Solar models and neutrinos (II)

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

Based on work done in collaboration with:
A. Serenelli, N. Vinyoles, M.C. Gonzales-Garcia, G. Pagliaroli, N.Song and many others ….

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	$\delta z_{\rm i}$
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
$({\rm Z/X})_\odot$	0.02292	0.01780	0.29

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

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<u>A quick remark on notation:</u>

Here and in the following, I use

$$\delta Q \equiv \frac{Q - \overline{Q}}{\overline{Q}}$$

to indicate the fractional variation of the generic quantity Q with respect to a reference value $\overline{Q}$.

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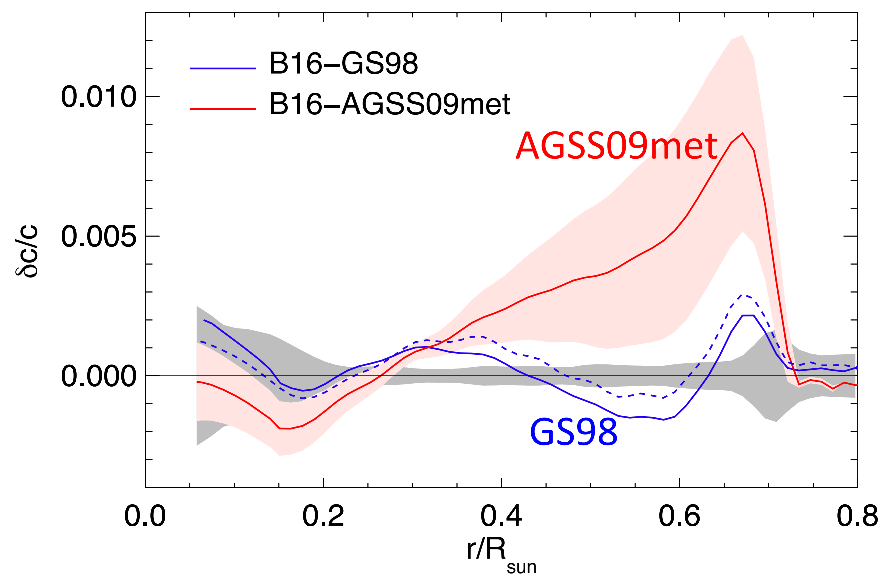
Vinyoles et al, ApJ 835 (2017) no.2, 202



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

Flux	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{cz}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
Φ_{pp}	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
Φ_{Be}	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
Φ_B	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
Φ_N	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
Φ_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.

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

- High-Z models are clearly preferred by helioseismology.
- The interpretation is however complicated by the **opacity-composition degeneracy** (see the following).

The role of metals in the Sun

- Metals give a negligible contribution to EOS

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

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

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

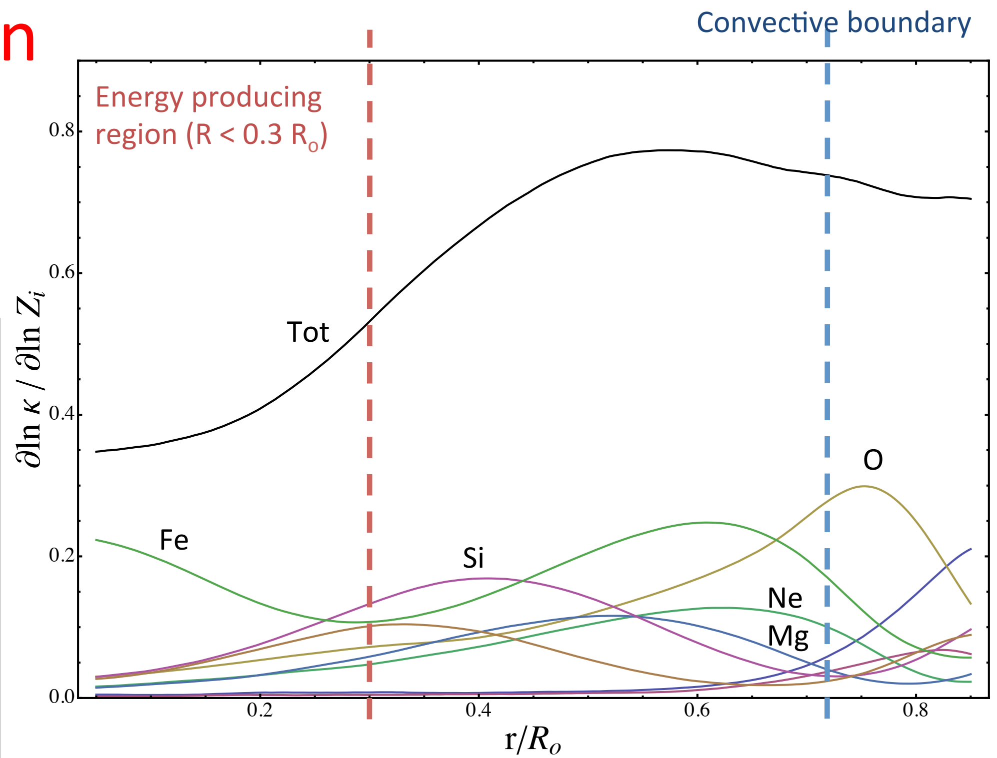
Fe gives the largest contribution.

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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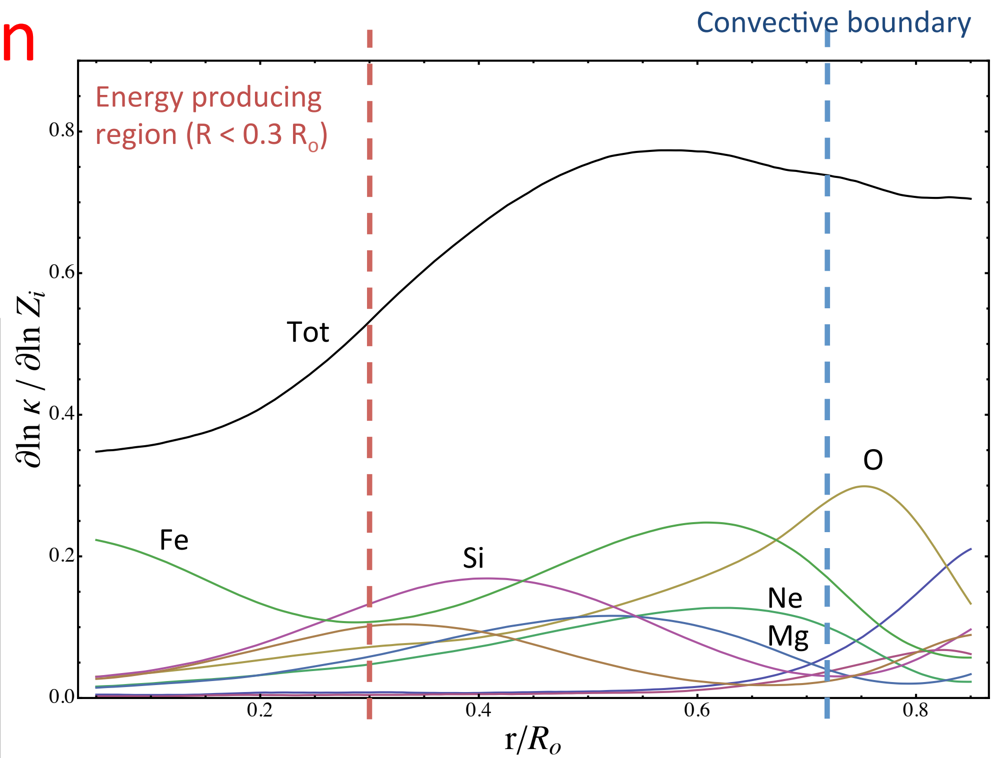


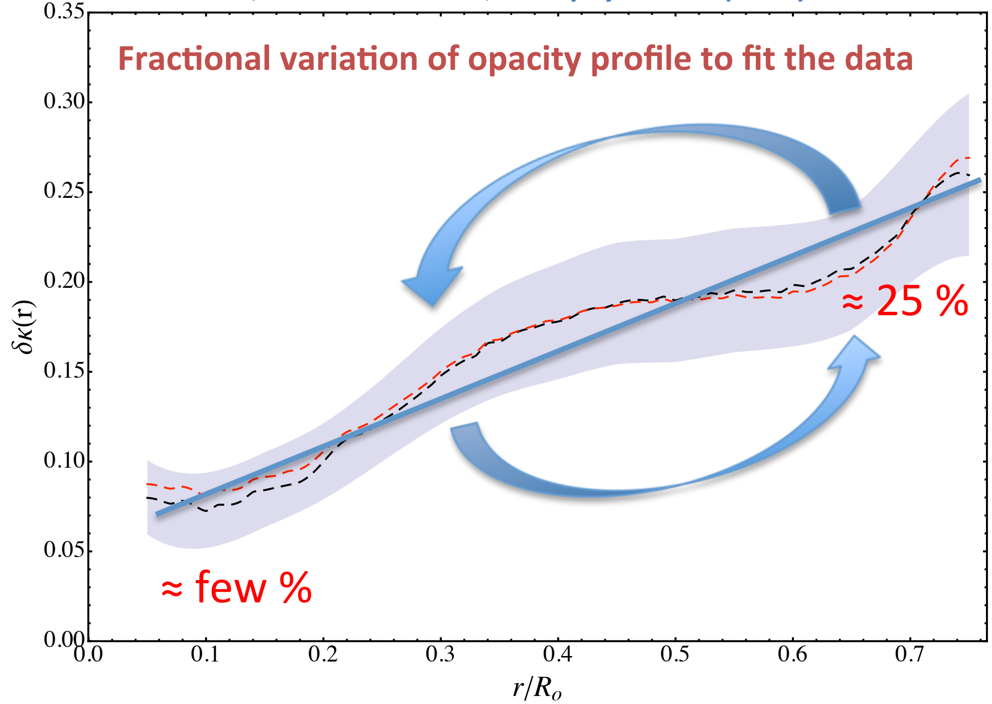
A change of the solar composition produces the same effects on the helioseismic observables and neutrino fluxes (except CNO) of a ***suitable change of the solar opacity profile δκ(r):***

$$\delta\kappa_Z(r) \equiv \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j}\delta z_j$$

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**
F.L. Villante, A. Serenelli et al., **Astrophys.J. 787 (2014) 13**

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 $\delta\kappa(r)$ (but not the scale)
- The surface helium and the neutrino fluxes determine the scale for $\delta\kappa(r)$

<u>Caveat</u>

- *Constraints are obtained by using parametrized $\delta k(r)$*
- *A non parametric approach is in progress (Song et al, 2017)*

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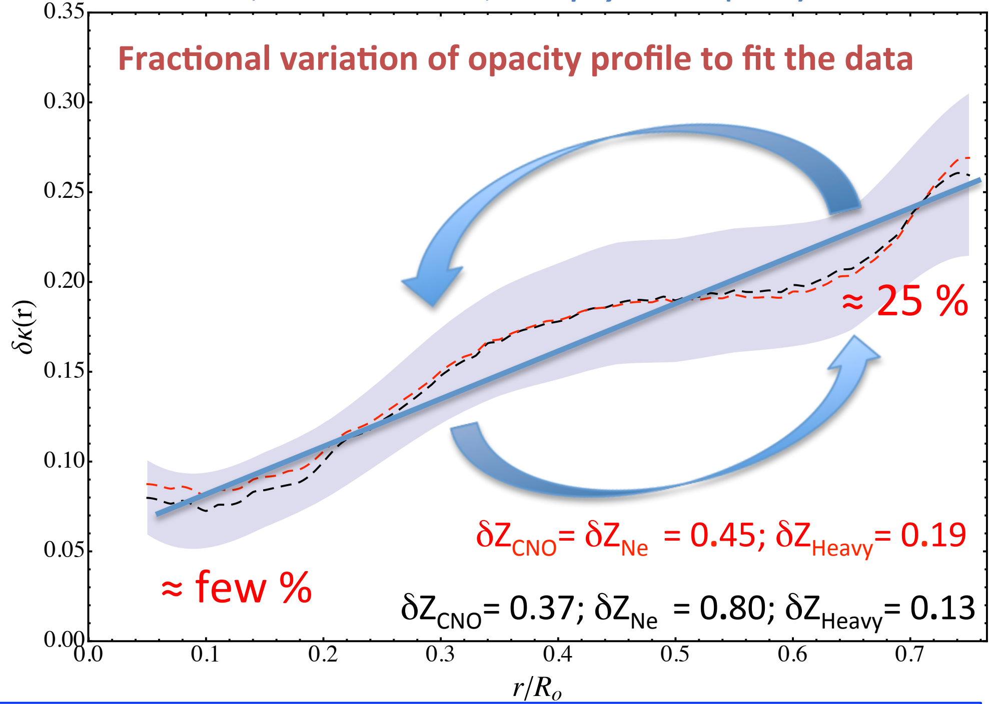


The interpretation is however complicated by the **opacity-composition degeneracy**. *Which fraction of the required δκ(r) has to be ascribed to intrinsic* ($\delta\kappa_I(r)$) *and/or composition opacity changes?*

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

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

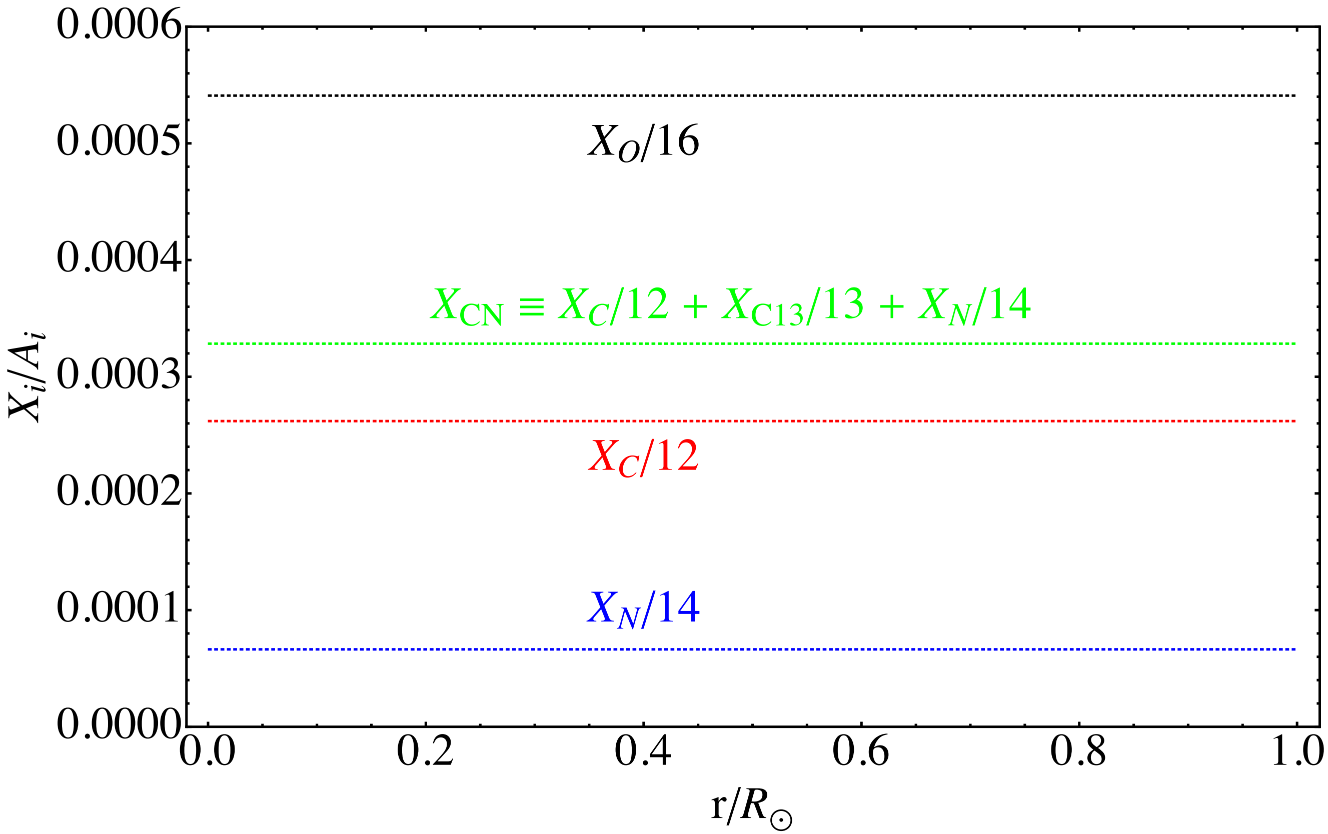
different admixtures {δz_i} can do equally well the job

The SSM chemical evolution paradigm

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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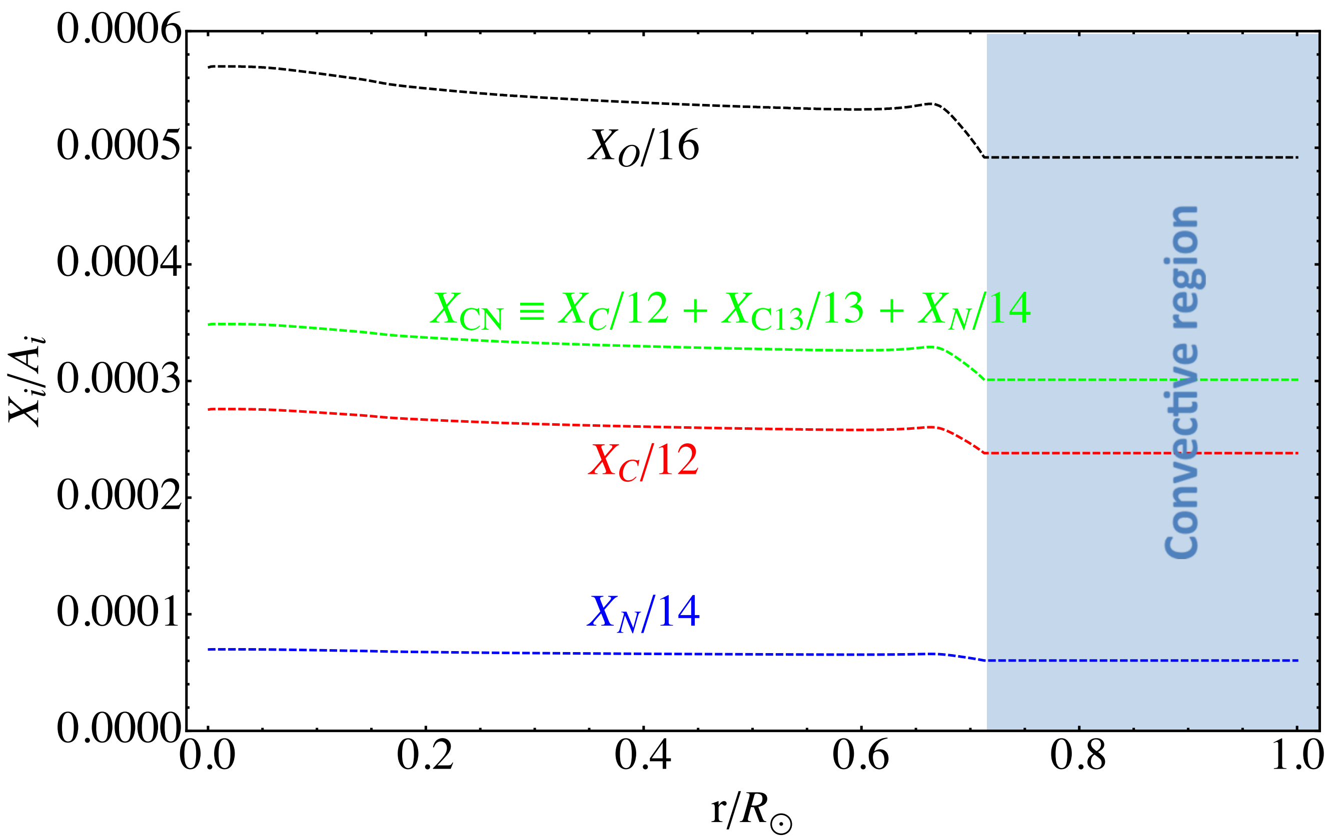

$$\frac{X_{\rm i,C} - X_{\rm i,S}}{X_{\rm i,ini}} \simeq 15\%$$

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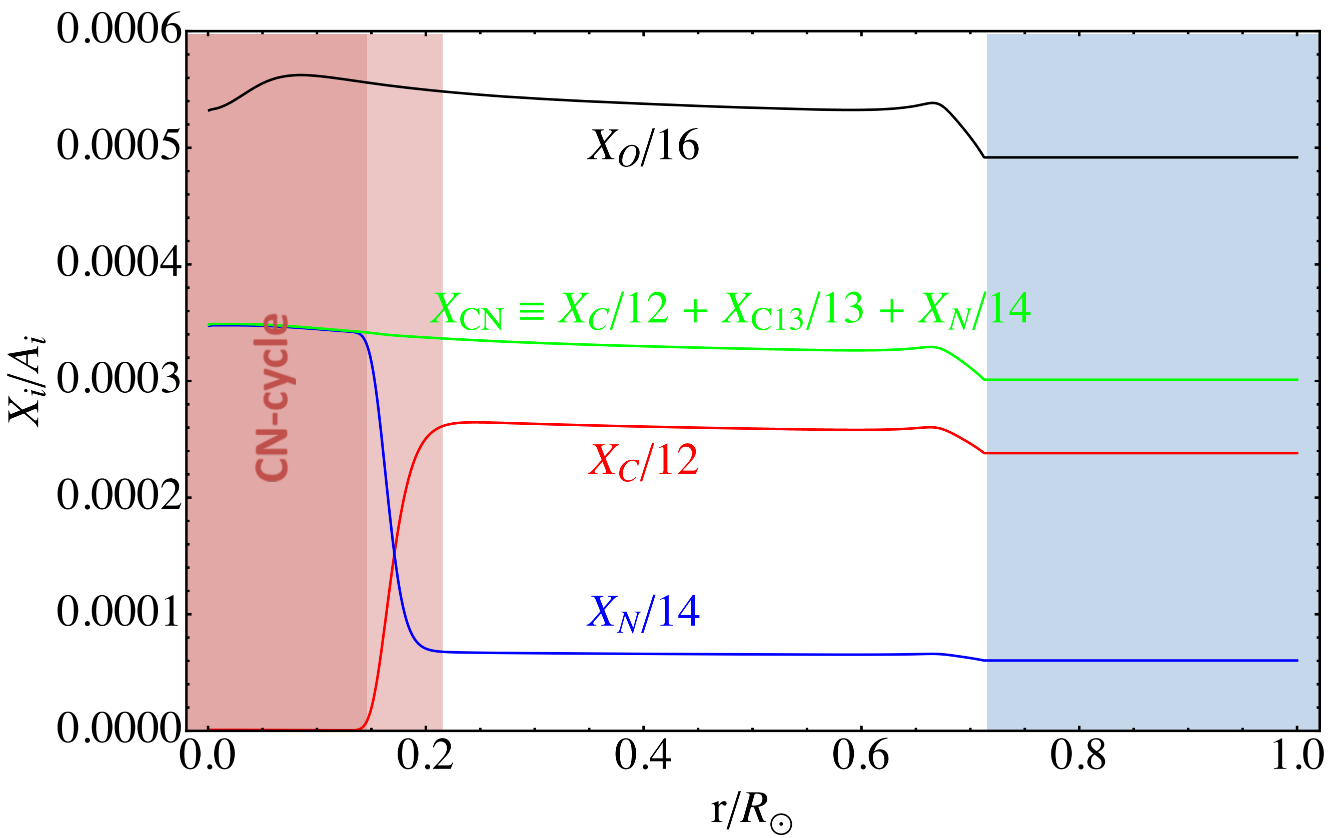

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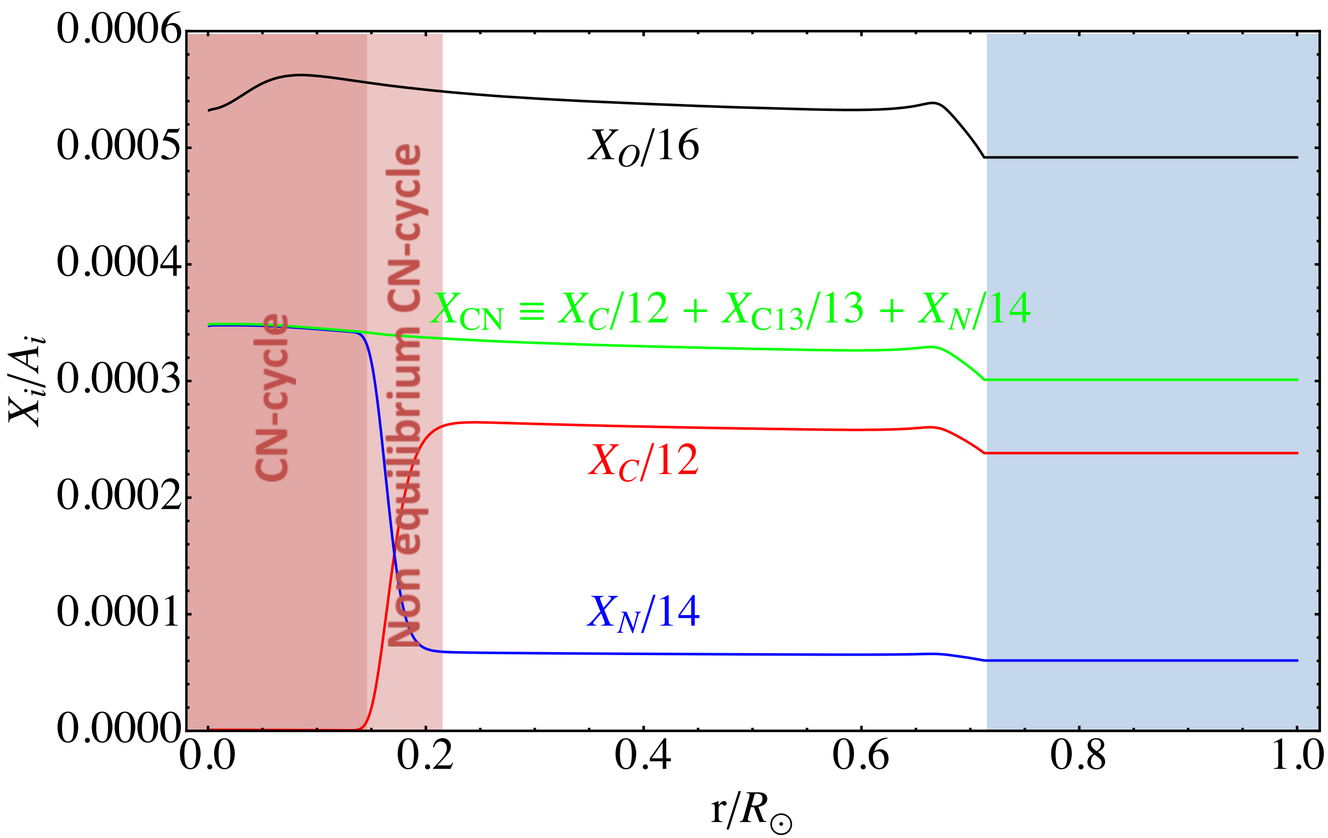
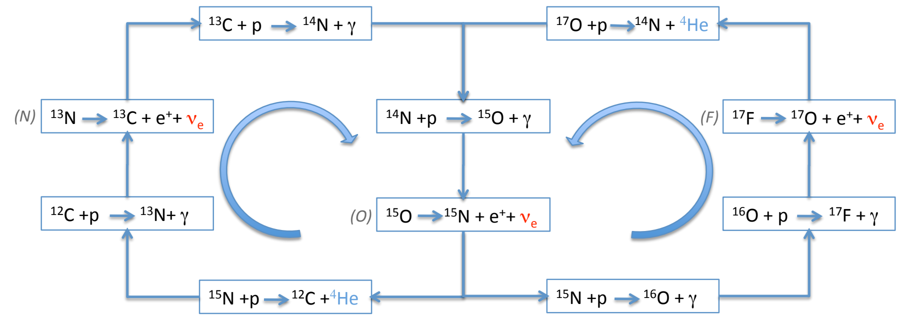
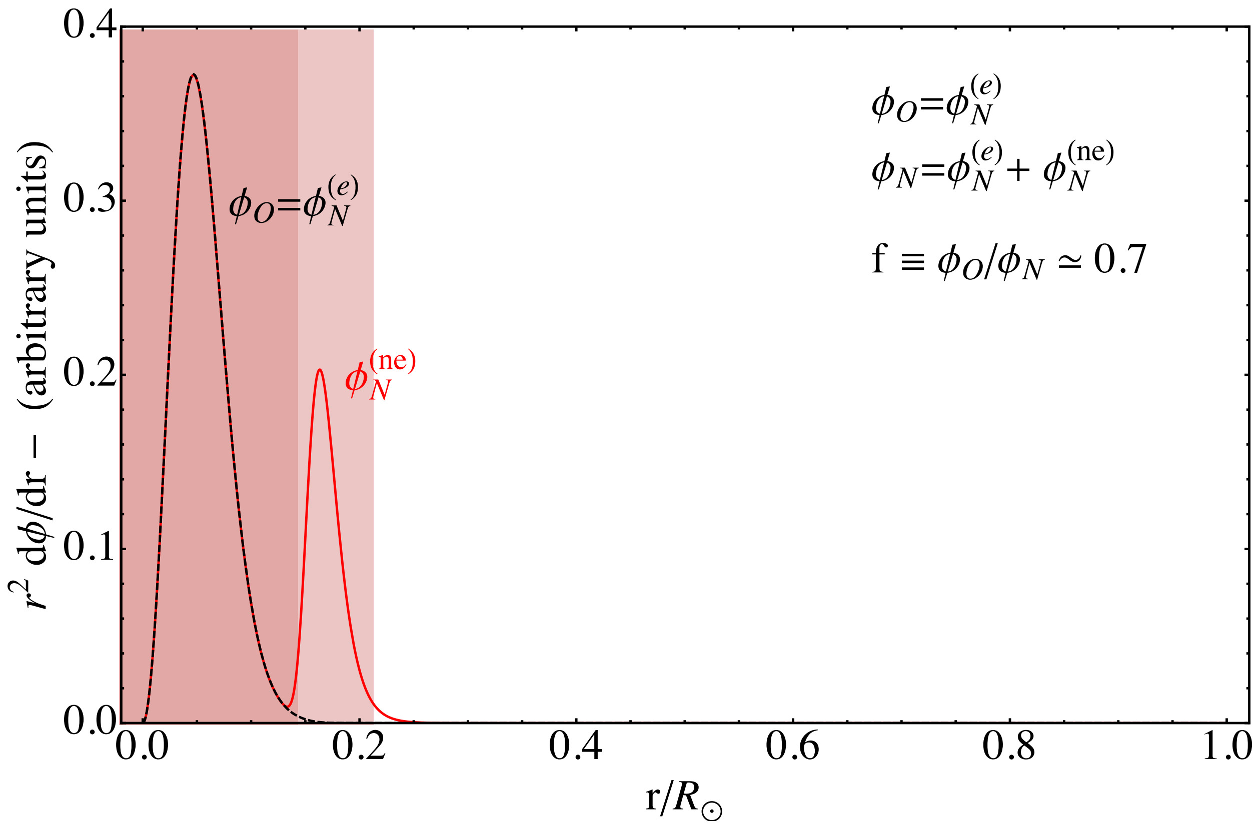


CN neutrino production

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





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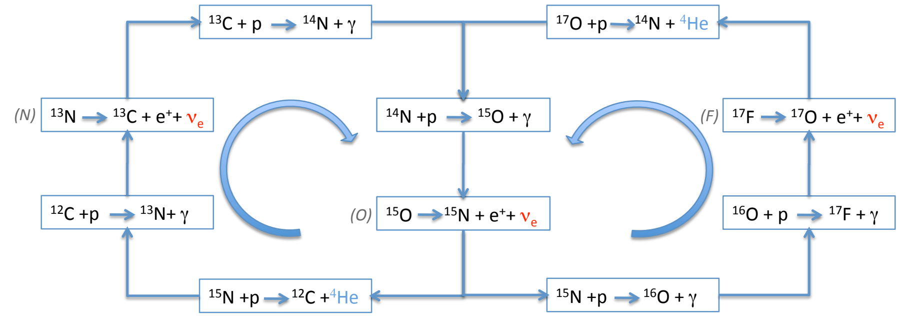

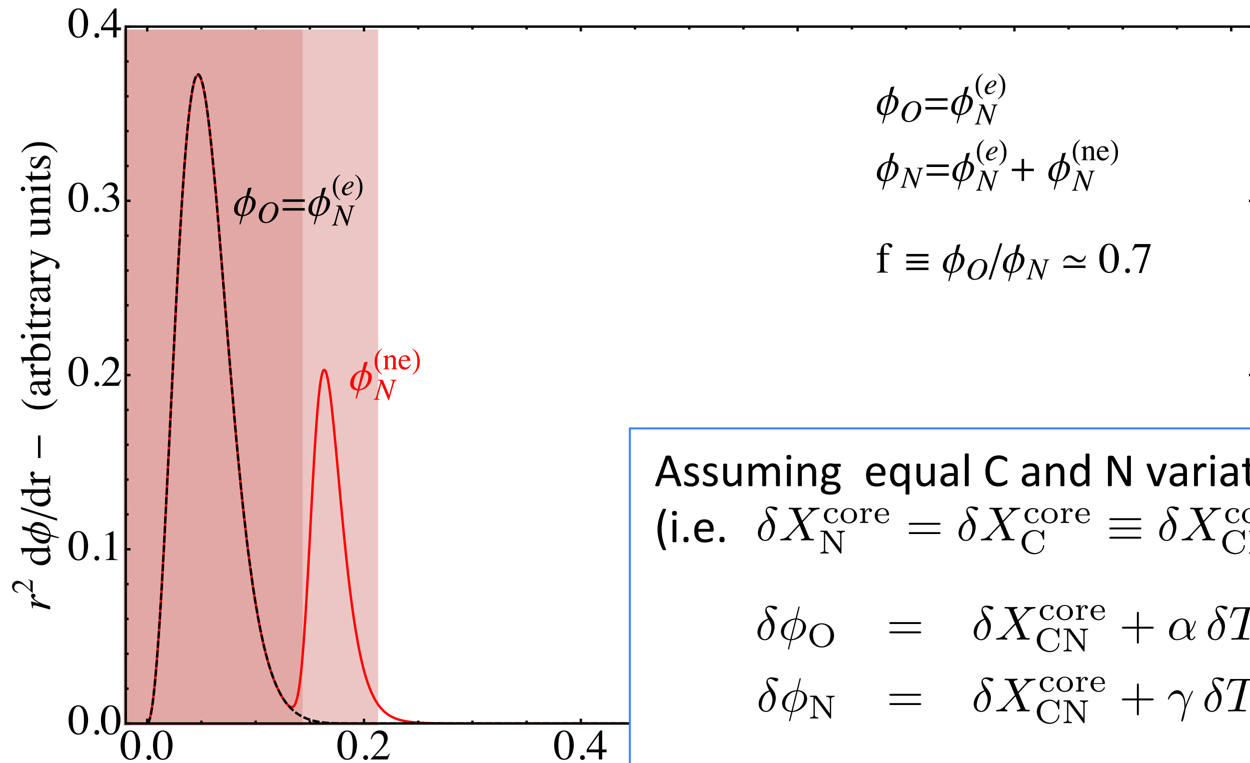

Assuming equal C and N variations
(i.e. $\delta X_{\rm N}^{\rm core} = \delta X_{\rm C}^{\rm core} \equiv \delta X_{\rm CN}^{\rm core}$):

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

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**:

$$
\begin{aligned}
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\end{aligned}
$$

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})
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Serenelli et al., PRD 2013

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High-Z .vs. Low-Z

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

Beyond solar composition problem (10%):

Using CNO neutrinos to probe for mixing processes in the Sun (and other stars)

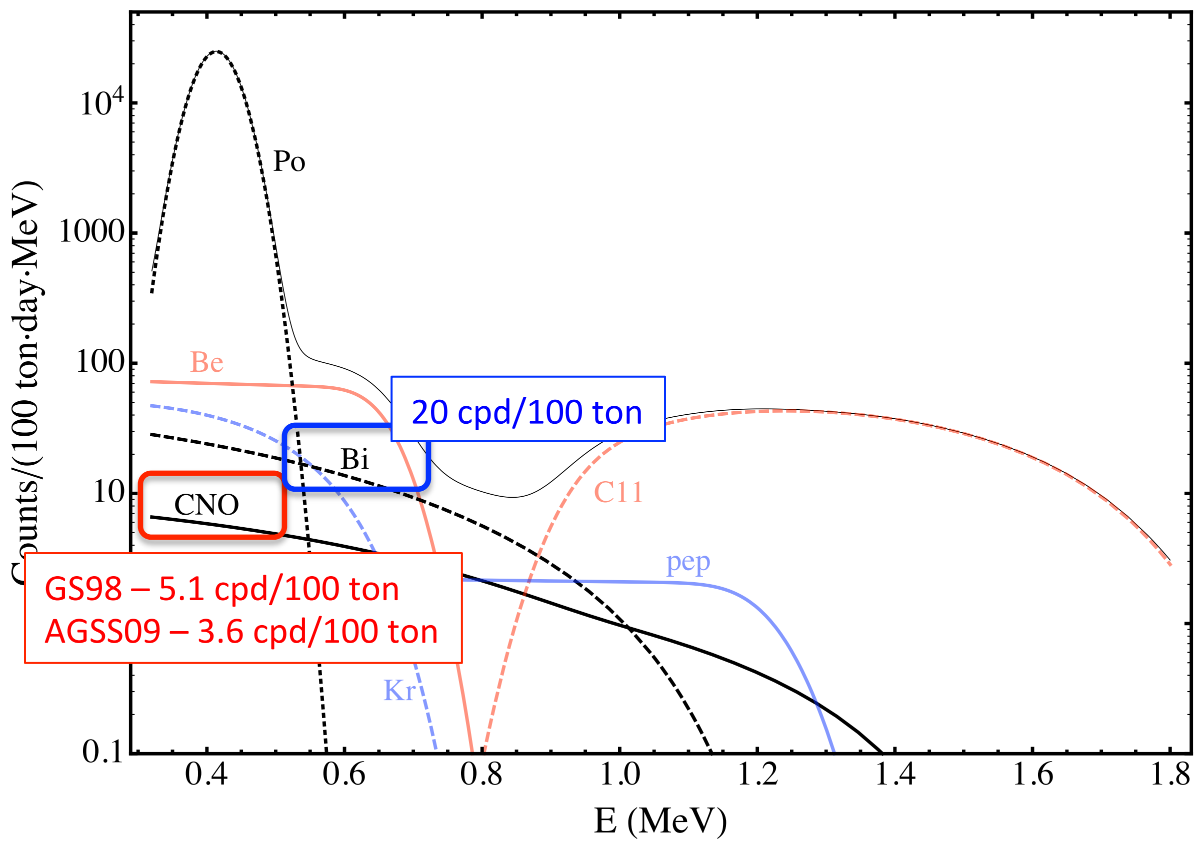
$$\delta X_{\rm CN} = \frac{X_{\rm CN}^{\rm core} - X_{\rm CN}^{\rm surf}}{X_{\rm CN,ini}} \simeq 15\%$$

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)



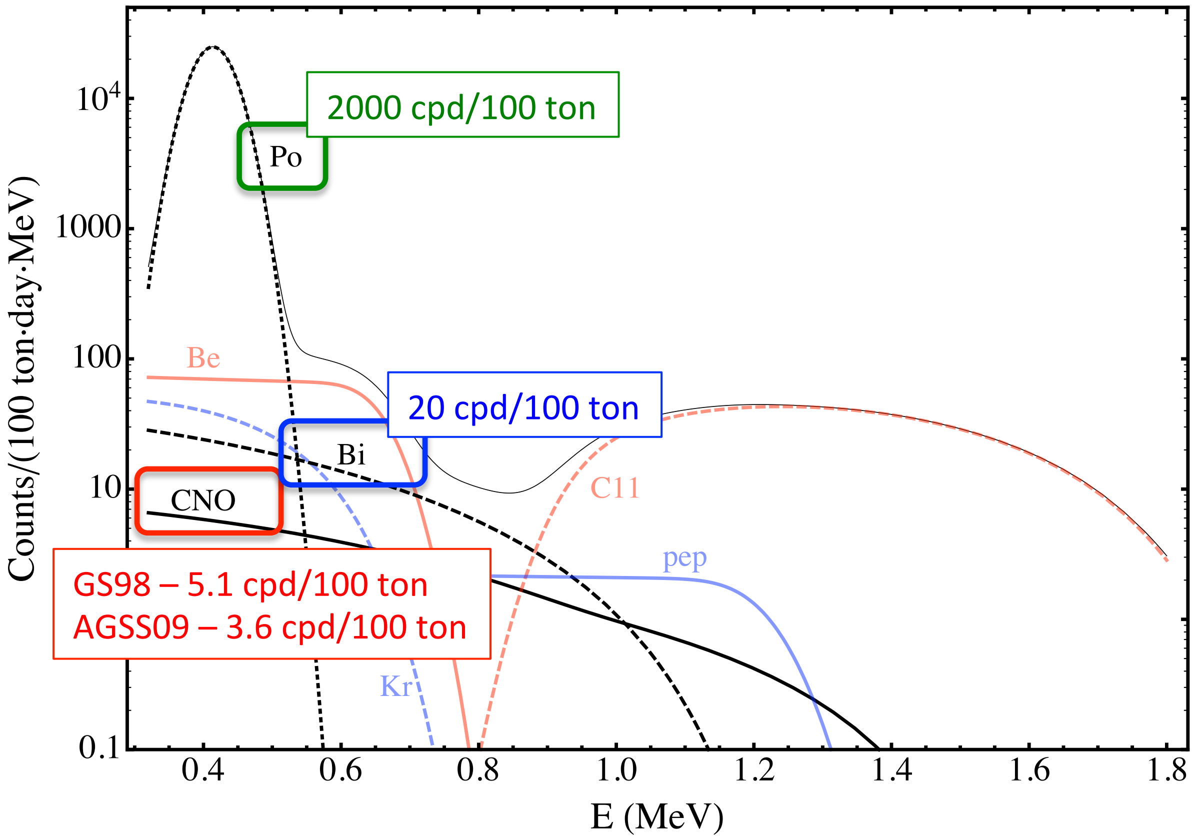
Determining ^{210}Bi with the help of ^{210}Po?

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

τ_{Bi} = 7.232 d

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

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

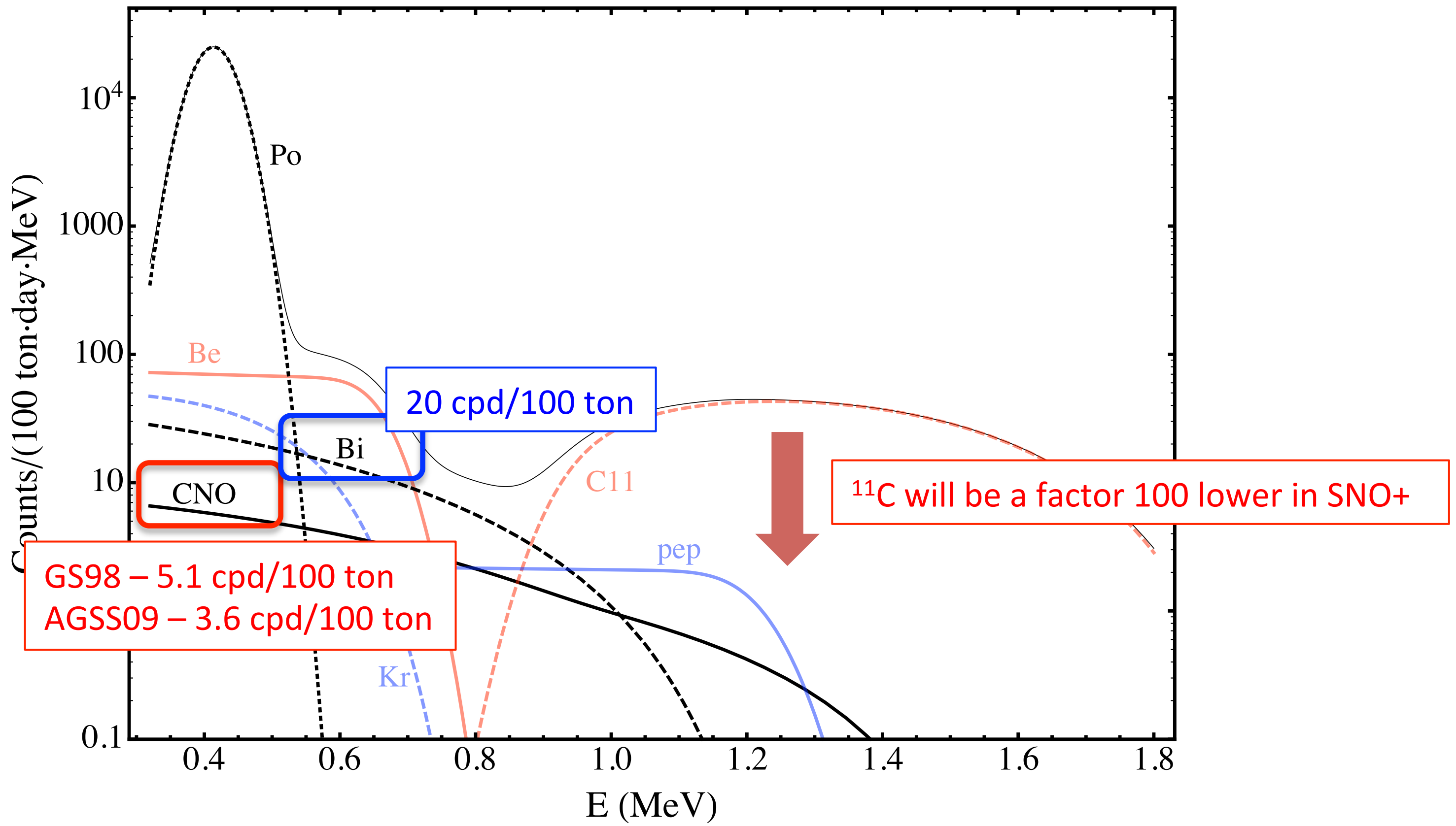
$$n_{\mathrm{Po}}(t) = [n_{\mathrm{Po},0} - n_{\mathrm{Bi}}]\ \exp(-t/\tau_{\mathrm{Po}}) + n_{\mathrm{Bi}}$$

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

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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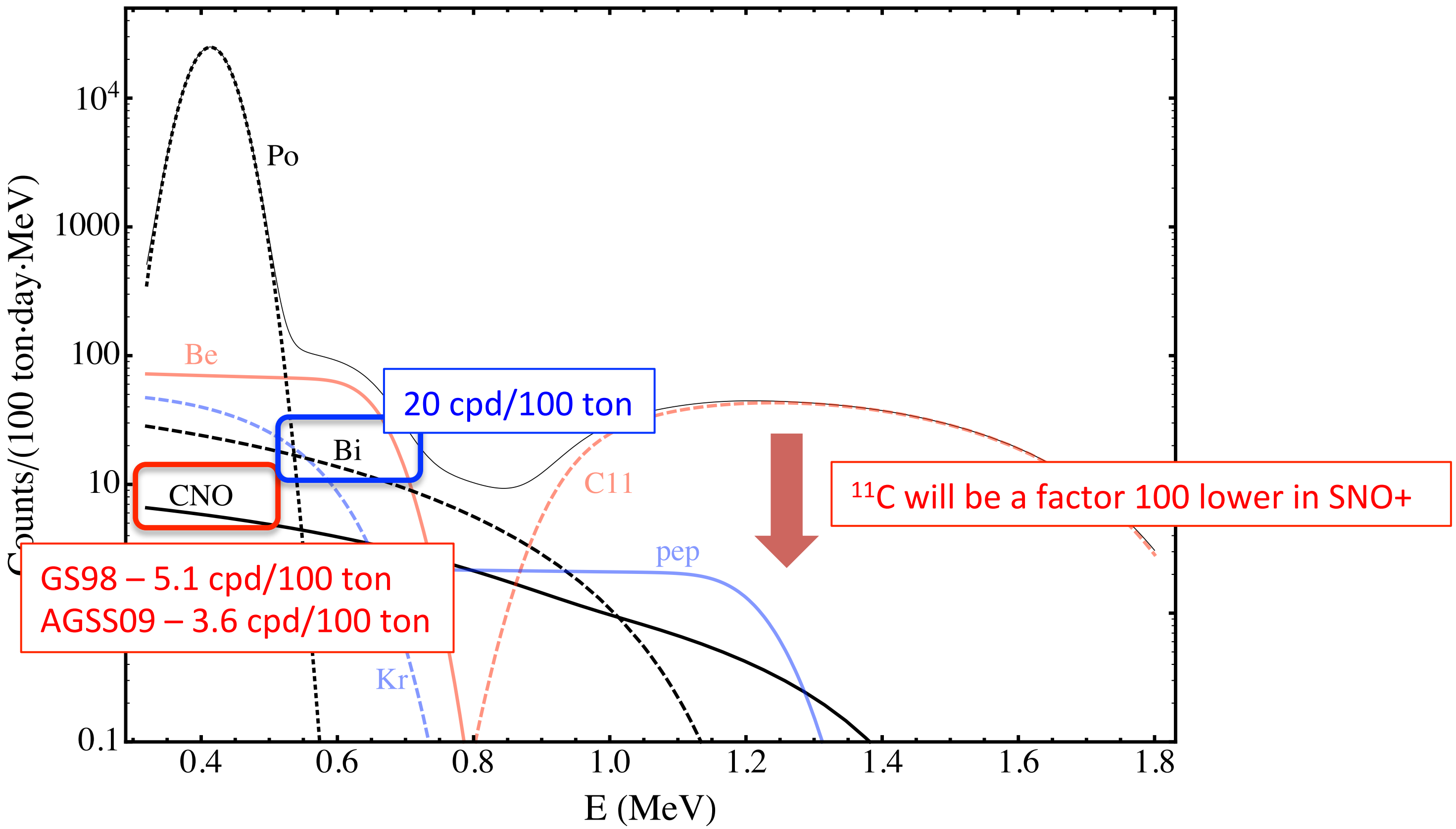


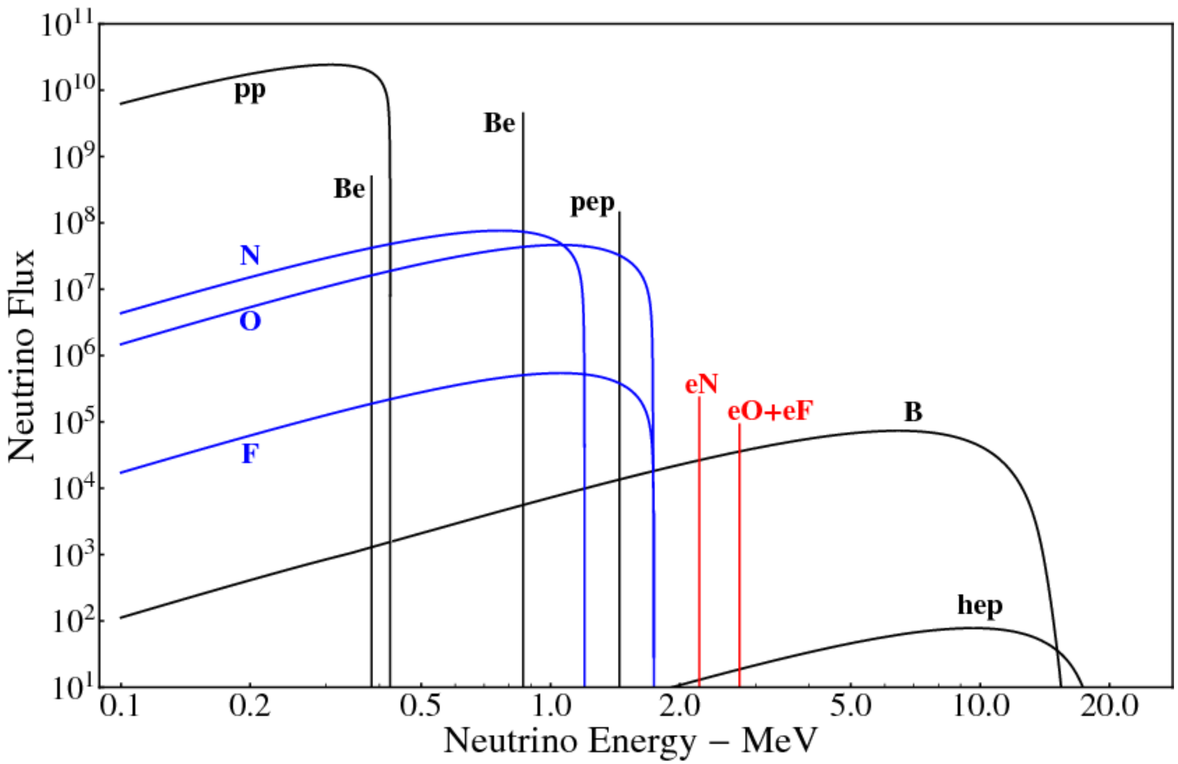
The final accuracy depends, however, on the internal background (^{210}Bi)

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

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:

$$
\begin{array}{llll}
{}^{13}\mathrm{N} + e^- & \rightarrow & {}^{13}\mathrm{C} + \nu_e & E_\nu = 2.220 \text{ MeV} \\
{}^{15}\mathrm{O} + e^- & \rightarrow & {}^{15}\mathrm{N} + \nu_e & E_\nu = 2.754 \text{ MeV} \\
{}^{17}\mathrm{F} + e^- & \rightarrow & {}^{17}\mathrm{O} + \nu_e & E_\nu = 2.761 \text{ MeV}
\end{array}
$$



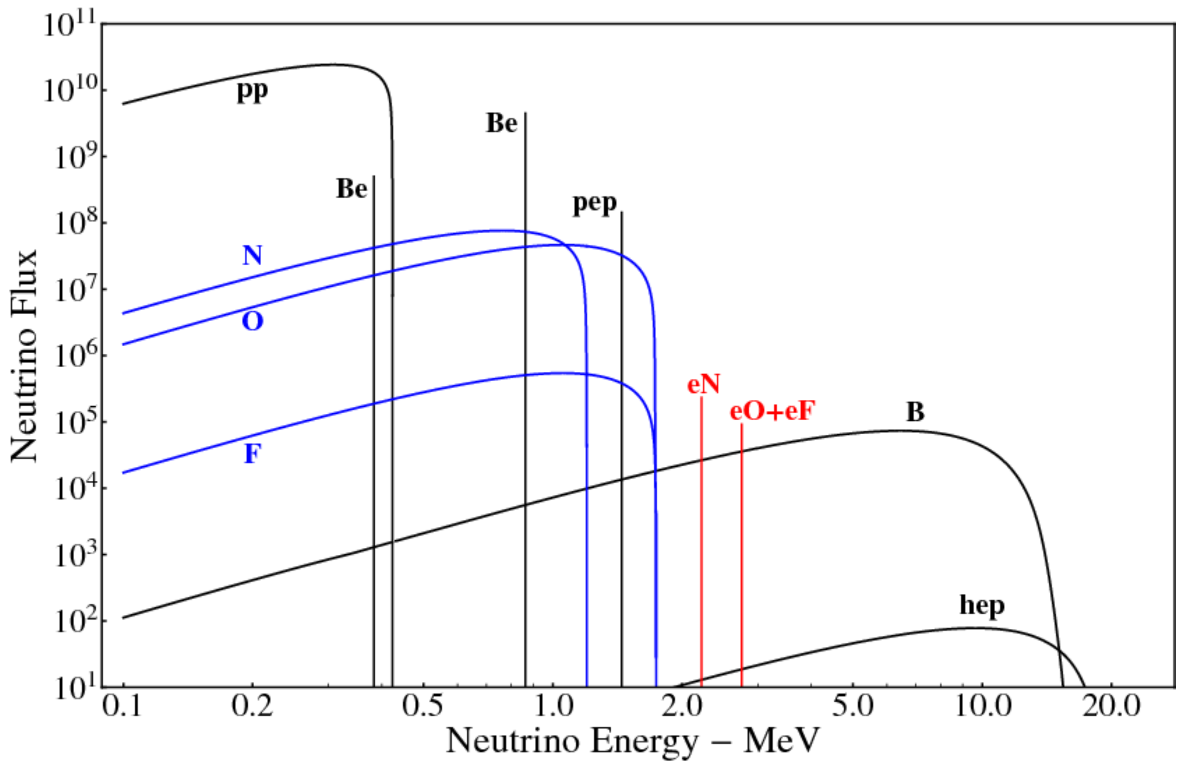
F.L. Villante, PLB 742 (2015) 279-284
L.C. Stonehill et al, PRC 69, 015801 (2004)
J.N. Bahcall, PRD 41, 2964 (1990).

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**.



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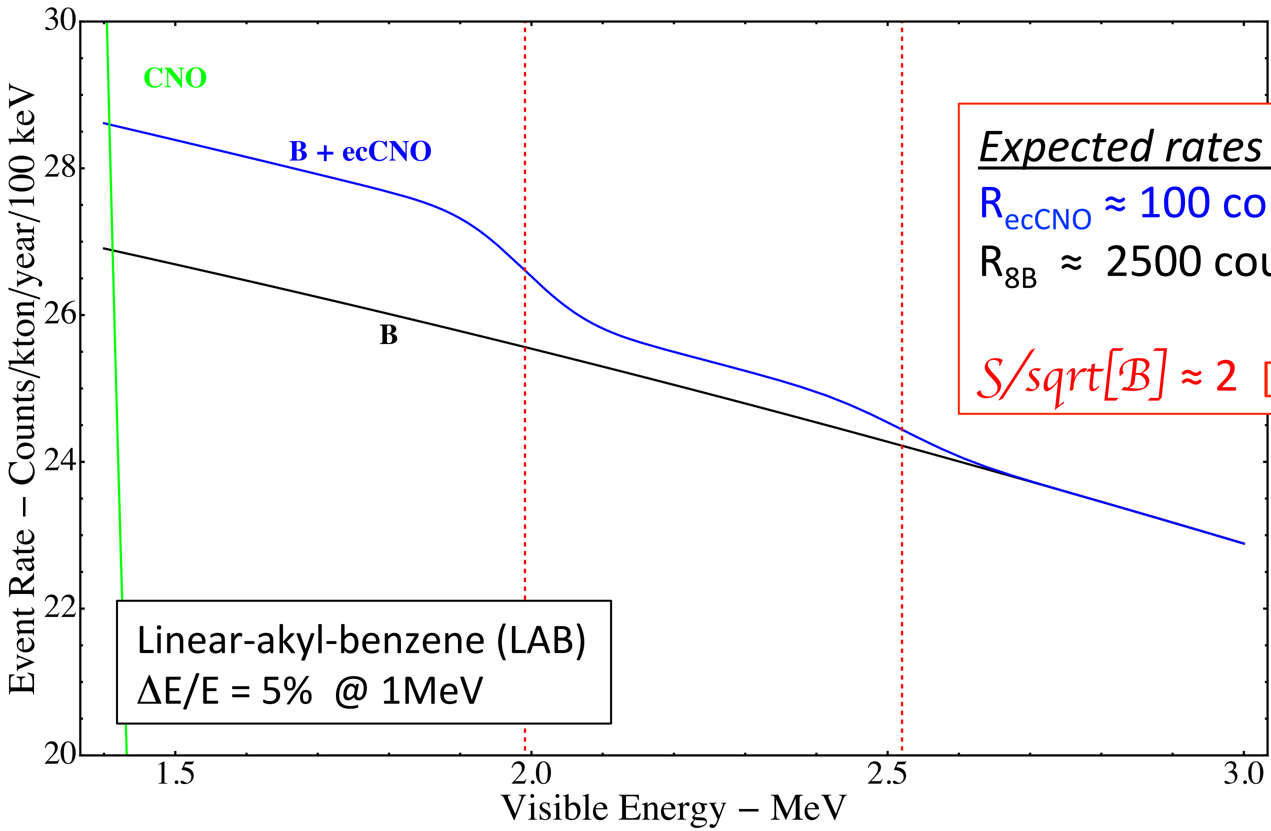
Expected rates in Liquid Scintillators

- ν − 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

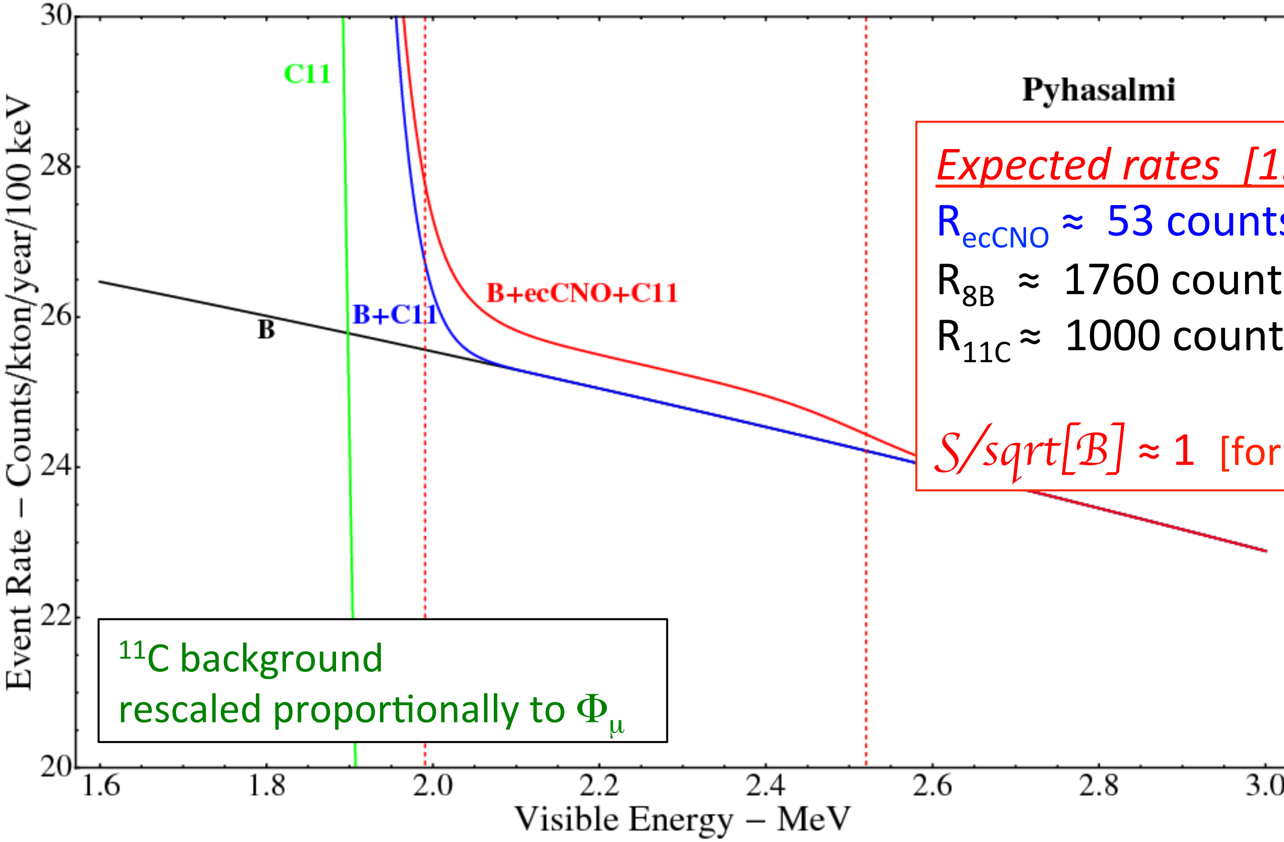
$S/sqrt[B]$ ≈ 2 [for 10kton × year exposure]

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.



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]

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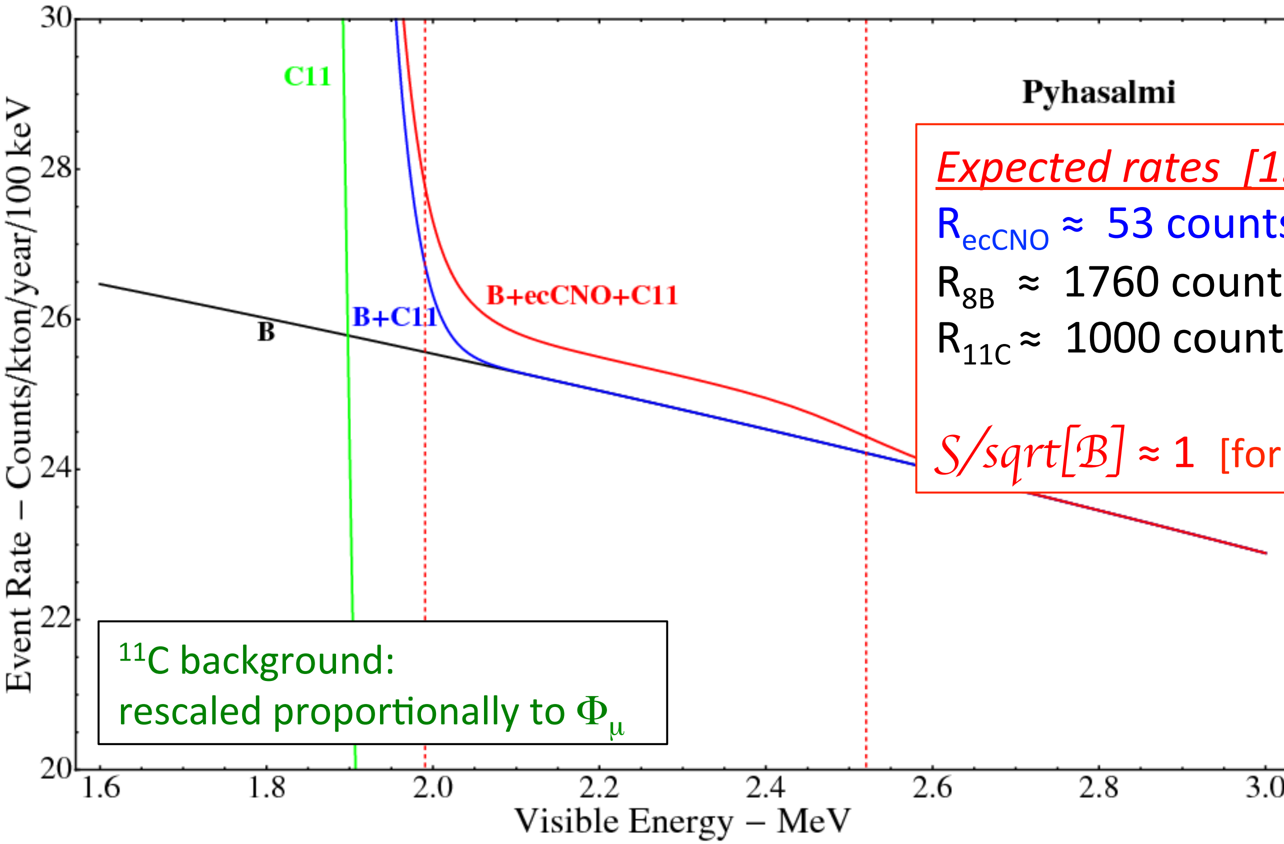

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Signal comparable to stat. fluctuations for exposures 10 kton × year or larger.

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