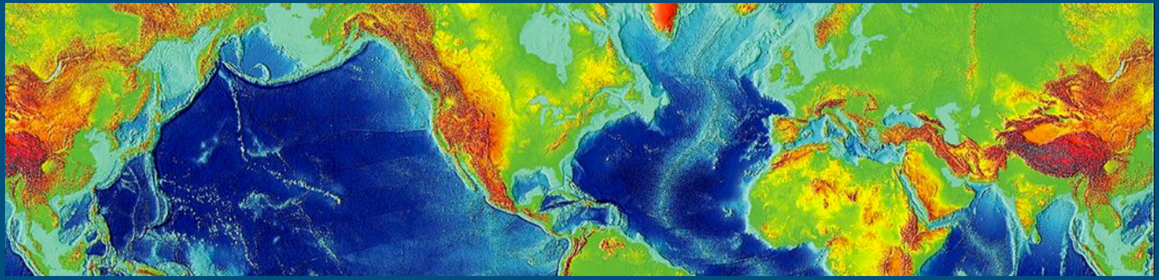
OVERVIEW ON SOLAR, GEO, AND REACTOR NEUTRINO EXPERIMENTS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GERMANY

NOVEMBER 26TH, 2018

WIEN, AUSTRIA

Symposium on Prospects in the Physics of Discrete Symmetries, DISCRETE 2018

OUTLINE

1. **Neutrino physics**
   - ✓ Introduction
   - ✓ Opened questions

2. **Solar neutrinos**
   - ✓ Motivation
   - ✓ Latest results from Borexino and SuperKamiokande

3. **Geoneutrinos**
   - ✓ Motivation
   - ✓ Latest results from Borexino and KamLAND

4. **Reactor neutrino experiments**
   - ✓ What to measure at different baselines
     - KamLAND oscillation results
     - Theta13-experiments (Daya Bay, Double Chooz, RENO)
     - Very short baseline experiments and sterile neutrino
     - JUNO and mass hierarchy

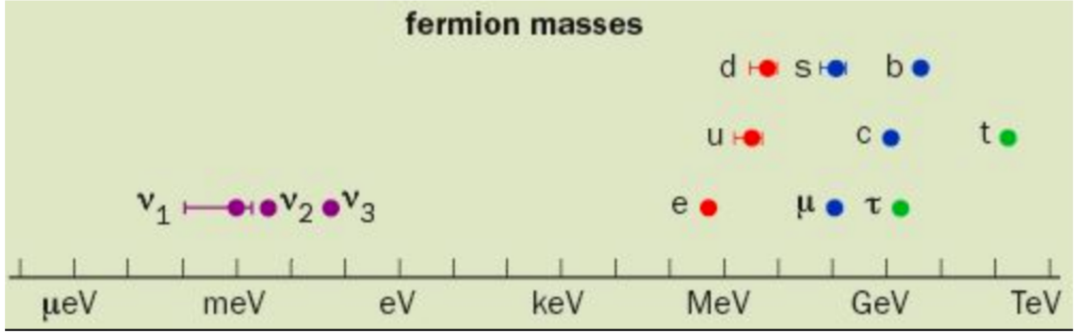
NEUTRINOS ARE SPECIAL

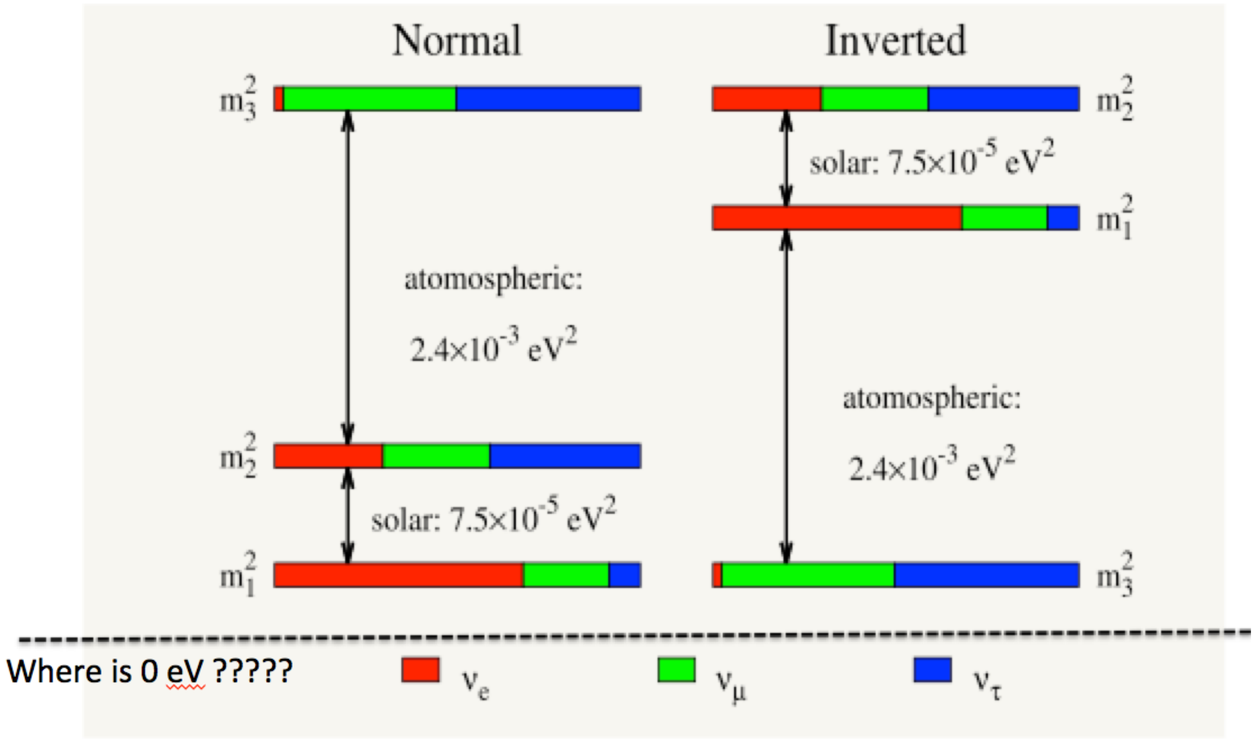
Only weak interactions

- ✓ **Difficult to detect**
  - o Large detectors
  - o Underground laboratories
  - o Extreme radio-purity
- ✓ **Bring unperturbed information about the source**

Opened questions in neutrino physics

- ✓ Absolute mass-scale
- ✓ Origin of neutrino mass (Dirac vs Majorana)
- ✓ Mass Hierarchy (Normal vs Inverted)
- ✓ CP-violating phase
- ✓ Octant of θ_{23} mixing angle
- ✓ Existence of sterile neutrino





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NEUTRINO MIXING AND OSCILLATIONS

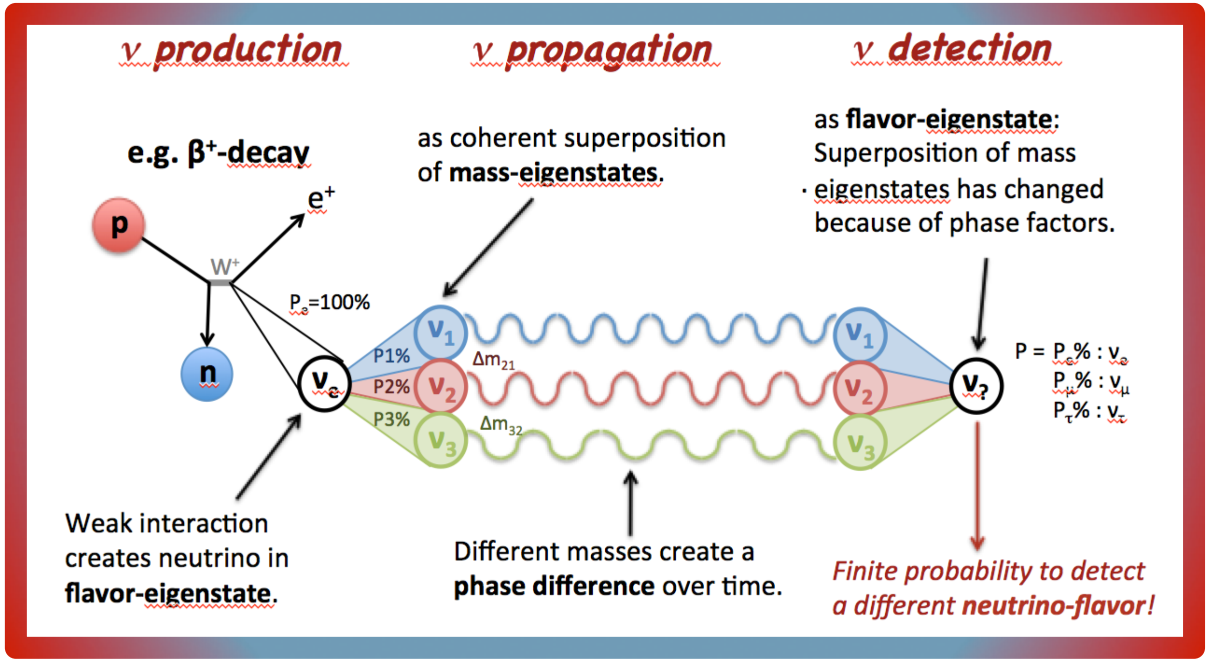
α = e, μ, τ
Flavour eigenstates
INTERACTIONS

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Reactor | Solar | Majorana



Courtesy M. Wurm

- **3 mixing angles θ_{ij}:**
  - $\theta_{23} \approx 45°$ (which quadrant?)
  - $\theta_{13} \approx 9°$ (non-0 value confirmed in 2012)
  - $\theta_{12} \approx 33°$
- **Majorana phases $\alpha 1$, $\alpha 2$** and **CP-violating phase δ** unknown

- **Neutrino oscillations**
  - Non-0 rest mass (Nobel prize 2015)
  - Survival probability of certain flavour = f(baseline L, E_ν)
  - Different combination (L, E_ν) => sensitivity to different (θ_{ij}, Δm_{ij}^2)
  - Appearance/disappearance experiments
  - Oscillations in matter -> effective (θ_{ij}, Δm_{ij}^2) parameters = f(e^- density N_e, E_ν)

See review talk of M. Tortola on Thursday!

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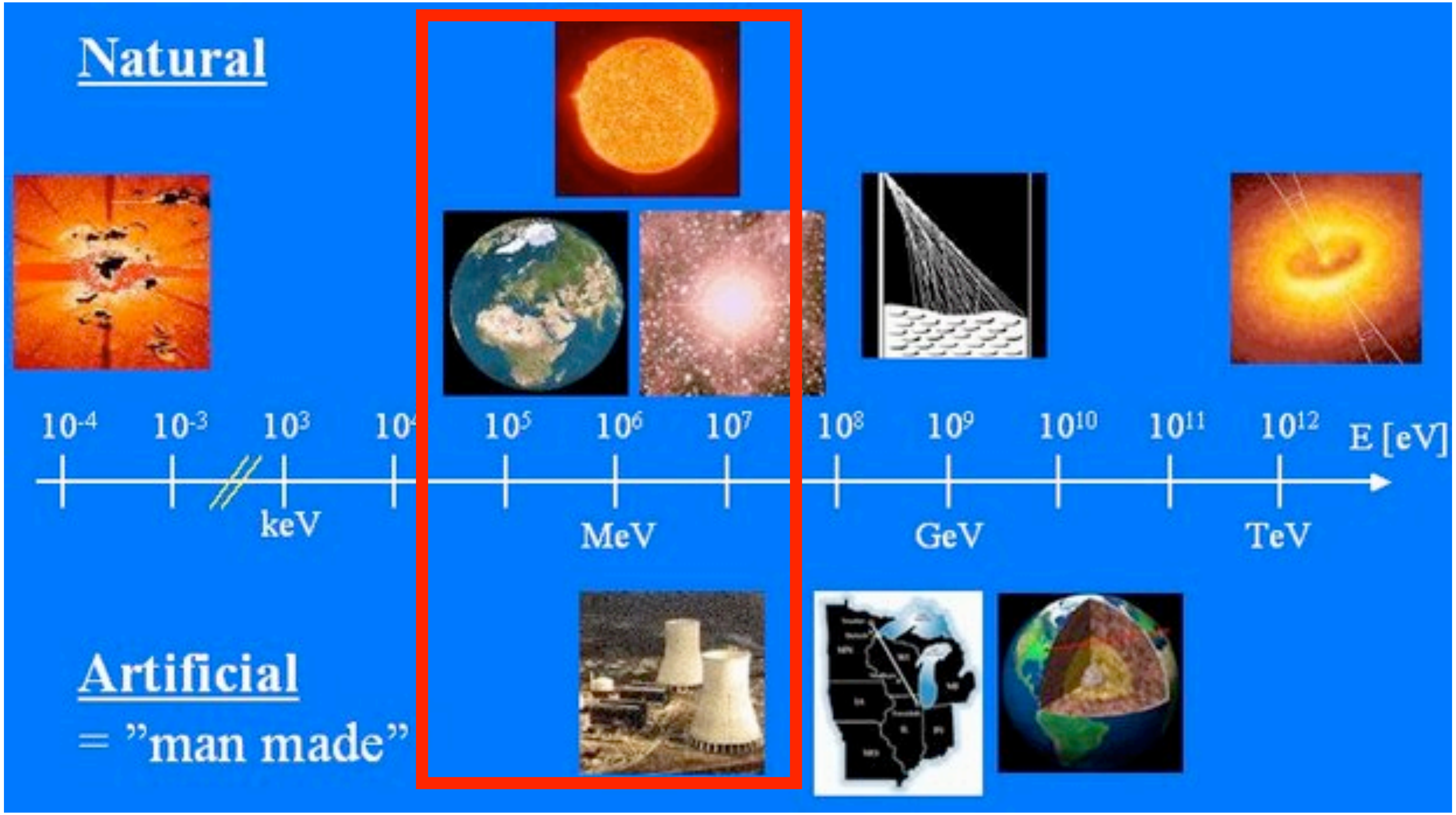
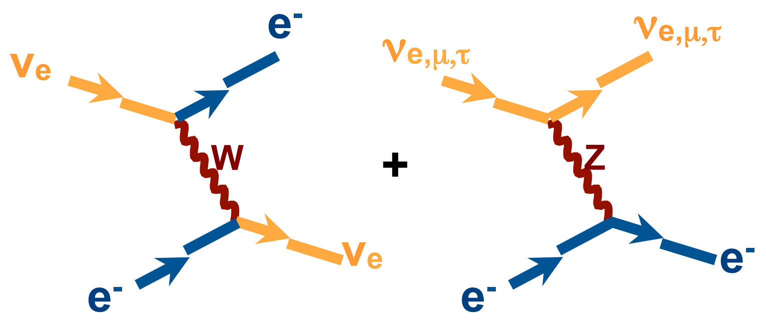
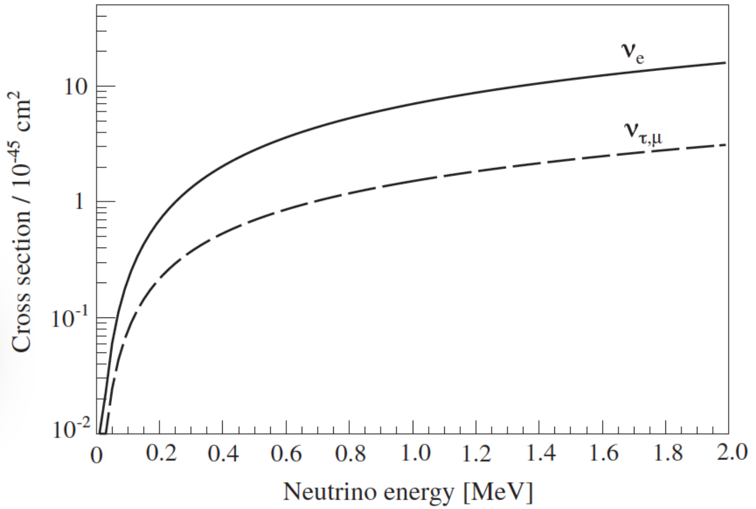
NEUTRINO SOURCES



MeV NEUTRINO AND ANTINEUTRINO DETECTION

Neutrino detection: SINGLES
- elastic scattering off electrons
- Liquid scintillator detectors
- Water-Cherenkov detectors

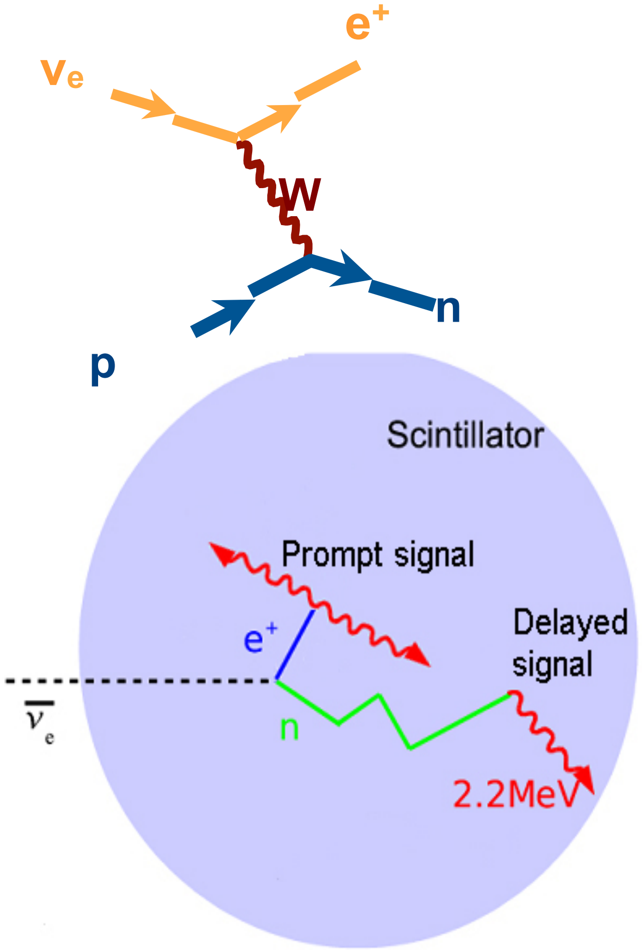




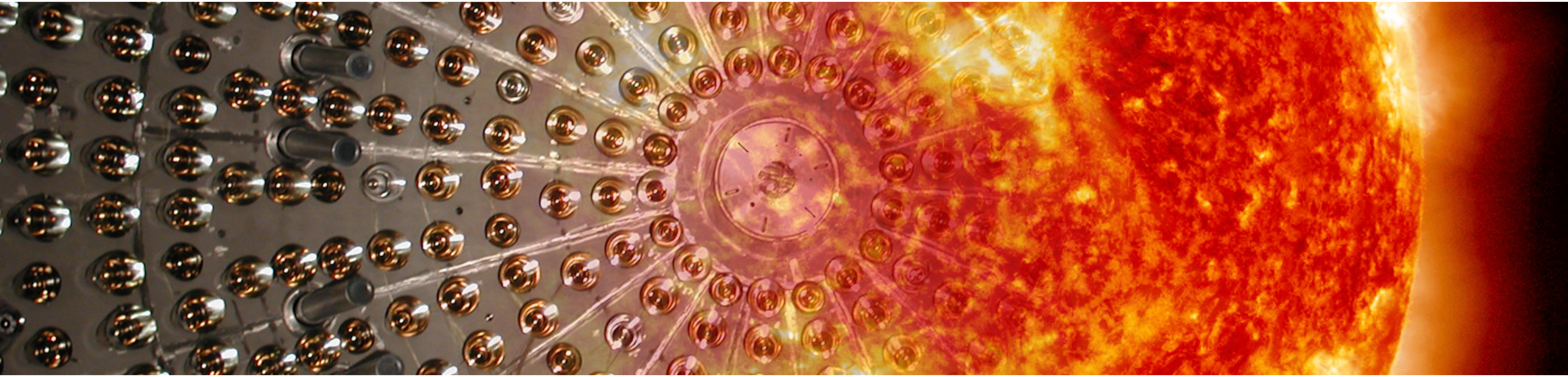
Antineutrino detection: Coincidences (BGR suppression)
- Inverse beta decay (IBD)
- Liquid scintillator detectors

Energy threshold = 1.8 MeV
Electron flavour only
σ@ few MeV: ~10^{-42} cm^2
(~100 x more than scattering)

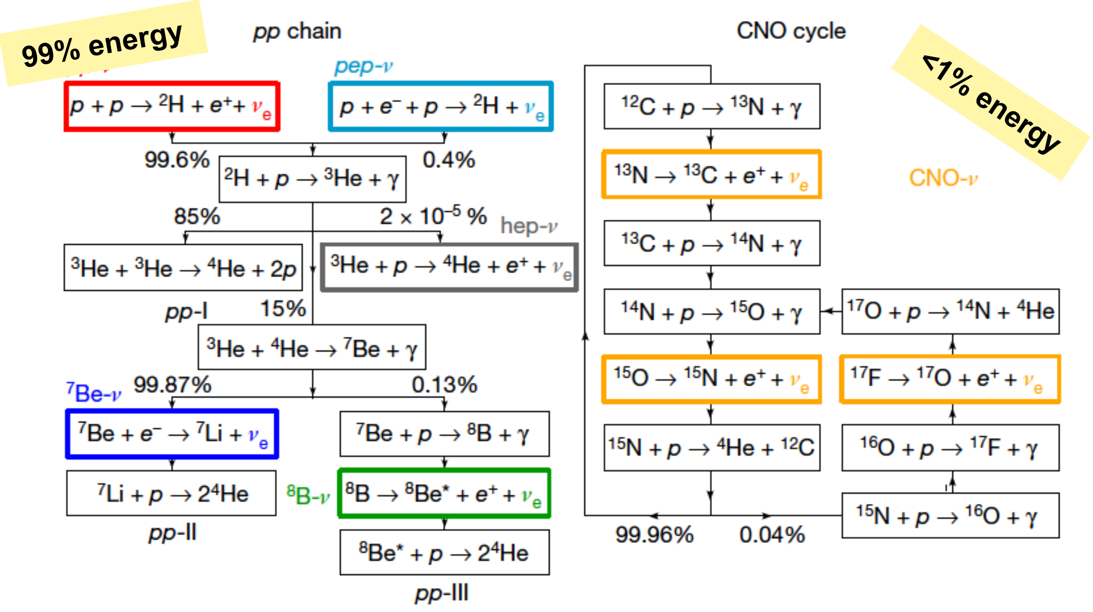
$$E_{prompt} = E_{visible} = T_{e+} + 2 \times 511\ \text{keV} = E_{antinu} - 0.784\ \text{MeV}$$

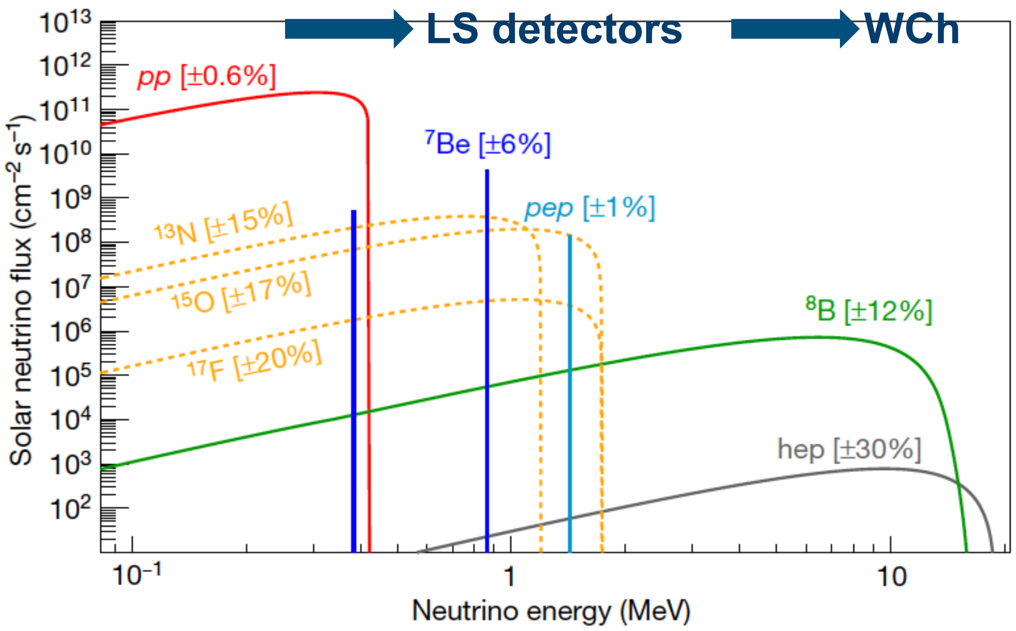


SOLAR NEUTRINOS



SOLAR NEUTRINOS AND WHY TO STUDY THEM





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

Solar and stellar physics

- Direct probe of **nuclear fusion**
- Testing **thermodynamical stability** of the Sun
- **Standard Solar Models**
  - ✓ Helioseimology
  - ✓ High-Z and Low-Z models (different ϕ_ν prediction)
  - ✓ Metallicity problem

Neutrino physics

- **Survival probability as f(E_ν)** and its upturn
- Matter effects
- Testing LMA-MSW predictions
- Searches for **Non-standard Neutrino Interactions**
- Solar mixing angle θ_{12} and global fits of **oscillation parameters**

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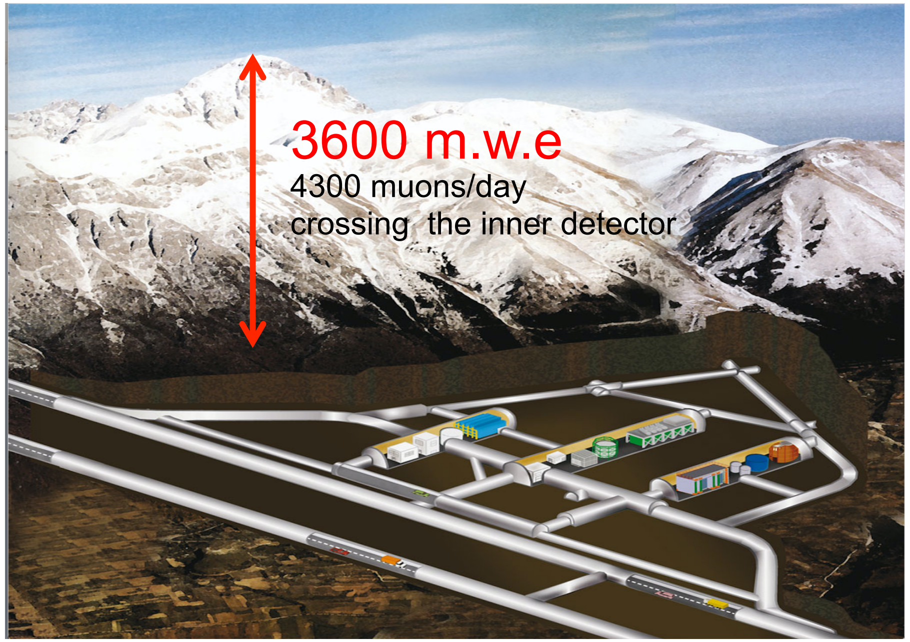
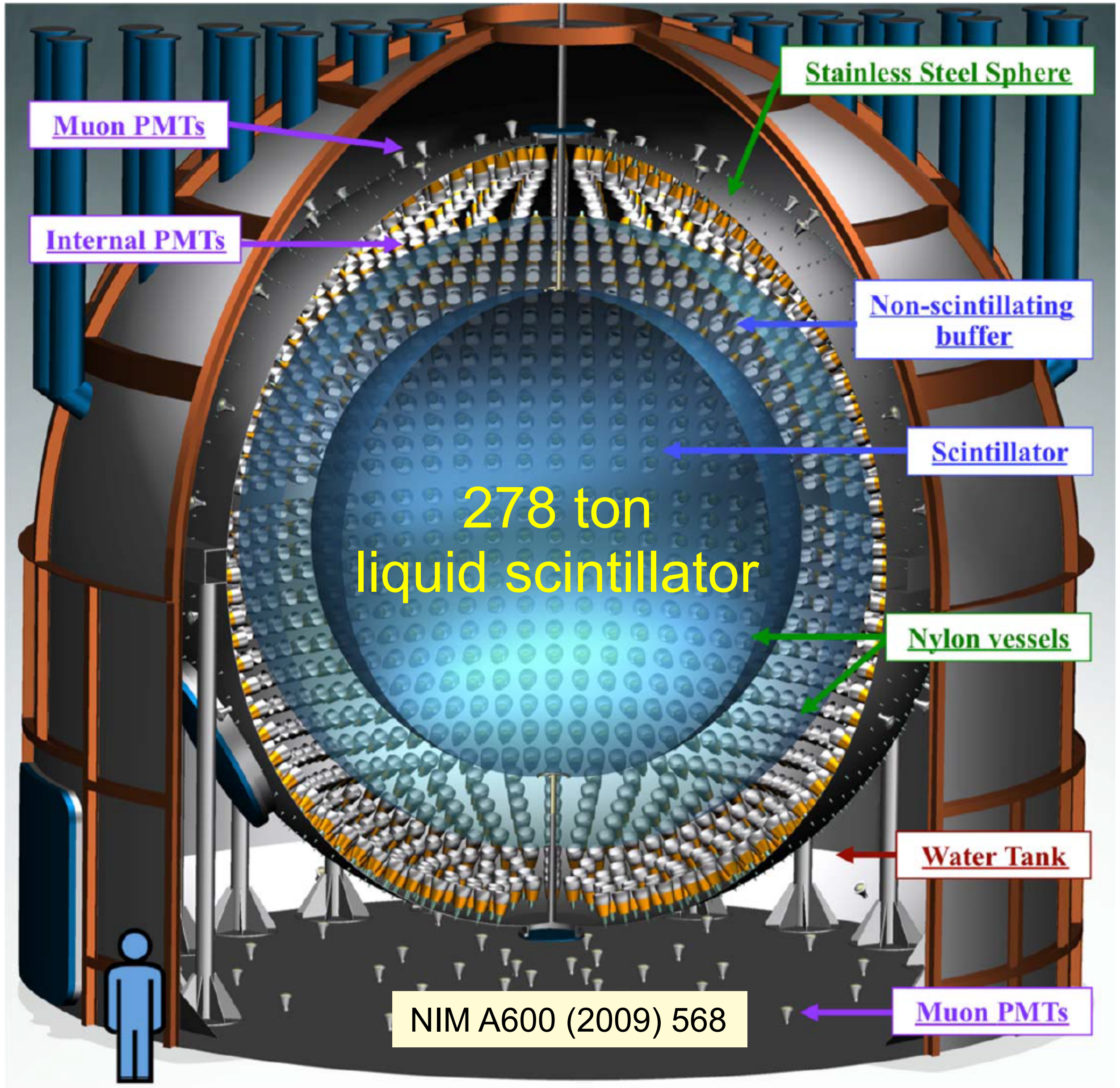
BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy

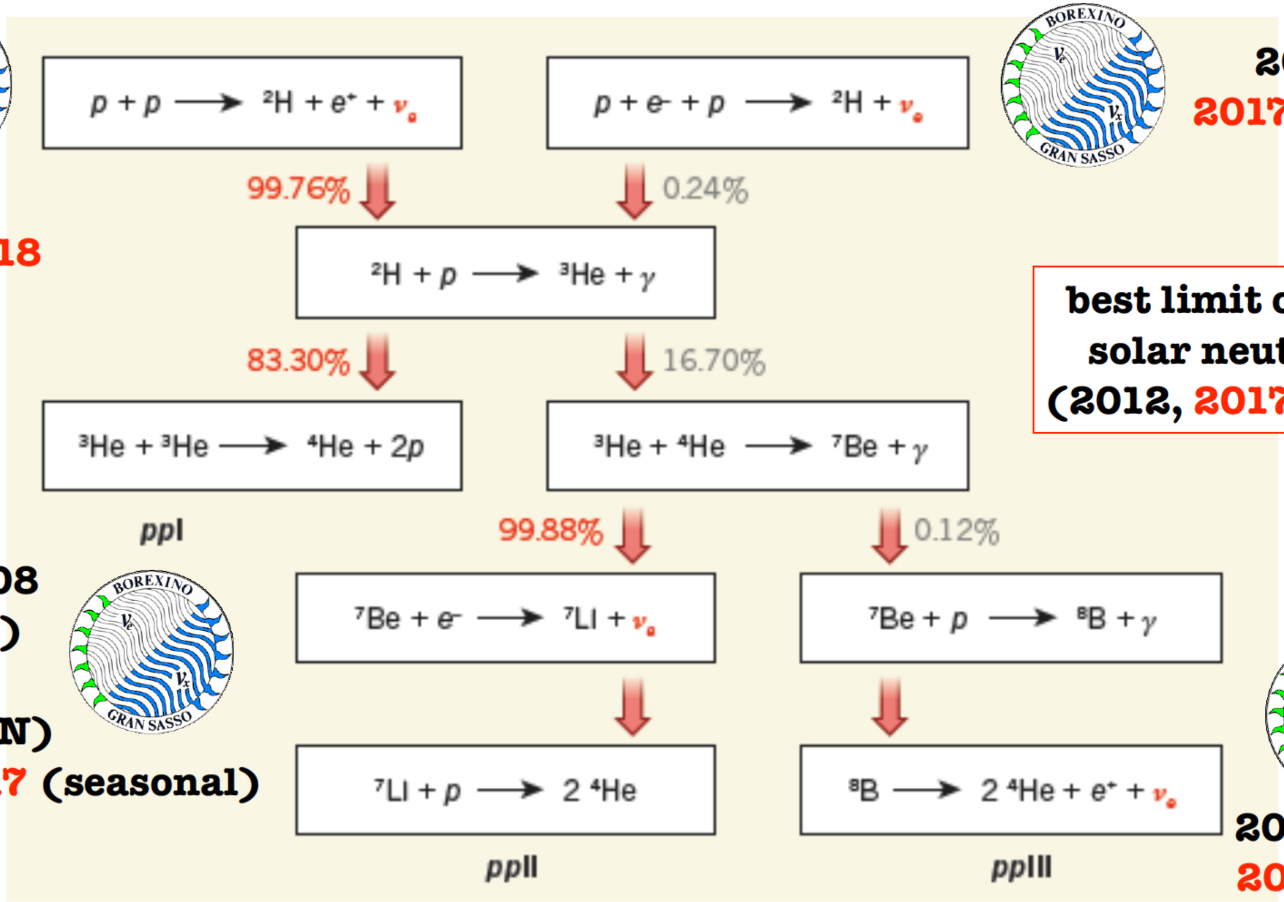


- **the world's radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g , $< 8 \times 10^{-20}$ g(U)/g
- **550 hit PMTs / MeV**
- energy reco: 5 keV (5%) @ 1 MeV
- position reco: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



Operating since 2007

BOREXINO MILESTONE RESULTS



2014
2017/2018

2012
2017/2018

best limit on CNO solar neutrinos (2012, 2017/2018)

2007/2008
2011 (5%)
2017
2012 (D/N)
2014, 2017 (seasonal)

2010, 2013
2017/2018

Courtesy A. Pocar, PIC 2018

- Geoneutrinos (2010, 2013, 2015)
- Search for solar, astro anti-ν (2011)
- Test of electric charge conservation (2015)
- Limit on ν-magnetic moment (2017)
- Search for solar axions (2008, 2012)
- Search for coincidence with GRB's (2016)
- Search for coincidence with GRB's (2016)
- Search for coincidence with GW's (2017)

LATEST BOREXINO RESULTS

Spectroscopy of all pp-cycle neutrinos at once

Low Energy Region (LER) 0.19 – 2.93 MeV:

pp (9.5%), **^{7}Be** (2.7%), ***pep*** (>5σ)

High Energy Region (HER) 3.2 – 16 MeV:

^{8}B (3 MeV threshold, 8%)

- First Borexino limit on **hep** neutrinos
- Limit on **CNO cycle** neutrinos
- Neutrino and photon luminosity in agreement

ARTICLE

Nature Oct 25th 2018

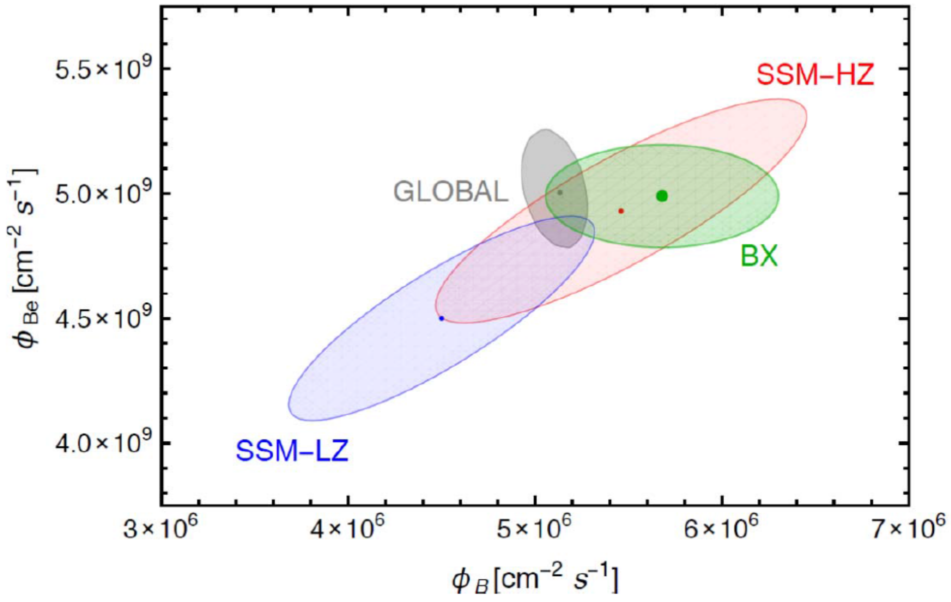
https://doi.org/10.1038/s41586-018-0624-y

NEW

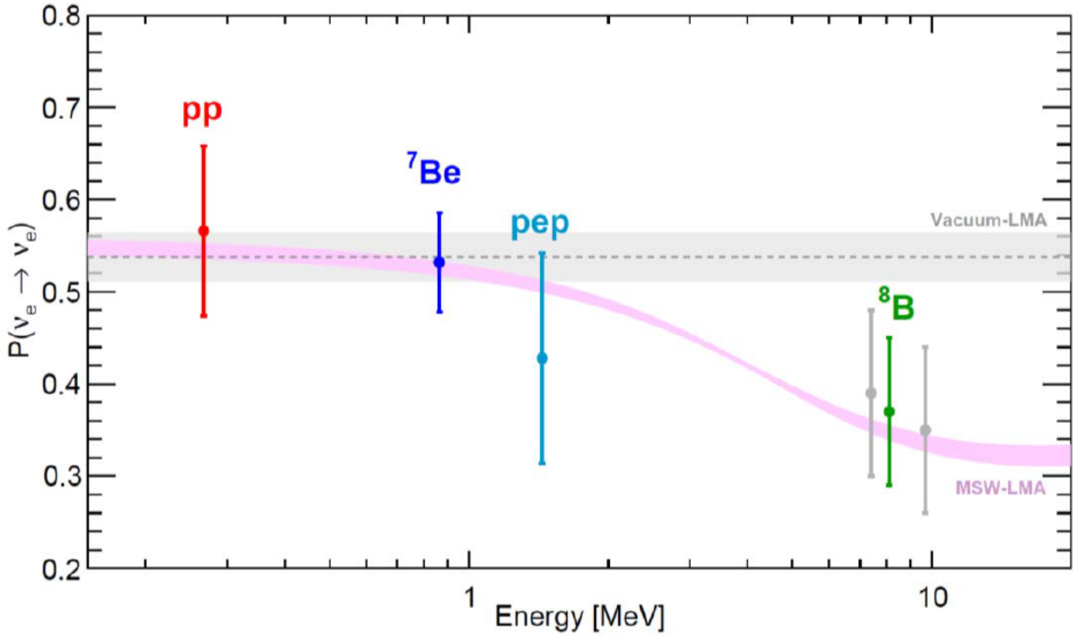
Comprehensive measurement of *pp*-chain solar neutrinos

The Borexino Collaboration*

- Indication towards **HZ Standard Solar Models**
- BR(pp_{II}/pp_{I})=<^{3}He+^{4}He>/<^{3}He+^{3}He> = 0.18±0.03
- Survival probabilities at different energies in both vacuum and matter domains
- **Vacuum-LMA model excluded at 98.2% CL**



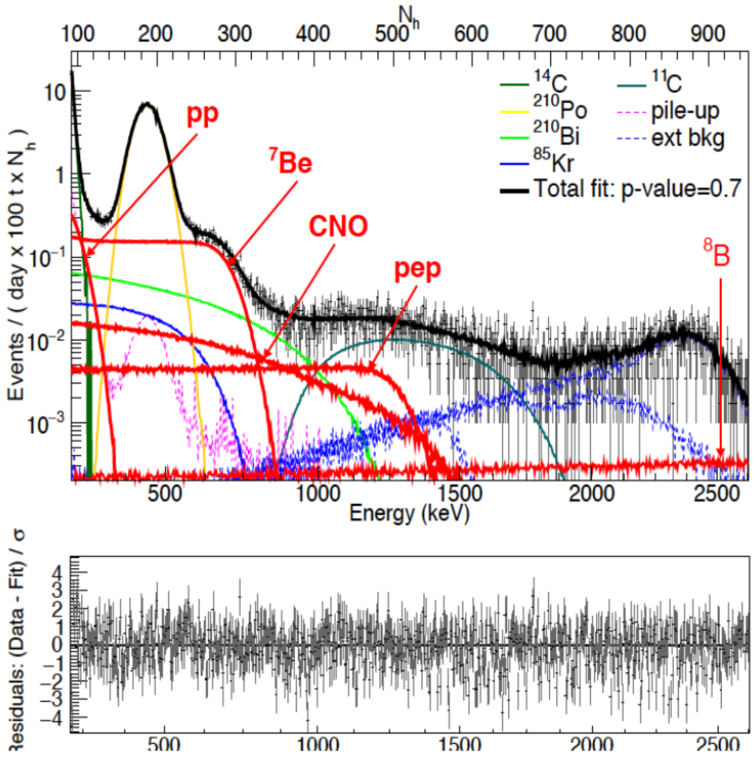
Solar ν		Rate [cpd/100 t]
pp	1.3x	$134 \pm 10^{+6}_{-10}$
^{7}Be	1.8x	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep (HZ)	1.6x	$2.43 \pm 0.36^{+0.15}_{-0.22}$
pep (LZ)		$2.65 \pm 0.36^{+0.15}_{-0.24}$
^{8}B$_{HE-I}$		$0.136^{+0.013+0.003}_{-0.013-0.003}$
^{8}B$_{HE-II}$		$0.087^{+0.080+0.005}_{-0.010-0.005}$
^{8}B$_{HE}$	> 2x	$0.223^{+0.015+0.006}_{-0.016-0.006}$

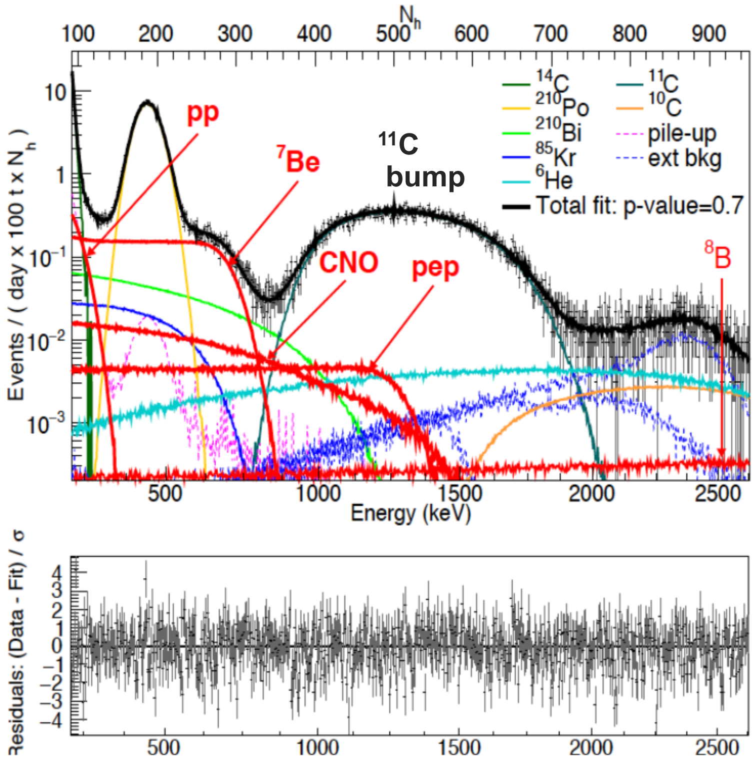


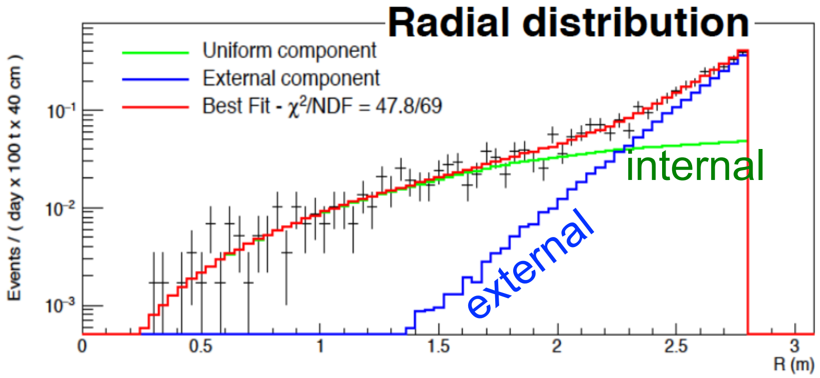
LOW ENERGY REGION (LER): MULTIVARIATE SPECTRAL FIT

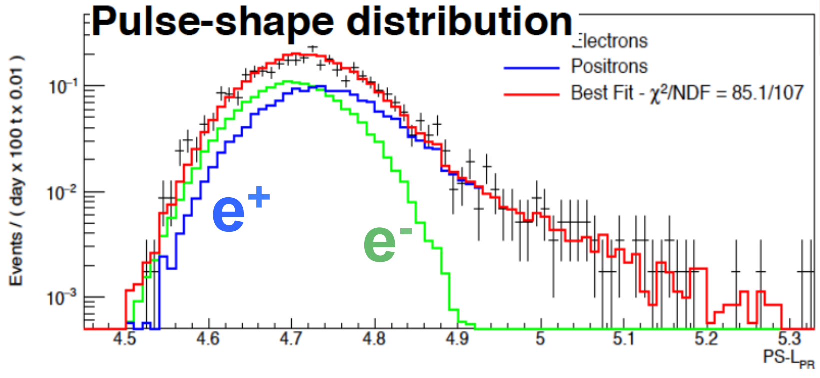
Results on *pp*, ^{7}Be, *pep*, and limit on CNO solar neutrinos

$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{sub}^{TFC}(\vec{\theta}) \cdot \mathcal{L}_{tag}^{TFC}(\vec{\theta}) \cdot \mathcal{L}_{PS}(\vec{\theta}) \cdot \mathcal{L}_{Rad}(\vec{\theta})$$









- 1291.51 days of Borexino Phase II
- Selection cuts in 71.3 ton FV

2 energy spectra

TFC-subtracted:

64% of exposure, 8% of ^{11}C

TFC-tagged:

46% of exposure, 92% of ^{11}C

Pulse-shape distribution

^{11}C(e+)/e- discrimination

Constraining ^{11}C in the TFC-subtracted spectrum

Radial distribution:

To better disentangle external background from internal signal

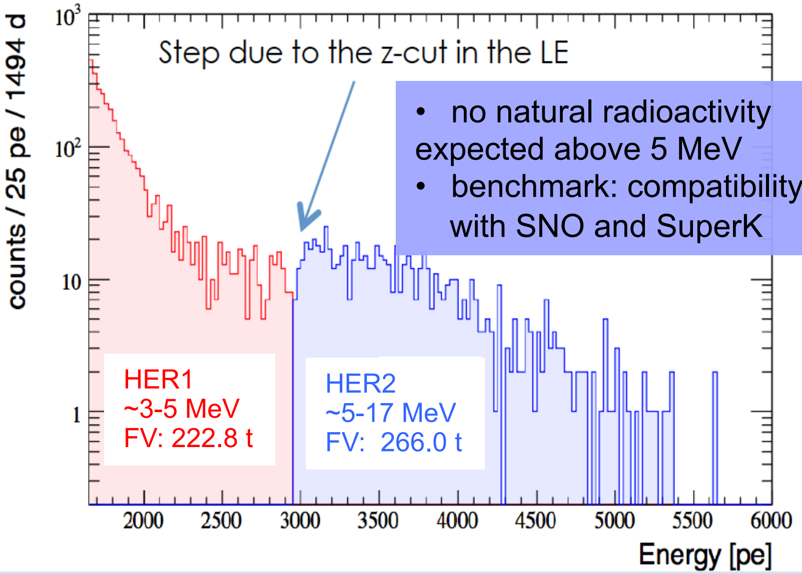
MC-based and analytical fit of the energy spectra

- Complementarity
- Thousands of fits
- Differences included in sys error

HIGH ENERGY REGION (HER) ANALYSIS

Results on ^{8}B solar neutrinos

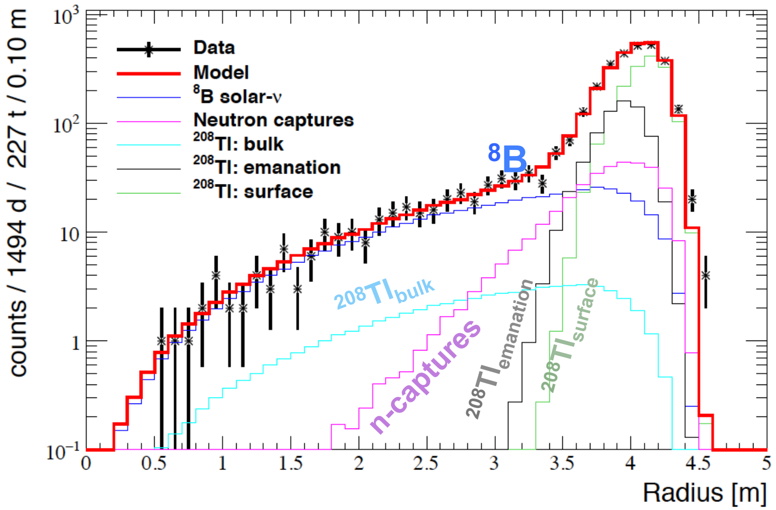
Analysis in 2 energy regions



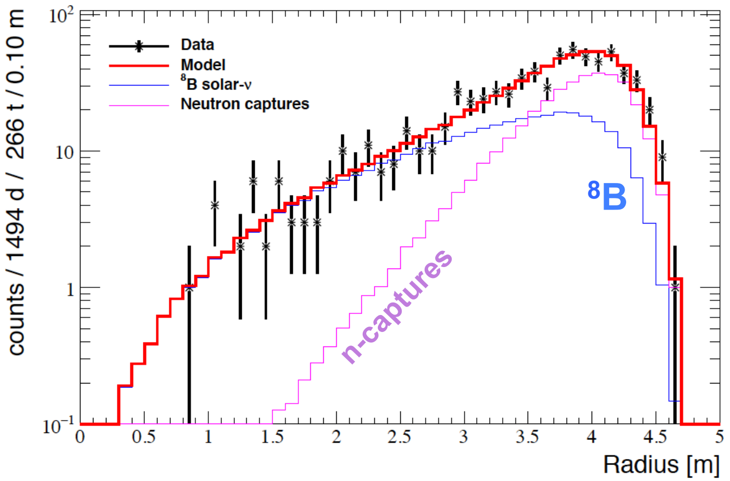
- no natural radioactivity expected above 5 MeV
- benchmark: compatibility with SNO and SuperK

No use of energy spectra is a choice: no assumptions on the $P_{ee}(E_\nu)$ shape

HER1: ~3-5 MeV



HER2: ~5-17 MeV



Backgrounds after selection cuts (neutron, cosmogenics, TFC(^{10}C), ^{214}Bi-^{214}Po, random coincidence)

HER1
- ✓ cosmogenic ^{11}Be
- ✓ ^{208}Tl (bulk , emanation and vessel surface)
- ✓ γ's from n-captures

HER2
- ✓ cosmogenic ^{11}Be
- ✓ γ's from n-captures

- Almost all scintillator volume used in the analysis.
- Factor 2 improvement wrt PRD 82 (2010) 033006.

BOREXINO QUEST FOR CNO SOLAR NEUTRINOS

^{210}Bi and CNO correlated
- external constraint on ^{210}Bi from ^{210}Po (time) needed

$^{210}Pb \xrightarrow{\beta\ (63\ KeV)} {}^{210}Bi \xrightarrow{\beta} {}^{210}Po \xrightarrow{\alpha} {}^{206}Pb$

^{210}Pb	^{210}Bi	^{210}Po	^{206}Pb
$T_{1/2}$=22y	5 days	138 days	stable

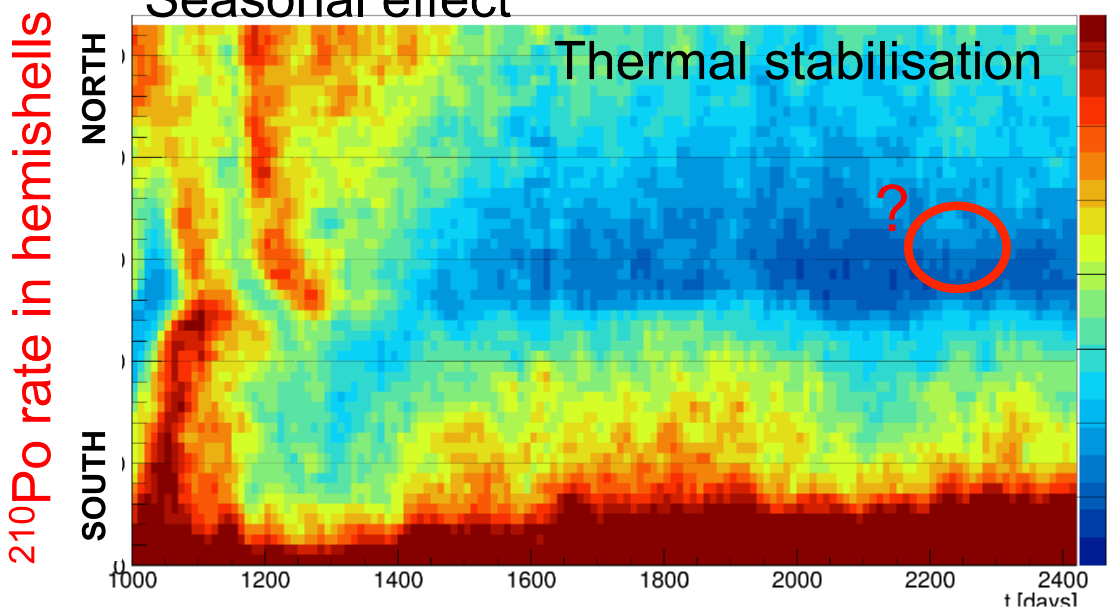
F. Villante et al., Phys. Lett. B 701 (2011)

Not in equilibrium

R(^{210}Po, Dec 2011) ~1400 cpd/100 ton
R(^{210}Bi, Phase II) = 17.5 + 1.9 cpd/100 ton fit with CNO constrained to SSM

- Nylon vessel holding the scintillator is a source of ^{210}Po
  - ✓ diffusion slow -> ^{210}Po cannot penetrate to the FV
  - ✓ block convection -> **thermal stabilisation**

$n_{Po}(t) = [n_{Po,0} - n_{Bi}] \exp(-t/\tau_{Po}) + n_B$: at regime R(^{210}Po) = R(^{210}Bi)



Strategy
- identify portion of the detector in which ^{210}Bi rate low, stable, and known
- additional water extraction campaign for further ^{210}Bi reduction

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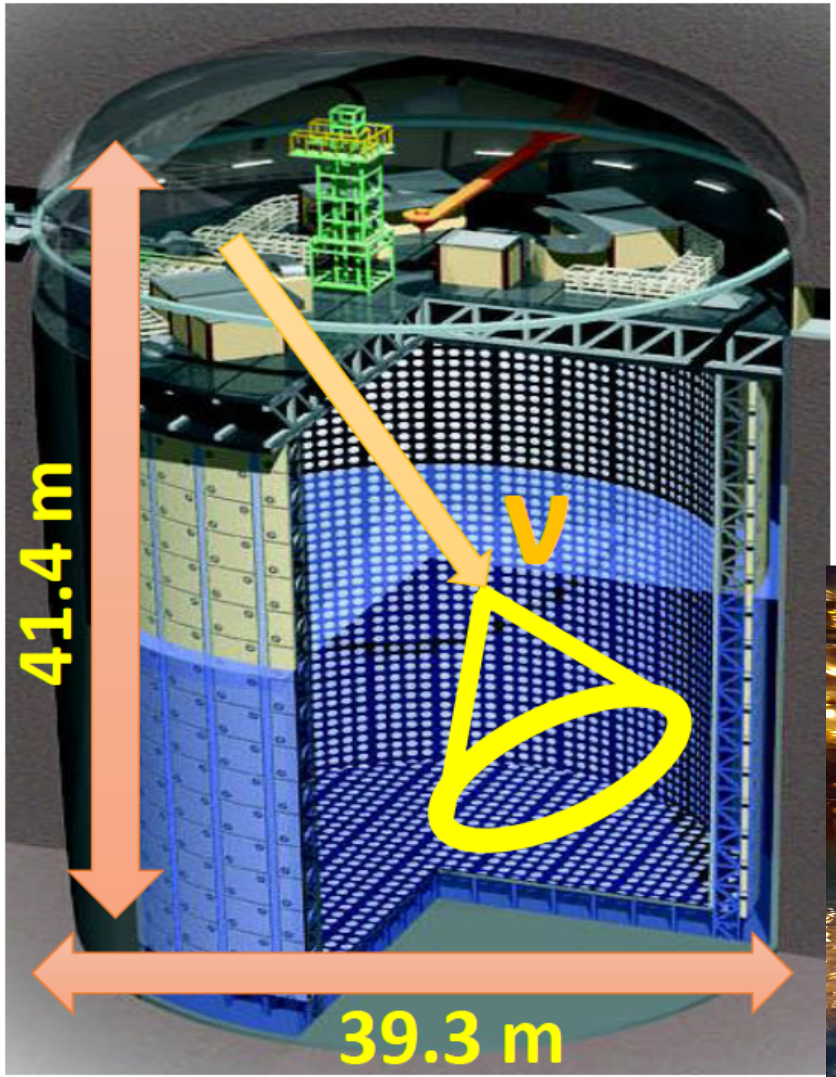
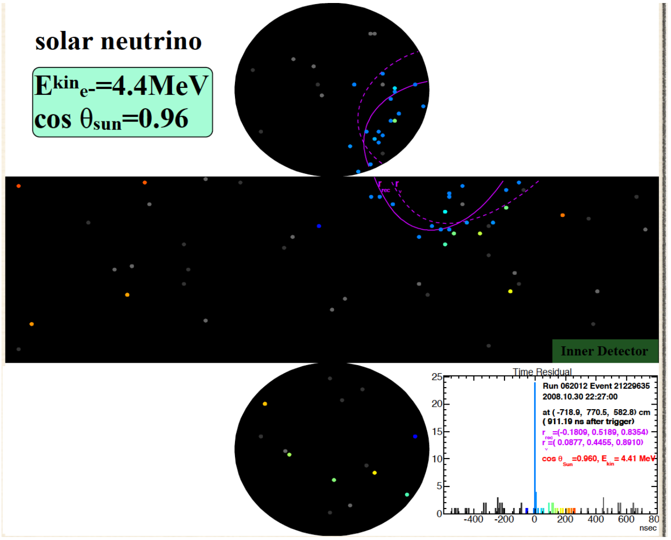
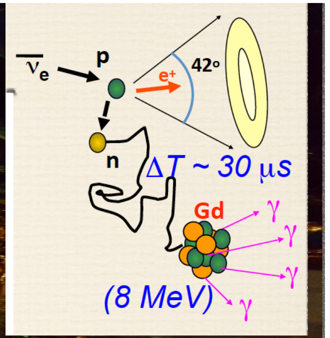
SUPERKAMIOKANDE DETECTOR





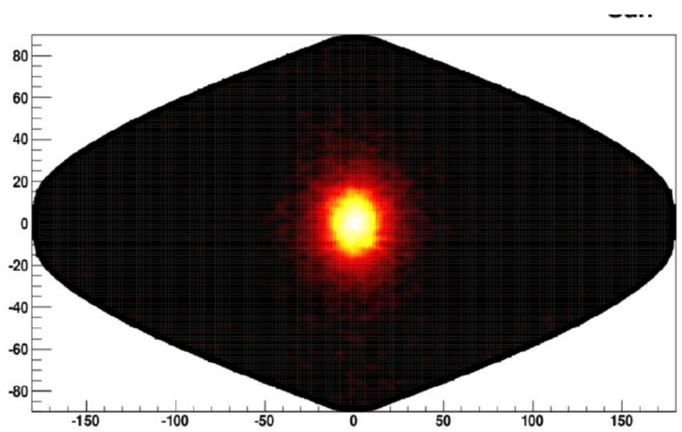
The world largest Water Cherenkov detector

- 50 (FV 22,5) kton ultra-pure water
- directionality
- Kamioka mine in Japan
- 2700 m water equivalent
- 11,100 20-inch PMTs
- **~6 hit PMTs / MeV** ($\Delta E/E$ ~ 14%, 55cm, 23 deg @ 10 MeV)



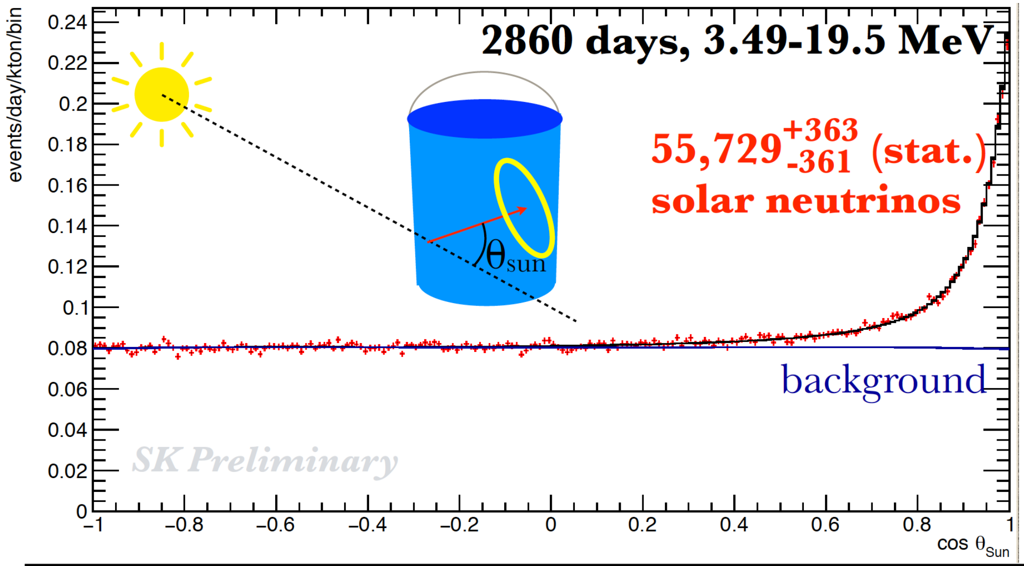
courtesy M.Smy (NNN2018)

SUPERKAMIOKANDE AND SOLAR NEUTRINOS



Average flux (SK-I~IV): $2.33 \pm 0.04(\text{stat.+sys.}) \times 10^6\ /\text{cm}^2/\text{sec}$

M. SMY, NNN 2018



- ^{8}B neutrinos via elastic scattering
- **2000:** solar mixing angle θ_{12} is large
- **2001**: discovery of solar neutrino flavour transformation with SNO
- **2013:** first direct indication of day-night asymmetry due to the matter effects in Earth

Next Solar Neutrino Goals:

- finalizing low-threshold SK-IV data
- observation of day-night asymmetry
- observation of the P_{ee} upturn
- search for Non-standard Neutrino Interactions

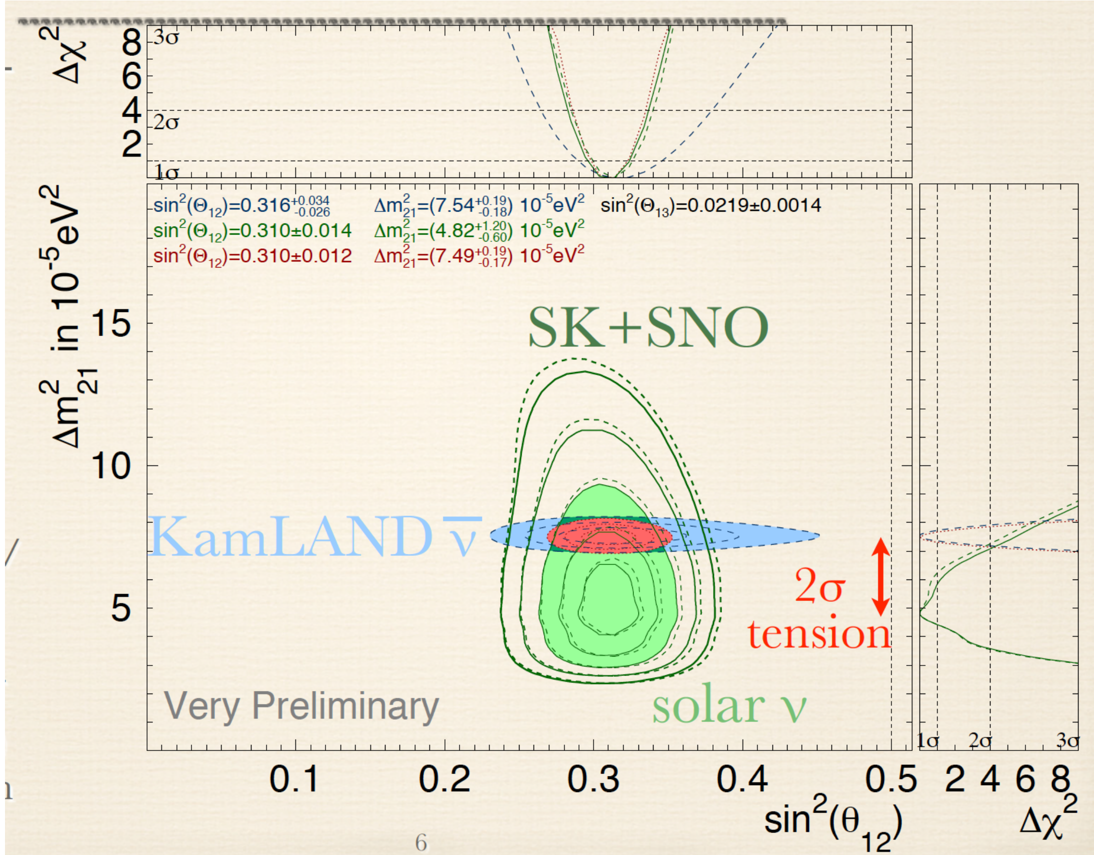
M. Ikeda, Neutrino 2018

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	2860	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		3.5

total 5695 days (coverage) (Kinetic energy)

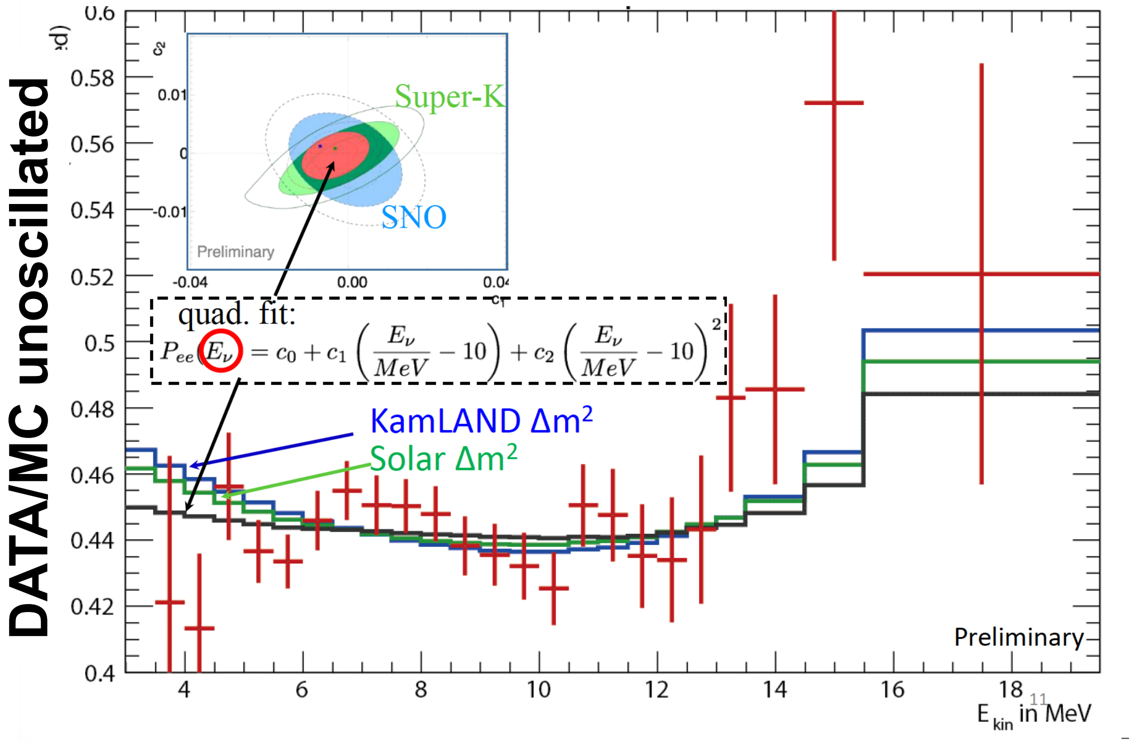
SuperK ^{8}B solar analysis

M. SMY, NNN 2018

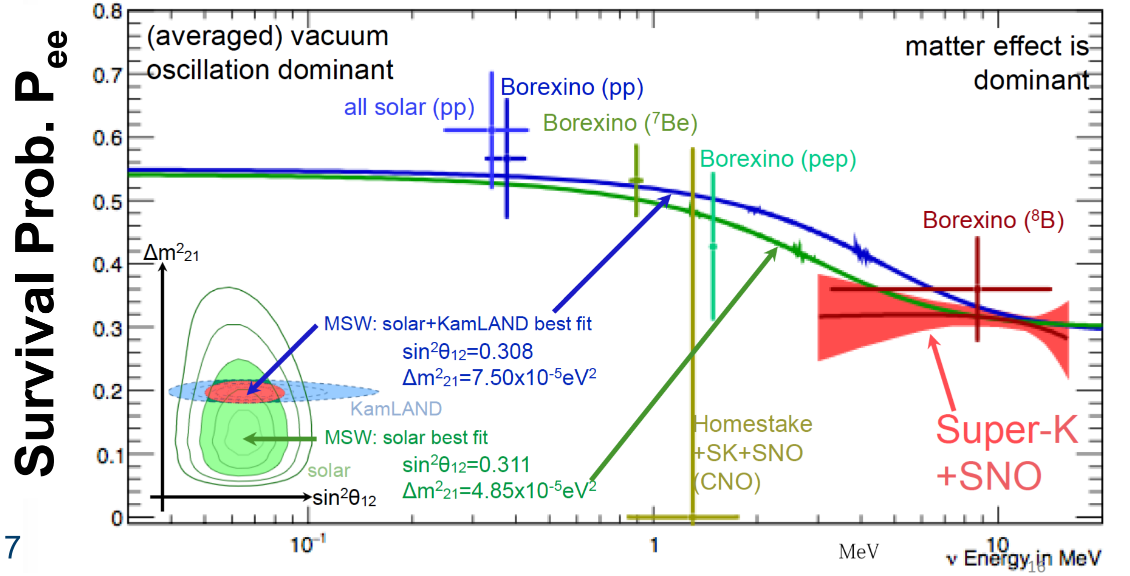


The SK recoil electron spectrum is consistent within **~1σ with the MSW upturn for the solar global best fit** parameters and shows **2σ tension with the MSW upturn for the solar+KamLAND best fit** parameters

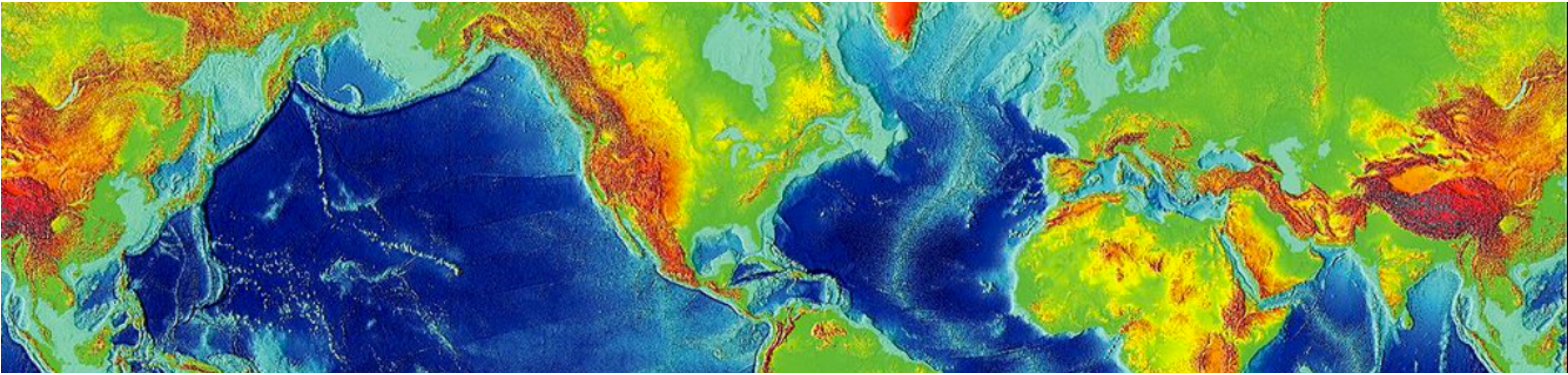
M. Ikeda, Neutrino 2018



M. Ikeda, Neutrino 2018



GEONEUTRINOS



GEONEUTRINOS AND WHY TO STUDY THEM

Abundance of radioactive elements

Nuclear physics

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

Radiogenic heat (Main goal)

Surface heat flux: 47 ± 3 TW

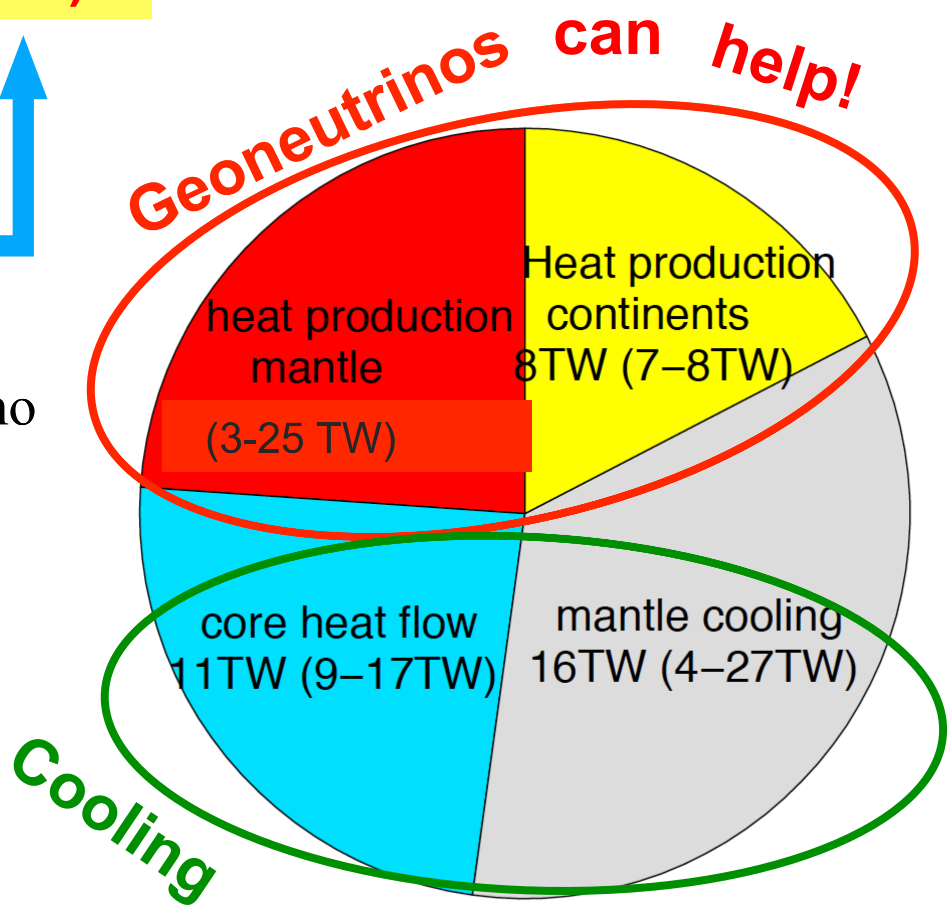
(based on the measured temperature gradients along 30,000 bore holes around the globe)

Distribution of radioactive elements (models)

To predict:

Geoneutrino flux

From geoneutrino measurement:



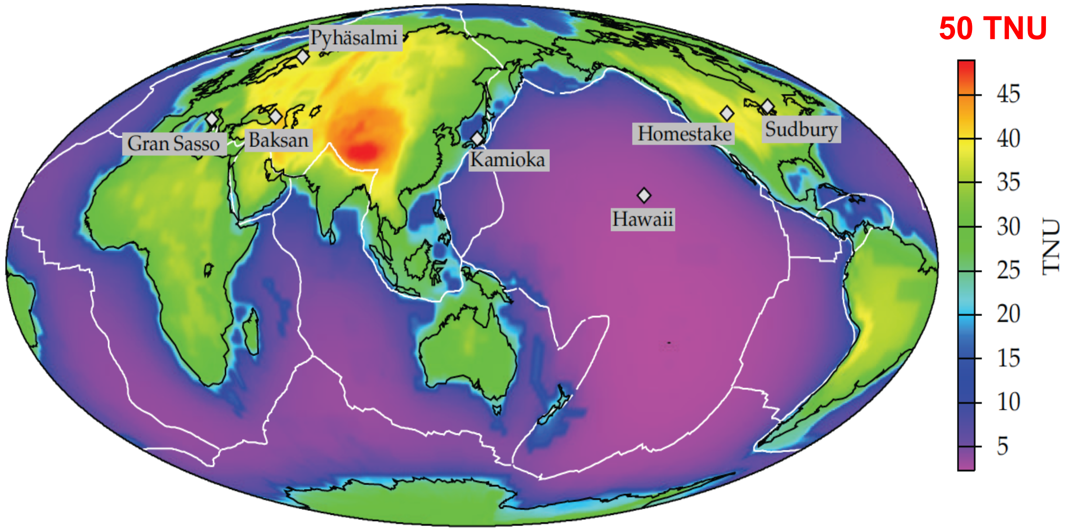
Earth shines in antineutrinos: flux ~10^6 cm^{-2} s^{-1}

leaving freely and instantaneously the Earth interior

(to compare: solar neutrino (NOT antineutrino!) flux ~10^{10} cm^{-2} s^{-1})

DETECTING GEONEUTRINOS (IBD with LS-detectors)

Expected "known" crustal signal



1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event /1 kton /1 year,
100% detection efficiency

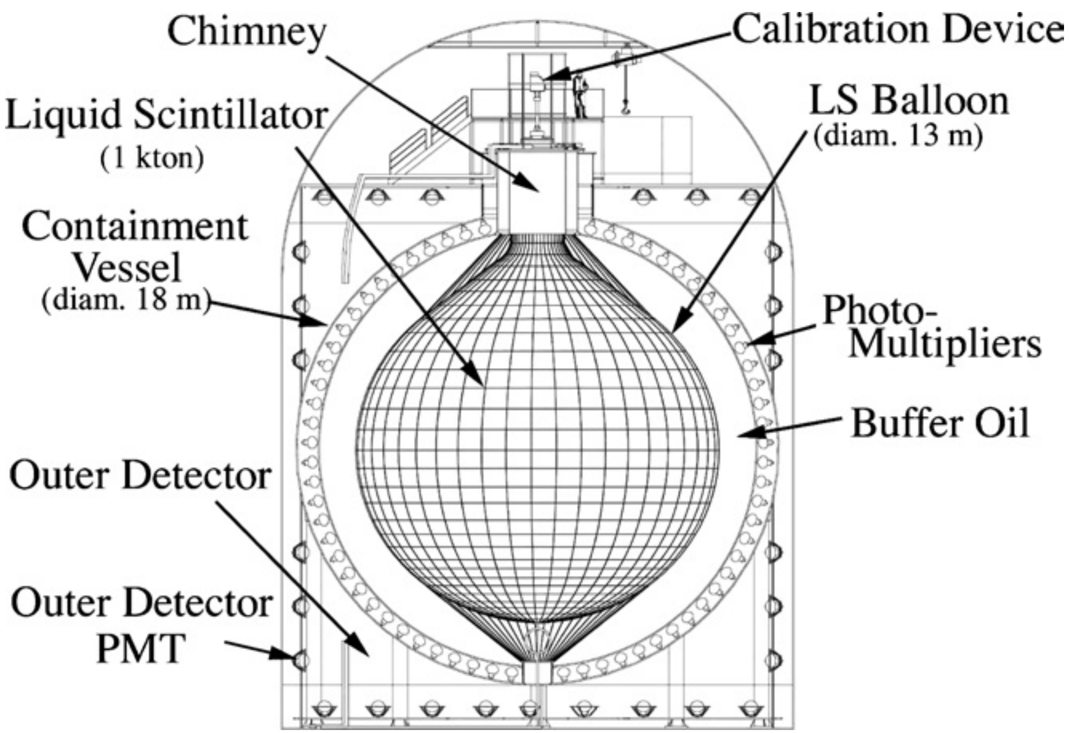
The signal is small, we need big detectors!

MANTLE = Bulk Silicate Earth model – CRUST

Only 2 experiments have measured geoneutrinos:

- Borexino in Gran Sasso, Italy (280 ton LS)
  - ✓ CONTINENTAL CRUST
- KamLAND in Kamioka, Japan (1000 ton LS)
  - ✓Border between OCEANIC / CONTINENTAL CRUST

KamLAND



BACKGROUNDS

B) Non-antineutrino background

1) Cosmogenic background

- **^{9}Li and ^{8}He** ($T_{1/2}$ = 119/178 ms)
- decay: β(prompt) + neutron (delayed);
- **fast neutrons**

  scattered protons (prompt)

Estimated by studying coincidences detected AFTER muons.

2) Accidental coincidences;

Estimated from OFF-time coincidences.

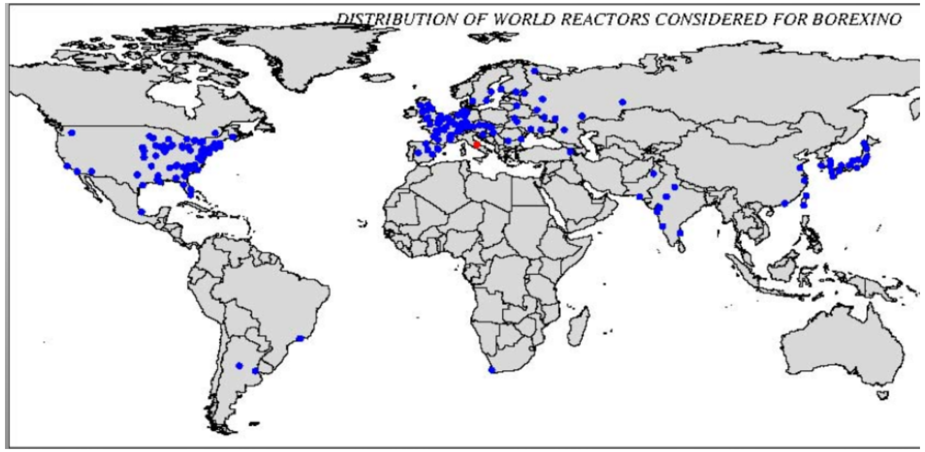
3) Due to the internal radioactivity:

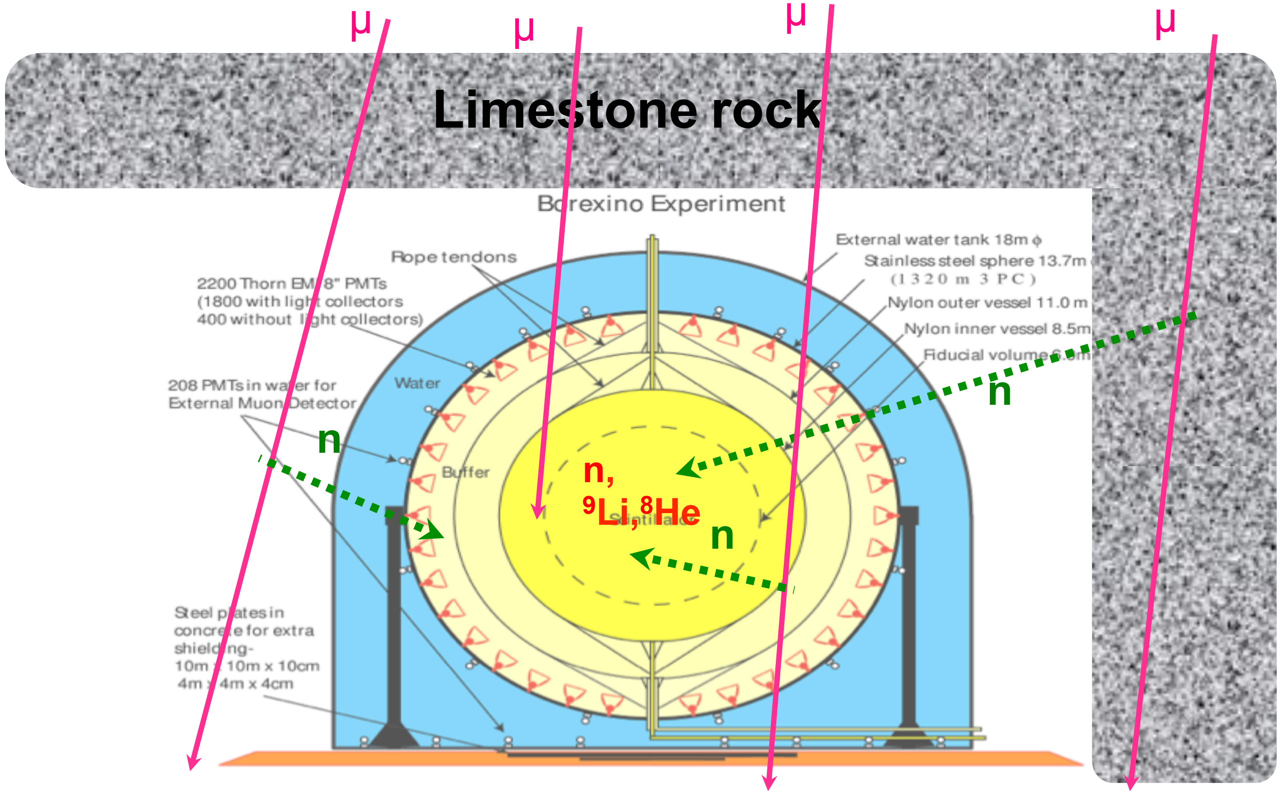
(α, n) reactions: $^{13}C(\alpha, n)^{16}O$

Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

Estimated from ^{210}Po(α) and ^{13}C contaminations, cross section.

A) Reactor antineutrino background





LATEST GEO-ν RESULTS

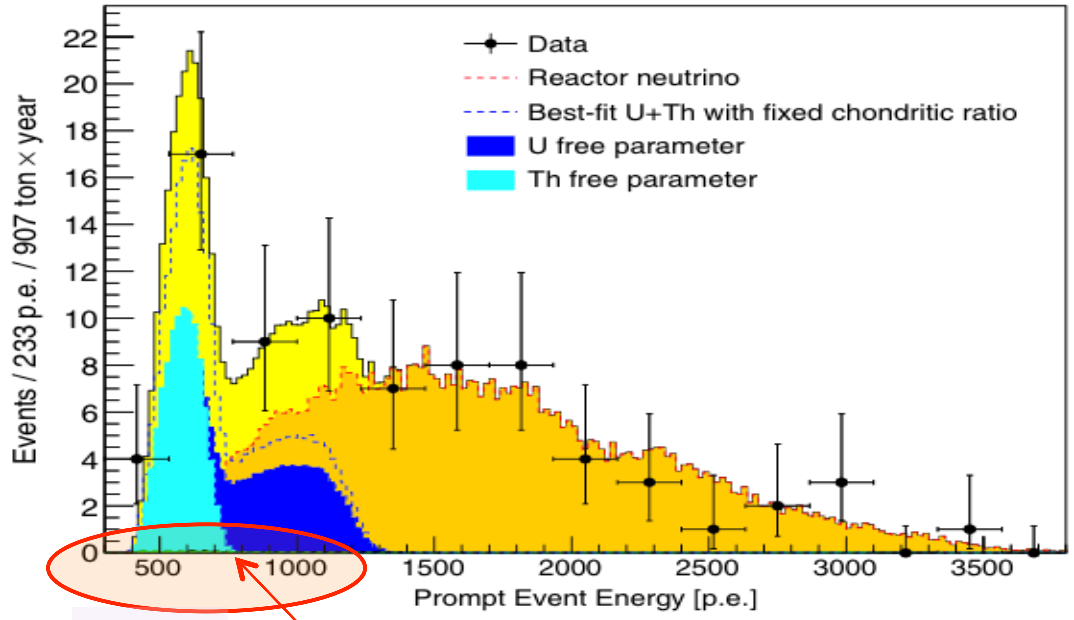
Borexino 2015: (PRD 92 (2015) 031101 (R))

$23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's

Error: 27% dominated by statistics

Exposure: 5.5 x 10^{31} target-proton year

5.9σ evidence



~1 MeV ~7 MeV

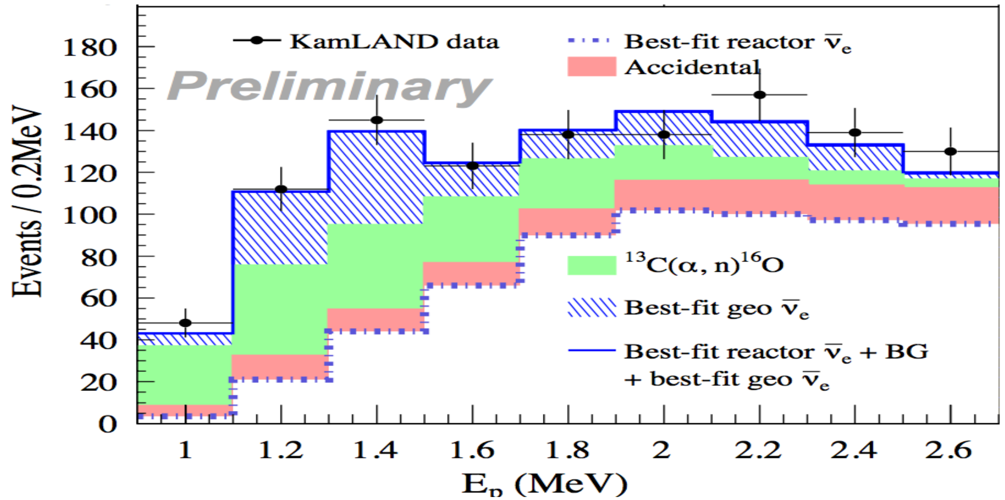
Non-antineutrino background almost invisible!

KamLAND 2016: International Workshop: Neutrino Research and Thermal Evolution of the Earth

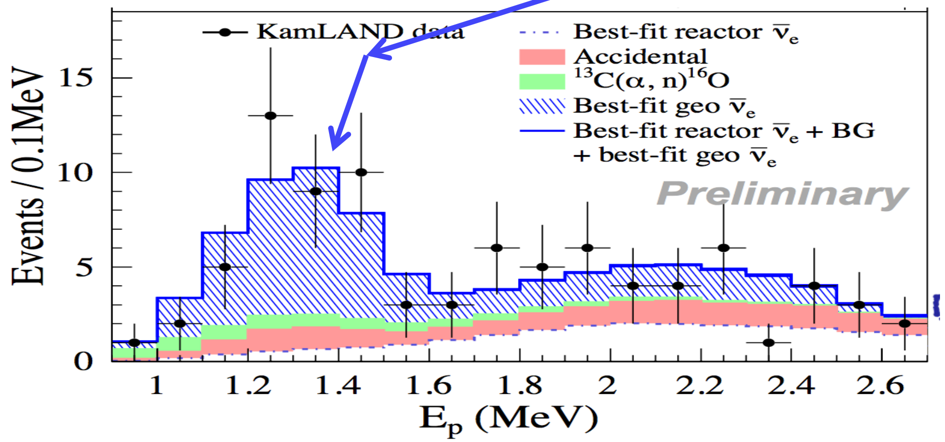
164^{+28}_{-25} geonu's **7.9σ evidence**

Error: 17% dominated by systematics

Exposure: 6.4 x 10^{32} target-proton year



after Fukushima disaster: 1/3 of data has little reactor antineutrino background and clear **geonu peak**



FIRST GEOLOGICAL INTERPRETATIONS

- Measured **geoneutrino signal is in agreement with expectations**, but we cannot distinguish among various geological models:

  Borexino: $S_{geo} = 43.5\ ^{+11.8}_{-10.4}\,(stat)^{+2.7}_{-2.4}(sys)$ TNU

  KamLAND: $S_{geo} = 34.9\ ^{+6.0}_{-5.4}$ TNU

- **U/Th ratio is compatible with chondritic ratio**, but the errors are too big:

  KamLAND: $Th/U = 4.1^{+5.5}_{-3.3}$

- First **indications of the measured non-zero mantle signal**

  Borexino 2015: $S_{mantle} = 20.1^{+15.1}_{-10.3}$ TNU

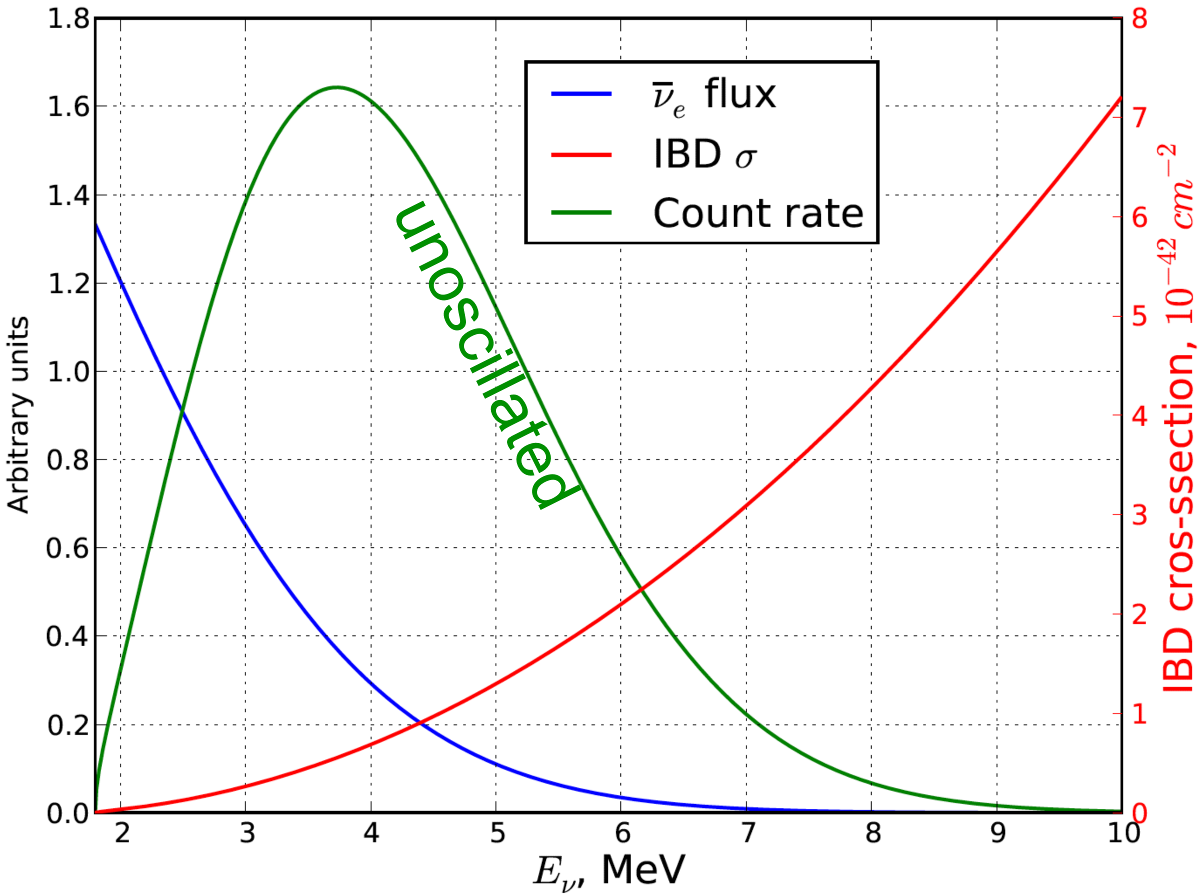
- Idea of Herndon about the **active geo-reactor in the Earth core excluded**

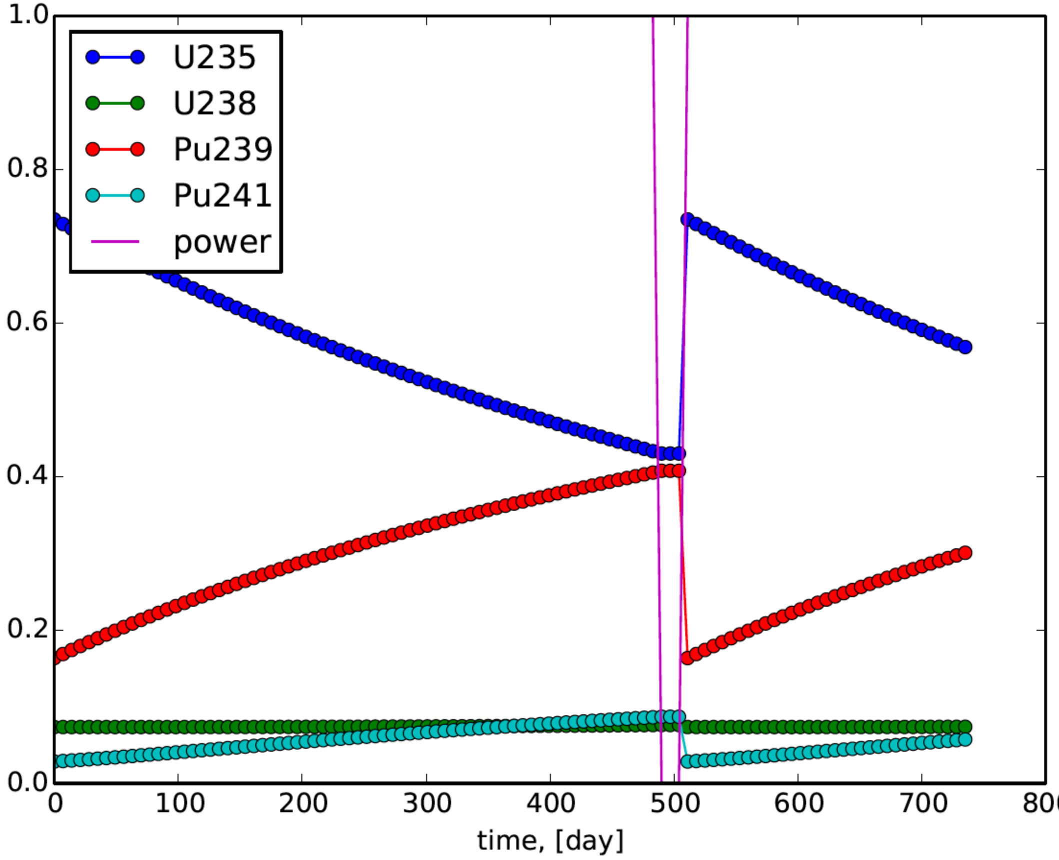
  Borexino 2010 < 3TW @95% CL

  KamLAND 2011 < 5.2 TW @ 90% CL

REACTOR NEUTRINO
the strongest human-made ν-source

TYPICAL REACTOR ANTINU SPECTRUM AND FUEL CYCLE



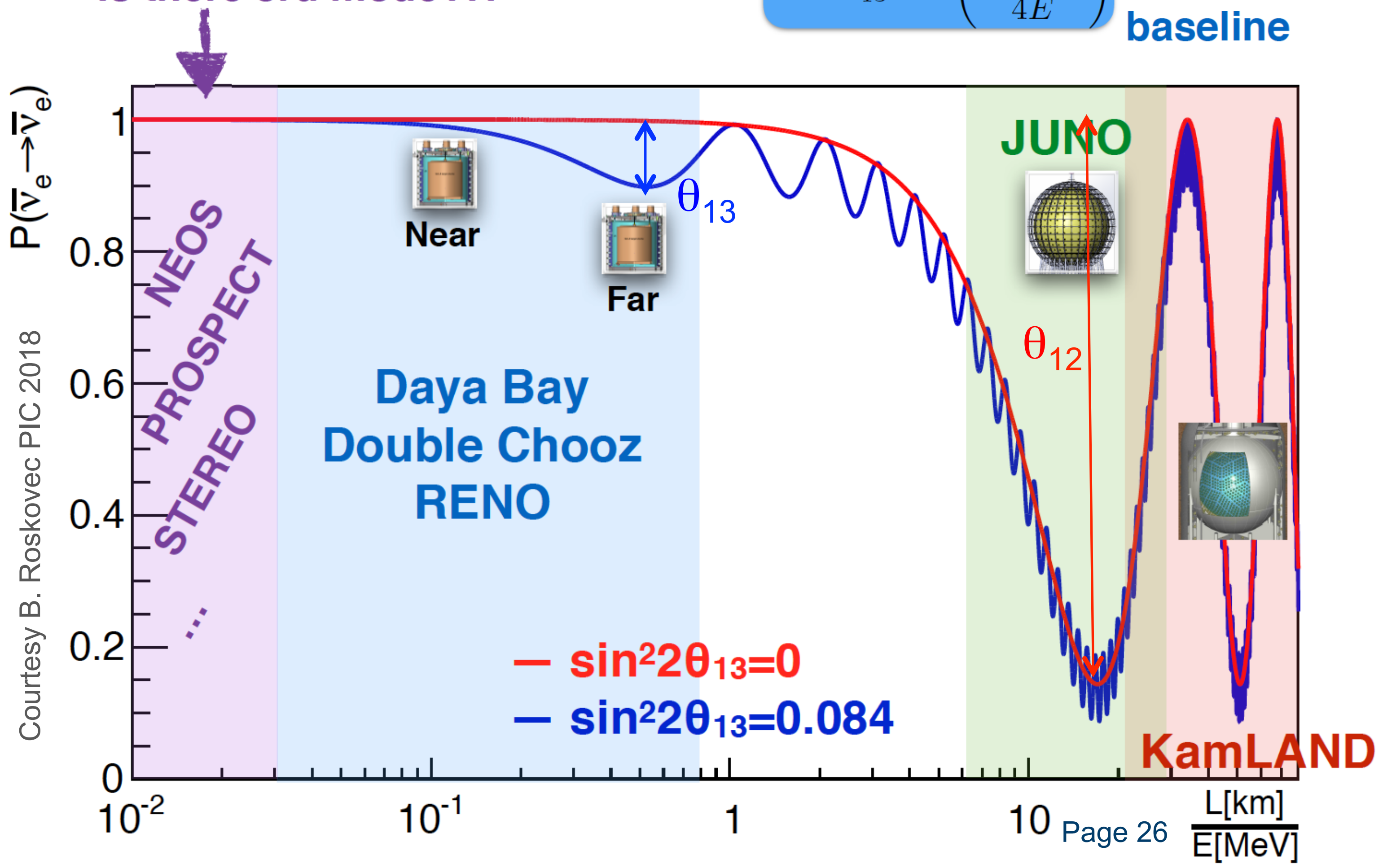


REACTOR NEUTRINO OSCILLATIONS

Two modes of oscillations: $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$ **Medium baseline**

$- \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$ **Short baseline**

Is there 3rd mode?!?



- 1950: Savannah River: discovery of (anti)neutrino
- 1980+90s: ILL, Bugey... Reactor neutrino flux measurements
- 2000s: KamLAND: 1st evidence for Δm^2_{12} – driven oscillations
- 2012: Daya Bay, Double Chooz, RENO – non-zero θ_{13} mixing angle
- 2014: Double Chooz, Daya Bay, RENO – "5 MeV bump" in energy spectrum
- Since 2014: Stereo, NEOS, DANS, PROSPECT, Double Chooz, Daya Bay, RENO··· – reactor anomaly and sterile neutrinos
- Since 2017: Daya Bay, RENO – fuel vs spectral time evolution
- DAQ start in 2021: JUNO – mass hierarchy, precision θ_{12}, Δm^2_{ee}, astro-particle goals

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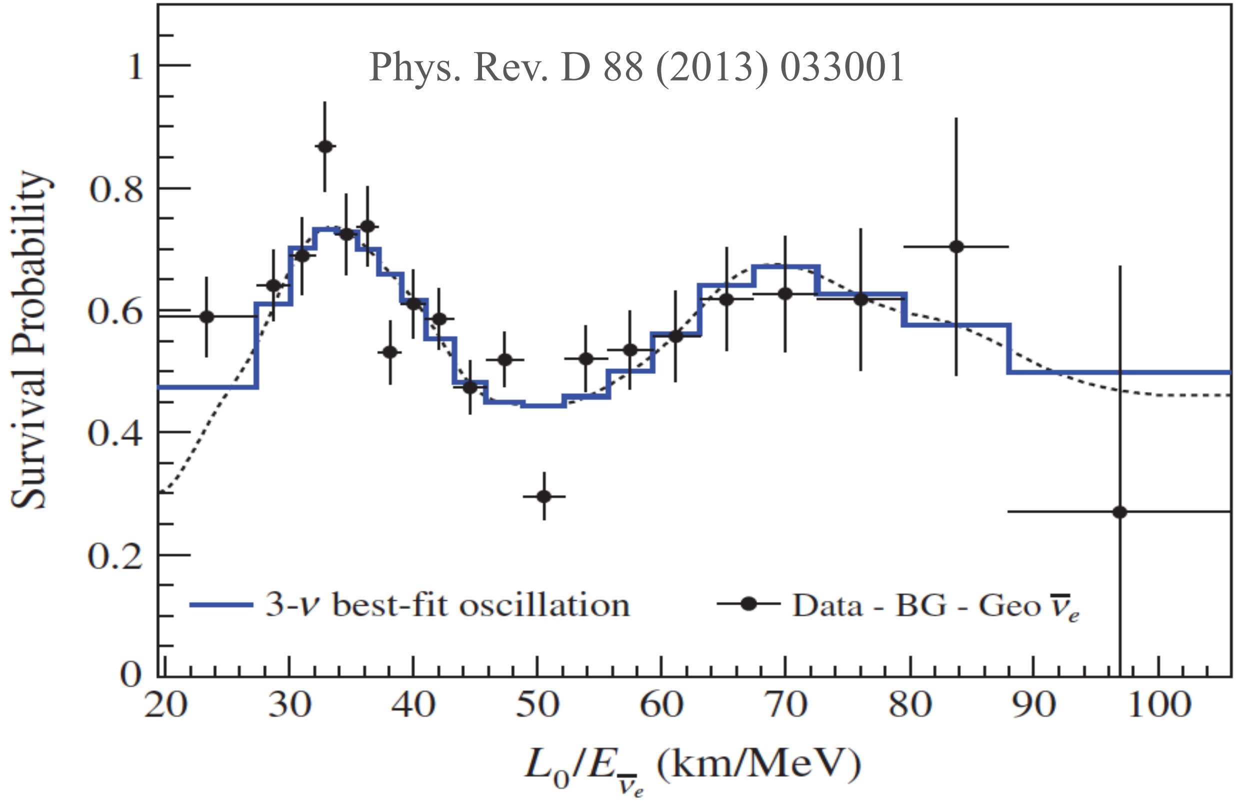
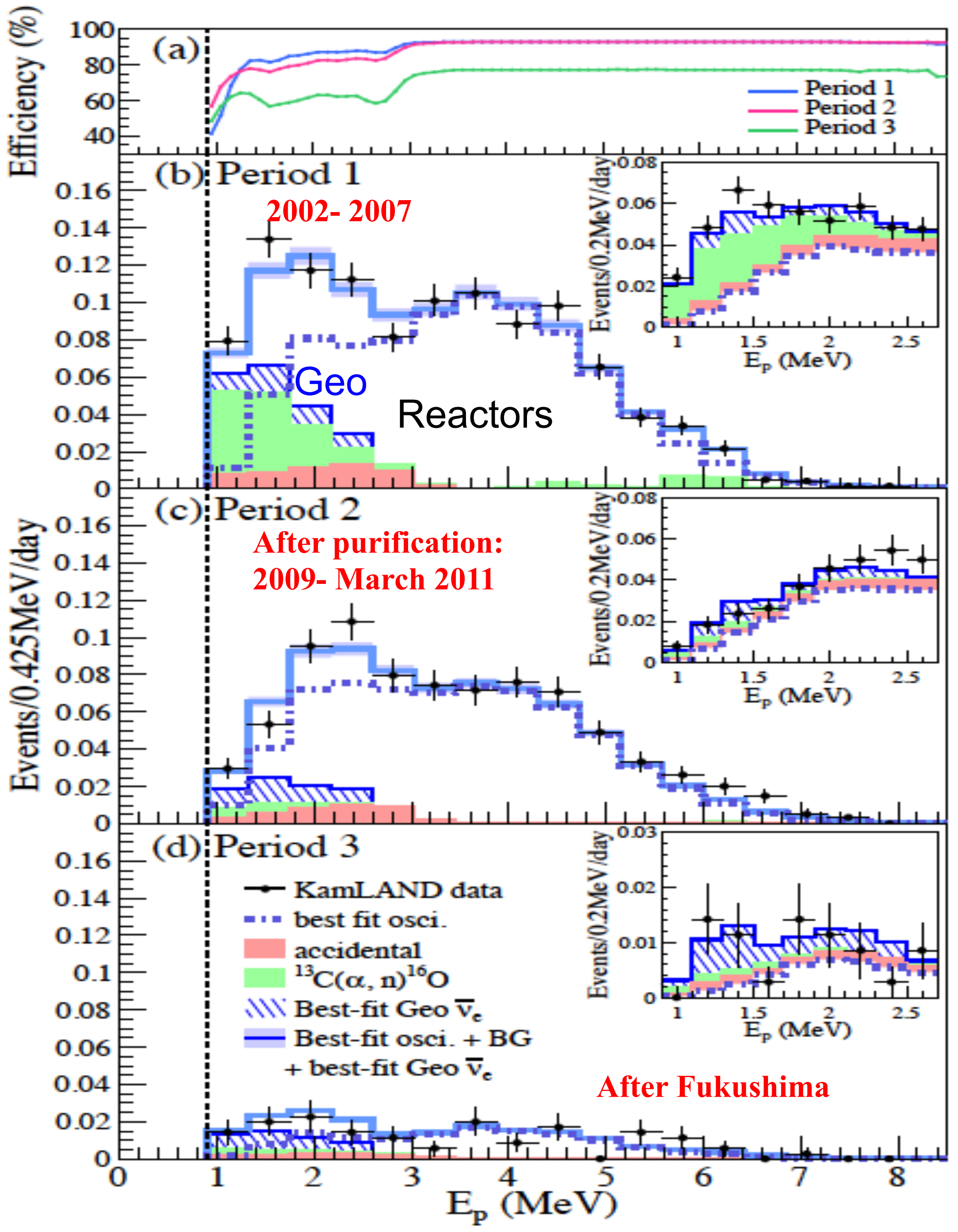
KamLAND OSCILLATION RESULT

Best sensitivity to solar mass splitting Δm^2_{12}



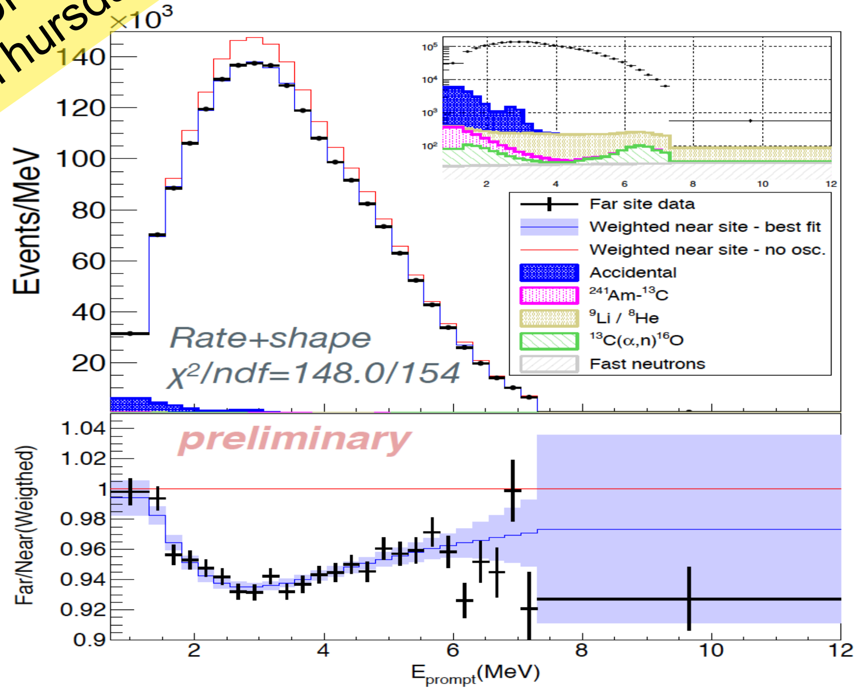
Data combination	Δm^2_{21}	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
KamLAND	$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$	$0.010^{+0.033}_{-0.034}$



QUEST FOR THETA13 MIXING ANGLE - I

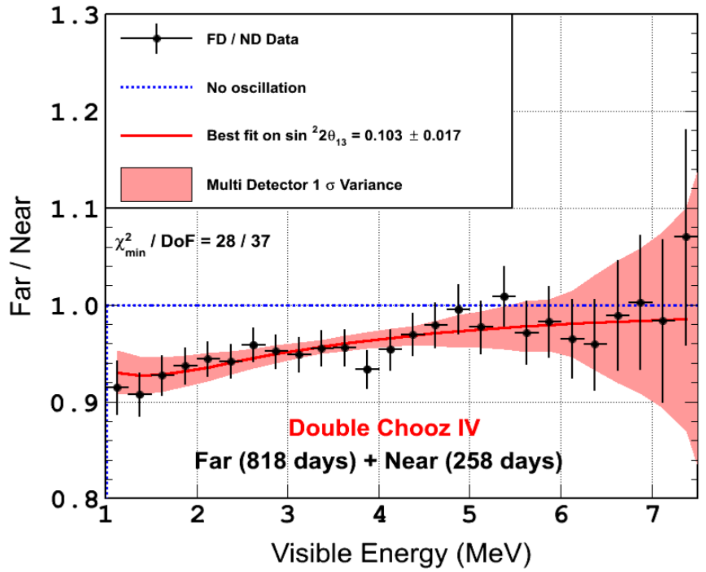
Talk of W. Wang on Thursday!

Daya Bay (China)

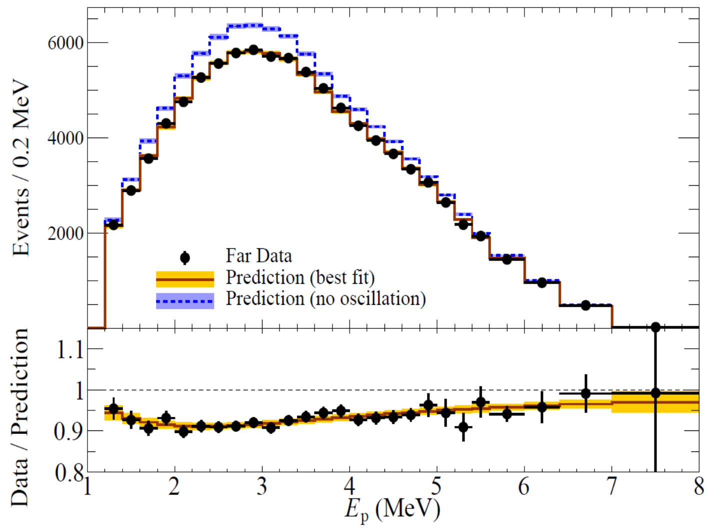


Double Chooz (France)

Data/data



RENO (South Korea)



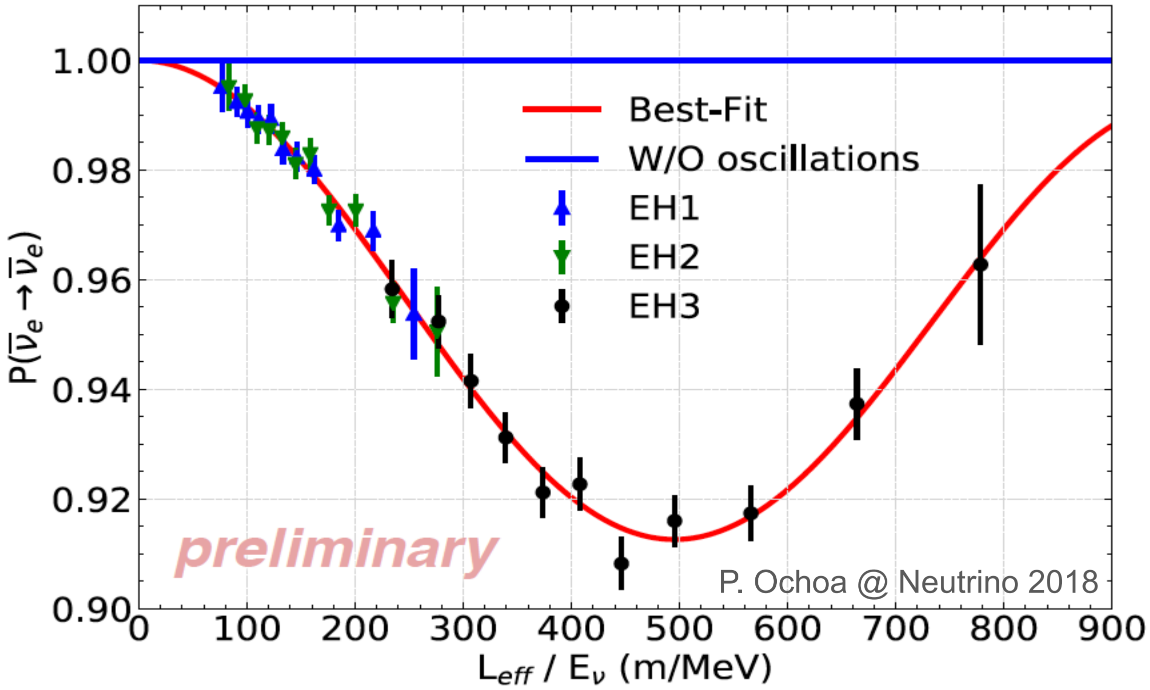
- Concept of near & far detector to cancel several systematic errors.
- Ton-scale Gd-loaded LS detectors.
- Gd: to increase the neutron (from IBD) capture cross-section.

	Power [GW_{th}]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]	Running until
Daya Bay	17.4	2×2×20 4×20	365, 490 1650	250 860	2020
Double Chooz	16.8	8 8	400 1050	120 300	Dec 2017 (Finished)
RENO	8.5	16 16	290 1380	120 450	2020-2021

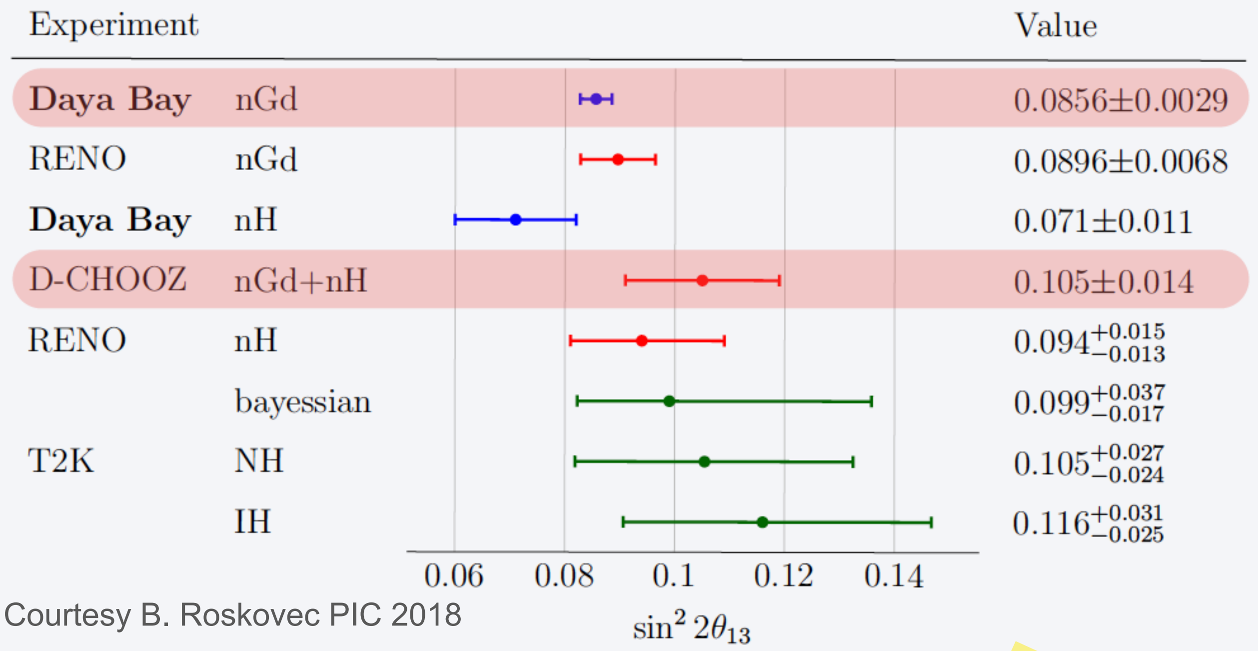
Courtesy B. Roskovec PIC 2018

QUEST FOR THETA13 MIXING ANGLE - II

Daya Bay with 1958 days
Highest Statistics of IBDs (~10^6)



$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$



Courtesy B. Roskovec PIC 2018

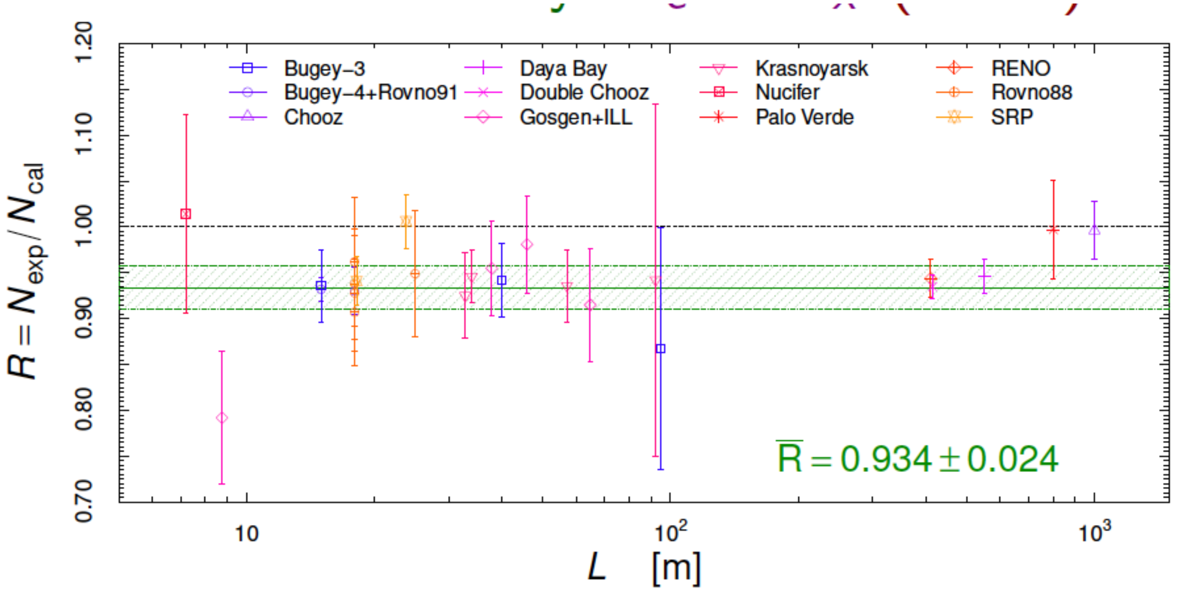
Importance of non-zero θ_{13} and its precise determination

- ✓ CP-violation in lepton sector and interpretation of dedicated experiments
- ✓ Mass hierarchy determination with reactor antineutrinos (JUNO)

Talk of M. Zito on Tuesday!

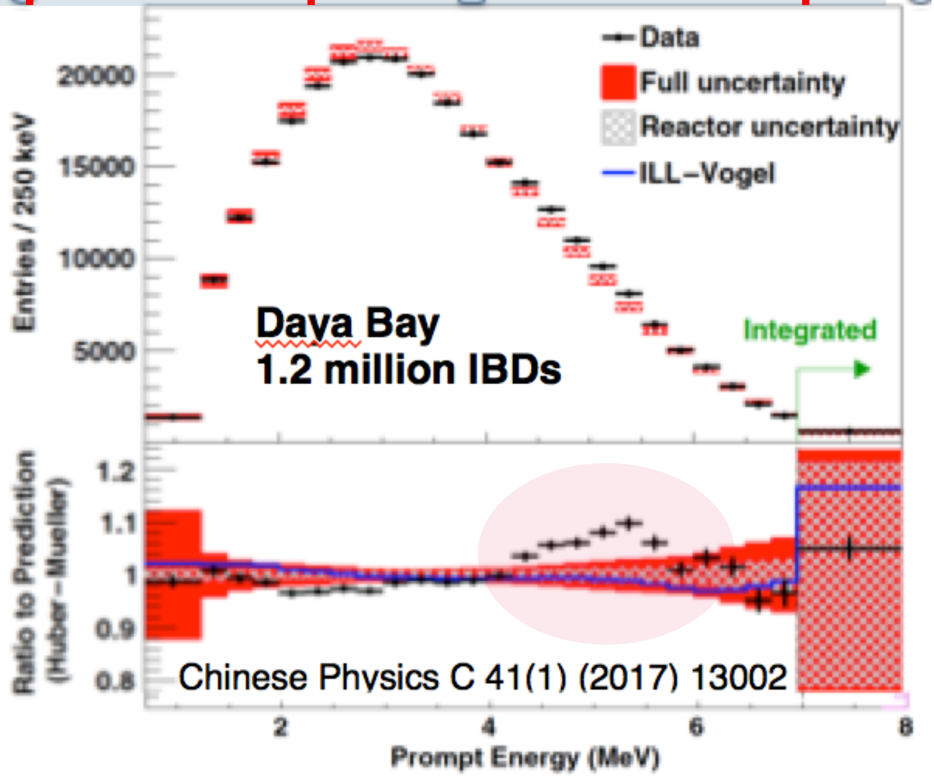
ISSUES WITH REACTOR ANTINU FLUX AND SPECTRUM

REACTOR ANOMALY (Mention et al. 2011) wrt to the Huber/Muller prediction (2011), all short baseline experiments show deficit:



Courtesy C. Giunti, NNN2018

Spectral shape and "5 MeV bump"

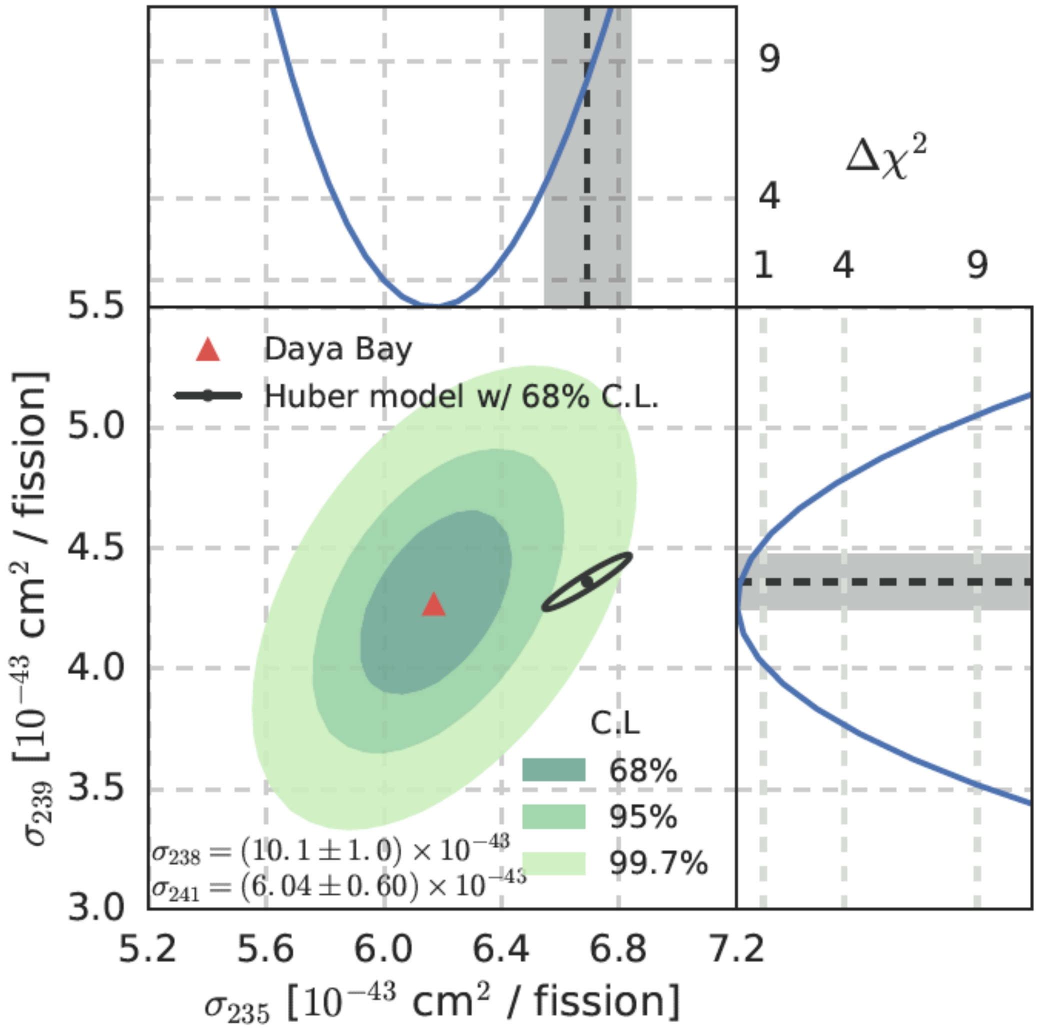


This anomaly could be interpreted due to

1. existence of **light sterile neutrino** ($\Delta m^2 \geq 1eV^2$)
2. **incorrect reactor flux prediction**

1. Confirmed by RENO, Double Chooz, NEOS, but not seen at Bugey, DANSS
2. Scales with the reactor power

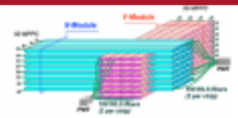
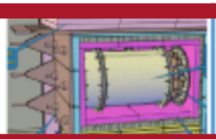
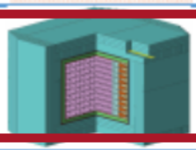
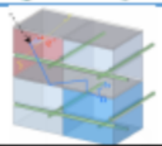
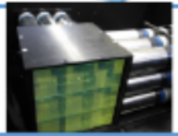
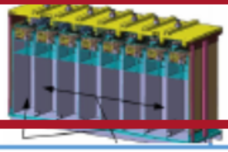
FUEL TIME EVOLUTION AND IBD YIELDS



PRL 118 (2017) 251801

- **Daya Bay (2017):**
  - ✓ Detailed information about the core composition time evolution: ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu,
  - ✓ Observation of the changes of the spectral shape
  - ✓ IBD yield of ^{235}U in disagreement with Hueber overestimated by 7.8%
- **RENO** claims similar results at NEUTRINO 2018
- Is it the solution to the reactor anomaly?

PLETHORA OF VERY SHORT BASELINE EXPERIMENTS

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

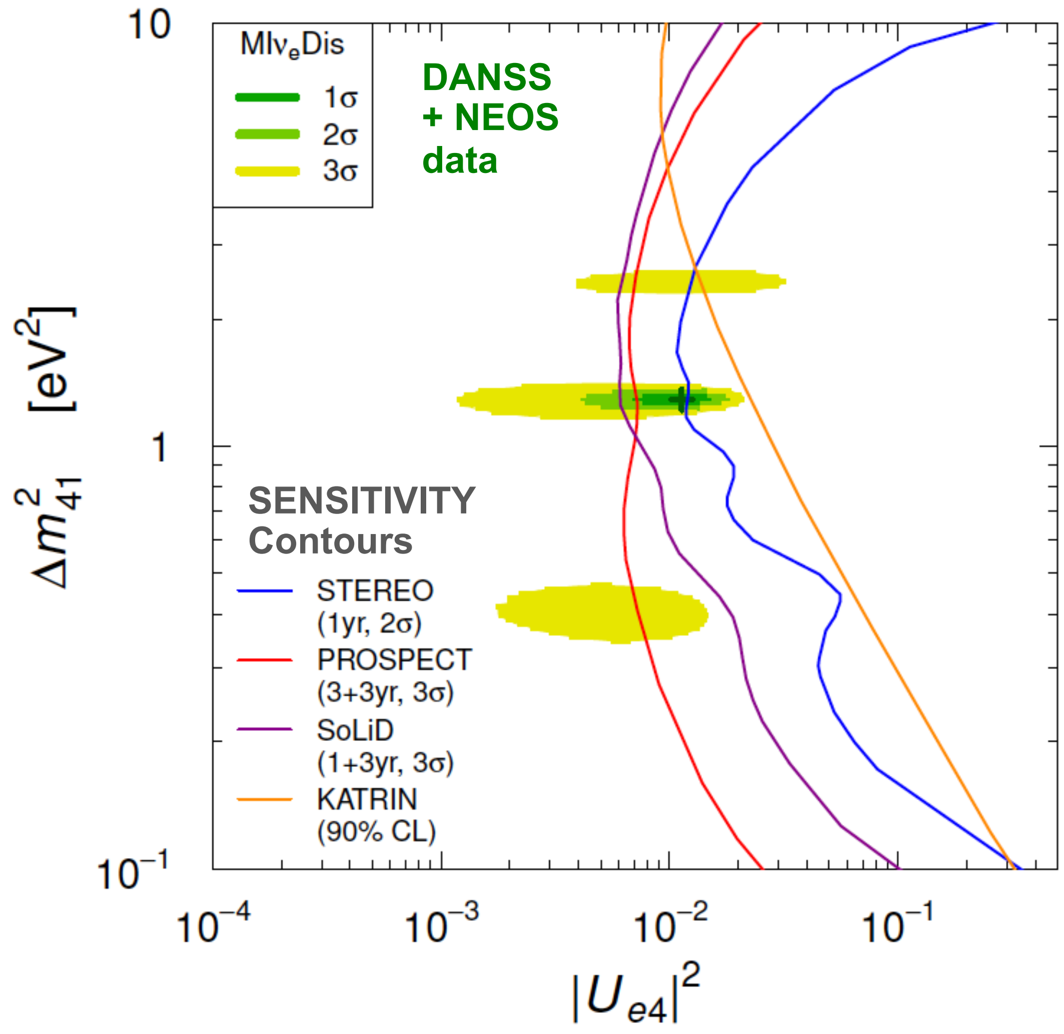
Courtesy J. Lee PIC 2018

VERY SHORT BASELINE EXPERIMENTS

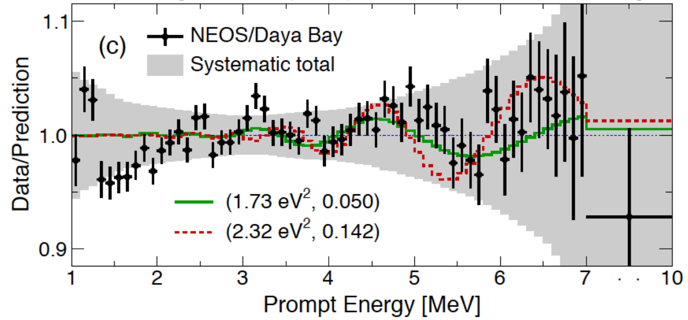
Related talk on A. Palazzo on Thursday!

First results are coming, but the situation still unclear:
- 4 experiments exclude best fit of reactor anomaly
- NEOS and DANSS best fit agree with each other

C. Giunti NNN2018

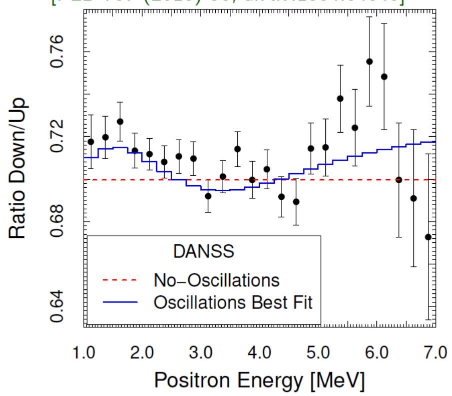


NEOS [PRL 118 (2017) 121802, arXiv:1610.05134]

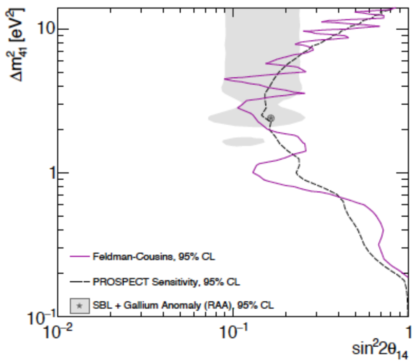


DANSS

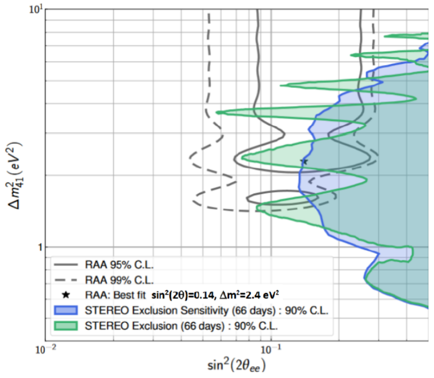
[PLB 787 (2018) 56, arXiv:1804.04046]



Prospect 1806.02784



Stereo 1806.02096



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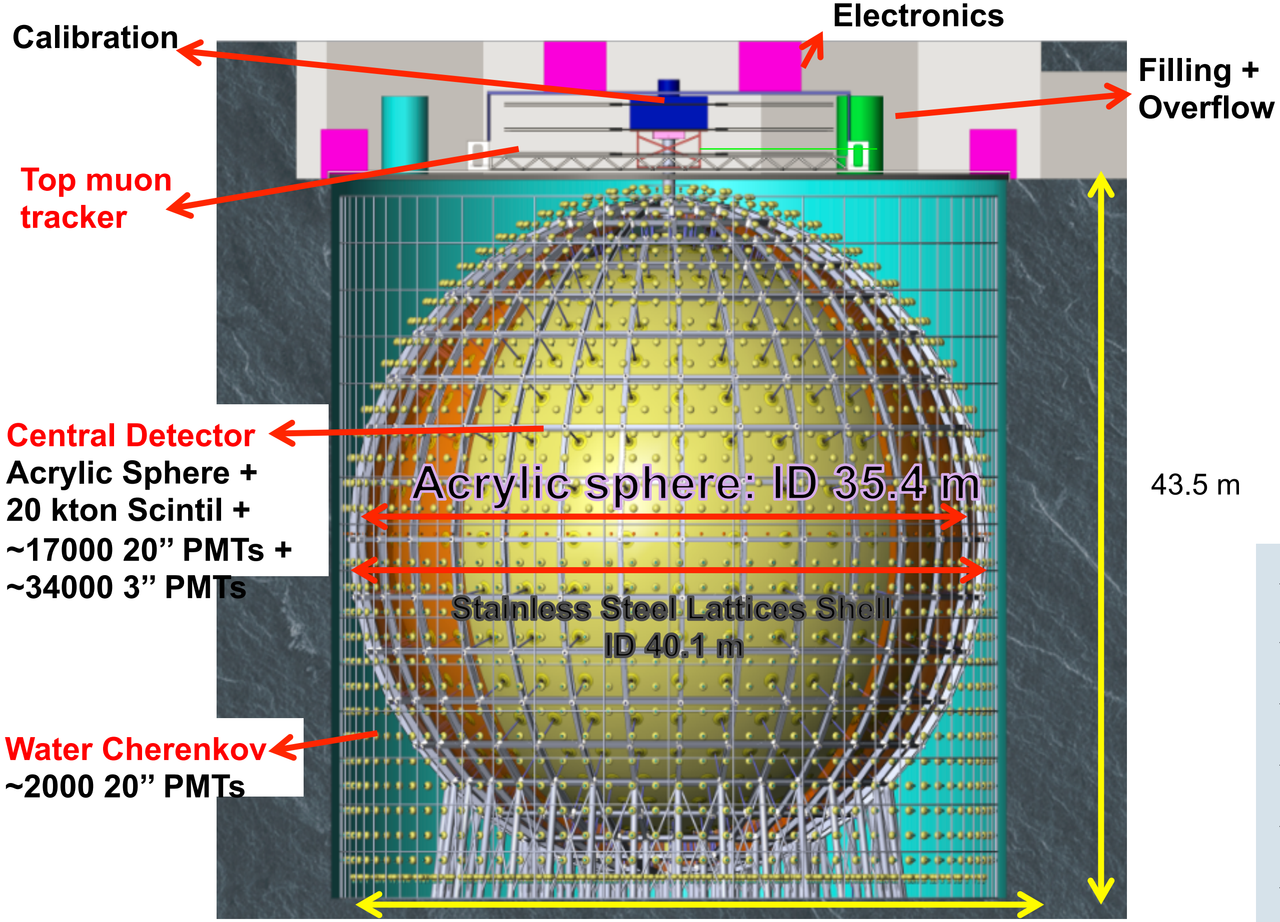
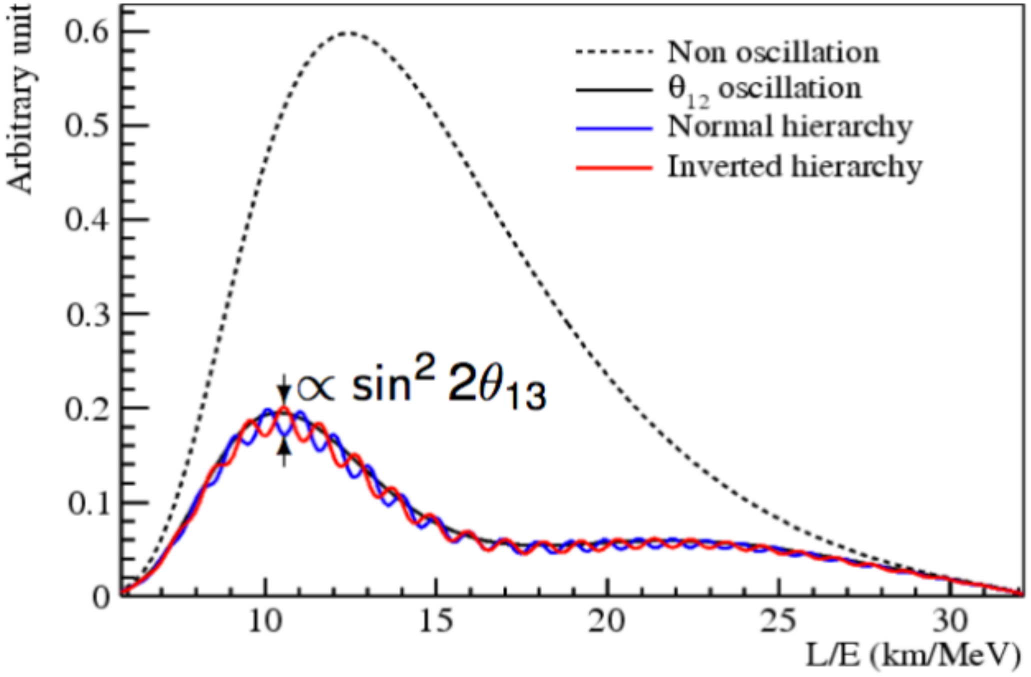
JUNO IN CHINA: THE FIRST MULTI-KTON LS DETECTOR

DAQ will start in 2021

Talk of F. Perrot on Tuesday!





- ✓ Mass hierarchy to 3-4σ in 6 years
- ✓ 53 km baseline at solar oscillation minimum
- ✓ 20 kton target
- ✓ Challenge: 3%@1 MeV energy resolution
- ✓ precision $\theta_{12,}$ Δm^2_{ee}
- ✓ astro-particle goals: DSNB, SN, solars, geoneutrinos..

SUMMARY AND OUTLOOK

Solar neutrinos:

- Borexino: comprehensive spectroscopy of pp-chain neutrinos and quest for CNO
- Super-K: ^{8}B precision spectroscopy, solar mixing angle and quest for P_{ee} upturn and observation of day-night asymmetry
- Future experiments: SNO+ in Sudbury (^{8}B), JUNO and Jinping in China

Geoneutrinos:

- Borexino and KamLAND observed geoneutrinos and provided first geological insights
- Borexino preparing an update with ~20% precision, KamLAND update expected soon
- More statistics needed for firm geological interpretations
- Future experiments: JUNO, SNO+, Jinping
- HanoHano (oceanic crust): the best option to measure mantle contribution: funding needed!

Reactor antineutrinos:

- Daya Bay, Double Chooz, RENO: precision measurement of θ_{13} and "5 MeV bump"
- Daya Bay, RENO: fuel evolution, ^{235}U IBD yield in disagreement with Huber model
- Reactor anomaly and plethora of short baseline experiments: sterile neutrino?
- JUNO in 2021: mass hierarchy and precision θ_{12}, Δm^2_{ee}

Thank you!

Back up slides

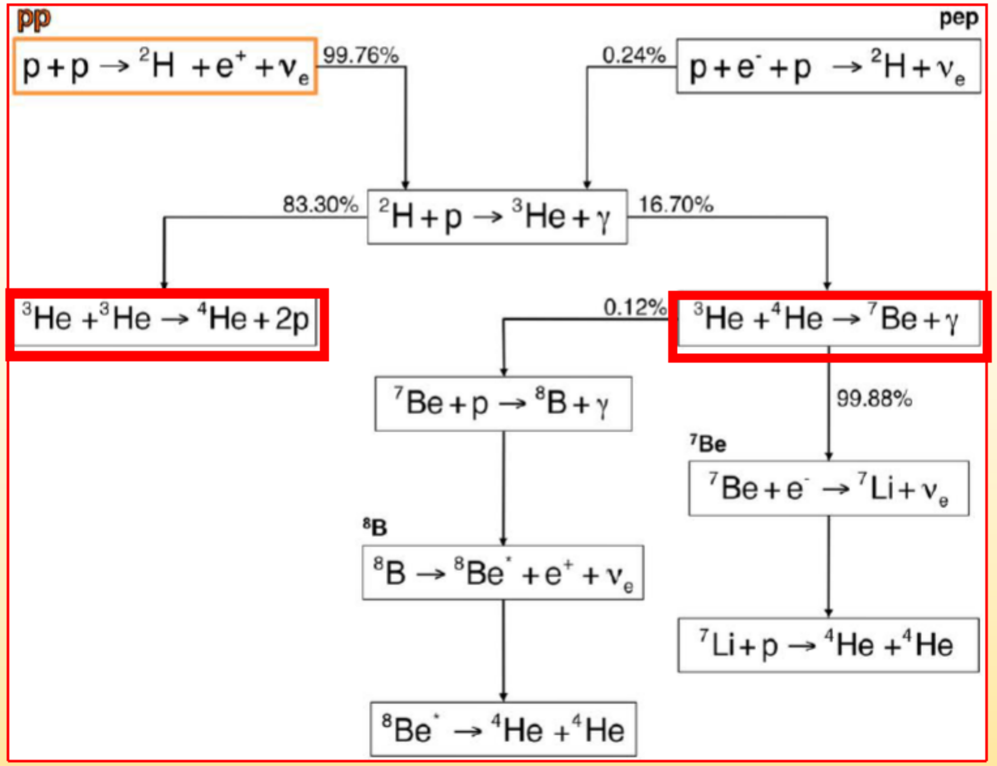
BOREXINO 2018 SOLAR NEUTRINO RESULTS

Solar ν		Rate [cpd/100 t]	Flux – non-oscillated [$cm^{-2}\ s^{-1}$]	Flux – e-equivalent [$cm^{-2}\ s^{-1}$]
pp	1.3x	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5})\times 10^{10}$	$(4.2 \pm 0.3^{+0.2}_{-0.3})\times 10^{10}$
^{7}Be	1.8x	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08})\times 10^{9}$	$(3.15 \pm 0.07^{+0.03}_{-0.05})\times 10^{9}$
pep (HZ)		$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12})\times 10^{8}$	$(0.78 \pm 0.12^{+0.05}_{-0.07})\times 10^{8}$
pep (LZ)	1.6x	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13})\times 10^{8}$	$(0.85 \pm 0.12^{+0.05}_{-0.08})\times 10^{8}$
$^{8}B_{HE-I}$		$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$(2.66^{+0.25+0.06}_{-0.25-0.06}) \times 10^{6}$
$^{8}B_{HE-II}$		$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$(2.44^{+0.22+0.14}_{-0.28-0.14}) \times 10^{6}$
$^{8}B_{HE}$	>2x	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$(2.57^{+0.17+0.07}_{-0.18-0.07})\times 10^{6}$

Implication of the results: probe solar fusion with R

$$R = \frac{Rate(^3He+^3He)}{Rate(^3He+^4He)}$$

Reaction from the main pp chain



$$R = \frac{2\,\Phi(^7Be)}{\Phi(pp) - \Phi(^7Be)}$$

Expected values: (C. Pena Garay, private comm,)

$$R = 0.180 \pm 0.011 \quad HZ$$

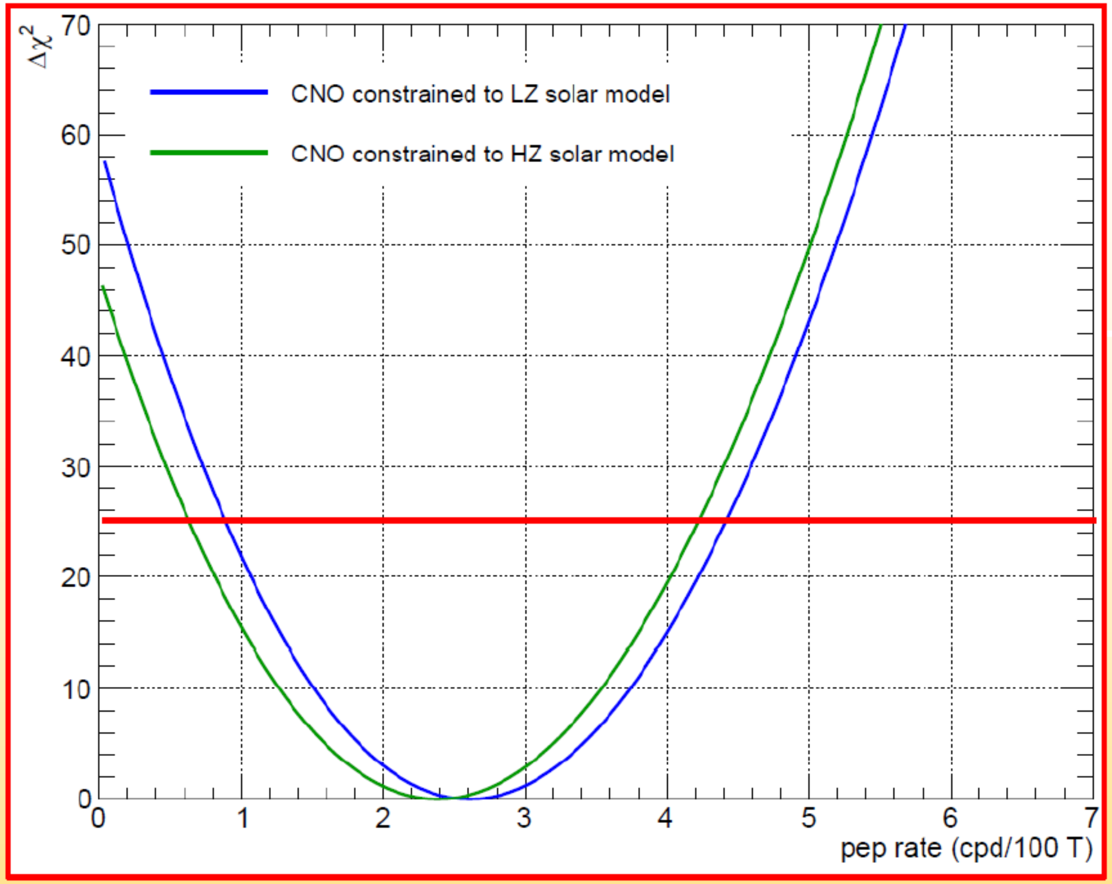
$$R = 0.161 \pm 0.010 \quad LZ$$

Measured value:

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

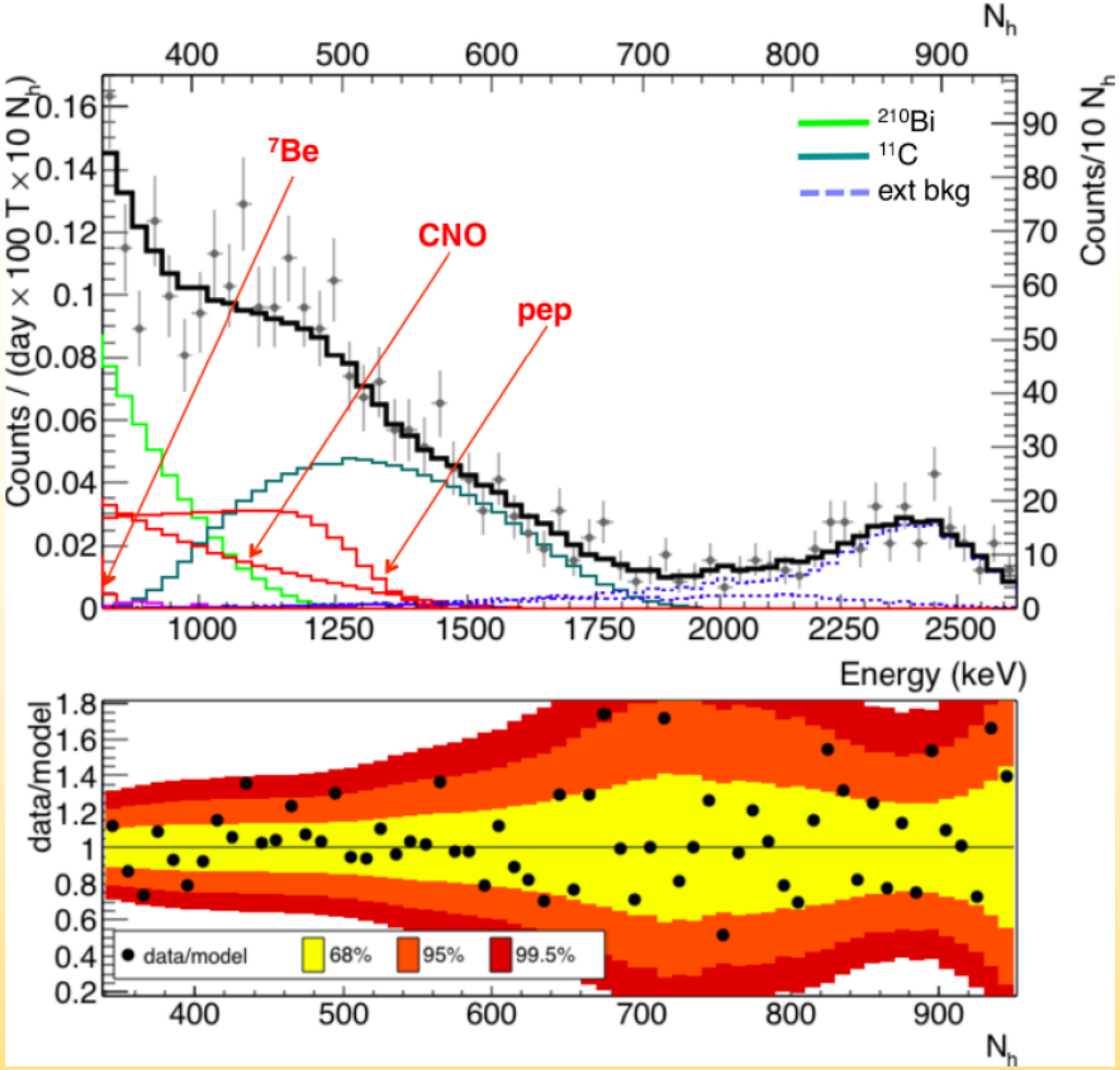
5 σ evidence of pep solar ν
(including systematics uncertainties)

Likelihood profile resulting from the multivariate fit



Select innermost β- like events

Radius<2.4 PS-LPR<4.8



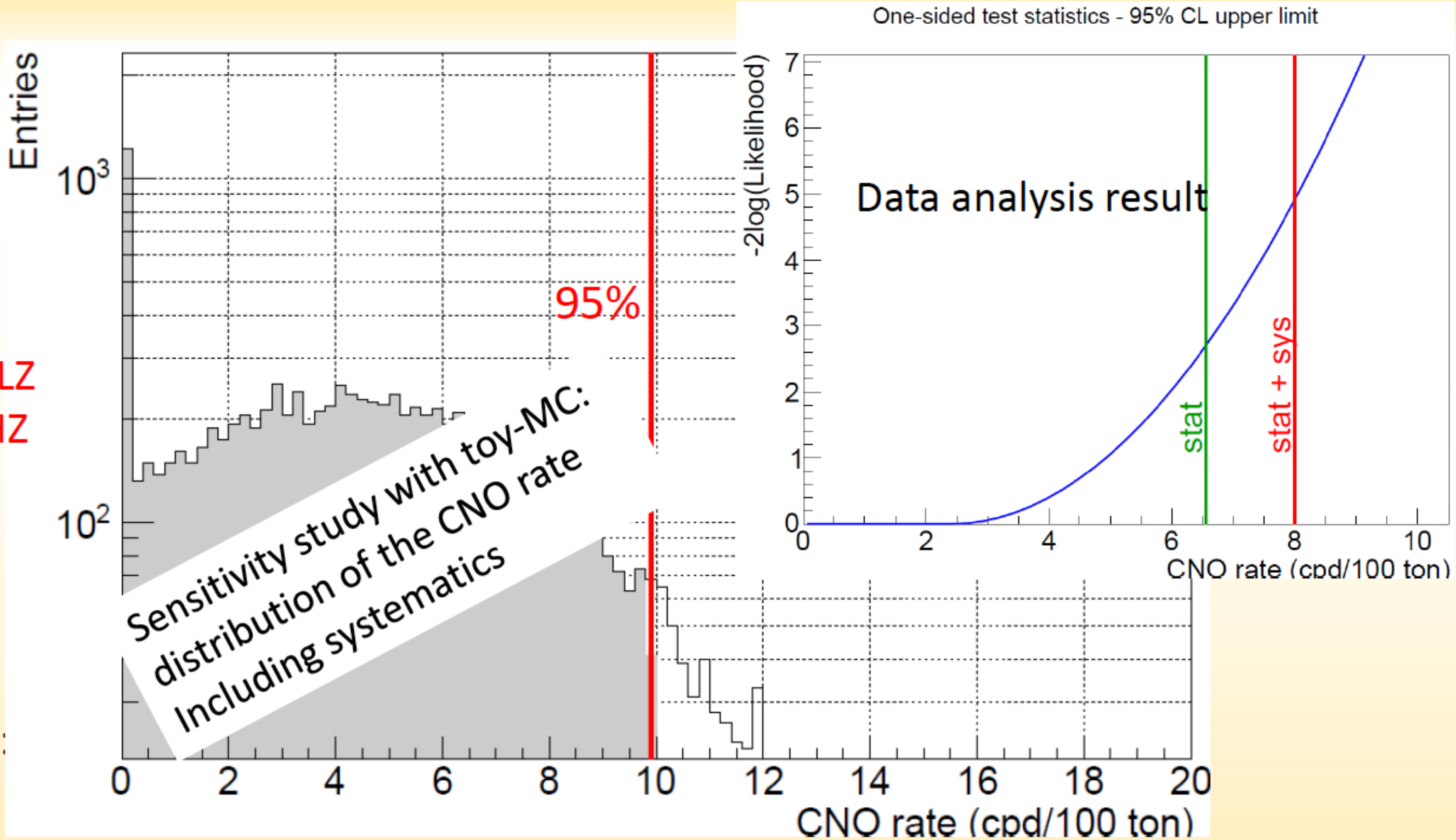
Upper limit on the CNO flux

- Set a constrain to the ratio pp/pep
- Very well know in the solar model
- Include oscillations LMA-MSW
- Toy MC study of the sensitivity :

the median 95% CL is 9 cpd/100t for LZ
10 cpd/100t for HZ

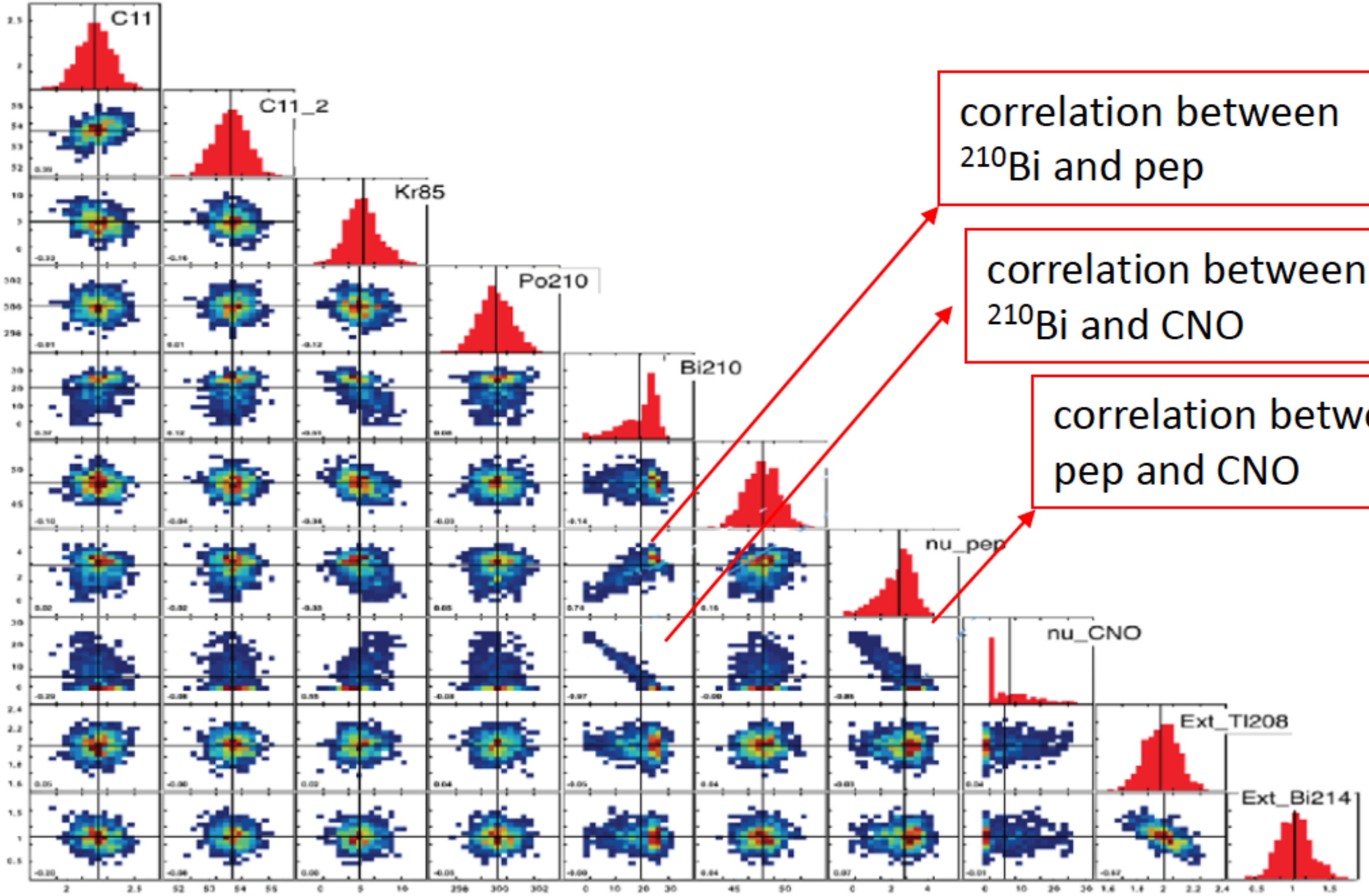
95% C.L. limit on the CNO n rate
8.1 cpd/100t
including systematics errors

Previous limit (set by Borexino Phase I):
7.9 cpd/100t



	Borexino result	Expected HZ	Expected LZ
CNO ν	< 8.1 95%C.L cpd/100t	4.91 +-0.56 cpd/100t	3.62 +- 0.37 cpd/100t

BOREXINO SENSITIVITY STUDIES



correlation between ^{210}Bi and pep

correlation between ^{210}Bi and CNO

correlation between pep and CNO

SYSTEMATIC ERRORS IN LER

Systematic errors in the *LER* analysis						
	***pp* neutrinos**		**7Be neutrinos**		***pep* neutrinos**	
Source of uncertainty	**-%**	**+%**	**-%**	**+%**	**-%**	**+%**
Fit models	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/MC)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the energy estimator	-2.5	+2.5	-0.1	+0.1	-2.4	+2.4
Pile-up modeling	-2.5	+0.5	0	0	0	0
Fit range and binning	-3.0	+3.0	-0.1	+0.1	-1.0	+1.0
Inclusion of the 85Kr constraint	-2.2	+2.2	0	+0.4	-3.2	0
Live Time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator Density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Fiducial Volume	-1.1	+0.6	-1.1	+0.6	-1.1	+0.6
Total systematics (%)	**-7.1**	**+4.7**	**-1.5**	**+0.8**	**-9.0**	**+5.6**

Fit models:
the shapes of fit functions are varied within the uncertainties allowed by the calibration data.

Fit methods:
analytical approach versus Monte Carlo shapes of the spectral components.

Energy estimators
#triggered PMTs in a fixed time window, #of hits, #photoelectrons.

Pile-up modelling:
Synthetic pile-up vs convolution with with random data spectrum.

^{85}Kr constraint:
Constrained based on the ^{85}Kr -> ^{85m}Rb fast coincidence (BR = 0.43%).

Fiducial Volume:
Position reconstruction precision based on calibration data.

THREE-FOLD COINCIDENCE (TFC) TO TAG ^{11}C

Critical for *pep* and CNO neutrinos

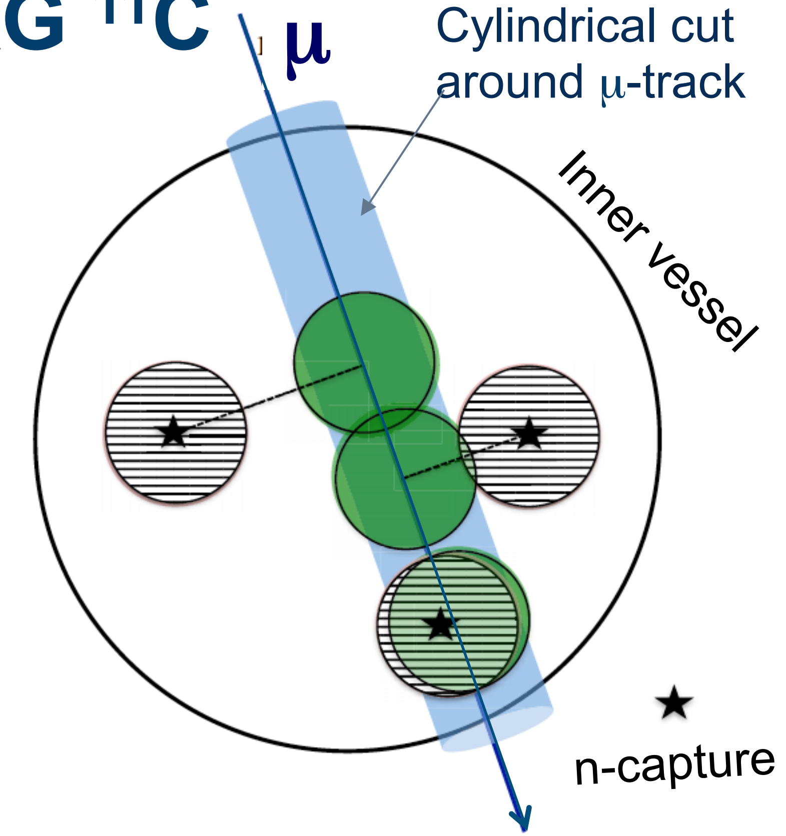
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
$\tau \sim 30$ min

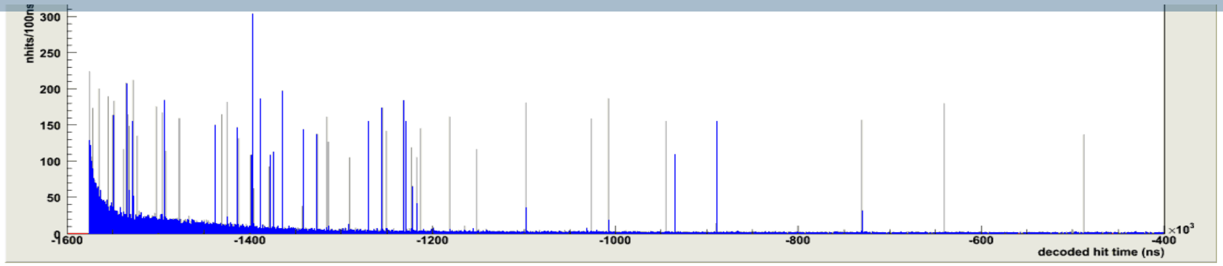
$n + p \rightarrow d + \gamma$ (2.2 MeV)
$\tau \sim 260\ \mu s$

Muon detection ε = 99.992%:

- Outer Detector triggers
- Cluster of hits in Outer Detector data
- Pulse-shape of Inner Detector data



Neutron detection: after each ID μ, 1.6 ms gate is opened to detect neutrons: example with several tens of neutrons.



Exposure divided to 2 categories:
TFC-tagged (46% of exposure, 92% of ^{11}C)
TFC-subtracted (64% of exposure, 8% of ^{11}C)

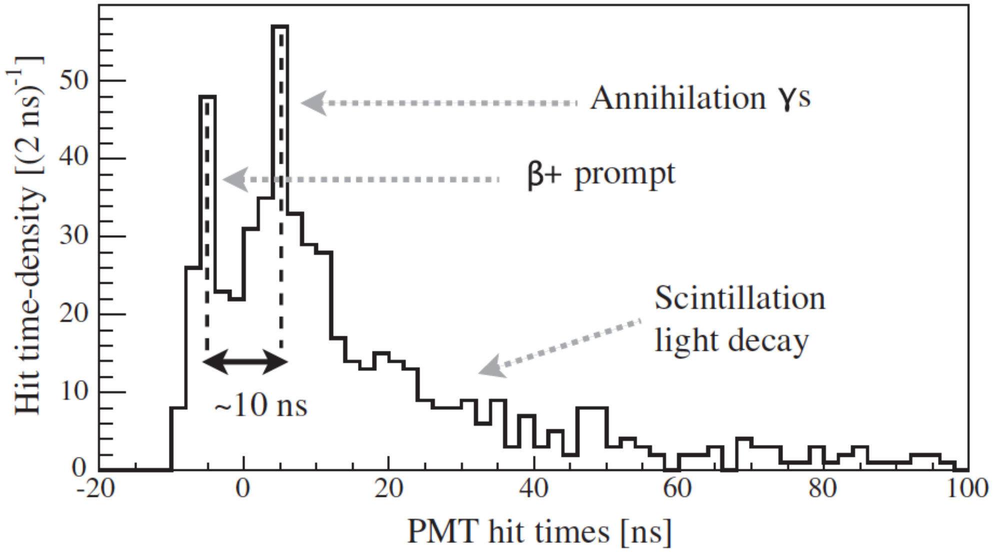
Likelihood that a certain event is ^{11}C uses in input time and space correlations between subsequent muons and cosmogenic neutrons.

JÜLICH Forschungszentrum

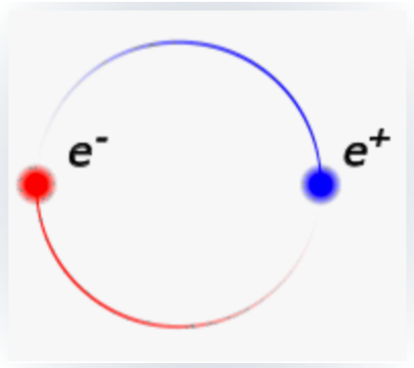
ELECTRON-POSITRON PULSE SHAPE DISCRIMINATION

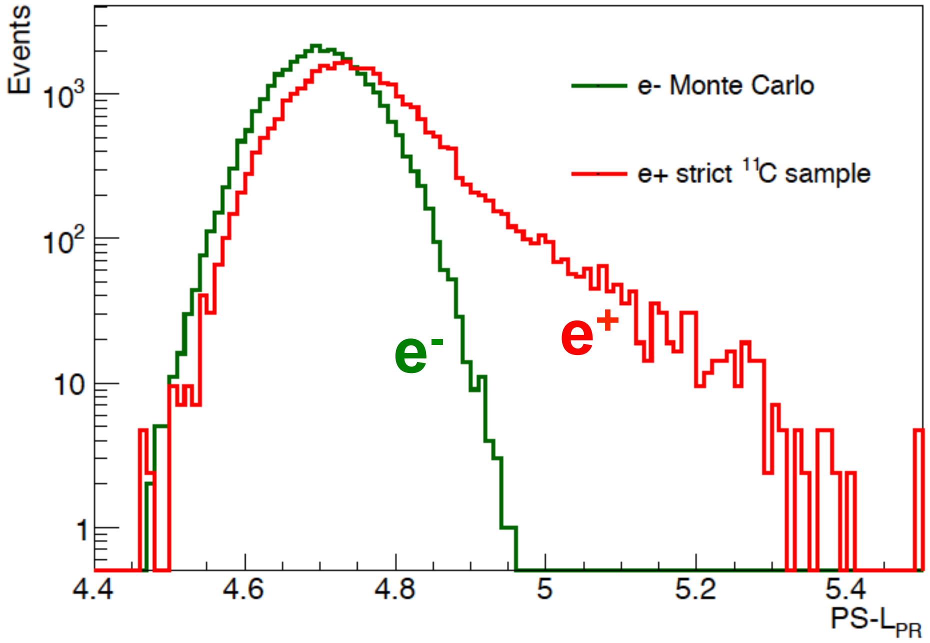
Critical for *pep* and CNO neutrinos

in ~50% of the cases, e^+ annihilation is delayed by ortho-positronium formation (τ ~3ns);



Single ortho-positronium event, in which annihilation occurs in 10 ns after o-Po formation





Pulse shape estimator:
normalized likelihood of the position reconstruction algorithm that uses light emission profiles for electrons.

Used to pin-down the remaining $^{11}C(e^+)$ in the TFC-subtracted spectrum.

RESULTS AND SYSTEMATIC ERRORS IN HER

Systematic errors in the *HER* analysis (8B neutrinos)						
	HER-I		*HER-II*		*HER* (tot)	
Source of uncertainty	**-%**	**+%**	**-%**	**+%**	**-%**	**+%**
Target Mass	-2.0	+2.0	-2.0	+2.0	-2.0	+2.0
Energy scale	-0.5	+0.5	-4.9	+4.9	-1.7	+1.7
z-cut	-0.7	+0.7	0	0	-0.4	+0.4
Live time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Total systematics (%)	**-2.2**	**+2.2**	**-5.3**	**+5.3**	**-2.7**	**+2.7**

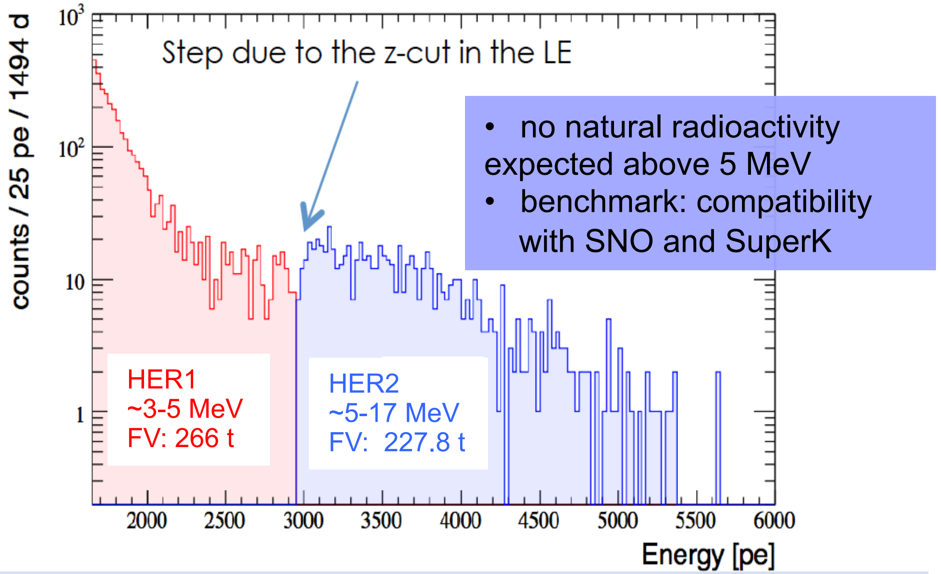
Additionally studied:
- PDF's radial distortion +3%.
- Emanation vessel shift +1%.
- Distortion of the emanation PDF's.
- Binning dependence.

SuperKamiokande	$2.345 \pm 0.014 \pm 0.036 \times 10^6$ cm^{-2} s^{-1}
BX 2010	$2.4 \pm 0.4 \times 10^6$ cm^{-2} s^{-1}
This measurement	**$2.55 \pm 0.18 \pm 0.07 \times 10^6$ cm^{-2} s^{-1}**

HIGH ENERGY REGION (HER) ANALYSIS

Results on ^{8}B solar neutrinos

Analysis in 2 energy regions

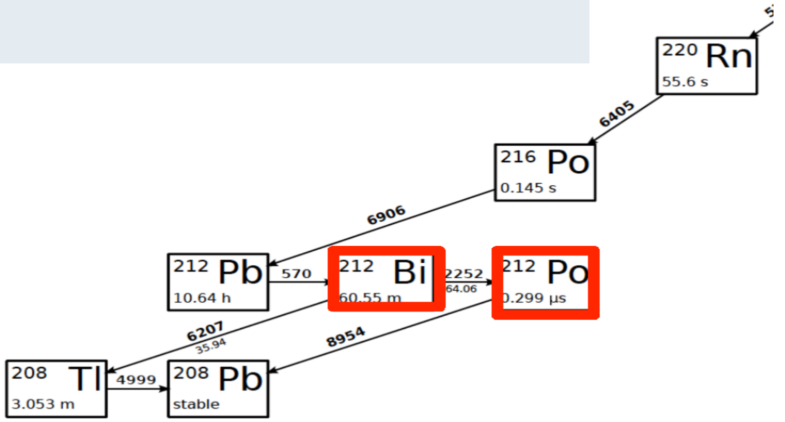


Backgrounds after selection cuts (neutron, cosmogenics, TFC(^{10}C), ^{214}Bi-^{214}Po, random coincidence)

HER1
- ✓ cosmogenic ^{11}Be
- ✓ ^{208}Tl (bulk , emanation and vessel surface)
- ✓ γ's from n-captures

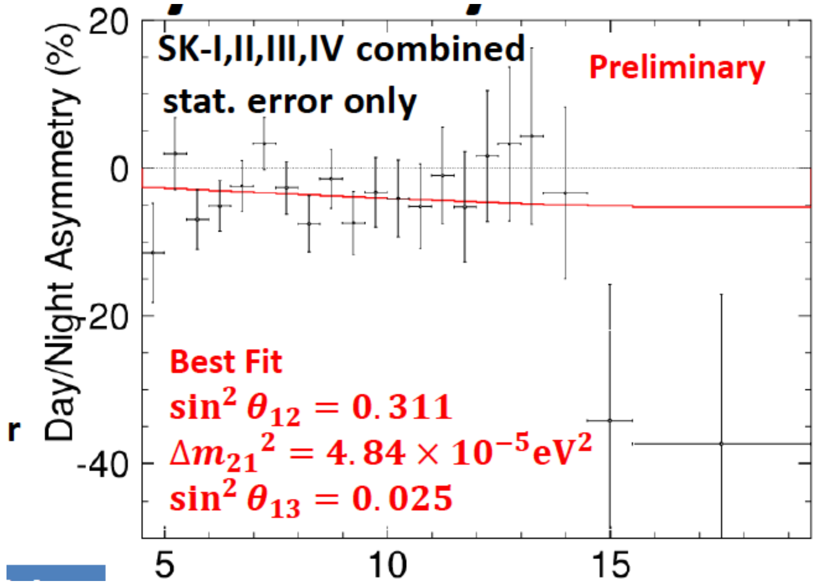
HER2
- ✓ cosmogenic ^{11}Be
- ✓ γ's from n-captures

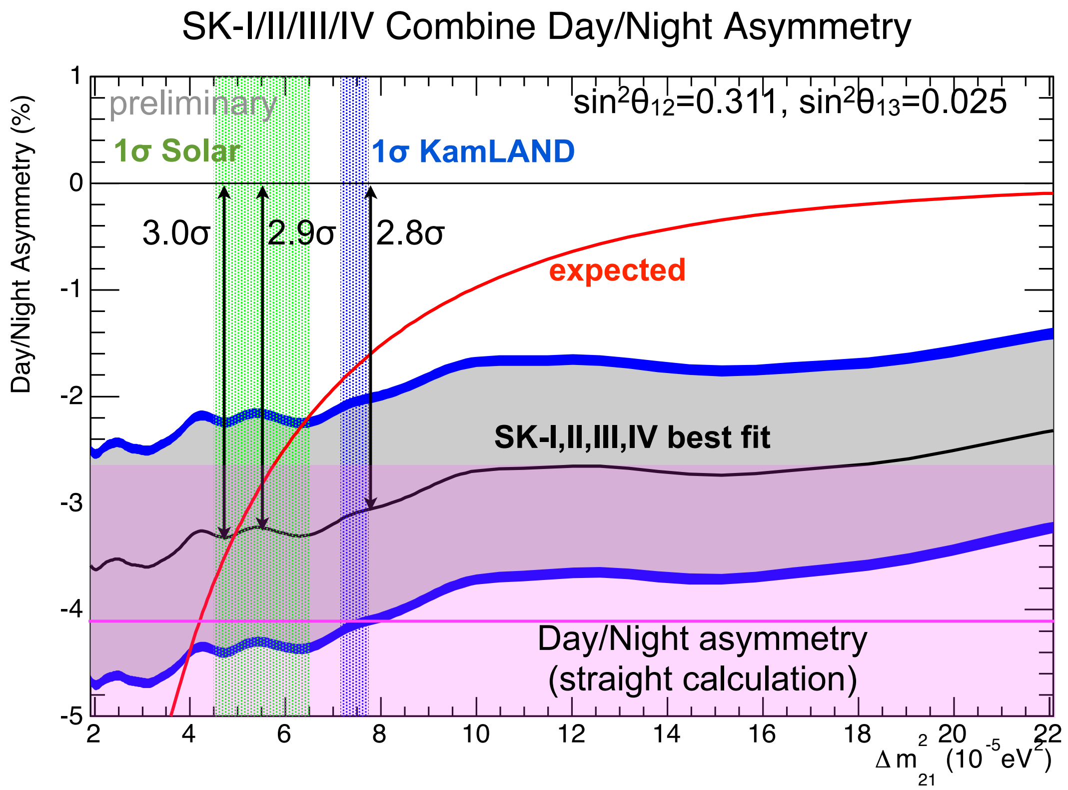
- Almost all scintillator volume used in the analysis.
- Factor 2 improvement wrt PRD 82 (2010) 033006.
- 5x lower internal ^{208}Tl background estimated from ^{212}Bi-^{212}Po coincidences within 3 m radius.
- Two components of the external ^{208}Tl background: pure surface and due to ^{220}Rn emanation.
- Identified new source of background: γ's from neutrons captured on materials different than H,C. The source of neutrons are (α,n) reactions and fissions from U and Th chains.
- New estimation of the ^{11}Be background compatible with 0.



SUPER-KAMIOKANDE DAY-NIGHT ASYMMETRY

SuperK @ ICRC, August 2015





Solar region

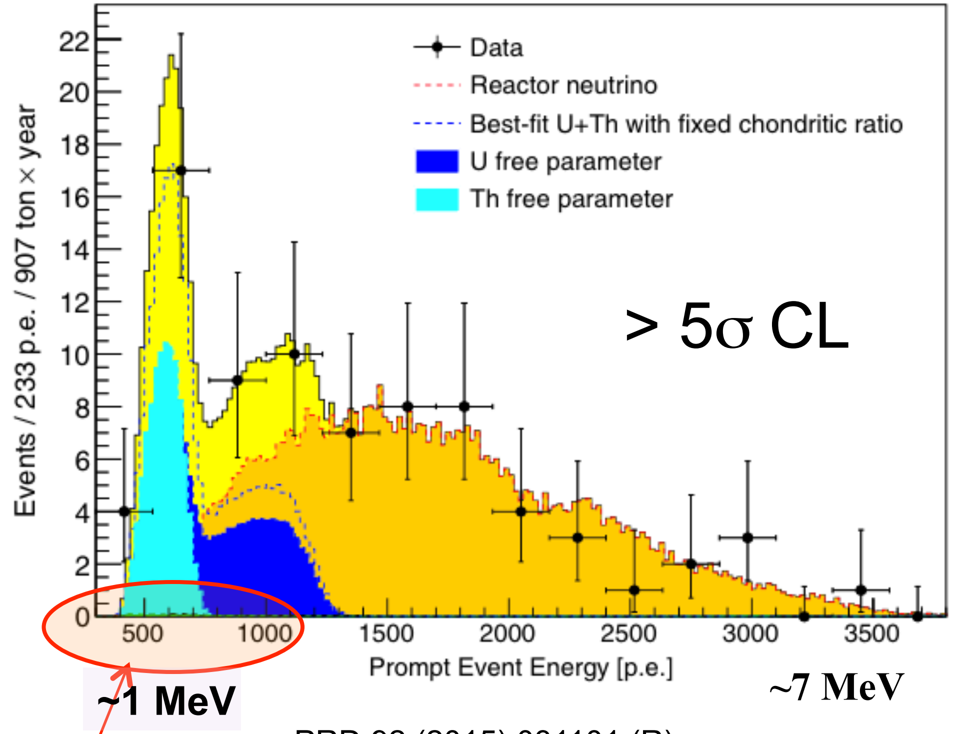
- ✓ differ from zero by 2.9~3.0σ
- ✓ agree with expect by 1.0σ

KamLAND region

- ✓ differ from zero by more than 2.8σ
- ✓ agree with expect by 1.3σ

BOREXINO GEONEUTRINO RESULTS AND ANALYSIS

Borexino 2015: **23.7 $^{+6.5}$ (stat) $^{+0.9}$ (sys)** geonu's



PRD 92 (2015) 031101 (R)

- ✓ Non-antineutrino background almost invisible!
- ✓ 5.5 x 10^{31} target-proton year

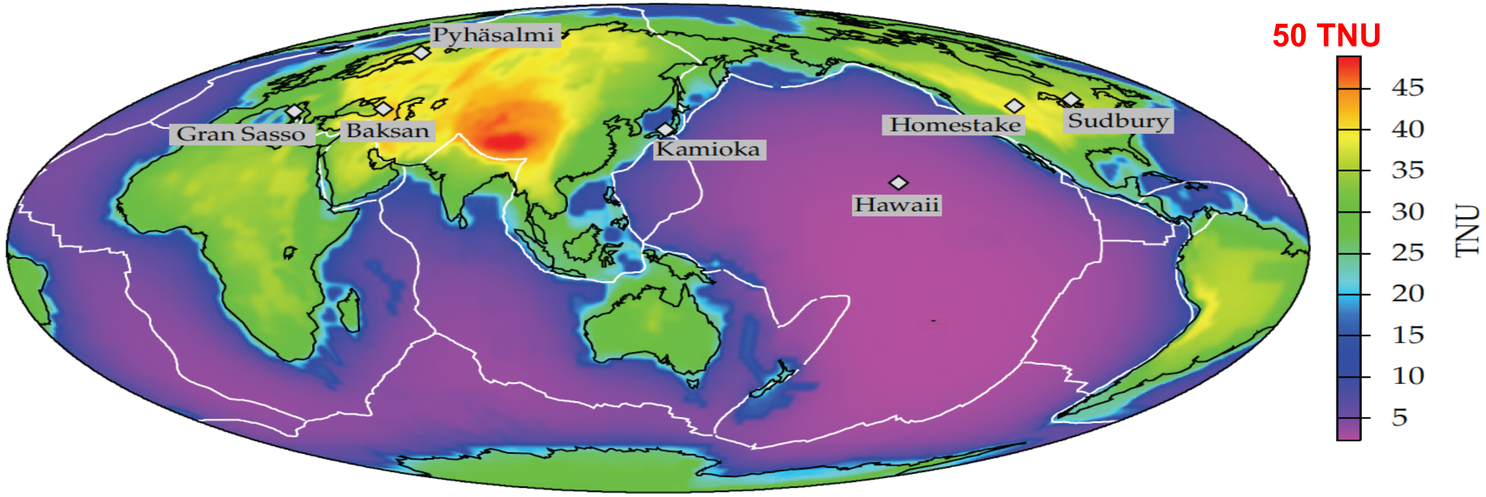
- Unbinned maximum likelihood fit of 77 candidates.
- Non-antineutrino background almost negligible (< 1 event) and constrained in the fit.
- Reactor background left free in the fit: results compatible with expectations.
- 2 kinds of fit:
  - ✓ U/Th left free;
  - ✓ U/Th constrained to chondritic value.
- **Statistical error largely dominates systematic uncertainty** (reactor spectra, uncertainty of backgrounds, and detector response).

New update with ~20% precision under preparation.

First geologically significant results available but more statistics needed!

Important new tool for future experiments

Expected “known and big” crustal signal



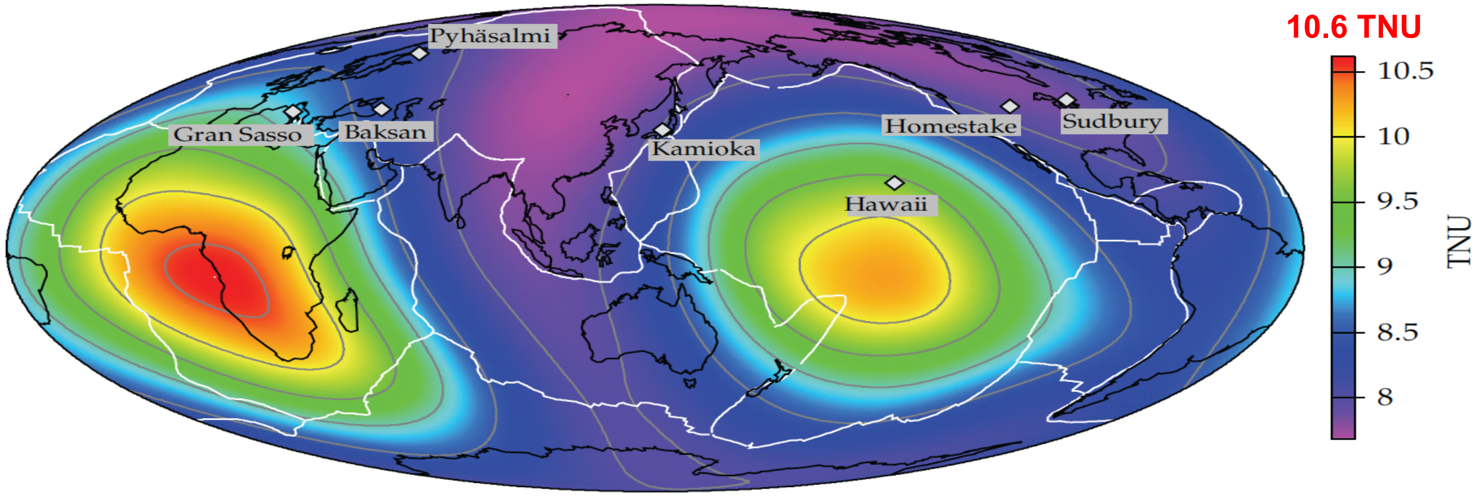
The signal is small, we need big detectors!

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event /1 kton /1 year,
100% detection efficiency

Expected mantle signal: hypothesis of heterogeneous composition

Motivated by the observed Large Shear Velocity Provinces at the mantle base

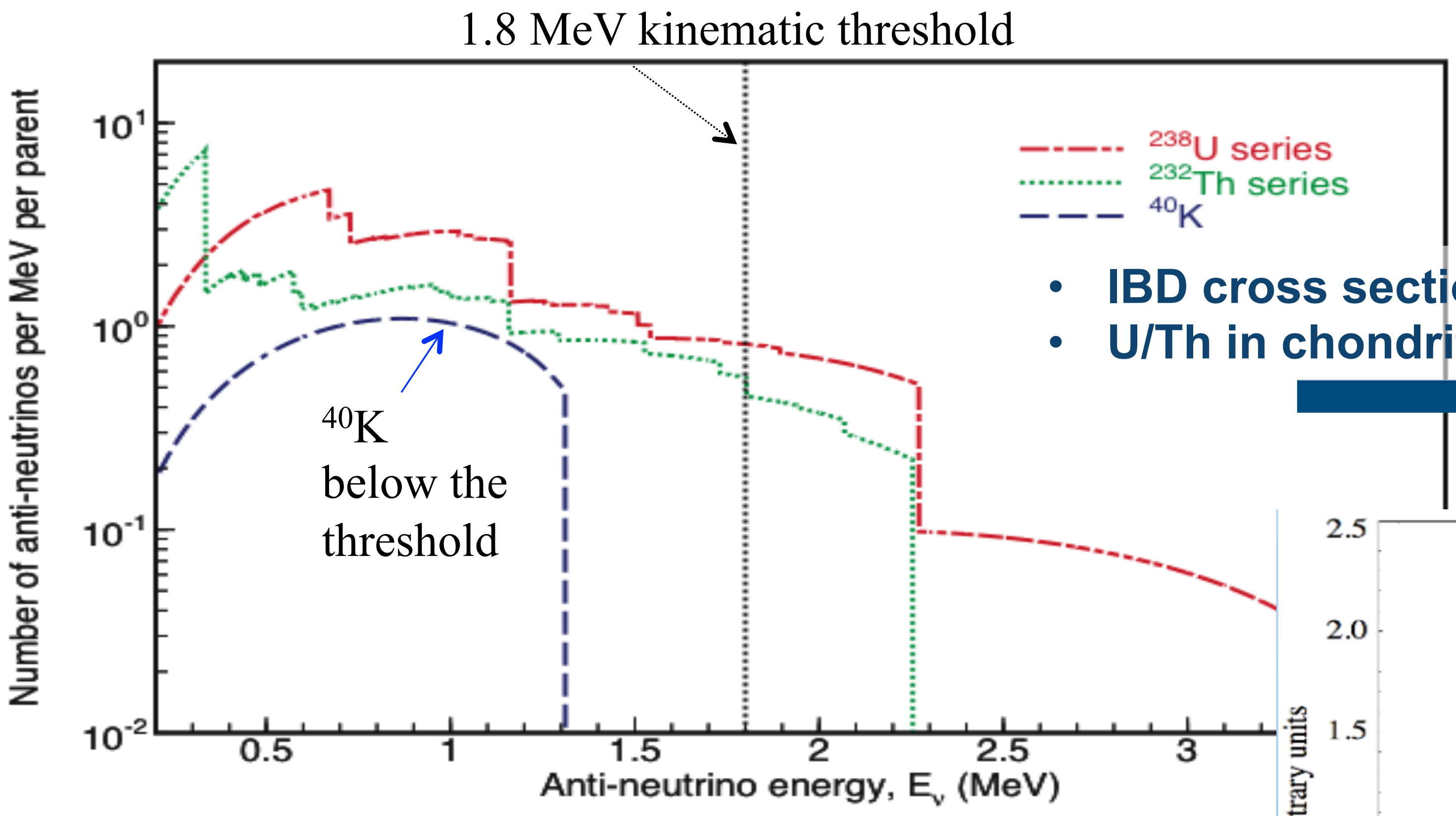
(from: C. Jaupart: remnants of a basal layer, now thinned and deformed by convection?)



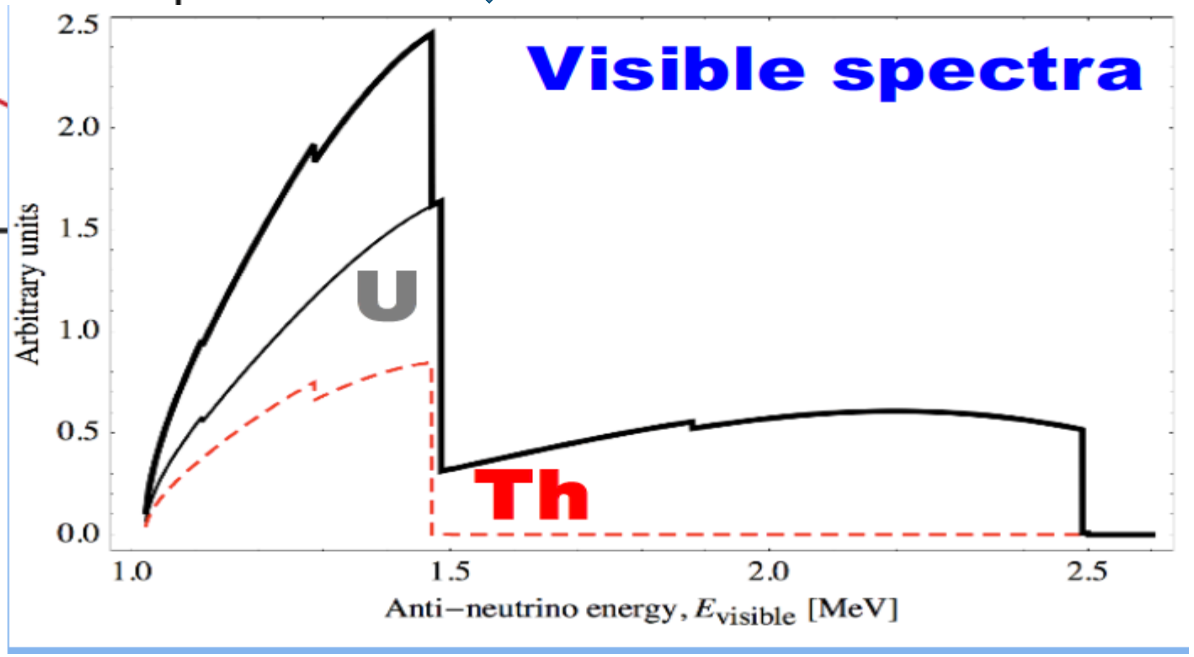
To measure mantle signal is even more challenging!

Ondřej Šrámek, William F. McDonough, Edwin S. Kite, Vedran Lekić, Steve Dye, Shijie Zhong “Geophysical and geochemical constraints on geoneutrino fluxes from Earths mantle”, Earth Planet. Sci. Lett., 361 (2013) 356-366)

GEONEUTRINOS ENERGY SPECTRA



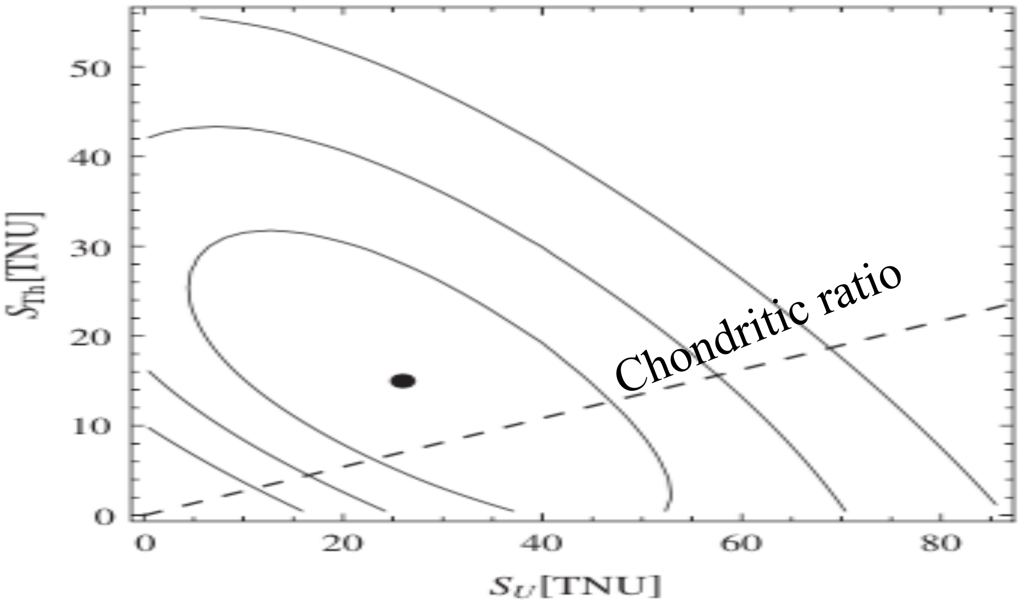
- IBD cross section
- U/Th in chondritic ratio

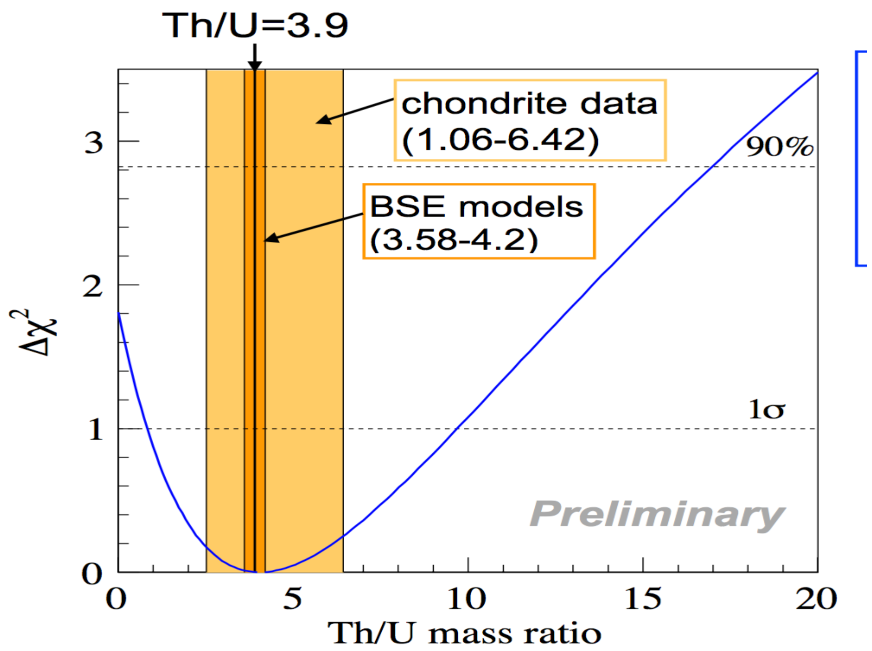


Geological implications

Borexino	KamLAND

2. **U/Th ratio**, when left as a free fit parameter, is compatible with the chondritic U/Th ratio.
The error on the measured ratio is still large.





Geological implications

Borexino	KamLAND

3. **Radiogenic heat**: the first geoneutrino-based measures of the Earth radiogenic heat available