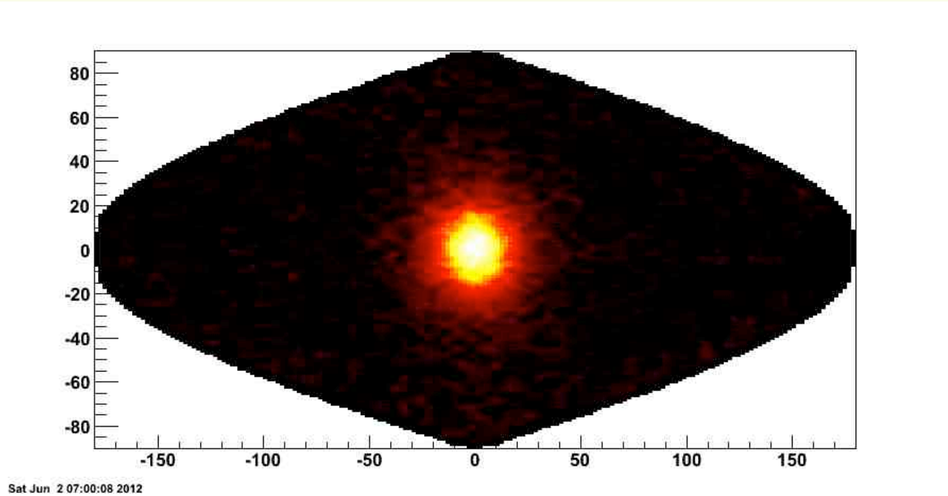
Present status and future prospect of the solar neutrino measurements for completing the PMNS picture and beyond



Yusuke Koshio
Okayama University

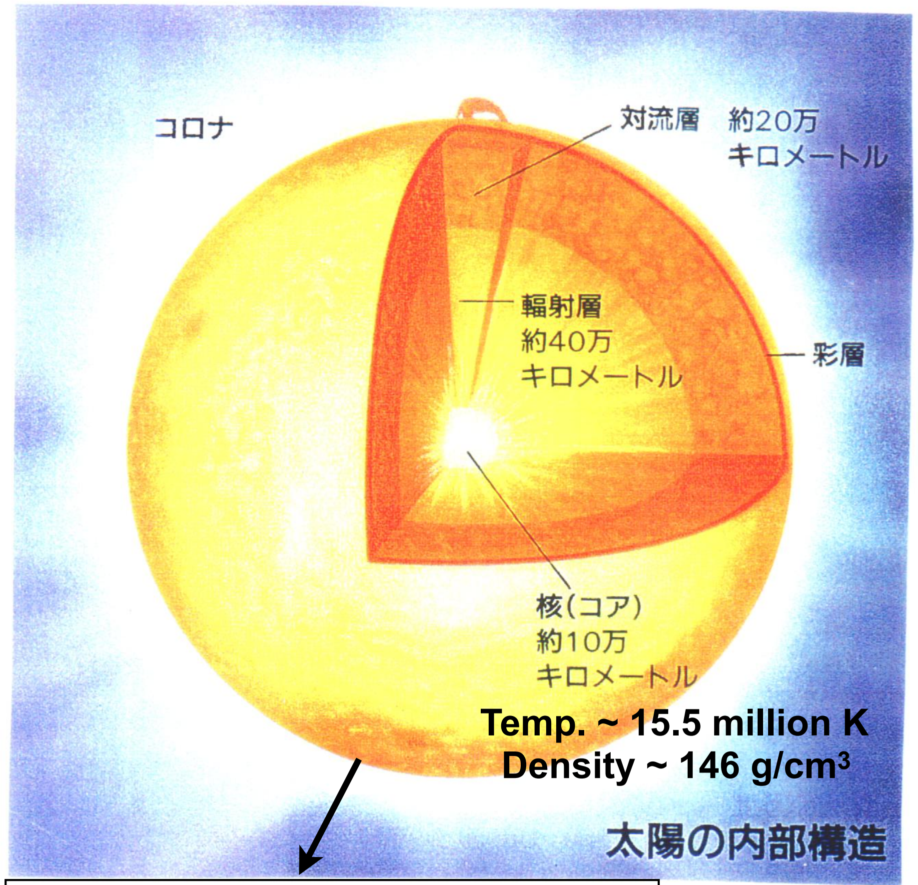
XVth Rencontres du Vietnam "3 neutrinos and Beyond"
ICISE center, Quy Nhon, Vietnam, 4-10 August, 2019

Contents

- Introduction of Solar neutrino
- Current experiments
  - Super-Kamiokande
  - Borexino
- Future prospects
  - Hyper-Kamiokande

Solar neutrino

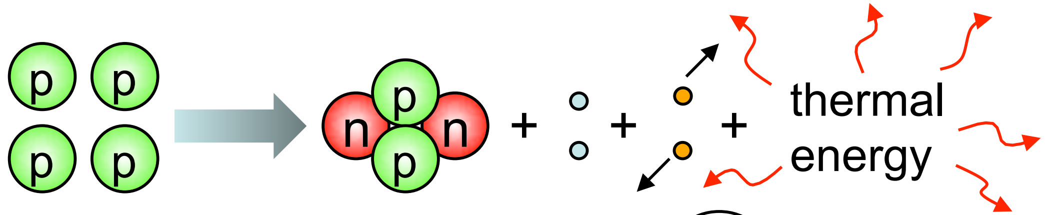
How does the Sun shine?



Photon-measured luminosity

→ ~10^7years radiated from the center to the surface.

Nuclear fusion reactions can occur deep inside the Sun.



$4p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e + 26.7\,MeV$

(~6.6×10^{10} neutrinos /sec/cm^2)

Particle physics : Neutrino oscillations
Astrophysics : Still open issues on our Sun

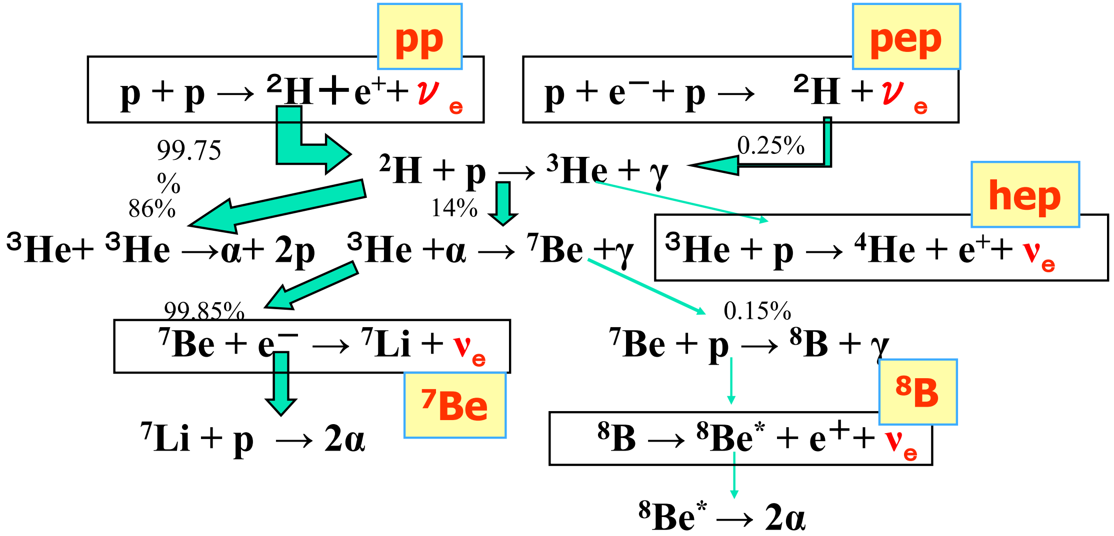
This reaction is actually realized via pp-chain and CNO cycle.

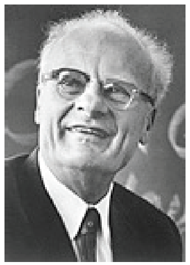
Solar neutrino

W.Fowler

pp-chain

Dominant process in the Sun (~99% of the energy)

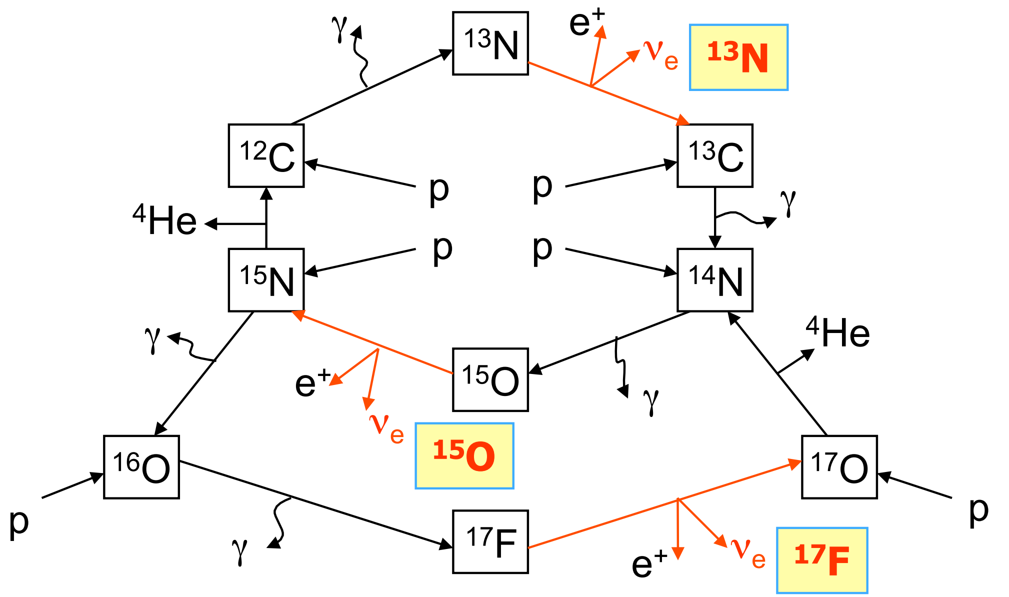




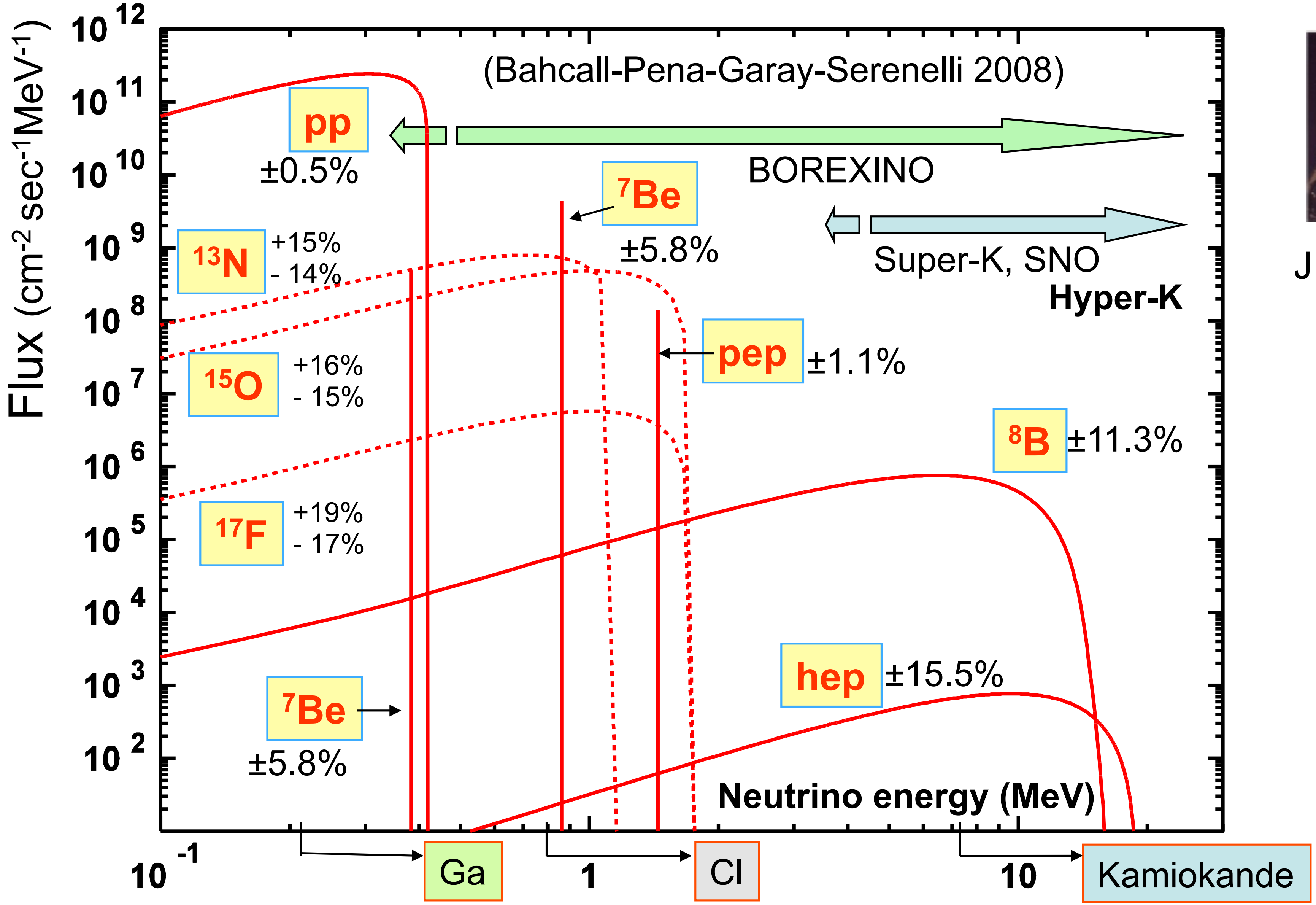
H.A.Bethe

CNO cycle

Small ratio (<1%) in the Sun, poorly know yet



Standard Solar Model

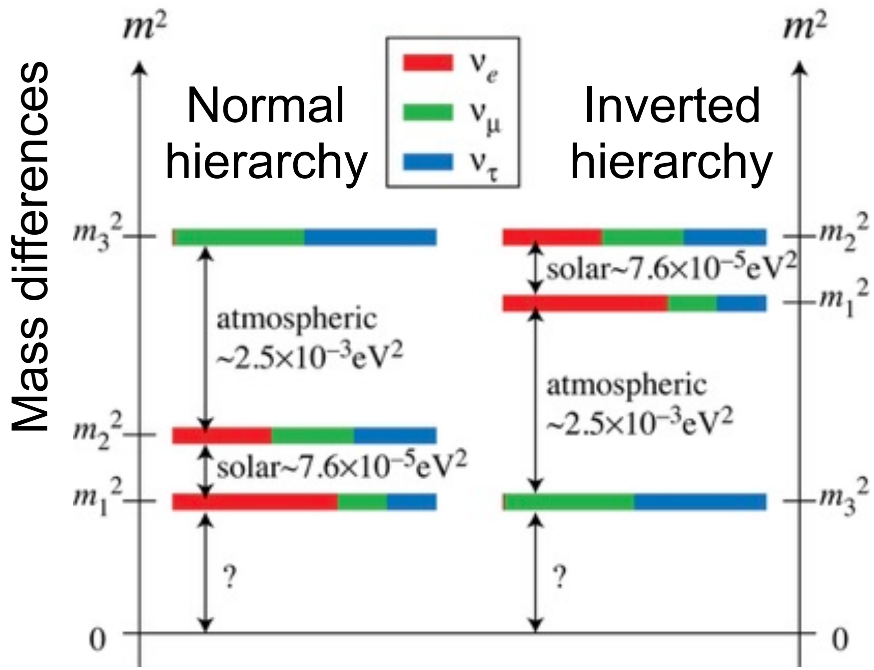


J.N.Bahcall

Solar neutrino in PMNS picture

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{-i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atm. and Acc.	Reactor and Acc.	**Solar** and KamLAND
$\theta_{23}\sim 45\pm 5^\circ$	$\theta_{13}\sim 9^\circ$	$\theta_{12}\sim 34\pm 3^\circ$



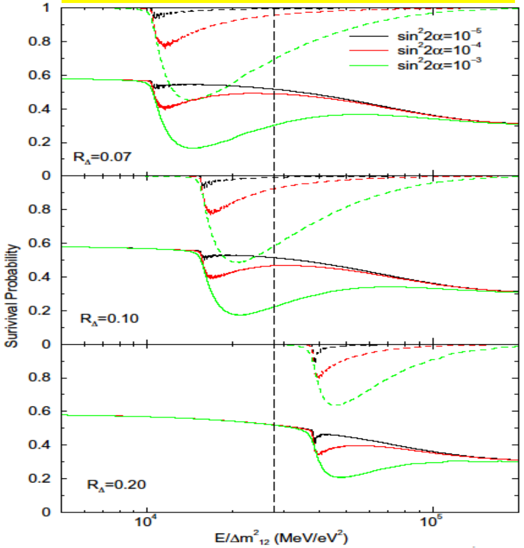
$\Delta m^2_{21} = 7.54$ for KamLAND

$\Delta m^2_{21} = 4.82$ for Solar

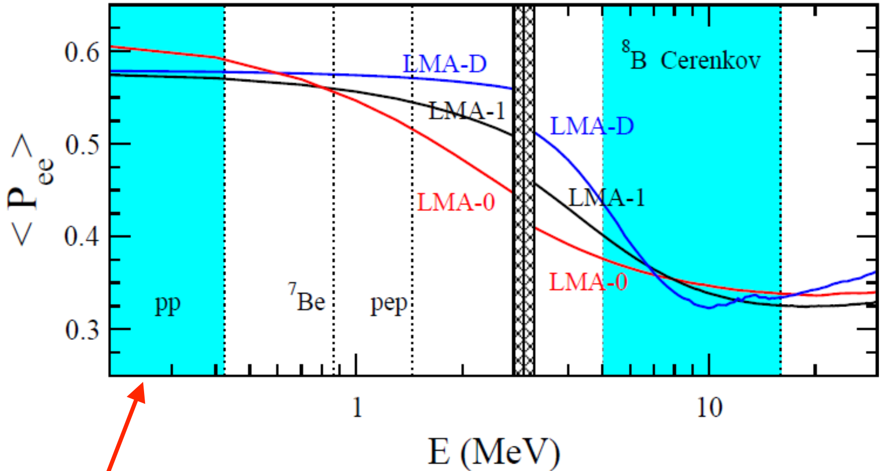
~2σ tension

Spectrum predicted by non-standard models

Sterile neutrino

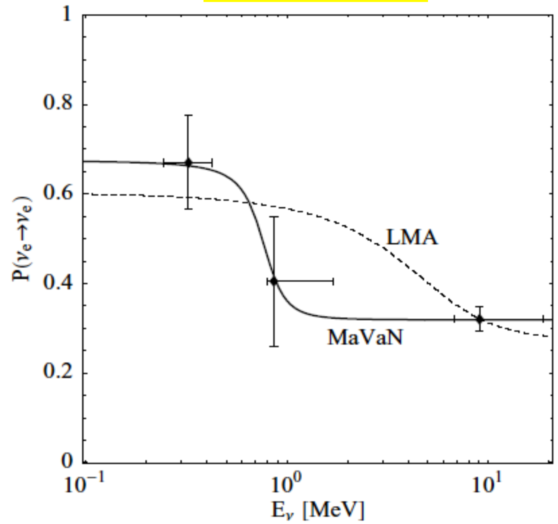


Holanda and Smirnov, Phys.Rev.D69(2004)113002. (hep-ph/0307266)



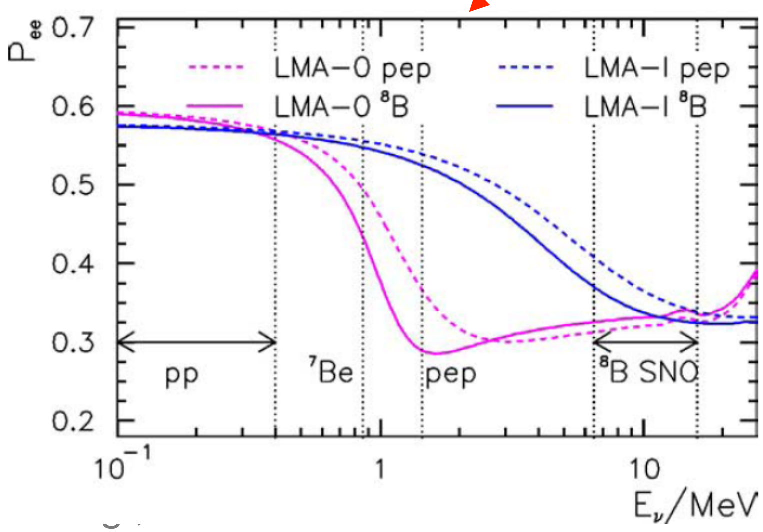
Miranda, Tortola and Valle, JHEP 0610:008,2006. (hep-ph/0406280)

MaVaN

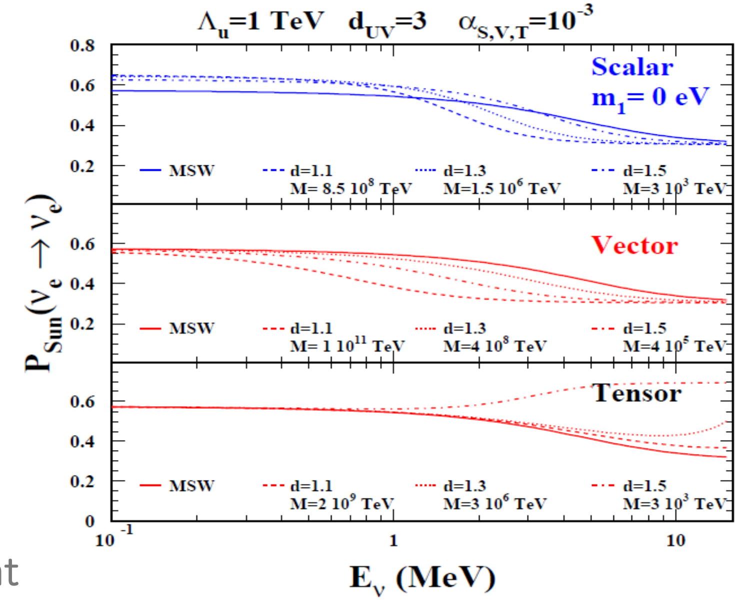


Barger, Huber and Marfatia, Phys.Rev.Lett.95:211802,2005 (hep-ph/0502196)

Non-standard interaction



encont



Unparticle

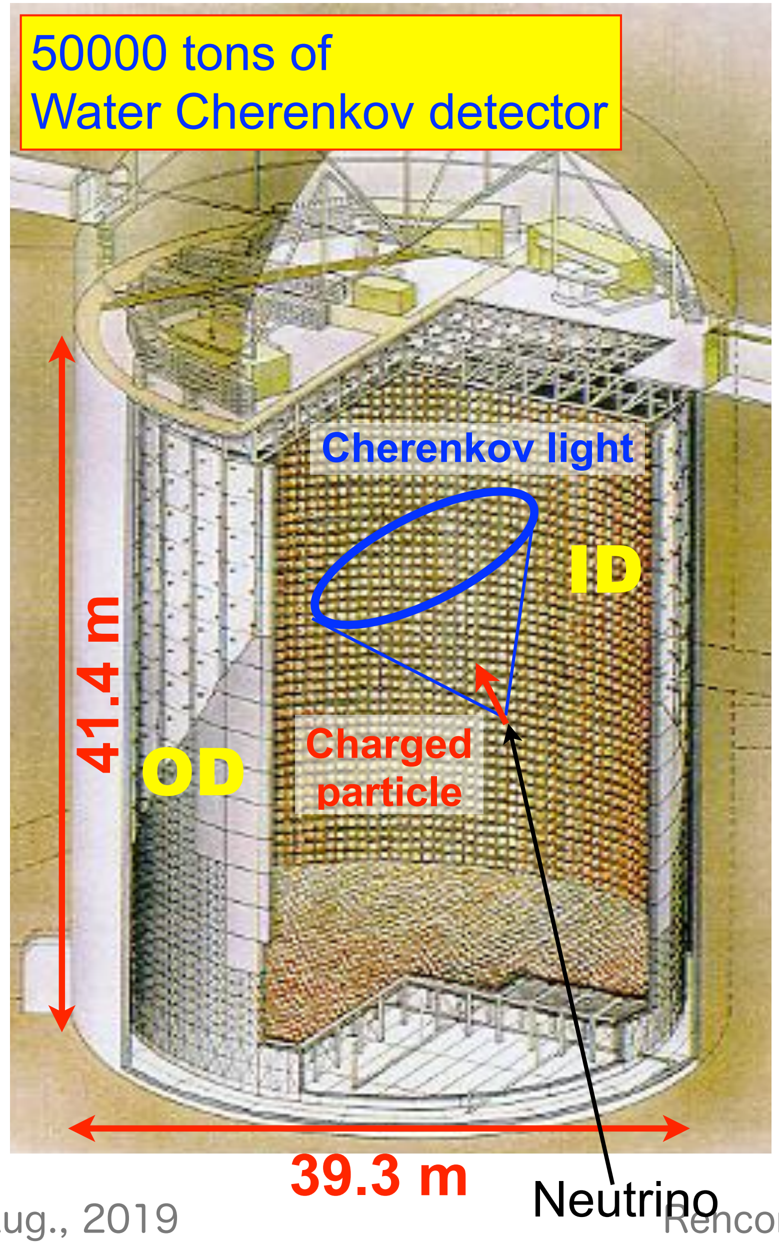
Gonzalez-Garcia,Holanda,Zukanovich ,Funchal, JCAP 0806:019,2008. (hep-ph/0803.1180)

Astrophysics : Metallicity puzzle

Flux (cm^{-2} s^{-1})	GS98 (HZ)	AGSs09met (LZ)	diff. (HZ-LZ)/HZ
pp (10^{10})	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8})	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9})	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6})	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8})	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8})	2.05(1±0.17)	1.44(1±0.16)	29.7%
^{17}F (10^{6})	5.29(1±0.20)	3.261±0.18)	38.3%

Metallicity determines the opacity of the solar plasma,
which affects the central temperature of the sun.

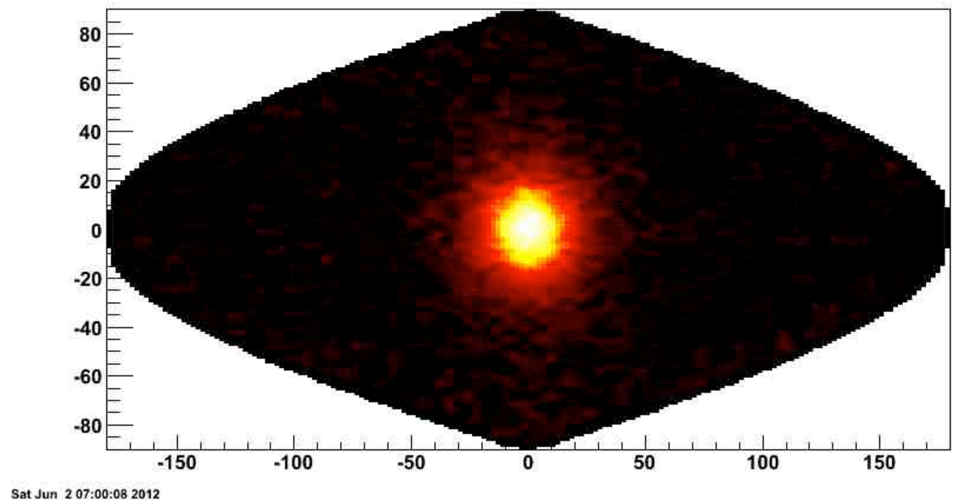
Super-Kamiokande (1996~)



neutrino-electron elastic scattering

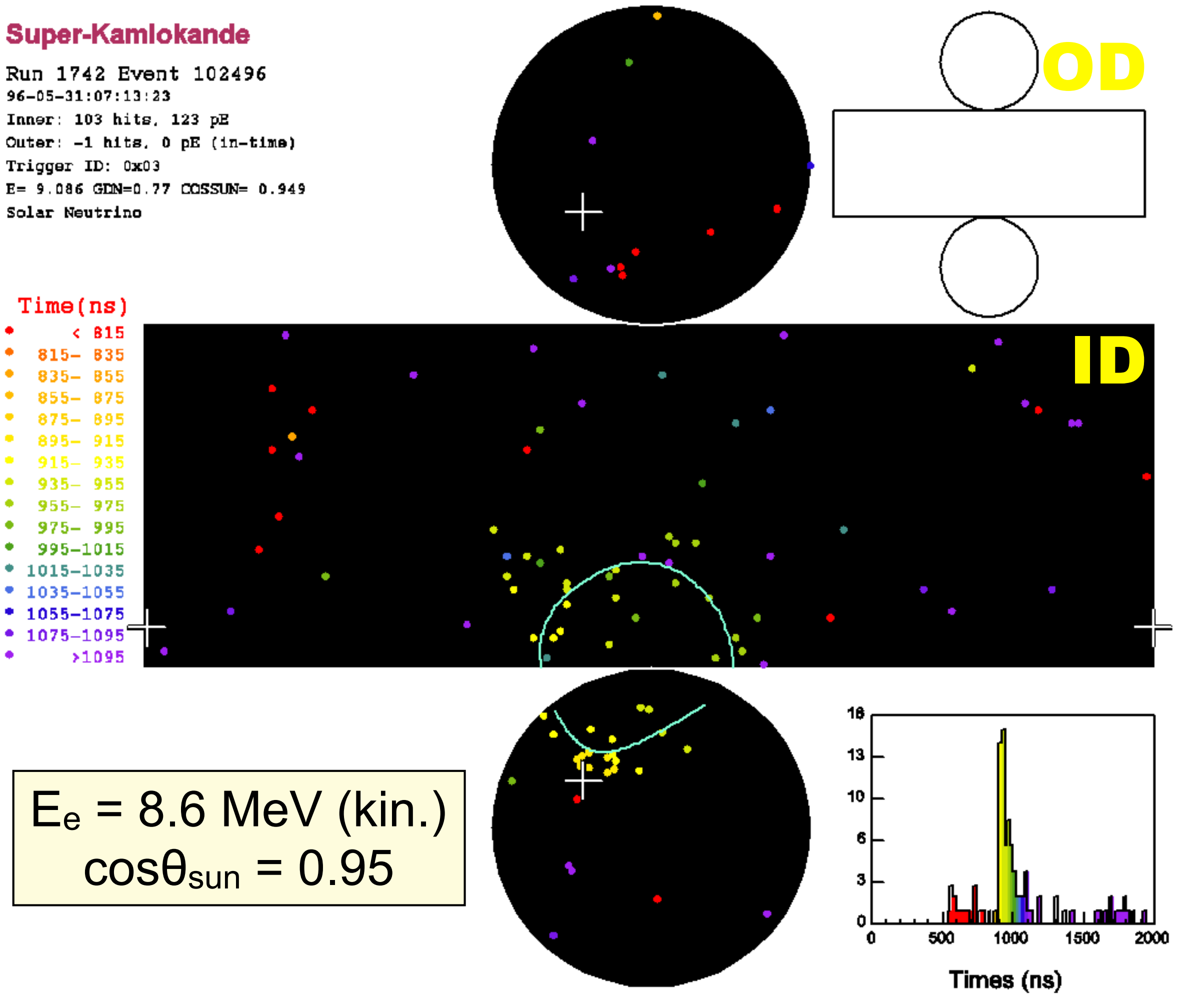
$\nu + e^- \rightarrow \nu + e^-$

✓Find solar direction
✓Realtime measurements
- day-night flux differences
- seasonal variation
✓Energy spectrum



Super-Kamiokande (1996~)

Typical event



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

neutrino-electron elastic scattering

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

- ✓Find solar direction
- ✓Realtime measurements
  - day-night flux differences
  - seasonal variation
- ✓Energy spectrum

Detector performance

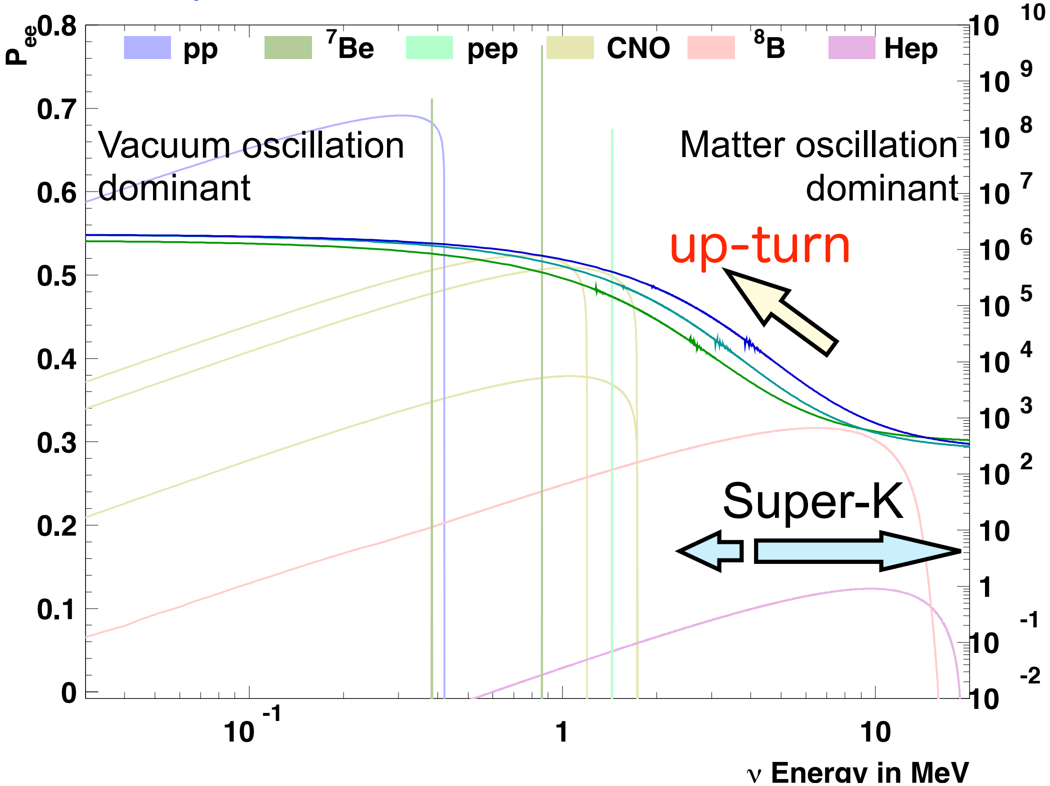
	resolution (10 MeV)	information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

~ 6 hits/MeV
well calibrated by LINAC and DT within 0.5% precision

Motivation of the measurement

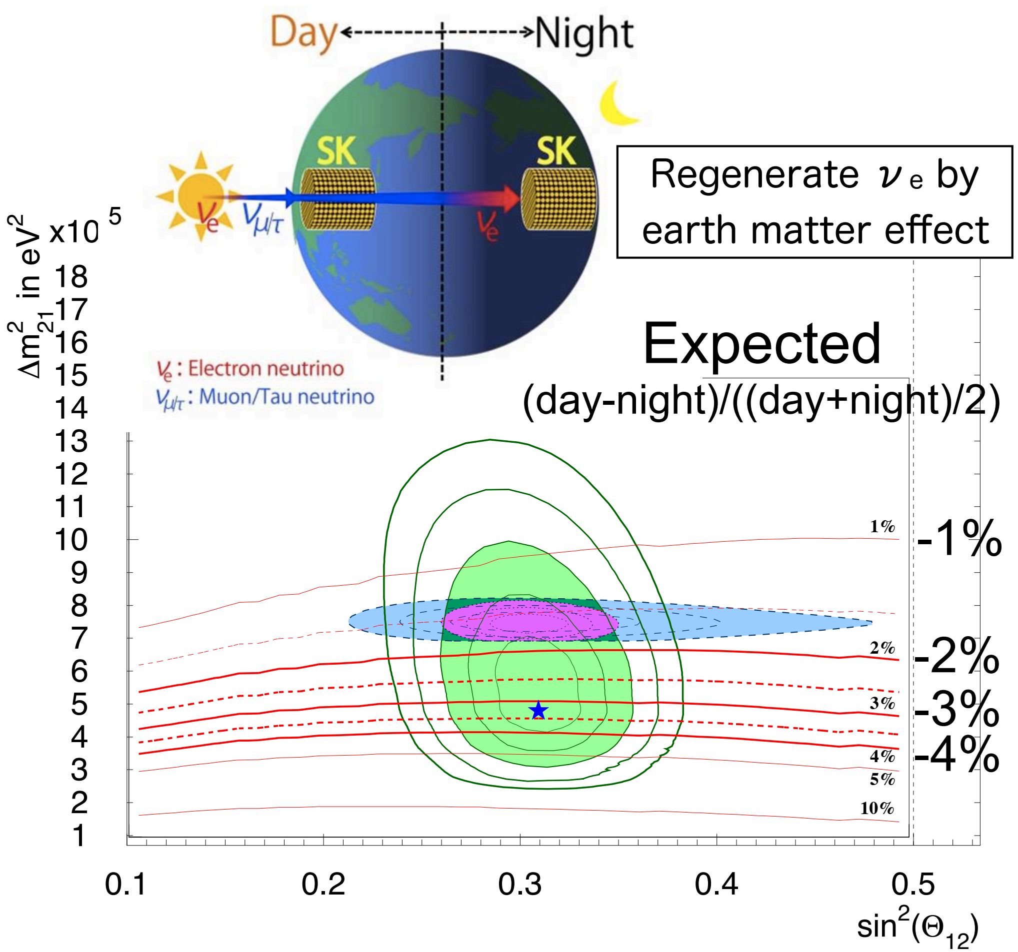
See the neutrino oscillation MSW effect directly

Spectrum distortion



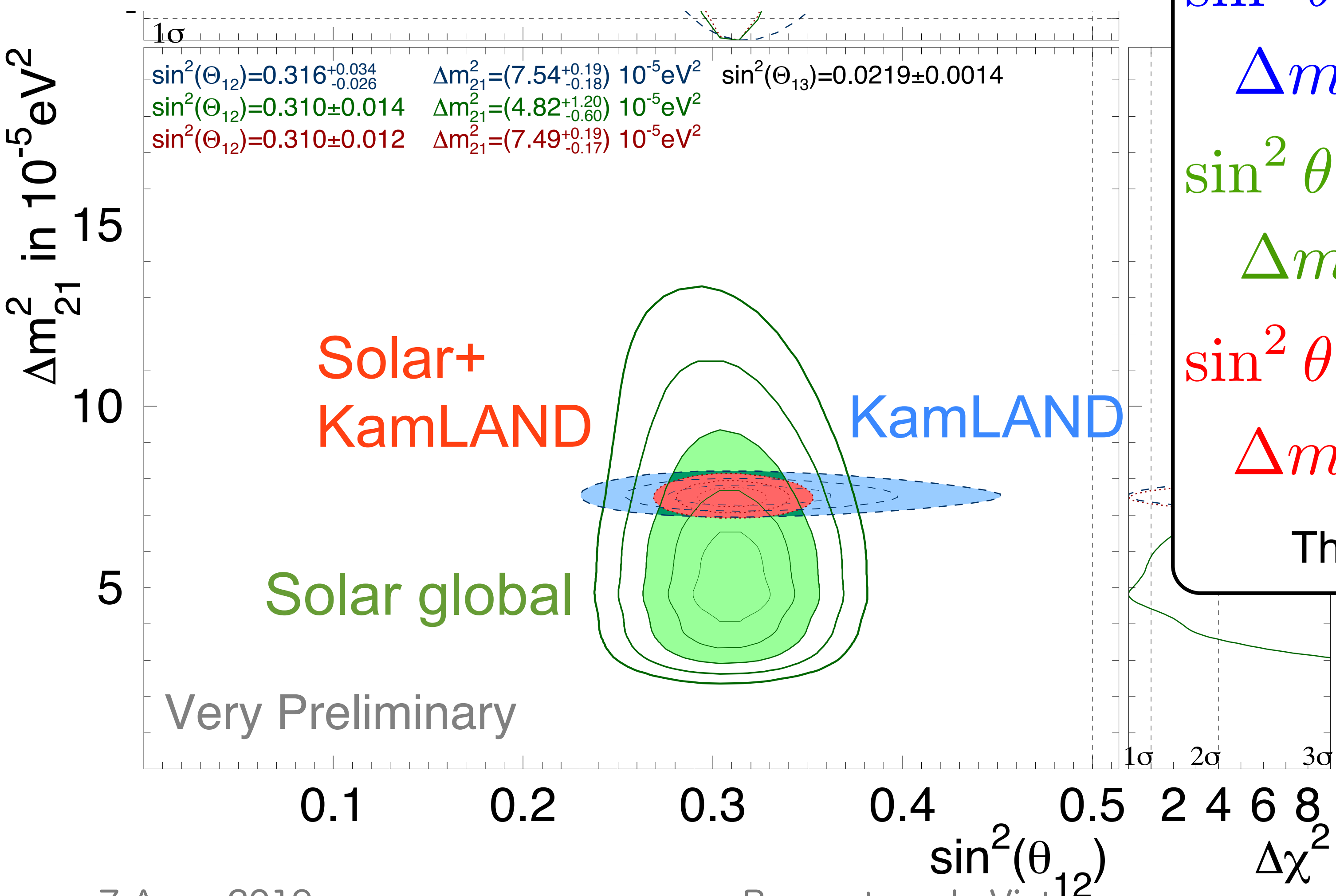
Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



Neutrino oscillation

~2σ tension between solar global and KamLAND in Δm^2_{21}



$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.310 \pm 0.014$$
$$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60}$$
$$\sin^2\theta_{12} = 0.310 \pm 0.012$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

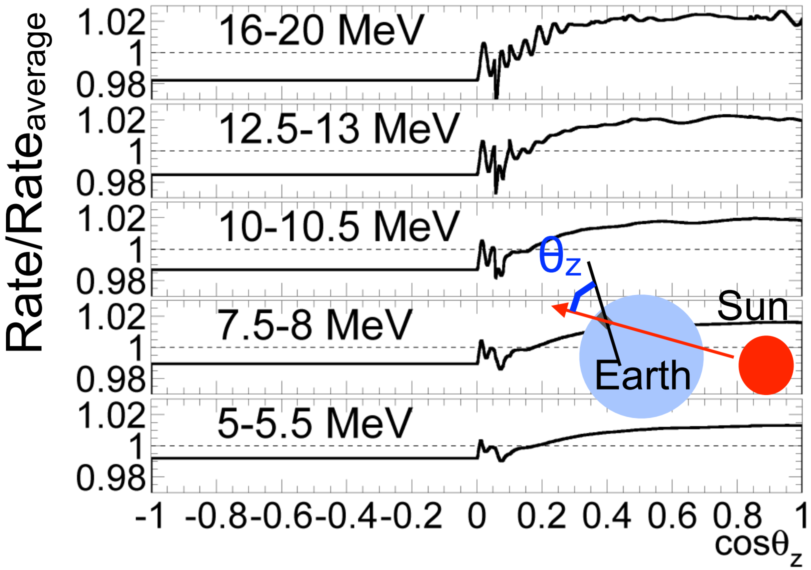
$\sin^2\theta_{13} = 0.0219 \pm 0.0014$

M. Ikeda, Neutrino 2018

DOI: 10.5281/zenodo.1286857

Day/Night asymmetry

expected time variation as a function of $\cos\theta_z$



PRD94, 052010 (2016)

Day/Night Amplitude was fitted to

-3.3±1.0±0.5%

$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2

$\sin^2\theta_{12}=0.311$

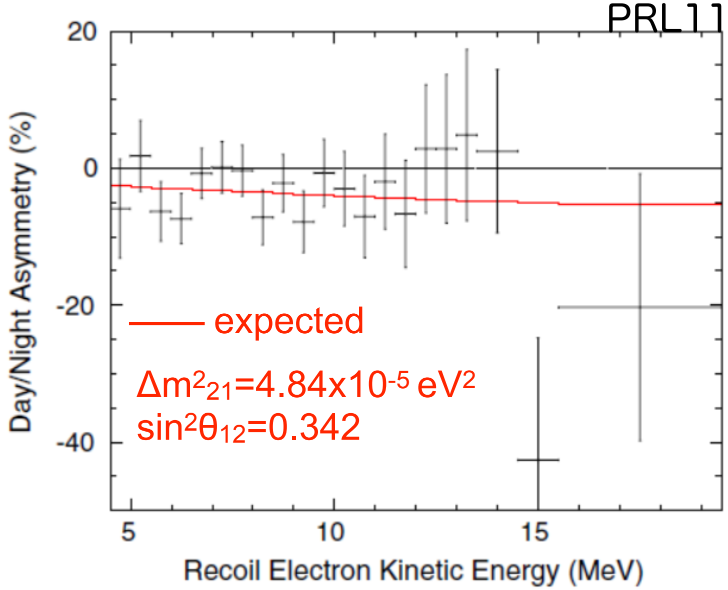
$\sin^2\theta_{13}=0.025$

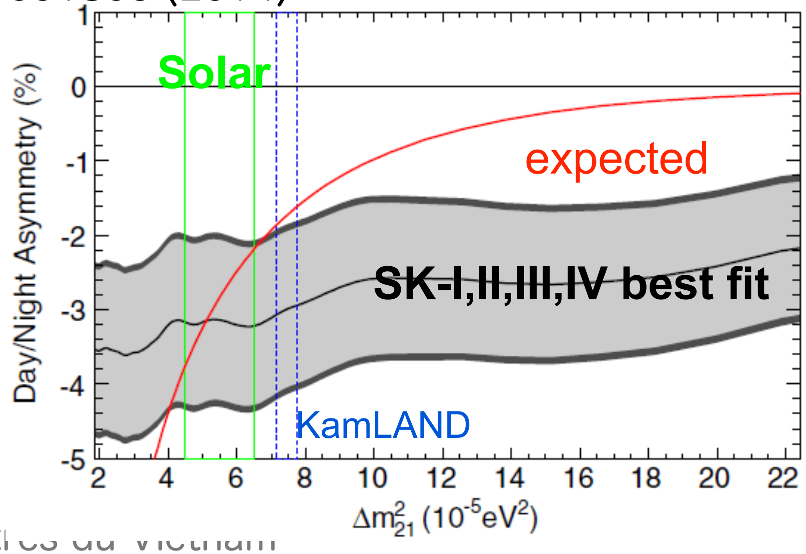
Non-zero significance was

2.9 σ

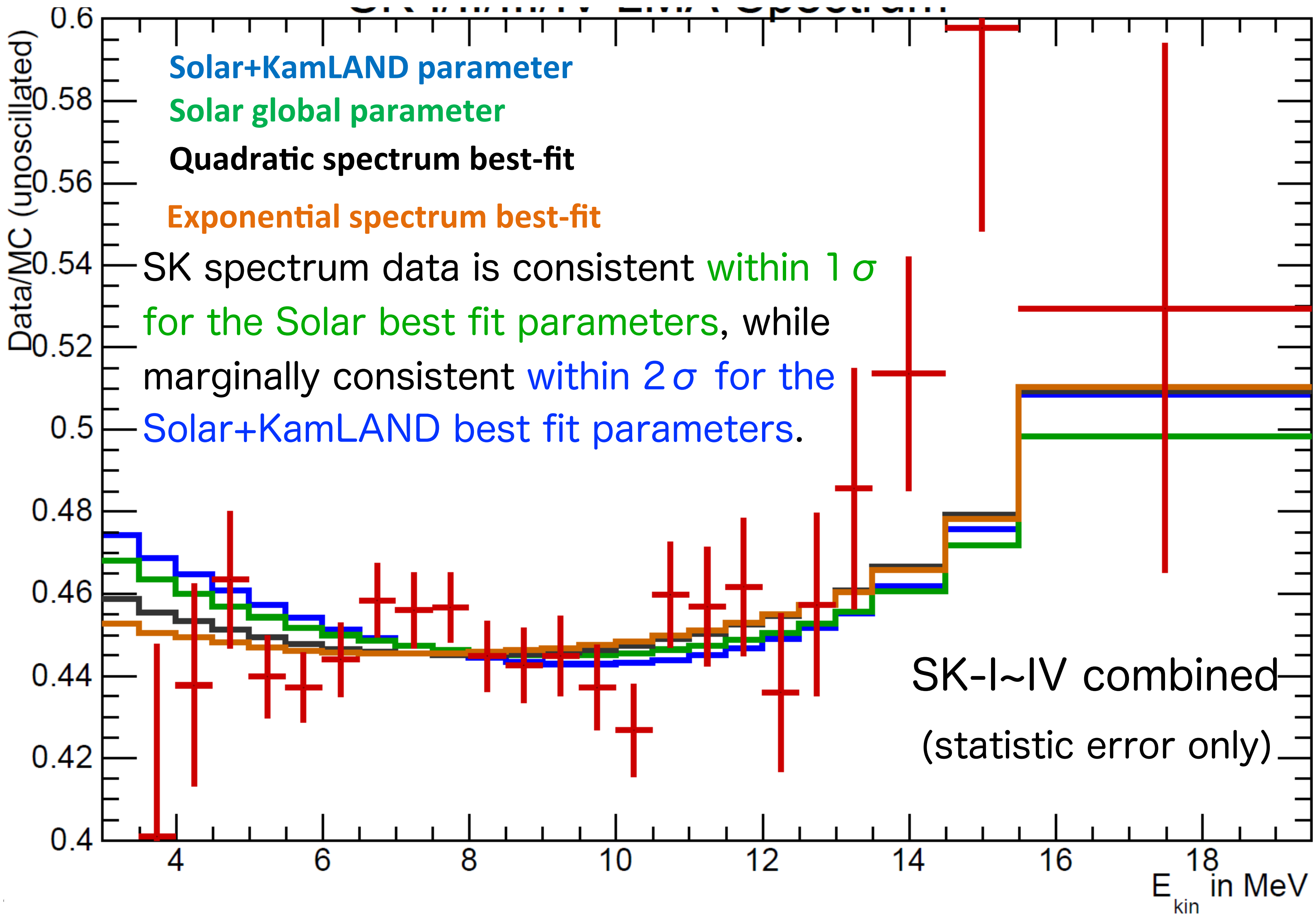
in SK-I to IV (4499 days)

PRL112, 091805 (2014)





Recoil electron spectrum



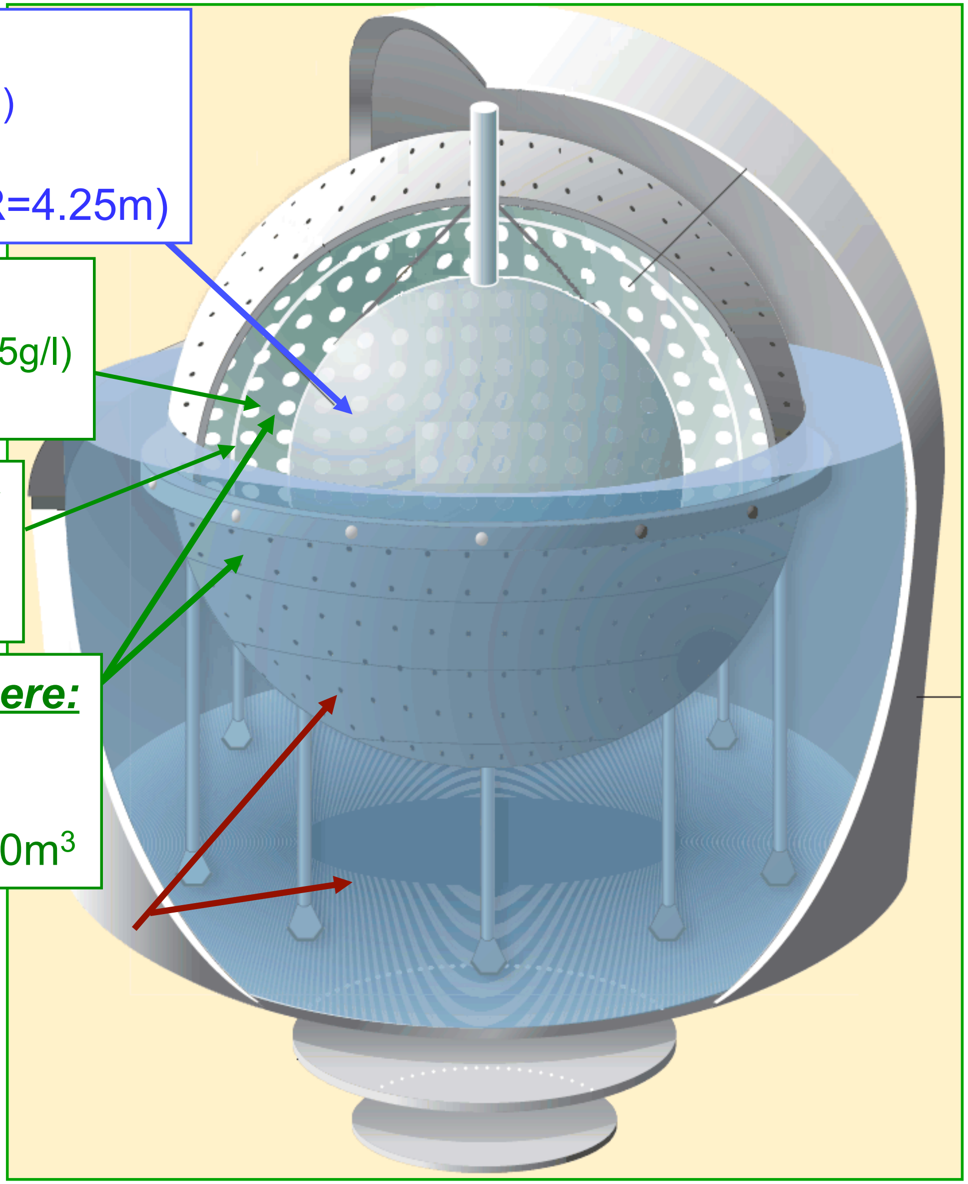
BOREXINO (2007~)

Liquid scintillator:
270 t PC+PPO (1.5g/l)
in a 150μm thick
Inner nylon vessel (R=4.25m)

Buffer region:
PC+DMP quencher (5g/l)
4.25m<R<6.75m

Outer nylon vessel:
R=5.50m
(^{222}Rn Barrier)

Stainless Steel Sphere:
R=6.75m
2212 8” PMTs with
light guide cone. 1350m^3



Experimental target :

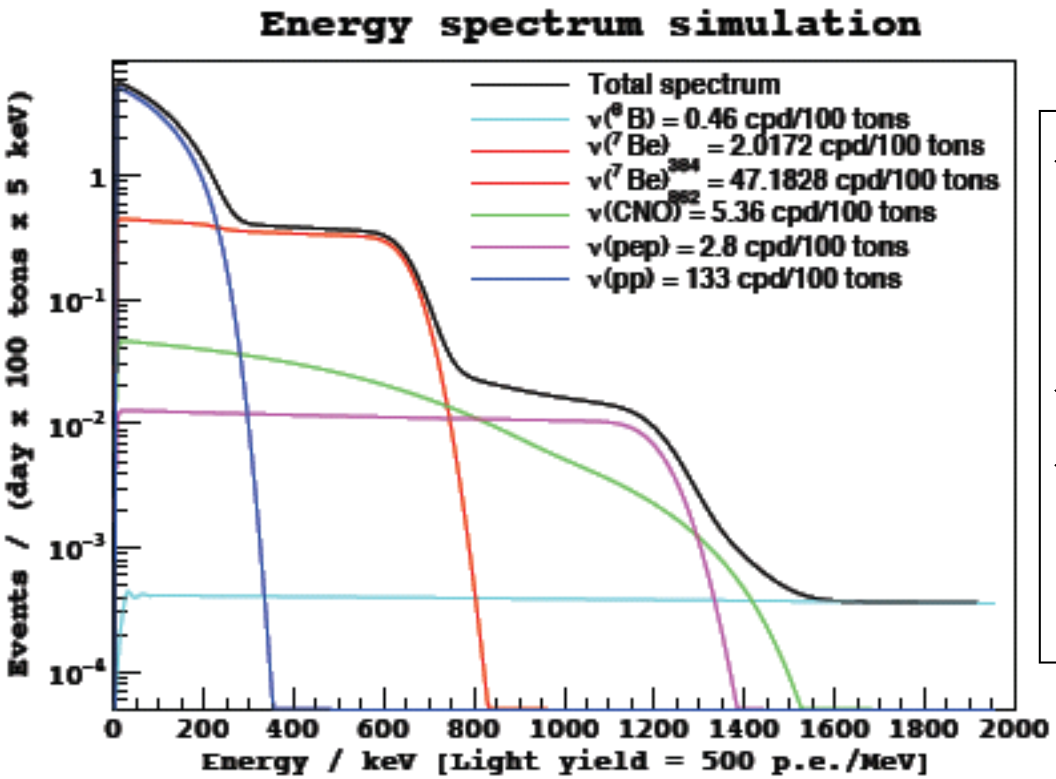
- Solar Neutrinos

The wide energy range in real time are measurable.

- Geo Neutrinos
- SuperNova neutrinos
- Long/Short base line neutrinos
- etc…

Solar neutrinos in BOREXINO

Detection principle



Elastic scattering (ES)

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

✓High light yield (~500p.e./MeV)
- lowering energy threshold
- good energy resolution

✓Realtime measurements

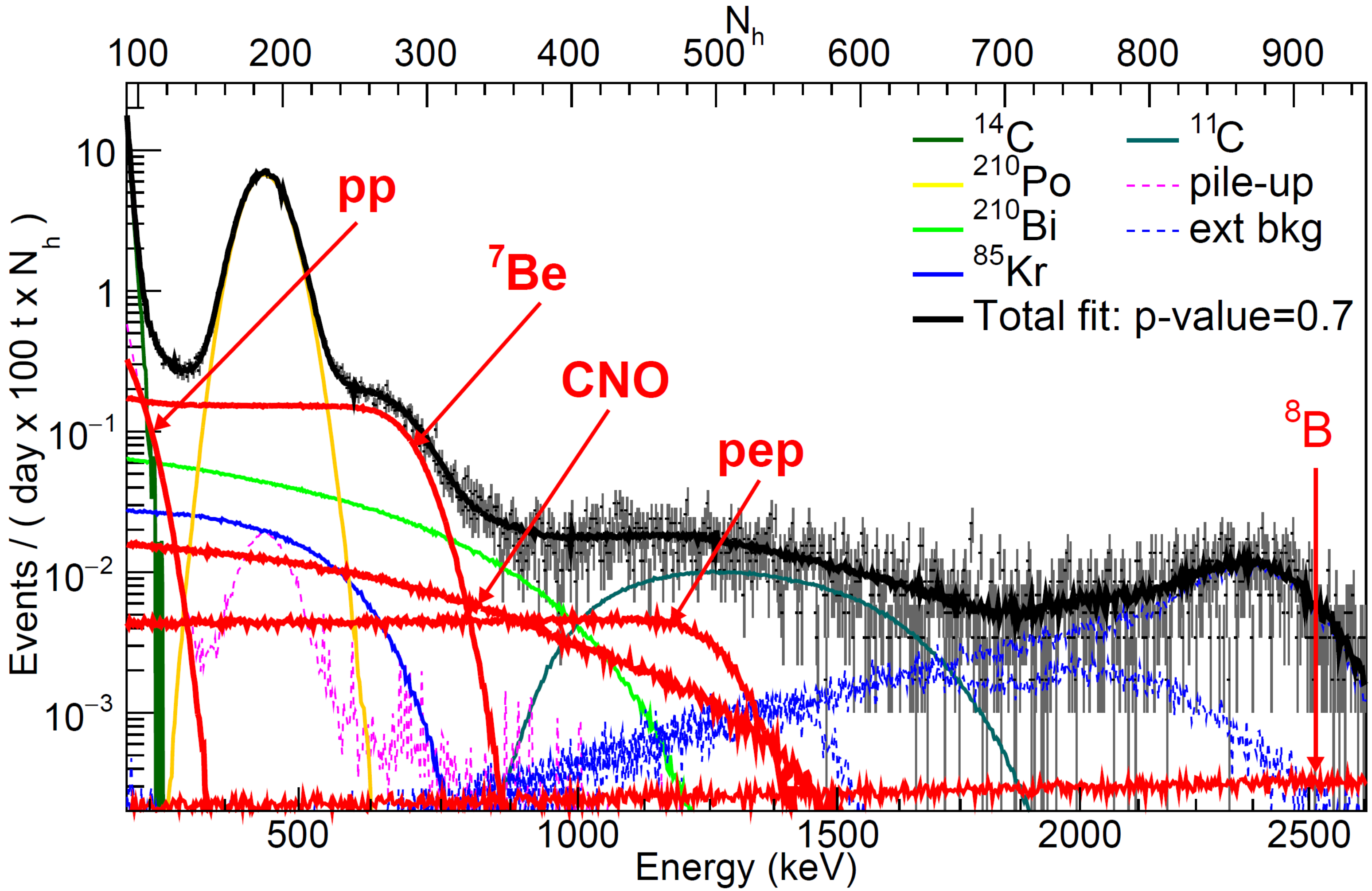
✓No neutrino directional inf.
- background reduction and understanding are critical

Radiopurity is crucial

Recent results in BOREXINO

B. Caccianiga, DOI : 10.5281/zenodo.2672266

Energy spectrum (TFC subtracted)



Recent results in BOREXINO

B. Caccianiga, DOI : 10.5281/zenodo.2672266

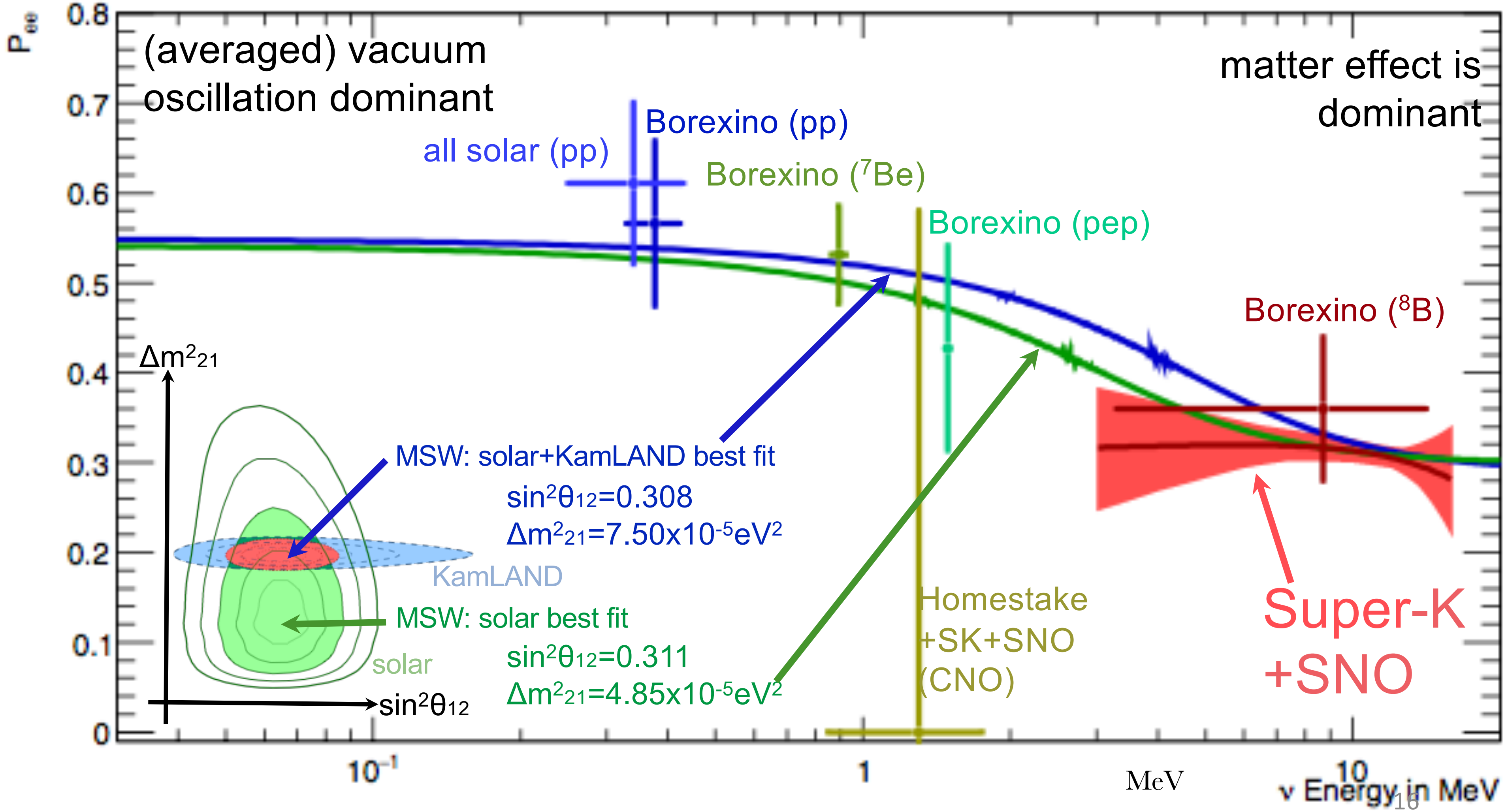
Solar ν	Borexino results Rate [cpd/100 t]
pp	$134 \pm 10\ ^{+6}_{-10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$

total uncertainties 2.7%

5σ evidence

Solar ν	Borexino results Flux [cm^{-2}s^{-1}]	Expected-HZ Flux [cm^{-2}s^{-1}]	Expected-LZ Flux [cm^{-2}s^{-1}]
pp	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	$5.98\,(1 \pm 0.006) \times 10^{10}$	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	$4.93\,(1 \pm 0.06) \times 10^{9}$	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	$1.44\,(1 \pm 0.009) \times 10^{8}$	$1.46\,(1 \pm 0.009) \times 10^{8}$

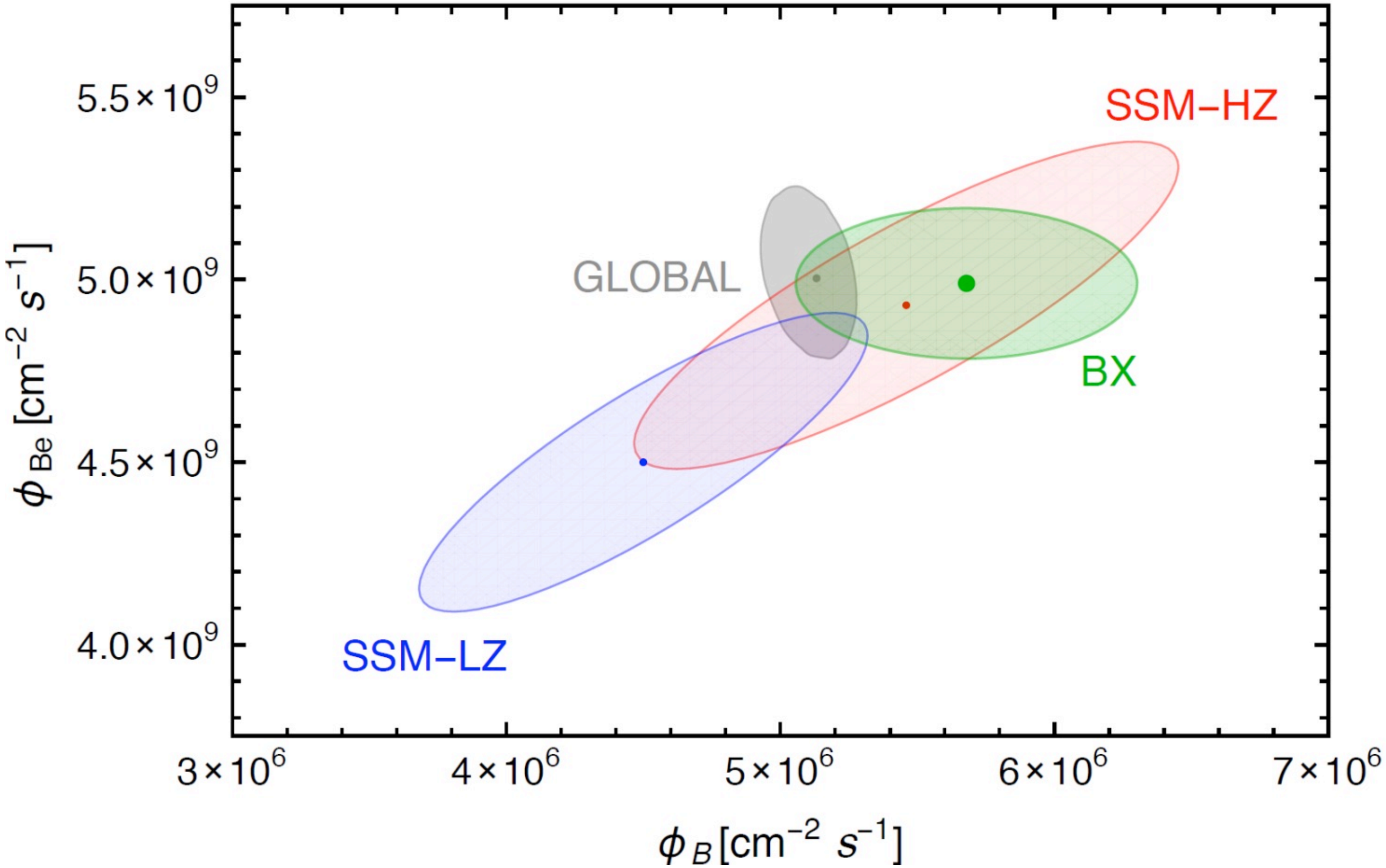
Survival probability



M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857

Metallicity puzzle

B. Caccianiga, DOI : 10.5281/zenodo.2672266

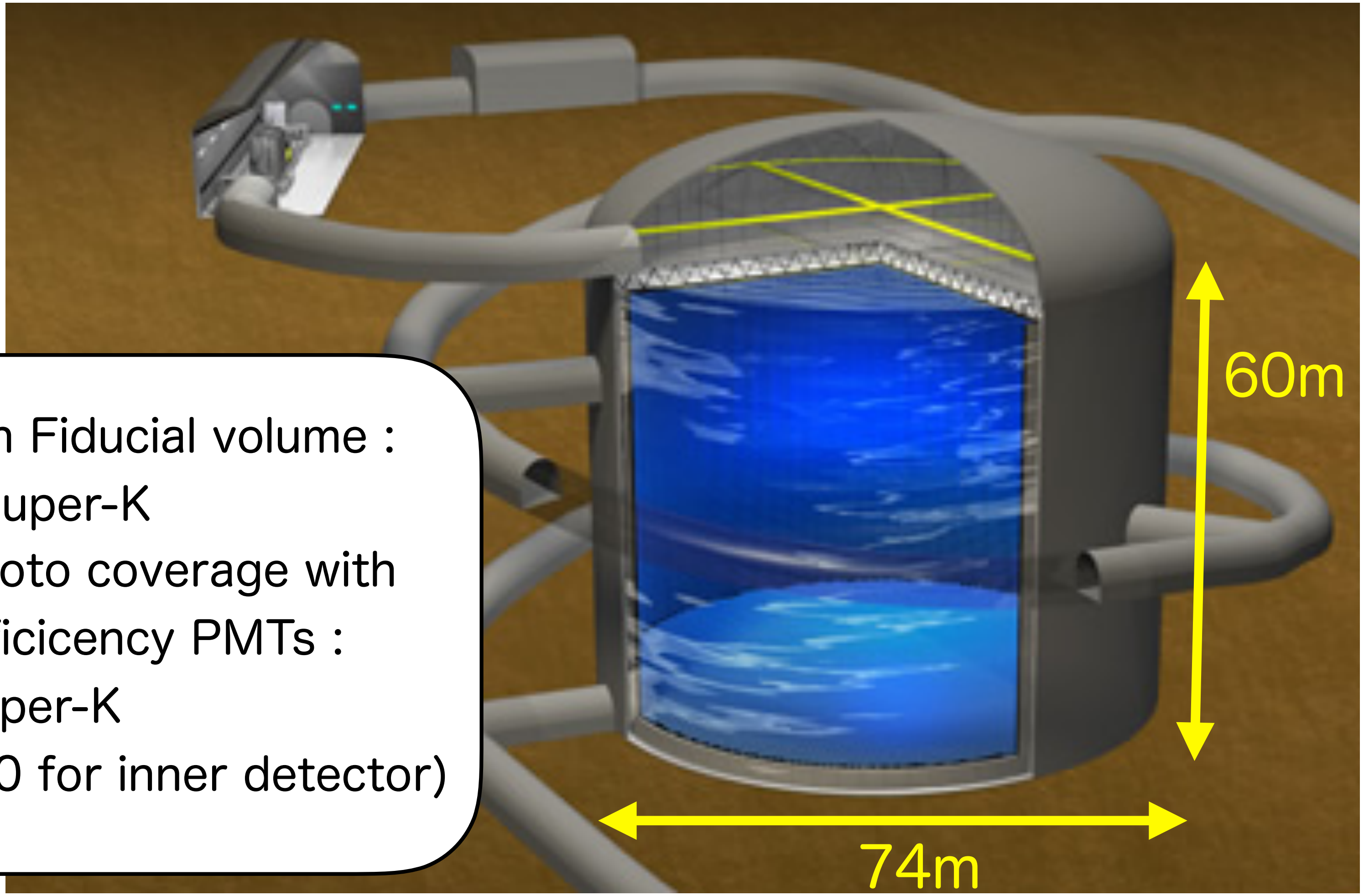


BX results seem to give a hint towards the HZ hypothesis in spite of the large theoretical error

Hyper-Kamiokande

(See also “Hyper-Kamiokande Design Report”, arXiv : 1805.04163)

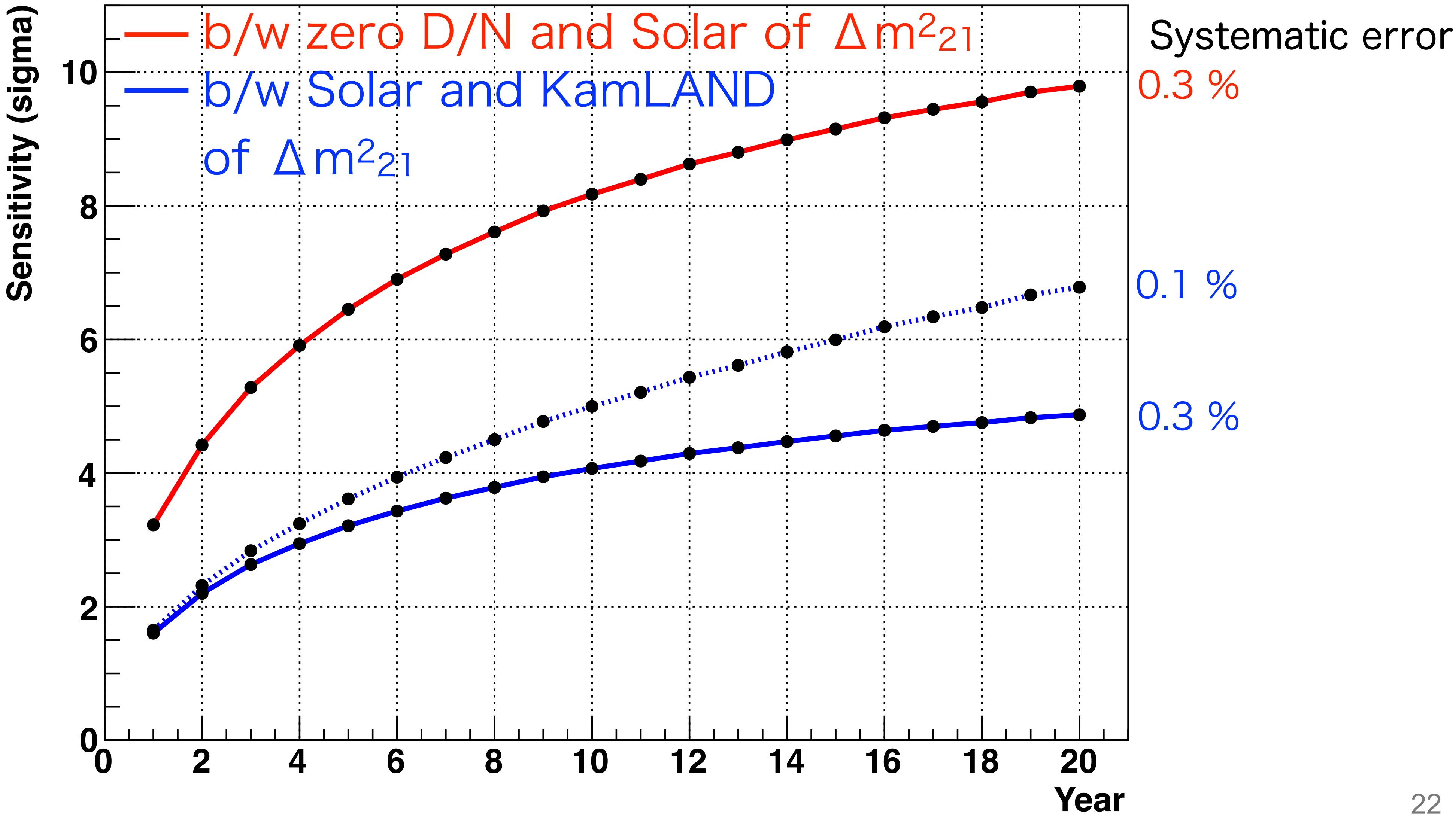
Next generation of large water Cherenkov detector
(~2027 -)



- 190kton Fiducial volume :
  ~10 x Super-K
- 40% photo coverage with
  high-efficicency PMTs :
  ~2 x Super-K
  (~40000 for inner detector)

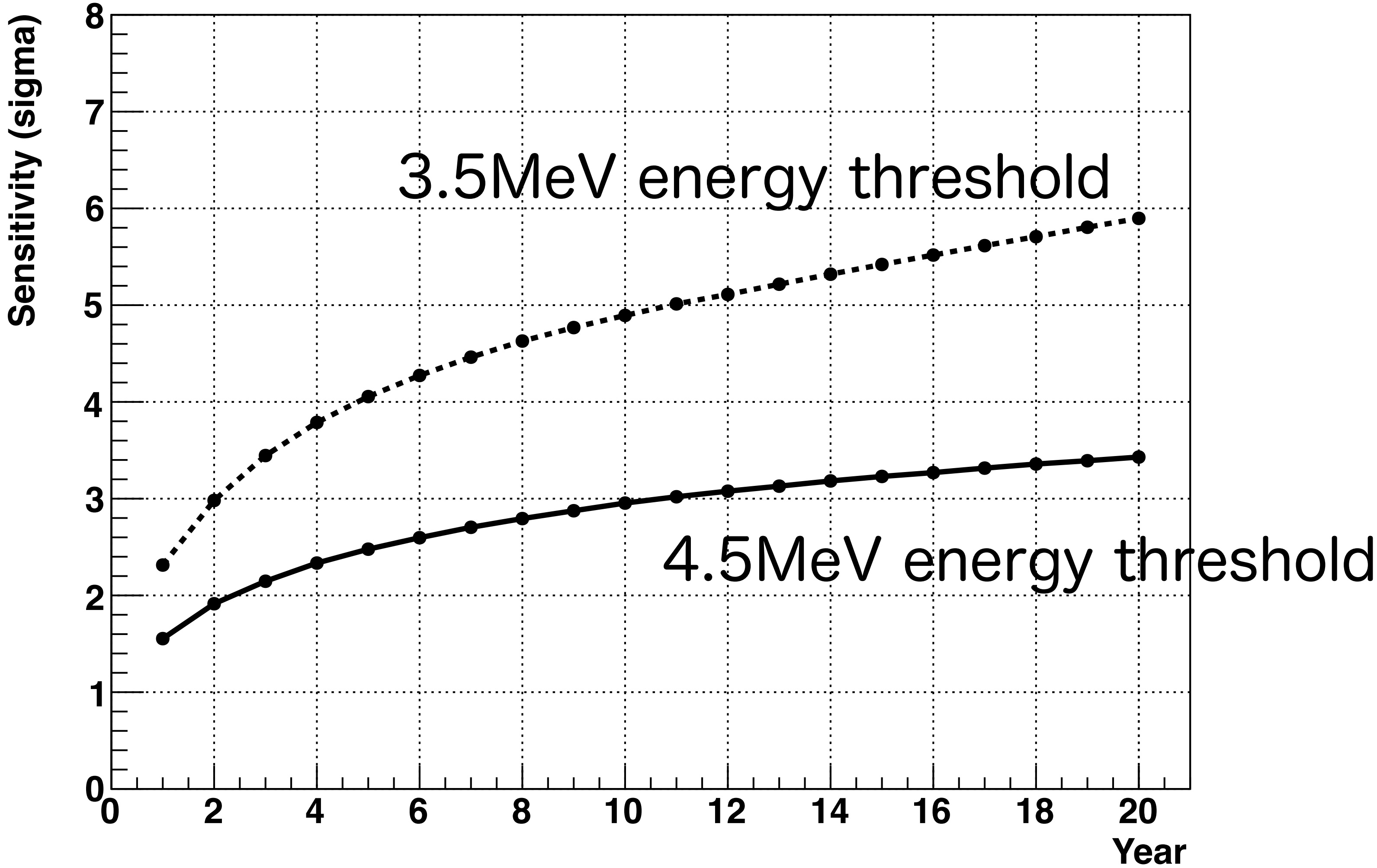
Solar neutrinos in Hyper-K

Sensitivity of Day/Night flux asymmetry



Solar neutrinos in Hyper-K

Sensitivity of spectrum upturn



Summary

- Solar neutrino experiments are important for both particle physics and astrophysics.
- Current running detectors of solar neutrino experiment are Super-Kamiokande and Borexino.
  - Indication of Day-Night asymmetry has been found in Super-K at 3σ level.
  - Precise measurements of pp, ^{7}Be, pep has succeeded in Borexino. Metallicity puzzle is still remaining.
  - 2σ tension between solar and KamLAND Δm_{21}^2 is seen. Future experiments, Hyper-K, JUNO, DUNE etc., are possible to solve this problem.