The Monte Carlo simulation of the Borexino detector

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Outline

1. Borexino: goals and achievements
2. The Borexino full Monte Carlo simulation
3. General validity of the method
4. A “novel” approach for external background simulations
5. Modeling the low energy response and the event pileup
6. Summary and outlook

Borexino and SOX Collaborations

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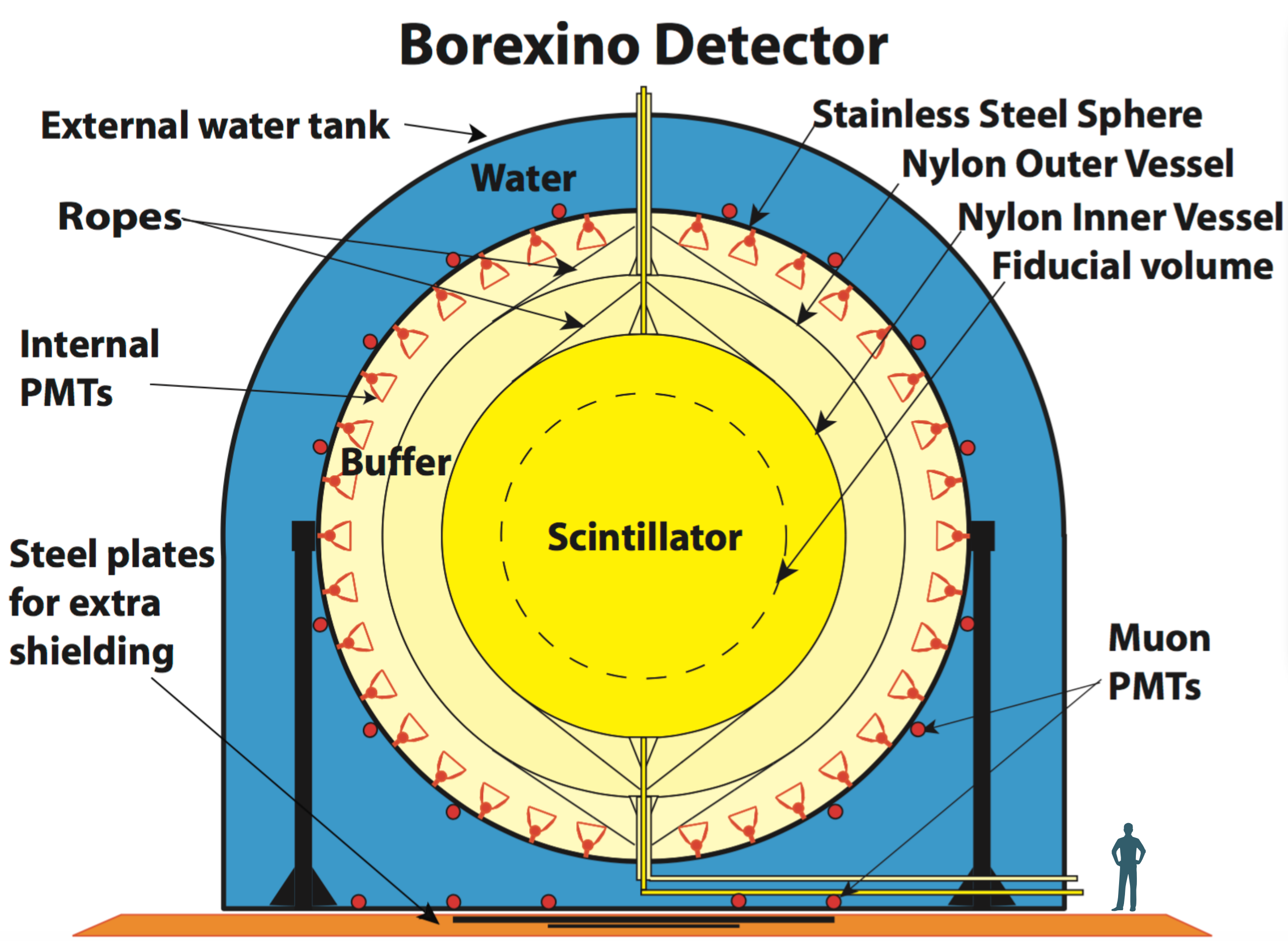
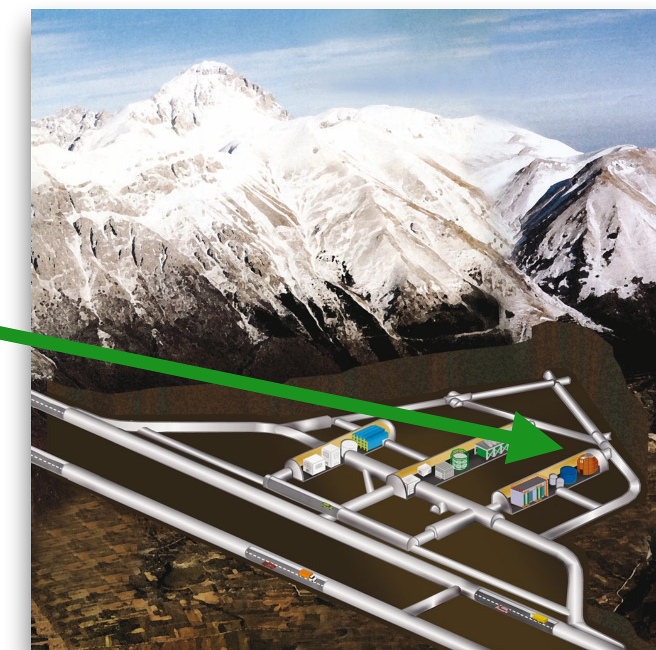
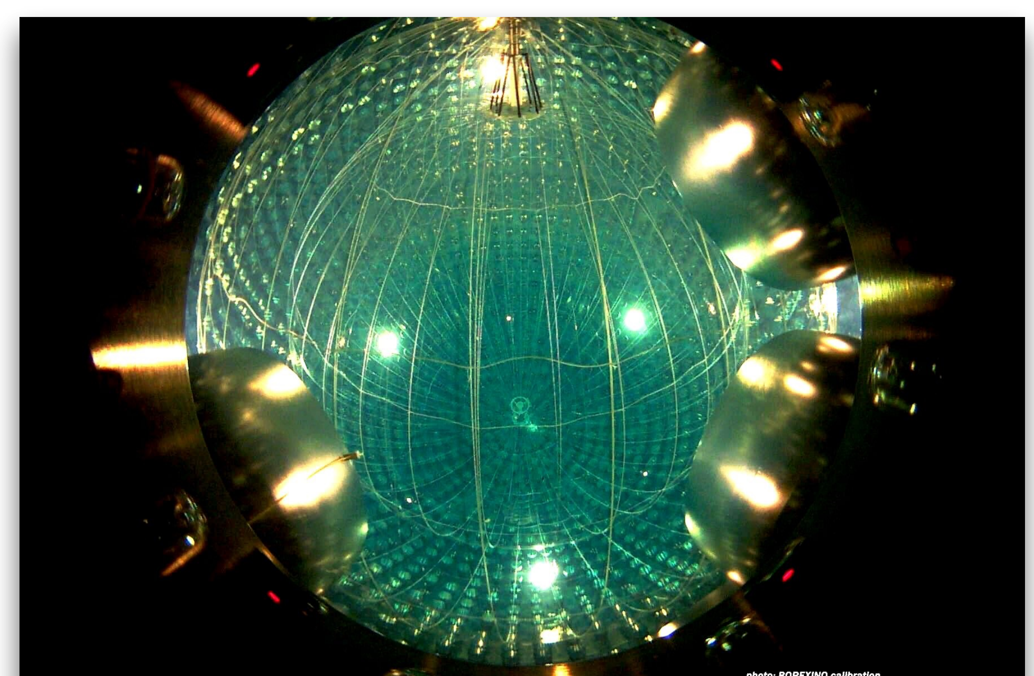
Borexino @ Laboratori Nazionali del Gran Sasso



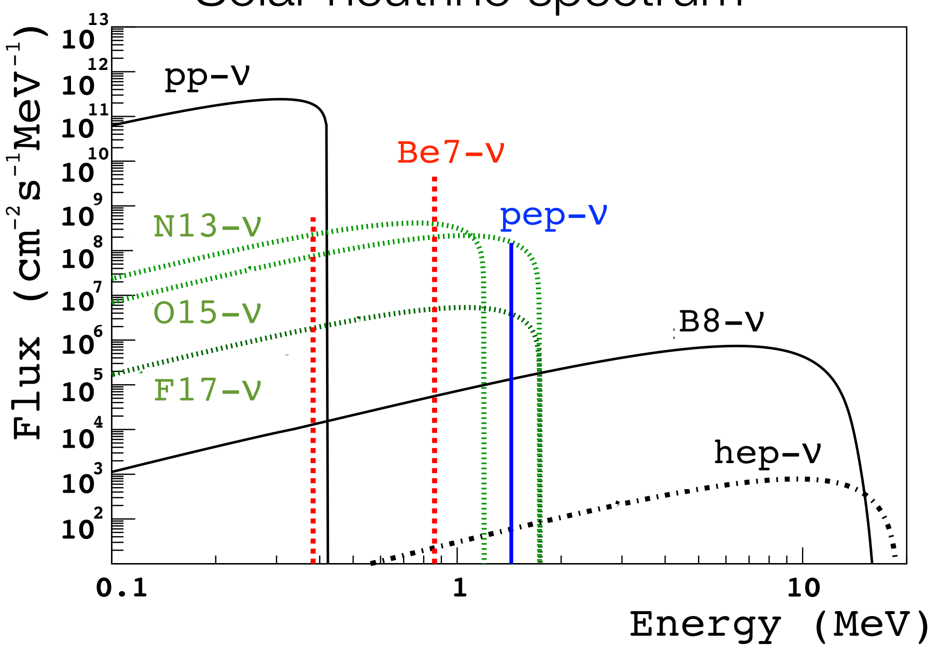


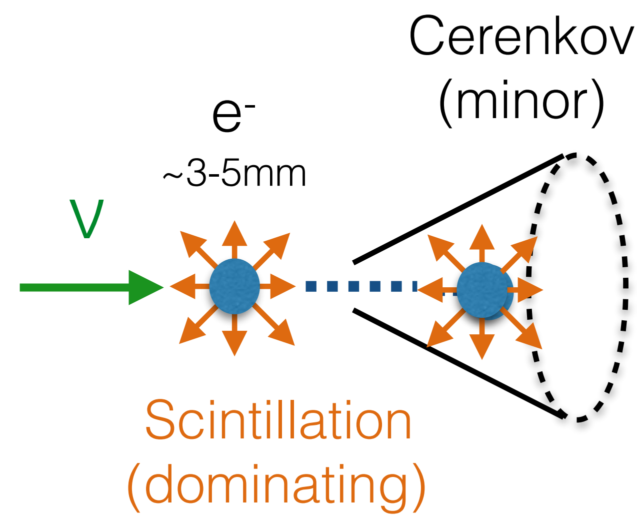
- 3800 m.w.e shielding against cosmic rays at LNGS
- active volume ~300 ton of liquid scintillator
- ~900 ton of ultra-pure buffer liquid
- 2212 PMTs detecting the scintillation light
- water Cherenkov veto equipped with 208 PMTs



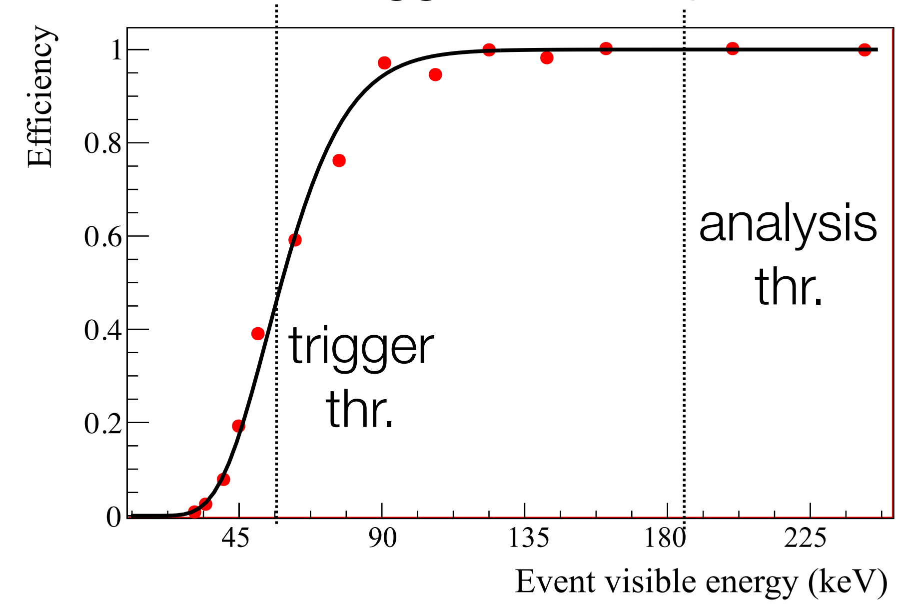
Borexino's strategy (PRD 89 112007 (2014))

Solar neutrino spectrum



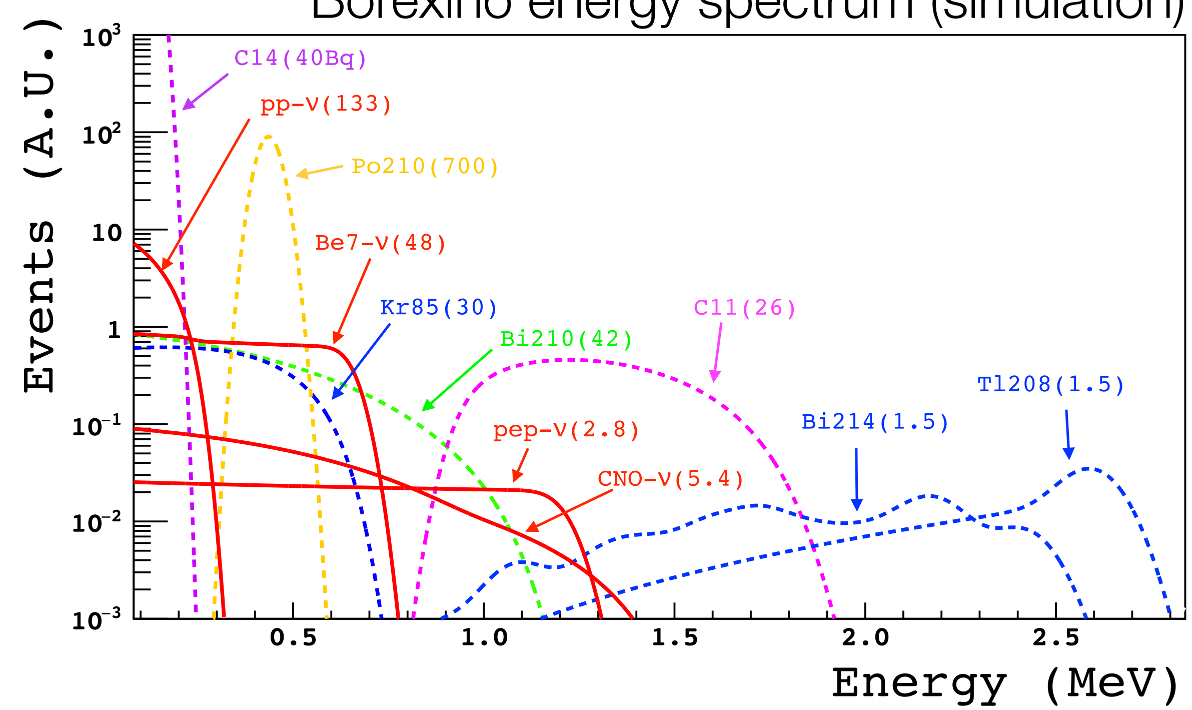


Trigger efficiency

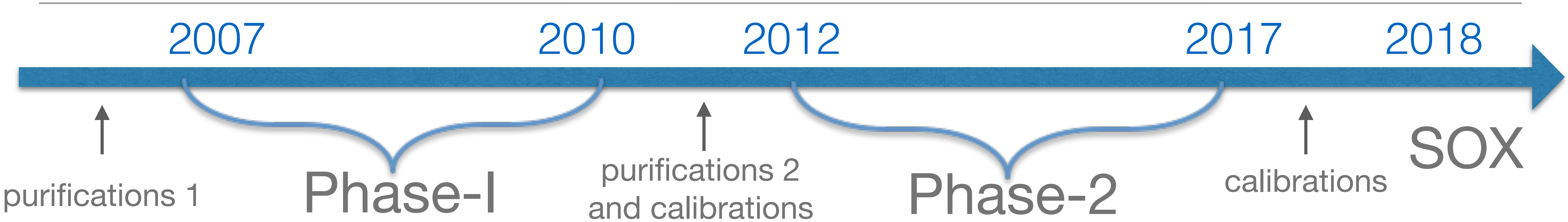


- Very low energy threshold (~100 keV) and good energy resolution ~ 5% @ 1MeV
- Pulse shape α/β, β+/β- but no directionality
- **Need of superb radio-purity** against β/γ backgrounds
- Strategy: spectral fit of event energy spectrum
- <u>Requirement: accurate understanding of detector's response</u>

Borexino energy spectrum (simulation)



Borexino's timeline and results

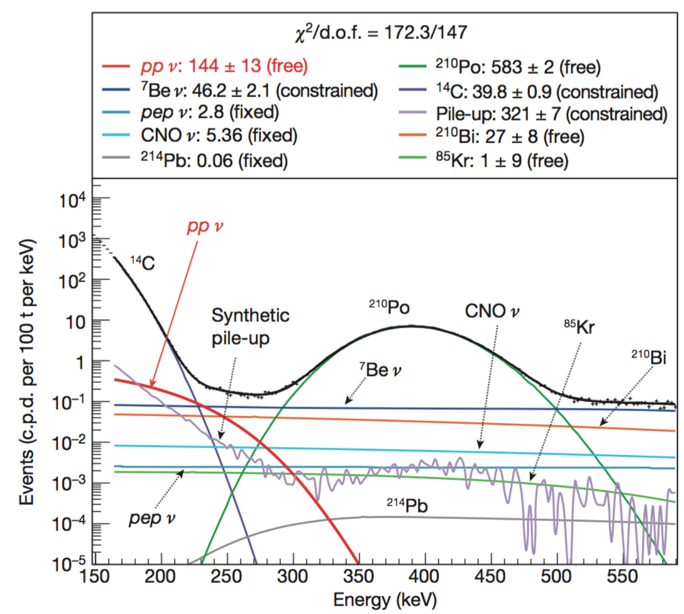


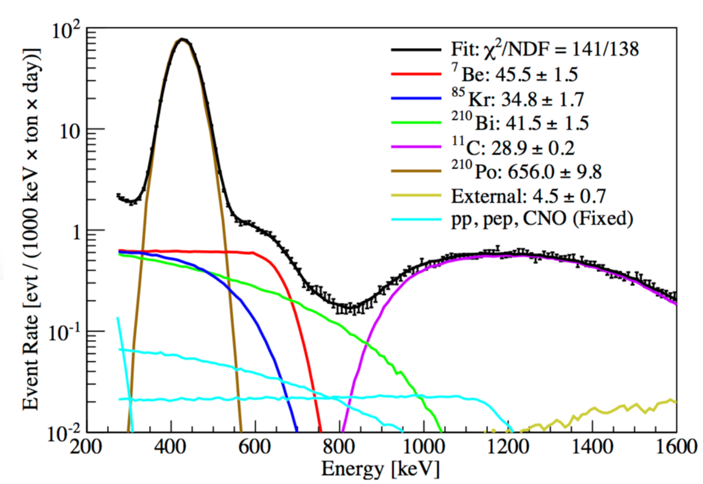
First Precision Measurement of
Be7 solar neutrino flux
Phys. Rev. Lett. 107, 141302 (2011)

First direct detection of **pep**
solar neutrinos
Phys. Rev. Lett. 108, 051302 (2012)

First realtime direction of
pp solar neutrinos
Nature 512, 383-386 (28 August 2014)

Lowest energy threshold
B8 neutrino detection
Phys.Rev.D82:033006 (2010)





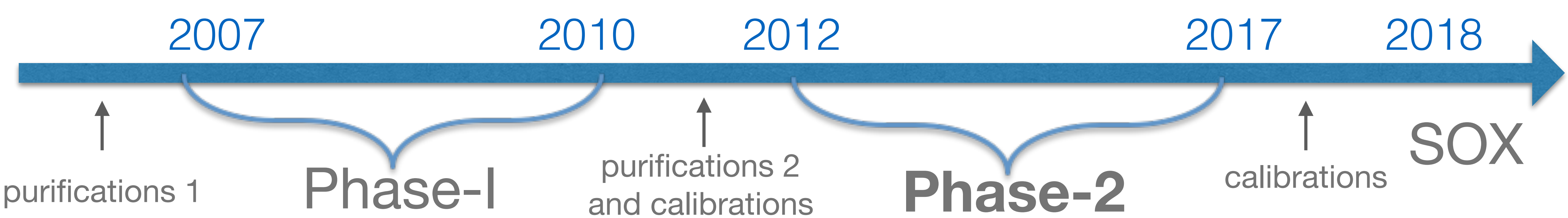
not only solar neutrinos…

5.9σ detection of **geoneutrinos**, signal from the mantle at 98% C.L (Phys. Rev. D 92, 031101 (2015))

search for **rare processes** (e.g. electron decay Phys. Rev. Lett. 115, 231802 (2015))

limit on **Neutrino Magnetic Moment**
see **L. Ludhova**'s talk on Monday
"Limiting the effective magnetic moment of Solar neutrinos with the Borexino detector"

What's left for Phase 2?



not possible in the past!

- **Model the detector more accurately in order to measure pp, pep and Be7 simultaneously on the whole energy scale for the purest Phase 2 data set**

  Poster 82: "Data selection strategy for the solar neutrino analysis with Borexino" by S. Caprioli

- Two approaches: analytical modeling and ***Monte Carlo simulation*** ← *this talk!*

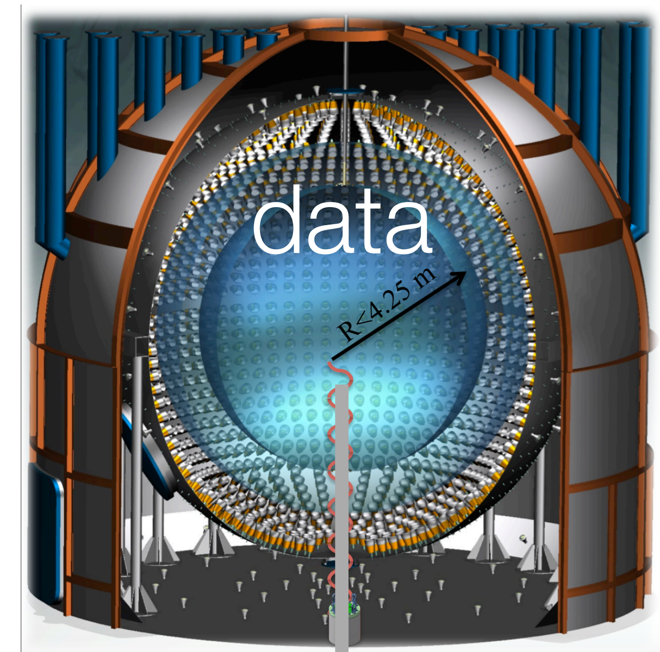
  Poster 83: Analytical response function for the Borexino solar neutrino analysis" by Dr. Z. Bagdasarian
  Poster 108: "GPU based spectral-fitter for Borexino solar neutrino analysis" by X. Ding

- See Gemma Testera's talk tomorrow **"Solar Neutrinos: Overview and New Results from Borexino"** for exciting new results!

The Monte Carlo simulation

Ab initio simulation of the detector response:

1. energy loss of charged particles
2. optical photon production, wavelength shifting and propagation
3. custom simulation of the electronics response of the detector



“The Monte Carlo simulation of the Borexino detector”
arXiv:1704.02291, submitted to Astroparticle Physics

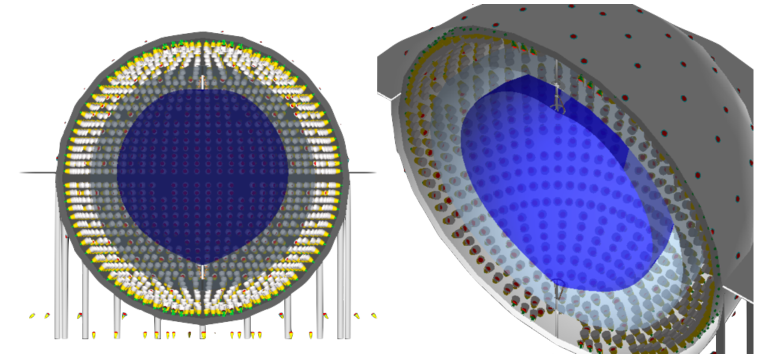
Tracking code → Electronics simulation → Reconstruction

Geant4 based. It simulates all the physical processes until the hit of optical photons on PMTs for various classes of events

Custom C++ software. It simulates the Borexino DAQ system (calibrations, trigger, noise, broken PMTs…) on a 6h time base (1 run)

Borexino reconstruction software (C++)

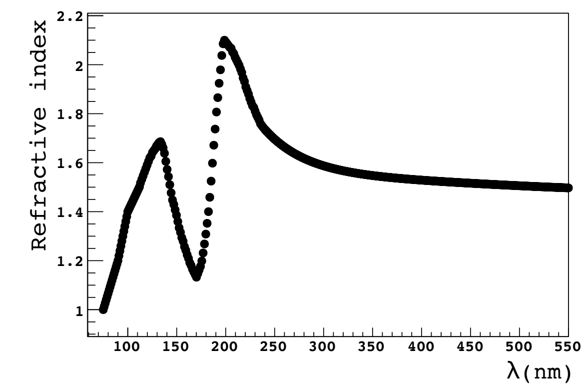
Optical processes and electronics simulation



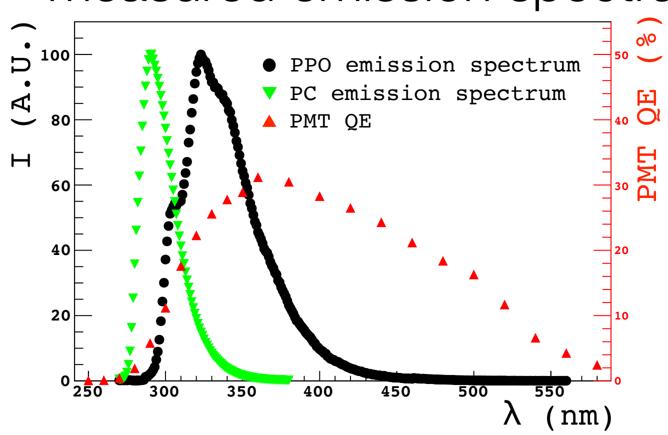
Detailed simulation (based on independent measurements) of:

- scintillation and Cerenkov
- single photon propagation
- absorption and reemission in scintillator and buffer
- weekly based effective quantum efficiency variations

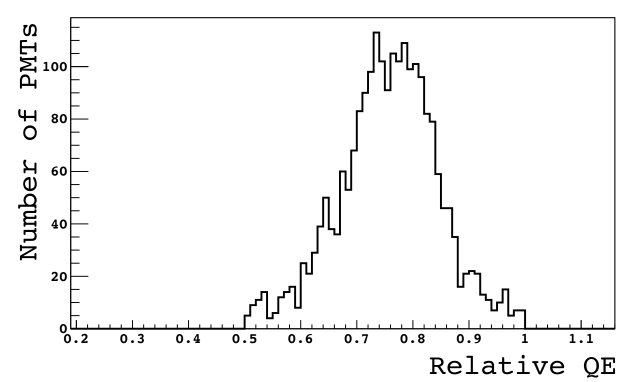
measured refractive index



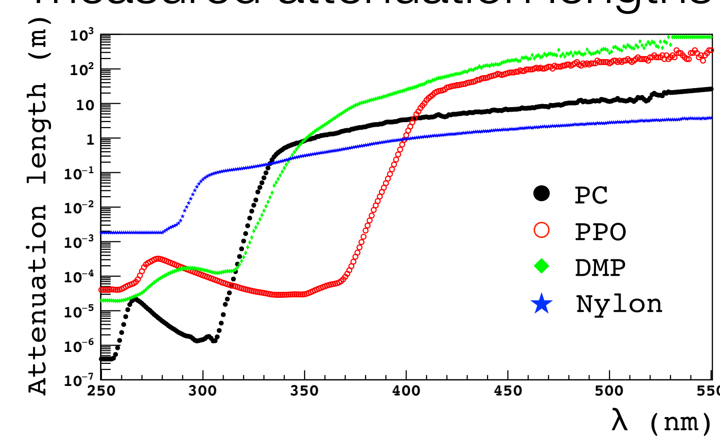
measured emission spectra



measured effective QE



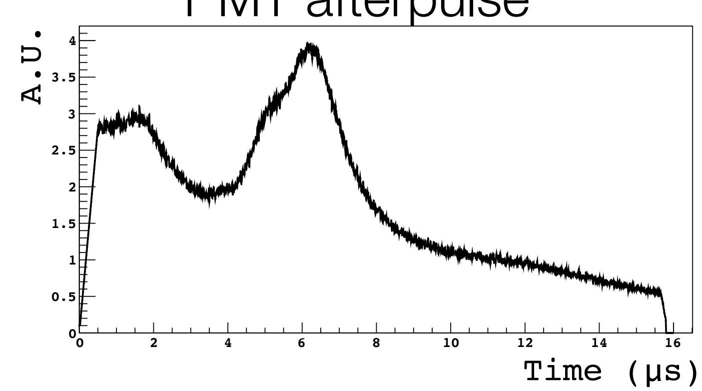
measured attenuation lengths



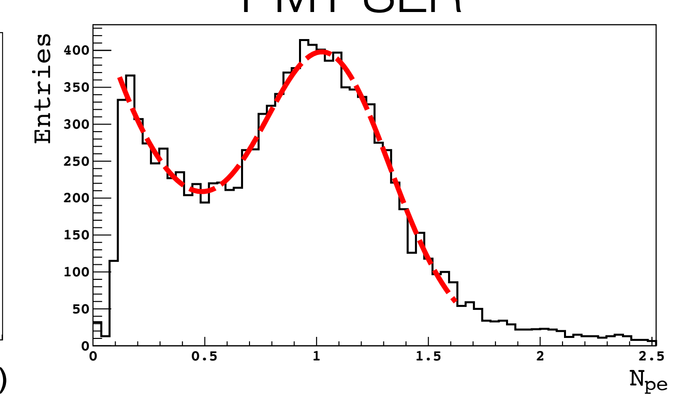
Detailed simulation of the electronics:

- event by event channel status simulation
- run and weekly based calibrations
- crucial to properly simulate the detector over years

PMT afterpulse



PMT SER

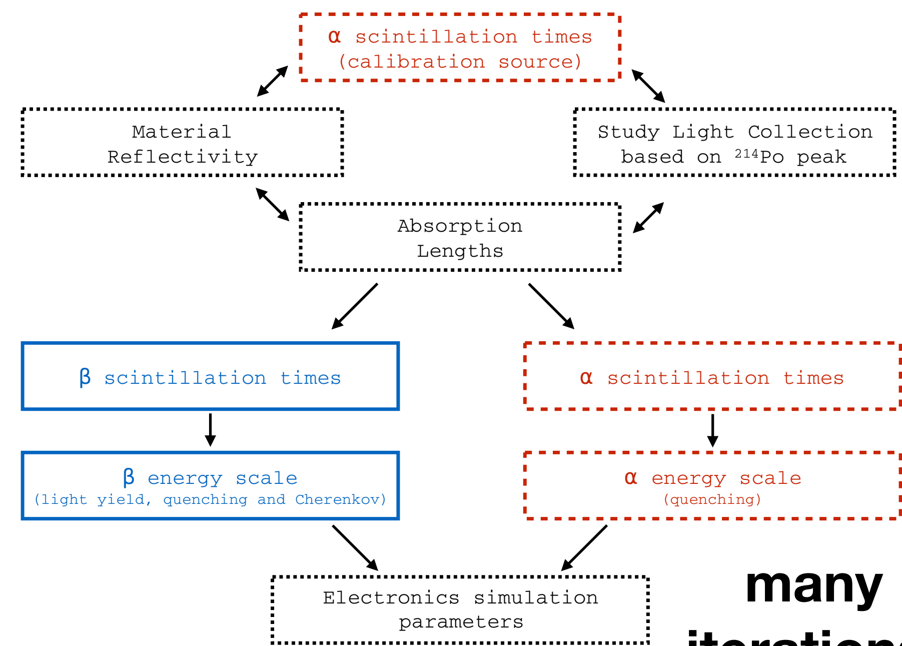


Calibrations and Monte Carlo tuning

- **Tuning and validation** require a well planned calibration campaign with both **internal and external sources** (JINST 7 (2012) P10018)
    1. many positions in the inner vessel to map the **light collection** and detector response in the volume
    2. many gamma sources in the center to tune the **energy scale** and **time response**
    3. external sources to study **external backgrounds**
- New calibrations in view of the SOX experiment

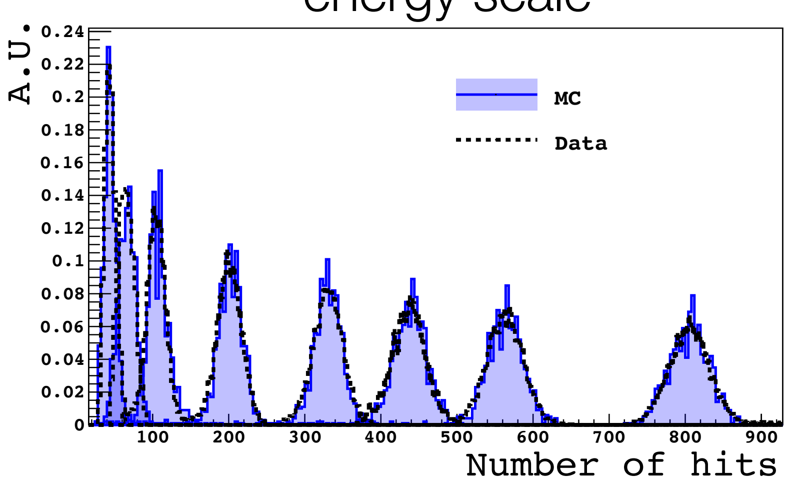
Poster 75: “Calibration campaign of the Borexino detector for the search of sterile neutrinos with SOX” by Dr. L. Collica

tuning strategy

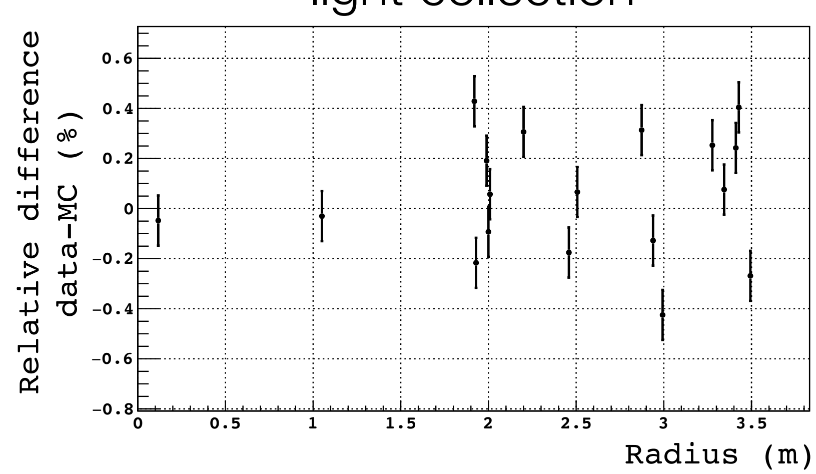


many iterations!

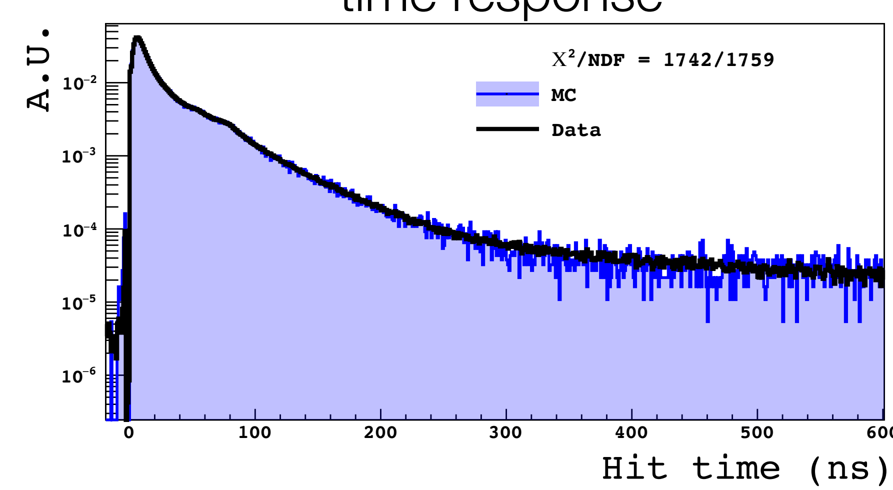
energy scale



light collection



time response



1% accuracy on light collection, energy and time responses

“The Monte Carlo simulation of the Borexino detector”
arXiv:1704.02291, submitted to Astroparticle Physics

Not only Borexino…

Experiment	Mass	Physics investigation	Status	Reference
Chooz	5 t LS+Gd (0.1%) + 107 t LS	ν oscillations	past	[19]
KamLAND	1 kt LS	ν oscillations	past	[20]
Karmen	56 t +Gd foils	ν oscillations	past	[21]
LSND	167 t LS	ν oscillations	past	[22]
Palo Verde	11 t LS+Gd (0.1%)	ν oscillations	past	[23]
Borexino	278 t LS	ν oscillations	ongoing	[24]
Daya Bay	20 t LS+Gd (0.1%) + 20 t LS	ν oscillations	ongoing	[25]
Double Chooz	8 t LS+Gd (0.1%) + 18 t+80 t LS	ν oscillations	ongoing	[26]
Reno	16 t LS+Gd (0.1%) + 30 t LS	ν oscillations	ongoing	[27]
LENS	125 t LS+In (8%)	ν oscillations	future	[28]
Juno	20 kt LS	ν oscillations	future	[29]
Reno-50	18 kt LS	ν oscillations	future	[30]
KamLAND-Zen	13 t LS+Xe (2.9%) + 1 kt LS	$0\nu\beta\beta$ decay	ongoing	[31]
SNO+	780 t LS+Te (0.5%)	$0\nu\beta\beta$ decay	commissioning	[32]
LVD	1.8 kt LS	SN ν	ongoing	[33]
Nucifer	0.75 t LS+Gd (0.2%)	reactor monitoring	ongoing	[34]
Neos	1 t LS+Gd (0.5%)	sterile ν	ongoing	[35]
Neutrino-4	0.35 t LS+Gd (0.1%)	sterile ν	ongoing	[36]
Prospect	3–13 t LS+^{6}Li	sterile ν	ongoing	[37]
Stereo	1.8 t LS+Gd (0.2%)	sterile ν	commissioning	[38]
SOX	278 t LS	sterile ν	future	[17]
Dark Side-50	30 t LS+TMB (5%)	DM veto	ongoing	[39]
Dark Side-20k	~250 t LS+TMB (20%)	DM veto	future	[40]
LZ	20.8 t LS+Gd (0.1%)	DM veto	future	[41]
SABRE	2 t LS	DM veto	future	[42]

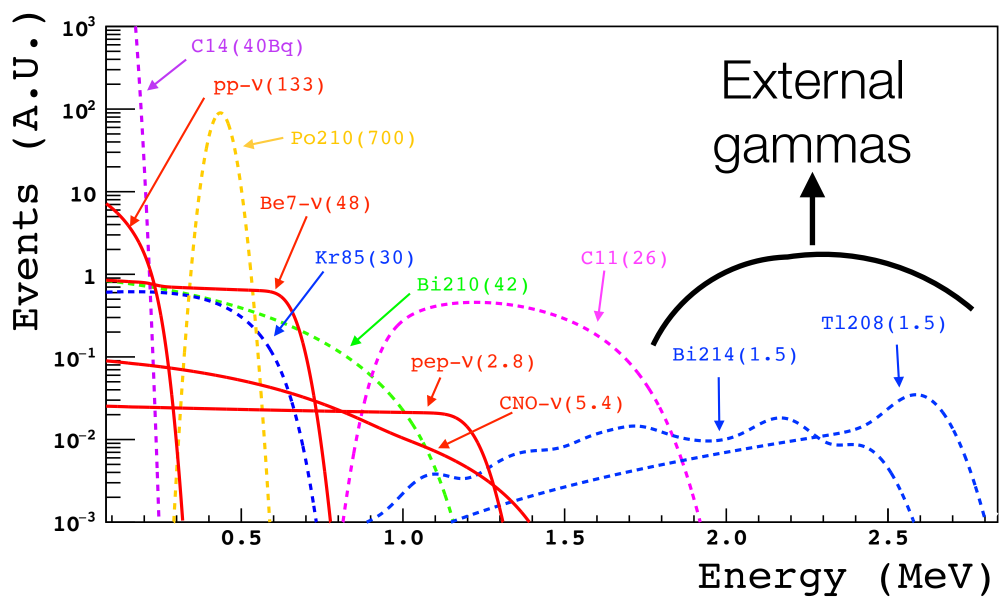
Many present and future experiments are large liquid scintillator detectors

Some dark matter detectors have liquid scintillator vetoes

The methods developed in Borexino is applicable to this whole category of detectors

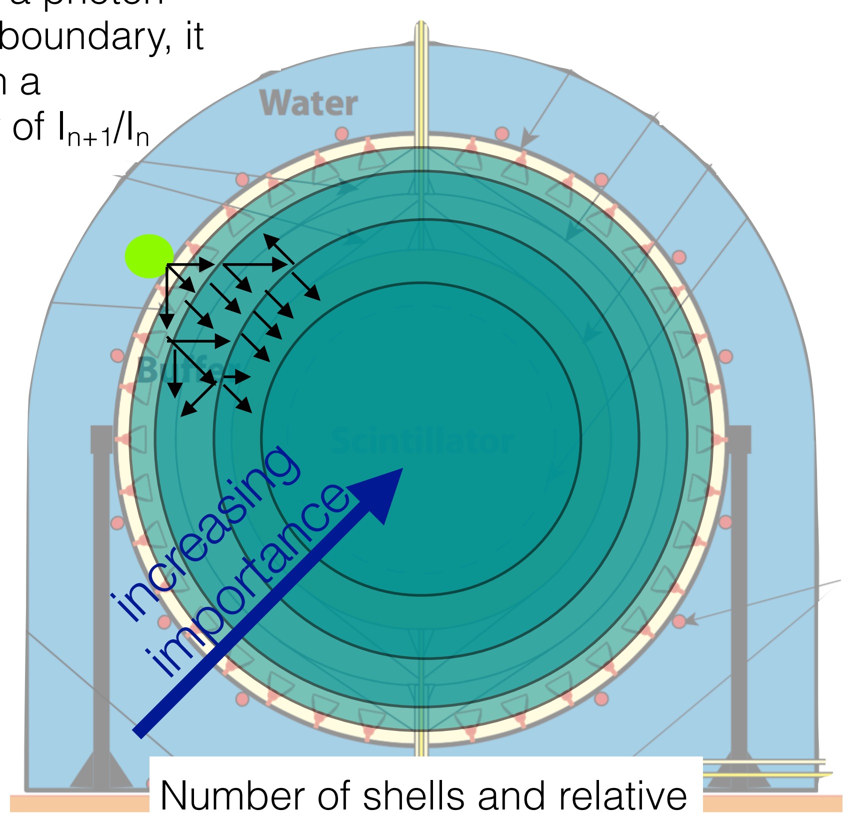
table shamelessly stolen from:
“The Monte Carlo simulation of the Borexino detector”
arXiv:1704.02291, submitted to Astroparticle Physics

External background

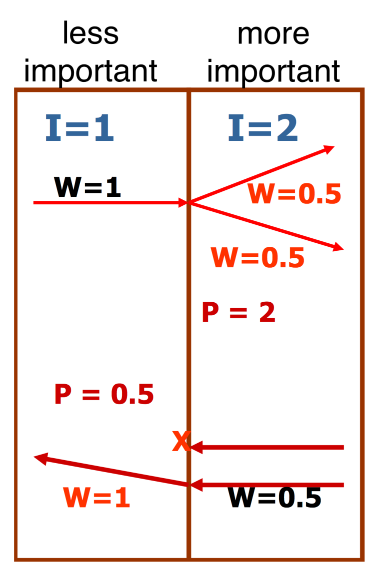


- External gammas coming from PMTs and stainless steel sphere are crucial for “high energy” measurements
- Brute force approach is not possible: shielding of ~10^7
- **Importance biasing technique** implemented in Borexino Monte Carlo (customization of a standard Geant4 feature)
- Three steps of simulation:
    1. Propagation of gammas with variance reduction
    2. Calculation of visible energy deposited at each step
    3. Standard tracking simulation of optical photons

every time a photon crosses a boundary, it is split with a probability of I_{n+1}/I_n



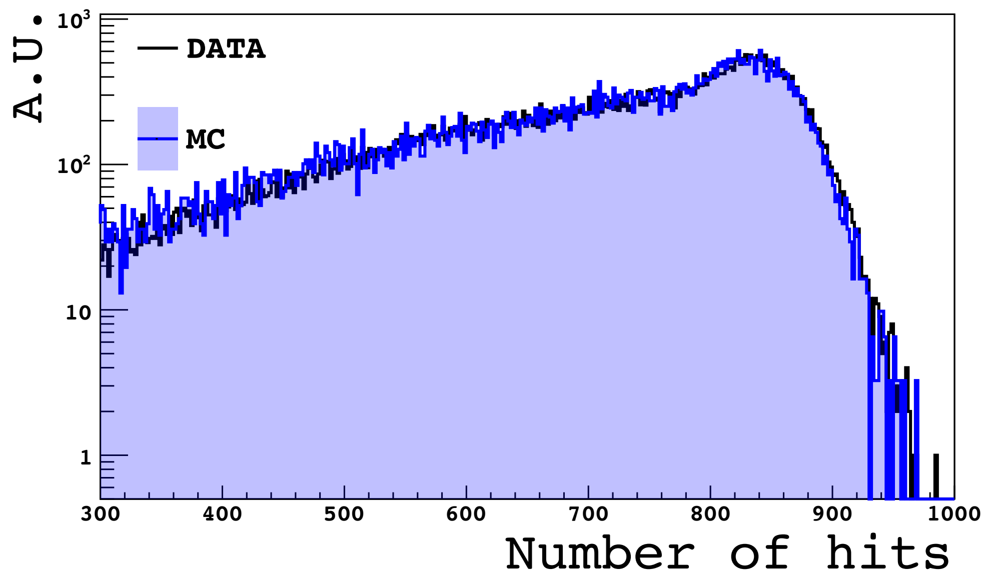
Number of shells and relative importance to be tuned to optimize the performance

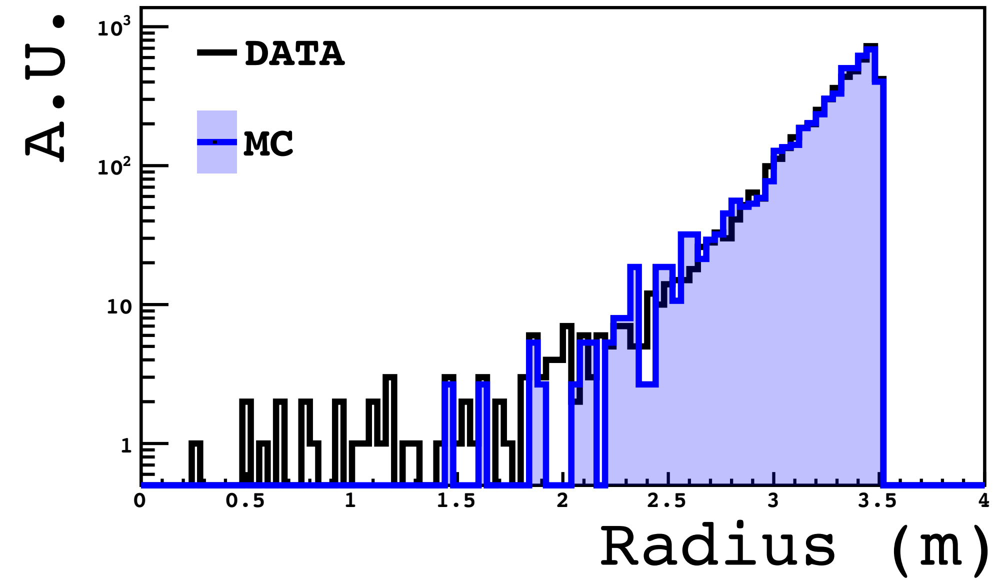


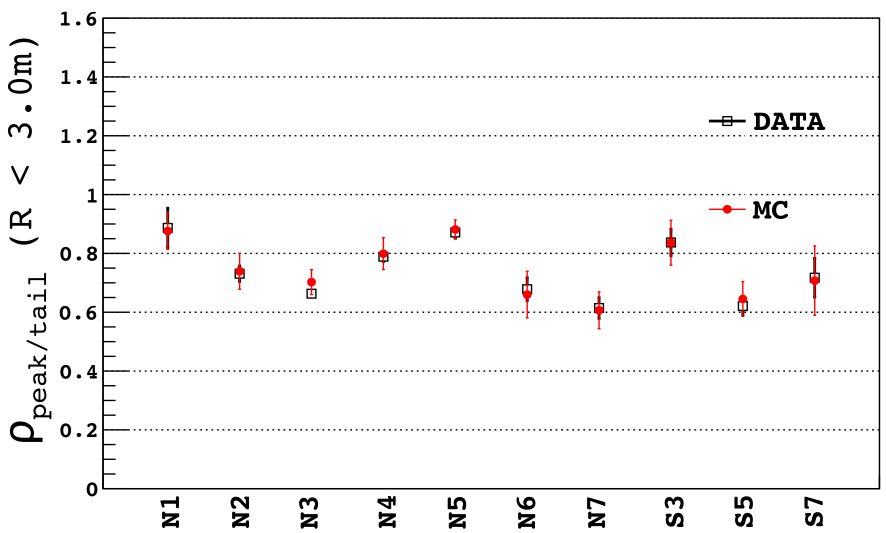
successfully working very proficiently!

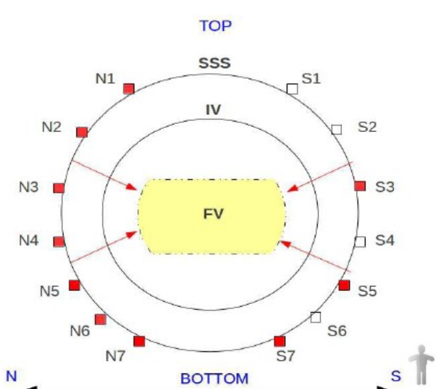
“The Monte Carlo simulation of the Borexino detector”
arXiv:1704.02291, submitted to Astroparticle Physics

External background: validation on calibrations





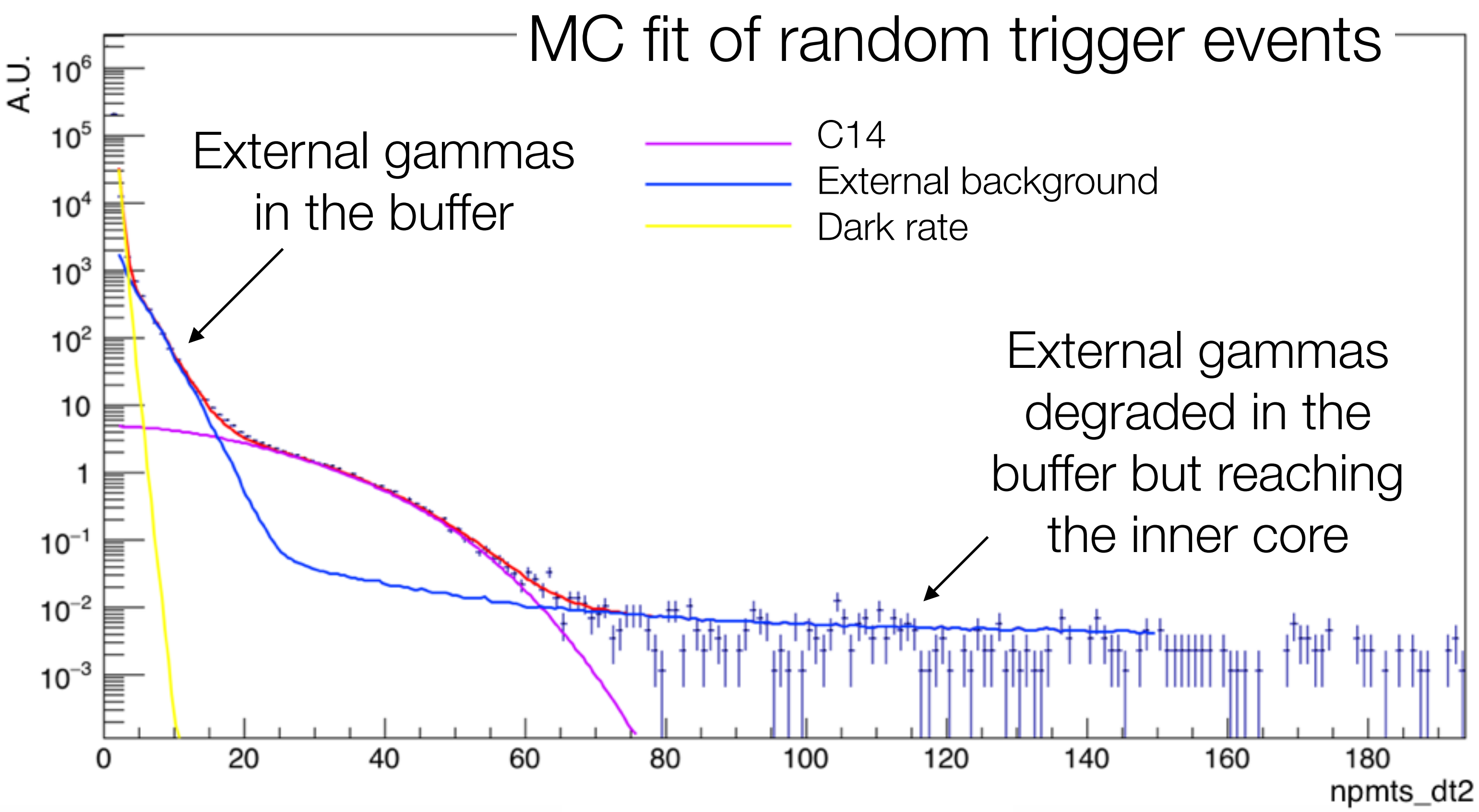




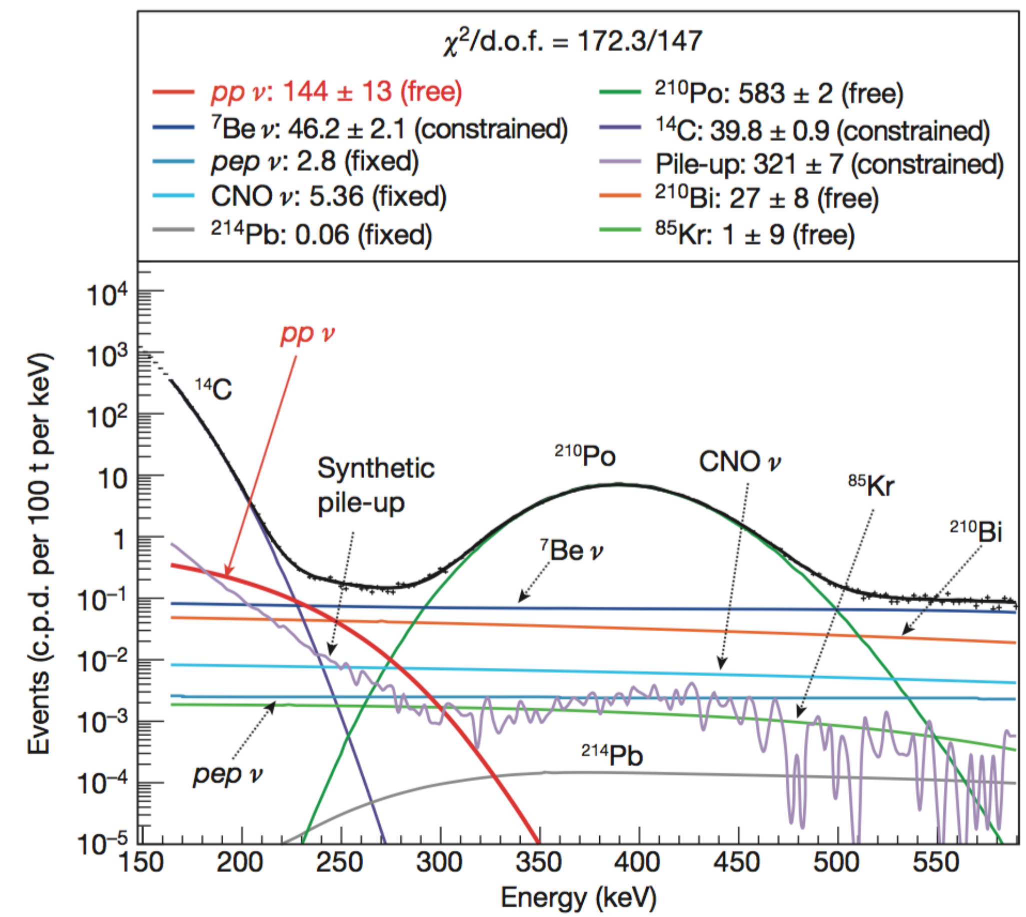
- The ratio of full absorption peak and Compton shoulder depends on the source position and the simulation can reproduce it
- There is **no new parameter** tuned to get agreement. These plots contemporarily validate:
    1. the external background simulation method
    2. the energy scale tuning
    3. the light collection simulation

Low energy response: pileup modeling

- event pileup is a **crucial background for low energy** analysis
- in Borexino, it is mostly C14 overlapping with itself
- in previous analysis, a **data driven method** allowed to predict the pileup contribution
- now, the simulation can answer the question: **what are the pileup events made of?**

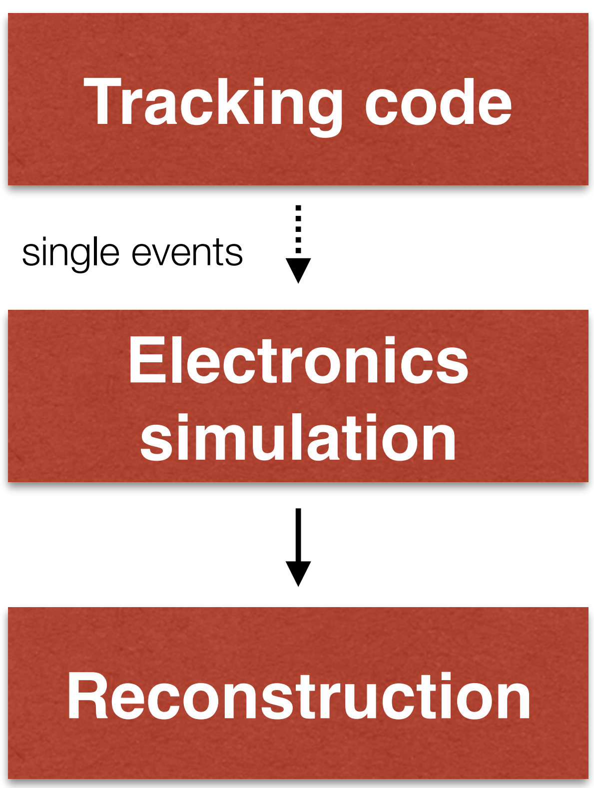


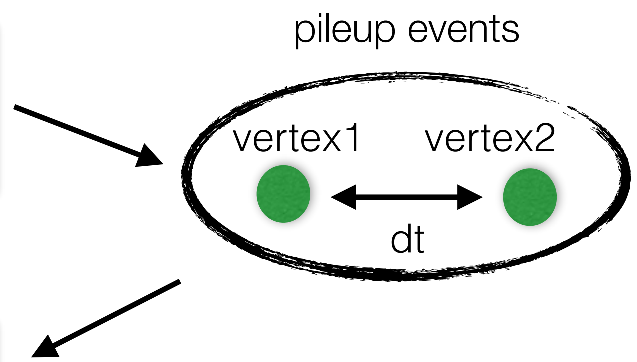
The efficient external background simulation was crucial for understanding the pileup composition



Nature 512, 383-386 (28 August 2014)

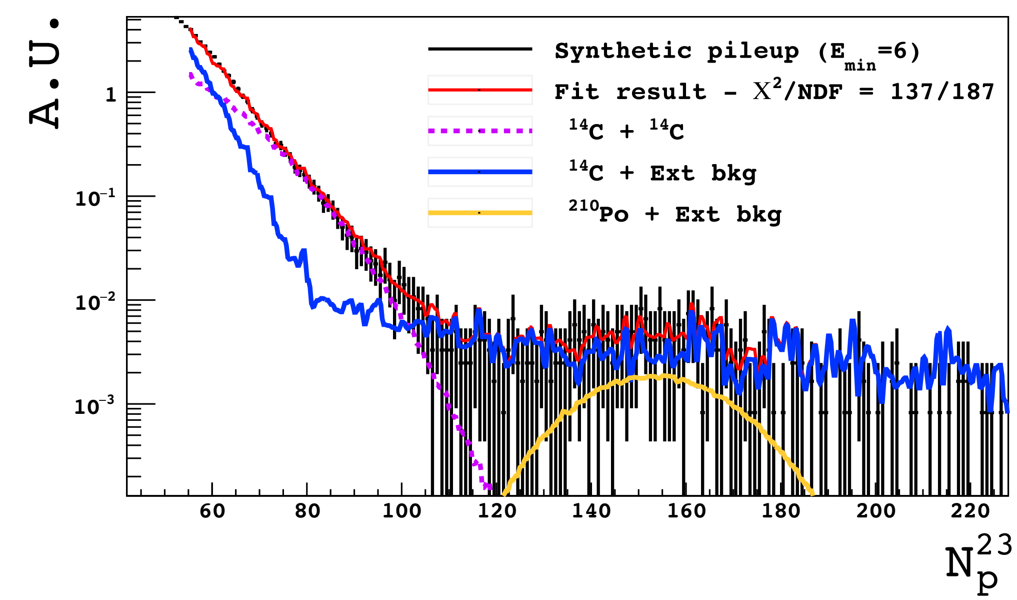
Monte Carlo pileup production



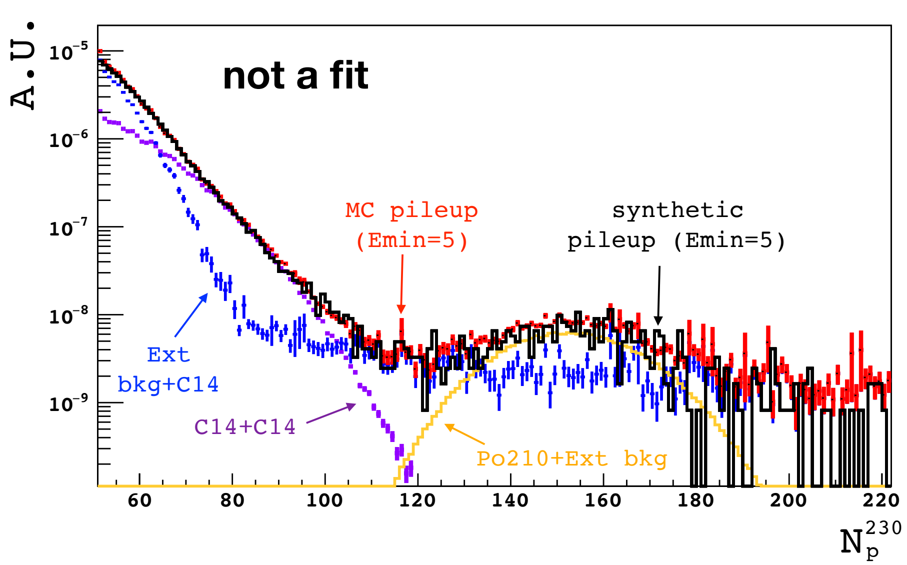


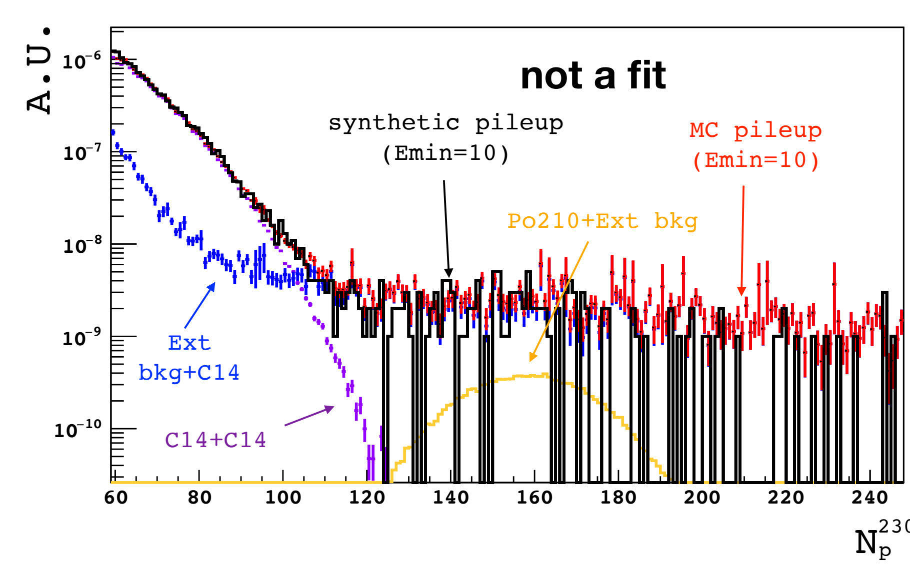
- need to know the pileup-ing components
- **E_{min}** is the increase in the energy estimator due to the addition of the second vertex

use data to measure pileup components with a fixed E_{min}…



…and validate for different E_{min}'s!





"The Monte Carlo simulation of the Borexino detector"
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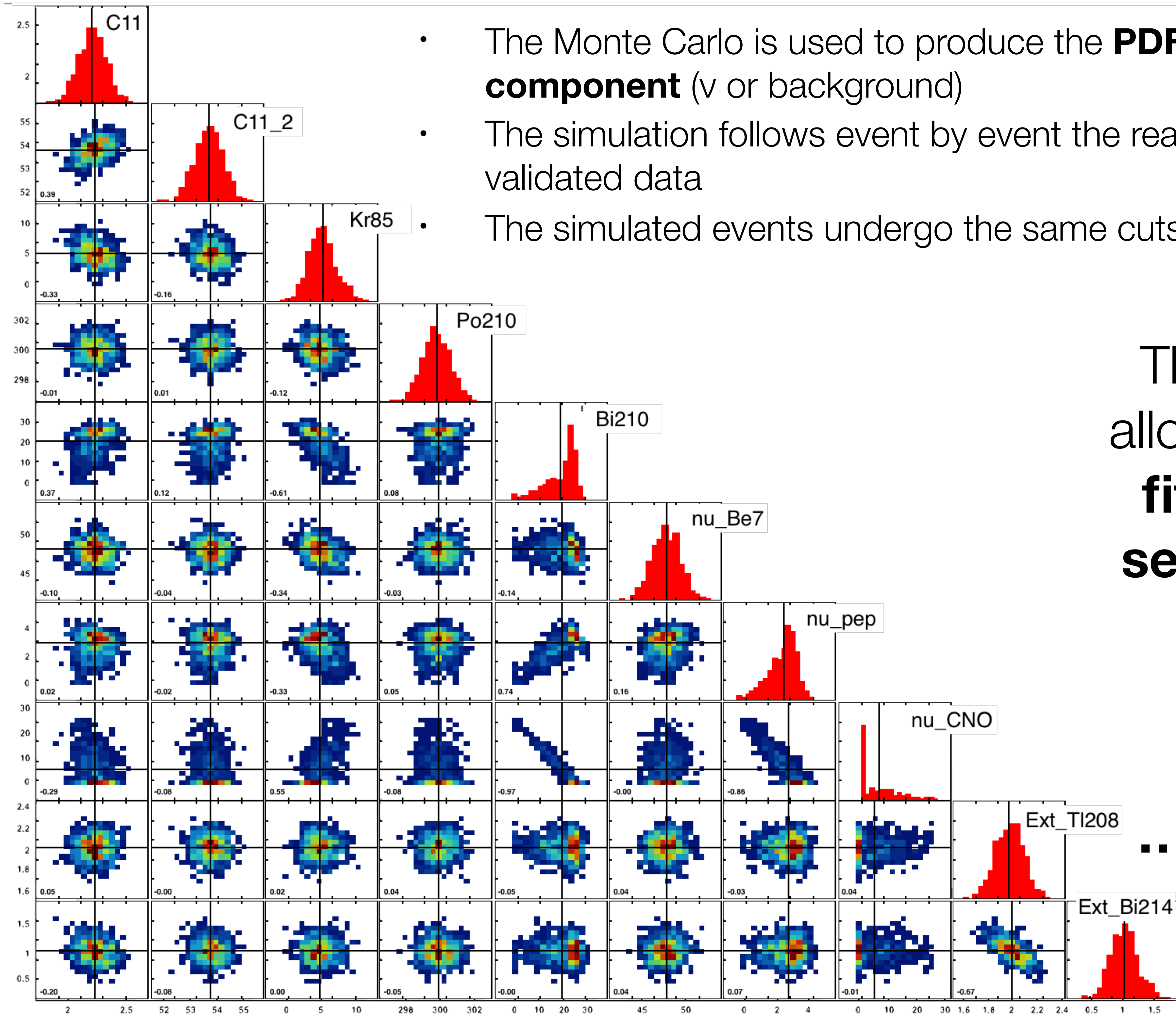
PDF production and fit validation



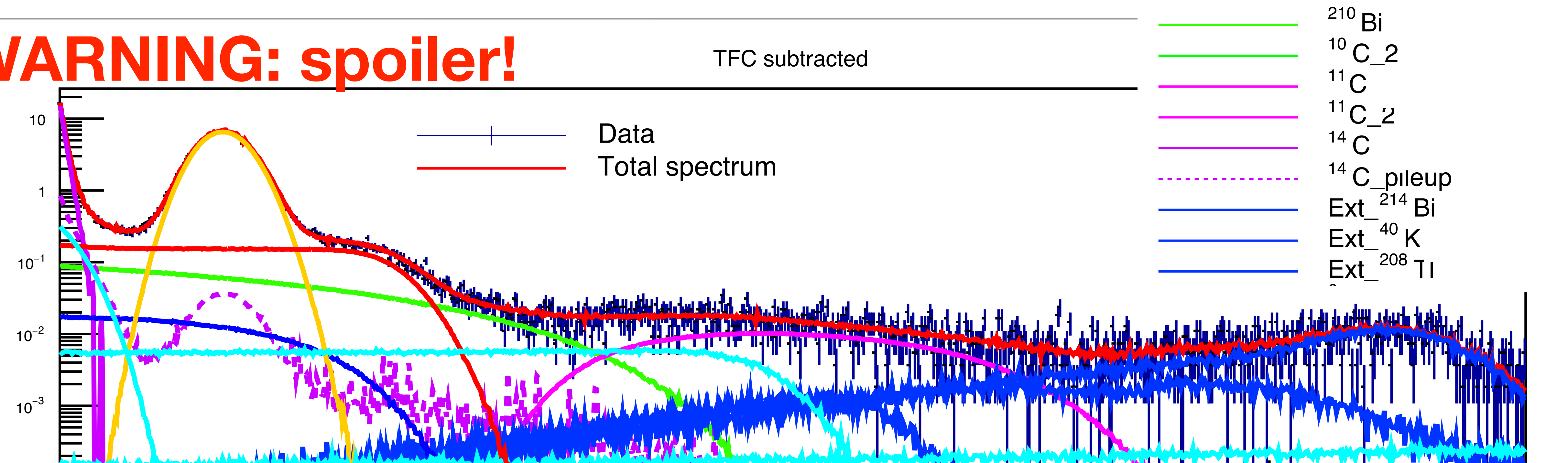
- The Monte Carlo is used to produce the **PDF of each spectral component** (ν or background)
- The simulation follows event by event the real status of the detector for the validated data
- The simulated events undergo the same cuts as real data

The Monte Carlo PDFs allow to develop the **final fit strategy**, study the **sensitivity**, **correlation patterns** and **systematics…**

…and to perform the final fit!

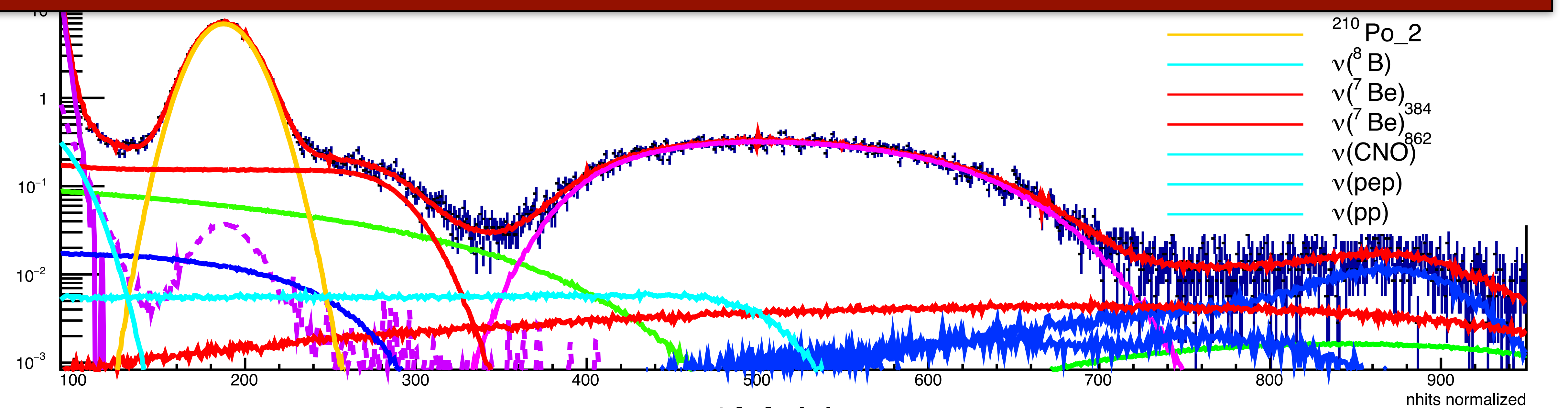
Whole energy scale (200keV-2.6 MeV) fit on data with the new Monte Carlo simulation

WARNING: spoiler!



Check out Gemma Testera's talk tomorrow morning

"Solar Neutrinos: Overview and New Results from Borexino" !!



~1MeV

Conclusions/Outlook

- The Borexino Monte Carlo is an **ab initio simulation** of
  - charged particle energy loss in the scintillator
  - light production/optical propagation
  - electronics effects and real time detector status
- The data/MC **agreement** is better than **1%** for all relevant quantities
- Borexino's approach is **general**, and applicable to all liquid scintillator detectors
- **Importance biasing** allows to get an efficient and precise external background simulation
- A new calibration campaign at the end of 2017 will allow to **further improve in view of** the **SOX** experiment

Backup

Variance reduction methods

- Goal: **reduce computing time** for obtaining sufficient precision
- Random walk sampling modification:
  - sample **“important”** particles at expenses of **“unimportant”** ones
- Many variance reduction techniques:
  - Geometry based
  - Physics based
  - Energy (cutoff) based
- **Need to clearly understand the problem** in order to pick the best biasing technique for a given application

Geant4 offers a set of standard tools allowing to bias geometry and/or physics

External background simulation

3 steps of simulation

BIASING

gammas are propagated through the geometry with the biased method. Information on each interaction is stored

↓

ENERGY DEPOSITS

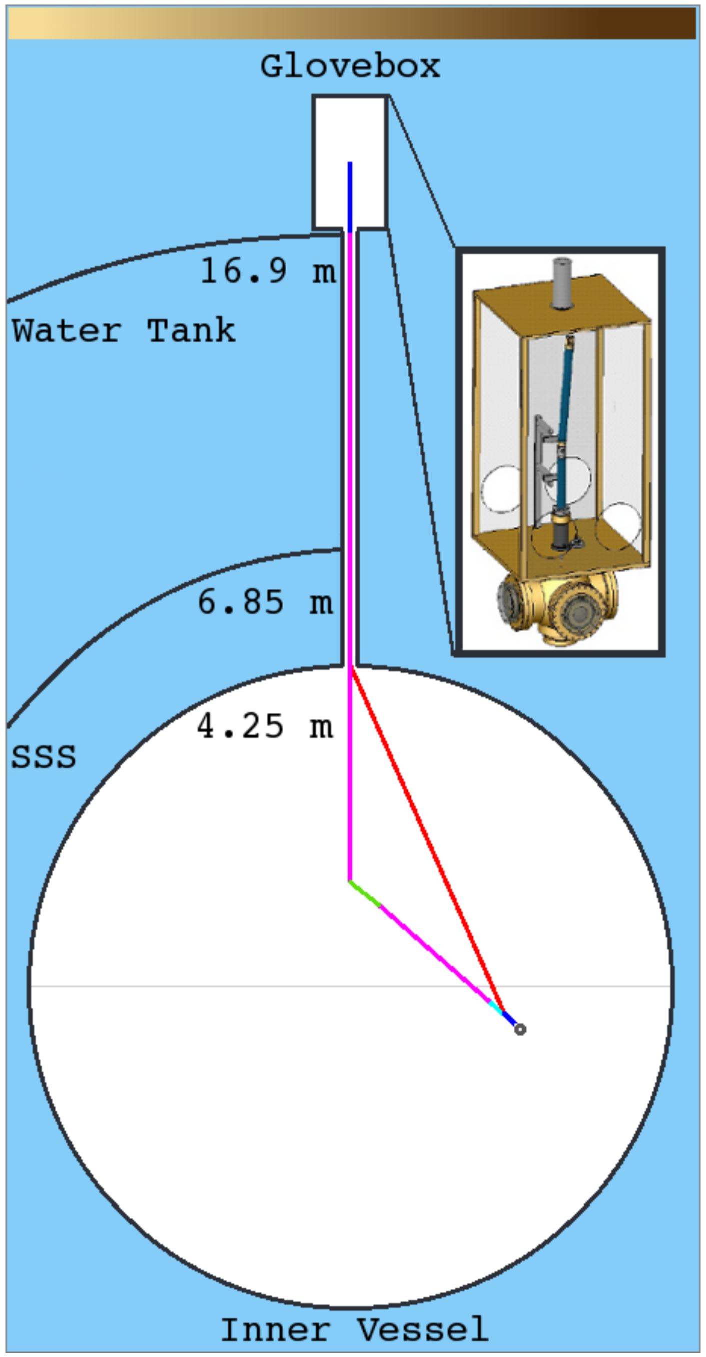
interaction vertexes from the previous step are reconstructed. The energy deposits for each vertex are simulated (no light!) according to their probability

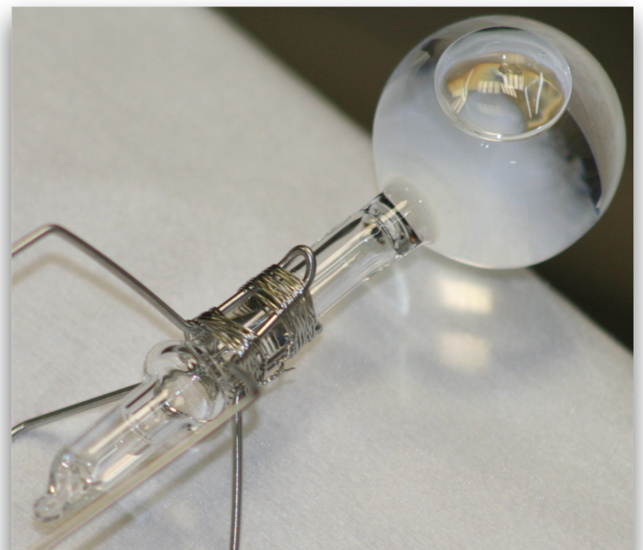
↓

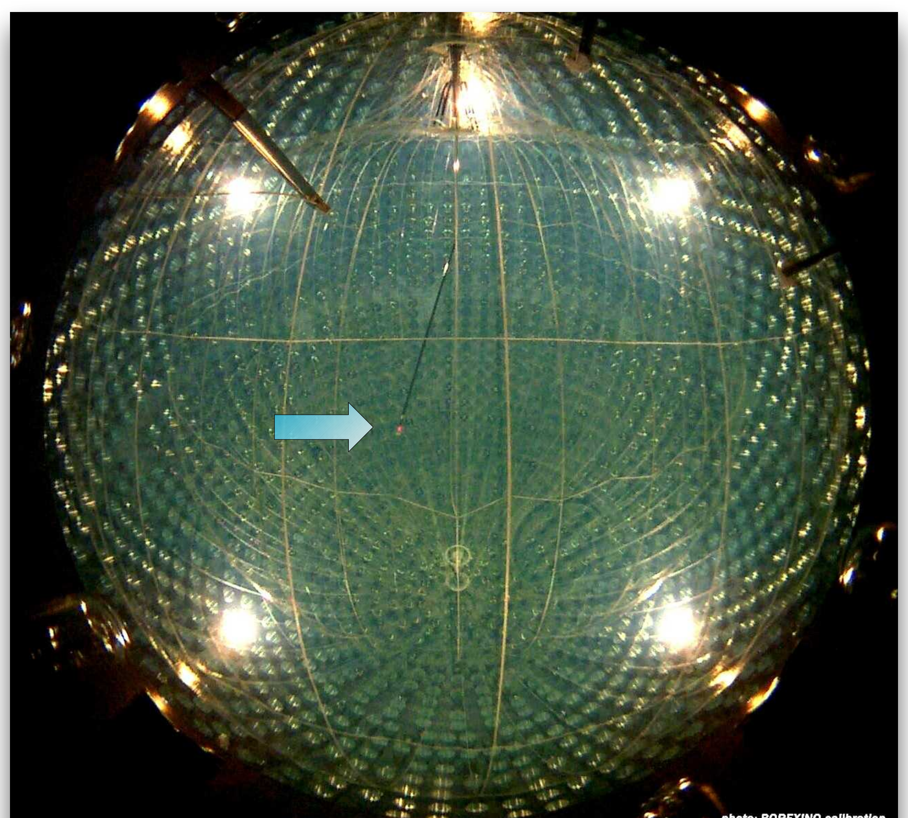
STD SIMULATION

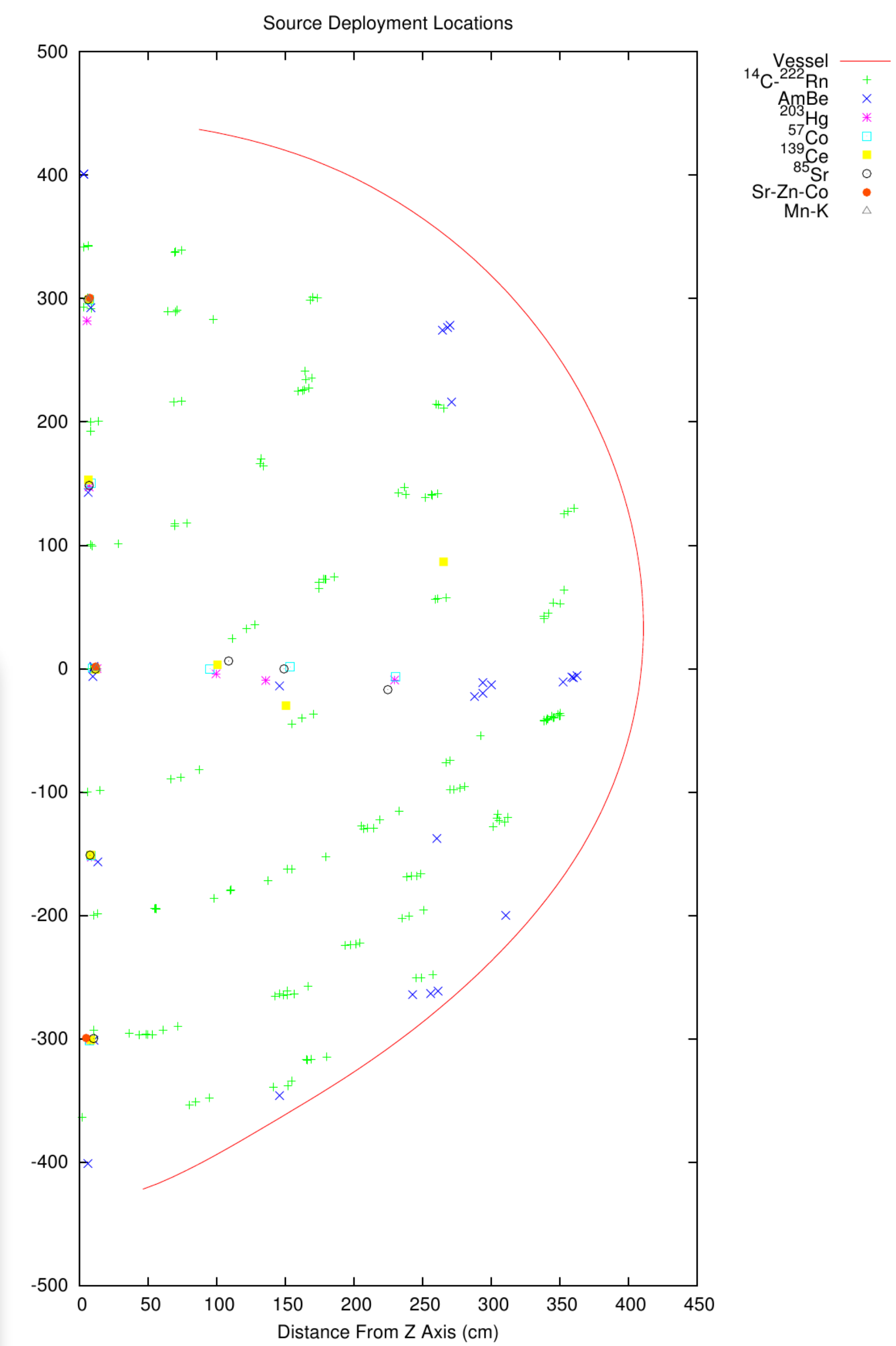
standard Geant4 simulation with the tracking of optical photons

Borexino calibrations (JINST 7 (2012) P10018)



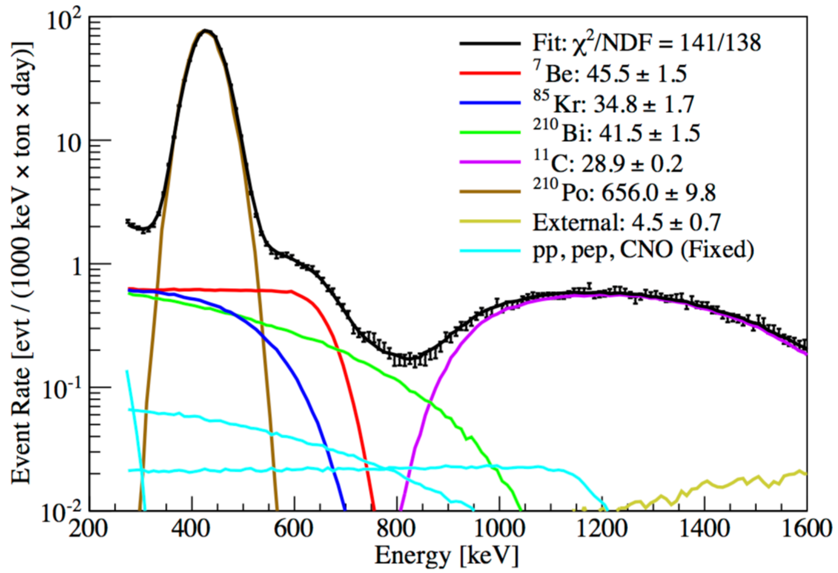




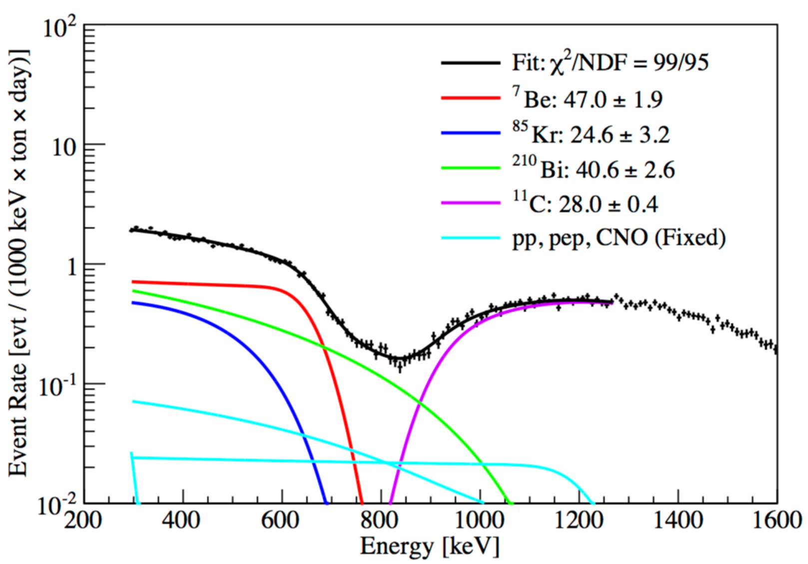


Be7 neutrinos

Montecarlo fit, without Po210 removal



Analytical fit, with α/β statistical subtraction



862 keV Be7 neutrinos flux result

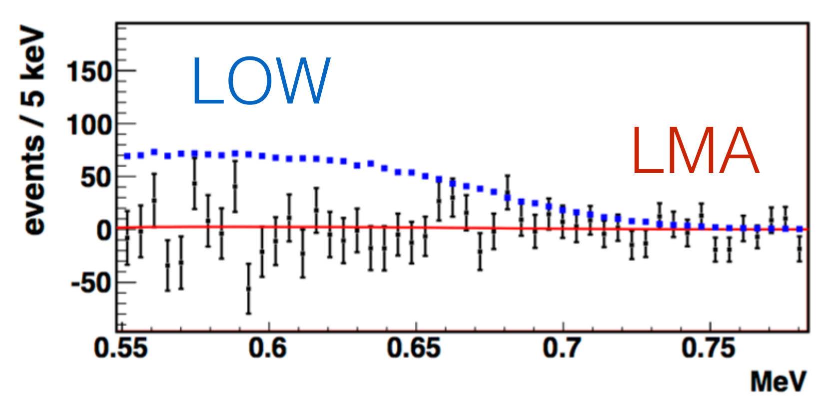
$$46.0 \pm 1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{syst})\ \mathrm{counts}/(\mathrm{day}\cdot 100\ \mathrm{ton})$$

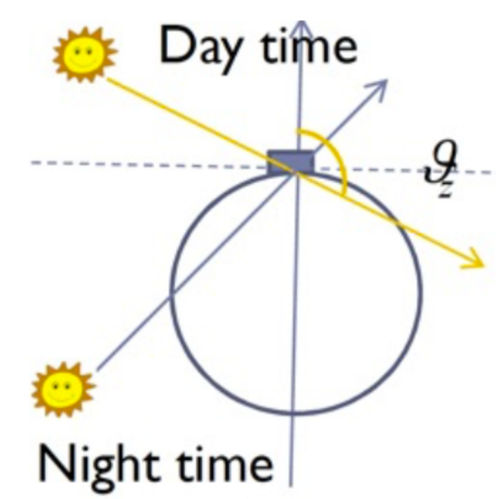
$$(3.10 \pm 0.15) \times 10^{9}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Phys. Rev. Lett. **107**, 141302

Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Fiducial volume	$^{+0.5}_{-1.3}$
Fit methods	2.0
Energy response	2.7
Total Systematic Error	$^{+3.4}_{-3.6}$

Absence of day-night asymmetry on Be7 flux

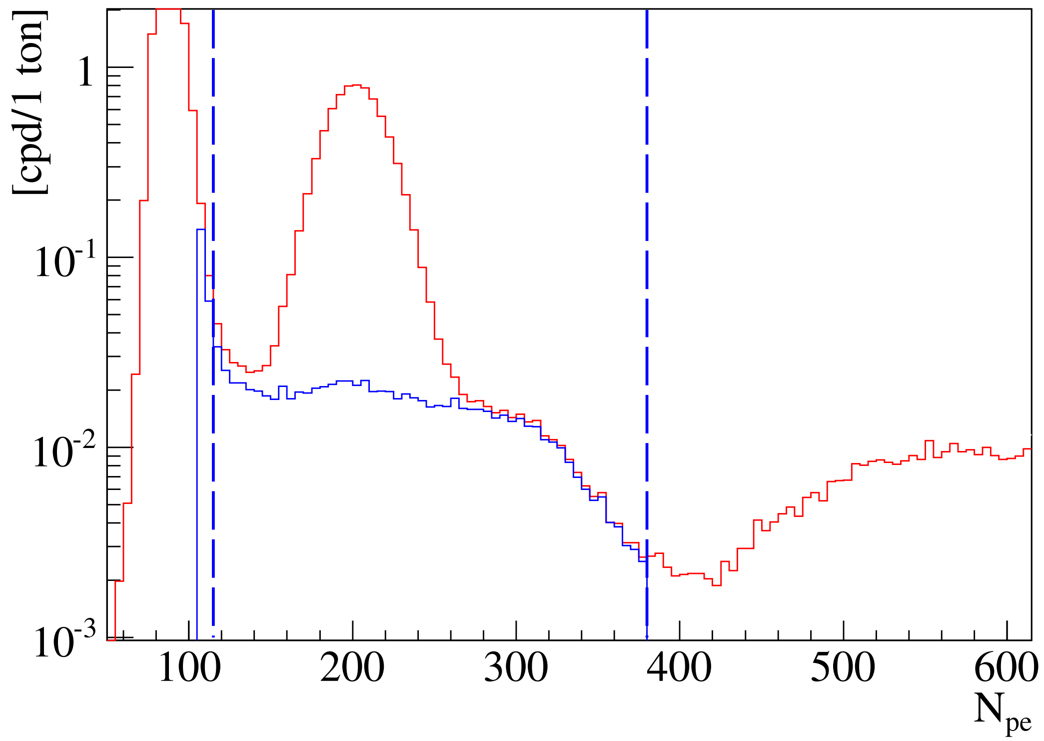


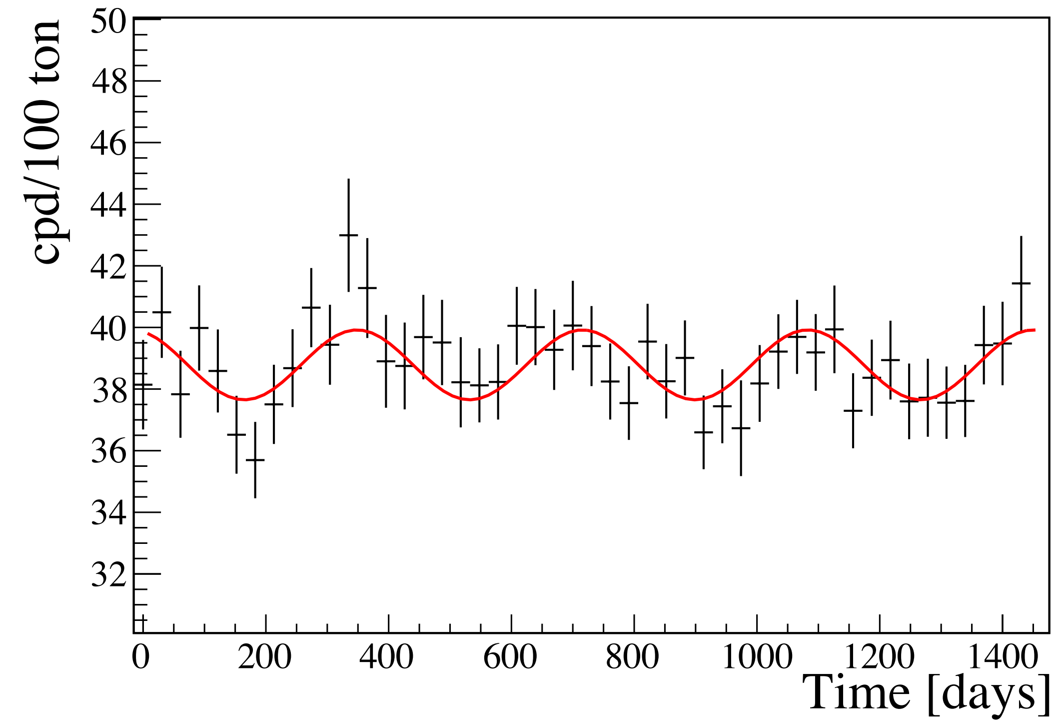


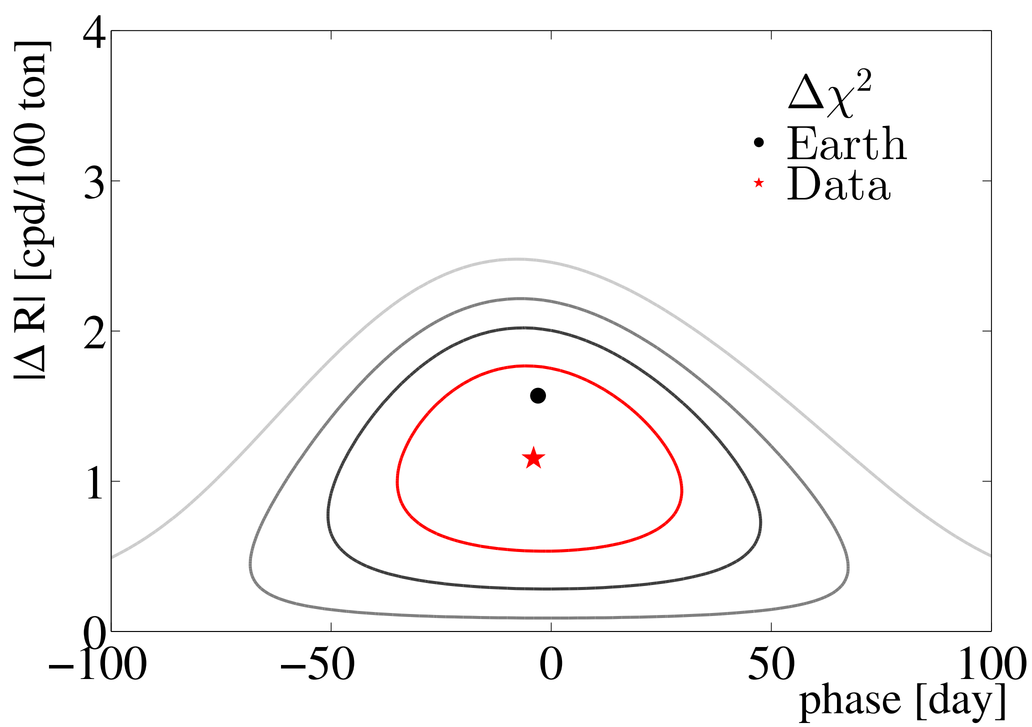
A_{dn} = 0.001 ± 0.012 (stat) ± 0.007 (syst)

Physics Letters B 707 (2012) 22-26

Be7 solar neutrinos - annual modulation

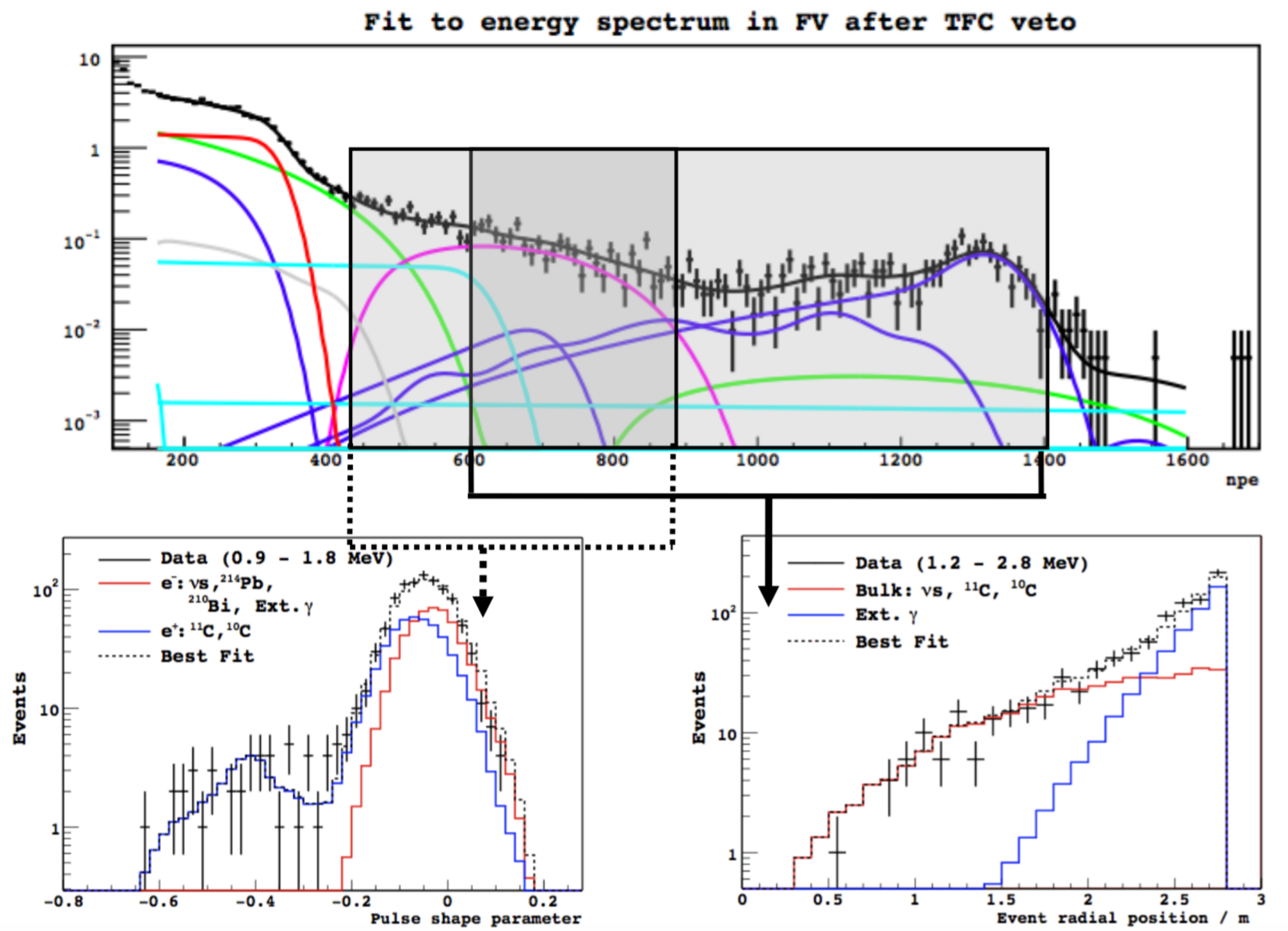




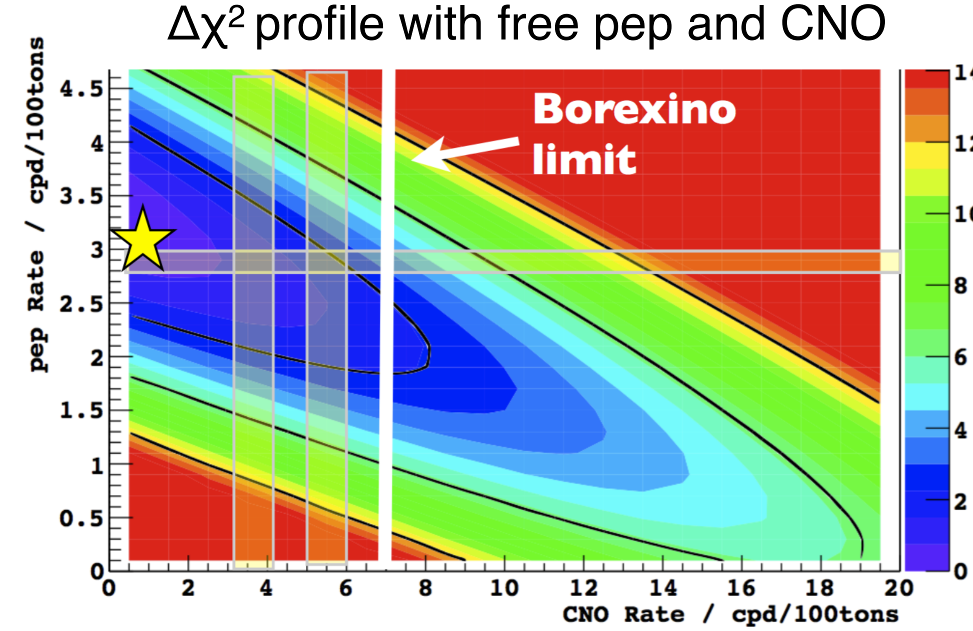


- Absence of annual modulation rejected at 99.99% C.L
- eccentricity = (1.74±0.45)%
- period = 1 year
- **"Seasonal modulation of the Be7 solar neutrino rate in Borexino"**, Astroparticle Physics, Volume 92, 2017, Pages 21-29, ISSN 0927-6505

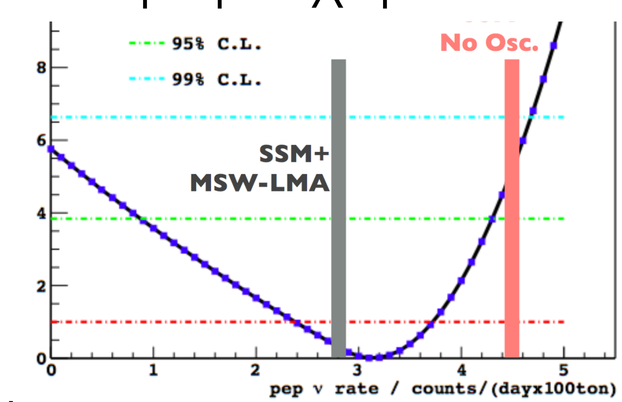
First evidence of *pep* neutrinos



$\Delta\chi^2$ profile with free pep and CNO



ν pep $\Delta\chi^2$ profile



pep neutrinos flux

$$(3.1\pm0.6_{stat}\pm0.3_{syst})\ \text{counts}/(\text{day}\cdot 100\ \text{ton})$$
$$(1.6\pm0.3)\times10^{8}\ \text{cm}^{-2}\text{s}^{-1}$$

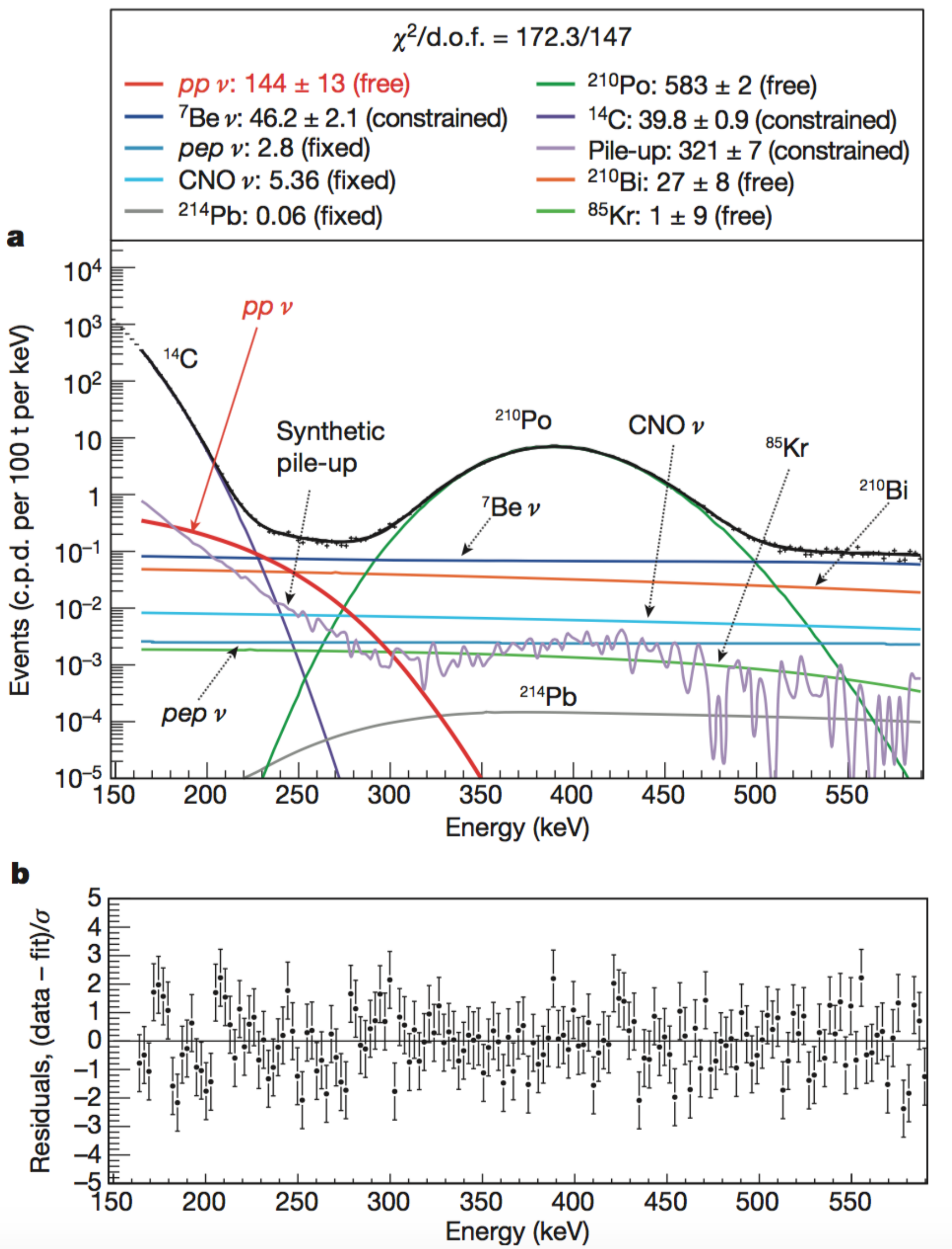
Physical Review Letters 108, 051302 (2012)

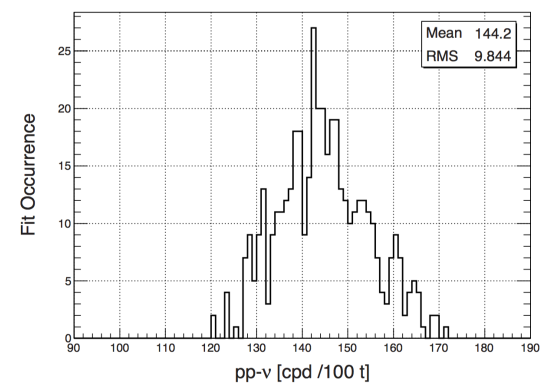
CNO neutrinos flux limit

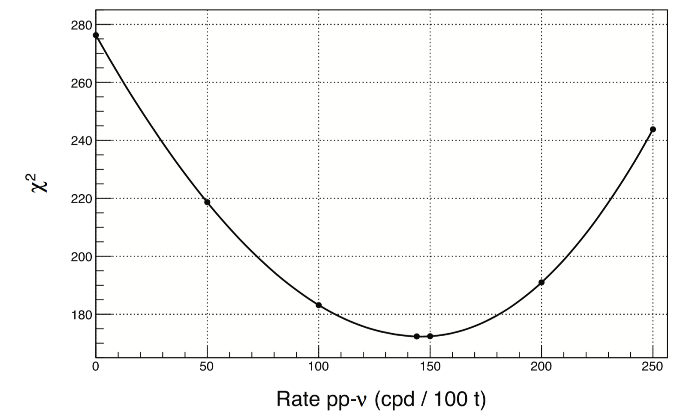
$$<7.9\ \text{counts}/(\text{day}\cdot 100\ \text{ton})$$
$$<7.7\times10^{8}\ \text{cm}^{-2}\text{s}^{-1}\ \ (95\%\ \text{C.L.})$$

Physical Review Letters 108, 051302 (2012)

First real time measurement of pp neutrinos







SCIENCE IDEAS

Solar Variability

Glacial Epochs, and Solar Neutrinos

by George A. Cowan and Wick C. Haxton

[Los Alamos Science, 1982]

physicsworld TOP 10 BREAKTHROUGH 2014

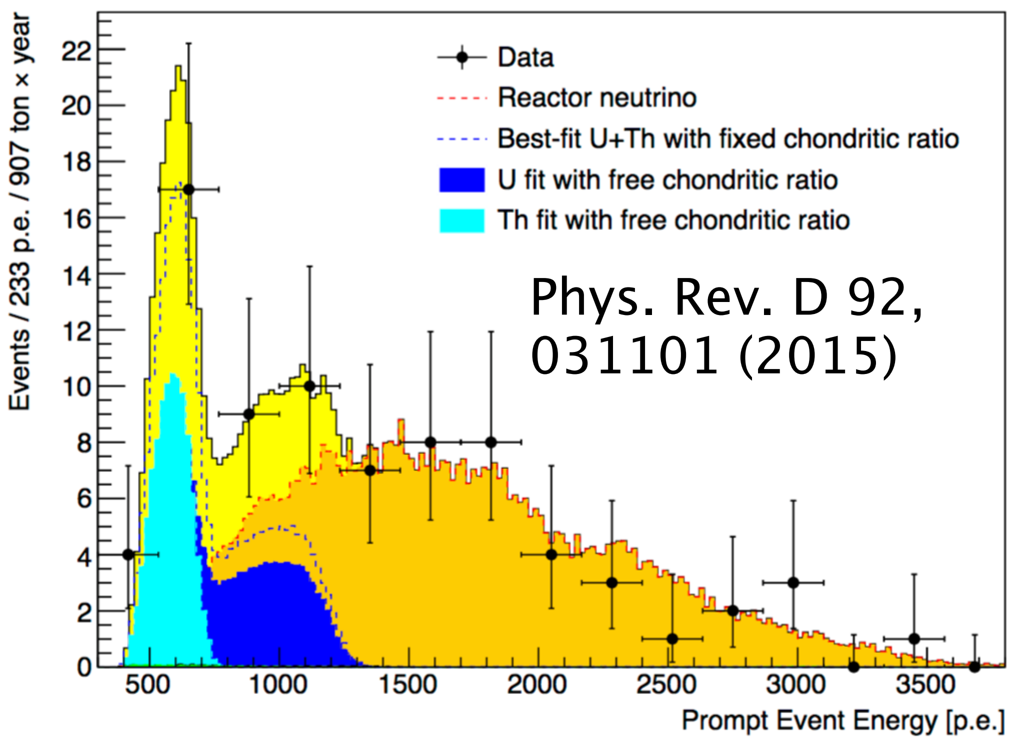
pp neutrinos flux

$$144 \pm 13\,(\text{stat.}) \pm 10\,(\text{syst.})\ \text{c.p.d. per 100 t.}$$

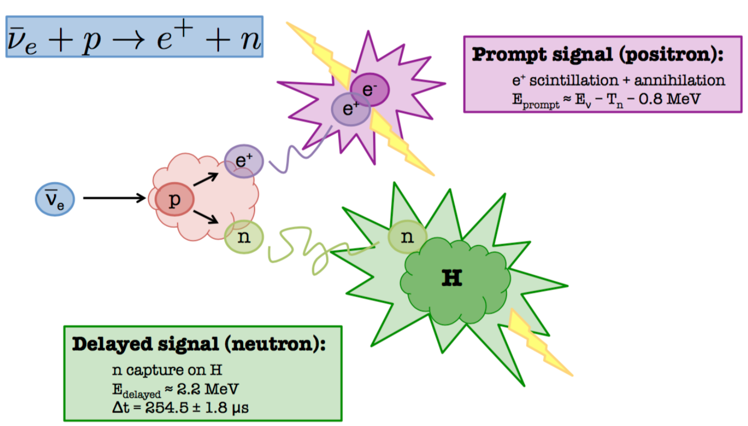
$$(6.6 \pm 0.7) \times 10^{10}\ \text{cm}^{-2}\,\text{s}^{-1}.$$

Nature 512, 383-386 (28 August 2014)

Not only solar neutrinos…



<u>5.9σ detection of geo-neutrinos</u> through inverse beta decay



geo-neutrino signal from the mantle obtained at 98% C.L

search for electron decay through

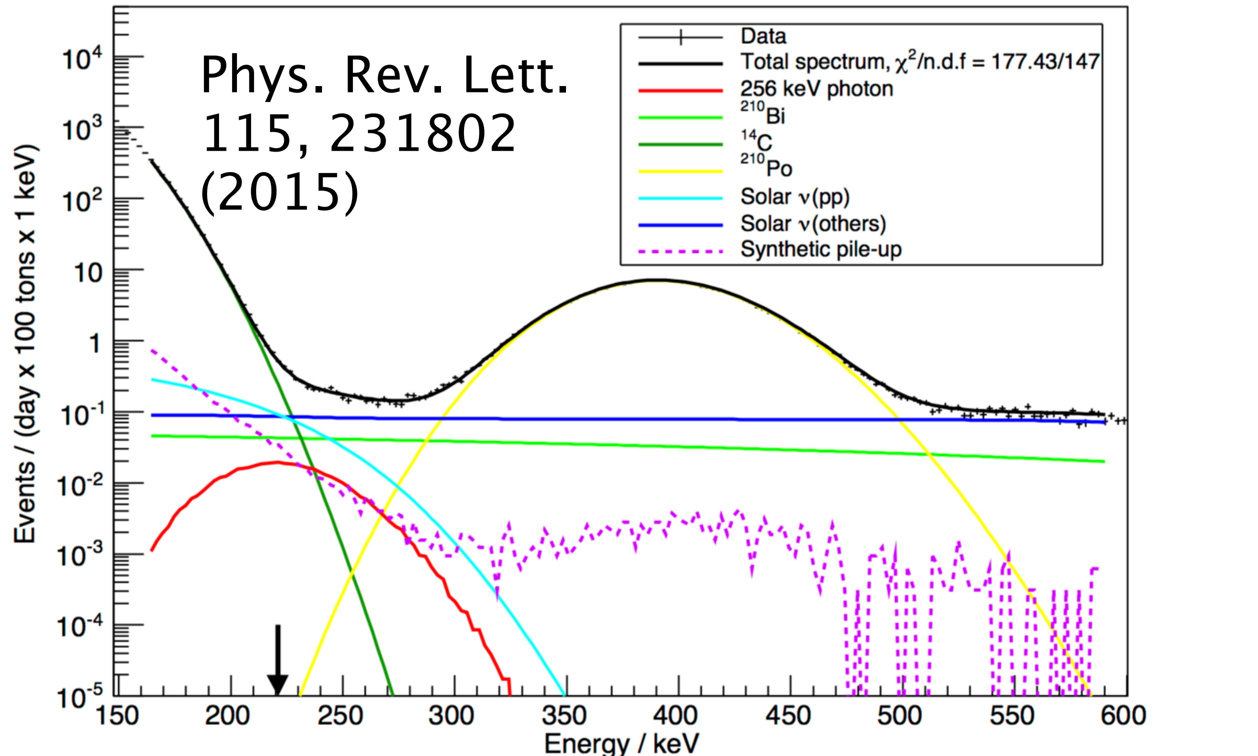
$$e^- \to \gamma + \nu$$

Borexino limit

$$\tau_{BX} \geq 6.6 \times 10^{28} \text{ yr (90\% C.L.)}$$

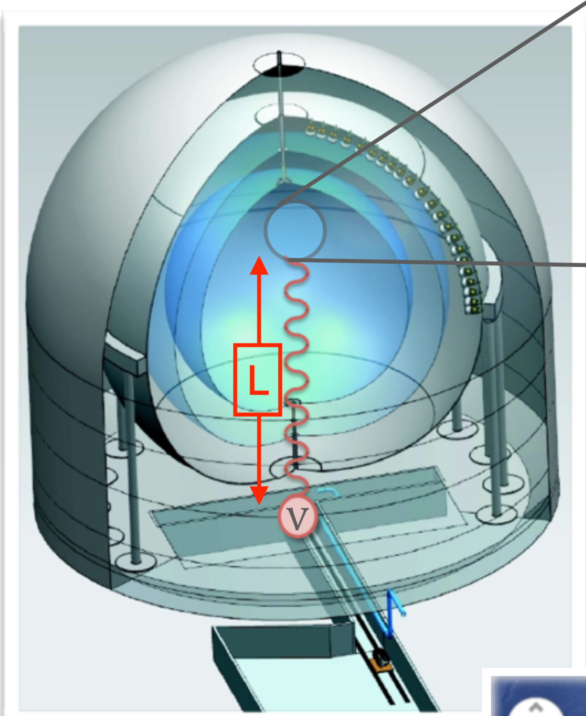
<u>2 orders of magnitude better than the previous limit</u>

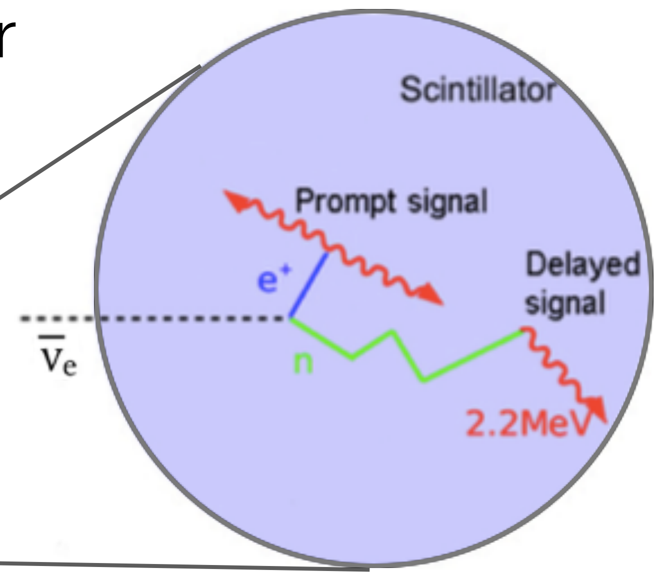
Fit result for the electron decay rate = 1.23 cpd/100 tons



SOX: Short Distance Oscillations with BoreXino

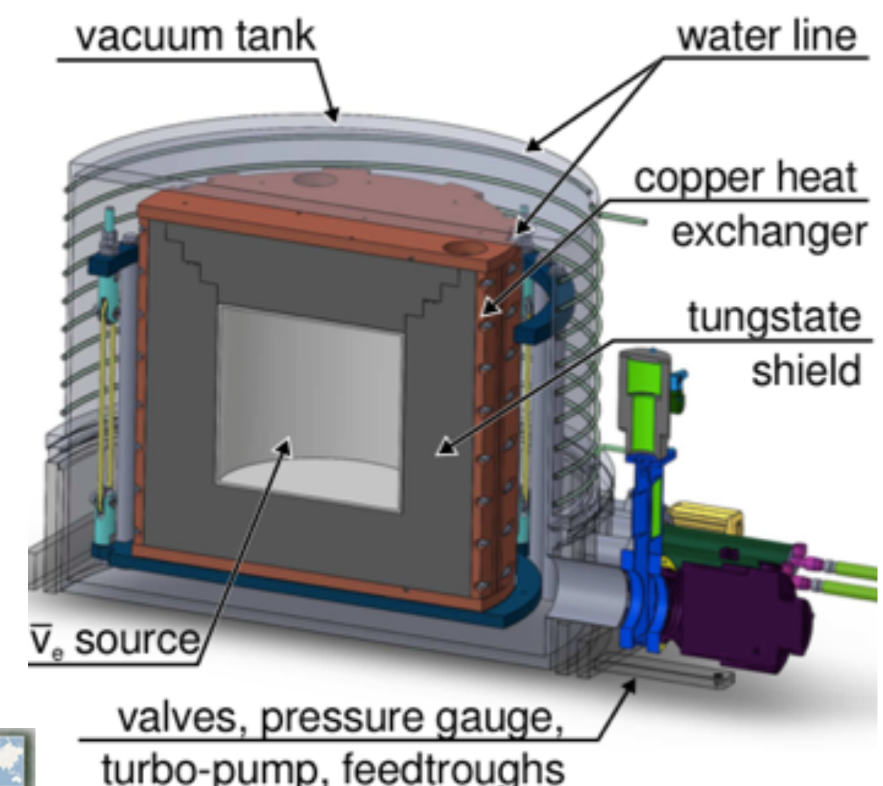
~(100-150) kCi ^{144}Ce-^{144}Pr anti-neutrino source (Q~3MeV>1.8MeV)



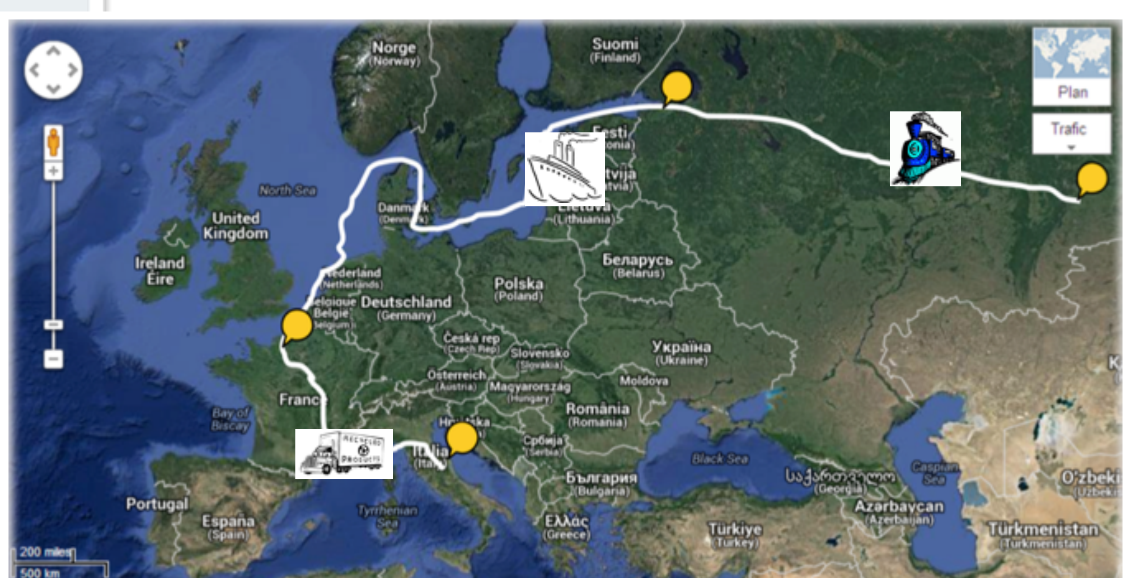


IBD detection is background free in Borexino

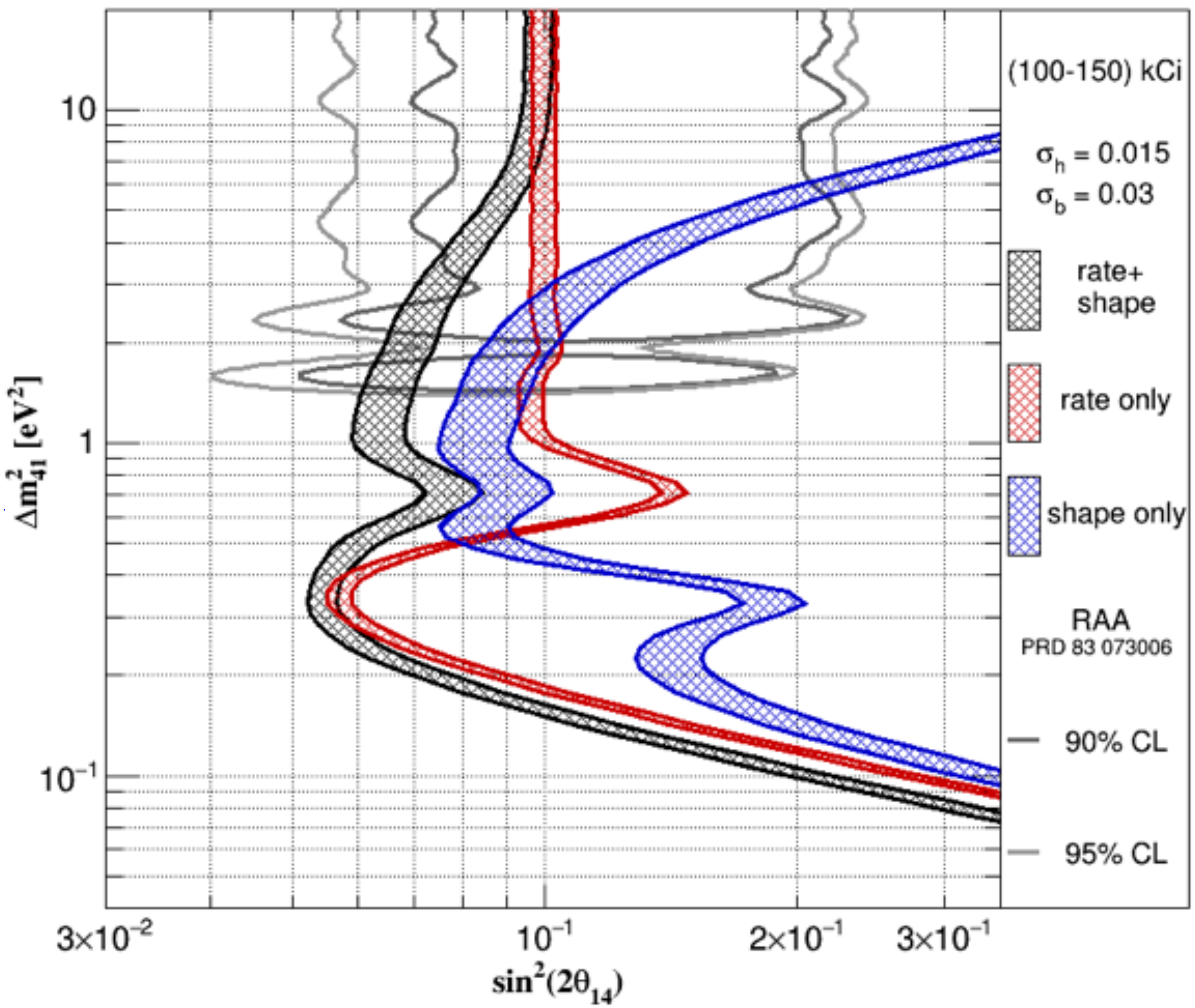
High precision (<1%) calorimetry for source activity determination



Poster 125 “The INFN-TUM calorimeter for the sterile neutrino hunt” by Dr. L. Di Noto



SOX: Short Distance Oscillations with Borexino



Talk tomorrow by T. Lasserre: "Search for light sterile neutrinos with the CeSOX experiment"

Poster 60: "Thermal management and modeling for precision measurements in Borexino's SOX and solar neutrino spectroscopy programs" by Dr. D. Bravo

Poster 118: "Search of sterile neutrinos with SOX: Monte Carlo studies of the experiment sensitivity and systematic effects related to the position reconstruction" by D. Basilico

The Borexino challenge

- Expected ~50 events/day on 100ton of liquid scintillator from Be7 neutrinos

  -> **~ 6 10^{-9} Bq/kg**

- **But**
  - Natural water is ~10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
  - Air is ~10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
  - Typical rock is ~100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

Borexino's scintillator must be 9/10 orders of magnitude less radioactive than anything on Earth!