SOLAR NEUTRINOS

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INFN-LNGS and Borexino Collaboration,
European Neutrino “Town” meeting
and ESPP 2019 discussion
CERN, April 22-24, 2018

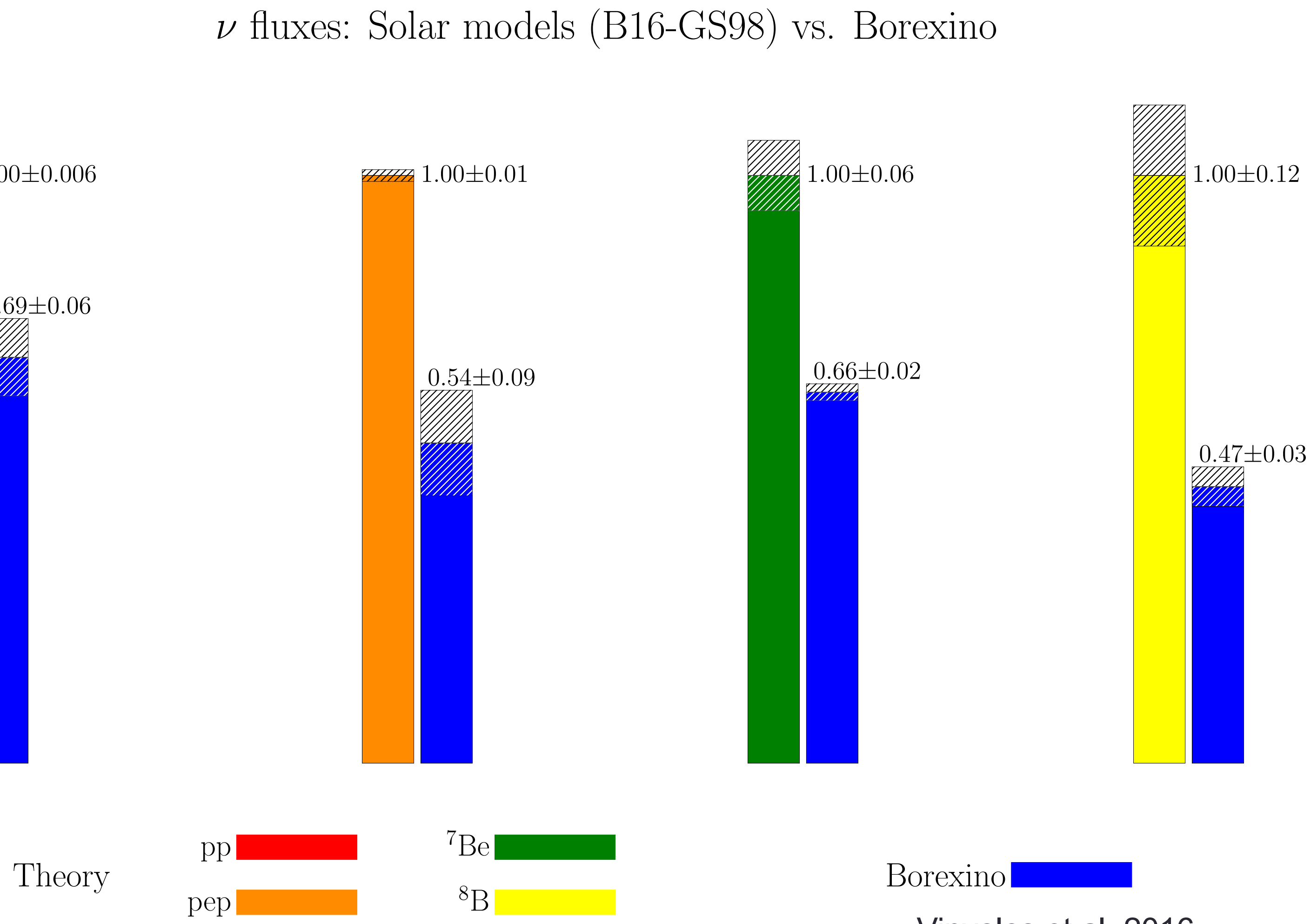
Solar Neutrino Experiments: past and present

Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1967-1994
Kamiokande II/III	3kton H_2O	9/7.5 / 7.0	1986-1995
SAGE	50tons molted metal Ga	0.233	1990-2007
GALLEX	30.3tons $GaCl_3$-HCl	0.233	1991-1997
GNO	30.3tons $GaCl_3$-HCl	0.233	1998-2003
Super-Kamiokande	22.5ktons	5 7 4.5 3.5	1996-2001 2003-2005 2006-2008 2008-2018
SNO	1kton D_2O	6.75/5/6/3.5	1999-2006
Borexino	300ton C_9H_{12}	0.2 MeV	2007-**present**
KamLAND	1kton LS	0.2 MeV	**2009-present**
SNO+	1kton H_2O	5 MeV	**2018**

Solar Neutrino Experiments: future

Detector	Target mass	Threshold [MeV]	Info
Borexino	300ton C_9H_{12}	Sub-MeV	present-???
KamLAND	1kton LS	Sub-MeV	Main goal DBD
Super-Kamiokande-Gd	22.5 kton H_2O	3.5/4.5	1/2019 resume data taking w/ pure water
SNO+	780 ton LAB	sub-MeV	2018 LS filling
JUNO	20 kton	Sub-MeV	2021 data taking
Hyper-Kamiokande	258 kton H_2O	3.5/4.5	2020 start construction 2027 start operation
DUNE	40 kton LAr	7-10	2024 (10kton 1st module)
Jinping LS	2 kton LS FV	sub-MeV	Prototype under construction
Theia	H_2O based LS at SURF	--	--
LAr / LXe	GADM or DARWIN size	--	--

The Solar Neutrino Problem viewed by Borexino



Vinyoles et al. 2016
http://www.ice.csic.es/personal/aldos

SNP solved in the framework of MSW-LMA
sub-leading effect still possible

ARTICLE

https://doi.org/10.1038/s41586-018-0624-y

Comprehensive measurement of *pp*-chain solar neutrinos

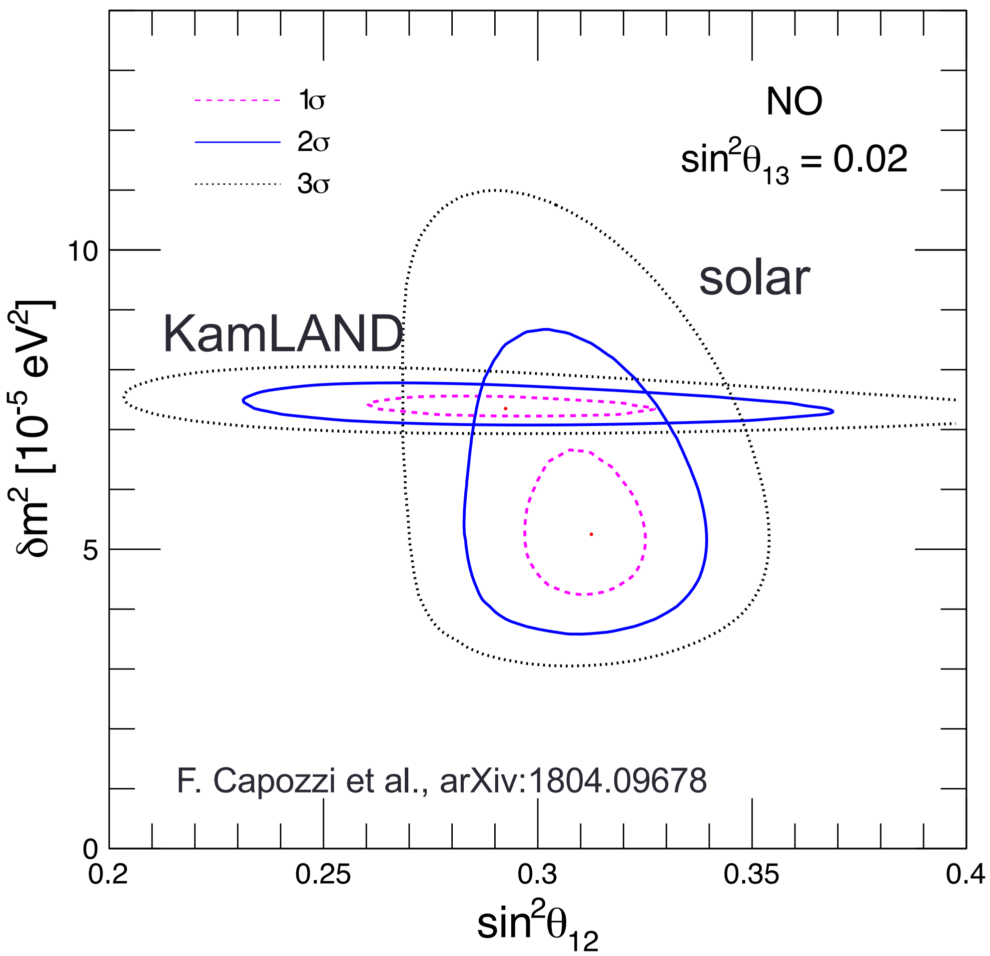
The Borexino Collaboration*

To be published Oct 25th, 2018

Astrophysics with Solar Neutrinos

Source	Flux [$cm^{-2}s^{-1}$] SSM-HZ	Flux [$cm^{-2}s^{-1}$] SSM-LZ	Flux [$cm^{-2}s^{-1}$] Data
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.005)\times10^{10}$	$6.1(1\pm0.10)\times10^{10}$ w/o luminosity constraint
pep	$1.44(1\pm0.009)\times10^{8}$	$1.46(1\pm0.009)\times10^{8}$	$1.27(1\pm0.17)\times10^{8}$ (HZ CNO) $1.39(1\pm0.15)\times10^{8}$ (LZ CNO)
^{7}Be	$4.93(1\pm0.06)\times10^{9}$	$4.50(1\pm0.06)\times10^{9}$	$4.99(1\pm0.03)\times10^{9}$
^{8}B	$5.46(1\pm0.12)\times10^{6}$	$4.50(1\pm0.12)\times10^{6}$	$5.35(1\pm0.03)\times10^{6}$
CNO	$4.88(1\pm0.11)\times10^{8}$	$3.51(1\pm0.10)\times10^{8}$	$<7.9\times10^{8}$ (2σ)
p-value (pp, Be, B)	0.96	0.43	

Solar and KamLAND neutrino oscillation analysis: **tensions**



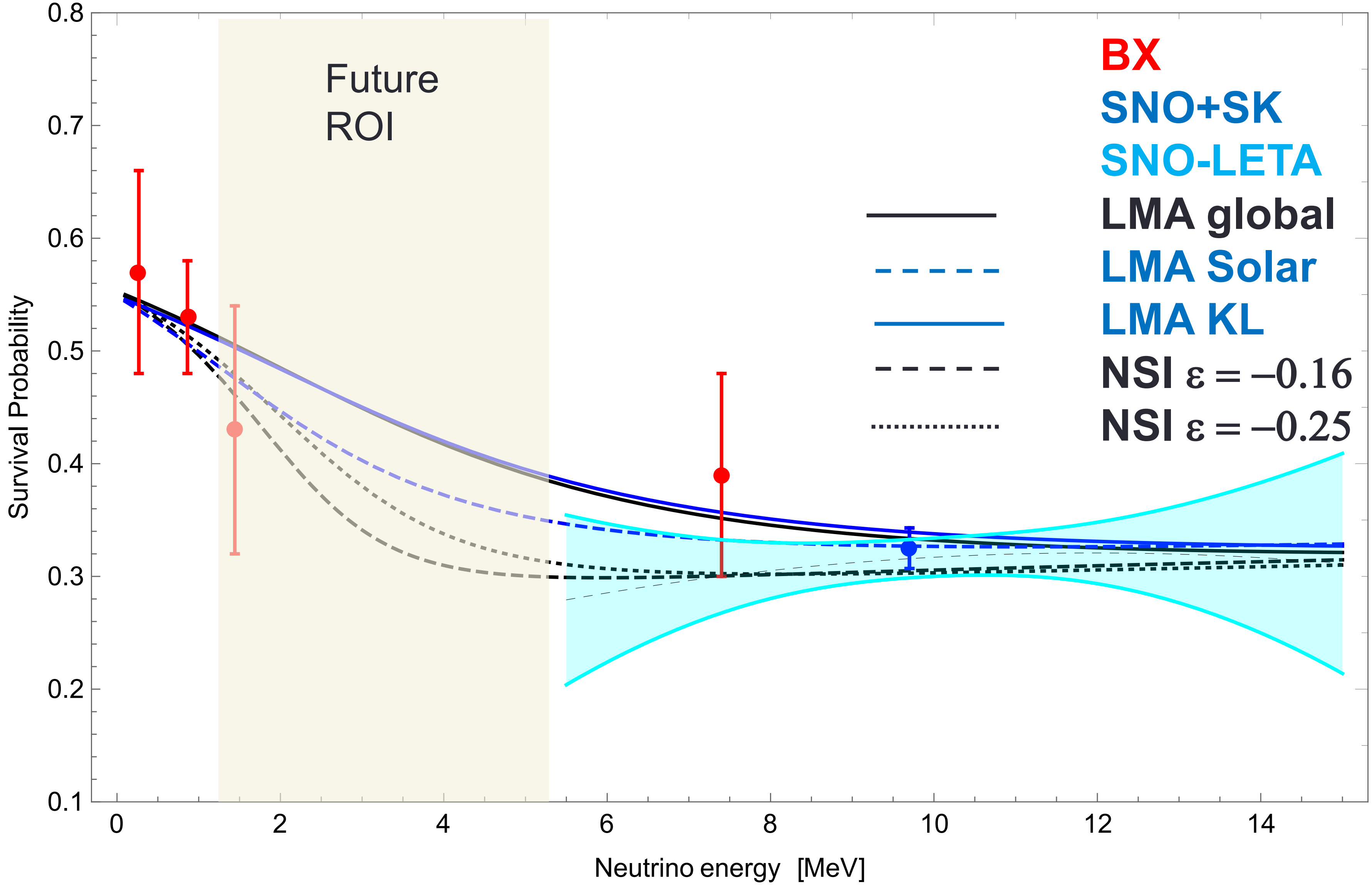
A) Longstanding tension at 2σ level on best-fit for δm^2 between solar and KamLAND oscillation analysis

1. CPT invariance?
2. Physics beyond the SM
3. Subtle unknown effect in present analysis?

B) Day-Night (DN) asymmetry in SuperKamiokande is -3.3±1.1% with DN = 2(D-N)/(D+N) $\propto$ E/ δm^2

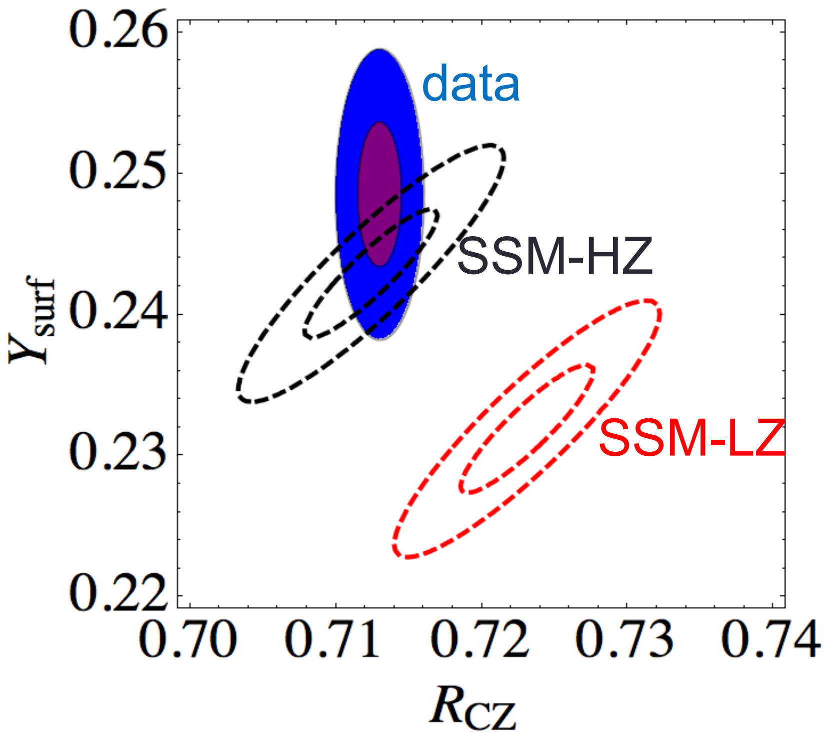
DNA for KL best-fit it should be -1.7%

Solar Neutrinos and neutrino oscillations



What physics from solar Neutrinos in the future?

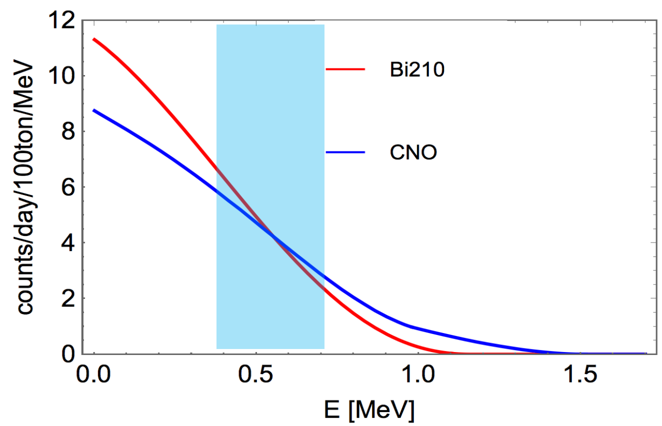
- **Particle physics (to be done)**
  - Measurement of expected matter-vacuum upturn
  - Measurement of day-night asymmetry
- **Astrophysics**
  - Solve the *solar abundance problem* by detecting CNO neutrinos
    (next future only Borexino, SNO+)
    ✓ improved calculations of solar metallicity do not agree with data
  - Use solar neutrinos to understand the Sun (*inverse problem*)
  - **The Sun in a unique laboratory!**



Borexino: next future

Main physics goal: CNO neutrinos

- Main challenge: constrain and reduce ^{210}Bi background
  - ✓ Constrain by using tagging of ^{210}Po and reduce convection inside the FV
  - Reduce by Water extraction purification



Underway activity and upgrade

- 2018-2019 improvement of thermal insultation system built in 2015 to reduce convection inside the LS
- 2018-2019 commissioning of fluid handling system for new Water Extraction purification
- 2019 commissioning of new water purification system (low ^{210}Po water)

SuperKamiokande: next phase

Achievements

- SuperKamiokande has observed solar neutrinos for 22 years (**2 solar cycles!)**
  - ✓ Some 93,000 solar neutrinos detected
  - ✓ No correlation with solar activity observed
  - ✓ ~3σ day-night asymmetry
  - ✓ Neutrino flux measured at 1.7% level

Underway upgrade

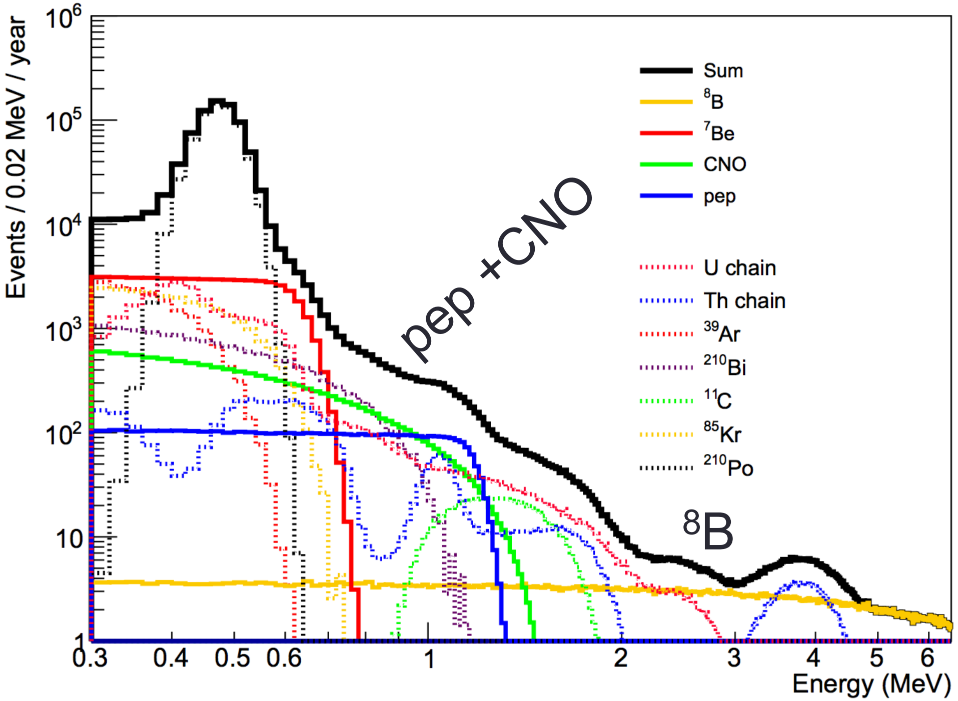
- Since June 2018 under refurbishment to be ready for operating with Gd salt
  - ✓ 0.2% Gd salt gives 90% neutron capture efficiency
  - ✓ Phase-I at 0.02%: 10ton of salt and 50% capture efficiency
- Resume data taking expected January 2019 with only water
- Critical point: radiopurity of Gd salt to keep current background level

Physics case

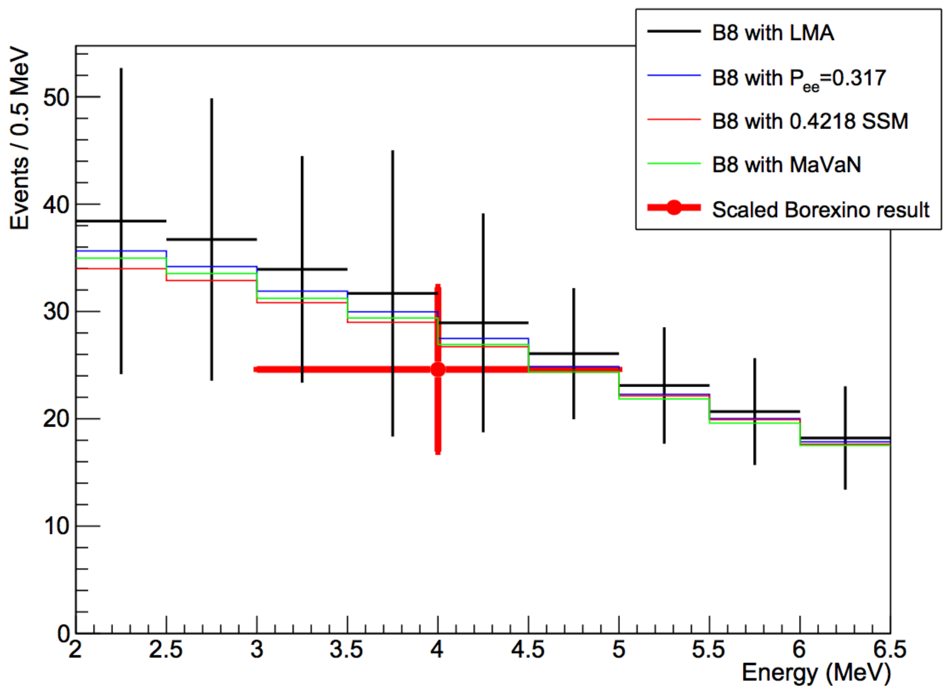
- ✓ Supernova relic neutrinos and electron anti-neutrino physics
- ✓ Day-Night asymmetry measurement at 3.9σ assuming systemtics at 0.4%
- ✓ Upturn measurement at 3σ assuming Δm^2 from best-fit in KamLAND, 22.5kton and 3.5MeV threshold
  - At present: 22.5kton (>5MeV); 16.5kton (>4.5MeV); 8.8kton (>3.5MeV)

Solar Neutrinos in SNO+ Liquid Scintillator

Goals: precision measurement of pep (upturn); ^{8}B (upturn+DN); CNO (SSM)



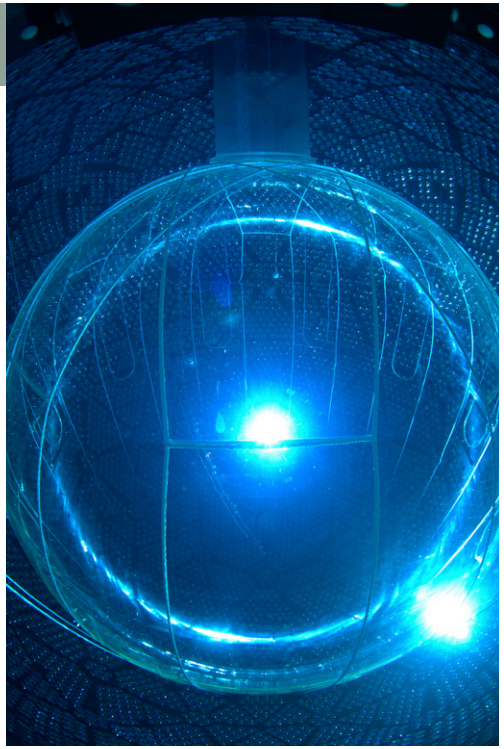
Solar neutrino-electron recoil energy spectrum
- simulated full spectrum
- no α/β PSD or Bi-Po coincidence cuts applied
- target background levels (w/slow ^{210}Pb leaching)



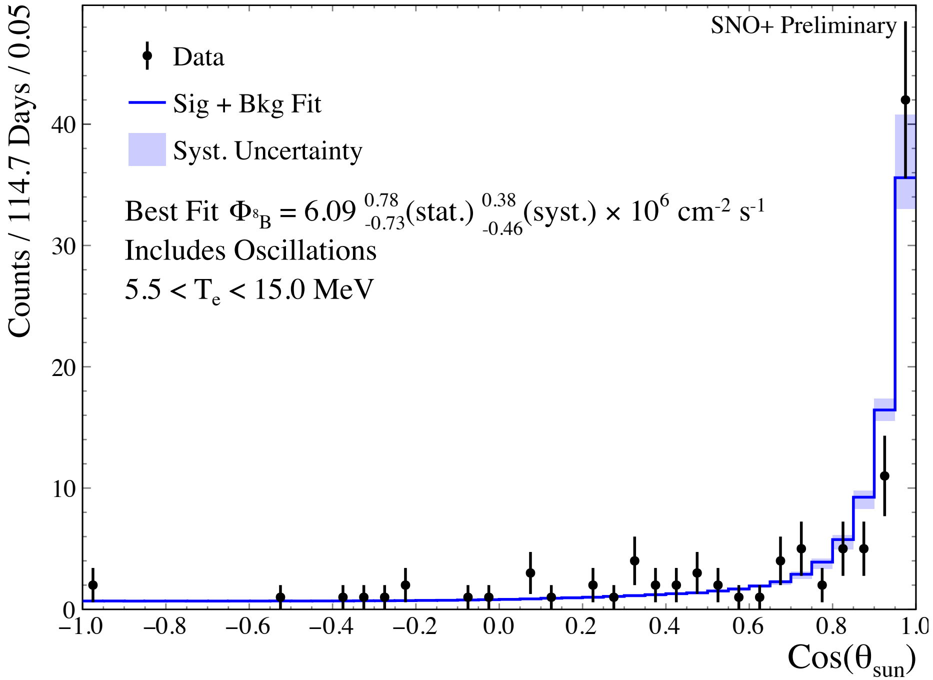
^{8}B solar neutrinos down to 2 MeV
- simulated 6 months of data

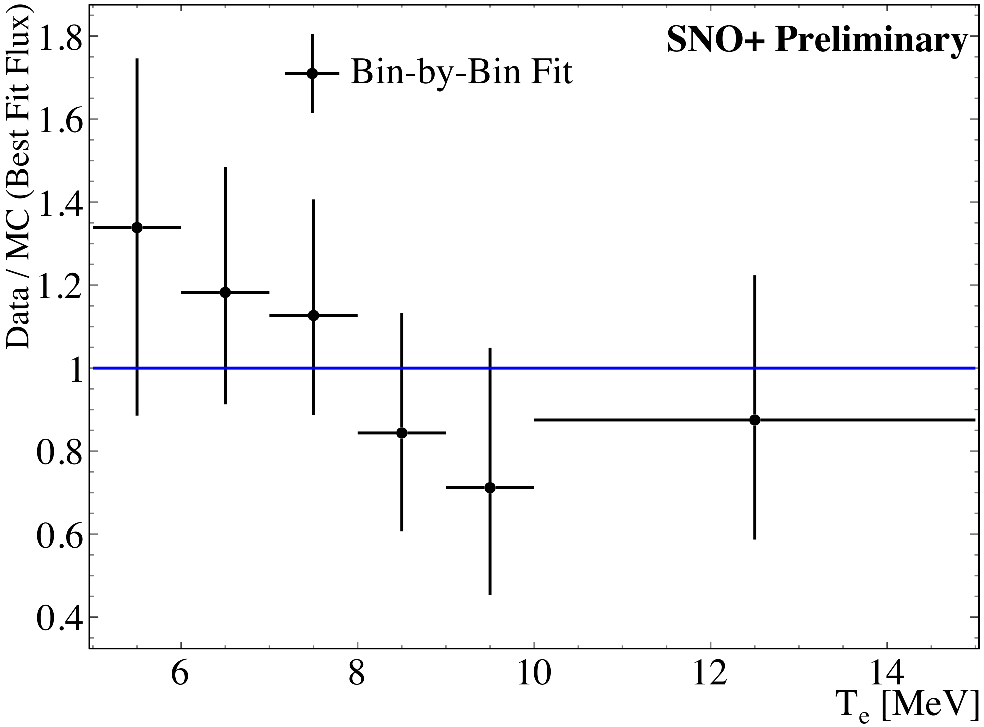
Adapted from M. Chen

^{8}B Solar Neutrinos in SNO+ Water



Measured with very low backgrounds!



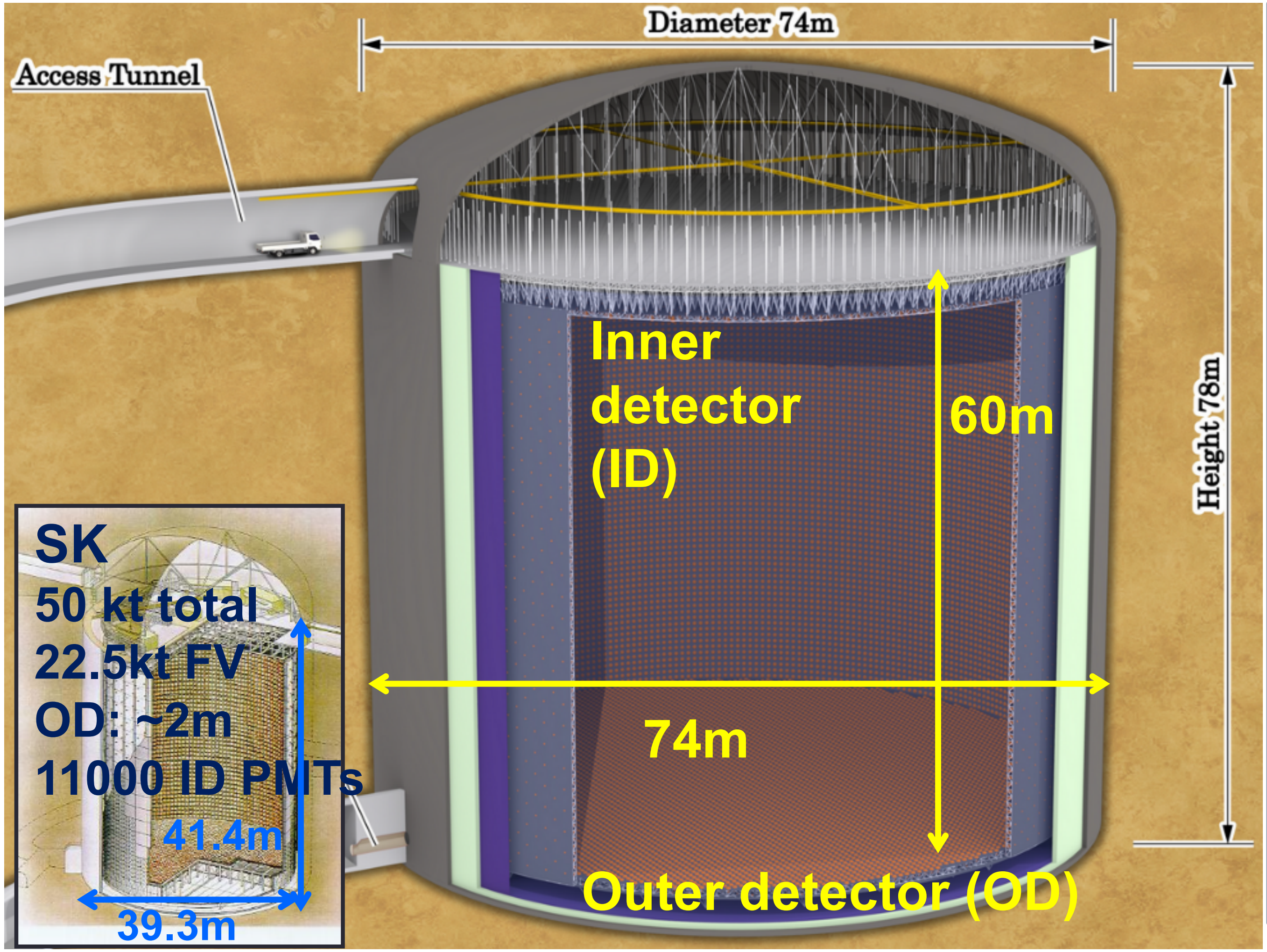


Adapted from M. Chen

Hyper-Kamiokande detector

Adapted from M. Shizowa

Design Report 2018: arXiv:1805.04163

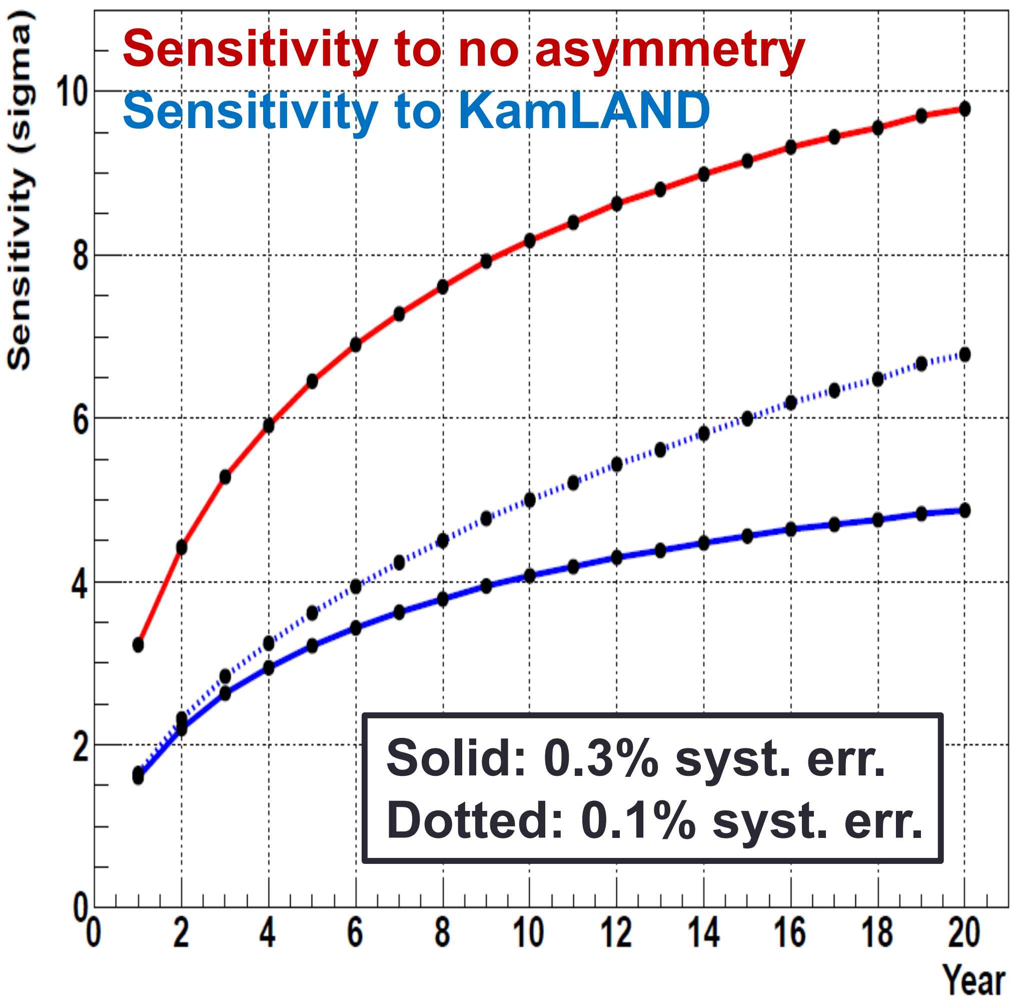


- 258 kt water
- 187 kt fid. vol. (1m from wall)
- OD: 1~2m thickness
- Photon detection efficiency: SK detector x 2
  - Better energy resolution
  - Better neutron tagging efficiency (~70%)
- Optional 2nd tank is under discussion.

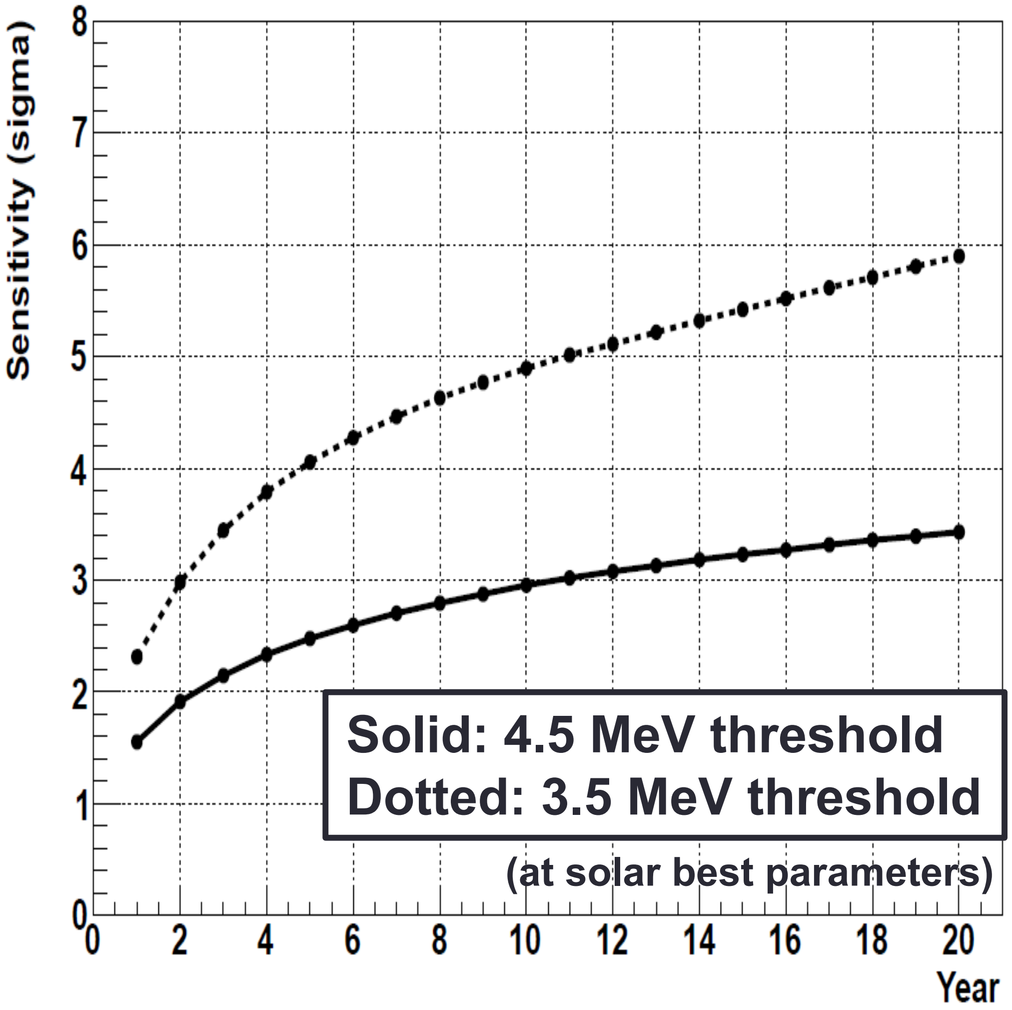
Inner Detector (ID): ~40,000 of new 50-cm photo sensors
Outer Detector (OD): ~6,700 of new 20-cm photo sensors

Solar neutrino measurements in HK

Day/Night sensitivity



Spectrum upturn



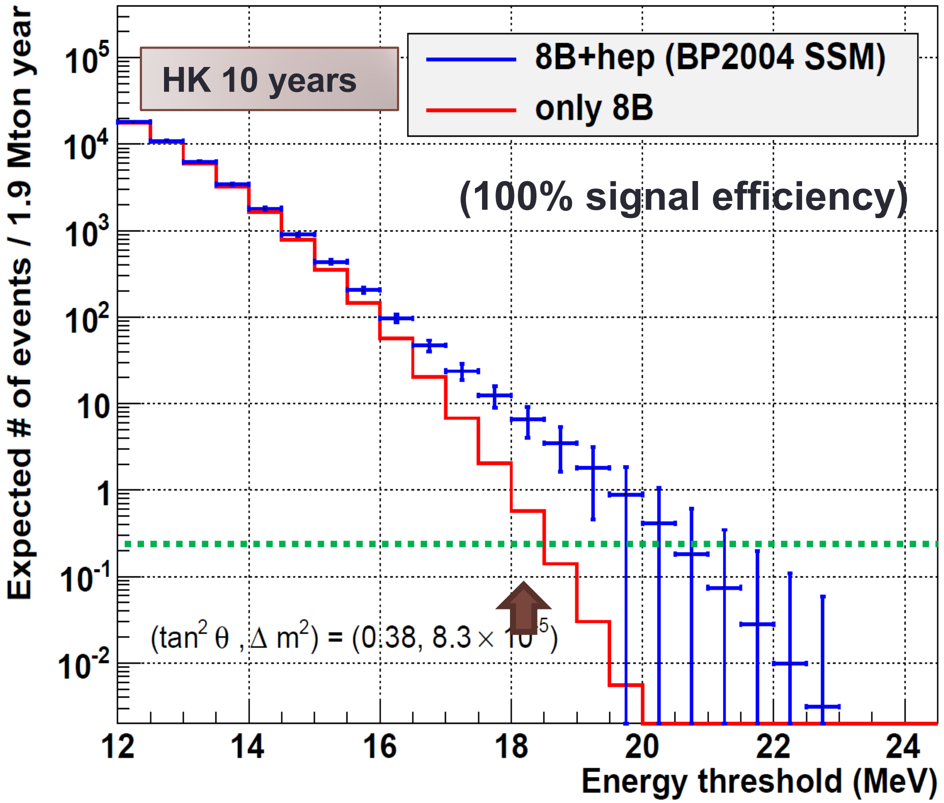
- Day/Night (solar vs reactor): 4~5 sigma in 10 years
- Spectrum upturn: ~3 sigma in 10 years

Adapted from M. Shizowa

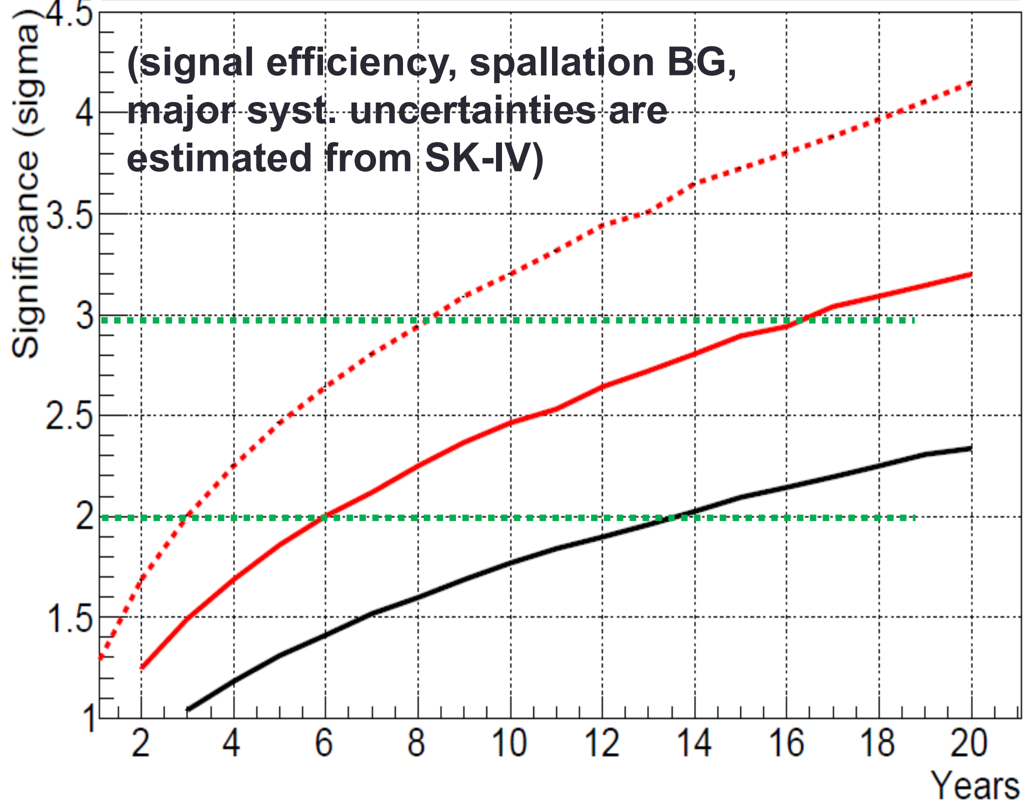
Solar hep neutrino at HK

Adapted from M. Shizowa

Integrated # of expected solar neutrino events



Non-zero significance of hep ν detection from a spectrum analysis



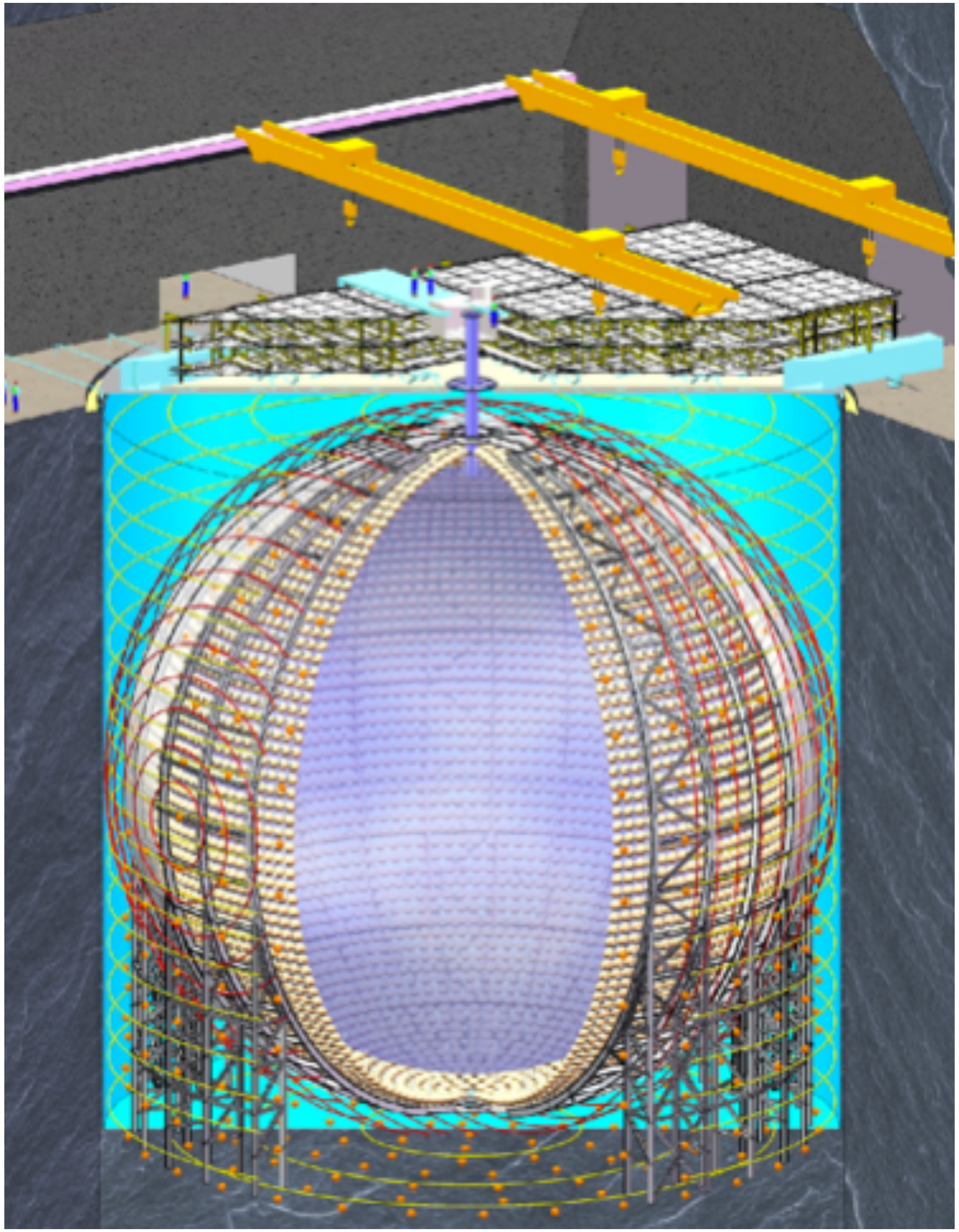
E_{total} [MeV]	^{8}B [/1.9 Mt yr]	Hep [/1.9 Mt yr]	Hep / ^{8}B
18-25	0.56	6.04	10.6

Black solid: at Tochibora site
Red solid: at Mozumi site
Red dotted: at Mozumi, no spallation BG

- **First direct observation of hep solar ν could be done at 2~3 sigma with a few Mton year data**

JUNO

- **Center Detector** (3% energy resolution)
  - Acrylic sphere with LS
  - PMT in water tank (18k 20” + 25k 3”)
  - 20k LS with 78% PMT coverage
- **Veto Detector**
  - Water Cherenkov
  - Top tracker (adapted from OPERA)
  - Muon tagging and track reconstruction
- **Calibration system**
  - Covering various particle type, full energy range and position
- **Timeline**
  - 2018: surface buildings + acrylic sphere production + PMTs delivery
  - 2019-2020: detector construction + electronics production
  - **2021: ready for data taking**



JUNO: solar neutrinos

- Precision measurement of pp-chain solar neutrino rates by ES
  - Borexino radiopurity assumed
- Precision measurement of Δm_{21}^2
  - will help solve tension between KL and solar fit (0.6% including systematics)
- ^{8}B solar neutrinos in [2,3] MeV ROI to probe P_{ee} upturn
  - ^{10}C cosmogenic background tagging efficiency at 98% level assumed for S/N ~ 1
  - ~ 6000 events in 6 years
- Possibility to search for Day-Night asymmetry and CNO neutrinos under investigation (?)

Solar neutrinos in DUNE

Two detection channels:

1. CC on ^{40}Ar

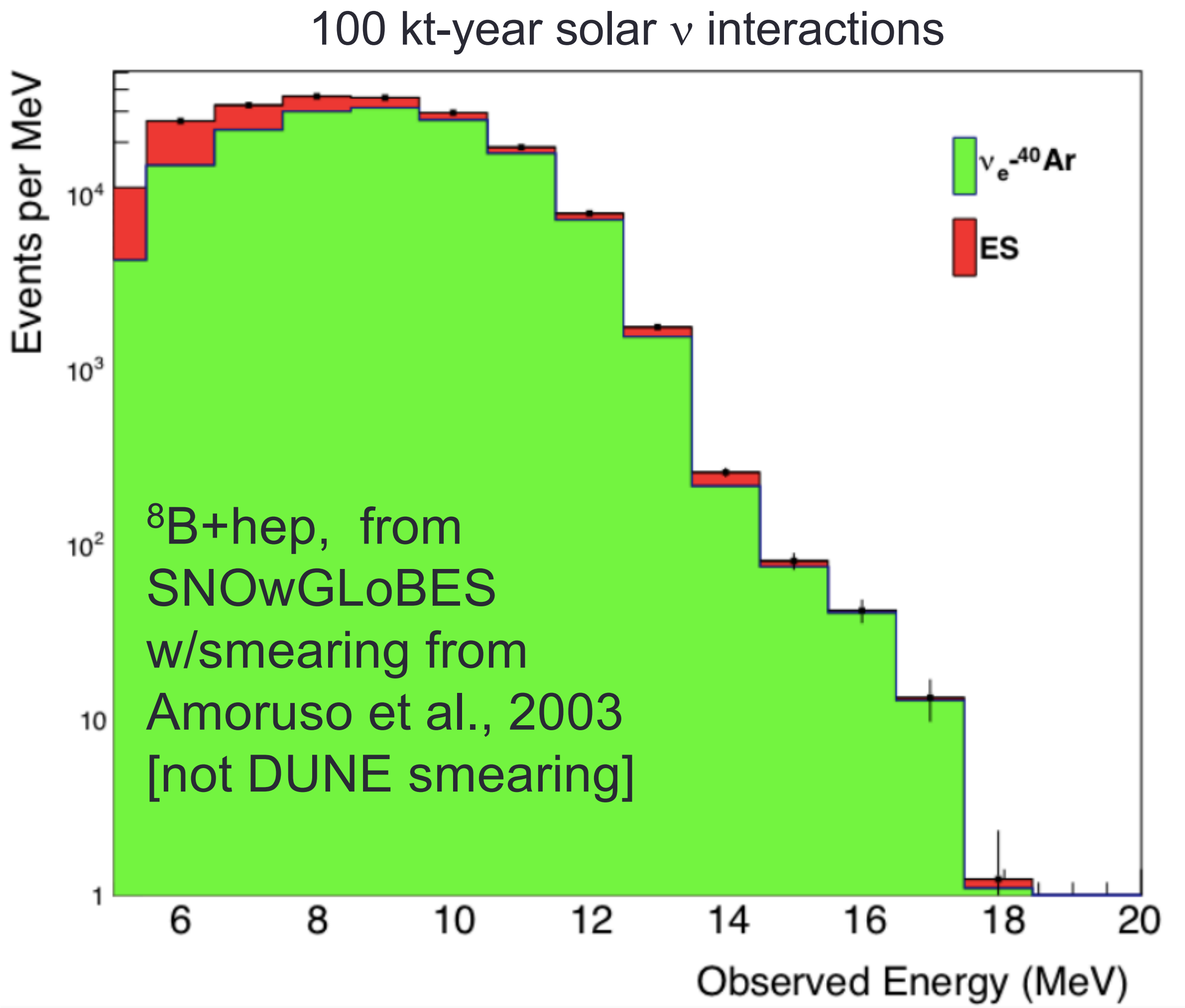
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

2. ES

This breaks the degeneracy between $\sin^2\theta$ and $\phi(^8B)$

These channels can be separated exploiting the imaging capabilities

DN asymmetry can be probed



- theoretical studies: A. Ioannisian et al., Phys.Rev. D96 (2017) no.3, 036005
- new paper arXiv:1808.08232

DUNE as the Next-Generation Solar Neutrino Experiment

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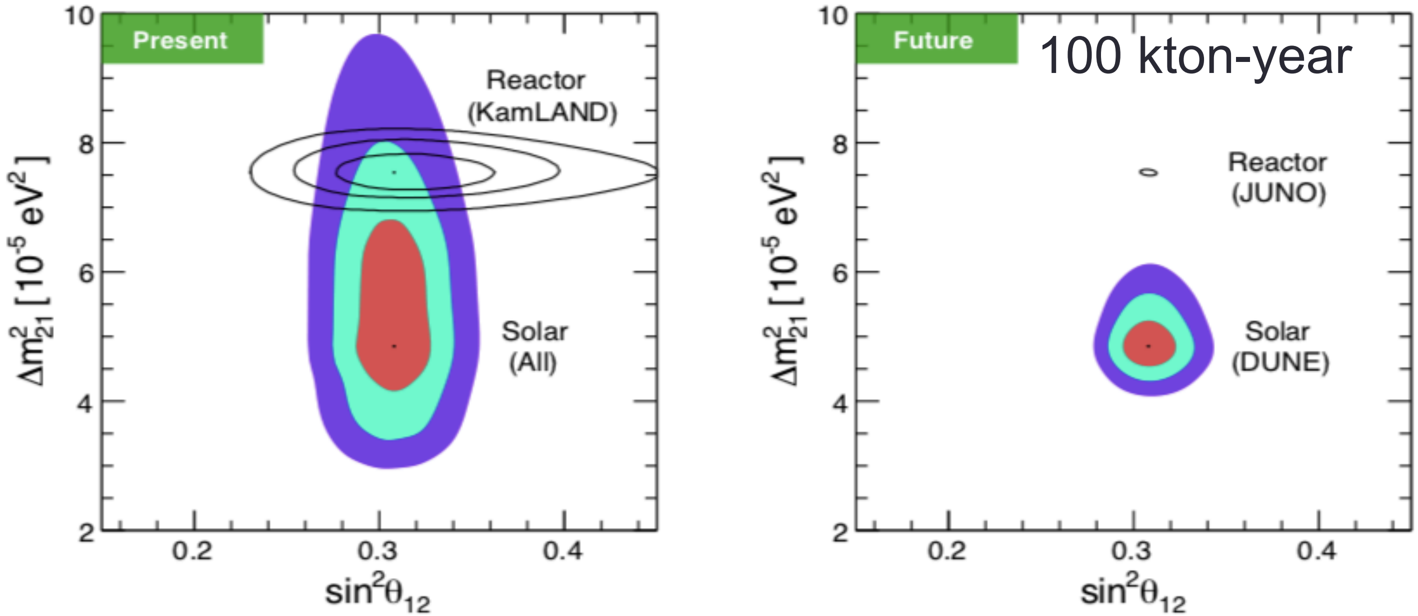
[5] *Department of Astronomy, Ohio State University, Columbus, OH 43210*

(Dated: 24 August, 2018)

Adapted from K. Scholberg

Capozzi et al. paper presents intriguing sensitivity with DUNE:



BUT: makes very optimistic assumptions
(7% energy resolution, 25% angular resolution, modest bg, no systematics, ...these may not be achieved*)

- Overall realistic sensitivity for solar νs still under study

Adapted fromK. Scholberg

*~20% energy resolution more likely, e.g., μBooNE 1704.02927

Conclusions

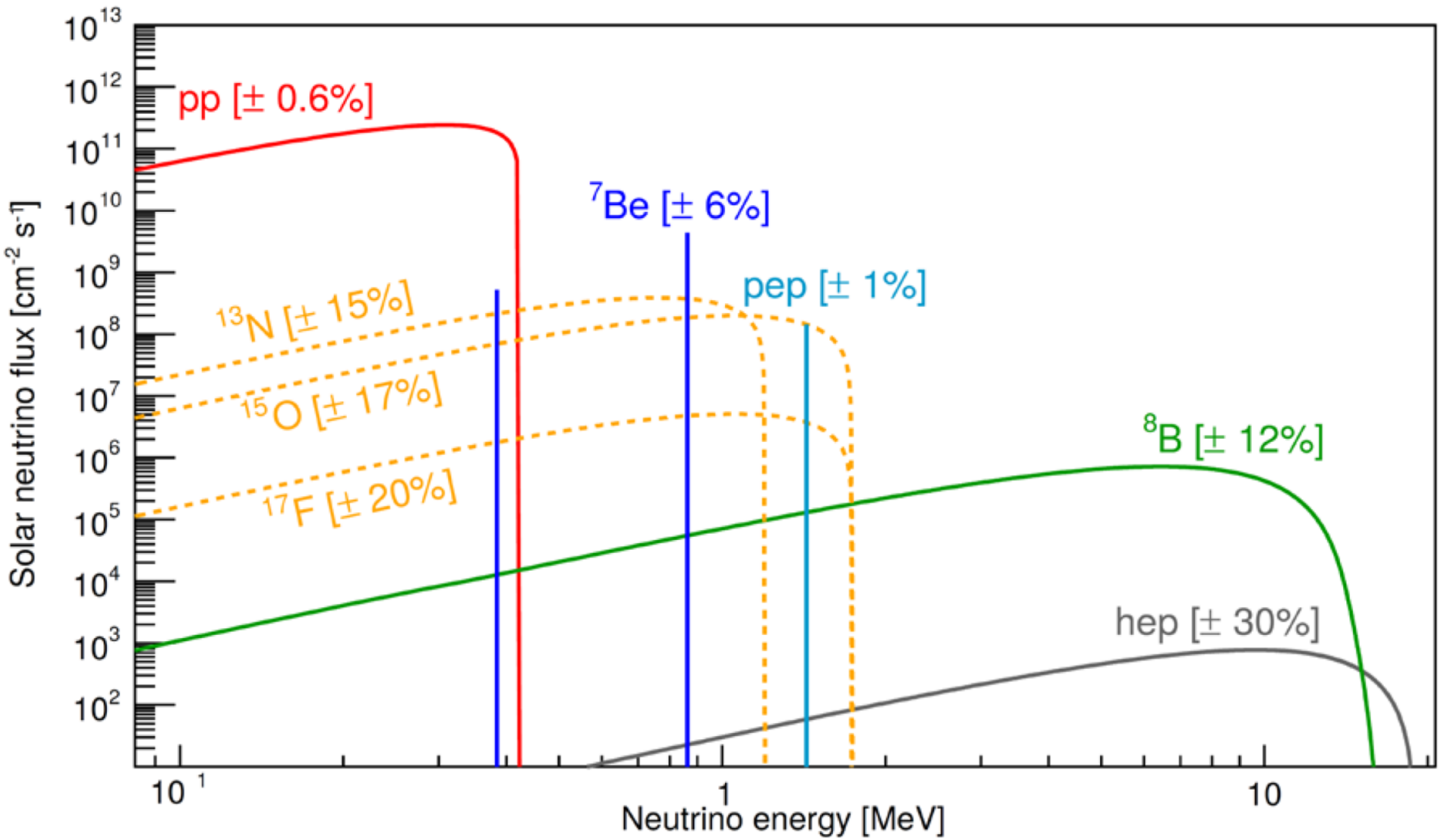
- 50 years experimental activity on solar neutrino detection
- Achieved an important contributions to particle physics and astrophysics,background reduction
- Yet, more effort needed for
  - A definitive measurement of day-night asymmetry with ^{8}B neutrinos
  - A definite measurement of the upturn energy region
  - Detection of CNO and pep neutrinos in upturn region
  - Probe possible sub-leading effects (NSI)
- The above program can be carried out in
  - Borexino, SuperKamiokande, SNO+ from present – 2027
  - Juno from 2021
  - DUNE and HyperKamiokande from 2024/2027 – 2037
- No long term solar neutrino detector in Europe

Acknowledgements

I would like to thank Masayuki Nakahata, Masato Shiozawa, Mark Chen, Kate Scholberg, Ding Xuefeng for providing information on SuperKamiokande, HyperKamiokande, SNO+, DUNE, and JUNO.

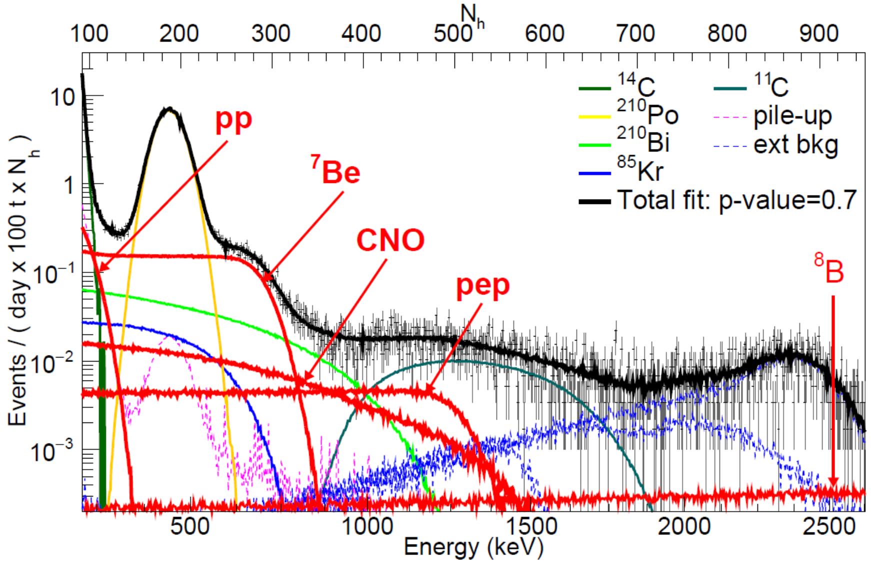
Solar neutrino spectra

A. Serenelli et al, **Astrophys.J. 835 (2017) no.2, 202**

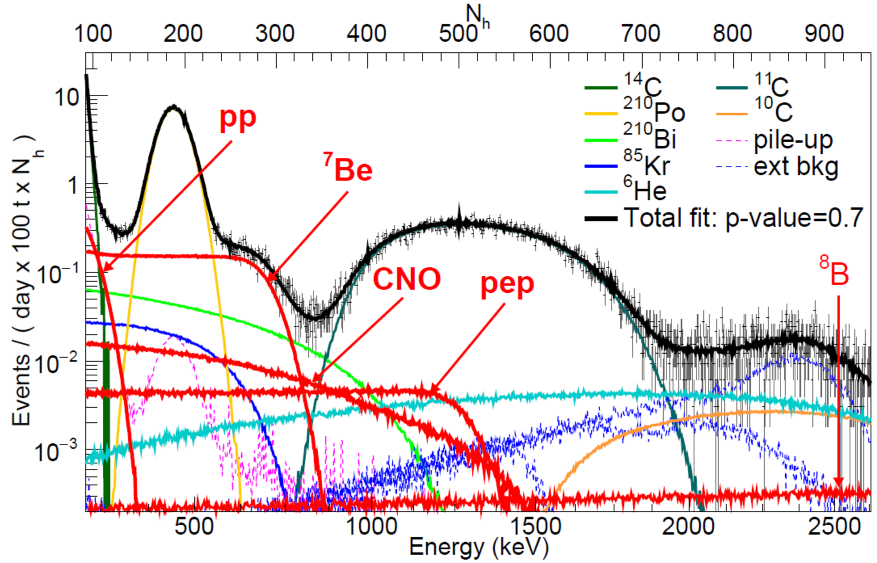


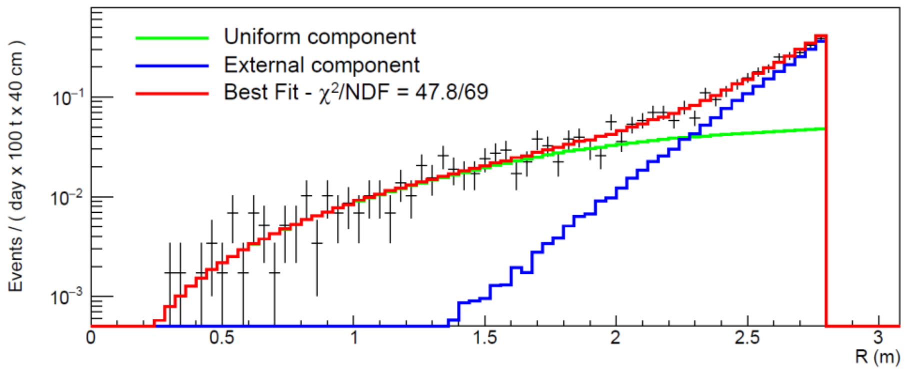
Multivariate fit example

L($^{11}C_{sub}$)

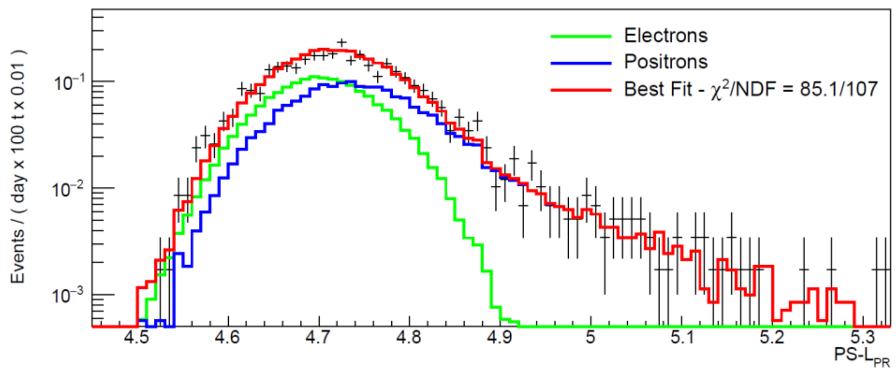


L($^{11}C_{tag}$)



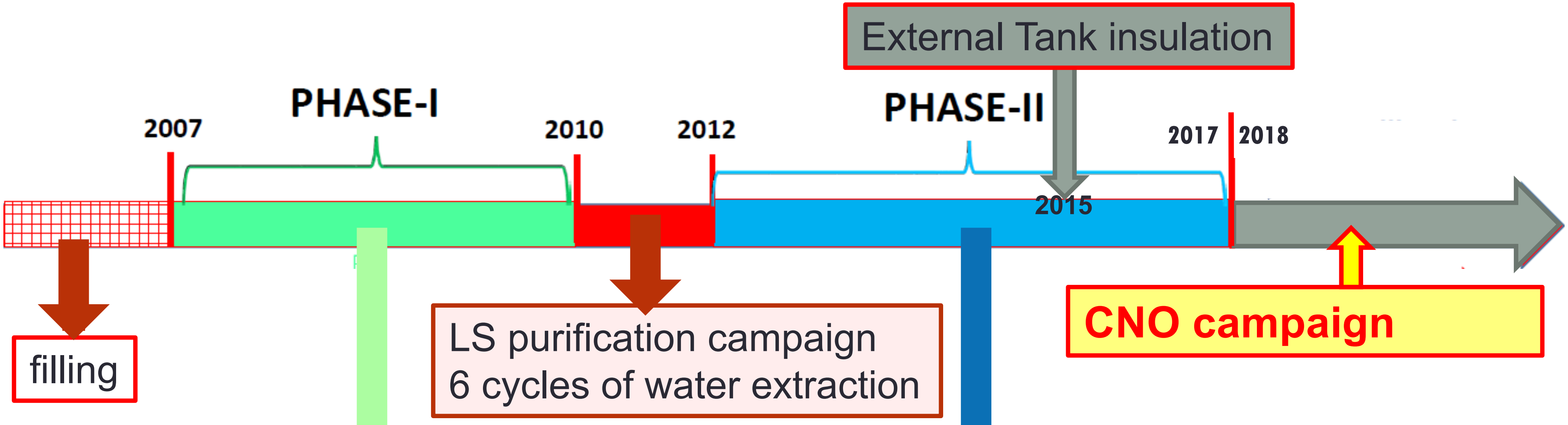


L(Rad)



L(PS)

Borexino



- R(^{7}Be) + D/N
- R(pep) – first observation
- R(^{8}B)– first with LS
- R(CNO) – limit

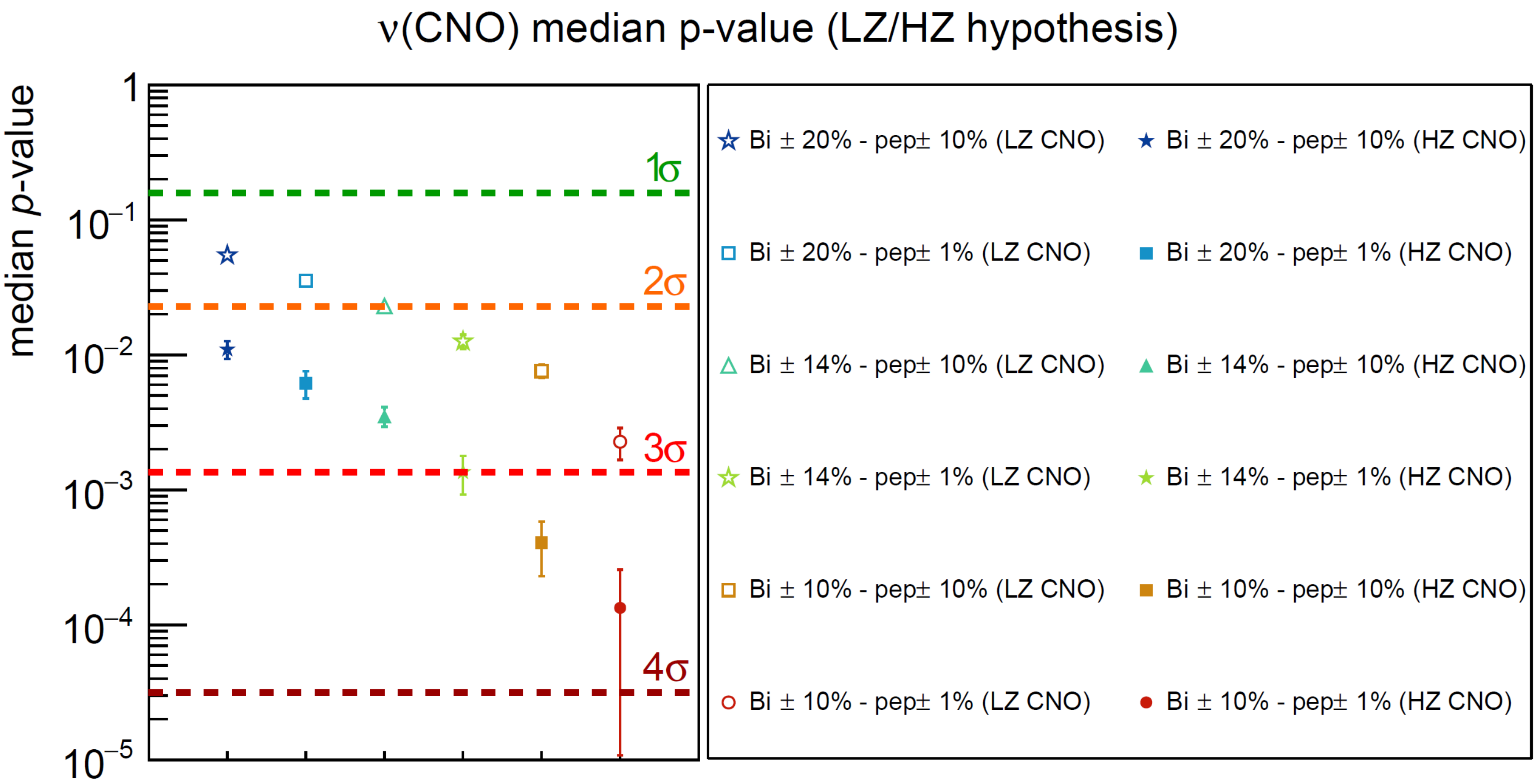
geo- ν – first robust observation
cosmic muons flux studies
rare processes

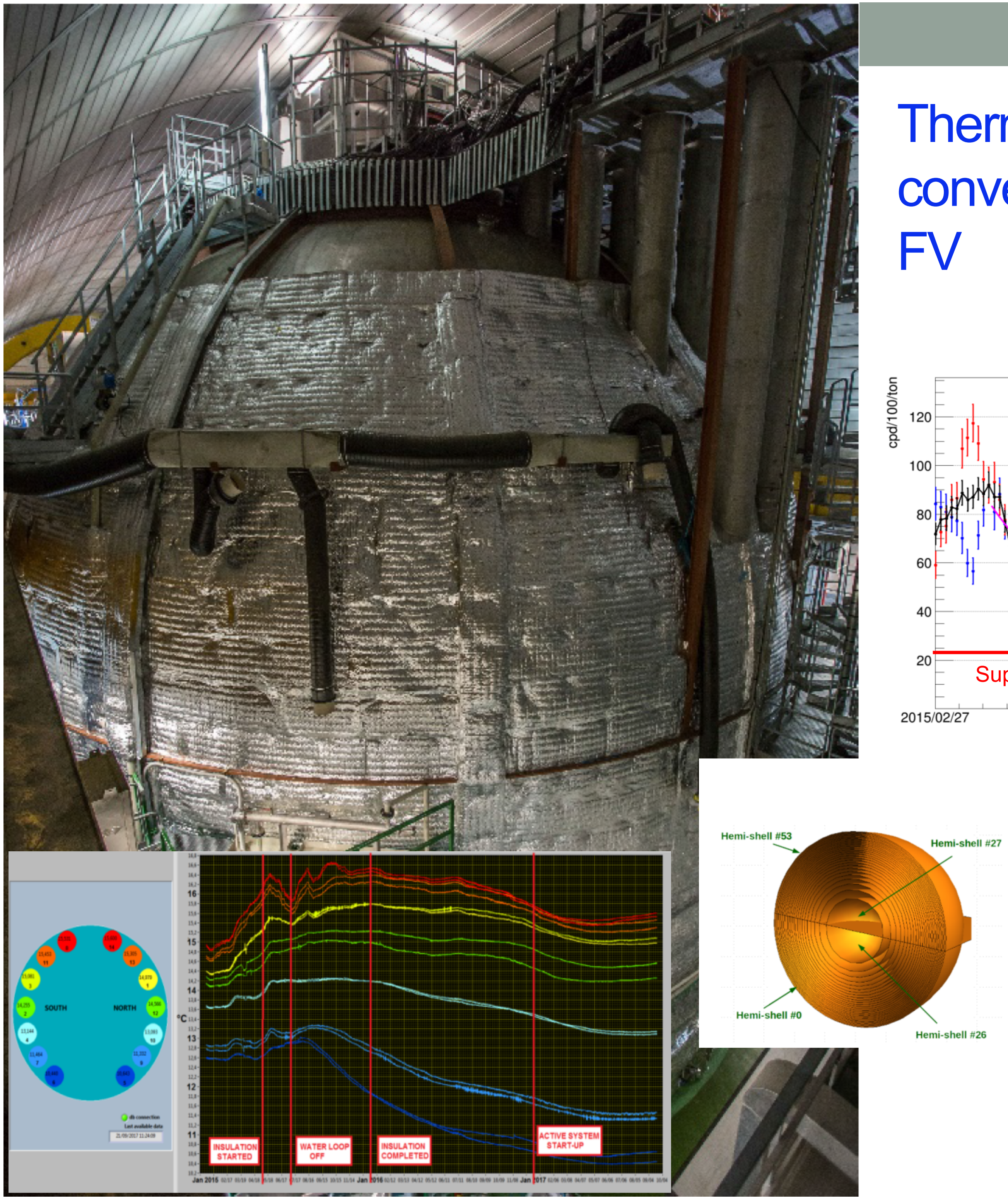
- R(pp) *first in real time*
- Seasonal variations of R(^{7}Be)
- Simultaneous spectroscopy of pp, ^{7}Be and pep ν
- R(^{8}B)–improved
- geo- ν
- ν magnetic moment
- NSI (under study)
- rare processes

CNO neutrino sensitivity

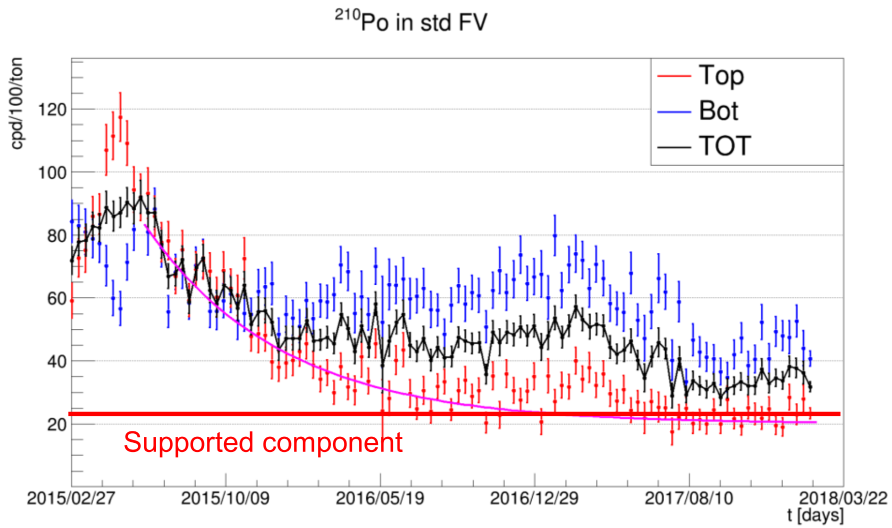
Depends on ^{210}Bi background.

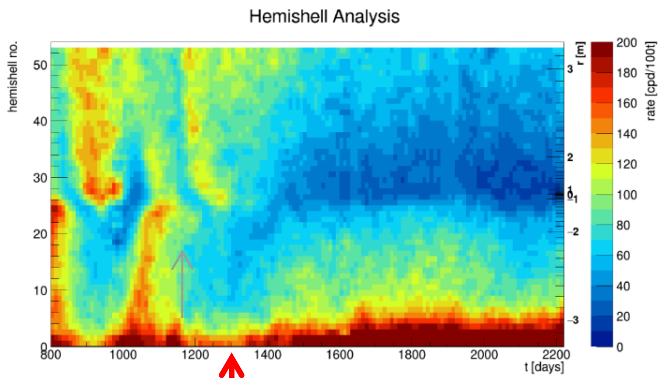
We assume that ^{210}Bi will be measured with 10-20% accuracy





Thermal insulation to reduce convection motion inside the FV





Thermal insulation (summer 2015)