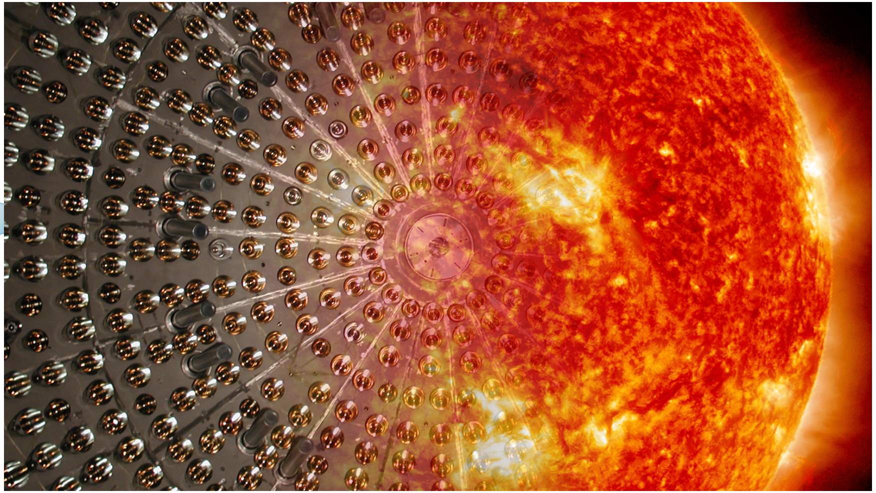


Lake Louise Winter Institute 2019
Chateau Lake Louise
Lake Louise, AB, Canada
10-16 February 2019

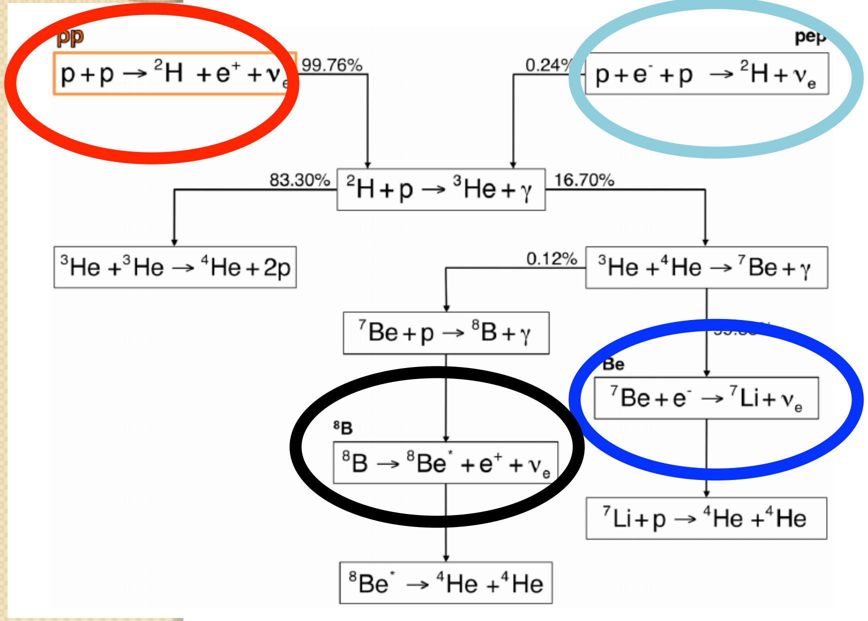
Borexino
Latest Solar Neutrino Results

Davide D’Angelo
on behalf of the Borexino Collaboration
Università degli Studi di Milano
Istituto Nazionale di Fisica Nucleare, sez. di Milano

INFN
Istituto Nazionale di Fisica Nucleare

Nuclear fusion in the Sun: the pp chain

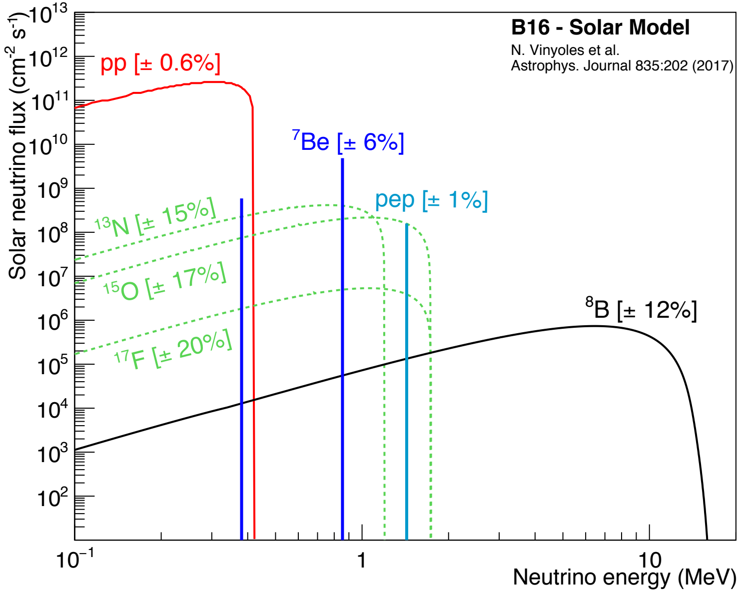
$$4H + 2e^- \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.7 MeV$$



~99% of the Sun energy

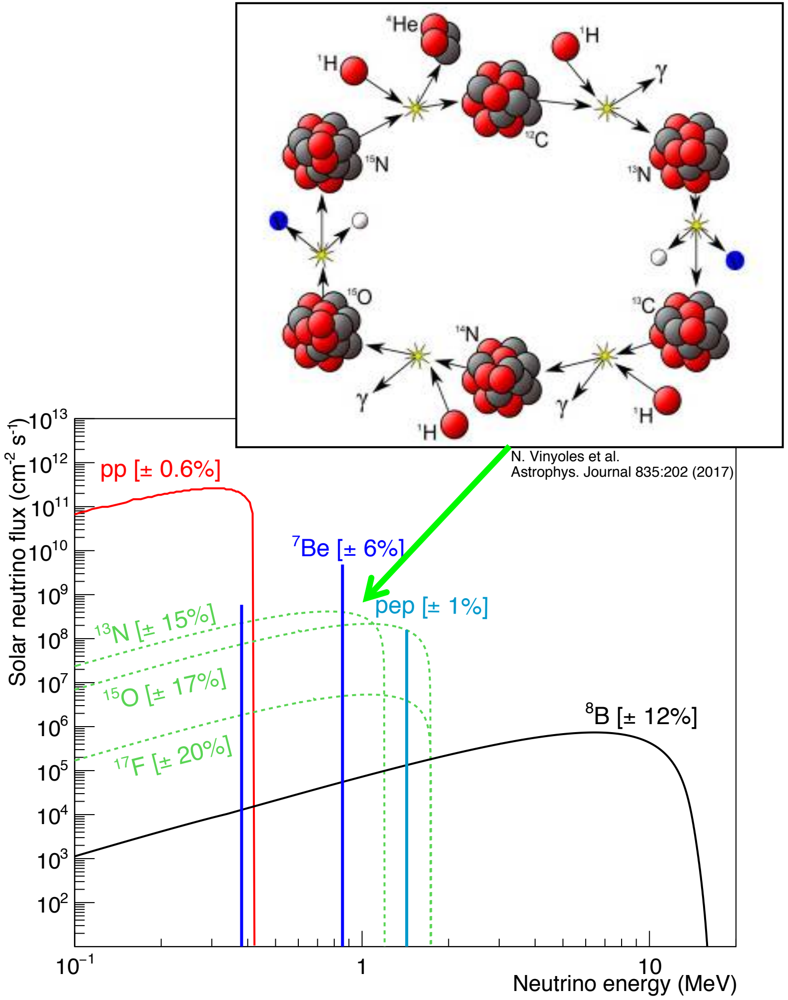
Neutrino species are labeled after the reaction in which it is emitted:

- pp-neutrinos
- pep-neutrinos
- ^{7}Be-neutrinos
- ^{8}B-neutrinos



The CNO cycle

- C, N, and O act as catalyzers of the same net reaction
- The CNO cycle has a strong temperature dependence
- It becomes dominant for stars heavier then the Sun
- In the Sun only about 1-2% of Energy is produced by CNO cycle
- The 3 neutrino species (^{13}N, ^{15}O, ^{17}F) emitted by the CNO cycle reactions have <u>never been observed so far.</u>



N. Vinyoles et al.
Astrophys. Journal 835:202 (2017)

Why measure solar neutrinos?

Astrophysics

Original motivation of the first experiments on solar ν was to test Standard Solar Model (SSM)

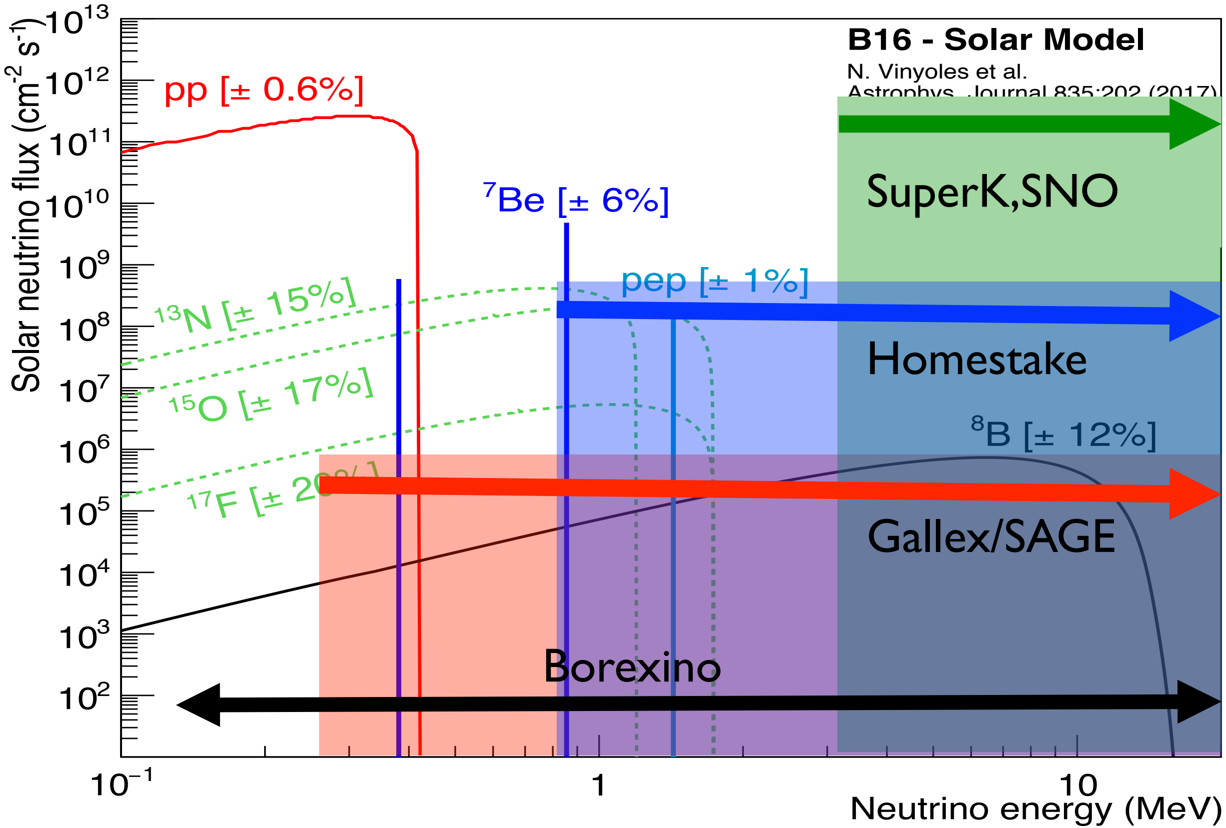
Study of the details of ν flux

Solar neutrino problem

Particle physics

Solar ν experiments played a major role in the discovery of oscillations

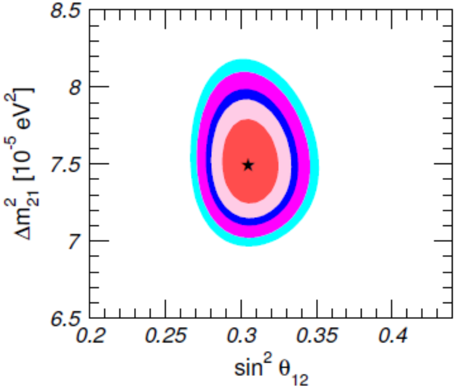
Solar neutrino detectors



We learned a lot...

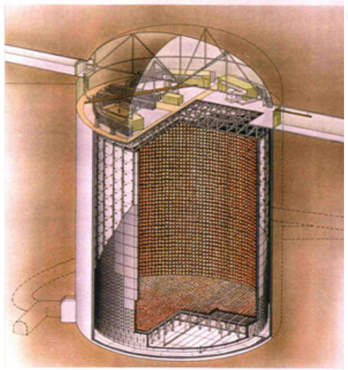
- Confirmation of the basic energy production mechanism in the Sun
- Solar Neutrino Problem was solved:
  - Evidence of ν oscillations
  - Interaction of ν with matter MSW

Global analysis of oscillation data



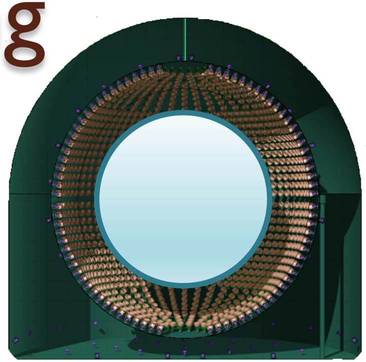
I. Esteban et al., JHEP 01 (2017).

...but we are still measuring



Water Cherenkov:
Super-Kamiokande

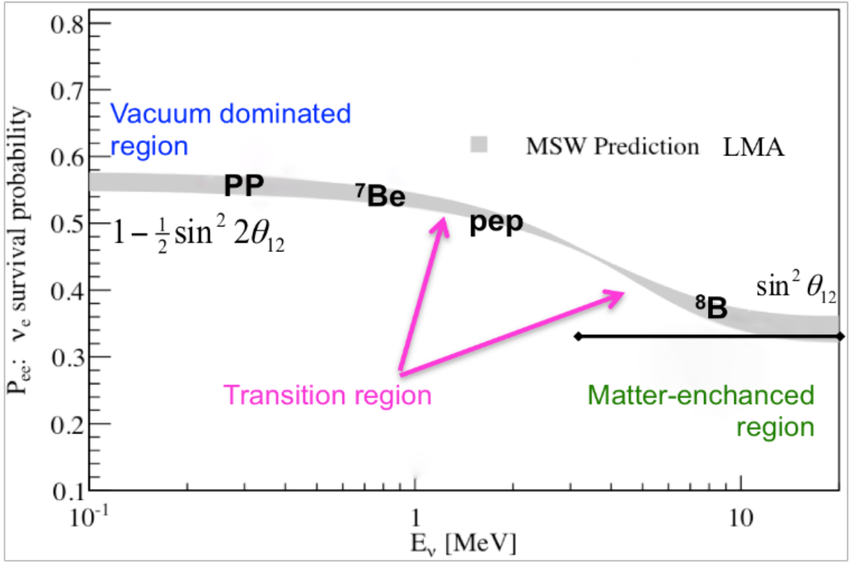
Liquid scintillator:
Borexino



Why still measure solar neutrinos? (1/2)

1. Particle Physics interest: confirm LMA-MSW

- P_{ee} should show a Vacuum-to-Matter transition
- Non Standard Interactions could modify P_{ee} in the transition region
- Precise flux measurements of single spectral components
- Measure ^8B with low threshold
- Have good accuracy for the lowest ^8B energy bin

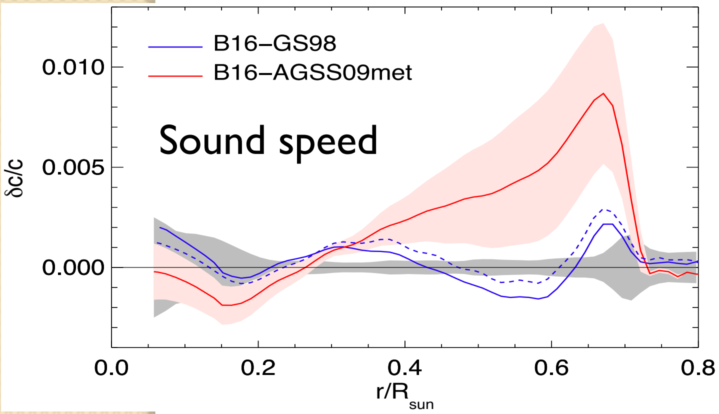


$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Why still measure solar neutrinos? (2/2)

2. Astrophysics interest: the metallicity puzzle

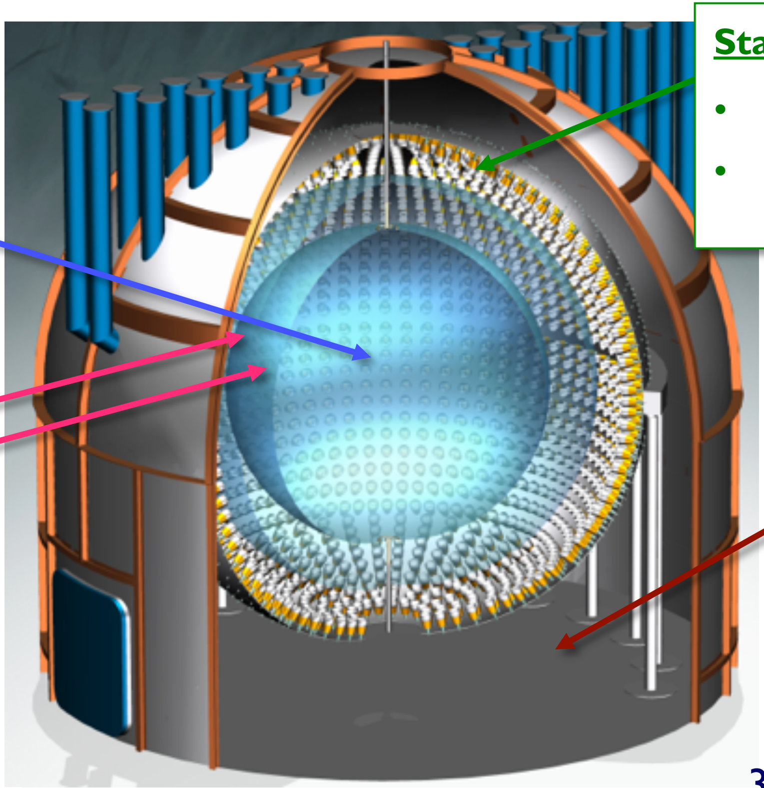
- Since 2001: a new 3D analysis of spectroscopic data from photosphere indicates lower values of surface solar metallicity (LZ)
- But solar models reproducing these new LZ values **disagree with helioseismology data**



ν flux	GS98 (HZ)	AGSS09met (LZ)	$cm^{-2}\ s^{-1}$	Δ
pp	5.98 (1±0.006)	6.03 (1±0.005)	x 10^{10}	+0.8%
pep	1.44 (1±0.01)	1.46(1±0.009)	x 10^{8}	+1.4%
^{7}Be	4.93 (1±0.06)	4.50 (1±0.06)	x 10^{9}	-8.7%
^{8}B	5.46 (1±0.12)	4.50 (1±0.12)	x 10^{6}	-18%
^{13}N	2.78 (1±0.15)	2.04 (1±0.14)	x 10^{8}	-27%
^{15}O	2.05 (1±0.17)	1.44 (1±0.16)	x 10^{8}	-24%

Solar ν fluxes are potentially sensitive to the Sun metallicity

The Borexino Detector



Scintillator:

278 t PC+PPO (1.4 g/l)

Nylon vessels:

(125 μm thick)

Inner r: 4.25 m

Outer r: 5.50 m

(radon barrier)

Stainless Steel Sphere:

- 2212 PMTs
- ~ 1000 m^3 buffer of pc+dmp (light quenched)

Water Tank:

γ and n shield

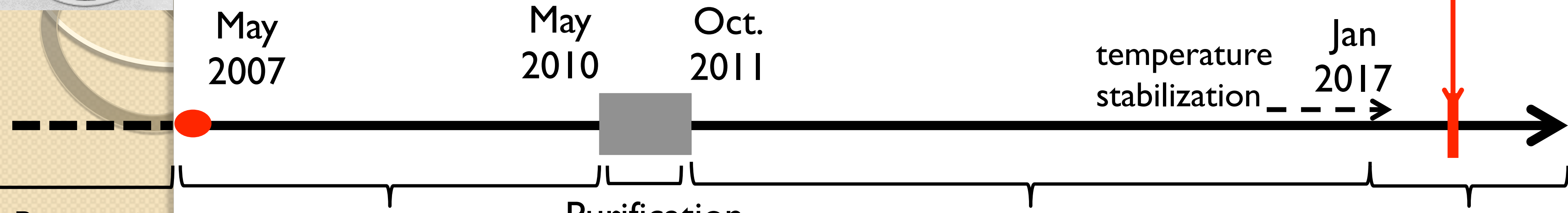
μ water Č detector

208 PMTs in water

2100 m^3

3800m w.e. of rock shielding

Borexino data taking campaign



now

May 2007

May 2010

Oct. 2011

temperature stabilization

Jan 2017

Preparation

Phase I

Purification

Phase 2 Solar neutrinos

CNO Campaign

Solar neutrinos

- ^{7}Be ν : 1st observation + precise measurement (5%); Day/Night asymmetry;
- pep ν : 1st observation;
- ^{8}B ν with low threshold;
- CNO ν : best limit;

6 cycles of water extraction

- pp ν: 1st observation (Nature 2014)
- seasonal modulation of ^{7}Be ν (Astr.Phys. 92 (2017) 21)
- ***Comprehensive measurement of pp-chain solar neutrinos:* Nature 562, 505–510 (2018)**
- more details pp, ^{7}Be, pep: arXiV:1707.09279
- more details ^{8}B: arXiV:1709.00756

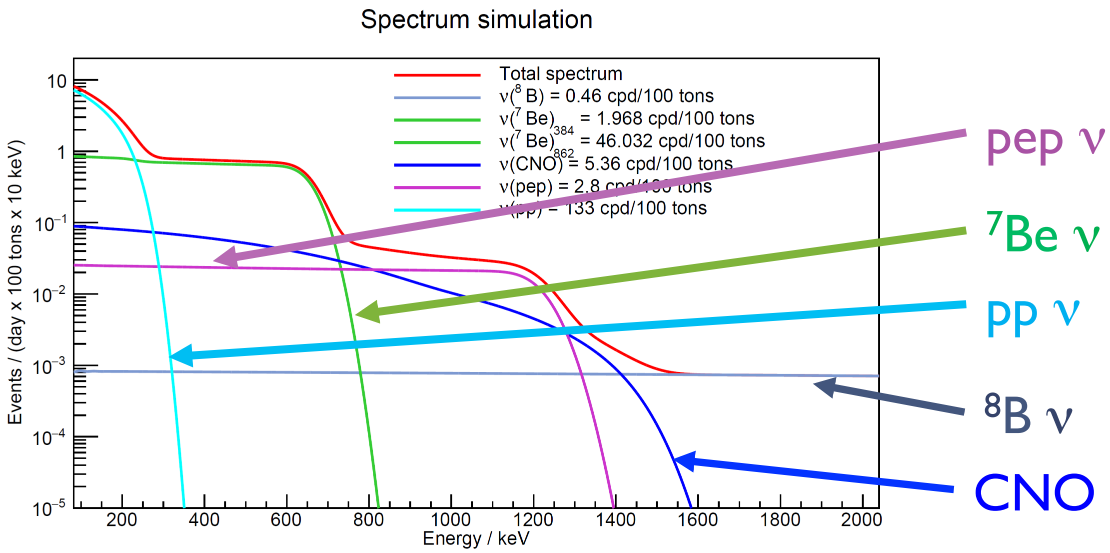
nature

NEW!

Borexino's solar neutrino signals

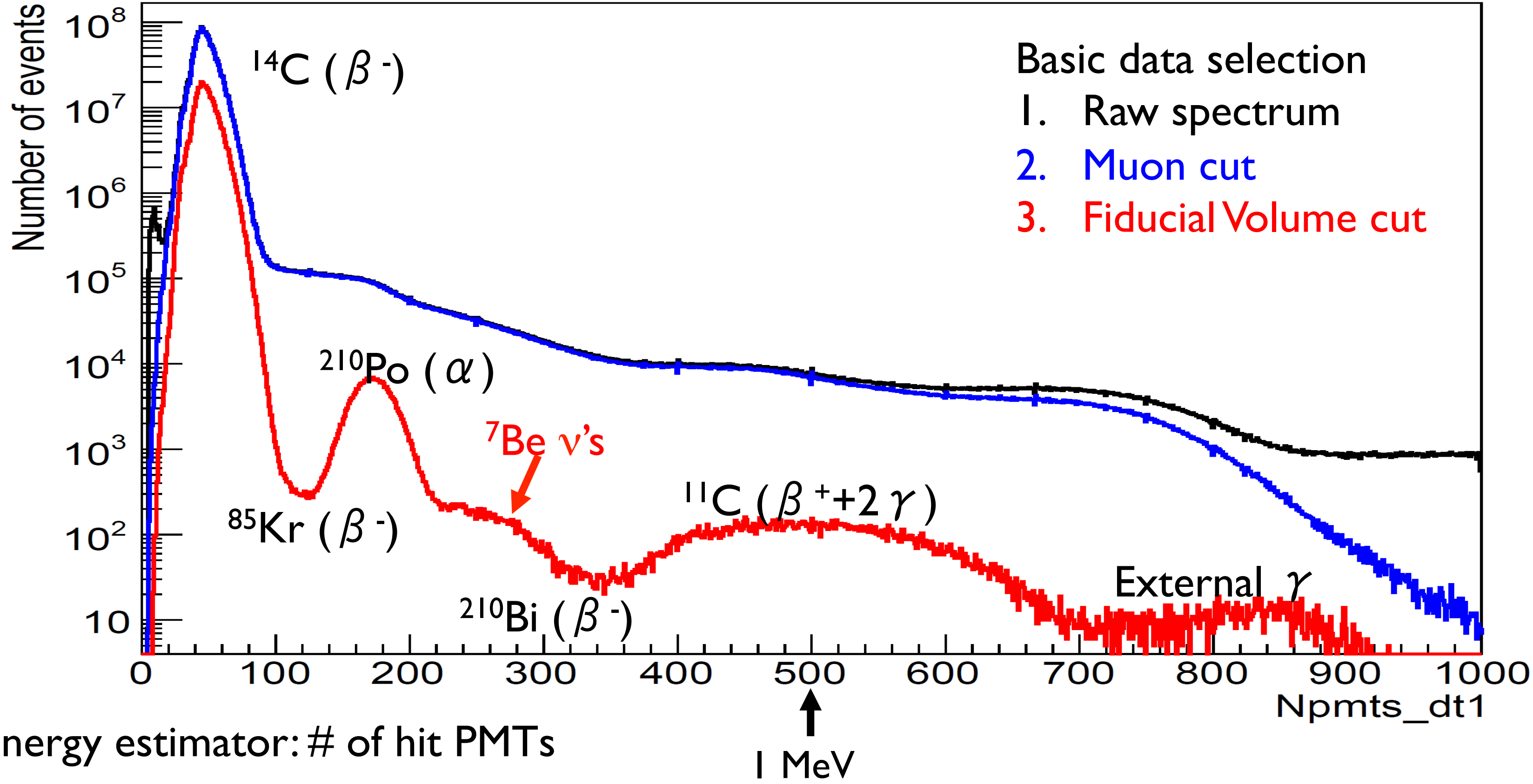
Elastic scattering on electrons

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



So, what we see is only the energy carried away by the electron, NOT the total neutrino energy

The Borexino Energy spectrum



Energy estimator: # of hit PMTs

Borexino performance

For each scintillation event Borexino records

Number of collected photons [photoelectron yield ~ 500 p.e./MeV]

Energy

$$\frac{\sigma(E)}{E} \sim \frac{5\%}{\sqrt{E}}$$

Time of arrival each photons

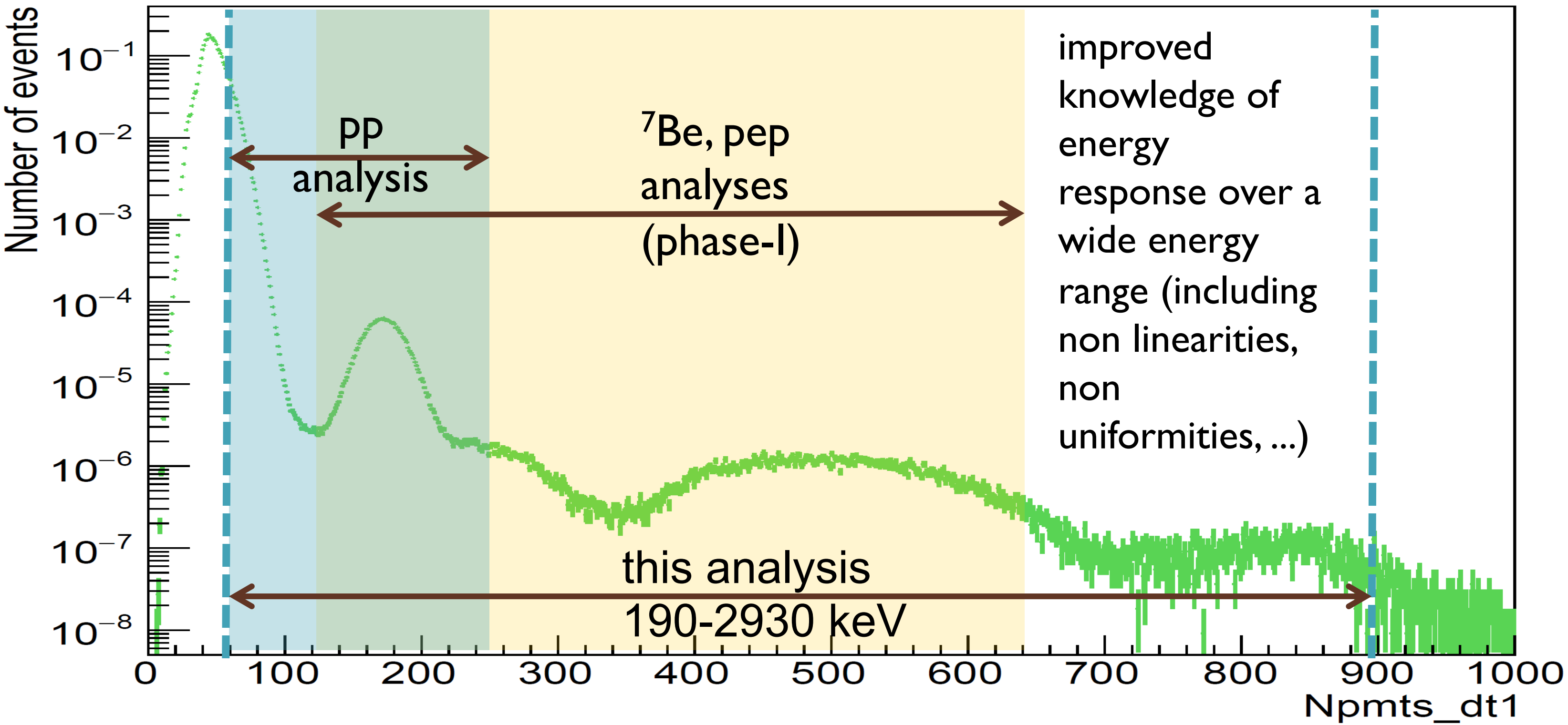
Position

$$\frac{\sigma(x)}{x} \sim \frac{10\text{cm}}{\sqrt{E}}$$

Pulse-shape discrimination

α, β^-, β^+

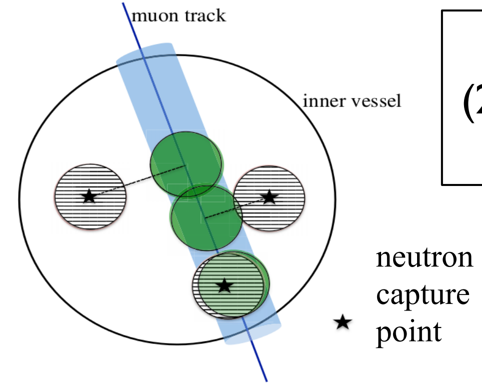
New wide energy range analysis



improved knowledge of energy response over a wide energy range (including non linearities, non uniformities, ...)

Data-set: Dec 14th 2011- May 21st 2016 Total exposure: 1291.51 days x 71.3 tons

Fight ^{11}C: Three-Fold Coincidence (TFC)



^{11}C rate
(28.5 ± 0.5)
cpd/100t

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

~30min

~250μs

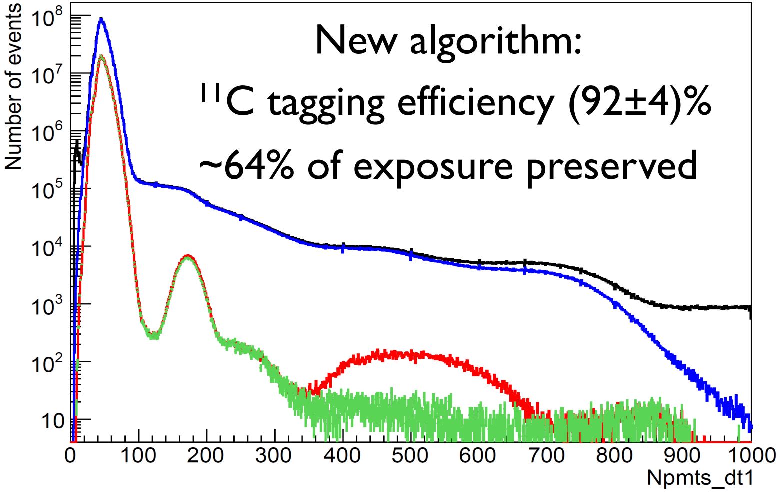
$${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$$

$$n + p \rightarrow d + \gamma_{2.2\,MeV}$$

The **likelihood** that an event is ^{11}C is computed from:

1. Space-time distance to the μ -track
2. Space-time distance to the neutron
and to the neutron-projection on the track
3. neutron multiplicity
4. Muon dE/dx

(in phase-1 we used a hard-cut based algorithm)



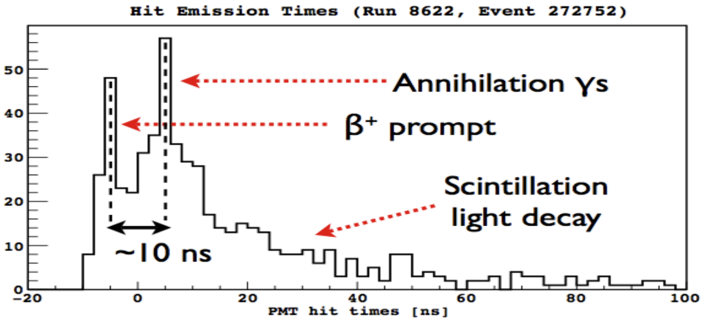
New algorithm:
^{11}C tagging efficiency (92±4)%
~64% of exposure preserved

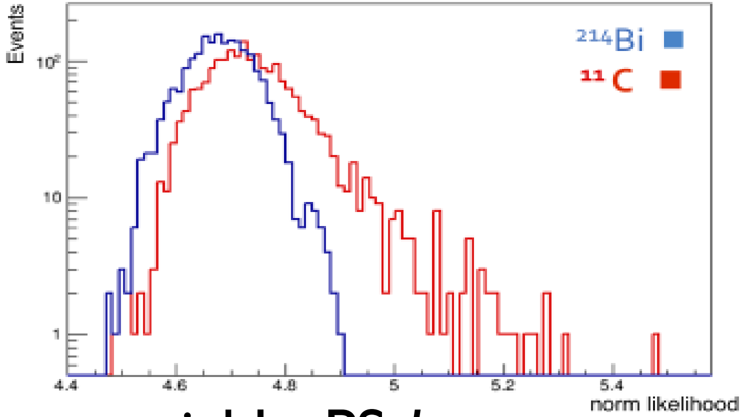
Fight ^{11}C: Pulse Shape Discrimination

^{11}C decays β^+!

The scintillation time profile is different for e$^-$ and e$^+$ for two reasons:

1. in 50% of the case e$^+$ annihilation is delayed by ortho-positronium formation (t~3ns)
2. e$^+$ energy deposit is not point-like because of the two annihilation gammas



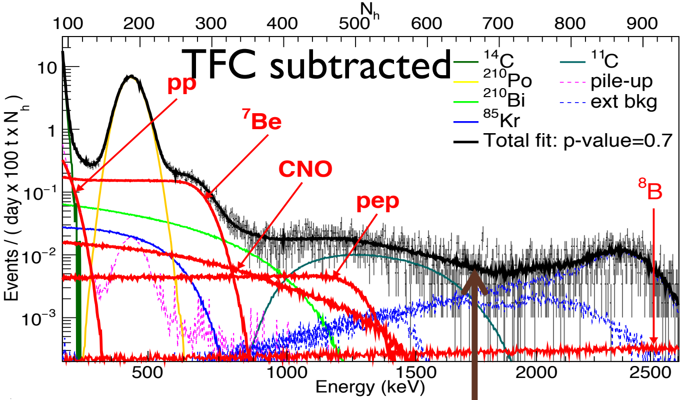


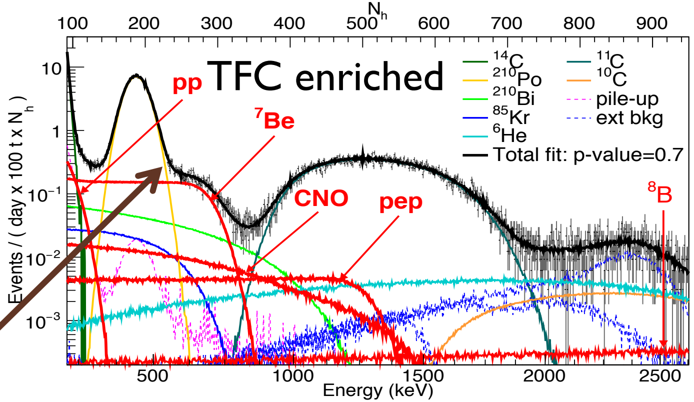
Identified a new pulse-shape variable: PS-L_{PR}

[the normalized output likelihood of the position reconstruction algorithm]

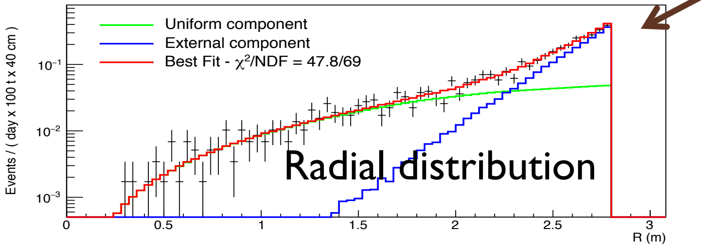
Multivariate fit

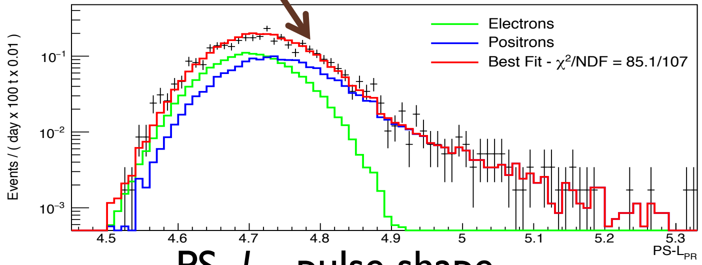
Maximize a binned likelihood through a multivariate approach





$$L(\vartheta) = L_{sub}(\vartheta) \cdot L_{tag}(\vartheta) \cdot L_{rad}(\vartheta) \cdot L_{PS-L_{pr}}(\vartheta)$$





PS_L_{Pr} pulse shape

Borexino Phase-II backgrounds

Background species	Rate (cpd/100t)
^{14}C (Bq/100t)	40.0±2.0
^{85}Kr	6.8±1.8
^{210}Bi	17.5±1.9
^{11}C	26.8±0.2
^{210}Po	260.0±3.0
Ext ^{40}K	1.0±0.6
Ext ^{214}Bi	1.9±0.3
Ext ^{208}Tl	3.3±0.1

^{85}Kr: factor 4.6 reduction with respect to Phase-I

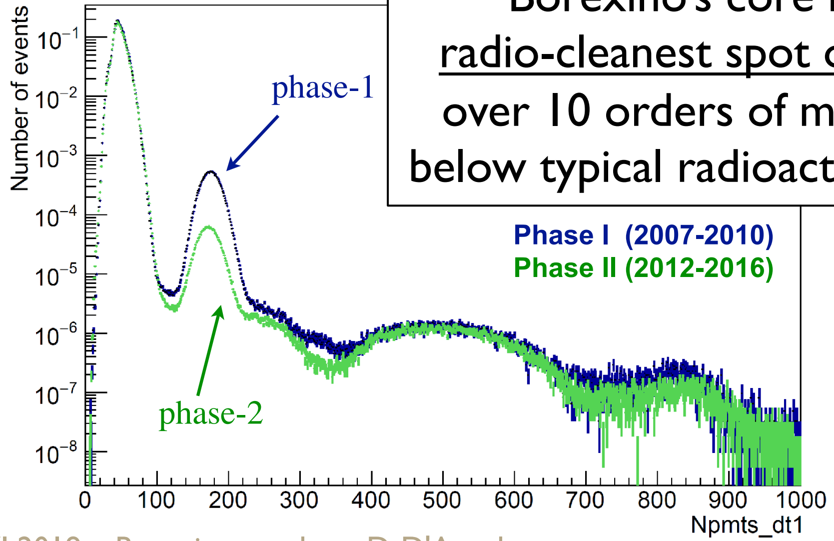
^{210}Bi: factor 2.3 reduction with respect to Phase-I

^{39}Ar, ^{40}K below detection limit

^{238}U (from ^{214}Bi-Po) < 9.4 10^{-20} g/g 95% C.L.

^{232}Th (from ^{212}Bi-Po) < 5.7 10^{-19} g/g 95% C.L.

Borexino's core is the <u>radio-cleanest spot on Earth</u>: over 10 orders of magnitude below typical radioactivity levels



Whole energy range fit results

Rates	Borexino results (cpd/100t)	expected HZ cpd/100t	expected LZ cpd/100t	Uncertaincy reduction
pp	$134 \pm 10^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.4	0.78
^{7}Be(862+384 keV)	$48.3 \pm 1.1^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6	0.57
pep (HZ-CNO)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05	0.61
pep (LZ-CNO)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05	

Fluxes	Borexino results ($cm^{-2}s^{-1}$)	expected HZ ($cm^{-2}s^{-1}$)	expected LZ ($cm^{-2}s^{-1}$)
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5})\ 10^{10}$	$5.98\ (1 \pm 0.006)\ 10^{10}$	$6.03\ (1 \pm 0.005)\ 10^{10}$
^{7}Be(862+384 keV)	$(4.99 \pm 0.13^{+0.07}_{-0.10})\ 10^{9}$	$4.93\ (1 \pm 0.06)\ 10^{9}$	$4.50\ (1 \pm 0.06)\ 10^{9}$
pep (HZ-CNO)	$(1.27 \pm 0.19^{+0.08}_{-0.12})\ 10^{8}$	$1.44\ (1 \pm 0.009)\ 10^{8}$	$1.46\ (1 \pm 0.009)\ 10^{8}$
pep (LZ-CNO)	$(1.39 \pm 0.19^{+0.08}_{-0.13})\ 10^{8}$	$1.44\ (1 \pm 0.009)\ 10^{8}$	$1.46\ (1 \pm 0.009)\ 10^{8}$

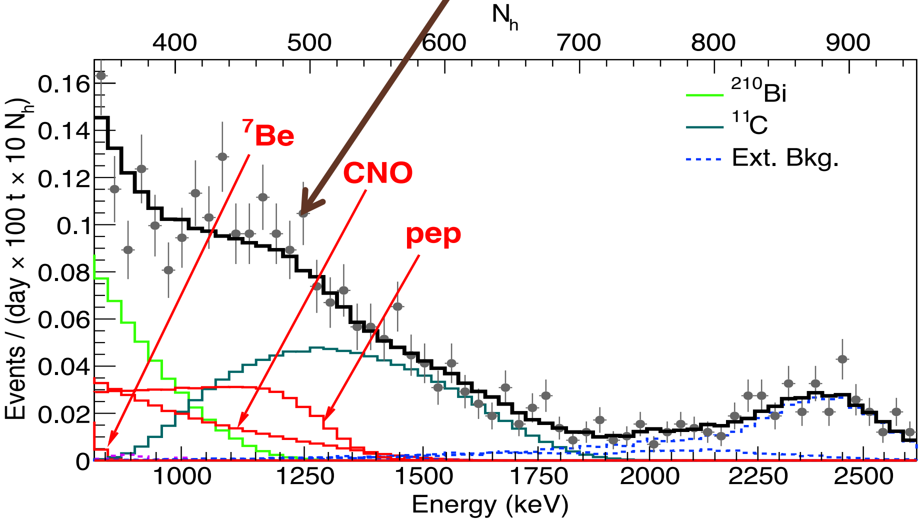
↑

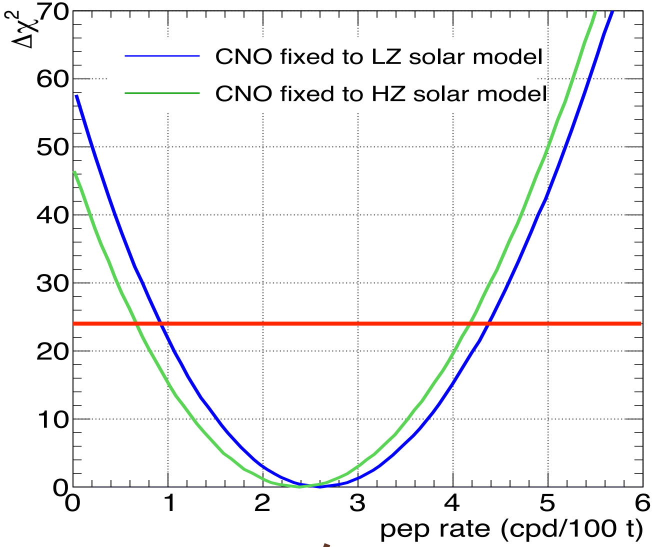
(compared to our previous results)

Nature 562, 505–510 (2018)

Evidence of pep ν signal

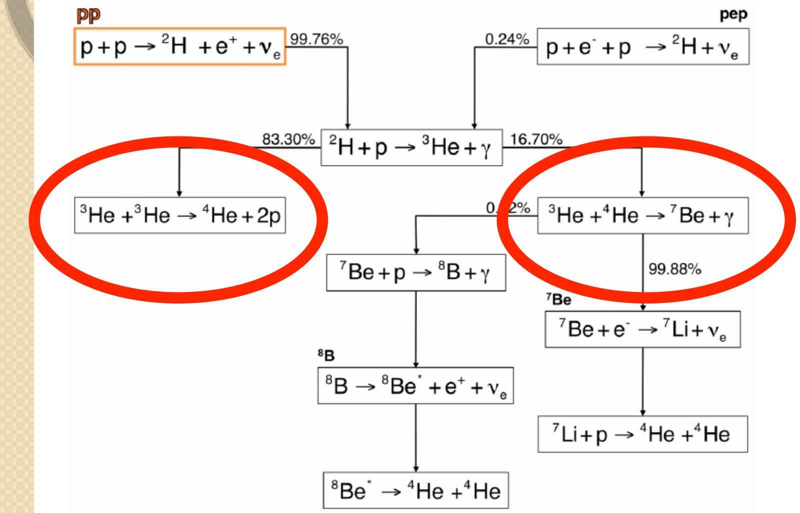
Applying more stringent cuts on FV and on the pulse-shape variable PS_L_{PR} we can actually see the pep n shoulder!





5 σ evidence of pep signal (including systematic errors)

A probe of solar fusion



From Borexino new flux measurements:

$$\boxed{R = 0.18 \pm 0.02}$$

- The competition between pp-I and pp-II branches of the pp chain is given by the ratio:

$$R \equiv \frac{\langle {}^3He + {}^4He \rangle}{\langle {}^3He + {}^3He \rangle} = \frac{2\,\Phi({}^7Be)}{\Phi(pp) - \Phi({}^7Be)}$$

- From the pp and ^{7}Be fluxes it is possible to determine the ratio R
- An important experimental test of the solar fusion
- Theoretical predictions:

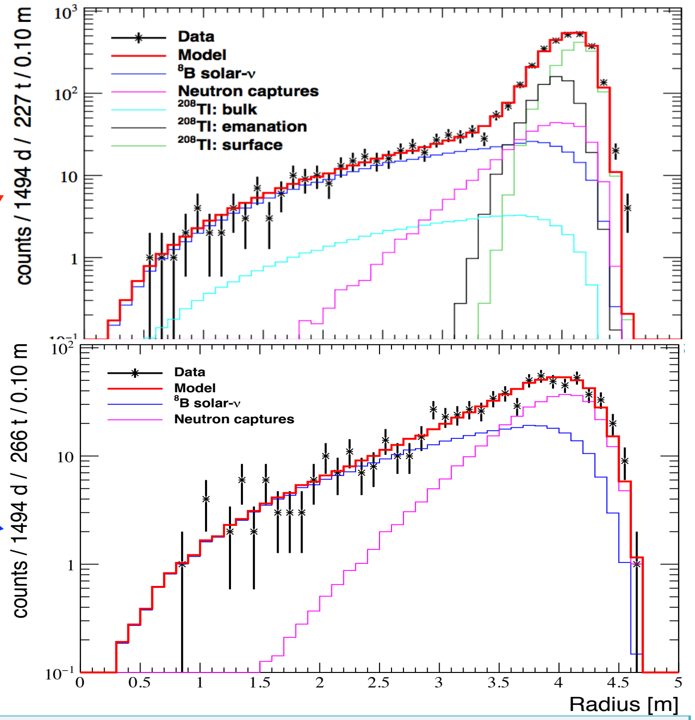
R(HZ)= 0.18 ± 0.01

R(LZ)= 0.16 ± 0.01

Updated ^{8}B neutrino flux

- Enlarged FV (most of scintillator)
- Data of Phase I+II: 2008 ➔ 2016
- Exposure: 1.5 kt y
- Fit of radial distributions in two energy ranges:

LE: 3.2-6MeV$_{kin}$
Mean ν energy: 7.9 MeV
HE: 6-17MeV$_{kin}$
Mean ν energy: 9.9 MeV



$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \mathrm{cpd/100\,t},$$

$$R_{HE} = 0.087^{+0.010}_{-0.008}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \mathrm{cpd/100\,t},$$

$$R_{LE+HE} = 0.220^{+0.016}_{-0.015}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd/100\,t}.$$

SuperKamiokande	2.345 ±0.014 ±0.036 x 10^6 cm^{-2} s^{-1}
Previous Bx	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}**

Implications for solar metallicity

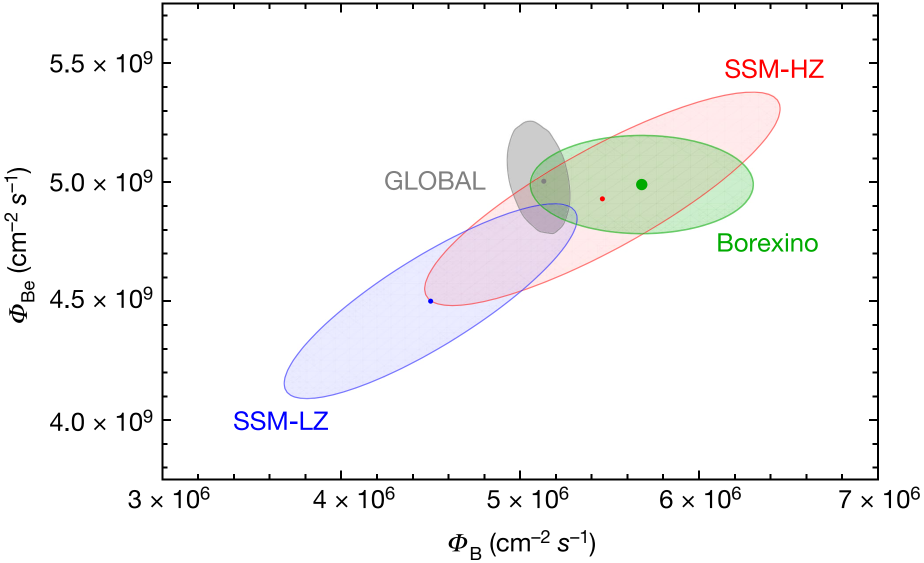
Global fit of all solar, Kamland reactors, and new Borexino results

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

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

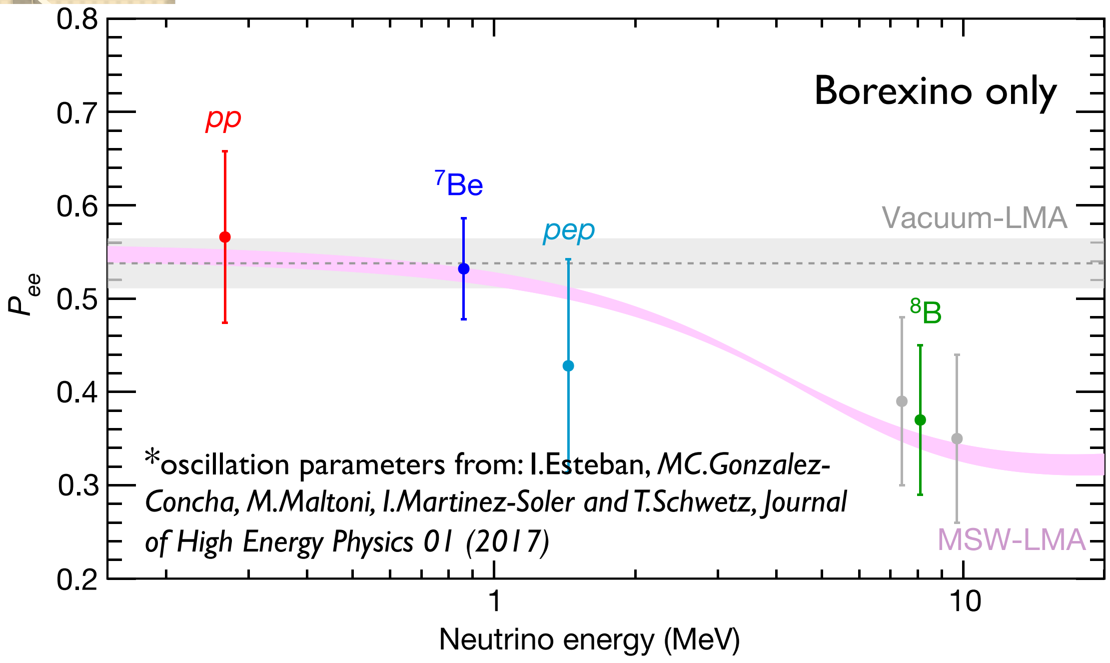
“Hint” towards High Metallicity?

LZ disfavoured at 96.6% C.L. (BX only)



- Note: only 1 σ theorethical uncertainty in the plot
- Important to reduce the theorethical uncertainty

Survival probability meas. by Borexino



*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

(assuming HZ-SSM)

- $P_{ee}(pp)=0.57\pm0.09$
- $P_{ee}(^7Be,862keV)=0.53\pm0.05$
- $P_{ee}(pep)=0.43\pm0.11$
- $P_{ee}(^8B, 8.7MeV)=0.37\pm0.08$

The whole pp-chain is measured by the same experiment!

Beyond solar neutrinos

- Neutrino magnetic moment, PR D96 (2017) 091103
- Geo-neutrinos, PR D 92, 031101(R) (2015)
- Correlation with GRB, Astropart. Phys. 86 (2017) 11
- Correlation with GW, Astrophys. J. 850 (2017) 21
- SuperNova neutrinos
- Muons and cosmic backgrounds

NEW! 10y update
arXiv:1808.04207
(will appear on JCAP these days)

10yr muon modulation analysis

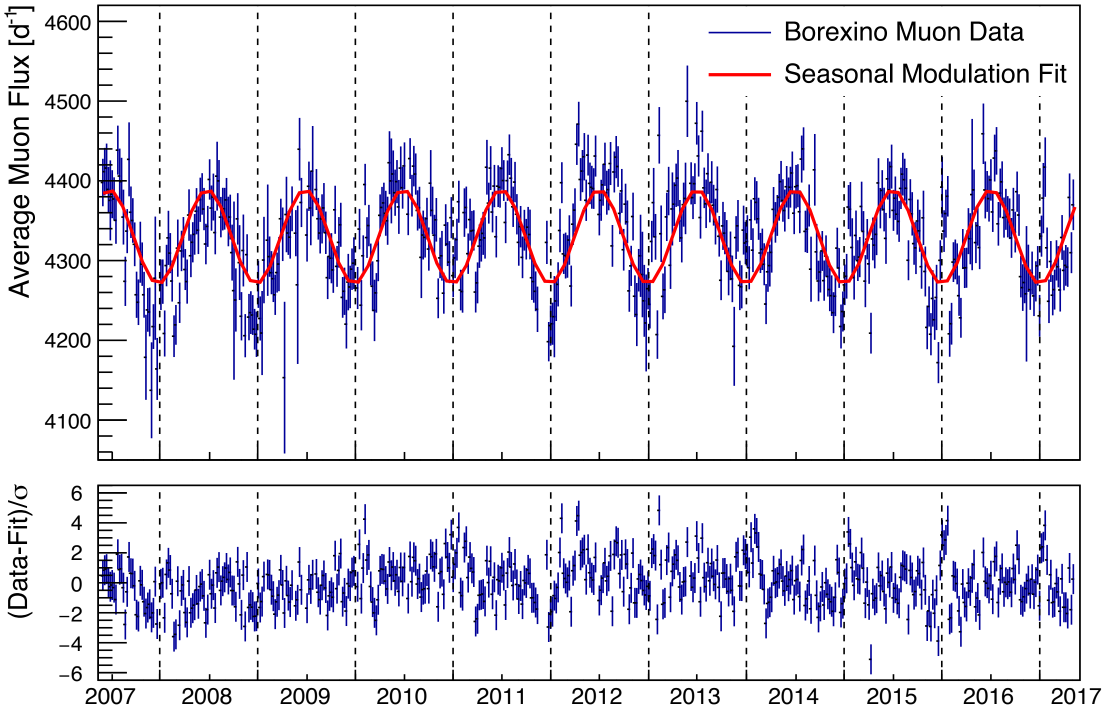
16th May 2007 – 16th May 2017

$$I_\mu(t) = I_\mu^0 + \delta I_\mu \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$

$$T = (366.3 \pm 0.6)\,\mathrm{d}$$

$$t_0 = (174.8 \pm 3.8)\,\mathrm{d}.$$

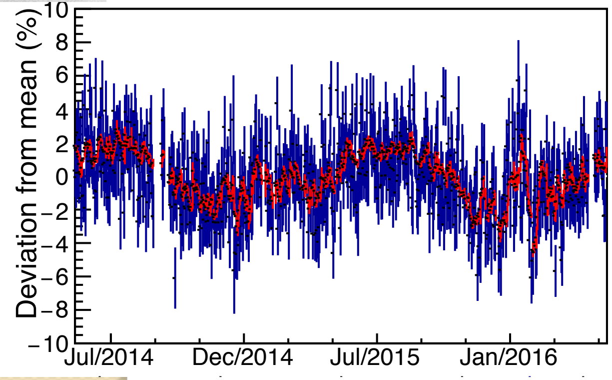
↖ June 25th



$$\delta I_\mu = (58.9 \pm 1.9)\,\mathrm{d}^{-1} = (1.36 \pm 0.04)\%$$

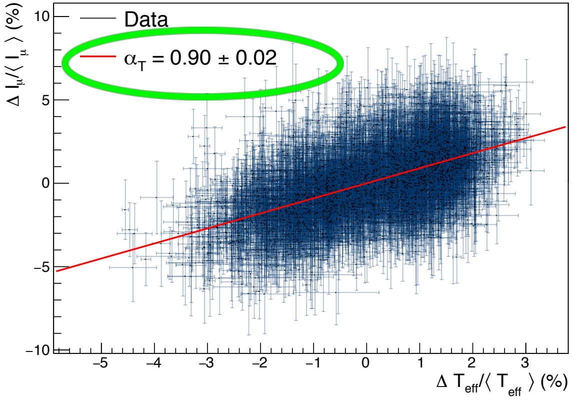
[check the paper for neutron modulation]

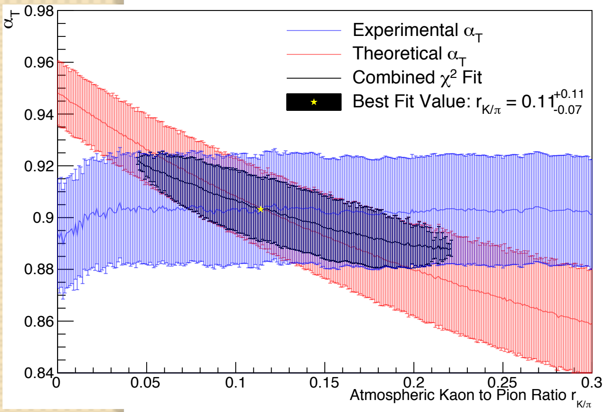
10yr muon modulation analysis



Modulation in agreement with atmospheric data.

Error halved on correlation parameter,



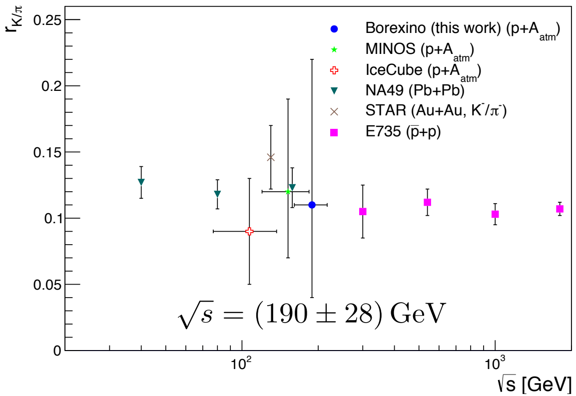


allows to measure kaon-to-pion ratio…

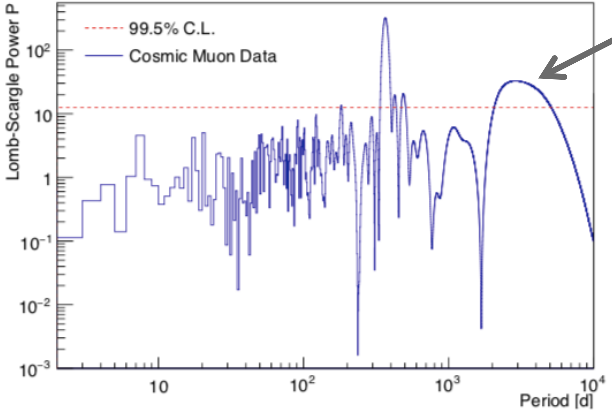
$$r_{K/\pi} = 0.11^{+0.11}_{-0.07}$$

$$r_{K/\pi} = 0.149 \pm 0.06$$

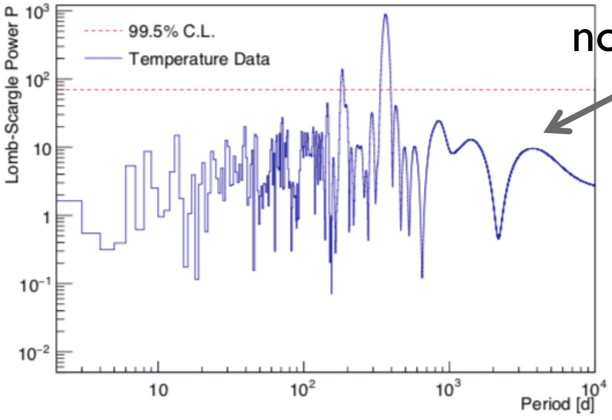
…and compare it with existing measurements



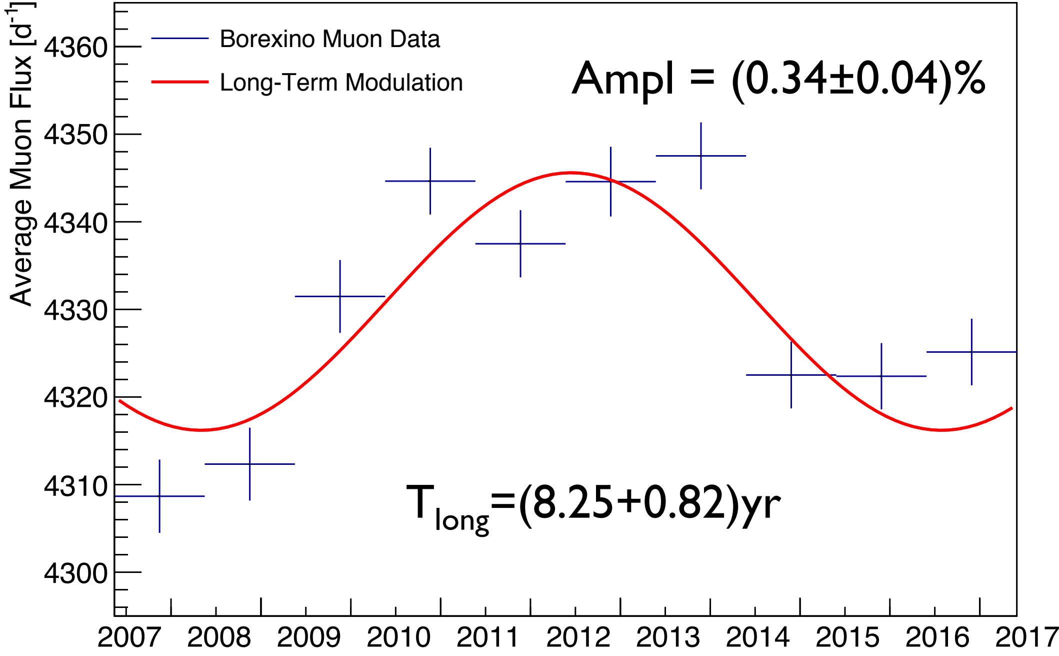
10yr muon modulation analysis



muon
flux
only



not in T!



Ampl = (0.34±0.04)%

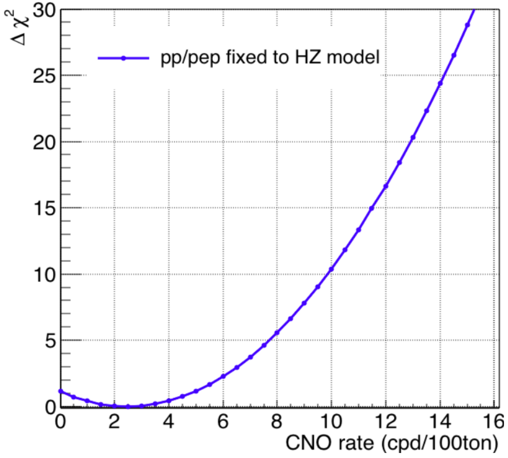
T_{long}=(8.25+0.82)yr

[check the paper for a speculative investigation on a possible correlation with the solar cycle]

What about measuring CNO?

- with this analysis we has set limits

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



- but can we make an actual observation?
- see next talk by Davide Basilico

Conclusions

- We are approaching 12 years of Borexino running with:
  - Unprecedented backgrounds
  - A thorough calibration-tuned MC effort
  - A new wide range multivariate fit strategy
- Borexino alone has performed the full spectroscopy of pp-chain neutrinos
  - ^{7}Be flux at 2.5% uncertainty (stat+sys)
  - 5 σ evidence of pep neutrinos
  - test of Sun's nuclear processes and its long term stability
- Stay tuned for more results!

Thank you for your attention!

ADDITIONAL MATERIAL

Borexino Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

TUM Technische Universität München

University of Houston

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH FORSCHUNGSZENTRUM

Virginia Tech

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Universität Hamburg

SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

Joint Institute for Nuclear Research

GSSI GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI FERRARA

THE UNIVERSITY OF CALIFORNIA UCLA

TECHNISCHE UNIVERSITÄT DRESDEN

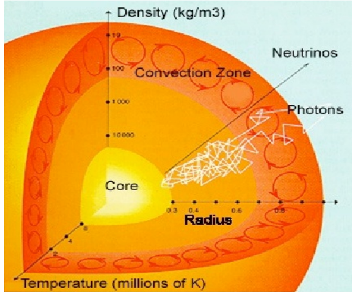
APC

STUDIUM GENERALE CIVITATIS PERUSII A.D. MCCCVIII

POLITECNICO MILANO 1863

The Standard Solar Model(s): SSM

- Most recent Standard Solar Model (SSM) is named B16
  - N.Vinyoles et al., Astroph. Journ. 835 (2017) 202
  - previous version was SFII (2011)
- Model the evolution of the star from formation until now 4.57 10^9y
  - assume equilibrium between gravitation and pressure
- Input:
  - Solar Luminosity and Radius
  - Homogeneous mixture of H, He and “heavy” elements: $X_{ini}, Y_{ini}, Z_{ini}$
  - α_{MLT} : parameter entering in the description of the convection
  - Cross sections for nuclear reactions (S factors)
  - Opacity
- Observables:
  - Helioseismology
  - Solar Neutrinos



Solar neutrinos on Earth

- Neutrino rate emitted by the Sun: **$N_\nu = 1.8 \cdot 10^{38}$ ν/s**
- only electron flavor neutrinos are produced in the Sun
- How many do reach the Earth?

$$\boxed{4H + 2e^- \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.7 \quad MeV}$$

2 neutrinos produced per reaction

Luminosity of the Sun: **3.846 · 10^{26} Watt**

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi D_\odot^2} \frac{2L_\odot}{(Q - \langle E_\nu \rangle)} = 6 \times 10^{10} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

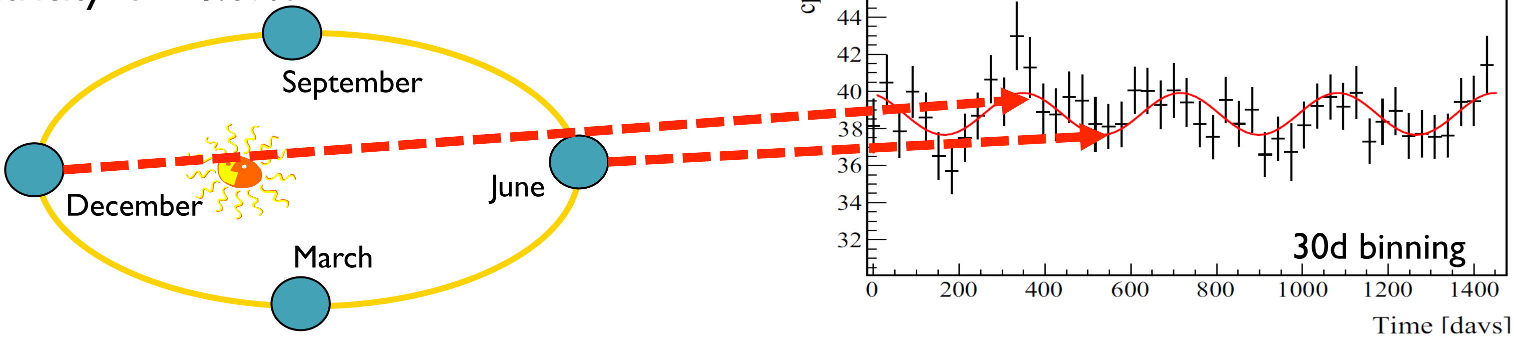
Distance Earth-Sun: **~1.5 · 10^{11} m**

Energy released in the reaction: **~26.7 MeV**

Energy carried away by ν : **~0.3MeV**

Seasonal Modulation

Expected yearly modulation due to Earth's orbit eccentricity ε = 1.67%

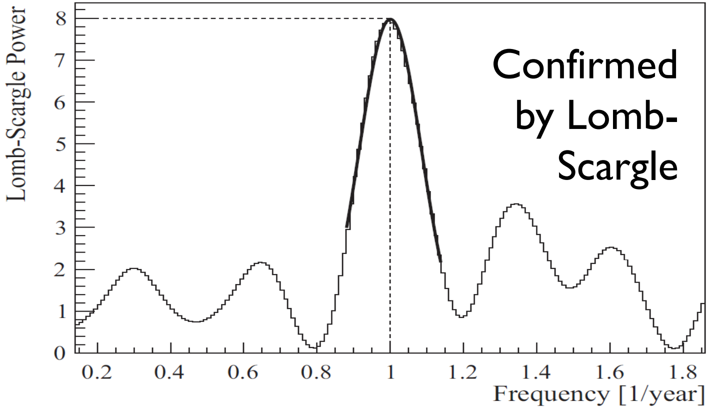


$$R(t) = R_0 + \overline{R}\left[1 + \epsilon\cos\frac{2\pi}{T}(t-\phi)\right]^2$$

Eccentricity ε = (1.74 ± 0.45)%

Period T = (367 ± 10) days

Phase Φ = (-18 ± 24) days



Confirmed by Lomb-Scargle

Borexino does indeed observe neutrinos from the Sun!

Fit strategy

Radial distr. (ext. gammas)

Pulse shape (^{11}C)

Maximize a binned likelihood through a multivariate approach

$$L(\vartheta) = \underbrace{L_{sub}(\vartheta) \cdot L_{tag}(\vartheta)}_{\text{Energy}} \cdot L_{rad}(\vartheta) \cdot L_{PS-L_{pr}}(\vartheta)$$

Monte Carlo

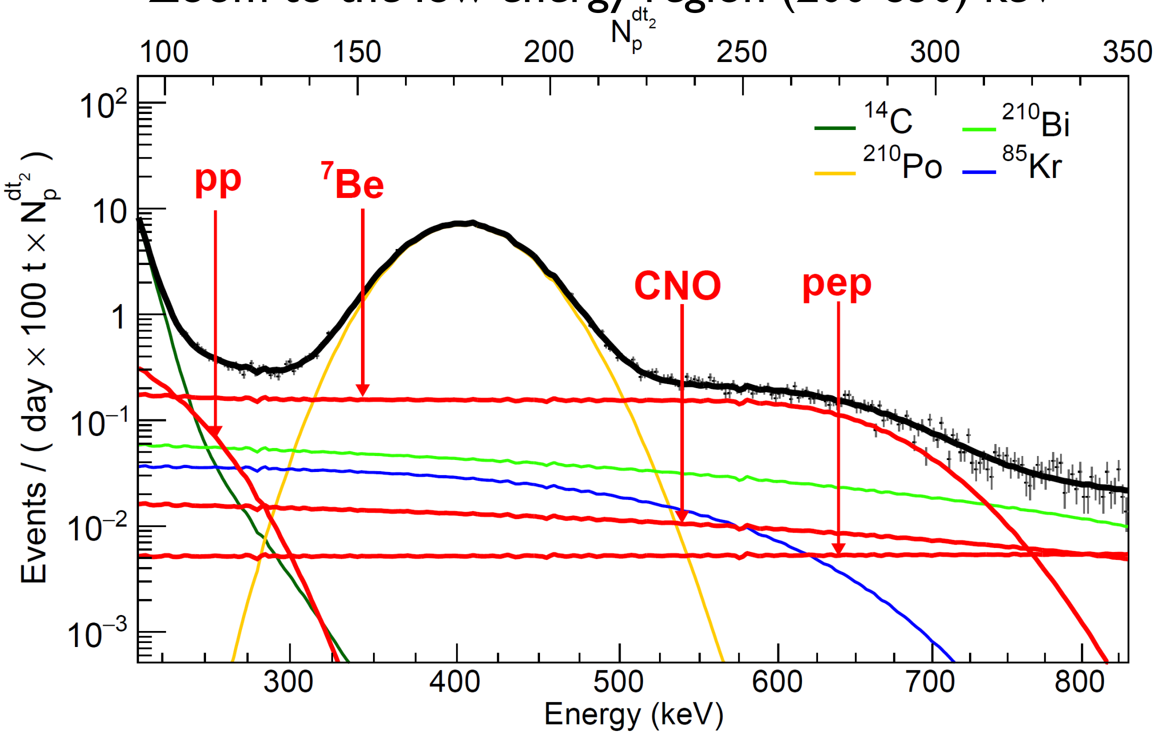
- Full simulation of energy loss, detector geometry, optical photons (scintill. & Cherenkov), PMTs & electronics response.
- Tuned with calibration data ➔ sub% accuracy (Astrop. Phys. 97 (2018) 136 -159)
- Included known time variations of the detector (vessel shape, PMT status)
- Only free parameters:
    - solar ν and background rate

Analytical

- Analytical model to link E to N_{pmt}, N_{hits}, N_{pe} (including scintillation and Cherenkov light)
- Models the E resolution
- Free fit parameters:
    - solar ν and background rate
    - 6 model parameters: Light Yield, 2 resolution param., position & width of ^{210}Po peak, start of the ^{11}C spectrum
- Possibility to descrive unknown time variations

Example using the analytical fit

Zoom to the low energy region (200-830) keV



Energy estimator: npmts_dt2

Sources of systematic errors

Two methods to take into account pile-up:

- Effects of non perfect modelling of the detector response;
- Uncertainty on theoretical input spectra (^{210}Bi)

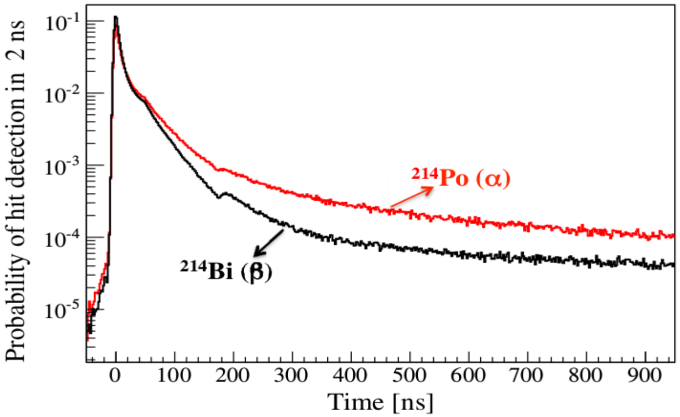
^{85}Kr constrained to be <7.5cpd/100t (95% C.L.) from Kr-Rb delayed coincidences

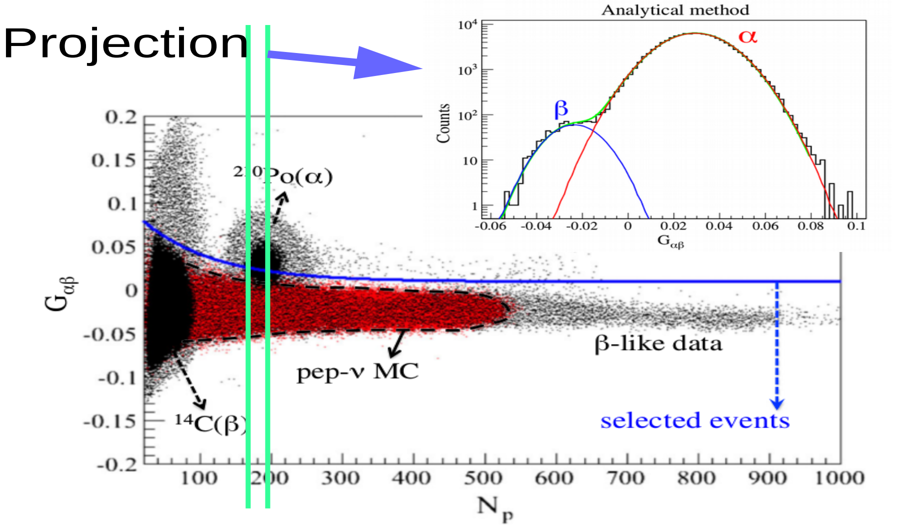
	pp		^{7}Be		*pep*	
Source of uncertainty	$-\%$	$+\%$	$-\%$	$+\%$	$-\%$	$+\%$
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr 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

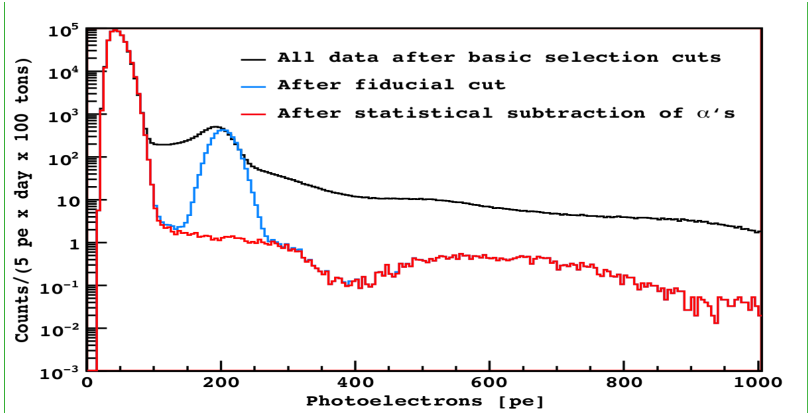
Improvement of the new analysis

	Phase I	Phase II	Uncertainty reduction $\frac{Phase\ II}{Phase\ I}$
pp	$144 \pm 13 \pm 10$	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be(862keV)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	0.57
pep	$3.1 \pm 0.6 \pm 0.3$	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61

PSD (α / β)







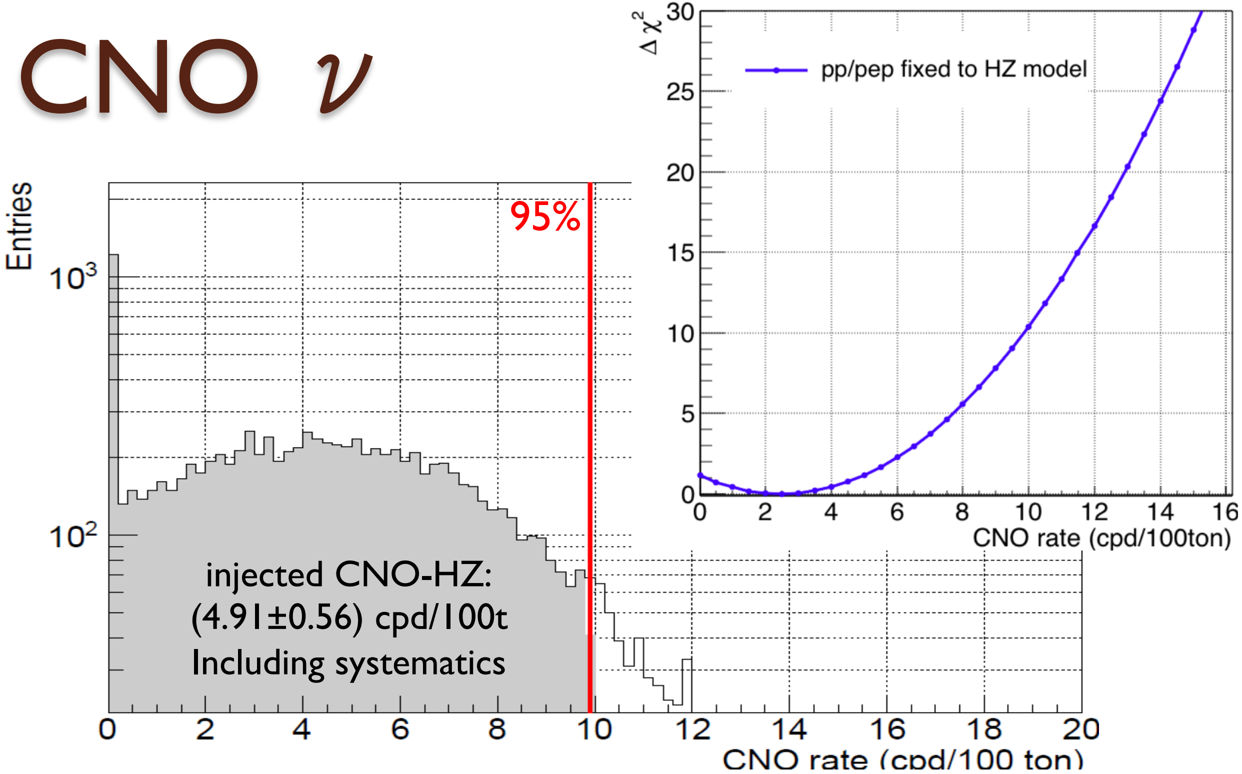
- Bin-by-bin statistical subtraction
- Formerly based on Gatti filter
- Now improving with Multi-Layer-Perceptron algorithm

Limits on CNO ν

- Problem: CNO is highly correlated to pep and ^{210}Bi background
- Strategy: constrain the ratio pp/pep to 47.7±1.2
  - Include oscillations LMA-MSW
- Toy MC study of the sensitivity: 95% CL is

  9 cpd/100t for LZ

  10 cpd/100t for HZ
- Previous limit (Phase I): 7.9 cpd/100t (but with pep fixed!)



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

Calibration and Monte Carlo

- 2008-2011: 4 internal + 1 external calibration campaigns
- Rn, neutrons, several gammas
- 184 locations covering the whole Inner Vessel
- Tuning MC for position, energy and PSD

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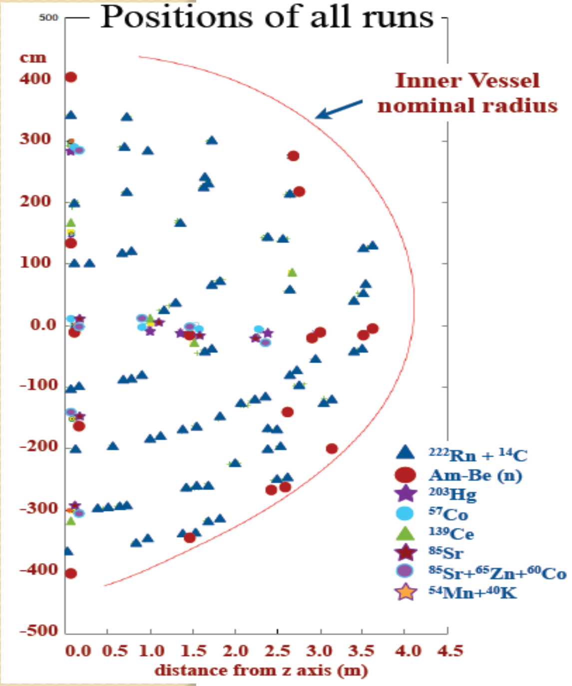
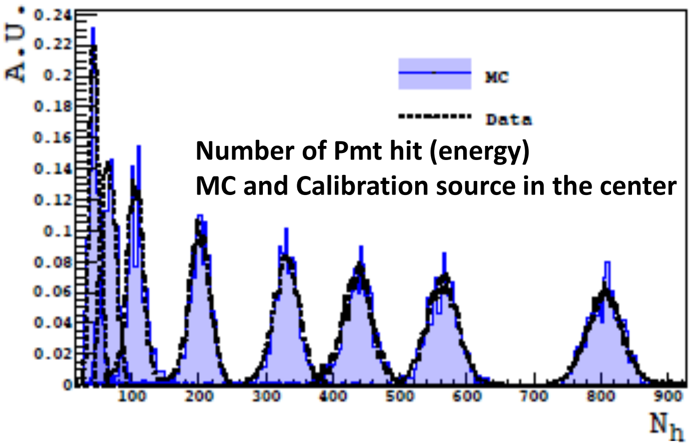
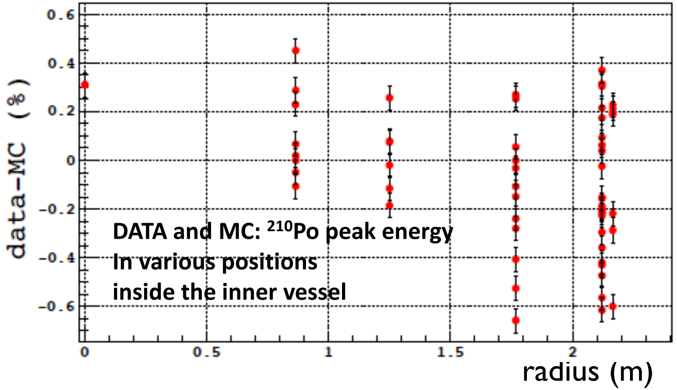

Positions of all runs

Inner Vessel nominal radius


Number of Pmt hit (energy)
MC and Calibration source in the center


DATA and MC: ^{210}Po peak energy
In various positions
inside the inner vessel

Experimental site

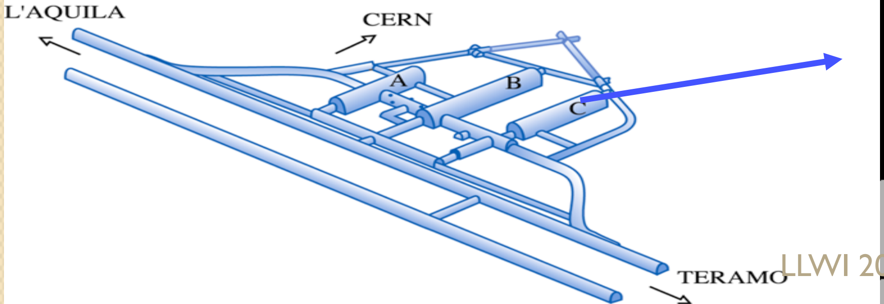

Abruzzo, Italy
120 km from Rome

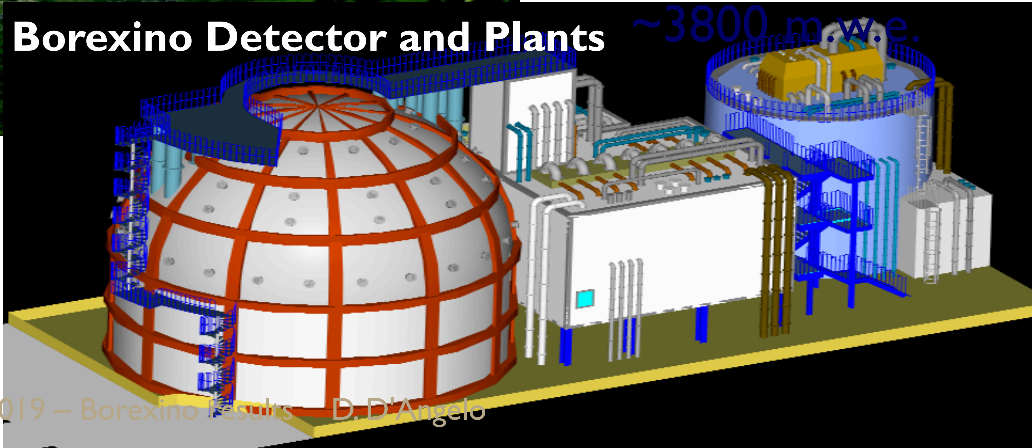
External Labs

Laboratori
Nazionali del
Gran Sasso

1400m of rock
shielding

~3800 m.w.e.




Borexino Detector and Plants

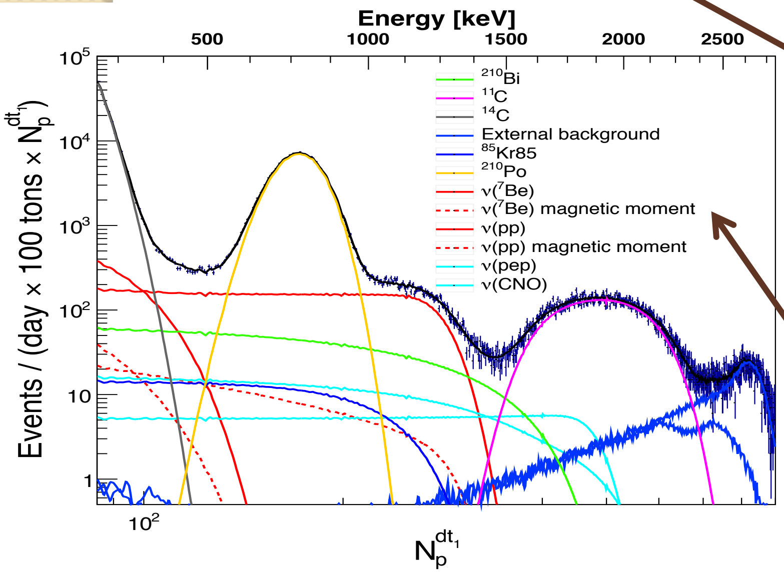
Limit on Neutrino Magnetic Moment

As neutrinos are massive, they can also have a MM
An EW term could show up in ν -e scattering

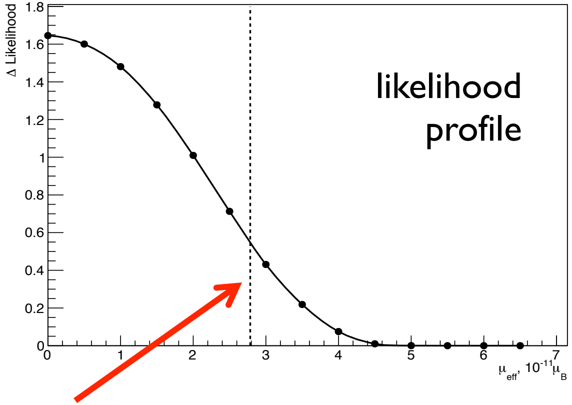
[effective as it refers to the admixture of mass eigenstates reaching Earth]

$$\frac{d\sigma_{\mathrm{EM}}}{dT_e}(T_e, E_\nu) = \pi\, r_0^2\, \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

low energy ν are sensitive (^{7}Be, pp)



Fit with different values of μ_{eff}



likelihood profile

$\mu_{eff} < 2.8\times10^{-11}\,\mu_B$ at 90% C.L.

about 2x lower than phase-I
best limit for μ_{eff}