JOHANNES GUTENBERG UNIVERSITÄT MAINZ

THE BOREXINO RECENT RESULTS AND SOX MEASUREMENT PERSPECTIVES

Alessio Porcelli on behalf of the Borexino/SOX Collaborations

– 27th October, 2017

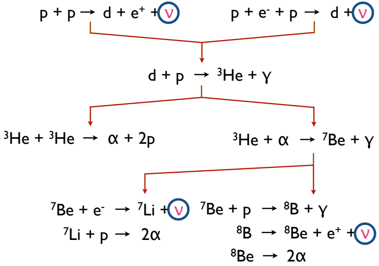
Borexino and SOX Collaborations

UNIVERSITÀ DEGLI STUDI DI MILANO
INFN
LNGS
PRINCETON UNIVERSITY
cea
NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"
St. Petersburg Nuclear Physics Inst.
TUM Technische Universität München
GSSI GRAN SASSO SCIENCE INSTITUTE — CENTER FOR ADVANCED STUDIES Istituto Nazionale di Fisica Nucleare
JAGIELLONIAN UNIVERSITY IN KRAKÓW
JÜLICH FORSCHUNGSZENTRUM
Virginia Tech
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
UH
POLITECNICO MILANO 1863
НИИЯФ МГУ
Joint Institute for Nuclear Research
UNIVERSITÀ DEGLI STUDI DI GENOVA
EBERHARD KARLS UNIVERSITÄT TÜBINGEN
TECHNISCHE UNIVERSITÄT DRESDEN

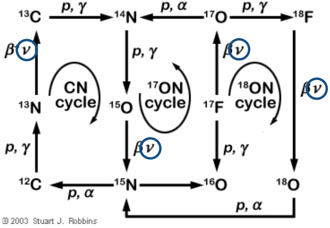
167 among scientists and students, and 291 produced articles

Physics questions. . .

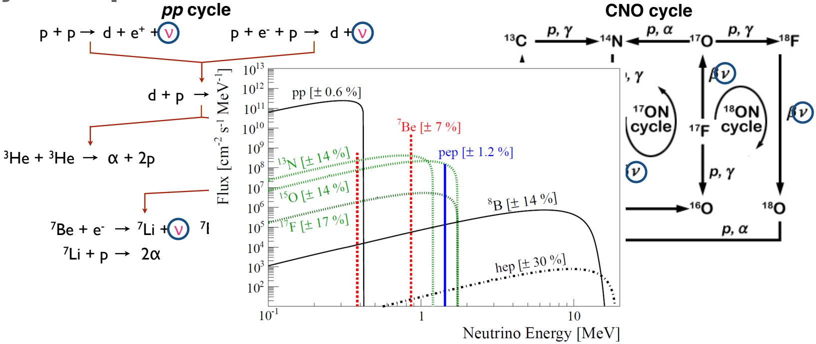
***pp* cycle**



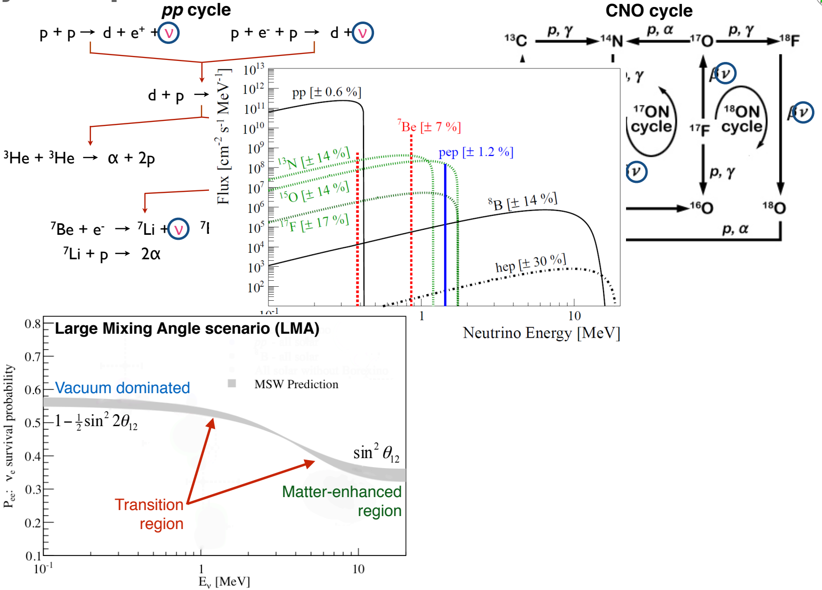
CNO cycle



Physics questions. . .



Physics questions. . .



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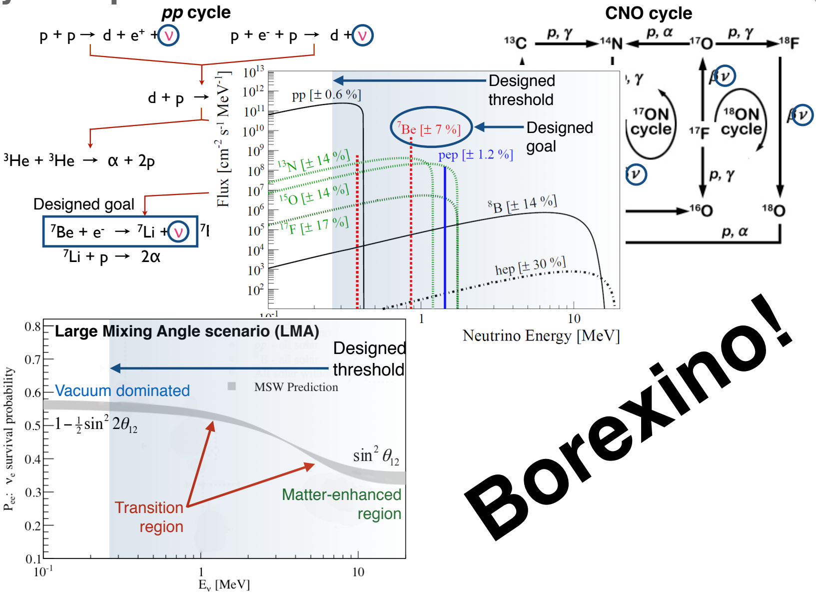
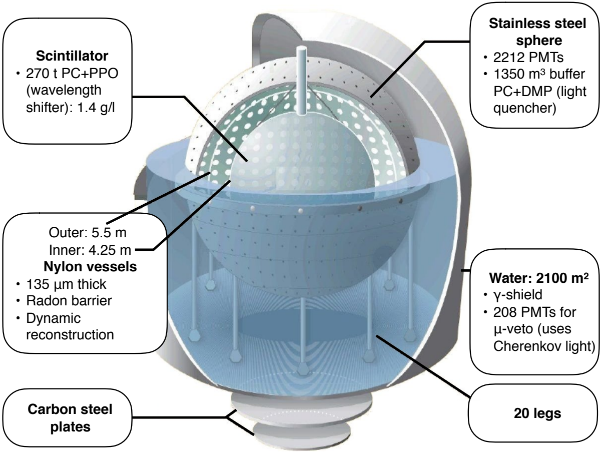


Borexino Detector

Sited beneath Gran Sasso mountain (1400m of rock shielding), Italy.



Borexino core is the most radio-clean spot on Earth
with over 10 orders of magnitude below typical radioactivity levels

- Very low background
  - Nitrogen stripping
  - Distillation
  - Water extraction
- 25% Coverage
- Light Yield (LY): 500 p.e./MeV
- Continuous temperature and contamination monitoring

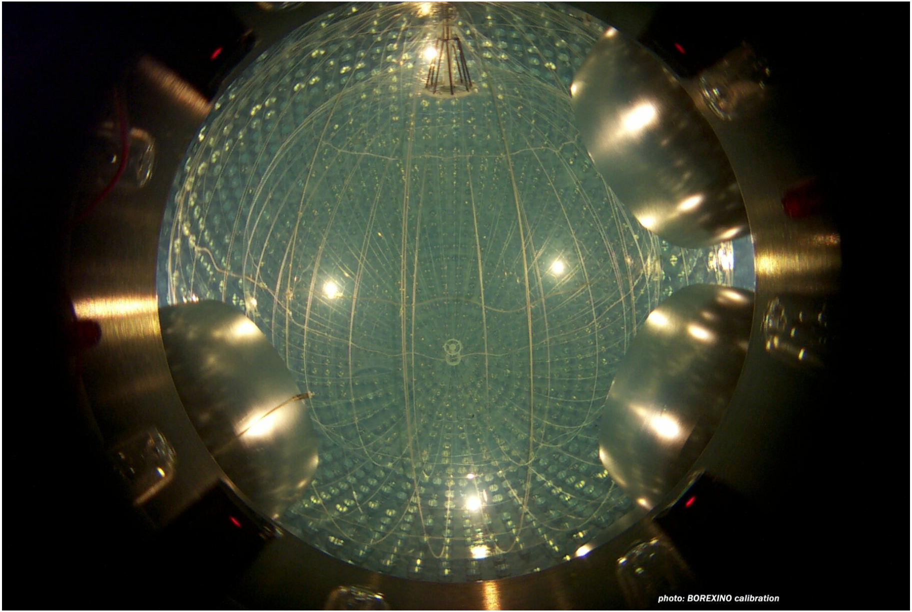
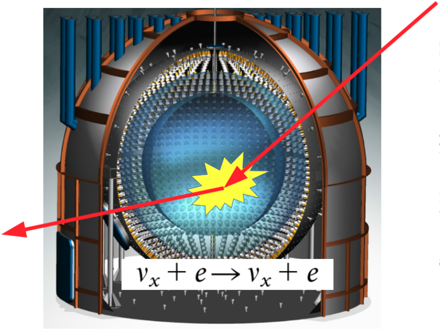
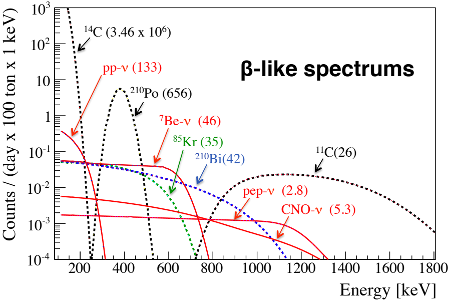


photo: BOREXINO calibration

Borexino signature

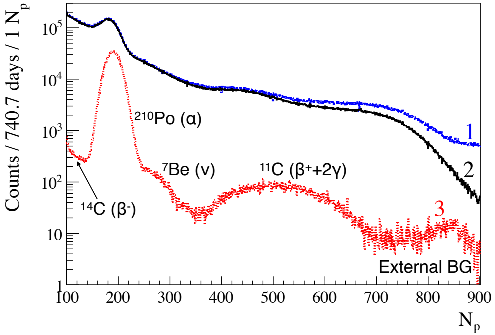
Indistinguishable from the natural radioactivity (β^-/γ components)





⇒ Extreme low background required!!!

Data selection



1. Raw spectrum
2. Muon cut
3. Fiducial Volume cut (every goal has an optimised FV)

(x-axis: number of PMTs triggered in the event cluster $\sim E \cdot$ LY)

Thorough statistical subtraction of cosmogenics, such as:

α/β Gatti's parameter and neural network discrimination (trained on ^{214}Bi-^{214}Po coincidence)

^{11}C Three Fold Coincidence (TFC): space-time veto applied on $\mu - n$ pairs coincidences. Average decay time of ^{11}C is 30 min.

…and more [arXiv:1308.0443]

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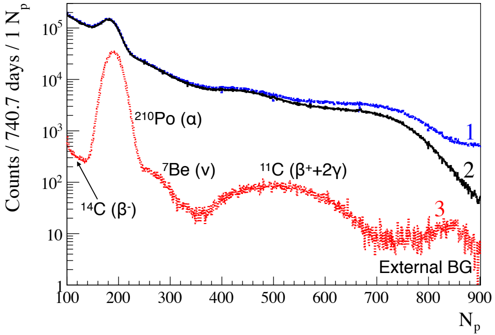

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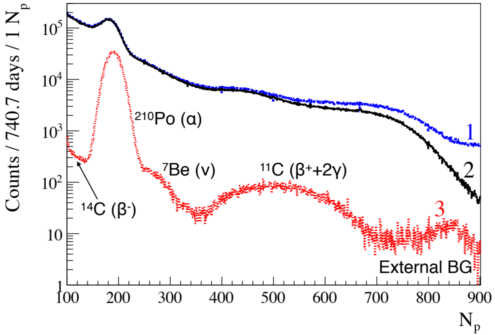

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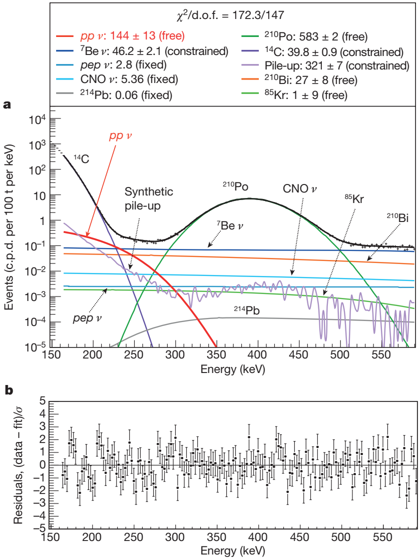
pp chain result



After first measurements of νs from ^{7}Be (862 keV) [PRL107(2011)141302], *pep* (1440 keV) [PRL108(2012)051302] and CNO (most stringent upper limit) [PRL108(2012)051302]

First direct observation of the low energy neutrinos coming from the *pp* fusion in the core of the Sun

exposure of 408 days × 71.3 ton

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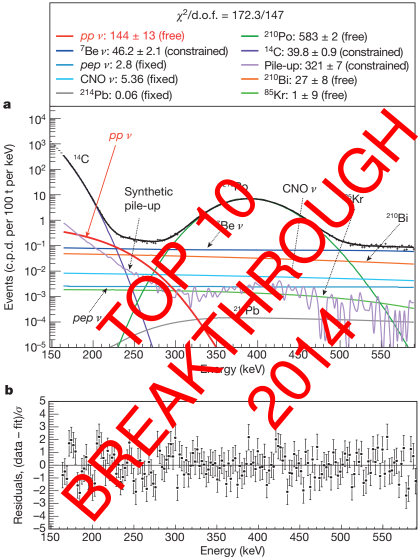

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First direct observation of the low energy neutrinos coming from the *pp* fusion in the core of the Sun

exposure of 408 days $\times$ 71.3 ton

Expected: 131 $\pm$ 2 cpd/100 t

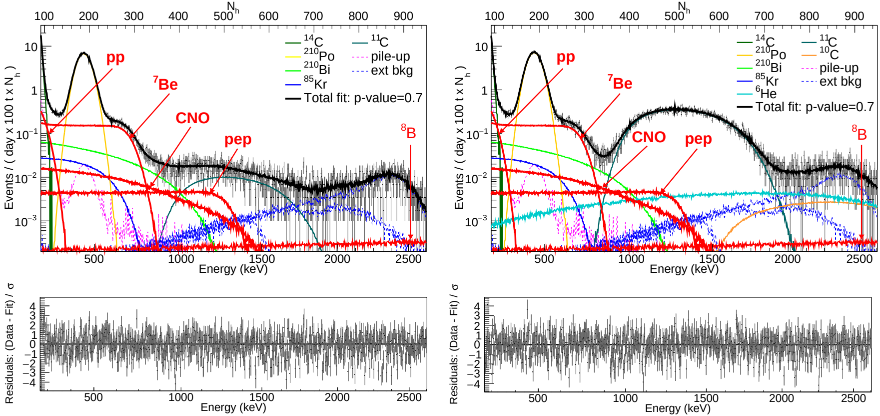
Rate: 144 $\pm$ 12$|_{stat}$ $\pm$ 10$|_{syst}$ cpd/100 t

Null hypothesis rejection: 10 σ

[Nature512(2014)383]

Simultaneous spectroscopy *pp*, ^{7}Be, *pep*

All spectrum fitted simultaneously;
exposure of 71.3 ton $\times$ 1291.51 days

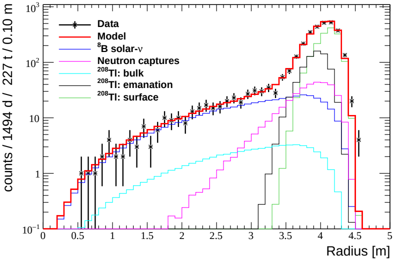


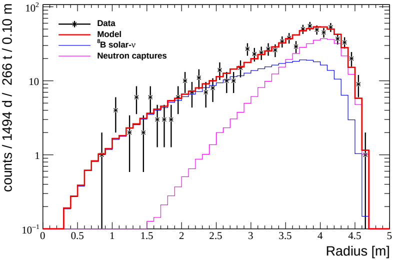
TFC subtracted TFC complementary

[arXiv:1707.09279]

Measurement of ^{8}B solar neutrinos

radial fit; exposure of 1.5 kton $\times$ year





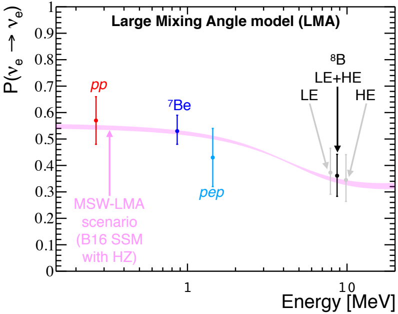
Low Energy (LE) range:
3.2÷5.8 MeV; $\langle E_\nu \rangle \sim$ 7.9 MeV
Background: faction of μ and n, fast cosmogenics and ^{214}Bi, ^{11}Be, ^{208}Tl, external γ from (n, γ) reactions

High Energy (HE) range:
5.8÷16.7 MeV; $\langle E_\nu \rangle \sim$ 9.9 MeV
Background: fraction of μ, fast cosmogenics, ^{11}Be, external γ from (n, γ) reactions

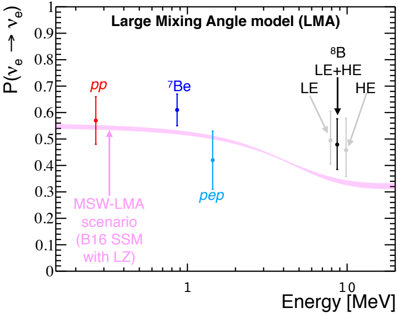
Combining distribution gives $\langle E_\nu \rangle \sim$ 8.7 MeV
[arXiv:1709.00756]

Implication on the neutrino physics

Survival probability $\Phi_{meas}/\Phi_{exp} \Rightarrow$ Solar Standard Model (SSM) depended



High metallicity model (HZ). *p*-value 0.998 (0.956 with all experiments)

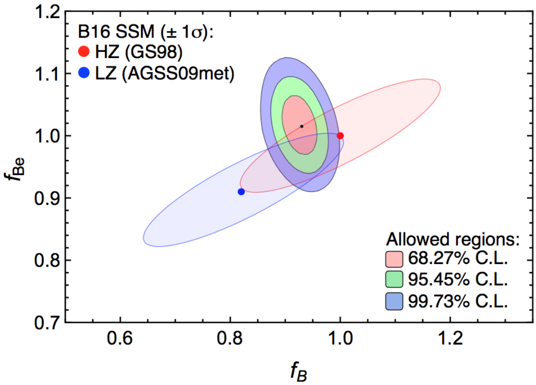


Low metallicity model (LZ). *p*-value 0.362 (0.465 with all experiments)

✓ confirms MSW-LMA (Mikheyev-Smirnov-Wolfenstein effect with Large Mixing Angle scenario)

- High metallicity favoured

Implication on the physics of the sun



Borexino-KamLand Data combined

HZ/LZ contour are 1σ theoretical prediction

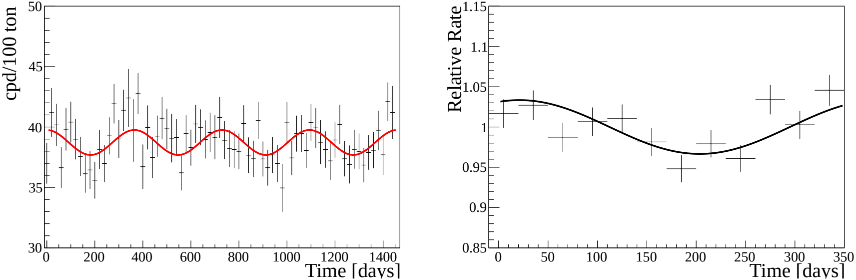
$f_X = \Phi(X)/\Phi(X)_{HZ}$ in the axis are the reduced fluxes

- ✓ confirms SSM (Solar Standard Model)
- ✓ confirms Sun's stability in the past 10^5 years
- ✓ discrimination between the HZ and LZ is now largely dominated by theoretical uncertainties (towards an high metallicity model -HZ-?)

^{7}Be Modulation

Periodical fluctuation on β-like signal from ^{7}Be [arXiv:1701.07970]:

- Sinusoidal Fit to the Event Rate



- Lomb-Scargle (spectral analysis with periodic signal assumption)
- Empirical Mode Decomposition (no periodic signal assumption)

Results: T = 1 y modulation and eccentricity $\epsilon = (1.66 \pm 0.45)\%$
(null hypothesis rejection: CL 99.99%), compatible with Earth revolution

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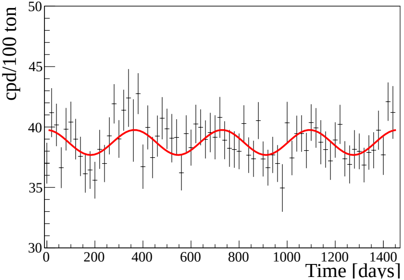

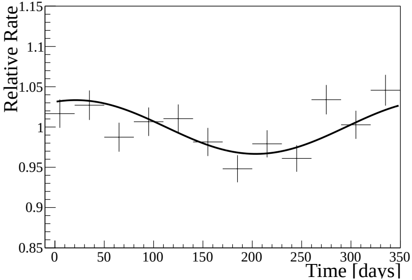

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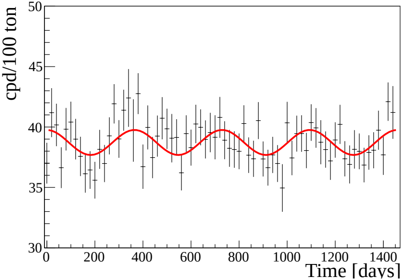

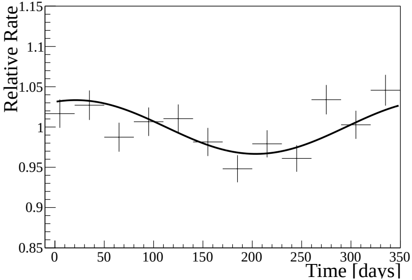

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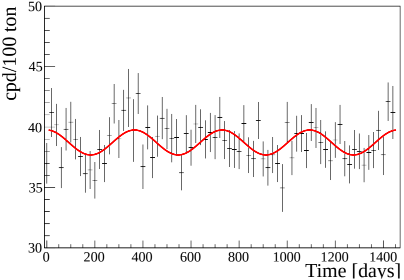

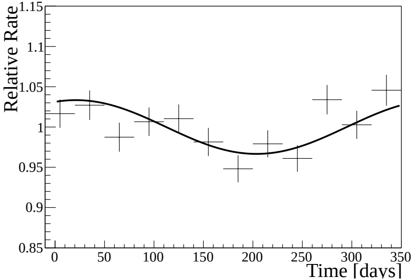

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$\Rightarrow$ **Low energy neutrinos detected in Borexino have solar origin**

Neutrino Magnetic Moment

Neutrino oscillation $\Rightarrow m_\nu \neq 0 \Rightarrow \mu_\nu \approx 3.2 \cdot 10^{-19} \left(\frac{m_\nu}{1\ \text{eV}}\right) \mu_B$
(μ_B = electron Bohr magneton)

- Current m_ν limits: $\mu_\nu < 10^{-18}\mu_B$:
  - 7-8 order of magnitude of the current experimental limits
- Further extension of the Standard Model and New Physics:
  - $\mu_\nu \propto m_\ell$ instead m_ν
  - expectations reach the levels of the current experimental limits

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$e^- - \nu$ scattering has additional term proportional to μ_{eff}

(μ_ν for a mixture of neutrino mass eigenstates)

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

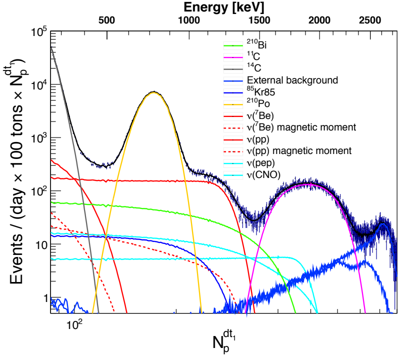
$\sigma_{\text{EM}} \sim 1/T_e \Rightarrow$ scattered electron spectrum influenced at low energies

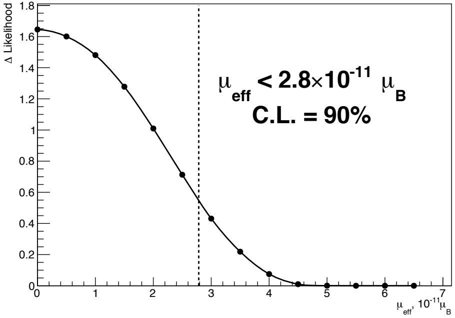
^{7}Be strong change of the shape: **major sensitivity to nmm**

pp change of the shape is almost equivalent to only the change of normalisation: **constraining pp flux helps!**

NMM constraining with Borexino

exposure of 71.3 ton × 1270.6 days [arXiv:1707.09355]





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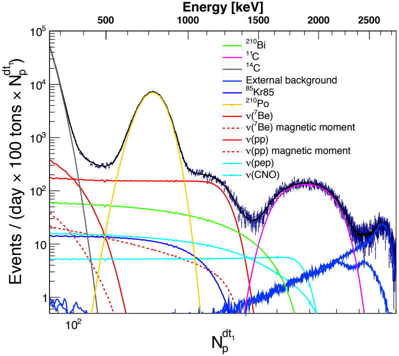
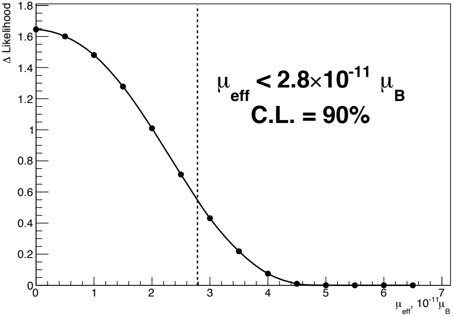




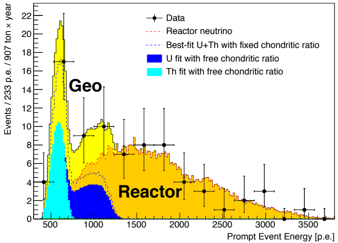
With MSW-LMA $\mu^2_{eff} = P^{3\nu}\mu^2_e + (1 - P^{3\nu})(\cos^2\theta_{23}\cdot\mu^2_\mu + \sin^2\theta_{23}\cdot\mu^2_\tau)$, where $P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13}P^{2\nu}$ and $P^{2\nu} = \sin^2\theta_{12}\sin^2\left(\Delta m^2_{12}L/4E\right)$, and using the most conservative (i.e. the worst case) mass hierarchy, a 90% C.L. limit on each contribution can be obtained by setting other two to zero:

$\boldsymbol{\mu_e < 3.9\cdot10^{-11}\mu_B}$ $\boldsymbol{\mu_\mu < 5.8\cdot10^{-11}\mu_B}$ $\boldsymbol{\mu_\tau < 5.8\cdot10^{-11}\mu_B}$

NMM constrainings comparison

	Source	$\times 10^{-11} \mu_B$ @ 90% C.L.	Reference
	(Reactor)		
GEMMA	$\bar{\nu}_e$	$\mu_{\nu e} < 2.9$	Phys.Part.Nucl.Lett.10(2013)139
TEXONO		$\mu_{\nu e} < 7.4$	PRD75(2007)012001
	(Astrophysical)		
Raffelt & Dearborn	red giant cooling	$\mu_{\nu e} < 0.3$	Phys.Rept.320(1999)319
Arcea-Díaz *et al.*		$\mu_{\nu e} < 0.22$	Astropart.Phys.70(2015)1
	(Solar)		
Super-Kamiokande	solar ^{8}B-ν above 5 MeV	$\mu_{eff} < 36$	PRL93(2004)021802
	combining solar+KamLAND	$\mu_{eff} < 11$	
Borexino (old)	solar ^{7}Be-ν (192 days)	$\mu_{eff} < 5.4$	PRL101(2008)091302
Borexino (new)	solar ^{7}Be-ν and *pp*-ν	$\mu_{eff} < 2.8$	arXiv:1707.09355

Geo-neutrinos



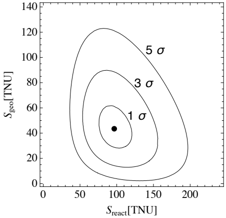
Detection through inverse β-decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$n + \mathrm{H} \rightarrow \mathrm{D} + \gamma\ (2.2\ \mathrm{MeV})$$

Exposure: 2056 days

[PRD92(2015)031101(R)]



Log-Likelihood fit: Geo-ν out of Reactor-ν:

- 5.9 σ of significance out of null hypothesis
- $S_{geo} = 43.5^{+11.8}_{-10.4}|_{stat}{}^{+2.7}_{-2.4}|_{syst}$ TNU
- $S_{react} = 96.6^{+15.6}_{-14.2}|_{stat}{}^{+4.9}_{-5.0}|_{syst}$ TNU

1 TNU (Terrestrial Neutrino Unit) = 1 event/year/10^{32} protons

Real time spectroscopy of geo-ν is possible with larger exposure

. . . it is also possibile to distinguish between different geological models

. . . and more physics is achieved

- ☺ Testing ν excess from LIGO and VIRGO events (Gravitational Waves) [arXiv:1706.10176]
- ☺ ν-GRB correlation: best limits on the neutrino fluence of all flavours below 7 MeV [Astro.Phys.86(2017)11]
- ☺ Limits on rare processes: i.e. $\tau_{e^- \to \gamma\nu} > 6.6 \cdot 10^{28}$ y @ 90% CL [PRL115(2015)231802]
- ☺ Muon seasonal modulation: $\phi = 179 \pm 6$ days, correlated to atmospheric temperature with $\alpha_T = 0.93 \pm 0.04$ [JCAP05(2012)015]
- ☺ Detailed studies of the cosmogenics in liquid scintillator [arXiv:1308.0443]
- ☺ $\nu_e \to \bar{\nu}_e$ oscillation: transition probability $< 1.3 \cdot 10^{-4}$ @ 90% CL for $E_{\bar{\nu}} > 1.8$ MeV [Phys.Lett.B696(2011)191]

. . . and more physics is achieved (and will be)

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- . . . a more stringent CNO limit (or a possible observation?)
- . . . LIGO+VIRGO+IceCube+LVD+KamLand+Borexino joint collaboration for multimessenger observation of next galactic Supernova

2003-2004

Phase I (2007-2010):
- ☑ ^{7}Be flux
- ☑ ^{8}B flux
- ☑ *pep* flux
- ☑ CNO limit

Intense purification campaign (2010-2011):
Record radiopurity level

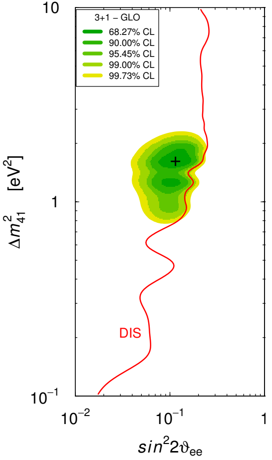
Phase II (2011-2017):
- ☑ *pp*
- ☑ CNO more stringent limit
- ☑ simultaneous *pp, pep,* ^{7}Be new fluxes
- ☑ ^{8}B new flux

New calibration campaign (January 2017)

SOX (April 2018-):
- ☐ Start data taking
- ☐ 2019 first results (~10^4 events in 1.5 y)

Sterile neutrino

ν_s: 4th neutrino eigenstate that doesn't interact weak (only gravitationally)



[PRD88(2013)073008]

experimental hints

- $\nu_e/\overline{\nu}_e$ disappearance:
  - reactor anomaly (solved with recent Daya Bay results [PRL118(2017)251801])
  - GALLEX/SAGE anomaly ($\approx 2.8\sigma$)
- $\nu_e/\overline{\nu}_e$ appearance:
  - miniBooNE and LSND accelerator anomalies ($\approx 3.8\sigma$)

$\Rightarrow$ sterile neutrino in eV mass range?

A global fit gives $0.82 < \Delta m^2_{41} < 2.14$ eV^2 (3σ)

(not yet updated after Daya Bay results)

$\Rightarrow$ more experimental data with a short-baseline:

☺ SOX (CeSOX now, CrSOX in the future?)

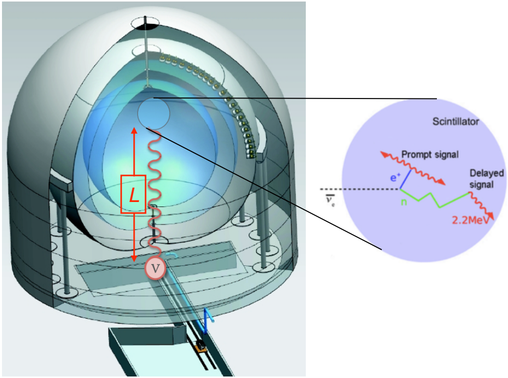
... further reactor experiments

SOX (Short distance Oscillation with boreXino)

A $\bar{\nu}_e$ source (^{144}Ce, 100÷150 kCi of activity) is placed underground, 8.5 m beneath the Borexino scintillator center (CeSOX)

Signature: $\bar{\nu}_e + p \to e^+ + n$ (inverse β-decay)

- e^+ Prompt: E and L info of $\bar{\nu}_e$ (resolution: 5% and 10 cm @ 1 MeV)
- n Delayed: time-space-energy coincidence (almost background free)



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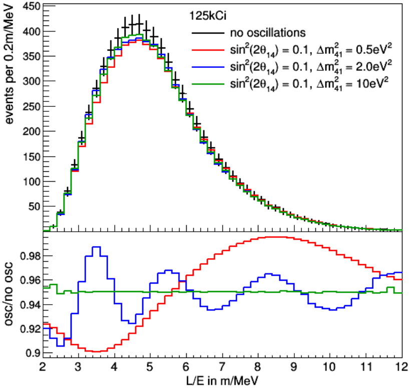


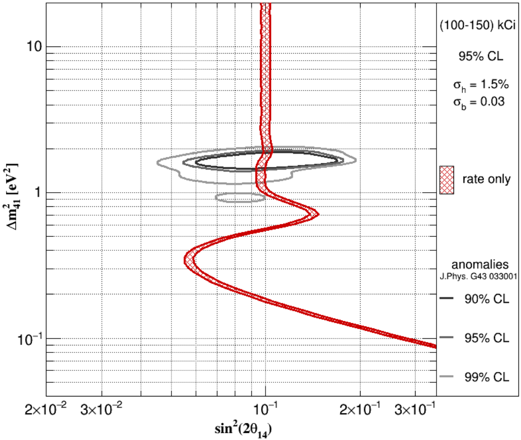
Observables (as a function of *E* & *L*):

1. Rate: counted/predicted w/o oscillation (disappearance)
2. Shape: periodic distribution

Examples:

- Disappearance + Periodic Oscillation (Rate+Shape)
- Disappearance + Periodic Oscillation (Rate+Shape)
- Disappearance only (Rate)

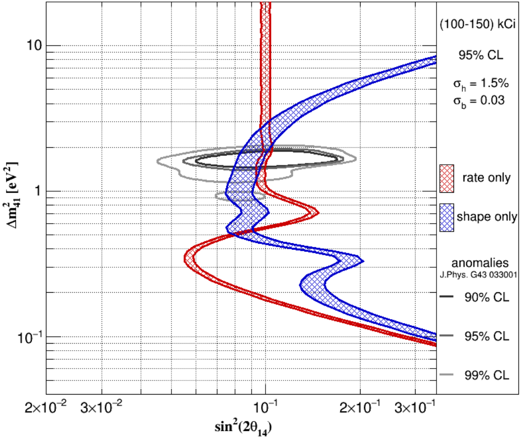
SOX sensitivity



- **Rate**: knowledge of
  - source activity monitoring
  - neutrino spectrum
  - fiducial volume
- **Shape**:
  - no dependence on systematics in scale
  - direct evidence of oscillation
- **Rate+Shape**: exclude great part of 99% region!

Grey contours: preferred region of the anomalous neutrino experiments @ CLs of 90%, 95% and 99% [J.Phys.G43(2016)033001]

SOX sensitivity



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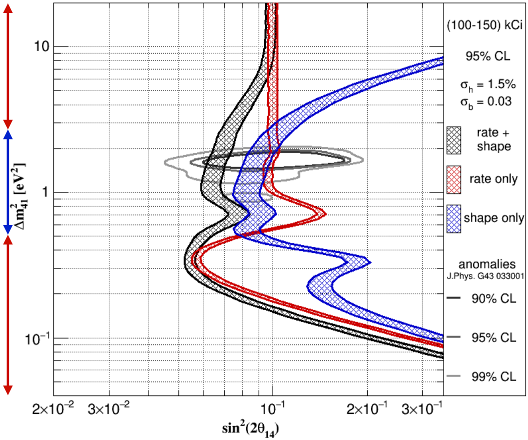

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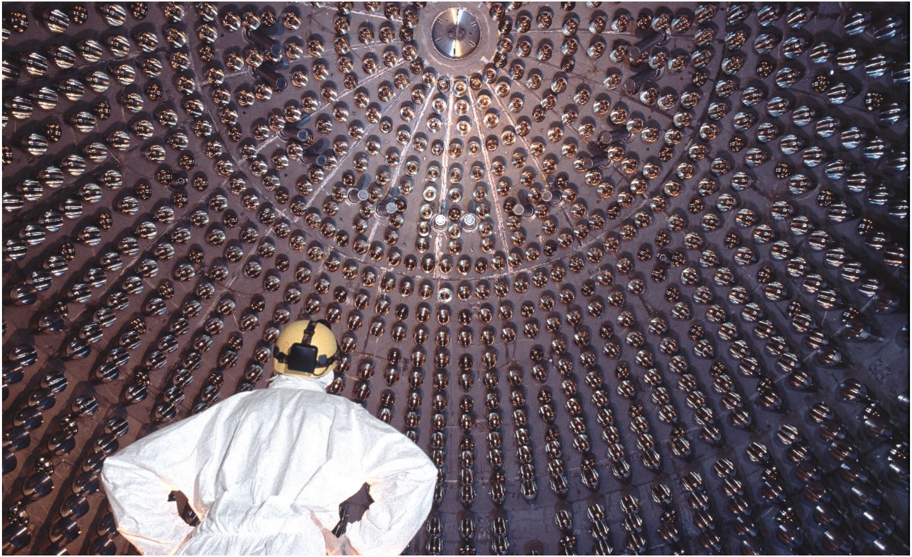
Stay tuned and Thank you!



Backups

Purification phase

Between Phase I and Phase II, 1 year of purification occurred:
6 cycles of water extraction reduced drastically the background contaminants!

Contaminants summary:

Isotope	Typical	Required	Phase I	Phase II
$^{14}C/^{12}C$	10^{-12} (cosmogenic)	$\leq 10^{-18}$	$(2.69 \pm 0.06) \cdot 10^{-18}$	unchanged
^{85}Kr	1 Bq/m^3 (air)	$\leq$ 1 cpd/100 t	(30 ± 5) cpd/100 t	$\leq$ 5 cpd/100 t
^{210}Bi		not specified	$\sim$ 40 cpd/100 t	(20 ± 5) cpd/100 t
^{210}Po		not specified	$\sim$ 20 cpd/100 t	unchanged
^{222}Rn	100 atoms/cm^3 (air)	$\leq$ 10 cpd/100 t	$\sim$ 1 cpd/100 t	unchanged
^{39}Ar	17 mBq/m^3 (air)	$\leq$ 1 cpd/100 t	$\ll ^{85}$Kr	$\ll ^{85}$Kr
^{40}K	$2 \cdot 10^{-6}$ (dust)	$\leq 10^{-18}$ g/g	$\leq 0.4 \cdot 10^{-18}$ g/g	unchanged
^{232}Th	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8) \cdot 10^{-18}$ g/g	$< 1.0 \cdot 10^{-19}$ g/g
^{238}U	$2 \cdot 10^{-5}$ (dust)	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5) \cdot 10^{-18}$ g/g	$< 0.8 \cdot 10^{-19}$ g/g

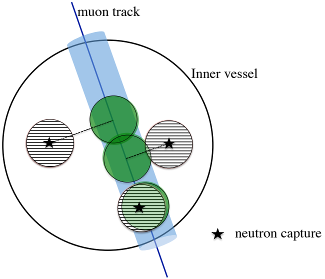
N.B.: Borexino core is the most radio-clean spot on Earth
with over 10 orders of magnitude below typical radioactivity levels

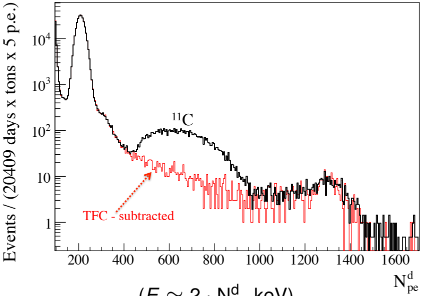
Three Fold Coincidence (TFC)

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

$$n + p \rightarrow \mathrm{D} + \gamma_{2.2\,\mathrm{MeV}} \qquad (250\ \mu\mathrm{s})$$

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e \qquad (\sim 30\ \mathrm{min})$$

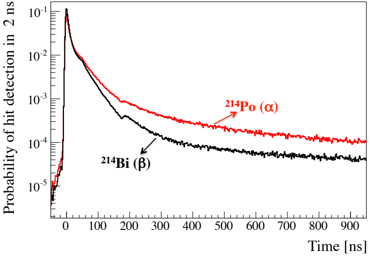


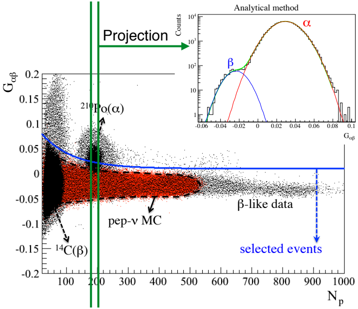


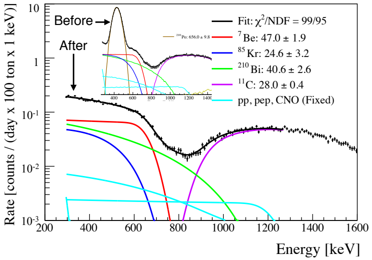
$(E \simeq 2 \cdot N^{d}_{pe}$ keV)

- Association of neutrons to a given μ track
- vetoing region in space and time to exclude decay signatures from ^{11}Cs associated to $\mu - n$ pairs

α/β Pulse-Shape Discrimination

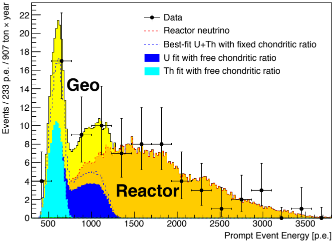






- Gatti's parameter $G_{\alpha\beta}$ is trained on ^{214}Bi-^{214}Po coincidences
- Current improvement with Multi-Layer-Perceptron (MLP) algorithm, based on neural network

Geo neutrinos: geological models



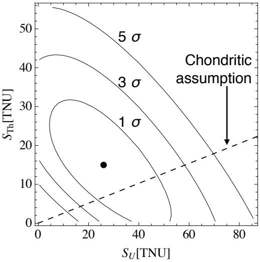
Detection through inverse β-decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$n + \mathrm{H} \rightarrow \mathrm{D} + \gamma \ (2.2\ \mathrm{MeV})$$

Exposure: 2056 days

[PRD92(2015)031101(R)]



Log-Likelihood fit: Geo-ν out of Reactor-ν:

- ^{232}Th and ^{238}U left free parameters
- Chondritic assumption: $m(^{238}\mathrm{U})/m(^{232}\mathrm{Th}) = 1/3.9$
- Real time spectroscopy of geo neutrinos is possible with larger exposure

1 TNU (Terrestrial Neutrino Unit) = 1 event/year/10^{32} protons