How can CNO neutrinos unravel the solar metallicity problem?

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on behalf of the Borexino collaboration

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University of Milan, INFN Milan

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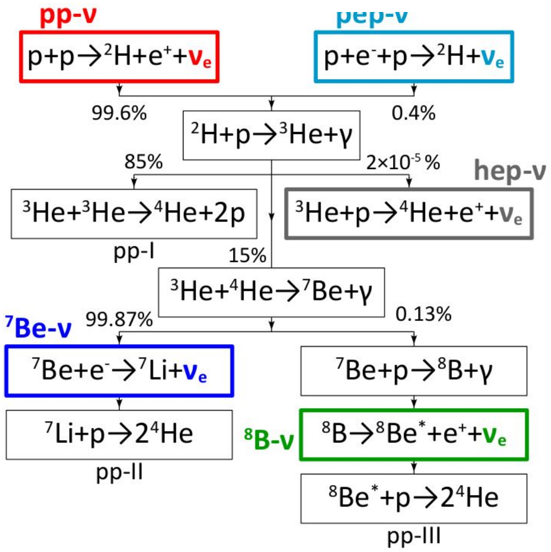
1) Solar-ν and SSMs

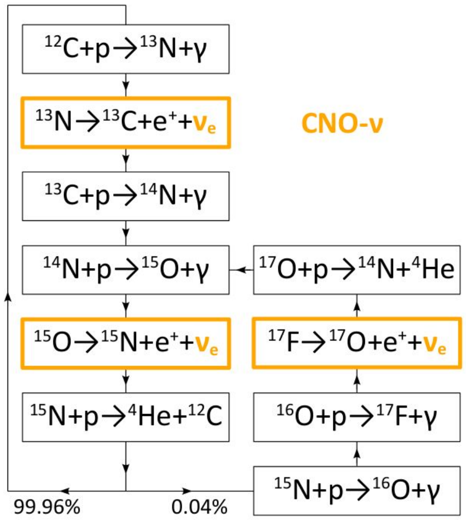
Solar neutrinos

- Sun is powered by nuclear fusion reactions → neutrino emission
- "Photography" of the Sun core
- Two sequences: pp-chain (primary in the Sun, ~99% lum.) and the secondary CNO cycle

pp chain



CNO cycle



Net reaction:

$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + Q$$

Q = 26.731 MeV

Solar neutrinos

strict interplay between astrophysics and particle physics

Astrophysics ← solar ν → **Particle physics**

Solar neutrinos as messengers

↓

Solar metallicity problem

↑

CNO neutrinos

Sun as neutrino source

↓

Flavor oscillations: matter effects, Non-Standard interactions...

Standard Solar Model

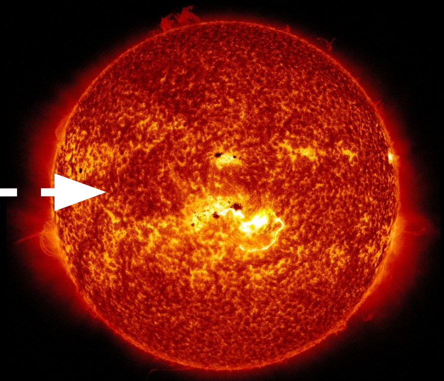
Describing the Sun evolution: from a protostar to the current star

Nuclear physics

Gravitation

Radiative opacity

Plasma physics



an interdisciplinary physics laboratory

Standard Solar Model

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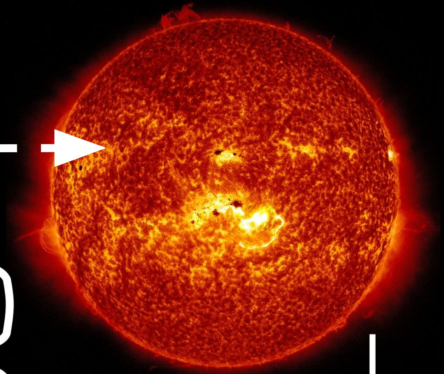


Building equations

Mass conservation

Nuclear reactions

Hydrostatic equilibrium

Energy transport

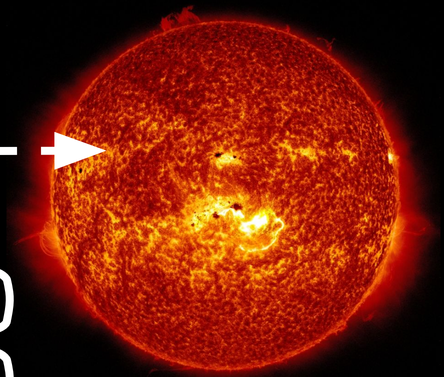
Input parameters:
mass; H, He, metal fractions (X,Y,Z);
nuclear astrophysical factors

Boundary conditions:
$L_\odot$, $\tau_\odot$, surface metal to H abundance $(Z/X)_\odot$

Standard Solar Model

Describing the Sun evolution: from a protostar to the current star

Nuclear physics | Gravitation
Radiative opacity | Plasma physics



Building equations

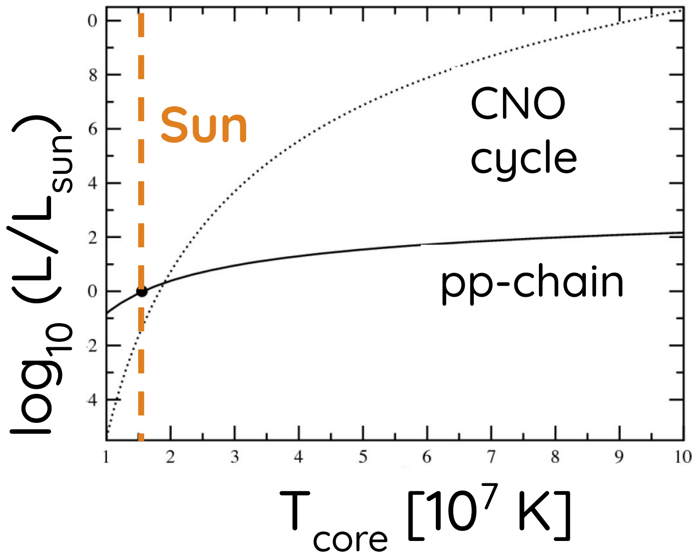
Mass conservation | Nuclear reactions
Hydrostatic equilibrium | Energy transport

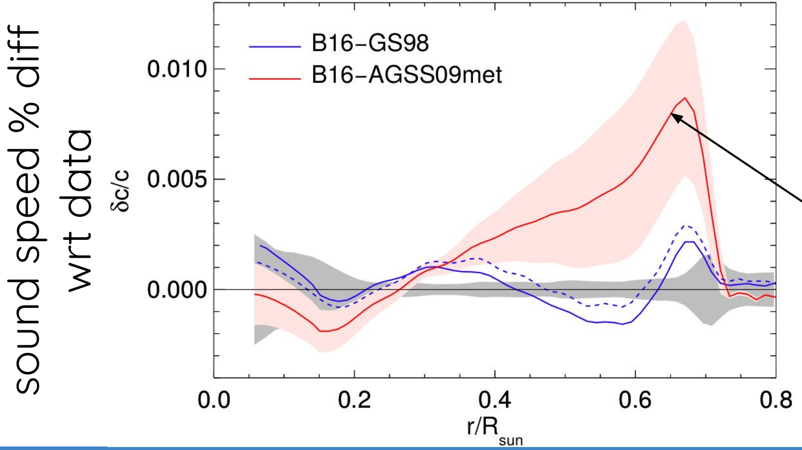
Predictions:
physical description of the global properties of the Sun
including solar neutrino fluxes and sound speed profiles

Why are CNO-ν interesting?

1) Missing tile of the solar fusion puzzle
2) Primary mechanism in massive and older stars →
3) Solar metallicity puzzle

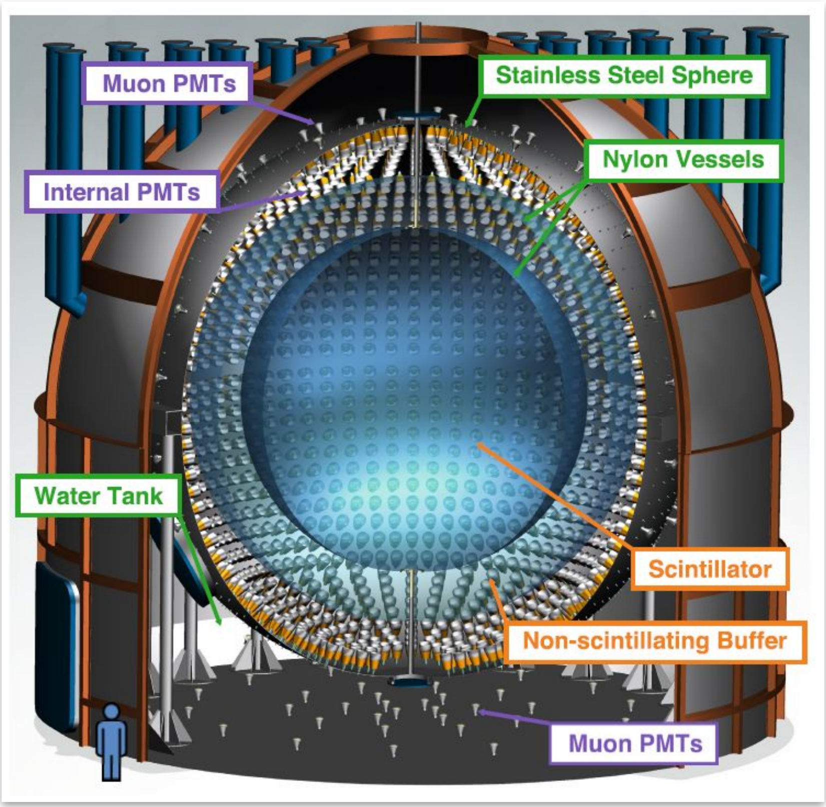
- re-evaluation of photospheric chemical composition → 20% reduction of solar metallicity (**from HZ to LZ**)
- new sound speed profile inconsistent with helioseismology
- Solar ν fluxes depend on metallicity (see later)





~1% discrepancy for LZ-SSM

Borexino detector

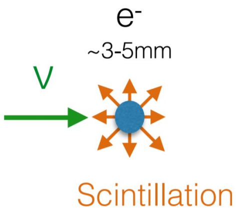


- **Low-energy spectroscopy of solar ν,** located at LNGS

- Data-taking since 2007

- **Active mass**: 300t of ultrapure liquid scintillator

- Detection via **elastic scattering**



$$\nu_x + e^- \rightarrow \nu_x + e^-$$
$$x = e, \mu, \tau$$

Graded shielding: buffer liquid and Gran Sasso

- **Low radioactivity**: 10^{-19} g/g ^{238}U, $5{\cdot}10^{-18}$ g/g ^{232}Th
  - Radiopure materials

Borexino timeline

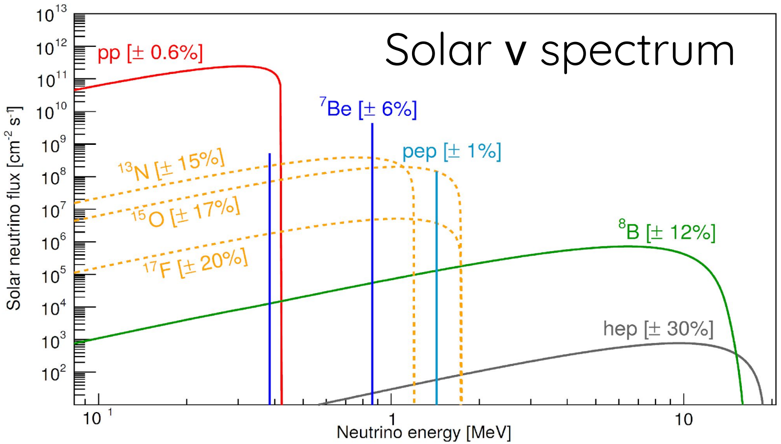
Phase-I 2007-10 | Purifications | **Phase-II** 2012-16 | **Phase-III** 2016-Feb 2020

^{7}Be-ν: 4.5% (original design goal)
ν day-night asymmetry

Simultaneous spectroscopy of the ν pp-chain

CNO-ν detection

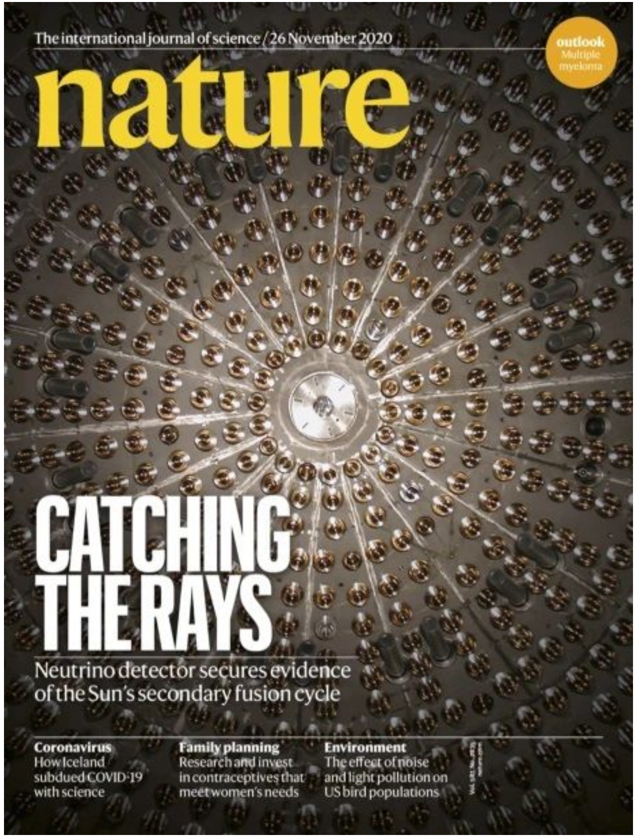
NEW



NeuTel talks

- G. Bellini: Neutrino, Solar and star physics with Borexino
- A. C. Re: A successful strategy for the CNO measurement with Borexino: the multivariate Fit
- A. Göttel: Data analysis for a low Po field for the discovery of CNO neutrinos in Borexino
- Ö. Penek: Sensitivity to CNO cycle solar neutrinos in Borexino

Borexino CNO-ν detection



"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun"

Borexino Collaboration, Nature 587 (2020) 577-582

CNO-ν flux: ϕ_{CNO}= 7.0 ($1^{+0.43}_{-0.29}$) x 10^8 $cm^{-2}s^{-1}$

No CNO-ν hypothesis excluded
at **5.0σ** significance level

Solar physics implications

- HZ/LZ discrimination
- C+N abundance in solar core

Borexino ν results

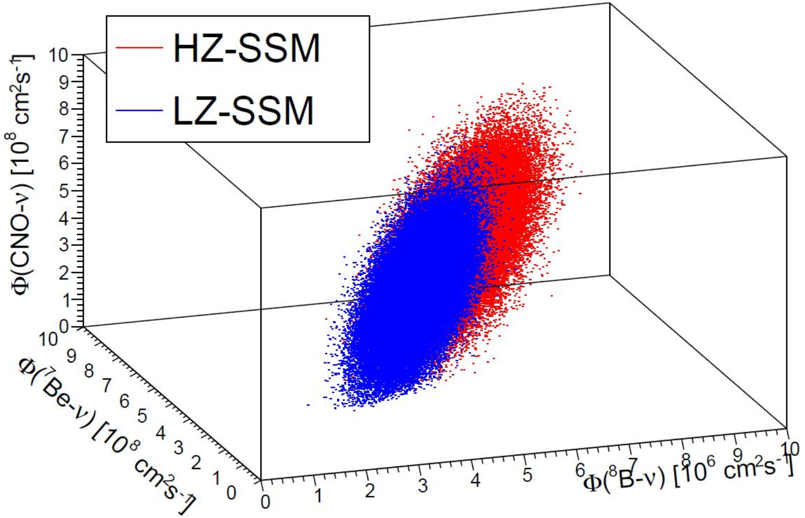
ν source	$\Phi(\mathrm{BX})\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\Phi(\mathrm{SSM})\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\Delta\Phi/\Phi$ [%]
CNO	$7.0(1^{+0.43}_{-0.29}) \cdot 10^{8}$	$4.88(1 \pm 0.16) \cdot 10^{8}$ (HZ) $3.51(1 \pm 0.14) \cdot 10^{8}$ (LZ)	28%
^{7}Be	$5.0(1 \pm 0.027) \cdot 10^{9}$	$4.93(1 \pm 0.06) \cdot 10^{9}$ (HZ) $4.50(1 \pm 0.06) \cdot 10^{9}$ (LZ)	17%
^{8}B	$5.68(1 \pm 0.076) \cdot 10^{6}$	$5.46(1 \pm 0.12) \cdot 10^{6}$ (HZ) $4.50(1 \pm 0.12) \cdot 10^{6}$ (LZ)	8%

CNO reactions are catalyzed by metals
→ CNO flux is strongly dependent on metallicity (**~28% difference**)

HZ vs LZ: hypothesis testing

Simulations of pseudo-datasets: triplets of 7Be, 8B, CNO fluxes according to **LZ-SSM** and **HZ-SSM**

1. 3D gaussian distributions
2. χ^2 and test statistics t



$$\mathbf{\Phi}^{\text{data}} = \left(\Phi^{\text{data}}_{\text{Be}}, \Phi^{\text{data}}_{\text{B}}, \Phi^{\text{data}}_{\text{CNO}}\right)$$ (Pseudo-)data results

$$\mathbf{\Phi}^{\text{SSM}} = \left(\Phi^{\text{SSM}}_{\text{Be}}, \Phi^{\text{SSM}}_{\text{B}}, \Phi^{\text{SSM}}_{\text{CNO}}\right)$$ SSM predictions

$$\Sigma^{\text{tot}} = \Sigma^{\text{BX}} + \Sigma^{\text{SSM}}$$ Th+Exp error matrix

$$\chi^2 = \left(\Phi^{\text{data}} - \Phi^{\text{SSM}}\right)^T \left(\Sigma^{\text{tot}}\right)^{-1} \left(\Phi^{\text{data}} - \Phi^{\text{SSM}}\right)$$

HZ vs LZ: hypothesis testing

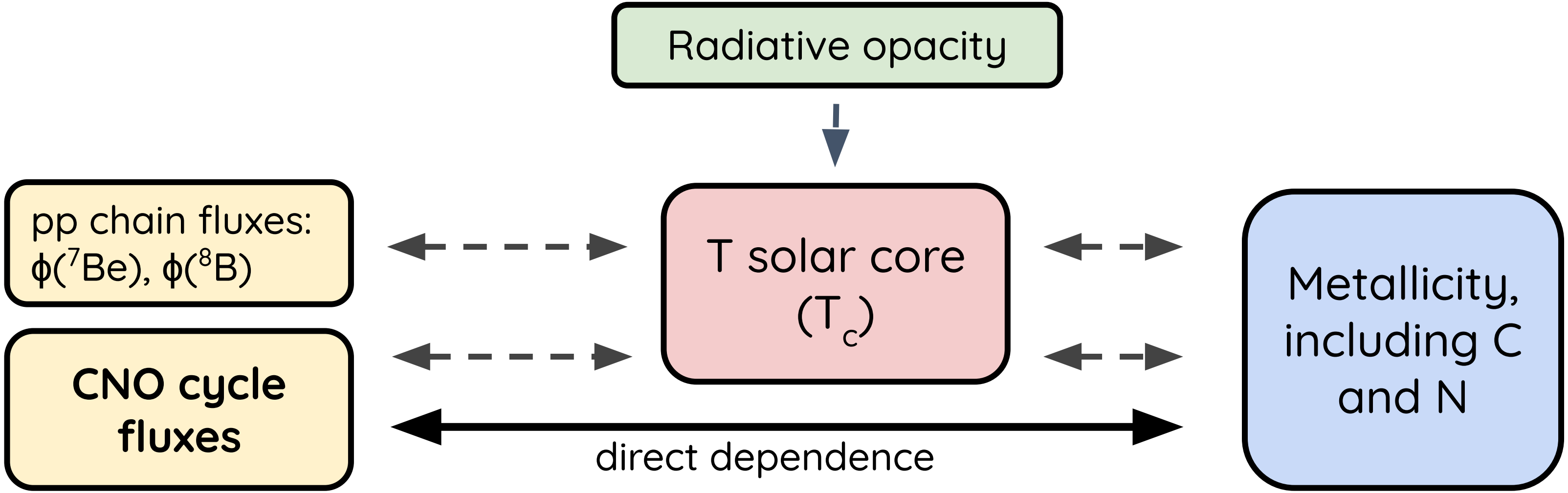
Borexino results	**LZ disfavoring**
^{7}Be-ν + ^{8}B-ν (Phase-II) "Comprehensive measurement of pp-chain solar neutrinos" Borexino Collaboration, Oct 24, 2018. Nature 562 (2018)	1.8σ
CNO-ν + ^{7}Be-ν + ^{8}B-ν (Phase-III and Phase-II) "Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun" Borexino Collaboration, Jun 26, 2020, Nature 587 (2020)	2.1σ

- Borexino CNO rate = $\mathbf{7.2_{-1.7}^{+2.9}}$ cpd/100t,
  - compatible with both HZ-SSM and LZ-SSM (0.5σ and 1.3σ)
- Limiting factors:

1) Experimental error (~23%) should be lowered to ~10% to impact on HZ/LZ testing.
2) The precision of the solar model predictions astrophysical S-factors S_{114} (CNO, 7.4%) S_{34}, (^{7}Be, 3.4%), S_{17} (^{8}B) → reduction of nuclear cross section uncertainties is crucial.

Determination of C+N core abundance

- CNO fluxes directly (and indirectly) depend on Carbon and Nitrogen content in solar core
- pp chain fluxes depend indirectly on metallicity, via T of solar core



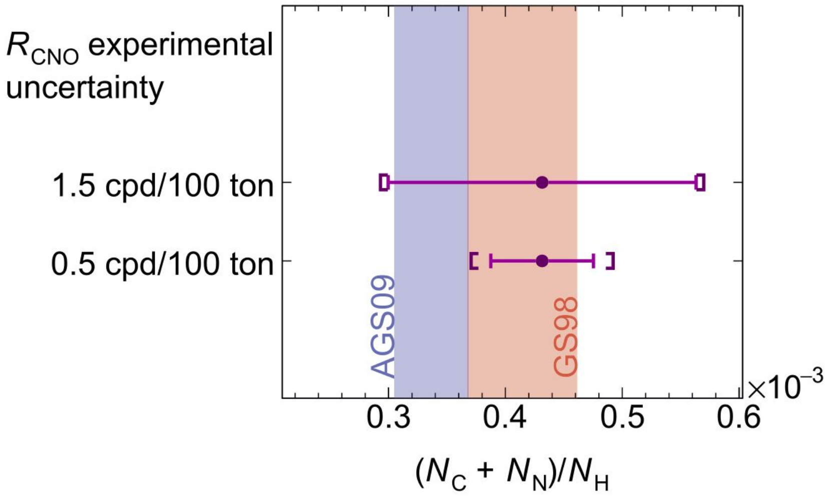
Solar-ν fluxes estimations → **degeneracy** of metallicity + T_c + opacity
How to disentangle them to extract C and N content?

Determination of C+N core abundance

^{8}B-ν as a thermometer of solar core:

- CNO-ν and ^{8}B-ν fluxes depends on T_c by power-laws; $\Phi_i \sim T_c^{\gamma_i}$
- Taking a ratio, dependence on T_c is nearly cancelled out
- Only the dependence on the C+N content holds

$$\frac{N_C + N_N}{N_C^{SSM} + N_N^{SSM}} = \left(\frac{\Phi_{^8B}}{\Phi_{^8B}^{SSM}}\right)^{-0.716} \times \frac{R_{CNO}^{BX}}{R_{CNO}^{SSM}} \times [1 \pm 0.5\%(\mathrm{env}) \pm 9.1\%(\mathrm{nucl}) \pm 2.8\%(\mathrm{diff})]$$



Projected uncertainty for C+N abundance from a CNO-ν measurement (**HZ** or **LZ**).

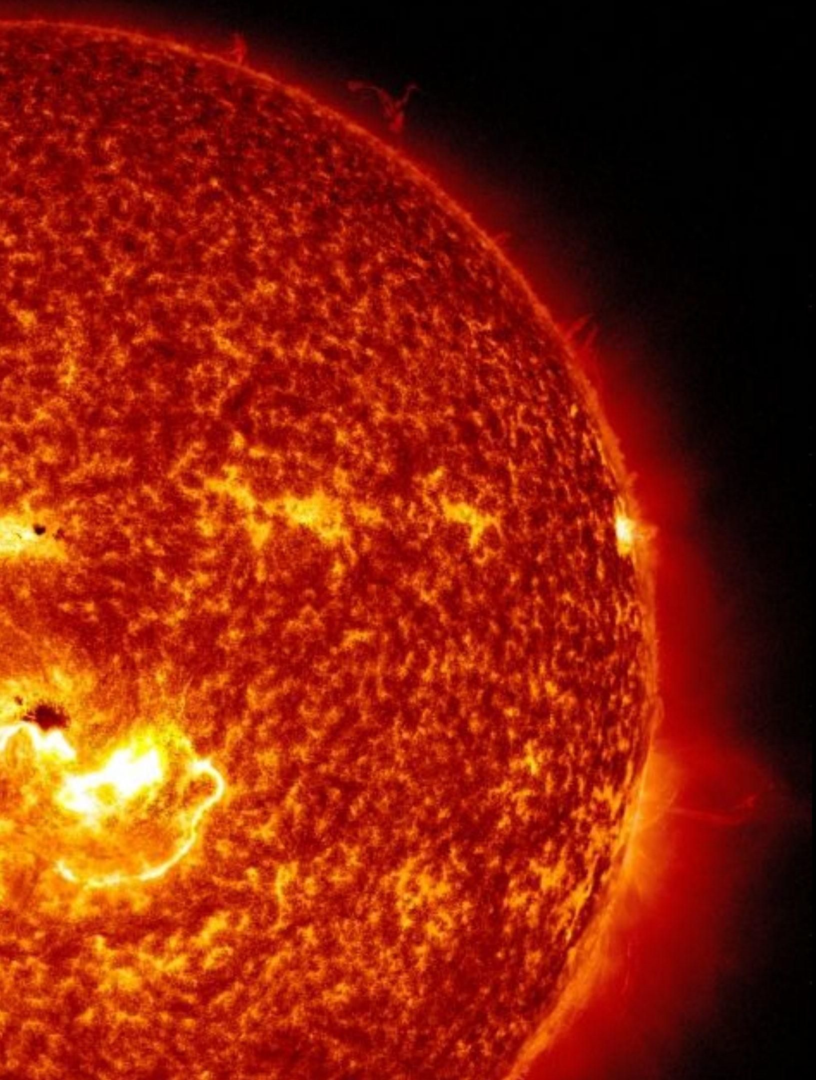
- Borexino CNO-ν rate: **$7.2_{-1.7}^{+2.9}$** cpd/100t
- Error dominated by experimental uncertainty
- Future measurement σ_{CNO}=0.5 cpd/100t (~10%) → C+N constrained at 15% level (as photospheric techniques)

Conclusions

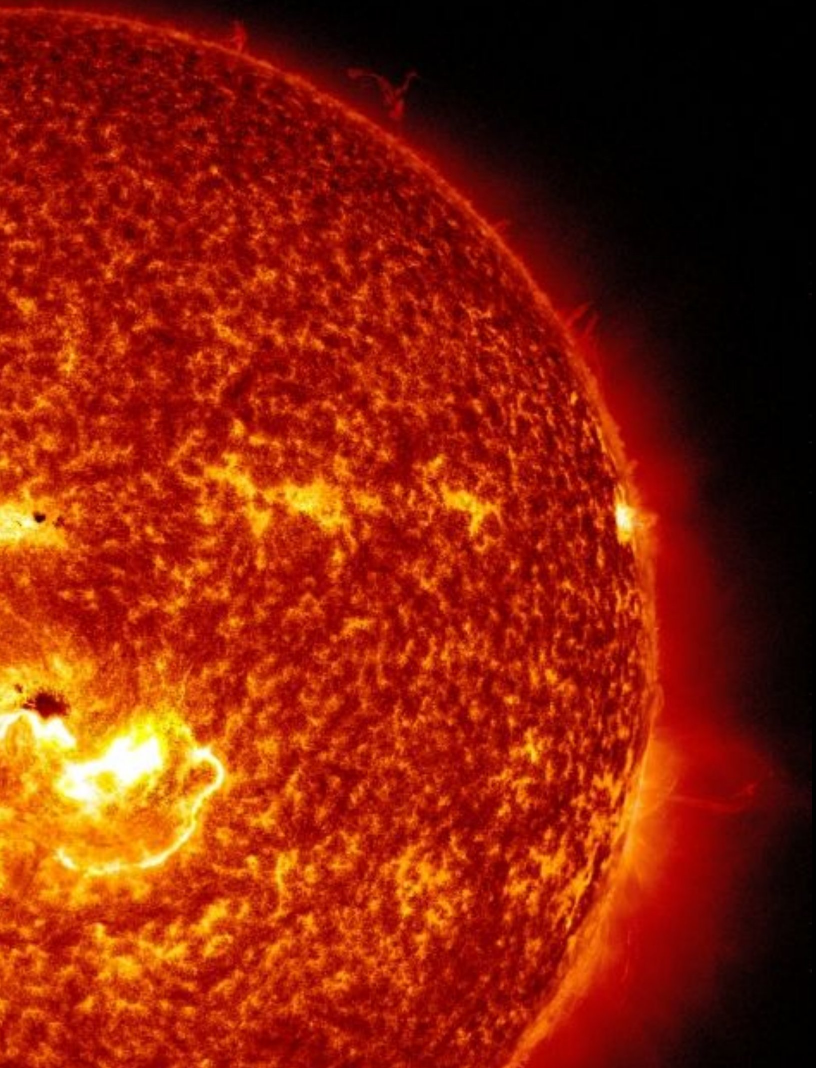
- Borexino provided the first direct experimental evidence of CNO-ν
- Combining Borexino CNO-ν + ^{7}Be-ν + ^{8}B-ν measurements, LZ scenario is mildly disfavoured (**2.1σ**)
  - Limiting factor: CNO-ν experimental error

Future perspectives

- If next-future experiments lower CNO error to 10%:
  - Statistically significant distinction between LZ/HZ
  - Determination of C and N abundance in the sun, combining ϕ(CNO) and ϕ(8B)



Thank you!



Thank you!

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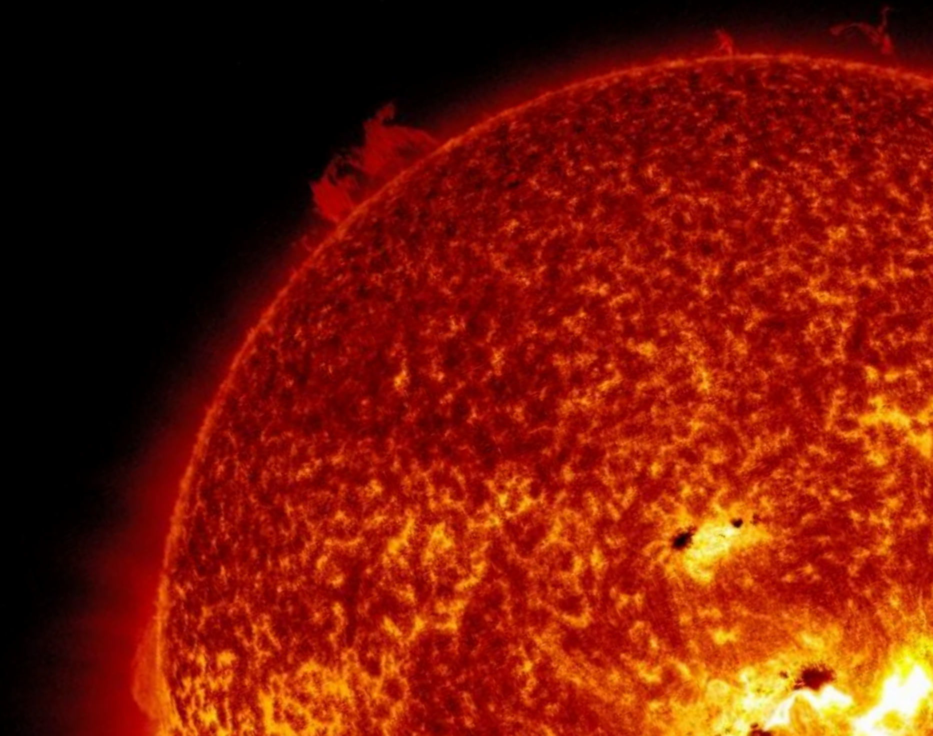
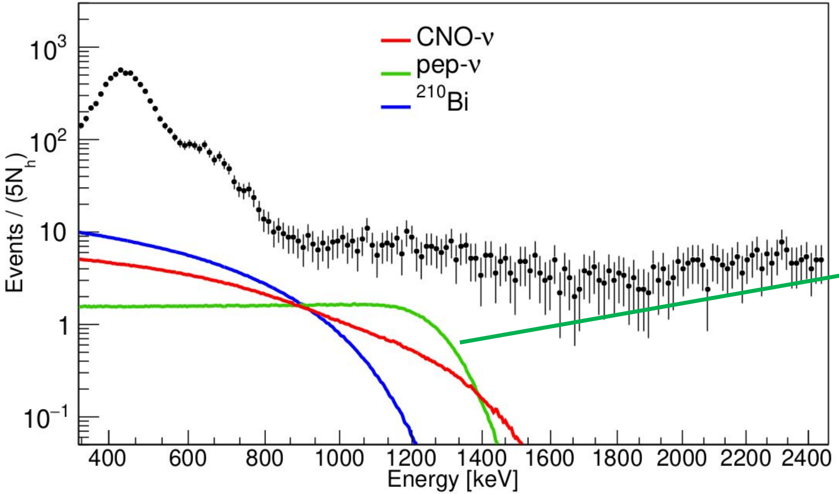
Backup



Why a CNO-ν measurement is challenging?

Borexino Phase-III energy spectrum



pep-ν neutrinos signal is constrained according to Standard Solar Model predictions (1.4% precision level)

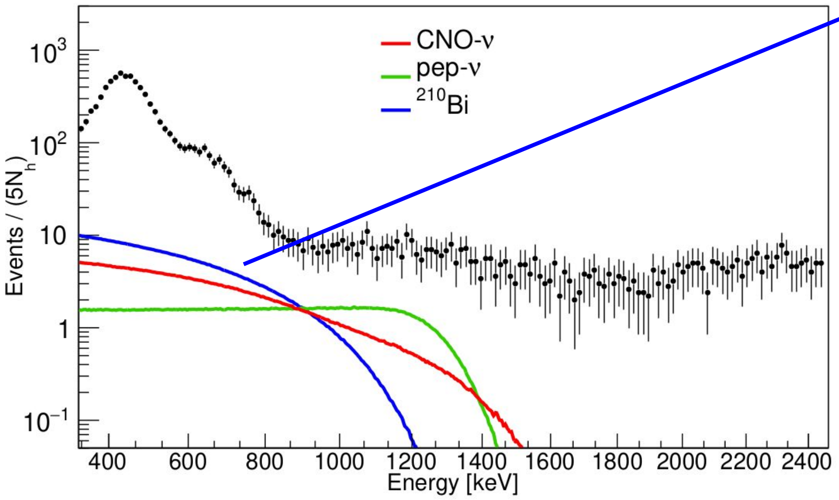
Spectral degeneracy between **CNO-ν**, **pep-ν**, ^{210}**Bi** background

+

Low **CNO-ν** signal/background ratio (~3-6 cpd/100t)

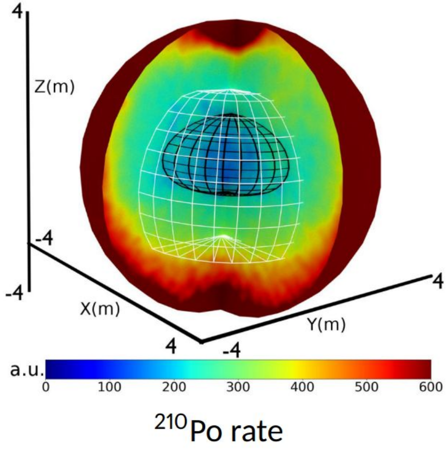
Why a CNO-ν measurement is challenging?

Borexino Phase-III energy spectrum



The annoying ^{210}**Bi background** is constrained independently on the spectral fit
→ secular equilibrium with its daughter ^{210}Po

$$^{210}\mathrm{Pb} \xrightarrow[32.2y]{\beta} {}^{210}\mathrm{Bi} \xrightarrow[7.23d]{\beta} {}^{210}\mathrm{Po} \xrightarrow[199.6d]{\alpha} {}^{206}\mathrm{Pb}$$



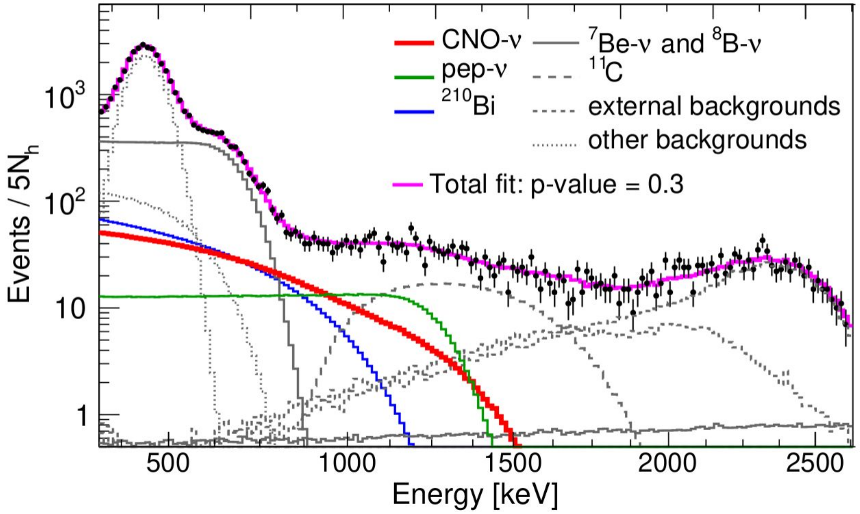
Spectral degeneracy between **CNO-ν**, **pep-ν**, ^{210}**Bi** background

See A. Göttel flash talk “Low Po field”

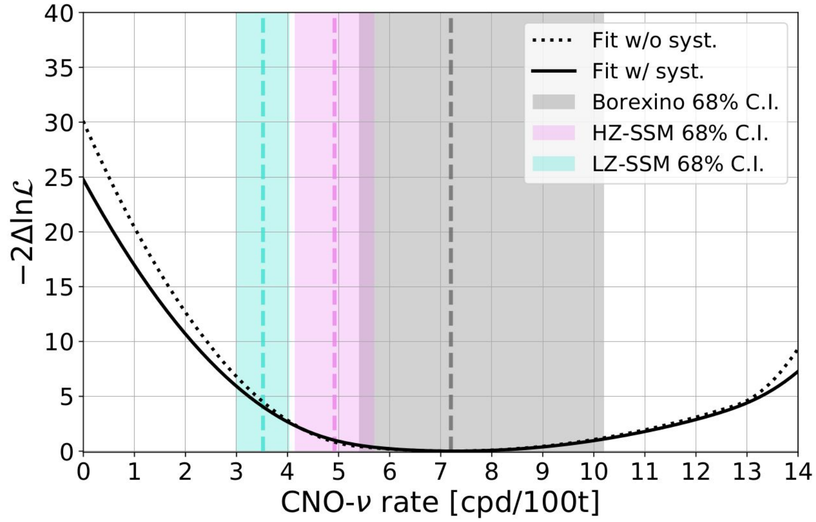
Borexino CNO-ν measurement

Multivariate fit (below, the energy fit)

See A. C. Re talk



-2LnL CNO rate profile



CNO rate: $7.2_{-1.7}^{+2.9}$ cpd/100t → CNO flux: $\phi_{CNO} = 7.0\ (1^{+0.43}_{-0.29}) \times 10^8\ cm^{-2}s^{-1}$

First CNO neutrino detection, **5.0σ significance level**

See G. Bellini talk on 23/2

HZ vs LZ: test statistics

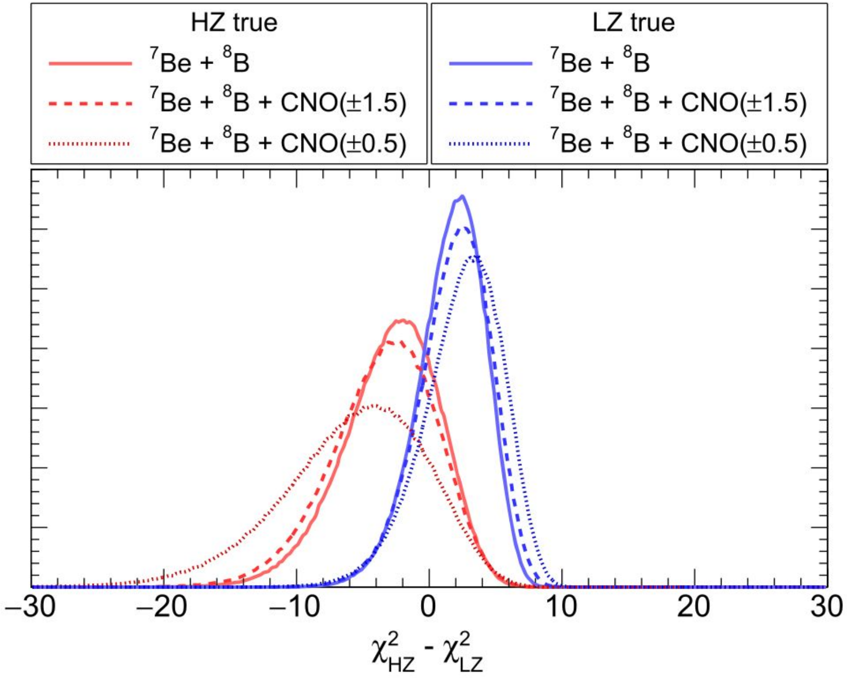
$$\chi^2(\mathrm{SSM}) = \left(\Phi^{\mathrm{SSM}} - \Phi^{\mathrm{Exp}}\right)^{\mathrm{T}} \left(\Sigma^{\mathrm{SSM}} + \Sigma^{\mathrm{Exp}}\right)^{-1} \left(\Phi^{\mathrm{SSM}} - \Phi^{\mathrm{Exp}}\right)$$

Distributions of the test statistics t:

$$t = -2\log\left[\mathcal{L}(\mathrm{HZ})/\mathcal{L}(\mathrm{LZ})\right] = \chi^2(\mathrm{HZ}) - \chi^2(\mathrm{LZ})$$

Median discovery power:

- σ_{CNO} = 1.5 cpd/100t (~30-40%): 1.7σ
- σ_{CNO} = 0.5 cpd/100t (~10-14%): 2.1σ



Power law fluxes-temperature

$$\Phi_i \sim T_c^{\gamma_i}$$

	pp	^{7}Be	^{8}B	^{15}O	^{13}N
γ_i	-0.8	10.5	23	19.6	14.7

D. Fuschini & F. Villante, private communication
J.N. Bahcall & A. Ulmer, *Phys. Rev. D* 53(8) (1996)