Detection of CNO solar neutrinos with Borexino experiment

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on behalf of the Borexino collaboration

IRN Neutrino Meeting
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University of Milan, INFN Milan

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN
Istituto Nazionale di Fisica Nucleare

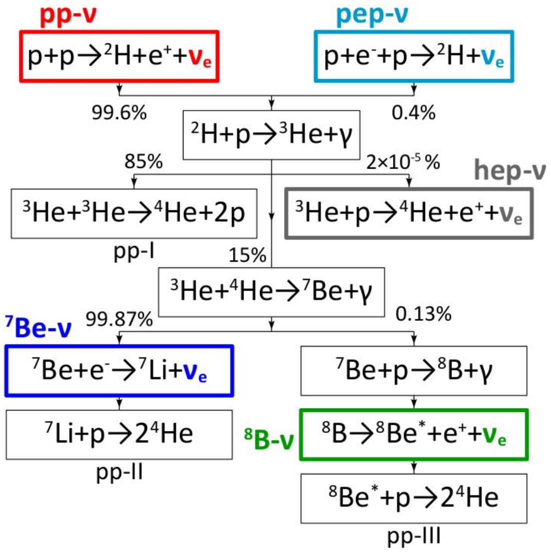
Outline

1. Solar neutrinos and Borexino detector
2. CNO analysis
3. Astrophysical implications

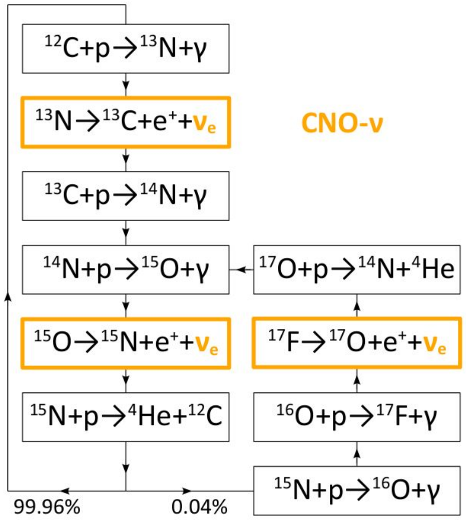
Solar neutrinos

- 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

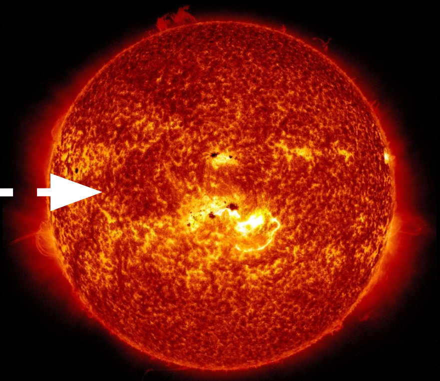
Describing the Sun evolution: from a protostar to the current star

Nuclear physics

Gravitation

Radiative opacity

Plasma physics

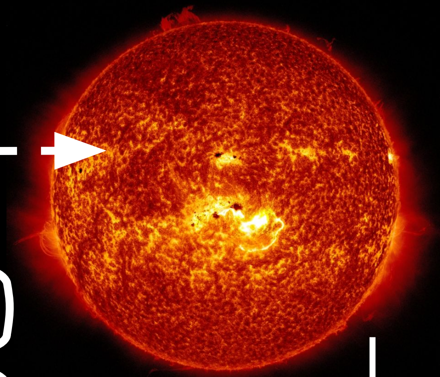


an interdisciplinary physics laboratory

Standard Solar Model

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

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

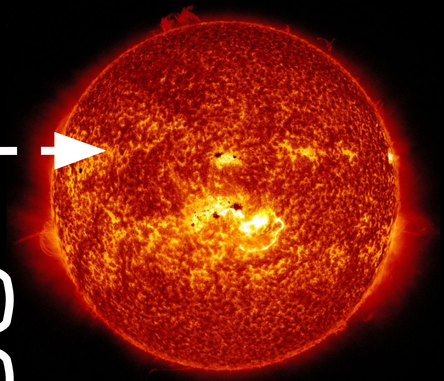
Boundary conditions:
$L_\odot$, $\tau_\odot$, surface metal to H abundance $(Z/X)_\odot$

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

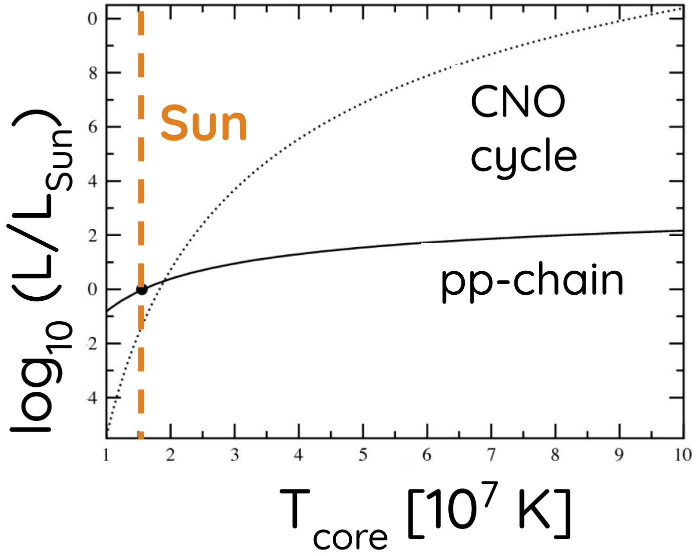
Why are CNO-ν interesting?

1) Missing tile of the solar fusion puzzle

→ never observed in a direct way!

2) Primary mechanism in massive and older stars →

$$L \sim M^{3.5}$$



Why are CNO-ν interesting?

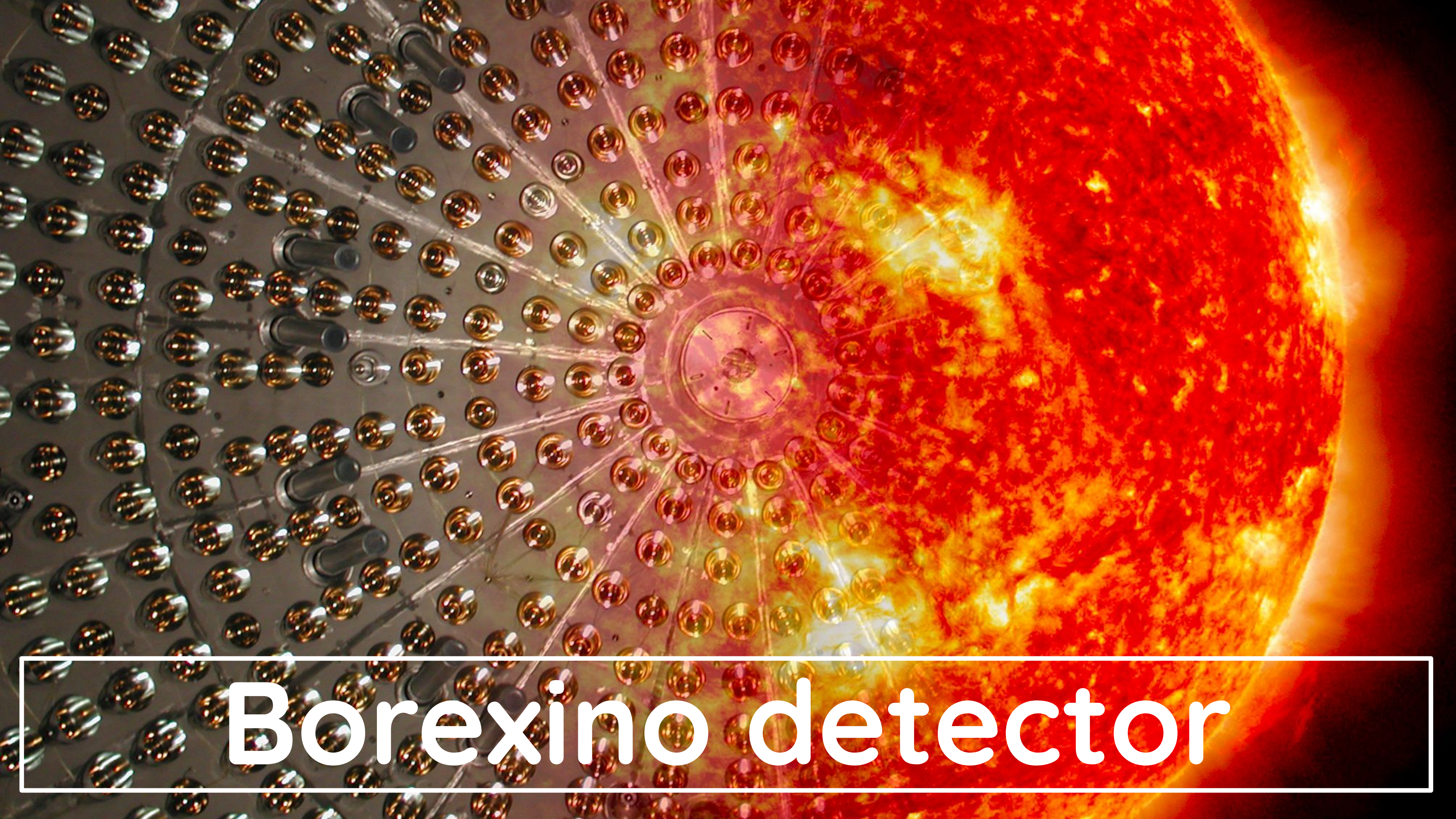
Metallicity: abundance of elements heavier than He

Two scenarios: **high** metallicity (**HZ**; Z/X = 0.023) and **low** metallicity (**LZ**; Z/X=0.0165)

Solar ν fluxes **depend on metallicity**, especially CNO (28% diff.)

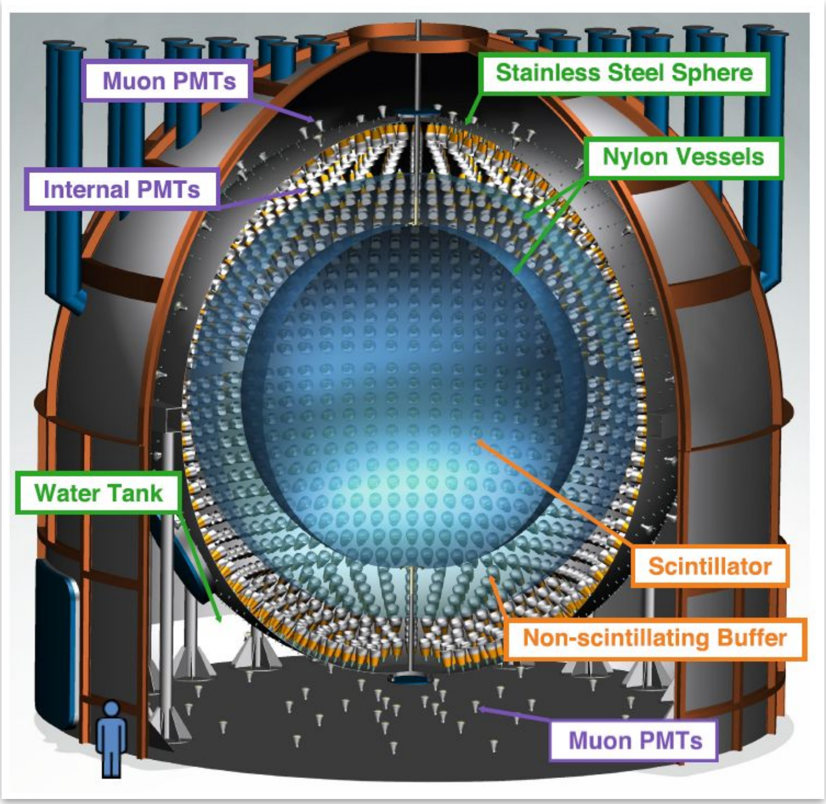
An accurate CNO measurements would help to settle down the SMP

Solar ν	Flux B16-GS98 (HZ) $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Flux B16-AGSS09met (LZ) $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	% diff.
pp	$5.98(1.0 \pm 0.006) \cdot 10^{10}$	$6.03(1.0 \pm 0.005) \cdot 10^{10}$	0.83
^{7}Be	$4.93(1.0 \pm 0.06) \cdot 10^{9}$	$4.50(1.0 \pm 0.06) \cdot 10^{10}$	8.7
pep	$1.44(1.0 \pm 0.01) \cdot 10^{8}$	$1.46(1.0 \pm 0.009) \cdot 10^{9}$	1.4
^{8}B	$5.45(1.0 \pm 0.12) \cdot 10^{6}$	$4.50(1.0 \pm 0.12) \cdot 10^{6}$	17.4
hep	$7.98(1.0 \pm 0.30) \cdot 10^{3}$	$8.25(1.0 \pm 0.12) \cdot 10^{3}$	3.4
All CNO	$4.88(1.0 \pm 0.16) \cdot 10^{8}$	$3.51(1.0 \pm 0.15) \cdot 10^{8}$	28.1

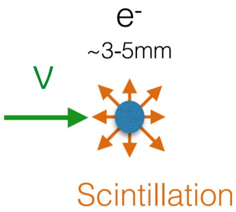

Borexino detector

Borexino detector

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, ~$6{\cdot}10^{-19}$ g/g ^{232}Th
  - Radiopure materials

Borexino timeline

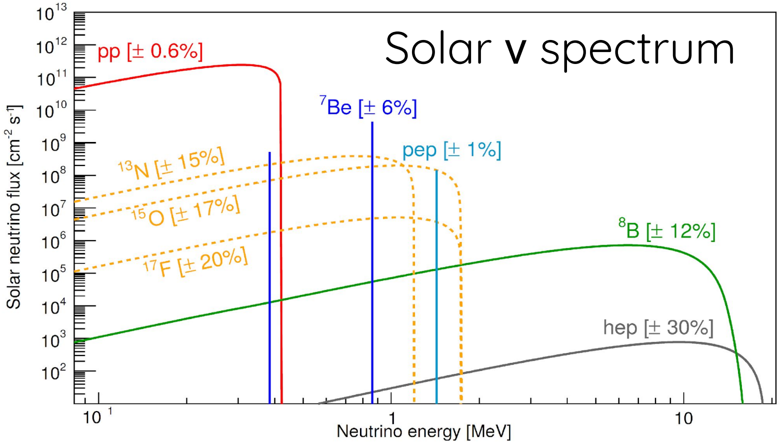
Phase-I 2007-10 | Purifications | **Phase-II** 2012-16 | **Phase-III** 2016-Feb 2020

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

Simultaneous spectroscopy of the ν pp-chain

NEW

CNO-ν detection

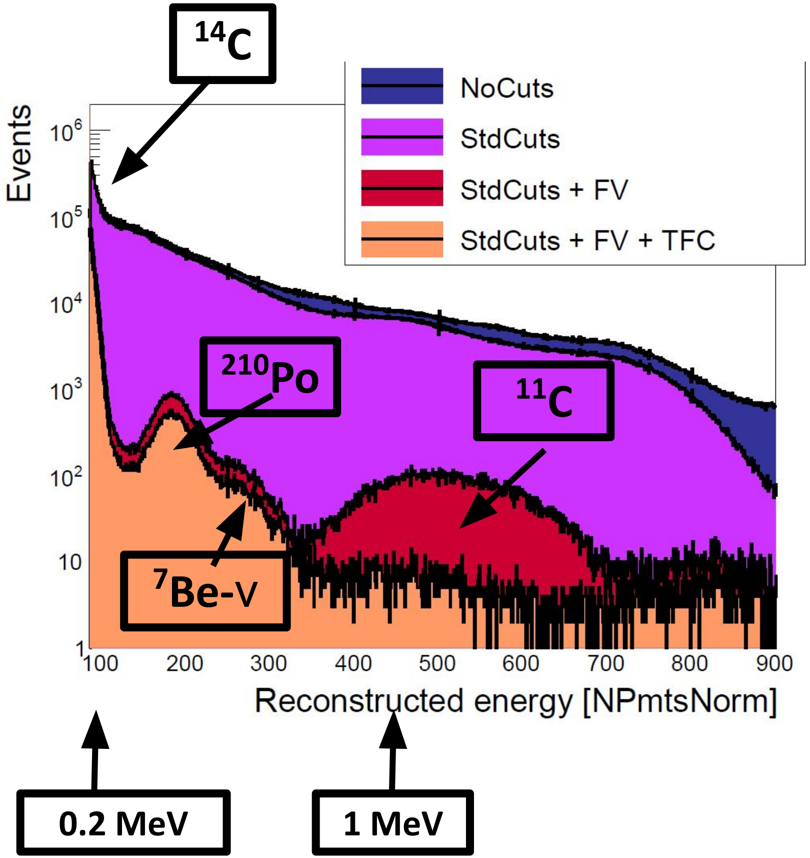


- *"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun"* Borexino Collab., Nature 587 (2020) 577-582

- *"Sensitivity to neutrinos from the solar CNO cycle in Borexino"* Borexino Collab., Eur. Phys. J. C 80 (2020) 11, 1091

CNO-ν analysis

Data selection



Raw spectrum

Standard cuts

- μ, cosmogenic, noise, delayed coincidences…

+ FV cut

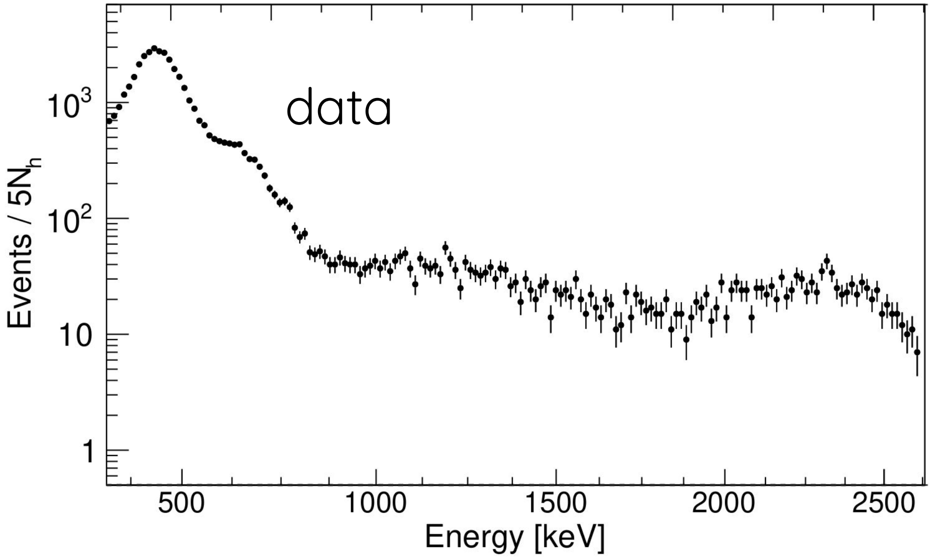
- Selecting an innermost scintillator volume
- Excluding external bkg

+ TFC cut

- To identify cosmogenic ^{11}C events
- μ+n coincidence

Still background (β,γ) is present, indistinguishable from ν signal on an event-by-event basis → **multivariate fit**

Analysis dataset

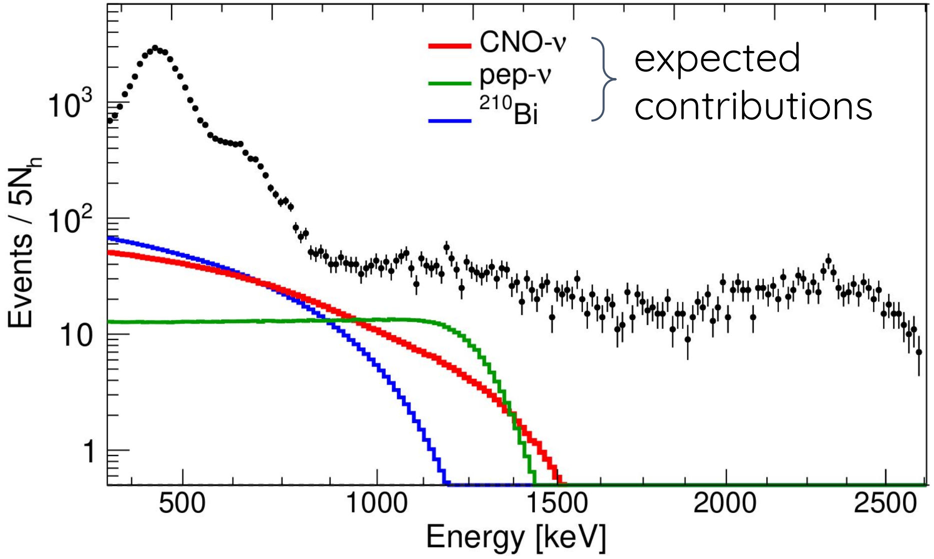


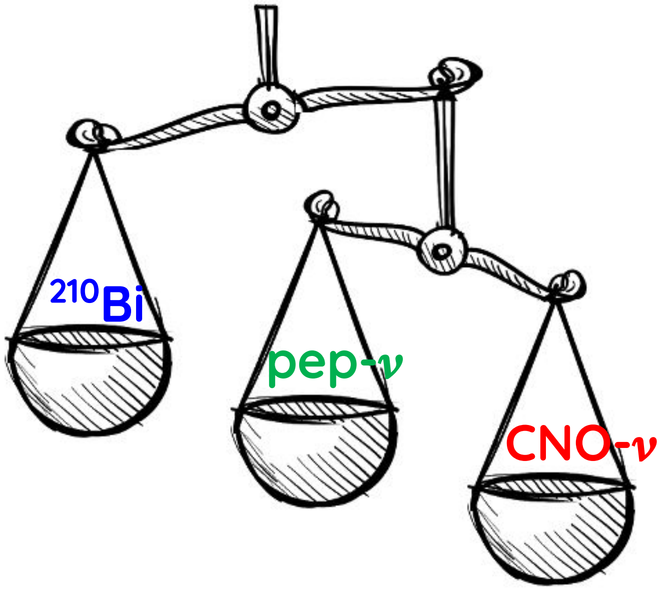
Borexino Phase-III energy spectrum

Still background (β,γ) is present, indistinguishable from ν signal on an event-by-event basis
→ **multivariate fit**

- Data-set: Phase-III (July 2016 - February 2020)
- Exposure: 1072 days x 71.3 t
- Fit energy range: 0.32 – 2.64 MeV

Analysis dataset

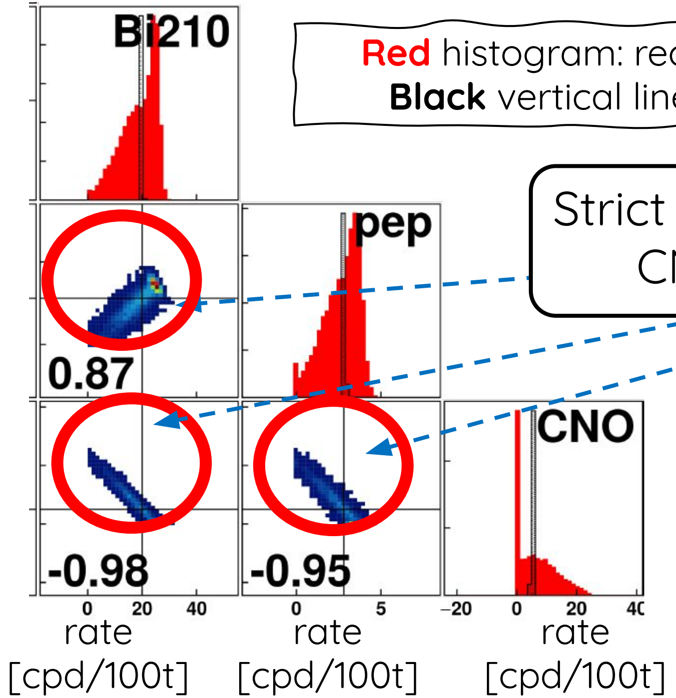




Spectral degeneracy between **expected** CNO-ν, pep-ν, ^{210}Bi background
→ Strict anti-correlation for the three rates

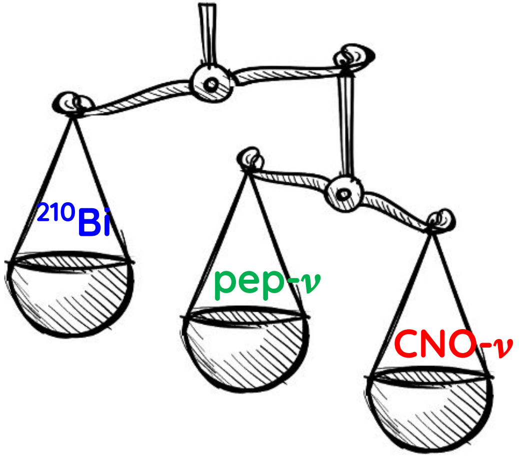
CNO-ν sensitivity studies

- Simulating Borexino Phase-III data taking: 10^4 toy-MC experiments
- Multivariate fit performed, as we will do on data
- **Rates distributions (diagonal plots) and correlations**



Red histogram: reconstructed rate
Black vertical line: injected rate

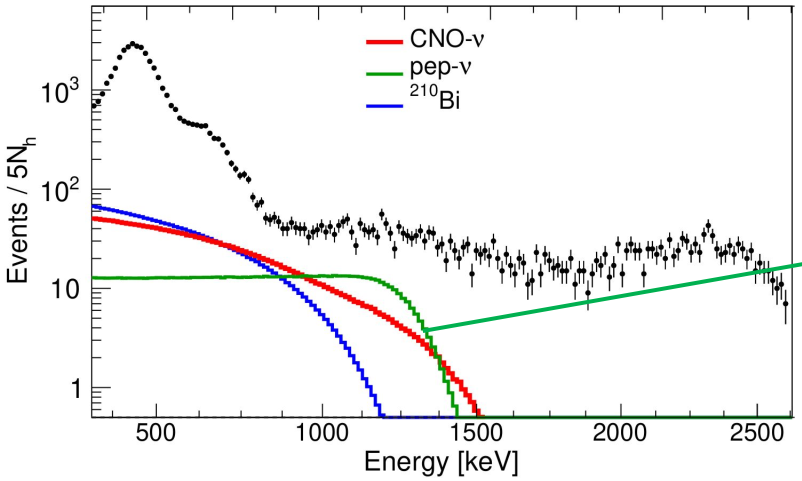
Strict anticorrelation between CNO ν, pep ν and ^{210}Bi



The spectral fit is **sensitive only to the sum of the three rates**, if all of them are left unconstrained

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)

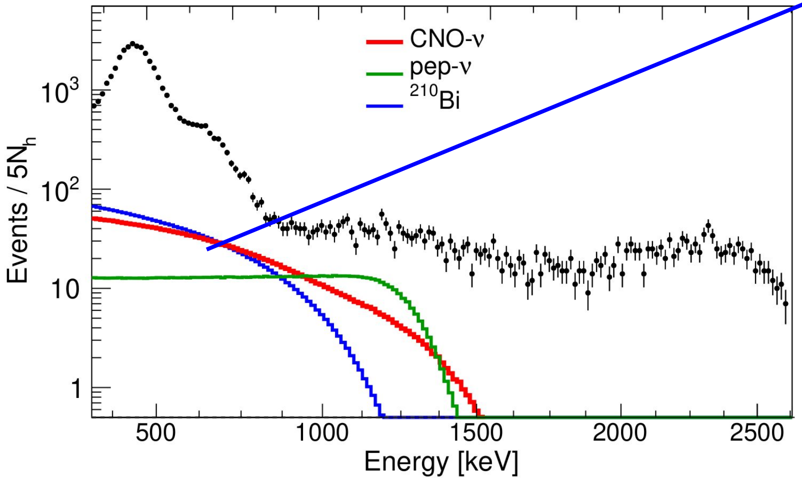
Spectral degeneracy between **CNO-ν**, **pep-ν**, ^{210}**Bi** background

+

Low CNO-ν signal/background ratio
^{210}**Bi** rate: ~12-20 cpd/100t
CNO-ν rate: ~3-8 cpd/100t
pep-ν rate: 2.8 cpd/100t

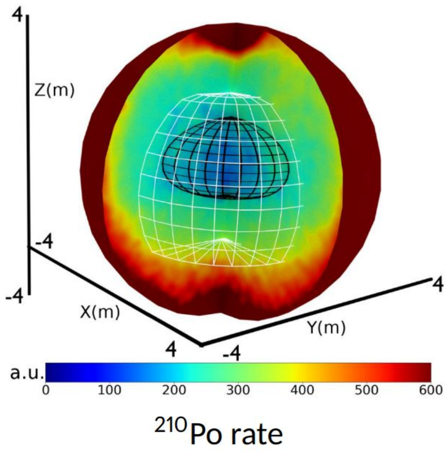
Why a CNO-ν measurement is challenging?

Borexino Phase-III energy spectrum



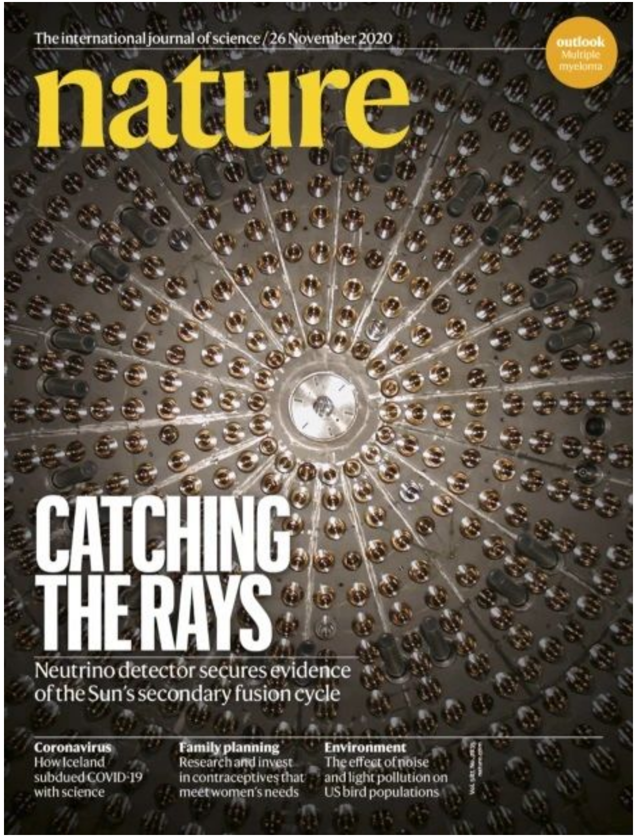
The annoying **^{210}Bi background** is constrained independently on the spectral fit
→ secular equilibrium with its daughter ^{210}Po

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



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

Borexino CNO-ν detection



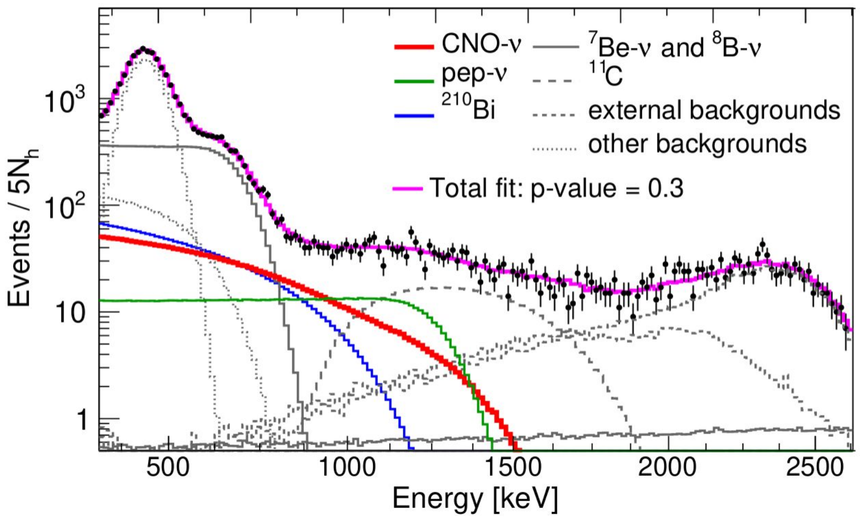
"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun"

Borexino Collaboration,
Nature 587 (2020) 577-582

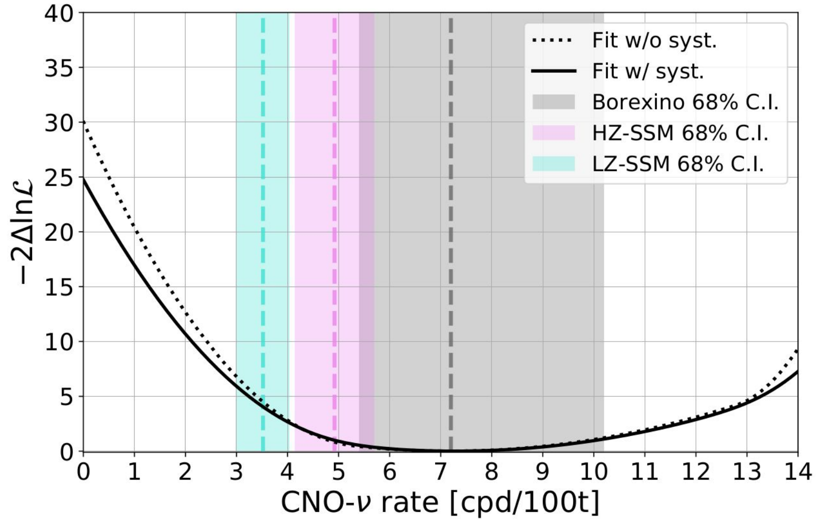
https://arxiv.org/pdf/2005.12829.pdf
https://inspirehep.net/literature/1803362

Borexino CNO-ν measurement

Multivariate fit (below, the energy fit)



-2LnL CNO rate profile



CNO rate: $7.2_{-1.7}^{+3.0}$ cpd/100t → CNO flux: $\phi_{CNO} = 7.0\,(1^{+3.0}_{-2.0}) \times 10^8\ cm^{-2}\ s^{-1}$

First CNO neutrino detection, 5.0σ significance level

Solar physics implications

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

Borexino ν results

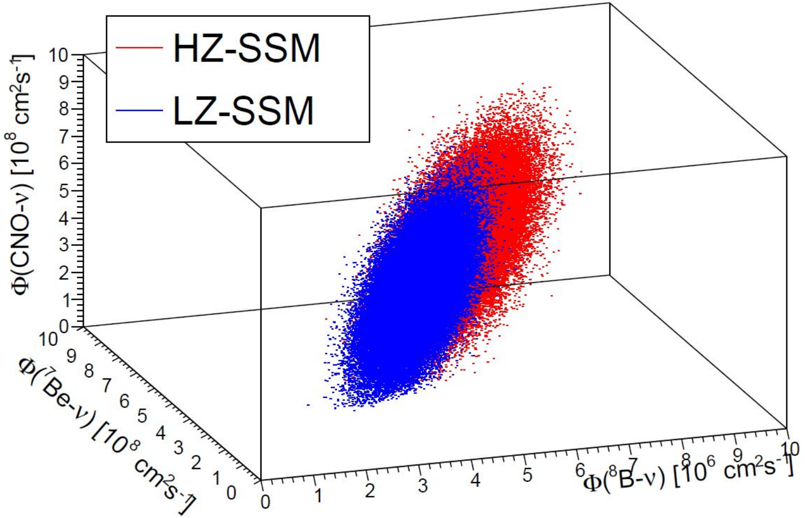
ν source	$\Phi(\mathrm{BX})\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\Phi(\mathrm{SSM})\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\Delta\Phi/\Phi\ [\%]$
CNO	$7.0\ (1^{+0.3}_{-0.2}) \cdot 10^8$	$4.88(1 \pm 0.16) \cdot 10^8$ (HZ) $3.51(1 \pm 0.14) \cdot 10^8$ (LZ)	28%
^{7}Be	$4.99\ (1^{+0.06}_{-0.08}) \cdot 10^9$	$4.93(1 \pm 0.06) \cdot 10^9$ (HZ) $4.50(1 \pm 0.06) \cdot 10^9$ (LZ)	17%
^{8}B	$5.69\ (1^{+0.39}_{-0.41}) \cdot 10^6$	$5.46(1 \pm 0.12) \cdot 10^6$ (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



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

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

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

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

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

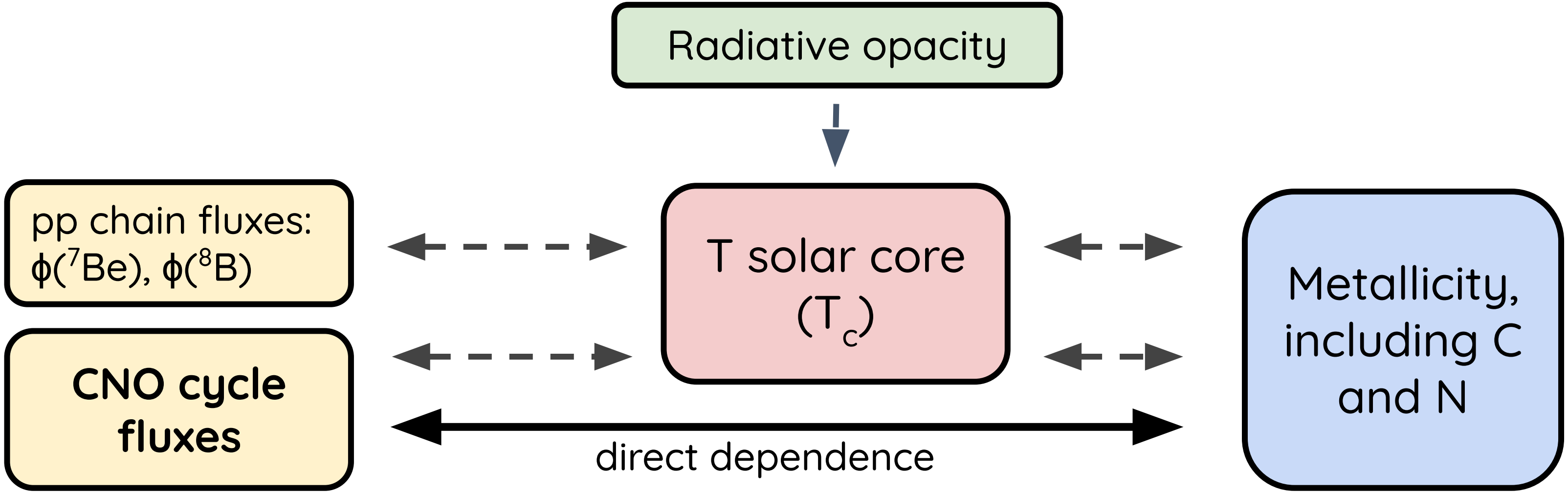
- Borexino CNO rate = $\mathbf{7.2_{-1.7}^{+3.0}}$ cpd/100t,
  - compatible with both HZ-SSM and LZ-SSM (0.5σ and 1.3σ)
- Limiting factors:

1) Experimental error (~23%) should be lowered to ~10% to impact on HZ/LZ testing.

2) Precision of the solar model predictions astrophysical S-factors S_{114} (CNO, 7.4%) S_{34}, (^{7}Be, 3.4%), S_{17} (^{8}B) → nuclear cross section uncertainties

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



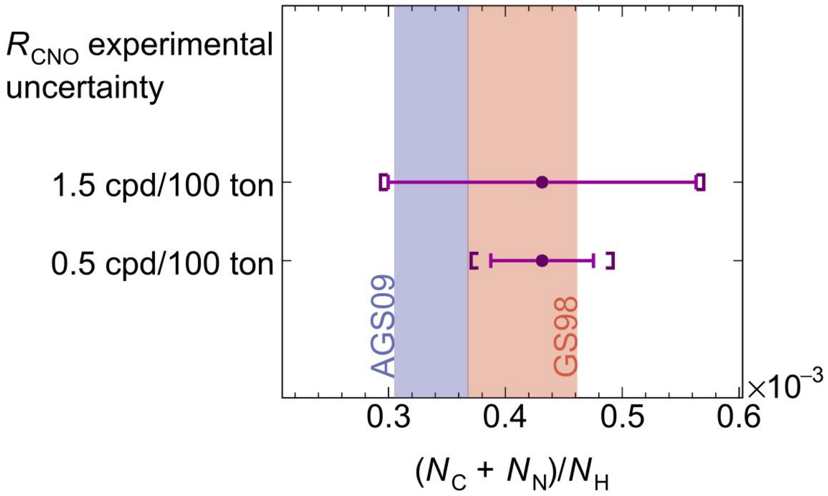
Solar-ν fluxes estimations → **degeneracy** of metallicity + T_c + opacity
How to disentangle them to extract C and N content?

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; $\Phi_i \sim T_c^{\gamma_i}$
- A fluxes ratio:
  - cancels out dependence on T_c
  - holds the C+N content dependence

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



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)

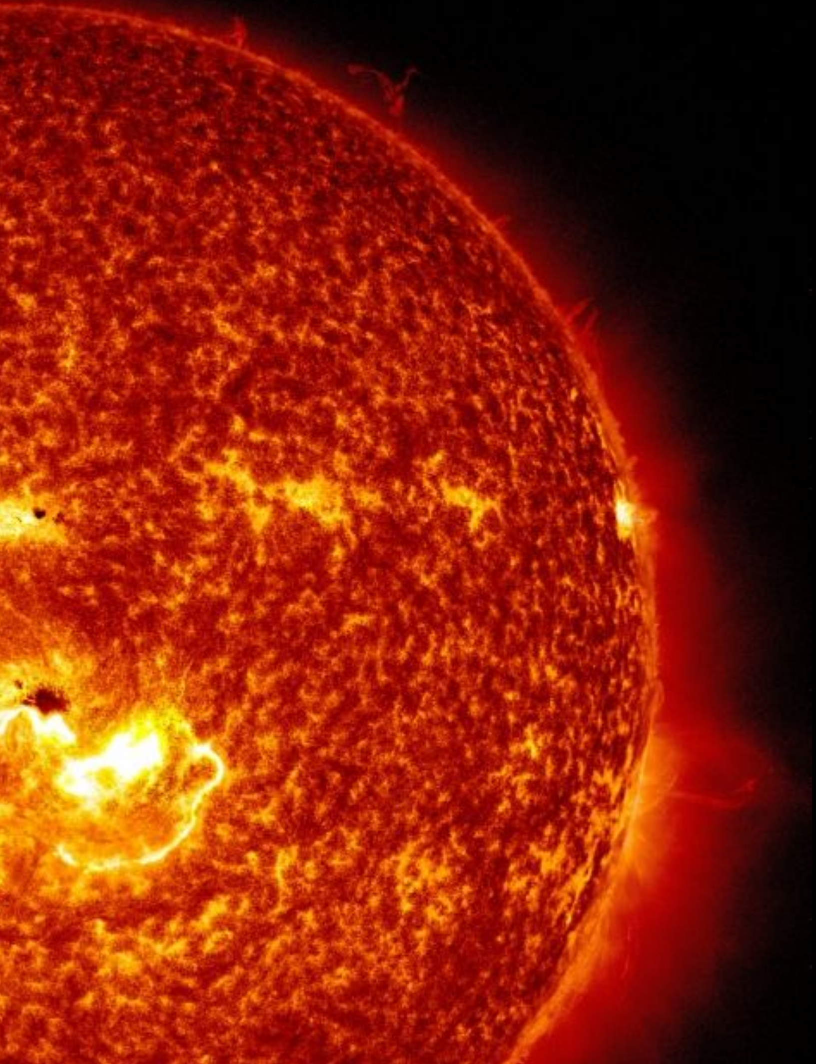
Conclusions

- Throughout its history, Borexino has measured all the solar neutrino fluxes (except hep): pp chain and CNO cycle

- Analyzing 2016-20 data, **first direct experimental evidence of CNO-$\boldsymbol{\nu}$** (5.0σ)

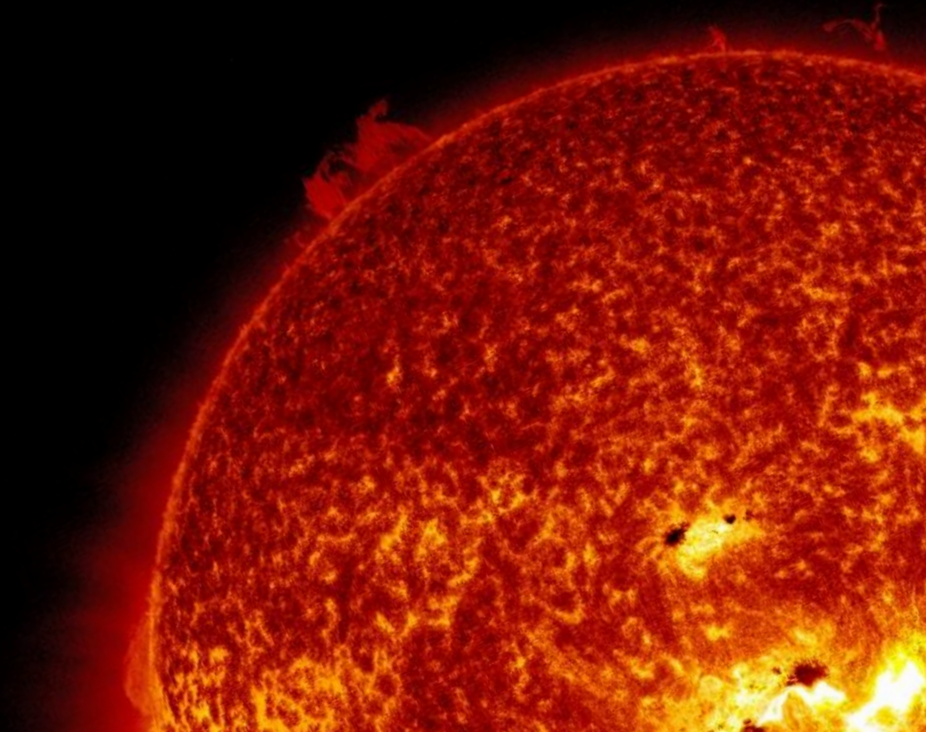
- The importance of CNO evidence: proof of theory about energy production in stars, pave the way for metallicity problem
  → dominant mechanism in older and more massive stars
  → complete framing of the fusion mechanisms

- Solar metallicity: combining Borexino CNO-ν + ^{7}Be-ν + ^{8}B-ν measurements, LZ scenario is mildly disfavoured (2.1σ)



Thank you!

Backup



HZ vs LZ: test statistics

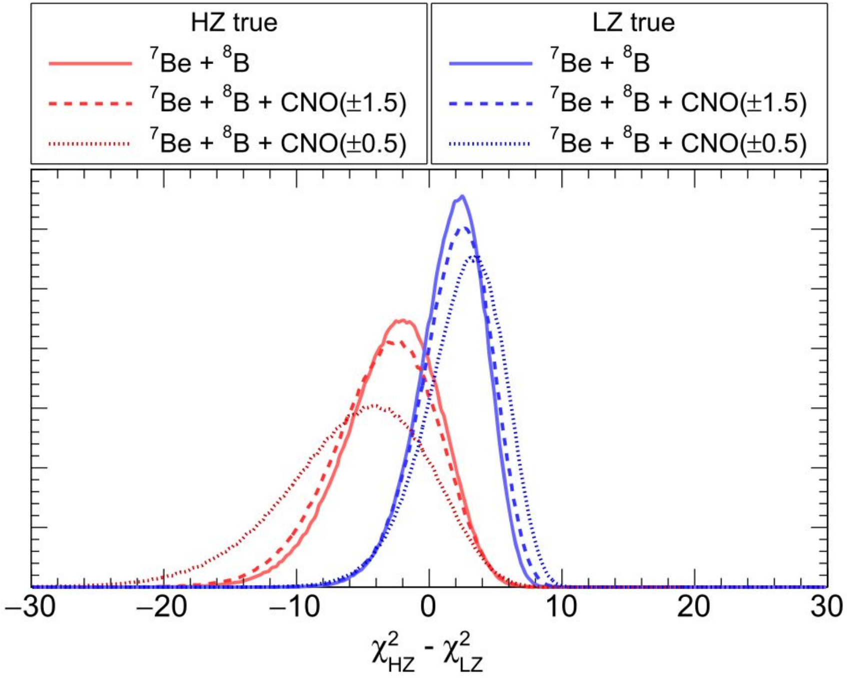
$$\chi^2(\text{SSM}) = \left(\Phi^{\text{SSM}} - \Phi^{\text{Exp}}\right)^{\text{T}} \left(\Sigma^{\text{SSM}} + \Sigma^{\text{Exp}}\right)^{-1} \left(\Phi^{\text{SSM}} - \Phi^{\text{Exp}}\right)$$

Distributions of the test statistics t:

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

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)