

# Neutrino Physics with Borexino



CPPM

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Davide Franco Milano University & INFN

# Outline

Neutrinos from the Sun
 The physics of Borexino
 The Borexino detector
 The "radio-purity" challenge
 The reached goals (<sup>7</sup>Be, <sup>8</sup>B and μ<sub>ν</sub>)
 Near and far future goals

### Neutrinos: cosmic messengers





## Messengers from the Sun's core

#### ✓ Core (0-0.25 R<sub>s</sub>)

✓ Nuclear reactions: T~1.5 10<sup>7</sup> °K
 ✓ energy chains pp e CNO (neutrino production)

#### ✓ Radiative region (0.25-0.75 Rs)

✓ Photons carry energy in ~  $10^5$  y

#### ✓ Convective region (0.75-1 Rs)

- ✓ Strong convection and turbulence
- ✓ Complex surface phenomena

#### ✓ Corona (> 1 Rs)

 ✓ Complex magneto-hydrodynamic phenomena
 ✓ Gas at T~ 10<sup>6</sup> °K





### **Neutrino Production In The Sun**

**pp chain**: **pp**, *pep*, <sup>7</sup>Be, *hep* ,and <sup>8</sup>B ν



CNO cycle:  $^{13}N,\,^{15}O,\,and\,^{17}F\,\,\nu$ 





# Solar Neutrino Spectra





# The Standard Solar Model before 2004

One fundamental input of the Standard Solar Model is the **metallicity** of the Sun - abundance of all elements above Helium:

The Standard Solar Model, based on the old metallicity derived by Grevesse and Sauval (Space Sci. Rev. **85**, 161 (1998)), was in **agreement within 0.5 in %** with the solar sound speed measured by helioseismology.





# The Standard Solar Model after 2004

Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) indicates a **lower** metallicity **by a factor ~2**. This result destroys the agreement with helioseismology

[cm <sup>-2</sup> s <sup>-1</sup> ]	рр (10 <sup>10</sup> )	pep (10 <sup>10</sup> )	hep (10 <sup>3</sup> )	<sup>7</sup> Be (10 <sup>9</sup> )	<sup>8</sup> B (10 <sup>6</sup> )	<sup>13</sup> N (10 <sup>8</sup> )	<sup>15</sup> O (10 <sup>8</sup> )	<sup>17</sup> F (10 <sup>6</sup> )
BS05 AGS 98	6.06	1.45	8.25	4.84	5.69	3.07	2.33	5.84
BS05 AGS 05	5.99	1.42	7.93	4.34	4.51	2.01	1.45	3.25
Δ	-1%	-2%	-4%	-12%	-23%	-42%	-47%	-57%

Solar neutrino measurements can solve the problem!



# Borexino goals: solar physics

- ✓ First ever observations of sub-MeV neutrinos in real time
- ✓ Check the balance between photon luminosity and neutrino luminosity of the Sun
- ✓ CNO neutrinos (direct indication of metallicity in the Sun's core)
- ✓ *pep* neutrinos (indirect constraint on *pp* neutrino flux)
- ✓ Low energy (3-5 MeV) <sup>8</sup>B neutrinos
- ✓ Tail end of *pp* neutrino spectrum?



# Borexino goals: neutrino physics

✓ Test of the matter-vacuum oscillation transition with <sup>7</sup>Be, pep, and low energy <sup>8</sup>B neutrinos

 $\checkmark$  I imit on the **neutrino** magnetic moment by analyzing the <sup>7</sup>Be energy spectrum and with Cr source

✓ SNEWS network for supernovae

 $\checkmark$  First evidence (>3 $\sigma$ ) of geoneutrinos



#### Solar Neutrino Survival Probability





# **Borexino Collaboration**



(Germany)

#### Abruzzo 120 Km da Roma

#### Laboratori esterni

Laboratori Nazionali del Gran Sasso

Assergi (AQ) Italy ~3500 m.w.e

#### Borexino – Rivelatore e impianti



# Detection principles and v signature

- Borexino detects solar v via their elastic scattering off electrons in a volume of highly purified liquid scintillator
  - ✓ Mono-energetic **0.862 MeV** <sup>7</sup>**Be** v are the main target, and the only considered so far
  - $\checkmark$  Mono-energetic pep  $\nu$  , CNO  $\nu\,$  and possibly pp  $\nu$  will be studied in the future
- Detection via scintillation light:
  - ✓ Very low energy threshold
  - ✓ Good position reconstruction
  - ✓ Good energy resolution

#### BUT...

- No direction measurement
- The v induced events can't be distinguished from other β events due to natural radioactivity

#### Extreme radiopurity of the scintillator is a must!



#### Typical v rate (SSM+LMA+Borexino)



# **Borexino Background**

Expected solar neutrino rate in 100 tons of scintillator ~ 50 counts/day (~ 5 10<sup>-9</sup> Bq/kg)

Just for comparison:

Natural water	~ 10 Bq/kg in $^{238}$ U, $^{232}$ Th and $^{40}$ K
Air	~ 10 Bq/m <sup>3</sup> in <sup>39</sup> Ar, <sup>85</sup> Kr and <sup>222</sup> Rn
Typical rock	~ 100-1000 Bq/kg in $^{238}$ U, $^{232}$ Th and $^{40}$ K

BX scintillator must be **9/10 order of magnitude less** radioactive than anything on earth!

 Low background nylon vessel fabricated in hermetically sealed low radon clean room (~1 yr)

✓ Rapid transport of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (<sup>7</sup>Be)

✓ Underground **purification plant** to distill scintillator components.

✓ **Gas stripping** of scintllator with special nitrogen free of radioactive <sup>85</sup>Kr and <sup>39</sup>Ar from air

✓ All materials **electropolished SS or teflon**, precision cleaned with a dedicated cleaning module



### **Detector layout and main features**





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#### Nylon vessel installation















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### **Counting Test Facility**

- ✓ CTF is a small scale prototype of Borexino:
- $\checkmark$  ~ 4 tons of scintillator
- ✓ 100 PMTs
- ✓ Buffer of water
- ✓ Muon veto
- ✓ Vessel radius: 1 m





# CTF demonstrates the Borexino feasibility





### May 15, 2007

photo: BOREXINO calibration



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# Borexino background

Radiolsotope		Concentrati	on or Flux	Strategy for Reduction		
Name	Source	Typical	Required	Hardware	Software	Achieved
μ	cosmic	~200 s⁻¹ m⁻²	~ 10 <sup>-10</sup>	Underground	Cherenkov signal	<10 <sup>-10</sup>
		at sea level		Cherenkov detector	PS analysis	(overall)
Ext.γ	rock			Water Tank shielding	Fiducial Volume	negligible
lnt.γ	PMTs, SSS			Material Selection	Fiducial Volume	negligible
	Water, Vessels			Clean constr. and handling		
<sup>14</sup> C	Intrinsic PC/PPO	~ 10 <sup>-12</sup>	~ 10 <sup>-18</sup>	Old Oil, check in CTF	Threshold cut	~ <b>10</b> <sup>-18</sup>
238U	Dust	~ 10 <sup>-5</sup> -10 <sup>-6</sup> g/g	< 10 <sup>-16</sup> g/g	Distillation, Water Extraction		~ <b>2</b> 10 <sup>-17</sup>
<sup>232</sup> Th	Organometallic (?)	(dust)	(in scintillator)	Filtration, cleanliness		~ 7 10 <sup>-18</sup>
<sup>7</sup> Be	Cosmogenic ( <sup>12</sup> C)	∼ 3 10 <sup>-2</sup> Bq/t	< 10 <sup>-6</sup> Bq/ton	Fast procurement, distillation	Not yet measurable	?
<sup>40</sup> K	Dust,	~ 2 10 <sup>-6</sup> g/g	< 10 <sup>-14</sup> g/g scin.	Water Extraction	Not yet measurable	?
	PPO	(dust)	< 10 <sup>-11</sup> g/g PPO	Distillation		
<sup>210</sup> Pb	Surface contam.			Cleanliness, distillation	Not yet measurable	?
	from <sup>222</sup> Rn decay				(NOT in eq. with <sup>210</sup> Po)	
<sup>210</sup> Po	Surface contam.			Cleanliness, distillation	Spectral analysis	~ 14
	from <sup>222</sup> Rn decay				$\alpha/\beta$ stat. subtraction	~ 0.01 c/d/t
<sup>222</sup> Rn	air, emanation from	~ 10 Bq/I (air)	< 1 c/d/100 t	Water and PC N <sub>2</sub> stripping,	Delayed coincidence	< 0.02 c/d/t
	materials, vessels	~100 Bq/l (water)	(scintillator)	cleanliness, material selection		
<sup>39</sup> Ar	Air (nitrogen)	~17 mBq/m³ (air)	< 1 c/d/100 t	Select vendor, leak tightness	Not yet measurable	?
<sup>85</sup> Kr	Air (nitrogen)	~ 1 Bq/m <sup>3</sup> in air	< 1 c/d/100 t	Select vendor, leak tightness	Spectral fit	= 25±3
				(learn how to measure it)	fast coincidence	= 29±14
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### The starting point: no cut spectrum



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# Energy scale



MC vs data comparison of photoelectron time distributions from  $^{14}\mathrm{C}$ 

![](_page_22_Figure_3.jpeg)

LY = 510 (1%) p.e./MeV kB = 0.0197 (15%) cm/MeV Ph.Y. ~ 12000 photons/MeV

![](_page_22_Picture_5.jpeg)

# Detecting (and rejecting) cosmic muons

- $\mu$  are identified by ID and OD
  - ✓ OD eff: ~ 99%

 $\checkmark$ 

- ✓ ID based on pulse shape analysis
- ✓ Rejection factor
  - > 10<sup>3</sup> (conservative)

![](_page_23_Figure_6.jpeg)

![](_page_23_Figure_7.jpeg)

 $\boldsymbol{\mu}$  crossing the buffer only

![](_page_23_Figure_9.jpeg)

 $\mu$  crossing the scintillator

10000

![](_page_23_Figure_11.jpeg)

![](_page_23_Picture_12.jpeg)

# Detecting (and rejecting) cosmogenic neutrons

![](_page_24_Figure_1.jpeg)

A dedicated trigger starts after each muon opening a gate for 1.6 ms. An offline clustering algorithm identifies neutron in high multiplicity events

![](_page_24_Figure_3.jpeg)

![](_page_24_Picture_4.jpeg)

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## Muon and neutron cuts

![](_page_25_Figure_1.jpeg)

![](_page_25_Picture_2.jpeg)

# **Position reconstruction**

- Position reconstruction algorythms (we have 4 codes right now)
  - $\checkmark$  time of flight fit to hit time distribution
  - $\checkmark\,$  developed with MC, tested and validated in CTF
  - cross checked and tuned in Borexino with <sup>214</sup>Bi-<sup>214</sup>Po events and <sup>14</sup>C events

![](_page_26_Figure_5.jpeg)

![](_page_26_Picture_6.jpeg)

# Spatial distributions and resolutions

![](_page_27_Figure_1.jpeg)

![](_page_27_Picture_2.jpeg)

### Spectrum after FV cut (100 tons)

![](_page_28_Figure_1.jpeg)

![](_page_29_Figure_0.jpeg)

Assuming secular equilibrium and looking in the FV only\_: 0.00256 cpd/ton corresponding to  $^{232}\text{Th} = (6.8 \pm 1.5) \times 10^{-18} \text{ g/g}$ 

![](_page_29_Picture_2.jpeg)

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# $\alpha/\beta$ discrimination

![](_page_30_Figure_1.jpeg)

Average time profiles of the scintillation pulses emitted by a PC+PPO (1.5 g/l) mixture under alpha and beta irradiation

![](_page_30_Figure_3.jpeg)

![](_page_30_Picture_4.jpeg)

# <sup>210</sup>Po contamination

![](_page_31_Figure_1.jpeg)

![](_page_31_Picture_4.jpeg)

# $\alpha/\beta$ statistical subtraction

![](_page_32_Figure_1.jpeg)

![](_page_32_Picture_2.jpeg)

### New results with 192 days of statistics

![](_page_33_Figure_1.jpeg)

### New results with 192 days of statistics

![](_page_34_Figure_1.jpeg)

![](_page_34_Picture_4.jpeg)

# Systematic and Final Result

#### Estimated 1σ Systematic Uncertainties<sup>\*</sup> [%]

Total Scintillator Mass	0.2
Fiducial Mass Ratio	6.0
Live Time	0.1
Detector Resp. Function	6.0
Cuts Efficiency	0.3
Total	8.5

\*Prior to Calibration

Expected interaction rate in absence of oscillations: 75±4 cpd/100 tons

for LMA-MSW oscillations: 48±4 cpd/100 tons, which means:

$$f_{\rm Be} = 1.03^{+0.24}_{-1.03}$$

<sup>7</sup>Be Rate: 49±3<sub>stat</sub>±4<sub>syst</sub> cpd/100 tons , which means

$$f_{
m Be}=1.02\pm0.10$$

![](_page_35_Picture_9.jpeg)

![](_page_36_Figure_0.jpeg)

![](_page_36_Picture_1.jpeg)

![](_page_36_Picture_2.jpeg)

# Constraints on pp and CNO fluxes

Combining Borexino 7Be results with other experiments, the expected rate in Clorine and Gallium experiments is

$$R_l \ [\text{SNU}] = \sum_i R_{l,i} f_i P_{ee}^{l,i}$$
 where  $l = \{\text{Ga, Cl}\}$   
 $i = \{pp, pep, \text{CNO}, \text{^7Be}, \text{^8B}\}$   
 $f_i \quad \text{measured over}$   
predicted flux ratio  
 $P_{ee}^{l,i}$  Survival Probability

- $\mathsf{R}_{i,k}$  and  $\mathsf{P}_{i,k}$  are calculated in the hypothesis of high-Z SSM and MSW LMA
- Rk are the rates actually measured by Clorine and Gallium experiments
- f<sup>8</sup>B is measured by SNO and SuperK to be 0.87 ±0.07
- f<sup>7</sup>Be =1.02 ±0.10 is given by Borexino results

Plus luminosity constraint:  $0.919 f_{pp} + 0.075 f_{Be} + 0.0068 f_{CNO} = 1$ 

$$f_{pp} = 1.004^{+0.008}_{-0.020}$$

![](_page_37_Picture_9.jpeg)

best determination of pp flux!

![](_page_37_Picture_13.jpeg)

# Neutrino Magnetic Moment

Neutrino-electron scattering is the most sensitive test for  $\mu_{\nu}$  search

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi} \left[g_L^2 + g_R^2 \left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

EM current affects cross section: spectral shape sensitive to  $\mu_v$  sensitivity enhanced at low energies (c.s.~ 1/T)

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_{\nu}^2 \frac{\pi \alpha_{em}^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_{\nu}}\right)$$

A fit is performed to the energy spectrum including contributions from  $^{14}\text{C},$  leaving  $\mu_{\rm v}$  as free parameter of the fit

Estimate	Method	10 <sup>-11</sup> µв
SuperK	<sup>8</sup> B	<11
Montanino et al.	<sup>7</sup> Be	<8.4
GEMMA	Reactor	<5.8
Borexino	<sup>7</sup> Be	<5.4

![](_page_38_Picture_8.jpeg)

# <sup>8</sup>B neutrinos with the lowest threshold: 2.8 MeV

![](_page_39_Figure_1.jpeg)

Expected <sup>8</sup>B v rate in 100 tons of liquid scintillator above <u>2.8</u> <u>MeV</u>: **0.26±0.03 c/d/100 tons** 

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# Background in the 2.8-16.3 MeV range

![](_page_40_Figure_2.jpeg)

✓ Cosmic Muons

- ✓ External background
- ✓ High energy gamma's from neutron captures

✓ <sup>208</sup>Tl and <sup>214</sup>Bi from radon
 emanation from nylon vessel

✓ Cosmogenic isotopes

✓ <sup>214</sup>Bi and <sup>208</sup>TI from <sup>238</sup>U and <sup>232</sup>Th bulk contamination

Count-rate: 1500 c/d/100 ton

# S/B ratio < 1/6000!!!

![](_page_40_Picture_11.jpeg)

# Muon and neutron cuts

Muon cut:

- All events detected by the outer detector are rejected
- Residual muon rate: <10-3 c/d

### Neutron cut:

- 2 ms veto after each muon detected by the outer detector, in order to reject induced neutrons (mean capture time ~250  $\mu$ s)
- Residual neutron rate: ~10<sup>-4</sup> c/d

![](_page_41_Figure_7.jpeg)

### Count-rate: 4.8 c/d/100 ton

![](_page_41_Picture_9.jpeg)

### Fiducial Volume Cut (radius < 3 m, ~100 tons)

![](_page_42_Figure_1.jpeg)

### Count-rate: 2.3 c/d/100 ton

![](_page_42_Picture_3.jpeg)

# Muon induced radioactive nuclides

Isotopes	$\tau$	Q	Decay	σ	$E_{\mu}$
		[MeV]		$[\mu \text{barn}]$	[GeV]
Short-lived	$(\tau < 2s)$				
$^{12}B$	$0.03 \mathrm{~s}$	13.4	$\beta^{-}$	$\sim \! 4500$	320
<sup>9</sup> Li	$0.26 \ s$	13.6	$\beta^{-}$	$<\!\!2$	190
<sup>8</sup> Li	$1.21 \mathrm{~s}$	16.0	$\beta^{-}$	5	320
$^{8}\mathrm{He}$	$0.17 \ s$	10.6	$\beta^{-}$	$<\!\!2$	190
$^{6}\mathrm{He}$	$1.17 \mathrm{~s}$	3.5	$\beta^{-}$	23	320
$^{9}C$	$0.19 \mathrm{~s}$	16.5	$\beta^+$	5	190
$^{8}B$	$1.11~{\rm s}$	18.0	$\beta^+$	11	320
unts/100 keV	Со	smoge energ	enic ca y spec	andidat strum	e
<sup>3</sup> <sup>10</sup> Entire mass 10 100 tons					

Energy [MeV]

![](_page_43_Figure_2.jpeg)

![](_page_43_Picture_3.jpeg)

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# Cosmogenic cut

### Cosmogenic cut:

- 5 s veto after each  $\mu$  crossing the  $\frac{1}{2}$  buffer
- Rejection efficiency cut: 99.7%
- Residual short-lived cosmogenic rate: **3x10**<sup>-3</sup> **c/d**
- Dead-time: 23.4%
- Effective detector live-time: 188
  days

![](_page_44_Figure_7.jpeg)

### Count-rate: 0.4 c/d/100 ton

![](_page_44_Picture_9.jpeg)

# Summary of the Cuts and Systematic

Counts 2.8-16.3 MeV	Counts 5.0-16.3 Me
60449	42314
3363	1135
3280	1114
567	≿ 10 <sup>3</sup> =
71	× t
65	10 I I
62	t 10-
14 <u>+</u> 3	U
48 <u>+</u> 8	10
50 <u>+</u> 5	
40 <u>+</u> 4	1
	Counts         2.8-16.3 MeV         60449         3363         3280         567         71         65         62         14 ± 3         48 ± 8         50 ± 5         40 ± 4

\*MSW-LMA:  $\Delta m^2$ =7.69×10<sup>-5</sup> eV<sup>2</sup>, tan<sup>2</sup>0=0.45

✓ Systematic errors:

 $\checkmark$  6% from the determination of the fiducial mass

✓ 3% (2%) uncertainty in the <sup>8</sup>B
 rate above 2.8 MeV (5.0 MeV)
 from the determination of the light
 yield (1%)

![](_page_45_Figure_6.jpeg)

### The <sup>8</sup>B v spectrum

![](_page_46_Figure_1.jpeg)

Neutrino oscillation is confirmed at 4.2  $\sigma$ , including the theoretical uncertainty (10%) on the <sup>8</sup>B flux from the Standard Solar Model

![](_page_46_Picture_3.jpeg)

# <sup>8</sup>B equivalent v flux

Equivalent unoscillated <sup>8</sup>B neutrino flux, as derived from the electron scattering rate

	2.8-16.3 MeV	5.0-16.3 MeV
Rate [c/d/100 tons]	0.26±0.04±0.02	0.14±0.03± 0.01
$\Phi^{\text{ES}}_{\text{exp}}$ [10 <sup>6</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	2.65±0.44±0.18	2.75±0.54±0.17
$\Phi^{\text{ES}}_{exp} / \Phi^{\text{ES}}_{th}$	0.96±0.19	1.02±0.23

<sup>8</sup>B solar neutrino flux measurements via elastic scattering

![](_page_47_Figure_4.jpeg)

Good agreement with the SK-I and SNO D20 measurements (same threshold at 5 MeV)

	Threshold	$\Phi_{8B}^{\text{ES}}$
	[MeV]	$[10^6 \text{ cm}^{-2} \text{ s}^{-1}]$
SuperKamiokaNDE I [8]	(5.0)	$2.35 {\pm} 0.02 {\pm} 0.08$
SuperKamiokaNDE II [9]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO $D_2O$ [7]	(5.0)	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase [6]	5.5	$2.35 {\pm} 0.22 {\pm} 0.15$
SNO Prop. Counter [10]	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
Borexino	(5.0)	$2.75 {\pm} 0.54 {\pm} 0.17$
Borexino	2.8	$2.65{\pm}0.44{\pm}0.18$

![](_page_47_Picture_7.jpeg)

# **Electron Neutrino Survival Probability**

 $\overline{P}_{ee}$  is defined such that:

R: measured rate  $E_v$  and  $T_e$ : neutrino and recoiled electron energies  $T_0 = 2.8$  MeV: energy threshold

 $\begin{array}{l} {\sf E}_0 = 3.0 \; \text{MeV: minimum neutrino energy at } {\sf T}_0 \\ {\sf N}_e \text{: number of target electrons} \\ {\sigma_x} \; (x{=}e,\mu{-}\tau) \text{: elastic cross sections} \end{array}$ 

$$R = \int_{T_e > T_0} dT_e \int_{E_\nu > E_0} dE_\nu \left( \overline{P}_{ee} \cdot \frac{d\sigma_e}{dT_e} (E_\nu, T_e) + (1 - \overline{P}_{ee}) \cdot \frac{d\sigma_{\mu-\tau}}{dT_e} (E_\nu, T_e) \right) N_e \cdot \frac{d\Phi_e}{dE_\nu} (E_\nu)$$

![](_page_48_Figure_5.jpeg)

 $\overline{P}_{ee}(^{8}B) = 0.35 \pm 0.10 (8.6 \text{ MeV})$  $P_{ee}(^{7}Be) = 0.56 \pm 0.10 (0.862 \text{ MeV})$ 

For the first time, we confirm at 1.8  $\sigma$ , using data from a single detector, the presence of a transition between the low energy vacuum-driven and the high-energy matter-enhanced solar neutrino oscillations, in agreement with the prediction of the MSW-LMA solution for solar neutrinos

![](_page_48_Picture_8.jpeg)

# Calibrations

Goal: <5% 7Be measurement

#### **Detector response vs position:**

✓ 100 Hz  $^{14}$ C+ $^{222}$ Rn in scintillator in >100 positions

#### **Quenching and energy scale:**

✓ Beta: <sup>14</sup>C, <sup>222</sup>Rn in scintillator
 ✓ Alpha: <sup>222</sup>Rn in scintillator
 ✓ Gamma: <sup>139</sup>Ce, <sup>57</sup>Co, <sup>60</sup>Co, <sup>203</sup>Hg, <sup>65</sup>Zn, <sup>40</sup>K, <sup>85</sup>Sr, <sup>54</sup>Mn

✓Neutron: AmBe

![](_page_49_Figure_7.jpeg)

![](_page_49_Picture_8.jpeg)

![](_page_49_Figure_9.jpeg)

![](_page_49_Picture_10.jpeg)

# Calibrations: Monte Carlo vs Data

Gamma sources in the detector center

![](_page_50_Figure_2.jpeg)

![](_page_50_Picture_3.jpeg)

# What next?

![](_page_51_Picture_1.jpeg)

#### BOREXino

![](_page_52_Figure_1.jpeg)

NA54 @ CERN: 100 and 190 GeV muon beams on a  $^{12}$ C target:  $^{11}$ C represents 80% of all the muon-induced contaminants and more than 99% in the CNO pep-v energy window

Hagner et al., Astropart. Phys. 14, 33 (2000)

![](_page_52_Figure_4.jpeg)

<sup>11</sup> C Rate				
(cts / day / 100 tons)				
All energy 0.8 – 1.4 MeV				
KamLAND	107	55		
BOREXino	15	7.4		
SNO+	0.15	0.074		

![](_page_52_Picture_6.jpeg)

# <sup>11</sup>C production and decay

 $\mu$  (+ secondaries) + <sup>12</sup>C  $\rightarrow \mu$  (+ secondaries) + <sup>11</sup>C + n

![](_page_53_Figure_2.jpeg)

Coincidence among:

- cosmic muon:
  - rate at LNGS (3700 mwe): 1.16 hr<sup>-1</sup> m<sup>-2</sup>
  - average energy: 320 GeV
- gamma from neutron capture:
  - energy: 2.2 MeV
  - capture time: 250  $\mu s$
- positron from <sup>11</sup>C decay:
  - deposited energy between 1.022 and 1.982 MeV
  - mean life: 30 min

![](_page_53_Picture_13.jpeg)

# Large scintillator detector potential

![](_page_54_Figure_1.jpeg)

![](_page_54_Picture_2.jpeg)

# Borexino potential on geoneutrinos

![](_page_55_Figure_1.jpeg)

Prompt signal energy spectrum (model) • Detection technique: inverse  $\beta$ -decay and delayed coincidence:

![](_page_55_Figure_3.jpeg)

• Energy range: 1-2.6 MeV

• Efficiency: 80%

Cosmogenic  $\beta$ -n background (<sup>8</sup>Li and <sup>6</sup>He) identified and rejected event by event

Prediction:

- geoneutrino signal: 6.3 / year / 300 tons
- reactor antineutrinos (in the geo-v range): **5.7 / year / 300 tons** (Balata *et al.,* 2006, ref. model Mantovani *et al.,* 2004)

![](_page_55_Picture_10.jpeg)

## Summary of the future measurements

#### pep and CNO v fluxes

- software algorithm based on a three-fold coincidence analysis to subtract efficiently cosmogenic <sup>11</sup>C background
- ✓ Muon track reconstruction

![](_page_56_Figure_4.jpeg)

✓ Purifications planned for 2010

![](_page_56_Picture_6.jpeg)

# Conclusion

- Borexino opened the study of the solar neutrinos in real time below the barrier of natural radioactivity (5 MeV)
  - ✓ Two measurements reported for <sup>7</sup>Be neutrinos
  - Best limits for *pp* and CNO neutrinos, combining information from SNO and radiochemical experiments
  - ✓ Opportunities to tackle *pep* and CNO neutrinos in direct measurement
  - ✓ First observation of <sup>8</sup>B neutrino spectrum below 5 MeV
- Borexino will run comprehensive program to study antineutrinos
  - ✓ **geoneutrino** analysis is coming soon!
- Borexino is a powerful observatory for neutrinos from Supernovae explosions within few tens of kpc
- Best limit on neutrino magnetic moment. Improve by dedicated measurement with <sup>51</sup>Cr neutrino source
- ...and do not forget the technological success of the high-radiopurity scintillator!

![](_page_57_Picture_11.jpeg)