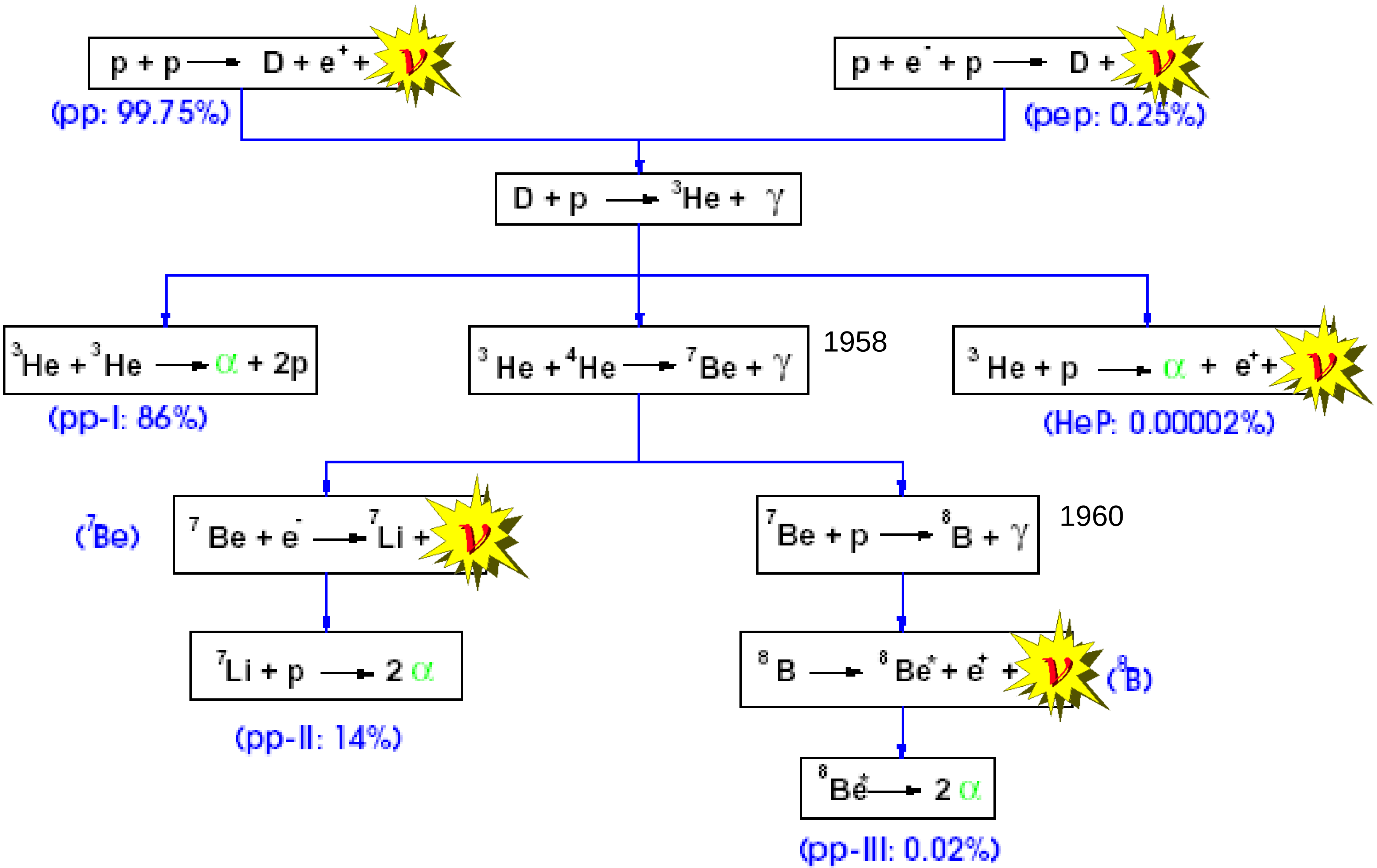
Solar and geo-neutrinos: current status and future directions

Oleg Smirnov,

JINR, Dubna

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
41st Course
Erice-Sicily: September 16-24, 2019

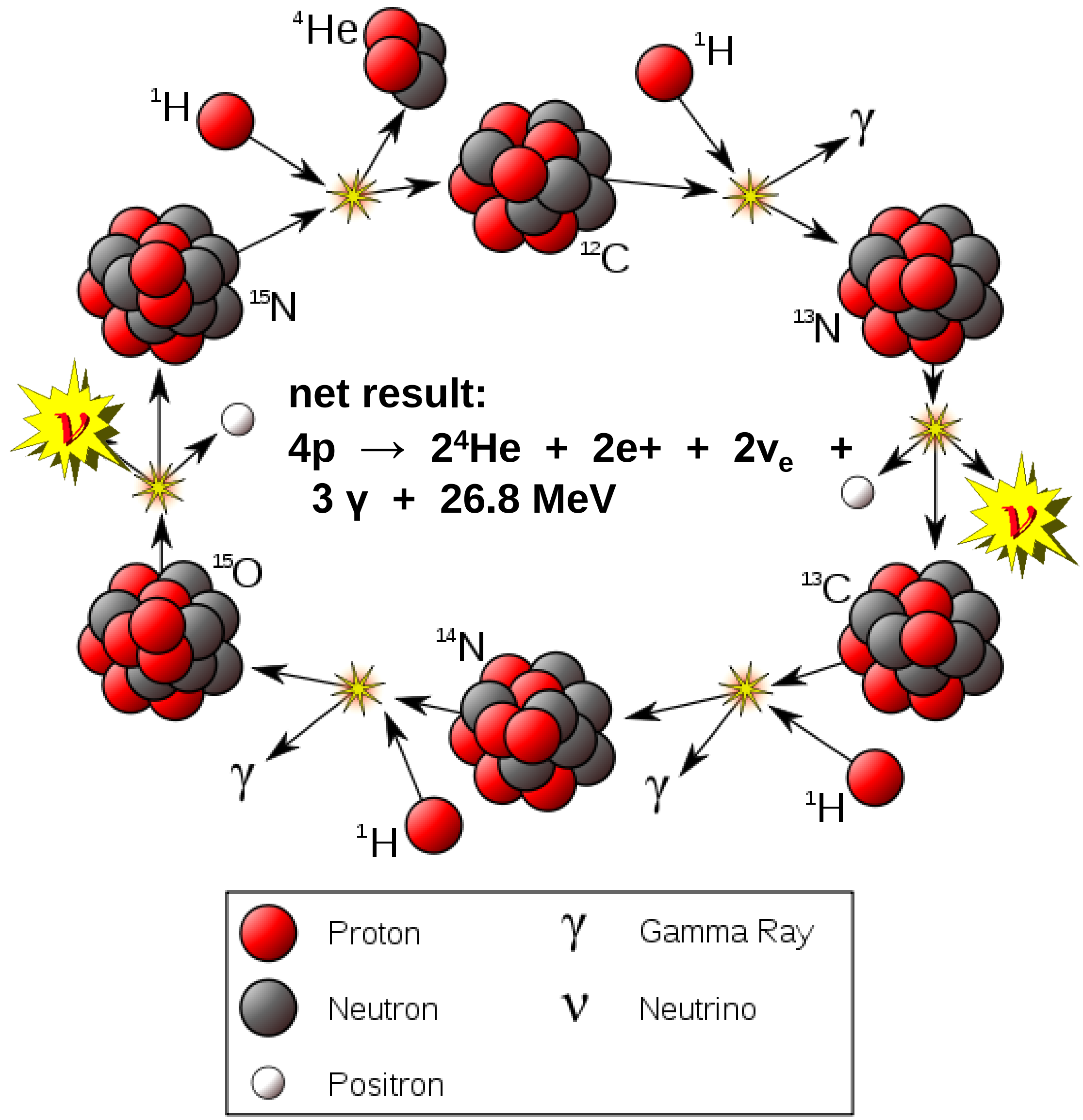
pp - chain


p + p → D + e⁺ + ν
(pp: 99.75%)
p + e⁻ + p → D + ν
(pep: 0.25%)
D + p → ³He + γ
³He + ³He → α + 2p
(pp-I: 86%)
³He + ⁴He → ⁷Be + γ
1958
³He + p → α + e⁺ + ν
(HeP: 0.00002%)
(⁷Be)
⁷Be + e⁻ → ⁷Li + ν
⁷Be + p → ⁸B + γ
1960
⁷Li + p → 2 α
(pp-II: 14%)
⁸B → ⁸Be* + e⁺ + ν
(⁸B)
⁸Be* → 2 α
(pp-III: 0.02%)

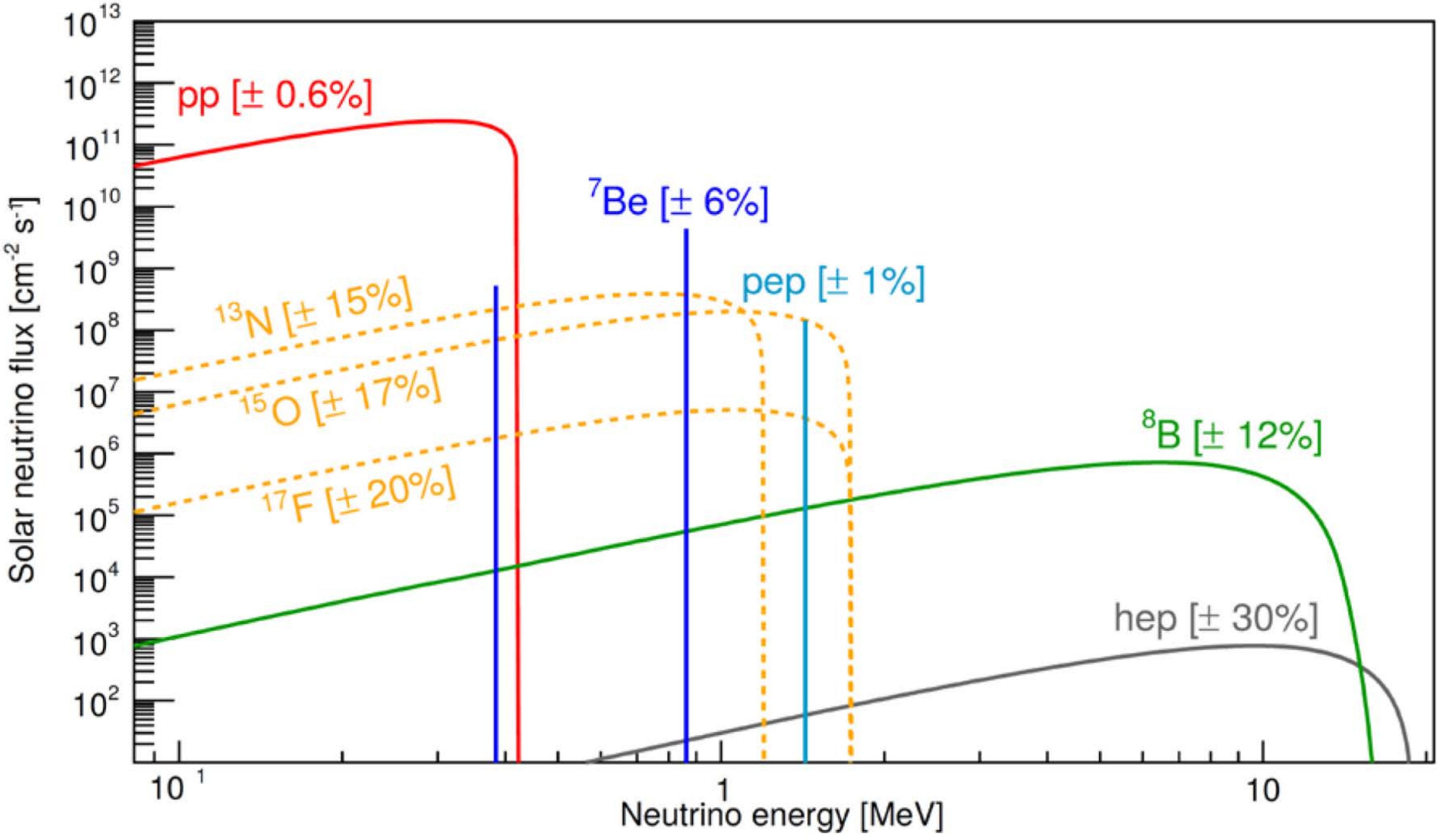
CNO-cycle

The CNO cycle (carbon-nitrogen-oxygen) is a catalytic cycle. CNO cycle dominates in stars more massive than about 1.3 times the mass of the Sun. pp-chain reactions start occurring at temperatures around 4×10^6K. A self-maintaining CNO chain starts at ~15×10^6 K, but its energy output rises much more rapidly with increasing temperatures and at ~ 17×10^6 K, the CNO cycle becomes dominant. The Sun has a core temperature of around 15.7×10^6 K and only 1.7% of He-4 nuclei being produced in the Sun are born in the CNO cycle.

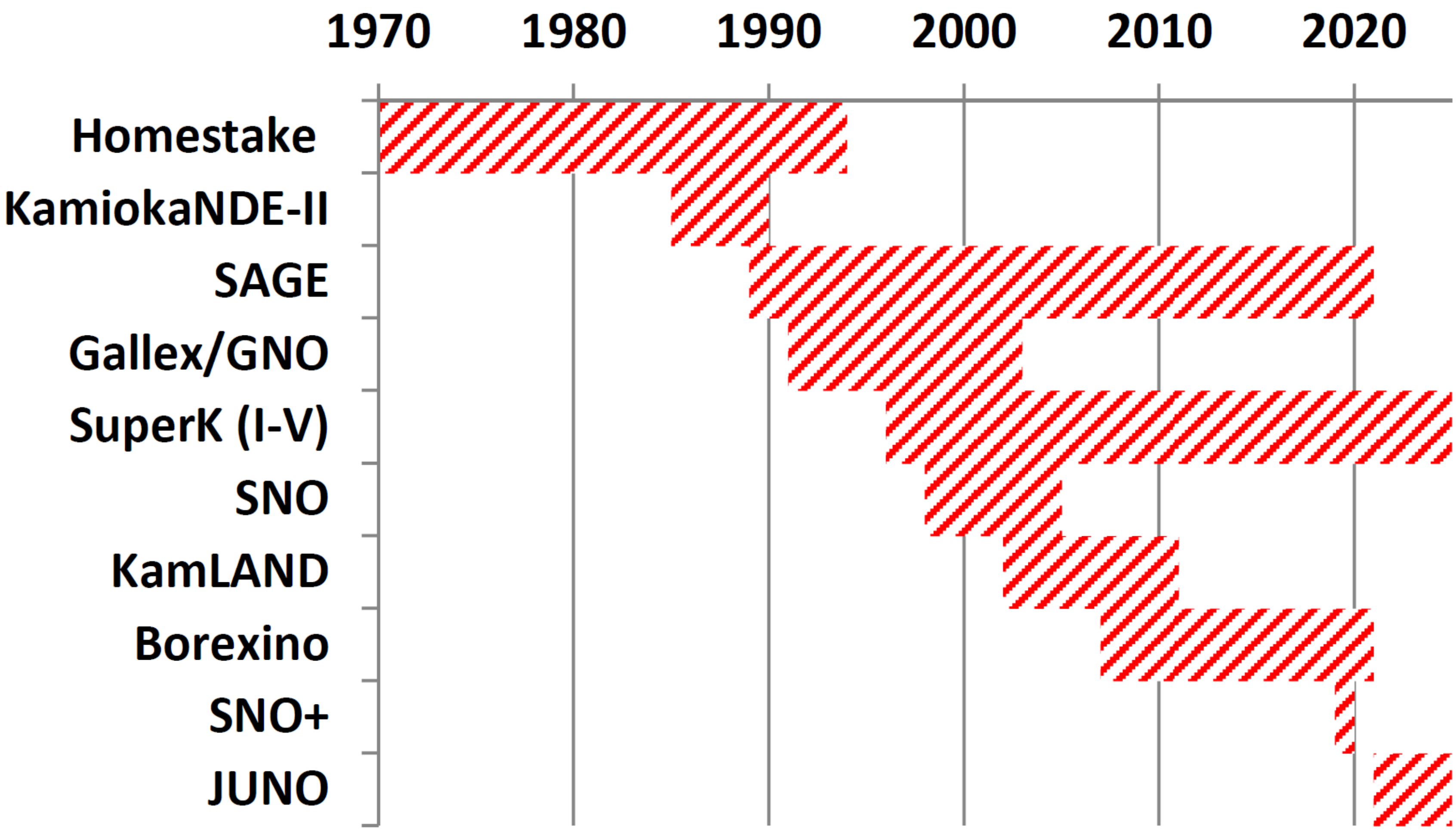
The simplest CN-cycle (CNO-I, or Bethe cycle or carbon cycle) was proposed by Hans Bethe in 1938 and, independently, in 1939 by Carl Friedrich von Weizsäcker).



Solar neutrino spectra



Solar neutrino experiments



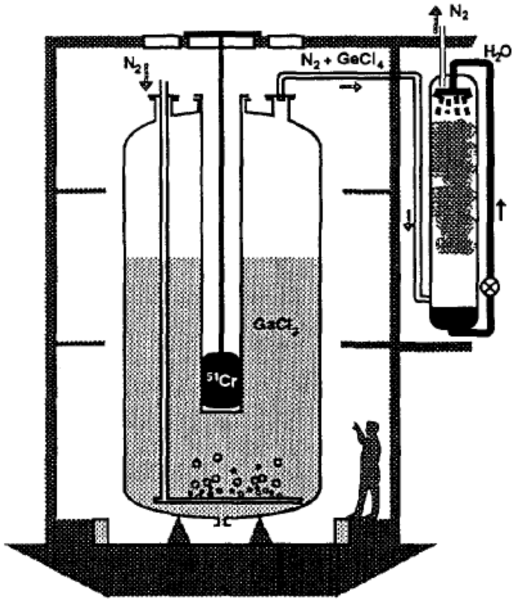
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Homestake

Gallex/GNO

SAGE



600 t perchloroethylene (C_2Cl_4)
1.5 km underground.

GaCl : 30 t

GaCl (metal) : 50-57 t

2.56 ± 0.23 SNU

~30% of SSM

Gallex+GNO+SAGE 66.1 ± 3.1 SNU

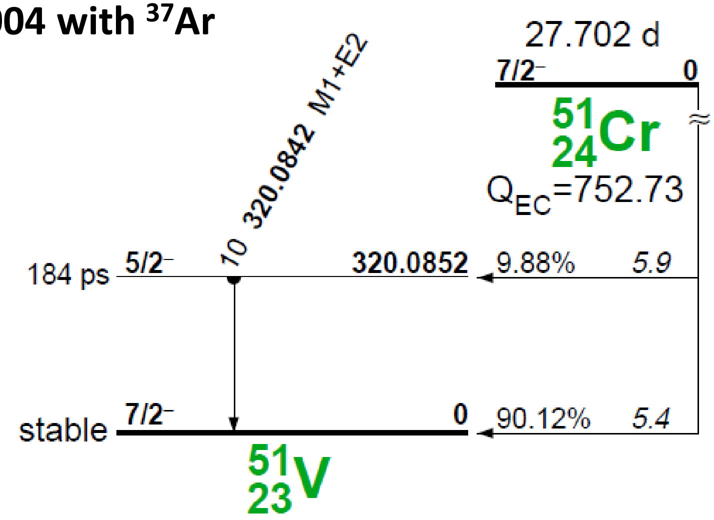
~50% of SSM

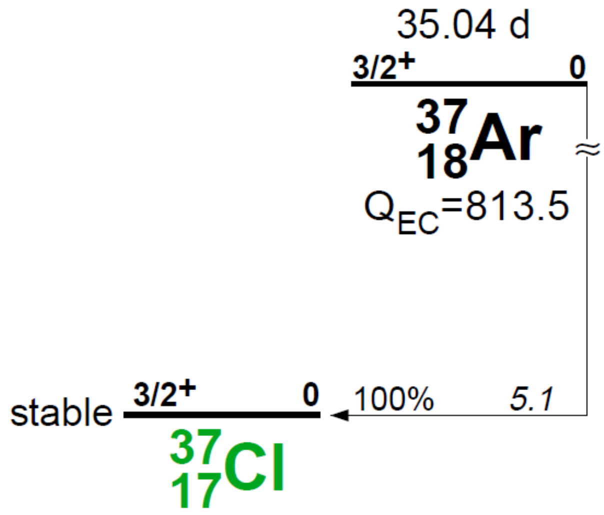
Solar Neutrino Unit, SNU= 1 event per 10^{36} target atoms in 1 second

Calibration with artificial neutrino sources

SAGE and Gallex were calibrated using neutrino source ^{51}Cr

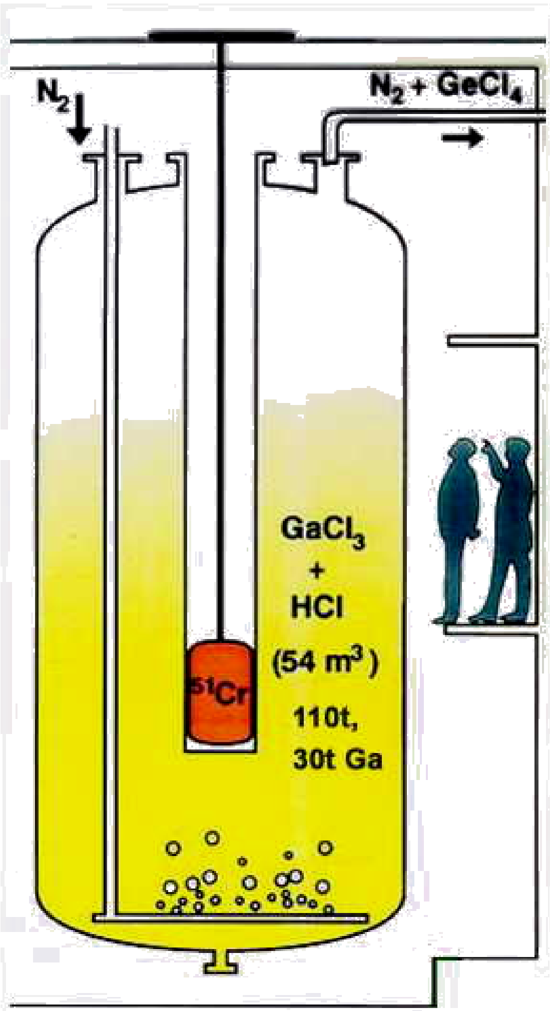
SAGE - in 2004 with ^{37}Ar

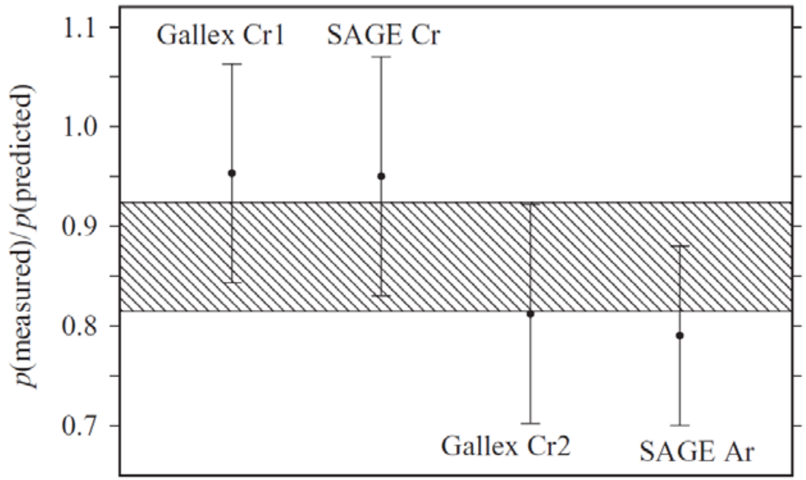




	GALLEX		SAGE	
	m(Ga)=30 t		m(Ga)=13 t	
Source	^{51}Cr -1	^{51}Cr -2	^{51}Cr	^{37}Ar
Activity, MCi	1.714	1.868	0.517	0.409
Measured production rate ρ (^{71}Ge/d)	11.9 ±1.1 ±0.7	10.7 ±1.2 ±0.7	14.0 ±1.5 ±0.8	$11.0^{+1.0}_{-0.9} \pm 0.6$
$R = (p_{meas}/p_{pred})$	0.95±0.11	0.81±0.11	0.95±0.12	0.79±0.10
R_{comb}	0.88 ± 0.08		0.86 ± 0.08	

Calibration with artificial neutrino sources

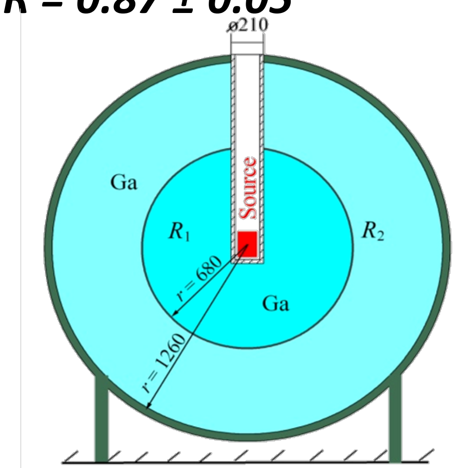


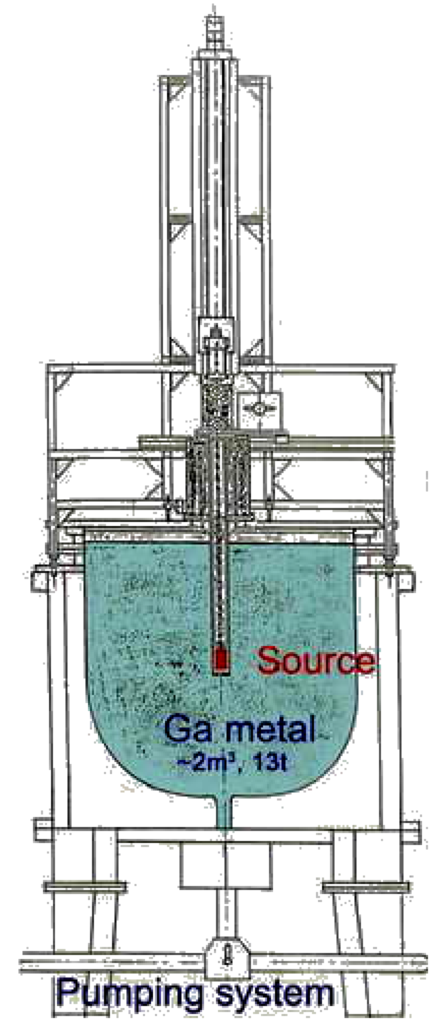


- **The weighted average for the four experiments *R = 0.87 ± 0.05***
- *χ^2/DOF=1.9/3*

Overestimated cross sections?

Sterile neutrino?
BEST





Baksan Experiment on Sterile Transitions (BEST)

proposal: 1006.2103, 1204.5379, ...

artificial source: ^{51}Cr of 3 MCi

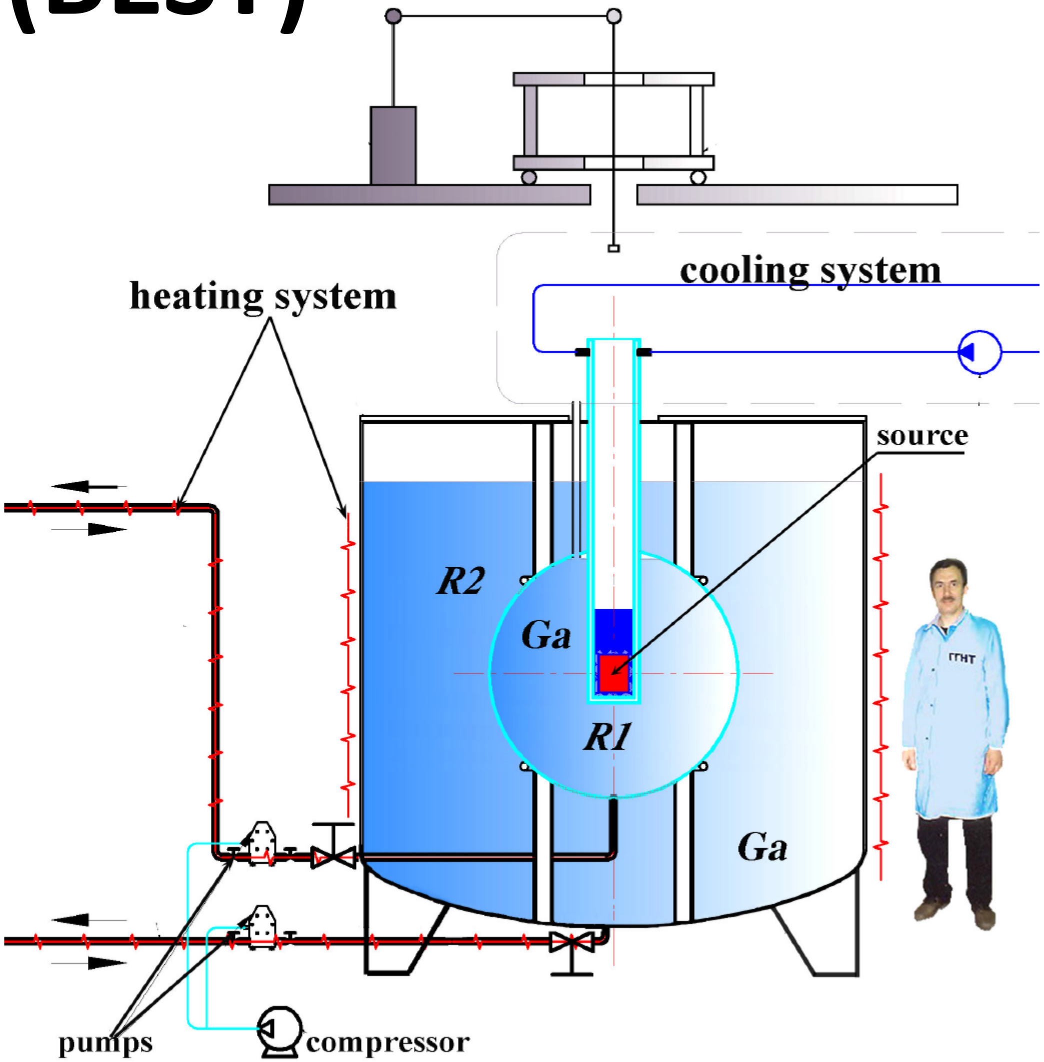
neutrino flux measurment:
$^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$

2 detector volumes:
for the flux cross check

geometry is chosen:
to search for $\simeq 1$ eV neutrino
must be sterile...

data taking:
July–September 2019

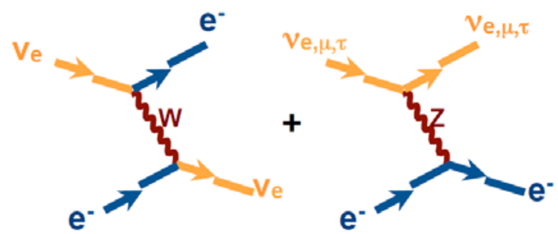
$\tau_{^{51}\mathrm{Cr}} = 27.7\mathrm{d}$

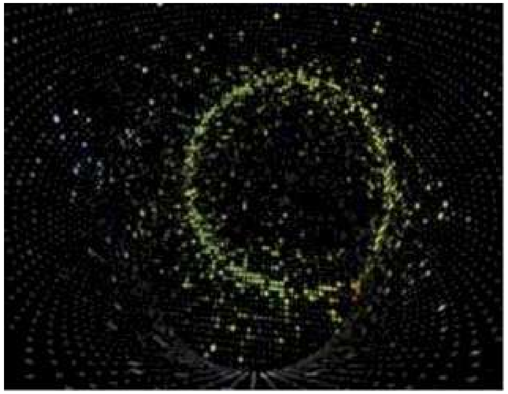


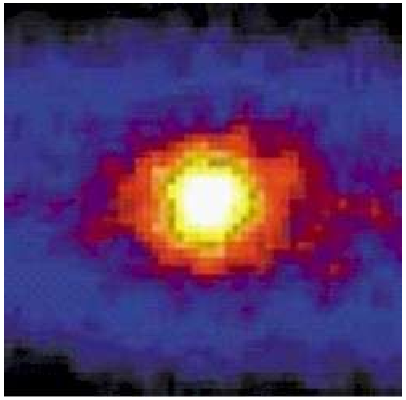
KamiokaNDE and SuperKamiokaNDE

Water Cherenkov detector
KamiokaNDE-II, 1988, Japan (1000 m depth in the Kamioka mine)

Neutrino detection:
elastic scattering off electrons







SuperKamiokande (or SuperK) — updated (scaled) version of Kamiokande-II, located 180 miles to the north from Tokyo. Japan-USA collaboration.

Construction ended in 1996.

50 ktones of higly purified water.

Equipped with 11146 PMTs

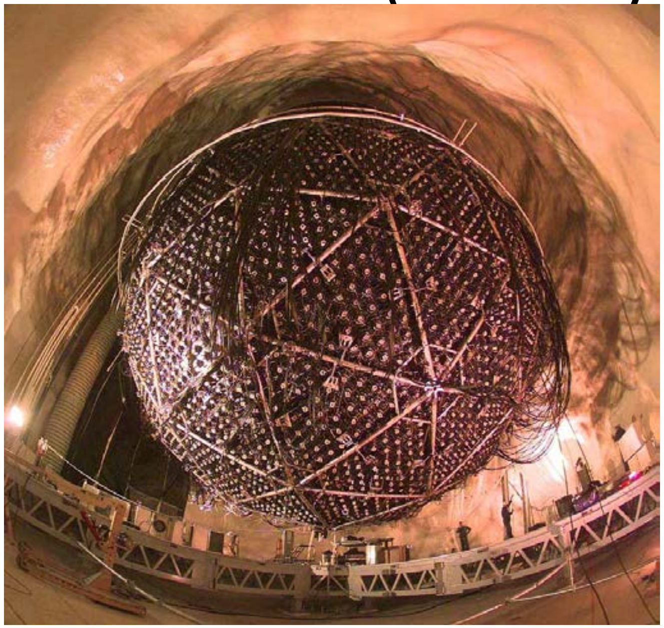
KamiokaNDE and SuperK results

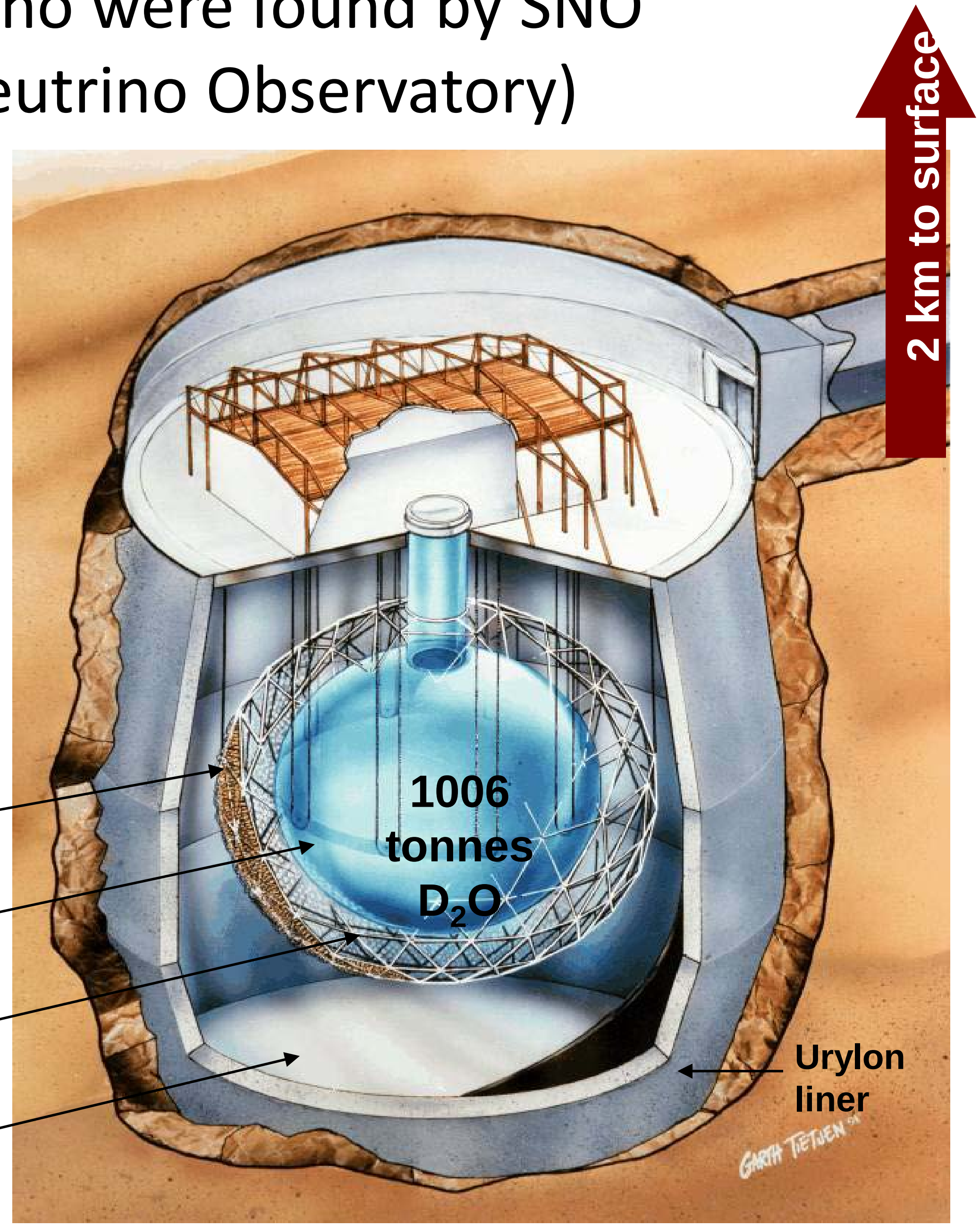
Detector		Years, exposure	FV mass	Cover age	E_{Thr} MeV	Result [$\times 10^6$ $cm^{-2}s^{-1}$]
KamiokaNDE-II +III		87-90 90-95 2079 d	H_20 3 kt	20% 25%	7.0	$2.82^{+0.25}_{-0.24}\pm0.27$
SuperK (50 kt)	I	96-01 1496 d	H_20 22.5 kt	40%	5.5	$2.380\pm0.024^{+0.064}_{-0.076}$
	II	02-05 791 d		19%	7.0	$2.41\pm0.05^{+0.16}_{-0.15}$
	III	06-08 548 d	22.5 (>5.5MeV) 13.3 (<5.5MeV)	40%	4.5	2.404±0.039±0.053
	IV (T2K phase)	08-18 1664 d (2014)	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)	40%	3.5	2.308±0.020±0.04 (2016)
		2970 d				2.29±0.02±0.04 (2018)
	V (Gd)	2019		40%	3.5	
HyperK (0.26 Mt)		2027	0.19 Mt	40%	4.5	Project

SK(I-IV) in 2019 had in total 5805 days of data

Combined (TAUP-2019) : 2.33±0.04 [1.7%]

Missing neutrino were found by SNO
(Sudbury Neutrino Observatory)





17.8m dia. PMT Support Structure
9456 20-cm dia. PMTs
56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

heavy water Cherenkov detector

10 neutrino events/day

Neutrino detection in heavy water Cherenkov detector

CC $\nu_e + d \rightarrow p + p + e^-$

- measurement of ν_e energy
- Weak directionality:

$$1 - 0.340\cos\theta$$

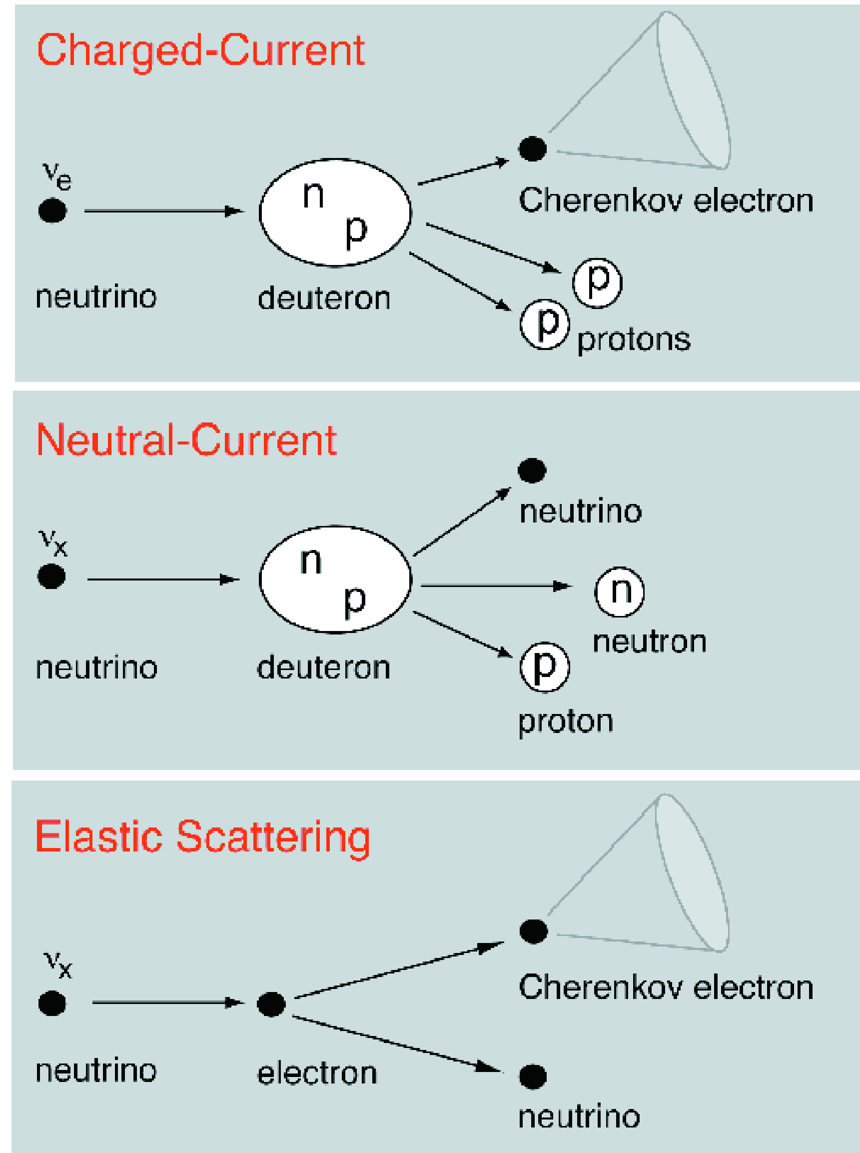
NC $\nu_x + d \rightarrow p + n + \nu_x$

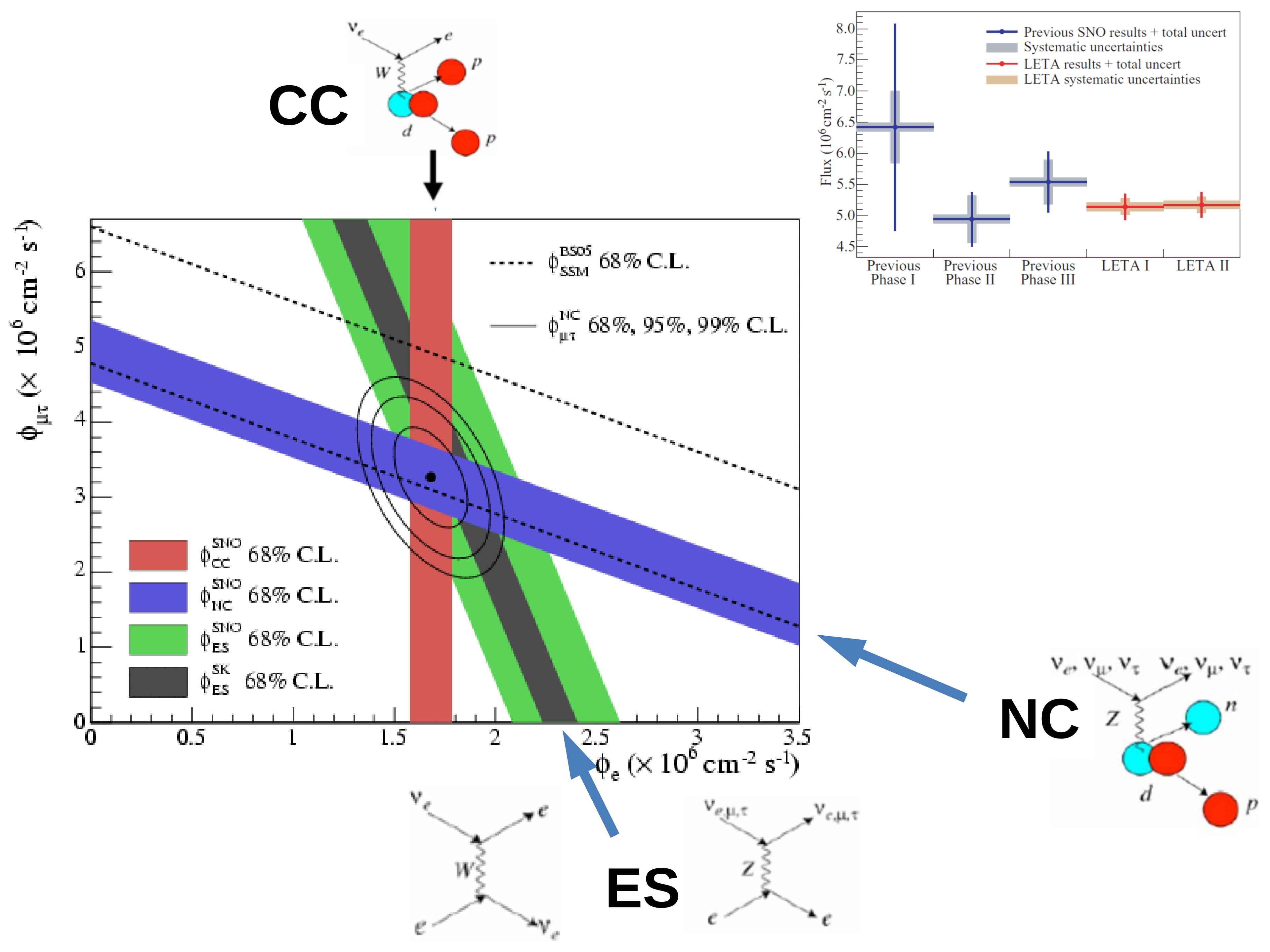
- Measurement of the total ^{8}B ν flux
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low statistics
- $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
- Strong directionality:

$$\theta_e \leq 18^\circ \quad (T_e = 10\ \text{MeV})$$





CC
NC
ES
ϕ^{BS05}_{SSM} 68% C.L.
$\phi^{NC}_{\mu\tau}$ 68%, 95%, 99% C.L.
ϕ^{SNO}_{CC} 68% C.L.
ϕ^{SNO}_{NC} 68% C.L.
ϕ^{SNO}_{ES} 68% C.L.
ϕ^{SK}_{ES} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
Previous SNO results + total uncert
Systematic uncertainties
LETA results + total uncert
LETA systematic uncertainties
Flux (10^6cm^{-2} s^{-1})
Previous Phase I
Previous Phase II
Previous Phase III
LETA I
LETA II

SNO results

Phase		Target, mass	Method	Threshold [MeV]	Result [$\times 10^6$ cm^{-2}s^{-1}]
I	99-01 306.4 d	$D_2 0$ 1006 t	$\nu_e + d \rightarrow p + p + e^-$ (CC)-1.4 MeV $\nu_x + d \rightarrow p + n + \nu_x$ (NC)-2.22 MeV $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)	5.0	$1.76 \pm 0.05 \pm 0.09$ (CC) $2.39^{+0.24}_{-0.23}$ (ES) $5.09^{+0.44}_{-0.43}$ (NC)
II	01-04 391d	+NaCl 2t	$^{35}Cl + n \rightarrow {}^{36}Cl + 8.6$ MeV (2-4 γ)	5.5	$1.72 \pm 0.05 \pm 0.11$ (CC) $2.34 \pm 0.23^{+0.15}_{-0.14}$ (ES) $4.81 \pm 0.19^{+0.28}_{-0.27}$ (NC)
I+II	Low energy threshold analysis (LETA: 3.5 MeV)			3.5	$5.046^{+0.159}_{-0.152}\ ^{+0.107}_{-0.123}$ (NC)
III	04-06	+^{3}He counters	$^3He + n \rightarrow p + {}^3H + 0.76$ MeV	6.0	$1.67^{+0.05}_{-0.04}\ ^{+0.07}_{-0.08}$ (CC) $1.77^{+0.24}_{-0.21}\ ^{+0.09}_{-0.10}$ (ES) $5.54^{+0.33}_{-0.31}\ ^{+0.36}_{-0.34}$ (NC)

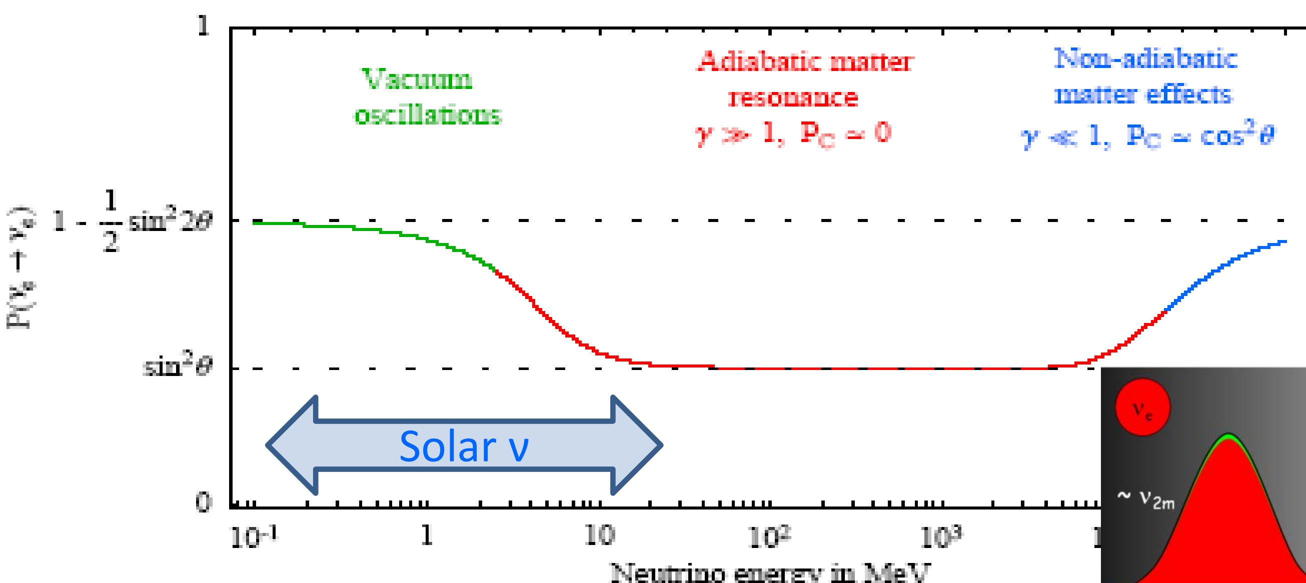
^{8}B flux $(5.25 \pm 0.16(\text{stat})^{+0.11}_{-0.13}(\text{syst})) \times 10^6$ cm^{-2}s^{-1}

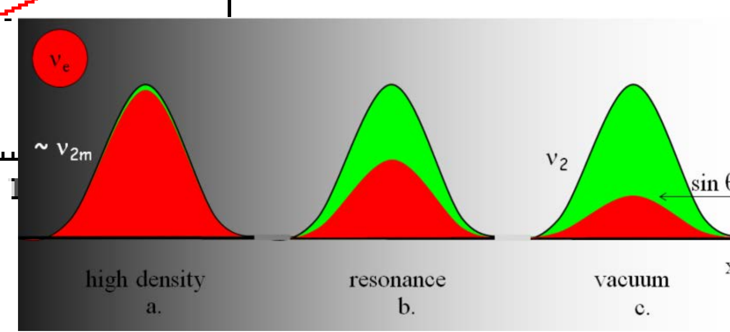
Solar Neutrino Problem

- **a large discrepancy between the predicted and measured fluxes of solar neutrinos:**
  - **Cl & KamiokaNDE ≈ 1/3 of predicted**
  - **Ga: ≈1/2 of predicted**

A lot of solutions have been proposed, now mainly of historical interest.

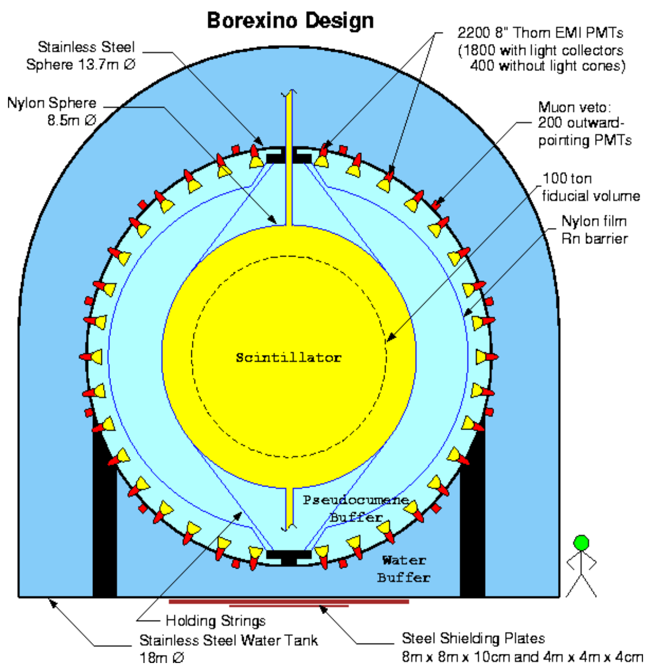
MSW/LMA has been established as the true solution of the SNP



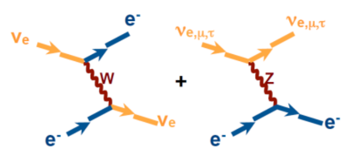


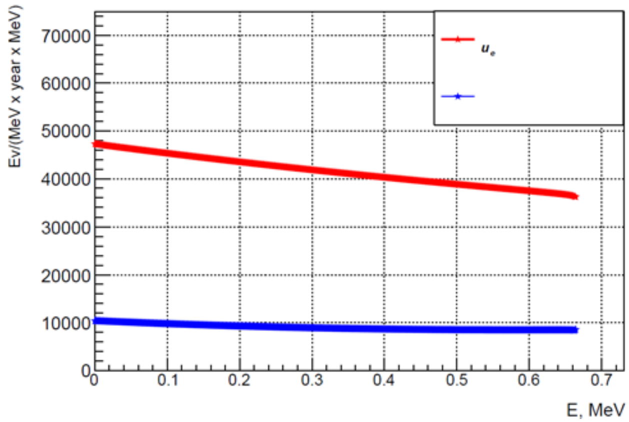
BOREXINO *(in operation from May,2007)*

- **278 t of liquid organic scintillator PC + PPO (1.5 g/l)**
- **(ν,e)-scattering with low threshold (~200 keV)**



Neutrino detection:
elastic scattering off electrons





~1 Bq

50 events/d/100t expected (ν_e and $\nu_{\mu,\tau}$ elastic scattering on e^-) or $5{\cdot}10^{-9}$ Bq/kg (typically: drinking water ~10 Bq/kg; human body in ^{40}K: 5 kBq)

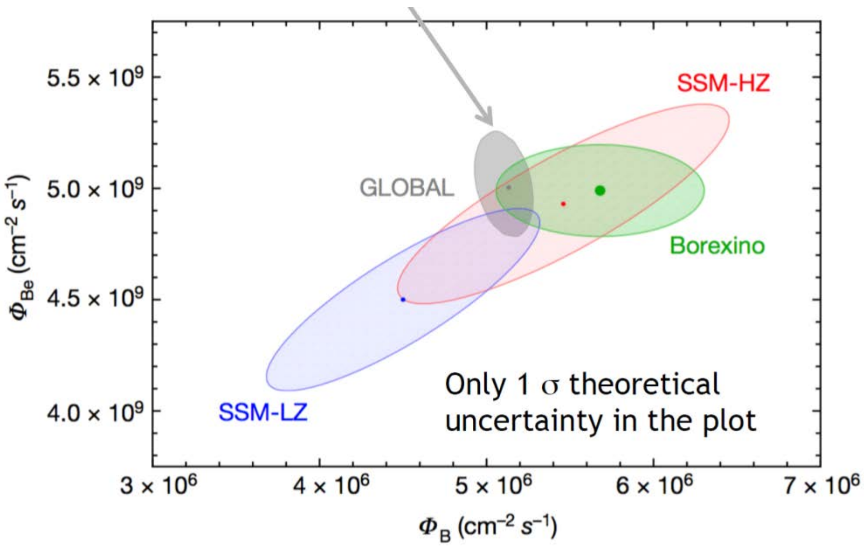
Low energy->no Cherenkov light->No directionality,
no other tags-> extremely pure scintillator is needed

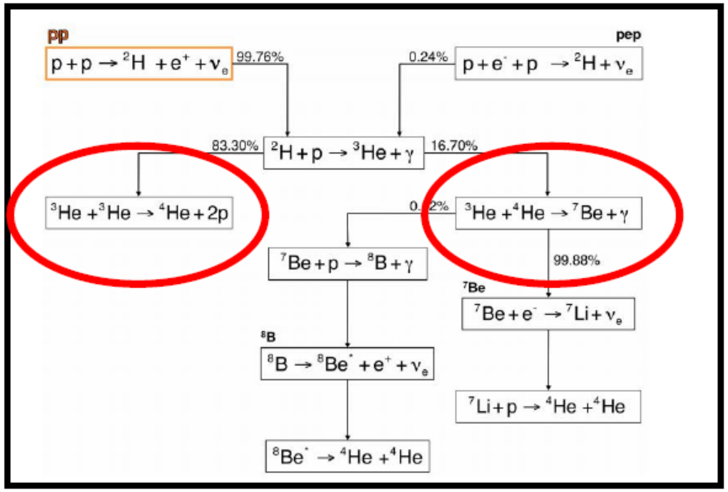
Borexino (phase-II) results (2018)

Nature 562, pp.505–510 (2018)

Rates	Borexino new results cpd/100t	Uncertainty reduction	Expected HZ cpd/100t	Expected LZ cpd/100t
pp	$134 \pm 10^{+6}_{-10}$	11 -> 9%	131.0 ± 2.4	132.1 ± 2.4
^{7}Be (862+384 keV)	$48.3 \pm 1.1^{+0.4}_{-0.7}$	4.7 -> 2.7 %	47.8 ± 2.9	43.7 ± 2.6
Pep (CNO fixed at HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	22 -> 16%	2.74 ± 0.05	2.78 ± 0.05
Pep (CNO fixed at LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	22 -> 16%	2.74 ± 0.05	2.78 ± 0.05
^{8}B (E_{e-}> 3MeV)	$0.223\ ^{+0.015}_{-0016} \pm 0.006$	18 -> 8%	0.211 ± 0.025	0.173 ± 0.021
Hep (E_{e-}> 11MeV)	<0.002 (90% C.L.)		$(8.0 \pm 2.2) \times 10^{-5}$	$(7.5 \pm 0.9) \times 10^{-5}$
CNO	< 8.1 (95% C.L.)		4.91 ± 0.56	3.62 ± 0.37

Solar metallicity problem





- **Global fit to all solar + Kamland data (including the new ^{7}Be result from BX)**

$$f_{\mathrm{Be}} = \frac{\Phi(\mathrm{Be})}{\Phi(\mathrm{Be})_{\mathrm{HZ}}} = 1.01 \pm 0.03$$

$$f_{B} = \frac{\Phi(\mathrm{B})}{\Phi(\mathrm{B})_{\mathrm{HZ}}} = 0.93 \pm 0.02$$

- **a hint towards the HM :**

LZ is excluded by BX data at 96.6% C.L. (1.8σ) level

- **theoretical errors are dominating**

$$R \equiv \frac{<^3\mathrm{He} + ^4\mathrm{He}>}{<^3\mathrm{He} + ^3\mathrm{He}>} = \frac{2\phi(^7\mathrm{Be})}{\phi(\mathrm{pp}) - \phi(^7\mathrm{Be})}$$

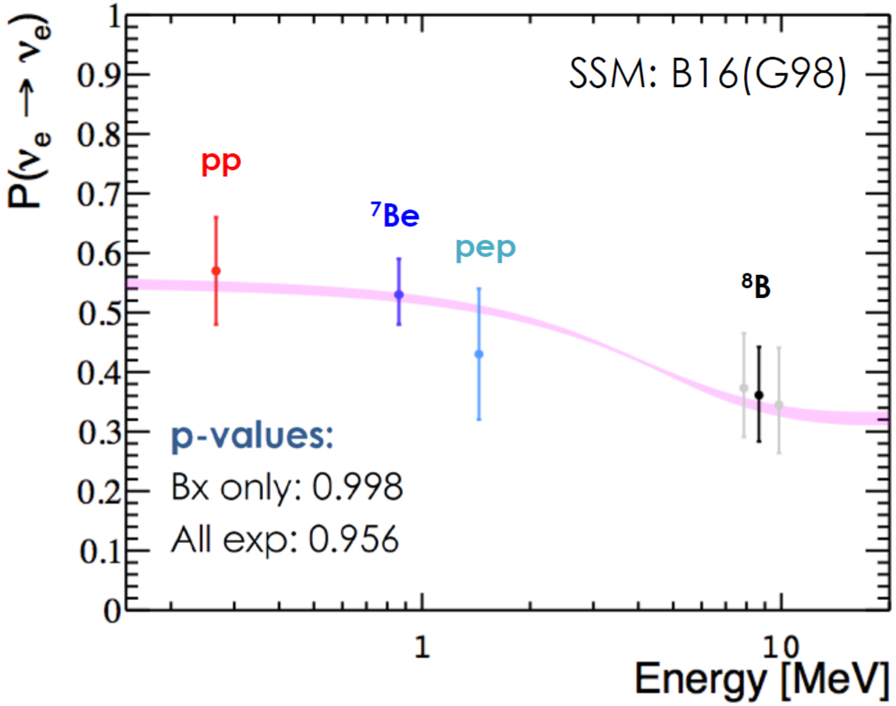
R(HZ)=0.180±0.011
R(LZ)=0.161±0.010

From the pp and ^{7}Be fluxes measurement

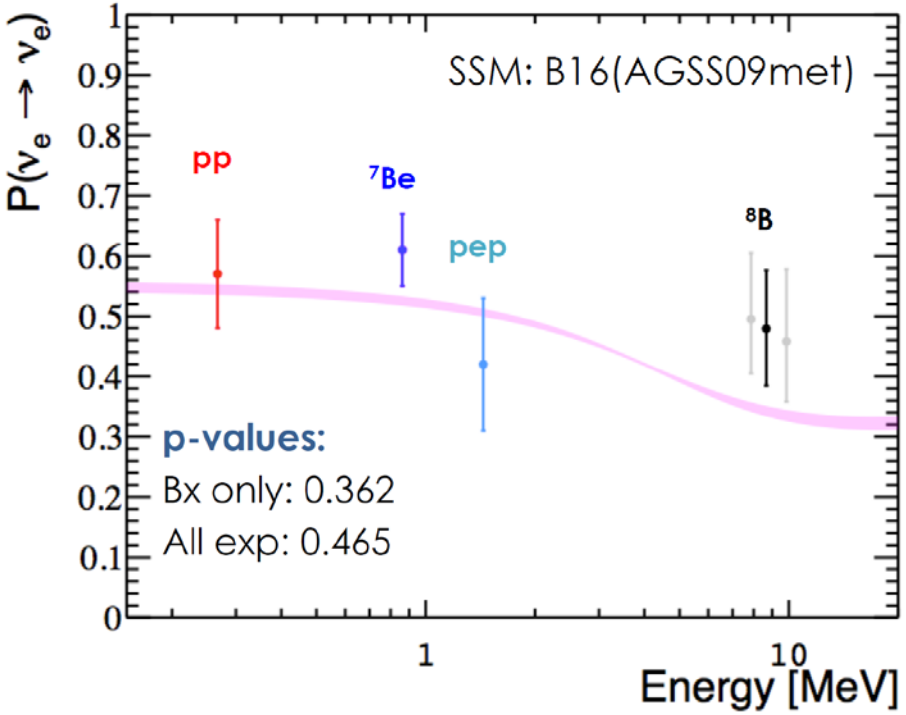
R(BRX)=$0.178^{+0.027}_{-0.023}$

MSW/LMA : electron neutrino survival probabilities

High metallicity SSM

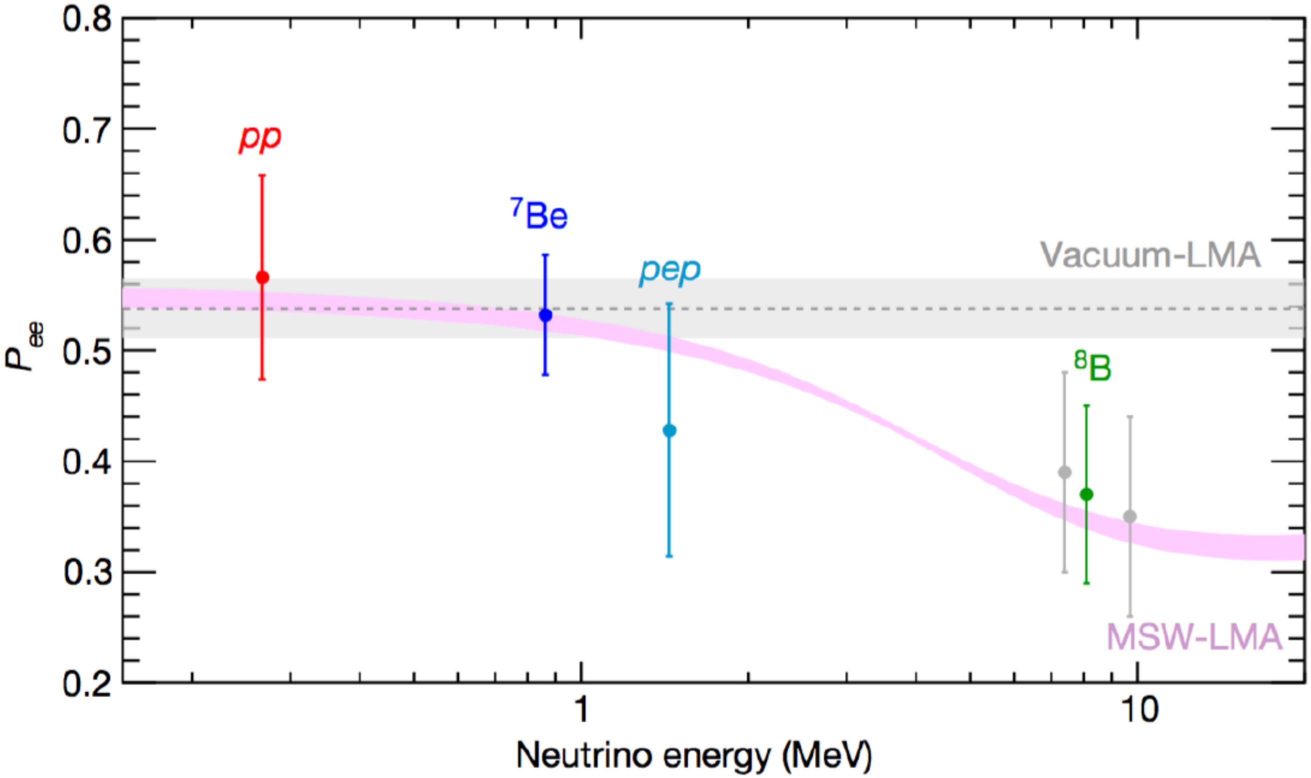


Low metallicity SSM



MSW errors (1σ) are shown by rose band

MSW/LMA for SSM(HZ)



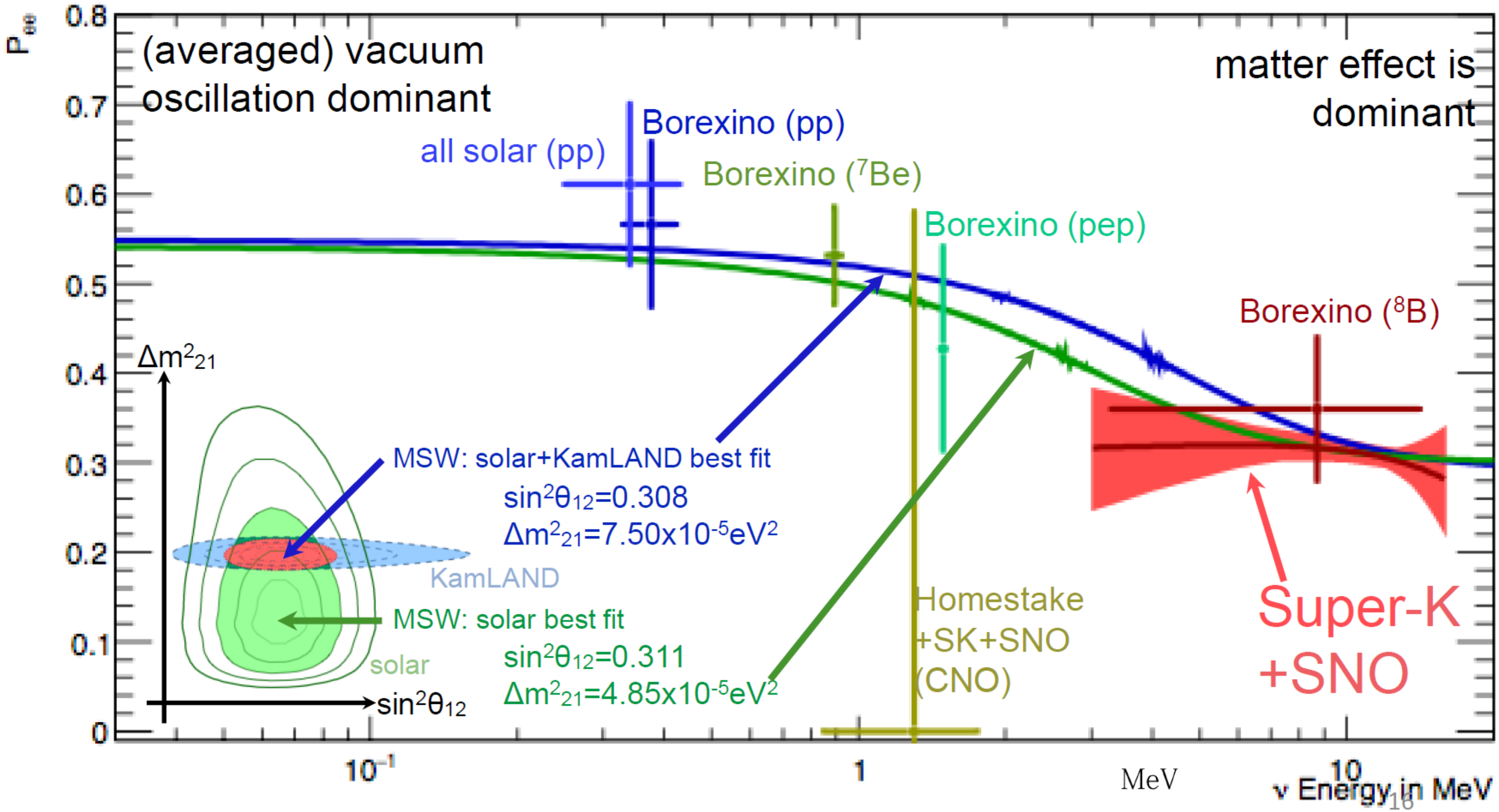
Rejected at 98.2% C.L.

Total error on P_{ee}:

- **for pp and pep neutrinos, contribution of experimental errors dominates (easy to predict, difficult to measure)**
- **for ^{7}Be and ^{8}B theoretical predictions of the Solar model are worse than measurements**

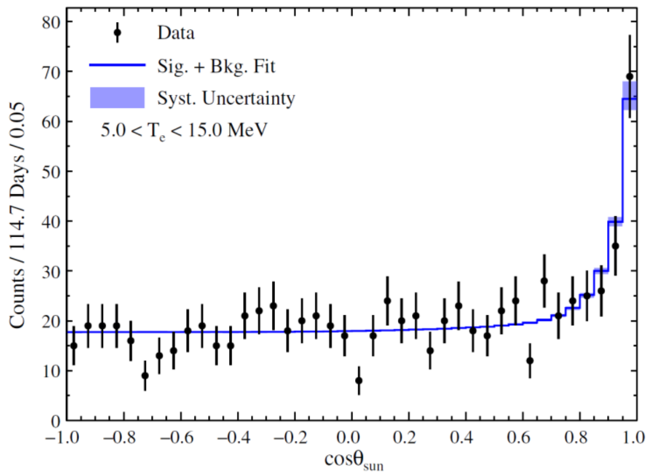
Survival probabilities from all solar ν results

“Upturn” predicted by standard MSW is not seen yet.



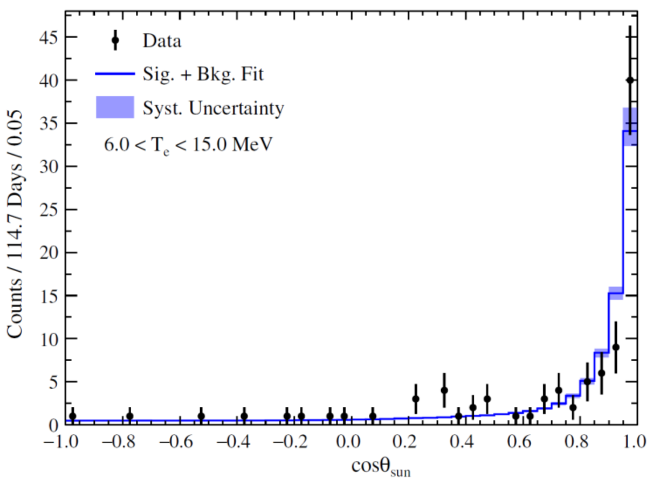
SNO+ water phase; 114.7 days

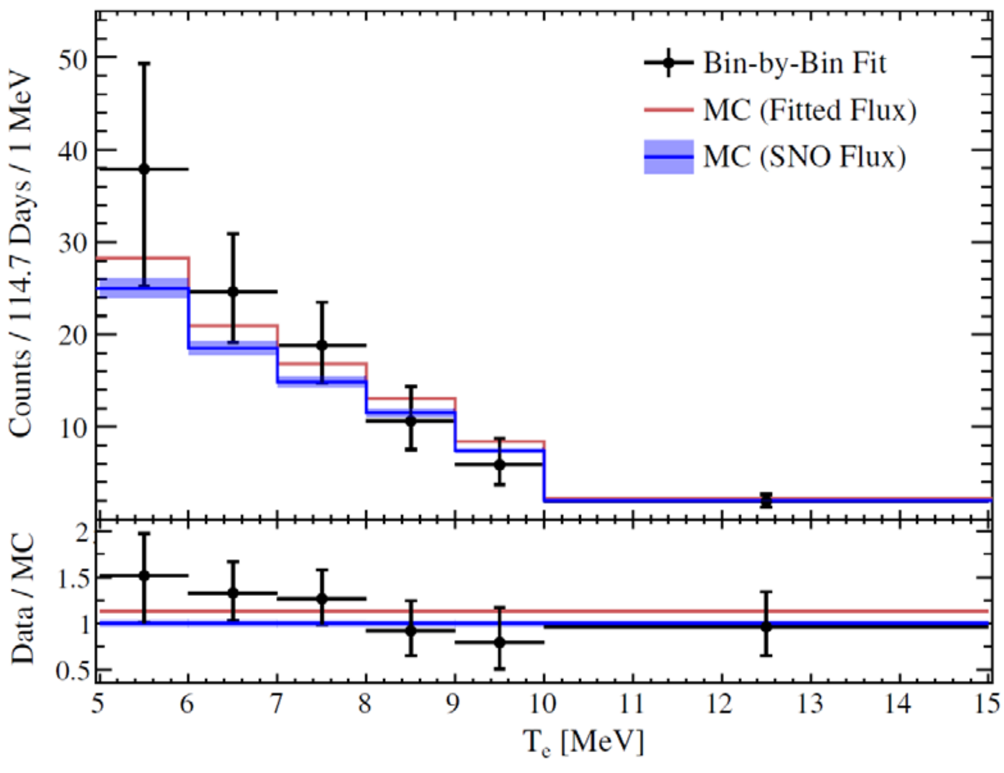
Phys.Rev. D 99, 012012 (2019)



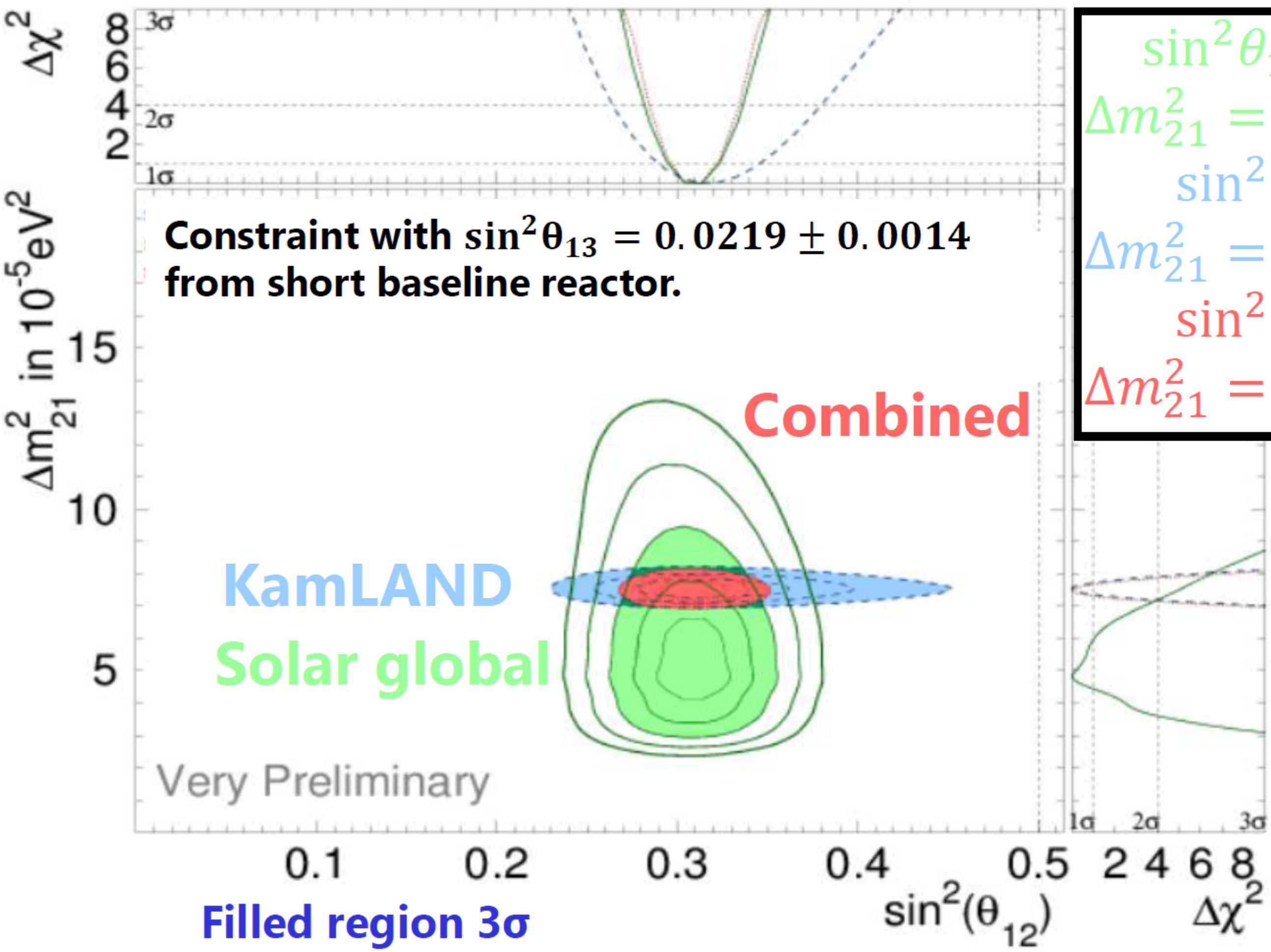
$$\Phi_{^8\mathrm{B}} = 5.95^{+0.75}_{-0.71}(\mathrm{stat})^{+0.28}_{-0.30}(\mathrm{syst}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Compatible with SNO measurement





Constraint on $\sin^2\theta_{12}, \Delta m^2_{21}$ (solar vs. KamLAND)



$\sin^2\theta_{12} = 0.309 \pm 0.014$

$\Delta m^2_{21} = 4.83^{+1.25}_{-0.60} \times 10^{-5}$ eV^2

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}$ eV^2

$\sin^2\theta_{12} = 0.309^{+0.013}_{-0.012}$

$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}$ eV^2

Filled region 3σ

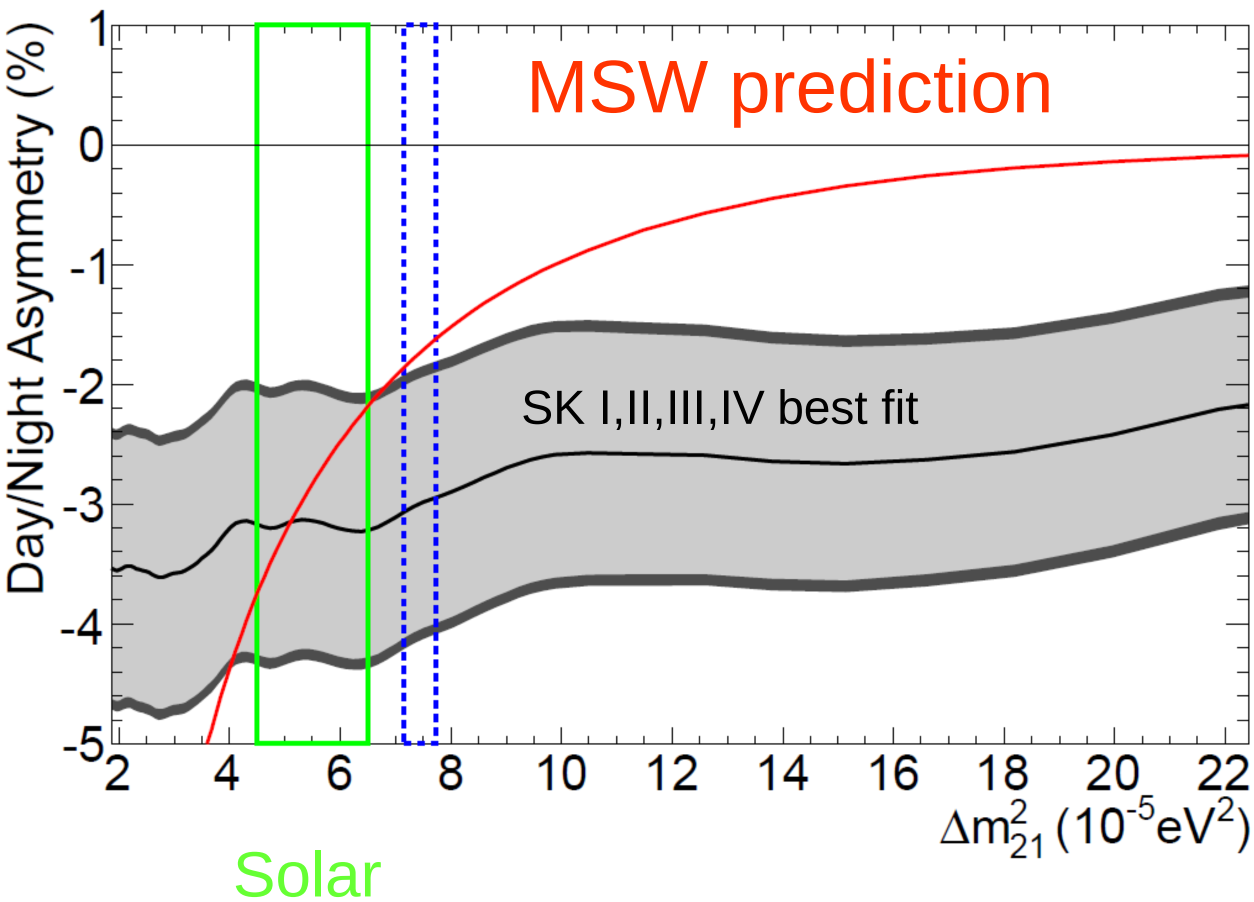
Oscillation parameters are determined using the latest solar ν data.

2σ tensition in Δm^2_{21} between the solar global and KamLAND.

Source:Nakano@TAUP-2019

SuperK : first Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

Phys.Rev.Lett. 112 (2014) no.9, 091805



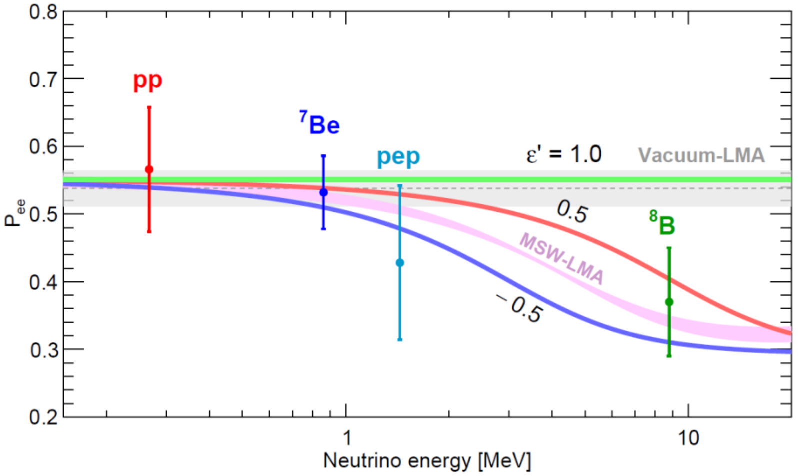
2014:
A_{DN}=-3.2±1.1±0.5 [%]
(2.8σ)

2016:
A_{DN}=-3.2±1.0±0.5 [%]
(2.9σ)

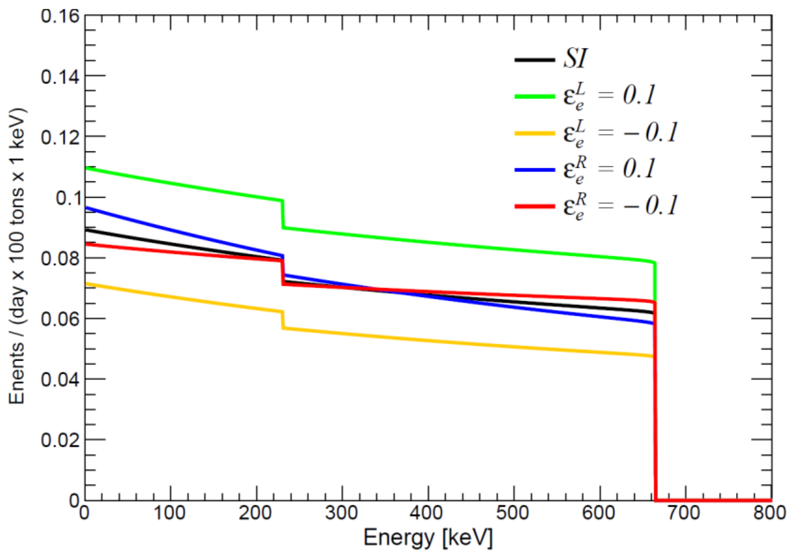
Non-standard interactions

The absence of the visible upturn triggered speculations on NSI

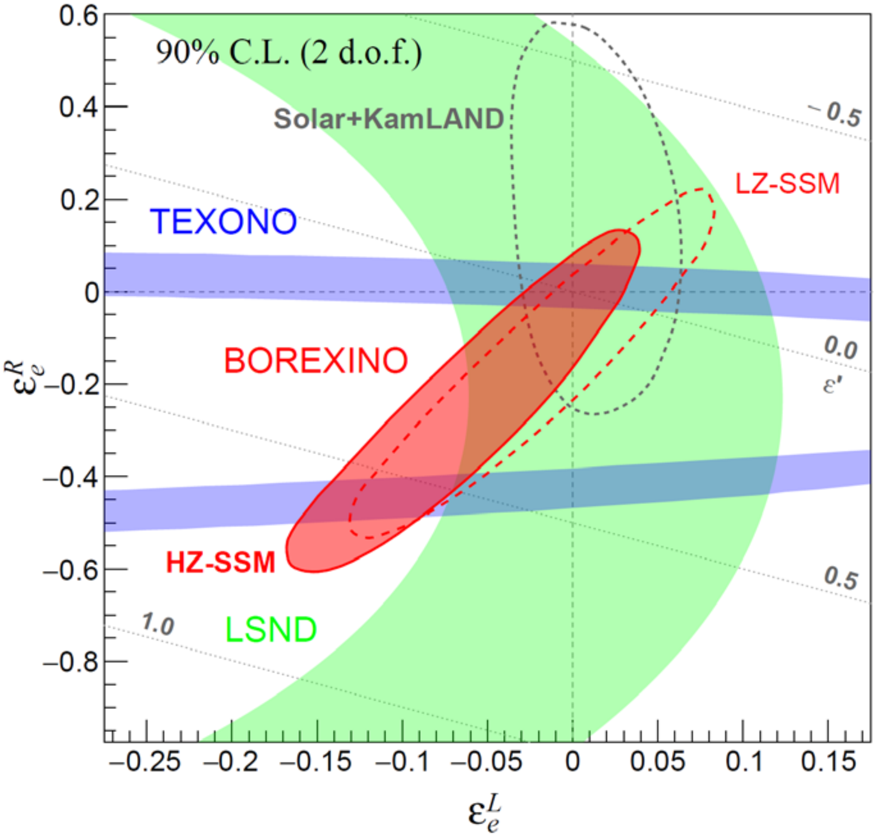
NSIs modifies Pee…

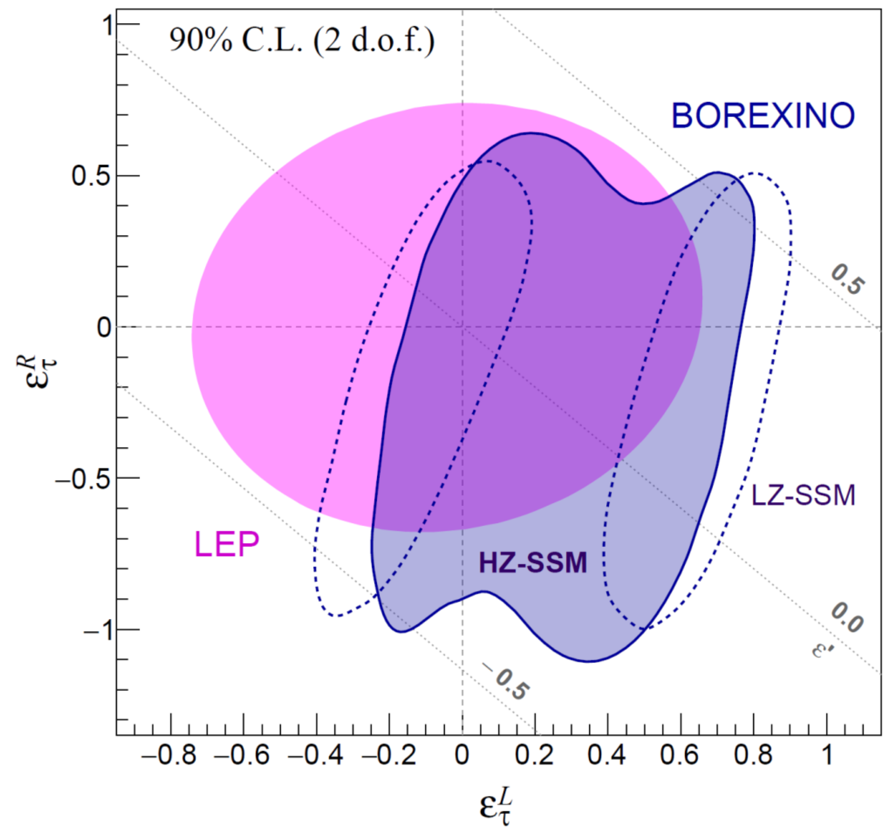


… and cross sections



Constrains on NSI



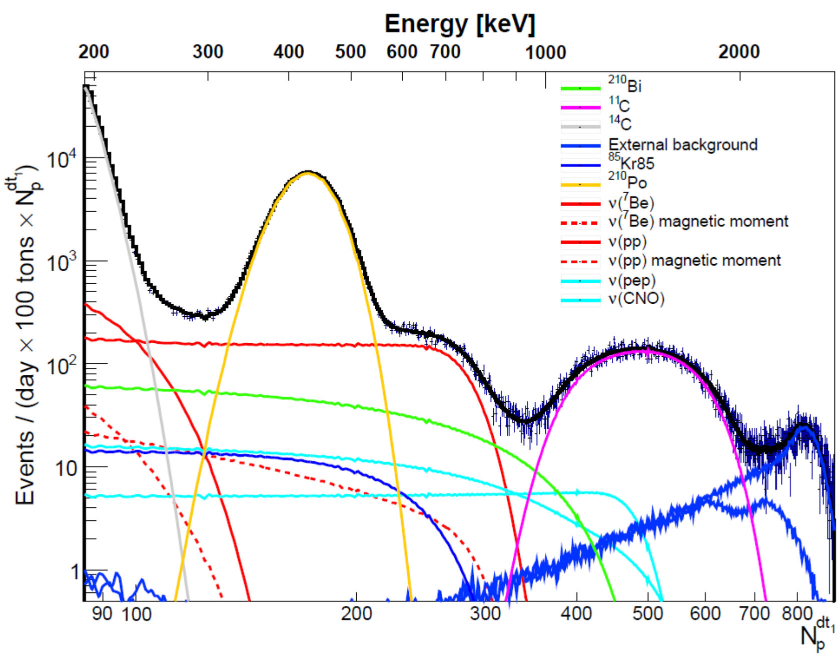


arXiv:1905.03512

Effective magnetic moment of Solar neutrino

Phys. Rev D 96, 091103(R) (2017)

Borexino is spectroscopical detector.
Solar neutrino analysis (spectral fit) is performed assuming SM cross sections
The shapes can be adjusted to take into account any non-standard interactions (NSI), including neutrino EM interactions



$$\boxed{\cancel{\chi^2 = \sum_{i=1}^{N_{bin}} \left(\frac{O_R^i - N_R^i(\mu_R)}{\Delta_i} \right)^2}}$$

Radiochemical (Ga) constraints

$$\sum_i \frac{R_i^{Brx}}{R_i^{Expected}} R_i^{Ga} \frac{\langle \sigma^{\odot}{}_i \rangle_{new}}{\langle \sigma^{\odot}{}_i \rangle_{old}} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}$$

Without Ga constraint: $\mu_\nu < 4.0 \cdot 10^{-11}\ \mu_B$, 90% C.L.

With Ga constraint: $\mu_\nu < 2.6 \cdot 10^{-11}\ \mu_B$, 90% C.L.

+ systematics: **$\mu_\nu < 2.8 \cdot 10^{-11}\ \mu_B$, 90% C.L.**

Limits on mm of neutrino flavours and mass eigenstates

In Solar neutrino experiments we measure: $(\mu_\nu)_{eff}{}^2 = \sum_\alpha P_{e\alpha}(\mu_\nu)_\alpha{}^2$

In frames of the MSW/LMA solution:

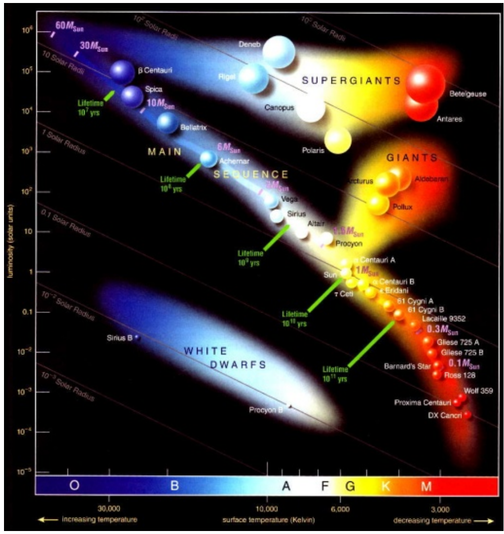
$$\mu^2{}_{eff} = P^{3\nu}\mu^2{}_e + (1 - P^{3\nu})(\cos^2\theta_{23}\,\mu^2{}_\mu + \sin^2\theta_{23}\mu^2{}_\tau)$$

$\mu_{\nu_e} < 3.9$
$\mu_{\nu_\mu} < 5.8$
$\mu_{\nu_\tau} < 5.8$

GEMMA:	$\mu_{\nu_e} < 2.9$
LSND:	$\mu_{\nu_\mu} < 68$
DONUT:	$\mu_{\nu_\tau} < 39000$

All @90% C.L.

units of $10^{-11}\mu_B$



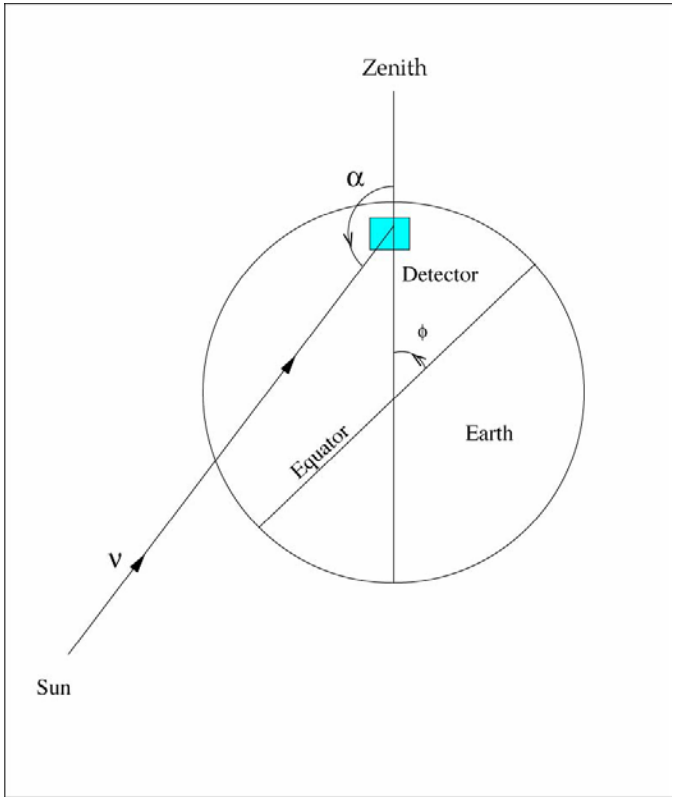
Mass eigenstates basis:

- $|\mu_{11}| \le 3.4 \quad |\mu_{22}| \le 5.1 \quad |\mu_{33}| \le 18.7$

  $|\mu_{12}| \le 2.8 \quad |\mu_{13}| \le 3.4 \quad |\mu_{23}| \le 5.0$

Astropysics: $\mu_\nu{}^2 = \sum_{\alpha,\beta}\left|\mu_\nu{}^{\alpha\beta}\right|^2 < 3\cdot 10^{-12}\mu_B$

Borexino
no diurnal variations of ^{7}Be neutrino flux



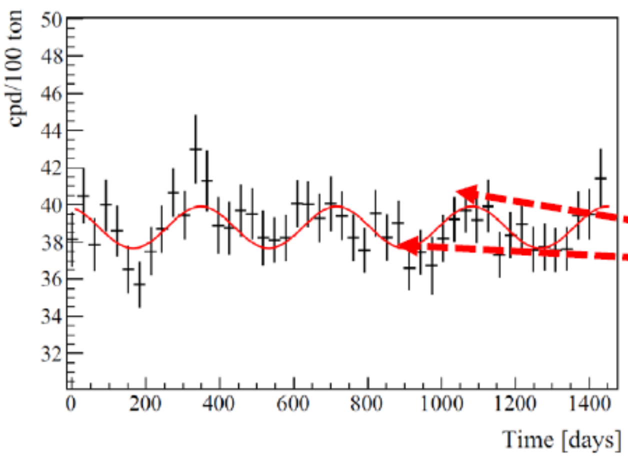
“negative” result on day/night assimetry with 3 years statistics (380.63 “nights” + 360.25 “days”) is in agreement with MSW/LMA predictions:

$$ADN = \frac{N-D}{N+D} = 0.001 \pm 0.012(stat) \pm 0.007(syst)$$

G. Bellini et al., Phys. Lett. B 707 (2012).

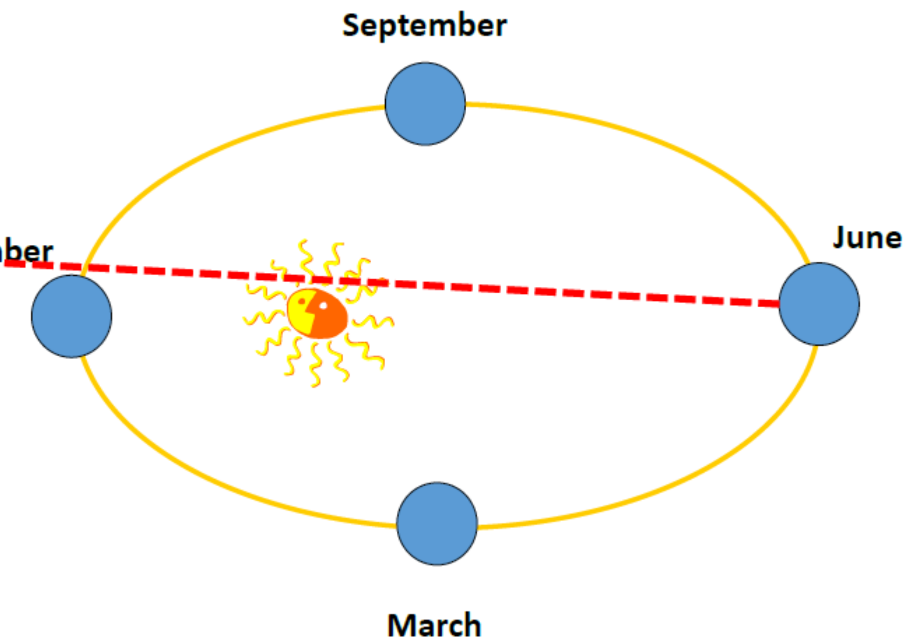
Seasonal modulations of ^{7}Be neutrino flux

M. Agostini et al. / Astroparticle Physics 92 (2017) 21–29



Fit to the evolution of the rate in time (bin of 30 days)

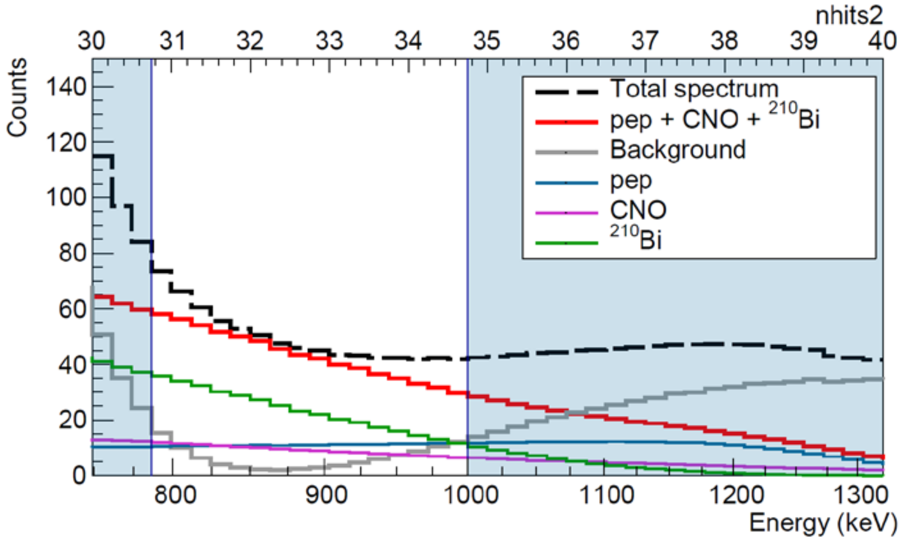
ε = (1.74 ± 0.45)%
T = (367 ± 10)days
Φ = (-18 ± 24) days



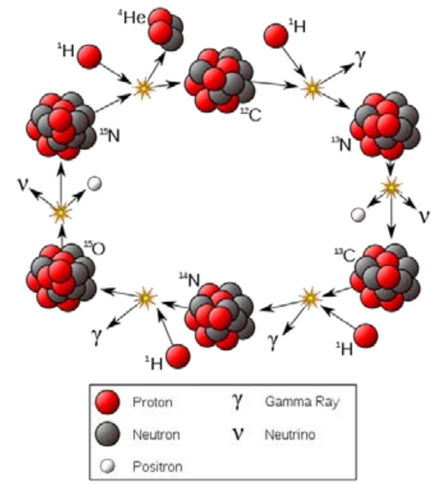
The duration of the astronomical year is measured from underground using neutrino!


NEXT
BIG THING
AHEAD

Key to the Solar metallicity : CNO neutrino flux



Expected spectrum assuming ν(CNO) HZ flux and other rates from last solar analysis



Predictions:

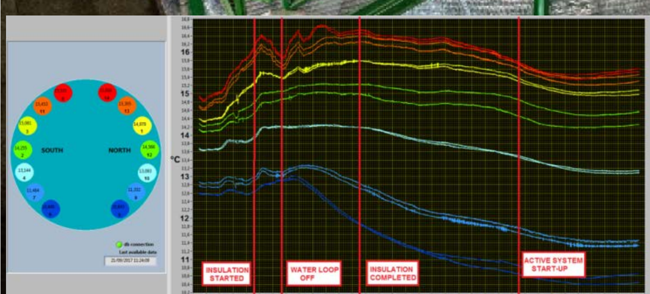
HZ : 4.91±0.56 cpd/100 t

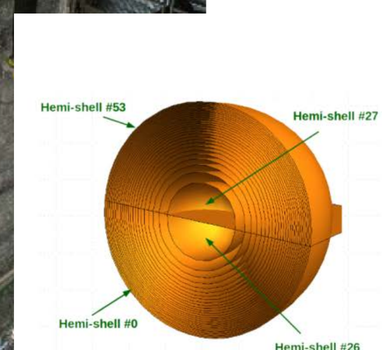
LZ : 3.62±0.37 cpd/100 t

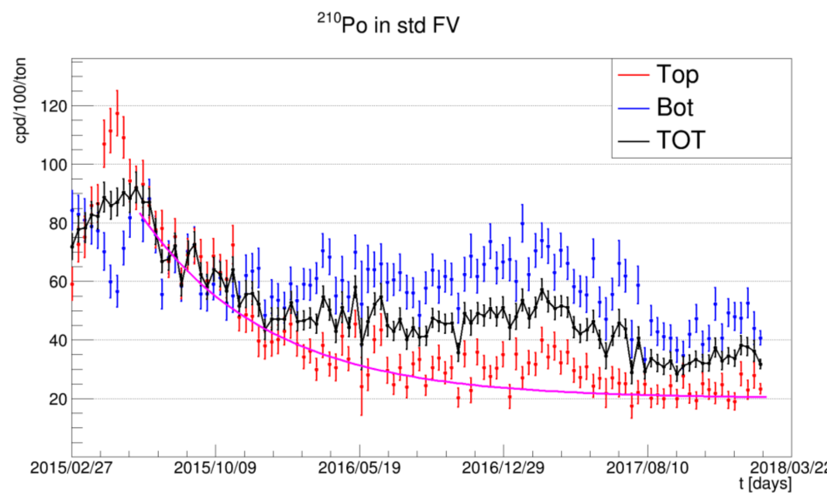
Main background from ^{210}Bi : ~20 cpd/100 t
Measure ^{210}Bi with few counts precision → constrain it in the spectral fit → extract the CNO flux.

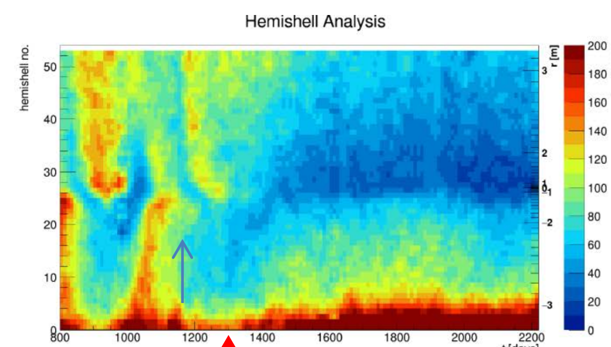
Another background in the region of sensitivity is pep-neutrino flux. Can be constrained through pp/pep ratio, using theoretical prediction for pp (luminosity constraint) or pp measured value.

Hardware solution for thermal stabilization : thermal insulation of the external tank









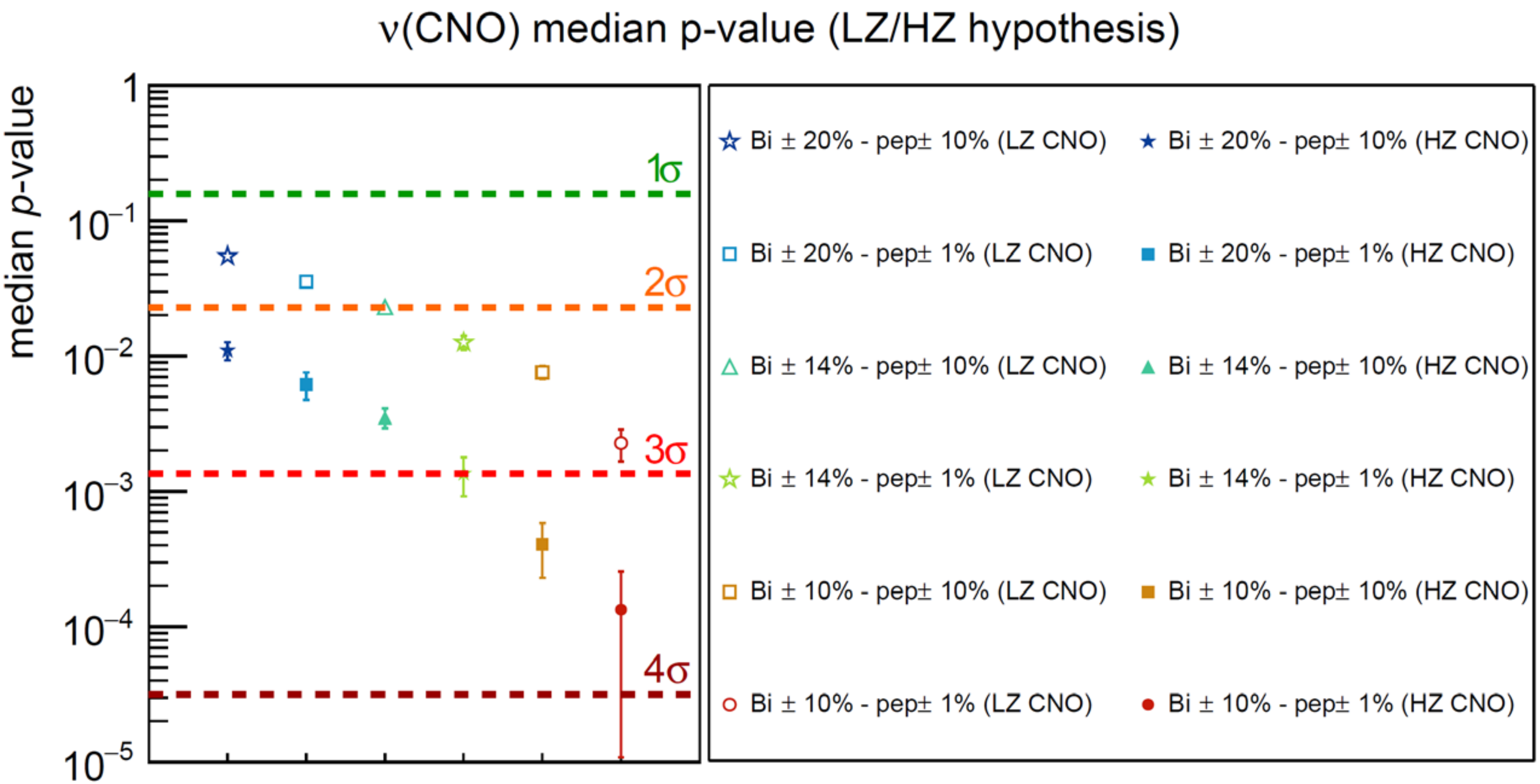
day 1300: insulation (summer 2015)

CNO sensitivity

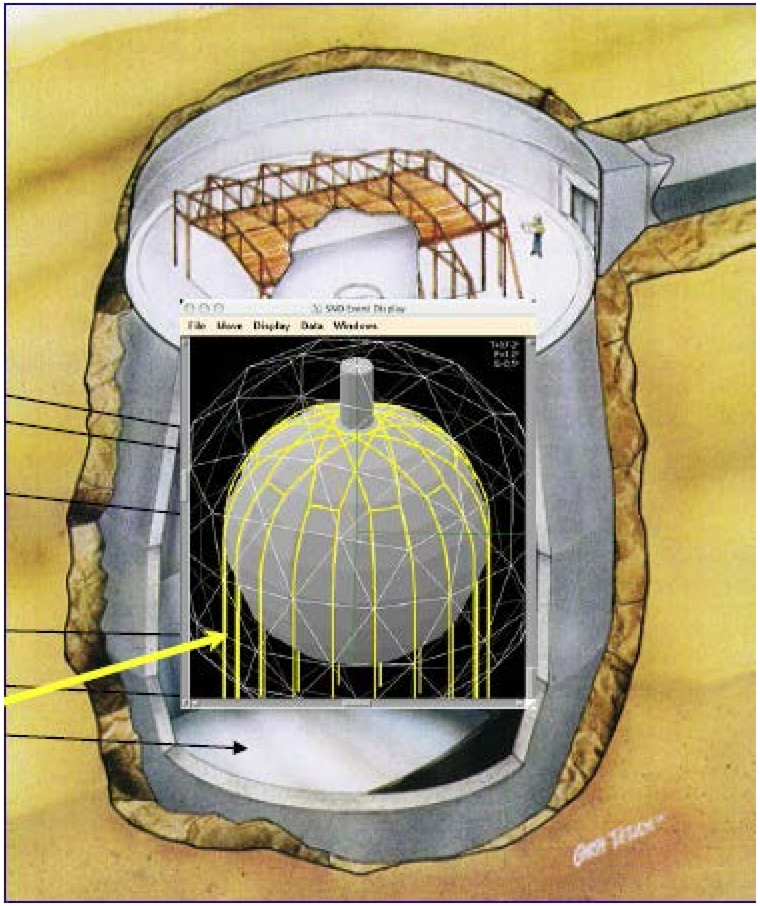
Depends on both ^{210}Bi and pep-neutrino rates.

Assumed that ^{210}Bi will be measured (10-20%) and

pep-rate can be constrained by constraining pp/pep ratio in the fit.



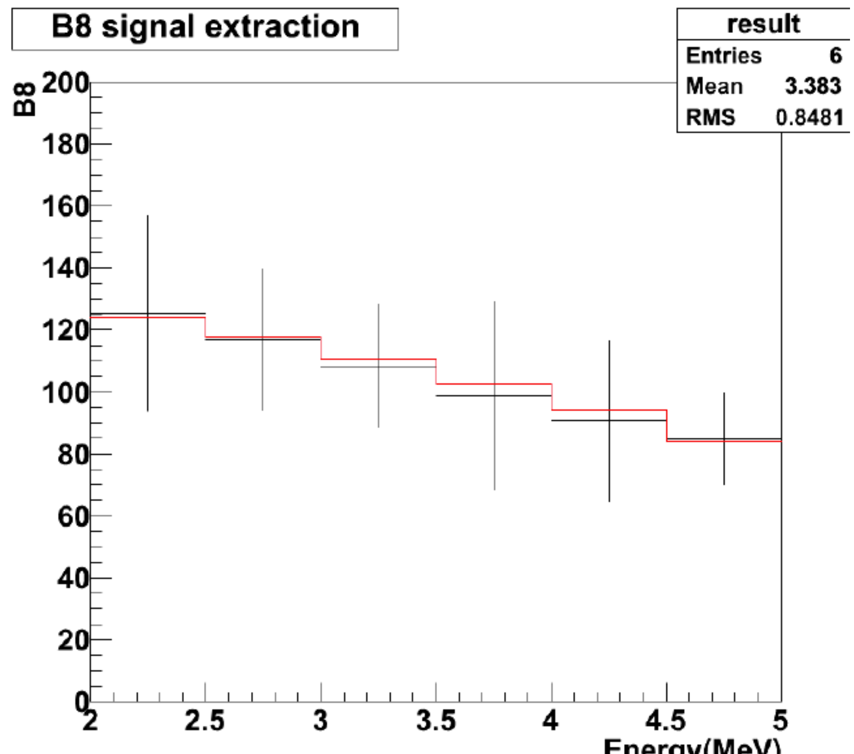
SNO+



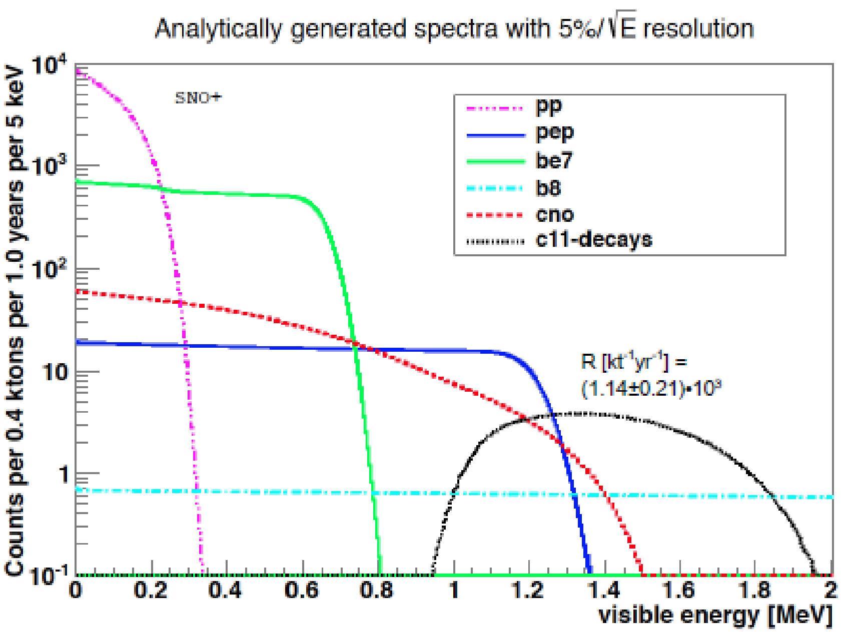
780 tons of Linear Alkyl Benzene (LAB)

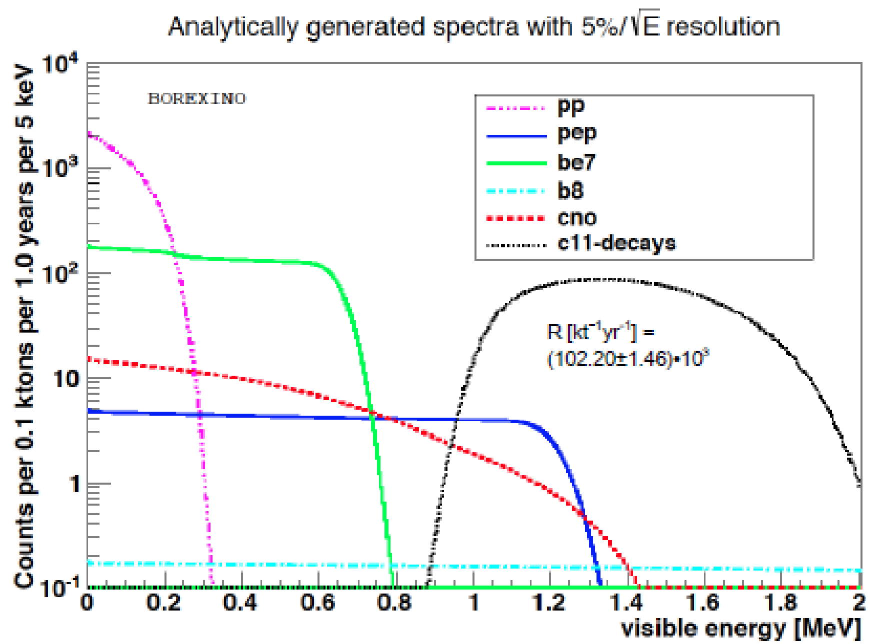
6000 m.w.e. rock shielding : 3 μ/hour.

^{8}B neutrino : 1 yr simulations



SNO+ Solar neutrino phase





^{7}Be and ^{8}B neutrinos
pep & CNO neutrinos: U and Th < 10^{-17} g/g.
^{210}Bi is the most important
3600 pep events/(kton·year), for electron recoils >0.8 MeV
goal: ±5% total uncertainty after 3 years (including systematic and SSM)
CNO measurement : ±10% after 3 years.

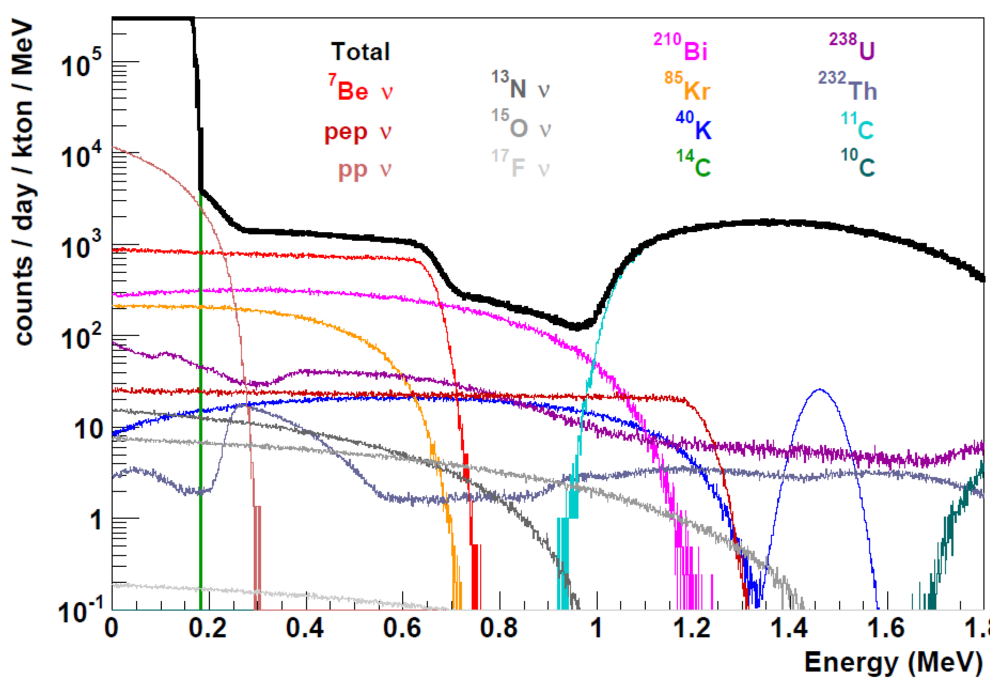
Solar neutrino

JUNO is large volume LS detector, bigger than successful Borexino with better resolution, but at shallower depth. Radiopurity?

"single" events (non tagged) from νe elastic scattering

Source	Rate [cpd/1kt]
pp ν	1378
^{7}Be ν	517
pep ν	28
^{8}B ν	4.5
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1

JUNO low-energy "singles" spectrum for "ideal" radiopurity



Remaining ? in Solar neutrino physics

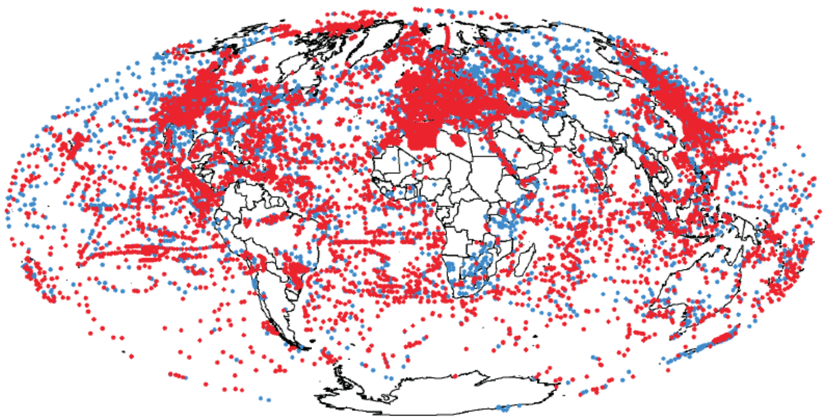
- Solar metallicity problem; will it be solved by Borexino?
- CNO neutrino flux measurement
- “Upturn” in the ^{8}B spectrum. Is it a hint for the NSIs or just a statistical fluctuation?
- The “tension” between SK and KL parameters
- The observation of the D/N variations of the ^{8}B signal still missing

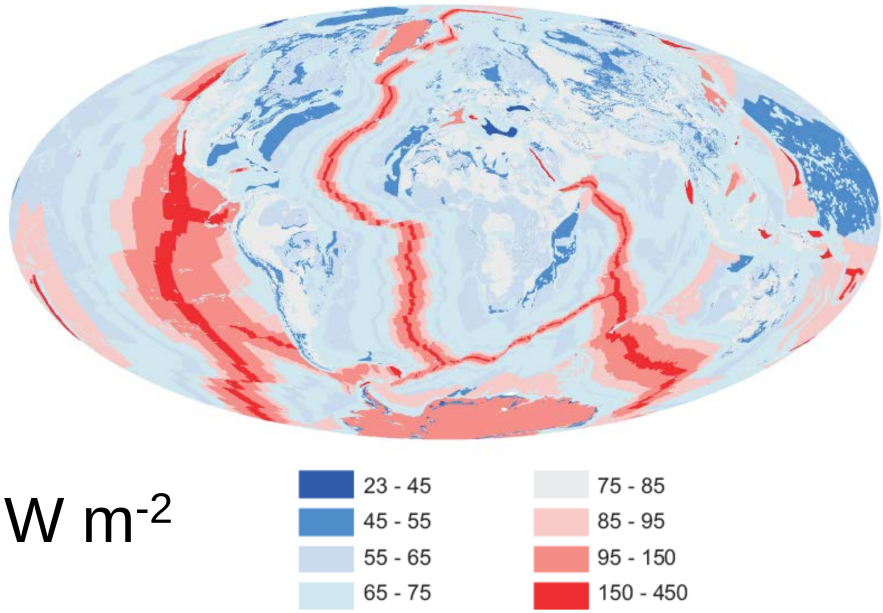
Geo-neutrinos

^{238}U, ^{232}Th and ^{40}K (^{87}Rb,^{235}U) release heat together with antineutrinos

$$\Phi_{\bar{\nu}} \sim 10^{6}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Heat flow through the surface of the Earth





mW m^{-2}

“Earth’s surface heat flux”, J. H. Davies and D. R. Davies (2010)

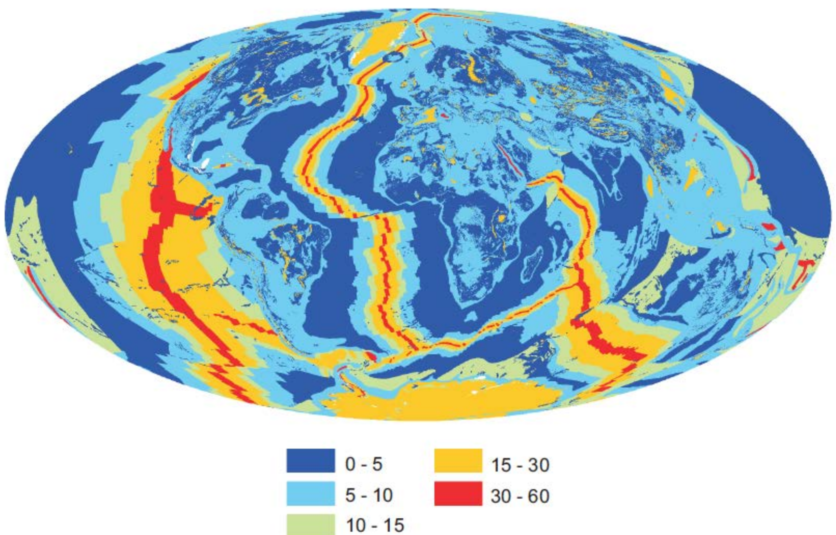
47±2 TW

38 347 measurements of the thermal flux

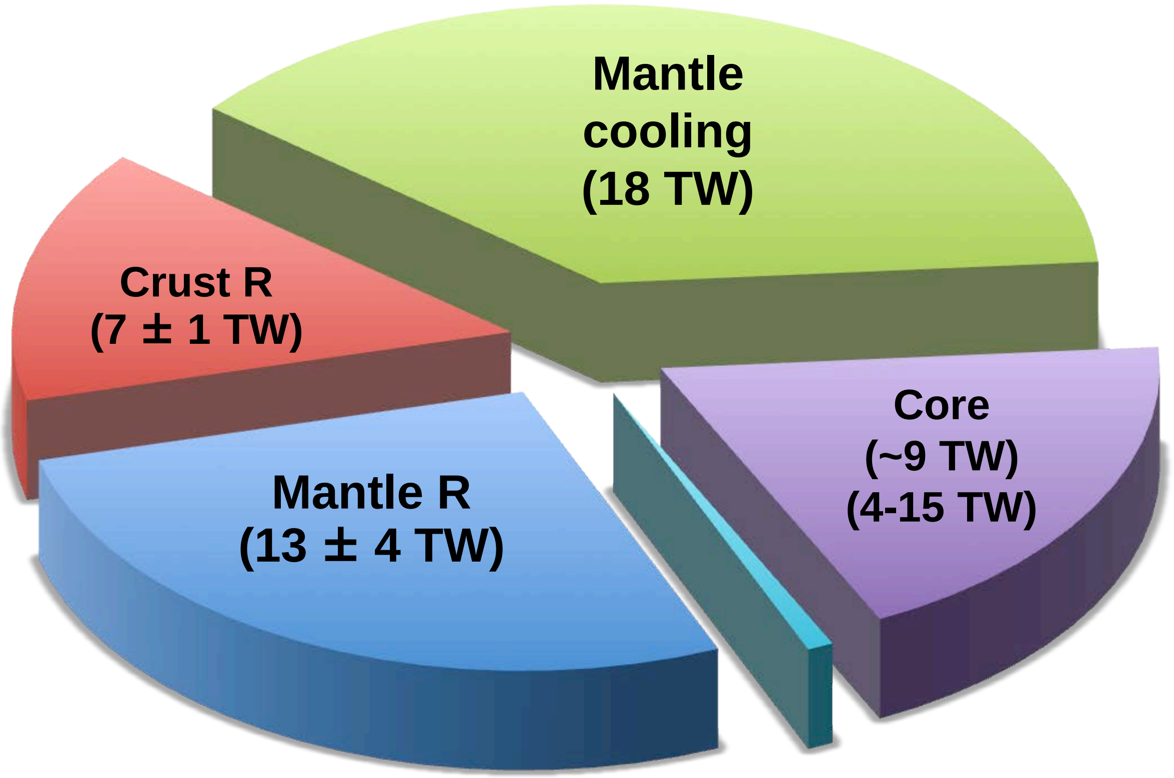
In agreement with previous estimations based on incomplete set of the same data

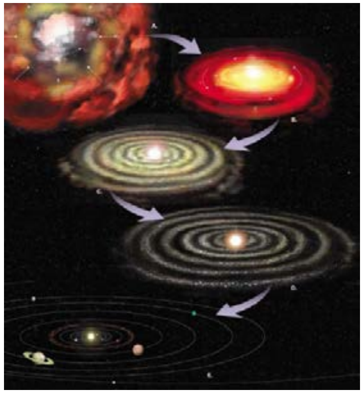
46±3 TW[Jaupart et al., 2007] and

44±1 TW [Pollack et al., 1993]



Earth's surface heat flow 47 ± 2 TW





total R: 20 ± 4

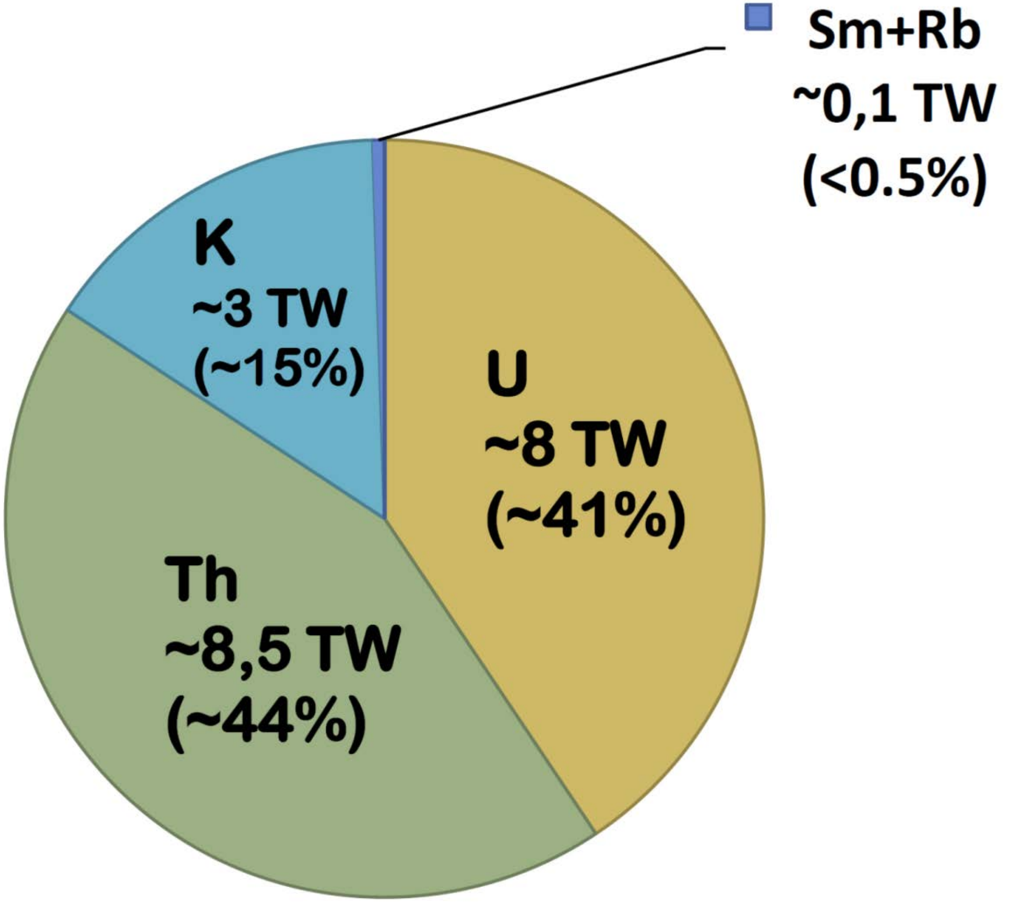
(0.4 TW) Tidal dissipation
Chemical differentiation

Urey=R/Tot

Primordial heat sources:
Gravitational energy
Short-lived isotopes decays
^{26}Al (7.17×10^{5} yr**)**

Open questions

- what is the radiogenic contribution to the total heat generated by the Earth?
- how much U, Th and K are distributed in the Earth's crust and mantle?
- what are the planetary Th/U and K/U mass ratios?
- how U and Th are distributed in the Earth's crust and mantle?

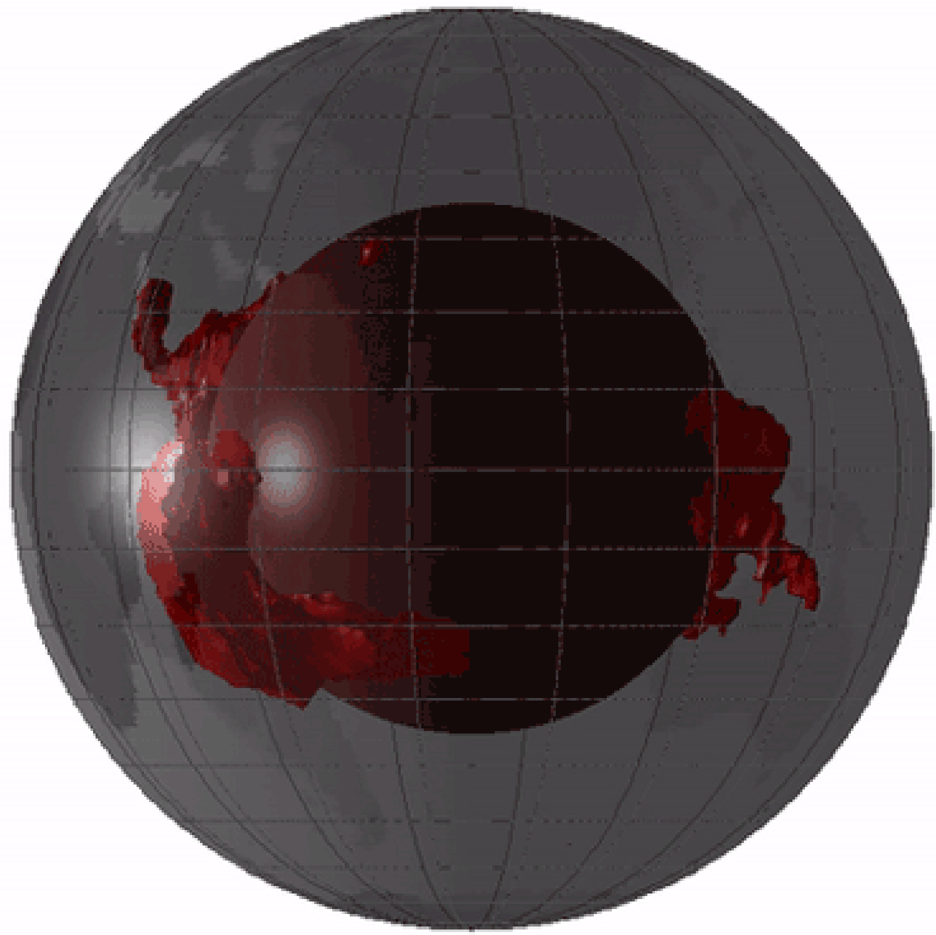


Open questions

- **is the mantle chemically uniform, layered, or more complicated?**
- **are there mantle reservoirs enriched in U and Th?**

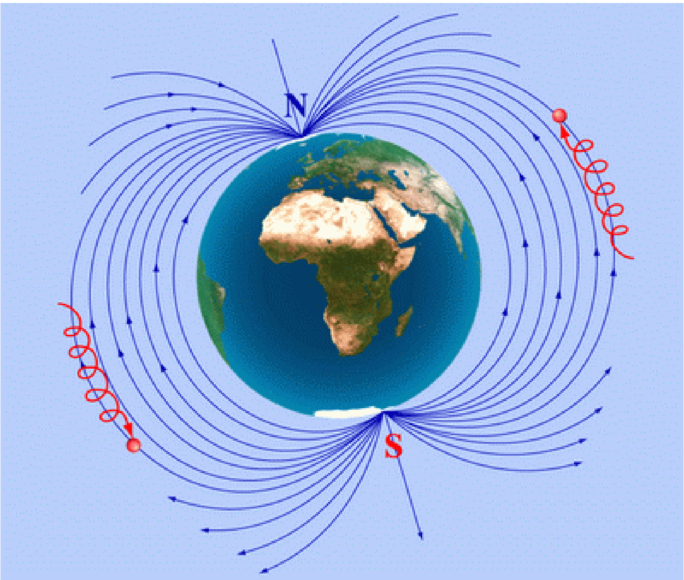
LLSVPs
by seismic tomography

(superwells, thermo-chemical piles, or hidden reservoirs)



Open questions

- is there any georeactor or hidden excessive ^{40}K in the Earth's core, as suggested by some theoreticians?
- are the geochemical Bulk Silicate Earth models consistent with geoneutrino data?
- which of the proposed Earth models will fit the observed geoneutrino flux?



Earth models and radiogenic heat

Sramek et al., Earth Planet. Sci. Lett., vol. 361, pp. 356-366, 2013

Cosmochemical (Low-Q) – based on the enstatine chondrites (E-chondrites), the only group of chondrites identical to the Earth composition **~10 TW**

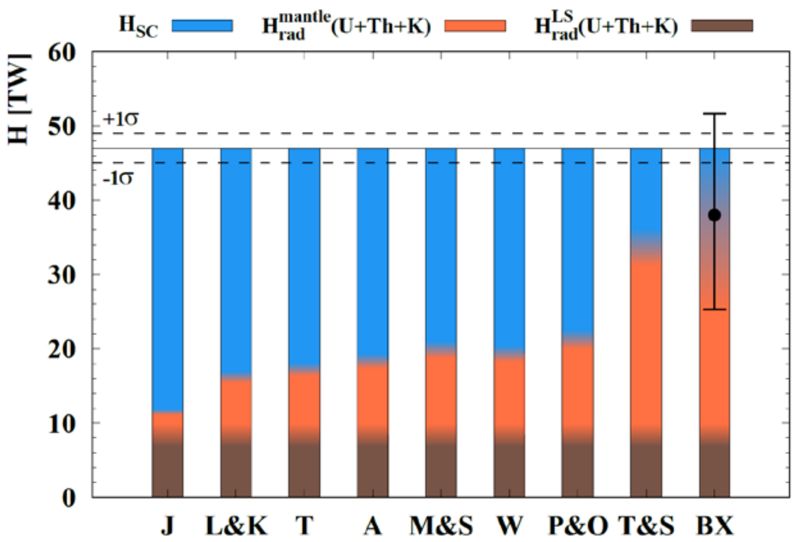
Geochemical (Med-Q) – based on carbonaceous chondrites CI with absolute abundancies from petrology **~20 TW**

Geophysical/geodynamical (High-Q) parametric convection – balancing mantle viscosity and heat dissipation **~30 TW**

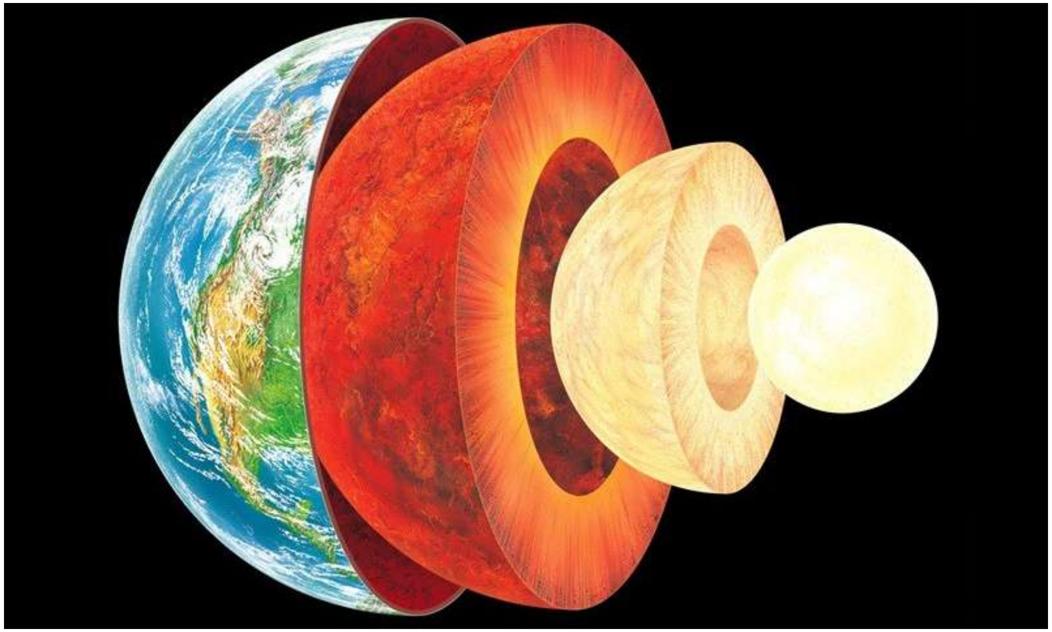
Secular cooling

Mantle

Lithosphere

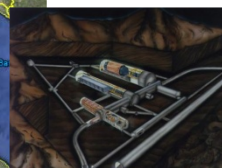


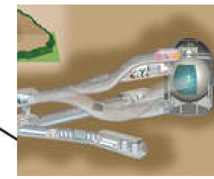
Models : mantle contribution

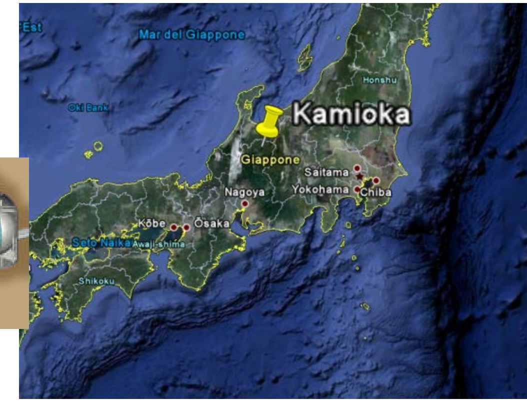


Model	Full flux,TW	Mantle, TW
Cosmochemical (Low-Q)	11 ± 2	3 ±2
Geochemical (Med-Q)	20 ± 4	12 ±4
Geophysical (High-Q)	33 ± 3	25 ±3

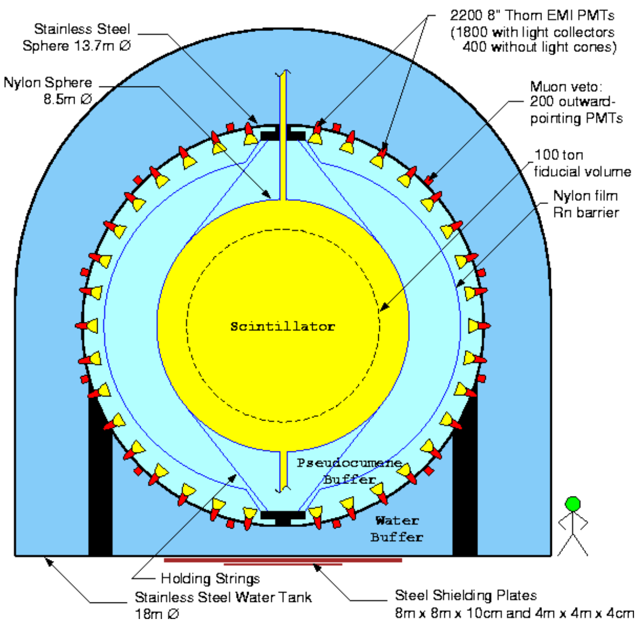
Two detectors measured geo-neutrino

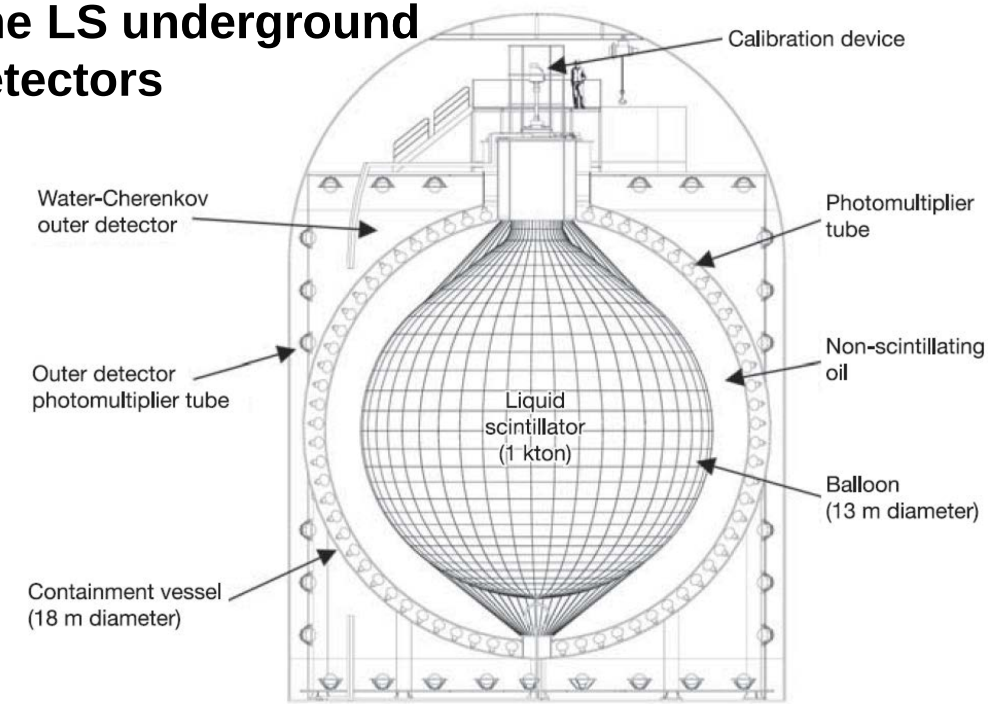






Large volume LS underground detectors





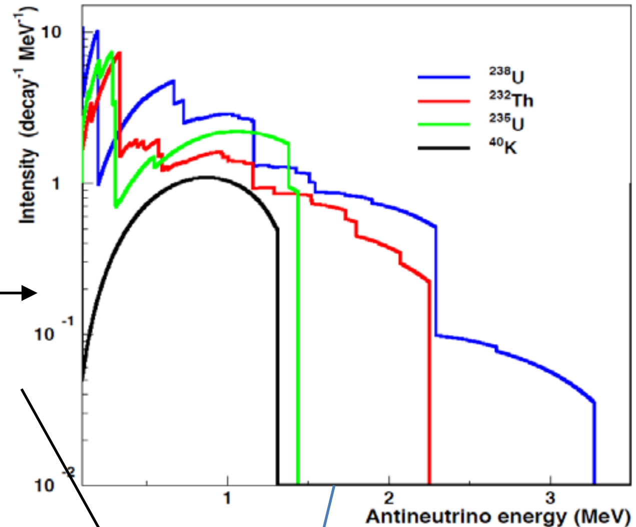
Borexino: 300 t LS (3500 mwe)

KamLAND: 1 kton LS (2200 mwe)

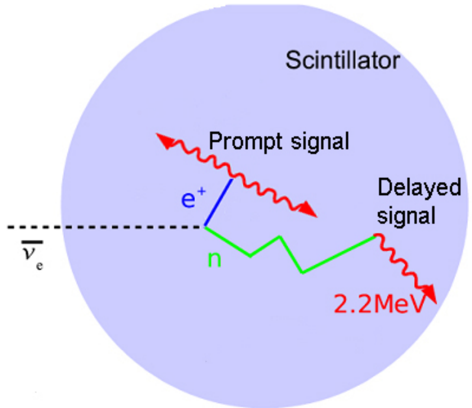
Detection of geo(anti)neutrino

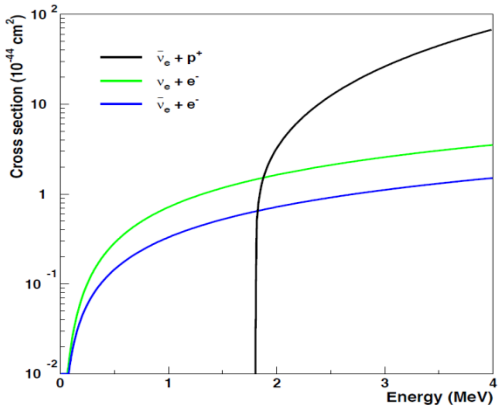
$$\Phi_{\bar{\nu}} \sim 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

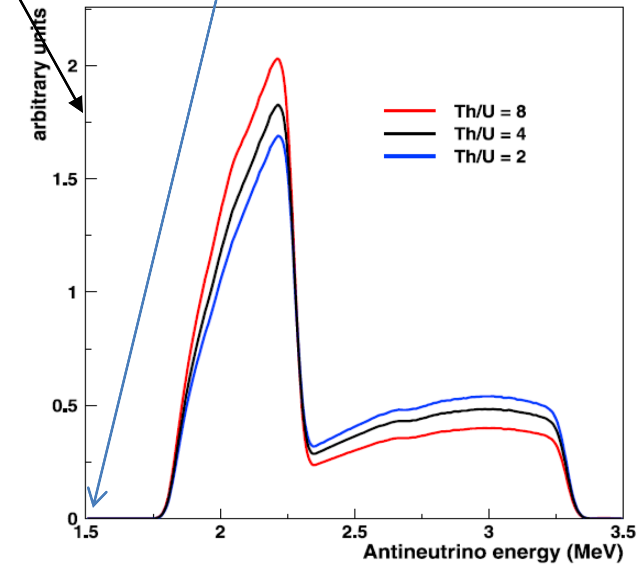
- Earth (in construst to the Sun) emits antineutrino.
- Part of antineutrino in the U and Th decay chains is emitted with E>1.8 MeV (IBD threshold)
- Contributions from U and Th are distinguishable
- Oscillations are averaged: <Pee>≈0.56±0.02



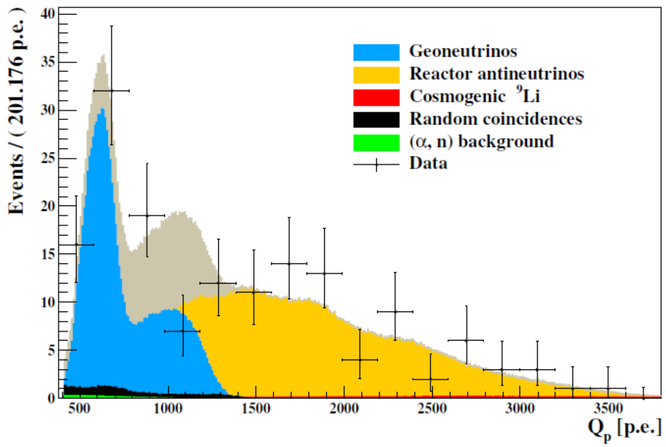
$$\bar{\nu} + p \rightarrow n + e^+ \qquad E_\nu > 1.8\ \mathrm{MeV}$$



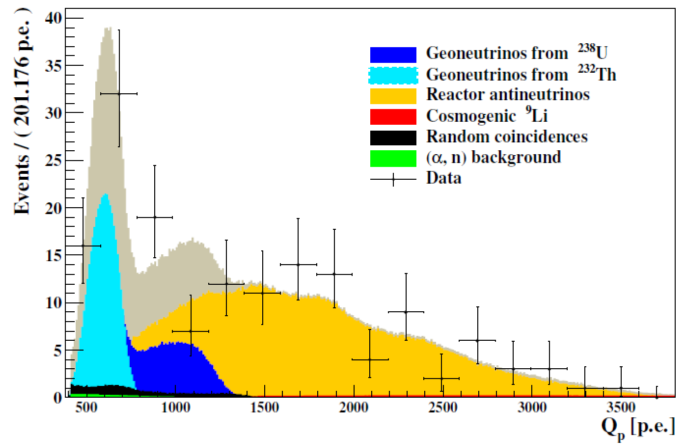




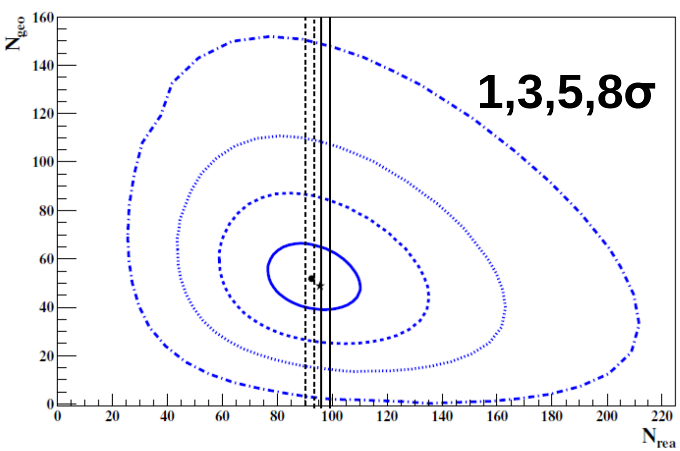
Borexino-2019 : 154 candidates

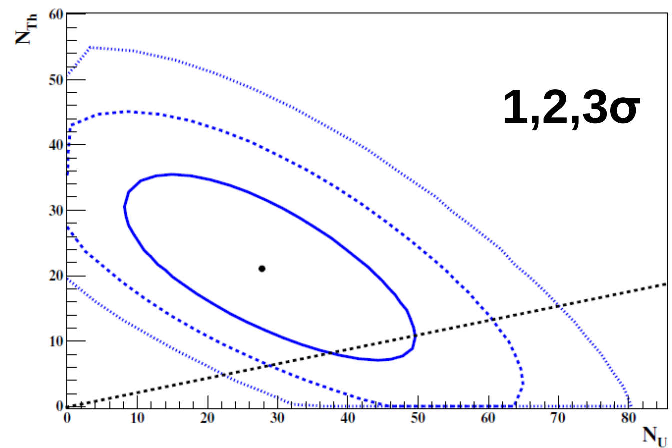


(a)



(b)





52.6 +9.4/-8.6(stat) +2.7/-2.1(syst) events (Th/U=3.9)

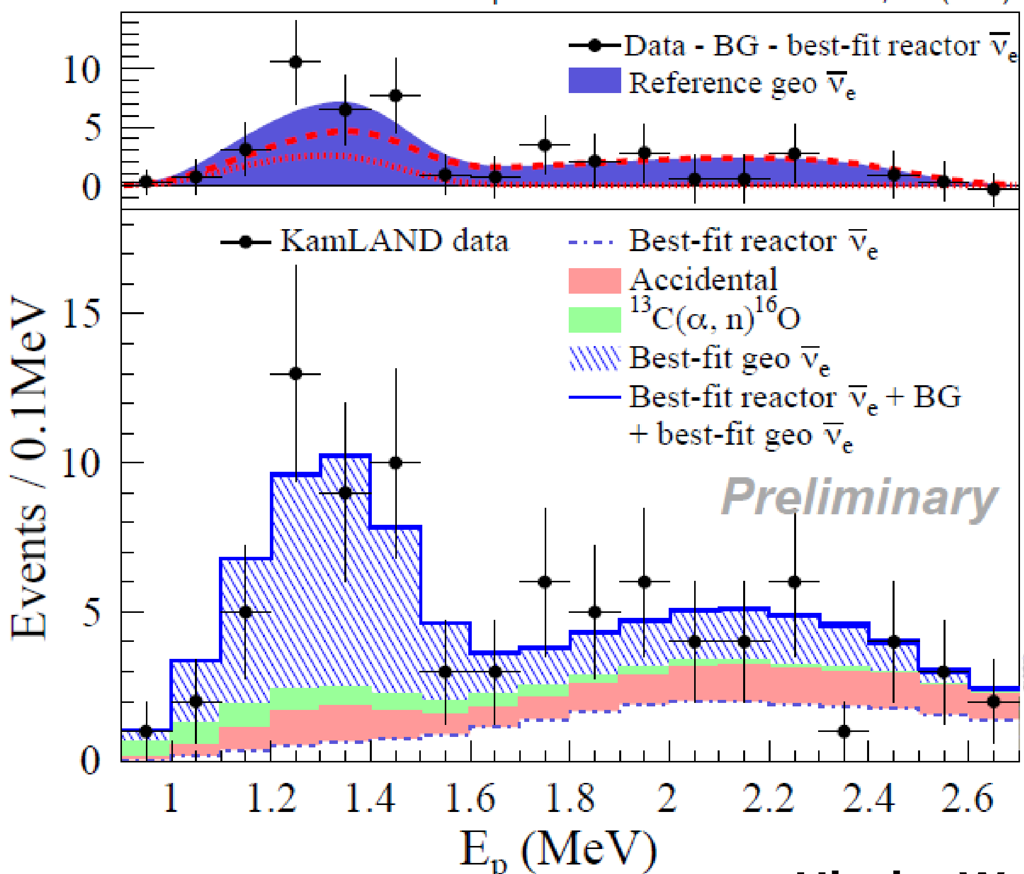
+17/-15 %   +18.3/-17.2 %

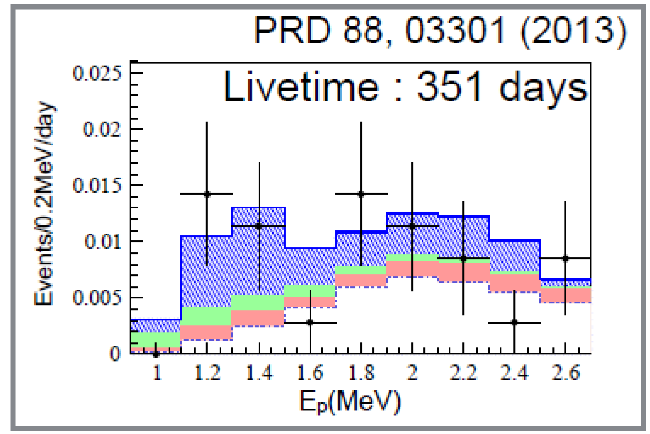
arXiv:1909.02257

KL energy spectrum : Period 3 (0.9-2.6 MeV)

Livetime : 1259.8 days <u>2016 Preliminary Result</u>

model prediction : Enomoto et al. EPSL 258, 147 (2007)



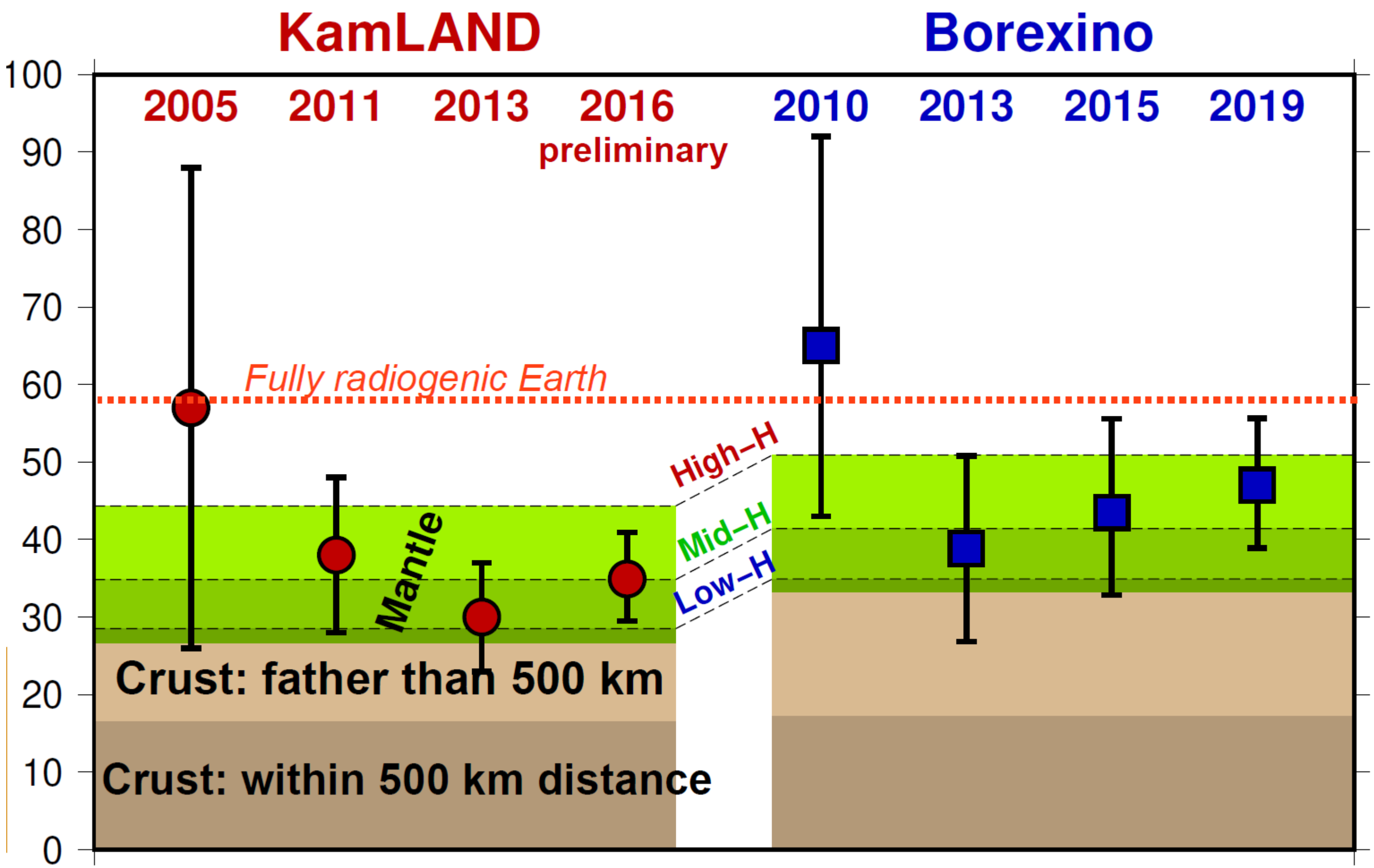


☑ We measured clear distribution of geo-neutrino events.

<u>best-fit : Period 3 analysis</u>

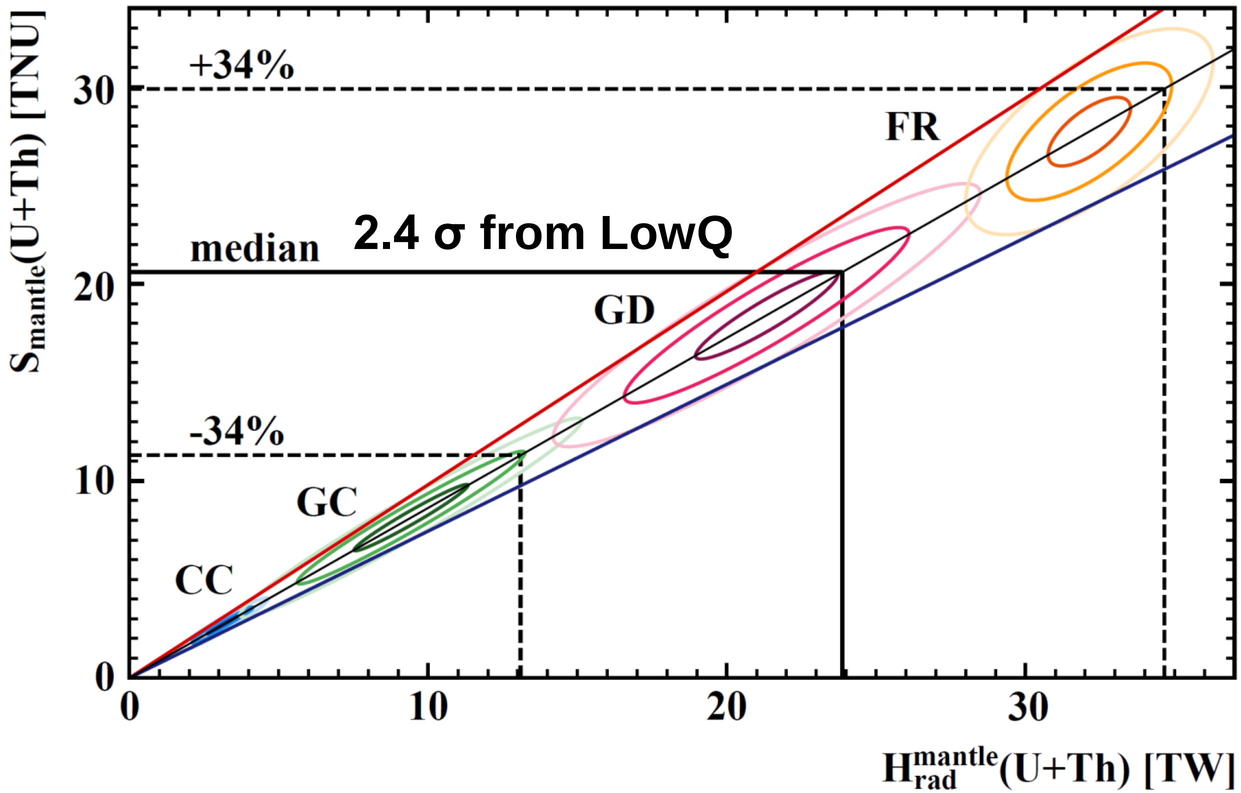
Hiroko Watanabe : NuGeoscience – 2016
New results : NuGeoscience-2019 (Prague, 20-23/X 2019)

KL & Borexino results



2.4 σ from LowQ

Radiogenic heat: Borexino

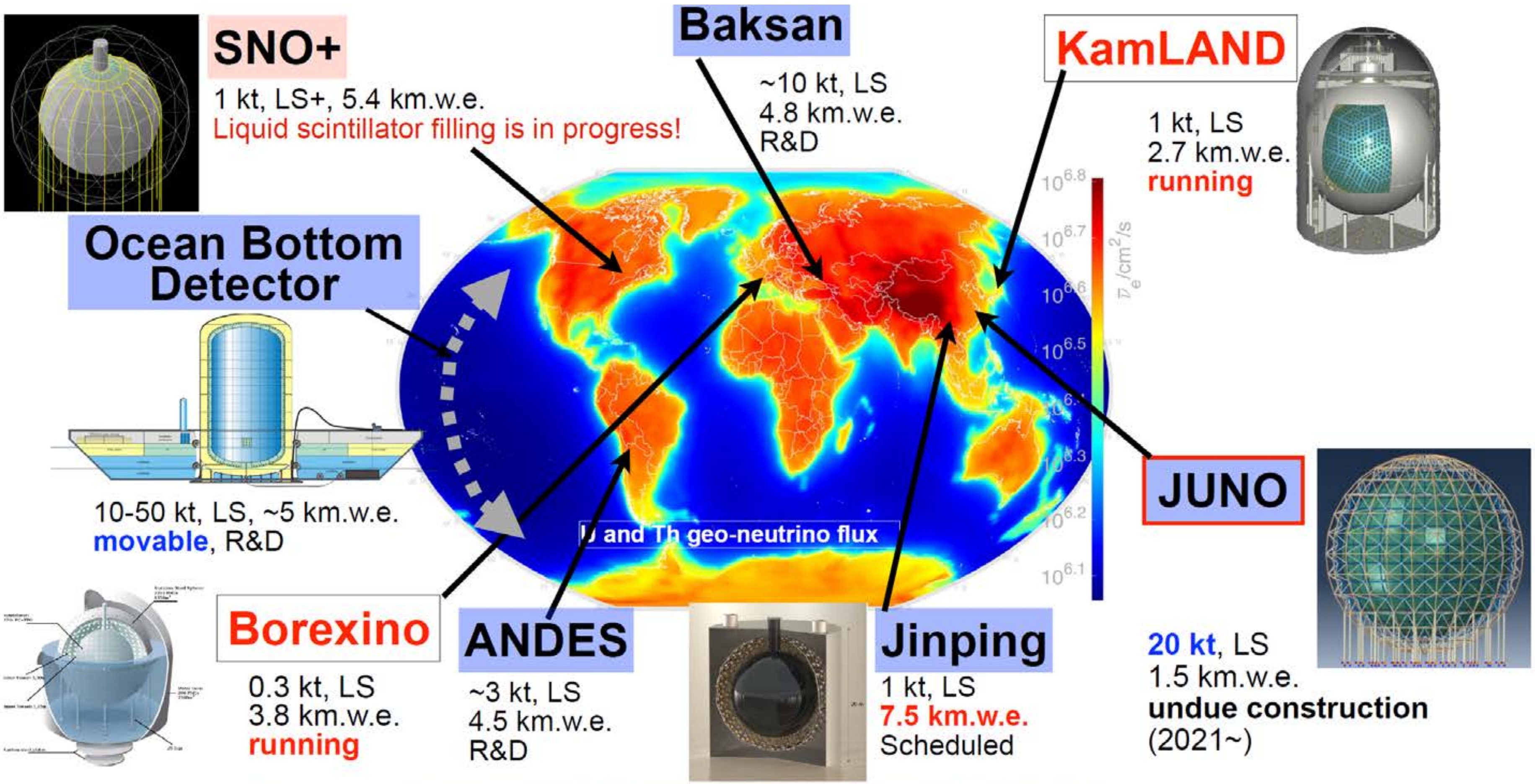


***1 TNU = 1 event on 10^{32} protons in 1 yr (~1 kt of LS)**

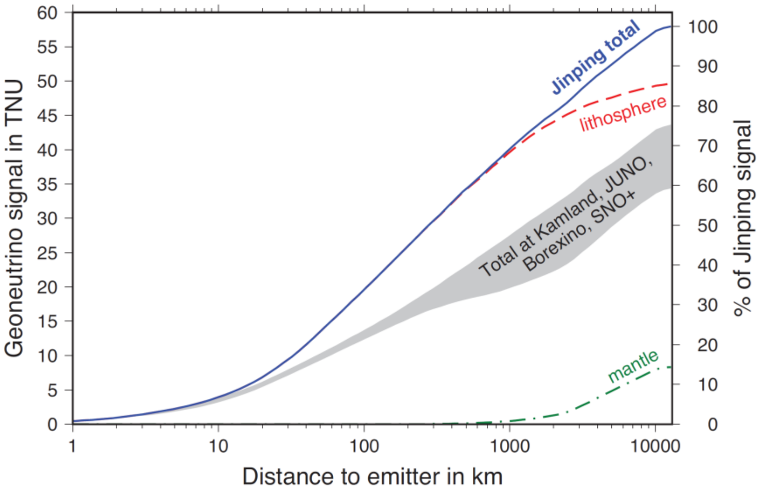
Lithospheric heat due to U+Th+K:
H_{LS} = $8.1^{+1.9}_{-1.4}$ TW
(direct samping**)**

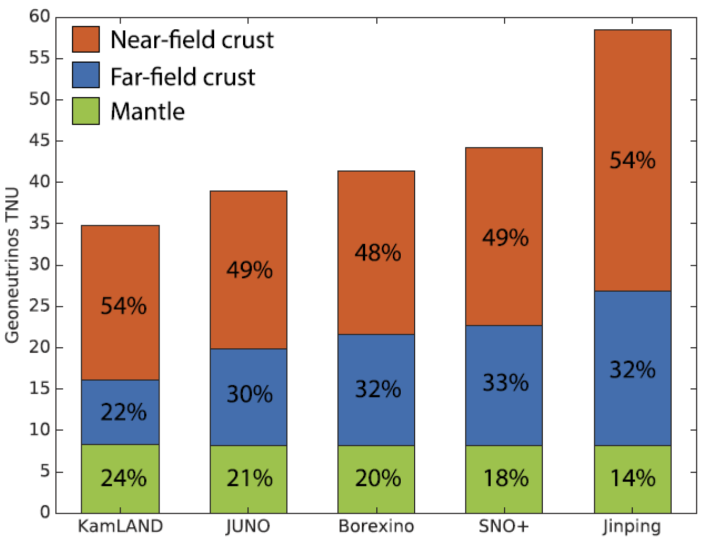
Assuming 18% ^{40}K contribution to the mantle heat:
H_{tot}(U + Th + K) = $38.2^{+13.6}_{-12.7}$ TW,
vs global terrestrial **47±2 TW**

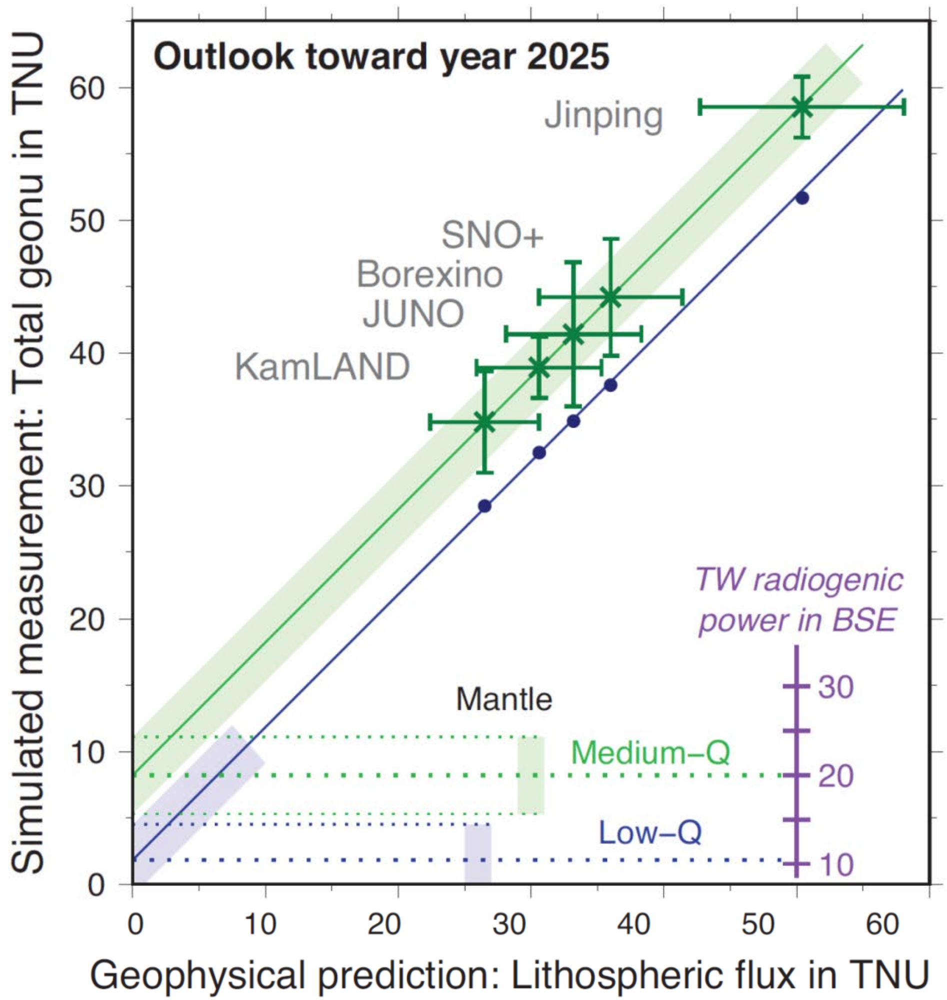
Current & future experiments



Extracting mantle signal from combined data

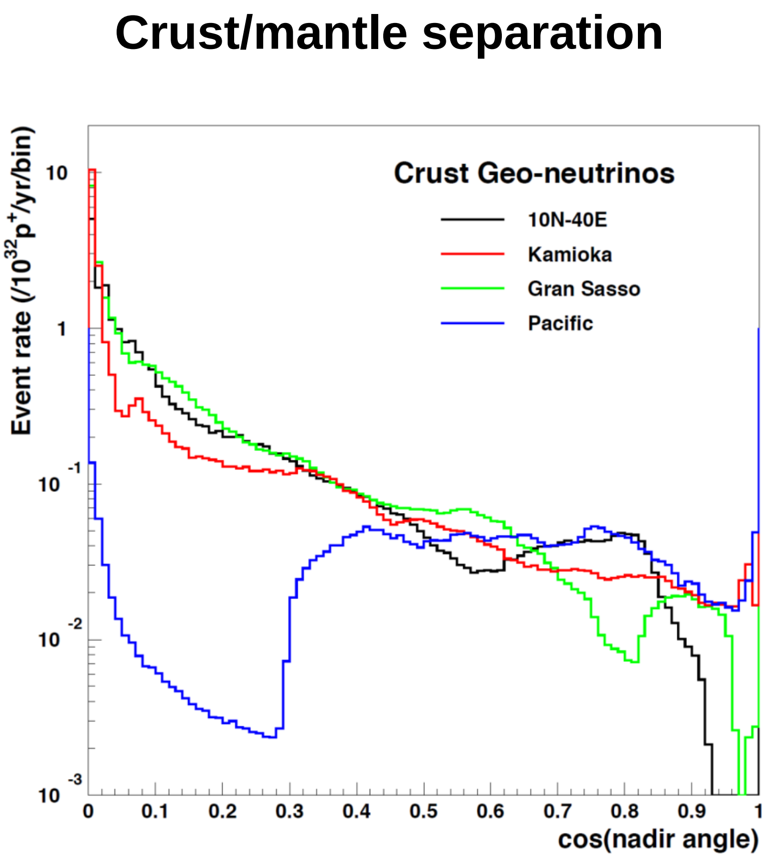


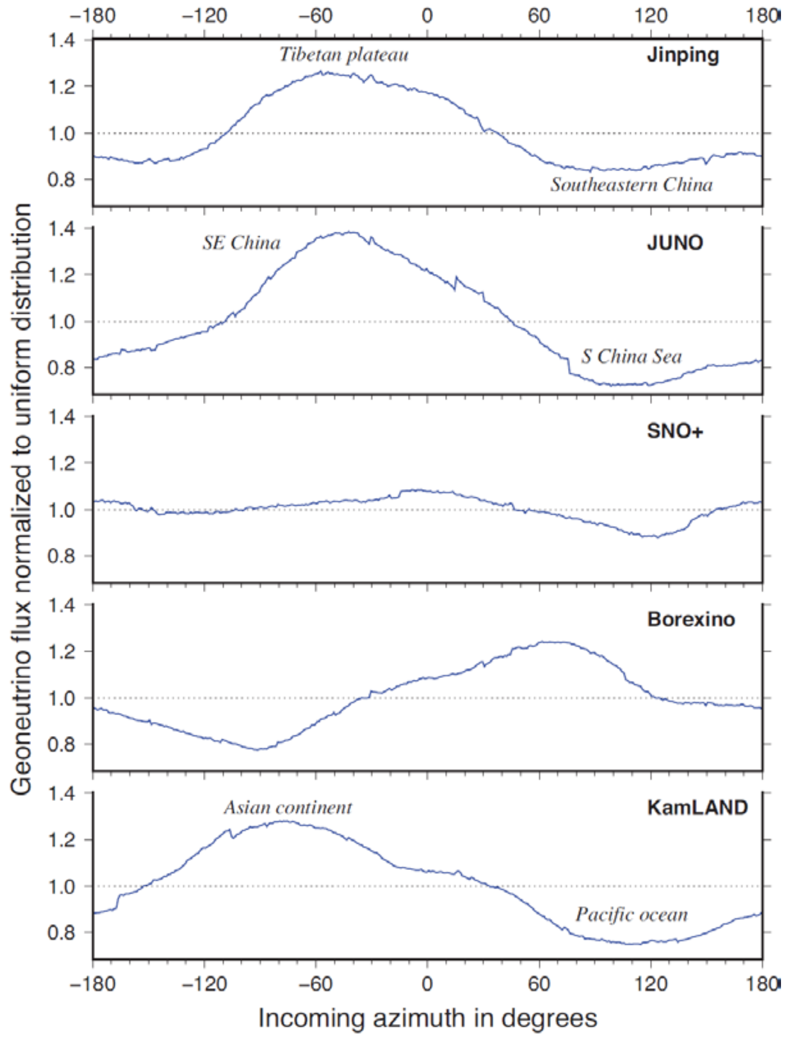




From O.Šrámek et al SCIENTIFIC REPORTS 6:33034

Directionality





Highlights

- **Geoneutrinos are a tool to study the deep Earth and new generation of experiments are needed for firm geological conclusions**

- Borex: **$52.6^{+9.4}_{-8.6}$(stat)$^{+2.7}_{-2.1}$ (sys)** events ($^{+18.3}_{-17.2}$ %)
- KL : **164^{+28}_{-25}** events (17%)

both with fixed M(Th)/M(U) ratio

- Mantle signal:

BRX: $21.2^{+9.6}_{-9.1}$ TNU; P(0)<0.01
KL : $8.2^{+6.6}_{-6.0}$ TNU

- KamLand: Th/U ratio:

$M(Th)/M(U)=4.1^{+5.5}_{-3.3}$

Experiment: events/yr

- **BRX : 4.2**
- **KL : 14**
- **SNO+ : 25**
- **Jinping : 100**
- **JUNO : 400**