9-Apr-2019 @Prospects of Neutrino Physics

SK RESULTS ON SOLAR NEUTRINO AND PROSPECTS WITH HK

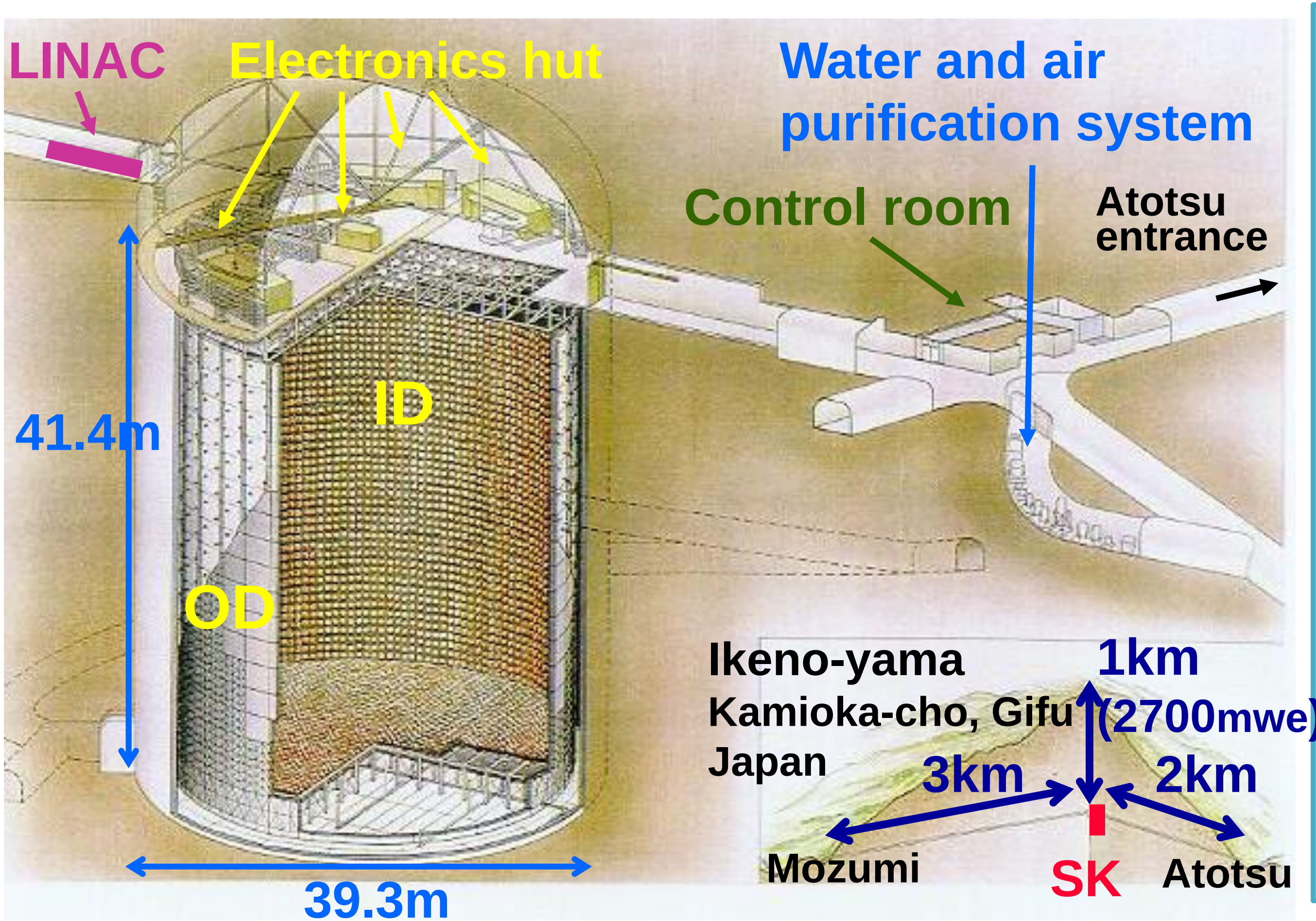
Yasuo Takeuchi
(Kobe University / Kavli IPMU)

Inside of SK detector during refurbishment work (July 15, 2018)

Outline

- SK detector
- Solar neutrinos
- Recent results from SK
- Prospects with HK
- Summary

Super-Kamiokande detector



- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-V is running
- For Solar ν: $\nu_x + e^- \rightarrow \nu_x + e^-$

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV,V), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

History & Plan of Super-Kamiokande

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

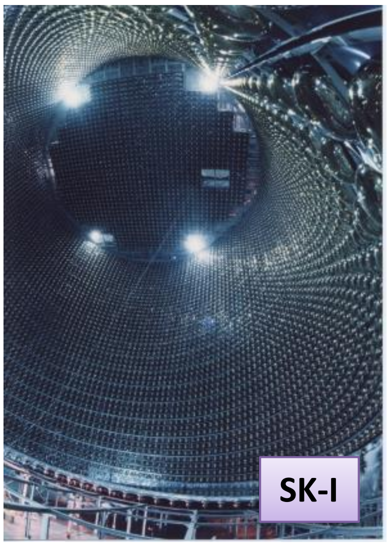
SK-I

SK-II

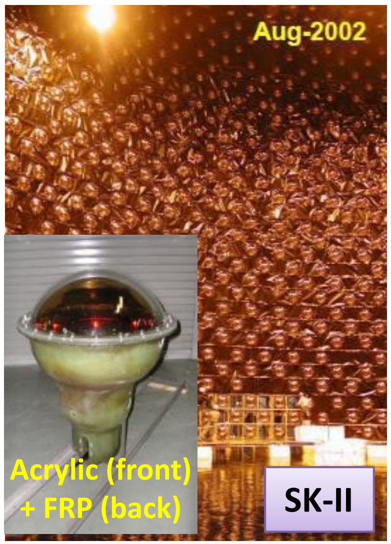
SK-III

SK-IV

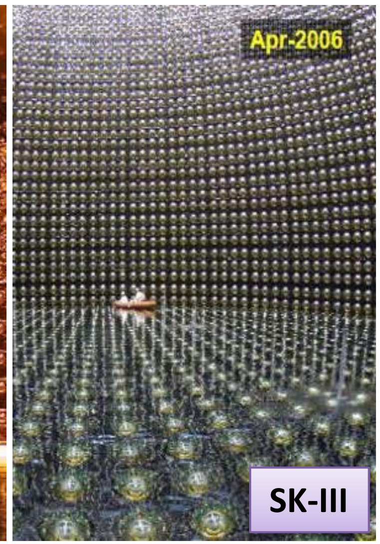
SK-V →
SK-Gd



11146 ID PMTs
(40% coverage)
4.5 MeV
1496 days



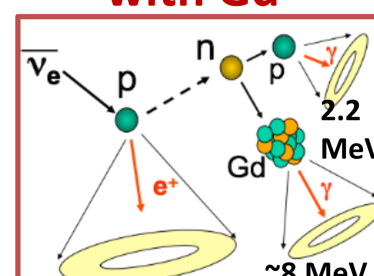
5182 ID PMTs
(19% coverage)
6.5 MeV
791 days



11129 ID PMTs
(40% coverage)
4.5 MeV
548 days

Electronics
Upgrade
3.5 MeV
2860 days
(~Dec. 2017)

Neutron tagging
with Gd



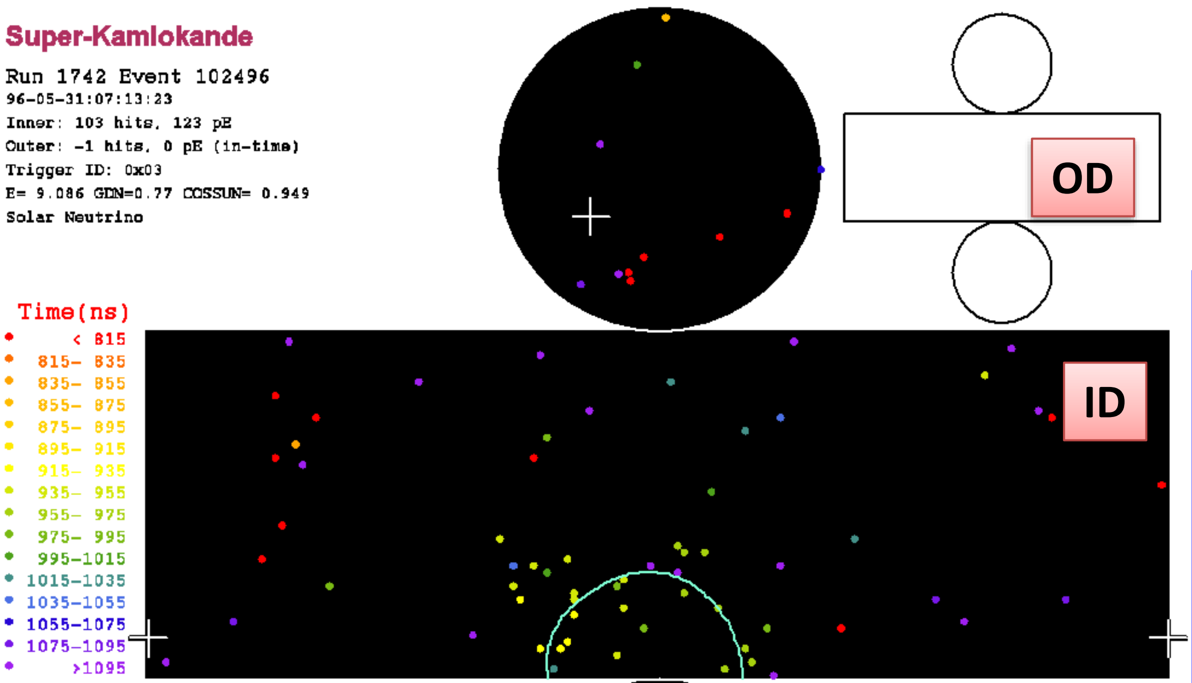
■ Analysis energy threshold (recoil electron kinetic energy)
■ Live time for solar neutrino analysis

Current total: 5695 days

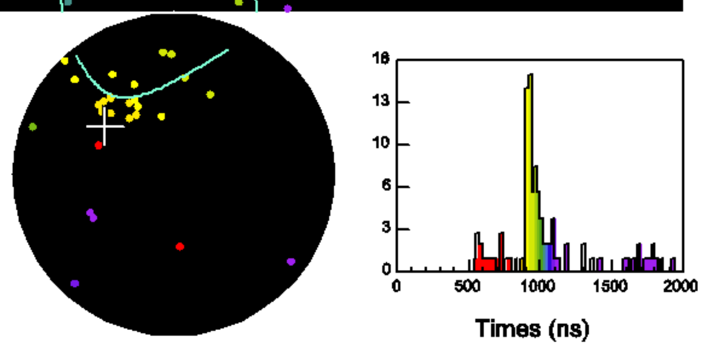
Typical low-energy event

$\nu + e^- \rightarrow \nu + e^-$

(for solar neutrinos)



(color: time)



$E_{e,total}$ = 9.1 MeV
$\cos\theta_{sun}$ = 0.95

- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

~6 hit / MeV
(SK-I, III, IV, V)

Resolutions (for 10 MeV electrons) (software improvement)

Energy: 14%	Vertex: 87cm	Direction: 26° SK-I
Energy: 14%	Vertex: 55cm	Direction: 23° SK-III, IV, V

Low-energy backgrounds in SK-I

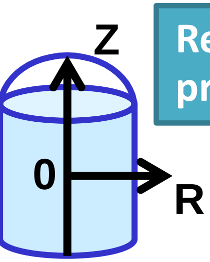
Spallation is dominant BG source in ~6.5-20MeV

Misfit

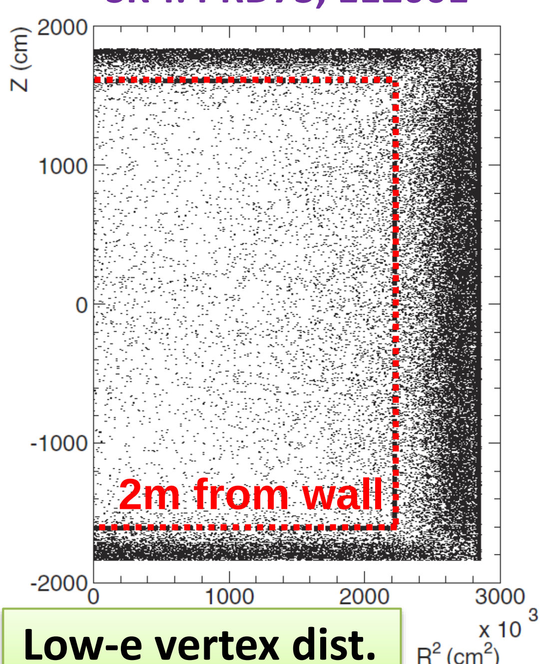
External gamma

Radon, Misfit, External gamma, etc.

Remaining spallation products (probably)

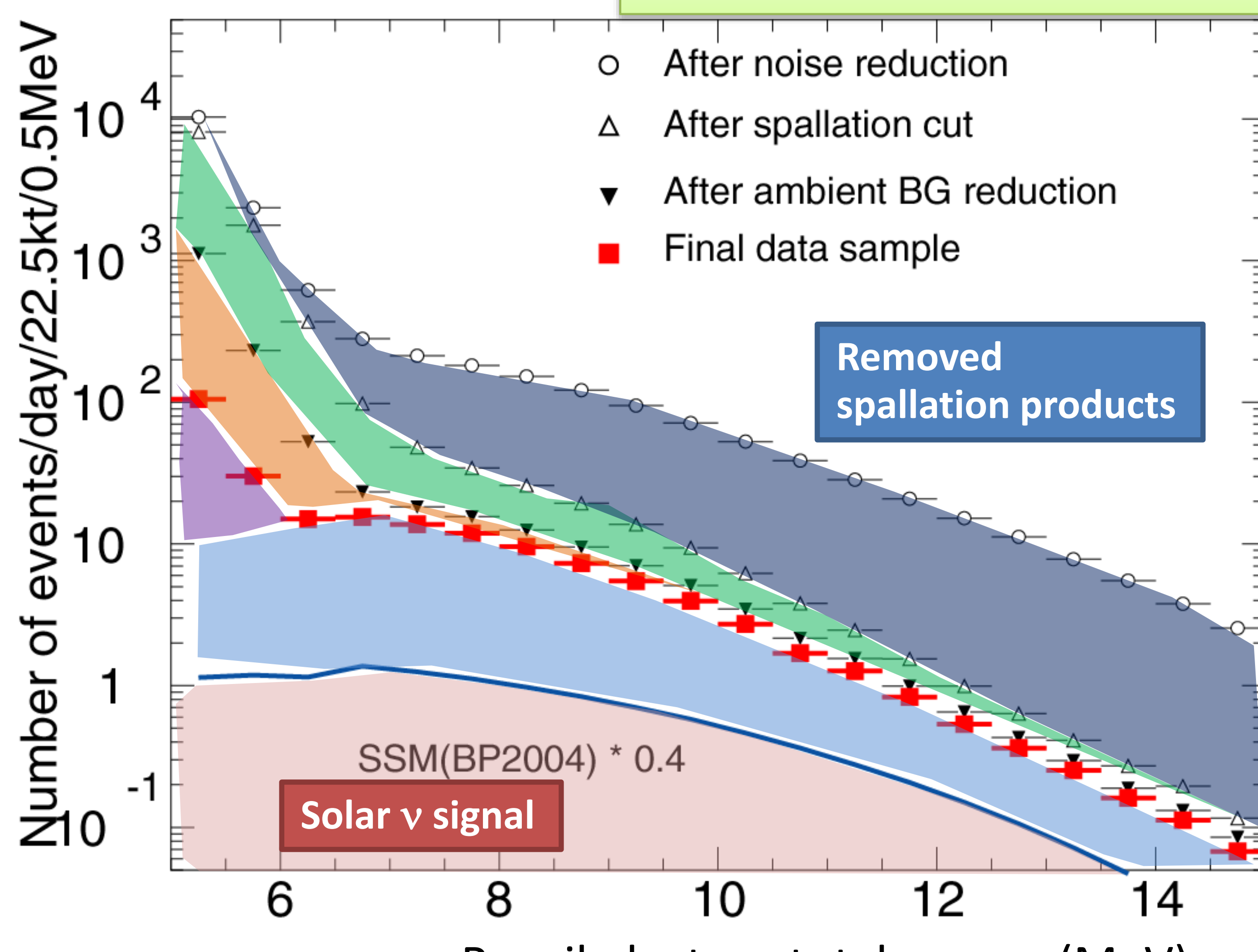


SK-I: PRD73, 112001



Low-e vertex dist.

Solar ν data reduction in SK-I (in 2m fiducial volume, 22.5kt)



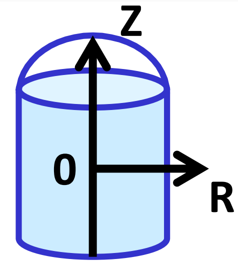
Vertex distribution in SK-IV

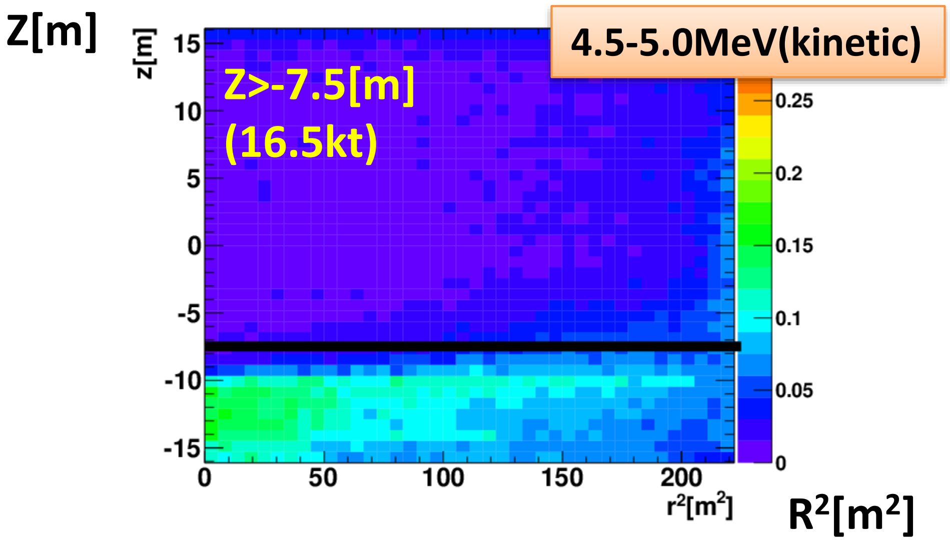
June 2017

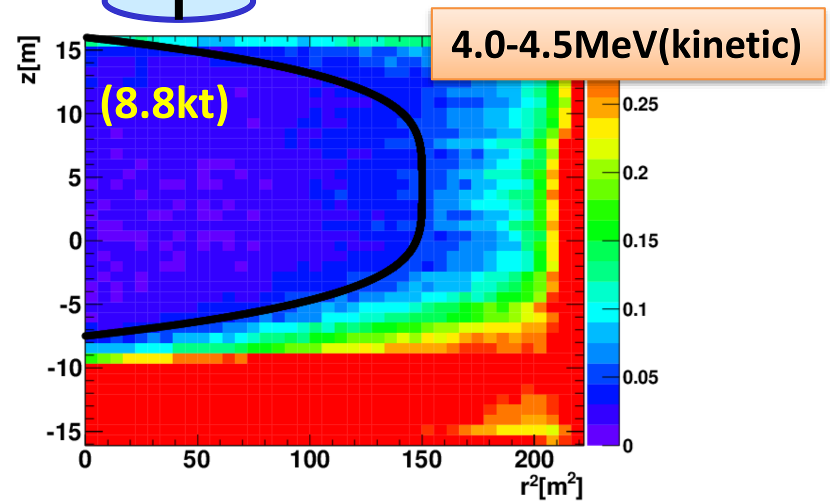
Preliminary

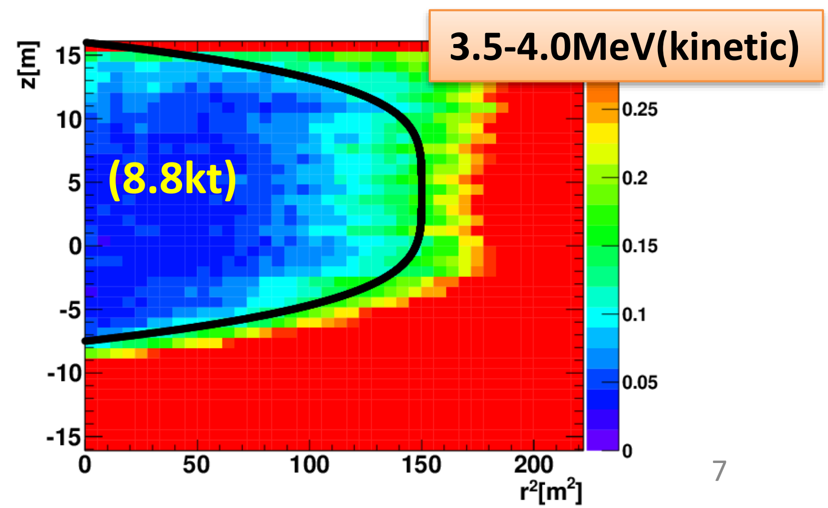
SK-IV 2645 days

Color : Events/day/bin low→high









- Whole area in these plots corresponds to 22.5kton
- Above 5.0MeV(kinetic energy), fiducial volume is 22.5kton
- Below 5.0 MeV(kinetic), tight fid. vol. cut is applied.

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- Solar neutrinos
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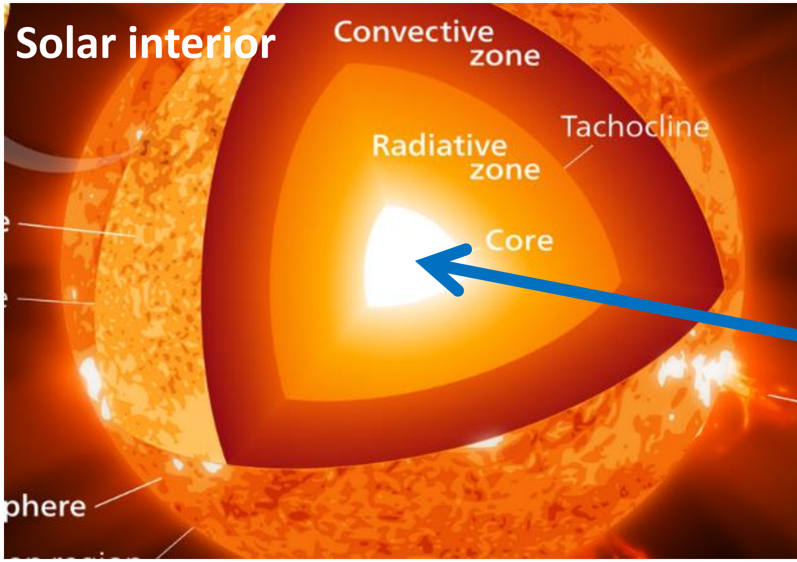
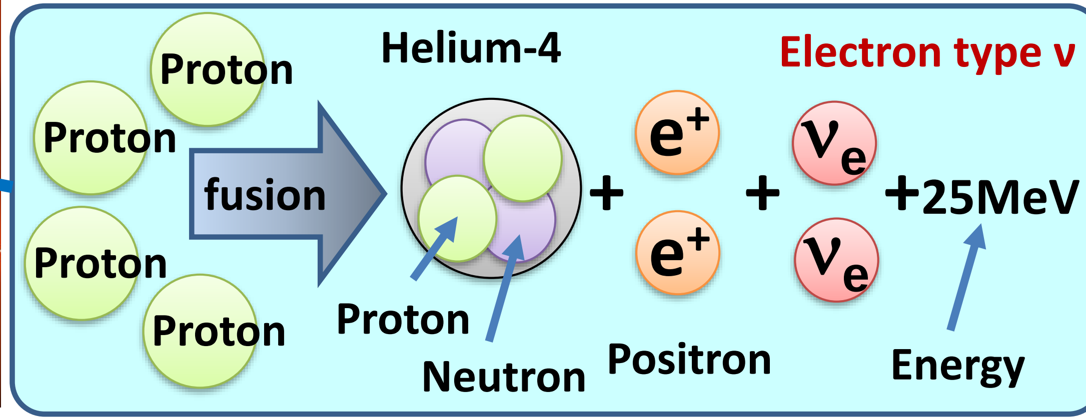
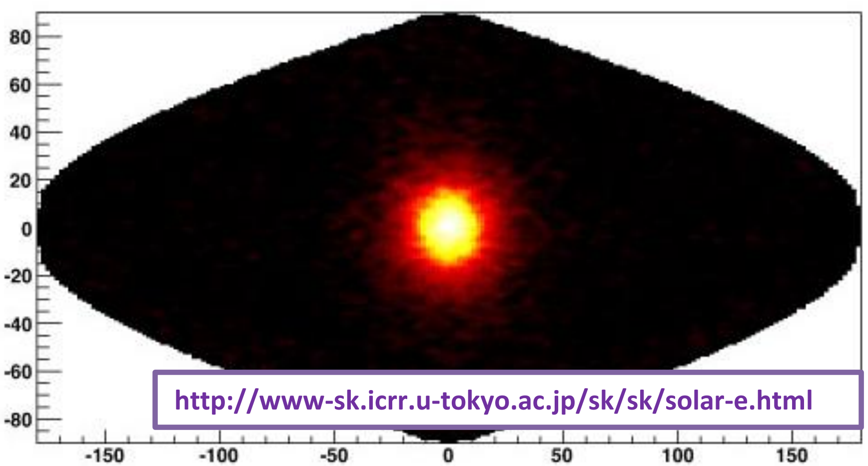
Solar neutrino



https://en.wikipedia.org/wiki/Sun#/media/File:Sun_poster.svg

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 25MeV$$





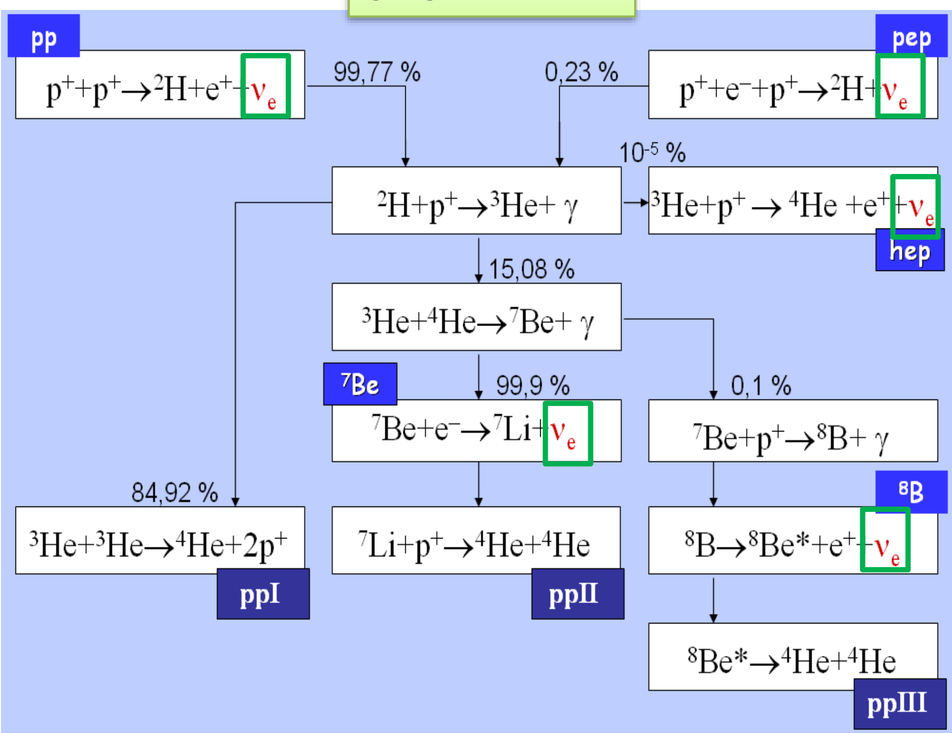
The Sun seen with neutrinos in SK. The coordinate system in which the Sun is places at the center is used. Color means event rates.

- **Standard Solar Model (SSM) predicts neutrino fluxes**
- **Most strong ν source on Earth**
  - **at Earth: ~66 billion ν/sec/cm²**
- **Photon: only surface**
- **ν: direct observation of interior of the *present* Sun**

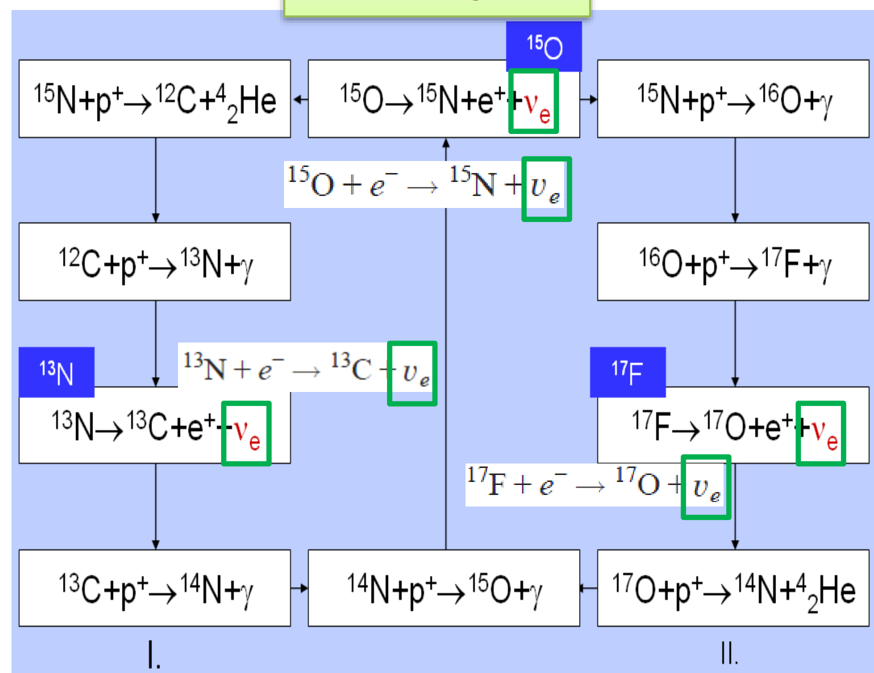
Solar neutrinos in SSM

Overall reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 25\text{MeV}$

p-p chain



CNO cycle



- **Solar fusion cross sections: SF-II (Rev. of Mod. Phys. 83 (2011) 195)**
- **B16 SSM: A New Generation of Standard Solar Models (ApJ 835 (2017) 202)**
- **Problem: Solar abundances: GS98 (High metallicity), AGSS09 (Low metallicity)**

http://upload.wikimedia.org/wikipedia/commons/a/a5/Proton_proton_cycle.png
http://upload.wikimedia.org/wikipedia/commons/f/fe/Cno_cycle.png

Expected solar neutrino spectrum

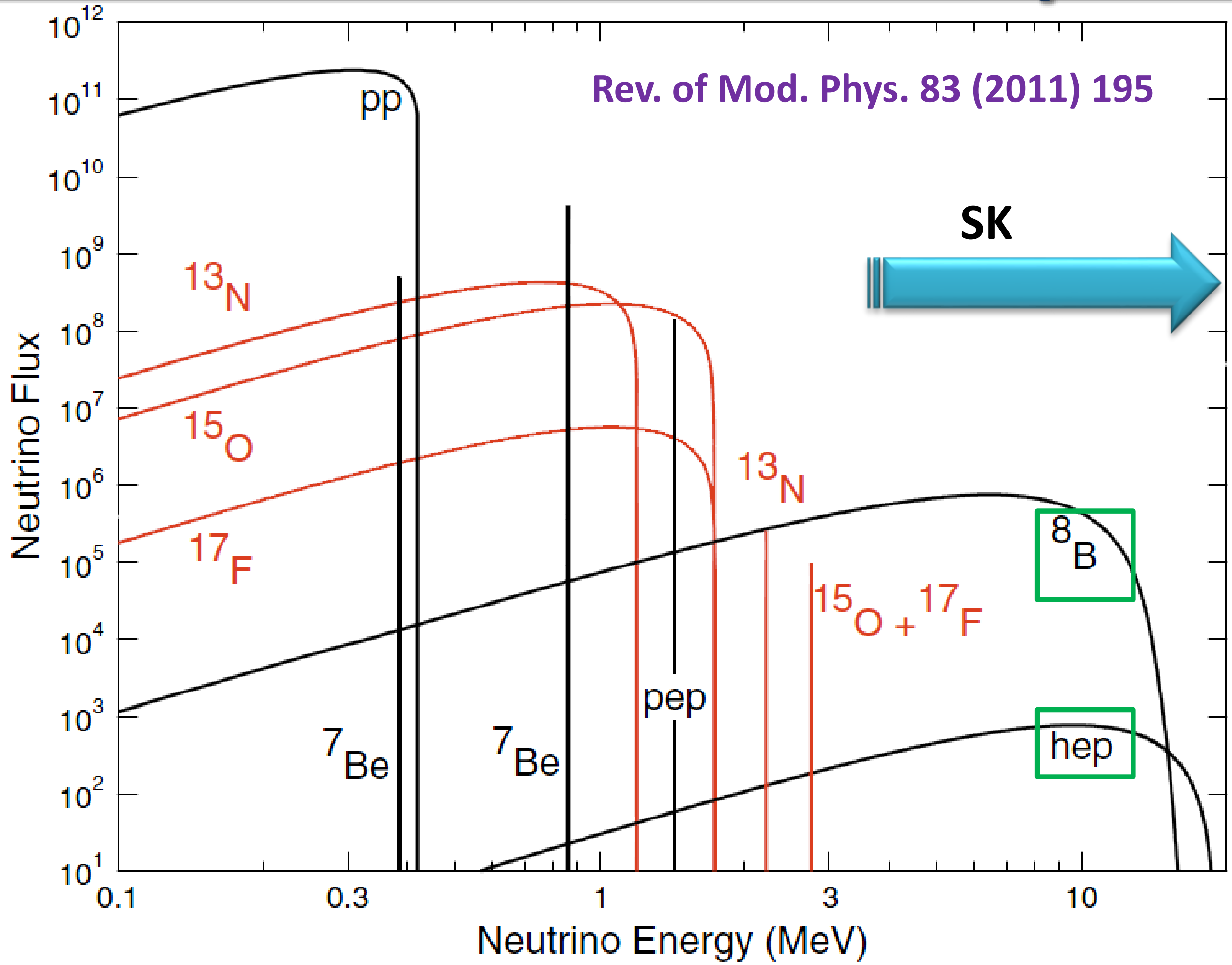


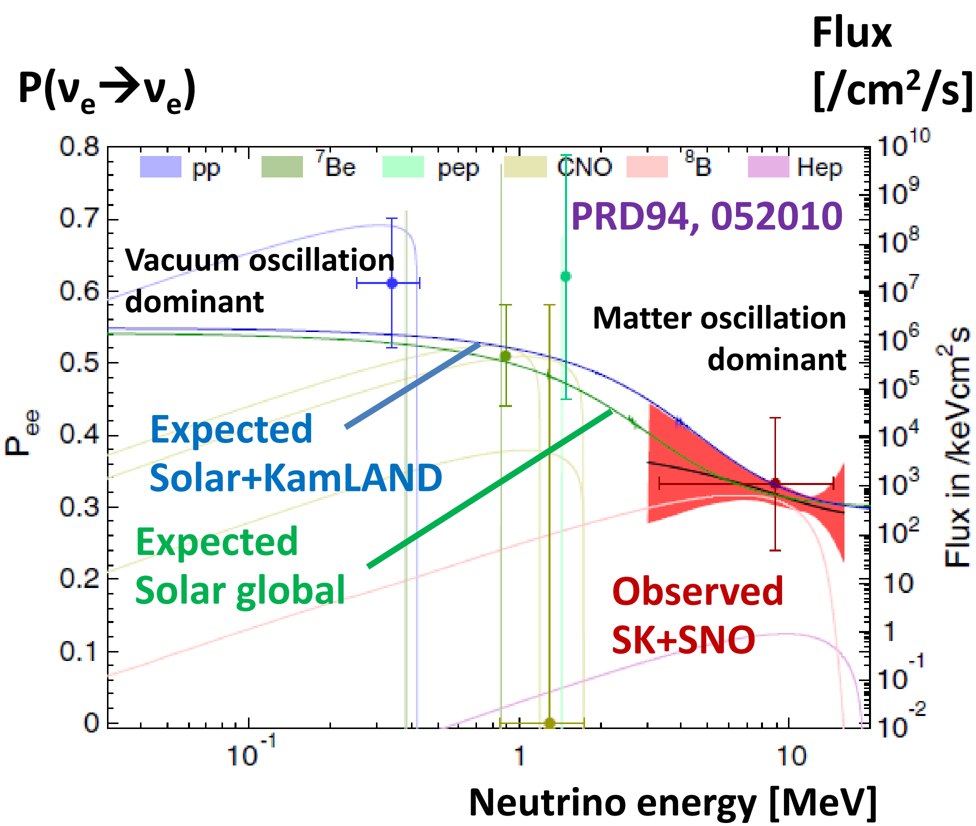
FIG. 7 (color online). Solar neutrino fluxes based on the "OP" calculations of Bahcall *et al.* (2005), with the addition of the new line features from CNO reactions. Line fluxes are in $cm^{-2}\,s^{-1}$ and spectral fluxes are in $cm^{-2}\,s^{-1}\,MeV^{-1}$. From Stonehill *et al.*, 2004.

Solar neutrinos at SK/HK

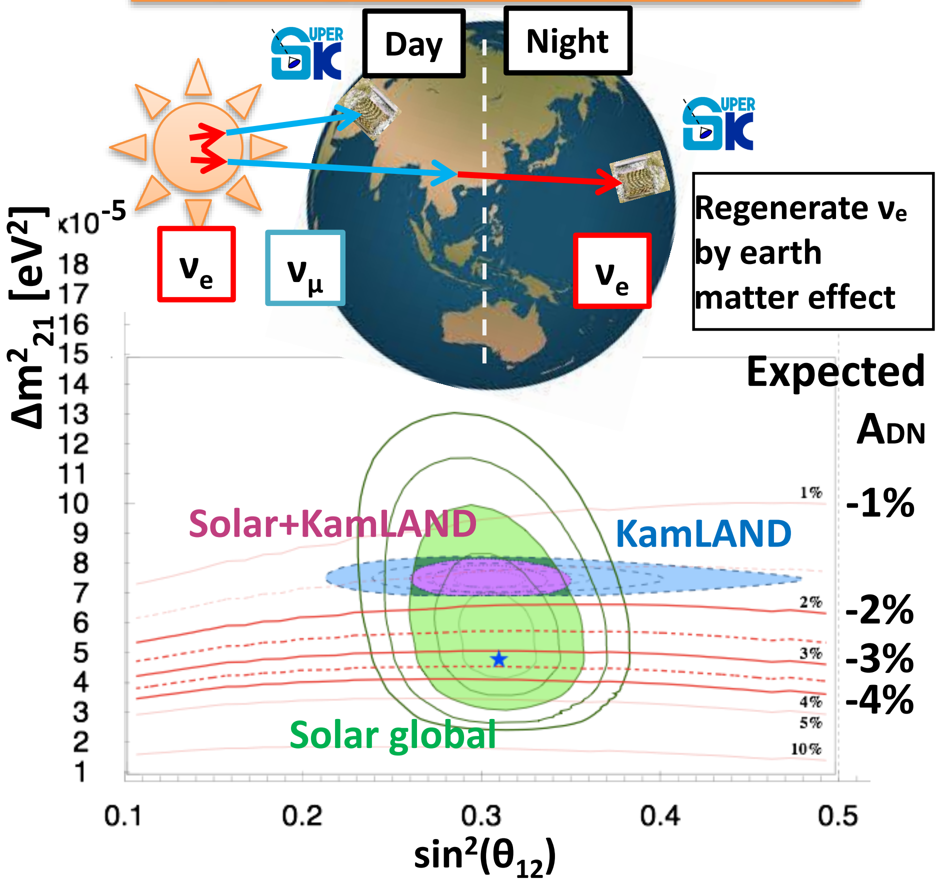
- High statistics measurement of ^8B solar neutrinos
  - Possible time variation of the flux
  - **Energy spectrum distortion** due to solar matter effect
  - **Day-night flux asymmetry** due to earth matter effect

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

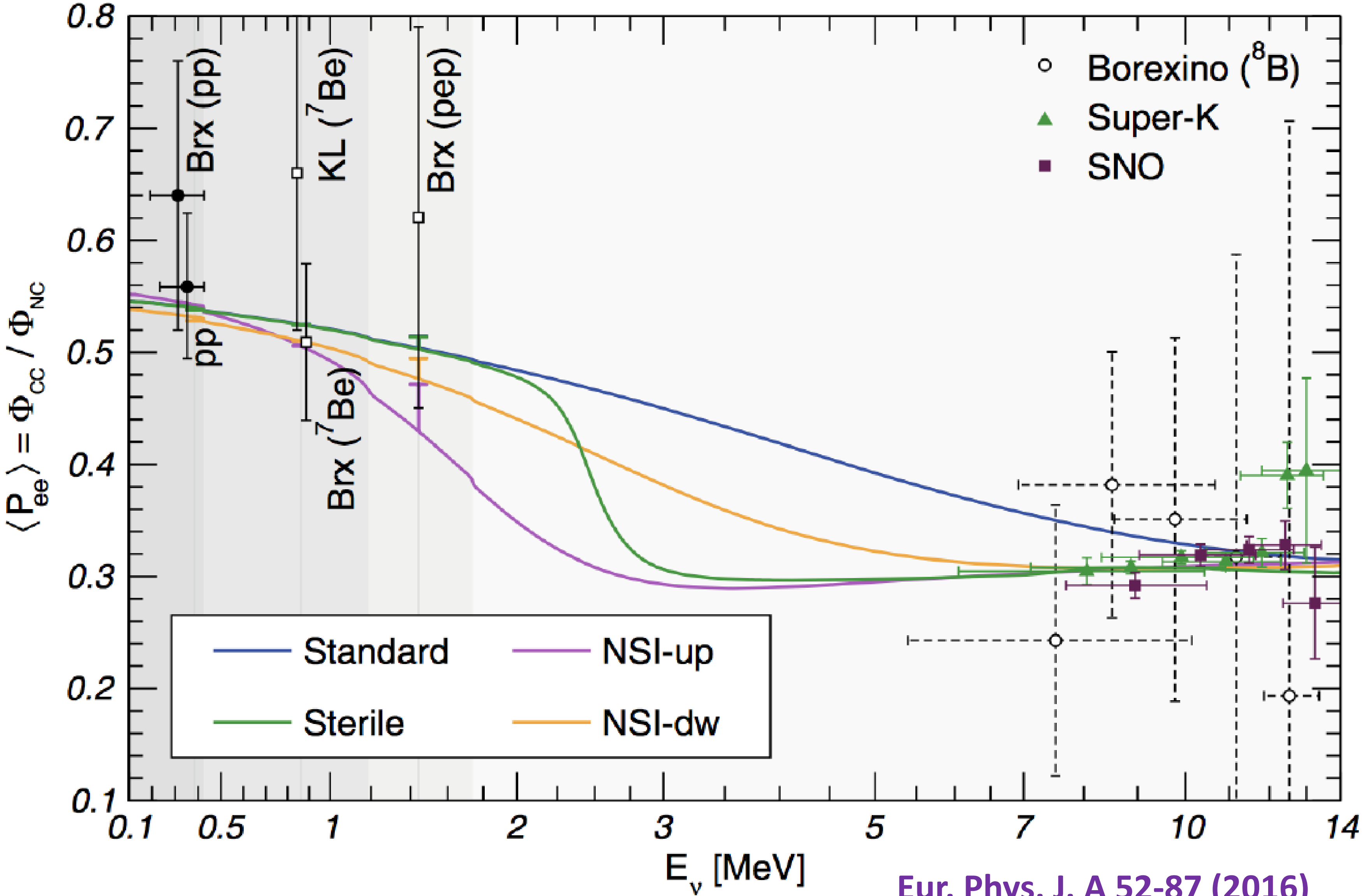
Spectrum distortion



Day-Night flux asymmetry



A theoretical expectation



Eur. Phys. J. A 52-87 (2016)

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Recent activities on solar ν analysis

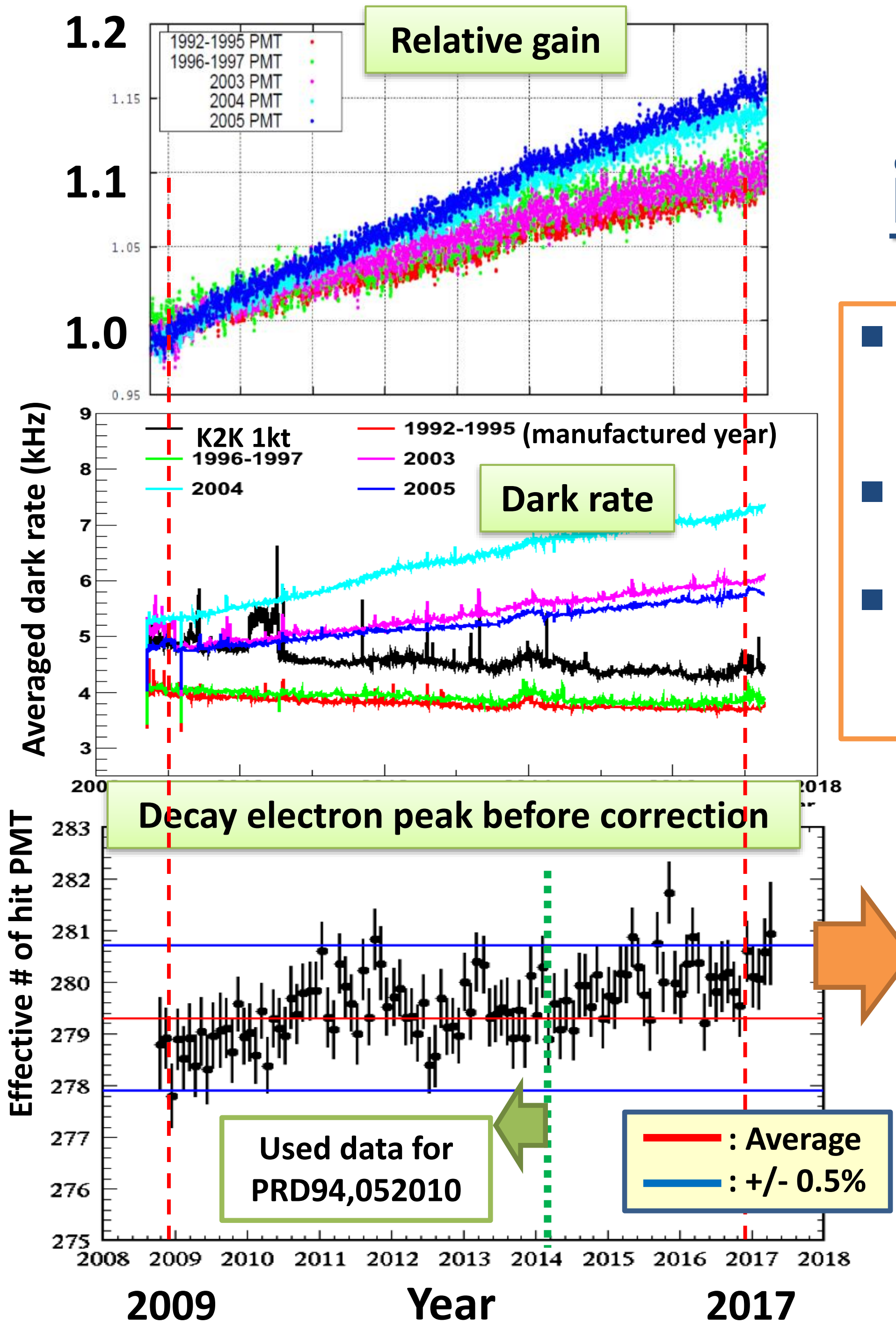
- **Energy scale improvements** Apr 2018
  - Taking into account PMT gain & dark rate effects
- **Preliminary update of spectrum analysis** Apr 2018
  - Total live time 5695 days (May 1996 - Dec. 2017)
  - SK-I (1496 days), SK-II (791 days), SK-III (548 days), SK-IV (1664 days → 2860 days)
- **Update of day/night analysis: On going (1664 days → ?)**
- **Preliminary periodic analysis in SK-IV**
  - Using same data set as PRD94, 052010
- **NSI analysis: On going**
- **Solar nu-e-bar: On going**
- **Study of spallation BG**
  - Using neutron events (2.2 MeV γ from n+p) in SK-IV
- **Study of radon BG**
  - "Measurement of Radon Concentration in Super-Kamiokande's Buffer Gas", NIM A (DOI: 10.1016/j.nima.2017.04.037)

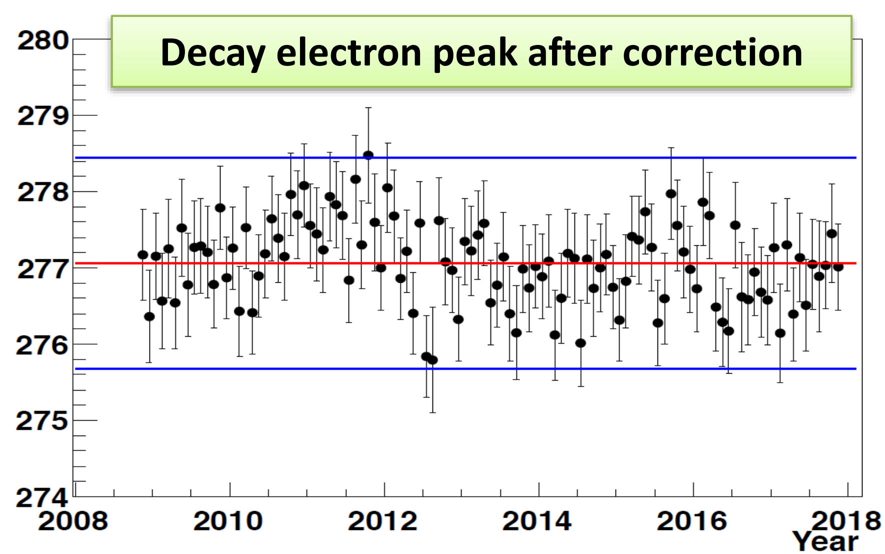
Energy scale improvement

Apr 2018

Preliminary

- PMT gain and PMT dark rate are changing, and it caused a slight drift of energy scale as a function of time.
- A new energy scale with gain and dark rate correction is implemented.
- It enables low-energy analysis of whole SK-IV period with a same systematic uncertainty.



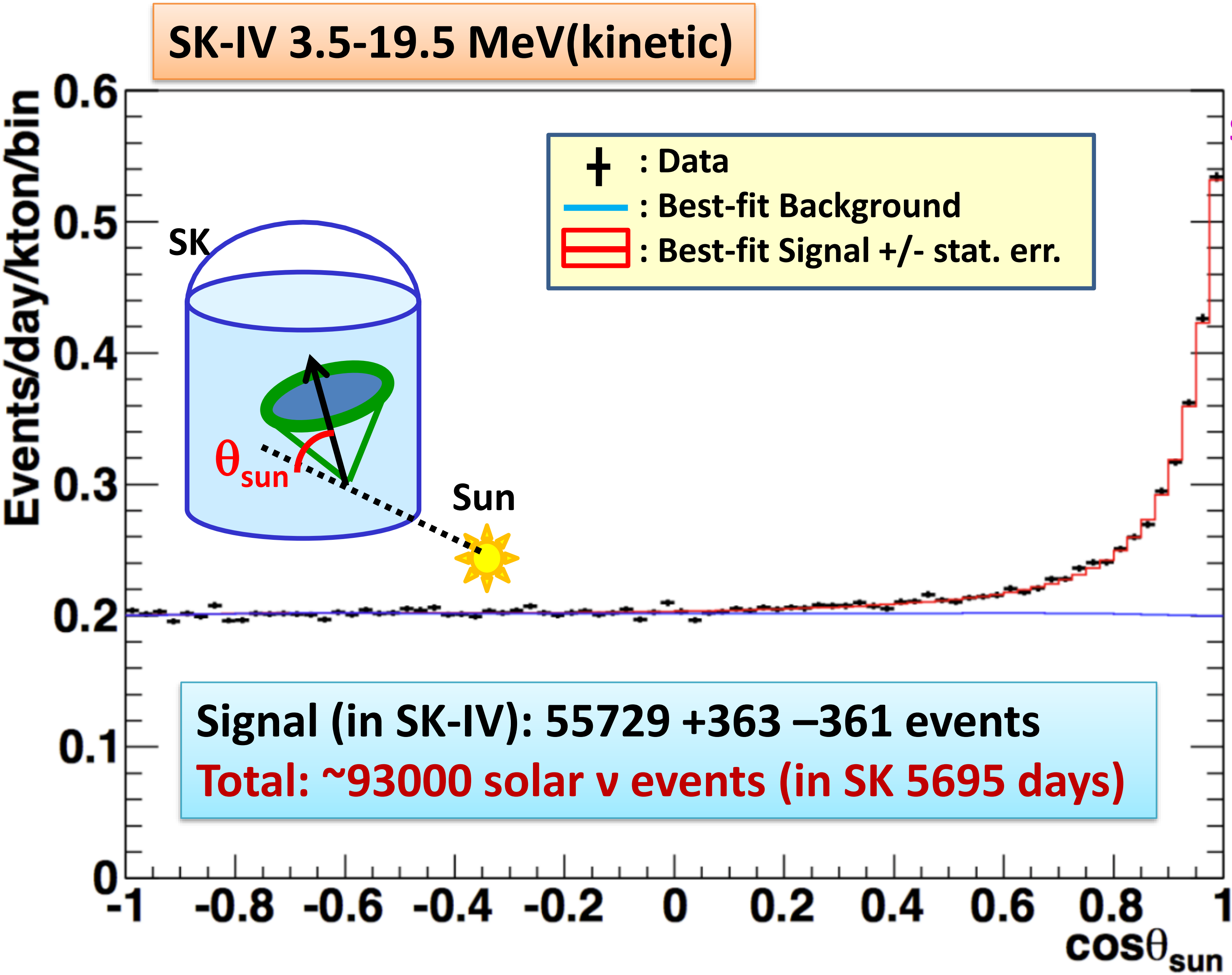


SK-IV solar neutrino signal

Apr 2018

Preliminary

SK-IV 2860days

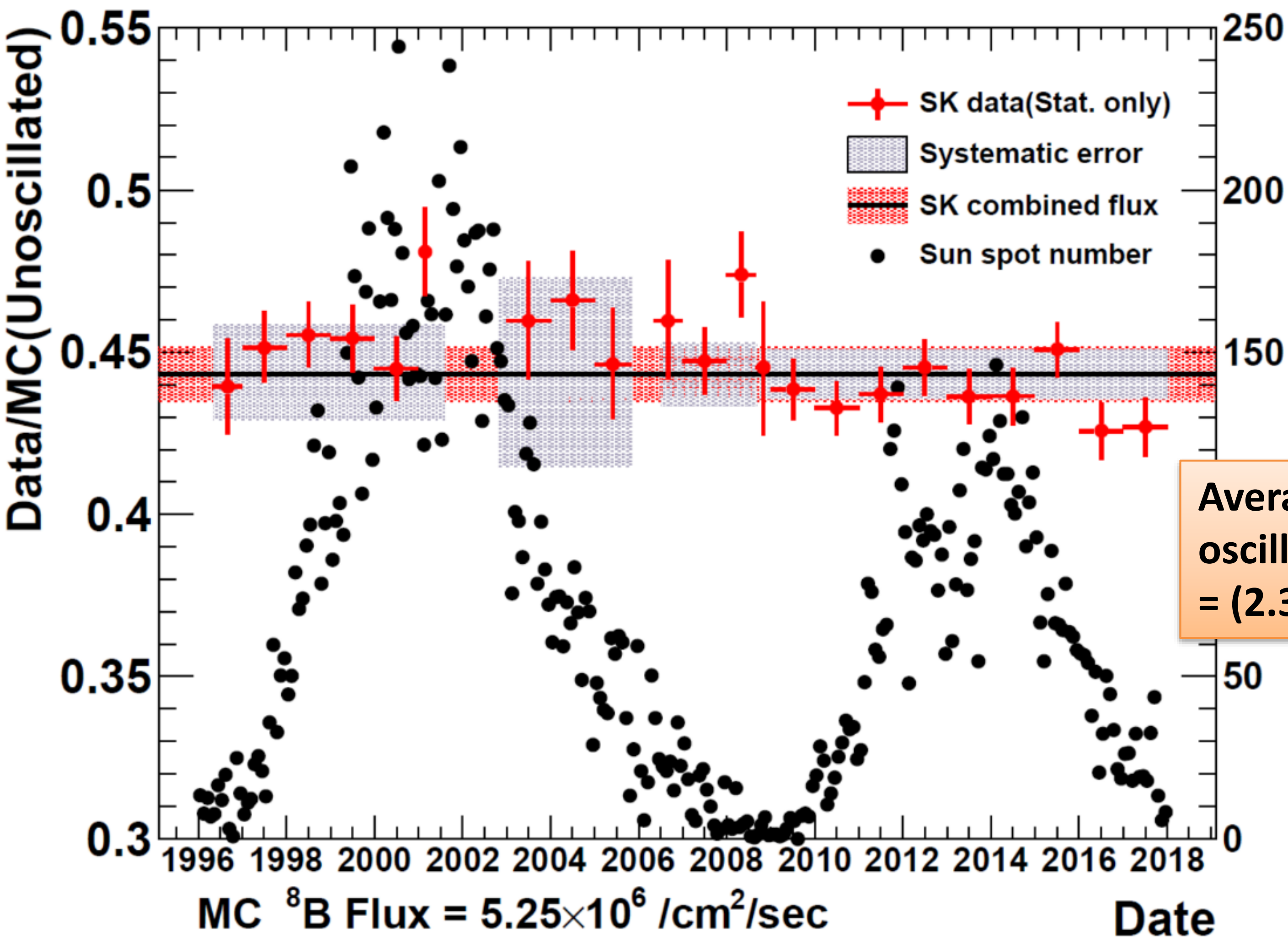


^{8}B solar neutrino flux: Yearly plot

Apr 2018

Preliminary

SK 5695 days



Averaged ^{8}B flux with no oscillation
= (2.33+/-0.04) x10^{6}/cm^{2}/s

χ^2 = 21.57 / 21 d.o.f. → Confidence level = 41.4 %

Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

Sun spot number: WDC-SILSO, Royal Observatory of Belgium, Brussels

Solar ν oscillation results

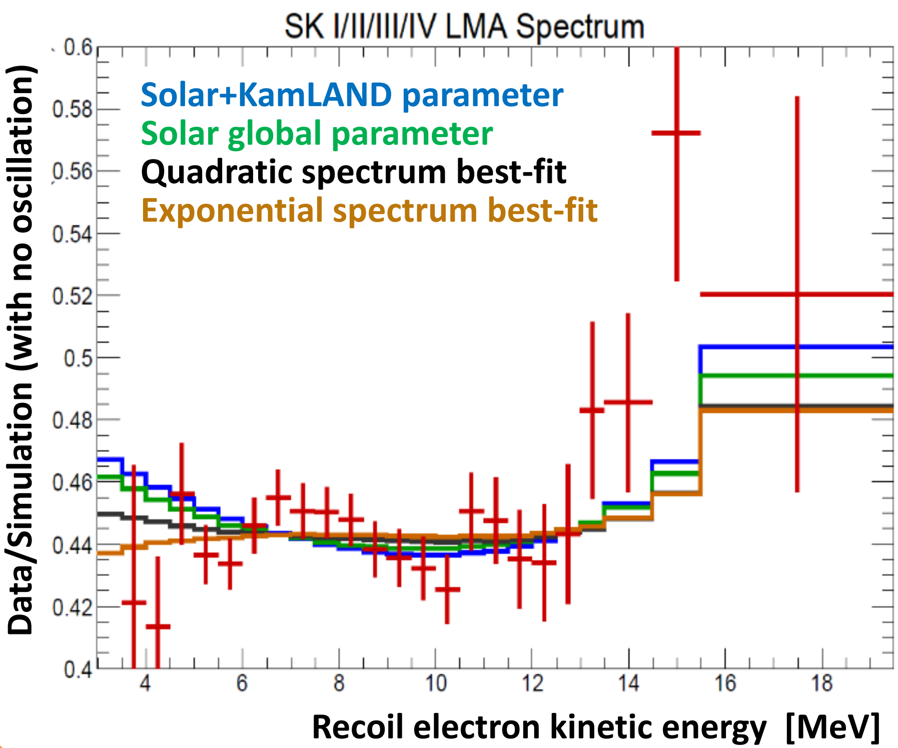
Apr 2018

Preliminary

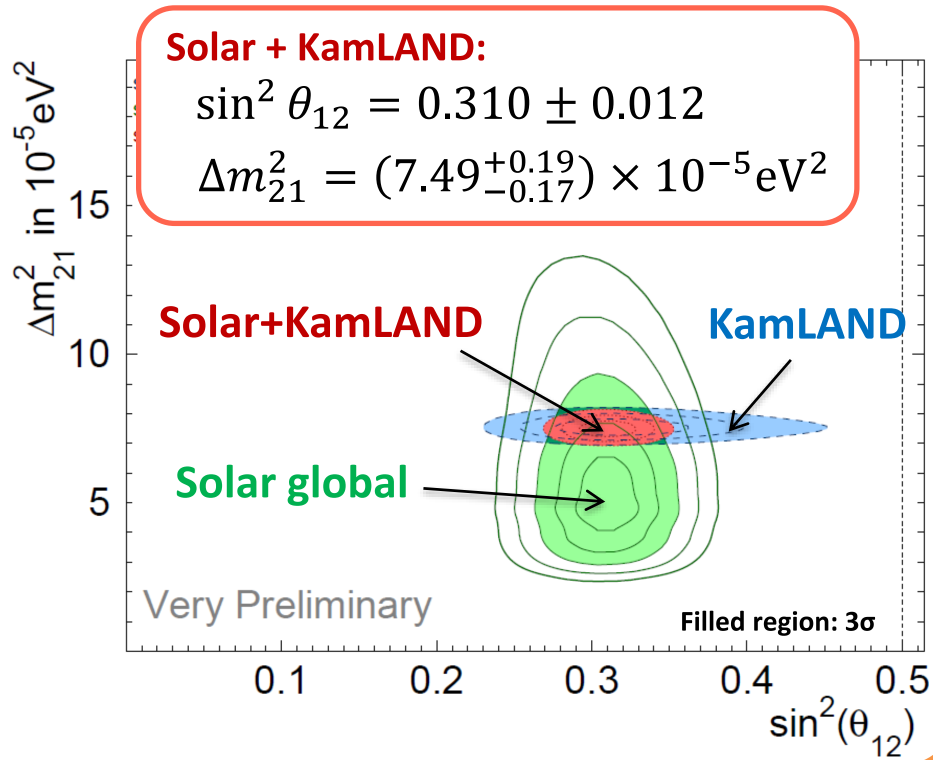
SK 5695 days

- Quadratic fit of SK spectrum is consistent with solar Δm^2_{21} within ~1.2 σ and disfavors KamLAND Δm^2_{21} by ~2.0 σ.
- ~2.0 σ level tension in Δm^2_{21} between solar global analysis and KamLAND is still remaining.

Solar ν energy spectrum



Solar ν oscillation parameters

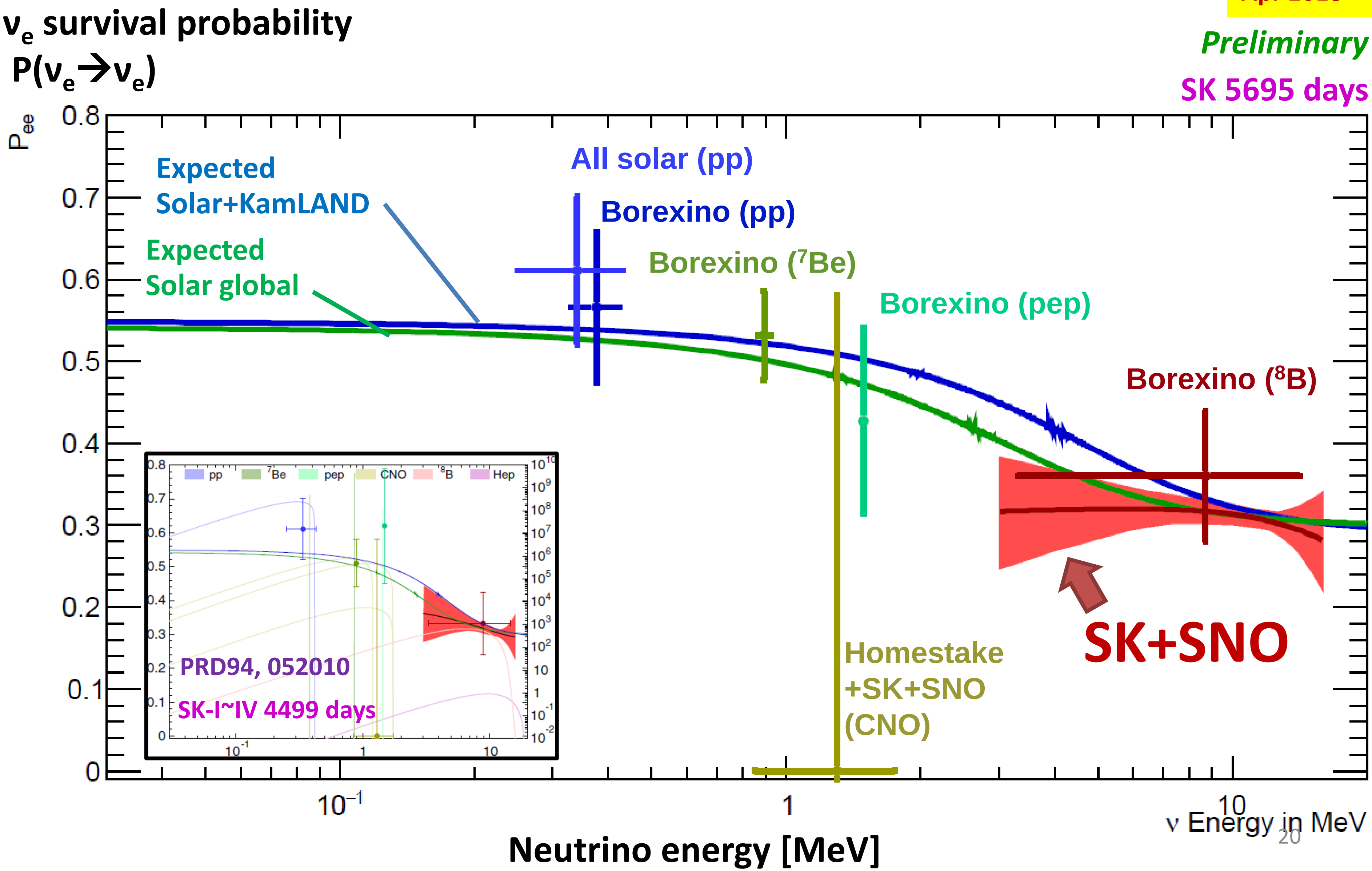


Super-K Spectral Data

Apr 2018

Preliminary

SK 5695 days



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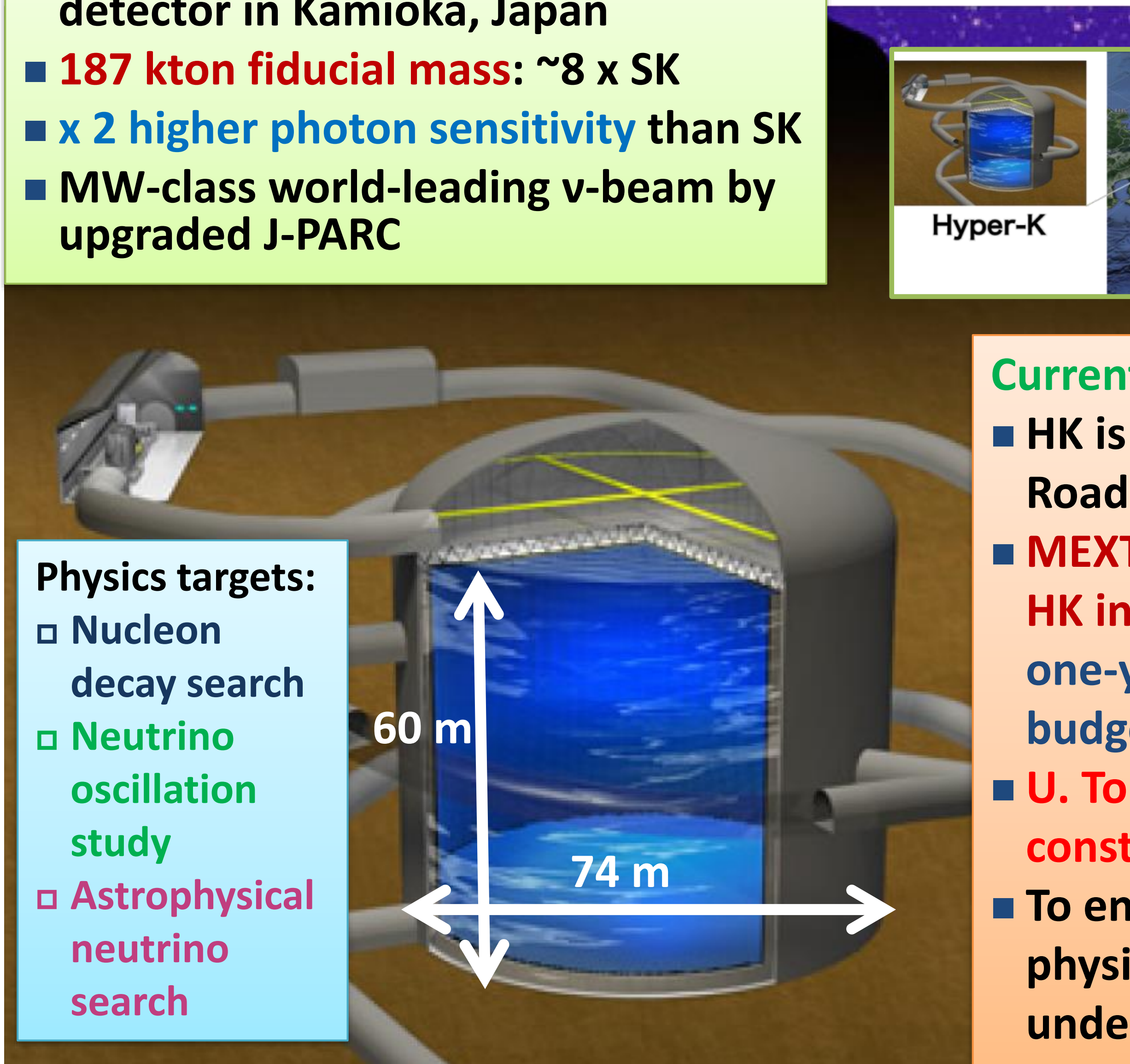
Hyper-Kamiokande (HK)

Design Report 2018: arXiv:1805.04163

- Gigantic neutrino and nucleon decay detector in Kamioka, Japan
- 187 kton fiducial mass: ~8 x SK
- x 2 higher photon sensitivity than SK
- MW-class world-leading ν-beam by upgraded J-PARC



Physics targets:
- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

Current status:
- HK is a priority project by MEXT's Roadmap 2017
- MEXT allocated a seed budget of HK in FY2019. (In SK, after the one-year seed budget, full budget was allocated)
- U. Tokyo decided to start HK constriction in April 2020.
- To enhance neutrino oscillation physics, a 2nd detector in Korea is under study

Solar neutrinos in HK

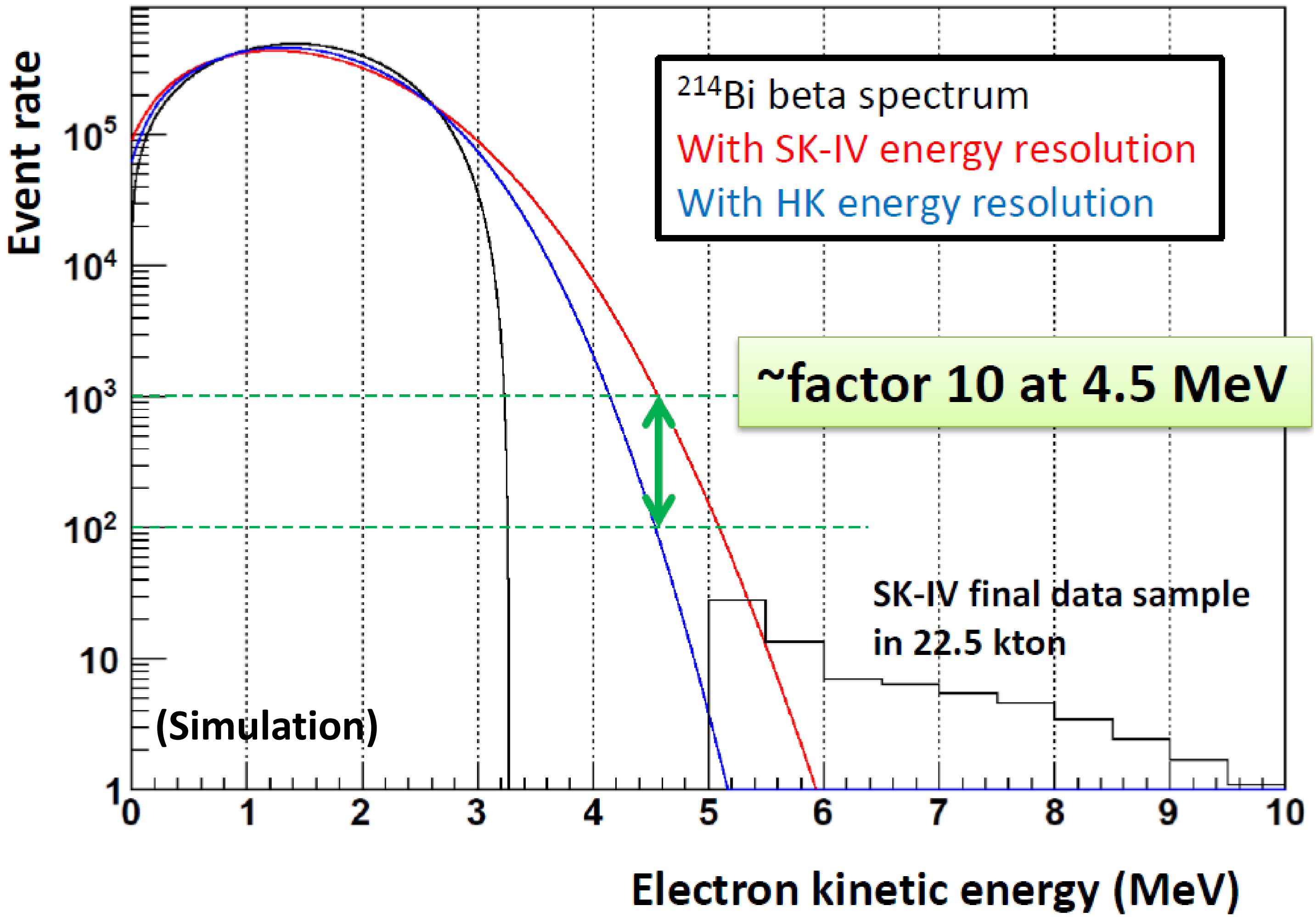
Design Report 2018: arXiv:1805.04163

- **Expected event rate**
  - ^{8}B solar neutrino: ~130 events/day
  - 4.5 MeV threshold (visible energy)
  - with oscillation, scaled from SK rate
- **Neutrino physics**
  - Oscillation parameters
  - NSI analysis
- **Solar physics**
  - *Hep* solar neutrino
  - Core temperature monitor
  - Solar g-mode oscillation
  - Neutrino from solar flare

An estimation of Rn background

Design Report 2018: arXiv:1805.04163

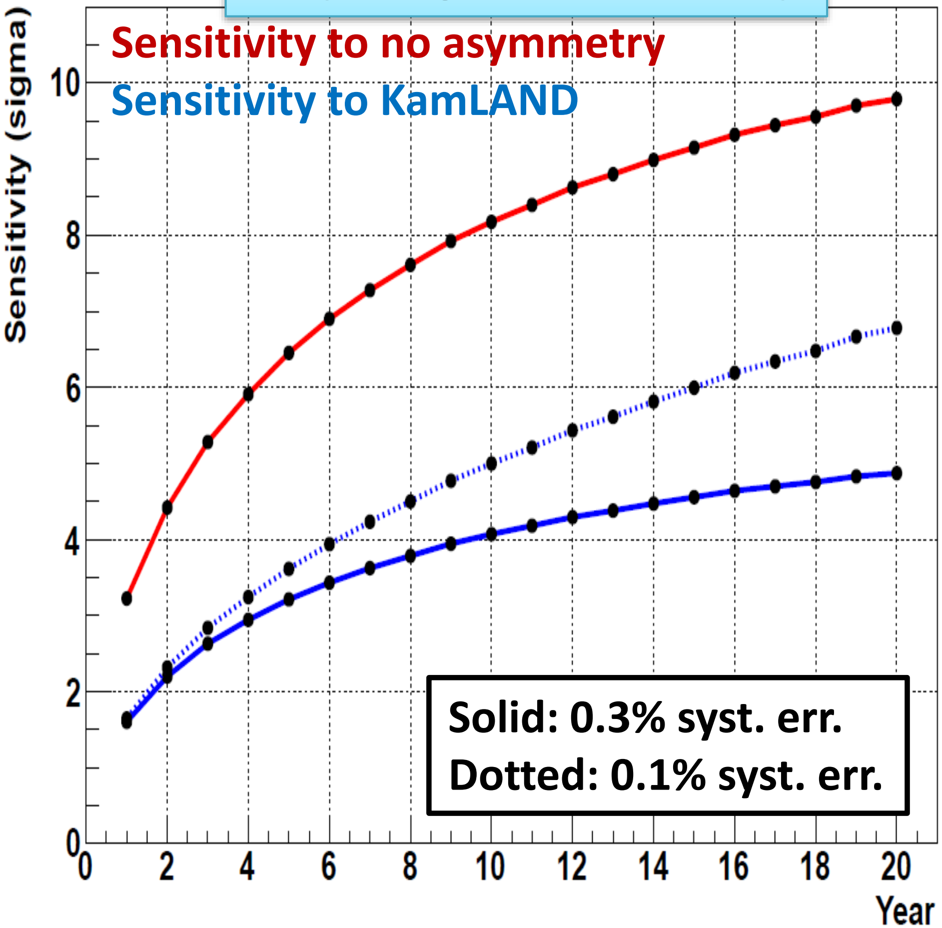
- Radon events could be reduced in HK thanks to **better energy resolution**.



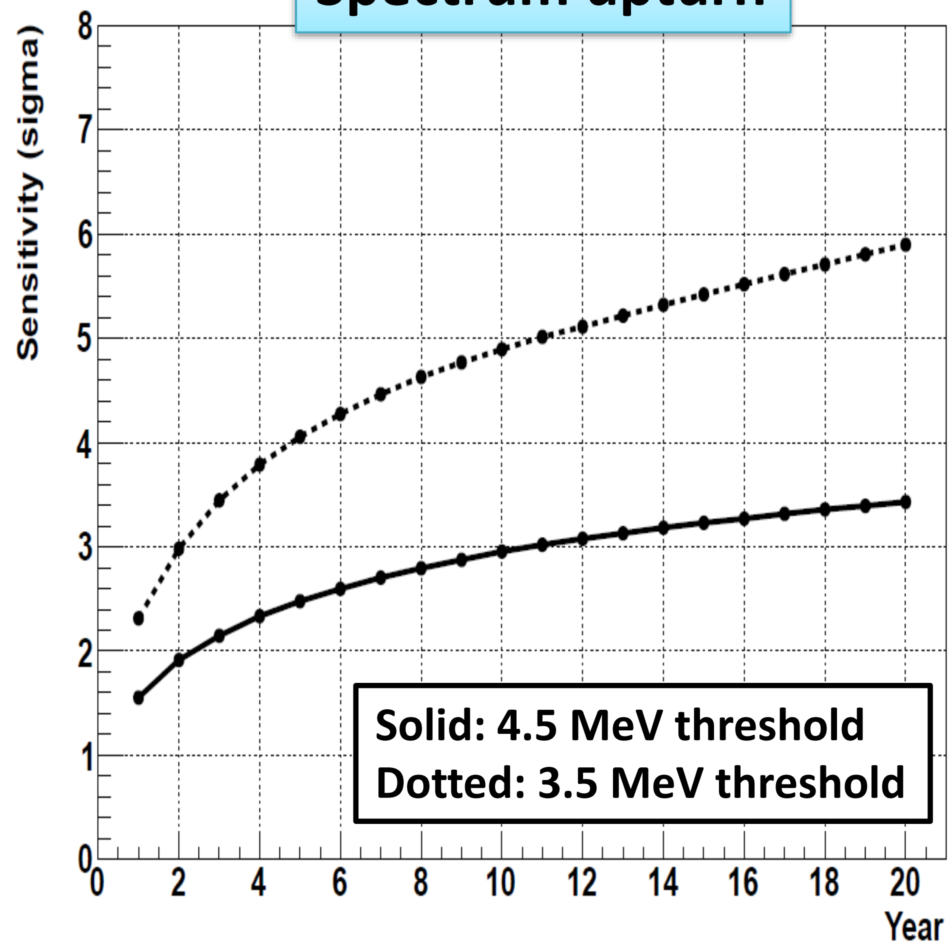
^{8}B Solar neutrino measurements

Design Report 2018: arXiv:1805.04163

Day/Night sensitivity



Spectrum upturn

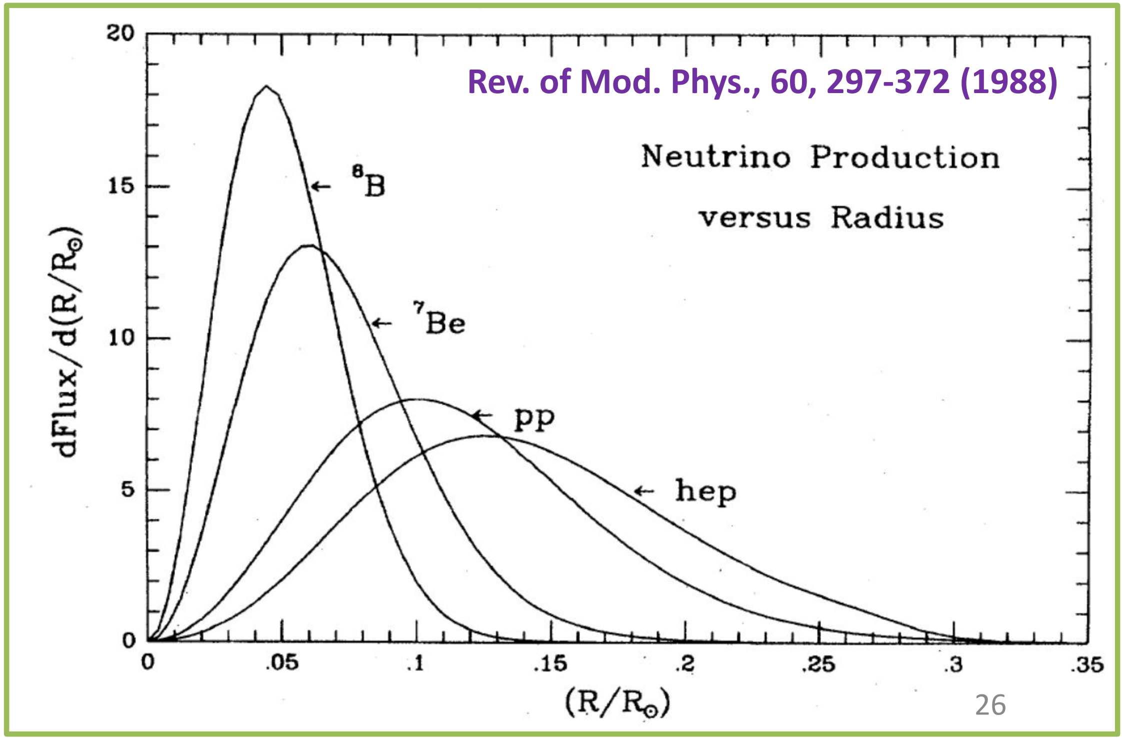


- Day/Night (solar vs reactor): 4~5 sigma in 10 years
- Spectrum upturn: ~3 sigma in 10 years

Hep solar neutrino

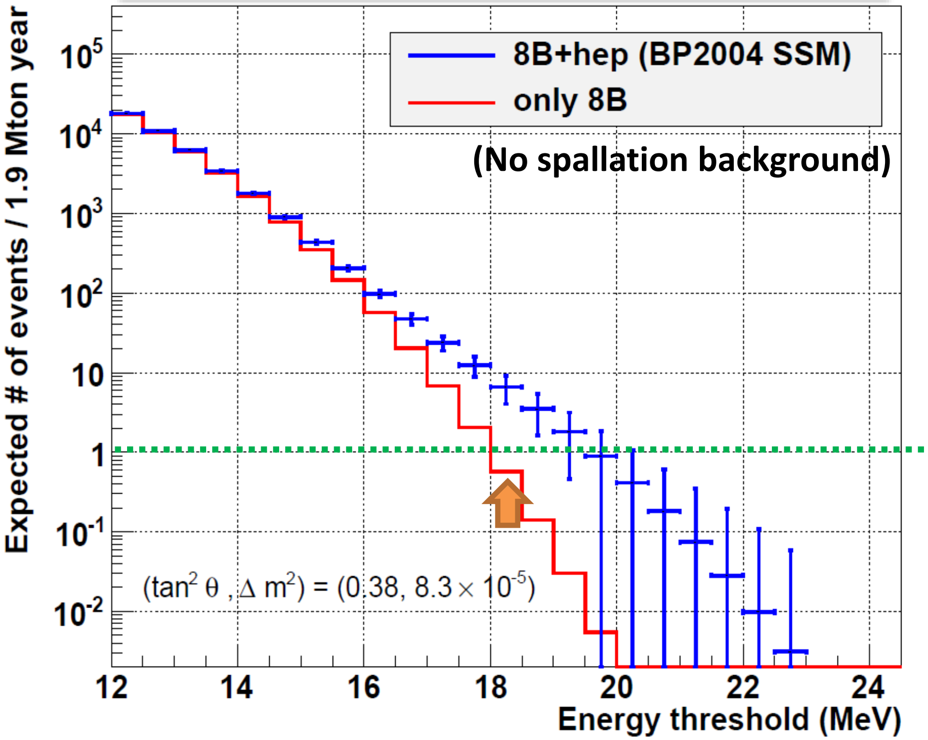
Design Report 2018: arXiv:1805.04163

- The last piece of the solar neutrinos in pp-chain.
- Theoretical calculation is difficult.
  - → Better understanding of solar physics
- Production area is different.
  - → A new probe of the solar interior around core region
- Non-standard solar models predict the potential enhancement of the hep neutrino flux.
- Could be additional input to the solar chemical composition problem.

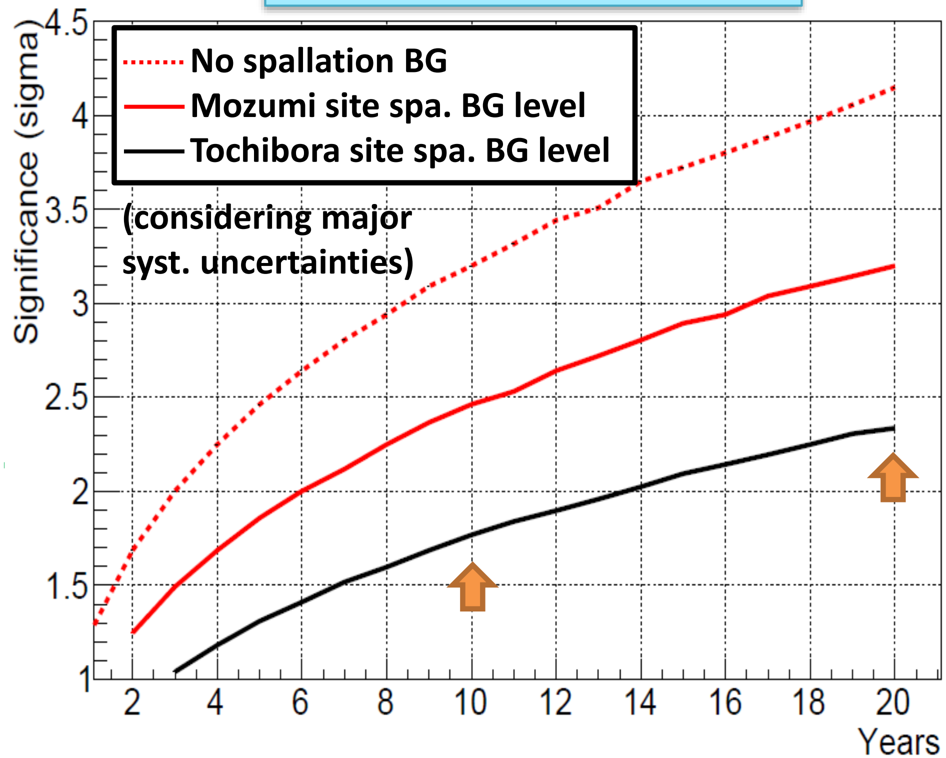


Hep solar neutrino at HK

Integrated # of expected solar neutrino events



Expected non-zero significance

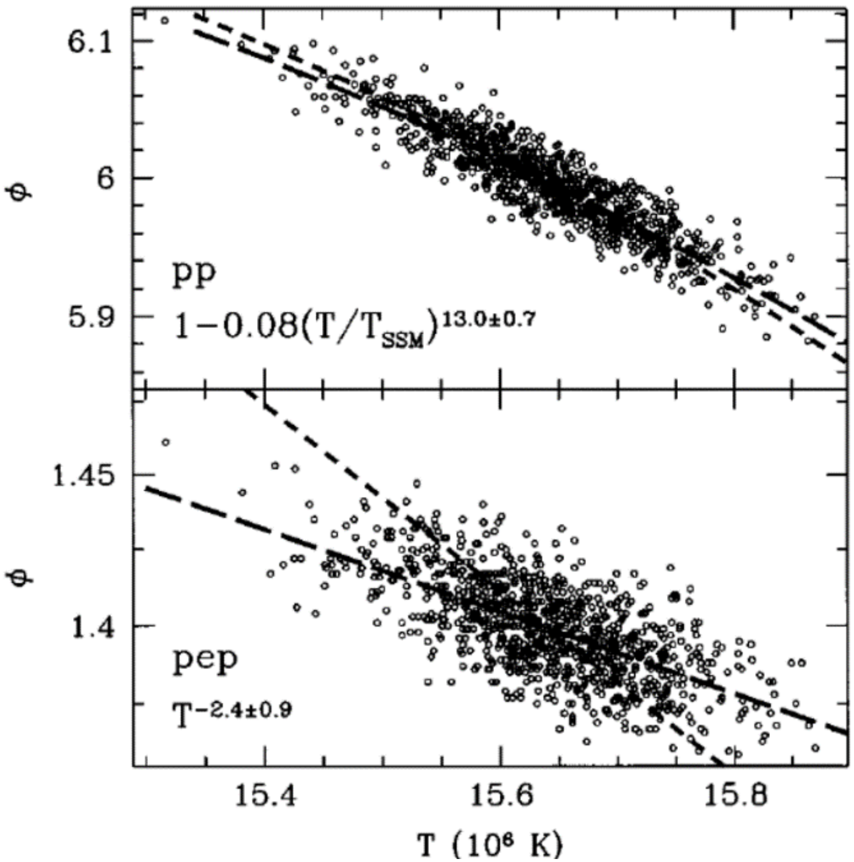


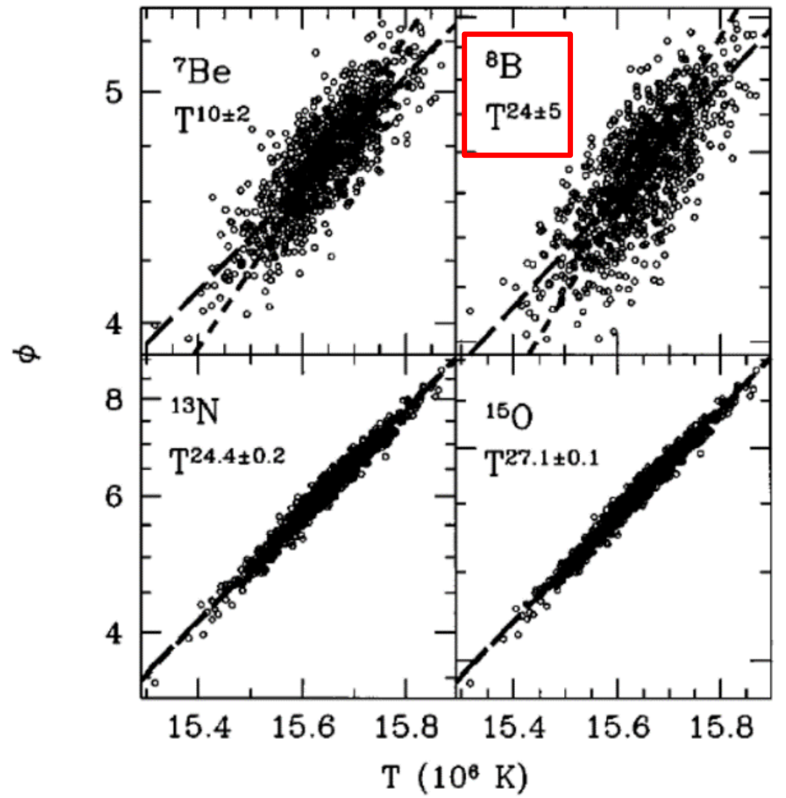
	E_{total} [MeV]	^{8}B [/1.9Mt yr]	Hep [/1.9Mt yr]	Hep / ^{8}B
SK	19.5-25.0	0.77	3.03	3.9
HK	18.0-25.0	0.56	6.04	10.6

- First direct observation.
- Energy resolution & spallation BG reduction are essential.

Temperature dependences of ν flux from SSM

J. N. Bahcall and A. Ulmer, Phys. Rev. D 53 (1996) 4202.

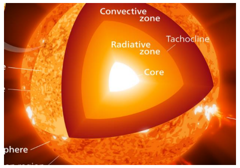


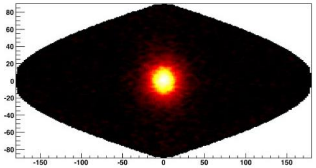


^{8}B flux is very sensitive to solar core temperature (flux ∝ T^{24})
→study of possible time variation of ^{8}B flux (Solar physics)

(Accuracy of core temperature measurement: ~0.8% day by day at HK)

Hyper-K





Summary

- Solar neutrino has been observed since 1970's
  - It could be used as a probe of solar physics
- Agreement between SSM + ν oscillation and solar neutrino experiments looks good, but there is some room for new physics
  - Tension between solar and reactor experiments
  - Energy spectrum in vacuum-matter transition region
- A very precise solar neutrino measurements could be done with HK for both ν properties and solar physics
  - Oscillation parameters, *hep* neutrinos, short time variations, solar flares, …