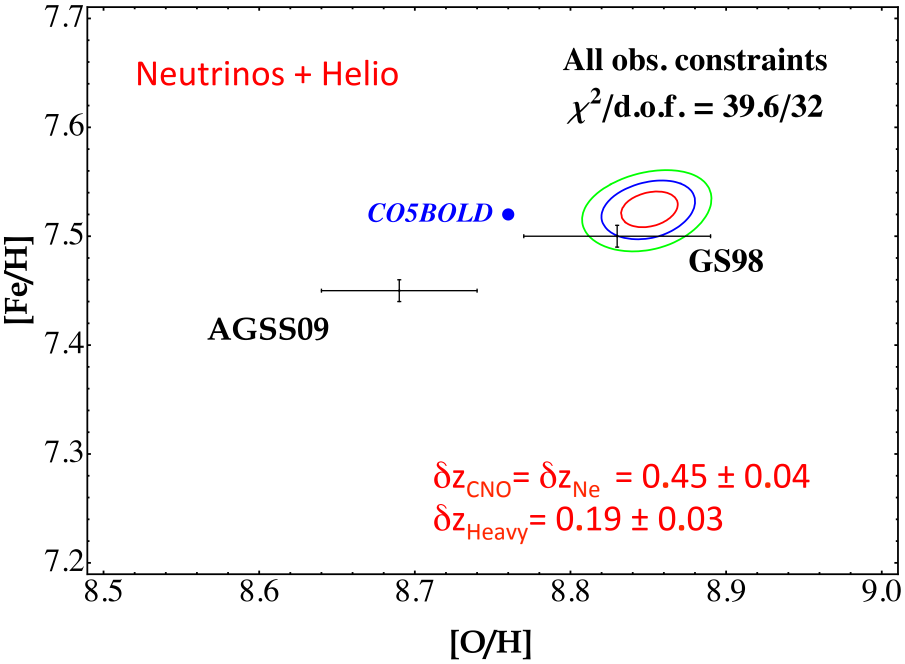
… no satisfactory solutions have been proposed up to now, in my opinion

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**.

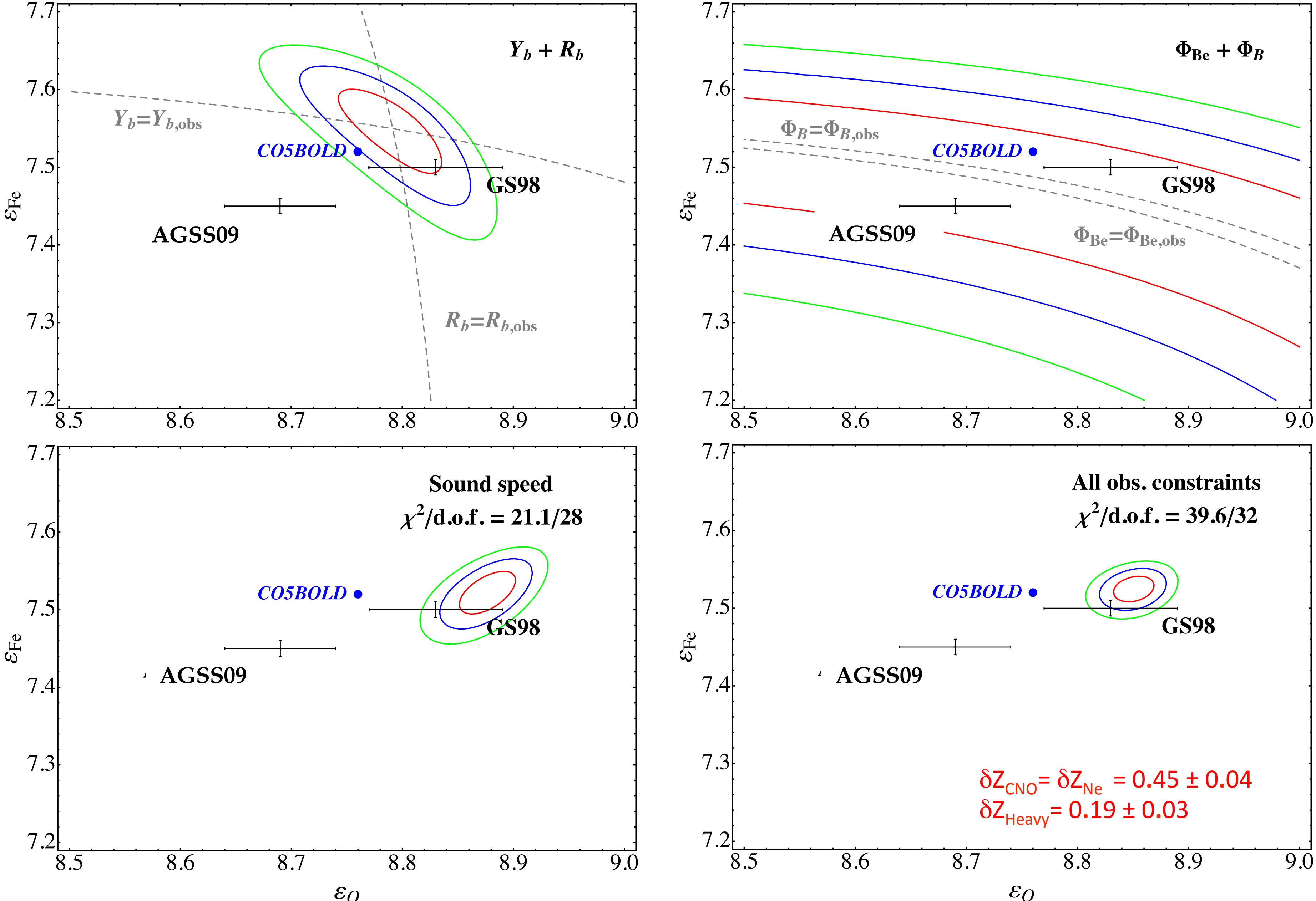
Two parameter analysis ($\delta z_{\rm CNONe}$; $\delta z_{\rm Heavy}$)



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

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

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

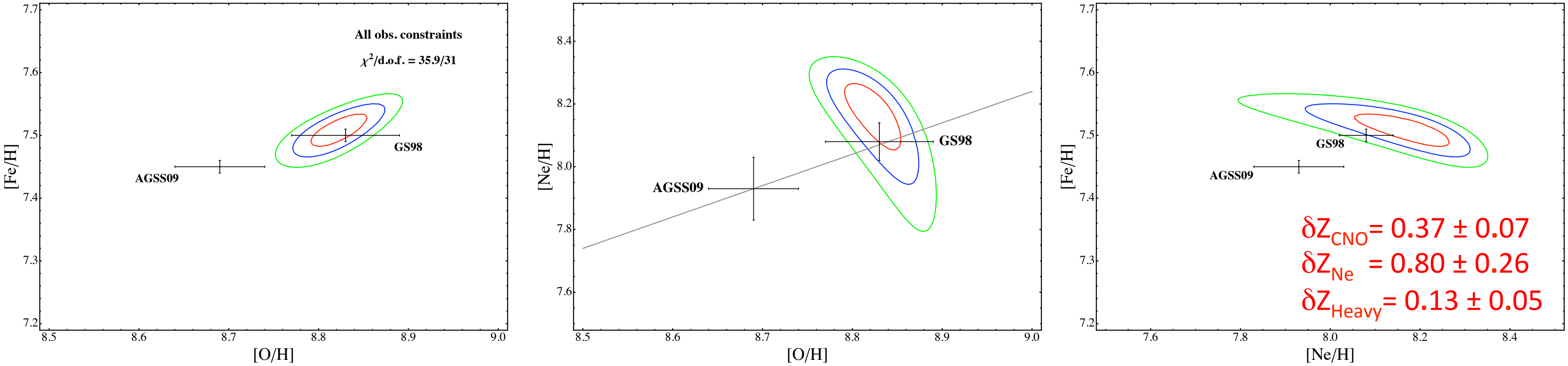


$\delta Z_{CNO} = \delta Z_{Ne} = 0.45 \pm 0.04$

$\delta Z_{Heavy} = 0.19 \pm 0.03$

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

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



δZ_{CNO} = 0.37 ± 0.07
δZ_{Ne} = 0.80 ± 0.26
δZ_{Heavy} = 0.13 ± 0.05

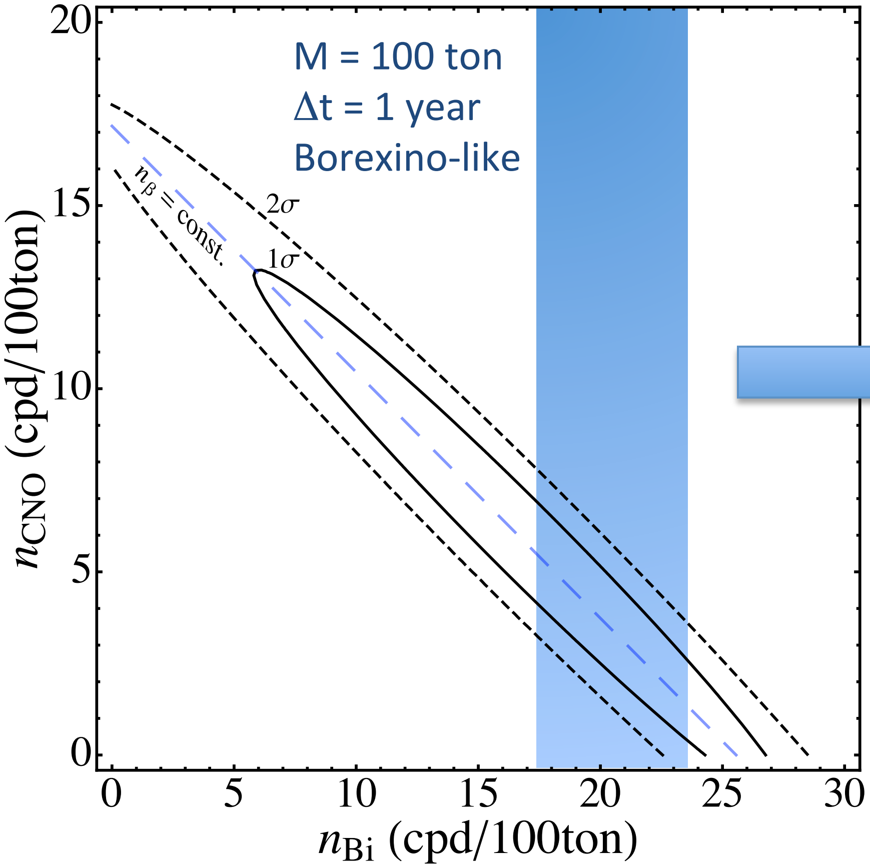
GS98 still favored by observational data but:

- 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).

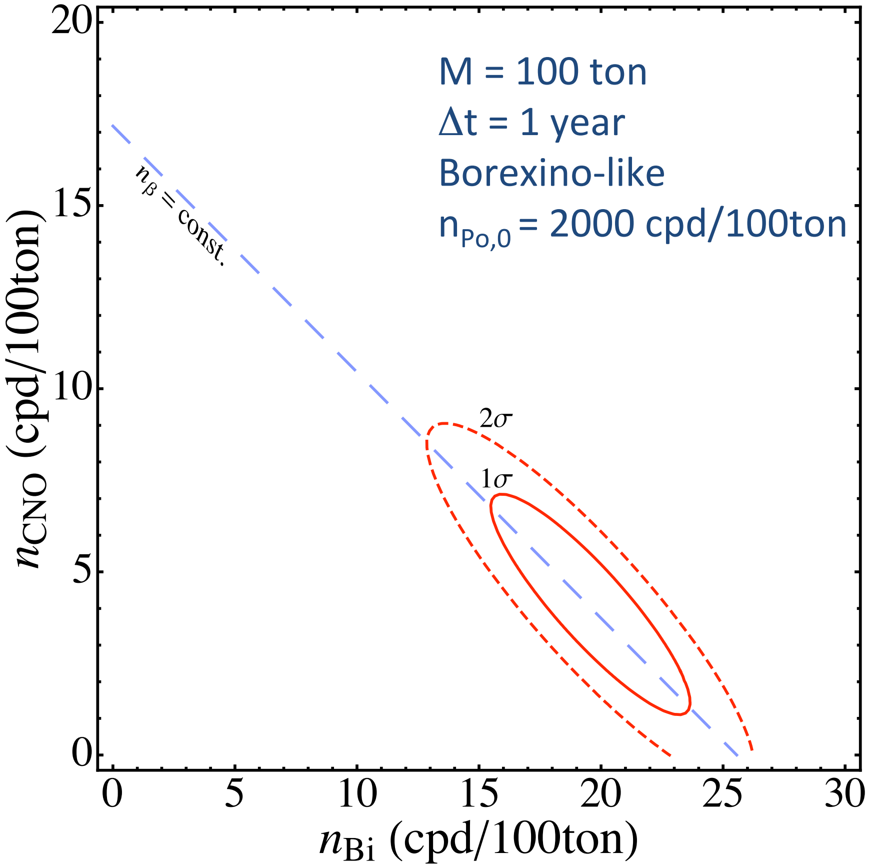
Borexino, already has the potential to probe the CNO neutrino flux

Future Kton-scale detectors (e.g. SNO+) will be able to start discriminating between high and low metallicity solar models (uncertainties scales as $1/M^{1/2}$)

Fit to simulated data (energy)



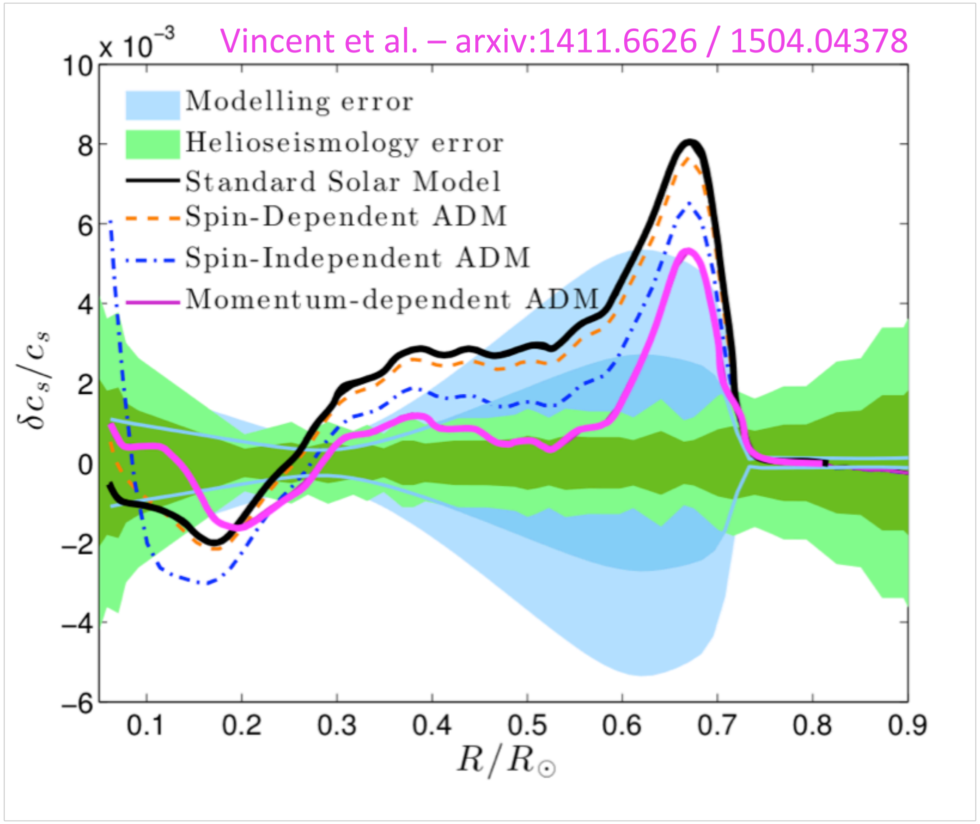
Fit to simulated data (**energy and time**)



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)

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

The “stability” of sound speed …

Schematically, we can note that:

$$\frac{GMm_u}{R} \sim \frac{k_B T}{\mu} = \frac{P}{\rho} = u$$

Virial theorem

↓

This quantity is fixed for the Sun

In a “normal star”, opacity determine luminosity:

$$L \sim \frac{E_\gamma}{t_{diff}} = \frac{M^3 \mu^4}{\kappa}$$

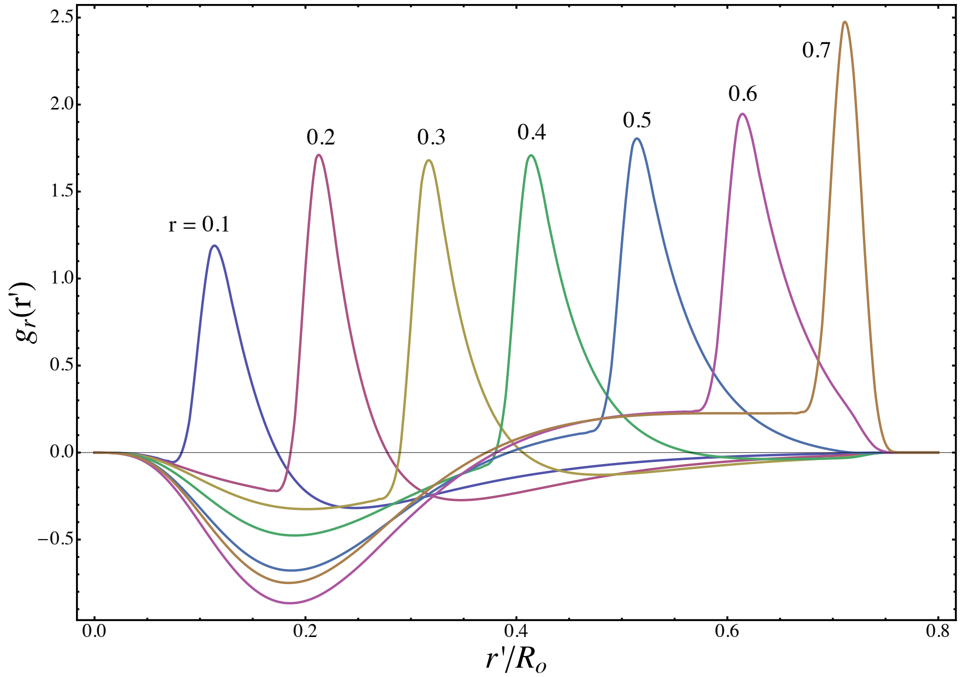
In the sun:

To keep L constant, we have to vary helium abundace.

An increase of Y implies a decrease of κ and an increase of μ).

The sound speed kernels

$$\delta u(r) = \int dr' \; K_u(r, r') \; \delta\kappa(r')$$



The kernels are not positive definite → compensating effects can occur …

$$\delta u_0(r) = \int dr' K_u(r, r') \simeq 0$$

The sound speed is *insensitive to a global rescaling of opacity*

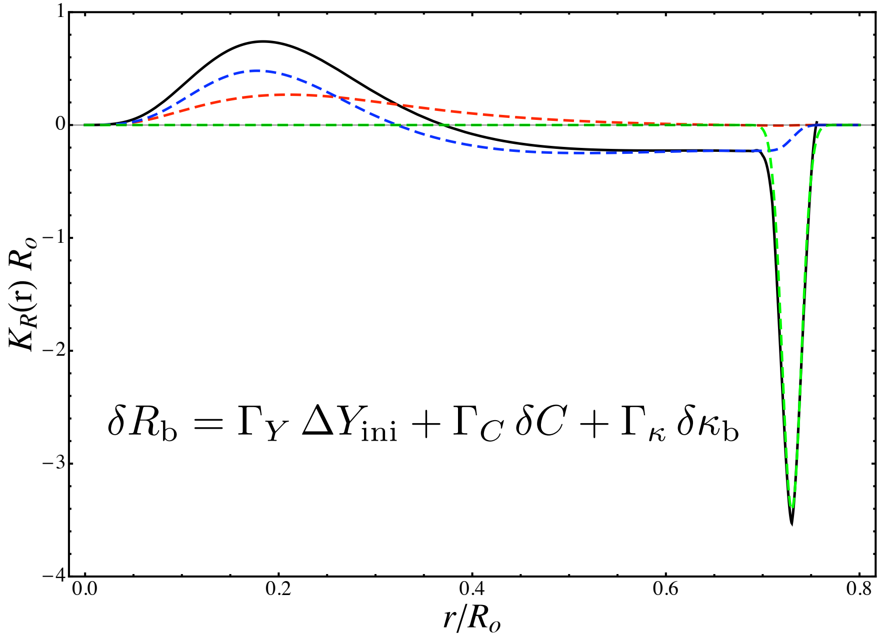
The convective radius and the surface helium abundance

Convective radius:

$$\delta R_{\rm b} = \int dr\; K_{\rm R}(r)\; \delta\kappa(r)$$

$$\begin{aligned}\delta R_{\rm b} &= 0.12\; A_{\rm in} - 0.14\; A_{\rm out}\\ &\simeq 0.13\; (A_{\rm in} - \; A_{\rm out})\end{aligned}$$

$$\delta R_{\rm b} \;=\; -0.02\; A_0 - 0.10\; A_1$$

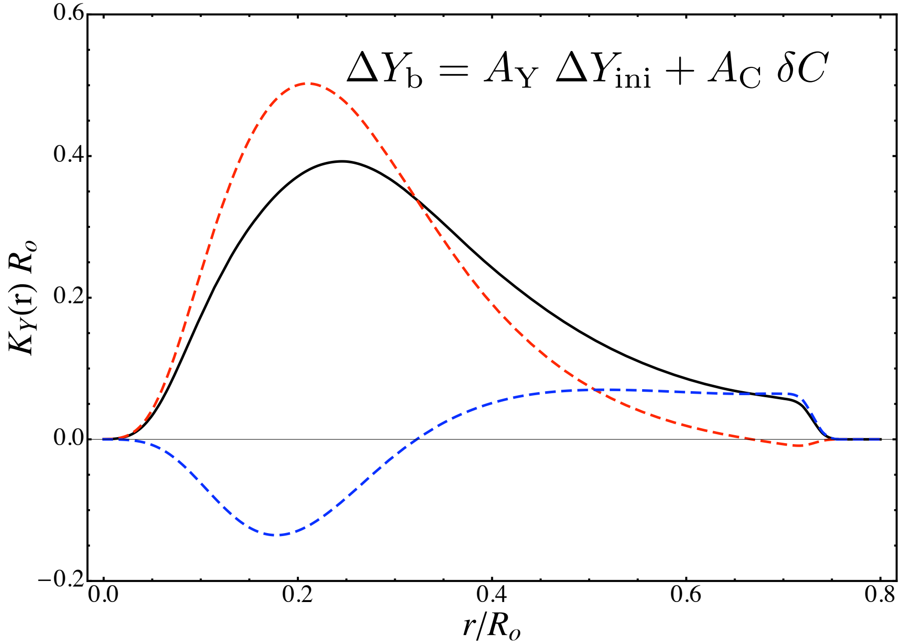


Surface helium:

$$\Delta Y_{\rm b} = \int dr\; K_{\rm Y}(r)\; \delta\kappa(r)$$

$$\begin{aligned}\Delta Y_{\rm b} &= 0.073\; A_{\rm in} + 0.069\; A_{\rm out}\\ &\simeq 0.07\; (A_{\rm in} + A_{\rm out})\end{aligned}$$

$$\Delta Y_{\rm b} \;=\; 0.142\; A_0 + 0.062\; A_1$$

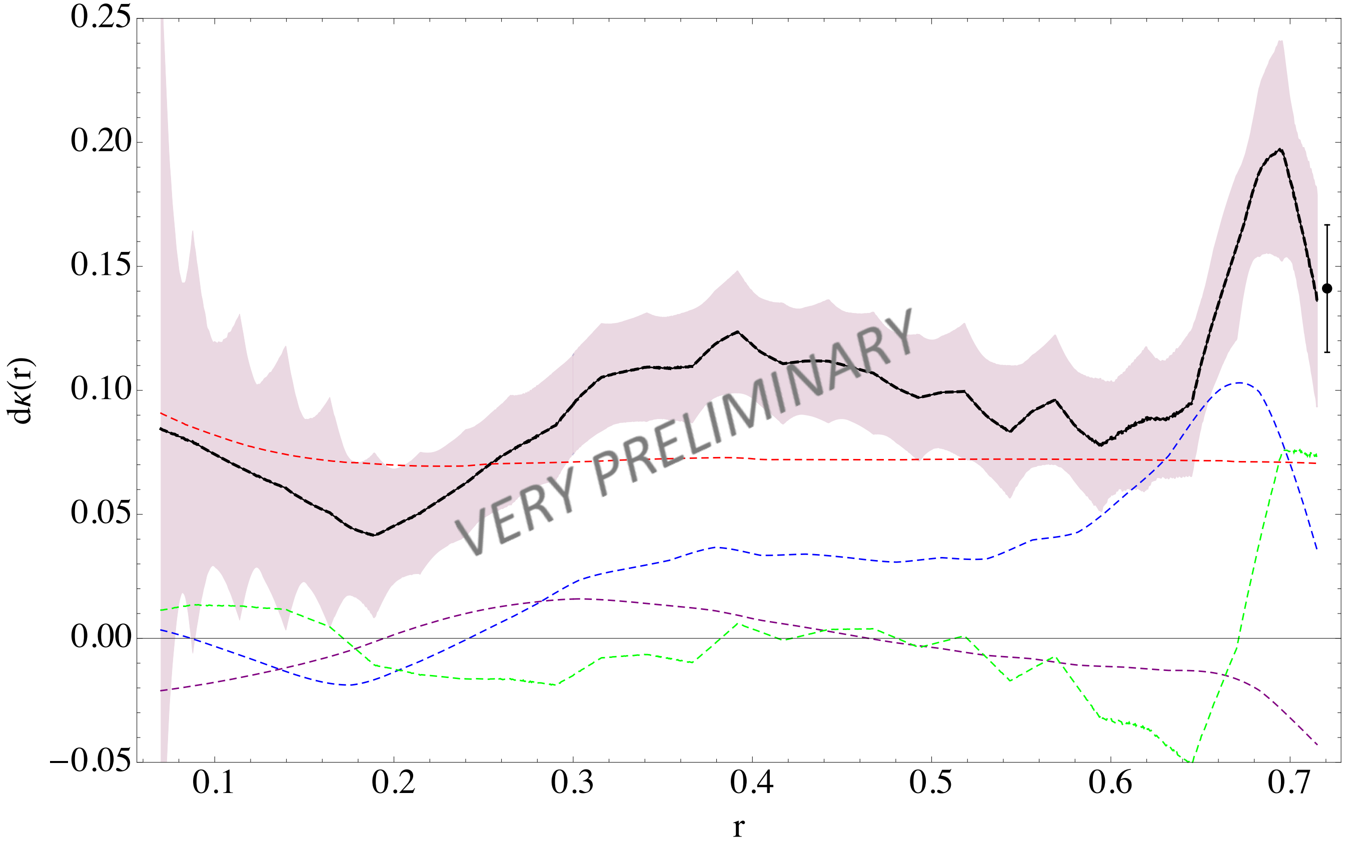


To reproduce helioseismic results:

$A_{\rm in} = 0.07 \pm 0.04 \qquad A_{\rm out} = 0.21 \pm 0.04$

The solar opacity profile from helioseismic data

Serenelli, Vinyoles and Villante, 2018 – In preparation



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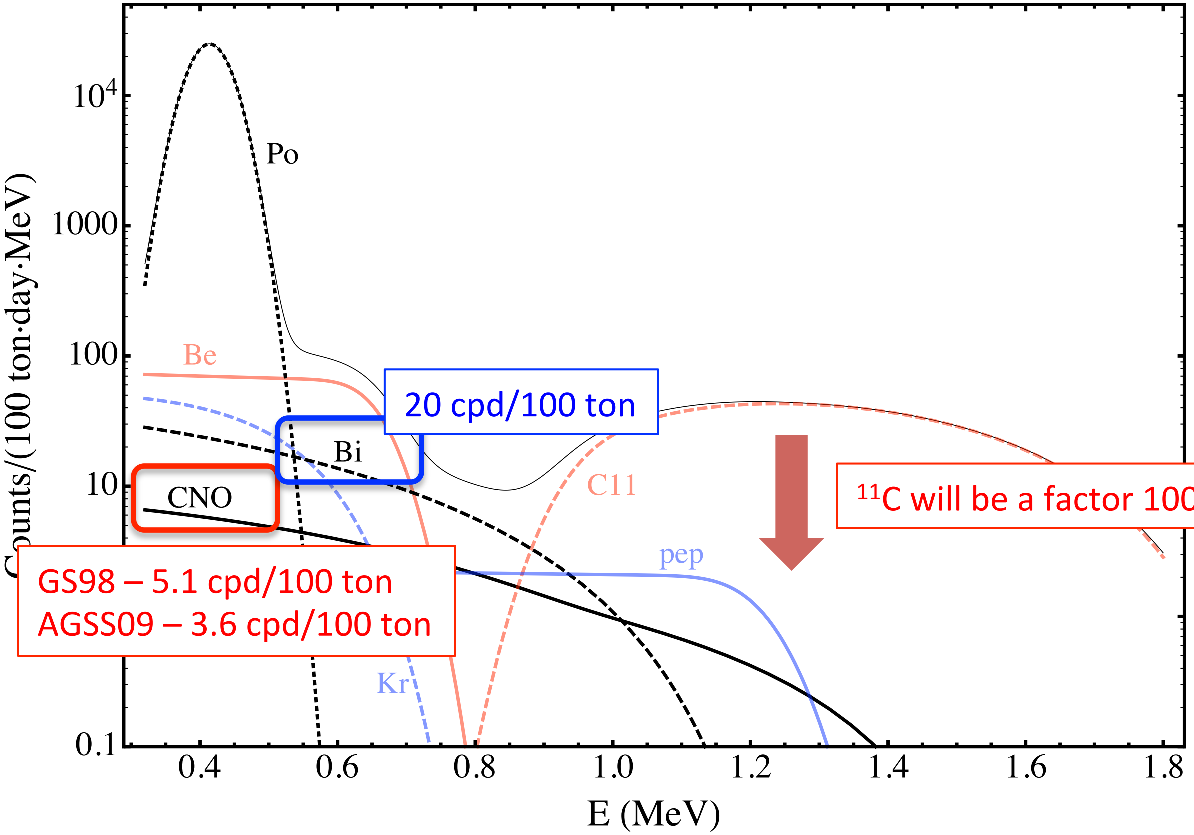

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^{11}C will be a factor 100 lower in SNO+

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