The role of Borexino in solar physics

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The Sun observed with:

neutrinos

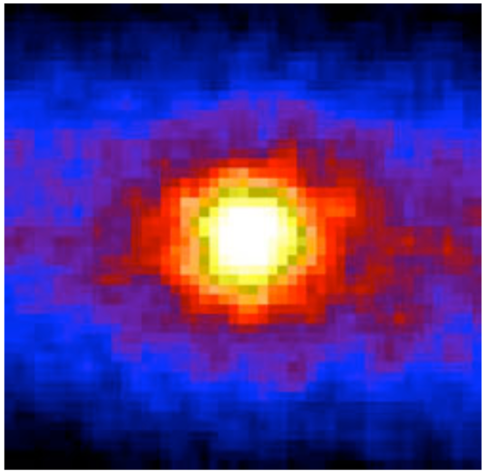
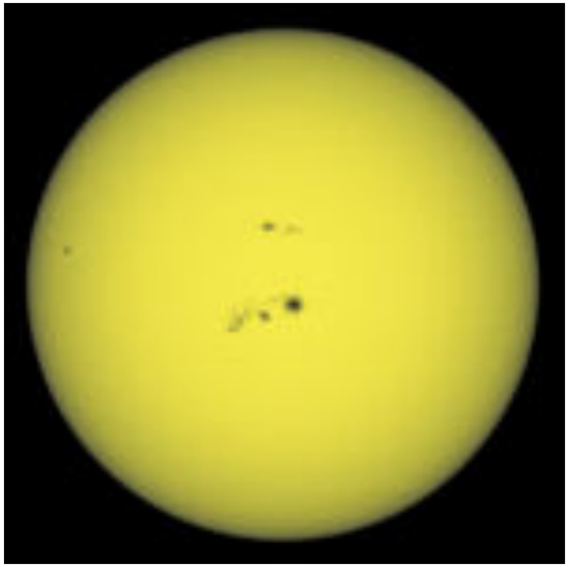
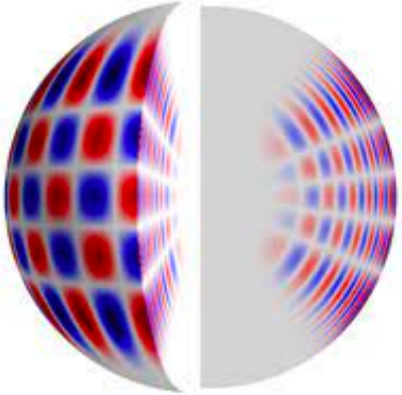


Image credits: Super-Kamiokande Coll.

photons



Helioseismology



*The Sun provides the **benchmark** for stellar evolution and a laboratory for fundamental physics.*

The Standard Solar Model (SSM)

Our comprehension of the Sun is based on the **Standard Solar Model (SSM).**
This implies: [Bahcall et al. 1969]

✓ 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} , $(Z/X)_{Surf}$

The Standard Solar Model (SSM)

Note that:
Given the calibration procedure, the observed luminosity, radius and surface composition of the Sun provide no test for solar models

The predictions of SSMs can be, however, **falsified** by other observations. e.g.:

- *Solar neutrinos:*
Hydrogen fusion in the solar core produce a huge amount of neutrinos that can be measured in suitable detectors (Davis 1964, Bahcall 1964)

Solar Neutrino Problem
Nuclear energy generation (cross sections, etc.)

- *Helioseismology:*
Solar oscillations originally discovered by Leighton at al. 1962 and interpreted as standing acoustic waves

Elemental Diffusion
Opacity, EoS, ...

Constant improvement in SSM constitutive physics was triggered during last decades by solar neutrino and helioseismic data

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:

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

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

$$Y_b = 0.2485 \pm 0.0035$$

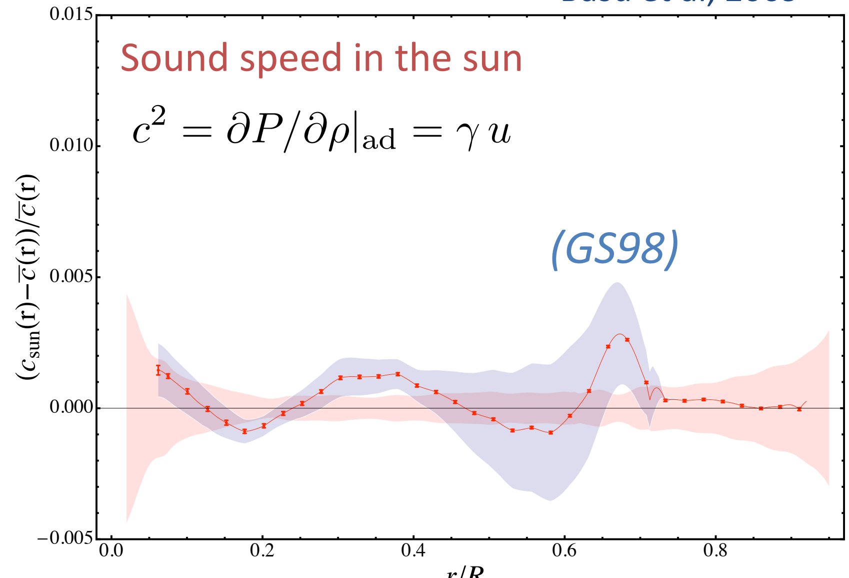
$Y_b = 0.243$ *(GS98)*

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



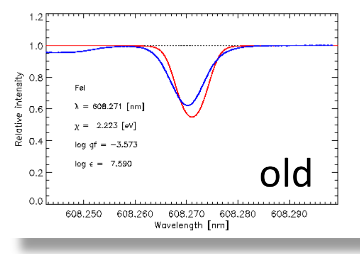
… till few years ago

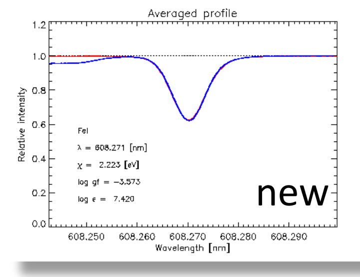
Asplund et al. 05 (AGS05); Asplund et al. 09 (AGSS09); Caffau et al. 2011, …

Downward revision of solar surface abundances

Solar surface composition is a fundamental input for SSMs → determined with spectroscopic techniques

N. Grevesse talk at PHYSUN10





- 3D hydrodynamic model instead of the classical 1D model of the lower solar atmosphere
- improvements in atomic properties
- NLTE instead of the classical LTE hypothesis

El.	GN93	GS98 (HZ)	AGSS09 (LZ)	C11	AGSS15	AAG20
C	8.55	8.52	8.43	8.50	—	8.46
N	7.97	7.92	7.83	7.86	—	7.83
O	8.87	8.83	8.69	8.76	—	8.69
Ne	8.08	8.08	7.93	8.05	7.93	8.06
Mg	7.58	7.58	7.60	7.54	7.59	7.55
Si	7.55	7.55	7.51	7.52	7.51	7.51
S	7.33	7.33	7.13	7.16	7.13	7.12
Fe	7.50	7.50	7.50	7.52	7.47	7.46
$(Z/X)_\odot$	0.0245	0.0230	0.0180	0.0209	—	0.0187

$\varepsilon_i = \log_{10}(n_i/n_H)+12$

-20% for C,N

-40% for O

Bergemann et al. 2021 - re-analysis oxygen abundance - $\varepsilon_O = 8.75 \pm 0.03$

The role of metals in the Sun

- Metals give a negligible contribution to EOS

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

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

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

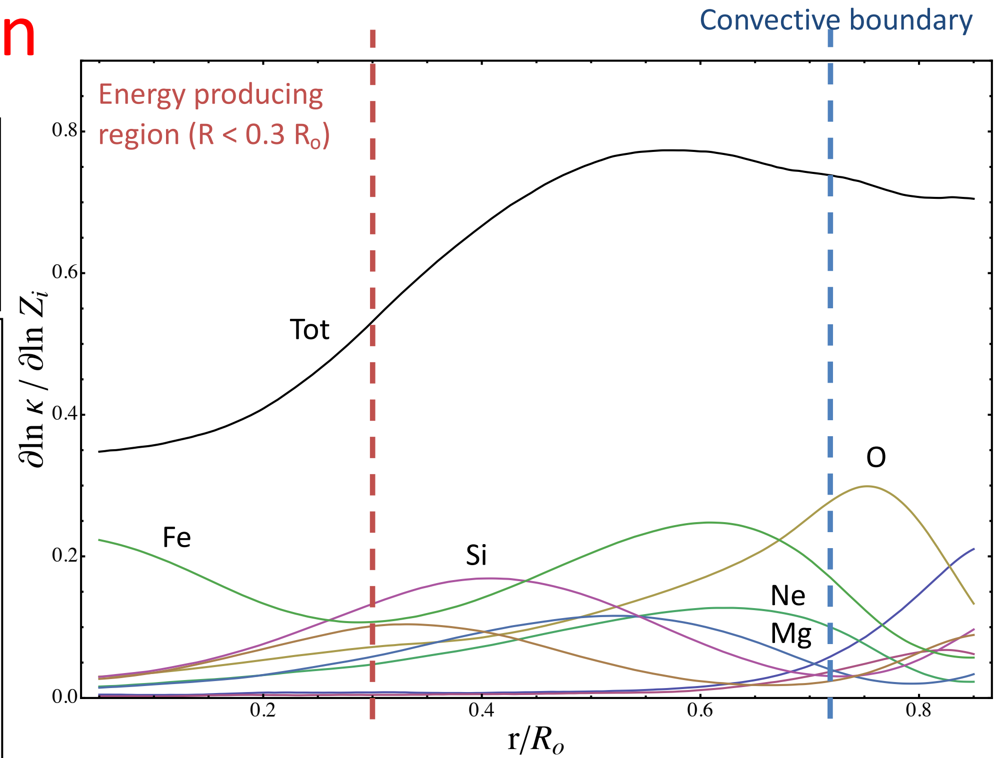
Fe gives the largest contribution.

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



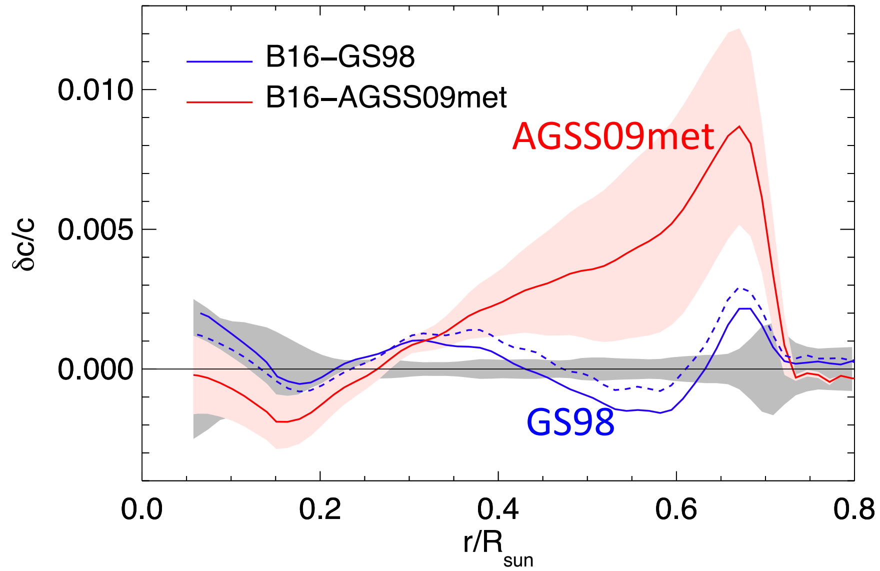
A change of the solar composition affects the efficiency of radiative energy transfer in the core of the Sun

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

Different temperature stratification

The solar abundance problem

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



The **downward revision** of heavy elements photospheric abundances leads to SSMs which **do not correctly reproduce helioseismic observables**

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

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

(≈ 2-3σ discrepancies)

Grevesse et al. 98 (**GS98**): 1D atm. model (old) – **High-Z**
Asplund et al. 09 (**AGSS09met**): 3D + NLT model (new) – **Low-Z**
(20% for C,N; 40% for O,Ne; 12% Fe,Si, S,Mg)

Note: GS98 and AGSS09met are used as references but do not exhaust the list of possible values.

The solar abundance problem

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

- Are the new abundances (i.e. the atmospheric model) **wrong**?
  [solar abundances are also used for other stars → implications for age and mass estimates]
  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:
We are testing our understanding of the Sun with potential implications for stellar astrophysics and/or fundamental physics.

Probing the Sun with neutrinos

Hydrogen Burning: PP chain and CNO cycle

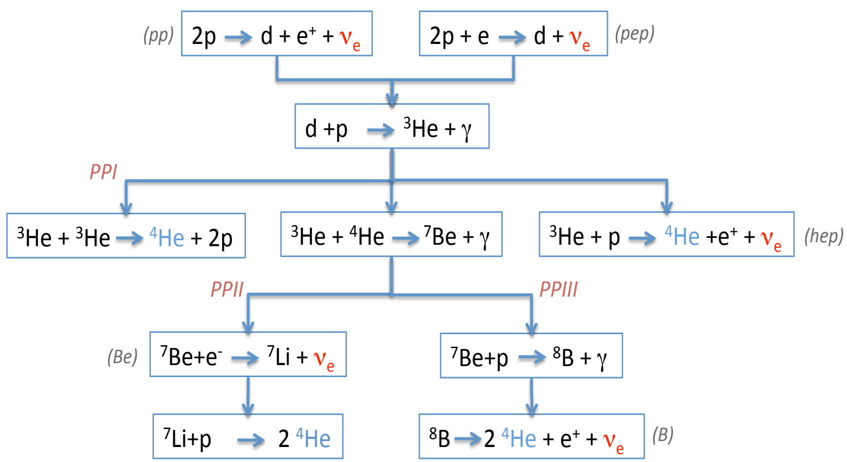
The Sun is powered by nuclear reactions that transform H into ^{4}He:

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

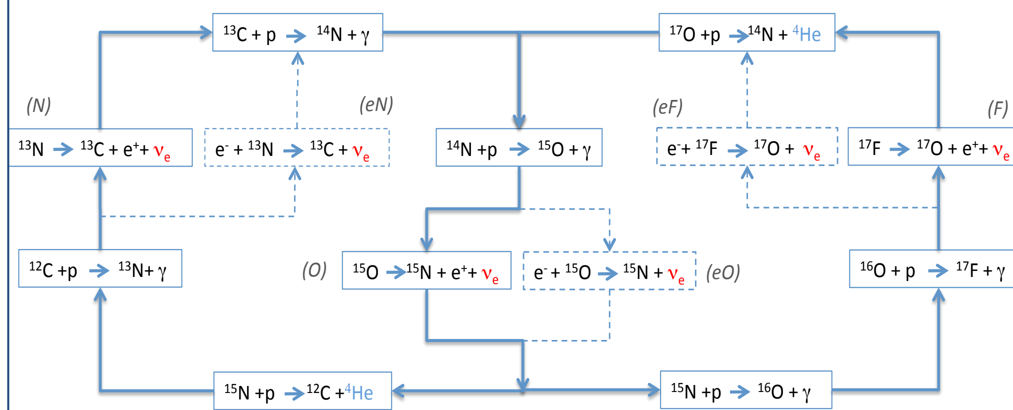
→ Q = 26,7 MeV (globally)

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

The PP-chain



The CN-NO (bi-)cycle

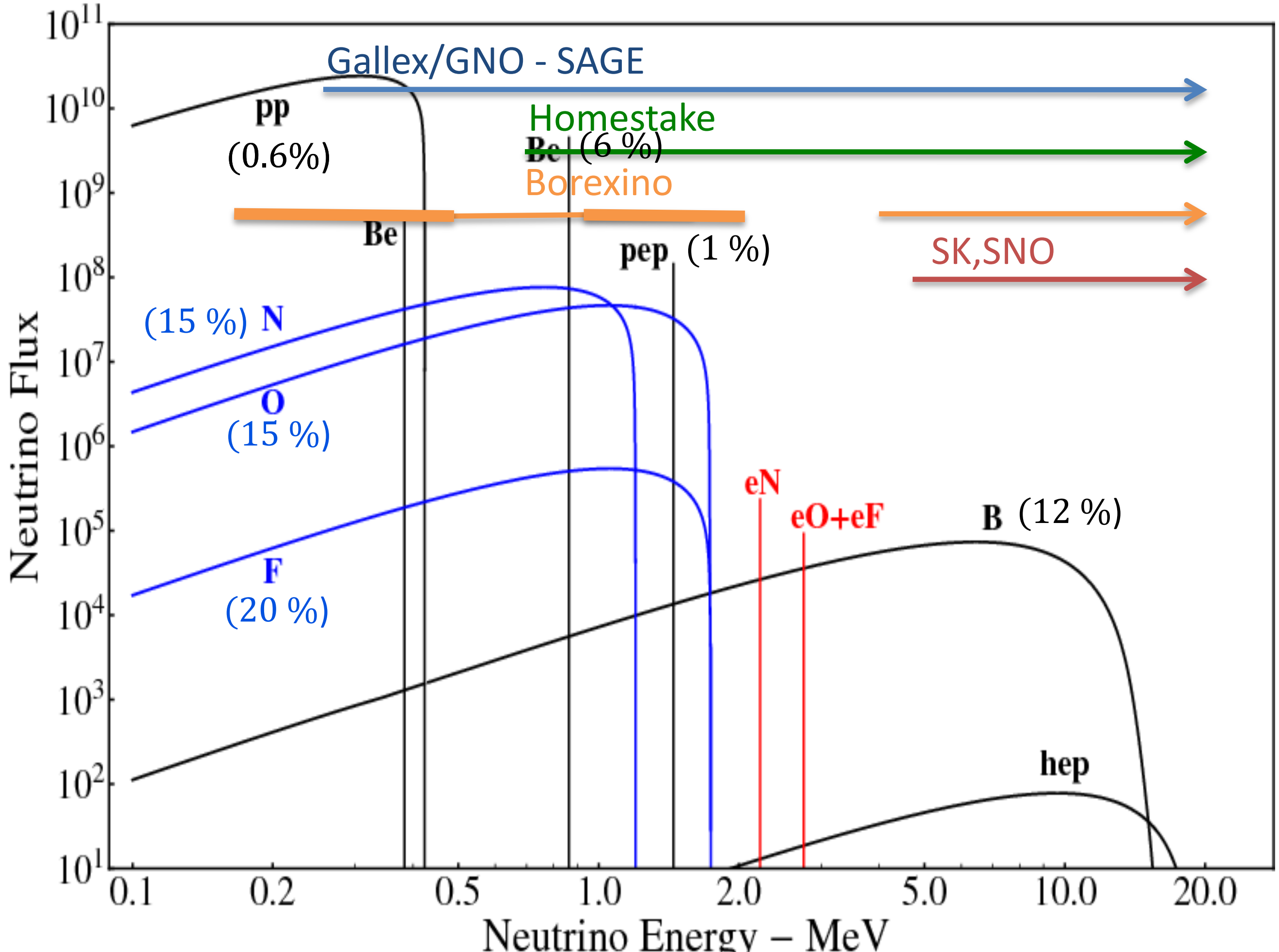


The pp chain is responsible for about 99% of the total energy (and neutrino) production.

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

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

The solar neutrino spectrum



The different comp. of the solar neutrinos flux have been **directly** determined by Borexino with accuracy level:

pp: ~ 10%
pep: ~ 10%
^{7}Be: ~ 3 %
^{8}B: ~ 2 % (SK,SNO)
CNO: ~ 30%

Milestones from **Borexino**:

- ^{7}Be (and ^{8}B) neutrino direct detection [PRL 2008]
- pp (and pep) neutrinos direct detection [Nature 2014, 2018]
- CNO neutrinos signal identification [Nature 2020]

The importance of measuring pp-neutrinos

Assuming that the Sun is **stable:**

$$L_\odot + L_\nu \; (+\, L_x) = \varepsilon_n + \varepsilon_g$$

Gravothermal energy prod. O(10^{-4} $L_\odot$)

where:

$L_\odot$ — **Radiative Luminosity**

$$L_\nu = 4\pi D^2 \sum_i \langle E_\nu \rangle_i \, \Phi_i$$ **Neutrino Luminosity**

$(+\, L_x)$ — **Additional (exotic) energy losses**

$$\varepsilon_n = 4\pi D^2 \sum_i \frac{Q}{2} \Phi_i$$

Energy released by nuclear reactions (Q=27.3 MeV)

up to O(10^{-3} $L_\odot$) corrections due to incomplete pp-chain and CNO-cycle

[Vescovi et al., 2021]

The importance of measuring pp-neutrinos

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up to $O(10^{-3}\, L_\odot)$ corrections due to incomplete pp-chain and CNO-cycle
[Vescovi et al., 2021]

$$\underbrace{L_\odot} \; (+L_x) = 4\pi D^2 \sum_i \left(\frac{Q}{2} - \langle E_\nu \rangle_i \right) \underbrace{\Phi_i}$$

Radiative luminosity
(Heat diff. time ≈ 10^5 year)

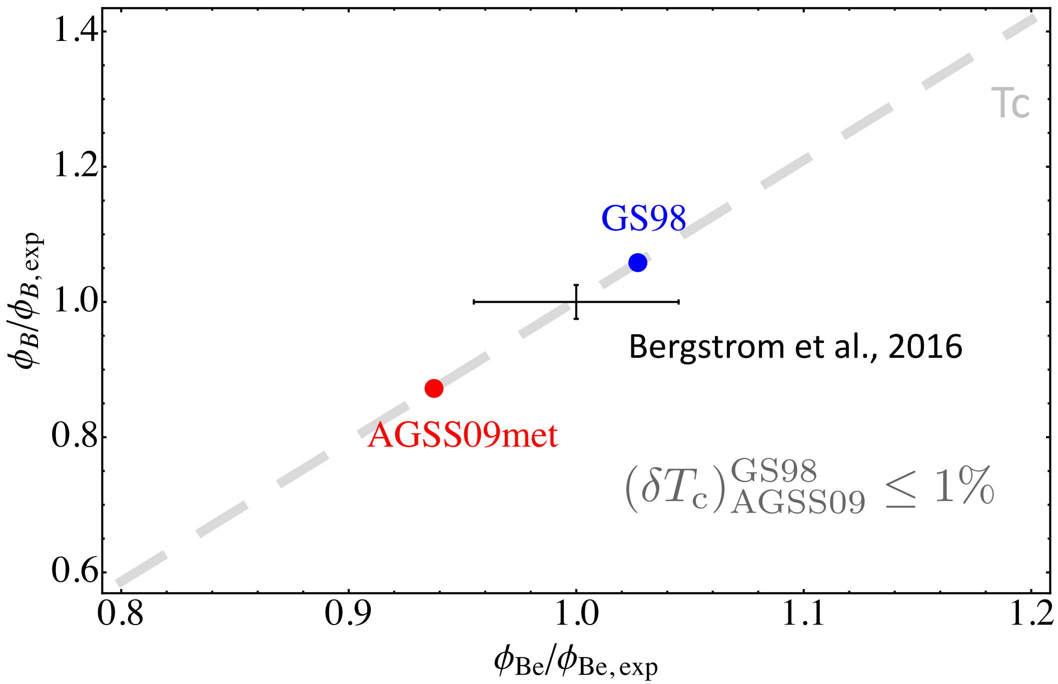
Neutrino fluxes
t_ν = 8 min

pp-neutrinos direct detection allows us to test:

- Solar stability
- Global energy balance of the Sun
- Additional energy losses/sources

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

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



^{7}Be and ^{8}B neutrinos depend on the core temperature T_c and on the cross sections that control the branching of different pp-chain terminations

$$\delta\Phi(^7\mathrm{Be}) = \delta S_{34} + \frac{1}{2}(\delta S_{11} - \delta S_{33}) + \beta_{\mathrm{Be}}\,\delta T_{\mathrm{c}}$$

$$\delta\Phi(^8\mathrm{B}) = (\delta S_{17} - \delta S_{e7}) + \delta S_{34} + \frac{1}{2}(\delta S_{11} - \delta S_{33}) + \beta_{\mathrm{B}}\,\delta T_{\mathrm{c}}$$

$$\begin{cases} \beta_{\mathrm{Be}} = \gamma_{34} + (\gamma_{11} - \gamma_{33})/2 \sim 11 \\ \beta_{\mathrm{B}} = \beta_{\mathrm{Be}} + \gamma_{17} + 1/2 \simeq 24 \end{cases}$$

N.B. The core temperature is a function of surface composition and enviromental parameters

$$\delta T_{\mathrm{c}} = f\,(\delta X_{\mathrm{i}}, \delta(\mathrm{opa}), \delta(\mathrm{diffu}), \ldots)$$

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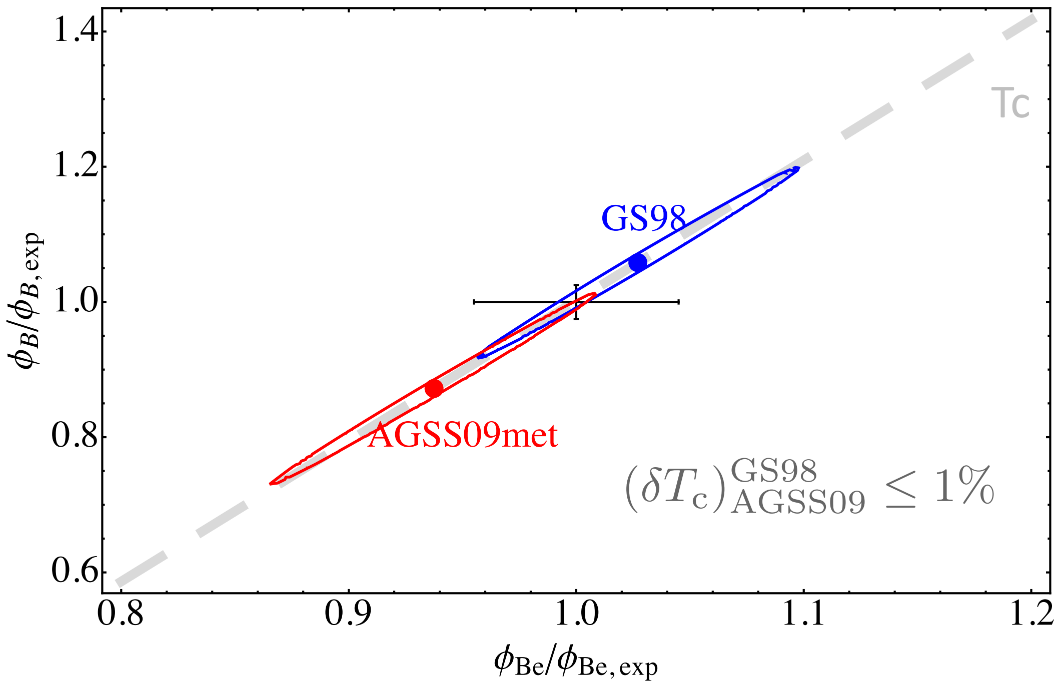

Theoretical uncertainties dominate the error budget. These are due to:

- 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:**

- constrain the core temperature at < 1% level

- do not determine the core composition with suff. accuracy (degenerate with opacity)

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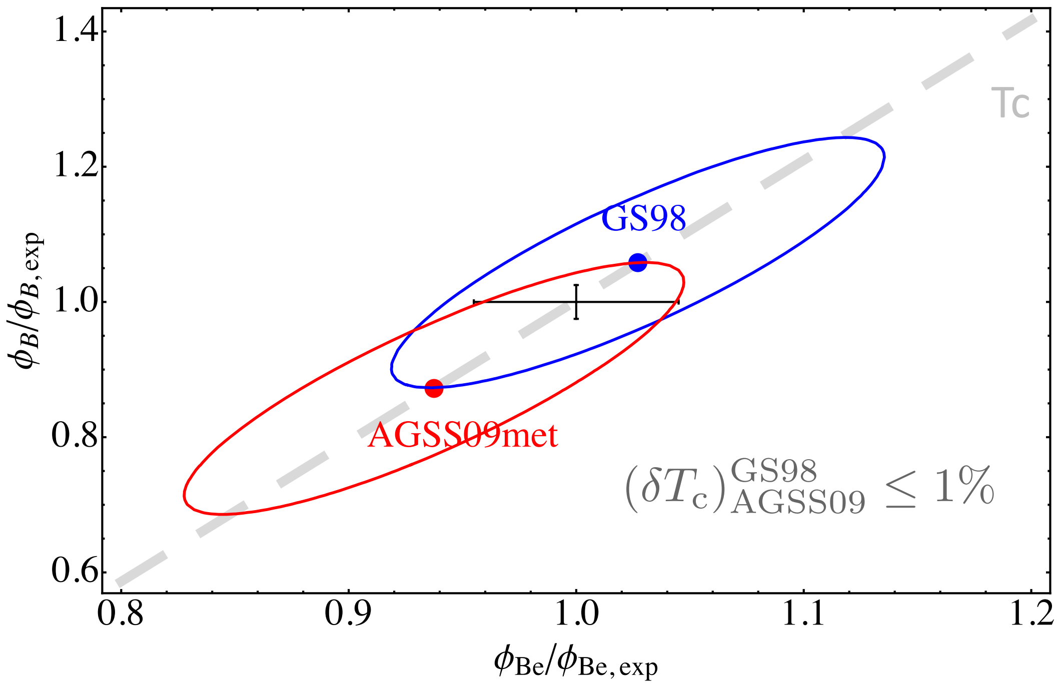

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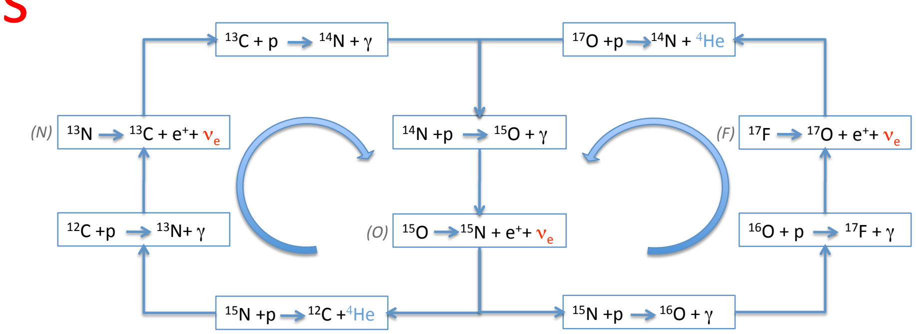
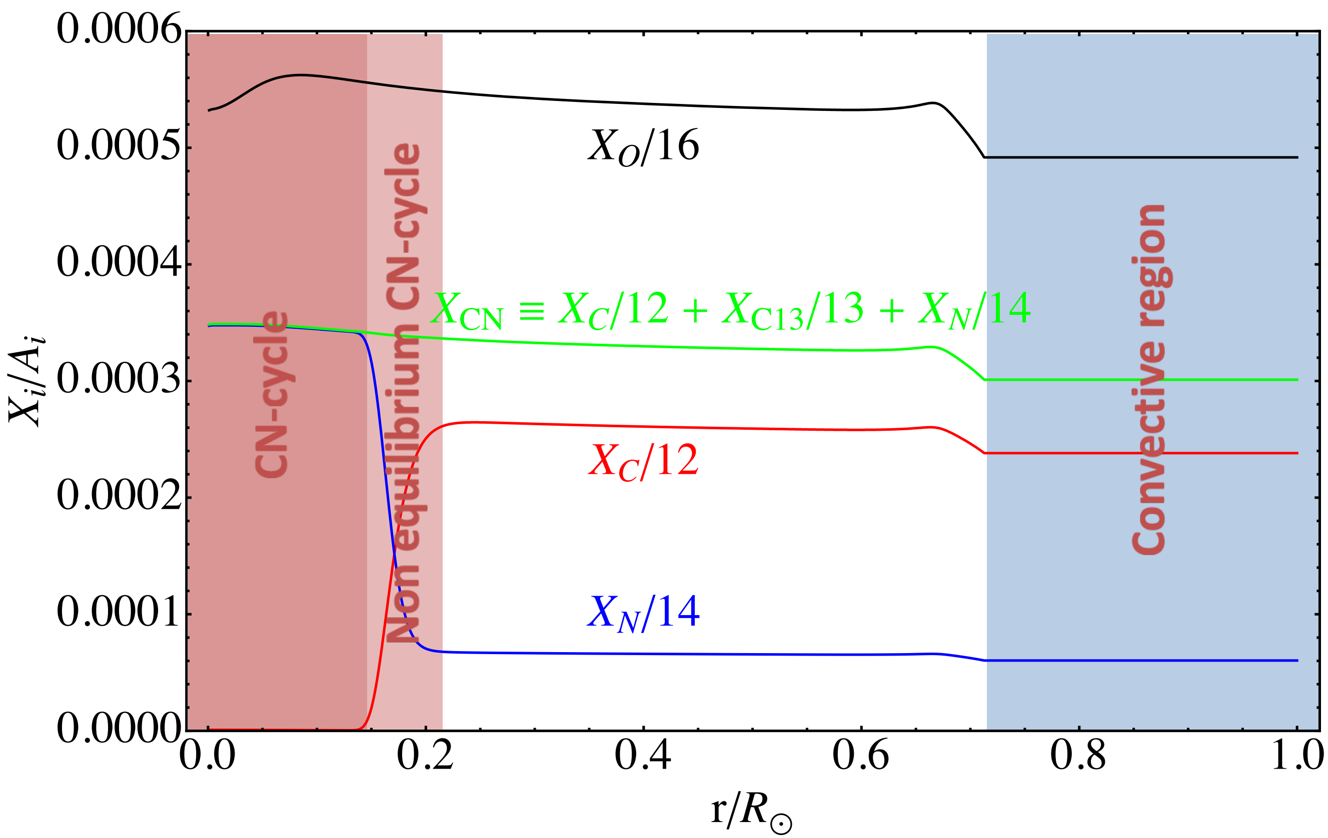
The importance of CNO neutrinos

Neutrinos produced in the CNO-cycle may provide the clues for the solution of solar composition problem because **they directly probe the C+N abundance in the solar core**





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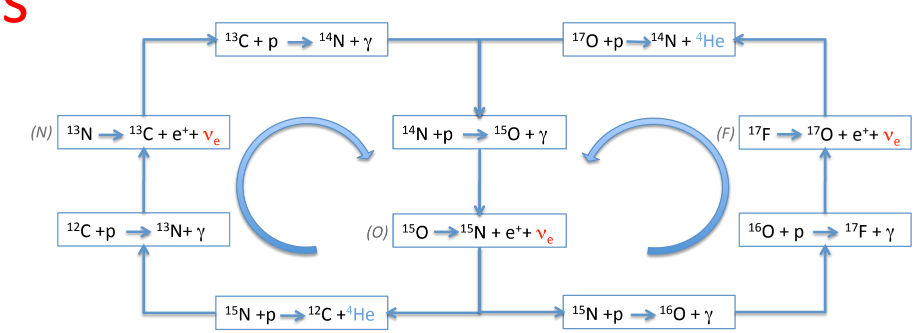
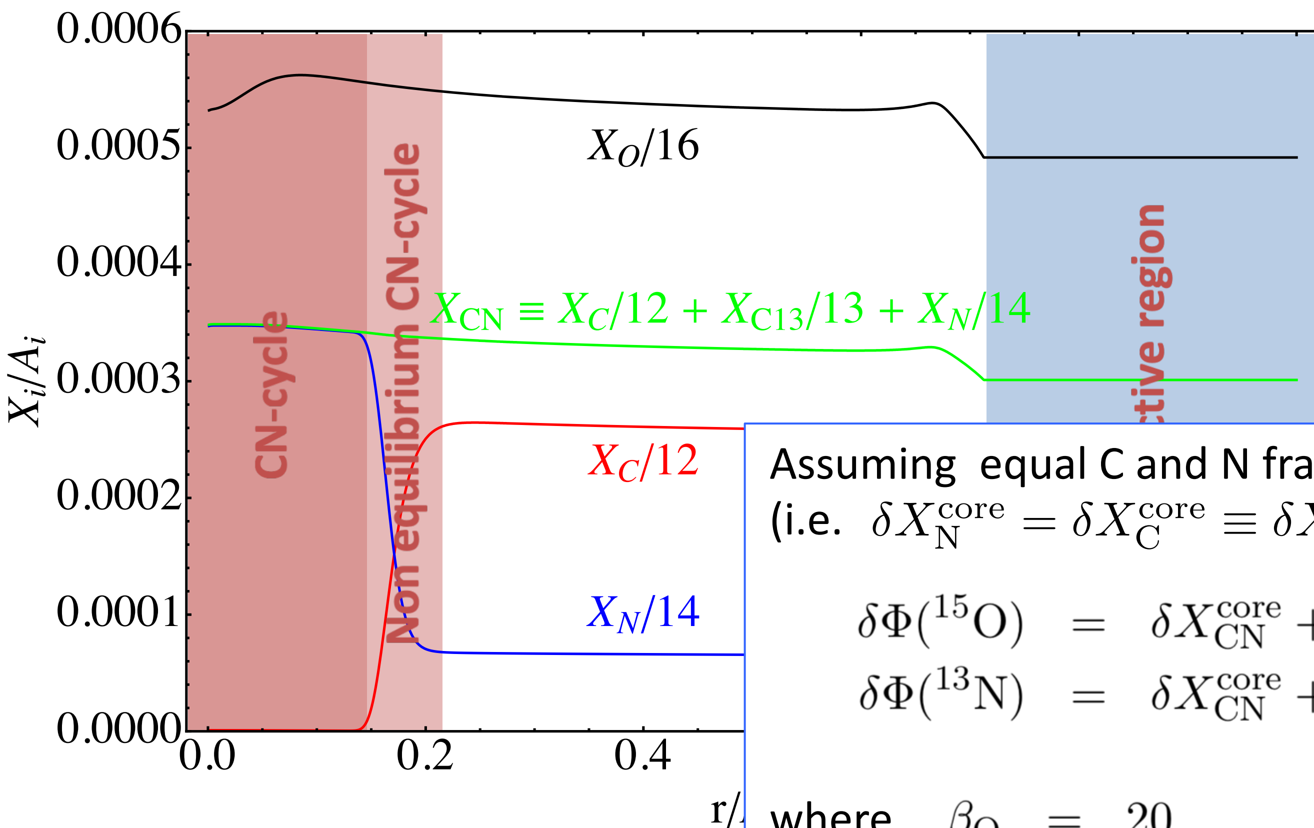




Assuming equal C and N fractional variations (i.e. $\delta X_{\rm N}^{\rm core} = \delta X_{\rm C}^{\rm core} \equiv \delta X_{\rm CN}^{\rm core}$):

$$\delta\Phi(^{15}{\rm O}) = \delta X_{\rm CN}^{\rm core} + \beta_{\rm O}\,\delta T_{\rm c} + \delta S_{114}$$

$$\delta\Phi(^{13}{\rm N}) = \delta X_{\rm CN}^{\rm core} + \beta_{\rm N}\,\delta T_{\rm c} + f\,\delta S_{114}$$

where $\beta_{\rm O} = 20$ and $f \simeq 0.7$

$\beta_{\rm N} = f\,\beta_{\rm O} = 15$

The importance of CNO neutrinos

The dependence of CNO neutrinos on CN-abundance can be used to **test solar core composition**

$$\delta\Phi(^{15}\mathrm{O}) = \delta X_{\mathrm{CN}}^{\mathrm{core}} + \beta_{\mathrm{O}}\,\delta T_{\mathrm{c}} + \delta S_{114}$$
$$\delta\Phi(^{13}\mathrm{N}) = \delta X_{\mathrm{CN}}^{\mathrm{core}} + \beta_{\mathrm{N}}\,\delta T_{\mathrm{c}} + f\,\delta S_{114}$$

BOREXINO is probing the combination:

$$\delta R_{\mathrm{CNO}}^{\mathrm{BX}} \simeq 0.76\,\delta\Phi(^{15}\mathrm{O}) + 0.24\,\delta\Phi(^{13}\mathrm{N})$$

Agostini et al, EPJ 2021

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

$$\delta R_{\mathrm{CNO}}^{\mathrm{BX}} - 0.716\,\delta\Phi(^{8}\mathrm{B}) \simeq \delta X_{\mathrm{CN}}^{\mathrm{core}} \pm 0.5\%\,(\mathrm{env}) \pm 9.1\%\,(\mathrm{nucl})$$

Serenelli et al., PRD 2013
See also (application to BX obs. rate):
Agostini et al, EPJ 2021
Villante & Serenelli, Frontiers 2021

The possibility to perform the above test is only limited by **nuclear reactions rate uncertainties.** The “nuclear uncertainty” is globally ~10 % with contributions:

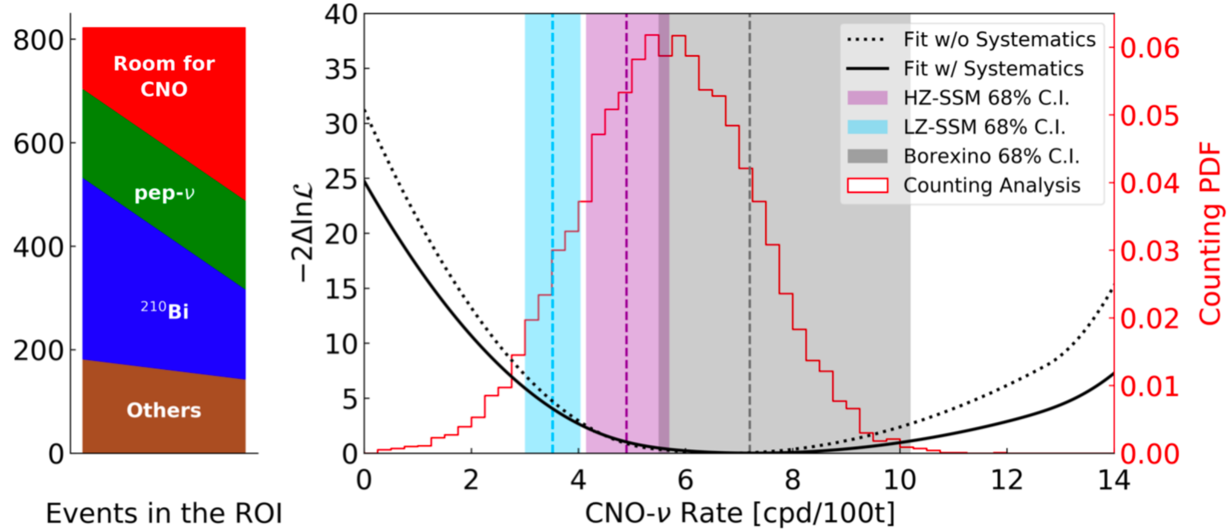
S_{114} → 7.6 %
S_{17} → 3.5 %
S_{34} → 3.4 %
….

B16-SSMs:

- S_{114} (accuracy 7.6%) from Marta et al 2011 [R-matrix fit of LUNA data]

The CNO neutrino flux measured by Borexino

The observed CNO solar neutrino interaction rate in Borexino is R_{BX} (CNO) = $7.0^{+3.0}_{-1.7}$ cpd/100t
[Absence of CNO neutrino signal disfavoured at 5.0σ] Nature, 2020



High-Z .vs. Low-Z

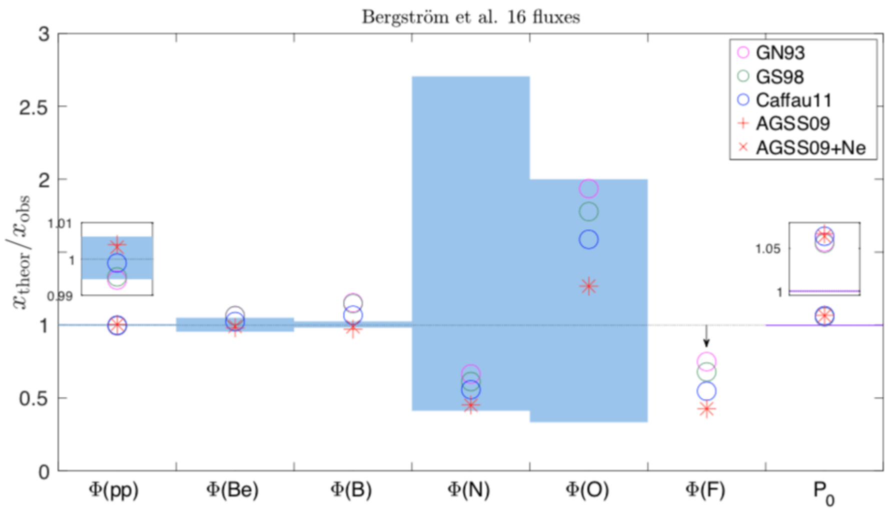
$$\delta\phi_{\rm O} = \frac{\phi_{\rm O}^{\rm HZ} - \phi_{\rm O}^{\rm LZ}}{\phi_{\rm O}^{\rm LZ}} \simeq 40\%$$

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

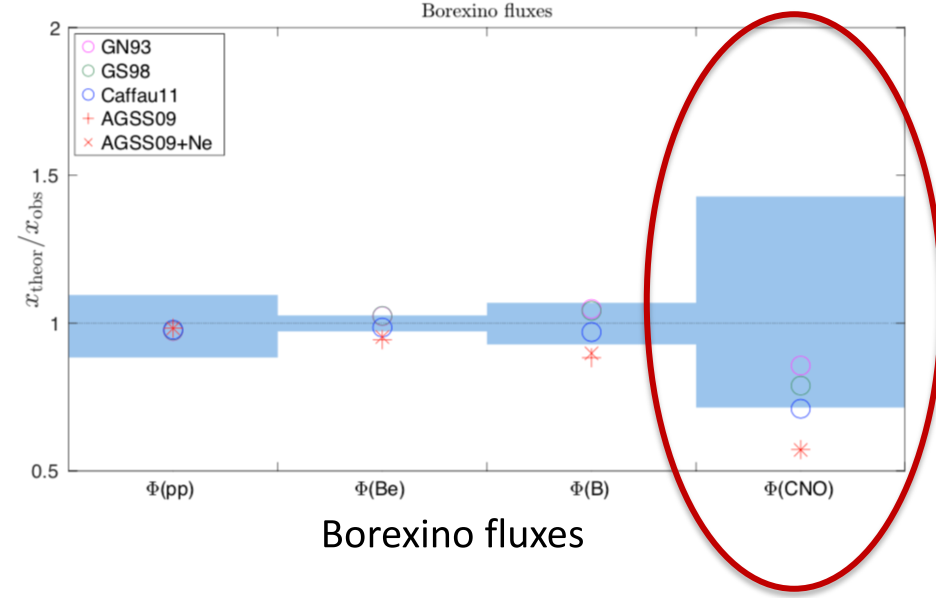
$$\delta X_{\rm CN} = \frac{X_{\rm CN}^{\rm core} - X_{\rm CN}^{\rm surf}}{X_{\rm CN,ini}} \simeq 15\%$$

Neutrino fluxes - the present situation

Comparison between theoretical predictions and observational results:
[Salmon et al. 2021]



Pre-2020 (Bergstrom et al, 2016)



Borexino fluxes

Borexino results favor HZ but uncertainty is still large.

If trends were confirmed → BX: HZ in the core + Asplund 2021: LZ at the surface
→ Could the Sun be less homogeneous in metals than expected?

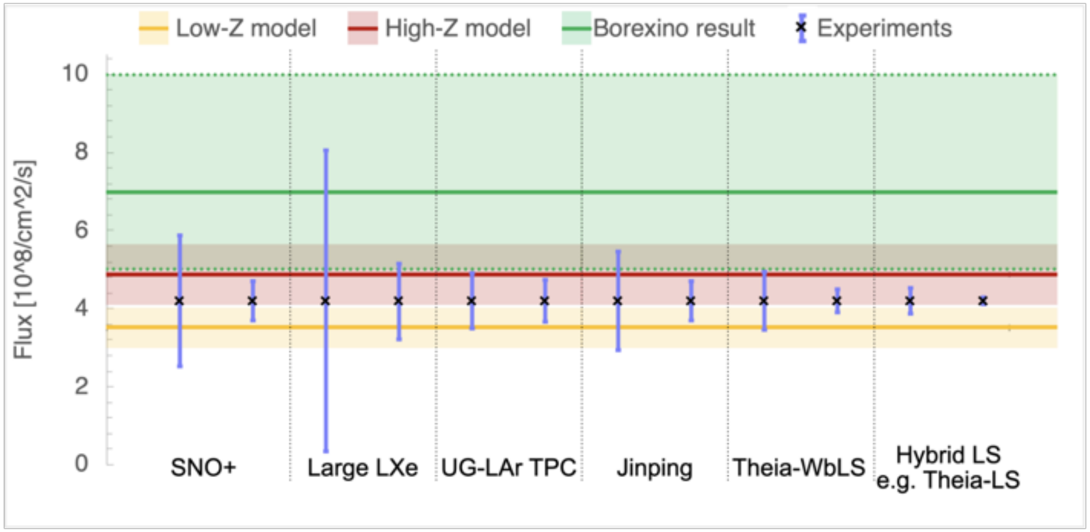
Future perspectives

Borexino <u>has opened the way</u> and it is still analyzing data

Improvements on the experimental side will be provided in the future by planned detectors, e.g.:

- SNO+
- JUNO
- Jinping
- Hyper-Kamiokande
- THEIA
- DUNE
- Dark Matter experiments

…….



ARNP – Orebi Gann et al. in press

Note that: some minor components (hep and ecCNO) of the solar neutrino flux are still undetected

- 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*

Conclusions

- Solar neutrino physics is entering the precision era

- Borexino solar neutrino measurements have provided a detailed knowledge of the of solar core → constraints on standard and non/standard energy generation and transfer mechanisms; solar core temperature; solar chemical evolution paradigm, etc.

- Some unsolved puzzles could be addressed → Future CNO neutrino measurements, combined with precise determinations of ^{8}B and ^{7}Be fluxes, can shed light on the solar abundance problem

- To exploit the full potential of future measurements → improvements in the SSM constitutive physics are needed [radiative opacities and nuclear cross sections]

Thank you

Standard Solar Models

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

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

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

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

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

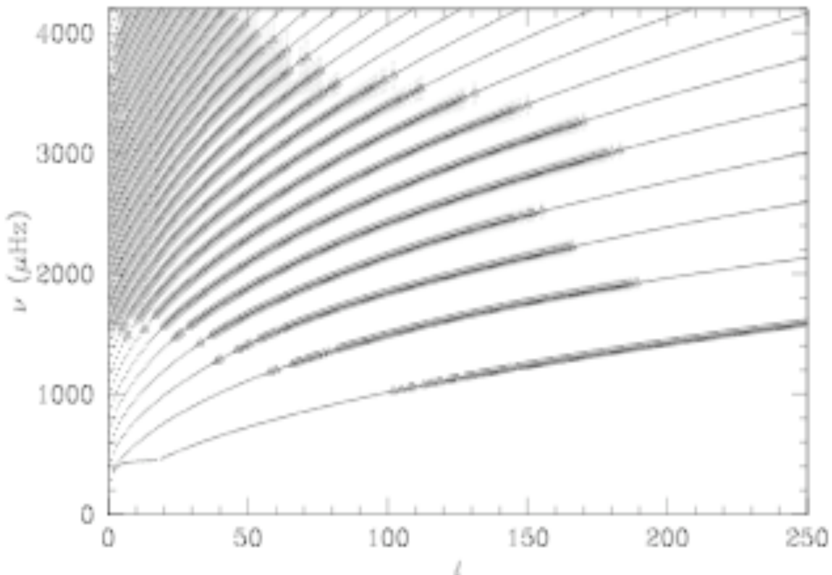
Free-parameters (mixing length, Y_{ini}, Z_{ini}) adjusted to match the observed properties of the Sun (radius, luminosity, Z/X).

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

The solar abundance problem

The **downward revision** of heavy elements photospheric abundances leads to SSMs which **do not correctly reproduce helioseismic observables**

Oscillation frequencies of the sun



360 days of observation of the MDI instrument (errors multiplied by 5000)

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

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

surface helium abundance

squared isothermal sound speed

Related to temperature stratification in the sun

See Basu & Antia 07 for a review

Recent results for photospheric composition

Asplund et al. 2021

re-analysis of the solar abundances for 83 long lived elements

It confirms the low solar abundances of C, N, and O obtained in previous studies:

$\log \varepsilon_C = 8.46 \pm 0.04$

$\log \varepsilon_N = 7.83 \pm 0.07$

$\log \varepsilon_O = 8.69 \pm 0.04$

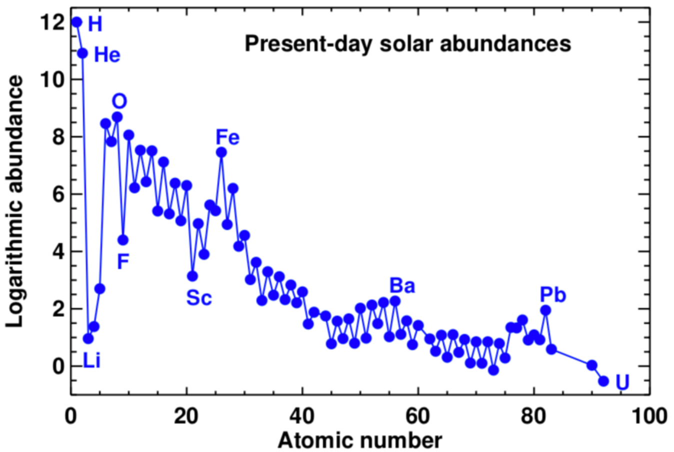
Source	Present-day photospheric			
	$X_{surface}$	$Y_{surface}$	$Z_{surface}$	$Z_{surface}/X_{surface}$
Asplund et al 2021	0.7438	0.2423	0.0139	0.0187
Lodders 2019	0.7389	0.2463	0.0148	0.0200
Caffau et al. 2011[a]	0.7321	0.2526	0.0153	0.0209
Asplund et al. 2009	0.7381	0.2485	0.0134	0.0181
Lodders et al. 2009	0.7390	0.2469	0.0141	0.0191
Asplund et al. 2005a	0.7392	0.2485	0.0122	0.0165
Lodders 2003	0.7491	0.2377	0.0133	0.0177
Grevesse & Sauval 1998	0.7347	0.2483	0.0169	0.0231
Grevesse & Noels 1993	0.7028	0.2800	0.0172	0.0245
Anders & Grevesse 1989	0.7065	0.2741	0.0194	0.0274

Bergemann et al. 2021

re-analysis of the solar photospheric oxygen (O) abundance

Larger value than Asplund 2021:

$\log \varepsilon_O = 8.75 \pm 0.03$

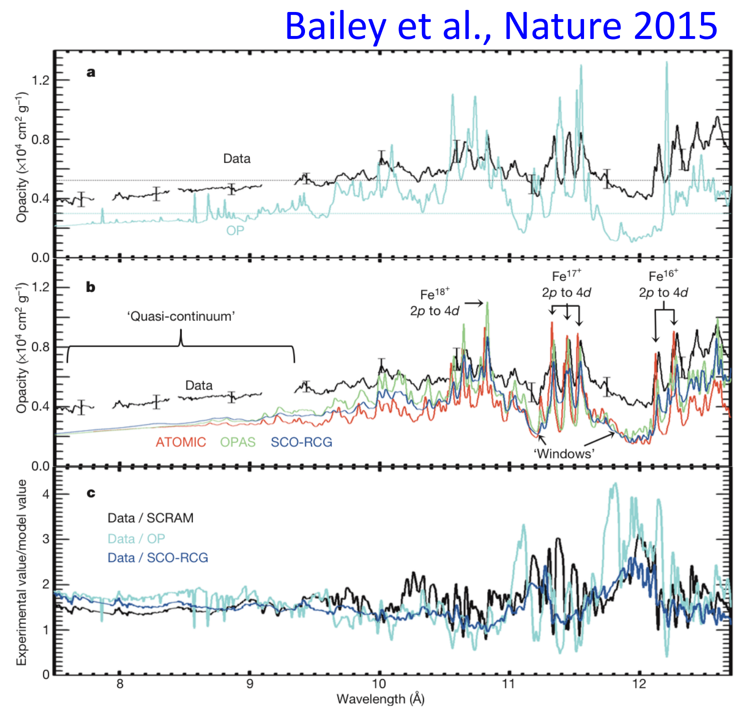


Asplund et al 2021

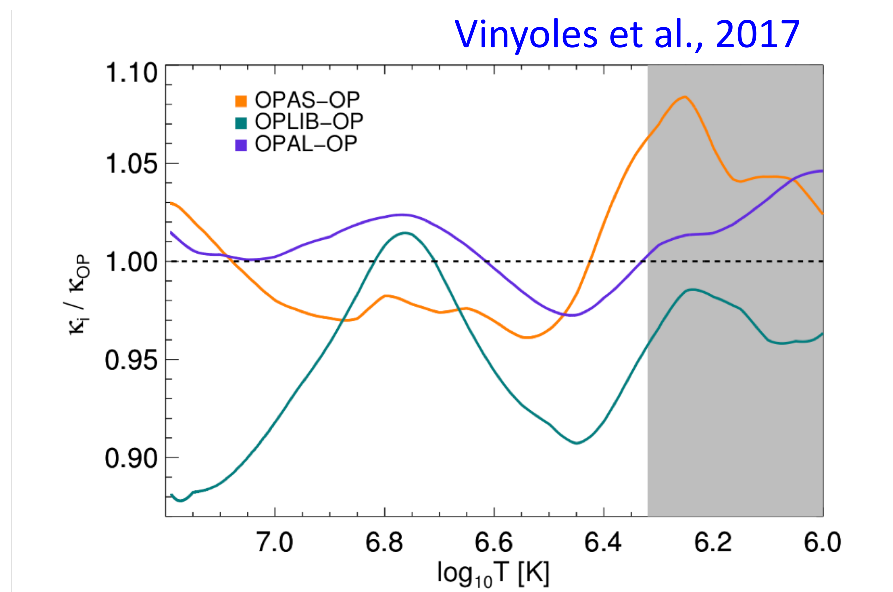
The two determinations are consistent with respect to quoted errors. However, the origin of the small difference seems to be understood

The solar abundance problem remains intact

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%



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

Experimental results for opacity: Fe

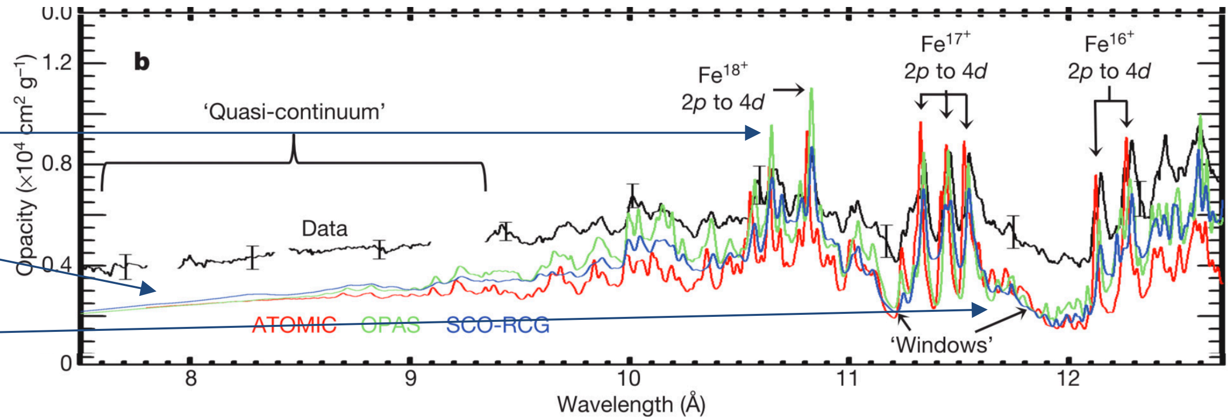
Bailey et al. 2015

Models have:

1) Narrower lines

2) Lower quasicontinuum

3) Deeper opacity windows



Experimental hint of higher opacity than theoretical calculations predict

Fe-Rosseland mean +40% → Total Rosseland mean +7±4%

Further experiments with Cr and Ni yield (Nagayama et al 2019):

1) Narrower lines present in all cases (problem in the models)

2) Deeper opacity windows – linked to open L-shell (present for Fe and Cr, not Ni)
Not present at low-T Fe experiment (Bailey et al. 2015)

3) No quasicontinuum problem for Cr and Ni – but experiments carried out at lower T
Fe experiment at low T also shows (smaller) problem (Bailey et al. 2015)

Unknown (non monotonic in Z) dependence missing in models?
Experimental flaw in the hot Fe (T > 180eV) experiments

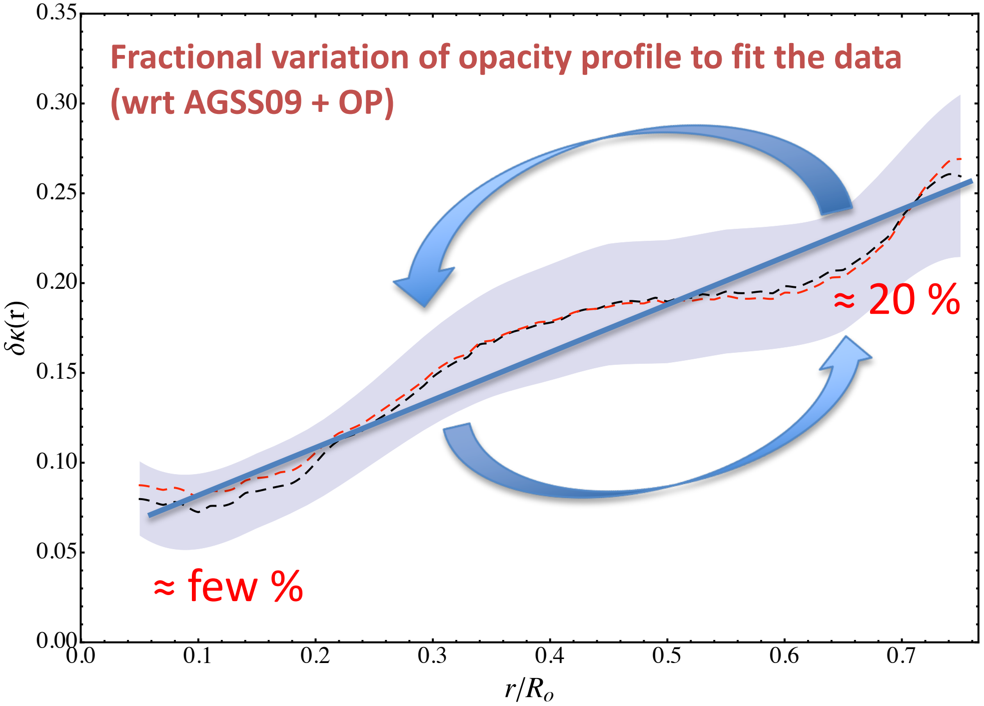
The solar opacity profile

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



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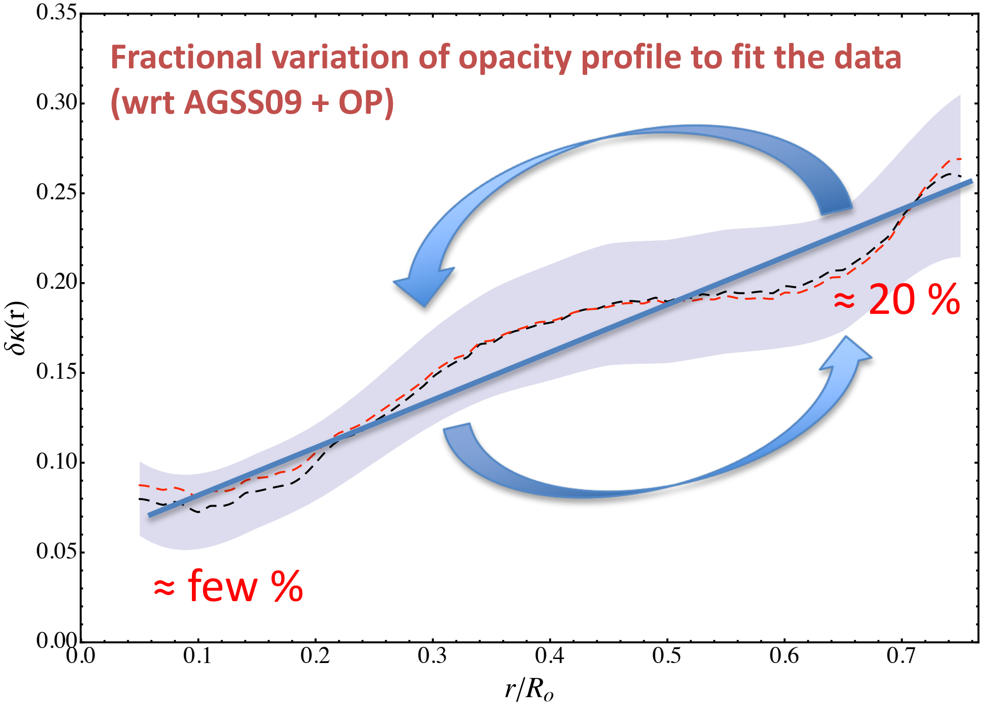

<u>*Caveat*</u>

- *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)*

The solar opacity profile

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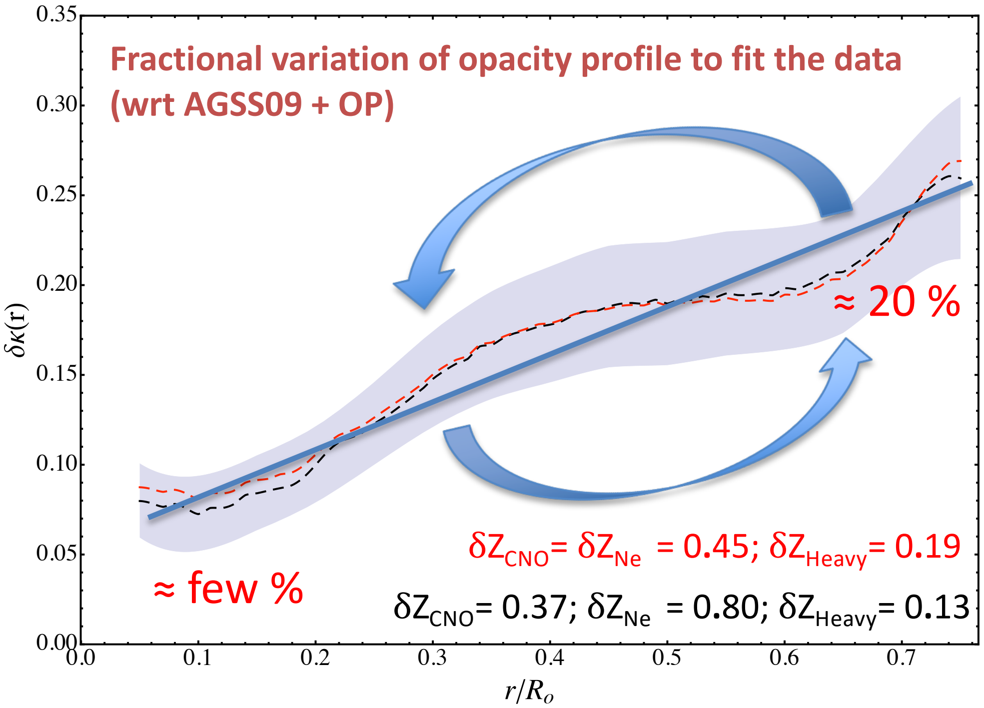
The **"optimal" opacity profile** of the Sun can be determined from obs. data

Note that:

- The sound speed and the convective radius determine the tilt of $\delta\kappa(r)$ (but not the scale)
- The surface helium and the neutrino fluxes determine the scale for $\delta\kappa(r)$



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

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

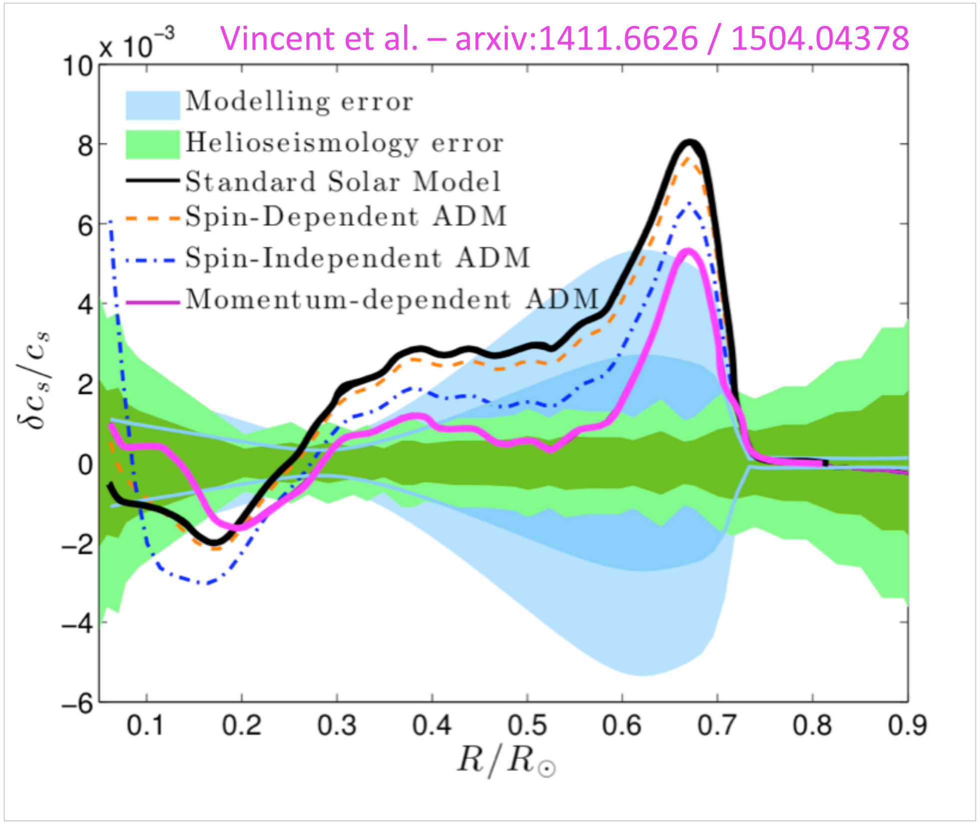
Opacity table "errors"
Non standard effects (WIMPs in solar core)
…

different admixtures $\{\delta z_i\}$ can do equally well the job

Asymmetric DM

DM accumulation in the solar core:

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

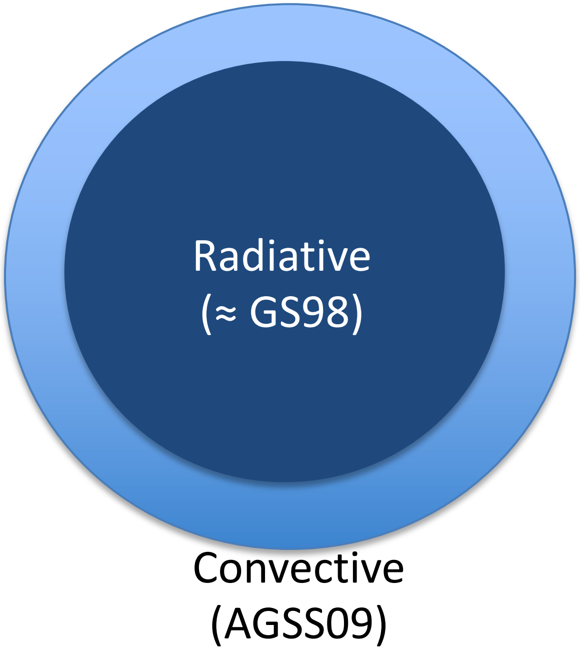


Agreement with helioseismic data can be improved. However:

→ 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)

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

Wrong chemical evolution?



Helioseismic observables and neutrino fluxes are sensitive to **the metallicity of the radiative interior 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

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

Future Proposals

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

See also G. Orebi-Gann talk@Neutrino2014

- G2 DD dark matter experiments will probe solar neutrinos, see e.g.

Cerdeno et al., arXiv:1604.01025;
Franco et al. arXiV:1510.04196 (300 ton Lar-detector@LNGS for solar-ν).

- 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;

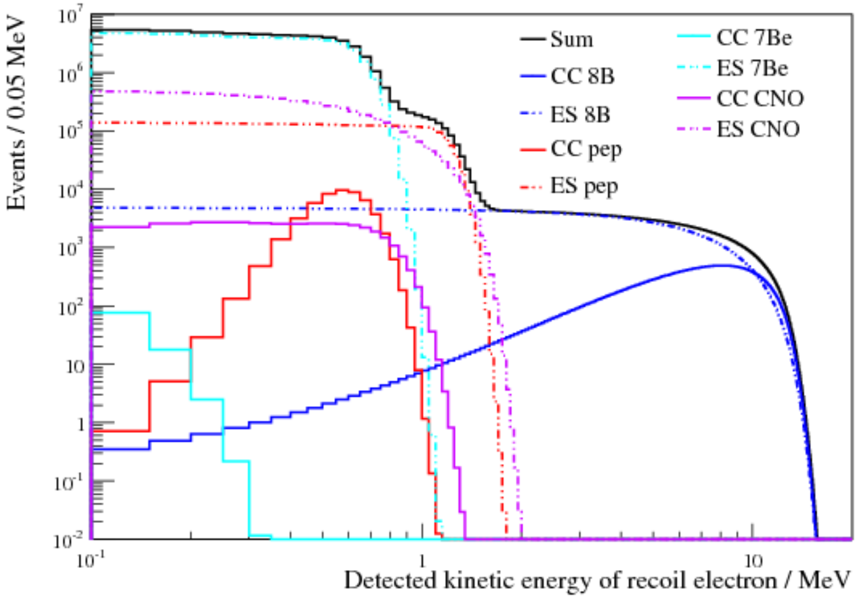
In the future … Advanced Scintillator Detector Concept (ASDC)

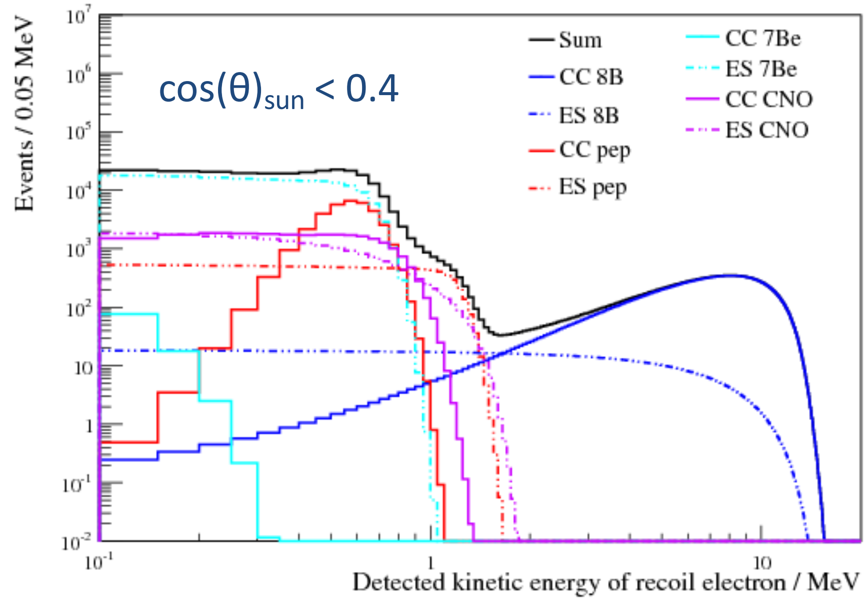
It combines:

- 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

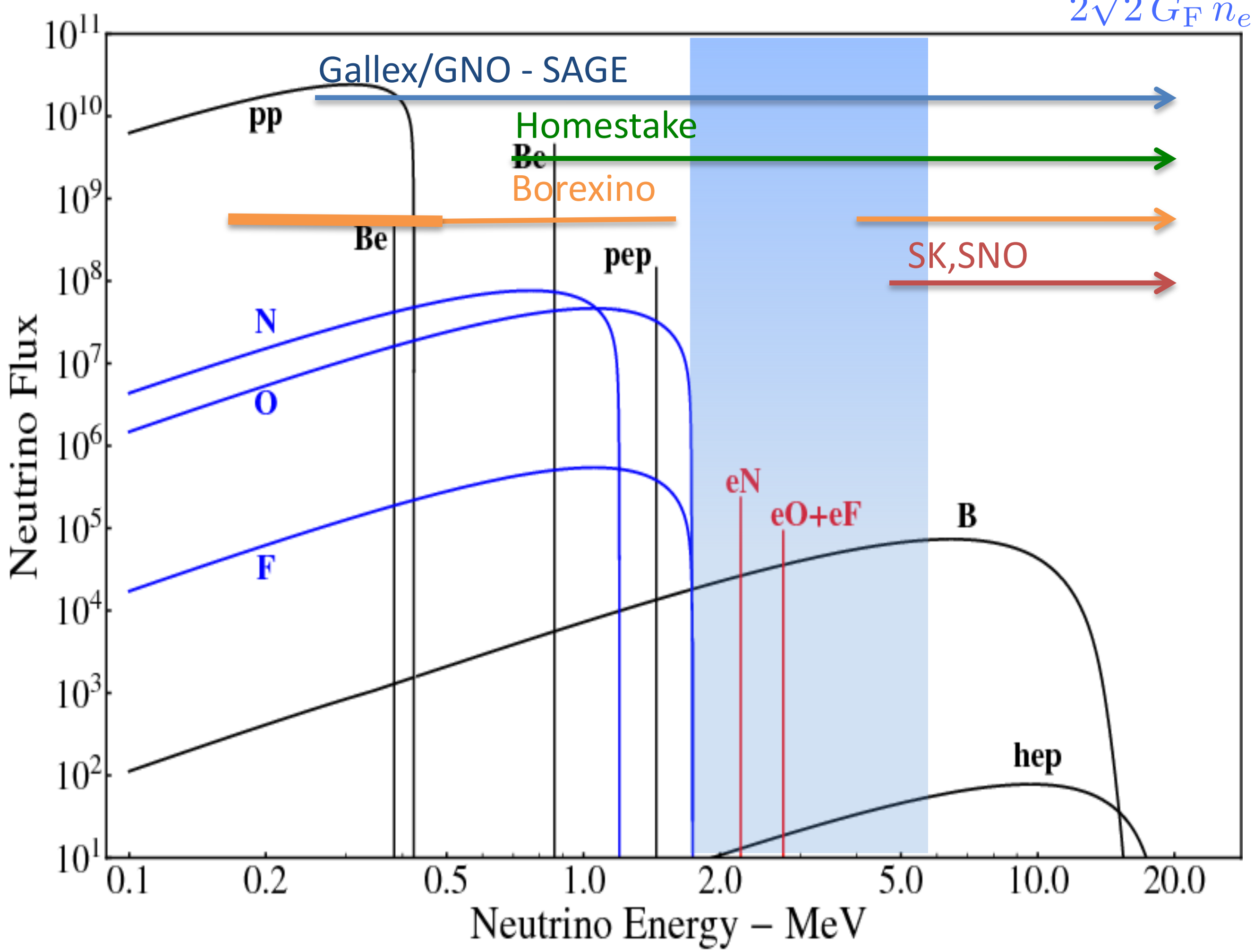




From arXiv:1409.5864

“Advertising” electron-capture CNO neutrinos …

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



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

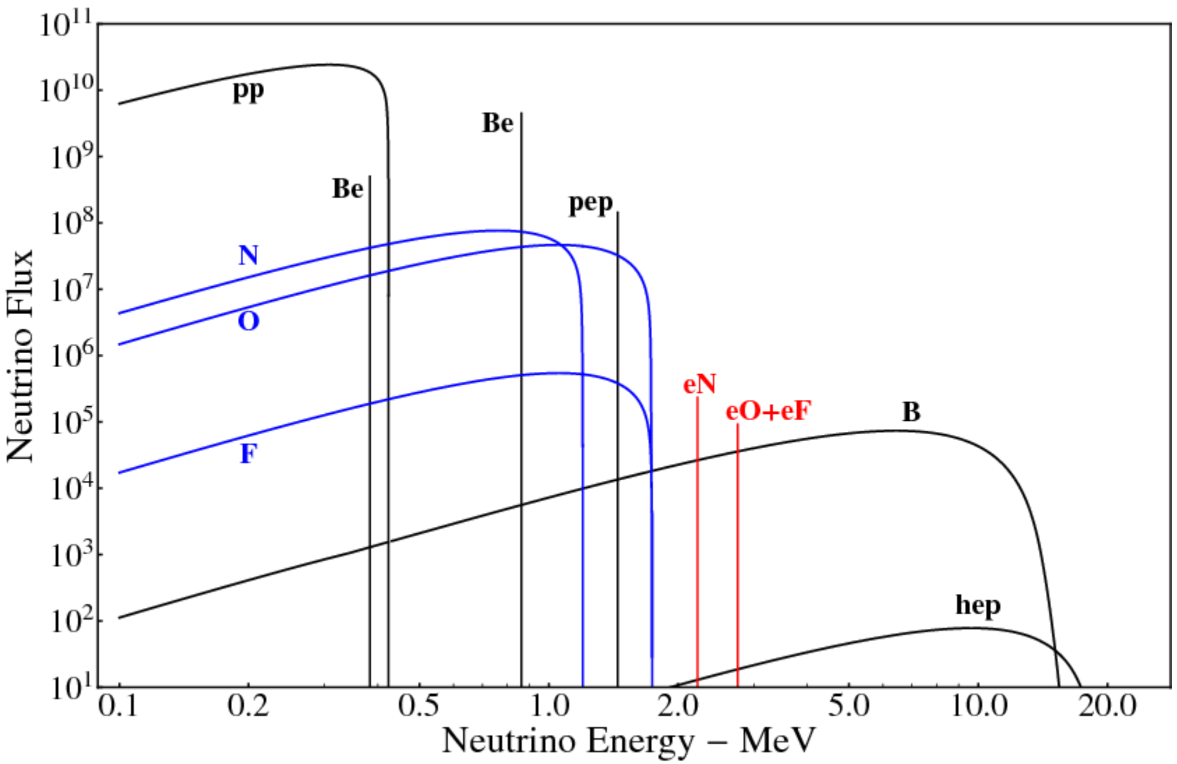
ecCNO neutrinos:

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

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:

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



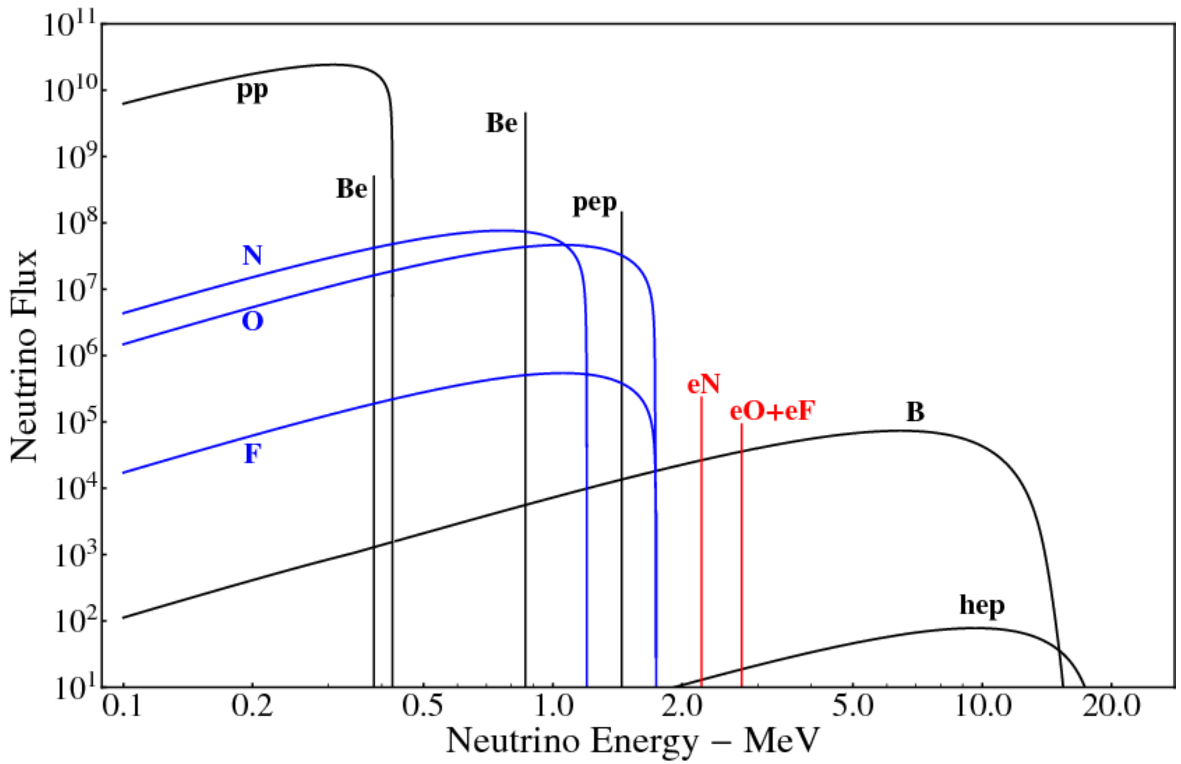
F.L. Villante, PLB 742 (2015) 279-284
L.C. Stonehill et al, PRC 69, 015801 (2004)
J.N. Bahcall, PRD 41, 2964 (1990).

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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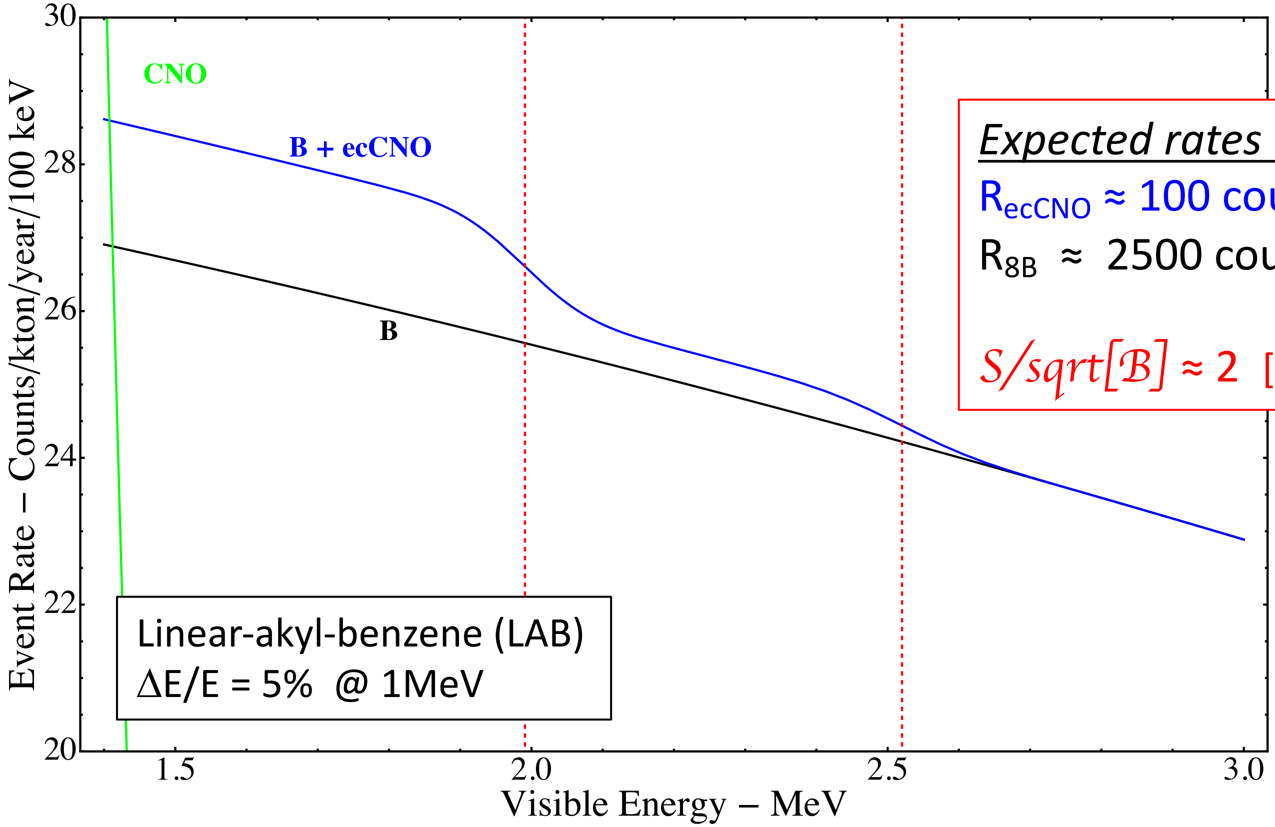
Expected rates in Liquid Scintillators

- $\nu - e$ 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]

$R_{ecCNO} \approx$ 100 counts/10 kton/year

$R_{8B} \approx$ 2500 counts/10kton/year

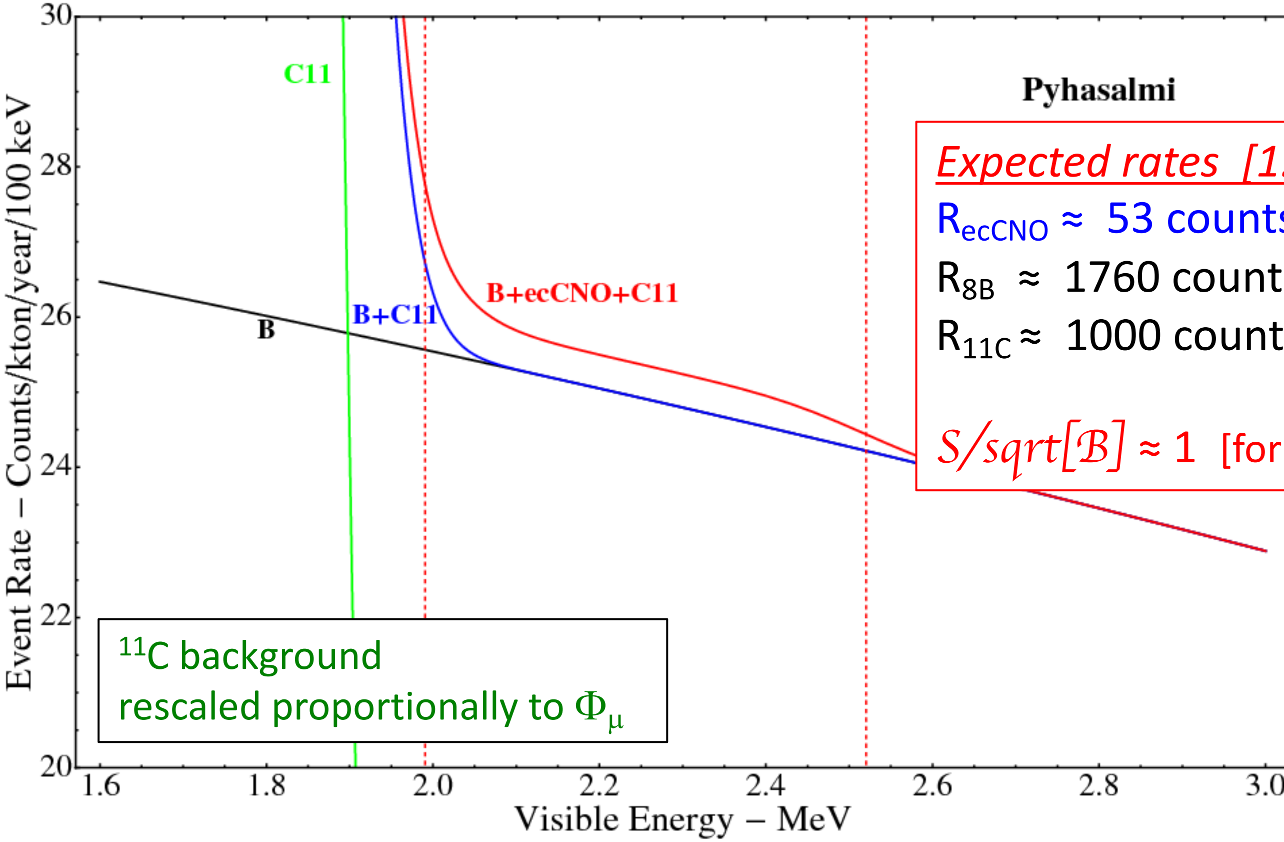
$\mathcal{S}/sqrt[\mathcal{B}] \approx 2$ [for 10kton × year exposure]

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

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

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

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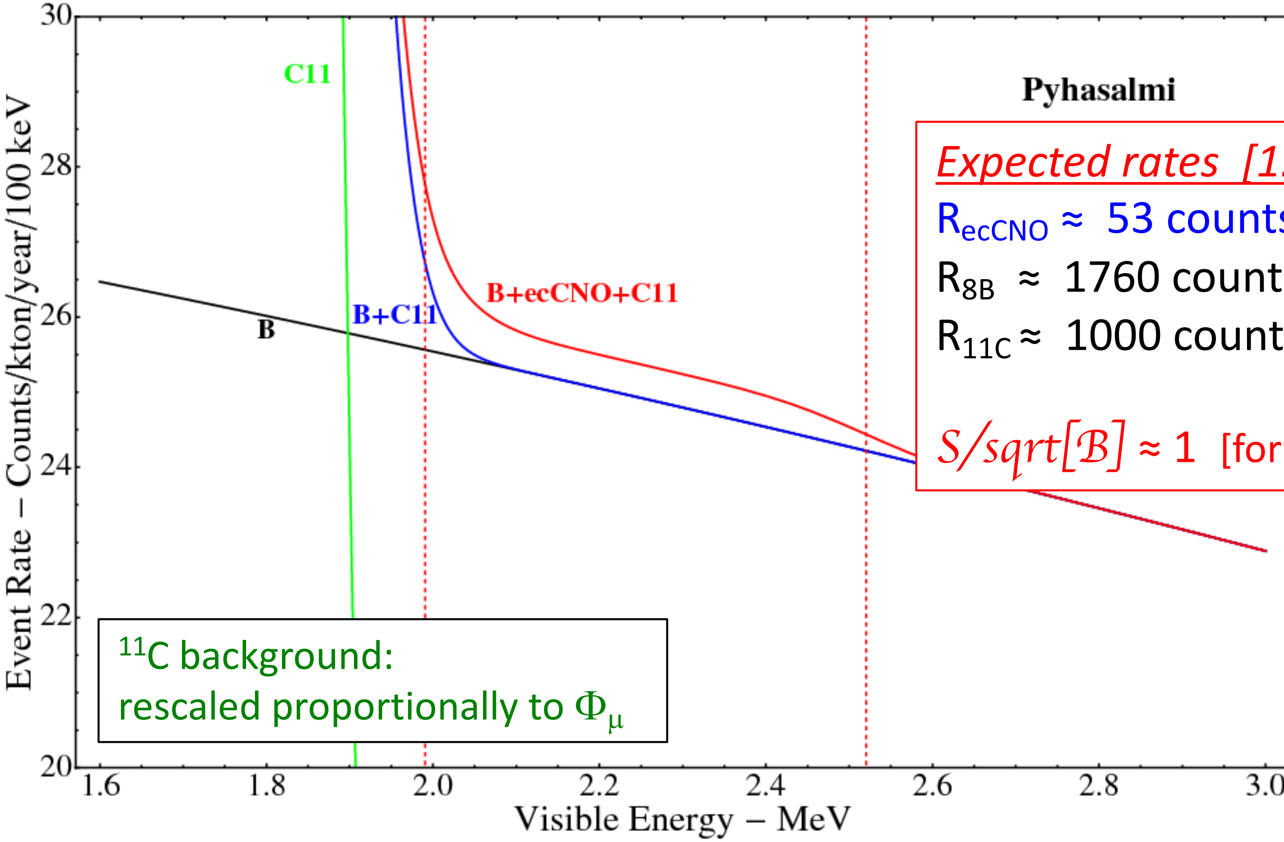

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$R_{11C} \approx$ 1000 counts/10kton/year

$S/sqrt[B] \approx 1$ [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