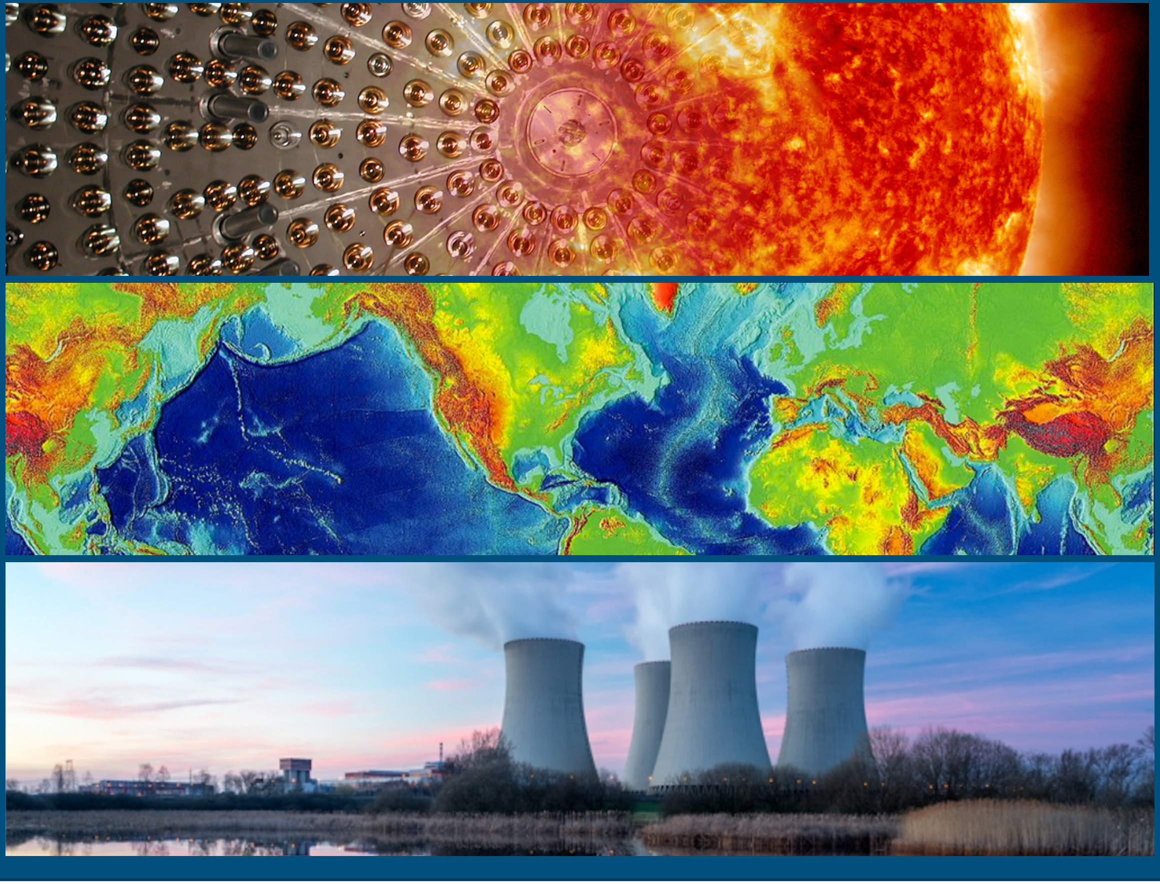
LOW-ENERGY NEUTRINO PHYSICS WITH BOREXINO AND JUNO



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IKP-2, FORSCHUNGSZENTRUM JÜLICH
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GERMANY

DECEMBER 14TH, 2018
BRUSSELS, BELGIUM

IIHE ULB-VUB Invited Seminar

OUTLINE

1. **Neutrino physics**
   - ✓ Introduction
   - ✓ Opened questions
   - ✓ Neutrino detection with liquid-scintillator based detectors
2. **Borexino**
   - ☐ Detector
   - ☐ **Solar neutrinos**
     - ✓ Motivation
     - ✓ Latest results from Borexino
   - ☐ **Geoneutrinos**
     - ✓ Motivation
     - ✓ Latest results from Borexino
3. **JUNO**
   - ✓ Reactor neutrino experiments at different baselines
   - ✓ JUNO experiment
   - ✓ JUNO physics potential: **mass hierarchy and not only**

NEUTRINOS ARE SPECIAL

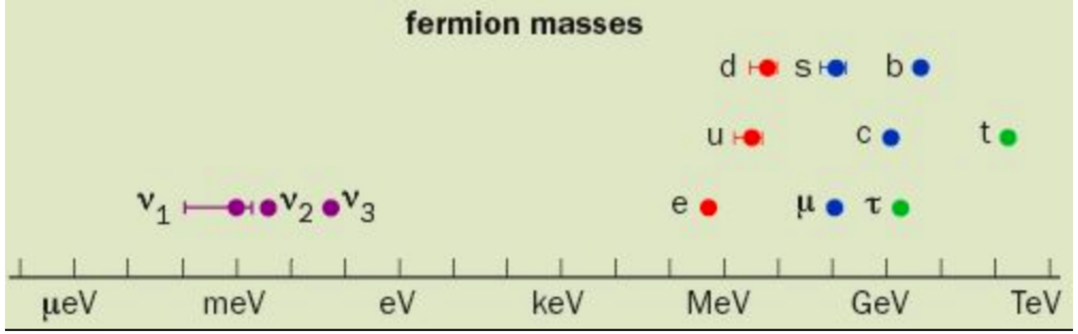
Only weak interactions

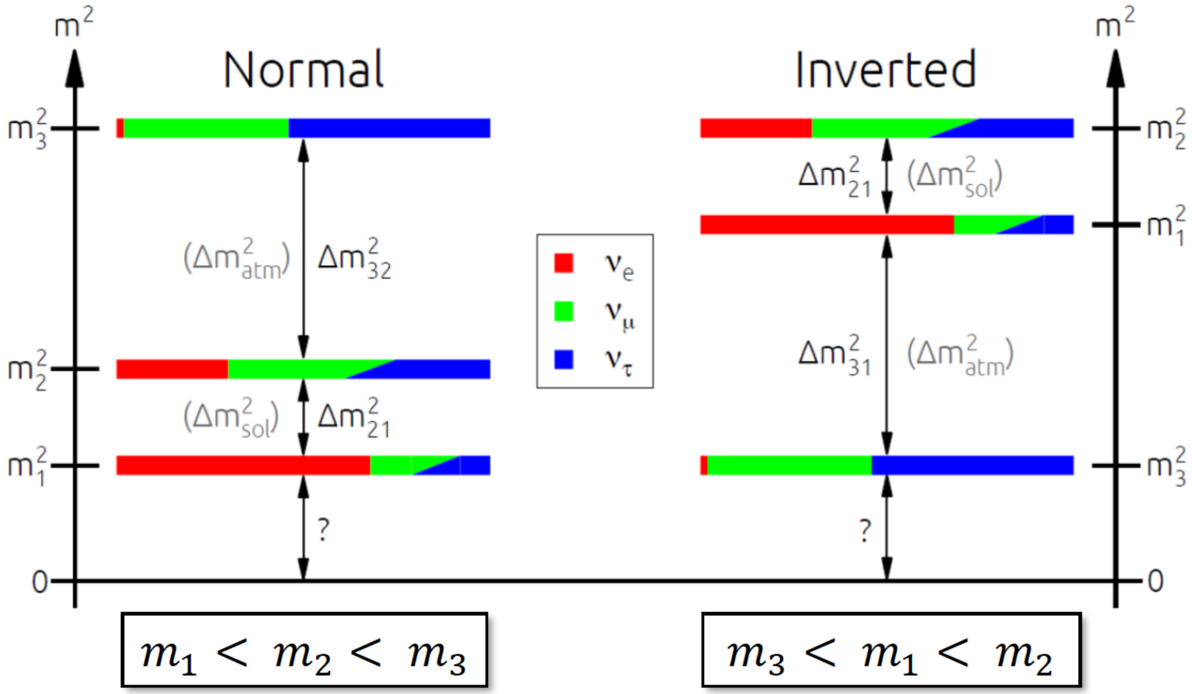
- ✓ **Difficult to detect**
  - ○ Large detectors
  - ○ Underground laboratories
  - ○ Extreme radio-purity
- ✓ **Bring unperturbed information about the source** (**Sun, Earth**, SN)

Open questions in neutrino physics

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

linked





$m_1 < m_2 < m_3$

$m_3 < m_1 < m_2$

$\Delta m^2_{31,\mathrm{normal}} > \Delta m^2_{31,\mathrm{inverted}}$

Δm^2_{31}= has opposite signs in the two hierarchies!

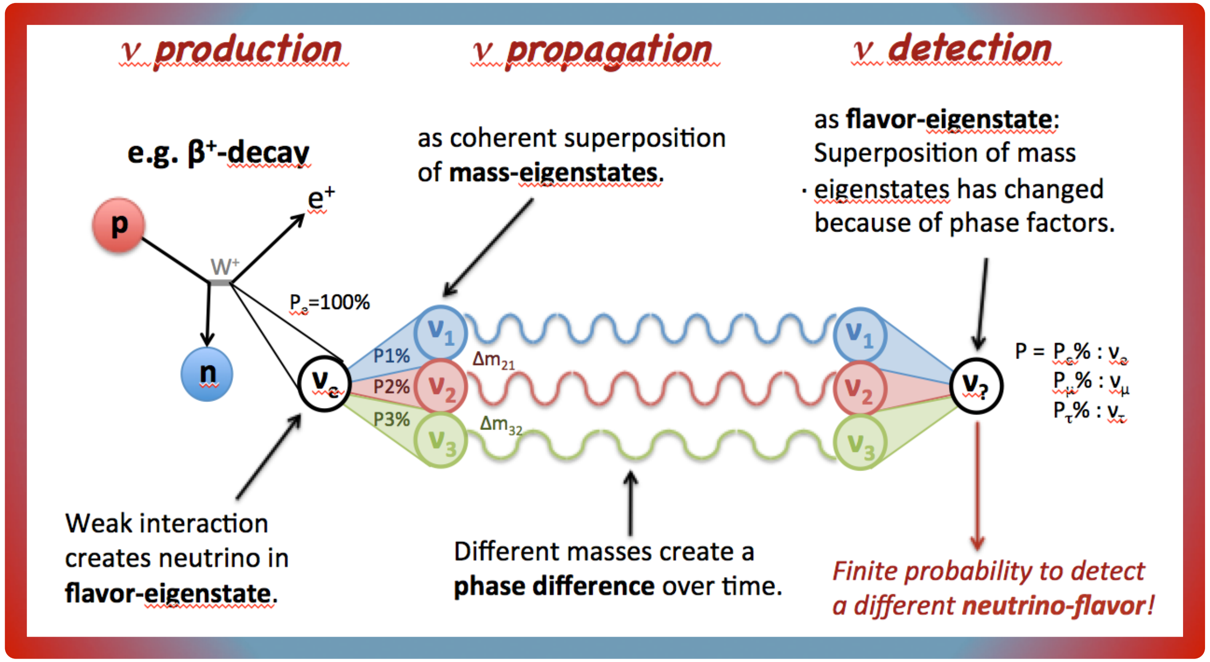
NEUTRINO MIXING AND OSCILLATIONS

$\alpha = e, \mu, \tau$
Flavour eigenstates
INTERACTIONS

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

$i = 1, 2, 3$
Mass eigenstates
PROPAGATION

$$\begin{array}{cccc}
\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} &
\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} &
\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} &
\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
\text{Atmospheric} & \text{Reactor} & \text{Solar} & \text{Majorana}
\end{array}$$



as coherent superposition of **mass-eigenstates.**

as **flavor-eigenstate**: Superposition of mass eigenstates has changed because of phase factors.

Weak interaction creates neutrino in **flavor-eigenstate.**

Different masses create a **phase difference** over time.

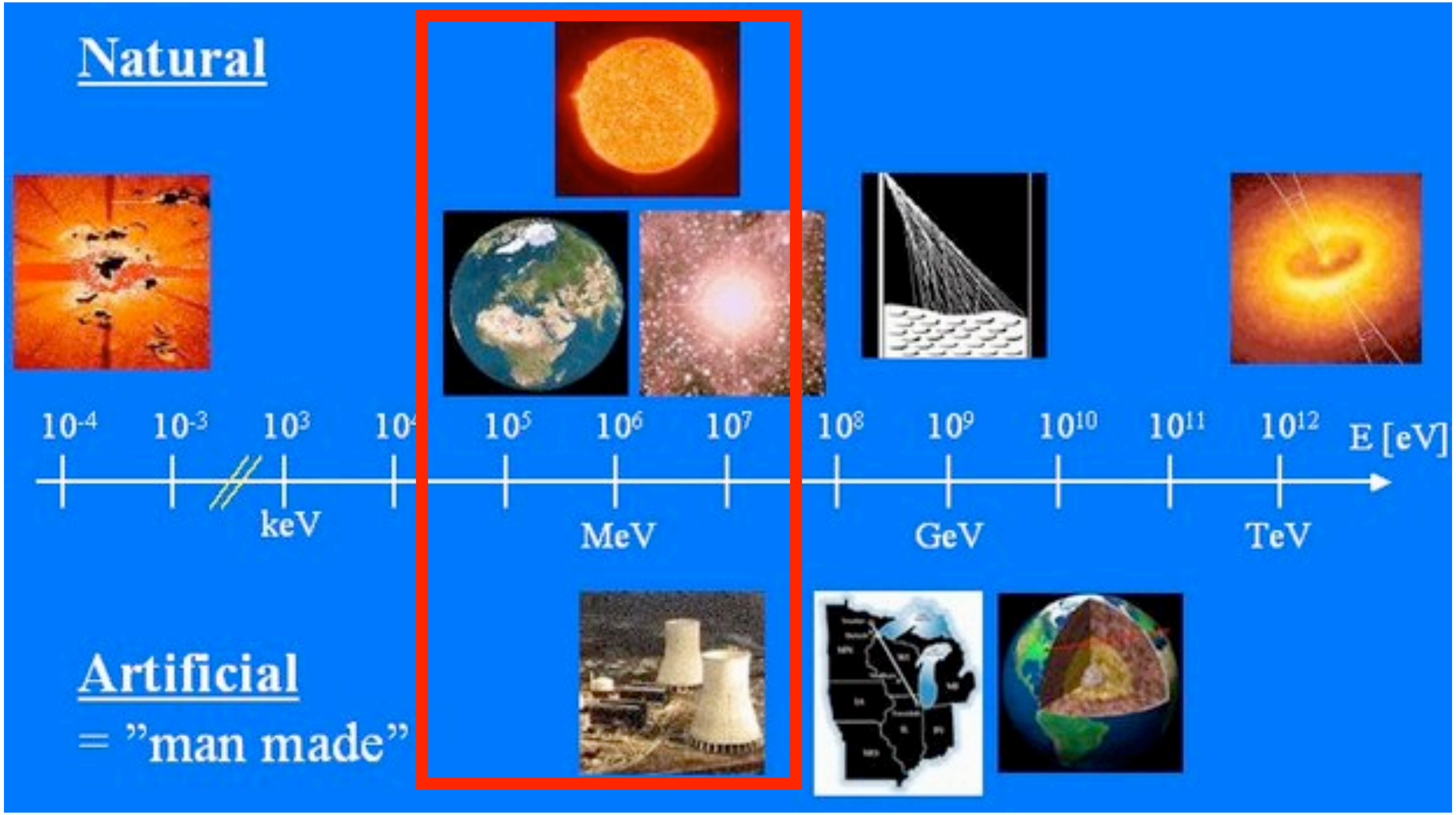
Finite probability to detect a different ***neutrino-flavor!***

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)

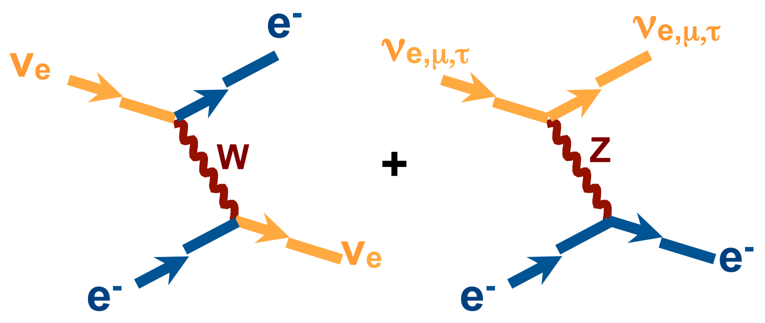
NEUTRINO SOURCES

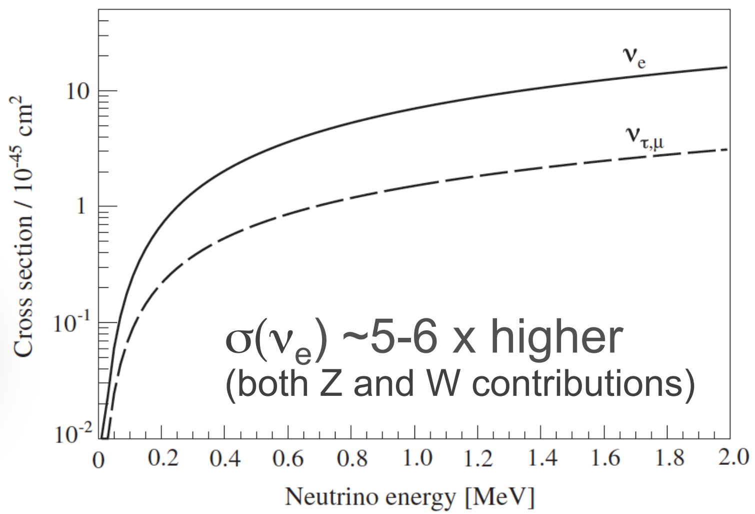


MeV (ANTI-)NEUTRINO DETECTION WITH LIQUID SCINT.

Neutrino detection: SINGLES

- Elastic scattering of electrons
- No threshold
- All flavours





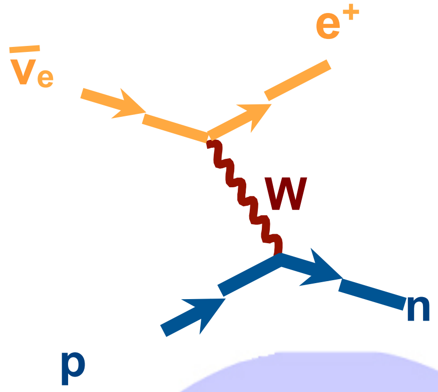
$\sigma(\nu_e)$ ~5-6 x higher
(both Z and W contributions)

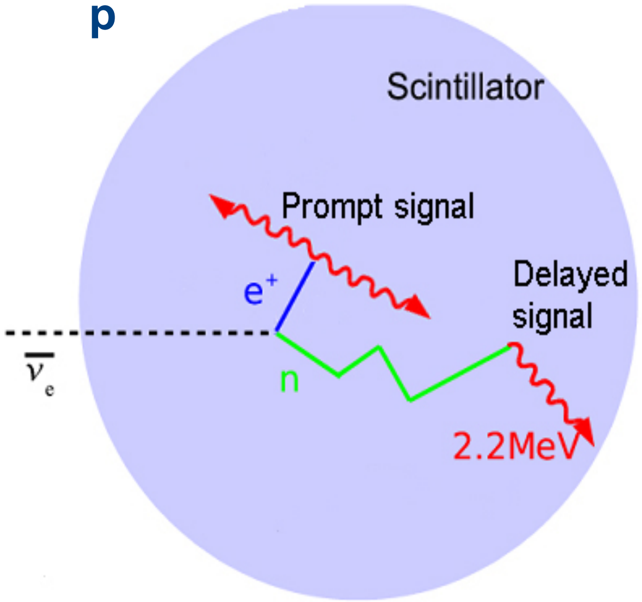
Antineutrino detection: Coincidences (BGR suppression)

- Inverse beta decay (IBD)
- Charge current, e-flavour only

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

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



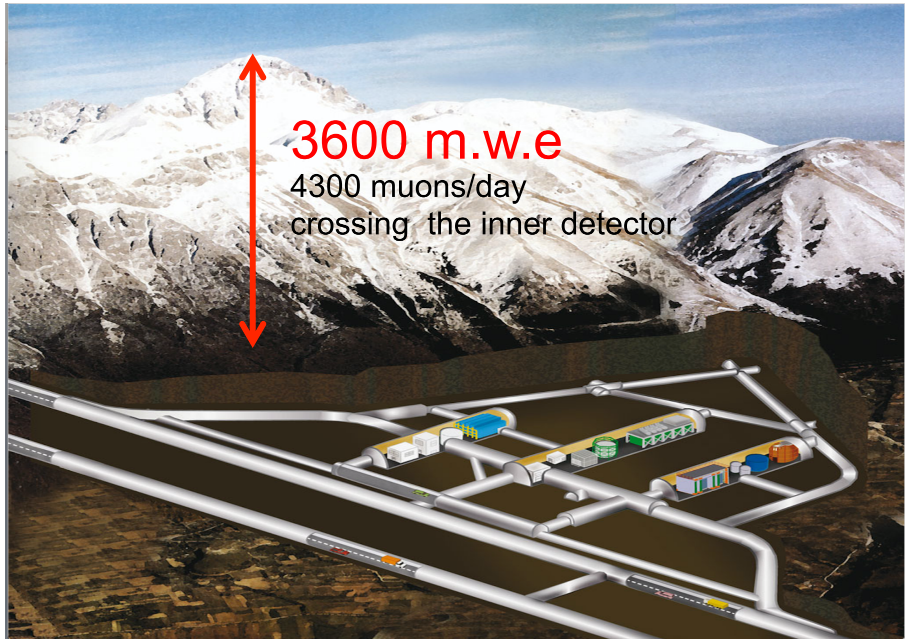


BOREXINO COLLABORATION

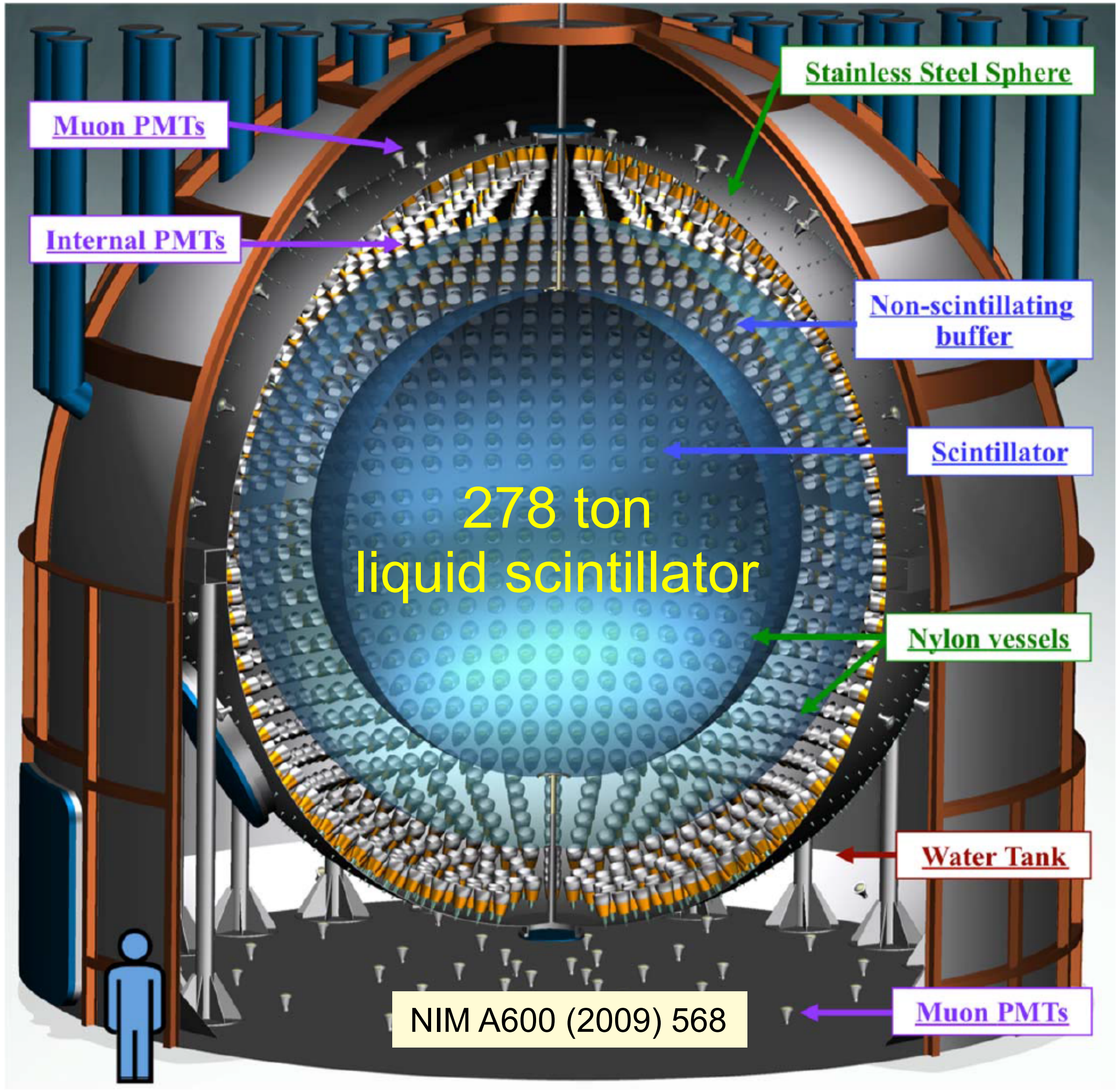
~100 scientists from
- Italy
- Germany
- Russia
- France
- USA
- Poland

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy

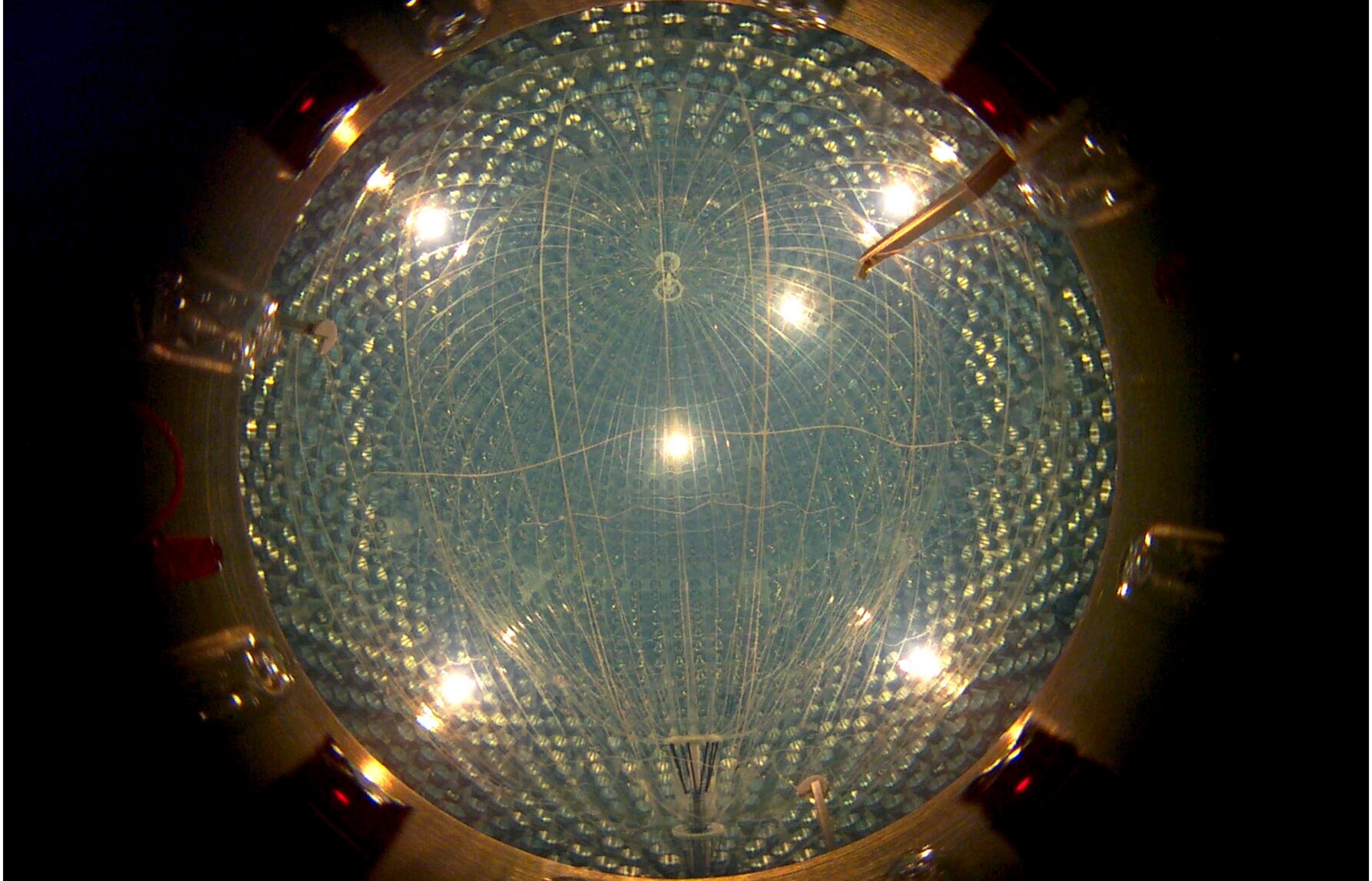


- **the world's radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g , $< 8 \times 10^{-20}$ g(U)/g
- **~500 hit PMTs / MeV**
- energy reconstruction: 5 keV (5%) @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



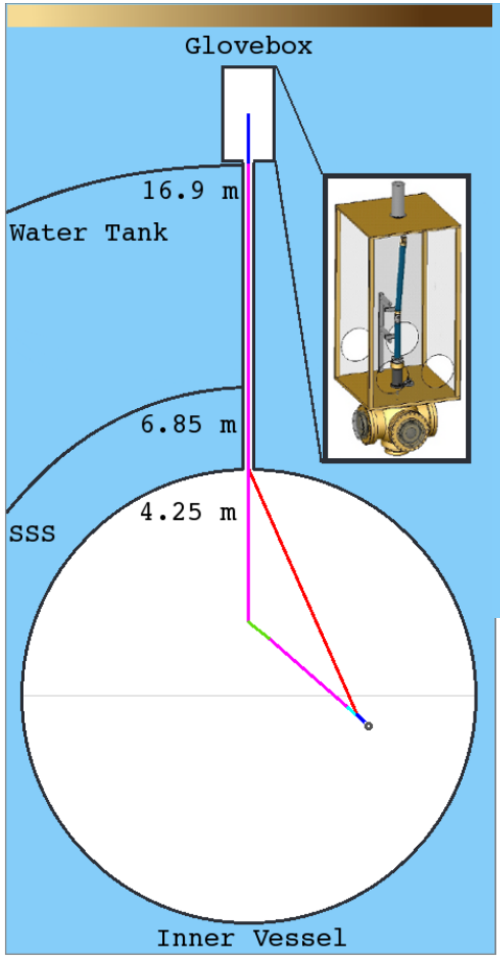
NIM A600 (2009) 568

Operating since 2007



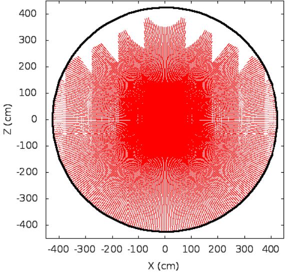
BOREXINO CALIBRATION

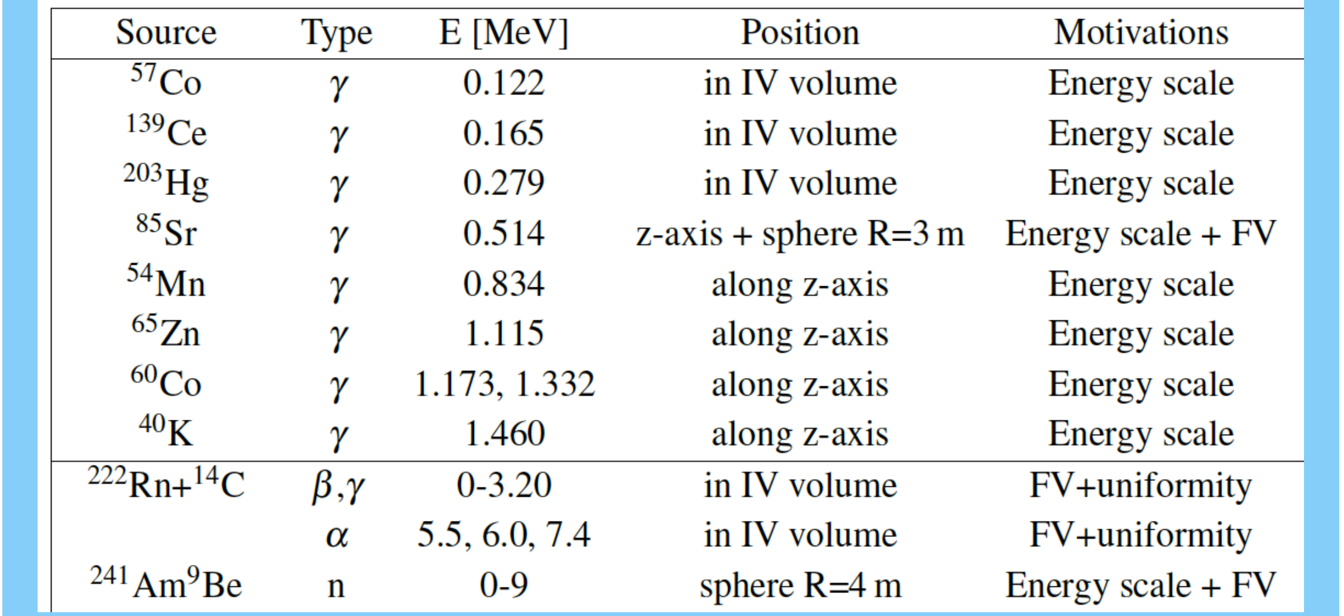
JINST 7 (2012) P10018



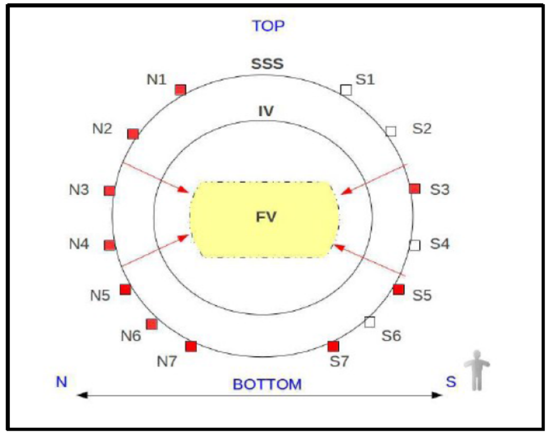
Internal calibration

- ~300 points in the whole scintillator volume
- LED-based source positioning system





Source	Type	E [MeV]	Position	Motivations
^{57}Co	γ	0.122	in IV volume	Energy scale
^{139}Ce	γ	0.165	in IV volume	Energy scale
^{203}Hg	γ	0.279	in IV volume	Energy scale
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV
^{54}Mn	γ	0.834	along z-axis	Energy scale
^{65}Zn	γ	1.115	along z-axis	Energy scale
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale
^{40}K	γ	1.460	along z-axis	Energy scale
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV

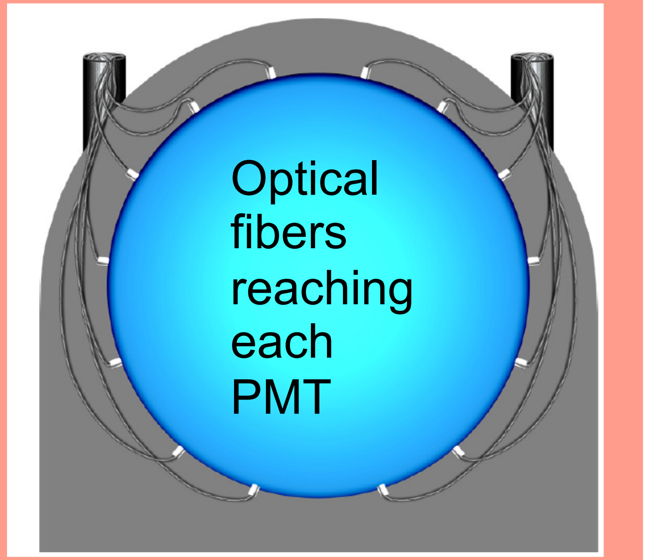


External calibration

9 positions with ^{228}Th source (γ 2.615 MeV)

Laser calibration

- PMT time equalisation
- PMT charge calibration (charge calib. also using ^{14}C)



Optical fibers reaching each PMT

BOREXINO MONTE CARLO

Astrop. Phys. 97 (2018) 136

Better than 1% (1.9%) precision
for all relevant quantities in the solar analysis <2 (>3) MeV

Geant-4 based

Tracking code

- Full detector geometry
- Energy loss
- Photon production & propagation

C++ Borexino custom

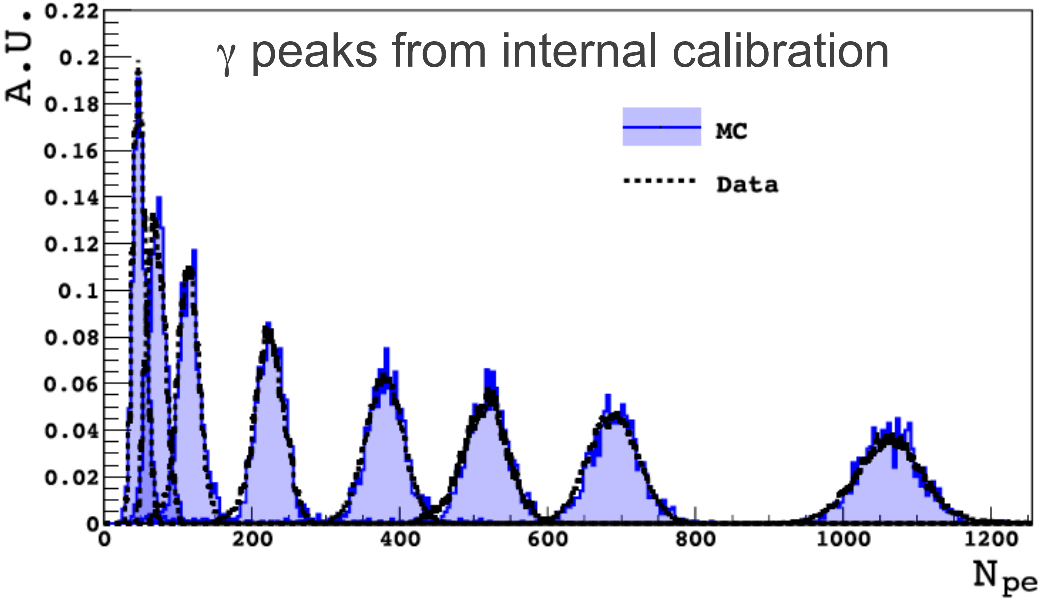
Electronics simulation

- Follows real DAQ conditions
- PMT quality and calibration
- Dark noise
- Trigger condition
- Number of working channels on an event-by-event basis

Echidna: C++ Borexino custom

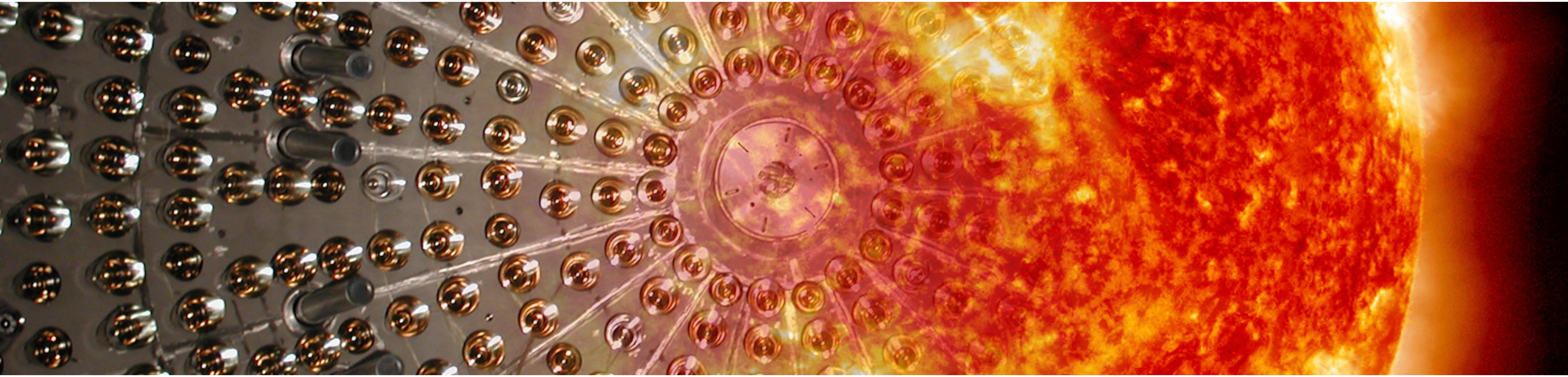
Reconstruction

- Several energy estimators
- Position reconstruction
- Pulse-shape variables
- Output in the same format as reconstructed data files

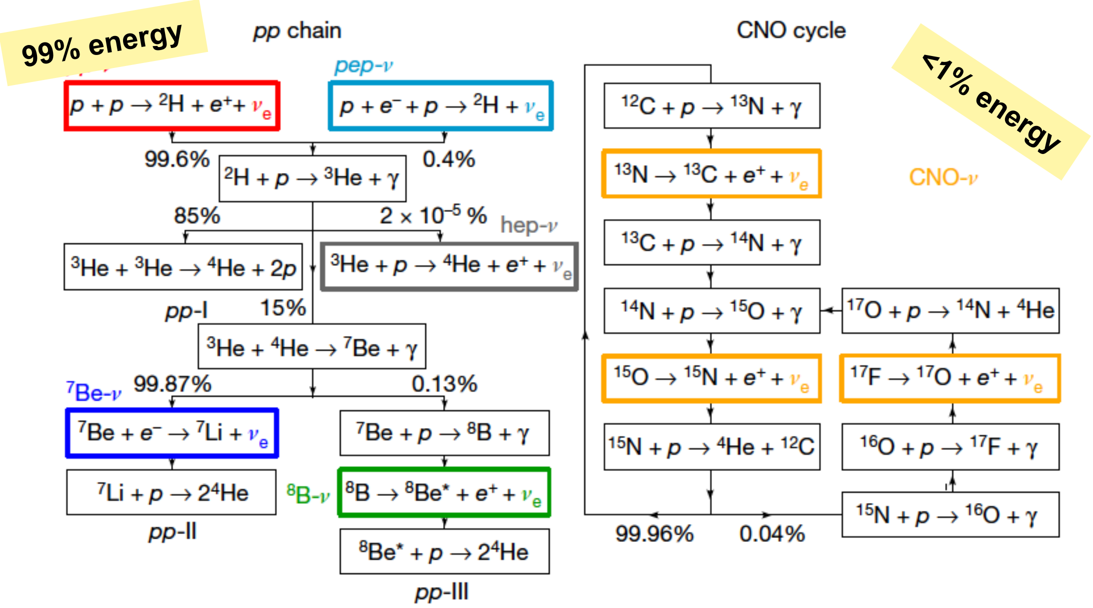

γ peaks from internal calibration

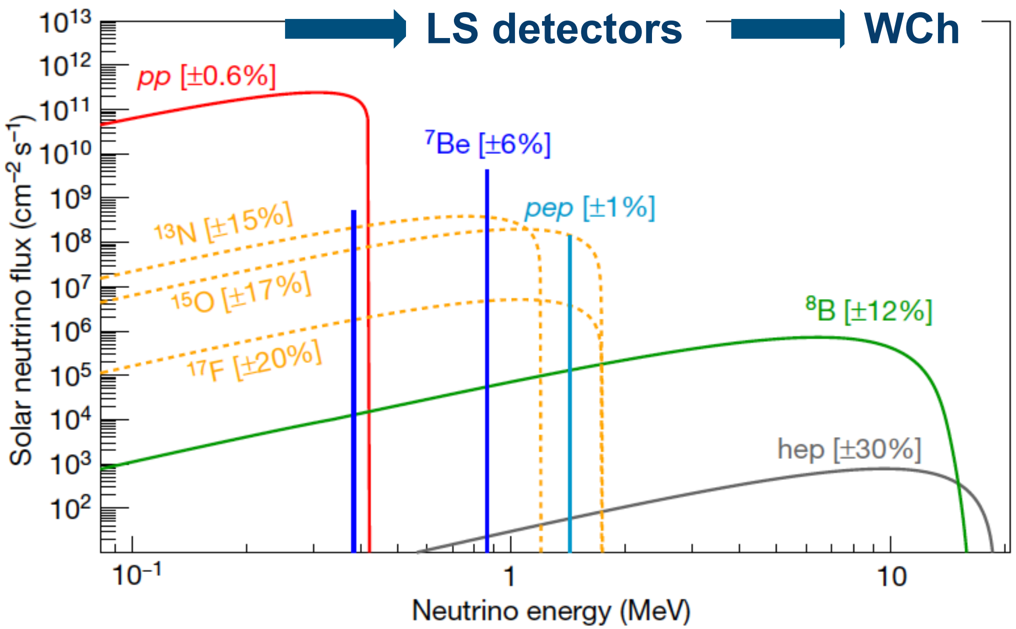
- **Tuning on calibration data.**
- **Independently measured input parameters**: emission spectra, attenuation length, PMT after-pulse, refractive index, effective quantum efficiencies.
- **Biasing technique for external background.**
- **Simulation of pile-up events.**

SOLAR NEUTRINOS



SOLAR NEUTRINOS AND WHY TO STUDY THEM





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

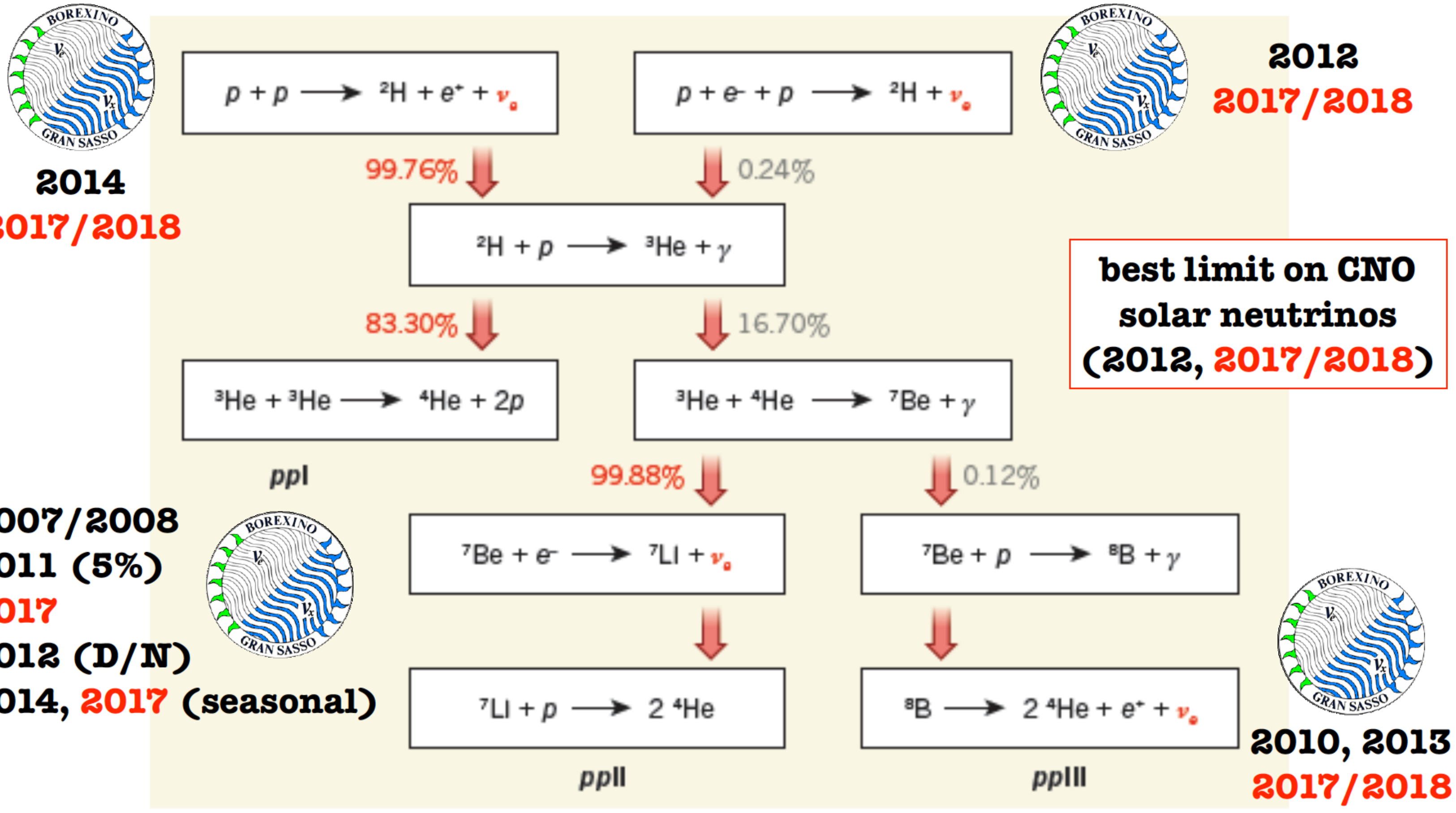
Solar and stellar physics

- 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$_\nu$)** 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**

BOREXINO MILESTONE RESULTS



2014
2017/2018

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

2012
2017/2018

99.76%

0.24%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

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

83.30%

16.70%

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

ppI

99.88%

0.12%

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

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow 2\,{}^4\mathrm{He} + e^+ + \nu_e$

ppII

ppIII

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

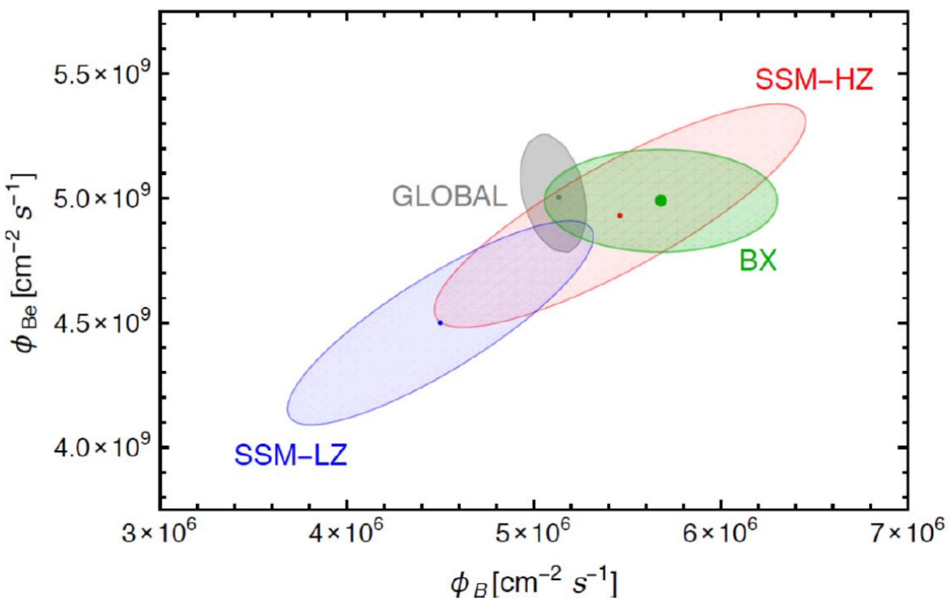
https://doi.org/10.1038/s41586-018-0624-y

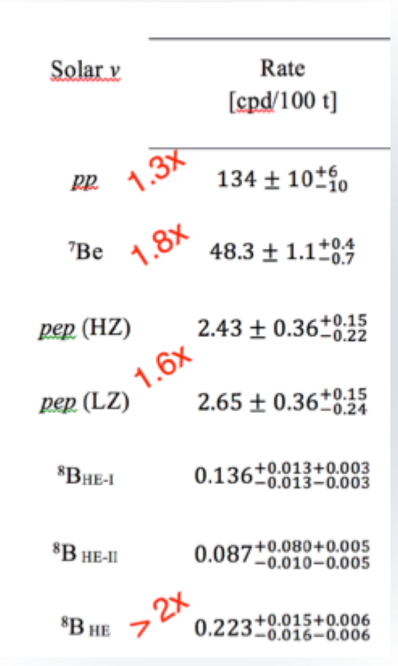
Comprehensive measurement of *pp*-chain solar neutrinos

NEW

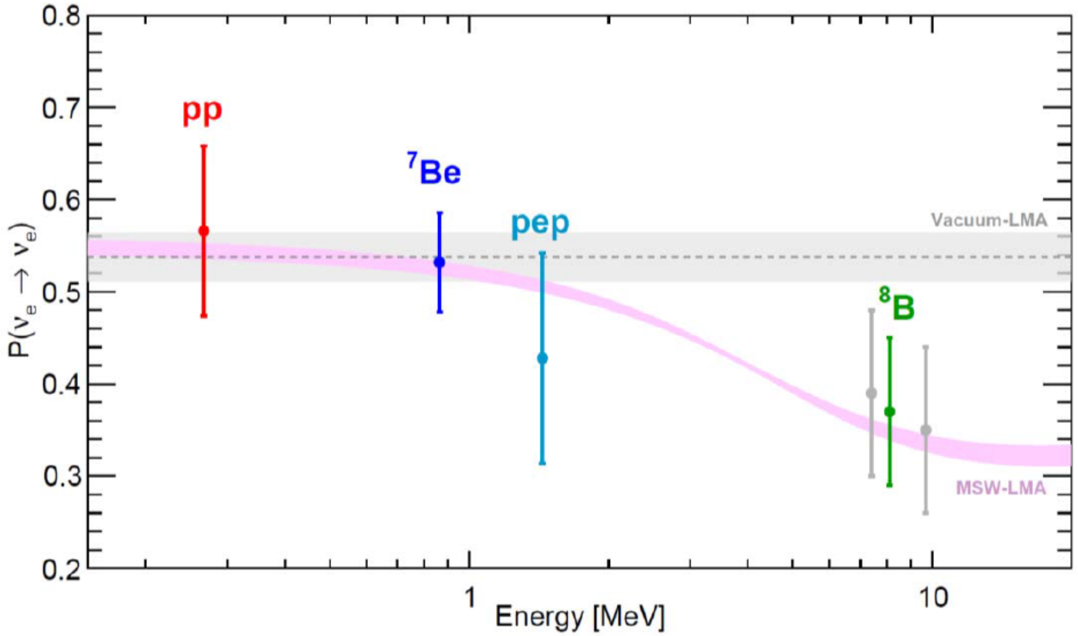
The Borexino Collaboration*

- 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**





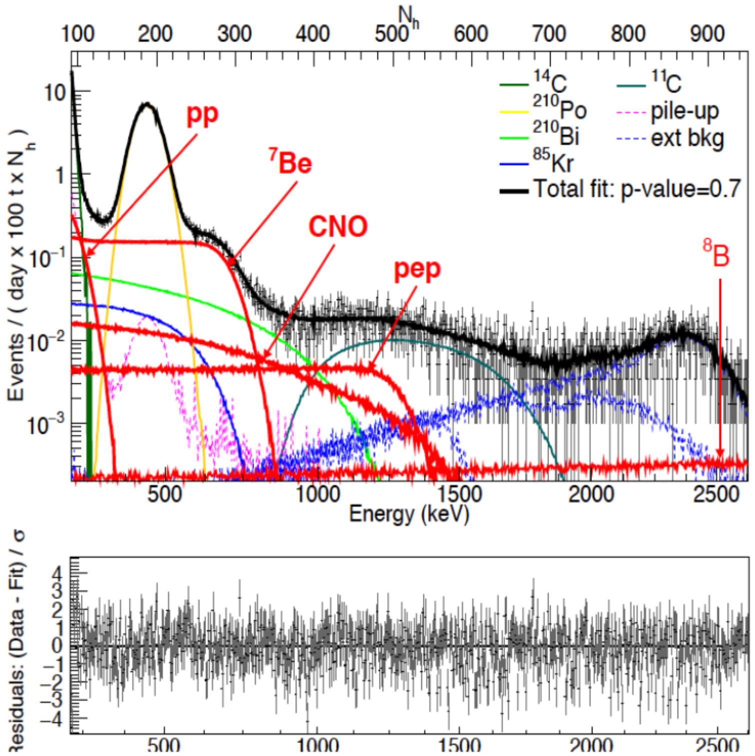
Solar ν		Rate [cpd/100 t]
pp	1.3x	$134 \pm 10^{+6}_{-10}$
^{7}Be	1.8x	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep (HZ)		$2.43 \pm 0.36^{+0.15}_{-0.22}$
pep (LZ)	1.6x	$2.65 \pm 0.36^{+0.15}_{-0.24}$
^{8}B$_{\text{HE-I}}$		$0.136^{+0.013+0.003}_{-0.013-0.003}$
^{8}B$_{\text{HE-II}}$		$0.087^{+0.080+0.005}_{-0.010-0.005}$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

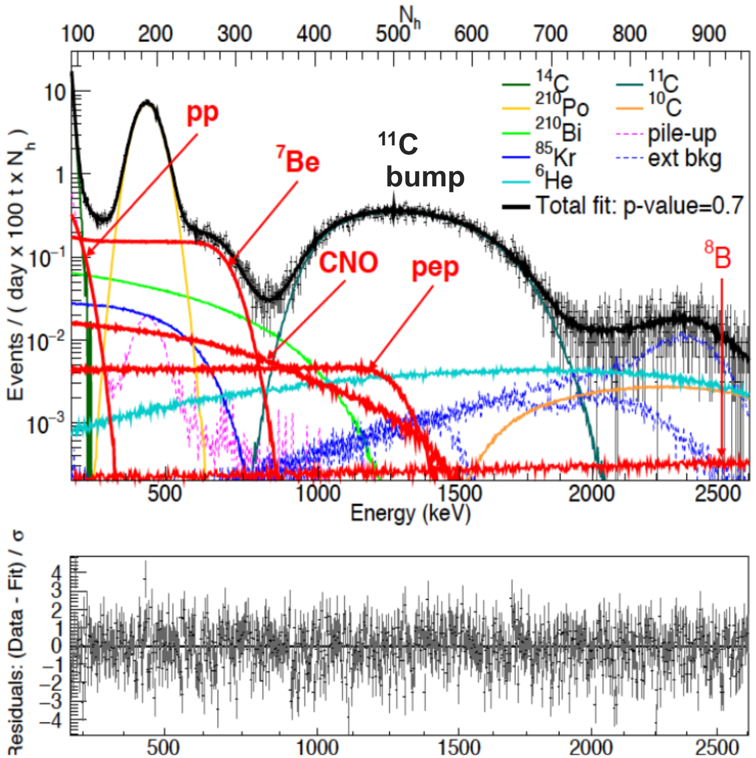


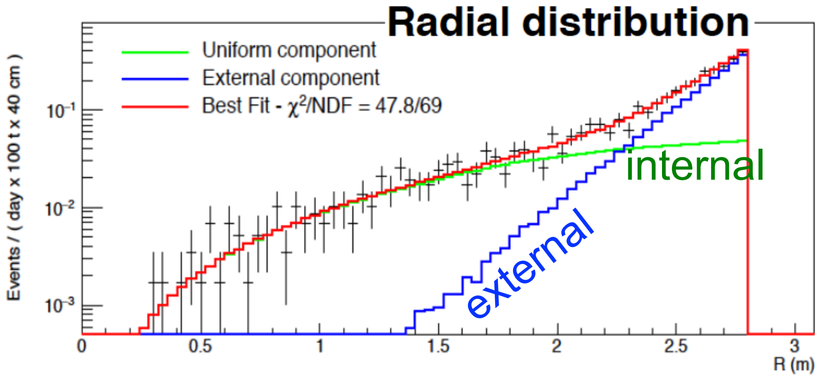
LOW ENERGY REGION (LER): MULTIVARIATE SPECTRAL FIT

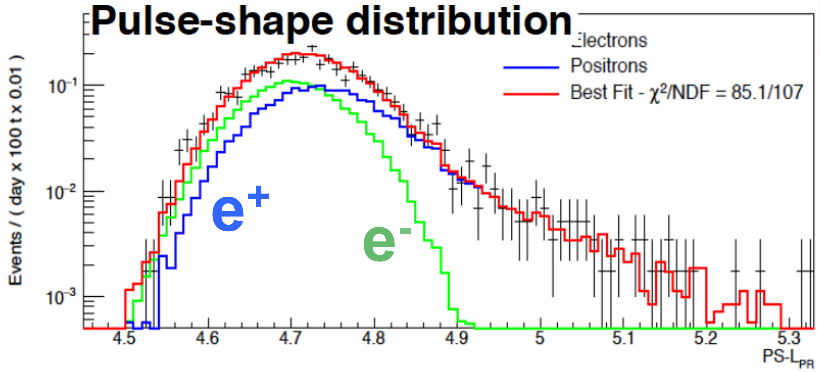
Results on *pp*, ^{7}Be, *pep*, and limit on CNO solar neutrinos

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






Radial distribution


Pulse-shape distribution

- 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:

36% of exposure, 92% of ^{11}C

Pulse-shape distribution

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

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

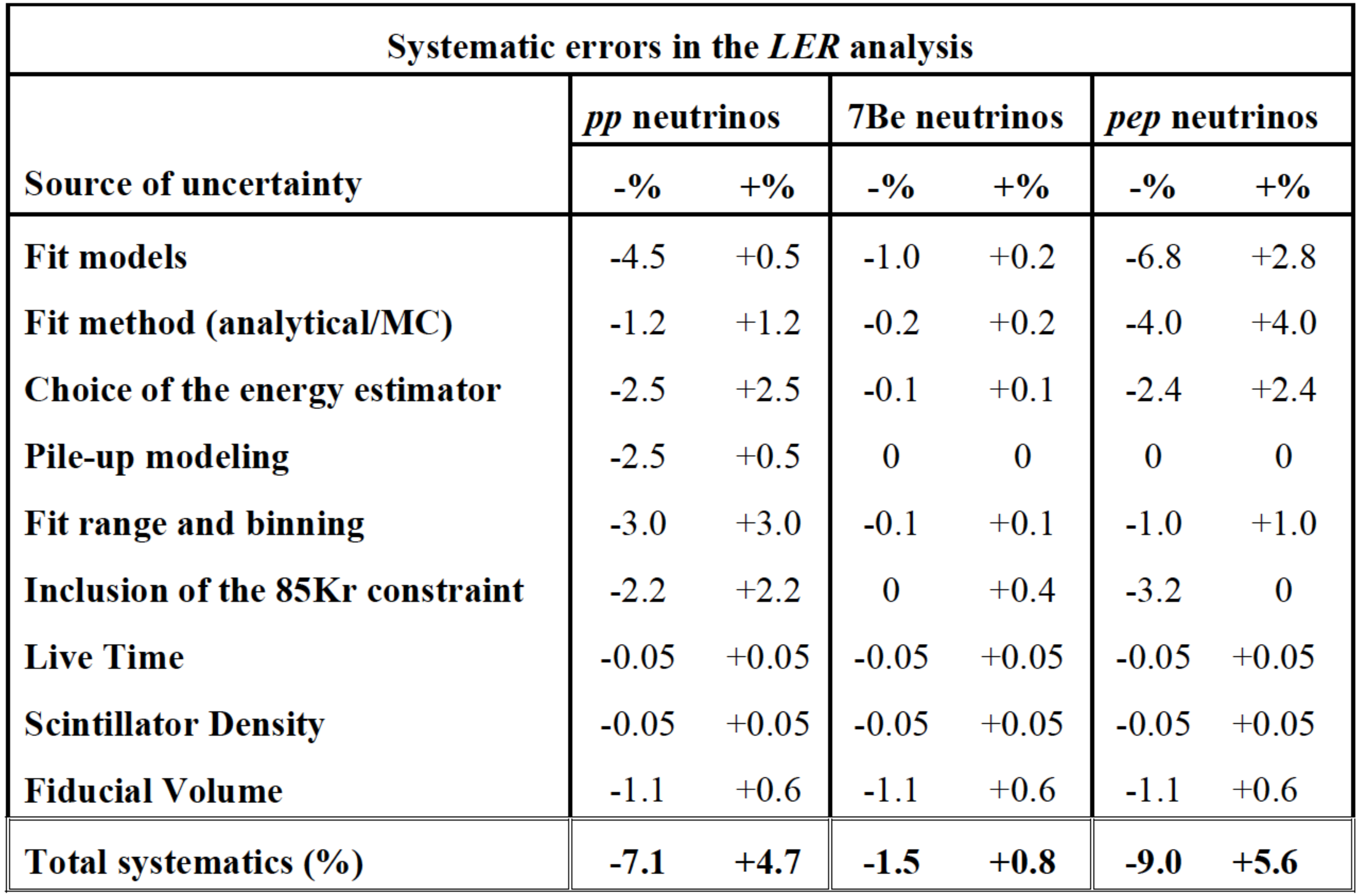
Radial distribution:

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

SYSTEMATIC ERRORS IN LER



Systematic errors in the *LER* analysis

Source of uncertainty	*pp* neutrinos -%	*pp* neutrinos +%	7Be neutrinos -%	7Be neutrinos +%	*pep* neutrinos -%	*pep* neutrinos +%
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 approach.

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.

^{14}C-DOMINATED PILE-UP

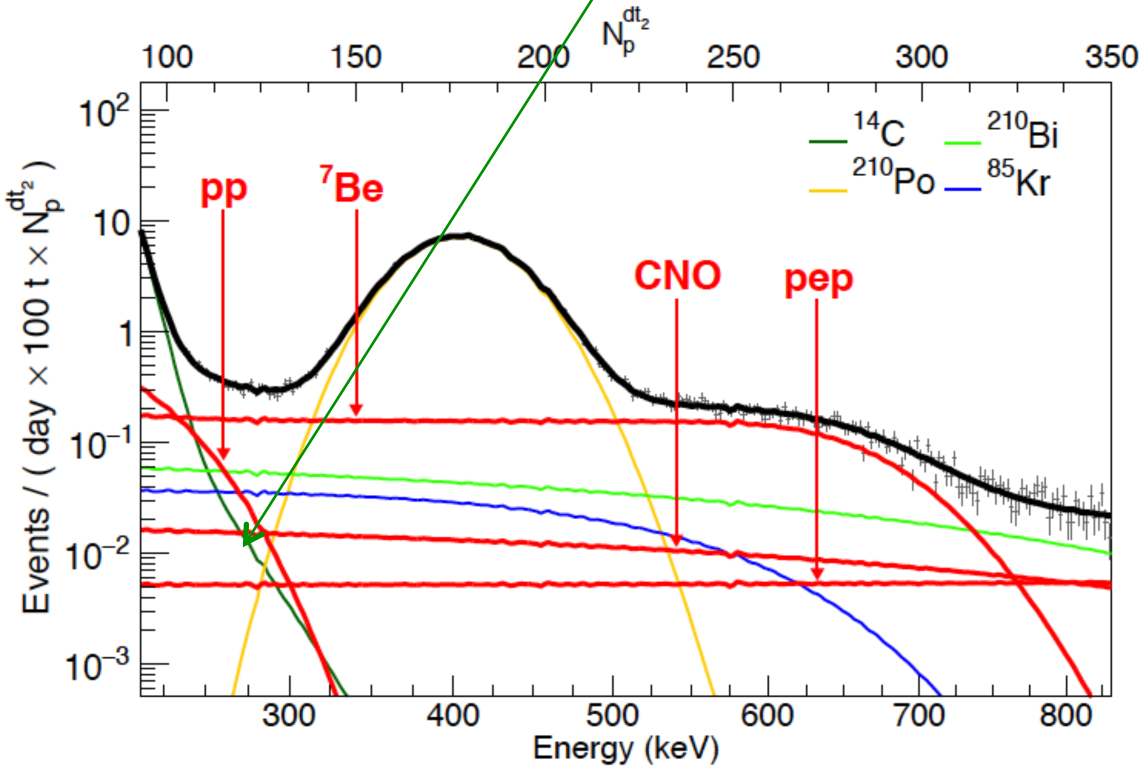
Critical for *pp* neutrinos: multiple events reconstructed as a single event

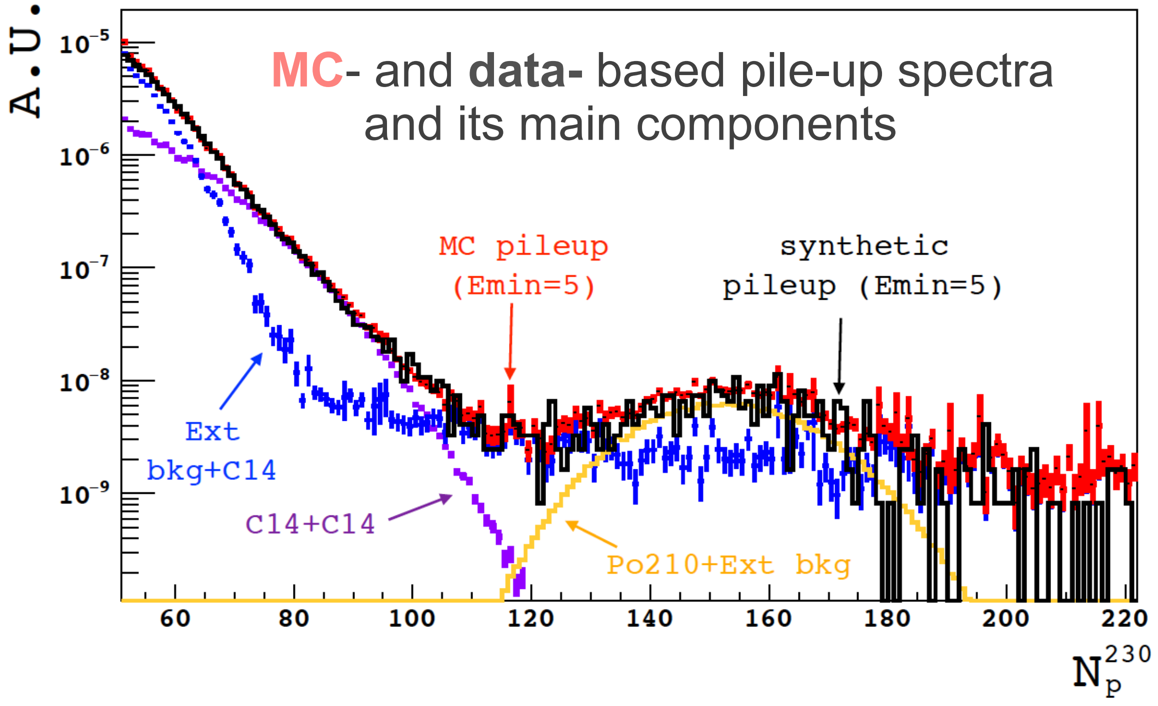
Borexino has 10^{-18} g/g of ^{14}C

40 ± 2 counts / s / 100 ton

Method A: convolution of all spectral shapes with random data spectrum (mostly visible as a **kink in ^{14}C spectrum**)

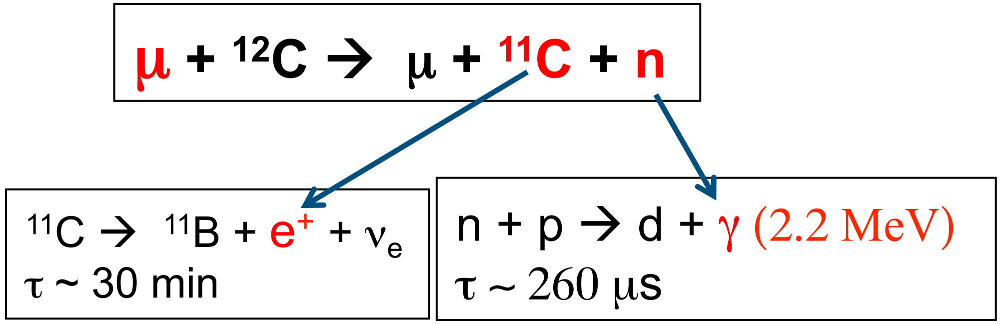
Method B: synthetic pile-up as a separate PDF, with constrained shape and rate (1. MC- and 2. data- based PDF construction)





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

Critical for *pep* and CNO neutrinos



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

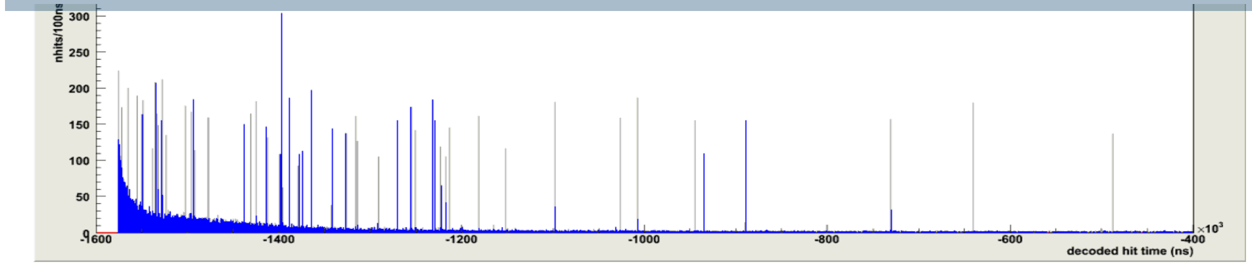
${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
$\tau \sim 30$ min

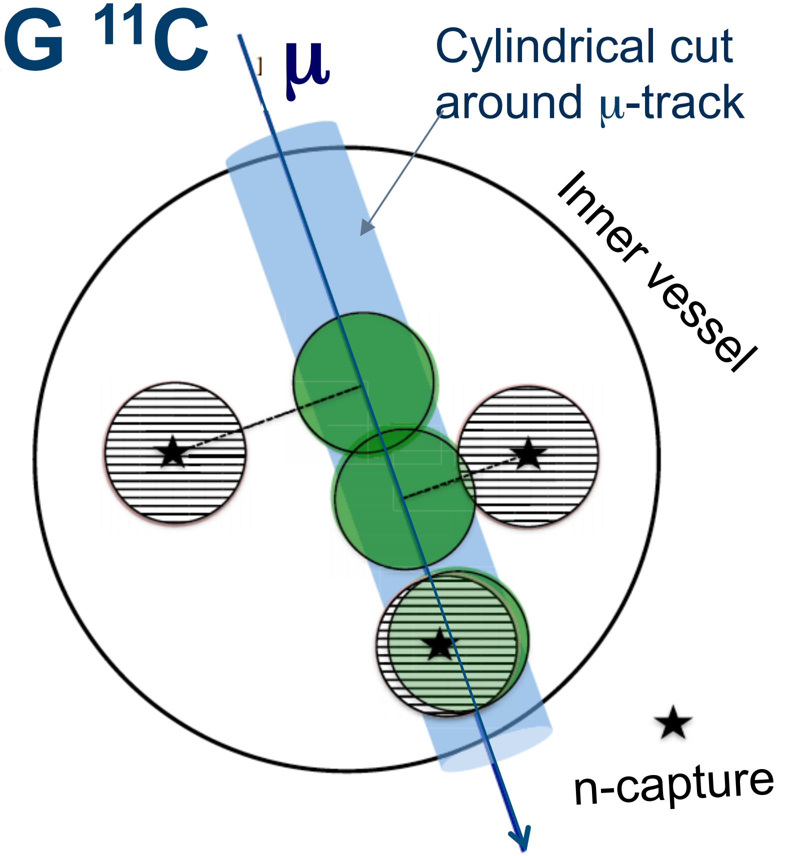
$n + p \rightarrow d + \gamma$ (2.2 MeV)
$\tau \sim 260\ \mu s$

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 (36% of exposure, 92% of ^{11}C)

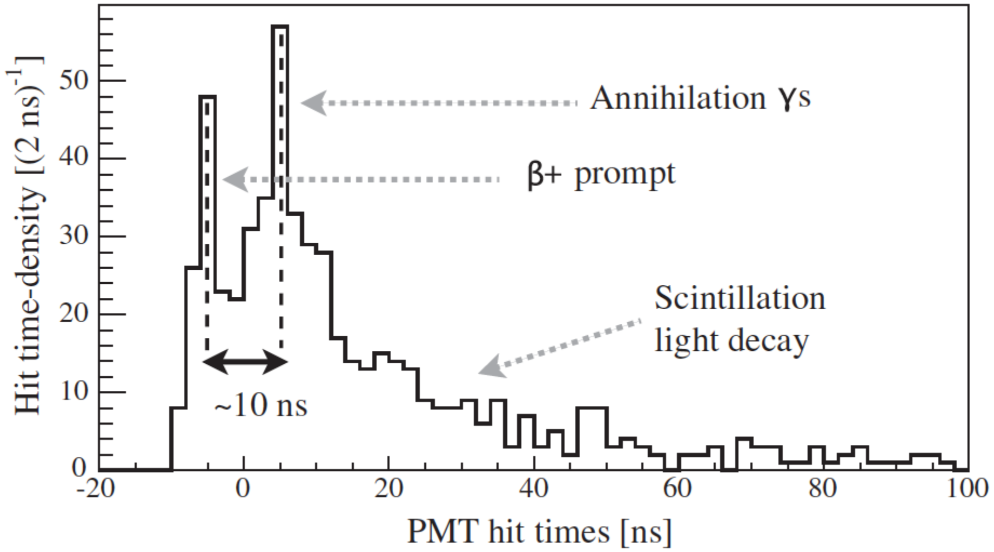
TFC-subtracted (64% of exposure, 8% of ^{11}C)

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

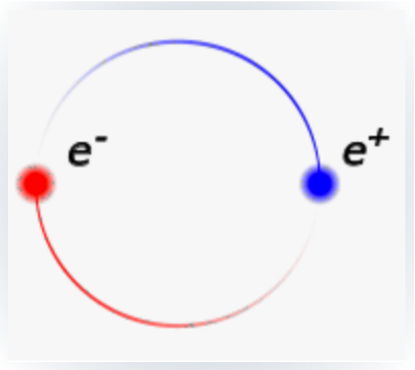
ELECTRON-POSITRON PULSE SHAPE DISCRIMINATION

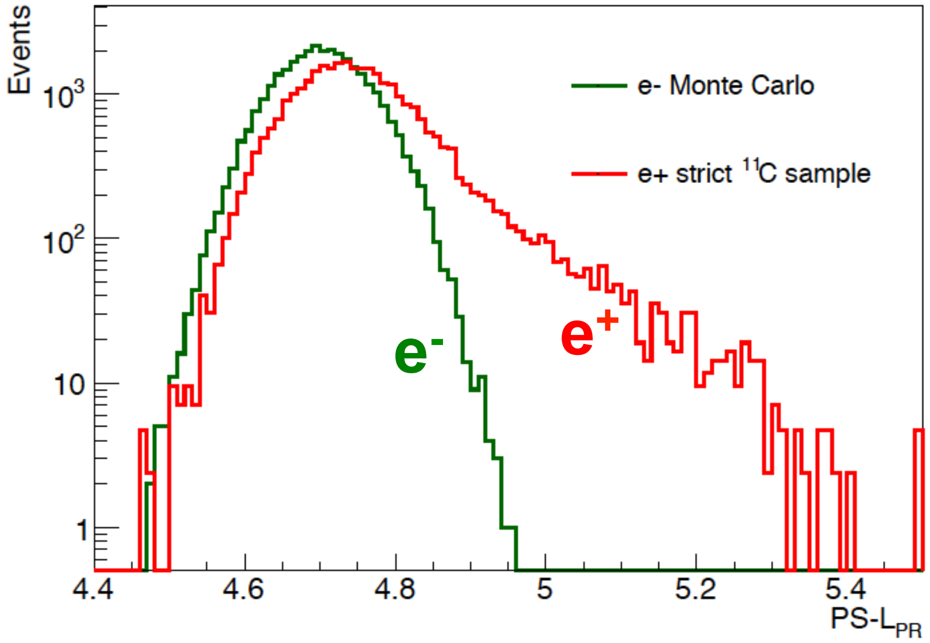
Critical for *pep* and CNO neutrinos

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



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





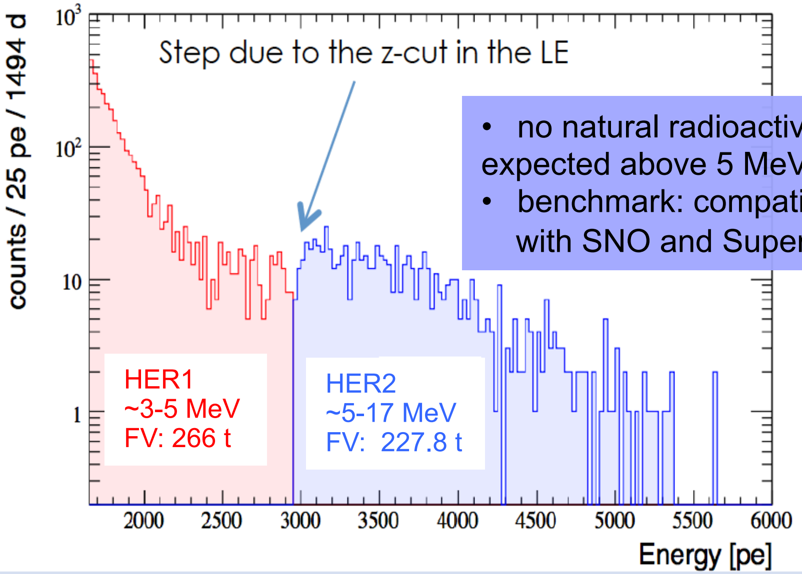
Pulse shape estimator:
normalized likelihood of the position reconstruction algorithm that uses light emission profiles for electrons.

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

HIGH ENERGY REGION (HER) ANALYSIS

Results on ^{8}B solar neutrinos

Analysis in 2 energy regions



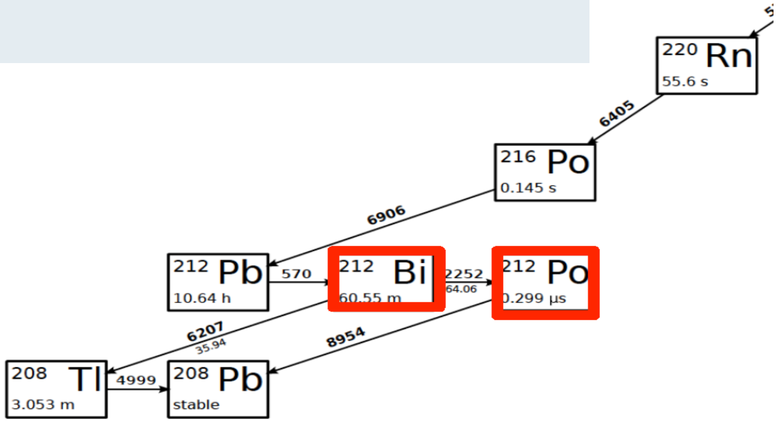
- no natural radioactivity expected above 5 MeV
- benchmark: compatibility with SNO and SuperK

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

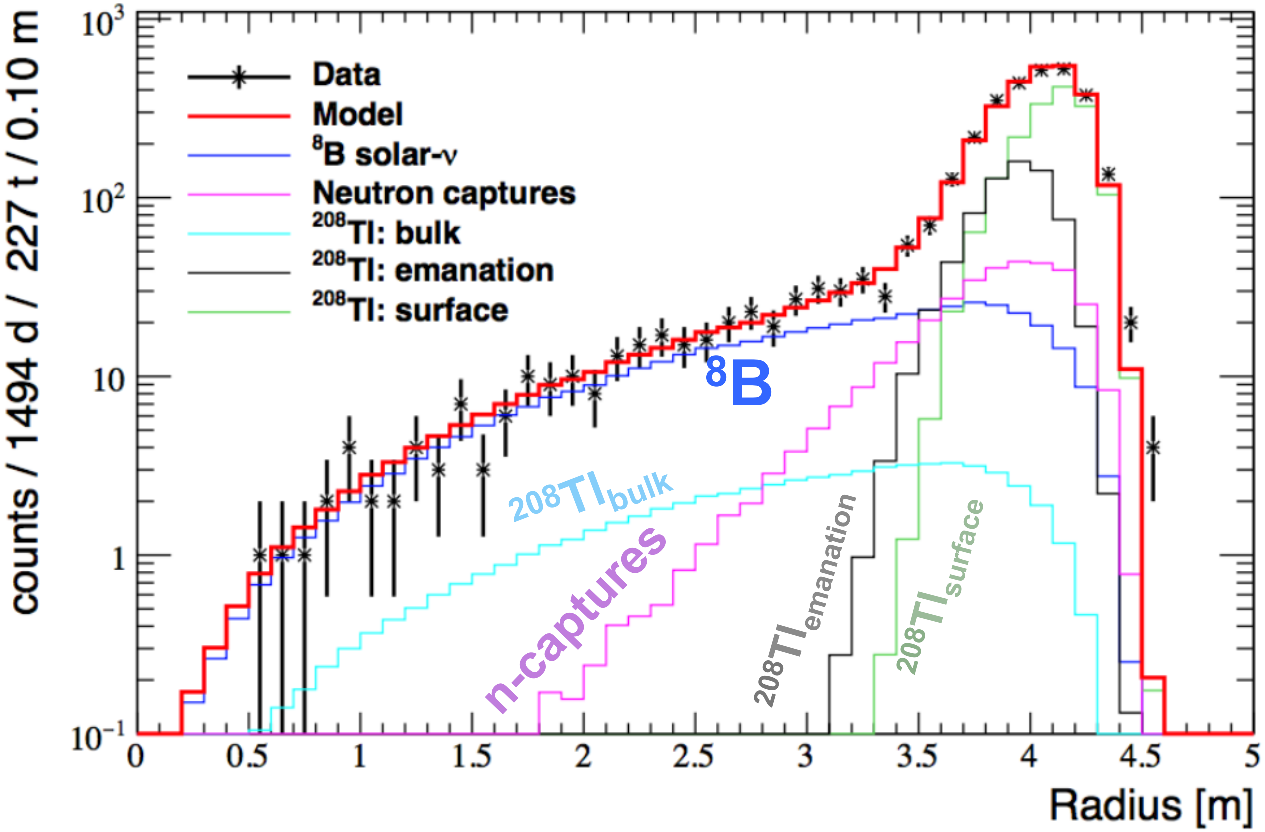
- Almost all scintillator volume used in the analysis.
- Factor 2 improvement wrt PRD 82 (2010) 033006.
- 5x lower internal ^{208}Tl background estimated from ^{212}Bi-^{212}Po coincidences within 3 m radius.
- Two components of the external ^{208}Tl background: pure surface (from IV) and due to ^{220}Rn 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.



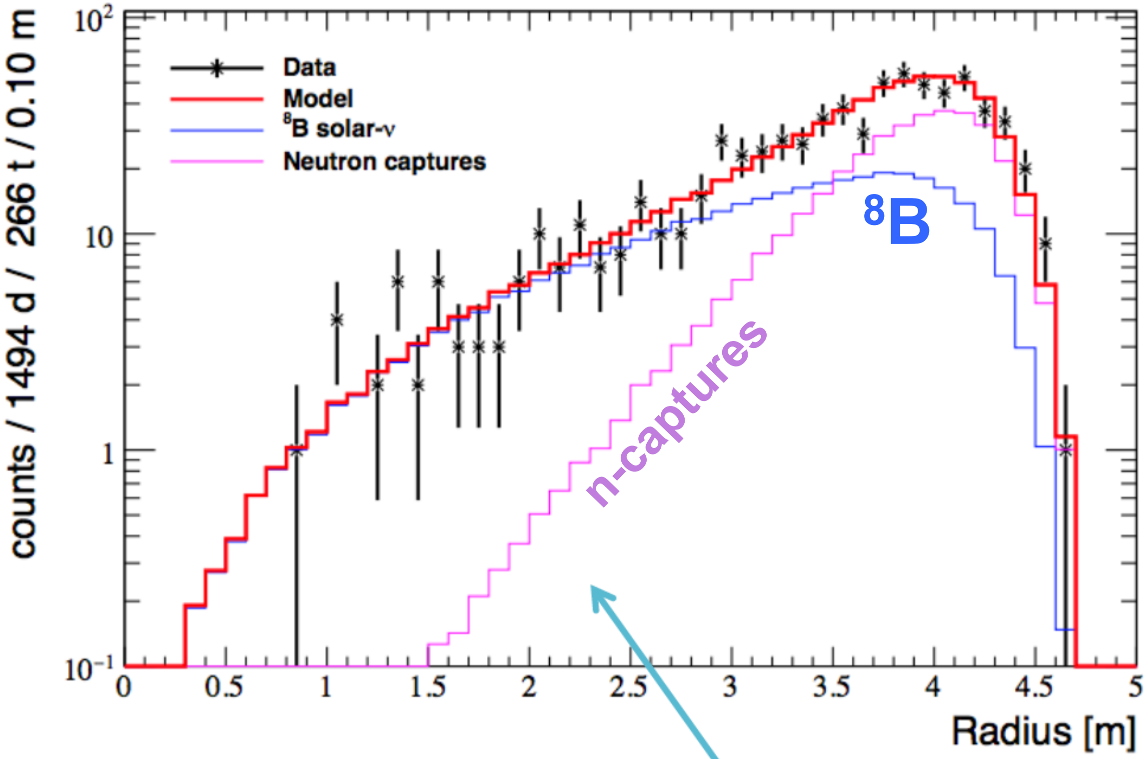
RADIAL FITS IN HER1 AND HER2

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

HER1: ~3-5 MeV

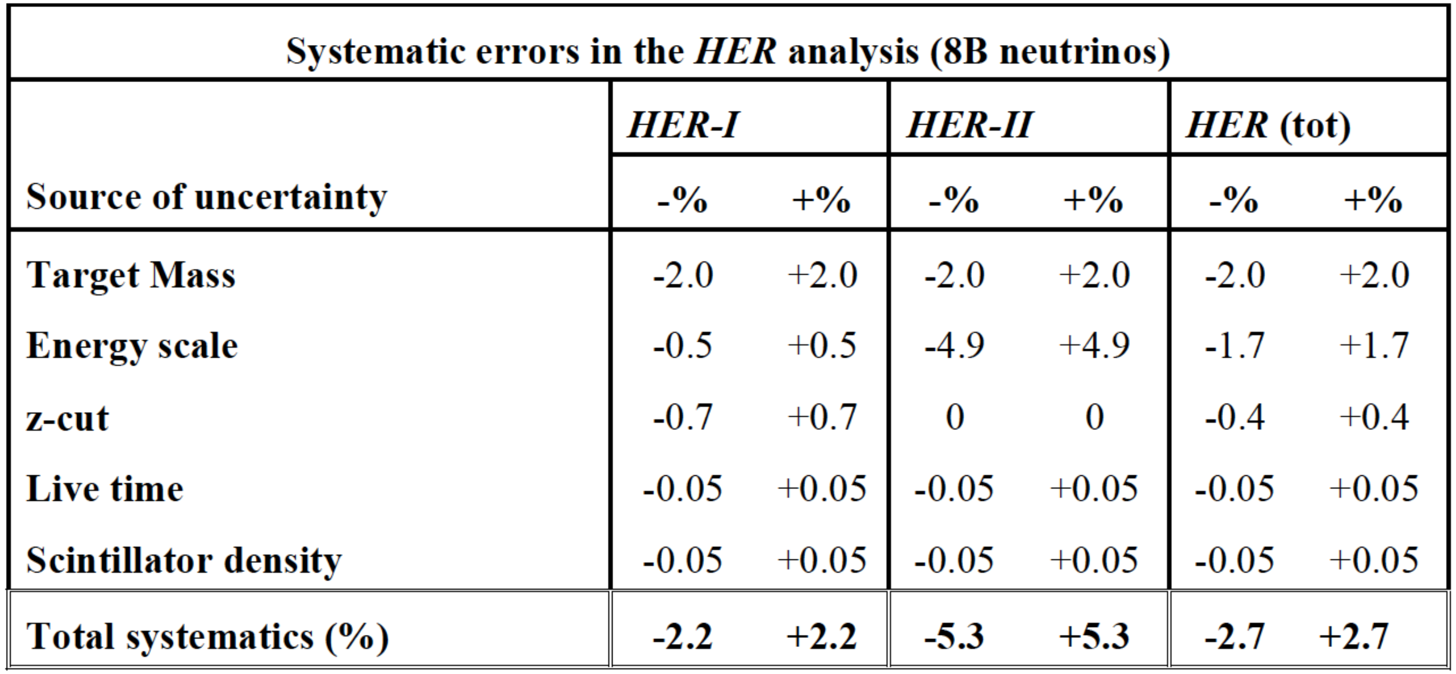


HER2: ~5-17 MeV



In the previous analysis this component was erroneously neglected

RESULTS AND SYSTEMATIC ERRORS IN HER



Systematic errors in the *HER* analysis (8B neutrinos)

Source of uncertainty	***HER-I***		***HER-II***		***HER* (tot)**	
	-%	**+%**	**-%**	**+%**	**-%**	**+%**
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 ±0.014 ±0.036 x 10^6 cm^{-2} s^{-1}
BX 2010	2.4 ±0.4 x10^6 cm^{-2} s^{-1}
This measurement	**2.55 ±0.18 ±0.07 x 10^6 cm^{-2} s^{-1}**

BOREXINO QUEST FOR CNO SOLAR NEUTRINOS

^{210}Bi and CNO correlated

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

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

$T_{1/2}$=22y — 5 days — 138 days — stable

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

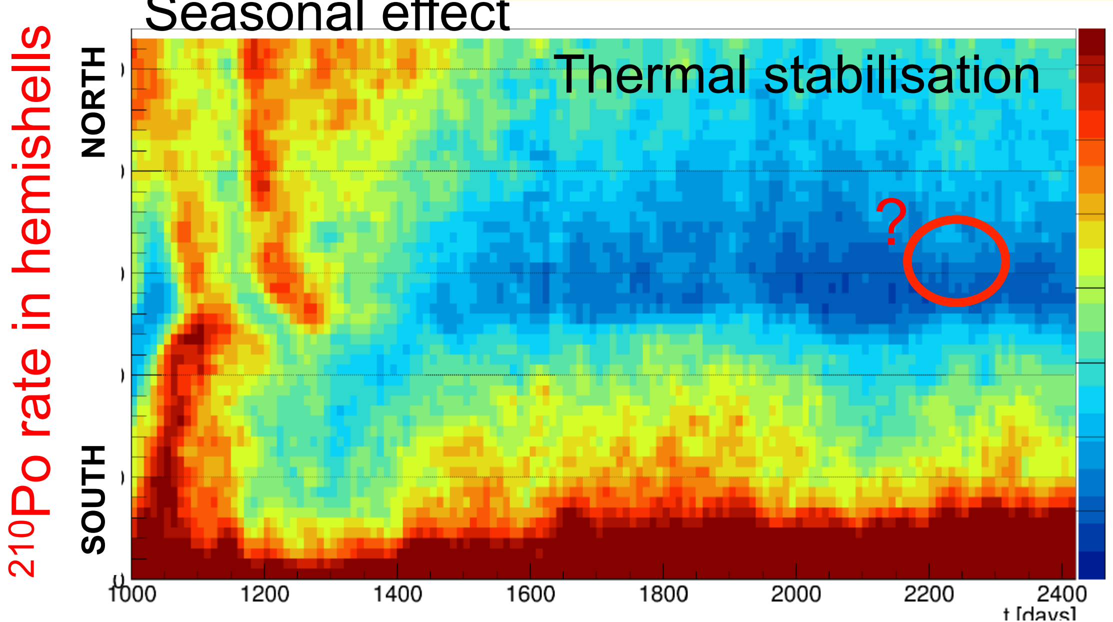
Not in equilibrium

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**

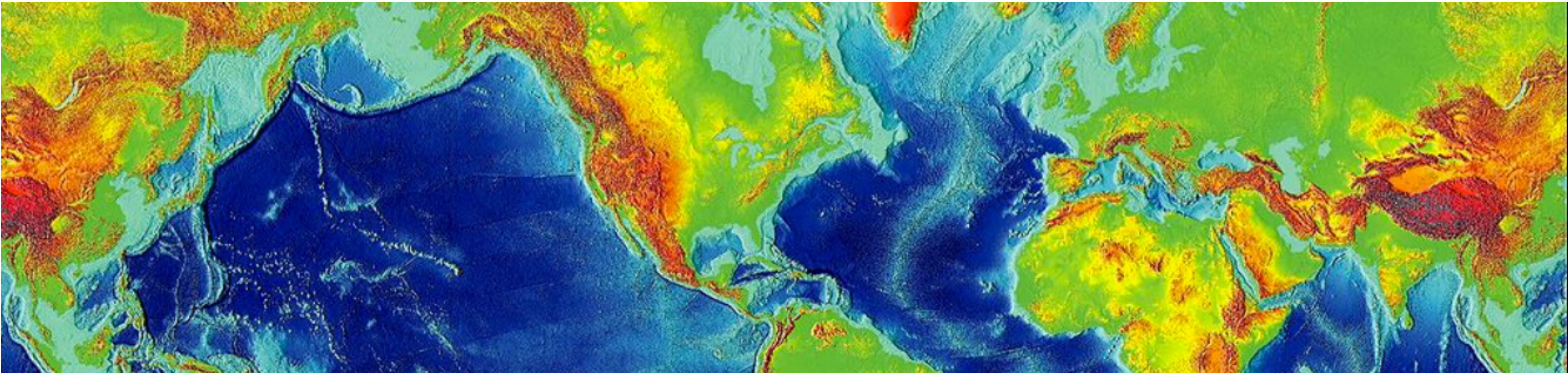
n_{Po} (t) = [$n_{Po,0} - n_{Bi}$] exp($-t/\tau_{Po}$) + n_B: at regime R(^{210}Po) = R(^{210}Bi)



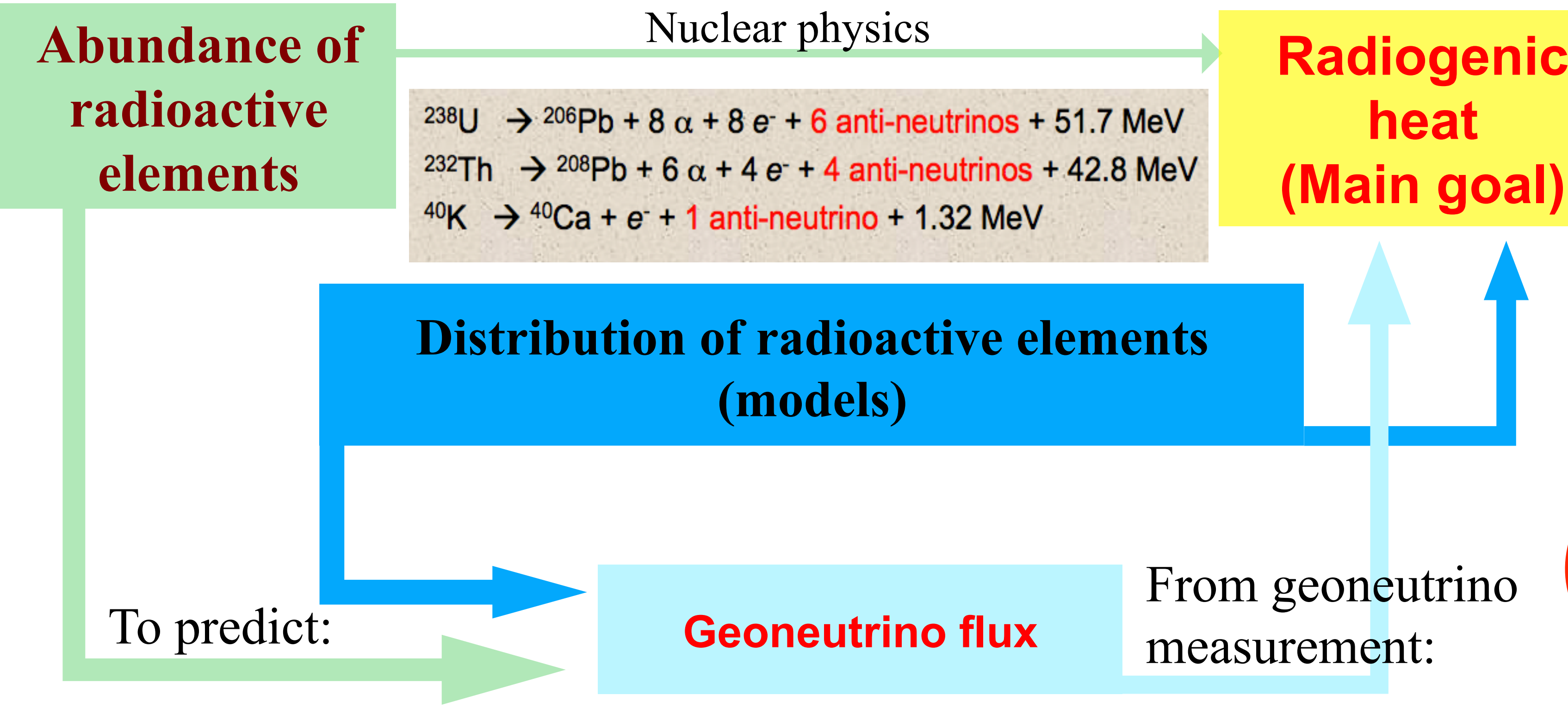
Strategy

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

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)

Distribution of radioactive elements (models)

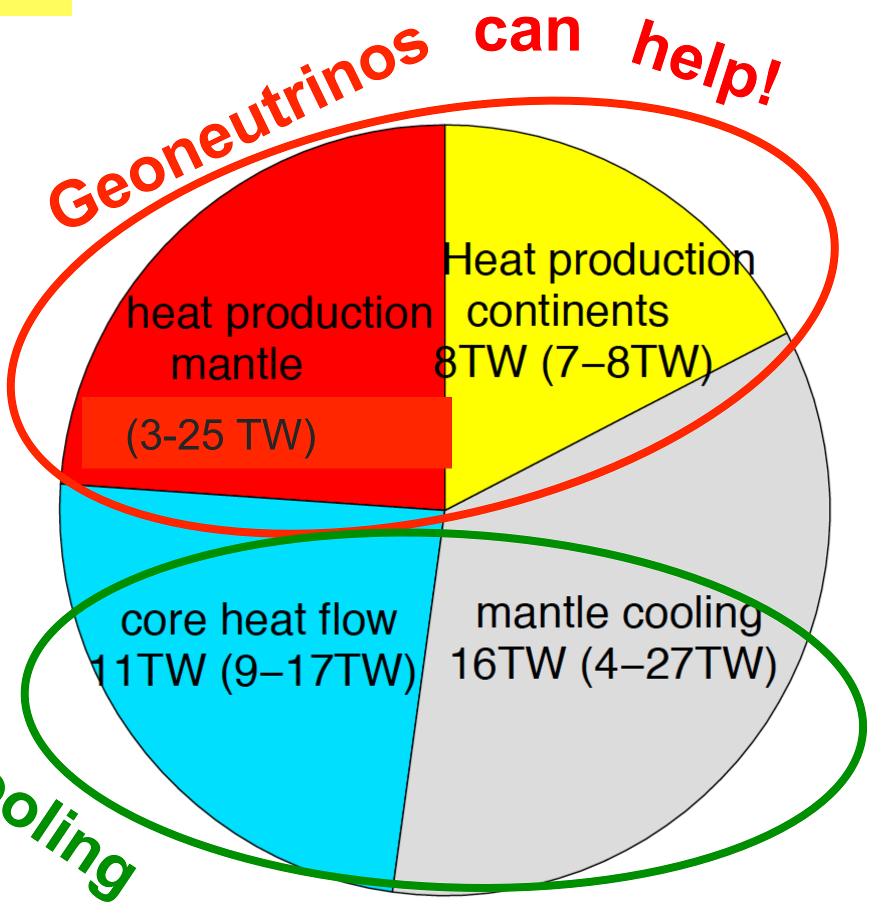
To predict:

Geoneutrino flux

From geoneutrino measurement:

Surface heat flux: 47 ± 3 TW

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



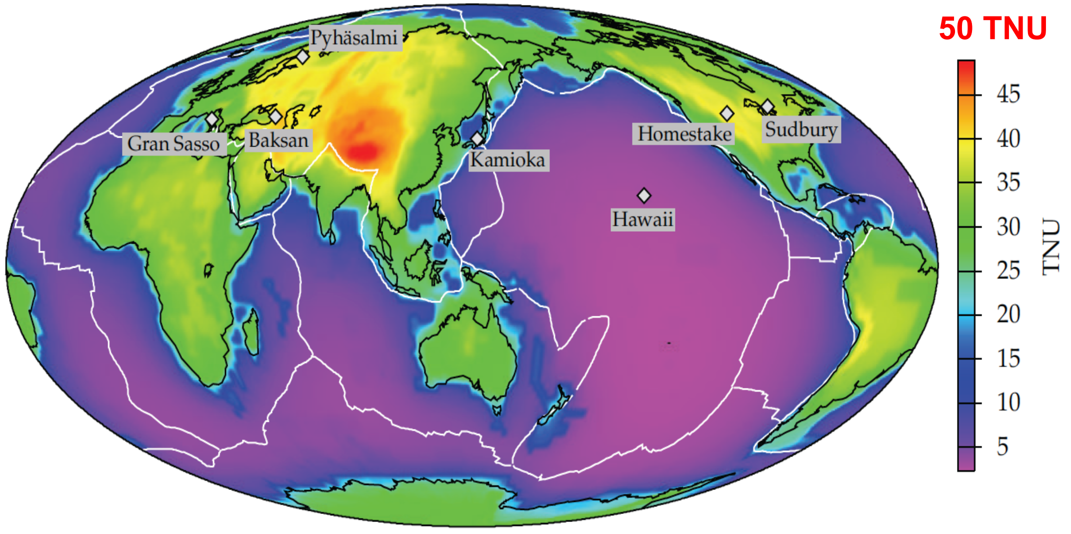
Earth shines in antineutrinos: flux ~10^6 cm^{-2} s^{-1}

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

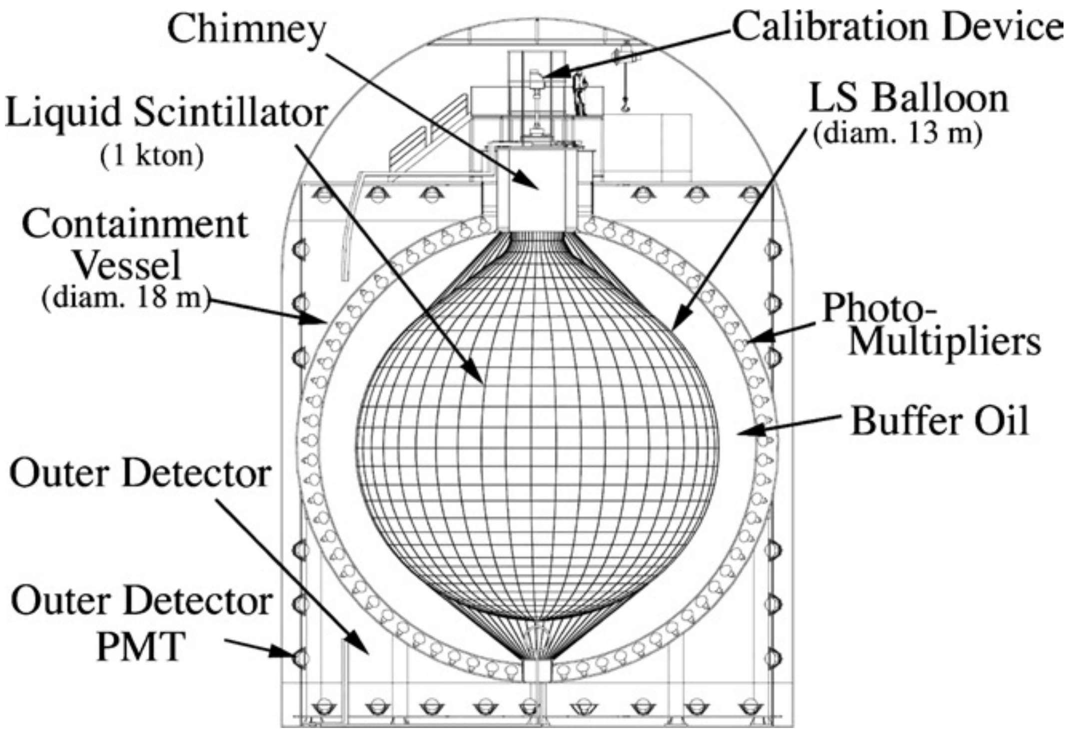
The signal is small, we need big detectors!

MANTLE = Bulk Silicate Earth model – CRUST

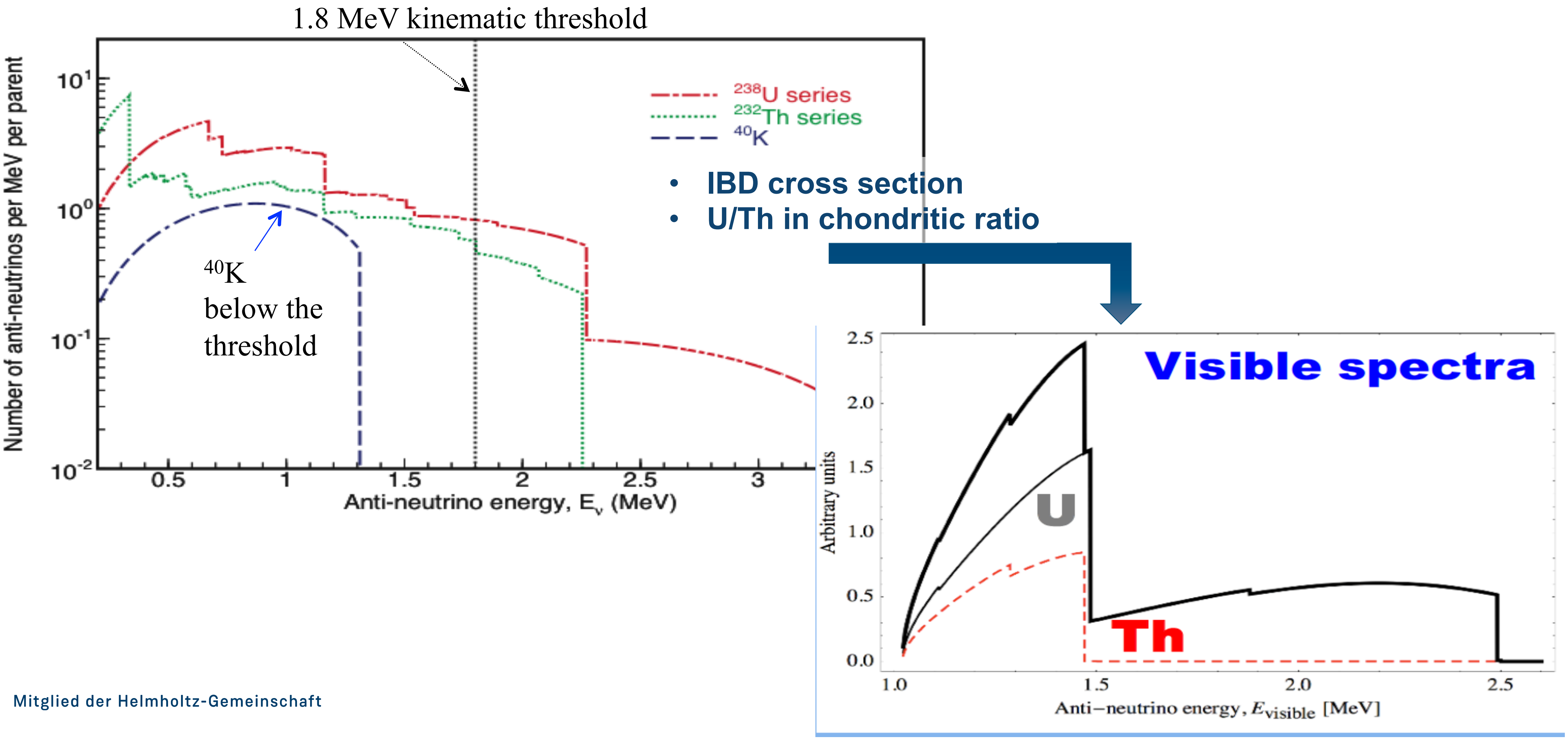
Only 2 experiments have measured geoneutrinos:

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

KamLAND



GEONEUTRINOS ENERGY SPECTRA



- **IBD cross section**
- **U/Th in chondritic ratio**

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.

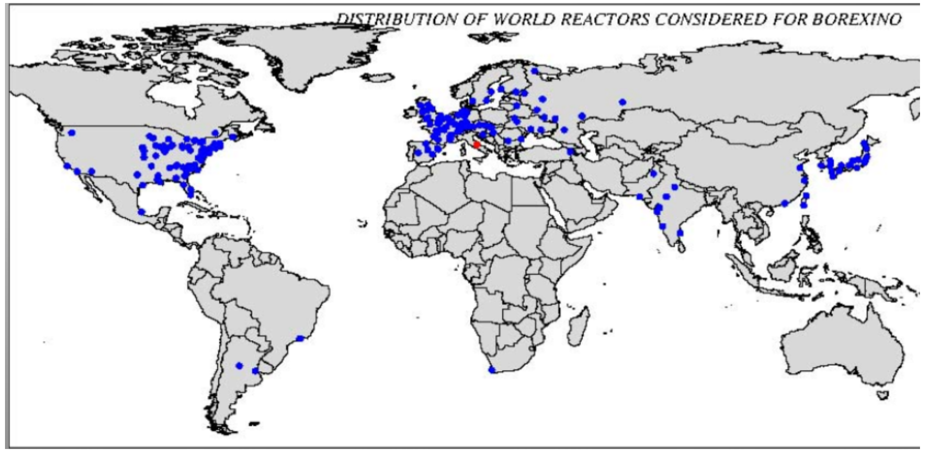
3) Due to the internal radioactivity:

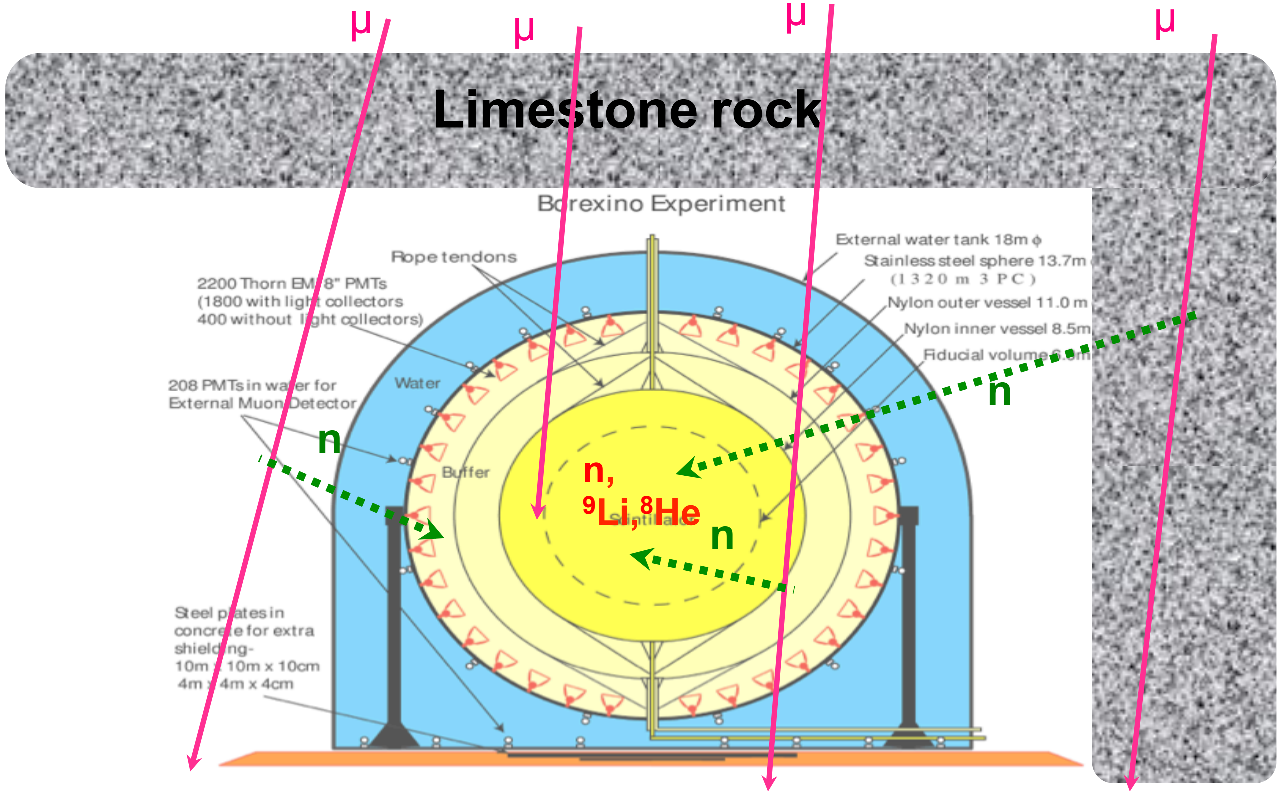
(α, n) reactions: $^{13}C(\alpha, n)^{16}O$

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

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

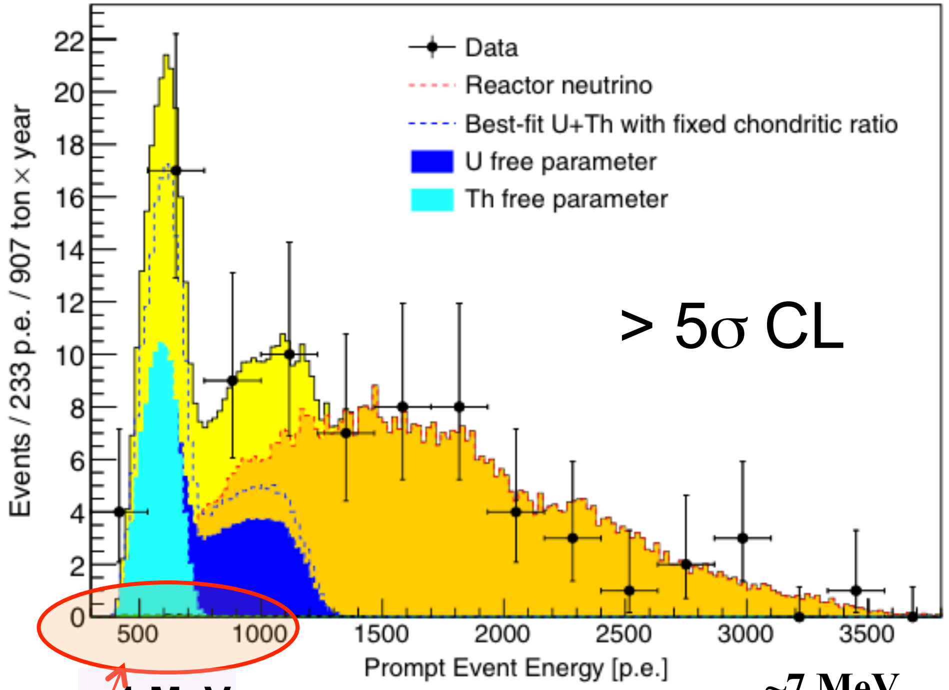
A) Reactor antineutrino background





BOREXINO GEONEUTRINO RESULTS AND ANALYSIS

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



> 5σ CL

~1 MeV

~7 MeV

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

FIRST GEOLOGICAL INTERPRETATIONS

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

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

More statistics

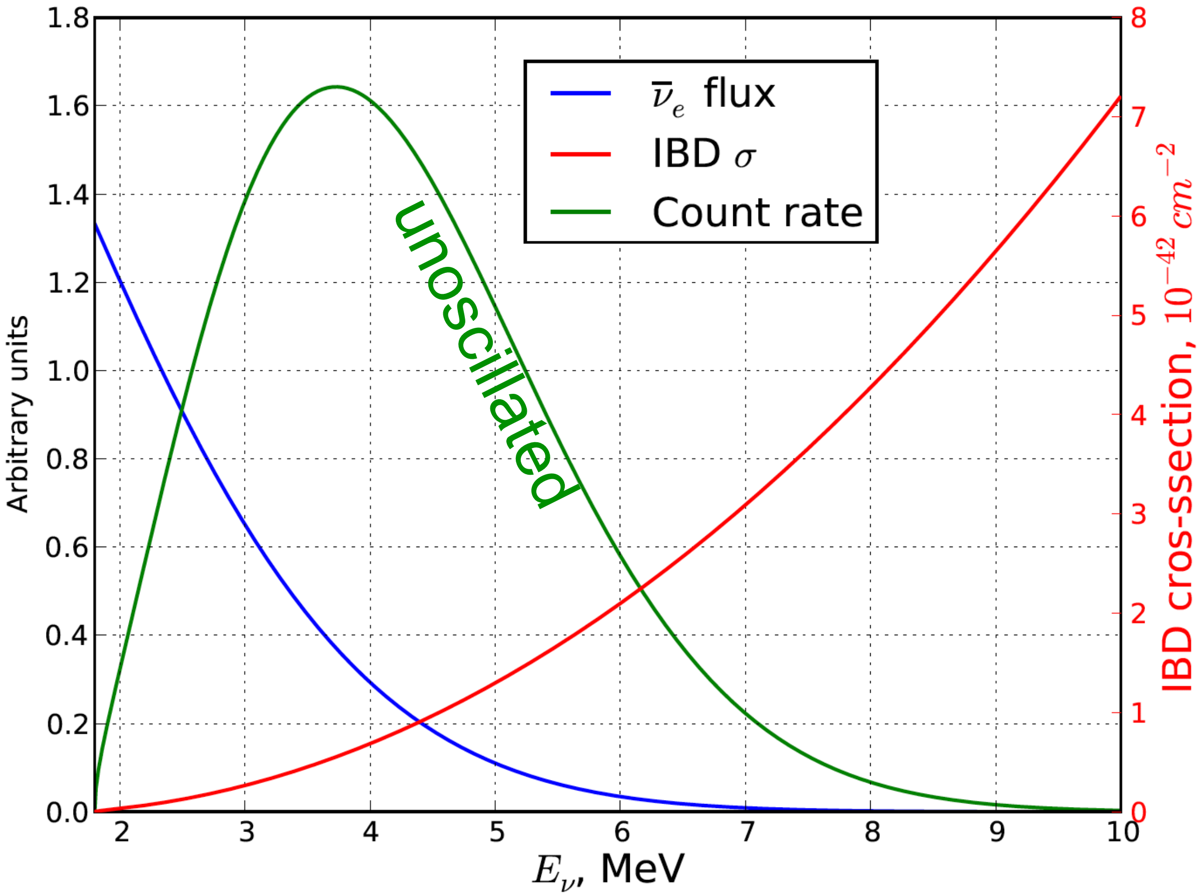
Multi-site experiments

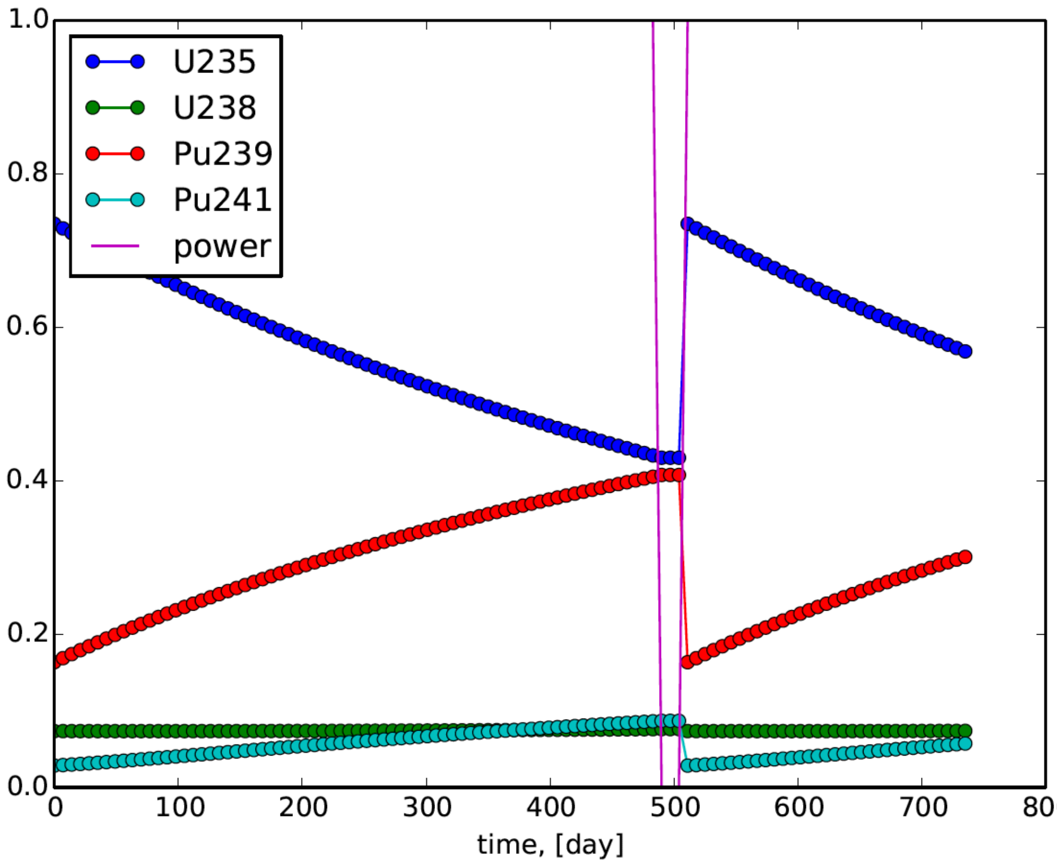
Experiments at geologically particular locations

JUNO AND REACTOR NEUTRINOS

the strongest human-made ν-source

TYPICAL REACTOR ANTINU SPECTRUM AND FUEL CYCLE





SURVIVAL PROBABILITY FOR REACTOR ANTINU

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

Slow

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Fast

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

Full oscillation probability

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Δm^2_{31} and Δm^2_{32} very similar: introducing effective $\mathbf{\Delta m^2_{ee}}$

Fast

Slow (solar)

short baseline

long baseline

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2(\Delta m^2_{ee}\frac{L}{4E}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta m^2_{21}\frac{L}{4E})$$

$$\sin^2(\Delta m^2_{ee}\frac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\frac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\frac{L}{4E})$$

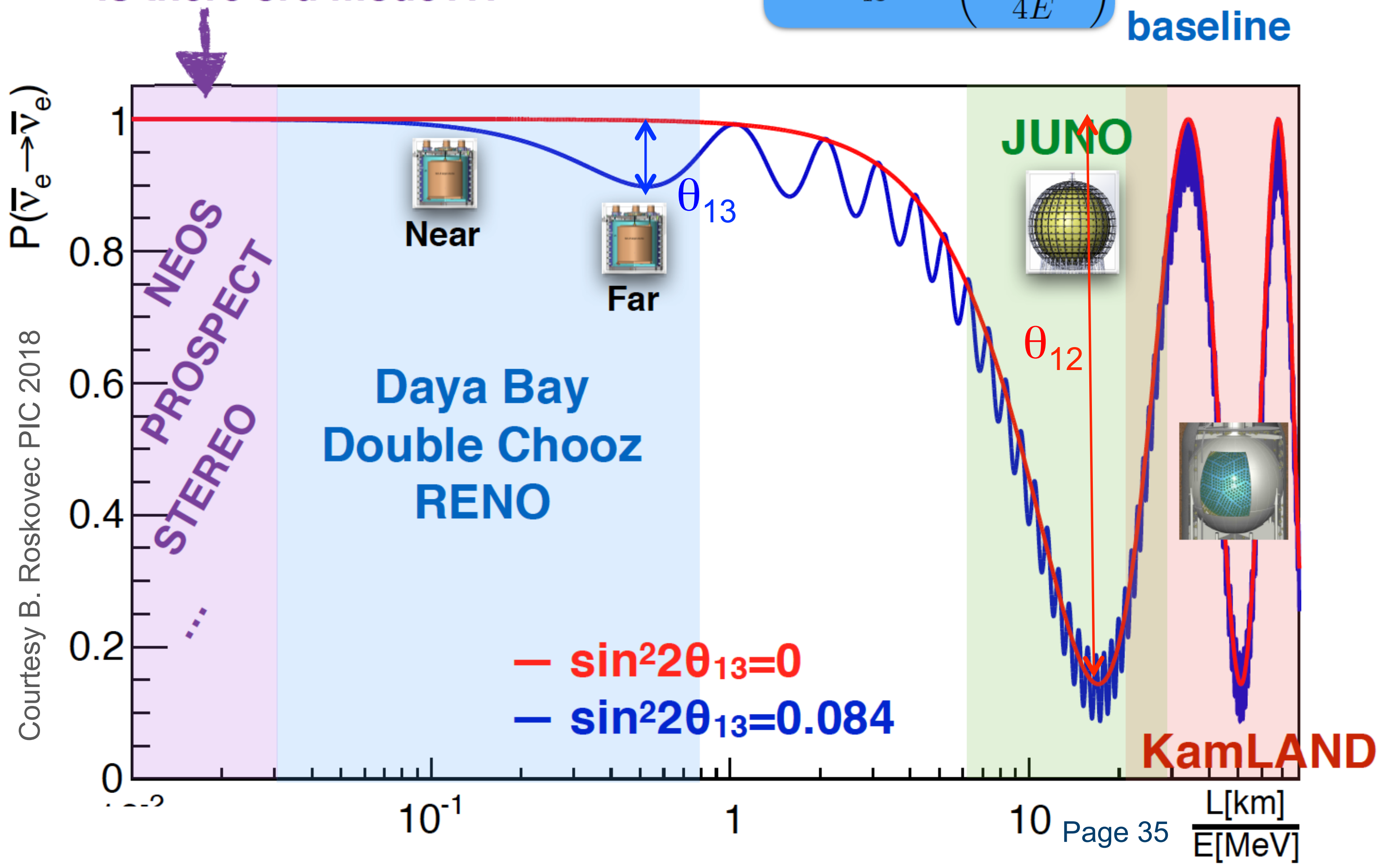
REACTOR NEUTRINO OSCILLATIONS

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

Medium baseline

Short baseline

Is there 3rd mode?!?



Courtesy B. Roskovec PIC 2018

- 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

Jiangmen Underground Neutrino Observatory

the first multi-kton liquid scintillator detector ever

start datataking in 2021

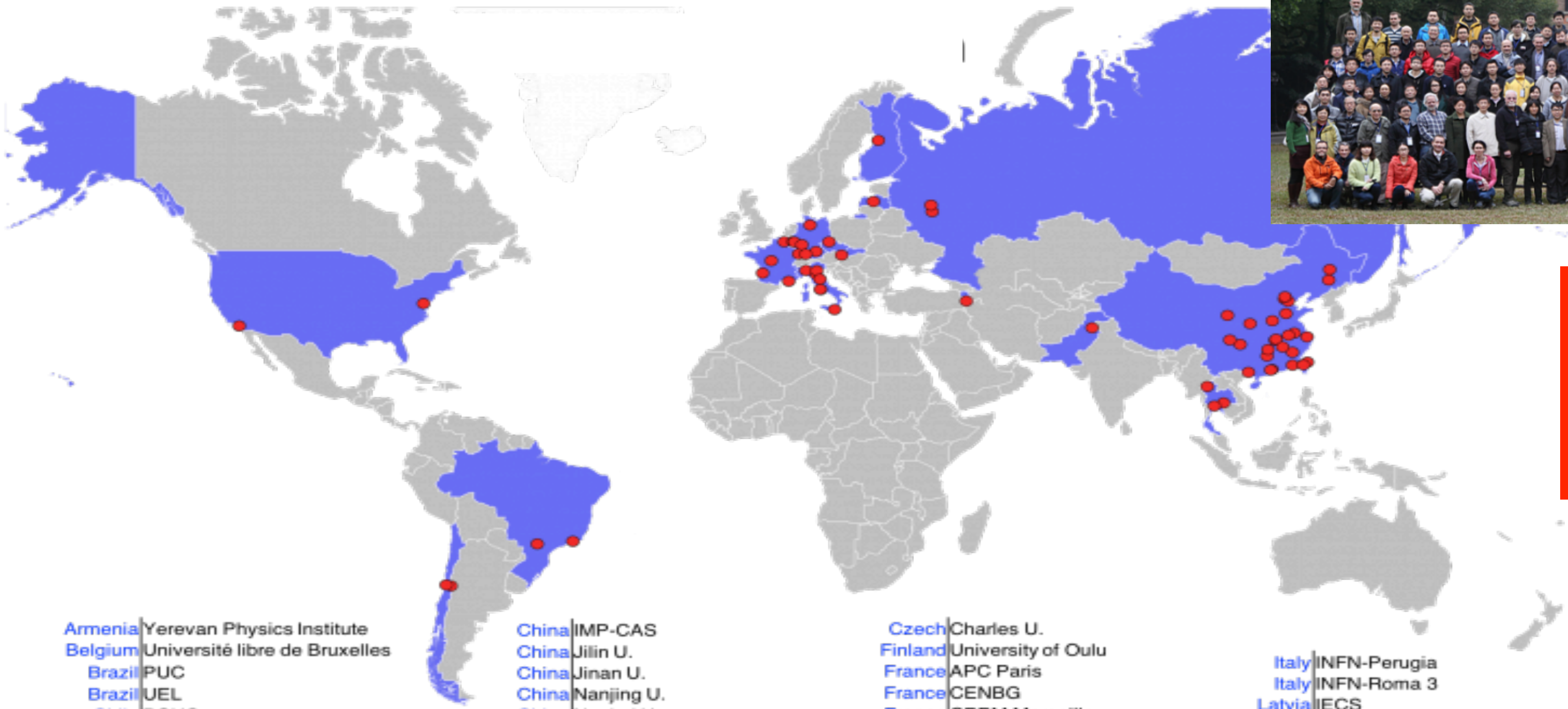
mass hierarchy to 3…4 sigma in 6 years

J. Phys.G: Nucl. Part. Phys. 43 (2016) 030401 (166 p)

JUNO COLLABORATION

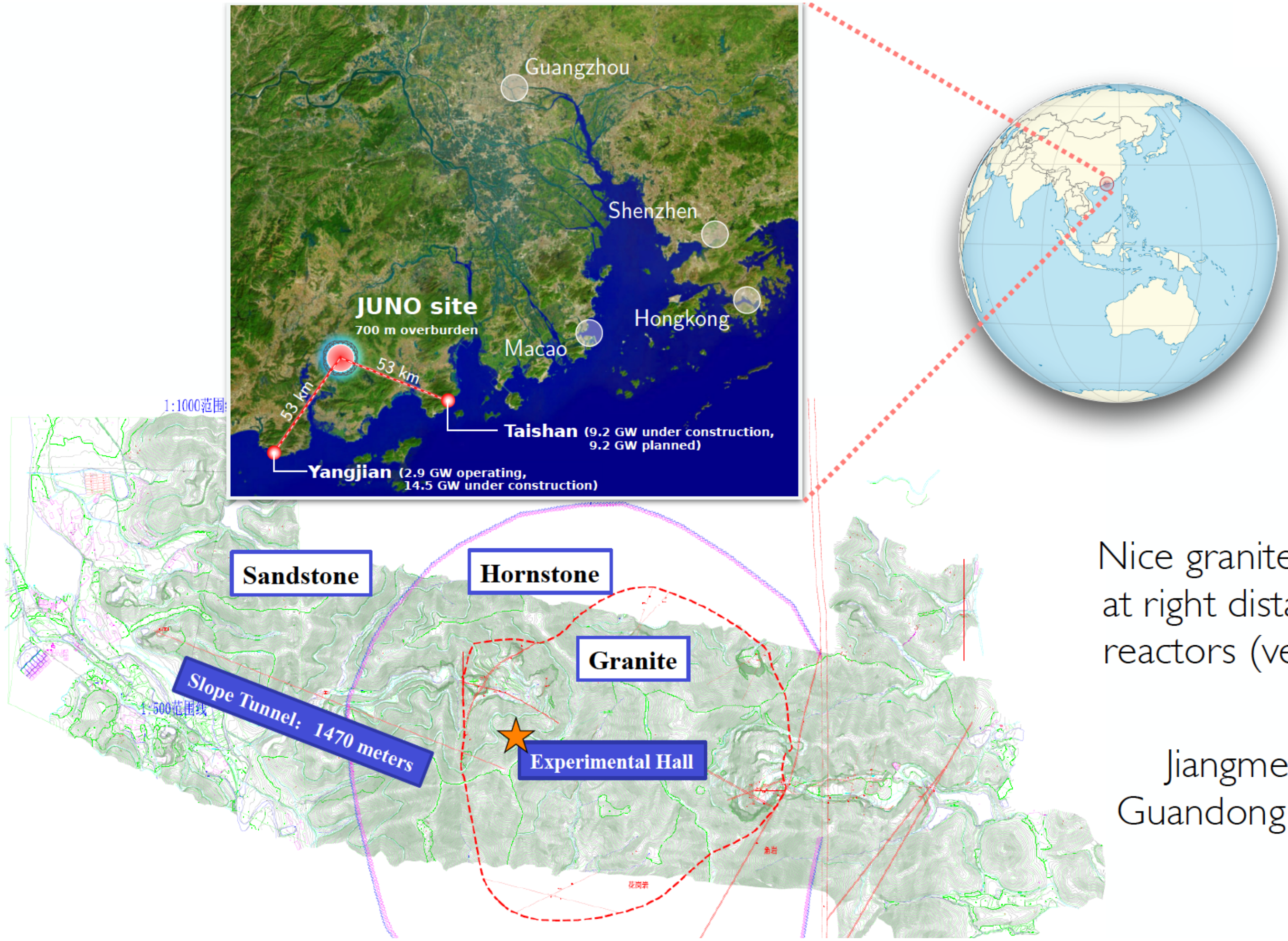
JUNO Collaboration

- established in 2014
- 79 institutions
- 600 collaborators



Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of Technology
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	NUDT
China	Peking U.
China	Shandong U.
China	Shanghai JT U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	Zhengzhou U.
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CENBG
France	CPPM Marseille
France	IPHC Strasbourg
France	Subatech Nantes
Germany	ZEA FZ Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZ Jülich
Germany	U. Mainz
Germany	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

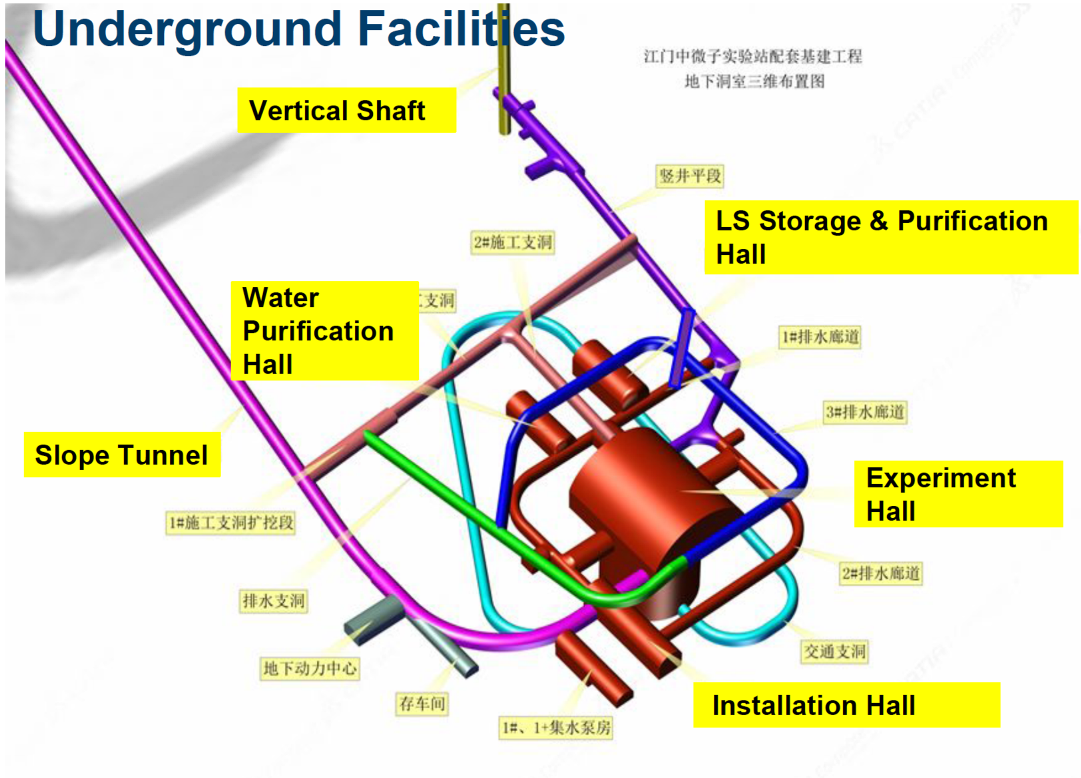
JUNO EXPERIMENTAL SITE



Nice granite structure at right distance from reactors (very lucky!)

Jiangmen City
Guandong province

Underground Facilities

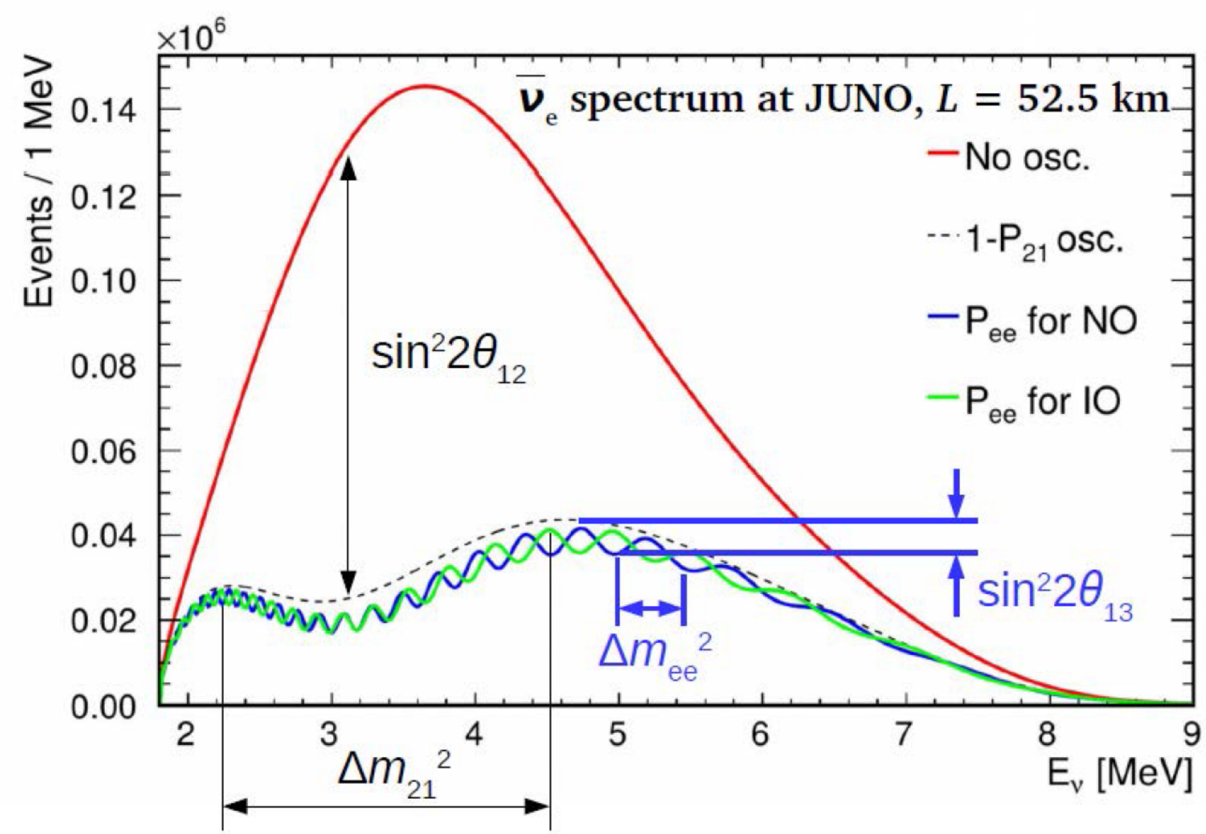


650 m underground

- Jan 10, 2015: civil constructions start
- June 22, 2017: slope tunnel finished
- July 1, 2017: vertical shaft finished
- Civil Construction of Experimental Hall ongoing

ACCESS TUNNEL TO EXPERIMENTAL HALL

JUNO OSCILLATED SPECTRUM, MH & OSCIL. PARAM.



Mass Hierarchy (MH) determination:

First: high resolution measurement of reactor antinu
Second: fit the (pseudo-) data with both hypothesis (normal and inverted hierarchies)
Third: define $\Delta\chi^2$ as standard statistics
Finally: use $\Delta\chi^2$ as the discriminator for design and optimization, as well as for the final MH discrimination

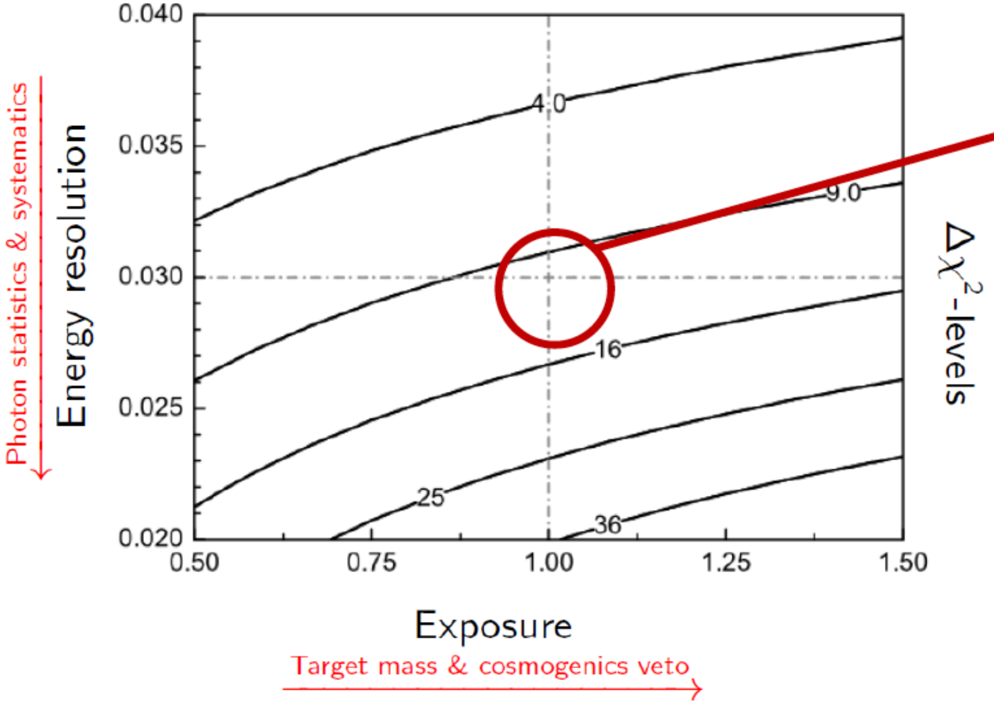
$$\boxed{\Delta\chi^2_{\text{MH}} = |\chi^2_{\text{min}}(\text{N}) - \chi^2_{\text{min}}(\text{I})|}$$

fit with NH assumption

fit with IH assumption

Parameter	$sin^2\theta_{12}$	Δm^2_{21}	$\lvert\Delta m^2_{ee}\rvert$
Precision (current)	2.2%	3.9%	1.2%
Precision (JUNO)	0.7%	0.6%	0.4%

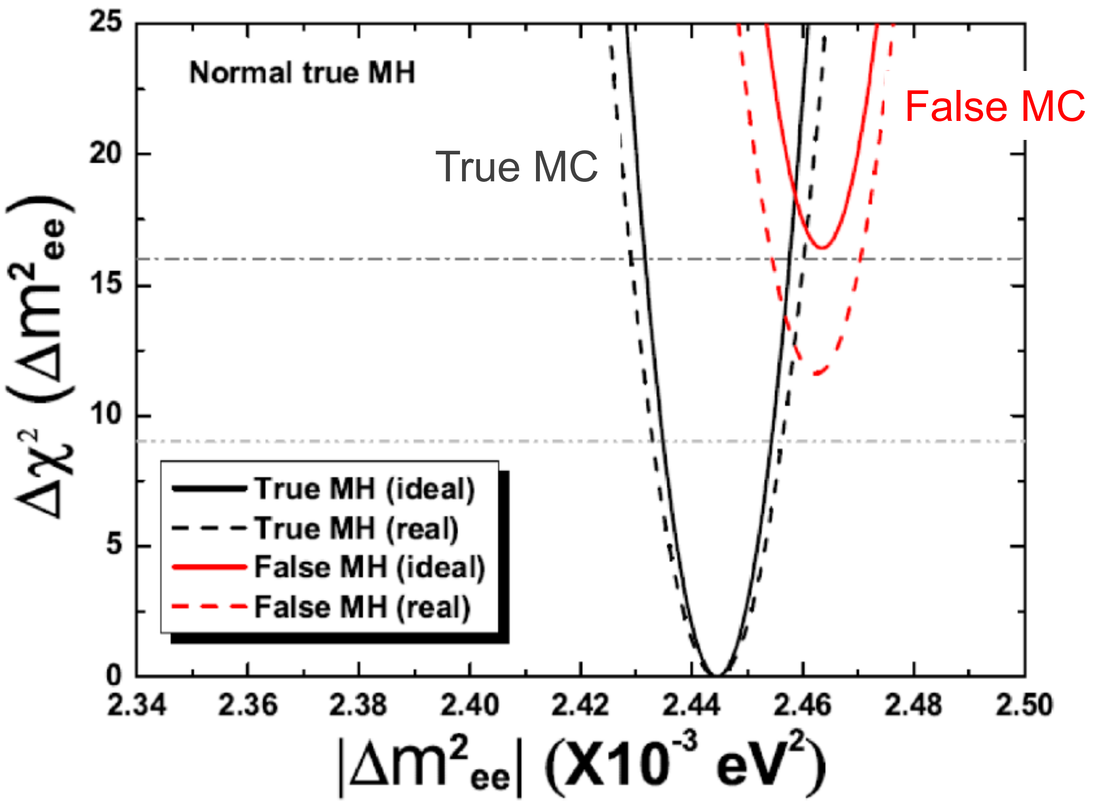
JUNO SENSITIVITY TO MASS HIERARCHY



Nominal exposure = 100k IBD events
≙ 6 years x 20 kt LS x 36 GW_{th}

Sensitivity on MH with nominal exposure and energy resolution

- $\Delta\chi^2 > 9$ with JUNO alone
- $\Delta\chi^2 > 16$ with external input of $\Delta m^2_{\mu\mu} \sim 1\%$



$$\Delta m^2_{ee} = \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$$

JUNO EXPERIMENTAL CHALLENGES

☐ Resolving signature wiggles in the L/E spectrum
  - excellent **energy resolution 3% @ 1 MeV**
  - better than **1% understanding of the energy scale**
  - **possible micro-structures in the spectrum under control** (e.g. PRL 114 (2015) 012502)

☐ Large statistics O(100k) = **large mass (20 kton)**

☐ **Backgrounds:** radio-purity and rock overburden of ~650 m

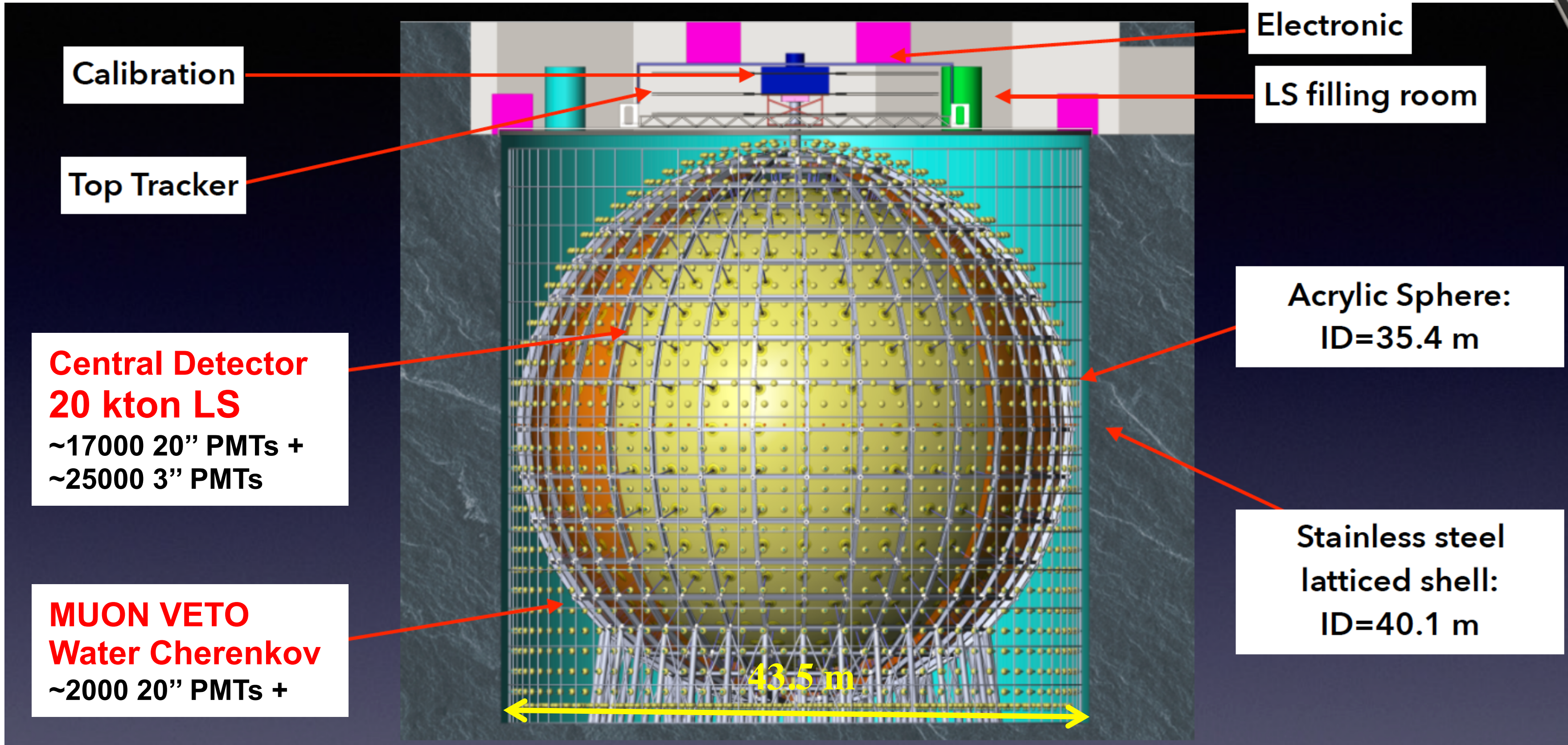
Stochastic terms (photon statistics)

- **High light yield (LY)**
- **Good transparency: λ_{att} > 20 m @ 430 nm**
- **PMT geometrical coverage: 78%**
- **PMT collection efficiency x quantum efficiency: ~27%**
- **Effective LY: ~1200 photoelectrons/MeV**

Systematic effects

- **Calibration**
  - ✓ $\alpha/\beta/\gamma$ sources, light pulses, UV-laser
  - ✓ 5 complementary systems under R&D
- **Double calorimetry concept**
  - ✓ large 20-inch and small 3-inch PMTs
- **TAO** – Taishan Antineutrino Observatory with excellent energy resolution 1.5% @ 1MeV

JUNO DETECTOR



Calibration

Top Tracker

Electronic

LS filling room

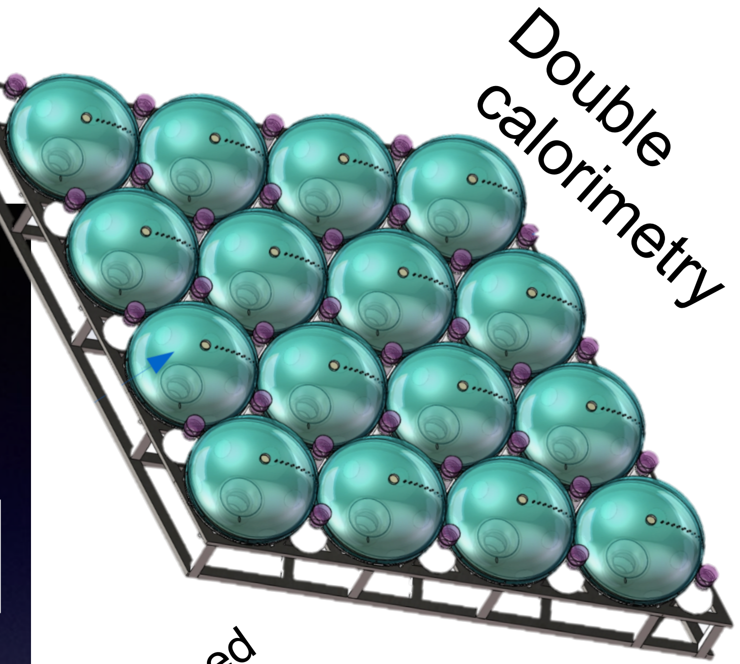
Central Detector
20 kton LS
~17000 20" PMTs +
~25000 3" PMTs

MUON VETO
Water Cherenkov
~2000 20" PMTs +

Acrylic Sphere:
ID=35.4 m

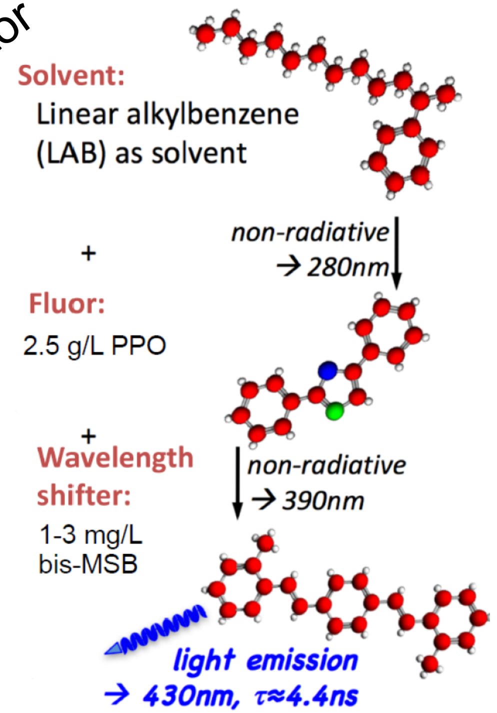
Stainless steel
latticed shell:
ID=40.1 m

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1200 p.e. / MeV



Double calorimetry

LAB-based scintillator



Solvent:
Linear alkylbenzene (LAB) as solvent

+

non-radiative
→ 280nm

Fluor:
2.5 g/L PPO

+

Wavelength shifter:
1-3 mg/L bis-MSB

non-radiative
→ 390nm

light emission
→ 430nm, τ≈4.4ns

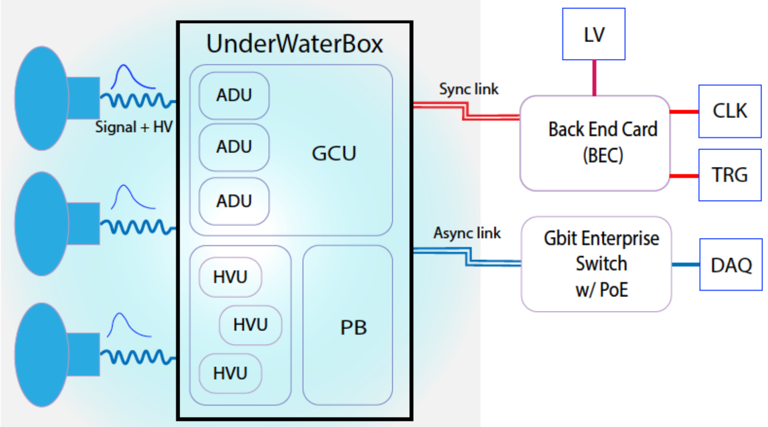
MORE ON JUNO DETECTOR

20-inch PMTs

- 15k MCP-PMTs from NNVT
- 5k dynode PMTs from Hamamatsu
- 12k delivered

Parameter	MCP	DYNODE
DE @ 420nm	27%	27%
P/V	3.5	3
TTS	12 ns	2.7 ns
Dark Rate	20 kHz	10 kHz
Pre/after Pulse	0.5%/1%	0.8%/10%

20-inch PMTs



Readout electronics

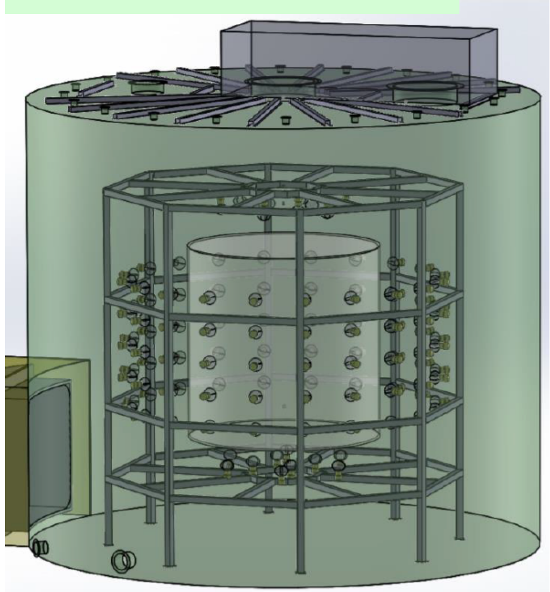
Waveforms sampled at 1GHz

LS Purification Pilot Plant

- Prototype tested at Daya Bay
- Low radioactivity < 10^{-15} g/g U/Th
- Achieved $\lambda_{att} = 23$ m

OSIRIS

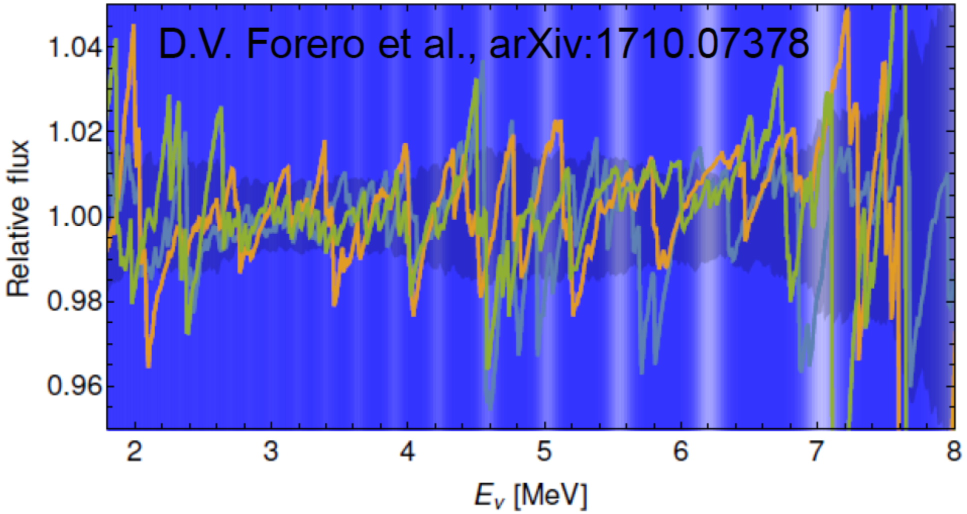
LS monitoring during filling (18 ton, 120 10”PMTs)



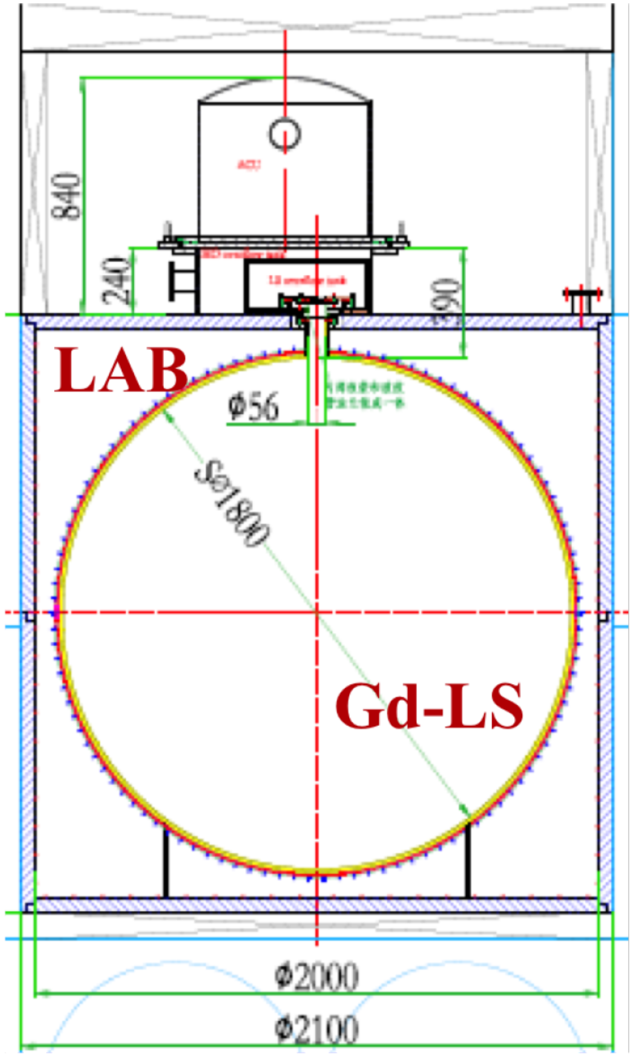
JUNO-TAO – TAISHAN ANTINEUTRINO OBSERVATORY

A ton-level, high-energy resolution LS detector at ~30 m from the Taishan-1 reactor core:

- Reference spectrum for JUNO
- Benchmark for nuclear DB



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)

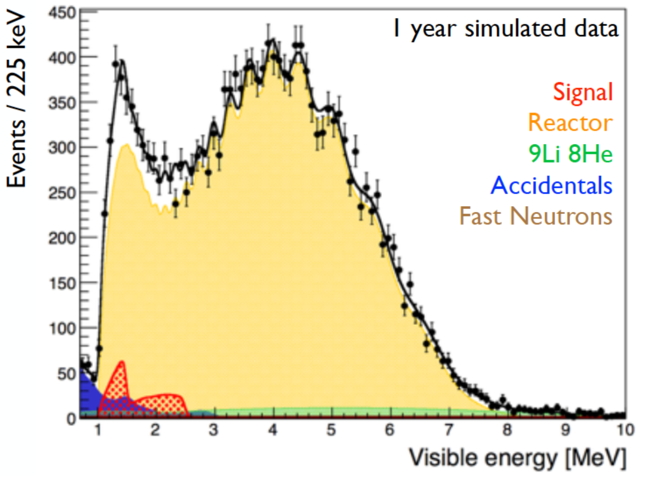


R&D ongoing

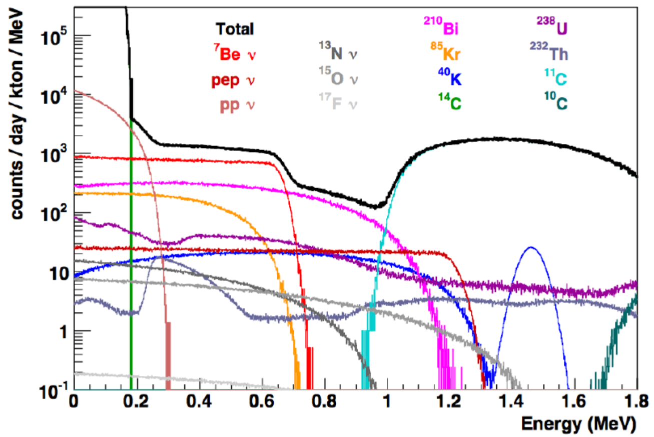
- 3 tons of Gd-LS
- 10 m^2 SiPM with 50% photon detection efficiency operated at -50 ^{o}C
- Cryogenice vessel, HDPE shielding, muon veto, calibration system
- 10 m udnerground
- Plan to be online in 2020

OTHER PHYSICS WITH JUNO

Geoneutrinos: 400/year!

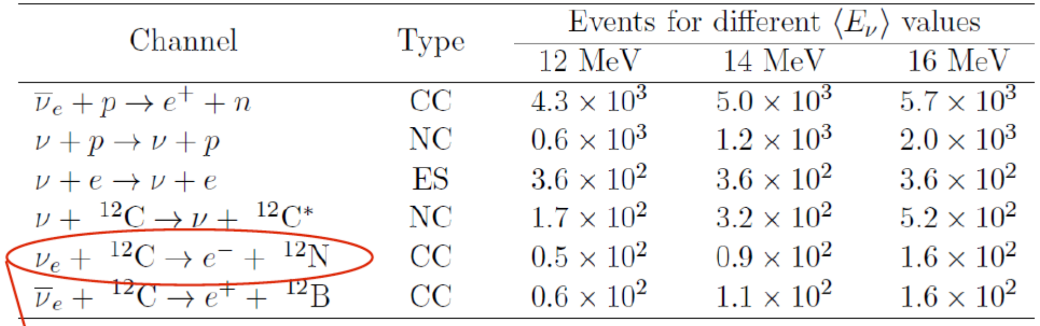


Solar neutrinos: ^{7}Be, ^{8}B



- Geoneutrinos
- Solar neutrinos
- SN neutrinos
- DSNB
- Proton decay
- Atmospheric neutrino
- Sterile neutrino
- Indirect DM searches
- Other exotic searches

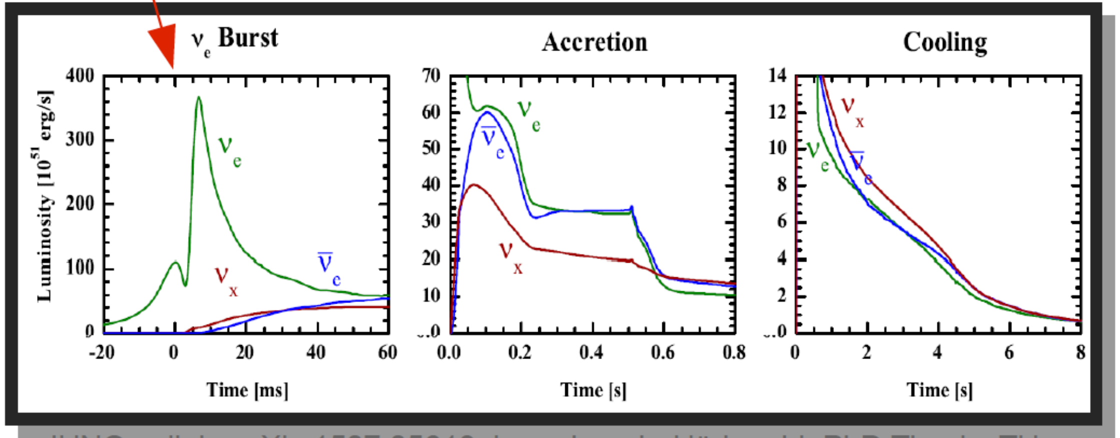
Super-novae neutrinos



Channel	Type	Events for different $\langle E_\nu \rangle$ values 12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\text{C} \rightarrow \nu + {}^{12}\text{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\text{C} \rightarrow e^+ + {}^{12}\text{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

JUNO collab., arXiv:1507.05613

Huge statistics + Flavour information

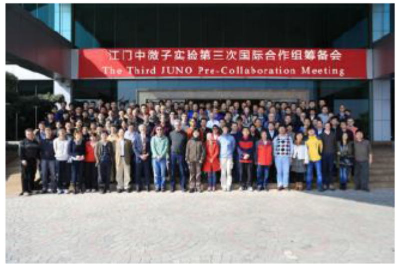


JUNO collab.,arXiv:1507.05613, based on: L. Hüdepohl, PhD Thesis, TU Munich (2013), A. Mirizzi et. al., arXiv:1508.00785

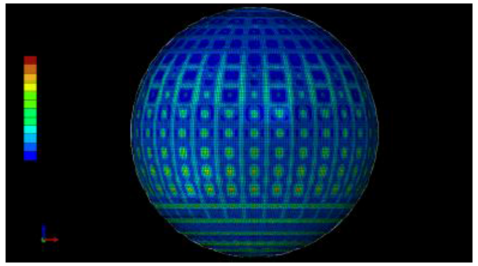
Time evolution

JUNO TIMELINE

Stay tuned!



2014:
- International collaboration established

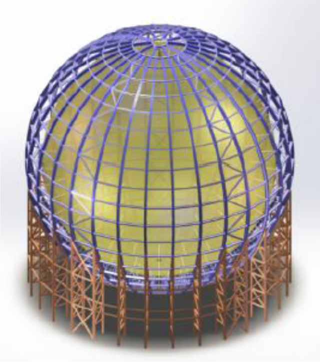


2015:
- PMT production line setup
- CD parts R&D
- Start of civil construction

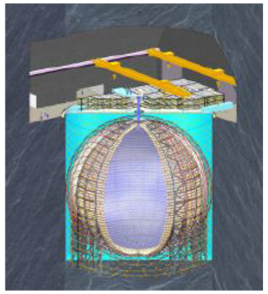
2016:
- Start of PMT production
- Start of CD parts construction

2017:
- Start PMT testing
- TT arrived

2018:
- PMT potting starts
- Delivery of surface buildings
- Start production of acrylic sphere



2019-2020:
- Electronics production starts
- Civil work and lab preparation completed
- Detector construction



2021:
- Detector ready
- Data taking!

SUMMARY AND OUTLOOK

Liquid scintillator detectors are fundamental in low-energy neutrino physics

Borexino

Solar neutrinos:

- comprehensive spectroscopy of pp-chain neutrinos
- quest for neutrinos from the CNO fusion cycle

Geoneutrinos:

- observed geoneutrinos and provided first geological insights
- preparing an update with ~20% precision

JUNO

- the first multi-kton detector ever to start DAQ in 2021
- reactor antineutrinos with 53 km baseline: mass hierarchy and <1% precision for θ_{12}, Δm^2_{12}, Δm^2_{ee}
- large potential in astrophysical neutrinos and exotic searches

Thank you!