Solar Neutrinos

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on behalf of the Borexino Collaboration

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UNIVERSITÀ DEGLI STUDI DI MILANO · INFN Istituto Nazionale di Fisica Nucleare · LNGS · PRINCETON UNIVERSITY · UNIVERSITÀ DEGLI STUDI DI GENOVA · NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE" · St. Petersburg Nuclear Physics Inst. · Technische Universität München · JAGIELLONIAN UNIVERSITY IN KRAKÓW · JÜLICH FORSCHUNGSZENTRUM · Virginia Tech · JOHANNES GUTENBERG UNIVERSITÄT MAINZ · SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY · Joint Institute for Nuclear Research · TECHNISCHE UNIVERSITÄT DRESDEN · RWTH AACHEN UNIVERSITY

Talk overview

1. **Introduction and motivation for solar neutrino program**

   - Direct probe of nuclear fusion
   - Standard Solar Models: metallicity
   - Neutrino oscillation parameters: solar sector (θ_{12}, Δm^2_{12})
   - Survival probability P_{ee} as $f(E_\nu)$: matter effects, testing LMA-MSW prediction and its upturn

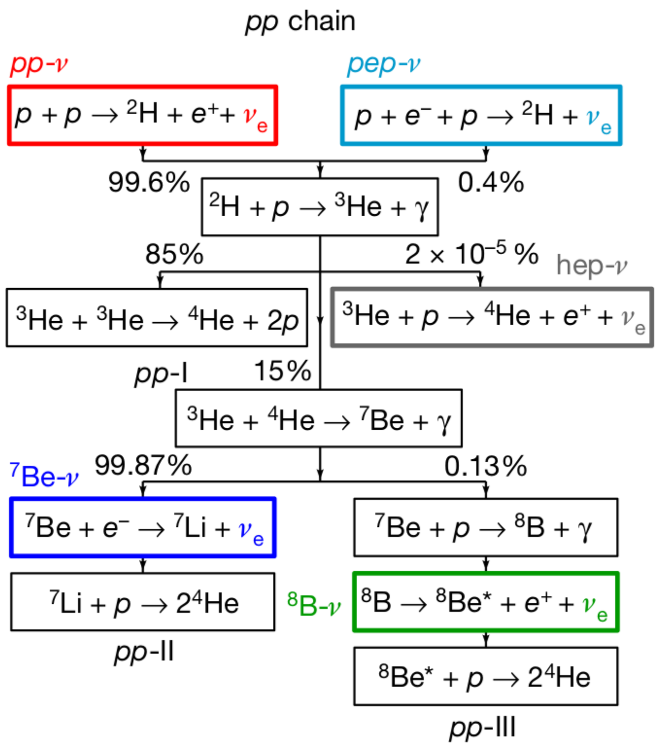
2. **Borexino**

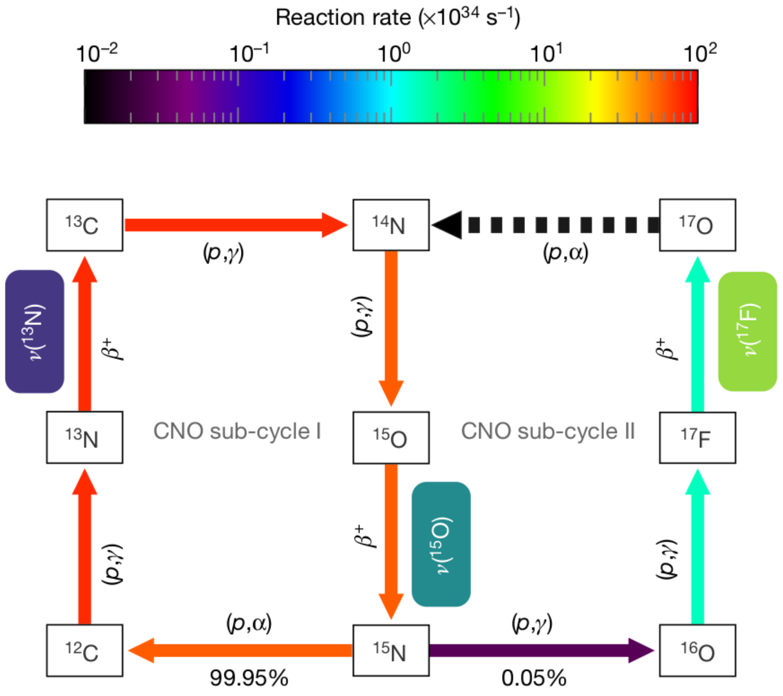
   - Spectroscopy of the *pp* chain neutrinos
   - Observation of the CNO cycle neutrinos

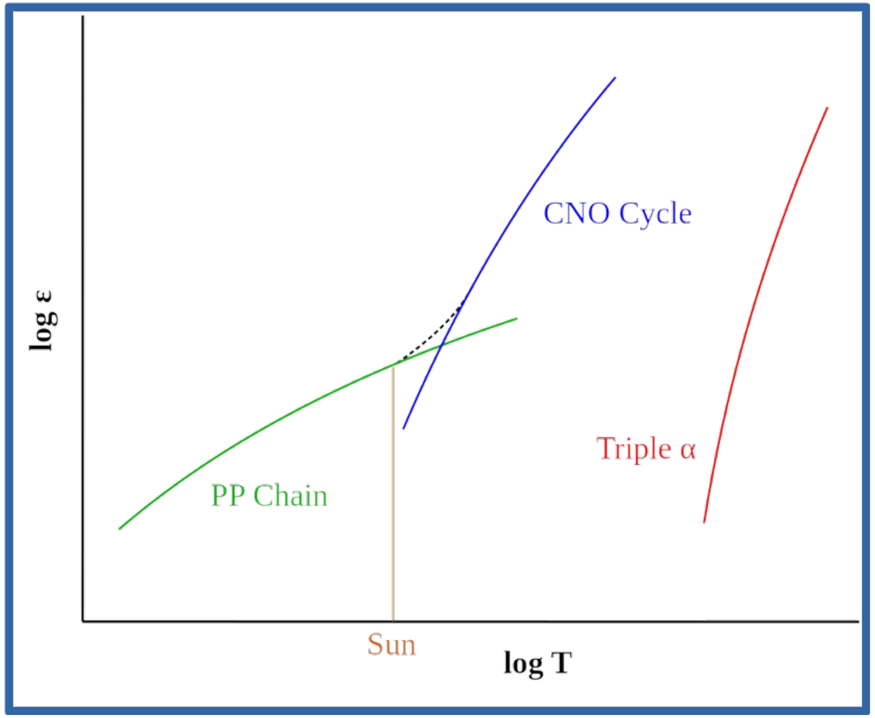
3. **SuperKamiokande**

   - Oscillation physics with ^8B solar neutrinos

PP vs CNO Competition







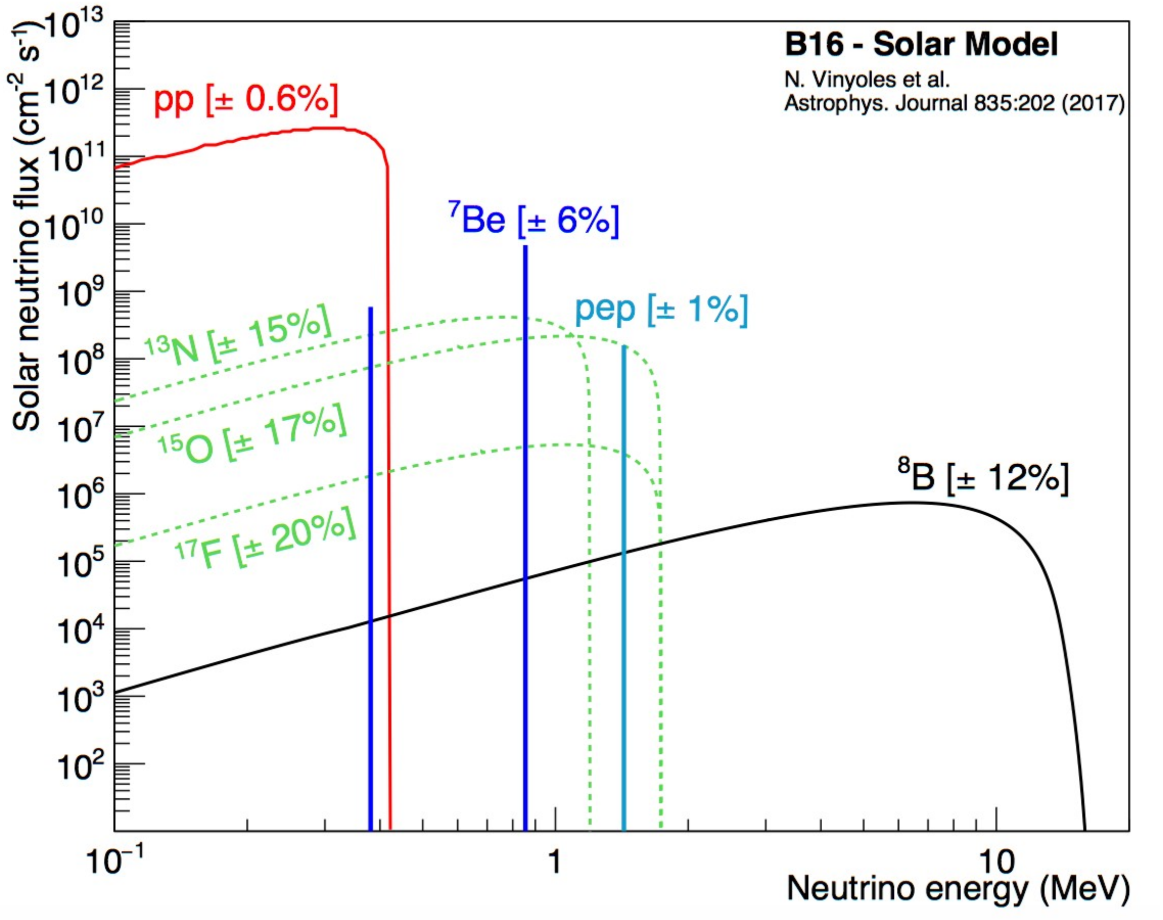
- Intense neutrinos from nuclear fusion in the Sun's core
- Majority (99%) from pp-chain with subdominant contribution from CNO cycle
- What's left in solar neutrinos?
    - Help understanding solar interior (metallicity problem)
- **Precision test of the MSW oscillation model**
    - Precise measurement of spectrum at the vacuum-to-matter transition region
    - Measurement of Day/Night asymmetry

The CNO cycle dominates in stars heavier than 1.3 M

Solar neutrinos as sensitive tool to test solar models: expected fluxes

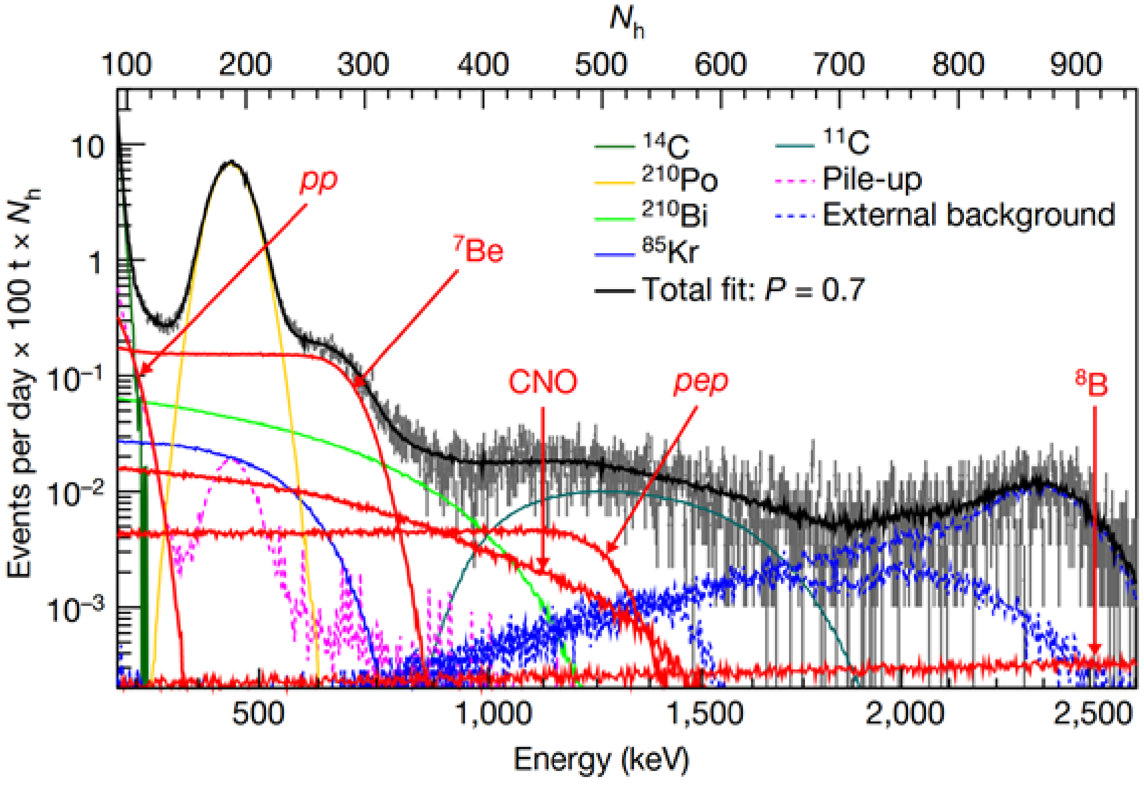
FLUX	B16-GS98
pp (10^{10} cm^{-2} s^{-1})	5.98(1±0.006)
pep (10^{8} cm^{-2} s^{-1})	1.44(1±0.01)
^{7}Be (10^{9} cm^{-2} s^{-1})	4.94(1±0.06)
^{8}B (10^{6} cm^{-2} s^{-1})	5.46(1±0.12)
^{13}N (10^{8} cm^{-2} s^{-1})	2.78(1±0.15)
^{15}O (10^{8} cm^{-2} s^{-1})	2.05(1±0.17)
^{17}F(10^{6} cm^{-2} s^{-1})	5.29(1±0.20)

N. Vinyoles et al., Astrophys. J. 835 (2017) 202



Original motivation of the first experiments on solar ν was to test the Standard Solar Model (SSM)

BOREXINO – real-time solar neutrino spectroscopy

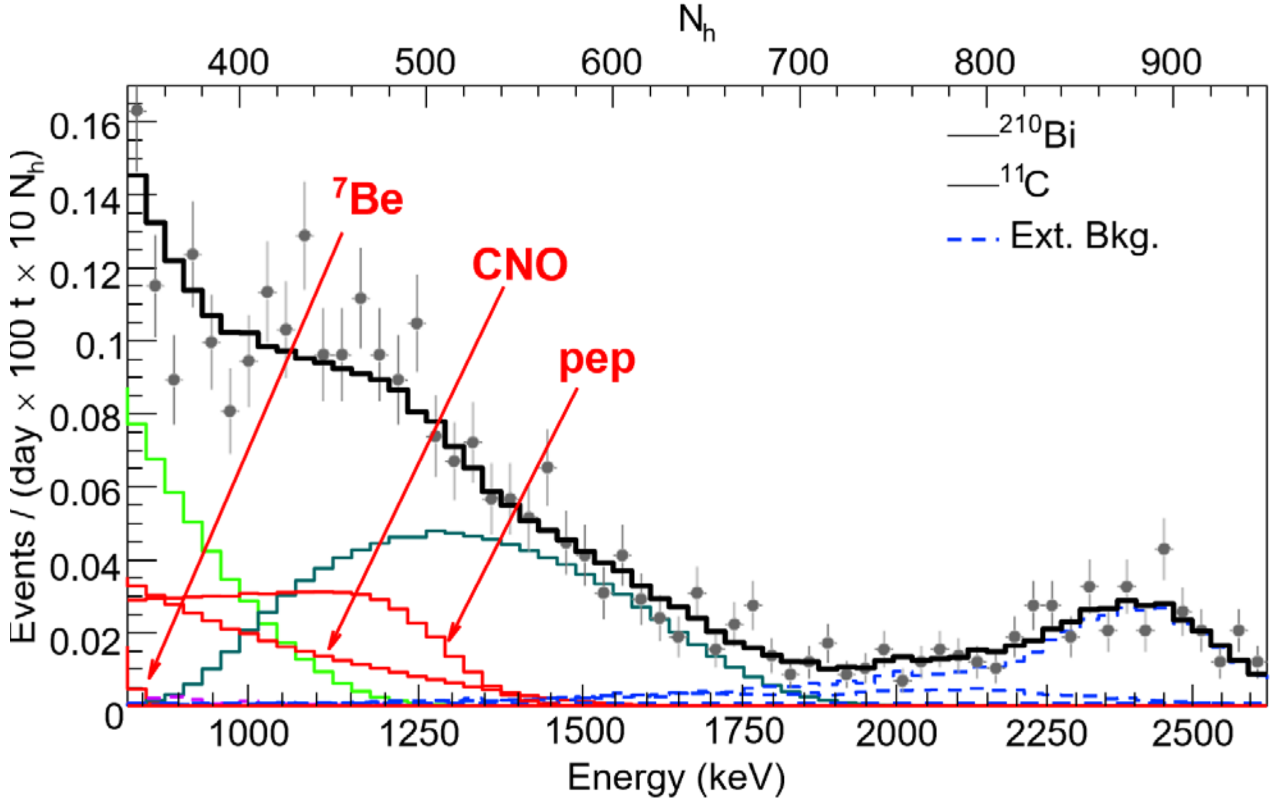


The Borexino Collaboration. *Comprehensive measurement of pp-chain solar neutrinos*. *Nature* **562,** 505–510 (2018)

From the measured interacton rates and assuming HZ-SSM fluxes we get electron neutrino survival probability from 60 keV to >10 MeV.

Selected the innermost β-like events

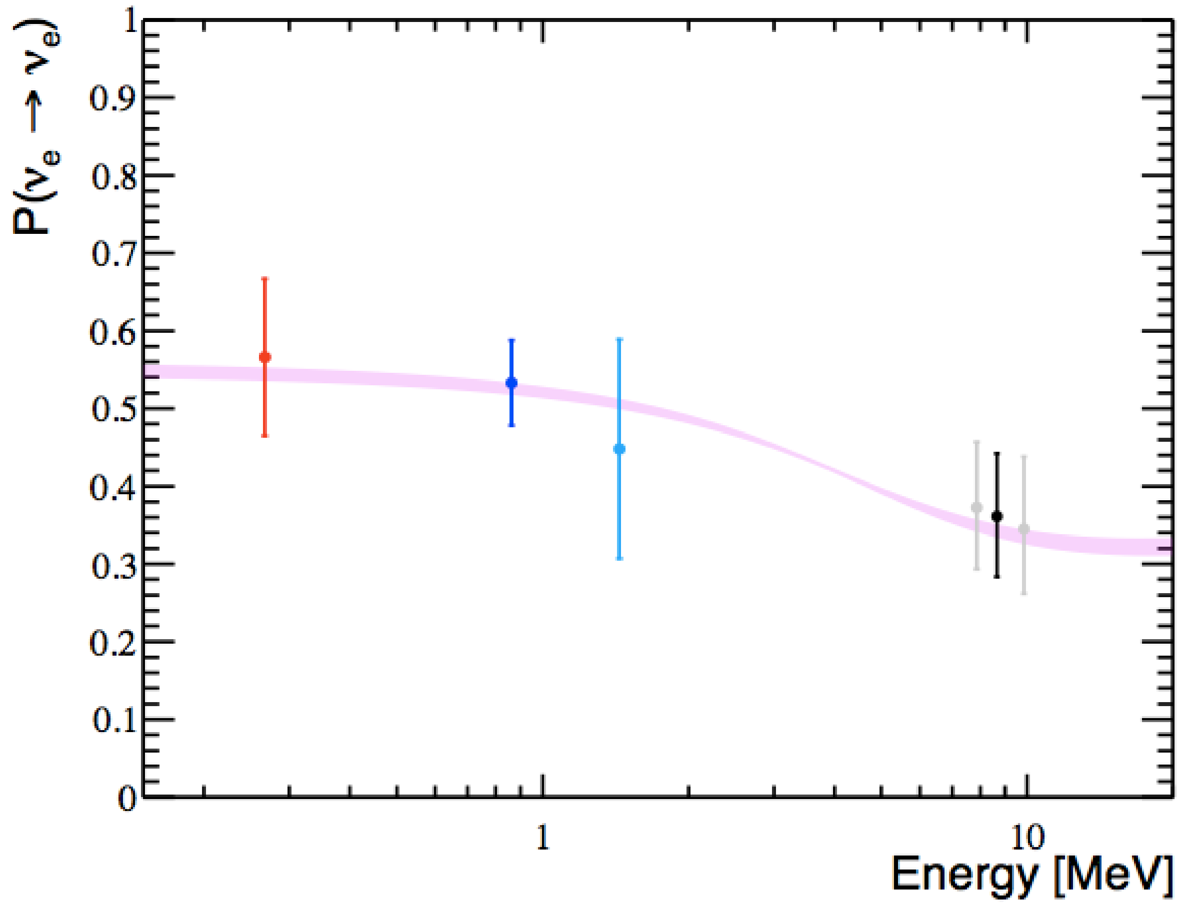
Radius <2.4 m Ps-LPR < 4.8



- $P_{ee}(pp) = 0.57 \pm 0.10$ $P_{ee}(^7Be, 862 keV) = 0.53 \pm 0.05$
- $P_{ee}(pep) = 0.43 \pm 0.11$ $P_{ee}(^8B) = 0.37 \pm 0.08$

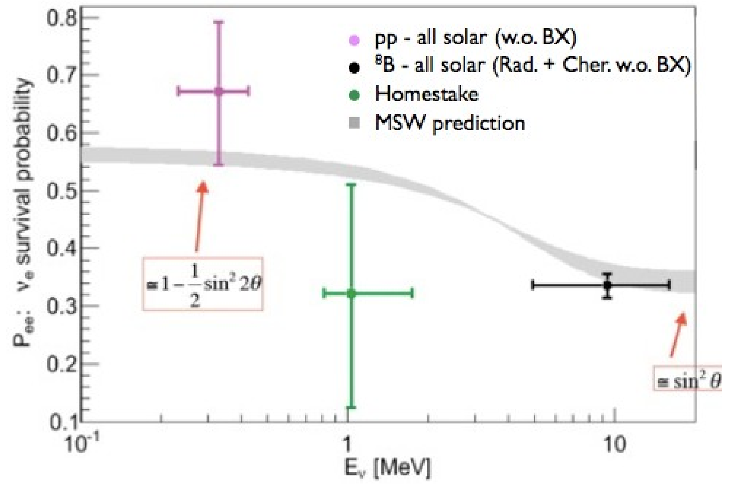
P_{ee}: Borexino impact

Borexino now



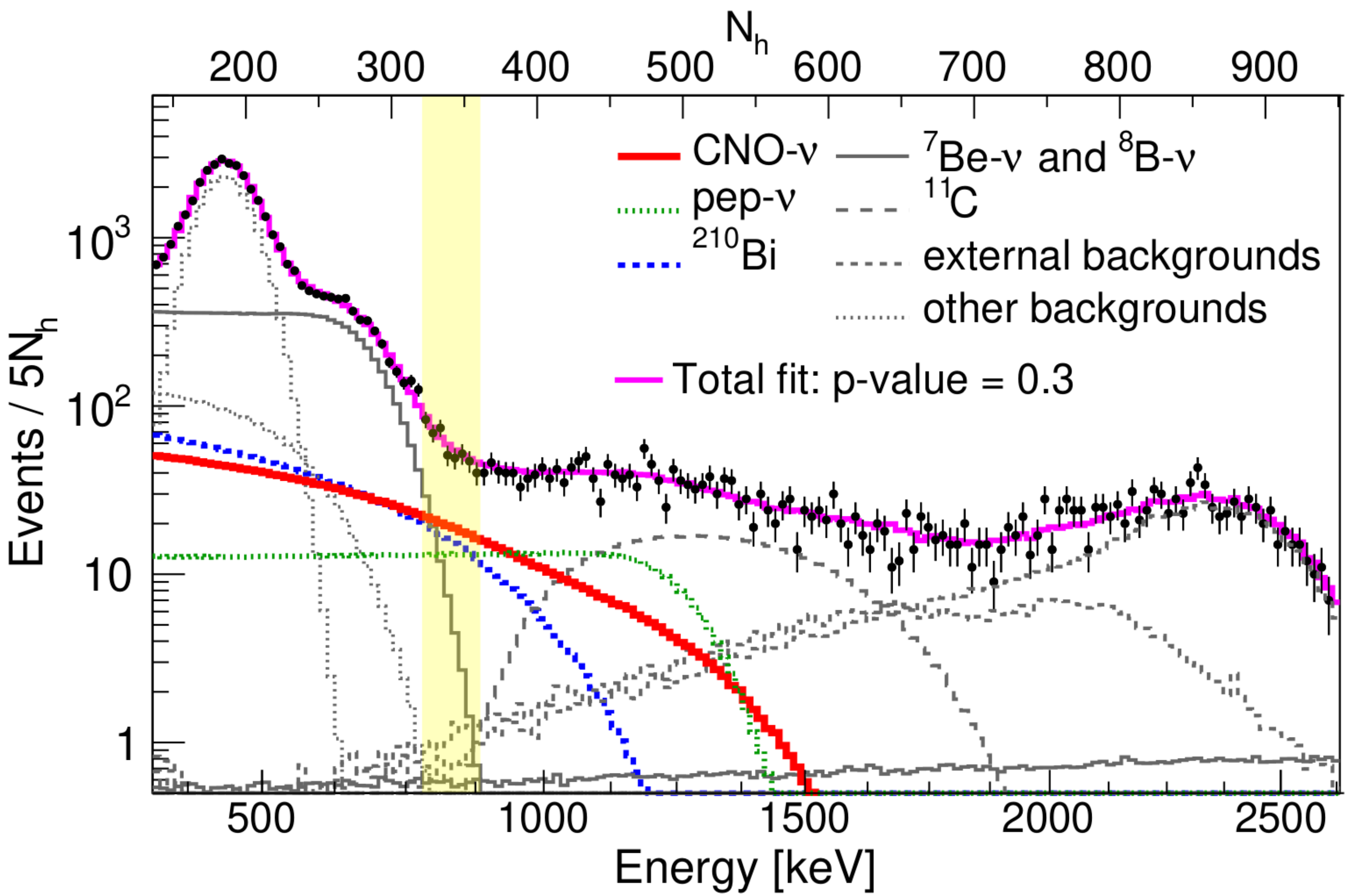
Pee - electron neutrino survival probability

Before Borexino

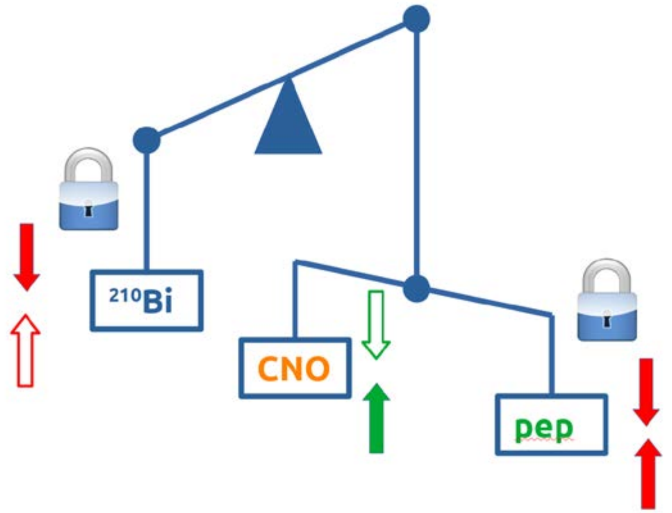


1. Borexino has measured the electron neutrino Pee in the *vacuum regime*, where, according to the MSW- LMA model, the vacuum dominates
2. The Borexino data allowed to probe the vacuum– matter transition from a single experiment.
3. Despite the uncertainty of the various points, that incorporate both the experimental errors and the SSM uncertainties, the experimental results seem in agreement with the predictions of the MSW-LMA model.

CNO - challenges

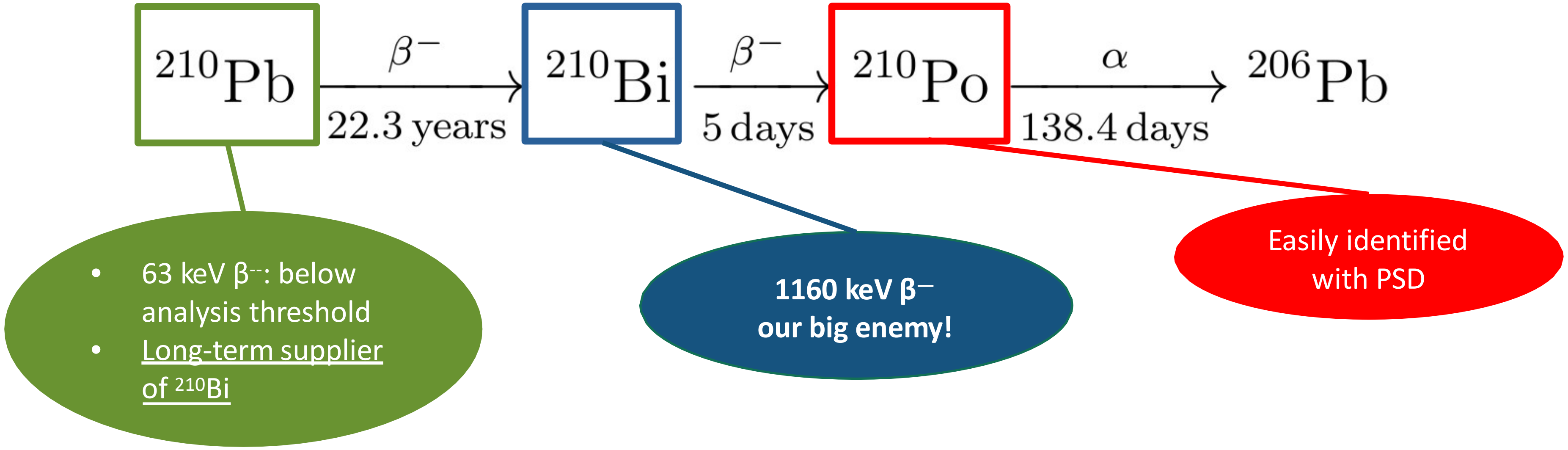


- *pep* rate: gaussian penalty at SSM prediction
- ^{210}Bi rate: semi-gaussian penalty at our upper limit



Strategy: independent constraint of pep and Bi-210

Strategy for ^{210}Bi constraint

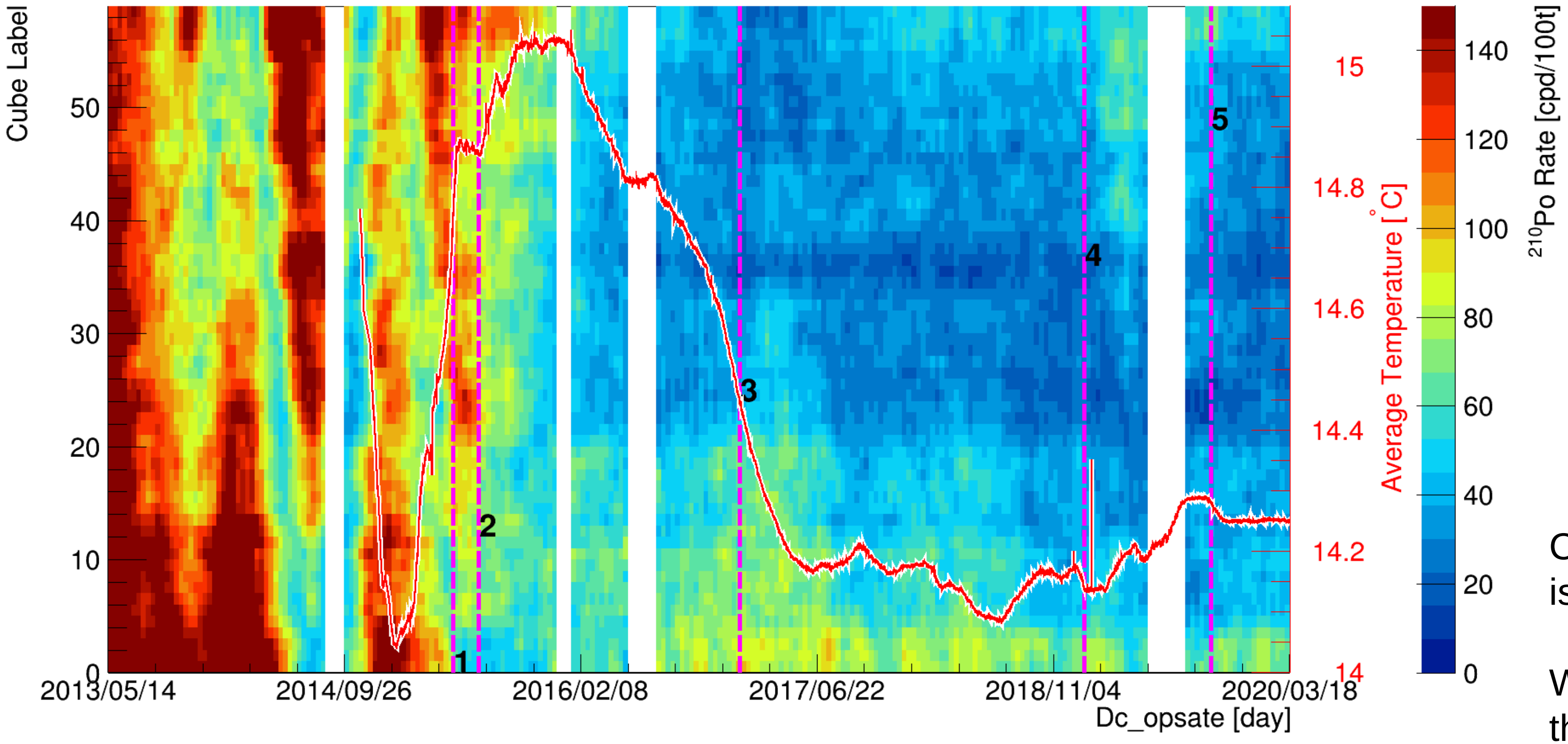


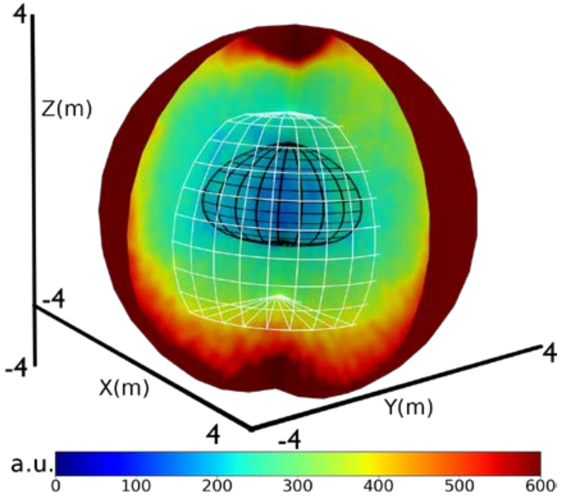
Measuring ^{210}Po could allow to constraint ^{210}Bi

…

If only we had secular exquilibrium!

The Low Polonium Field





Clean region in the core of the detector is created: LPoF

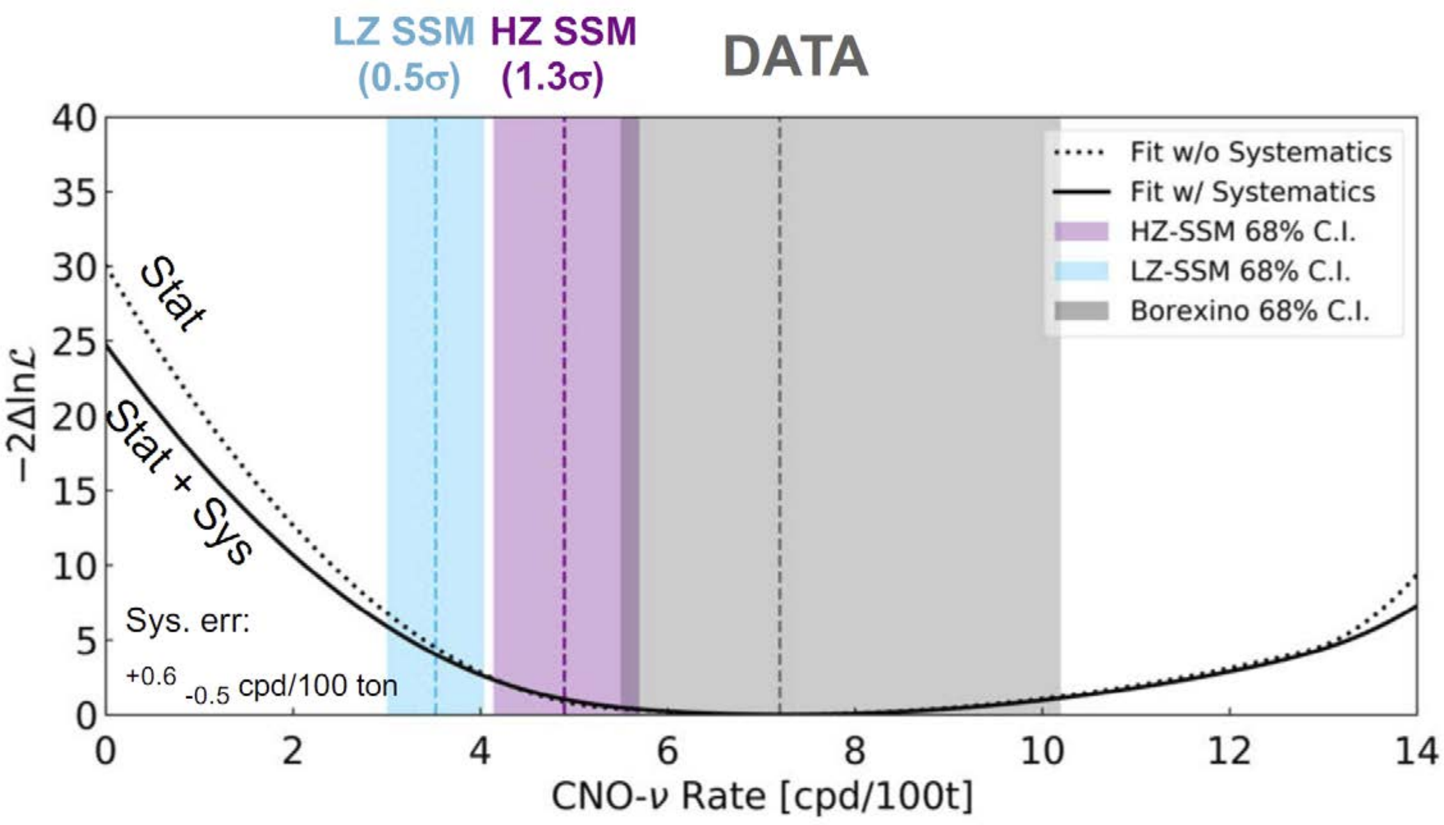
We extract the minimal ^{210}Po rate value, that is an upper limit on ^{210}Bi rate as a half-Gaussian constraint in the analysis

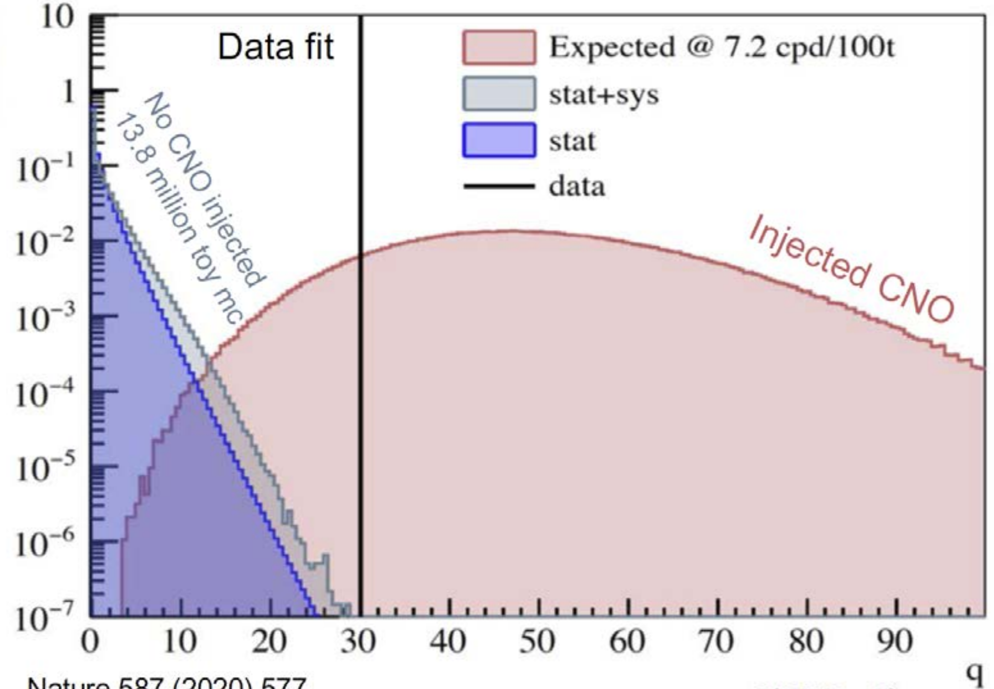
Bi < 11.5 +/- 1.04 cpd/100t (stat + sys)

$R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po_{vessel}) > R(^{210}Bi)$

CNO fit results

The Borexino Collaboration. *Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun*. Nature **587,** 577–582 (2020).





Nature 587 (2020) 577

$$q = -2\log\frac{\mathcal{L}(\mathrm{CNO}=0)}{\mathcal{L}(\mathrm{CNO})}$$

Result (68% CL stat + sys) = R_{CNO} = $7.2^{+3.0}_{-1.7}$ cpd/100 t

Φ(CNO with sys) = $7.0^{+3.0}_{-2.0} \times 10^8$ cm^{-2} s^{-1}

Null-hypothesis exclusion:
5σ significance at 99% CL

Borexino

1. Borexino has been the first experiment probing **sub-MeV neutrinos in real-time,** and is still now **the unique experiment** able to proceed with these studies.
2. Borexino has measured for **the first time all pp chain nuclear reactions producing neutrinos**, measuring, in particular, simultaneously the pp, ^{7}Be, and pep neutrino flux, ^{8}B neutrinos with a low threshold and probing hep neutrinos.
3. These results paved the way to actual breakthroughs not only on Solar physics, but also on neutrino physics. **The ν_e survival probability in the vacuum regime is measured** for the first time by Borexino and the **vacuum–matter transition** has been probed by a single experiment. In addition, a number of non-standard neutrino interactions has been studied by Borexino with world leading limits.

Borexino

European Physical Society
PRIZE

The 2021 Giuseppe and Vanna Cocconi Prize
for an outstanding contribution to Particle Astrophysics and Cosmology
is awarded to the
Borexino Collaboration
for their ground-breaking observation of solar neutrinos from the pp chain and CNO cycle that provided unique and comprehensive tests of the Sun as a nuclear fusion engine.

Luc Bergé
President
European Physical Society

Thomas Gehrmann
Chair
EPS High Energy and Particle Physics Division

Mulhouse, France, 26 July 2021

4. The detection of the CNO cycle closes a long history, which began in the 30s of the last century, when Hans Bethe and Carl Friedrich von Weizsacker, independently, proposed that the fusion of hydrogen in stars could also be catalyzed by nuclei heavier than He. Then the theory of energy generation hypothesizes that the CNO would be the primary channel for hydrogen burning in stars more massive than the Sun , and it is in fact the primary channel for hydrogen burning in the Universe. This hypothesis never received an observational confirmation until now, when Borexino **has observed CNO neutrinos** proving also that its contribution in the Sun is of the order of 1%.
5. When all solar neutrino fluxes measured by Borexino, including CNO, are combined, the LZ hypothesis is **disfavored at a level of 2.1σ.**
6. Again, thanks to the low intrinsic background, Borexino has **observed geo-neutrinos** with 5σ statistical significance and studied them to obtain Earth geo-physical and geo-chemical information.

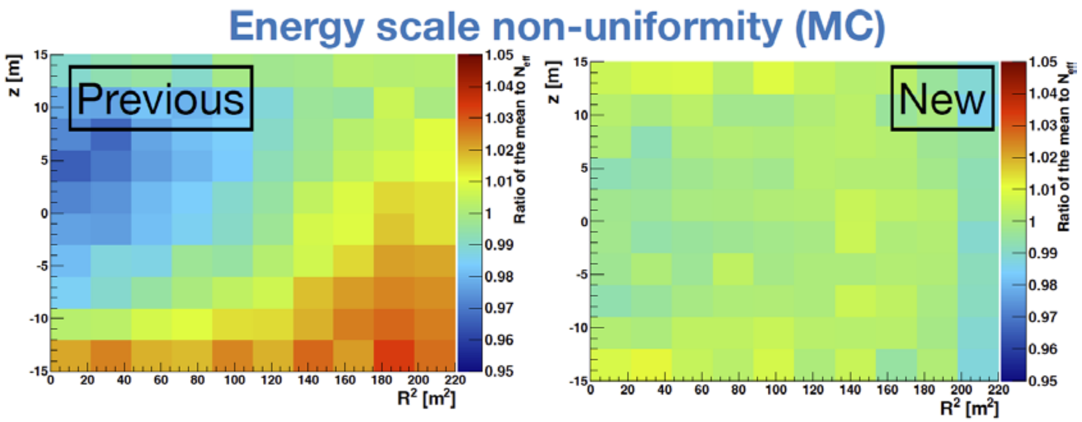
SuperK – ^{8}B Solar neutrino analysis improvements

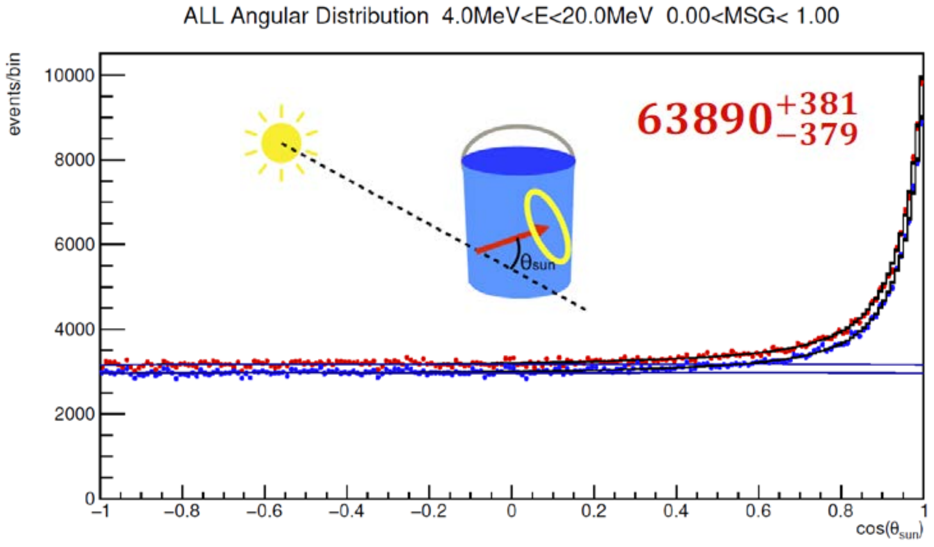
- **Detector simulation improvements**
  - Improved PMT hit timing simulation
  - Improved modeling of water quality non-uniformity
- **Analysis improvements**
  - Correction for PMT gain drift
  - Improved correction for non-uniform energy response

  E-scale non-uniformity (MC) 1.7% → 0.5%
- **Improved spallation cut**
  - 12% more signal efficiency while keeping spallation rejection efficiency at a similar level (~90%)

  Gained ~1 year worth statistics

Yasuhiro Nakajima *Recent results and future prospects from Super-Kamiokande* Neutrino 2020

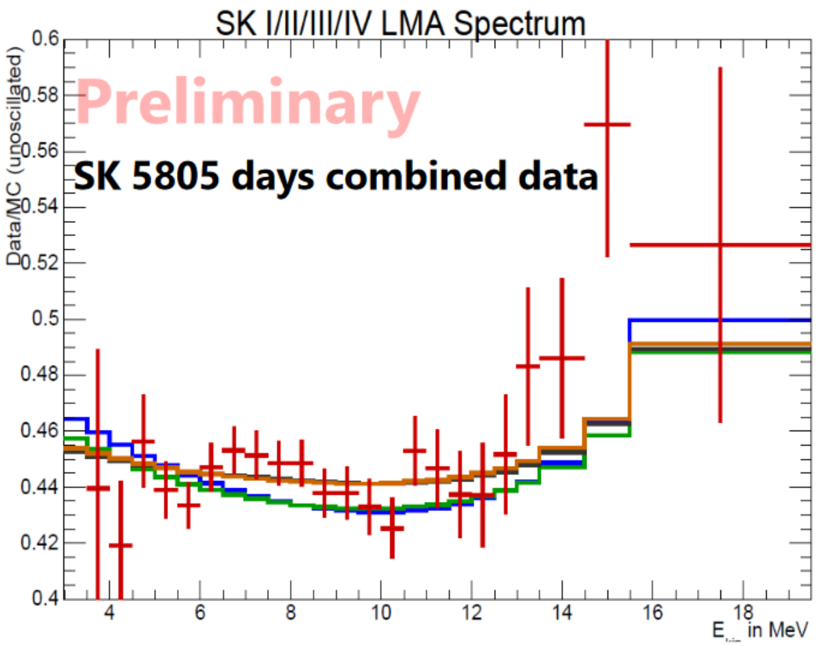




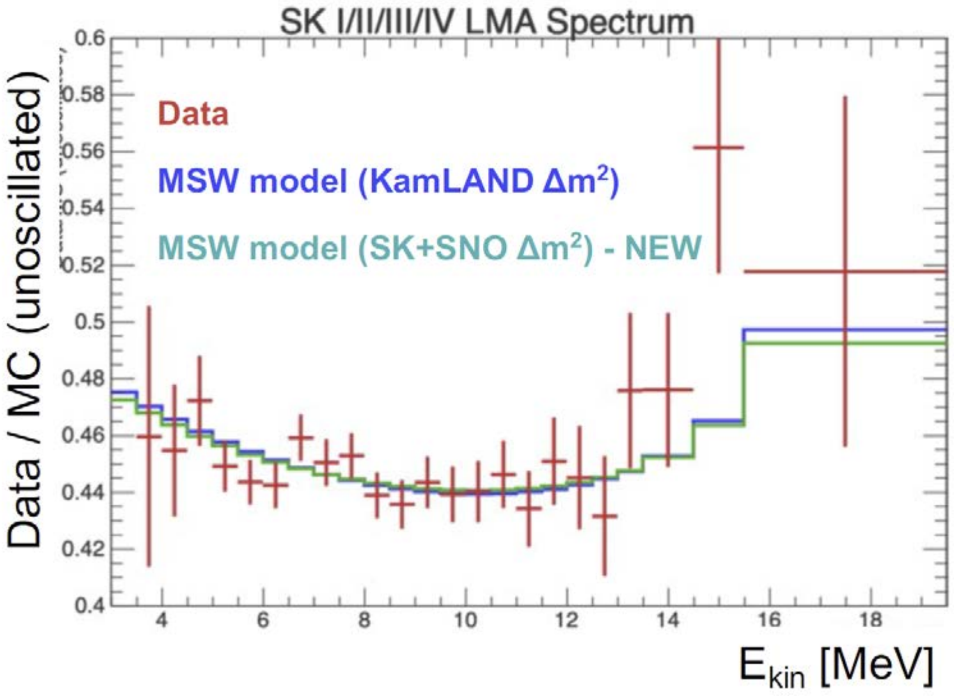
Locke, S. M. (2020). New Methods to Reduce Cosmogenic Backgrounds of Super-Kamiokande in the Solar Neutrino Energy Regime. *UC Irvine*.

New spectrum and Day/Nigth asymemetry measurements to test MSW

- Energy dependent survival probability Pee



TAUP 2019 - Yuuki Nakano and for the Super-Kamiokande collaboration 2020 J. Phys.: Conf. Ser. 1468 012189



TAUP 2021 – Livia Ludhova talk: Solar and Geoneutrinos

- Day/Night effect

$$A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\% \rightarrow A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$$

Neutrino 2020 Yasuhiro Nakajima *Recent results and future prospects from Super-Kamiokande*

Data/MC ratio at E < 6 MeV slightly shifted upward

Shift of prediction due to improved detector simulation. Added statistics due to improved spallation cut.

Event migration due to new reconstruction

Day/Night asymmetry shift

Previous analysis used data up to Feb 2014 (SK-IV: 1664 days)

Added ~1200 days of data fluctuated towards smaller D/N asymmetry

Both impacted to the shift of best fit Δm^2_{21}

SuperK - Oscillation Parameter Extraction

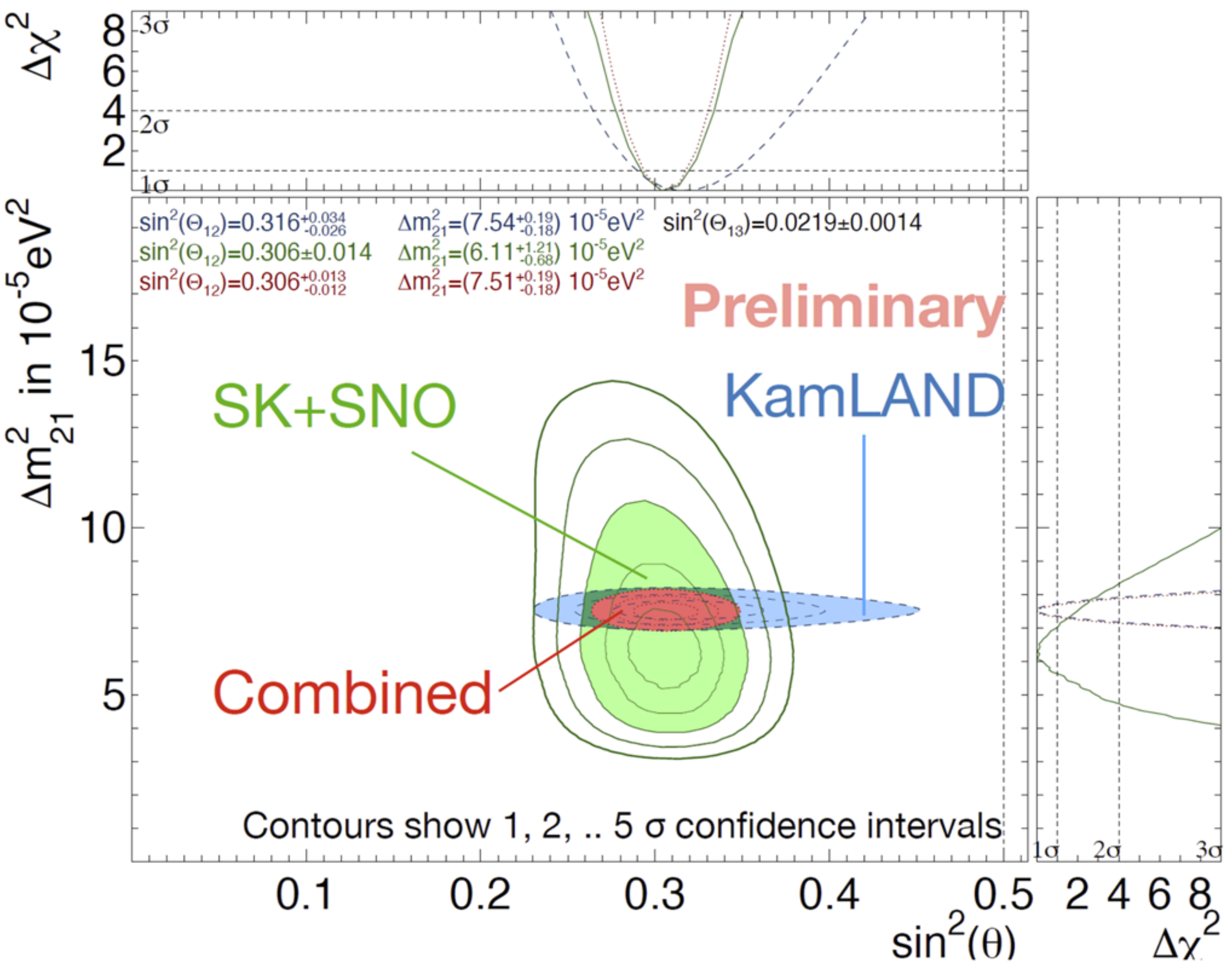
- use rate, spectral and day/night rate variation
- larger value of Δm^2 than before
- less tension (1.4 σ) with KamLAND (reactor antinu) -

- Oscillation parameters extracted by combining all SK data, as well as SNO and KamLAND data

	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

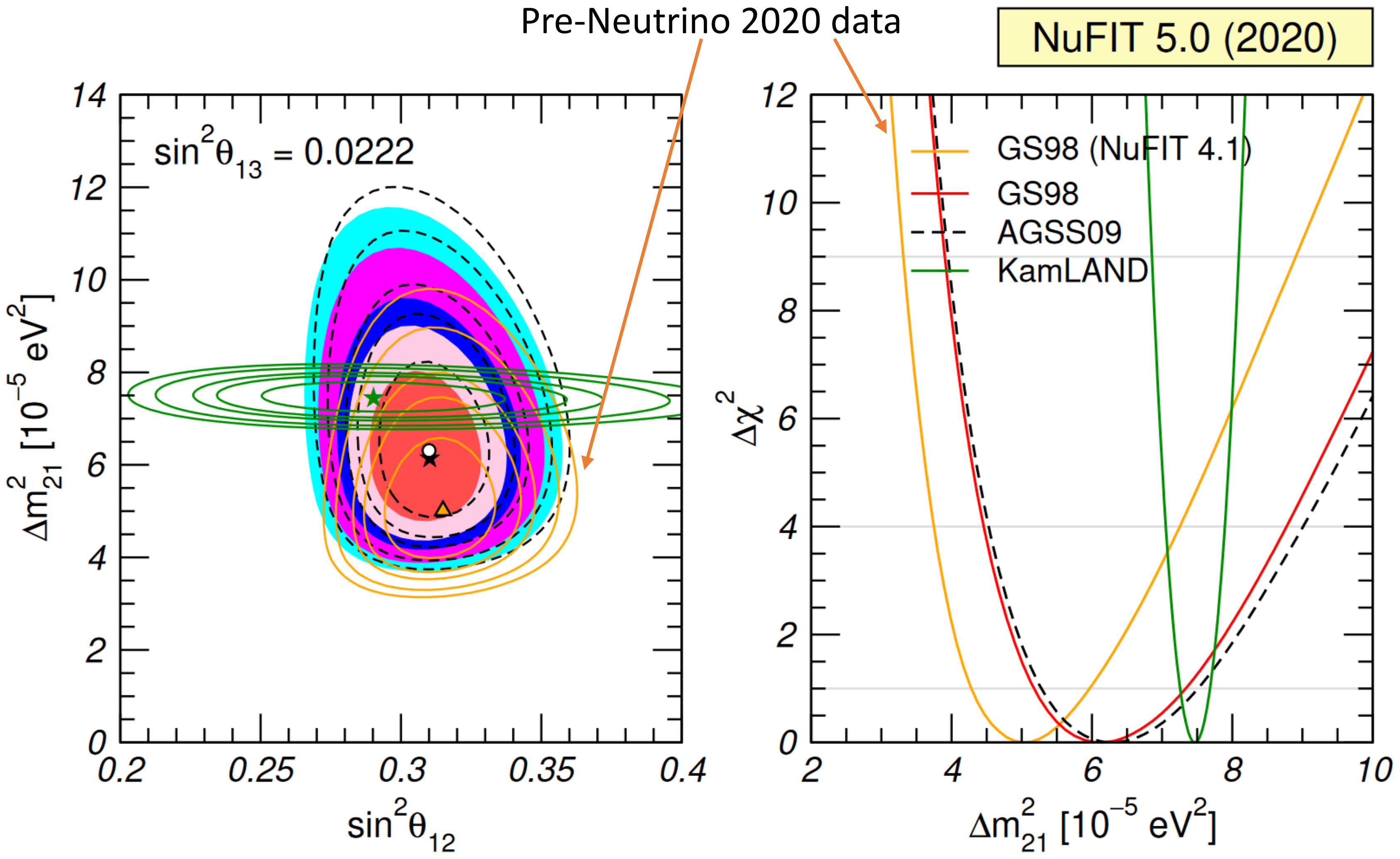
- Consistent θ_{12} values among experiments
- Solar best fit Δm^2_{21} lower than KamLAND, but difference is less than the previous analysis.

SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)



Yasuhiro Nakajima *Recent results and future prospects from Super-Kamiokande* Neutrino 2020

Resolved tension in the solar sector



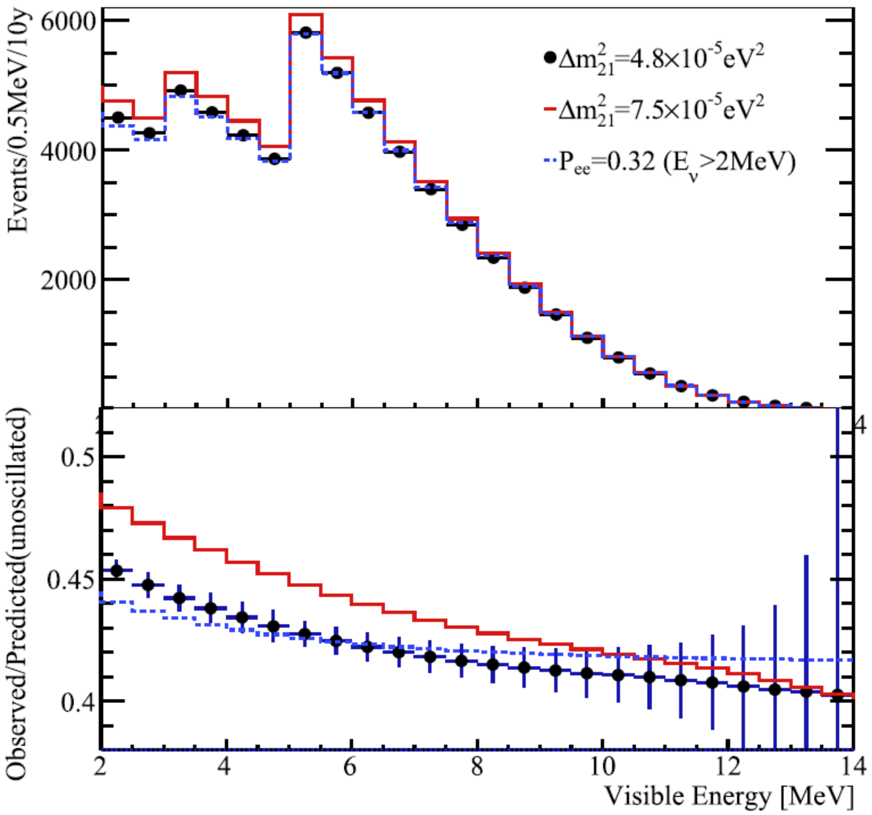
- With the new data the tension between the best fit Δm^2_{21} of KamLAND and that of the solar results has decreased.
- The best fit of KamLAND lies at 1.14σ in the analysis with the GS98 fluxes.
- This decrease in the tension is due to both, the smaller day-night asymmetry (and the slightly more pronounced turn-up in the low energy part of the spectrum which lowers it one extra unit.

Esteban, I., Gonzalez-Garcia, M., Maltoni, M. et al. *The fate of hints: updated global analysis of three-flavor neutrino oscillations.* J. High Energ. Phys. 2020, 178 (2020).

Future detectors

JUNO

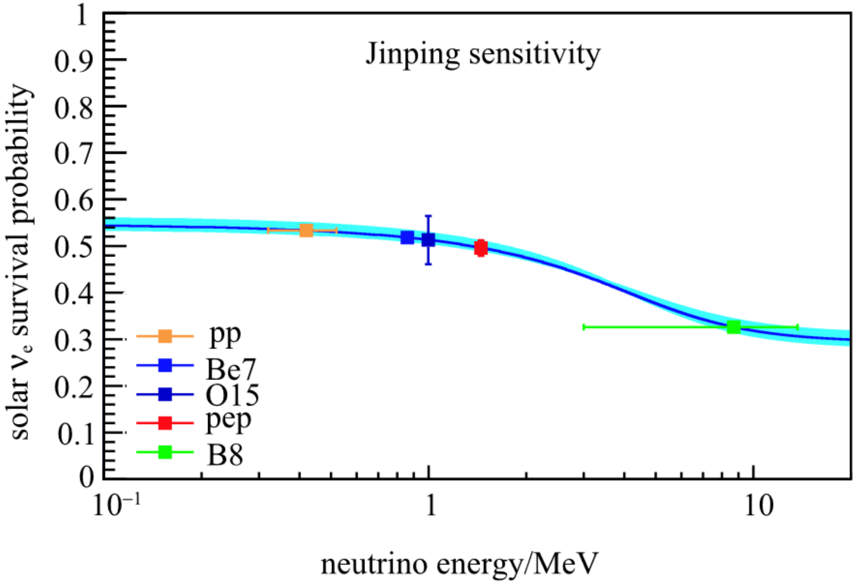
- 20 kt liquid scintillator
- excellent for B solar neutrino measurements,
- low-energy threshold,
- high energy resolution compared with water Cherenkov



Chinese Physics C 2021, Vol. 45 Issue(2) : 023004
DOI: 10.1088/1674-1137/abd92a

Jinping

- slow liquid scintillator
- total fiducial target mass of 2000 tons for solar neutrino



John F. Beacom *et al* 2017 *Chinese Phys. C* 41 023002

HyperKamiokande

- next generation large water Cherenkov detector
- water tanks provide the fiducial (total) volume of 0.19 (0.26) million metric tons