Looking at the Sun's core
-
CNO and pep solar neutrino detection in Borexino

IFAE 2012, Ferrara
April 13th 2012

Stefano Davini
University of Houston

Talk outline

Solar neutrinos
- Introduction to solar **neutrino observations**
- **Motivations** of solar neutrino experiments

The Borexino experiment
- **S**olar neutrino **detection** in Borexino

Detection of pep and CNO solar neutrinos in Borexino
- **Motivation** of the measurment
- **Cosmogenic** backgrounds rejection
- **Analysis**
- **Results**

The solar neutrino flux

Provide details on stellar structure and working,
directly addresses **Solar Standard Model**

Energetically **broadband**
Free of *flavour* **background**

Loooooong **baseline**
and passes through quantities of **matter**
unavailable to terrestrial experiments

Opportunity to study neutrino **oscillations**
and **matter** effects (**MSW**)

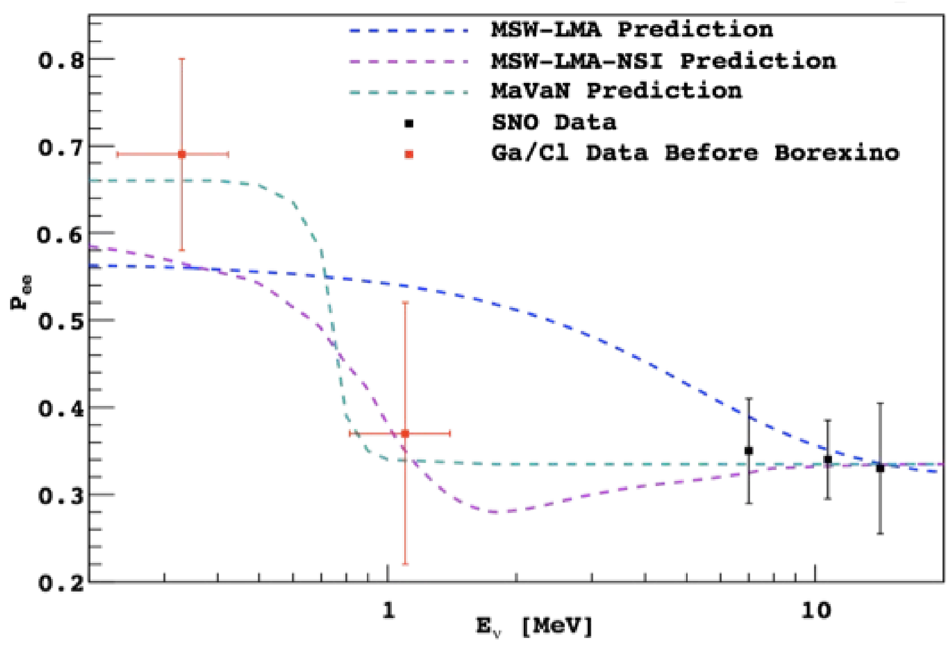
Solar neutrino experiments - current status and motivations

MSW-LMA → **current understanding solar neutrino oscillation**
Mainly from ^{8}B ν (*E>5MeV*) + radiochemical experiments

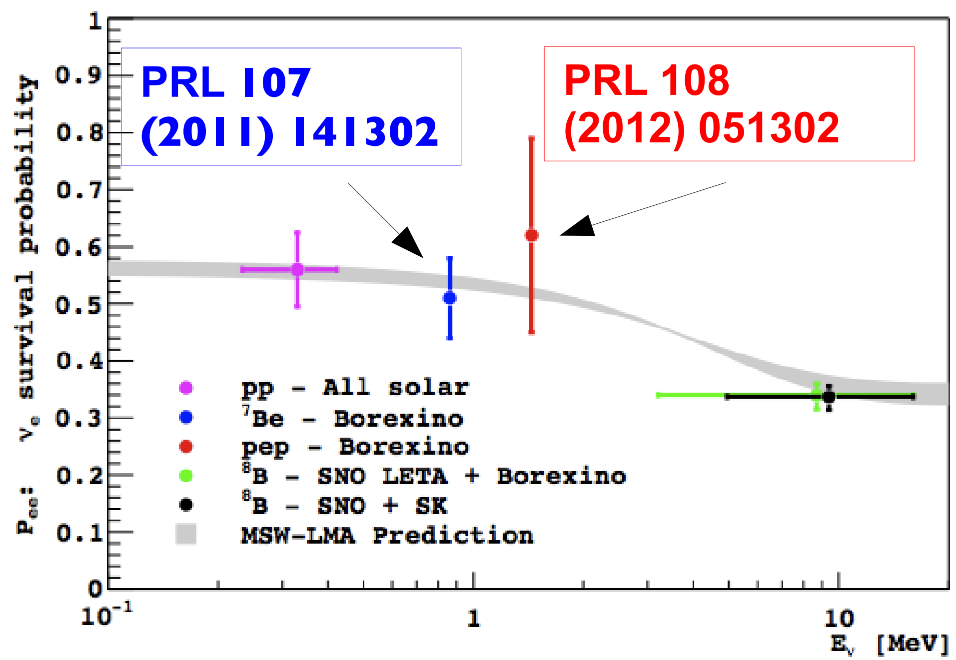
No spectroscopy measurment of solar-**ν** of *E<1-2 MeV* before **Borexino**

^{7}Be, pep ν → precision test of MSW-LMA **Pee**
in vacuum and transition regions
constrain exotic models of oscillations (NSI, MaVaN...)

Pee measurment before BOREXINO



2012



Solar neutrino experiments - Motivations

Measure solar neutrino flux → test Solar Standard Model
Astro-ph probe: neutrinos allow to look at the Sun's core

Solve ***solar metallicity problem:***
Tension between **High Metallicity** (**High Z**)
and **Low Metallicity** (**Low Z**) Solar Models

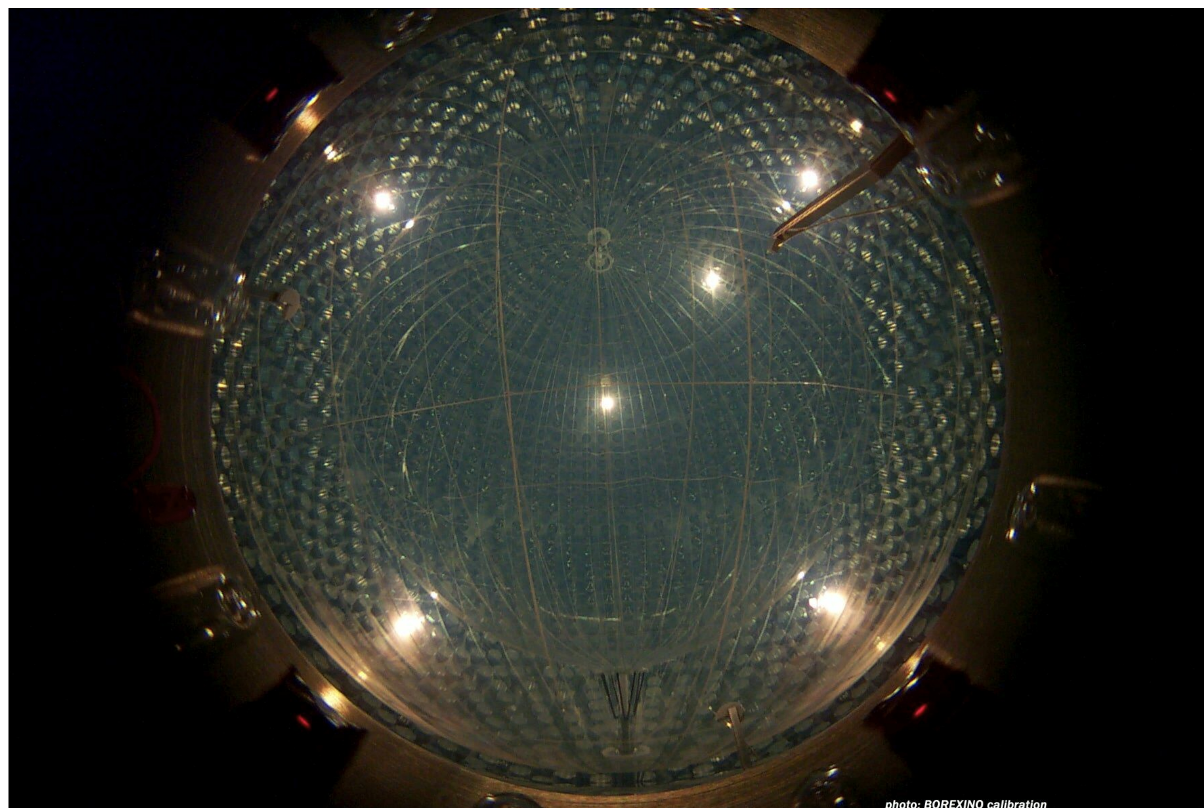
- **High Z (GS)** → older model, higher heavy element abundances, agrees with helioseismology measurments
- **Low Z (AGSS)** → recent model based on new solar atmosphere optical spectroscopy measurments, lower heavy element abundances, in disagreement with helioseismology

Reaction	Abbr.	Flux ($cm^{-2}\ s^{-1}$)
$pp \to d\, e^+\, \nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^- p \to d\, \nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
$^3He\, p \to {}^4He\, e^+ \nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
$^7Be\, e^- \to {}^7Li\, \nu + (\gamma)$	^7Be	$5.07(1 \pm 0.06) \times 10^{9}$
$^8B \to {}^8Be^*\, e^+ \nu$	^8B	$5.94(1 \pm 0.11) \times 10^{6}$
$^{13}N \to {}^{13}C\, e^+ \nu$	^{13}N	$2.88(1 \pm 0.15) \times 10^{8}$
$^{15}O \to {}^{15}N\, e^+ \nu$	^{15}O	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
$^{17}F \to {}^{17}O\, e^+ \nu$	^{17}F	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$

pp, pep neutrino flux:
predicted with SMALL uncertainties

CNO neutrino flux:
predicted with BIG uncertinties

The Borexino experiment at LNGS

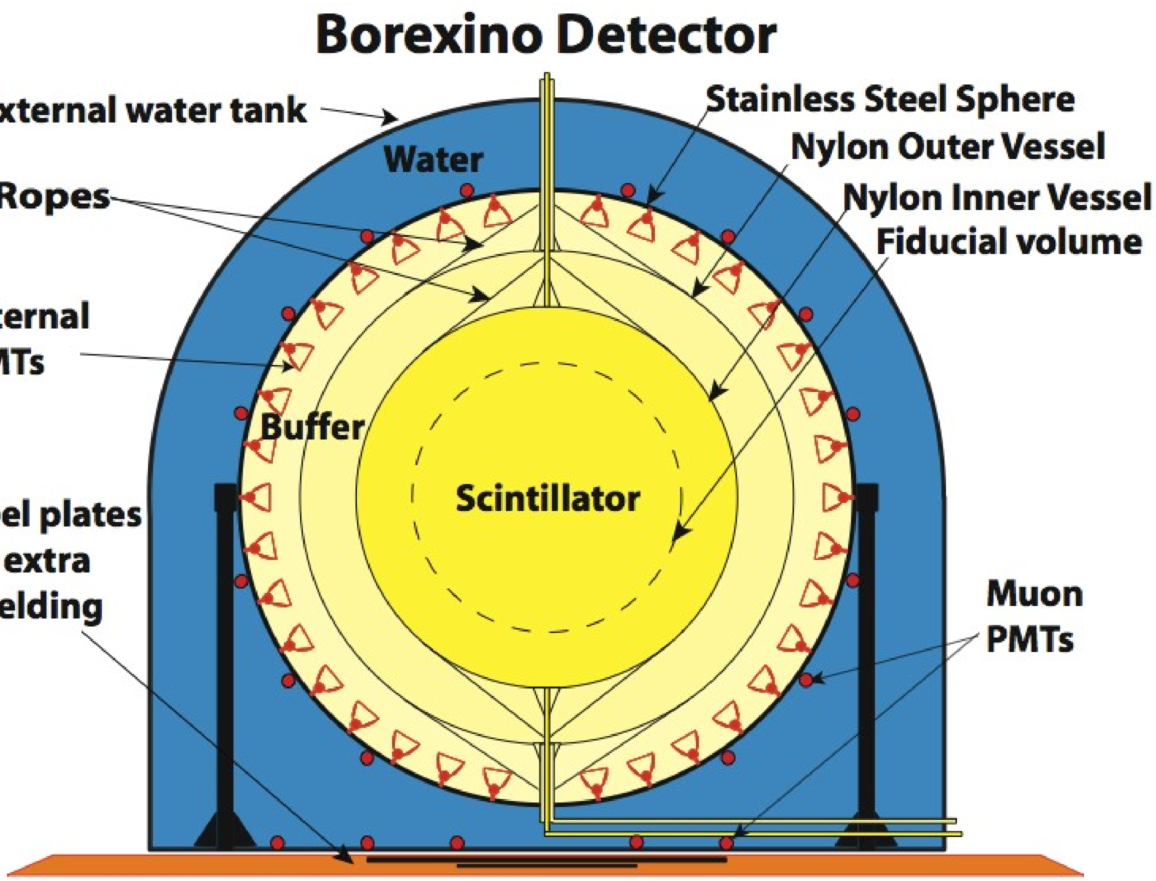


Laboratori Nazionali del Gran Sasso

Under ~1400 meters of rock *(3500 m w.e.)*

Cosmic-ray shielding

The Borexino detector



Ultrapure organic liquid scintillator

~278 tons of **scintillator** (PC)
~75 tons of fiducial mass

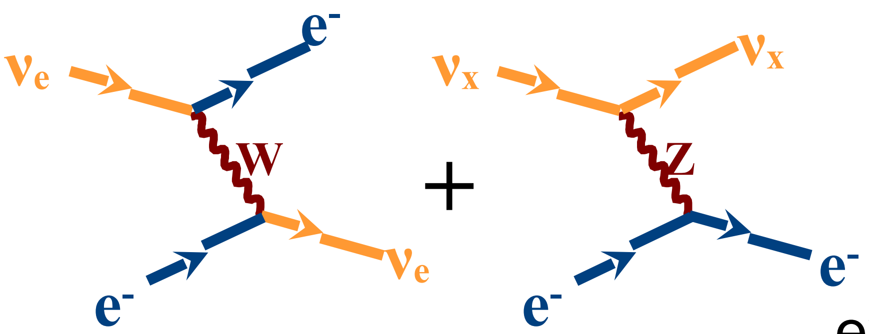
~2200 PMTs on the SSS

External Water Tank
shielding for n and γ
Cherenkov detector for μ

Signal (^{7}Be neutrinos) → **50 events/day/100tons** → **6 10^{-9} Bq/kg**

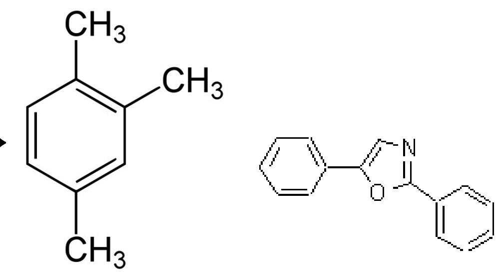
Borexino **scintillator** → **9-10 orders of magnitude** more radiopure than anything on Earth

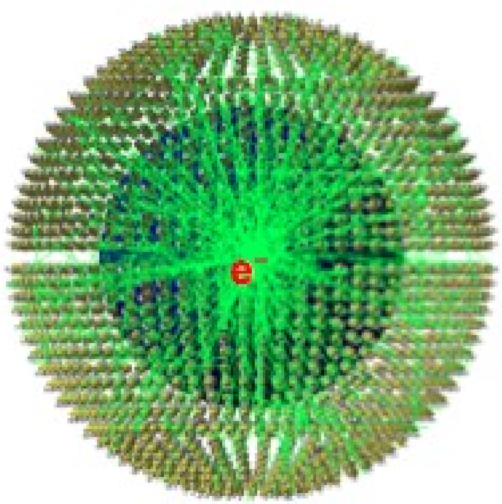
Solar neutrino detection in Borexino



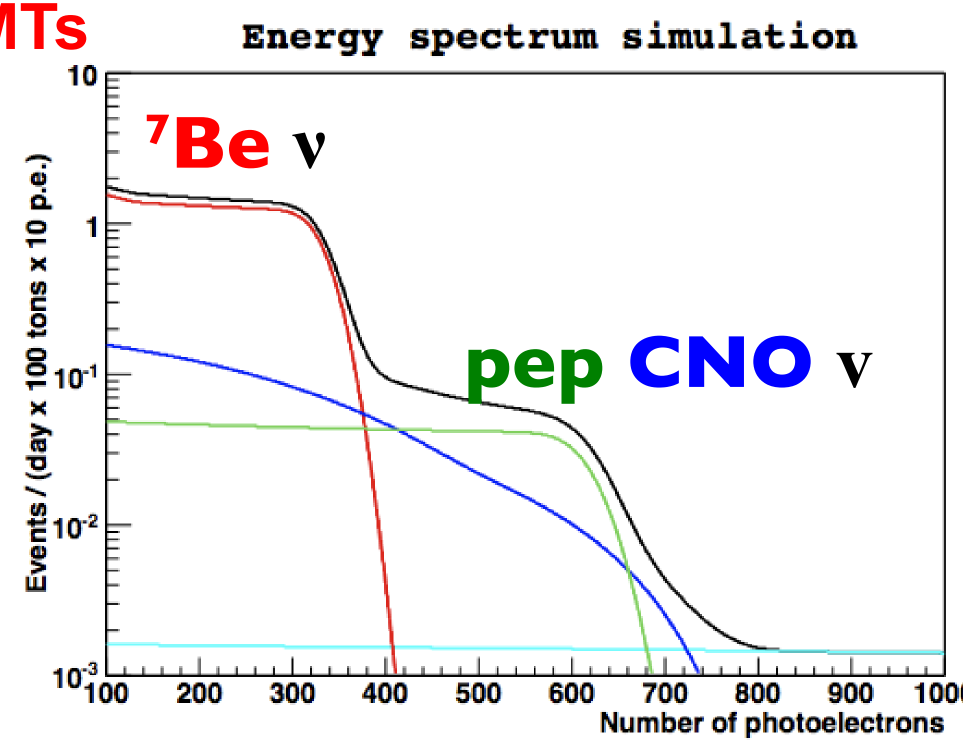
Neutrinos detected via **elastic scattering** on **electrons**

Recoil electron excites **scintillator** → **emission of light**





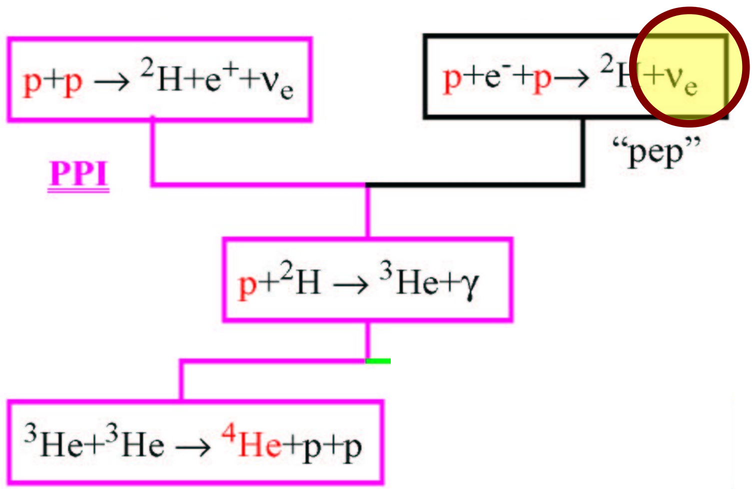
Scintillation light detected by **PMTs**



Number of **hit PMTs**
→ **Energy**
Pattern of **hit PMTs**
→ **position**

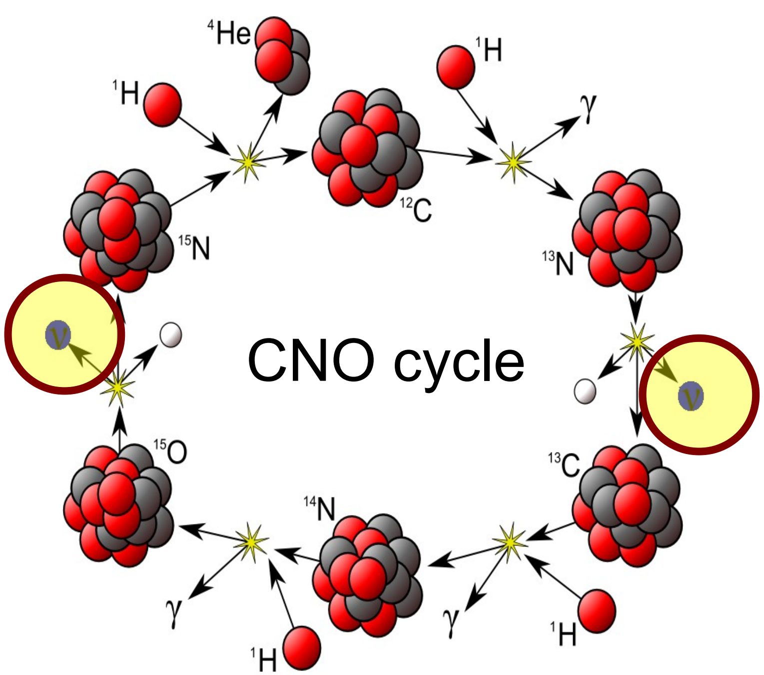
Measurment of pep and CNO solar neutrino rates in Borexino

pep and CNO solar neutrinos



p-e-p process, in **proton-proton** chain
Mono-E neutrinos **E=1.44 MeV**
Low flux (1/400 total solar flux)
but predicted with **high accuracy**
Expected rate in BX ~ 3 cpd/100tons

C-N-O cycle
Neutrinos from ^{13}**N** and ^{15}**O decay**
Continous spectrum Q = 1.74 MeV
Low flux, predicted with low accuracy,
sensibile to Solar **metallicity**
Expected rate in BX ~ 3-5 cpd/100tons

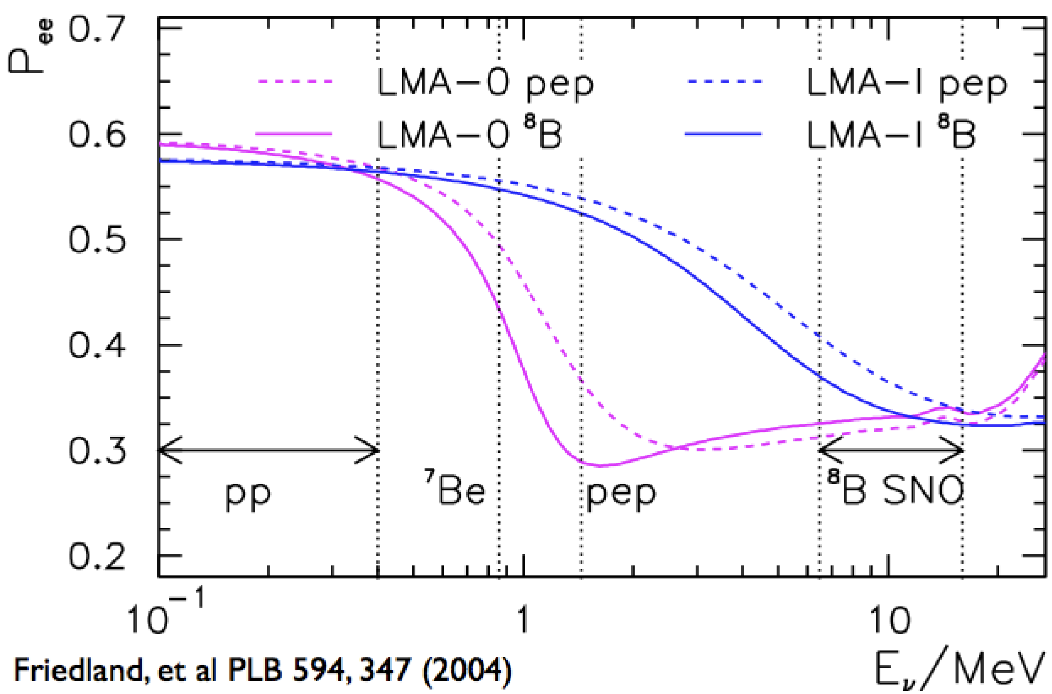


Why measure pep neutrinos?

pep neutrino **flux** predicted by *Standard Solar Model* with **high accuracy** (1.2%)

pep neutrino **energy** (1.44 MeV) in **Pee vacuum-matter transition region**

Precision test of MSW effect and oscillation models



Friedland, et al PLB 594, 347 (2004)

Why measure CNO neutrinos?

Proof that **CNO cycle** happens in **Sun**

Abbundance of heavy elements in Sun have great **impact** on **CNO** neutrino **flux magnitude**

Test of *Solar Models* (**HighZ** vs **LowZ**)

Serenelli, Haxton, Pena-Garay arXiv 1104.1639	**CNO Flux** (10^8 cm^{-2} s^{-1})
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
$\Delta\Phi$	28%

pep and CNO neutrino detection in Borexino

Low signal: *few events/day/100tons*

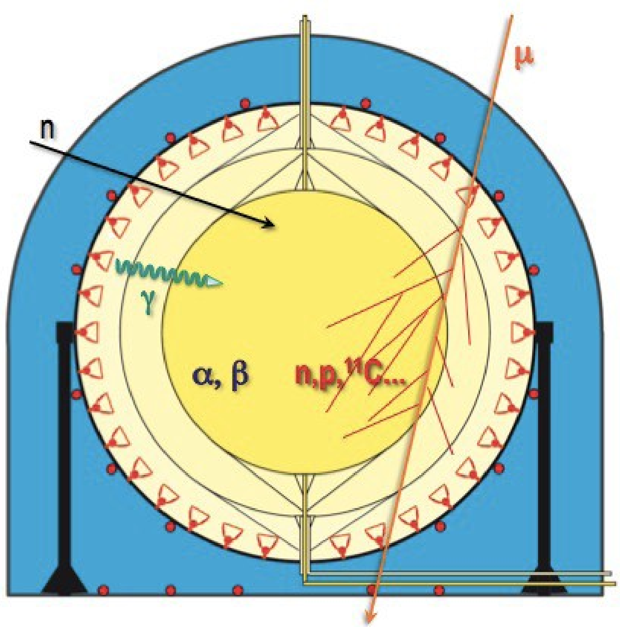
Dominant **background**: cosmogenic **β+** emitter **^{11}C**

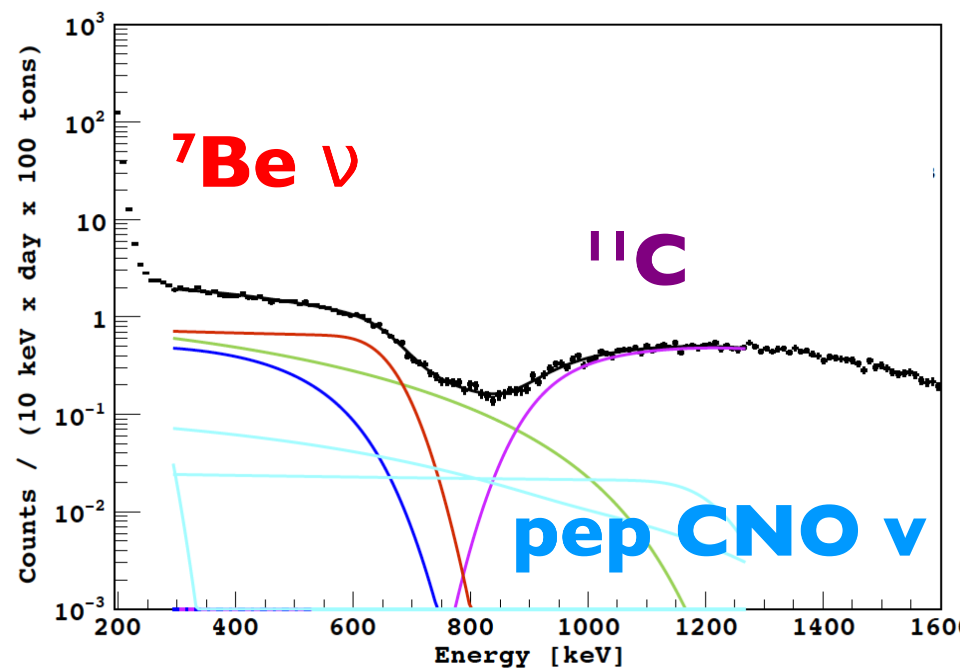
27cpd/100tons → signal/background ~ 0.1

Need **novel techniques** to suppress **^{11}C background**:

Three **F**old **C**oincidence

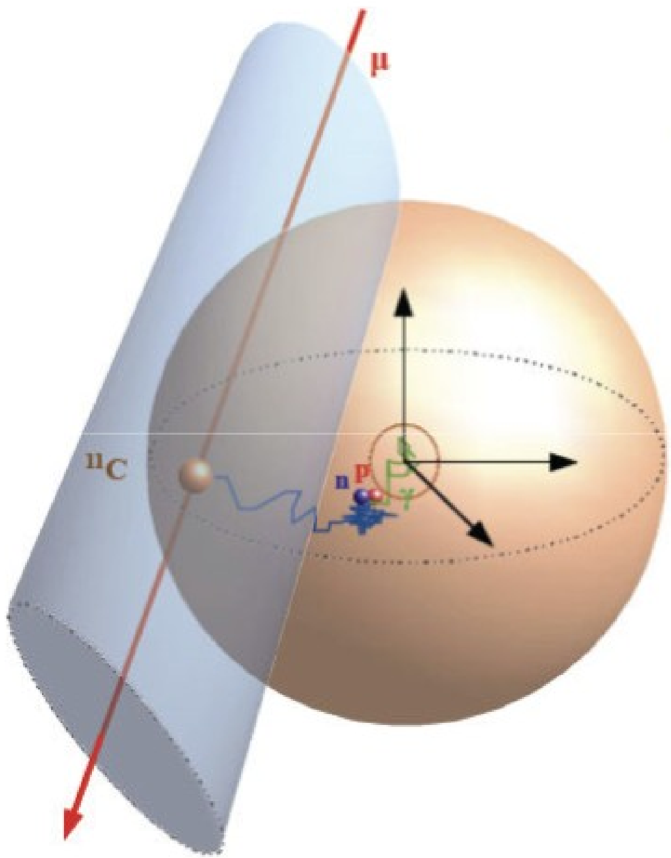
e$^+$/e$^-$ pulse **s**hape **d**iscrimination





Suppress ^{11}C - Three Fold Coincidence

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



~4300 muons/day in Borexino

Spallation neutron in 95% cases
n termalize and captured, mean life **~250 μs**
capture on **H** → **γ** (**2.2 MeV**)

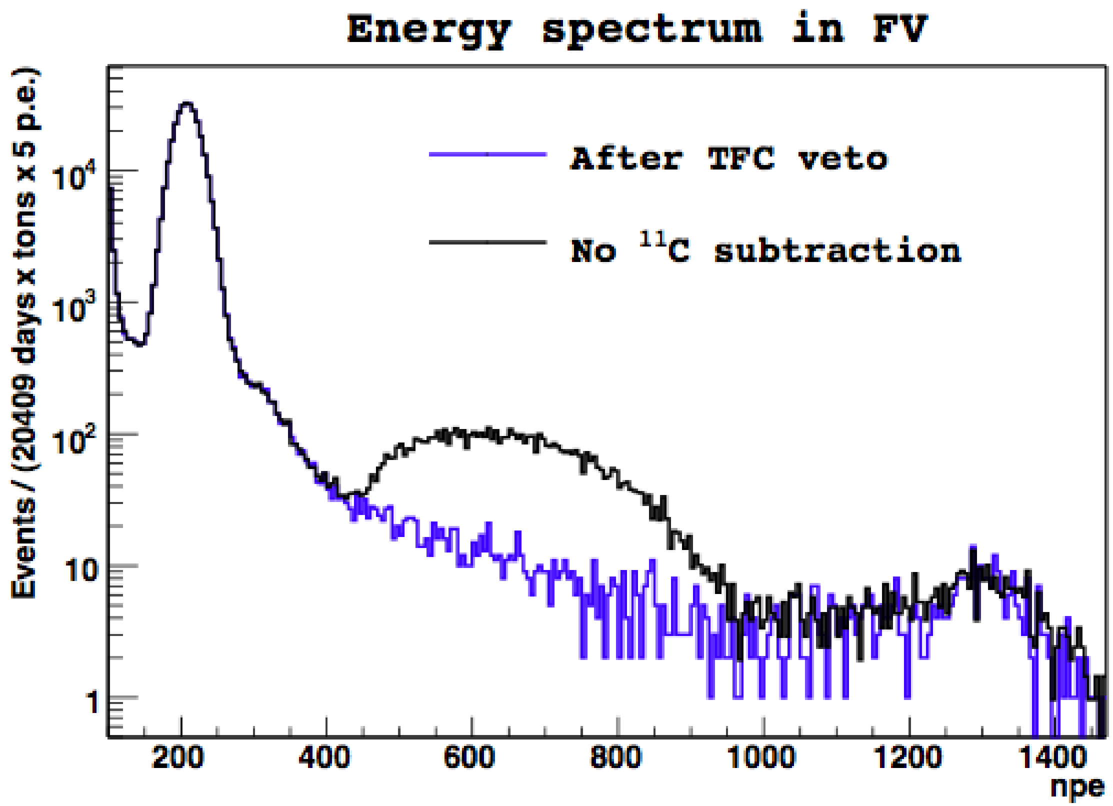
^{11}C decays β+ mean life **29.4 minutes**
Stays where produced (no convective motions)

Space-time correlation between **muon** track, **neutron** capture, **^{11}C** decay**:**
Three Fold Coincidence (TFC)

We exclude from analysis space-time regions where we expect ^{11}C decays

Suppress ^{11}C - Three Fold Coincidence

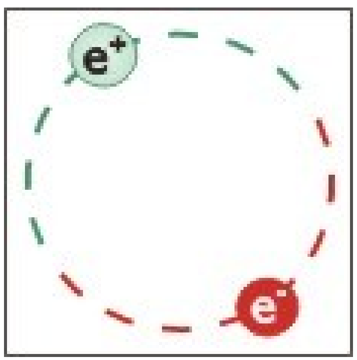
Removed **91%** ^{11}C, keeping **48.5%** scintillation events
^{11}C rate: **27** → **2.5** cpd/100tons



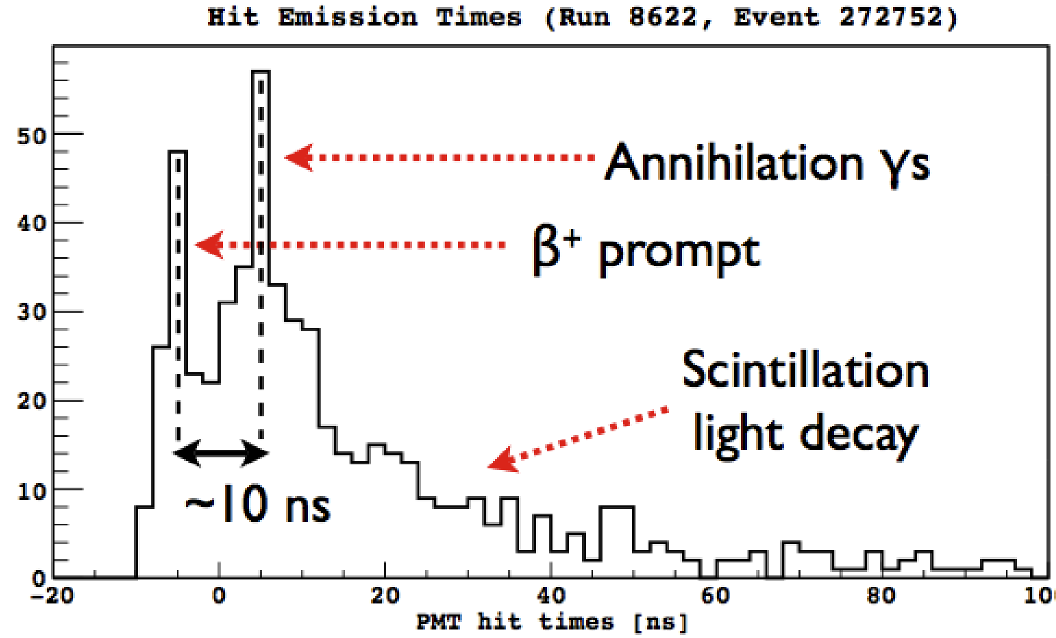
e^+/e^- Pulse Shape Discrimination

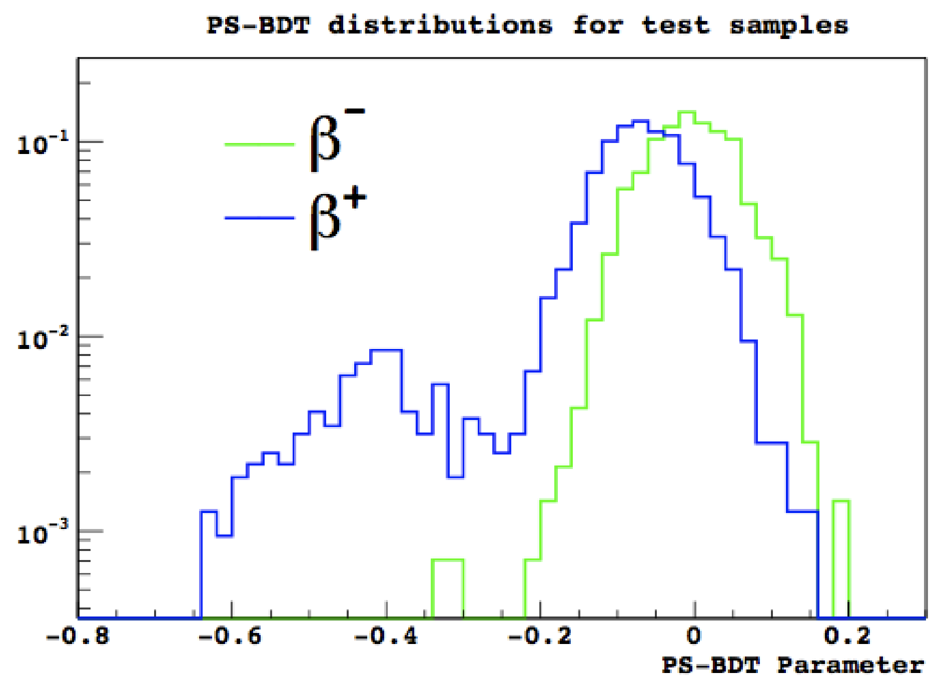
Distribution of scintillation **time signal** for **e+ delayed** with rispect to **e-**
[Phys. Rev. C 83, 0105504]

***Ortho*-positronium** formation in **50%** cases, **3 ns** mean life



We use such difference to discriminate e+/e- events: Pulse Shape Discrimination





pep-CNO neutrino rate measurment: analysis strategy

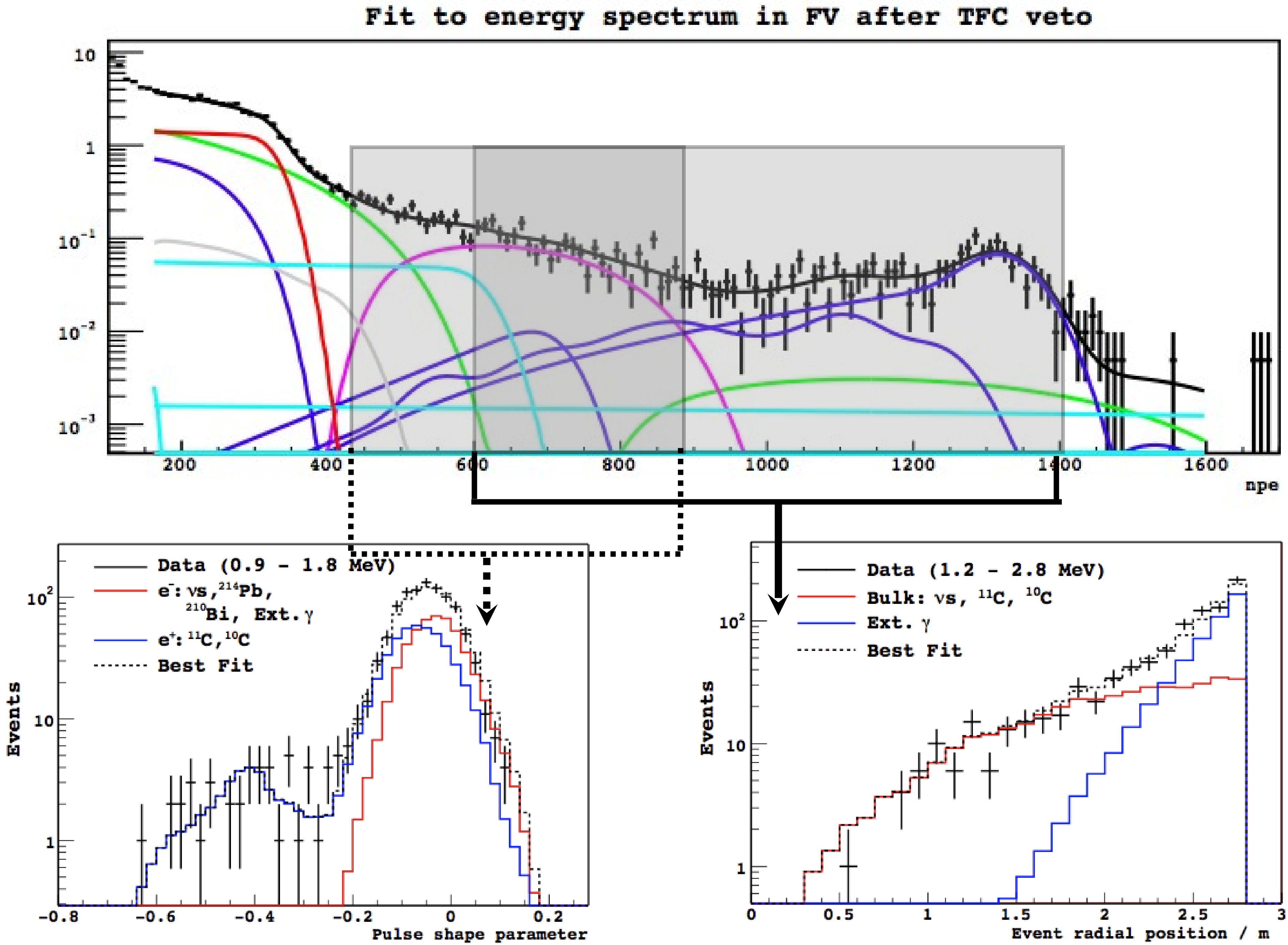
M**ultivariate maximum likelihood test to event distribution**

Considering:
energy distribution
e+/e- pulse shape (PS-BDT) distribution
radial distribution

Likelihood maximized at the same time on different variables:

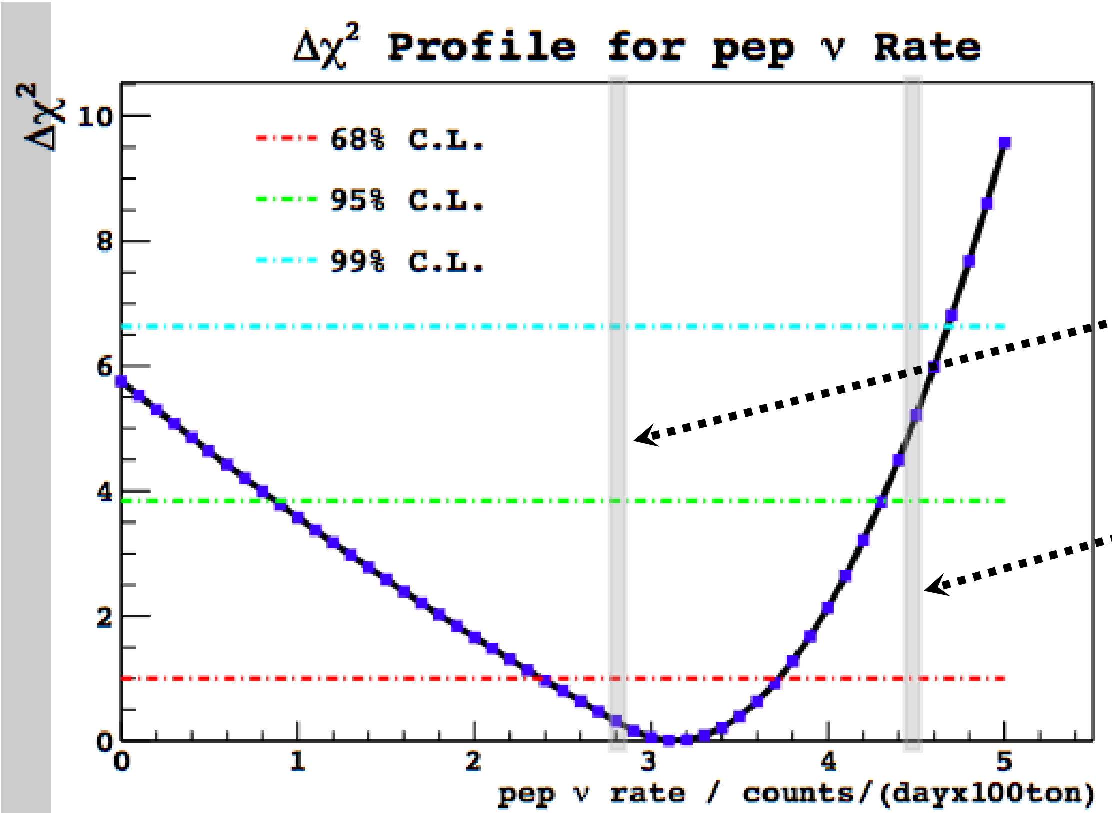
$$L_{TOT} = L_{ENE} \, L_{RAD} \, L_{e+/e-}$$

Multivariate Fit



Results

First direct measurment *pep* ν rate



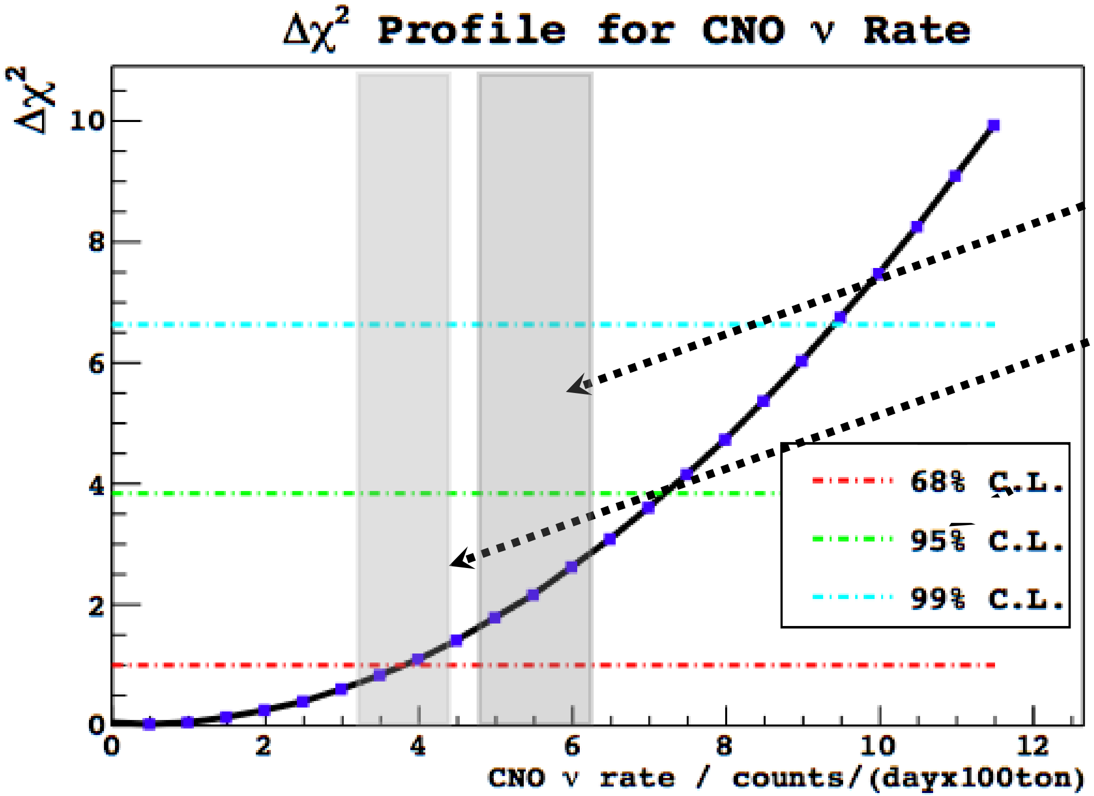
Standard Solar Model + MSW-LMA oscillation Predicted rate

No Oscillations

No oscillation hypotesis disfavoured at 97% CL

$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$ counts/day/100tons

Strongest limit on CNO neutrino rate



Standard Solar Model
High Z prediction

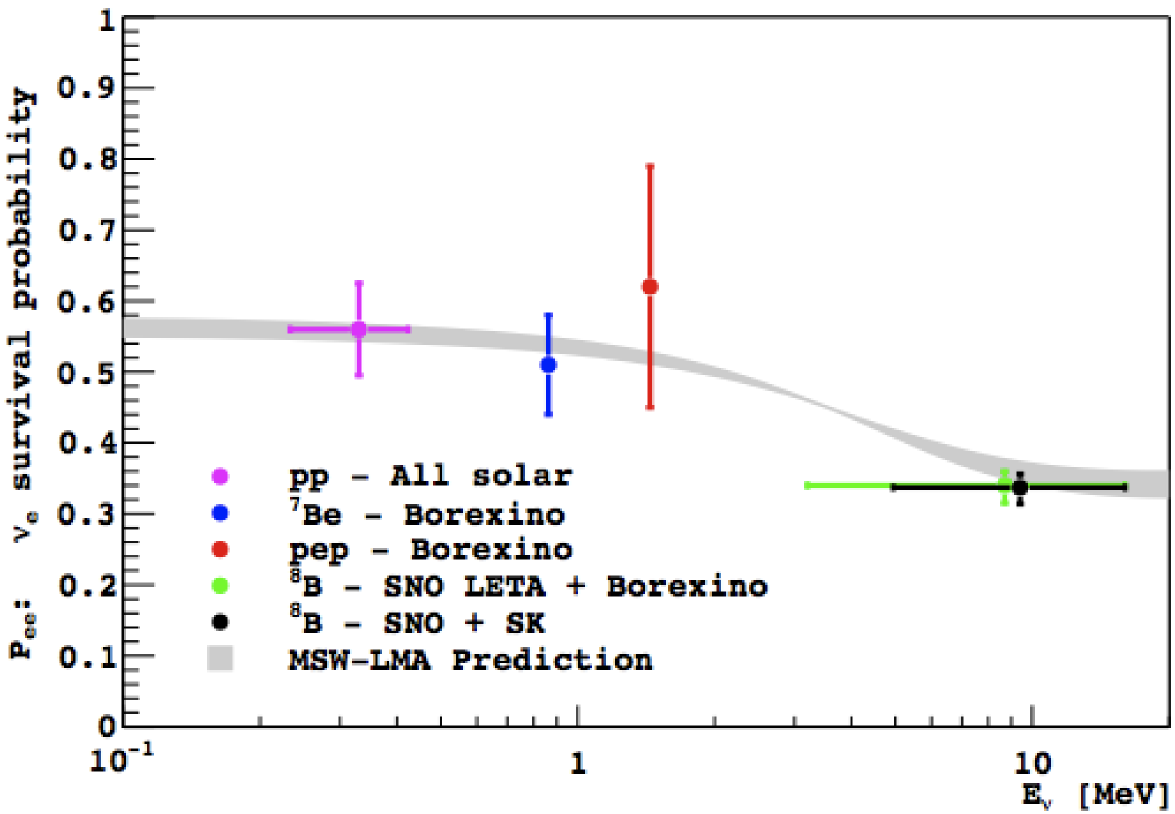
Low Z prediction

pep interaction fixed to SSM + MSW-LMA prediction:
2.8 cpd/100tons

Limit (95% CL) <7.1 $_{stat}$ counts/day/100tons

pep and CNO solar ν flux

ν	Interaction rate [counts/(day·100 ton)]	Solar-ν flux [$10^8 cm^{-2} s^{-1}$]	Data/SSM ratio
pep	$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$	1.6 ± 0.3	1.1 ± 0.2
CNO	< 7.9 ($< 7.1_{stat\ only}$)	< 7.7	< 1.5



PRL 108 (2012) 051302

Conclusions and Outlook - I

Borexino is the first experiment to perform
solar neutrino spectroscopy
at low energy (<2 MeV)

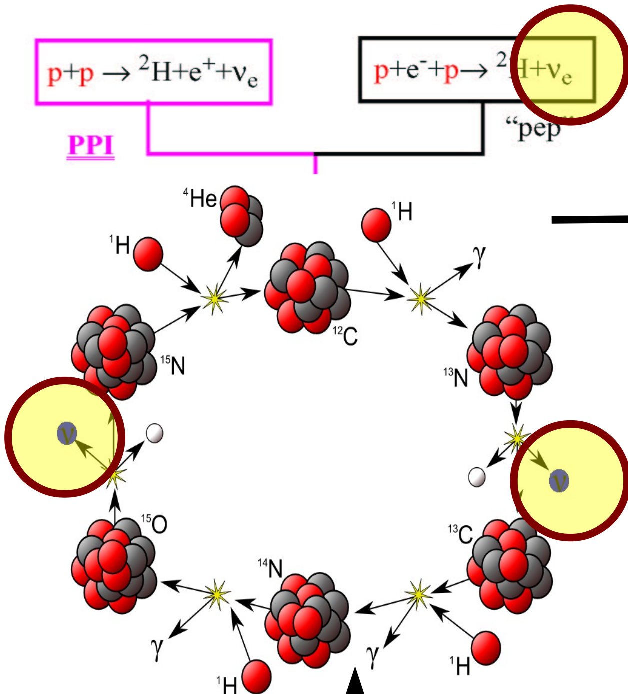
Implication of the measurments important for
Stellar Astropysics (*Solar Standard Model*)
and
Neutrino Physics
(*masses, mixing, oscillation, beyond SM*)

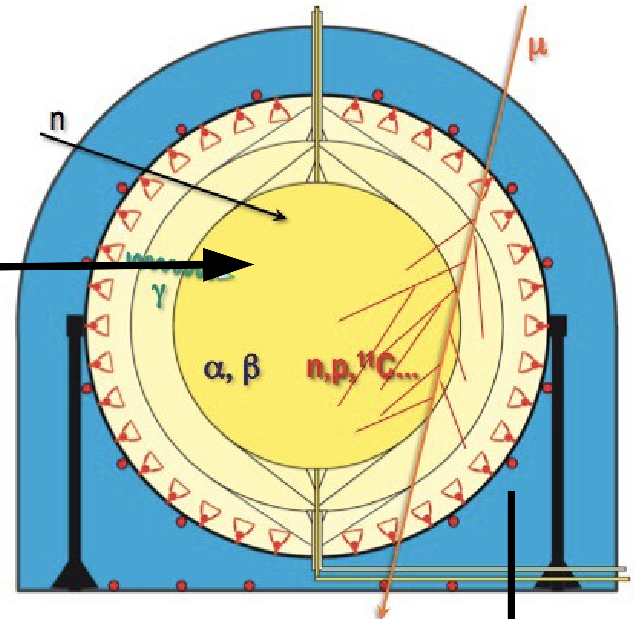
Conclusions and Outlook - II

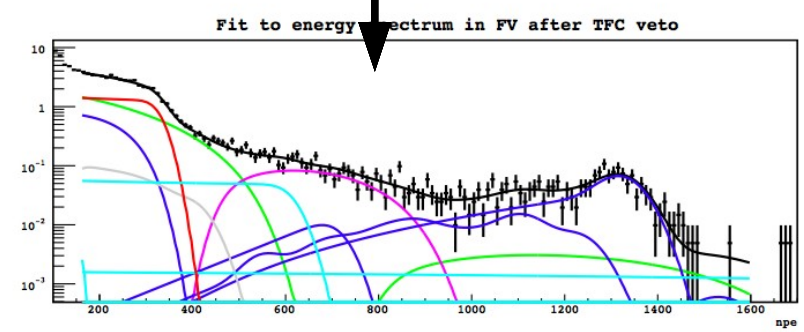
First direct measurment of
pep solar neutrino **rate**:
direct measurment of **Pee** at *E=1.44 MeV*
probes **MSW-LMA** in **transition** region

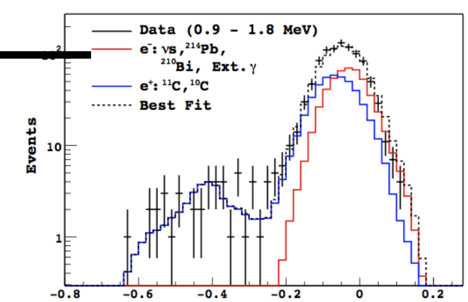
Best limits on **CNO** solar neutrino **flux**:
test of Solar **Metallicity**
in agreement with **S**olar **S**tandard **M**odels

Thanks for your attention!







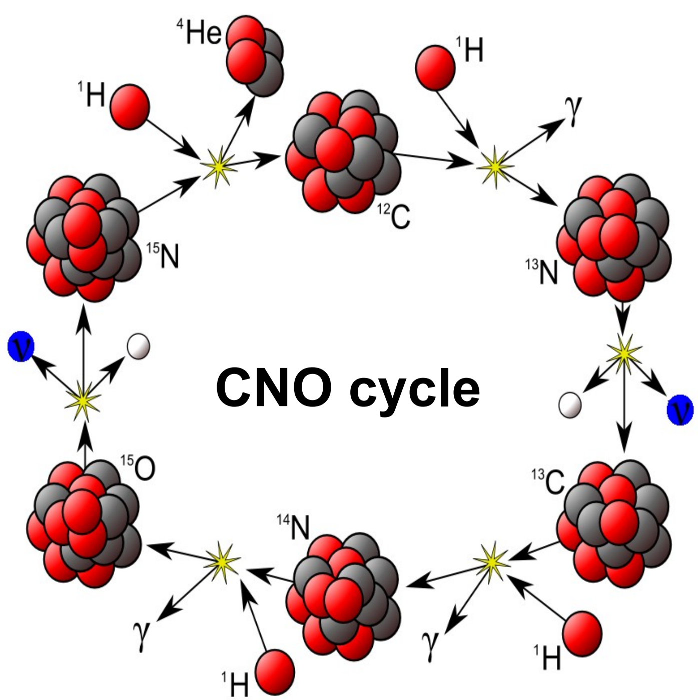


ν	Interaction rate [counts/(day·100 ton)]	Solar-ν flux [$10^8 cm^{-2} s^{-1}$]	Data/SSM ratio
pep	$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$	1.6 ± 0.3	1.1 ± 0.2
CNO	< 7.9 ($< 7.1_{stat\ only}$)	< 7.7	< 1.5

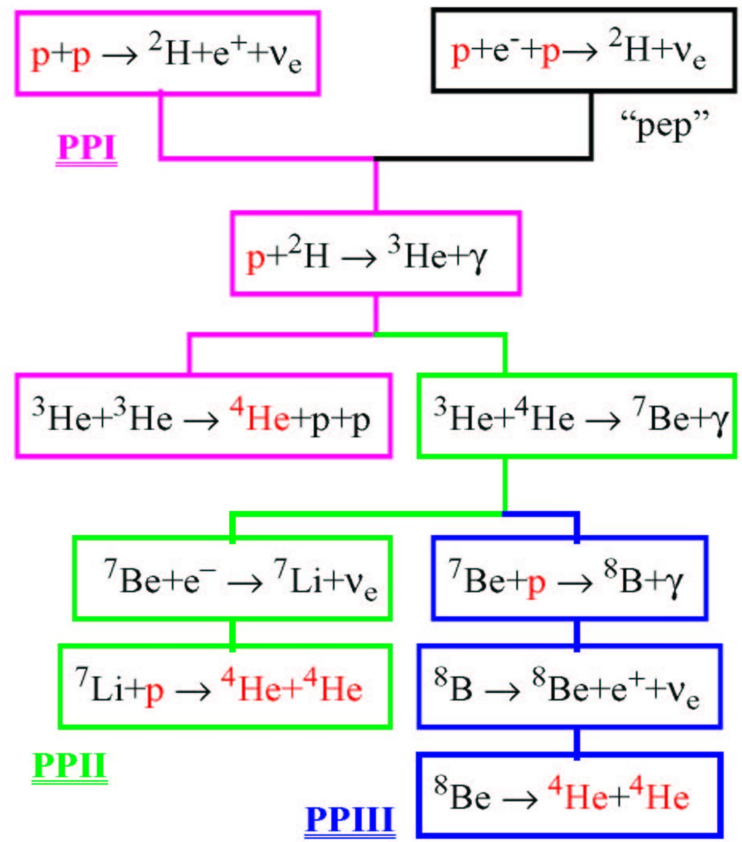
Backup slides

Nuclear reactions in the Sun

Energy production in the **Sun**:
- •**pp** chain→ 99% of energy in Sun
- •**CNO** cycle→ minor contribution (<1%)

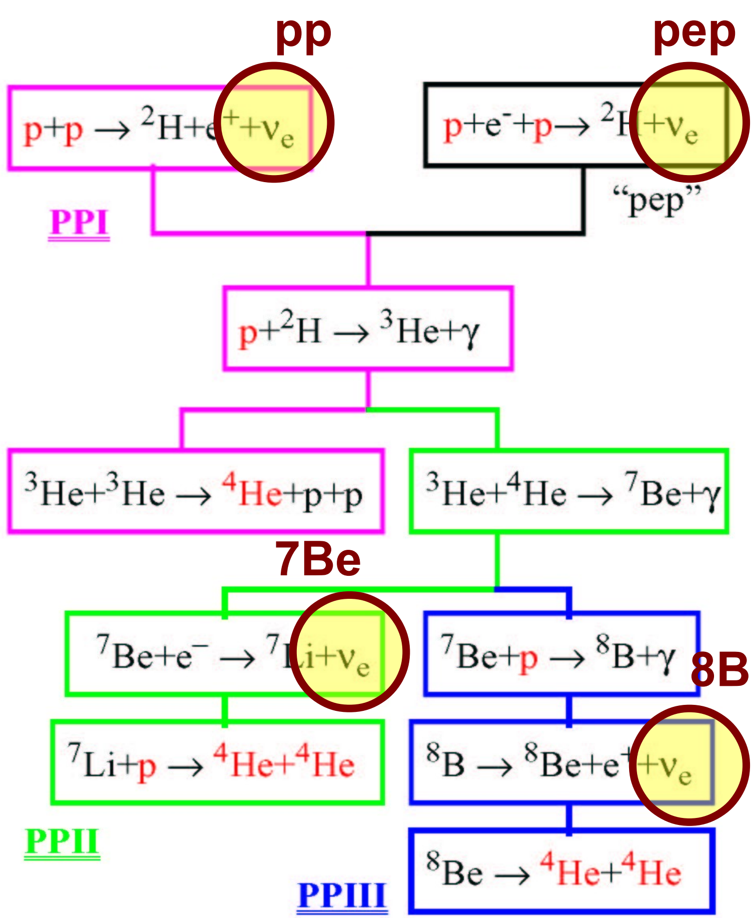


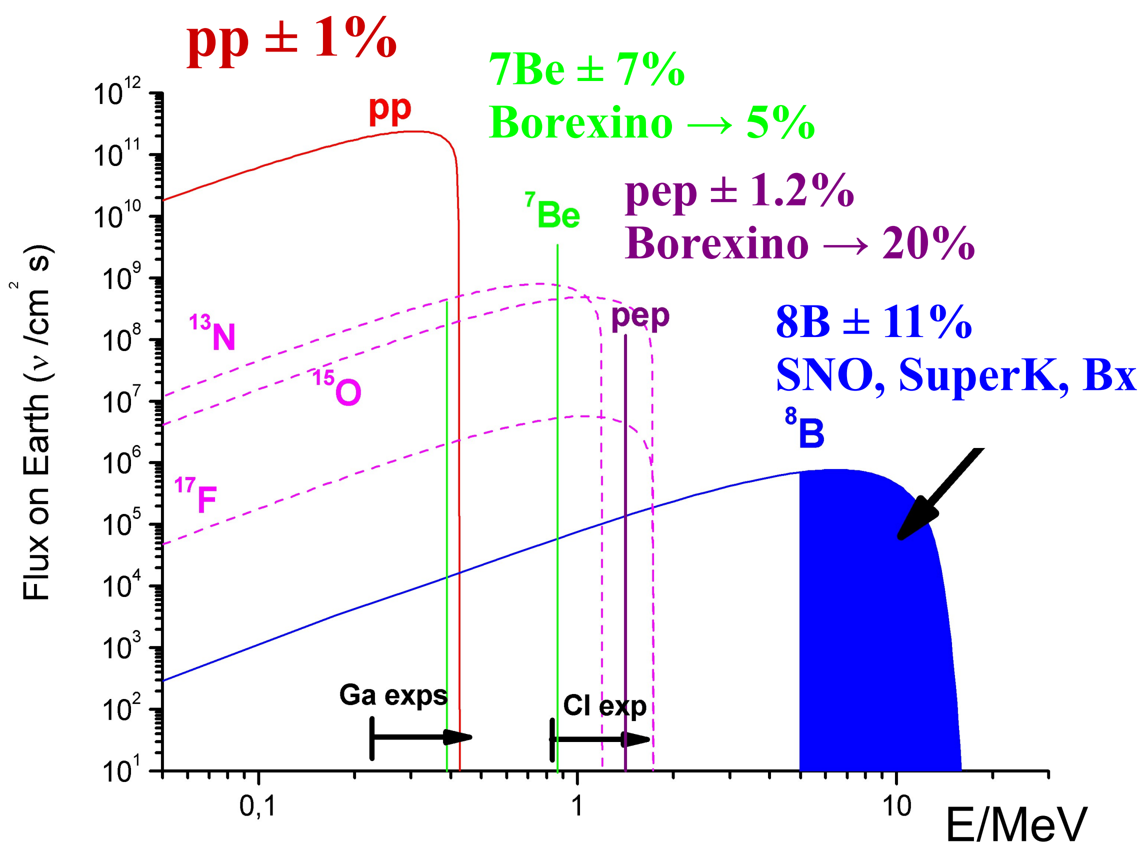
pp chain



Nuclear reactions in the Sun

Solar-ν flux and spectrum computed by Standard Solar Model

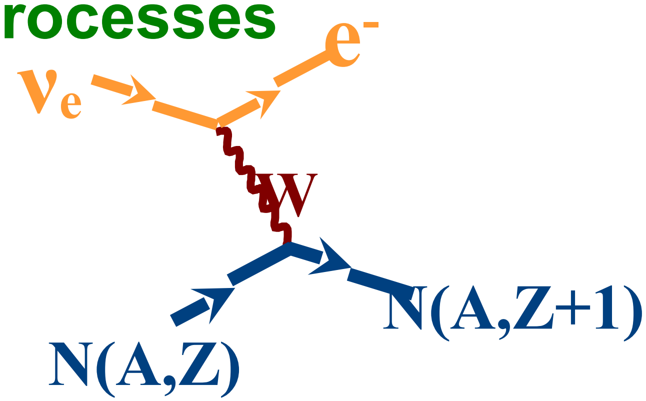




Detection of solar neutrinos

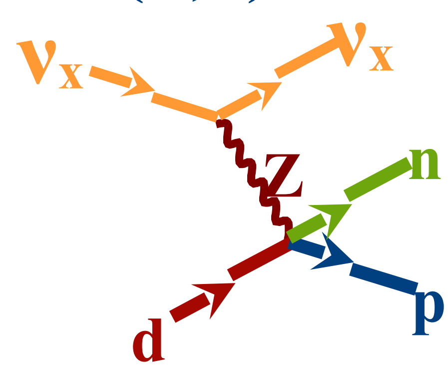
The sun produces ν_e

Detection possible via **3 fundamental processes**



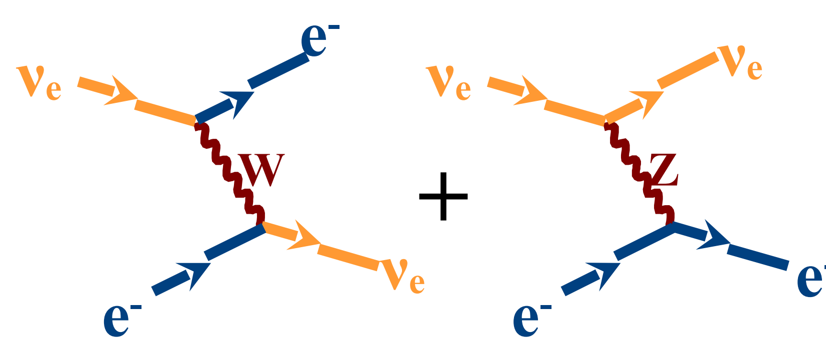
Inverse β decay on proton or nucleus

- **Charged Current** (CC) interaction
- E~MeV → ν_e **only**



Elastic scattering on nucleus

- **Neutral Current** (NC) interaction
- neutrino not assorbed
- **same** cross section for ν_e, $\nu_{\mu,\tau}$



Elastic scattering on electron

- Charged Current + Neutral Current
- **different** cross section for ν_e e $\nu_{\mu,\tau}$

$\sigma \sim 10^{-44}\ cm^2$

Short history of solar neutrino experiments

70's-80's: Homestake (R. Davies)

- radiochemical experiment: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ **(E >1.4 MeV)**

✓ Deficit observed → new physics or Solar Model unaccurate?
✓ Nobel prize 2002

80's-90's: (Super) KamioKande

✓ Confirm deficit on ${}^{8}B$ ν **(E> ~5MeV)**
✓ Direction of solar neutrinos

90's: Gallex (GNO), Sage

- Radiochemical experiment: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ **(E > 200 keV)**

✓ Observed deficit on pp ν **(low energy)**
✓ Calibrazion with neutrino souce → real effect

2001: SNO

➢ Separate detection of $\boldsymbol{\nu_e}$ and $\boldsymbol{\nu_{\mu,\tau}}$
✓ Confirm flavor transition of solar neutrinos
✓ Total flux agrees with Standard Solar Model

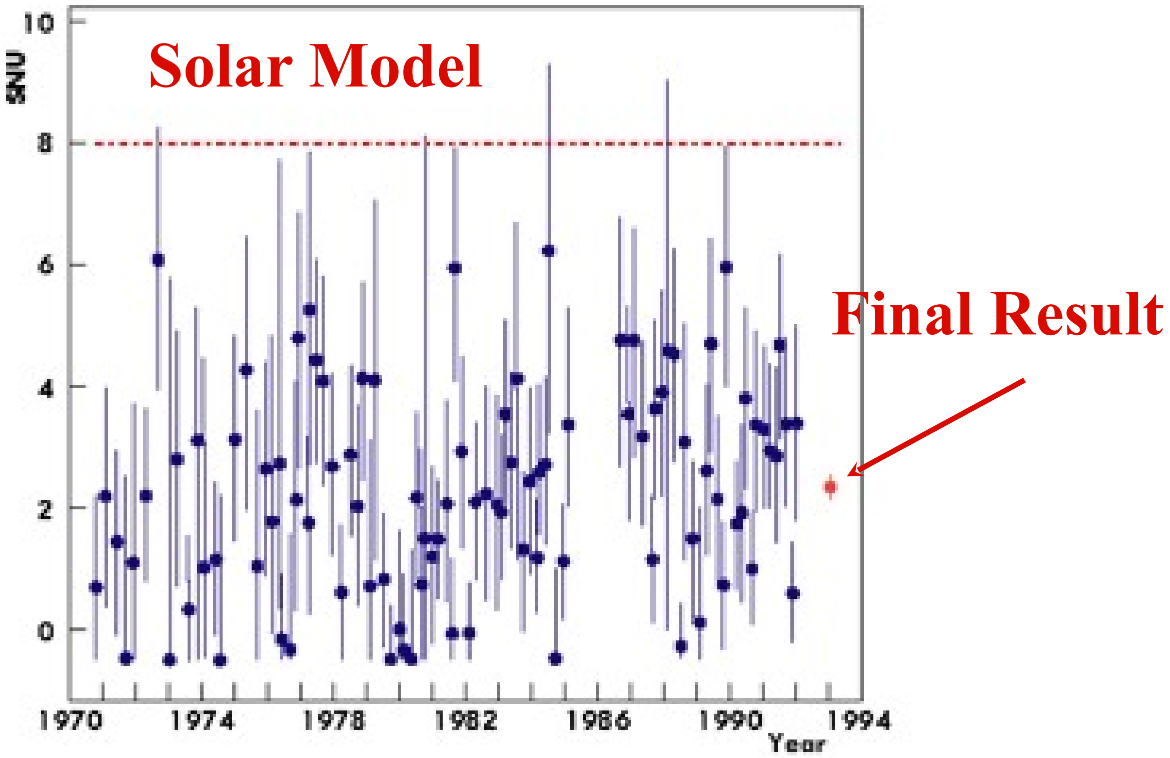
Short history of solar neutrino experiments - I

70's-80's: Homestake (R. Davies)

- radiochemical experiment: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ **(E >1.4 MeV)**

✓ Deficit observed → new physics or Solar Model unaccurate?

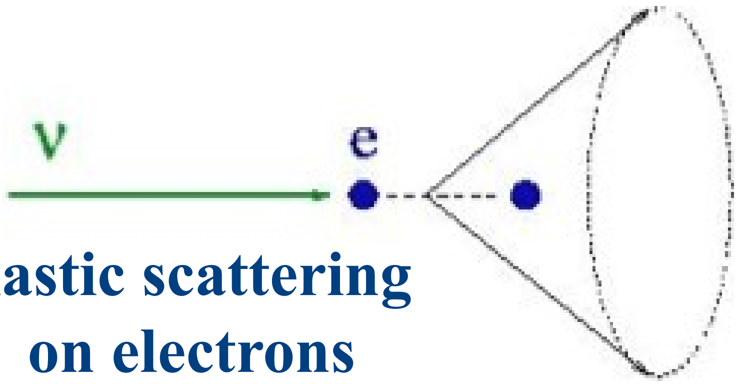
✓ Nobel prize 2002



Short history of solar neutrino experiments - II

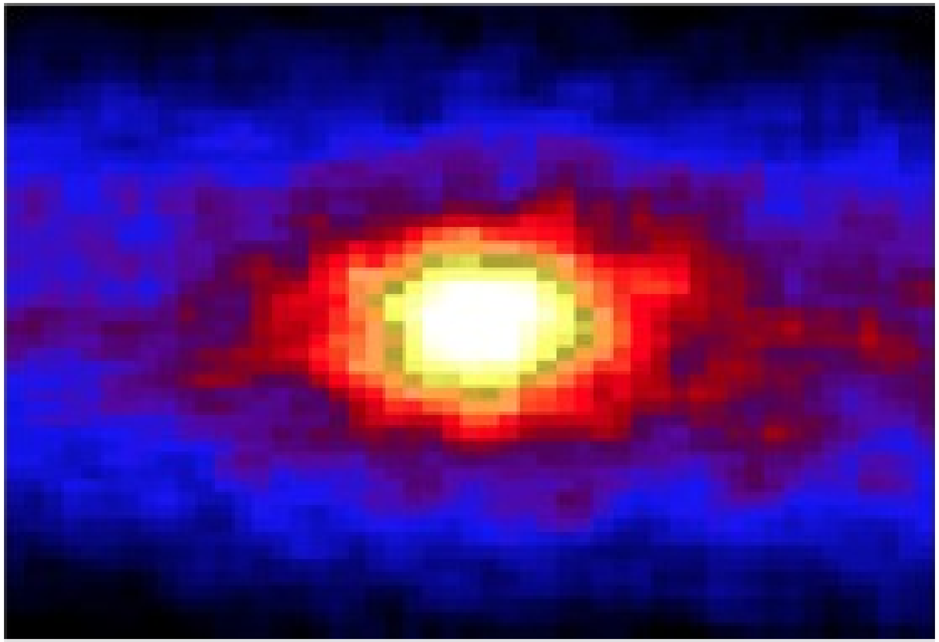
80's-90's: (Super) KamioKande

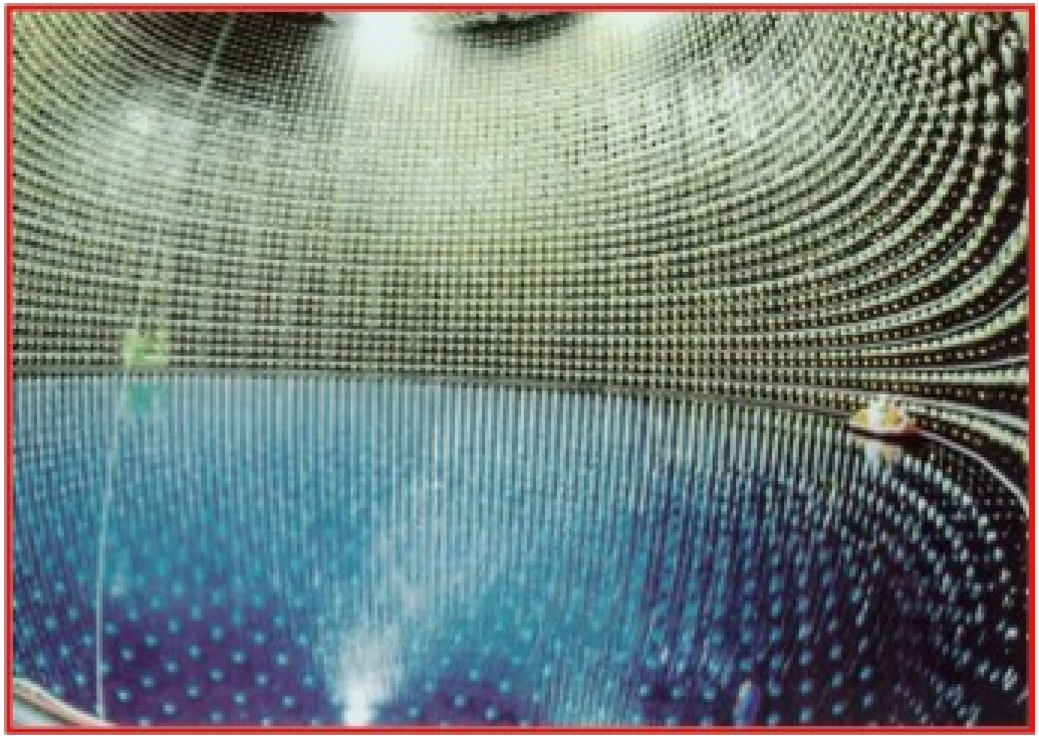
- Confirm deficit on $^{8}B\ \nu$ **(E> ~5MeV)**
- Direction of solar neutrinos



elastic scattering on electrons

A beautiful image of the Sun in neutrinos





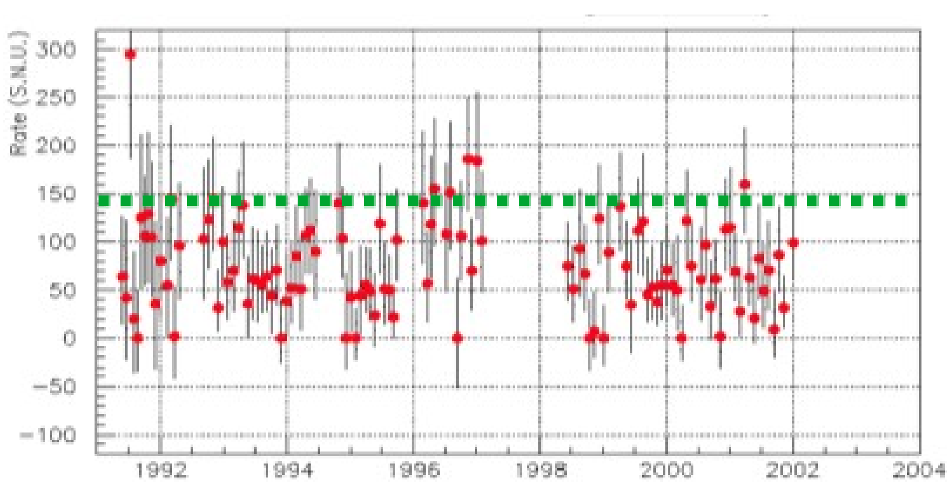
Short history of solar neutrino experiments - III

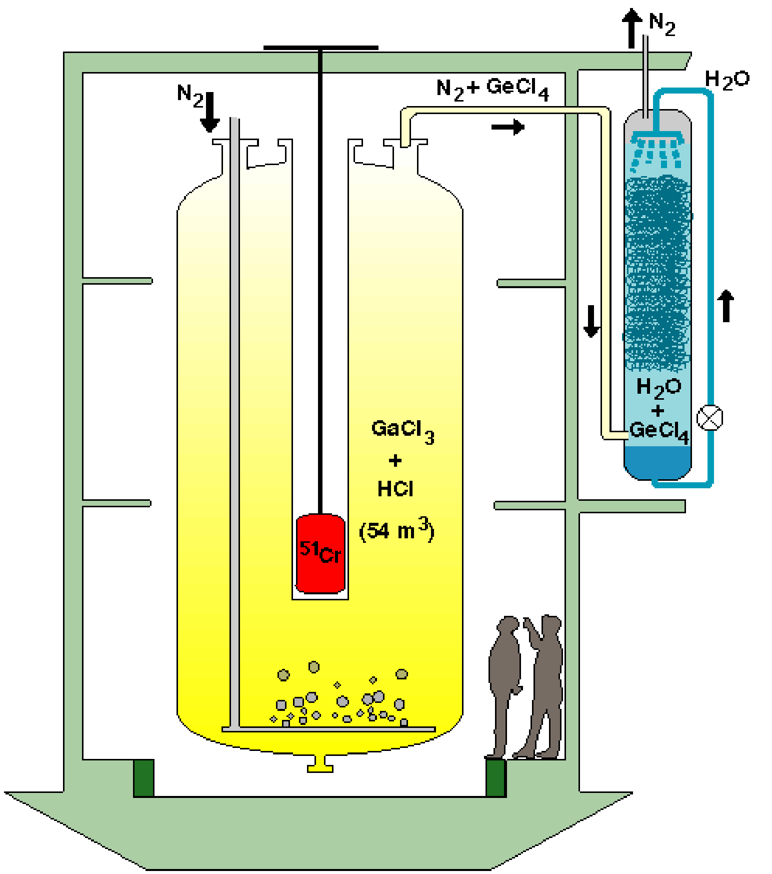
90's: Gallex (GNO), Sage

- Radiochemical experiment: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ **(E > 200 keV)**

✓ Observed deficit on pp ν **(low energy)**

✓ Calibration with neutrino source → real effect





Solar neutrino oscillations

Explaination of *solar neutrino deficit:*

if neutrino has **mass** + **flavor** defined state is **not** mass eigenstate → **flavor oscillation** during propagation

(analogy in quark sector: CKM-mixing → neutral K oscillations...)

if only ν_e detected → **deficit**

With just 2 flavors and perfect coherence

$$P_{e\to\mu} = \sin^2(2\theta)\sin^2\left[\frac{1.27\Delta m^2 L}{E_\nu}\right]$$

Δm in eV
L in m
E_ν in MeV

Solar neutrinos: production region >> oscillation length → oscillation term averaged out

Solar neutrino oscillation in vacuum

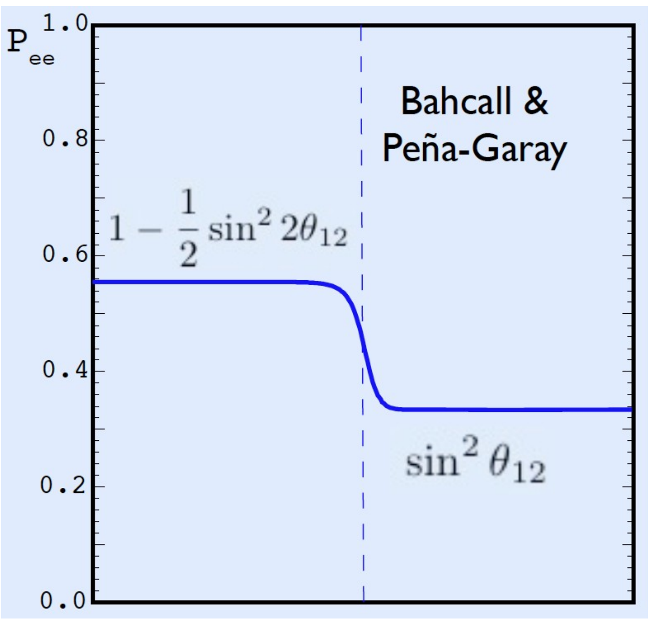
$$P_{e\to\mu} = \frac{1}{2}\sin^2(2\theta)$$

But propagation NOT in vacuum: Sun matter

Neutrino oscillations in matter

Matter made of e^- (no μ, τ)

- coherent ν-e^- scattering affects oscillations (**W**olfenstein, '78)
- $\boldsymbol{\nu_e}$ ineractions different from $\boldsymbol{\nu_{\mu,\tau}}$
- *"Refraction index"* for ν_e different from $\nu_{\mu,\tau}$



Resonant effect (Mikheyev & **S**mirnov, 1985)

- **Survival probability** (**Pee**) becomes **energy depedent**

MSW Effect in the Sun

- Low energy neutrinos (pp ν) → oscillations as in **vacuum**
- High energy neutrinos (^{8}B ν) → **Matter enhanced** oscillations
- **Transition region** between 1-3 MeV

Discovery of solar neutrino oscillations

SNO, 2001:

- Detects ν_e and $\nu_{\mu,\tau}$ ^8B ν

  CC** and **NC** interactions on **d

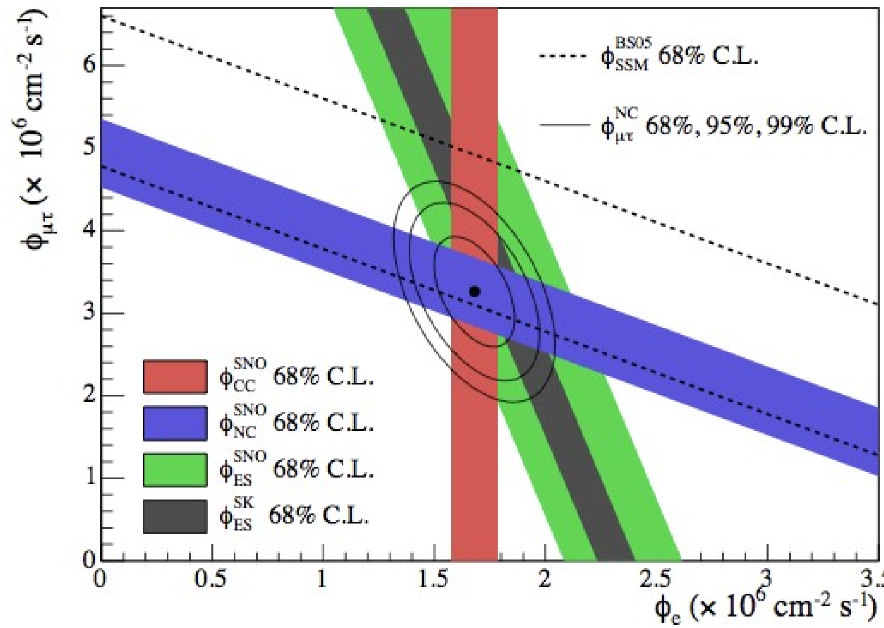
  ES** interactions on **e^-

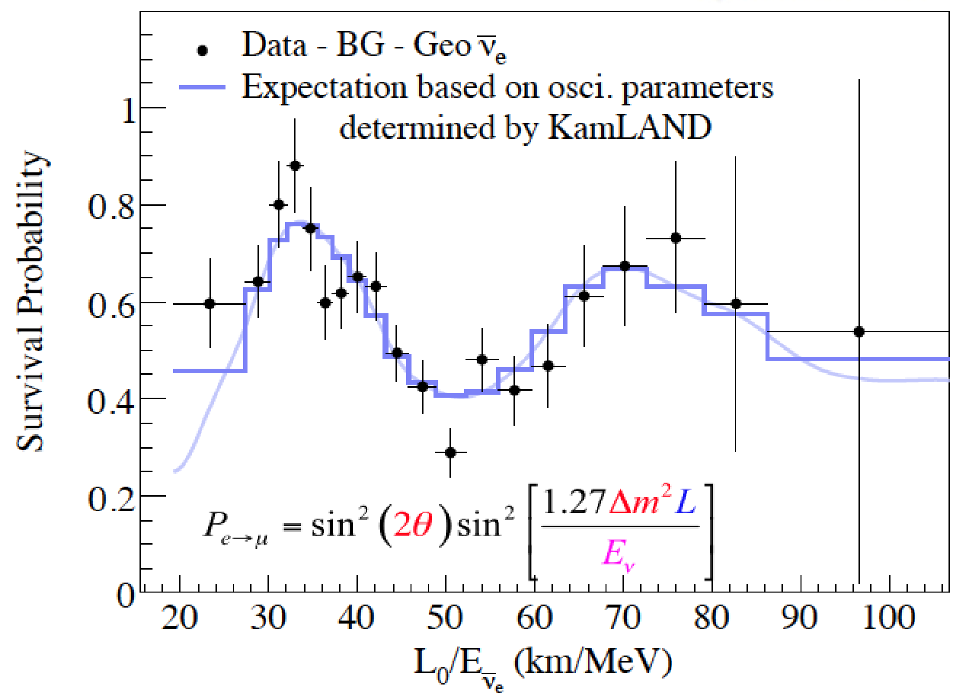
- **Total** $\nu_e + \nu_{\mu,\tau}$ flux is SSM predicted flux
- **Disappearance of ν_e**
- **Apperance of $\nu_{\mu,\tau}$**

KamLAND, 2002:

- Observation of reactor anti ν_e oscillations

- Precise Δm^2 measurment





MSW-LMA scenario

SNO and KamLAND measurments evidence

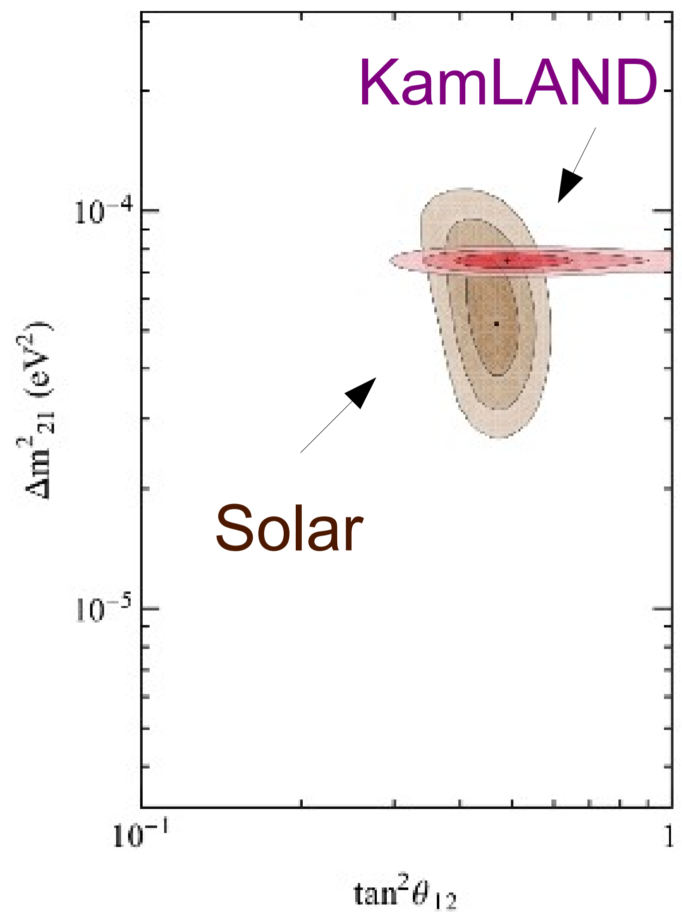
ν_e oscillation into $\nu_{\mu,\tau}$ in trip from Sun's core to Earth

Total flux $(\nu_e + \nu_{\mu,\tau})$ agrees with Standard Solar Model

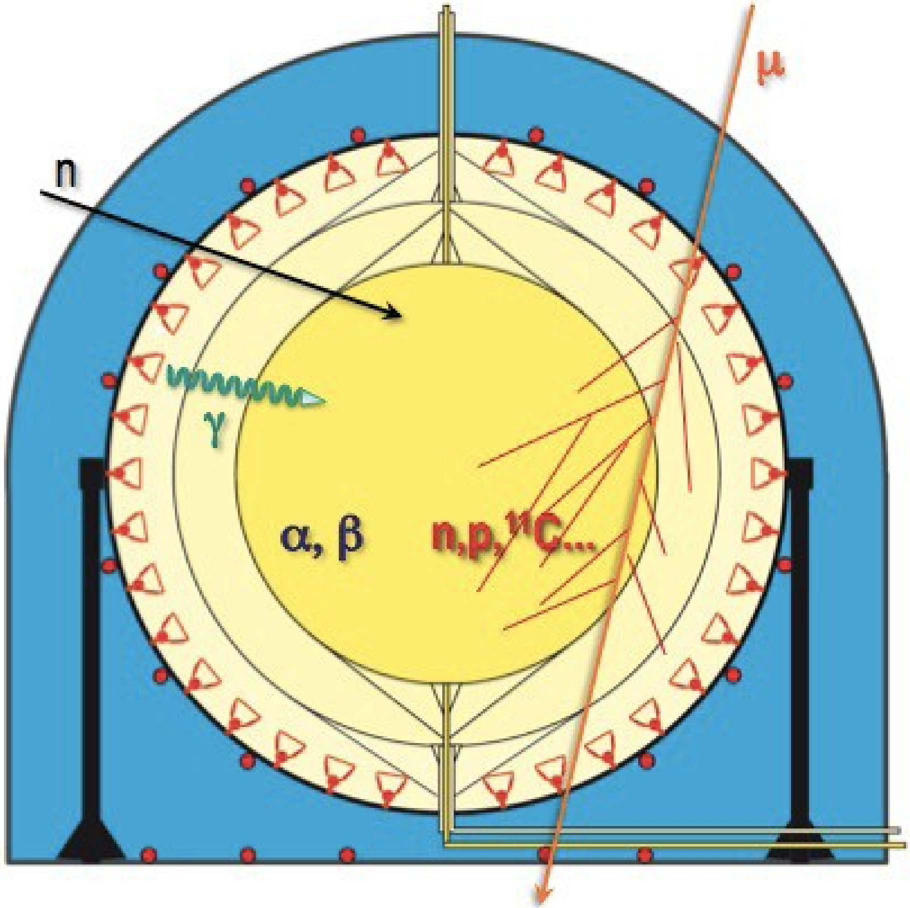
MSW effect → Energy dependent **Pee**

Global Fit
Solar exp + KamLAND
evidence:
Large **M**ixing **A**ngle

Solar neutrino oscillations
described by
MSW-LMA scenario



Borexino detector - Backgrounds



Radioactive backgrounds
radioactive traces in **scintillator**
radioactivity from **PMT**s, ...

Neutrino interaction
NOT distinguishable from **β/γ**
radioactive decays in scintillator

Strict radiopurity requirements on materials
graded shielding:
closer to **FV** → more **pure**

Signal (^{7}Be neutrinos) → **50 events/day/100tons** → **6 10^{-9} Bq/kg**

Typical radiactive concentration (air, water): **~10 Bq/kg**

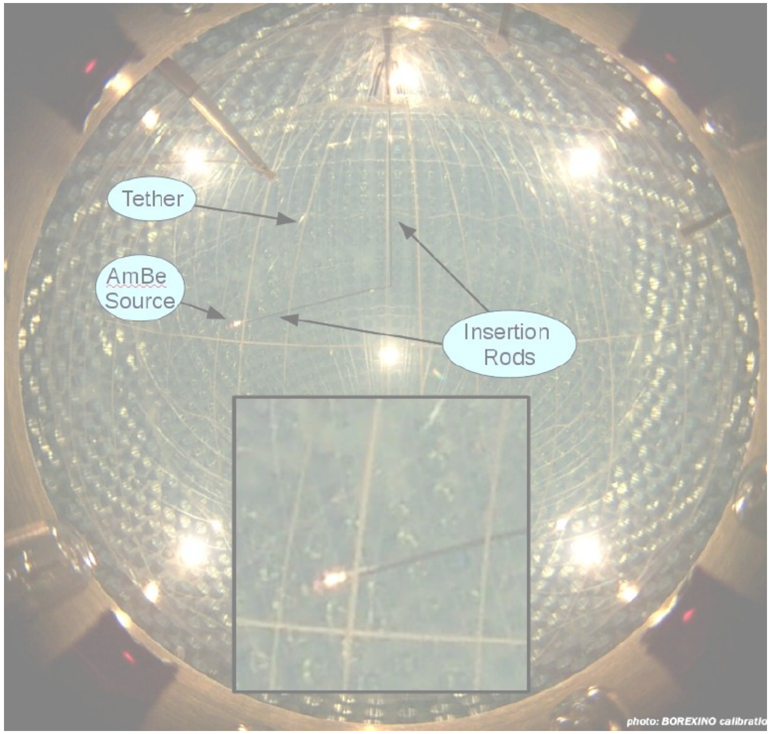
Solar neutrino spectroscopy with **scintillator** → **detector 9-10 orders of magnitude** more radiopure than anything on Earth

Borexino detector – Internal Backgrounds

Radio-Isotope		Concentration		Reduction Strategy		Final
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	**Achieved**
^{14}C	intrinsic organic scint.	~10^{-12} g/g	**~10^{-18} g/g**	Scintillator selection	threshold	~ 2 10^{-18} g/g
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	**<10^{-16} g/g**	distillation, W.E., filtration, material selection, cleanliness	tagging, α/β	**1.6±0.1 10^{-17} g/g 5.1±1 10^{-18} g/g**
^{40}K	dust	~2. 10^{-6} g/g (dust)	**<10^{-18} g/g**	distillation,W.E.	--	**< 10^{-18} g/g**
^{210}Po	Surface cont. from ^{222}Rn		**<1 c/d/t**	distillation, W.E., filtration, cleanliness	fitting	**from 70 c/d/t to ~1 c/d/t (decaying)**
^{222}Rn	Emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	**<10 cpd 100 t**	N_2 stripping cleanliness	tagging, α/β	**<1 cpd 100 t**
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	**< 1 cpd 100 t**	N_2 stripping	fitting	**30 ± 5 cpd/100 t**

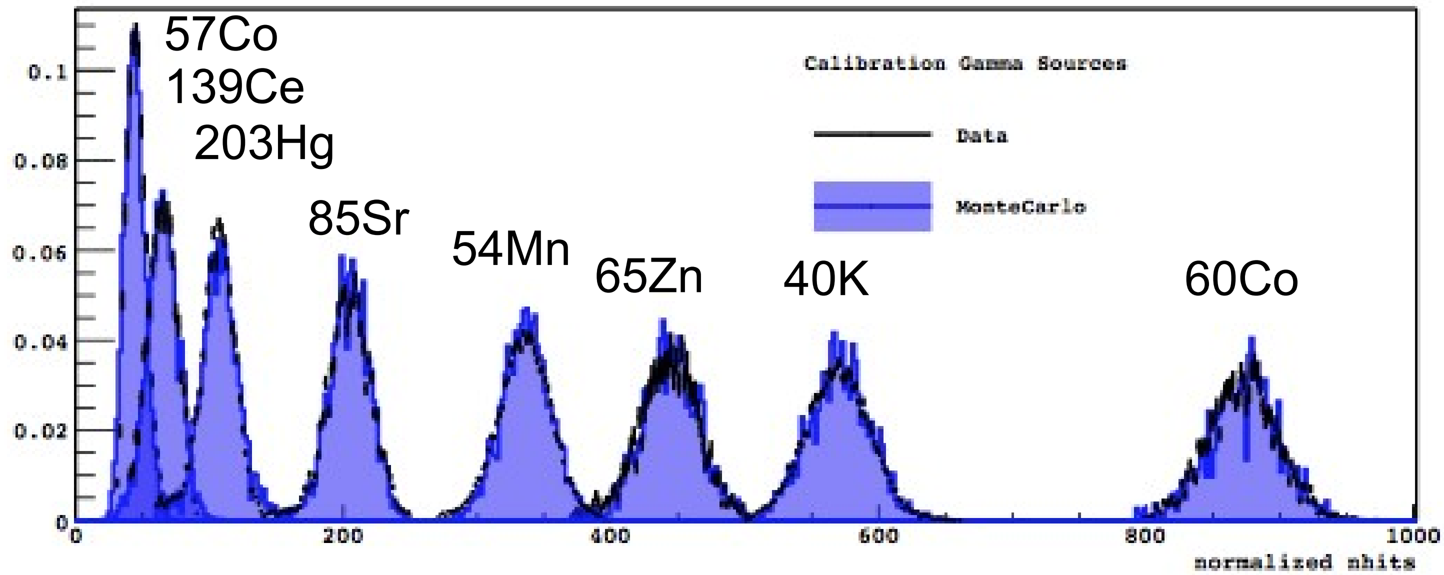
Borexino Detector Calibration

Study **detector response** as function of **position** and **energy** using *α, β, γ, n* **sources**

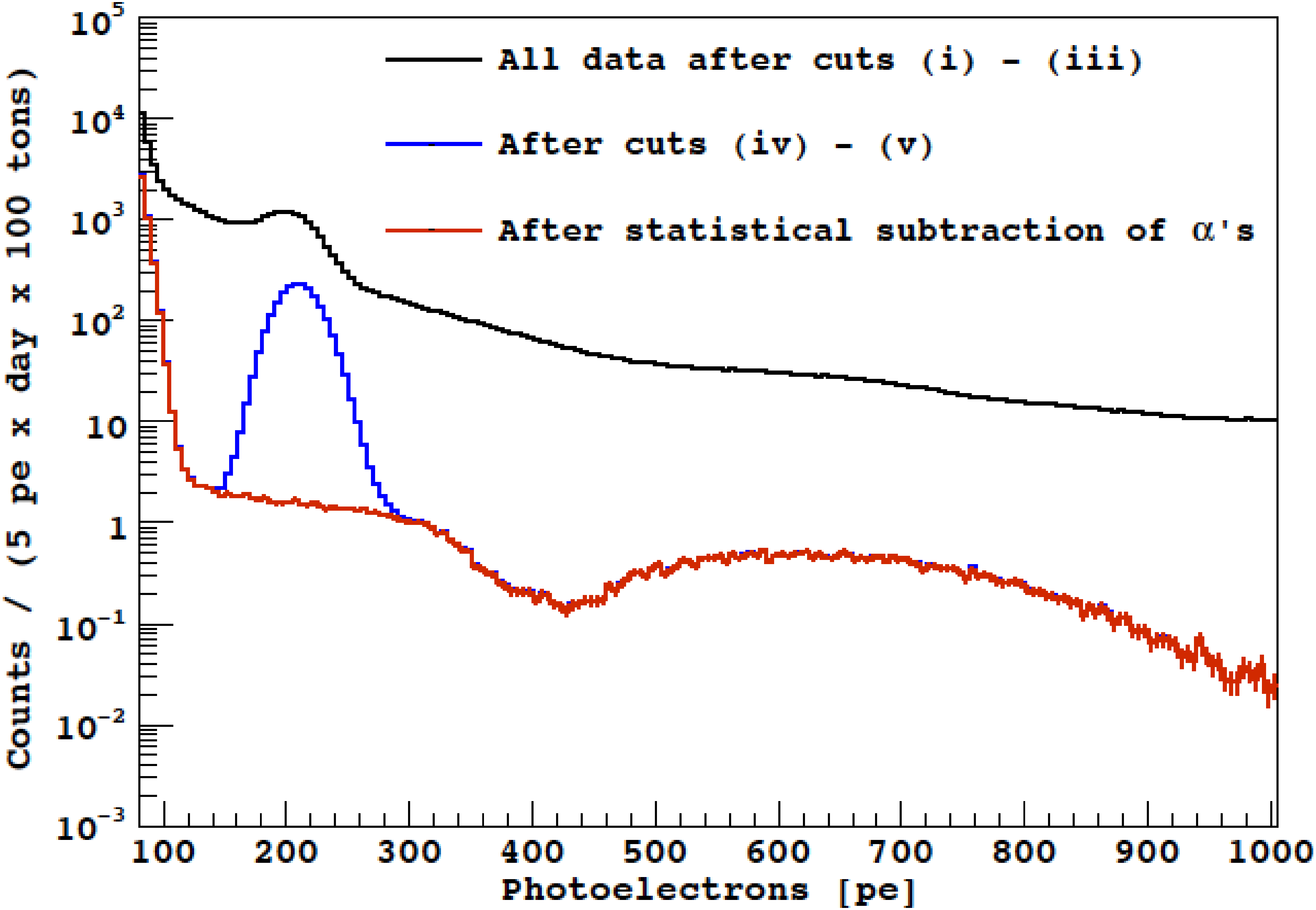


Improved **energy** response **understanding** and **modeling**
Improved **position reconstruction** algorithm

Calibration
γ sources:
Data VS MC

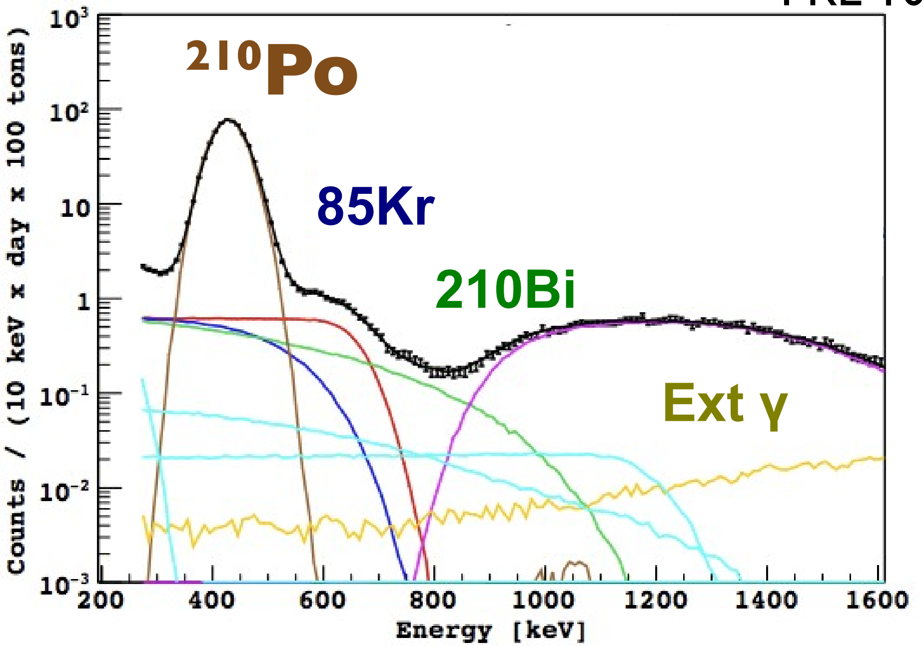


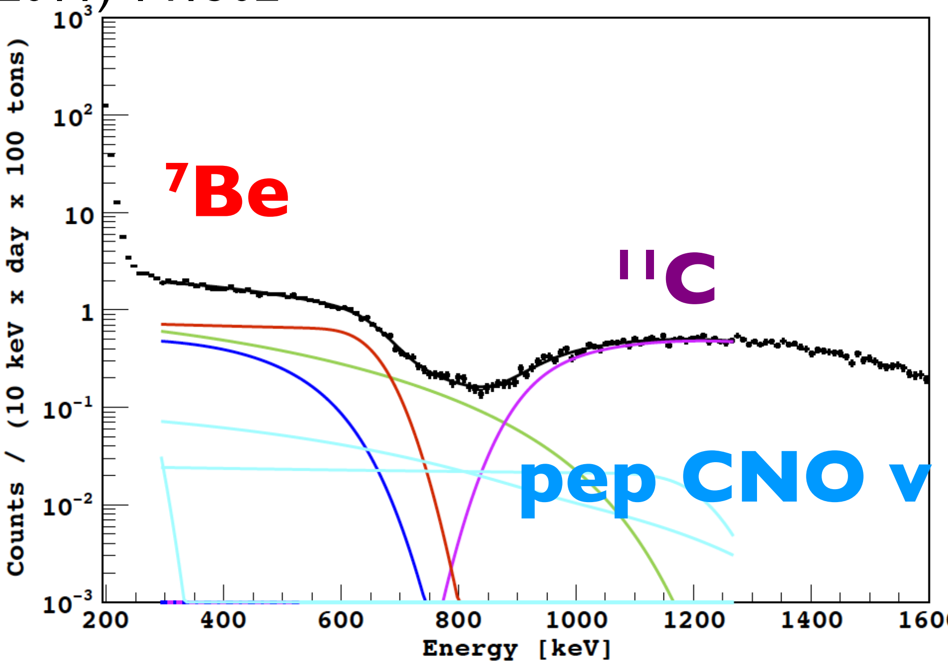
^{7}Be analysis: Data Selection



^{7}Be solar ν spectroscopy in Borexino

PRL 107 (2011) 141302





Few residual radioactive backgrounds: ^{210}Po, ^{85}Kr, ^{210}Bi

Fit to energy spectrum to separate signal/backgrounds contibutions

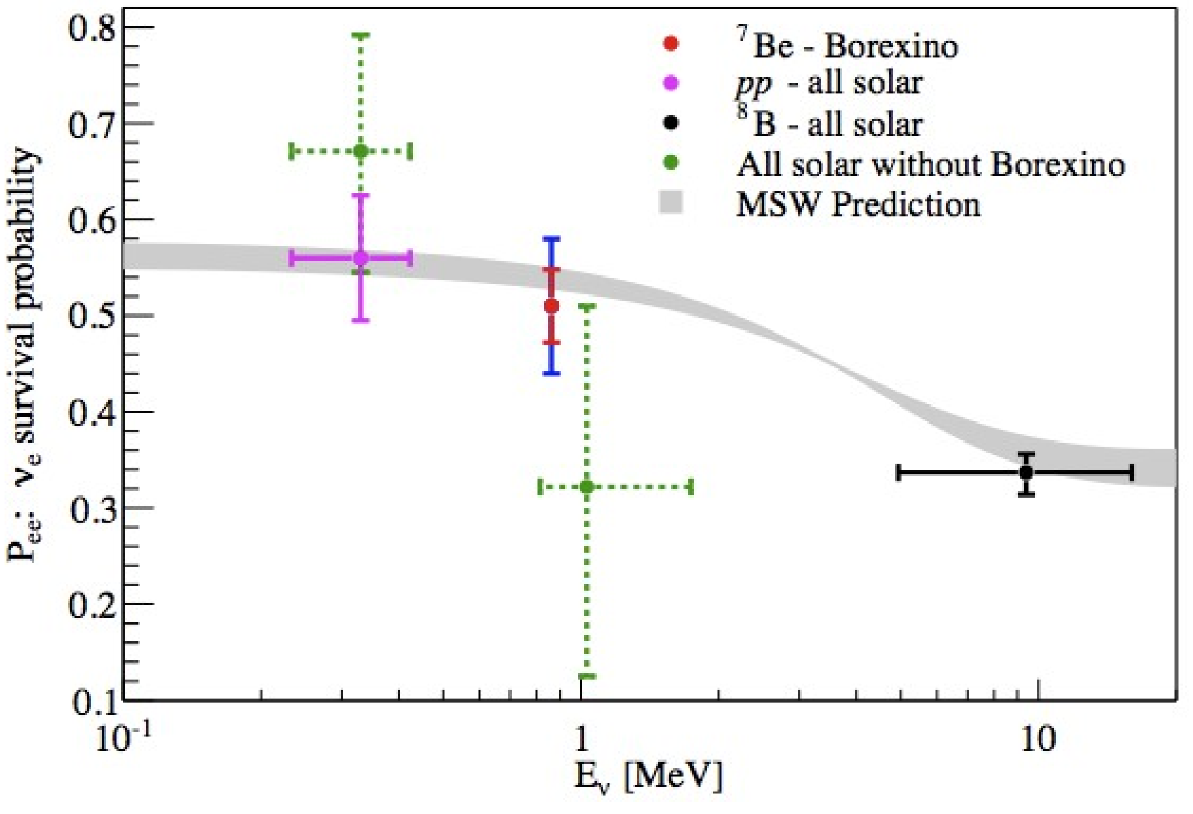
Two independent method to generate energy spectra pdfs:

MC and analytical

Precision measurment of the ^{7}Be solar ν interaction rate

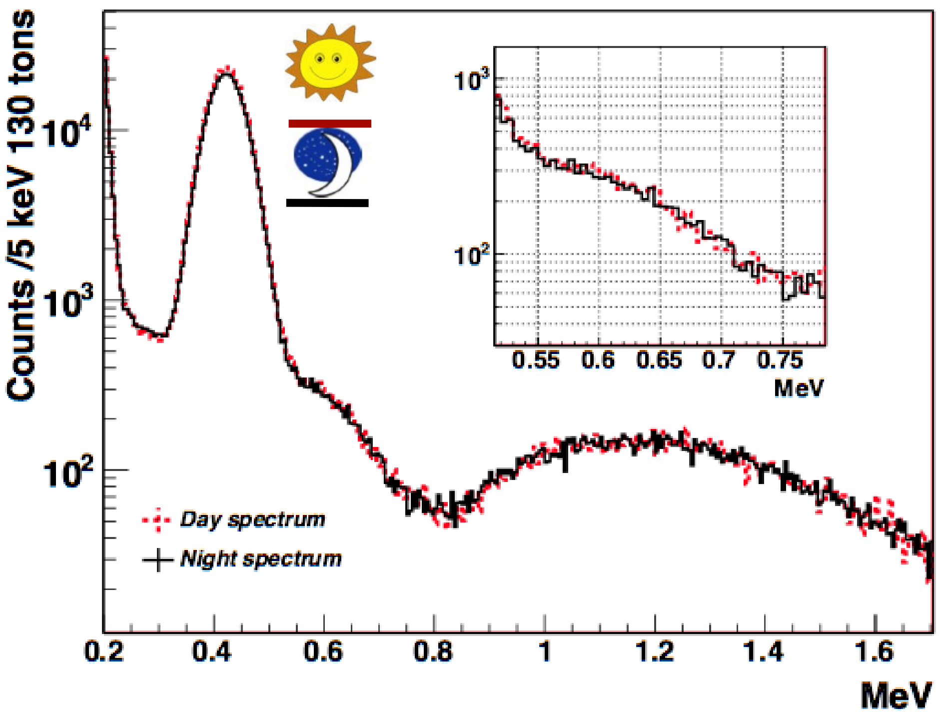
$46.0 \pm 1.5_{stat}\,{}^{+1.6}_{-1.5syst}$ counts/day/100tons

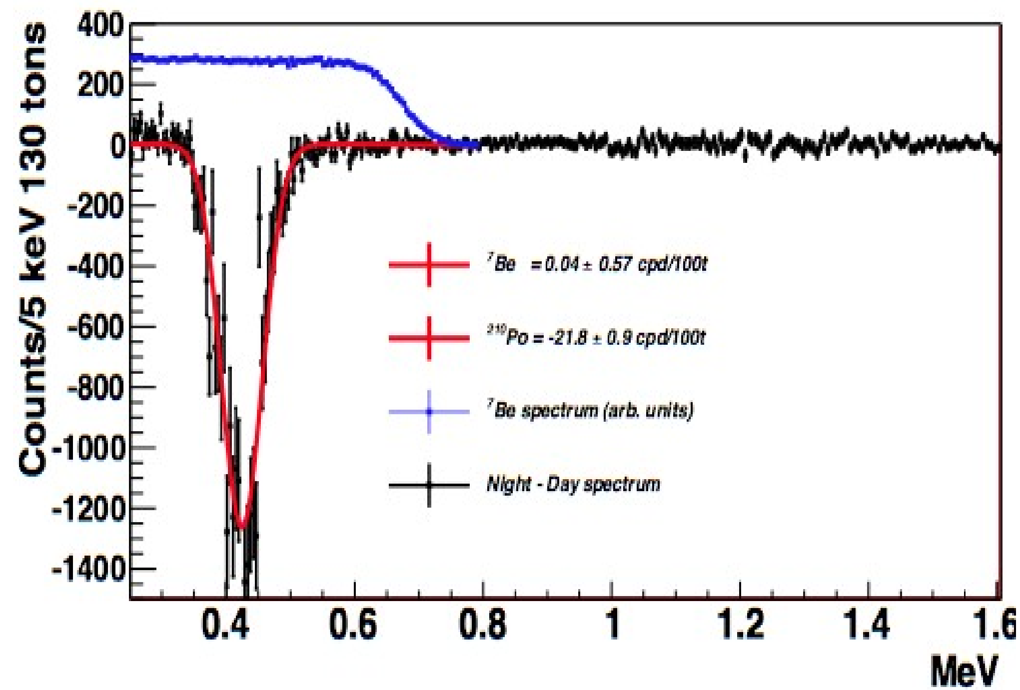
No oscillations hypotesis rejected at 4.8 σ [74±5 cpd / 100 t]



Day-night asymmetry

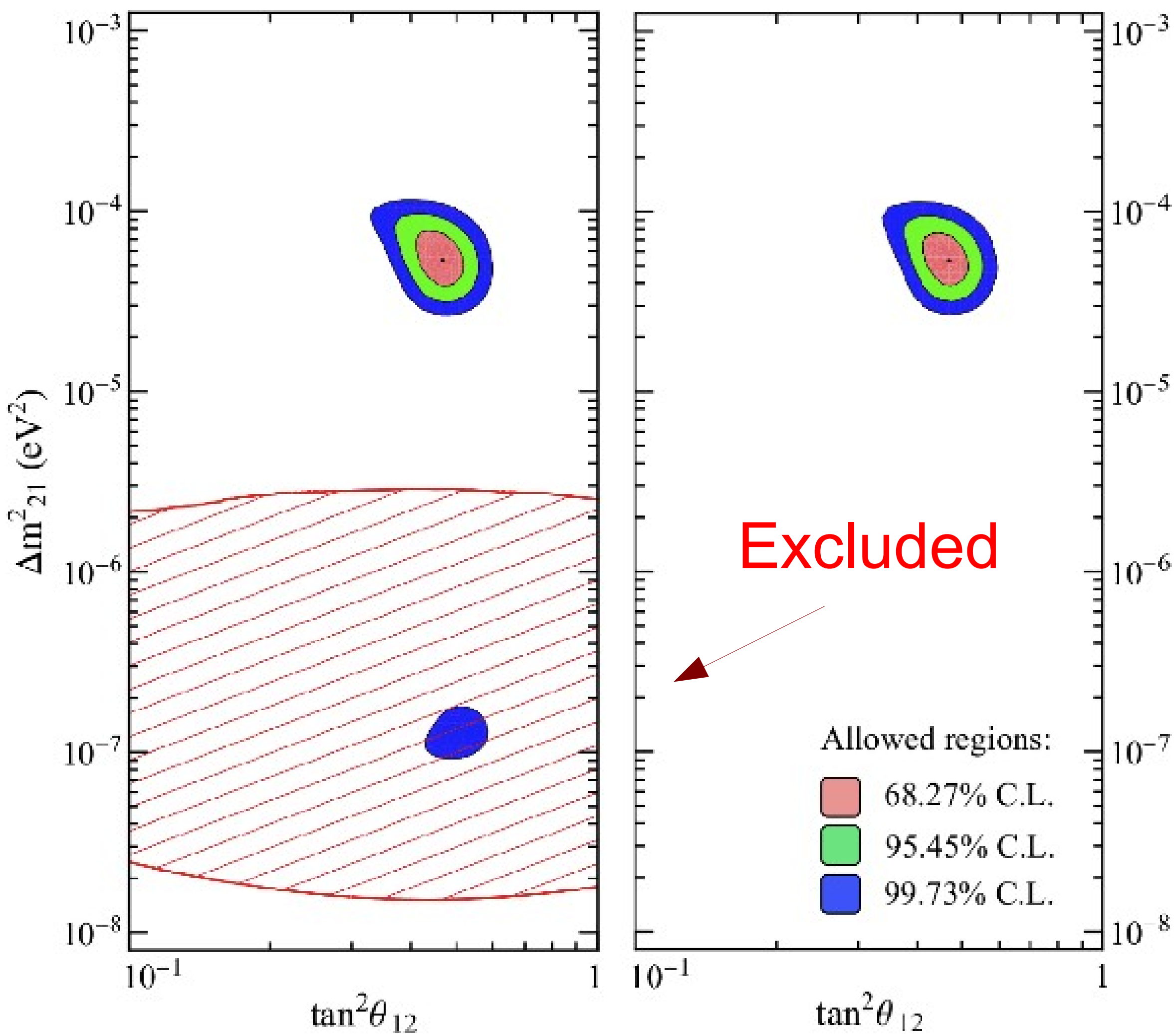
As neutrinos pass through the earth (at night),
matter effect can cause **regeneration**:
ν_μ can be converted back to ν_e
if $\mathbf{\Delta m^2_{21}}$ in a certain range





$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = 0.001 \pm 0.012 \pm 0.007$$

Absence of day-night asymmetry



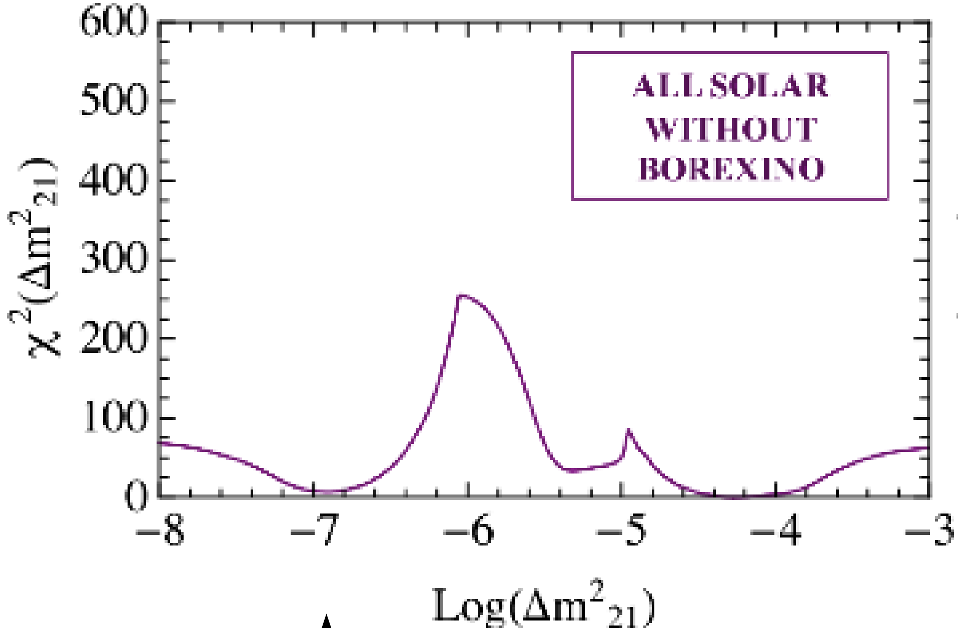
Rules out the **low** Δm^2 parameter space at more than 8σ

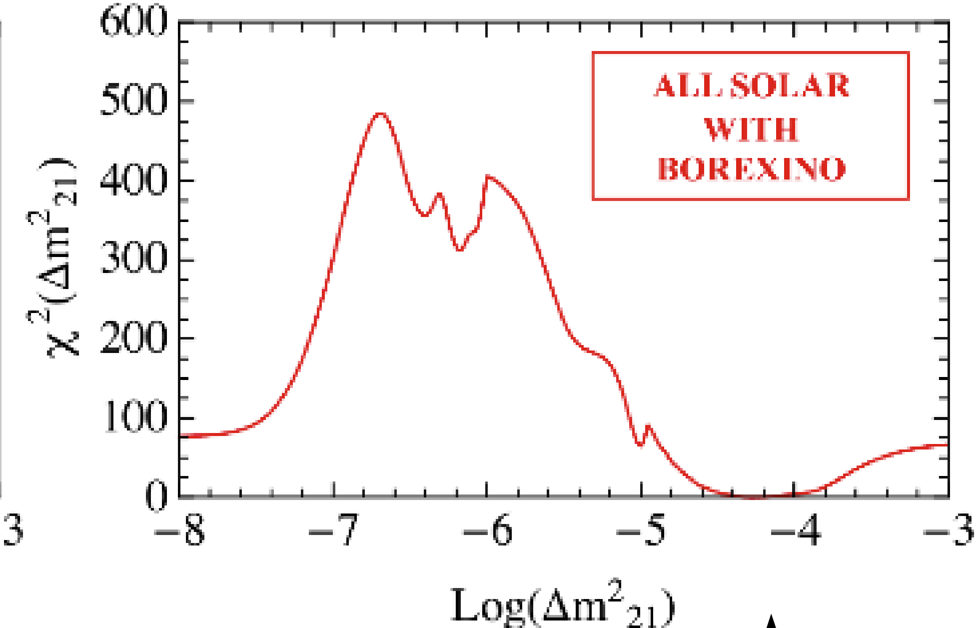
Confirms **MSW-LMA** oscillations without using KamLand anti v_e data

i.e. whithout assuming **CPT** invariance in neutrino sector

PLB 707 (2012) 22-26

Implication of the absence of ^{7}Be rate day-night asymmetry: Δm^2_{21} profile



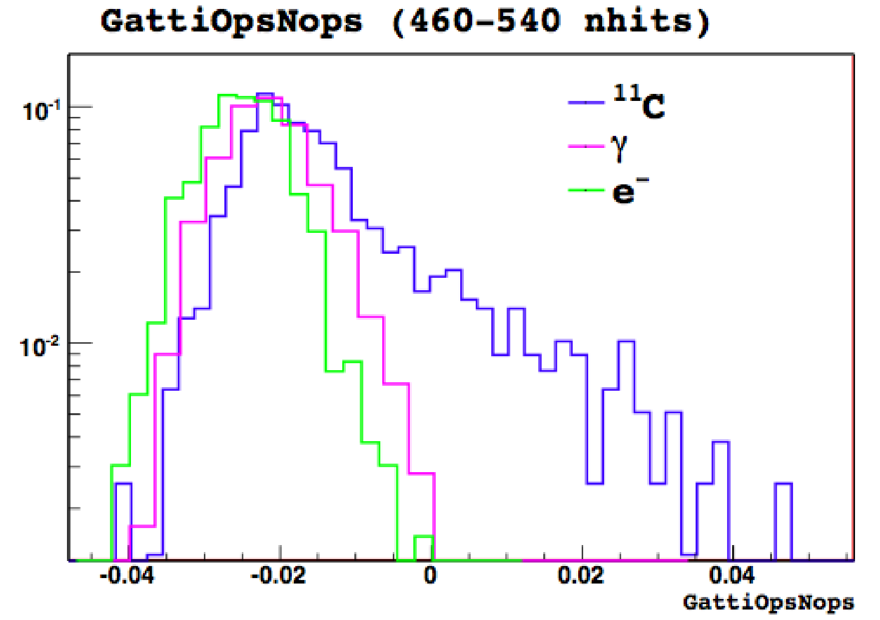


LOW Δm^2_{21} parameter space

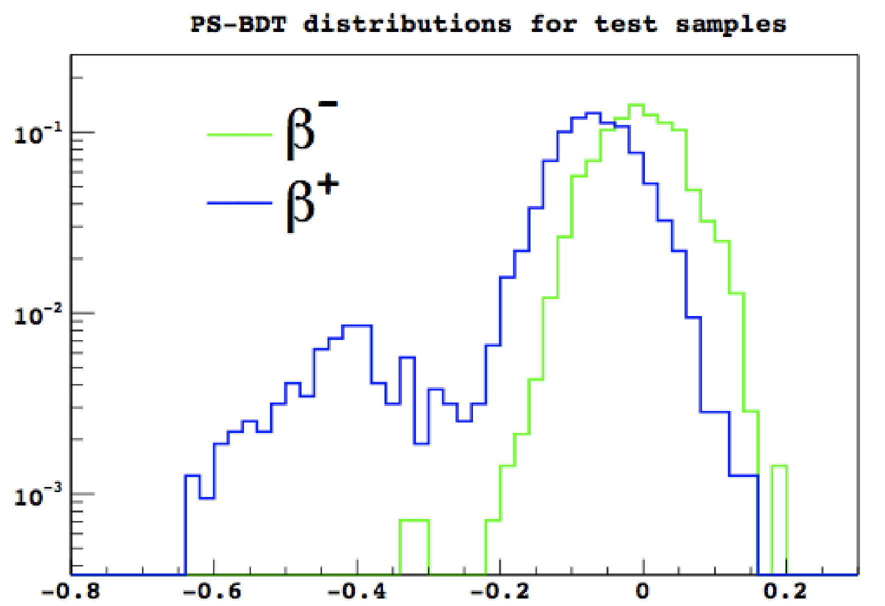
LMA parameters

e^+/e^- Pulse Shape Discrimination

Development of
Pulse **S**hape **D**iscrimination
variables to discriminate
β^-/ν interactinos from **β+ (^{11}C)**



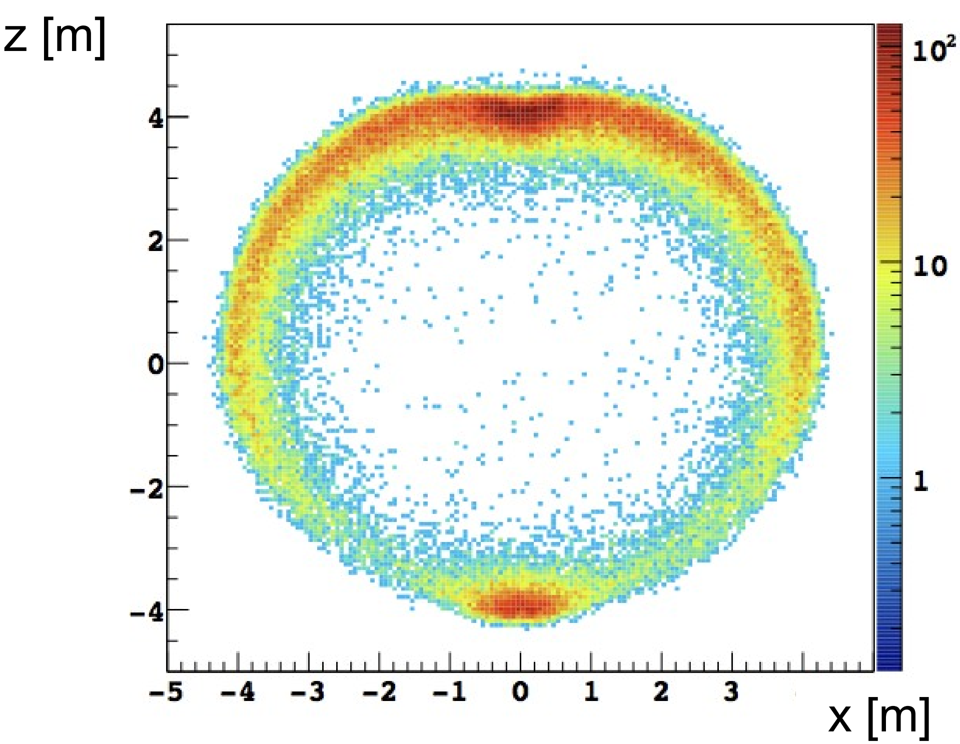
Optimized **PS** parameter
using **B**oosted **D**ecision **T**ree
(TFC pure ^{11}C sample for training)

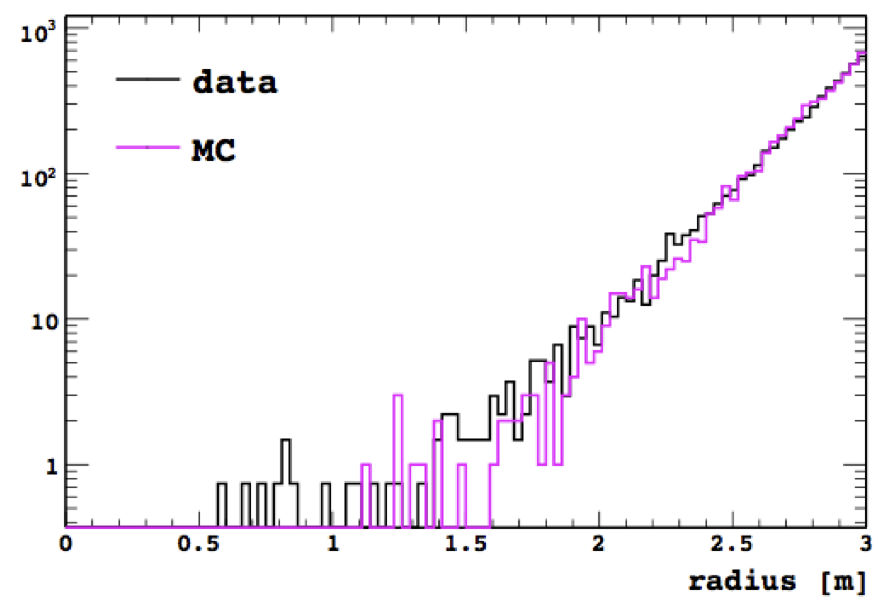


External Background

- Radioactive **decays** in **peripheral structure:** **^{208}Tl** from PMTs...
- **Fiducial Volume**:
  minimize γ-rays without sacrifice too many events

- Spatial distribution **external bkg** → **NON homogeneus**
- Spatial distribution **internal bkg** and **ν** → **homogeneus**
- **Spatial distribution** from **Monte Carlo** simulation
  and external **calibration** source (^{228}Th)



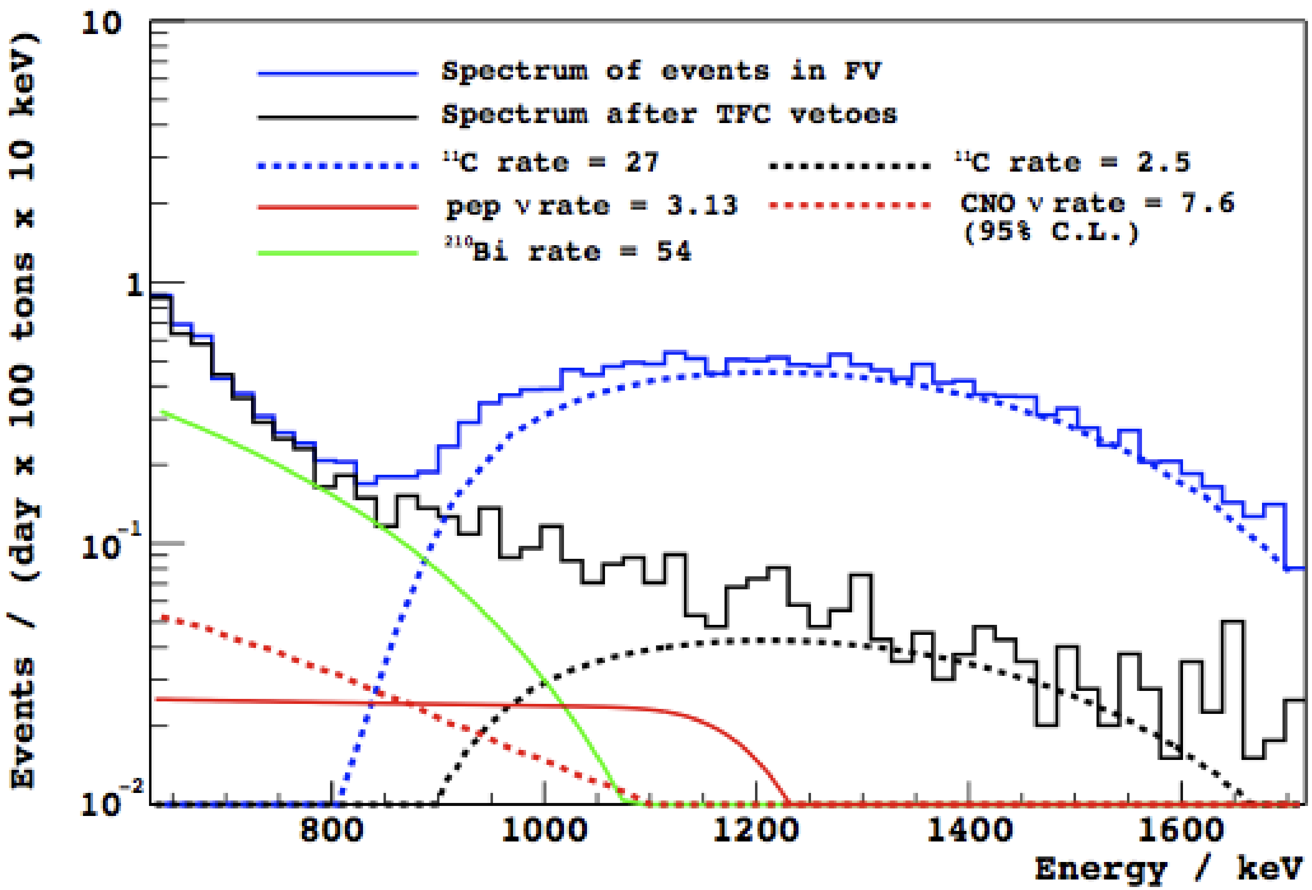


Internal ^{210}Bi background

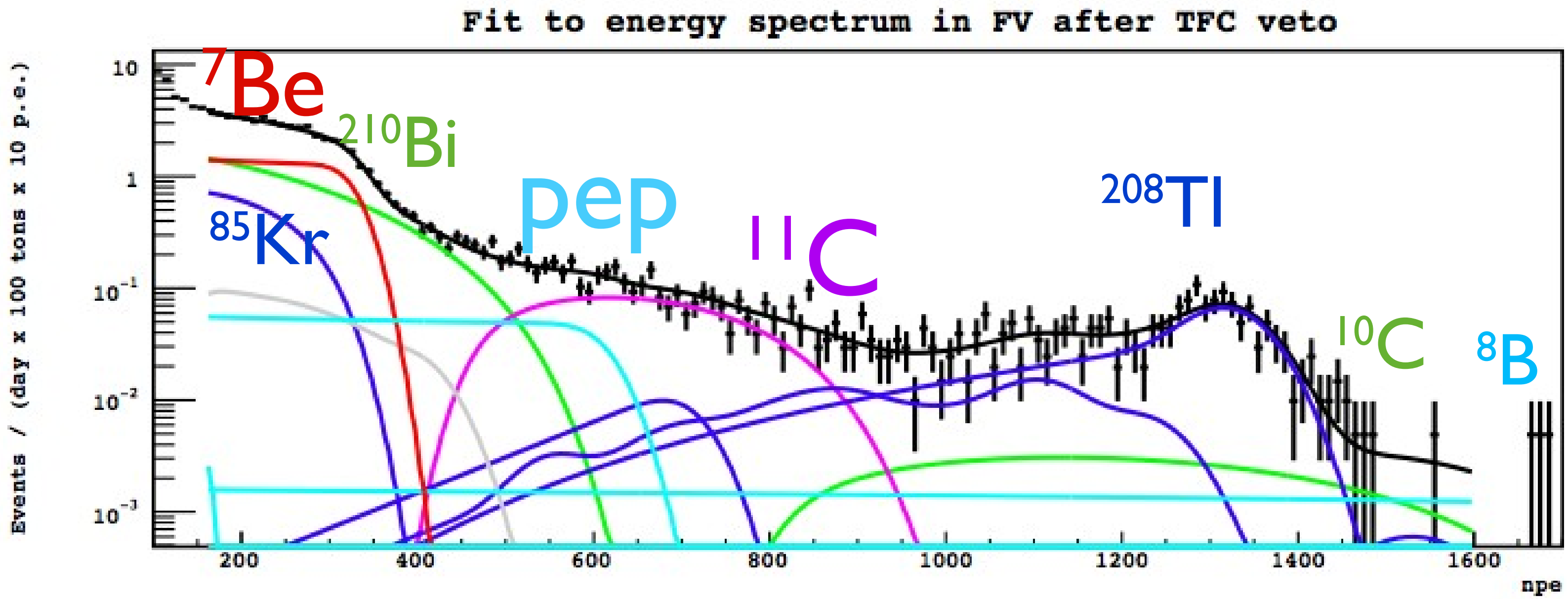
Only **residual** radioactive internal **background** in **pep-CNO** region of interest→ ^{210}**Bi decay**(~54 cpd/100ton)

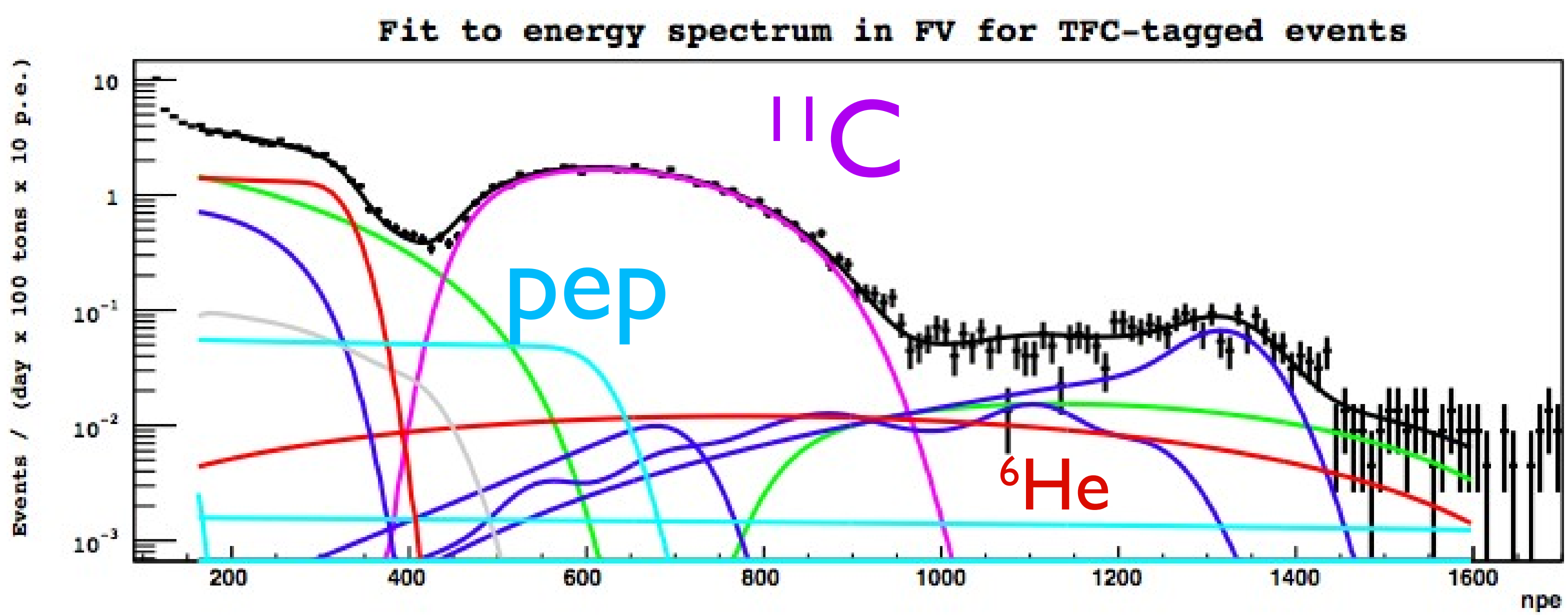
^{210}**Bi** spectal shape **similar** to e- recoil spectrum from **CNO**

CNO neutrino **spectroscopy** is **tough**

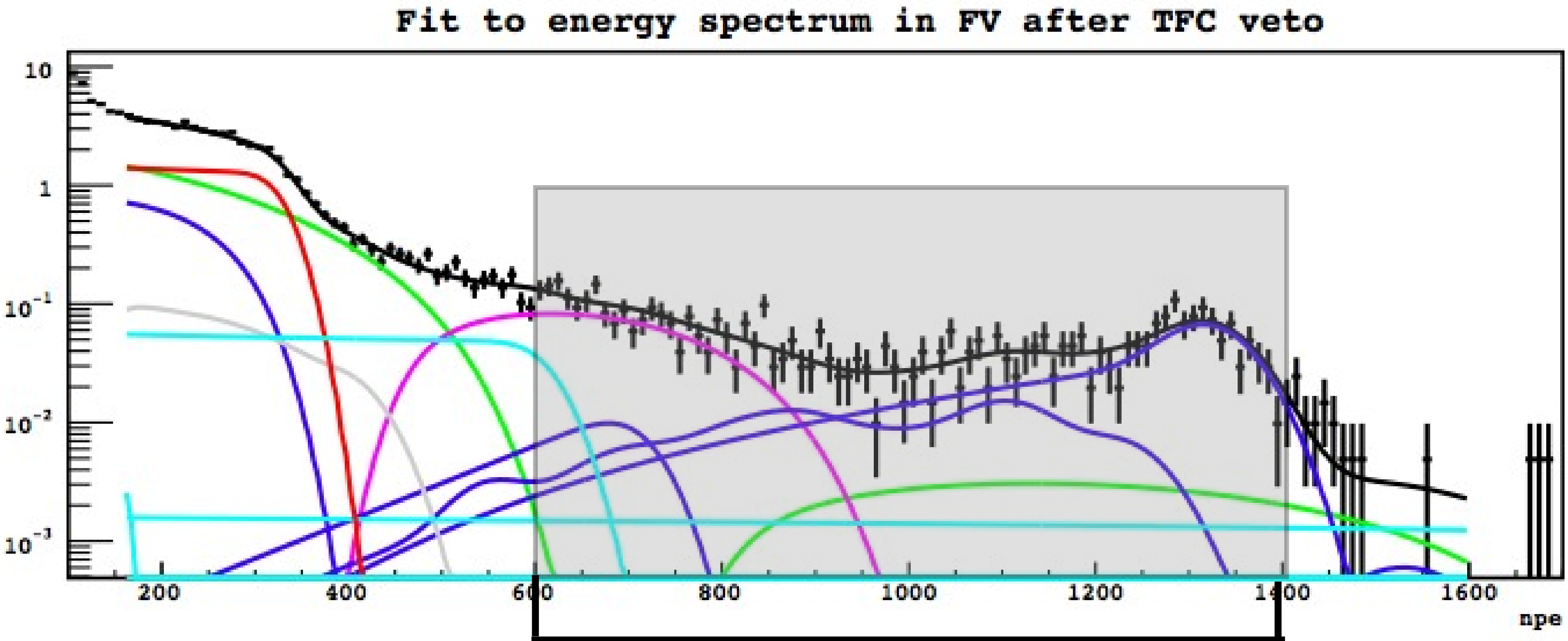


Fit to energy spectrum

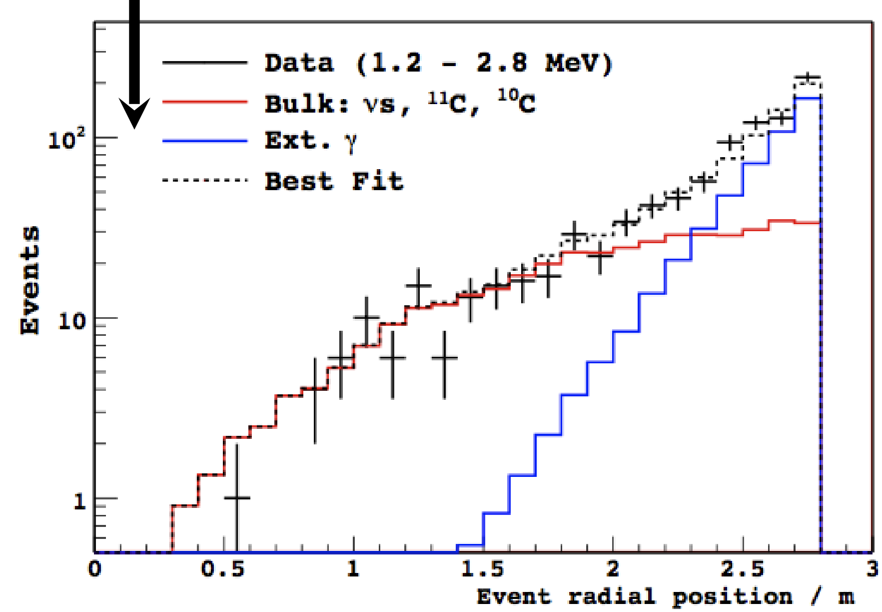




Multivariate Fit – radial distribution



Radial distribution of events - Compute **likelihood** for hypotesis:
homogeneus distribution (neutrino interactions and internal background rates) + **External background** rate



pep systematics

- Float fit **parameters** (binning, range...)
- **Detector** response, energy **scale**
- Uncertainty in ^{210}**Bi** energy **spectrum**
- **γ** in **PS-BDT** distribution
- Low **statistics** for **PS-BDT** **training**
- Fiducial **Volume**, position recostruction
- **Fixed** species in the fit (pp and ^{8}B nu, ^{214}Po)
- Impact of short lived **cosmogenics**

Total systematic uncertainty in *pep* rate: 10%

$\Delta\chi^2$ profile pep – CNO rate