CNO neutrinos and Metallicity of Stars

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Why CNO neutrinos?
Why metallicity of stars?

The accuracy of the physical description of the Sun provided
by Solar Standard Models
has been challenged
by developments in stellar spectroscopic techniques
over the last decade.

Experimental determination
of CNO neutrino fluxes
is the key to settle the challenge.

Why is this critical?

Solar Standard Models
play fundamental **role**
for understanding the Universe.

SSM is the calibration input for **stellar evolution**.
Stellar evolution plays fundamental role in **Cosmology**.

The SSM is fundamental

- Convection models in stars are calibrated forcing solar models to reproduce present day solar radius and temperature

- Evolution of metals and helium in the Universe needs input from both BBN and initial SSM composition

- Benchmark against additional physics processes in Stars

Solar abundance problem

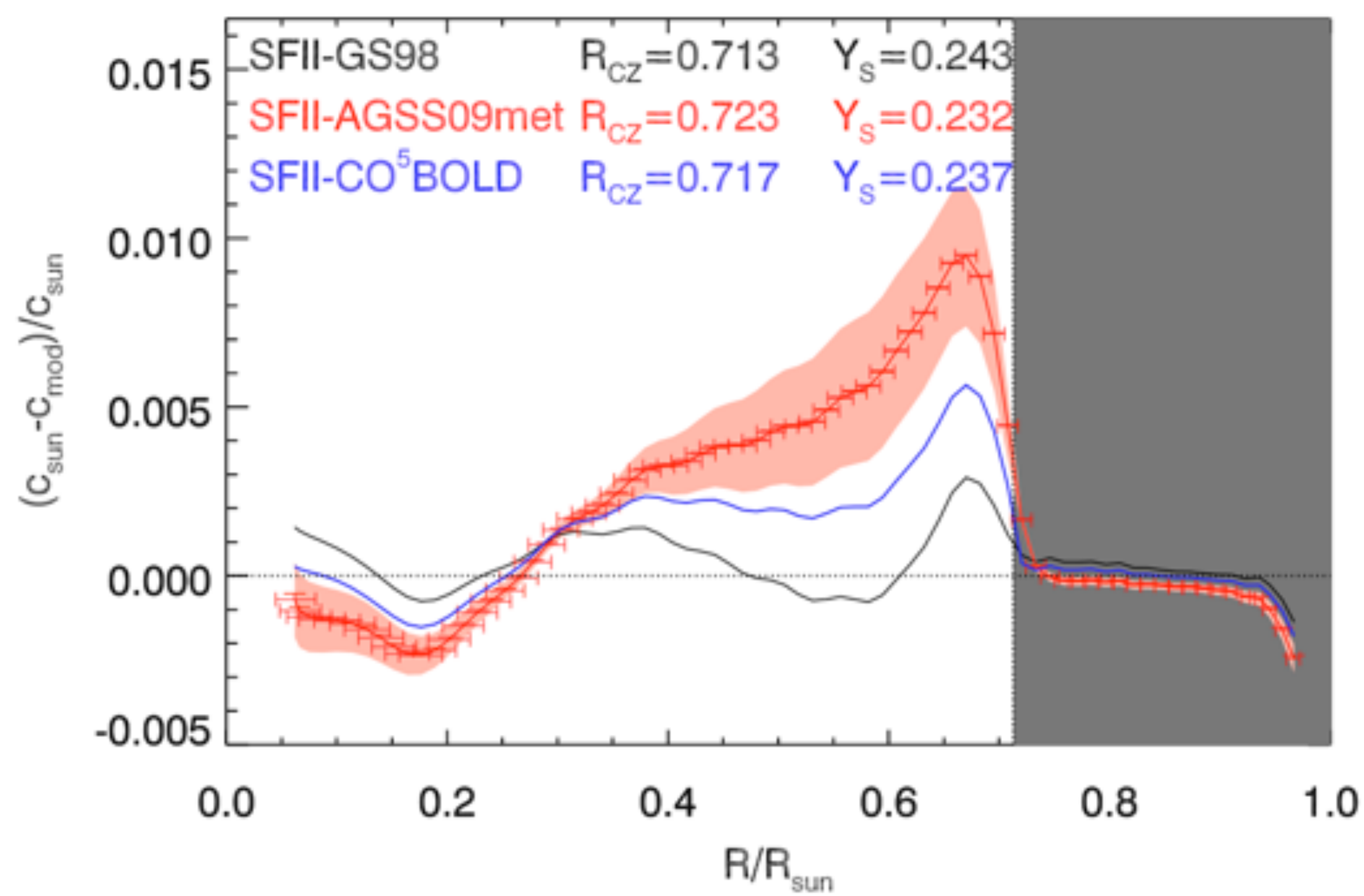
- **Agreement** between solar models and helioseismology **altered** after new spectroscopic determination of **photosphere** composition
    - advanced 3D hydrodynamic model instead of 1D
    - better atomic and molecular data
    - non local thermodynamic equilibrium (NLTE) calculations
- **C**, **N**, **O** abundances **lower** by 20-30%
- New abundances challenging for SSM, **lost agreement** with helioseismic data

Solar abundance problem

photospheric abundances ...

Element	GS98	AGSS09	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
Z/X	0.0229	0.0178	0.29

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



Basu et al., 2009

Serenelli, 2016, 1601.07179

Solar abundance problem

Does it question validity of SSM and stellar models?
No easy answer.

Lower metallicity abundances are here to stay -
Serenelli (2016) *1601.07179*

The problem motivated further work on solar models
nuclear reaction rates, opacities, state equation …

Opacity, metallicity, CNO

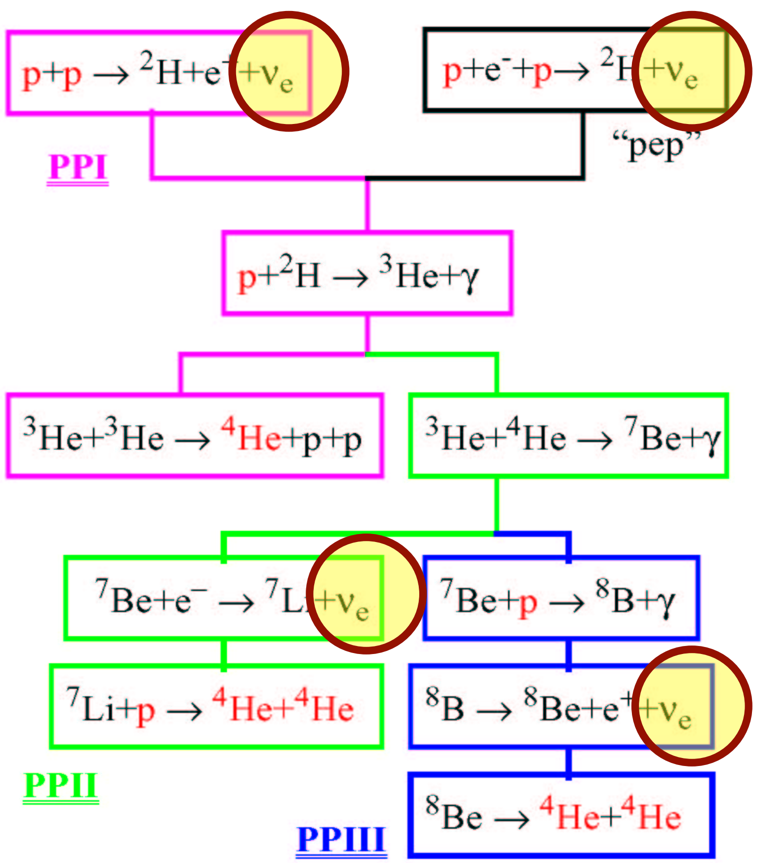
A suitable change of solar opacity profile produces same effects on helioseismic observable and neutrino fluxes of a change of solar composition

… except for CNO neutrinos

CNO neutrinos can break this degeneracy

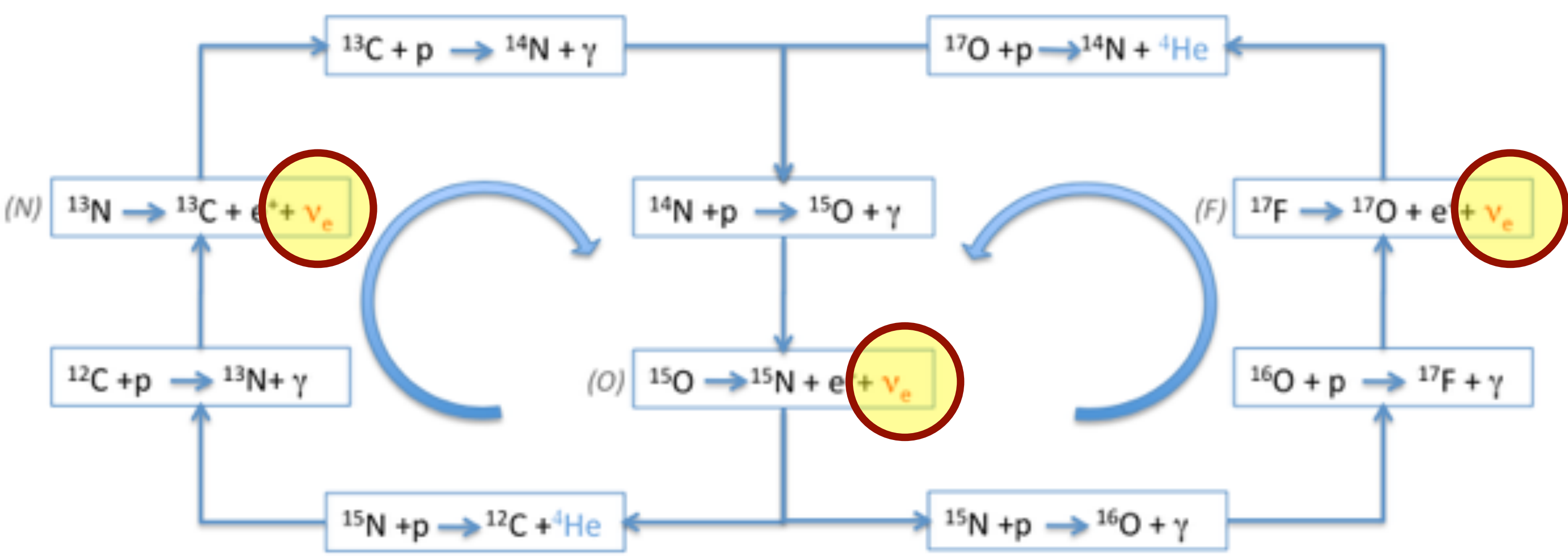
Solar Neutrinos

pp chain



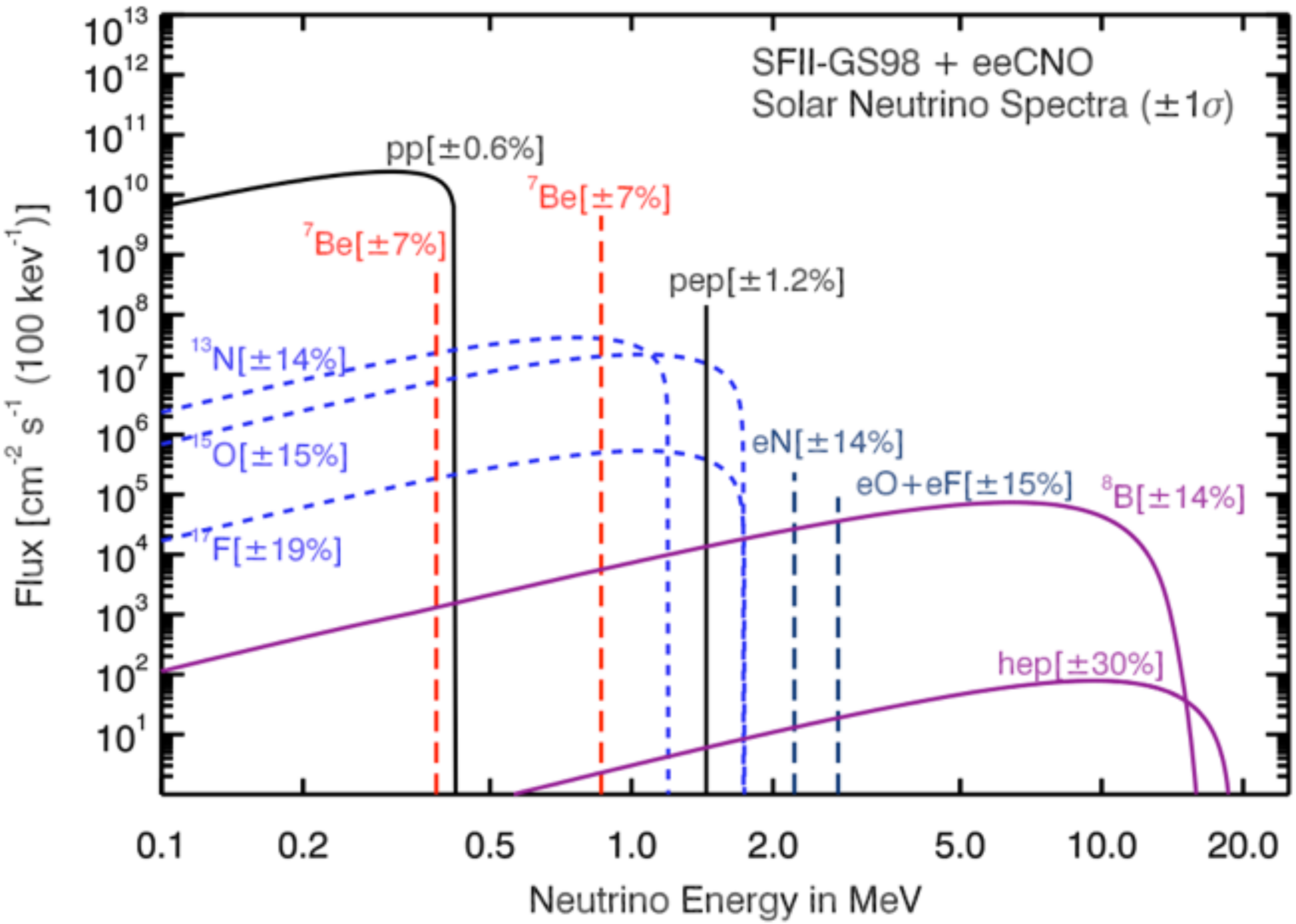
main

CNO bi-cycle



marginal

Solar Neutrinos



Solar Neutrino fluxes

Flux	SFII GS98	SFII C11	SFII AGSS09met	Solar
pp	5.98 [0.6%]	6.01	6.03	6.05 [0.6%]
pep	1.44 [1.1%]	1.46	1.47	1.46 [1.2%]
hep	8.04 [3%]	8.19	8.31	18 [45%]
^{7}Be	5.00 [7%]	4.74	4.56	4.82 [4.5%]
^{8}B	5.58 [14%]	4.98	4.59	5.00 [3%]
^{13}N	2.96 [14%]	2.62	2.17	≤ 6.7
^{15}O	2.23 [15%]	1.92	1.56	≤ 3.2
^{17}F	5.52 [19%]	4.27	3.40	≤ 59
χ^2/P^{a}	3.5/90%	3.2/92%	3.4/90%	—
eN	2.34 [14%]	2.07	1.71	—
eO	0.88 [15%]	0.76	0.62	—
eF	3.24 [19%]	2.51	2.00	—

pp, pep
Luminosity constraint

pp (Borex) 11% accuracy
pep (Borex) 25% accuracy

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};
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^{7}Be, ^{8}B

Differences in flux due to
core temperature - degeneracy:
composition vs opacity

^{7}Be (Borex) 5% accuracy
^{8}B (SNO, SK) 3% accuracy

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CNO
flux linear on C+N abundance,
can determine core abundance

CNO (Borex) upper limit
But essentially unconstrained

Units:
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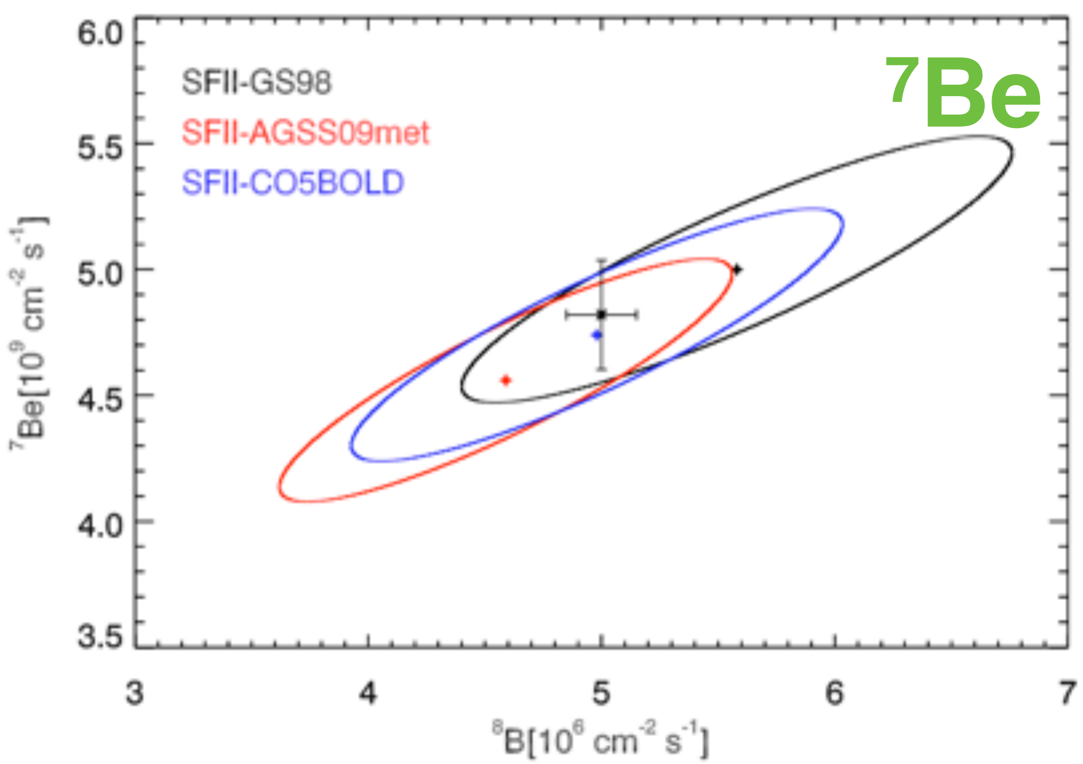
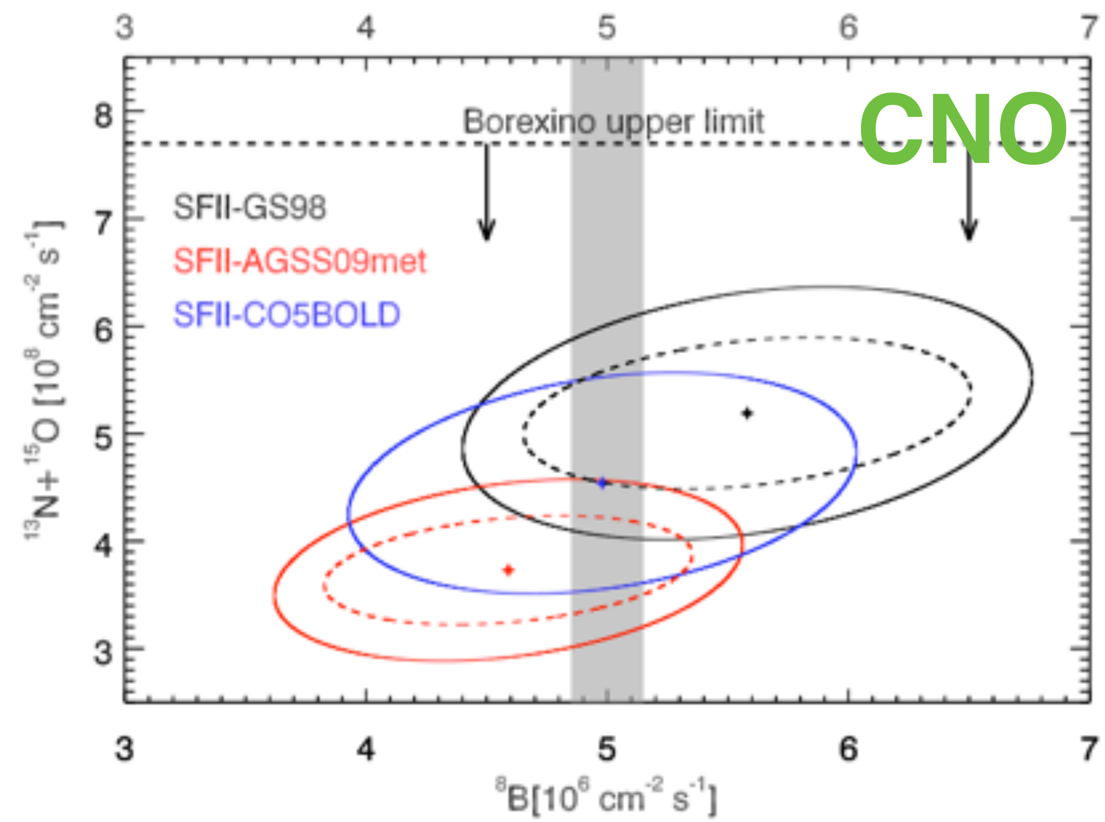
Solar Metallicity and neutrino fluxes





SSM neutrino flux vs ^{8}B flux

^{8}B flux is used as thermometer of solar core

Temperature profile in solar core established by pp-chain, not CN-cycle

CNO neutrino flux, probe to determine solar abundance

Goal:
measuring CNO neutrino

It is extremely challenging

CNO neutrino fluxes

solution

CNO neutrino **flux** could **discern** High vs Low Z **models**

but

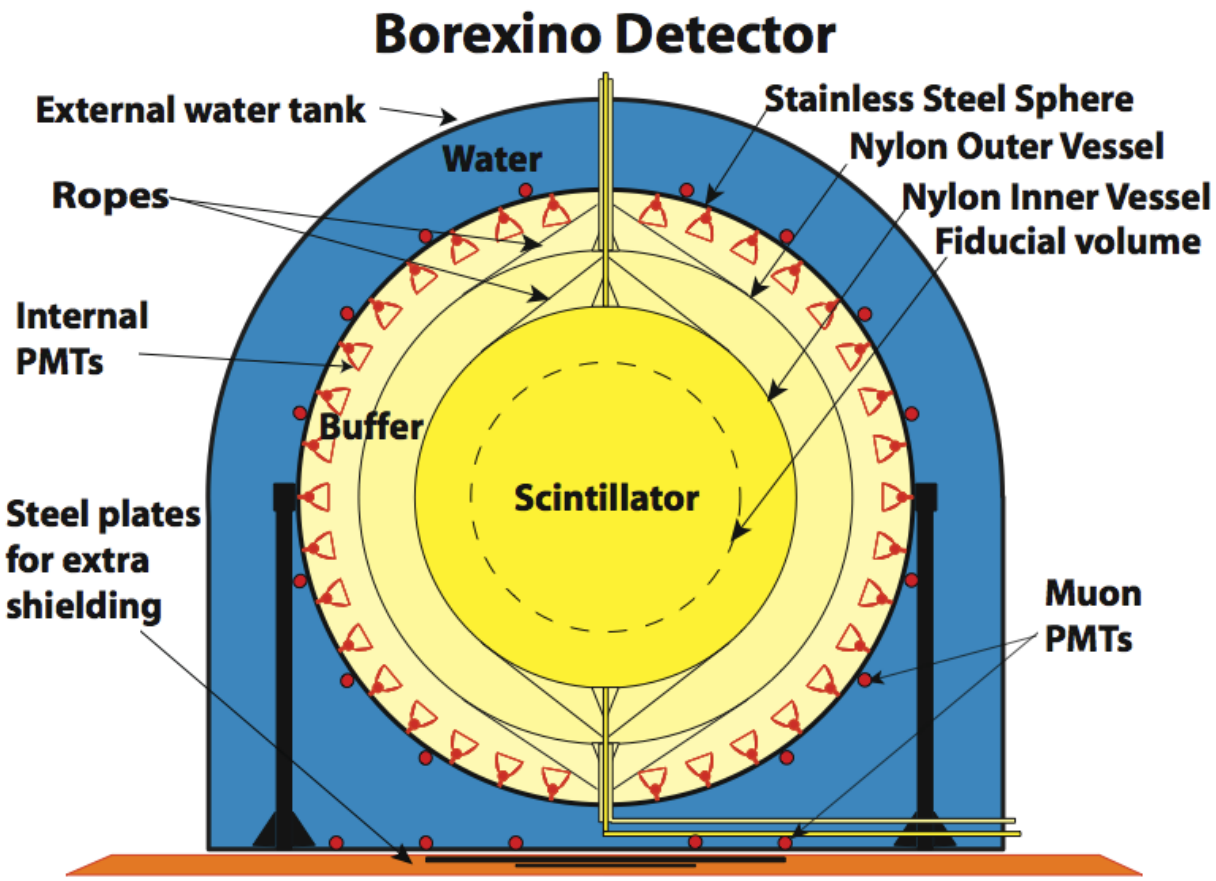
CNO-bicycle **marginal** source of energy in Sun
therefore **CNO** neutrino **fluxes** are **very low**

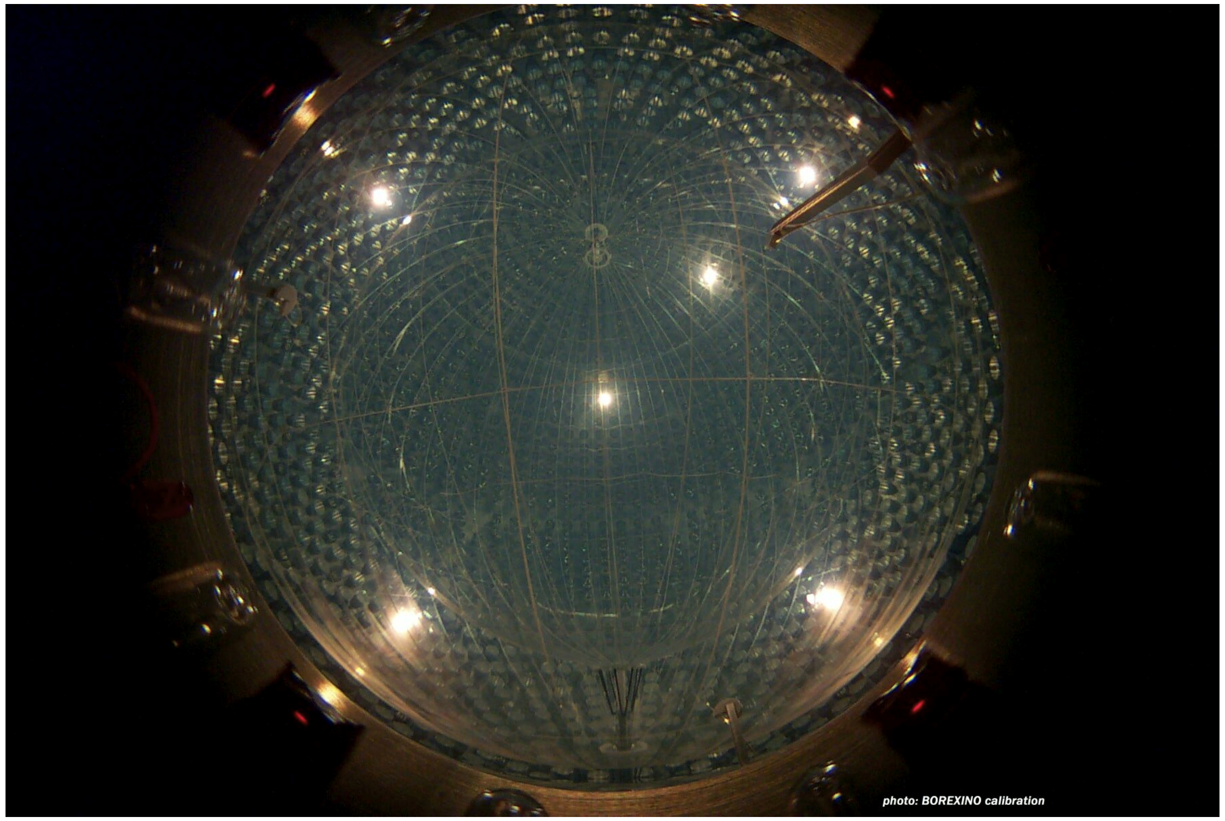
and

CNO energy spectrum endpoint < 2 MeV
overwhelmed by natural radioactivity background

(

Borexino Detector at LNGS



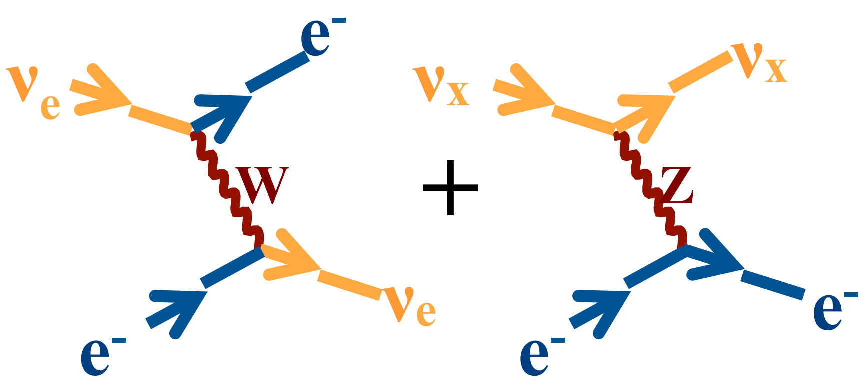


Ultra-pure liquid scintillator calorimeter

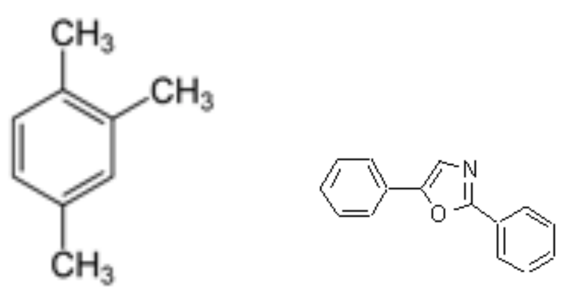
low energy **threshold**

superb **radio-purity**

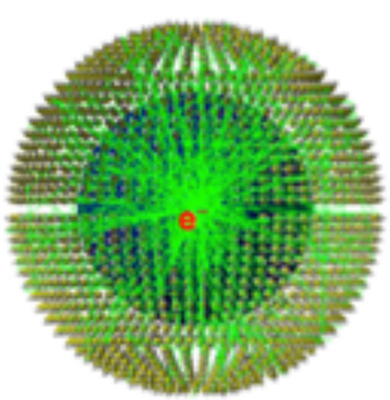
Solar-ν detection in Borexino



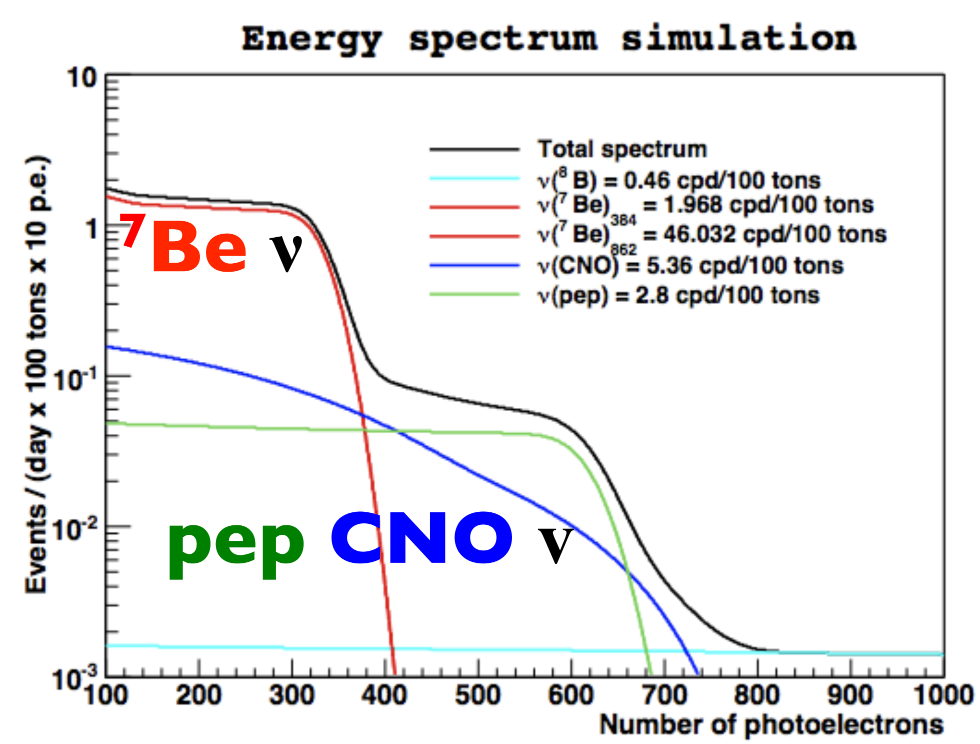
Elastic scattering
on **electrons** (ν_X-e^-)



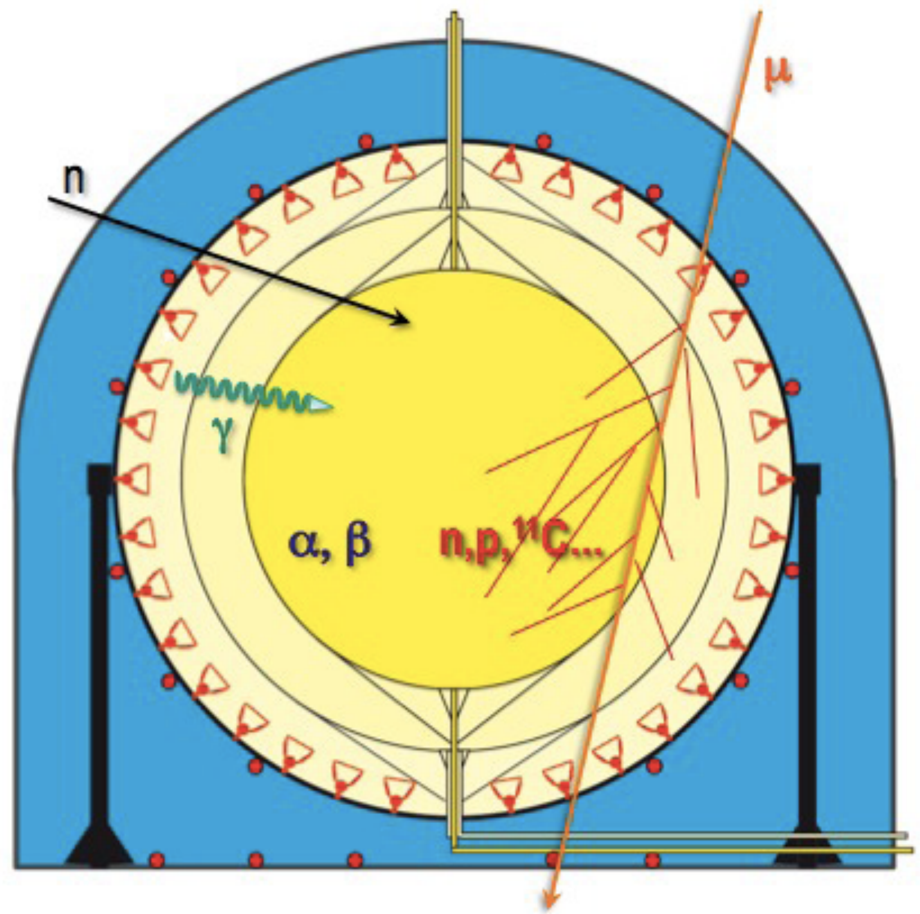
Emission of **scintillation light**



Scintillation light
detected by **PMTs**



Backgrounds



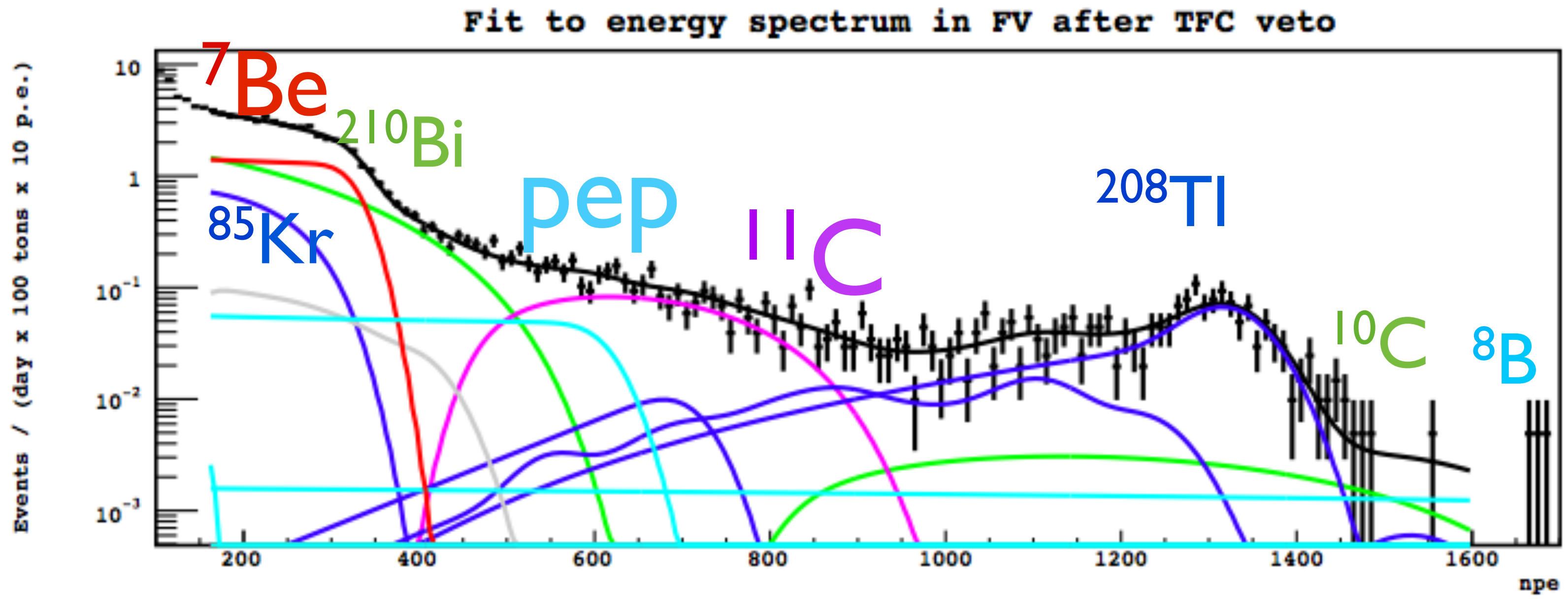
ν induced events not distinguishable from
β/γ due to natural **radioactivity**

LS-based solar neutrino detectors
requires extreme **purity**
from **all** radioactive contaminants

)

but follow S. Marcocci's and A. Caminata's talks for more info

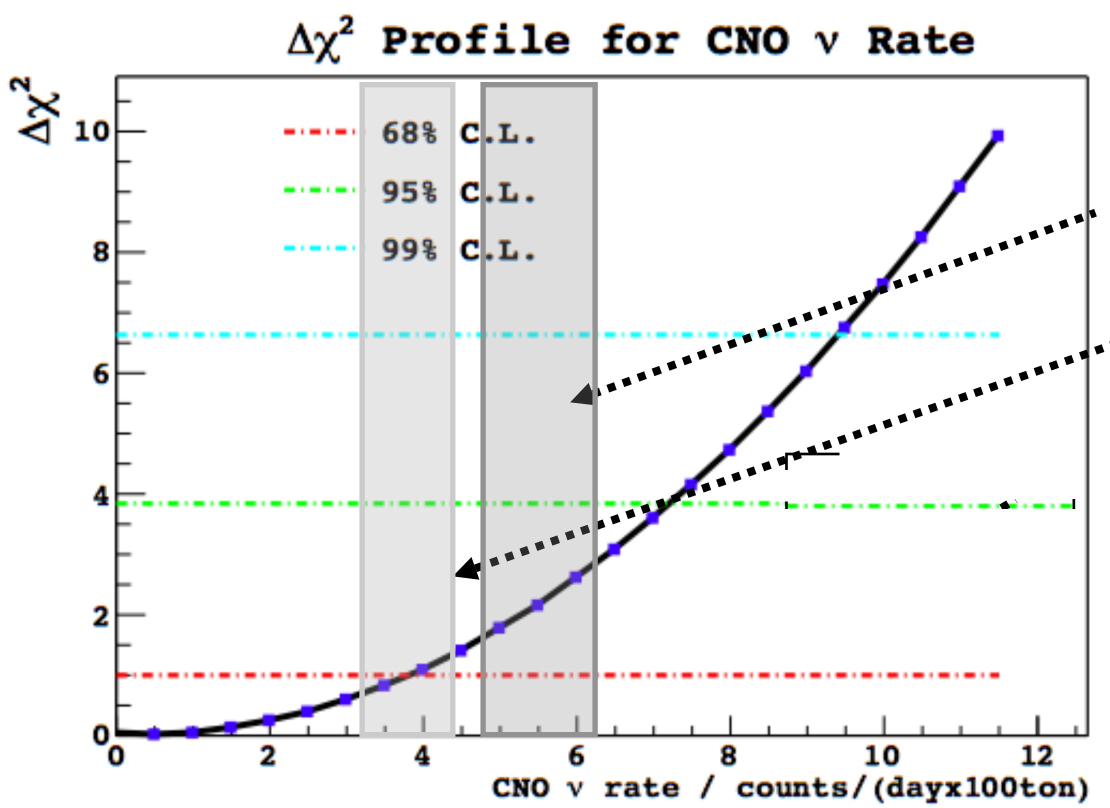
CNO neutrinos in Borexino



Borexino is the most radio pure detector of the world between 200 keV and 2 MeV …

… still, can you recognise CNO neutrinos between other solar neutrinos and residual radioactive backgrounds?

CNO ν best limit



HighZ SSM

LowZ SSM

Borexino's limit (2012)

ν	Interaction rate [counts/(day·100 ton)]	Solar-ν flux [$10^8 cm^{-2} s^{-1}$]	Data/SSM ratio
pep	$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$	1.6 ± 0.3	1.1 ± 0.2
CNO	< 7.9 ($< 7.1_{\text{stat only}}$)	< 7.7	< 1.5

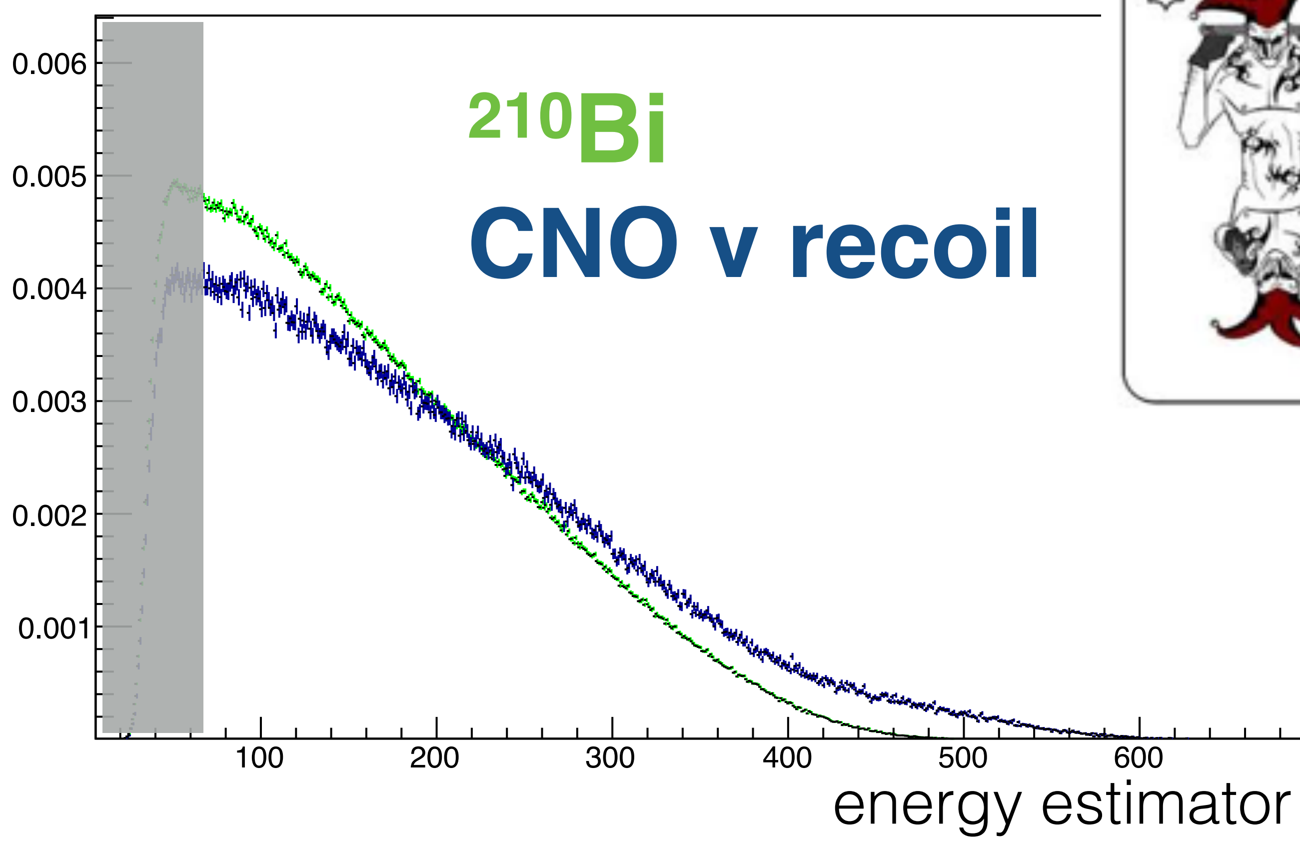
Phys Rev Lett 108, 051302 (2012)

CNO enemies

^{210}Bi, decays β-
Part of ^{238}U chain, parent of ^{210}Po
Not trivial to remove
Energy spectrum very similar to CNO recoil

Cosmogenics radioactive isotopes
In organic scintillator is **^{11}C**, decays β+
Can be reduced increasing detector depth or applying space-time cuts (but sacrificing exposure)

^{210}Bi and CNO neutrinos



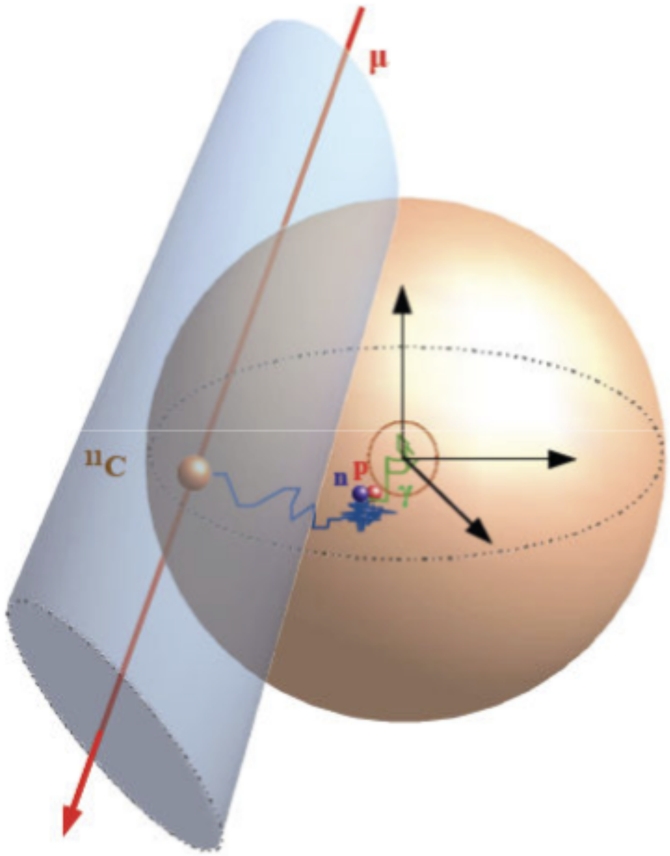
Example from Borexino, spectra from S. Marcocci

very similar spectral shapes
no distinct features

Determining ^{210}Bi from ^{210}Po time evolution?
Not impossible in principle, but challenging

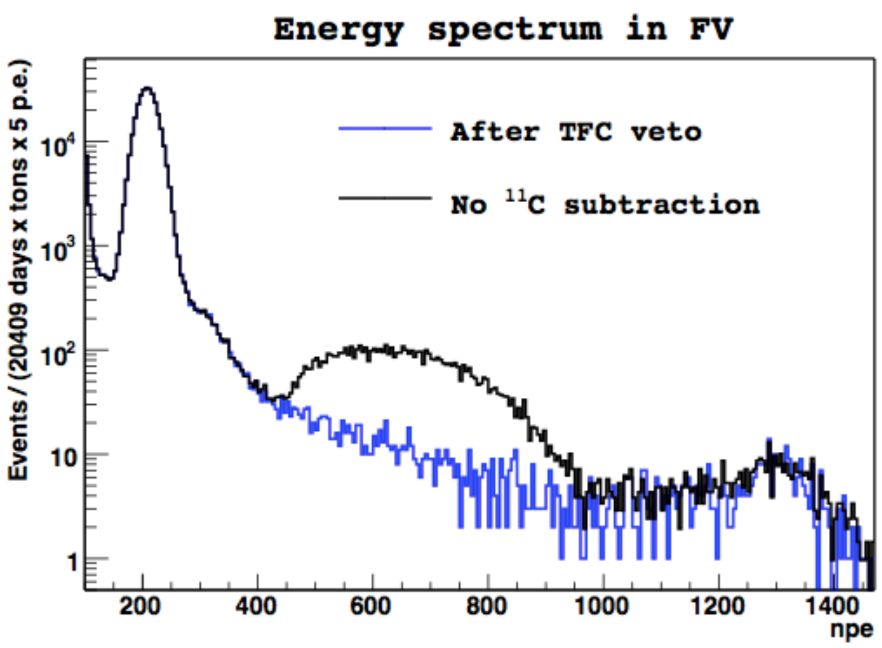
F.L. Villante et al., Phys.Lett. B701 (2011) 336

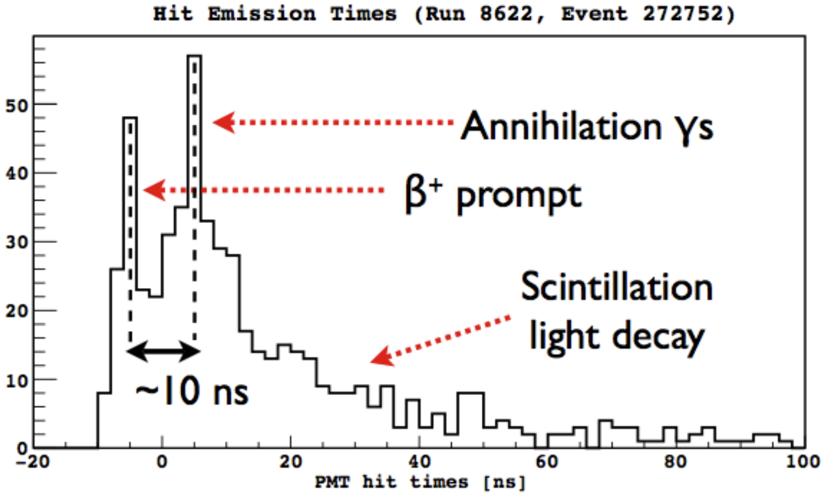
^{11}C and CNO neutrinos



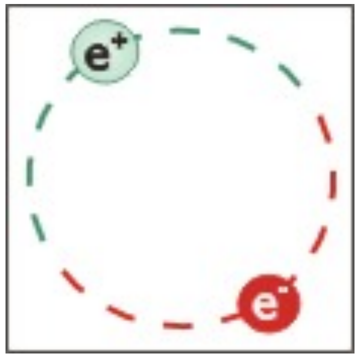
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

space and time correlation between **muon** track, **neutron** capture, **^{11}C** decay (τ ~ 29 min)





slightly **different** scintillation **pulse shape** for **e^-** and **e^+** due to o-Ps formation



G. Bellini et al. Phys. Rev. D89 (2014) 112007

D. Franco et al., Phys.Rev. C83 (2011) 0105504

The ideal CNO ν hunter

- **Very large detector** (CNO flux is low)
- **High energy resolution** (discriminate CNO from other neutrinos recoils)
- **Ultra-radiopure detector** (in particular from ^{210}Bi)
- **Very deep detector** (cosmogenics are not an issue)
- **Very stable detector** (measuring ^{210}Bi from ^{210}Po decay, no convective motions of backgrounds)
- **Pulse shape discrimination** (αβ for ^{210}Po, β+β- for cosmogenics, βγ for external and surface backgrounds)

Future CNO ν hunters

- **SNO+ at SNOLAB**
  - low energy solar phase after Te (0νββ) phase
  - SNOLAB deeper than LNGS (factor 100 less ^{11}C)
  - SNO+ larger than BX (1 kton detector)
  - all depends on ^{210}Bi levels …
- **Proposal: ARGO at LNGS**
  - 300 ton Argon TPC (ultimate DarkSide detector)
  - Follow D. Franco’s presentation

Conclusion and Outlook

- There is a **solar abundance problem**
- Experimental measurement of **CNO neutrino** flux can settle the problem
- Experimental CNO neutrino detection is **challenging**
- Not trivial in Borexino Phase-II
- Future detectors will inherit Borexino’s will

References

- Most of figures, numbers, and notions about SSM from Aldo Serenelli's “Alive and well: a short review about standard solar models” in 1601.07179, and references therein

- Material about solar neutrinos also from F. Villante's “Review of solar physics and neutrinos”

- Borexino's figures and numbers mostly from PRD 89 (2014) 112007 and references therein

- Batman pictures from the web. I do not own Batman.

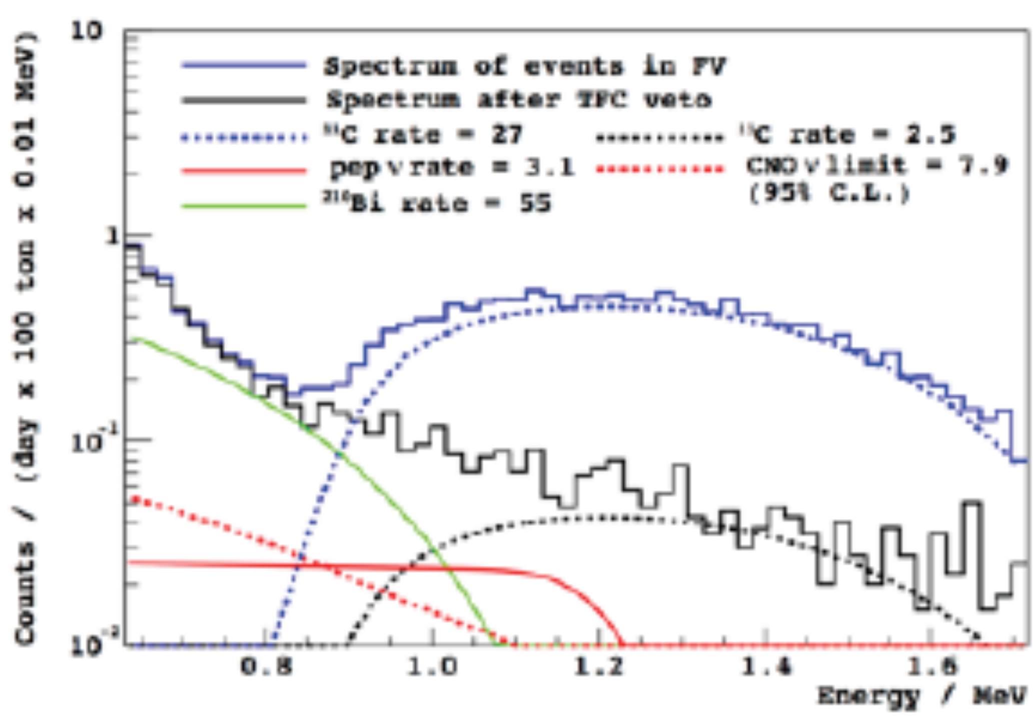
Backup

CNO neutrino fluxes

CNO neutrino flux could **discern** High vs Low Z **models**

but

CNO-bicycle **marginal** source of energy in Sun
therefore **CNO** neutrino **fluxes** are **very low**



But small CNO rates:
~3-5 interactions/day/100tons
Overwhelmed by
^{11}C β^+ background
~25 interactions/day/100tons