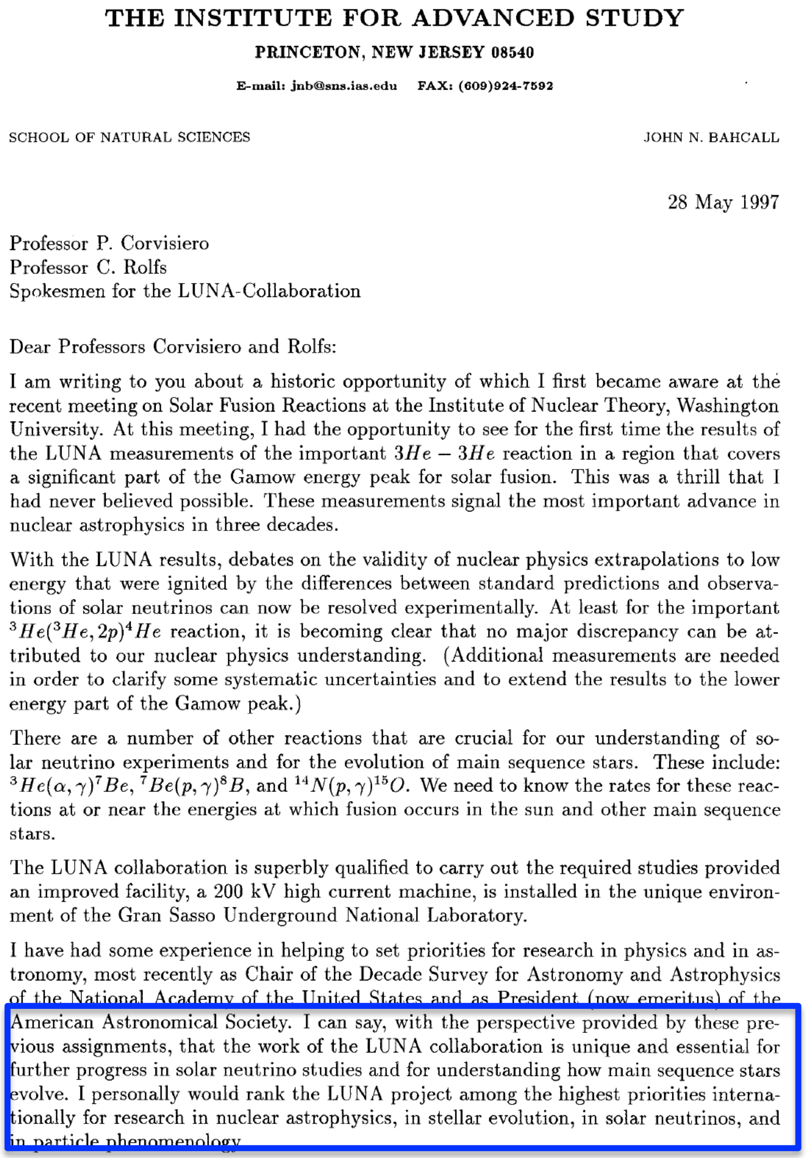
Laboratori Nazionali del Gran Sasso

Nuclear and neutrino astrophysics



THE INSTITUTE FOR ADVANCED STUDY
PRINCETON, NEW JERSEY 08540
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SCHOOL OF NATURAL SCIENCES JOHN N. BAHCALL

28 May 1997

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collaboration

Dear Professors Corvisiero and Rolfs:

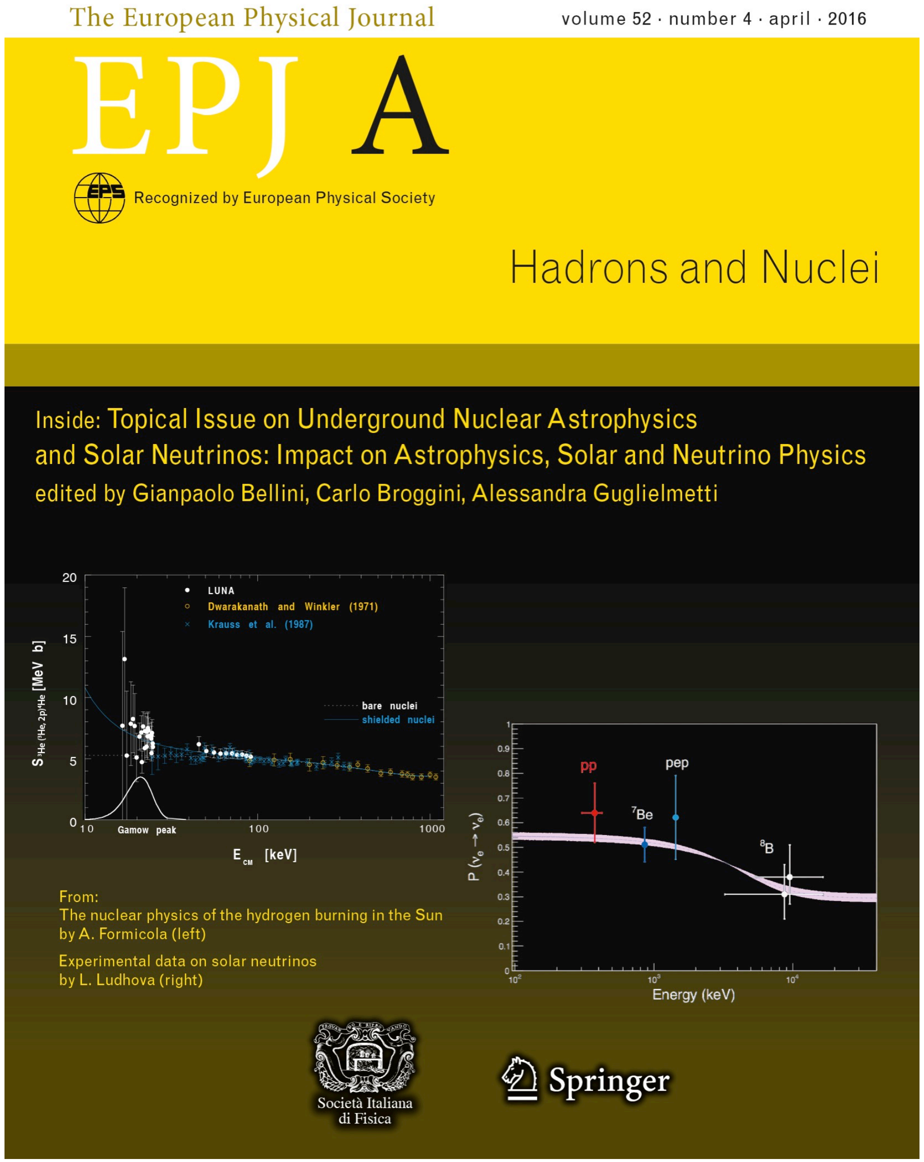
I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He-3He$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

With the LUNA results, debates on the validity of nuclear physics extrapolations to low energy that were ignited by the differences between standard predictions and observations of solar neutrinos can now be resolved experimentally. At least for the important $^3He(^3He,2p)^4He$ reaction, it is becoming clear that no major discrepancy can be attributed to our nuclear physics understanding. (Additional measurements are needed in order to clarify some systematic uncertainties and to extend the results to the lower energy part of the Gamow peak.)

There are a number of other reactions that are crucial for our understanding of solar neutrino experiments and for the evolution of main sequence stars. These include: $^3He(\alpha,\gamma)^7Be$, $^7Be(p,\gamma)^8B$, and $^{14}N(p,\gamma)^{15}O$. We need to know the rates for these reactions at or near the energies at which fusion occurs in the sun and other main sequence stars.

The LUNA collaboration is superbly qualified to carry out the required studies provided an improved facility, a 200 kV high current machine, is installed in the unique environment of the Gran Sasso Underground National Laboratory.

I have had some experience in helping to set priorities for research in physics and in astronomy, most recently as Chair of the Decade Survey for Astronomy and Astrophysics of the National Academy of the United States and as President (now emeritus) of the American Astronomical Society. I can say, with the perspective provided by these previous assignments, that the work of the LUNA collaboration is unique and essential for further progress in solar neutrino studies and for understanding how main sequence stars evolve. I personally would rank the LUNA project among the highest priorities internationally for research in nuclear astrophysics, in stellar evolution, in solar neutrinos, and in particular phenomenology.



The European Physical Journal volume 52 · number 4 · april · 2016

EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

Inside: Topical Issue on Underground Nuclear Astrophysics and Solar Neutrinos: Impact on Astrophysics, Solar and Neutrino Physics
edited by Gianpaolo Bellini, Carlo Broggini, Alessandra Guglielmetti

From:
The nuclear physics of the hydrogen burning in the Sun by A. Formicola (left)
Experimental data on solar neutrinos by L. Ludhova (right)

Società Italiana di Fisica
Springer

Globular cluster M 10

Red giant stars:
H→He via CNO cycles in
H shell surrounding He core

Horizontal branch stars:
He→C, O in core
H→He in shell

Main sequence stars:
H→He via pp chains in core

Relate CN and ^{8}B fluxes

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794}\, x_N^{0.212}\, D^{0.172}$$

$$\times \left[L_\odot^{0.515}\, O^{-0.016}\, A^{0.308}\right]$$

⟶ Temp. dep.

$$\times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]$$

⟶ Nuclear rates

$$\times \left[x_{\mathrm{O}}^{0.003}\, x_{\mathrm{Ne}}^{-0.005}\, x_{\mathrm{Mg}}^{-0.003}\, x_{\mathrm{Si}}^{-0.001}\, x_{\mathrm{S}}^{-0.001}\, x_{\mathrm{Ar}}^{0.001}\, x_{\mathrm{Fe}}^{0.003}\right]$$

⟶ Temp. dep.

Borexino is a low energy threshold (~ 200 keV) real time experiment

Core of the detector

≈100 tons

Ultra high-purity liquid scintillator

PC+PPO

Detection principle

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

Neutrino-electron elastic scattering interaction

It is possible to distinguish the different neutrino contributions: **Spectroscopy**

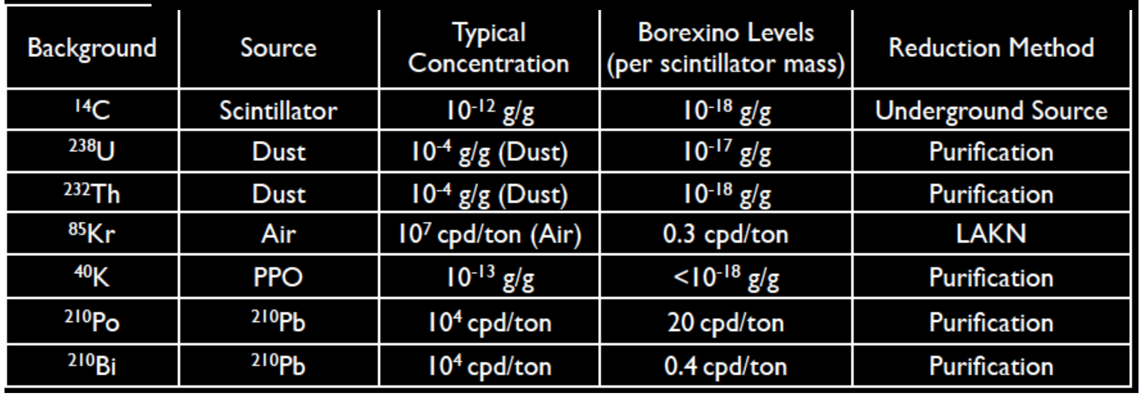
Unlike Cherenkov light, the scintillation **light is emitted isotropically**; this means that the ν induced events can't be distinguished from other γ/β events due to **natural radioactivity**.

Signal to noise ratio:
In order to have a signal to noise ratio on the order of 1, the ^{238}U (and ^{232}Th) intrinsic contamination can't exceed **10^{-16} g/g**! (*this means 9-10 orders of magnitude less radioactive then anything on Earth*)

Several techniques have been applied:

- Distillation,
- Water extraction,
- Nitrogen stripping,
- ecc…..

Unprecedented low levels of background



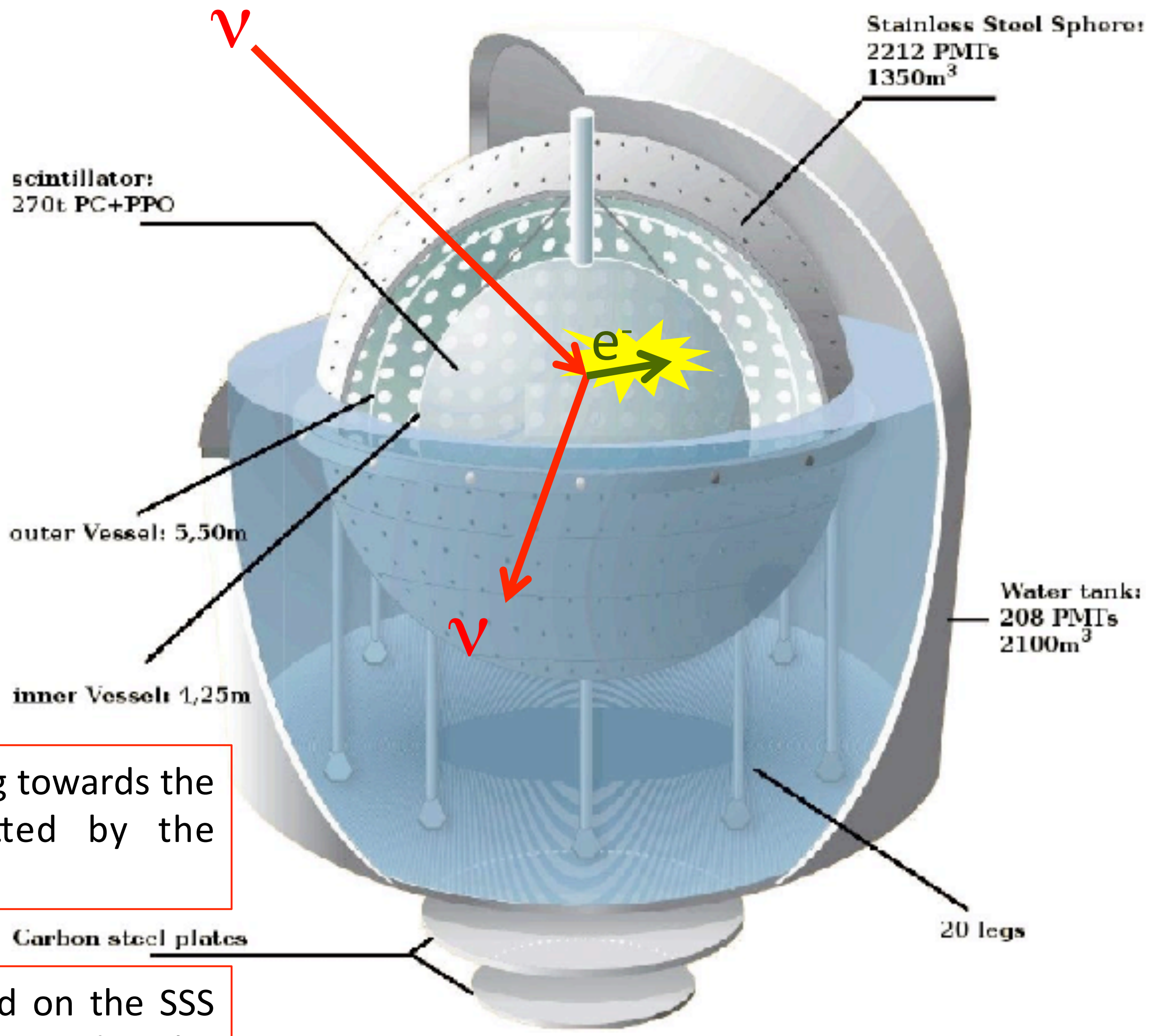
Background	Source	Typical Concentration	Borexino Levels (per scintillator mass)	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Underground Source
^{238}U	Dust	10^{-4} g/g (Dust)	10^{-17} g/g	Purification
^{232}Th	Dust	10^{-4} g/g (Dust)	10^{-18} g/g	Purification
^{85}Kr	Air	10^{7} cpd/ton (Air)	0.3 cpd/ton	LAKN
^{40}K	PPO	10^{-13} g/g	$<10^{-18}$ g/g	Purification
^{210}Po	^{210}Pb	10^{4} cpd/ton	20 cpd/ton	Purification
^{210}Bi	^{210}Pb	10^{4} cpd/ton	0.4 cpd/ton	Purification

Borexino al LNGS

300 tons of liquid scintillator (PC+PPO) *contained in a* ***nylon vessel*** *of 4.25 m radius*

1000 tons of ultra-pure buffer liquid (pure PC) *contained in a* ***stainless steel sphere*** *of 7 m radius*

2000 tons of ultra-pure water *contained in a* ***cylindrical dome***



2200 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator

200 photomultiplier tubes mounted on the SSS pointing outwards to detect light emitted in the water by muon scrossing the detector

Borexino's history

Improved radiopurity

^{85}Kr rate compatible with 0
^{210}Bi reduced by a factor ≈ 3;
^{232}Th and ^{238}U negligible;

1° Purification

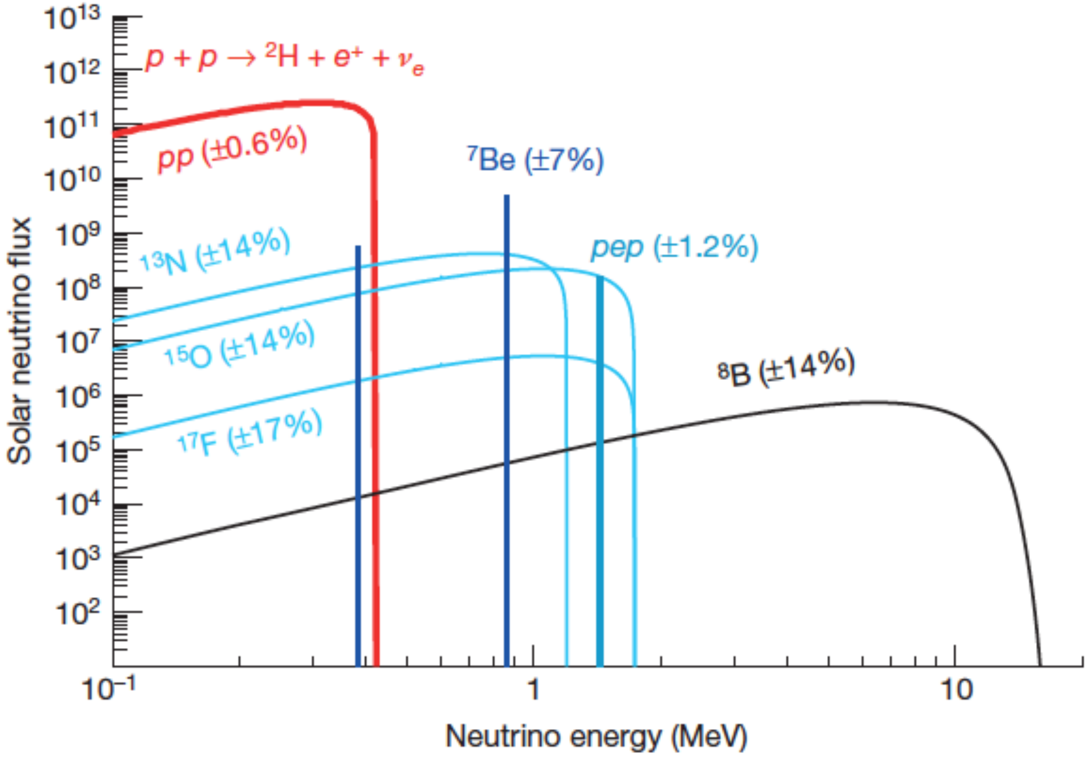
2007 **Phase I** 2010

2° Purification

2012 **Phase II** 2015

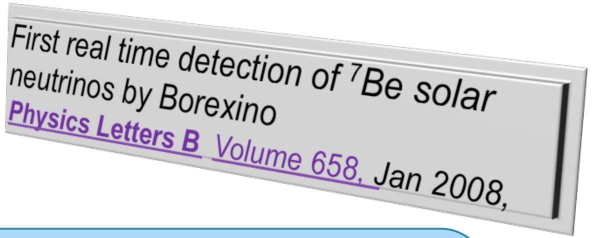
- pp-ν: 1st observation in real time
- Seasonal modulation of ^{7}Be signal

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



We have to add the systematic error:

$$\boxed{49 \pm 3_{stat} \pm 4_{syst} \quad cpd/100\ tons}$$


First real time detection of ⁷Be solar neutrinos by Borexino
Physics Letters B Volume 658, Jan 2008,

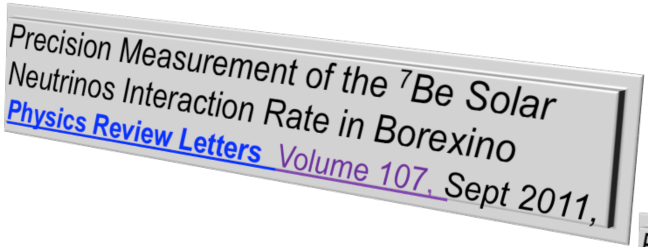
Expected ^{7}Be interaction rate for MSW-LMA oscillations:

$$\boxed{48 \pm 4 \quad cpd/100\ tons}$$ High Metallicity

$$\boxed{44 \pm 4 \quad cpd/100\ tons}$$ Low Metallicity

After 740 live days and a **calibration campaign** Borexino published the new result on **^{7}Be rate with a total error at 4.6%** (SSM prediction at 7%)

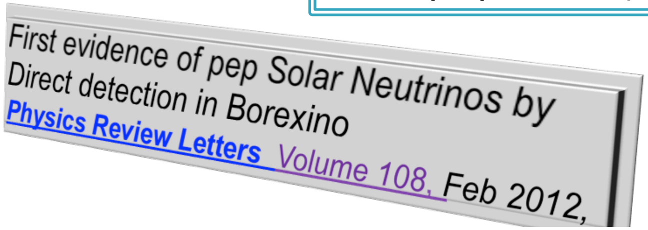
$$\boxed{46.0 \pm 1.5(stat) \begin{matrix} +1.5 \\ -1.6 \end{matrix} (syst) \quad cpd/100\ tons}$$


Precision Measurement of the ⁷Be Solar Neutrinos Interaction Rate in Borexino
Physics Review Letters Volume 107, Sept 2011,

Total fluxes from direct measurement:

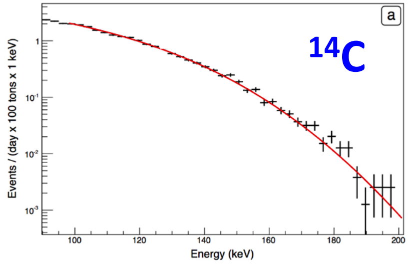
pep flux: $(1.6 \pm 0.3) \cdot 10^8\ cm^{-2}s^{-1}$
CNO flux: $< 7.4 \cdot 10^8\ cm^{-2}s^{-1}$

SSM pep flux: $(1.44 \pm 0.02) \cdot 10^8\ cm^{-2}s^{-1}$


First evidence of pep Solar Neutrinos by Direct detection in Borexino
Physics Review Letters Volume 108, Feb 2012,

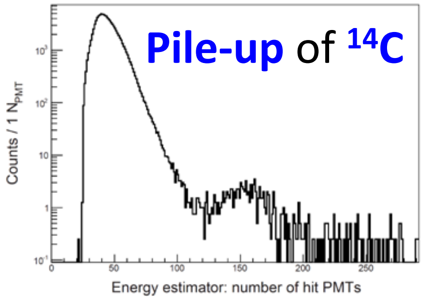
In order to disentangle the signal from the background we need a spectral fit

We have to determine independently the rate of the two main backgrounds (^{14}C and pile-up of ^{14}C) in order to constrain them in the fit procedure.



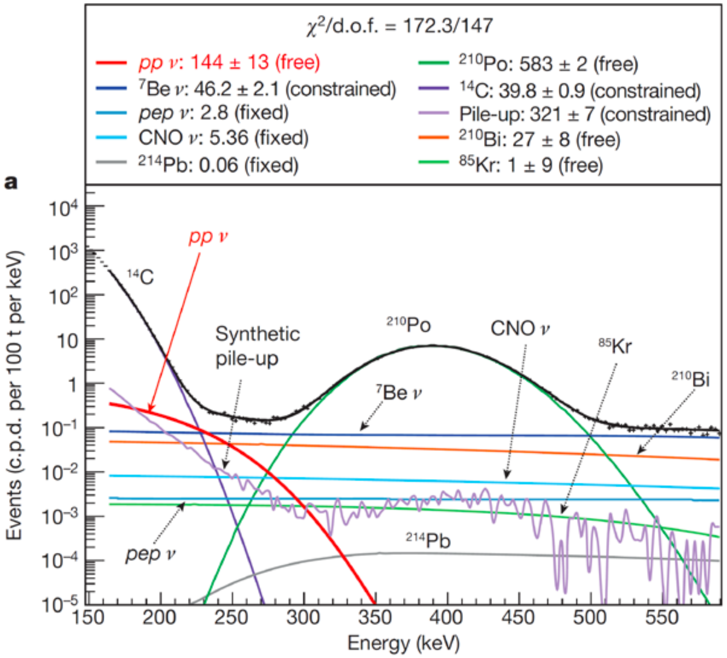
- **^{14}C** rate determined from an independent class of events less affected by the trigger threshold;

$$^{14}\text{C rate} = (40 \pm 1)\ \text{Bq/100tons}$$



- **Pile-up** of **^{14}C** rate and shape determined by a data-driven method (synthetic pile-up);

$$Pile-up\ \text{rate}\ (^{14}\text{C-}^{14}\text{C}) = (154 \pm 10)\ cpd/\text{100tons}$$



$$pp - \nu\ rate = 144 \pm 13(stat) \pm 10(sys) \quad cpd / 100tons$$

$$predicted\ rate\ SSM(HM) + MSW(LMA) = 132 \pm 2 \quad cpd / 100tons$$

Neutrinos from the primary proton-proton fusion process in the Sun
Nature 512, Aug 2014,

what next?

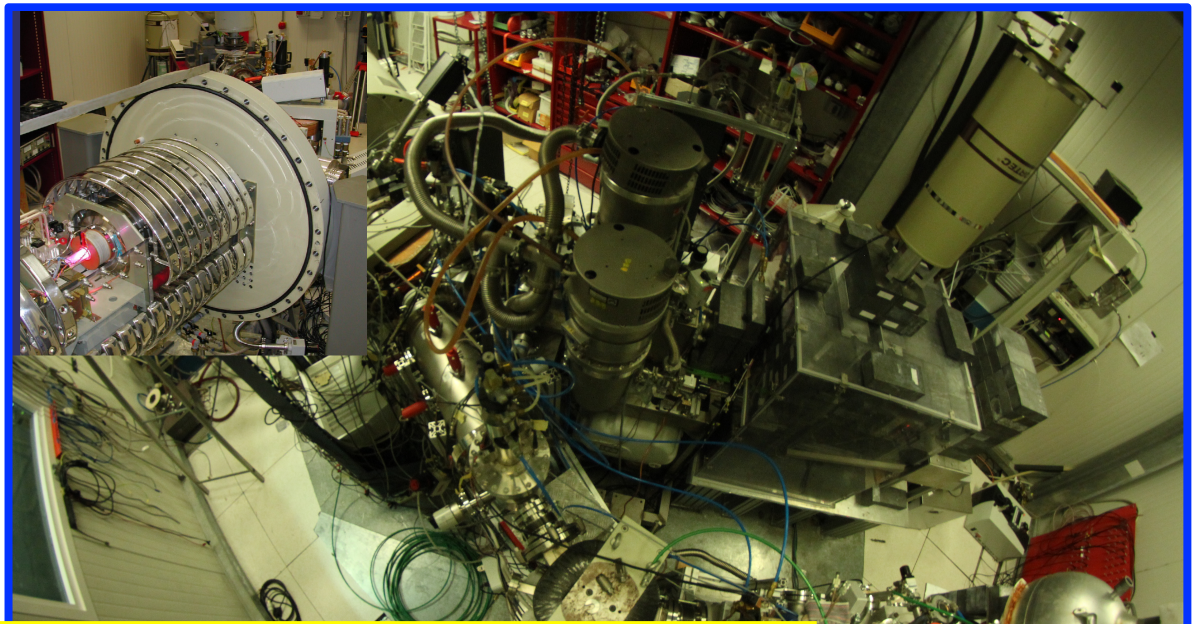
A **new calibration campaign** will take place this year for a complete analysis of Phase II in order to further reduce systematic uncertainties

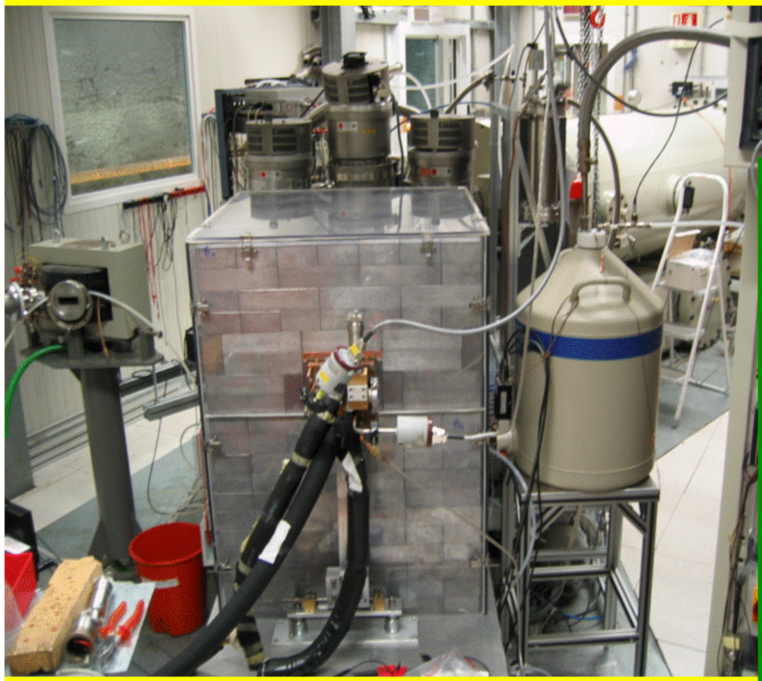
- **Improve measurements** (reduced errors) obtained so far;
- Attempt to measure neutrino from **CNO**-cycle;
- Plus others **non-solar neutrinos** measurements (Geo-neutrinos. Artificial ν-sources).

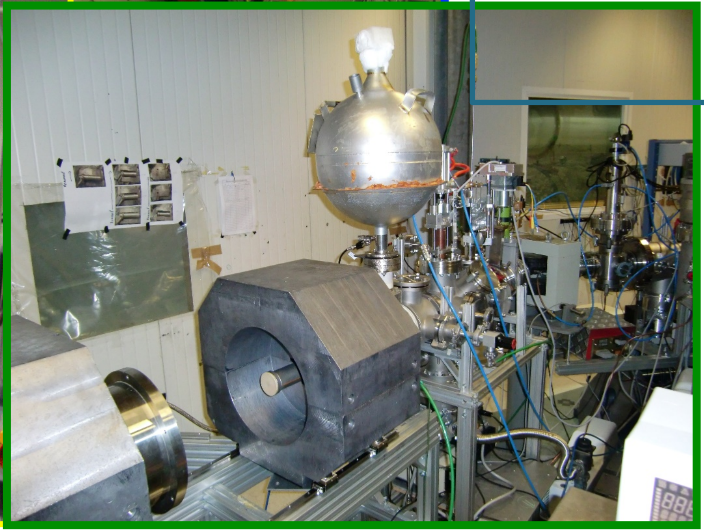
the Borexino Collaboration

INFN
Milano
München
Heidelberg
Hamburg
Mainz
Gran Sasso
Perugia
Genova
Napoli
TU Dresden
Jagiellonian Kraków
JINR Dubna
Virginia Tech
Princeton
Houston
UMass Amherst
Paris
Moscow
St. Petersburg
Kurchatov Moscow
Los Angeles

LUNA is dedicated to direct cross section measurements for astrophysics interest







$U_{terminal} = 50 – 400\text{kV}$

$I_{max} = 500\mu\text{A}$ (on target)

$\Delta E = 0.07\text{keV}$

Allowed beams: H^+, ^4He, (^3He)

$R_{lab} = \sigma \cdot \varepsilon \cdot I_p \cdot \rho \cdot N_{av}/A$

$\text{pb} < \sigma < \text{nb}$

$\varepsilon \sim 10\ \%$

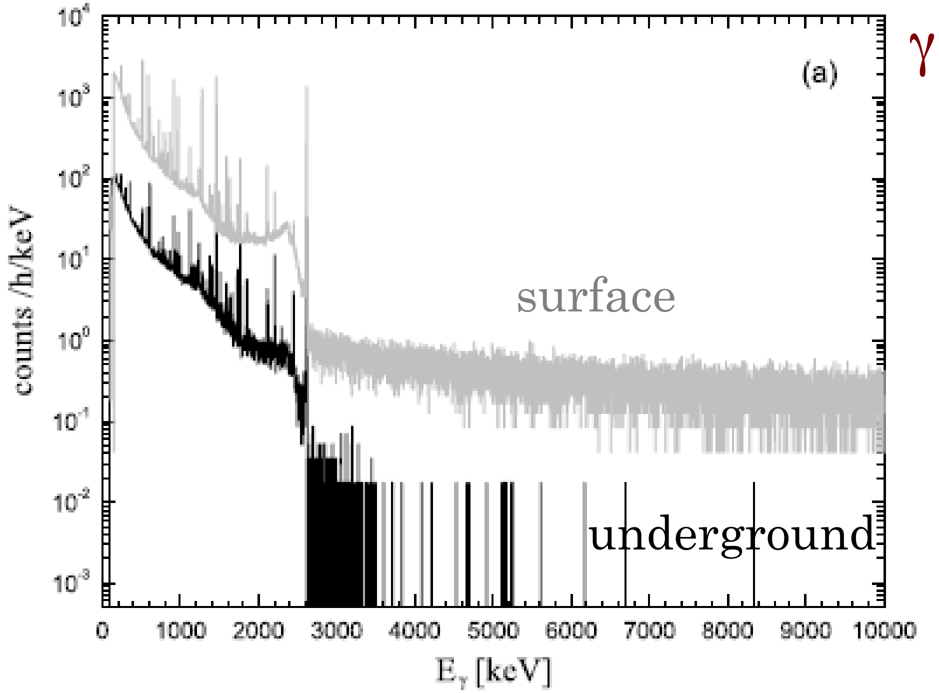
$I_P \sim \text{mA}$

$\rho \sim \mu\text{g/cm}^2$

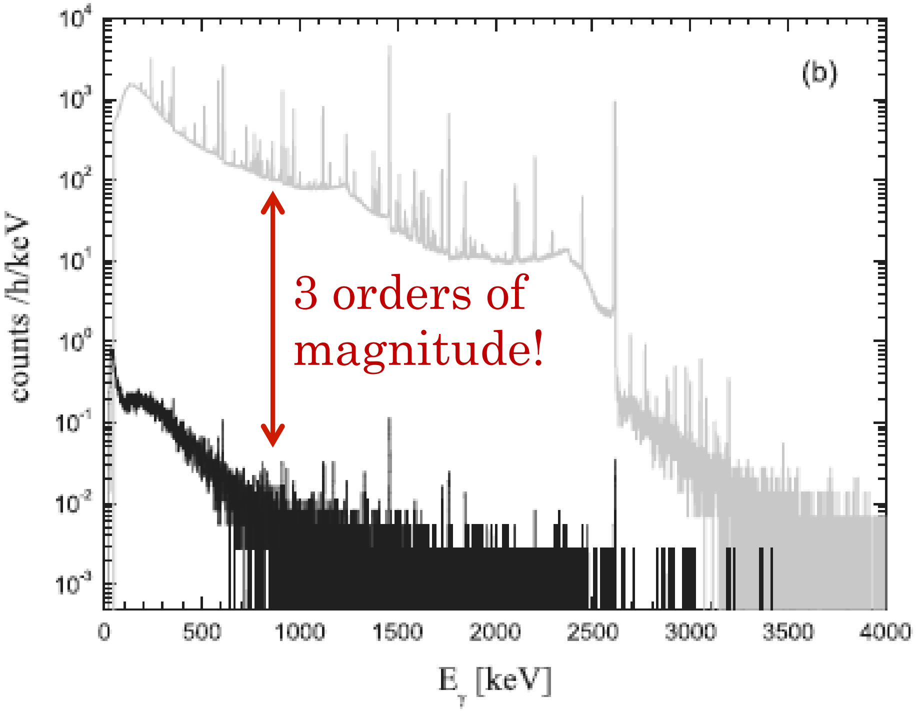
event/month $< R_{lab} <$ event/day

$\sigma(E) = \mathbf{S(E)}/E\exp(-2\eta\pi)$

γ-ray natural background



between E_γ =7 and 12MeV the bck suppression factor is 100 times better than was achieved in laboratories using active shielding



underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed

0.3 m^3 Pb-Cu shield suppression three orders of magnitude below 2MeV

Key reactions measured at LUNA 50kV-400kV

pp chain

$p + p \rightarrow d + e^+ + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

84.7 %

13.8 %

${}^3He + {}^3He \rightarrow \alpha + 2p$

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

13.78 %

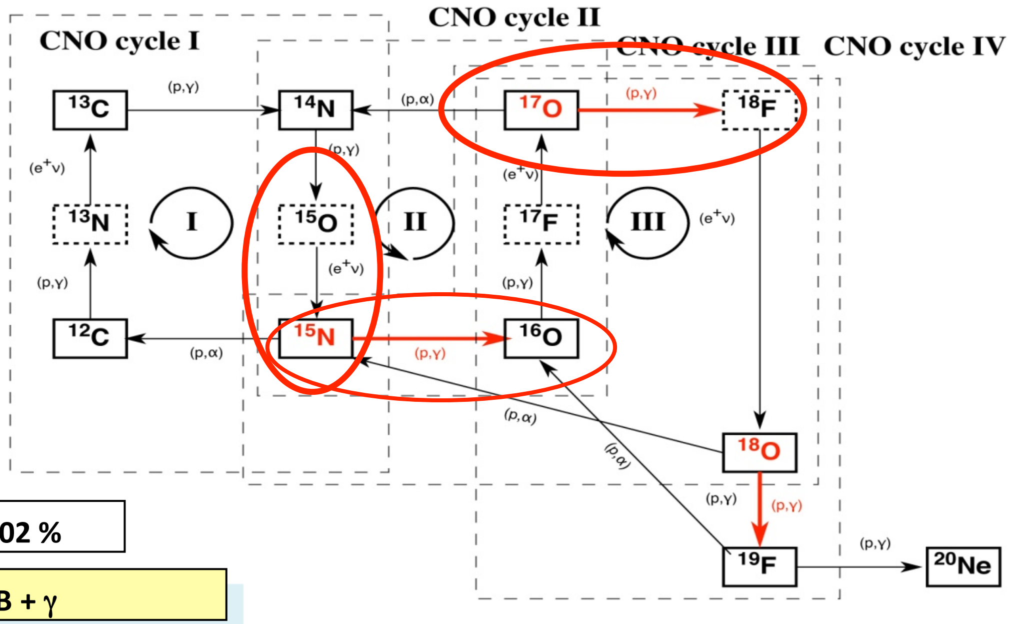
0.02 %

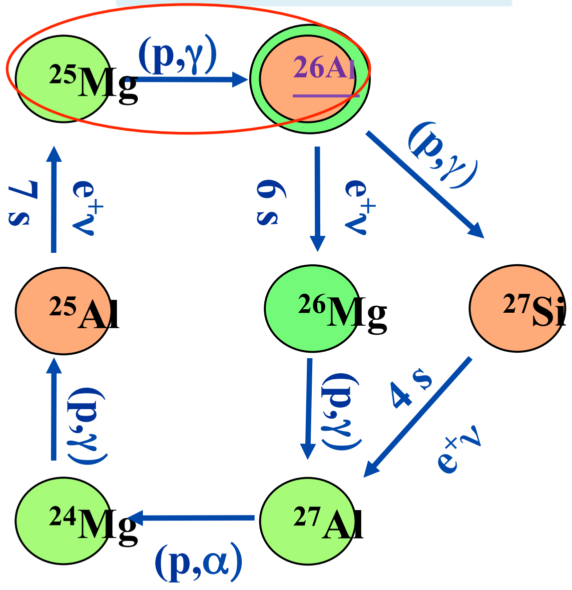
${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

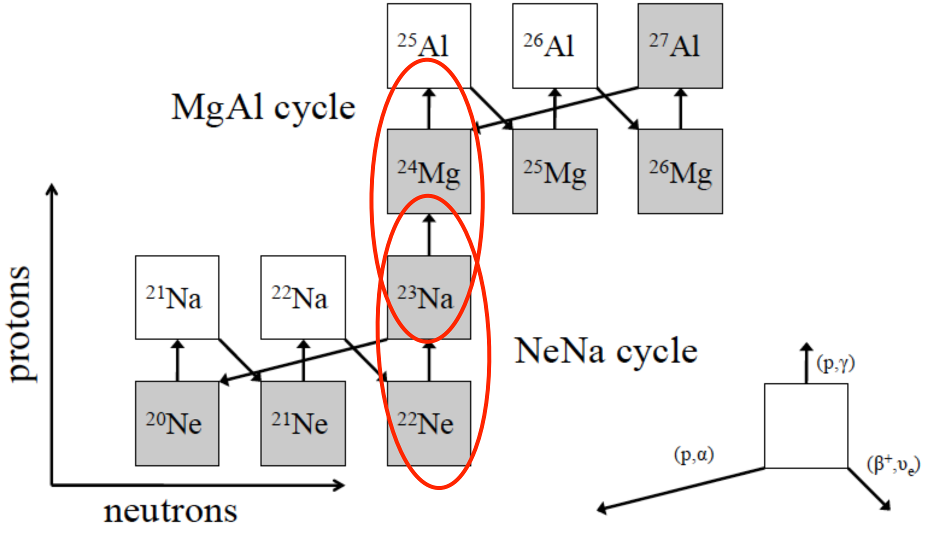
${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$

${}^8B \rightarrow 2\alpha + e^+ + \nu_e$







Importance of experimental reaction rates for understanding of nucleosynthesis, energy production in stars, solar neutrino problem, theories of stellar evolution

The case of the $^{14}N(p,\gamma)^{15}O$ reaction

The rate of the energy production in the CNO cycle ($T>10^7$K and $M>1.1M_\odot$) is governed by the $^{14}N(p,\gamma)^{15}O$ slowest reaction, a variation of its rate can influence:

- Neutrino fluxes of $\Phi(^{13}N)$ and $\Phi(^{15}O)$ depend almost linearly on $S_{14}(0)$
- Age of Globular Cluster

After LUNA measurments

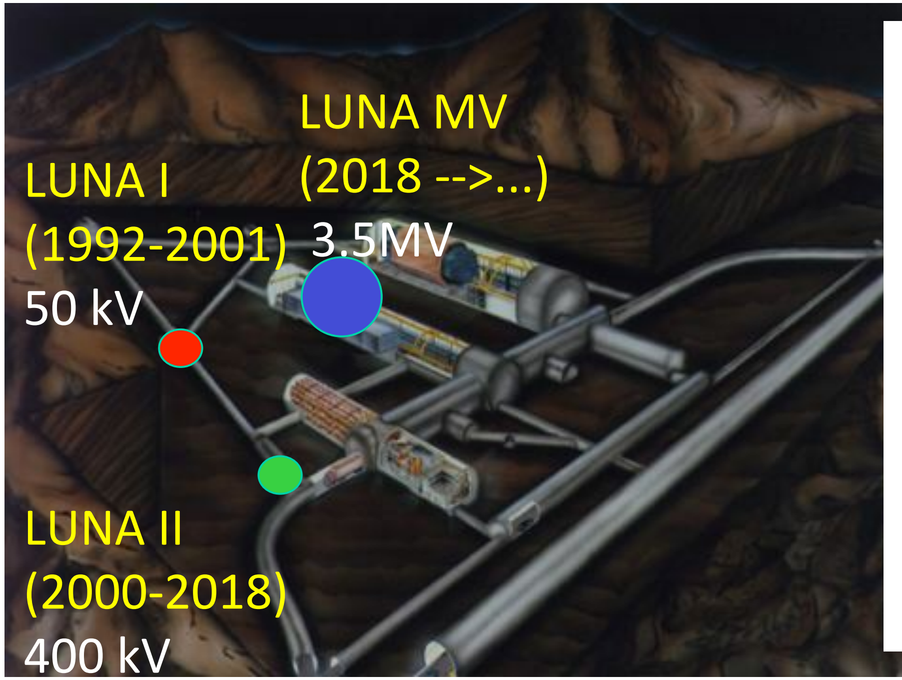
- CNO neutrino flux decreases a factor ≈ 2
- Globular Cluster age increases of 0.7 – 1 Gyr

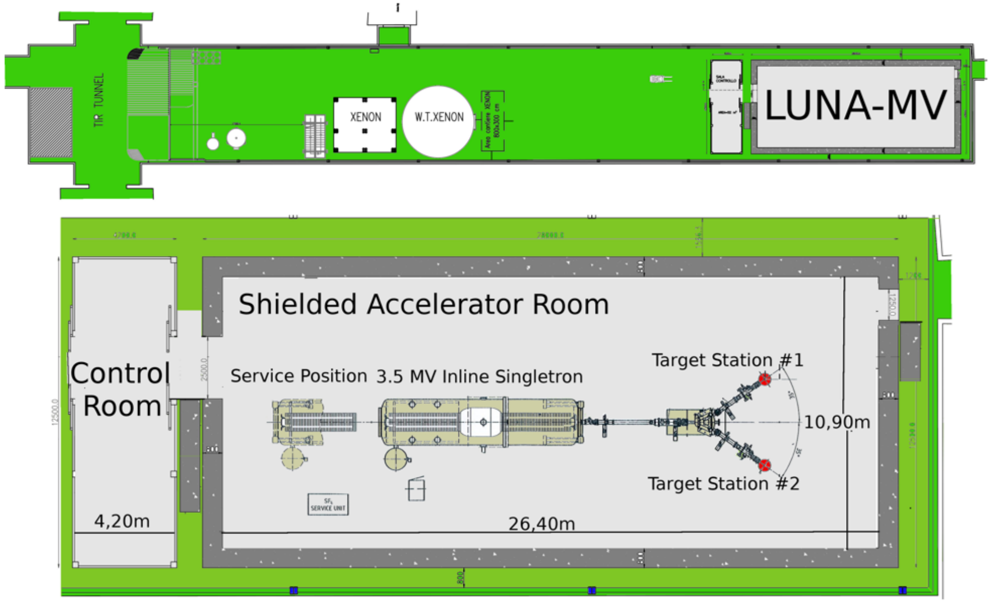
Formicola et al. Phys.Lett.B 591 (2004) 61
G.Imbriani et al. (2005)

Marta et al. PRC 78 (2008) 022802

LUNA MV project

LUNA MV will be installed in the North part of Hall B of LNGS





Funded by the Italian Research Ministry as a “premium project” with 5.3 Meuro.
HVEE has been selected through a public tender as provider
of the new accelerator (0.3<TV<3.5 MV) able to deliver intense H, He and C beams
Expected installation at LNGS in 2018. First experiment in 2019

PI of the project: P.Prati
DirectorExecutiveContract for the accelerator : M.Junker

LUNA MV- scientific program (2019 ….)

$^{13}C(\alpha,n)^{16}O$: enriched ^{13}C solid or gas target. Neutron detector
Data taking at LUNA 400 kV in 2017-2018.

$^{22}Ne(\alpha,n)^{25}Mg$: enriched ^{22}Ne gas target. Neutron detector.

$^{12}C(\alpha,\gamma)^{16}O$: ^{12}C solid target depleted in ^{13}C and alpha beam or a jet gas target and ^{12}C beam.

$^{12}C+^{12}C$: solid state target. Gamma and particle detectors

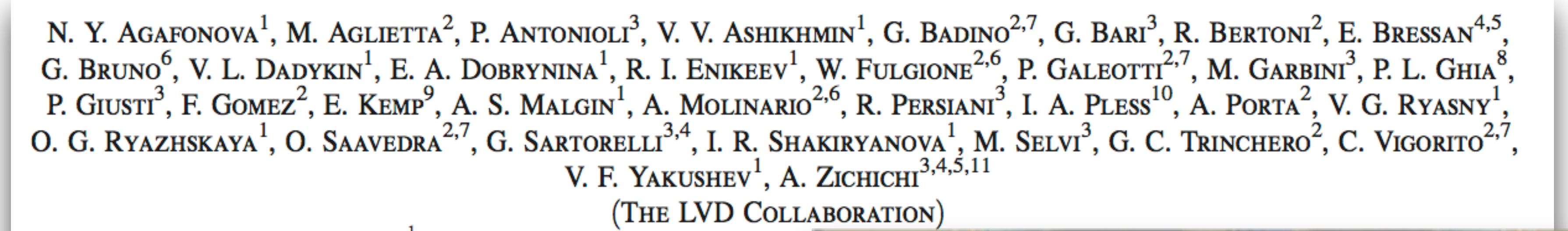
Commissioning measurement: $^{14}N(p,\gamma)^{15}O$. High scientific interest for revised data covering a wide energy range (400 keV- 3.5 MeV).

On December 1st, 2016 a workshop will be organized at LNGS both to celebrate the first 25-year period of LUNA activities ("*Silver Moon*") and to present the perspectives for the next decades :http://silvermoon.lngs.infn.it/

The LUNA COLLABORATION (as of May 2016)

- A. Boeltzig*, G.F. Ciani*, L. Di Paolo, A. Formicola, I. Kochanek, M. Junker, **-** INFN LNGS / *GSSI, Italy
- D. Bemmerer, M. Takacs, T. Szucs **-** HZDR Dresden, Germany
- C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo, D. Piatti **-** Università di Padova and INFN Padova, Italy
- C. Gustavino **-** INFN Roma1, Italy
- Z. Elekes, Zs. Fülöp, Gy. Gyurky **-**MTA-ATOMKI Debrecen, Hungary
- O. Straniero **-**INAF Osservatorio Astronomico di Collurania, Teramo, Italy
- F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli **-**Università di Genova and INFN Genova, Italy
- A. Guglielmetti, D. Trezzi **|** Università di Milano and INFN Milano, Italy
- A. Best, A. Di Leva, G. Imbriani, **|** Università di Napoli and INFN Napoli, Italy
- G. Gervino **|** Università di Torino and INFN -Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson **|** University of Edinburgh, United Kingdom
- G. D'Erasmo, E.M. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino, L. Schiavulli, A. Valentini**|** Università di Bari and INFN Bari, Italy

The LVD SN neutrino observatory



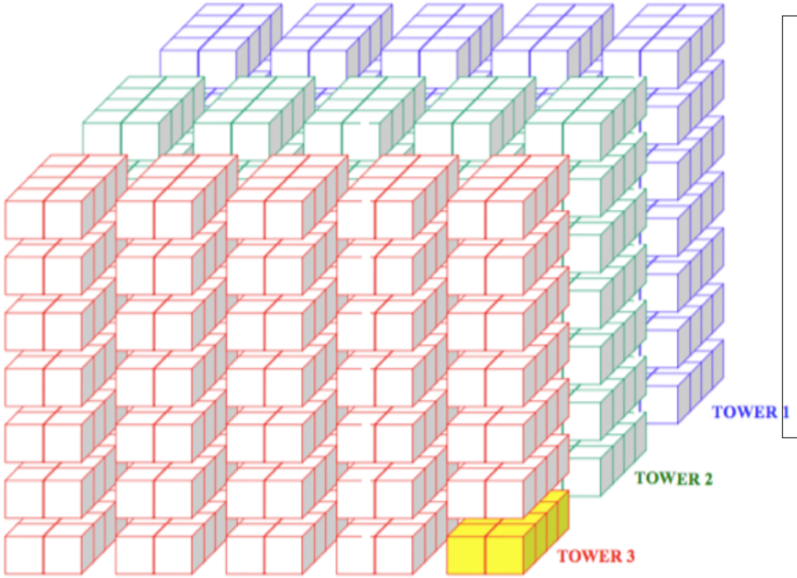
N. Y. Agafonova[1], M. Aglietta[2], P. Antonioli[3], V. V. Ashikhmin[1], G. Badino[2,7], G. Bari[3], R. Bertoni[2], E. Bressan[4,5], G. Bruno[6], V. L. Dadykin[1], E. A. Dobrynina[1], R. I. Enikeev[1], W. Fulgione[2,6], P. Galeotti[2,7], M. Garbini[3], P. L. Ghia[8], P. Giusti[3], F. Gomez[2], E. Kemp[9], A. S. Malgin[1], A. Molinario[2,6], R. Persiani[3], I. A. Pless[10], A. Porta[2], V. G. Ryasny[1], O. G. Ryazhskaya[1], O. Saavedra[2,7], G. Sartorelli[3,4], I. R. Shakiryanova[1], M. Selvi[3], G. C. Trinchero[2], C. Vigorito[2,7], V. F. Yakushev[1], A. Zichichi[3,4,5,11]

(The LVD Collaboration)

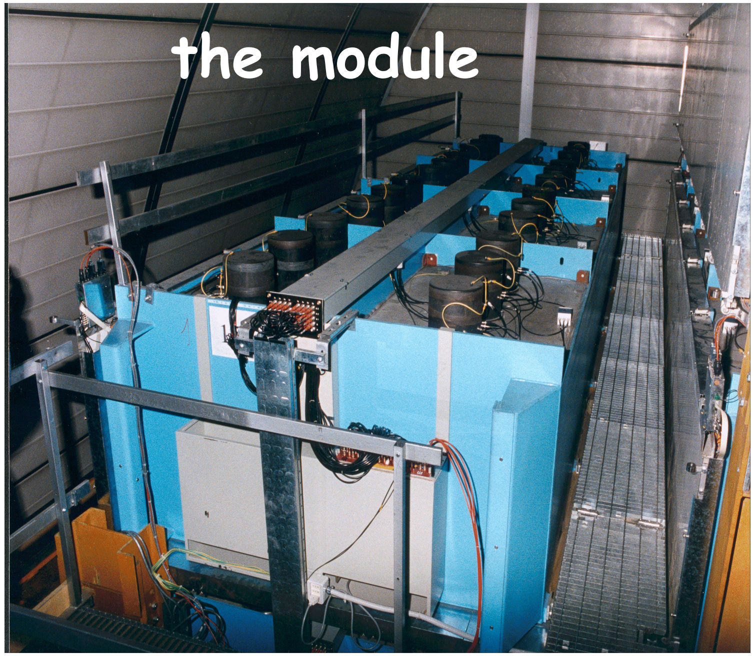
[1] Institute for Nuclear Research, Russian Ac
[2] INFN-Torino, OATo-Torino, I-10100 Torino, Ita
[3] INFN-Bologna, 4012
[4] University of Bologna, I-4
[5] Centro Enrico Fermi, I-
[6] INFN-Laboratori Nazionali del Gran Sasso and Gran
[7] Dep. of Physics, University of T
[8] CNRS-IN2P3, Paris, Laboratoire de Physique N
Universités Paris 6 et
[9] University of Campinas, 13083-
[10] Massachusetts Institute of Technology,
[11] CERN, Geneva,

The Large Volume Detector
taking data since 1992.
LVD is sensitive to neutrino burst from
gravitational stellar collapses
with full detection prabability over the Galaxy

Detector characteristics



- 1260 m^3 of scintillator
- 3 towers
- 105 modules
- 840 counters
- 2520 PMTs



Each counter is viewed on the top by 3 PMTs FEU49b or FEU125.

Detector sensitivity

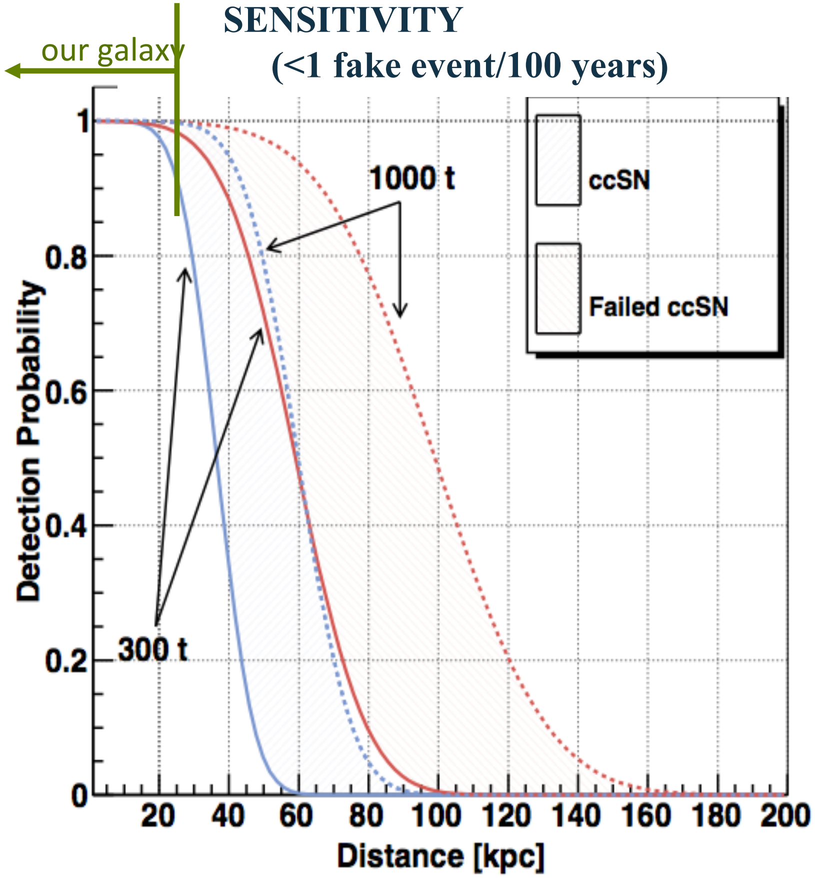
Search for neutrino bursts from Core Collapse Supernovae

LVD is observing the Galaxy since 1992 with a total duty cycle of 93.7% over 24 years (>99% since 2001).

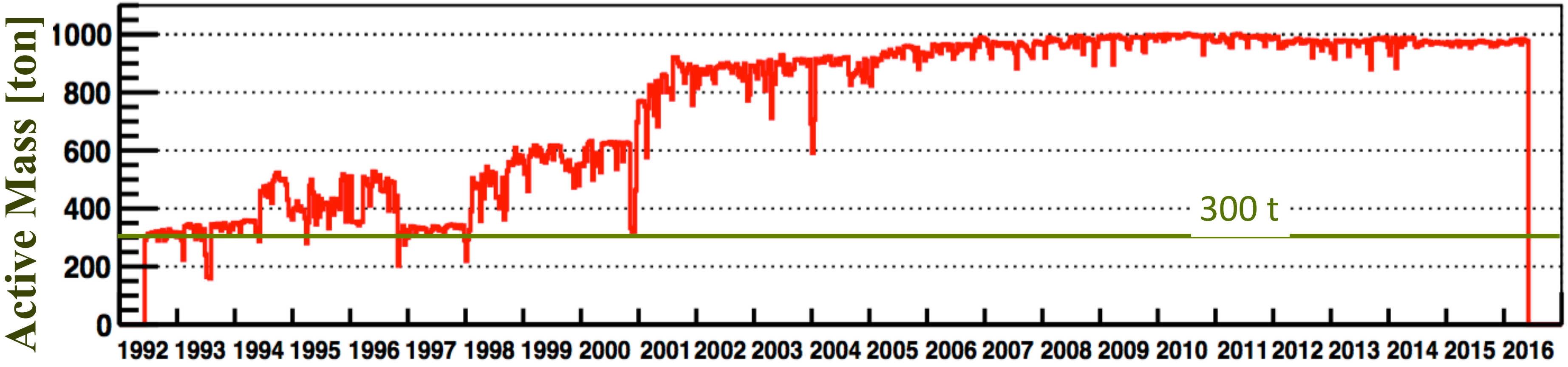
The resulting 90% c.l. upper limit to the rate of gravitational stellar collapses at distances ($D \leq 25$ kpc), is the most stringent existing limit [ApJ, 802:47, 2015].

The up-to date limit is: **R < 0.10 events/year**

LVD STAND ALONE SENSITIVITY
(<1 fake event/100 years)



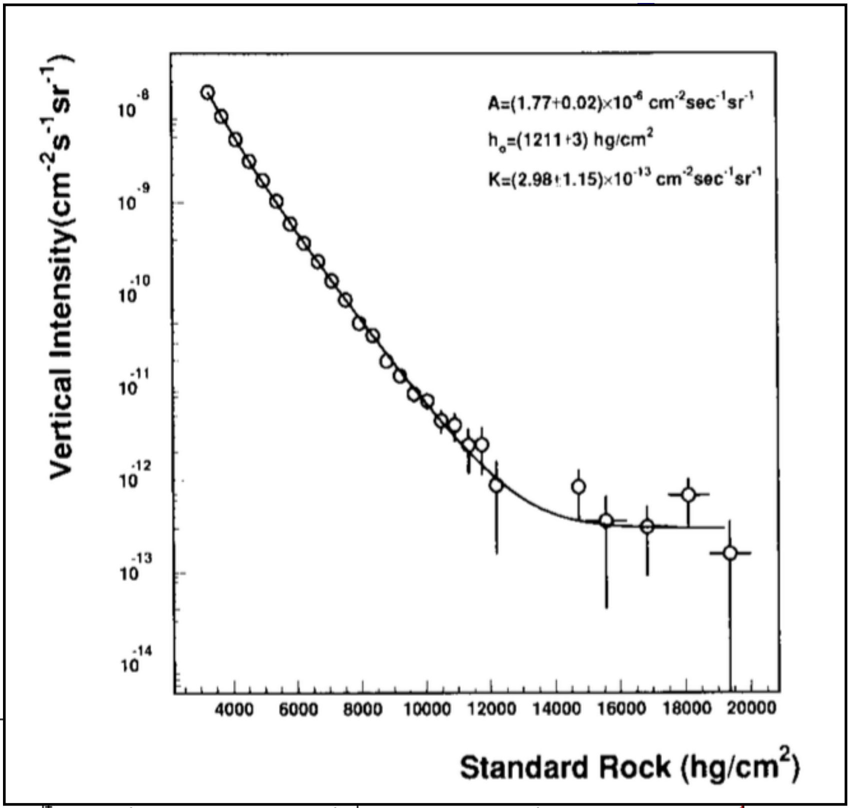
LVD detection probability versus source distance for the imitation frequency of 1/100 yr^{-1}. The blue and red bands correspond to the case of standard core-collapse (ccSN) and failed supernovae, respectively.

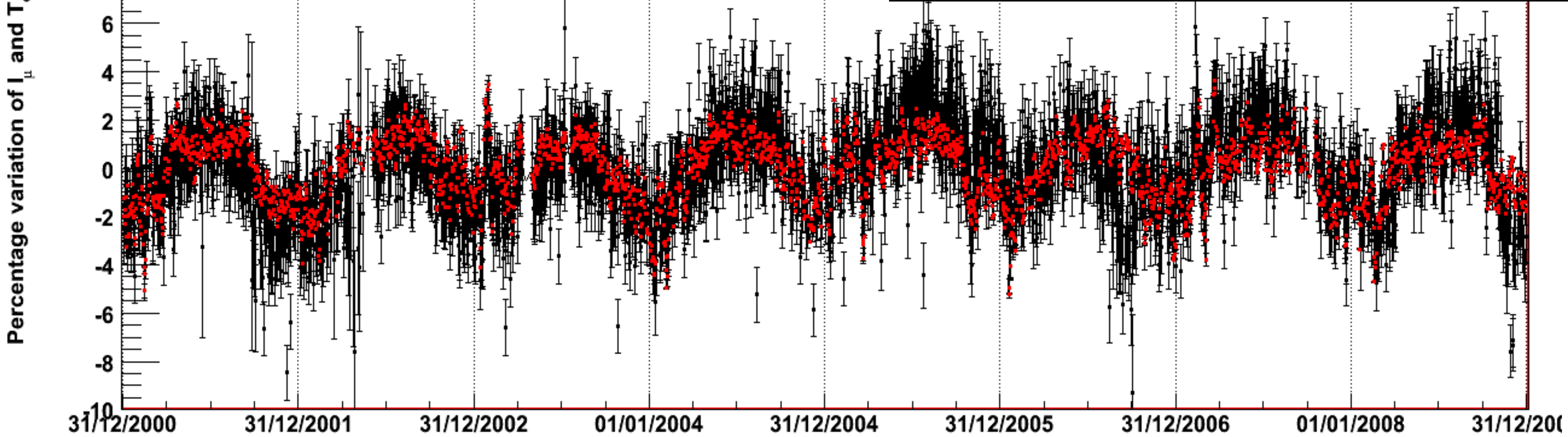


LVD and cosmic muons

More than 10 publications regarding atmospheric muons and neutrino induced muons underground.

Analysis of the seasonal modulation of the cosmic muon flux in the LVD detector.





Competitors

$E_{tot}=2.6\cdot10^{53}$ erg. D = 10 kpc
normal hierarchy - adiabatic

$\bar{\nu}_e$ radius of neutrino-sphere Rc = 17.4 km
initial temp. of cooling phase Tc = 4.47 MeV

ν_e initial temp. of cooling phase = 0.8·Tc

ν_x initial temp. of cooling phase = 1.3·Tc

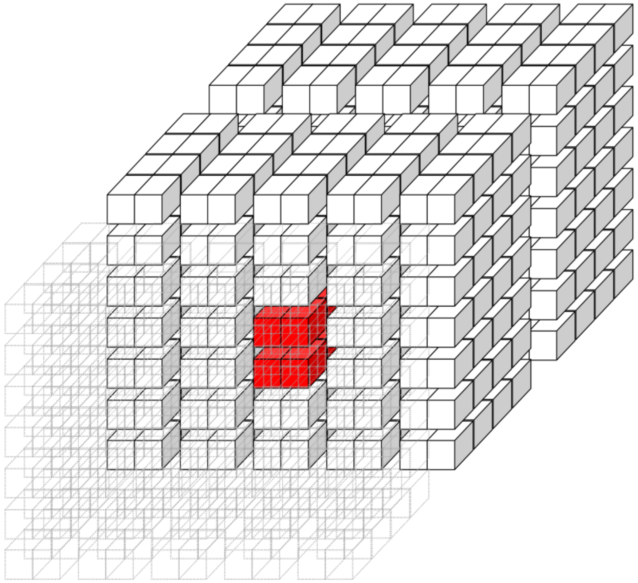
	Interaction	LVD	Borexino	KamLAND	SuperK	IceCube
$\bar{\nu}_e$	$\bar{\nu}_e + p$	274	65	304	7150	613000
ν_e	$\nu_i + e^-$	10	4	14	260	18000
	$\nu_e +^{12} C$ (CC)	5	2	5	-	-
	$\bar{\nu}_e +^{12} C$ (CC)	3	1	4	-	-
	$\nu_i +^{12} C$ (NC)	7	4	13	-	-
	$\nu_e +^{56} Fe$ (CC)	13	-	-	-	-
	$\bar{\nu}_e +^{56} Fe$ (CC)	2	-	-	-	-
	$\nu_i + {}^{56}Fe$ (NC)	7	-	-	-	-
ν_x	$\nu_i + p$ (NC)	-	17	46	-	-
	$\nu_e +^{16} O$ (CC)	-	-	-	120	19000
	$\bar{\nu}_e +^{16} O$ (CC)	-	-	-	80	9000
	$\nu_i +^{16} O$ (NC)	-	-	-	60	1000
	Total	321	93	386	7670	$660\cdot10^3$

The future

Another detector inside LVD?

An inner region inside the LVD structure could be effectively exploited by a compact detector, such as a lead based detector to study electron neutrino interactions from Core Collapse SN.

This facility could be realized with a negligible impact on LVD operation and sensitive mass.



PRL **109,** 070801 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Measurement of the Velocity of Neutrinos from the CNGS Beam with the Large Volume Detector

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Eur. Phys. J. A (2016) **52**: 79
DOI 10.1140/epja/i2016-16079-0

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Review

Techniques and methods for the low-energy neutrino detection*

The Astrophysical Journal, 802:47 (9pp), 2015.
IMPLICATION FOR THE CORE-COLLAPSE SUPERNOVA RATE FROM 21 YEARS OF DATA OF THE LARGE VOLUME DETECTOR

PRL **109,** 202501 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

First Direct Measurement of the $^{17}O(p,\gamma)^{18}F$ Reaction Cross Section at Gamow Energies for Classical Novae

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Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

384 | NATURE | VOL 512 | 28 AUGUST 2014

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Rep. Prog. Phys. **72** (2009) 086301 (25pp) doi:10.1088/0034-4885/72/8/086301

LUNA: a laboratory for underground nuclear astrophysics

LUNA MV

LVD

BOREXINO
GRAN SASSO