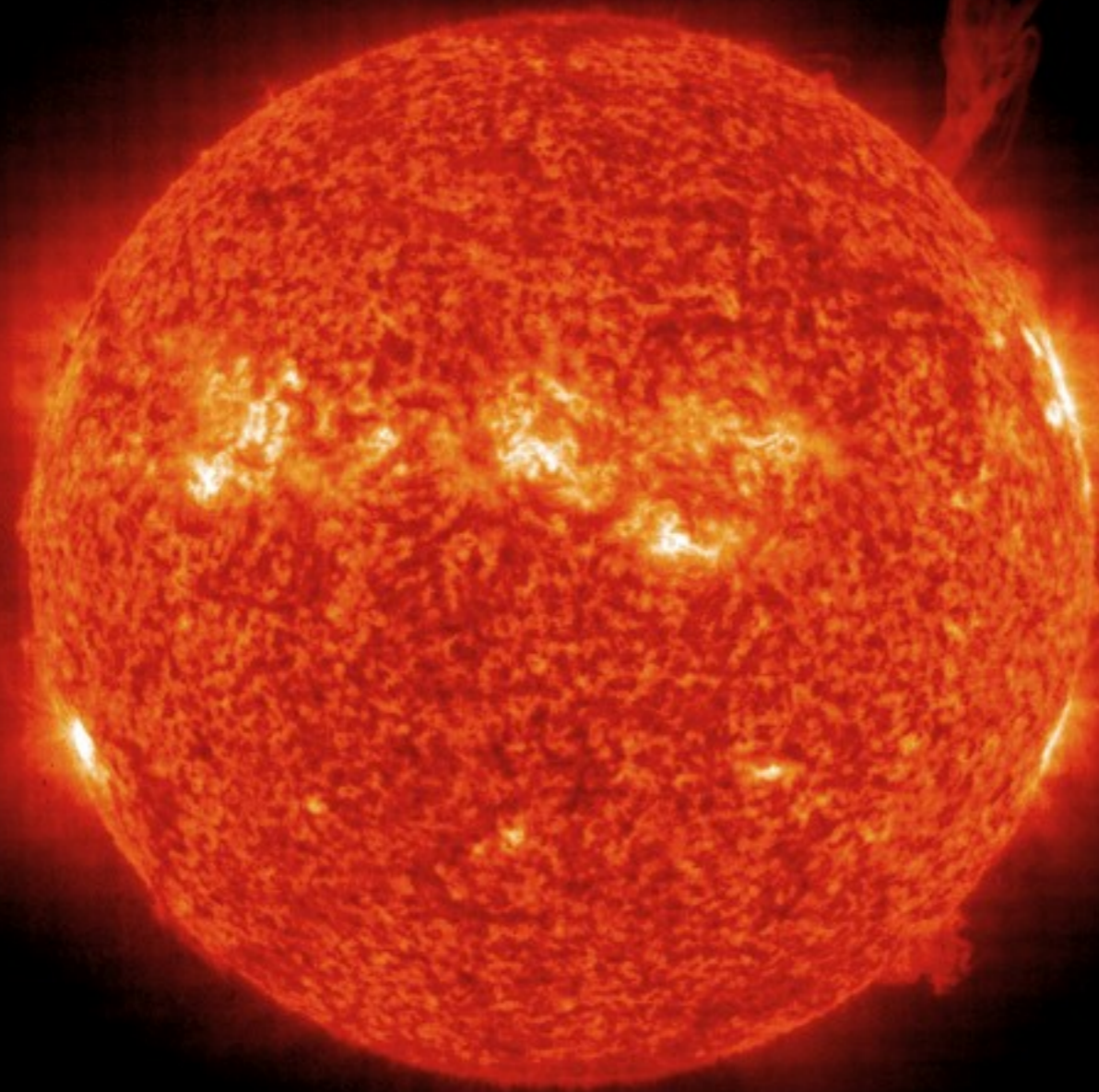


Solar Neutrino Spectroscopy: New results from BOREXINO



Stefano Davini, Genova University
On behalf of the
Borexino Collaboration

How does the Sun work?



How does the Sun work?

The Sun is a god fueled by human sacrifice



Energy Production in Stars*

H. A. Bethe

Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the most important source of energy in ordinary stars is the reaction of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced, viz. $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α -particle (§7).

The carbon-nitrogen reactions are unique in their typical character (§8). For all nuclei lighter than carbon, reactions with protons will lead to the emission of an α -particle so that the original nucleus is permanently destroyed. For all nuclei heavier than iron, only radiative capture of the proton occurs, also destroying the original nucleus. Oxygen and heavier nuclei have had their nitrogen. Besides these heavier nuclei, only such are so close that C and N and are therefore indispensable for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§9, §10) is excellent. In order to give the present energy evolution in the sun, the central temperature of the sun must have been 15.5 million degrees when

integration of the Boltzmann equations gives 18. For the brilliant star γ Cygni the corresponding figures are 30 and 32. This great agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For brighter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production (§10).

It is shown further (§5-8) that no elements heavier than He^{4} can be built up in ordinary stars. This is due to the fact, mentioned above, that all elements up to iron are destroyed by proton bombardment (see appendix) rather than built up by radiative capture. The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the proposed mechanism of energy production is used to draw conclusions about astrophysical problems, such as the star-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper. The discussion being restricted primarily to main sequence stars. The results will be in accordance with some current hypotheses.

The first major result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up before the stars reached their present state of temperature and density. No attempt will be made at speculations about the previous state of stellar matter.

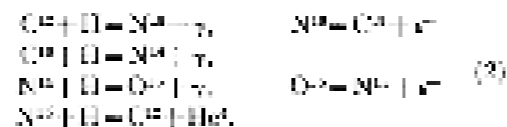
The energy production of stars is then due entirely to the combination of four protons and two electrons into an α -particle. This simplifies the discussion of stellar evolution inasmuch as

the amount of heavy matter, and therefore the masses, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, viz.



The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction



The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

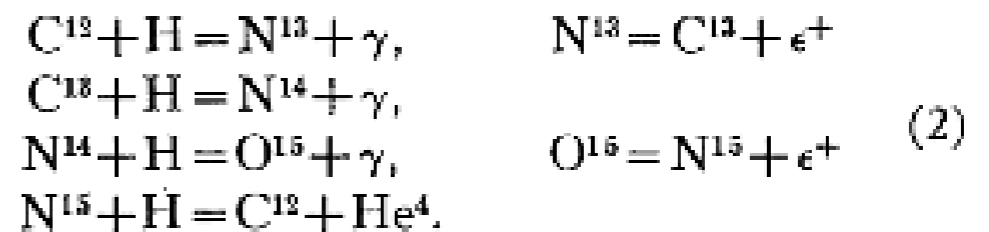
In Bethe's original paper, neutrinos are not even in the picture.

(H.A. Bethe, Phys. Rev. 33, 1939)

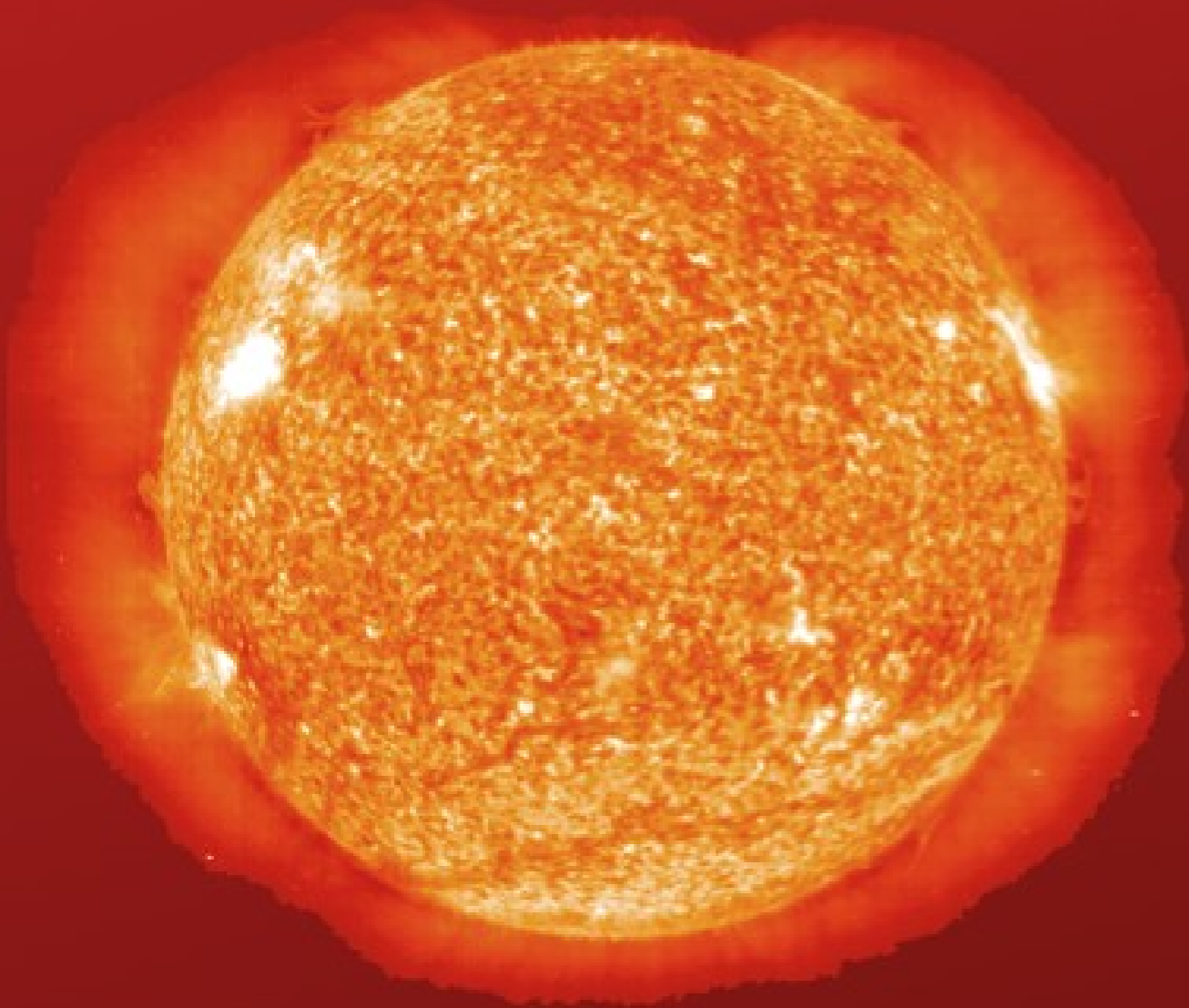
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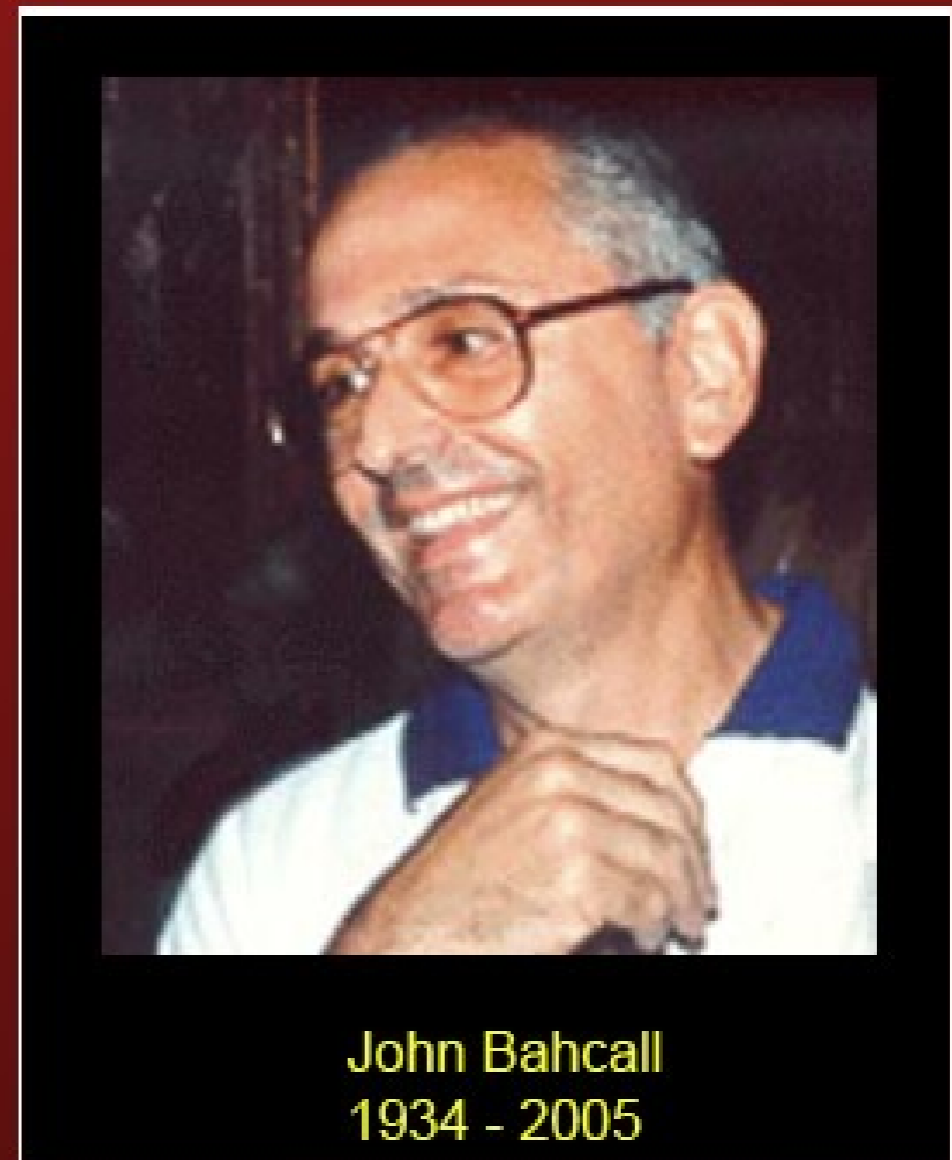
* Awarded an A. Loomis Morrison Prize in 1938 by the New York Academy of Sciences.



In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

Basic assumptions of what is known as the Standard Solar Model...

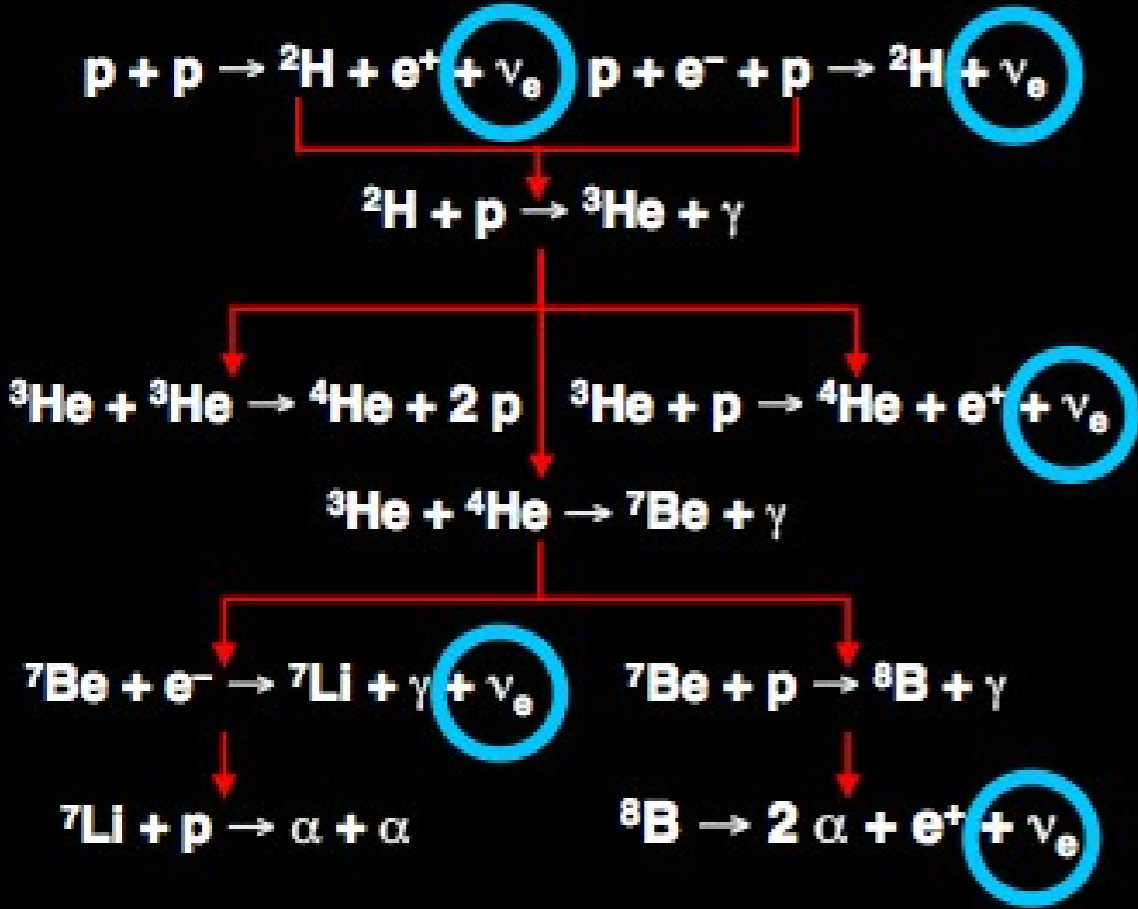
- (1) Sun is in hydrostatic equilibrium.
- (2) Main energy transport is by photons.
- (3) Primary energy generation is nuclear fusion.
- (4) Elemental abundance determined solely from fusion reactions.



John Bahcall
1934 - 2005

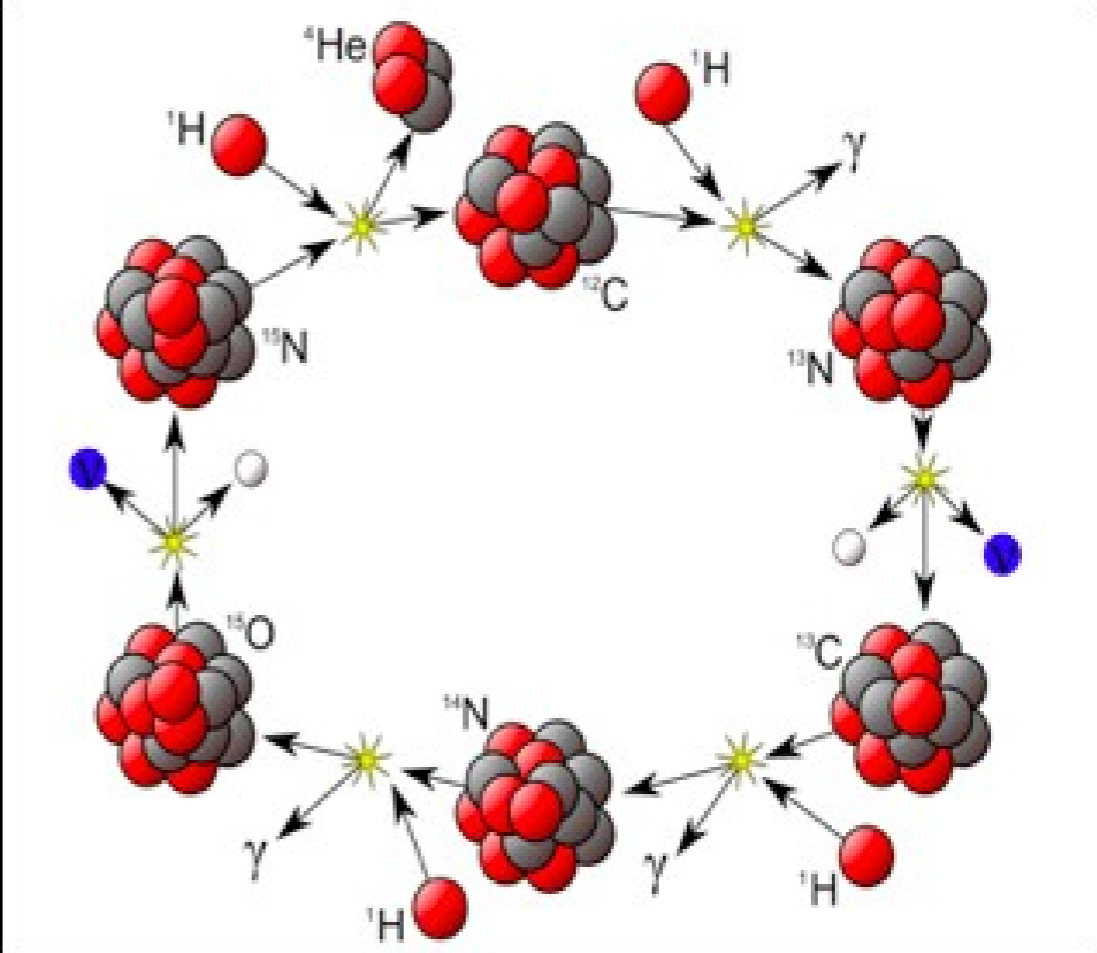
Solar Neutrinos

p-p Solar Fusion Chain



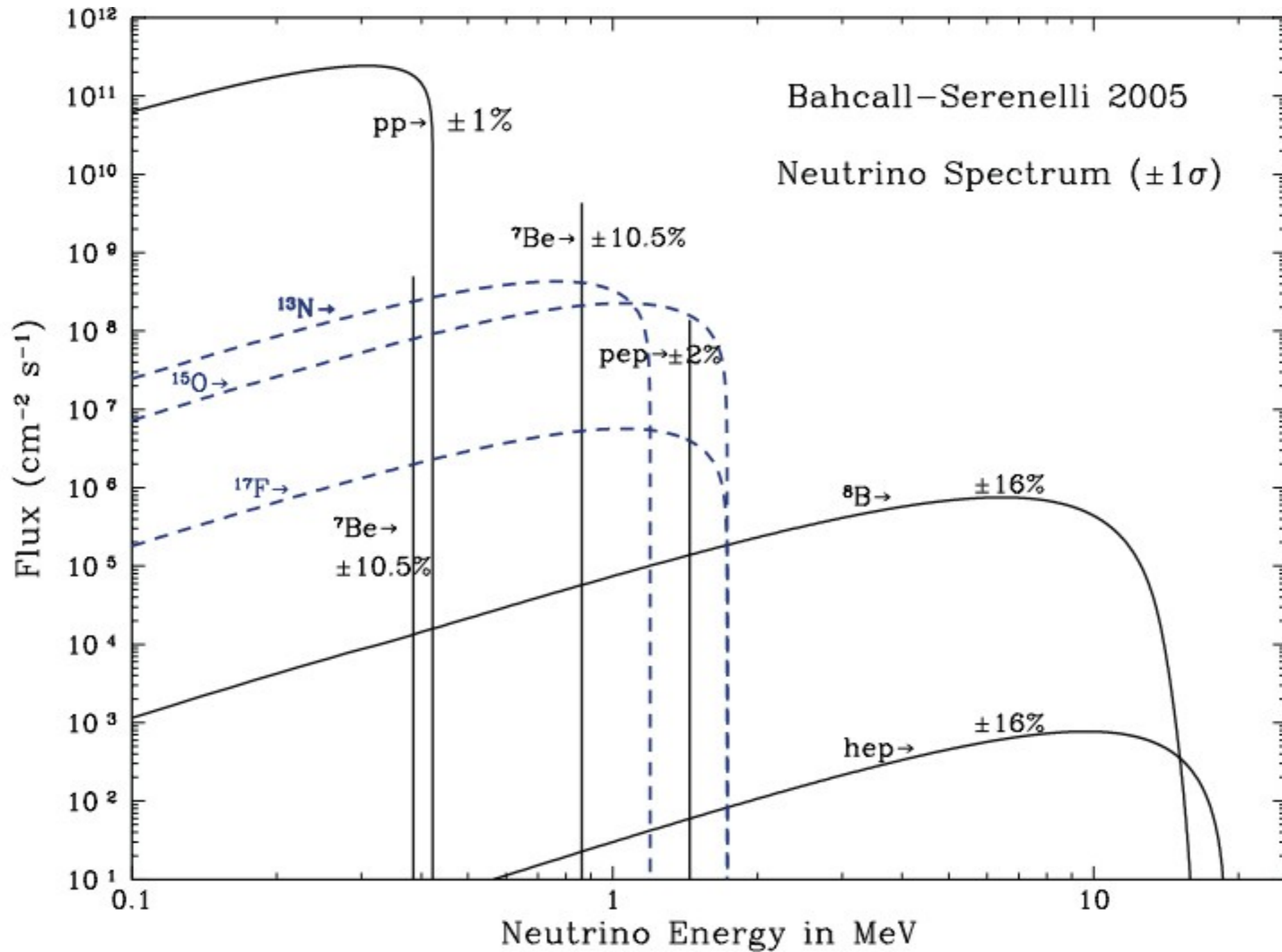
Dominant fusion mechanism
in the Sun

CNO Cycle



Related to solar metallicity
Important in larger stars
Contribution in Sun ?

Solar Neutrinos



Solar Standard Models predict spectra, fluxes of solar ν
Solar Neutrino experiments can test SSM ⁷

Solar Standard Model predicted ν fluxes

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

**Small
uncertainties**

**Large
uncertainties**

Tension between High and Low Metallicity SSM

High Z SSM (GS) → older model, higher heavy element abundances, agrees with helioseismology

Low Z SSM (AGSS) → new model based on solar atmospheric spectroscopy, lower heavy element abundances, does not agree with helioseismology

Solar Neutrino Propagation

Neutrinos undergo **oscillation**

Non null neutrino **masses** & mismatch between flavor states and mass states (**mixing**)

Neutrinos produced in one flavor can be detected as another flavor neutrinos

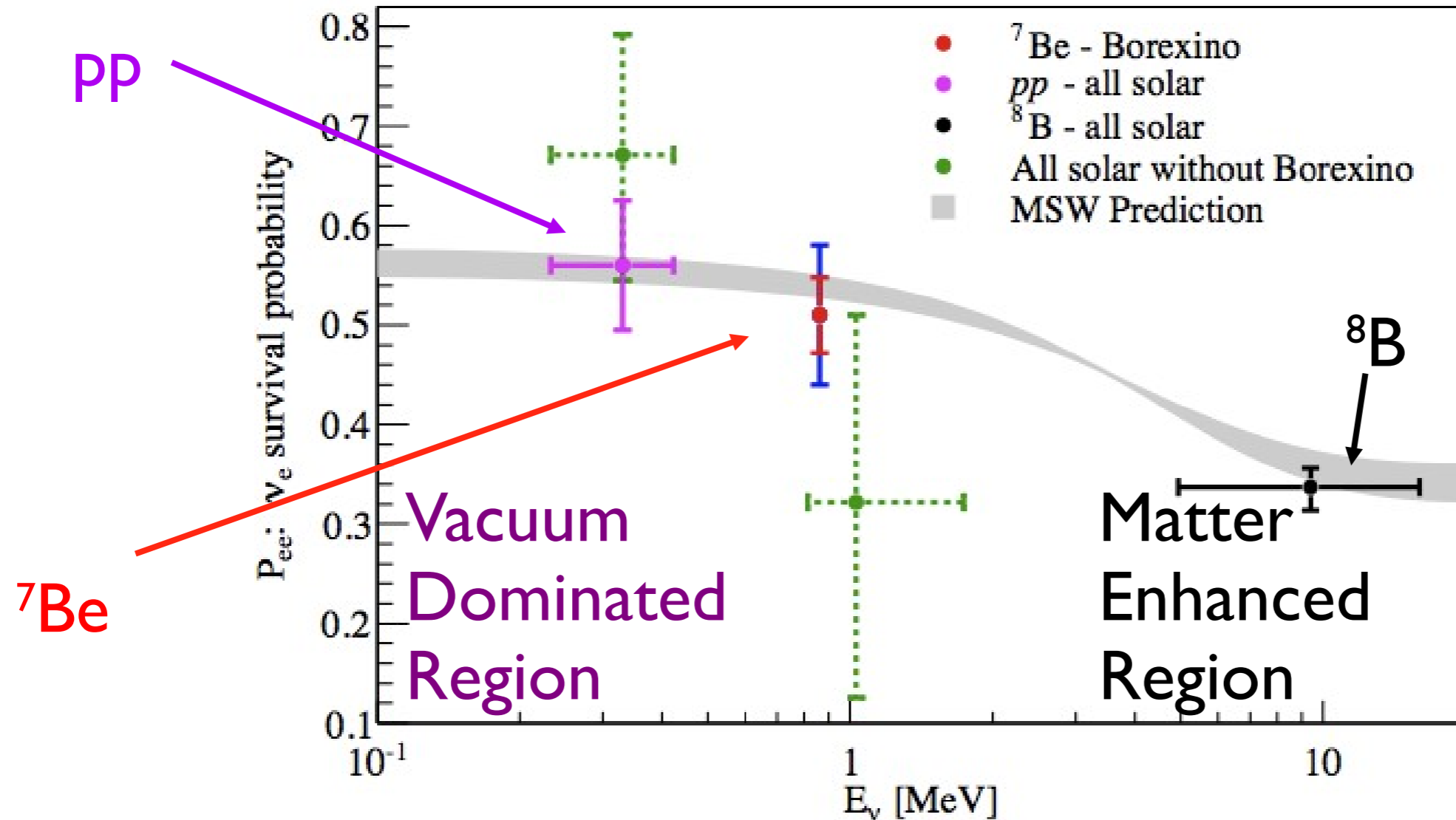
In **vacuum**:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 [1.27 \Delta m^2 L / E]$$

Because $\Delta m^2 L / E \gg 1$

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2} \sin^2 2\theta$$

Solar Neutrino Propagation



MSW-LMA scenario: coherent scattering in matter enhances oscillation probability → **Energy dependent P_{ee}**

Large Mixing Angle

Physics beyond Standard Model can affect Energy dependence of P_{ee}

The Past

- Radiochemical experiments discovered Solar Neutrinos (1960s). The Sun is powered by nuclear fusion!
- Kamiokande measured solar ν_e ^8B neutrinos (1980s).
- **But** detected ν_e flux $\sim 1/3$ of expected: “The Solar Neutrino Problem”
- SNO measured (2000) the total ν_e and ν_x flux from ^8B neutrinos demonstrating neutrino oscillations.

The present: Solar Neutrino and Astrophysics wish list

- Particle physics:
 - Test **MSW-LMA** P_{ee} with high accuracy
 - Probe the P_{ee} in the **transition region**, sensitive to Physics beyond Standard Model
- Solar Astrophysics:
 - Test SSM predictions, prove **CNO** cycle in Sun
 - Test two competing models of **SSM: High and Low Metallicity**

Borexino Detector



**Gran Sasso National Laboratory
(Under Apennine Mountains)**

**Rock Shielding
~ 1400m (3500 m.w.e)**

**Cosmic Muon Flux
~ 1/m²/hr
(4300/day through detector)**



Borexino Detector

Design based on principle of graded shielding

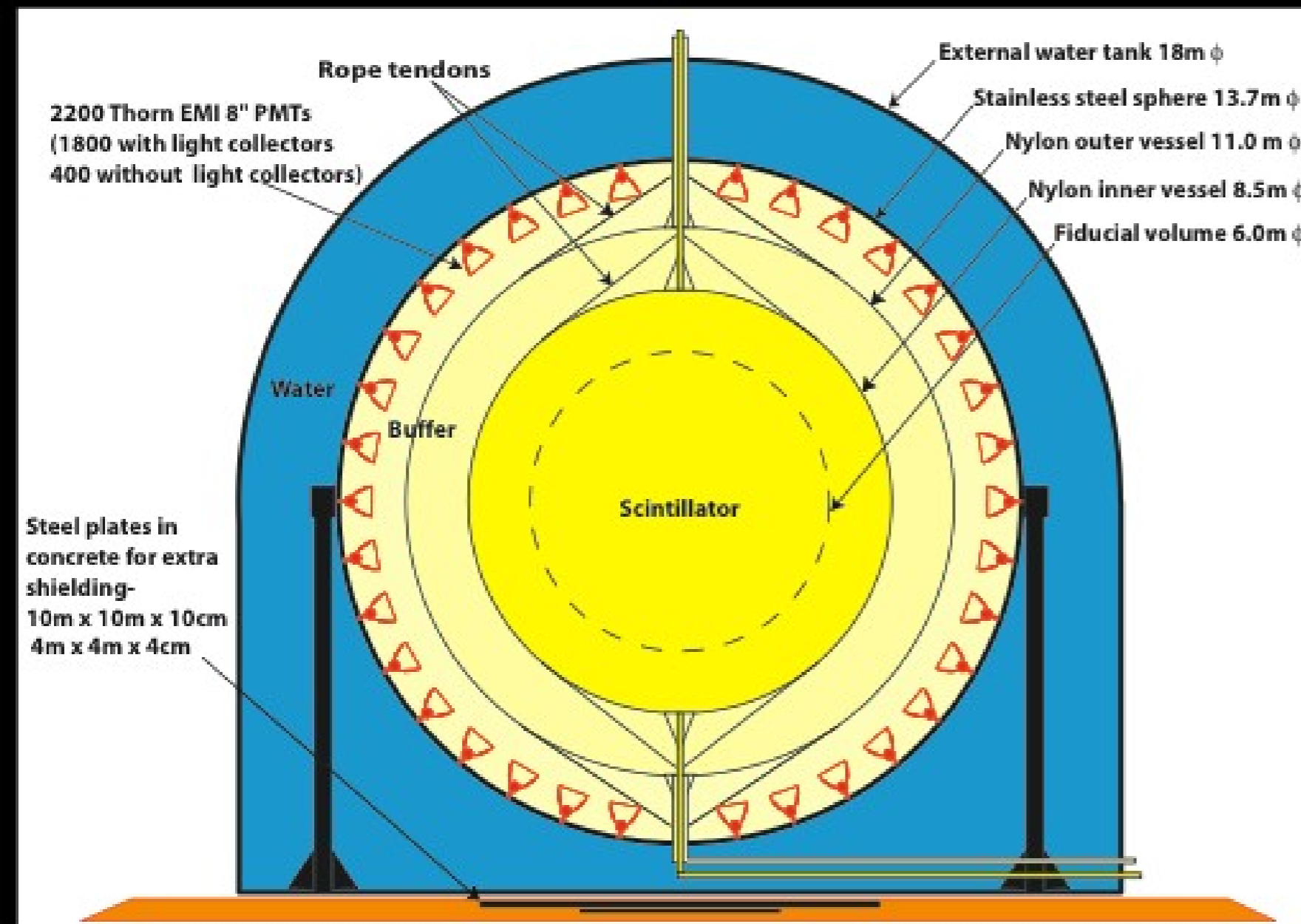
Exterior instrumented
water tank
(Cherenkov detector)

Stainless Steel Sphere
with ~2200 PMTs

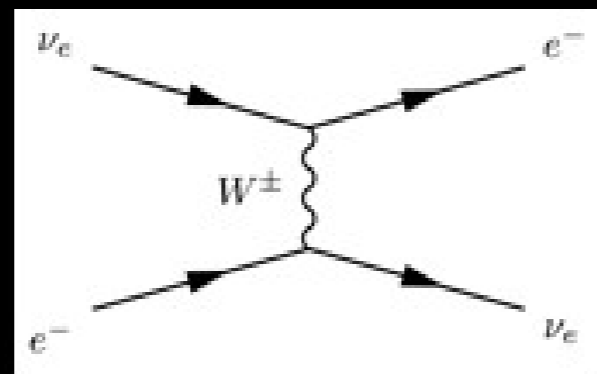
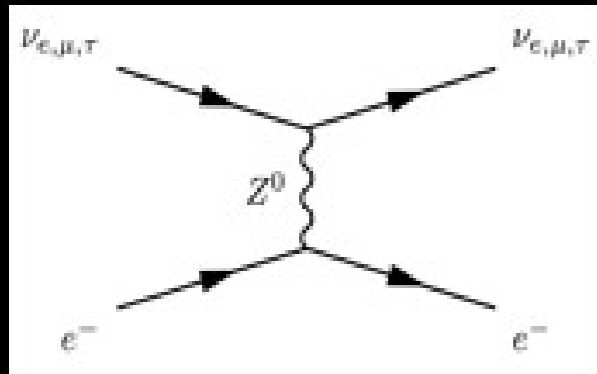
898 tons of quenched
scintillator as buffer

278 tons of active
scintillator

Fiducial Mass ~ 75 tons

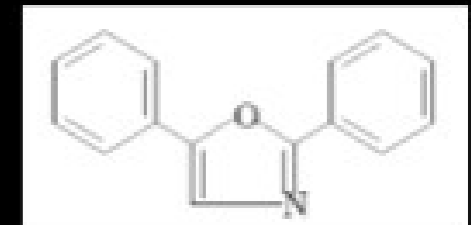
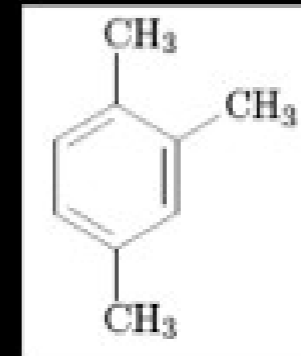


Borexino Detector

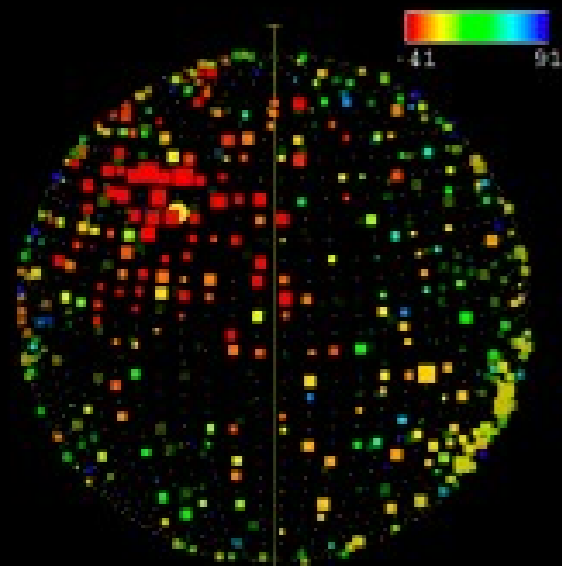


Neutrinos are detected through elastic scattering on electrons

Recoiling electrons excite scintillator molecules which emit light

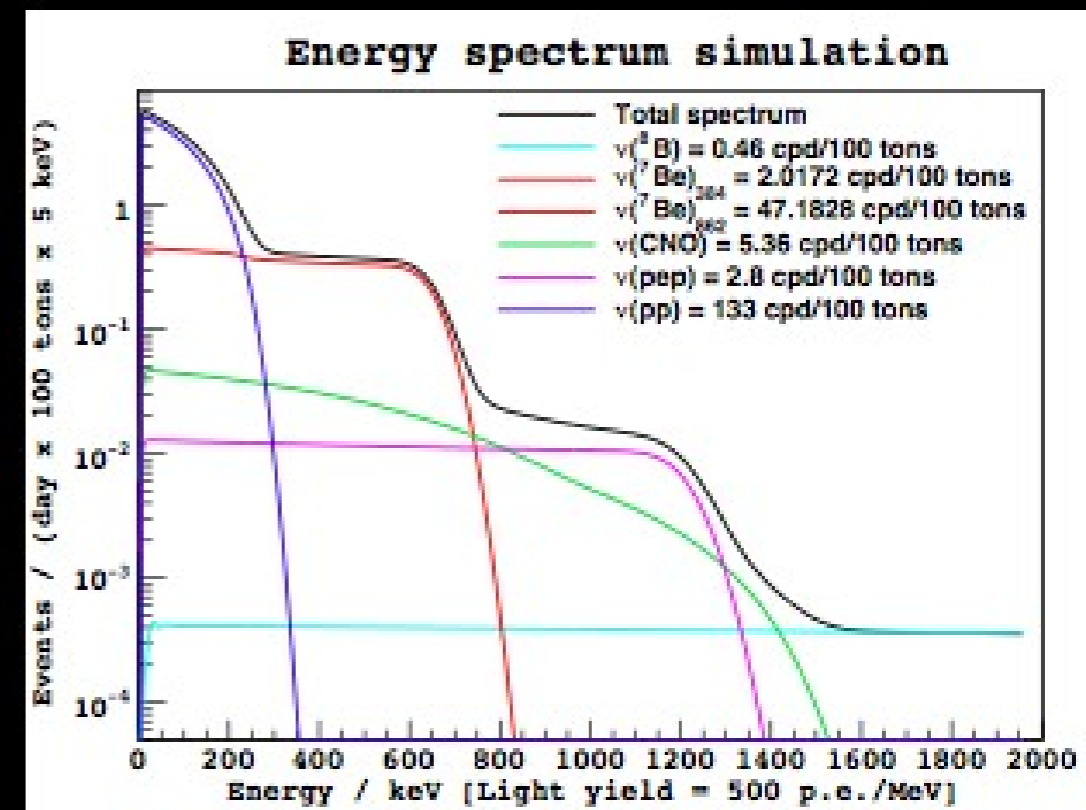


PC + 1.5g/l PPO



Scintillation light is detected by photomultiplier tubes

Amount and timing of light give energy and position information

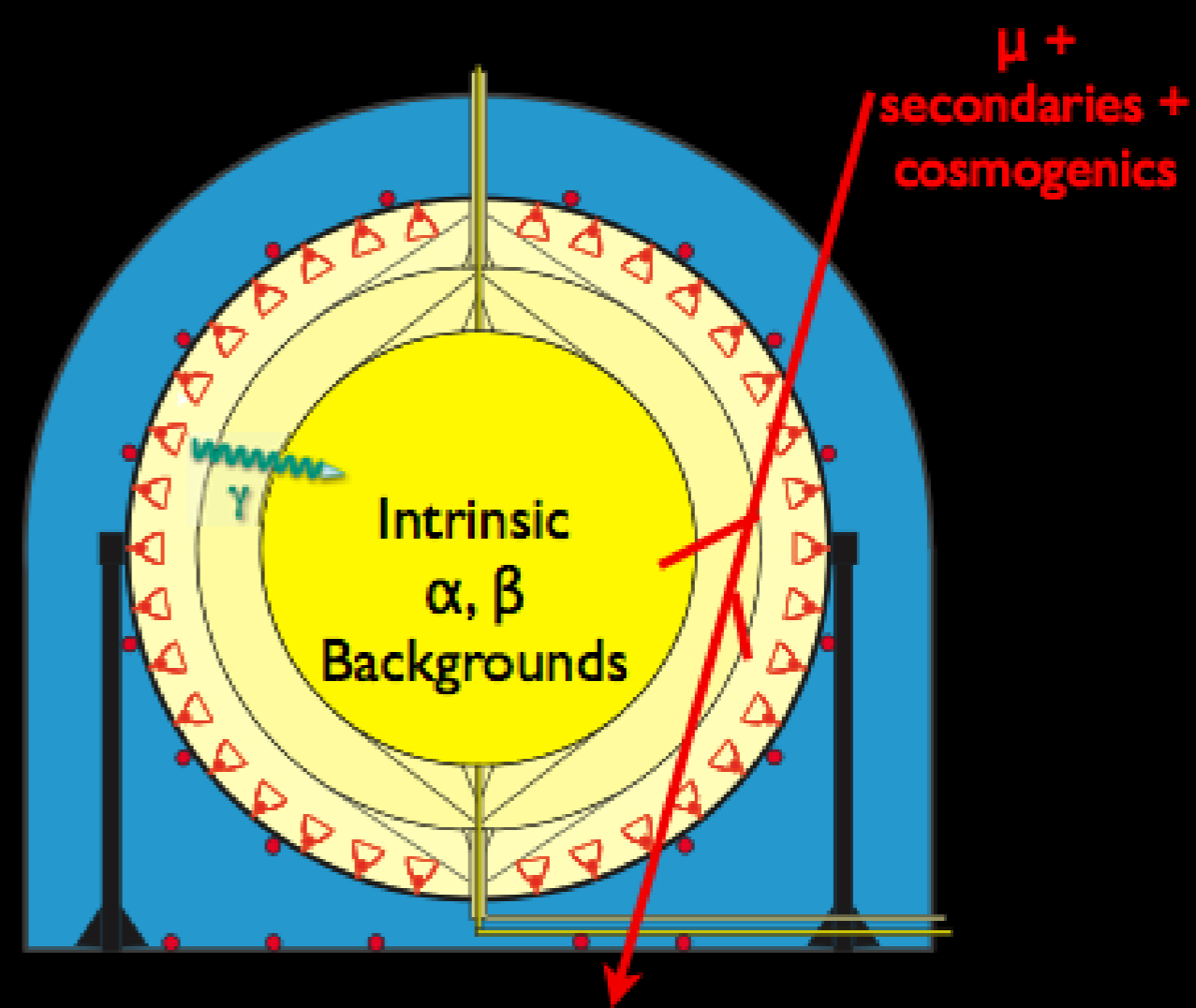


Backgrounds

No directional information from scintillation light

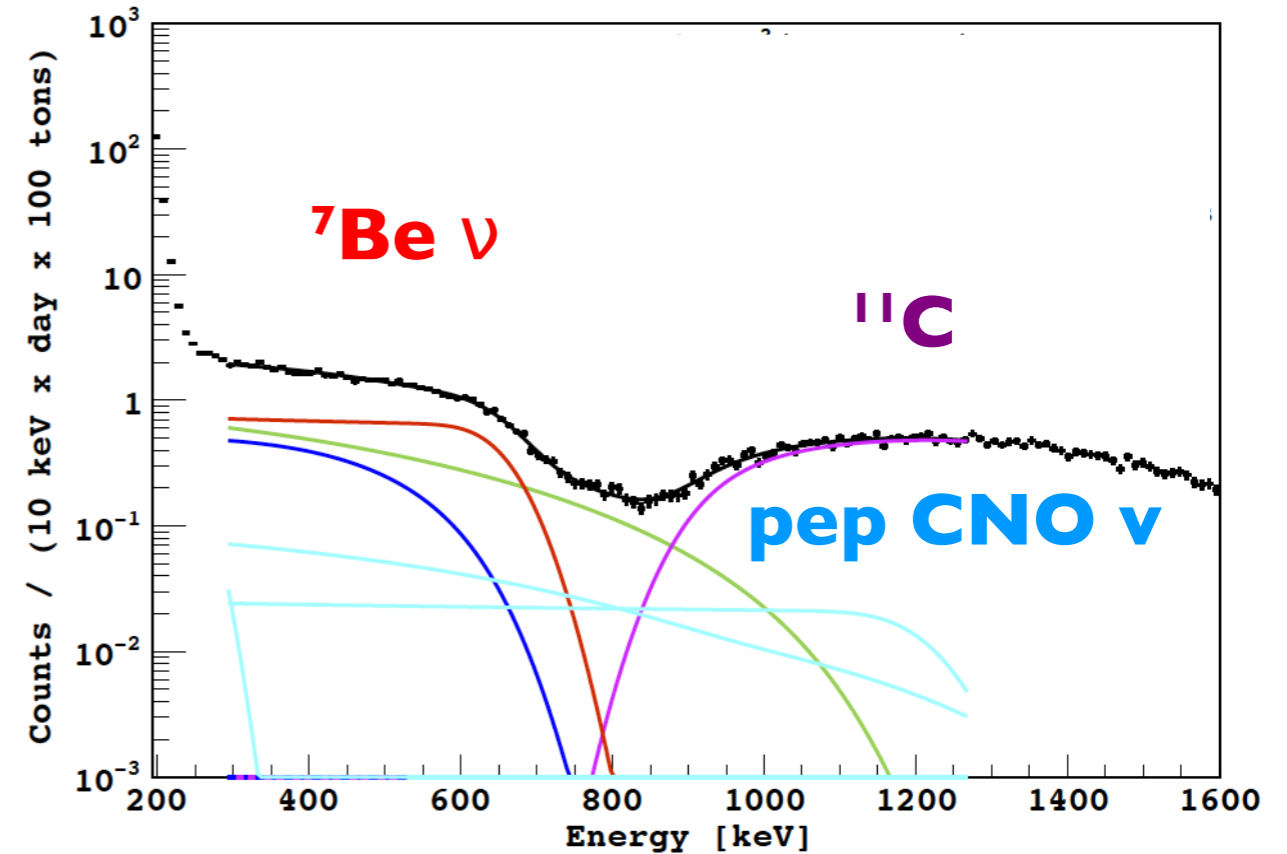
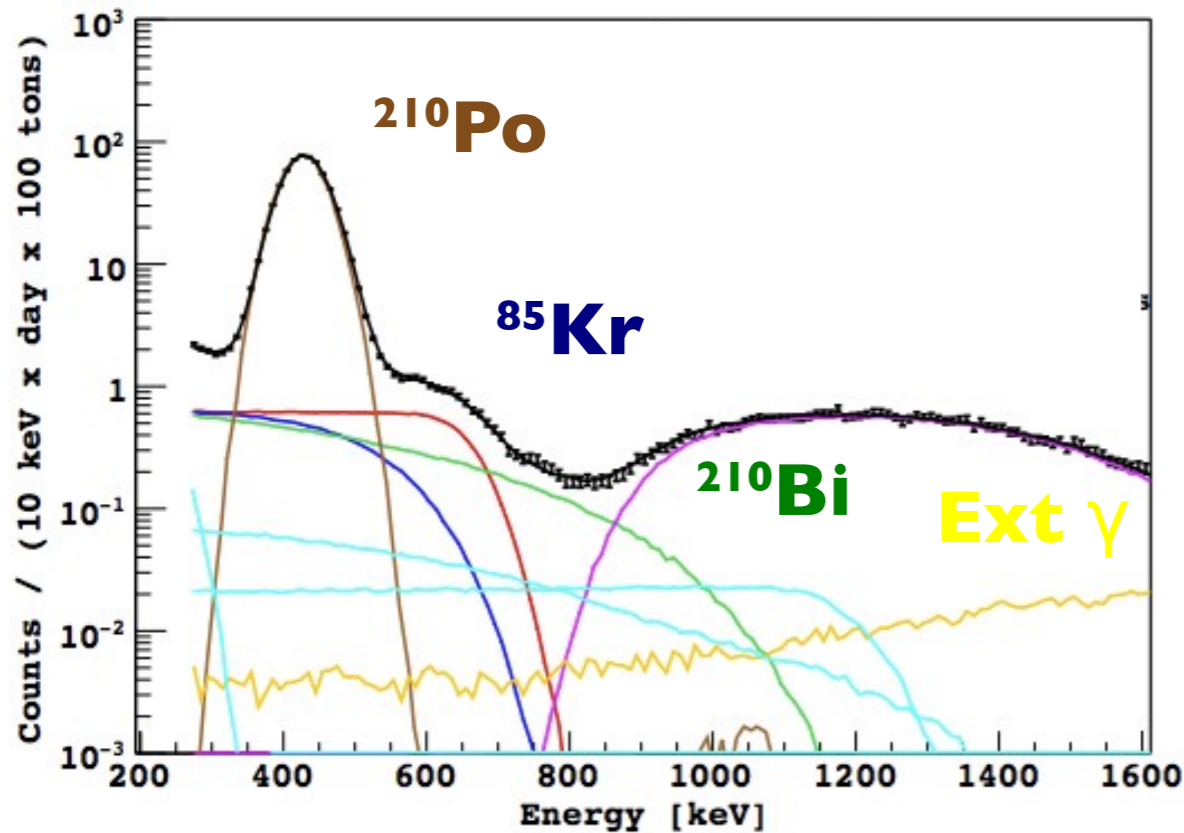
Cannot discriminate between electron recoils and β/γ backgrounds

Need 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

Solar Neutrino Spectroscopy in Borexino



arXiv: 1104.1816

Purification \rightarrow Low background rates

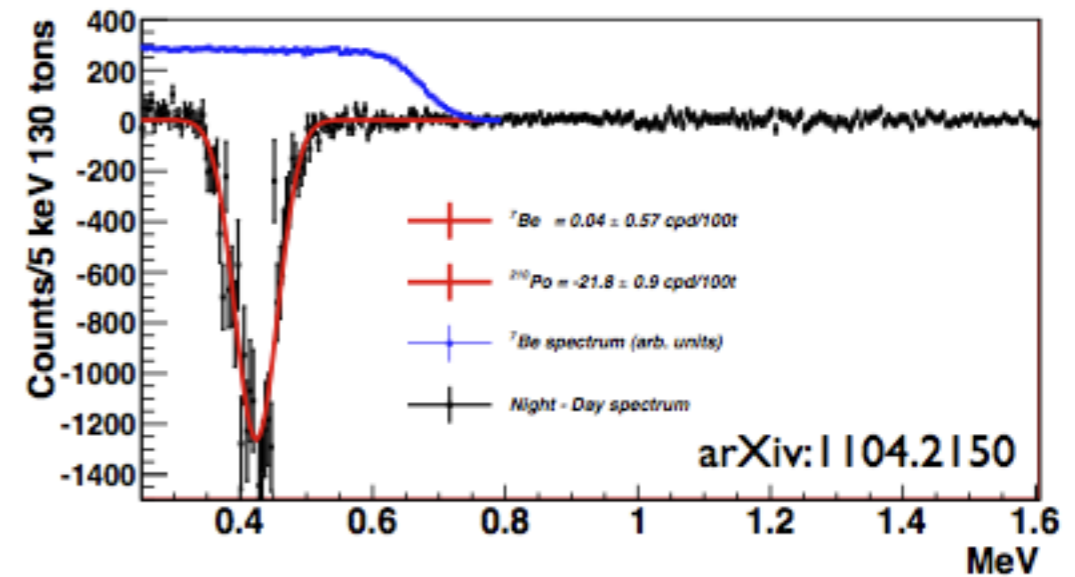
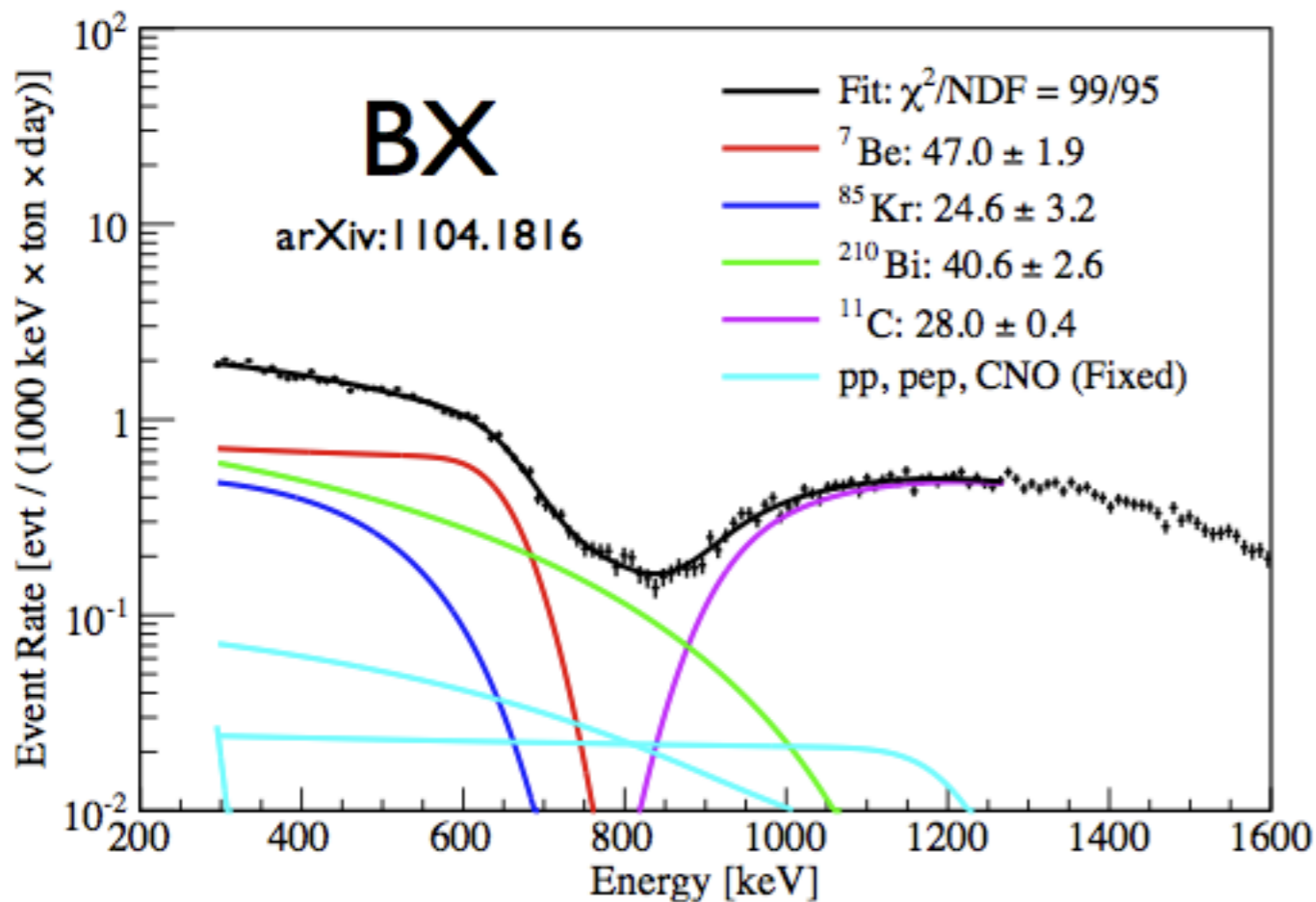
High Light Yield \rightarrow High Energy Resolution

Calibration \rightarrow Detector response understood

^7Be neutrinos

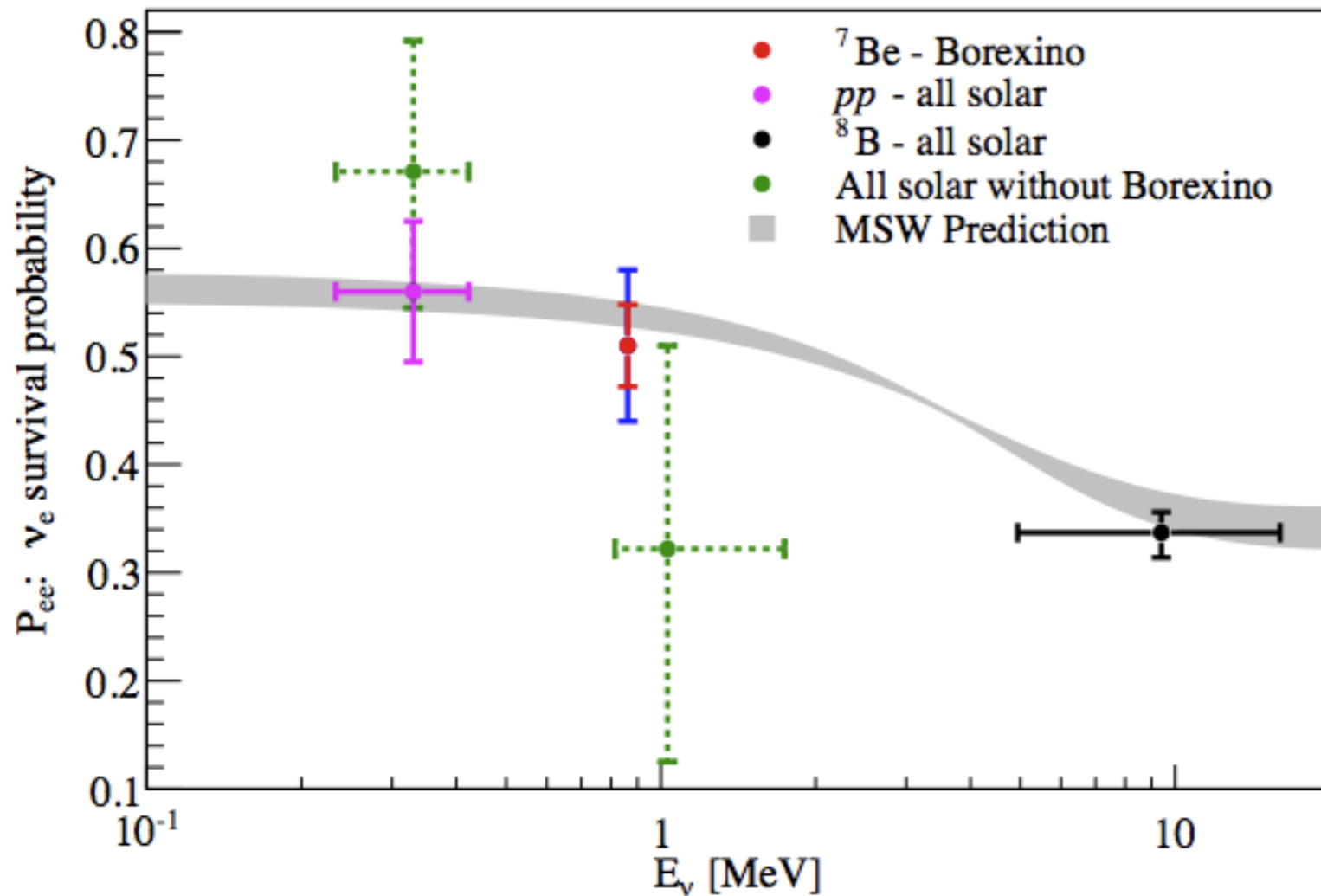
- $^7\text{Be} + e \rightarrow ^7\text{Li} + \nu_e$
- Flux predicted with 7% uncertainty.
- Mono-energetic $E = 862 \text{ keV}$.

Day/Night
Asymmetry



$$2 \frac{\Phi_n - \Phi_d}{\Phi_n + \Phi_d} = 0.001 \pm 0.014$$

^7Be ν_e flux:
 $(3.10 \pm 0.15) \times 10^9 \text{ cm}^2\text{s}^{-1}$



+ Global solar analysis
Total fluxes

pp flux:
 $(6.06^{+0.02}_{-0.06}) \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$

CNO flux:
 $< 1.3 \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$

Result consistent with MSW-LMA. 5σ from no oscillation

Measured rate uncertainty smaller than flux uncertainty

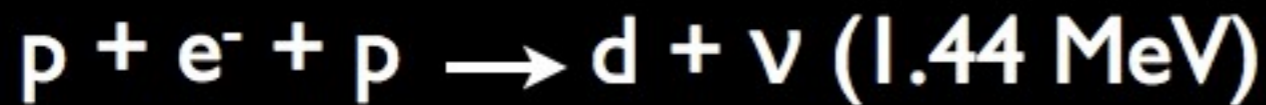
Absence of Day/Night asymmetry supports MSW-LMA and strongest constraint on matter effects on ~ 1 MeV neutrinos

$< 1\%$ uncertainty in pp flux

CNO flux limit 2.5 times High Z prediction

Solar pep and CNO vs

pep reaction, part of the proton-proton chain, at a rate $\sim 1/400$ of pp reaction:



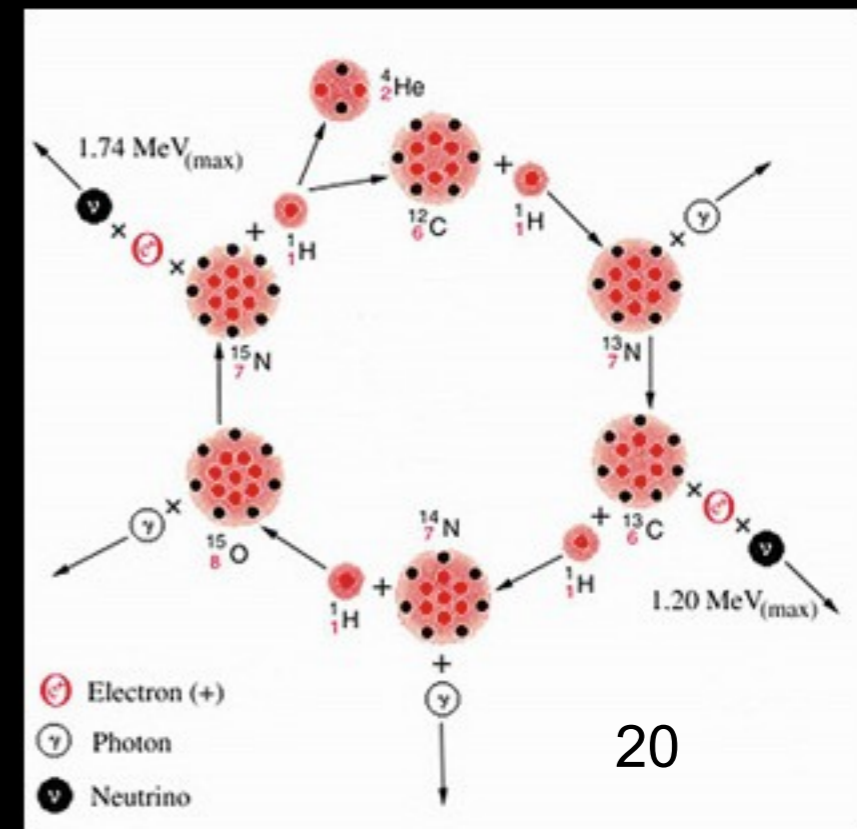
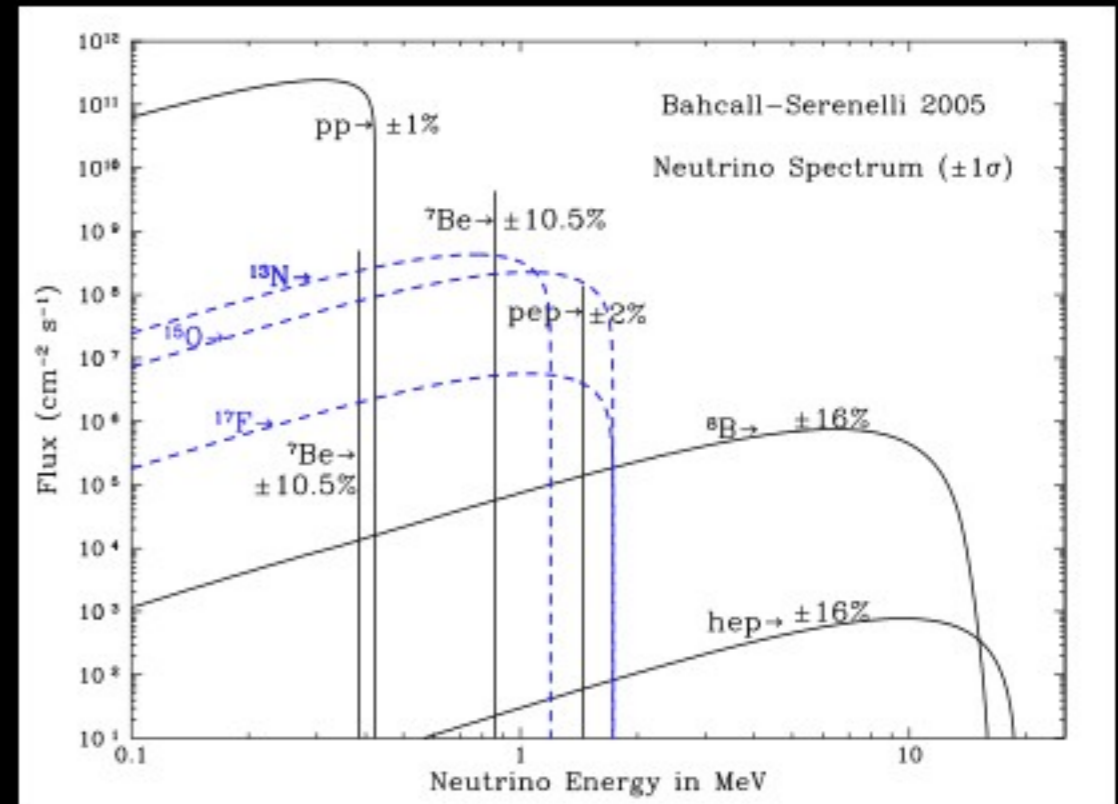
~ 3 cpd/100 tons

CNO cycle, alternate energy production mechanism in the Sun

ν from ^{13}N ($E_{\text{max}} = 1.20 \text{ MeV}$)

ν from ^{15}O ($E_{\text{max}} = 1.74 \text{ MeV}$)

$\sim 3 - 5$ cpd/100 tons

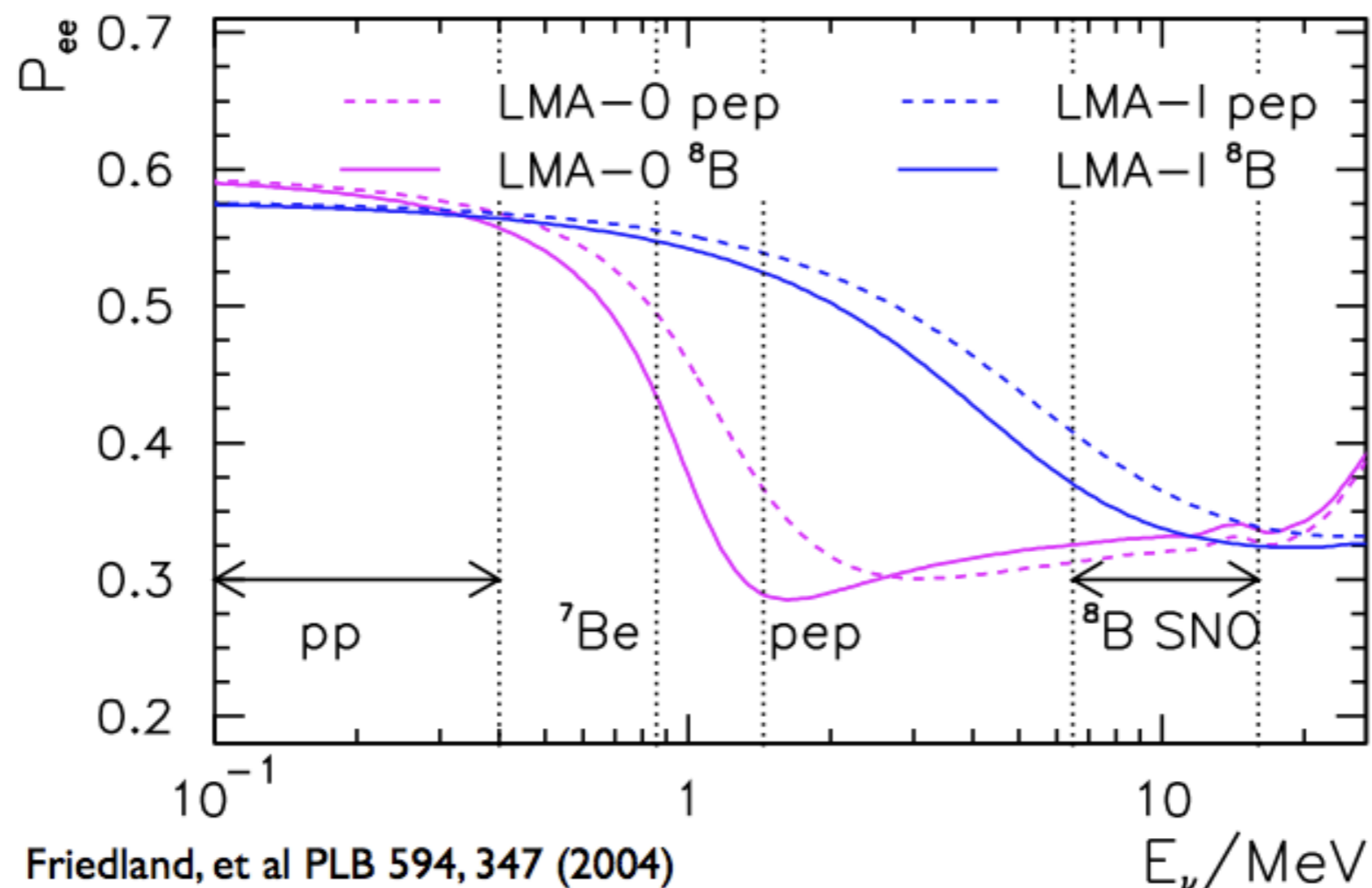


pep ν measurement motivations

pep neutrino **flux predicted** with **high precision**: 1.2% SSM uncertainty

pep neutrino energy (1.44 MeV) in **P_{ee} transition region**, sensitive to Physics beyond Standard Model

Allows for more **stringent tests** of oscillation models



CNO ν measurement motivations

Detecting CNO ν prove that CNO cycle happens in Sun

Abundance of heavy elements in Sun have high impact
on CNO ν flux magnitude

Test of High vs Low Z SSM

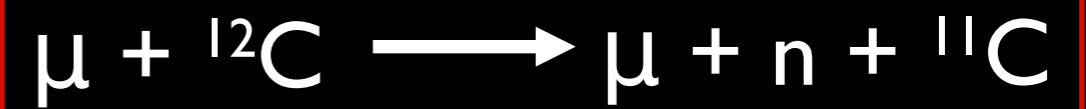
Serenelli, Haxton, Pena-Garay
arXiv 1104.1639

	CNO FLUX ($10^8 \text{ cm}^{-2} \text{ s}^{-1}$)
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
$\Delta\Phi$	28%

pep and CNO neutrino measurement in Borexino

- More **challenging** than ${}^7\text{Be}$ ν measurement
- **Low rates**: few interaction per day/100tons
- Dominant **background** in *pep* energy region:
 - β^+ **emitter cosmogenic ${}^{11}\text{C}$** (27 cpd/100tons)
- Adoption of **novel techniques** to suppress ${}^{11}\text{C}$:
 - Three Fold Coincidence
 - e^+/e^- pulse shape discrimination

■ Cosmogenic ^{11}C

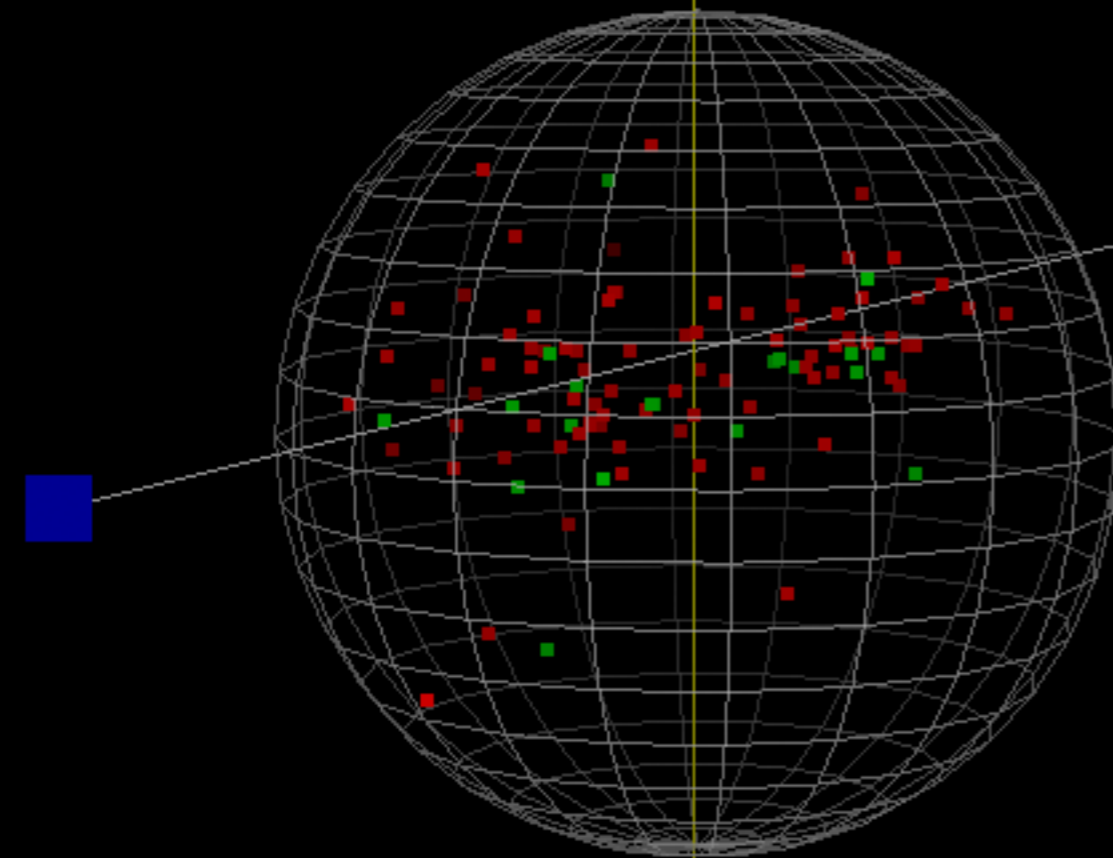


4200 μ /day

■ Spallation neutron in 95% cases
n captured in scintillator

^{11}C rate 27 cpd/100ton

Lifetime: 29.4 min

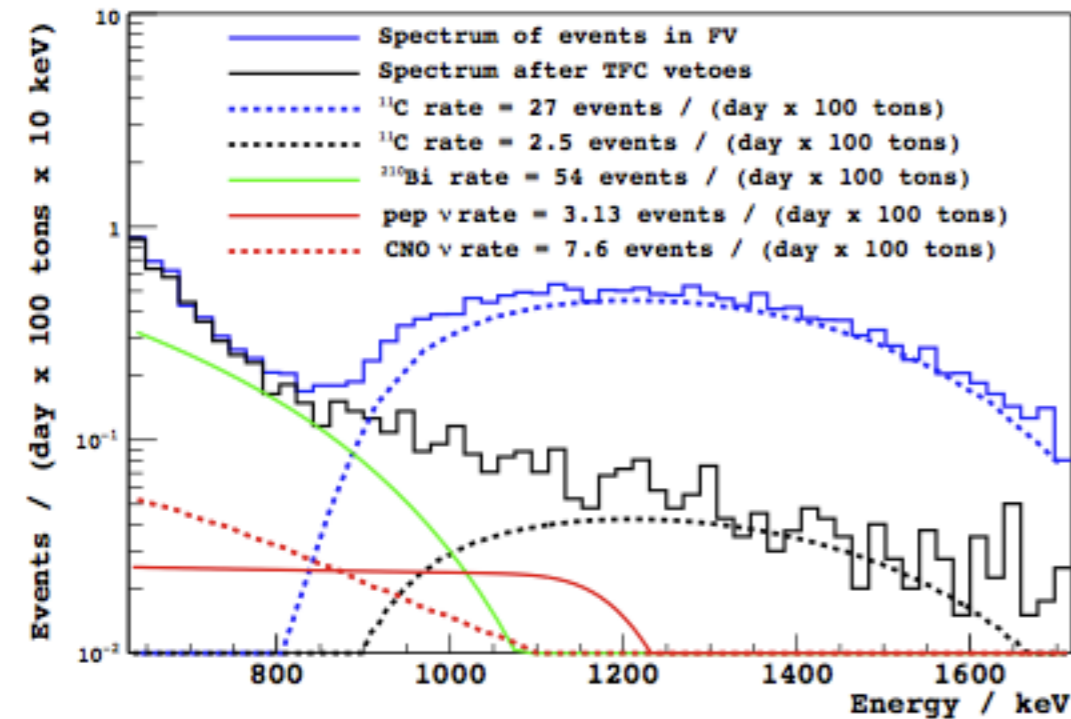


- Reconstructed μ entry/exit points
- Reconstructed position of neutron
- Reconstructed position of ^{11}C

Can use space + time correlation with $\mu + n$ to veto regions of the detector with higher ^{11}C background:
Three-fold coincidence (TFC) technique

^{11}C suppression in Borexino

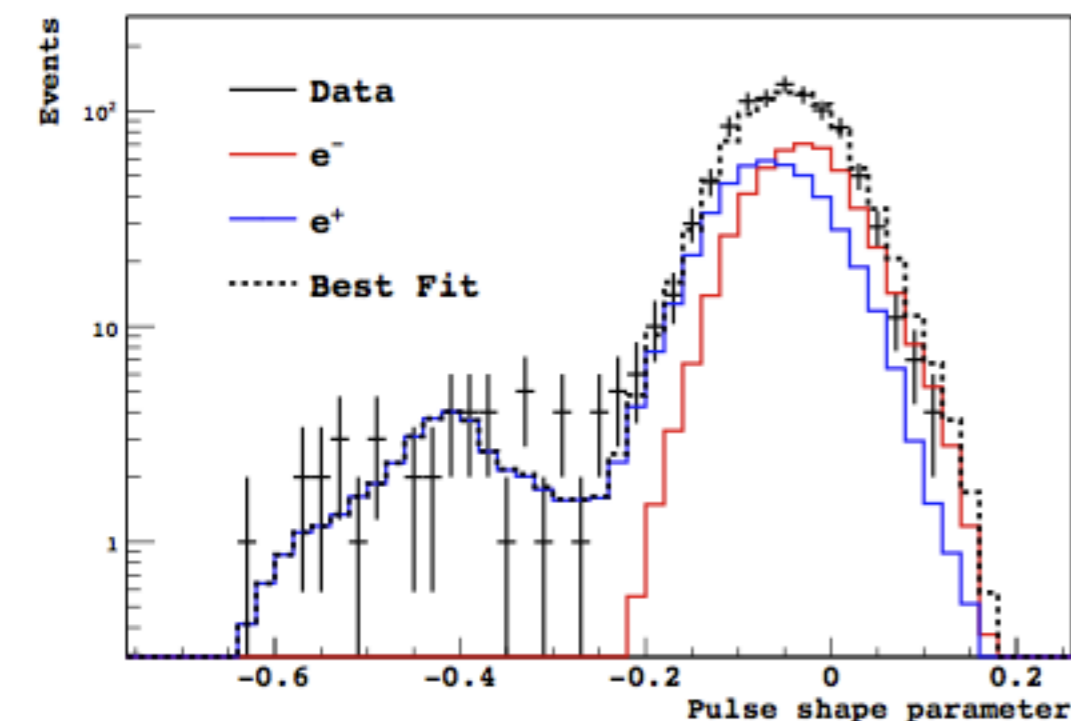
Effect of TFC on the spectrum



TFC decreases ^{11}C rate to ~10% of its original value with ~50% loss of exposure.

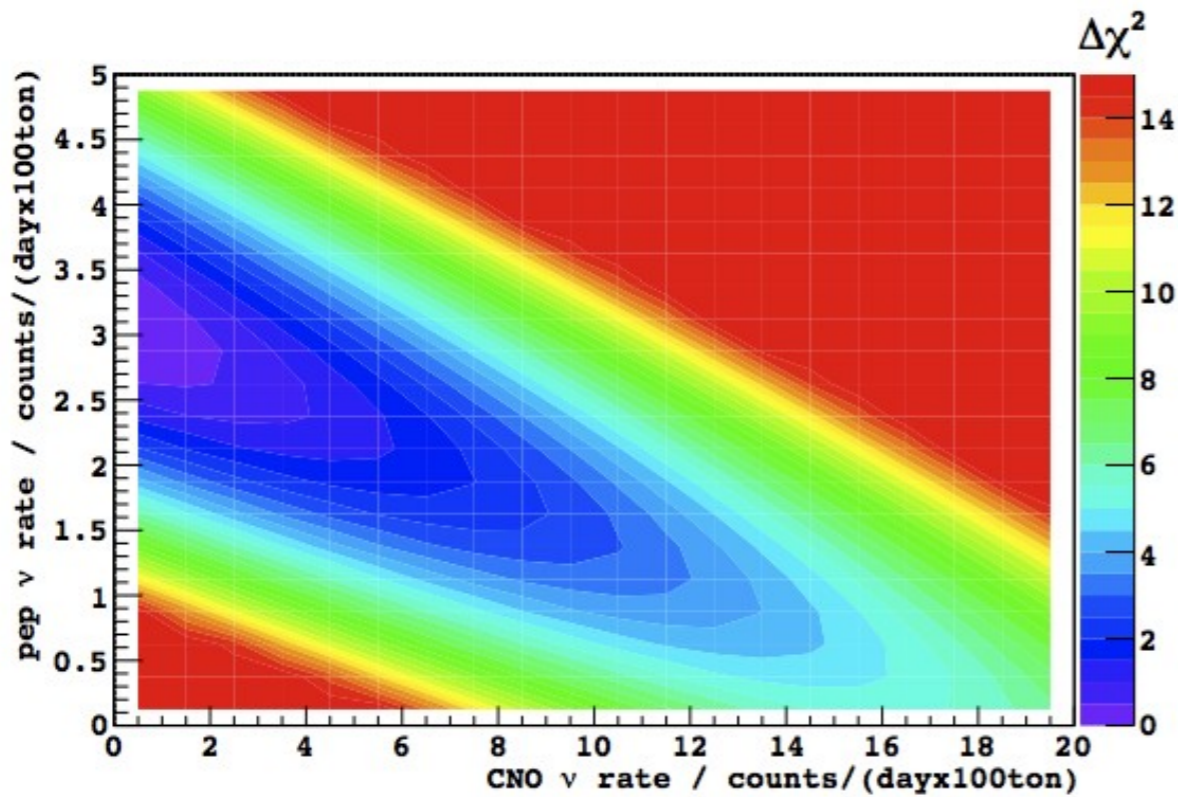
Limiting background is now internal ^{210}Bi .

Pulse shape parameter distribution in 0.9 - 1.8 MeV



β^-/β^+ Pulse Shape discrimination

Formation of positronium and multiple energy deposits from annihilation γ 's lead to different reconstructed emission time profiles.

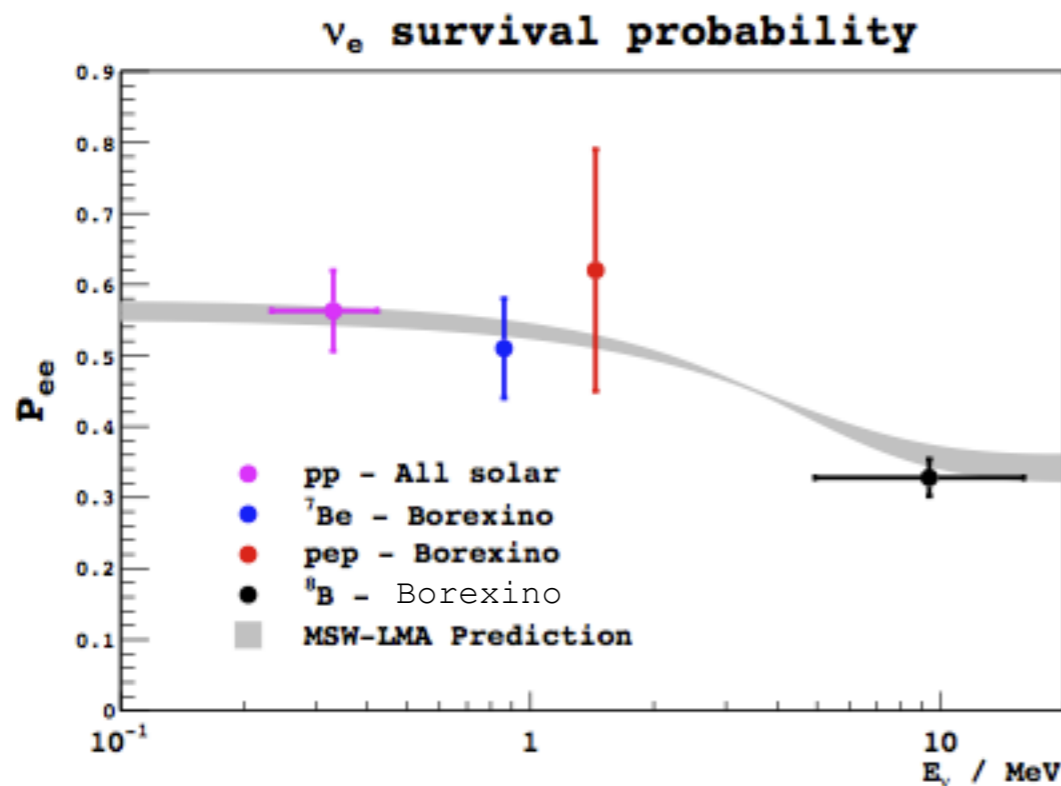


Statistical significance
of pep measurement
97% C.L.

Total fluxes from direct
measurement

pep flux:
 $(1.6 \pm 0.3) \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$

CNO flux:
 $< 7.4 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$



No oscillation hypothesis disfavored at 96% C.L.

CNO flux limit **1.4** times High Z prediction
Results consistent with MSW-LMA and SSM

Summary & Outlook

40 years of Science with Solar Neutrinos: from proving nuclear reactions happening in the Sun to precise test of Astrophysics and Particle Physics

Precision measurement of ${}^7\text{Be}$ solar neutrino flux in agreement with MSW-LMA scenario of neutrino oscillation

First evidence of pep solar neutrinos opens the doors to future tests of solar neutrino oscillations

Strongest limits so far on CNO solar neutrino flux. Next Borexino phase could measure CNO ν flux and solve the Solar Metallicity Problem


THE END

Astroparticle and Cosmology Laboratory – Paris, France 

INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy 

INFN e Dipartimento di Fisica dell'Università – Genova, Italy 

INFN e Dipartimento di Fisica dell'Università – Milano, Italy 

INFN e Dipartimento di Chimica dell'Università – Perugia, Italy 

Institute for Nuclear Research – Gatchina, Russia 

Institute of Physics, Jagellonian University – Cracow, Poland 

Joint Institute for Nuclear Research – Dubna, Russia 

Kurchatov Institute – Moscow, Russia 

Max-Planck Institute fuer Kernphysik – Heidelberg, Germany 

Princeton University – Princeton, NJ, USA 

Technische Universität – Muenchen, Germany 

University of Massachusetts at Amherst, MA, USA 

University of Moscow – Moscow, Russia 

Virginia Tech – Blacksburg, VA, USA 

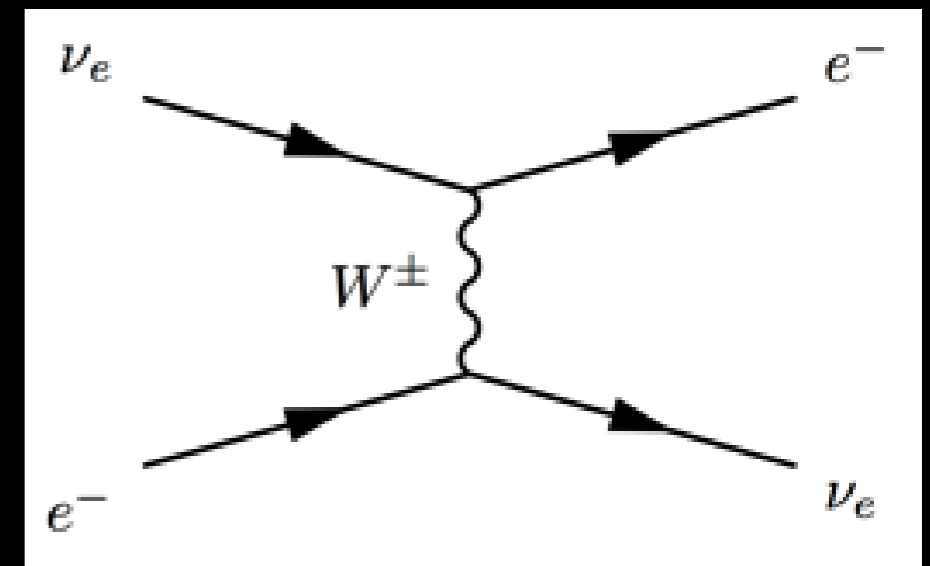
University of Hamburg – Hamburg, Germany

Backup Slides

Solar Neutrinos Propagation

MSW EFFECT: Neutrino oscillation parameters are modified in the presence of matter (eg Sun's core)

Charged current interaction of electron neutrinos introduces new term to mass matrix:



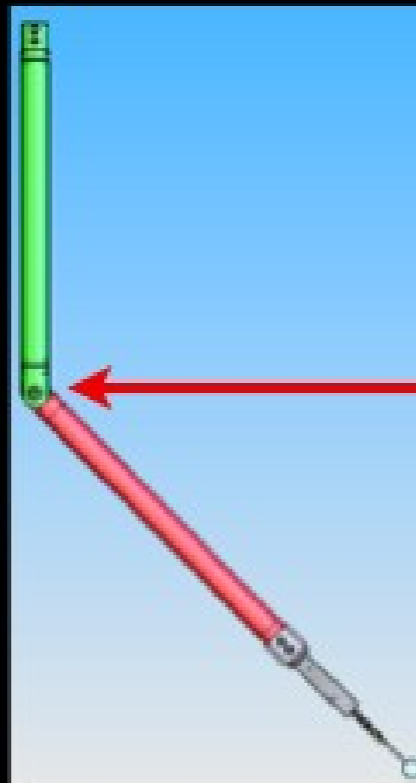
$$\begin{bmatrix} -\frac{\Delta m_{12}^2}{4E} \cos(2\theta_{12}) + \sqrt{2}G_F N_e & \frac{\Delta m_{12}^2}{4E} \sin(2\theta_{12}) \\ \frac{\Delta m_{12}^2}{4E} \sin(2\theta_{12}) & \frac{\Delta m_{12}^2}{4E} \cos(2\theta_{12}) \end{bmatrix}$$

Detector Calibration

Study position and energy reconstruction by deploying radioactive sources throughout active volume

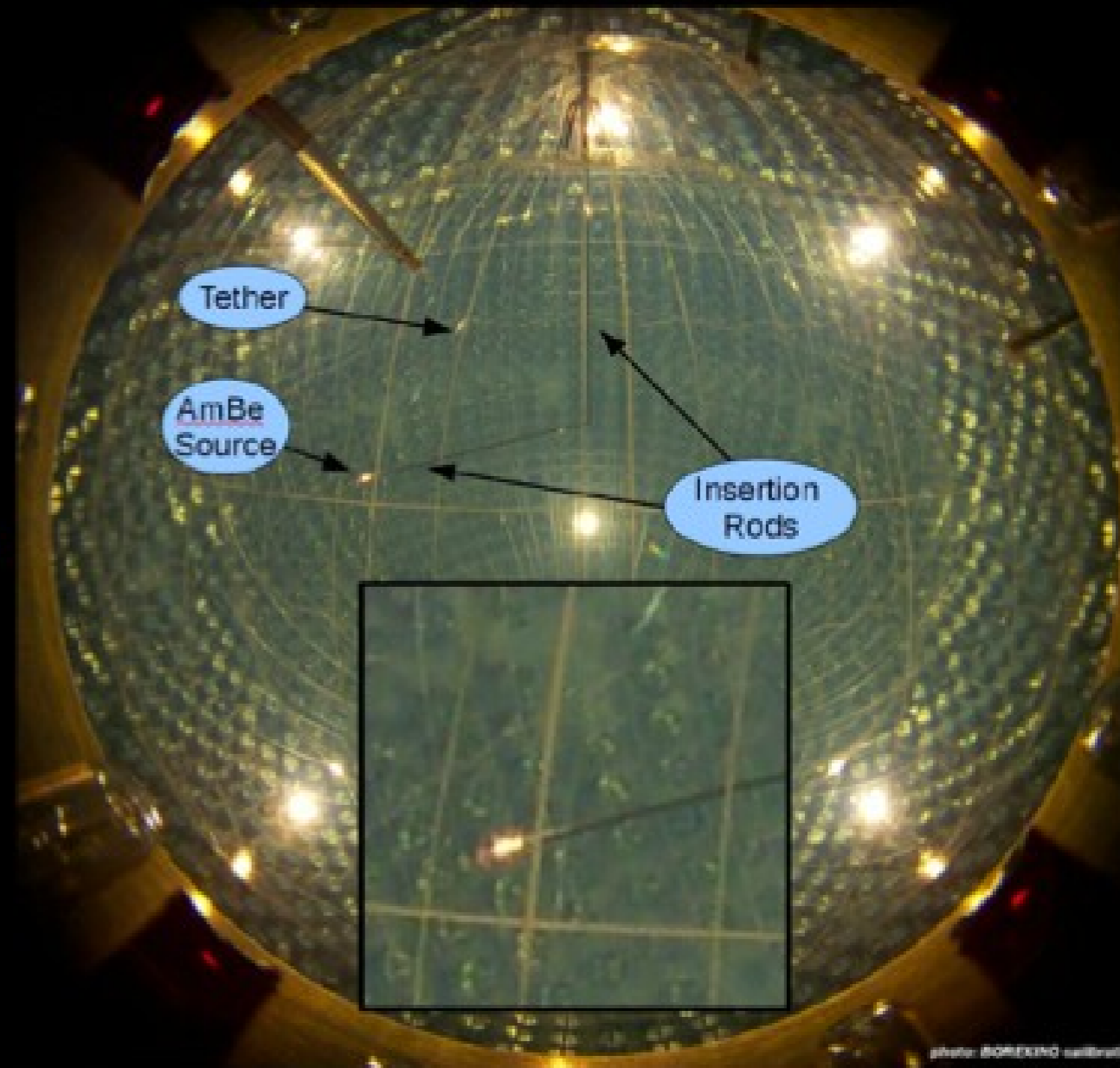


Laser Diffuser



Pivot for
off-axis
deployment

Source Vial



Steve Hardy (Thesis)

Day-Night Asymmetry

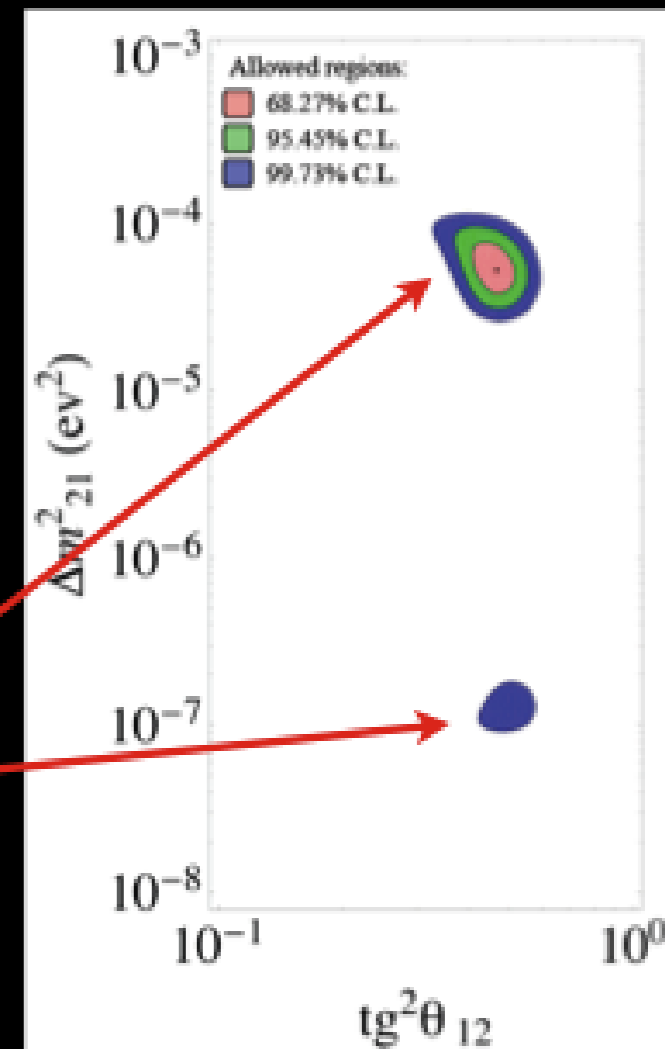
As neutrinos pass through the earth (at night), certain oscillation parameters can cause solar ν_μ to be converted back to ν_e

This effect would lead to a day-night asymmetry in the rate of detected neutrinos

$$A_{dn} \equiv 2 \frac{R_n^{7\text{Be}} - R_d^{7\text{Be}}}{R_n^{7\text{Be}} + R_d^{7\text{Be}}}$$

Model	Predicted A_{dn}
LMA	< 0.001
LOW	0.11 - 0.80
MaVan	0.20

Global Solar - Borexino

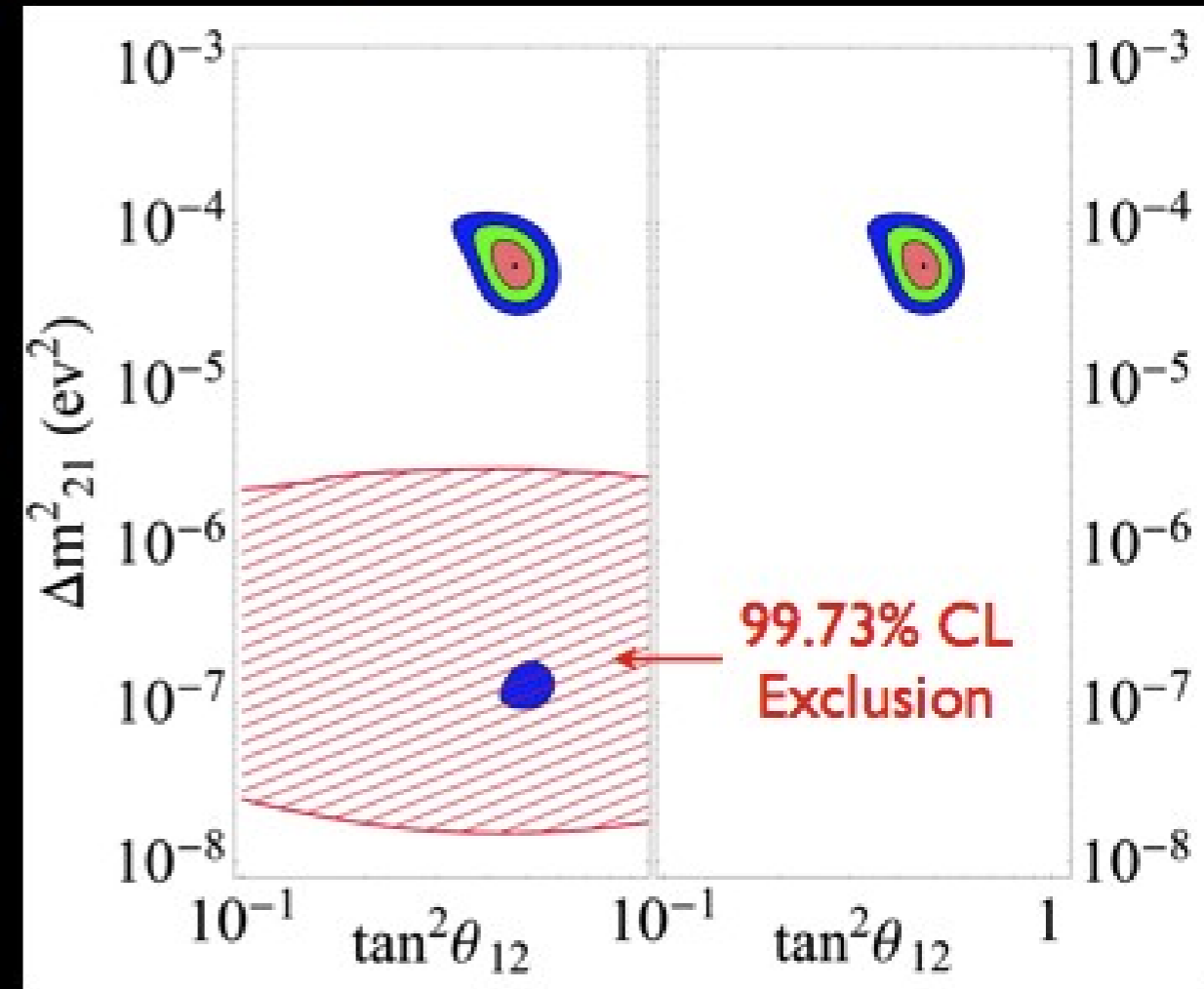


Implications

Day-Night Asymmetry

$$A_{\text{dn}} = 0.001 \pm 0.012(\text{stat}) \pm 0.007(\text{sys})$$

Rules out LOW solution at $> 8\sigma$



Global Best Fit (All Solar Data)

$$\Delta m^2 = 5.3 \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta_{12} = 0.46$$

^8B Measurement

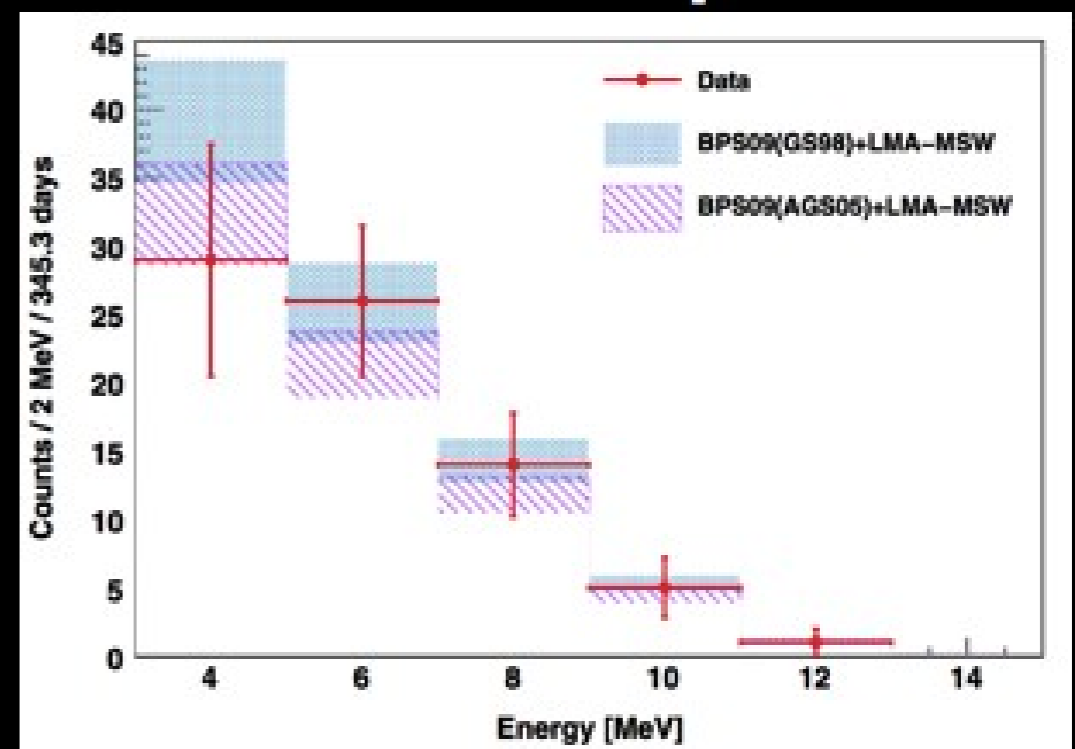
Physical Review D 82, 03306 (2010)

Final Result:

	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	$0.22 \pm 0.04 \pm 0.01$	$0.13 \pm 0.02 \pm 0.01$
$\Phi_{\text{exp}}^{\text{ES}}$ [$10^6 \text{ cm}^{-2} \text{ s}^{-1}$]	$2.4 \pm 0.4 \pm 0.1$	$2.7 \pm 0.4 \pm 0.2$
$\Phi_{\text{exp}}^{\text{ES}} / \Phi_{\text{th}}^{\text{ES}}$	0.88 ± 0.19	1.08 ± 0.23

Result consistent with other experiments / SSM predictions

	Threshold [MeV]	$\Phi_{^8\text{B}}^{\text{ES}}$ [$10^6 \text{ cm}^{-2} \text{ s}^{-1}$]
SuperKamiokaNDE I [3]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D ₂ O [4]	5.0	$2.39^{+0.24}_{-0.23} \text{ }^{+0.12}_{-0.12}$
SNO Salt Phase [25]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [26]	6.0	$1.77^{+0.24}_{-0.21} \text{ }^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$



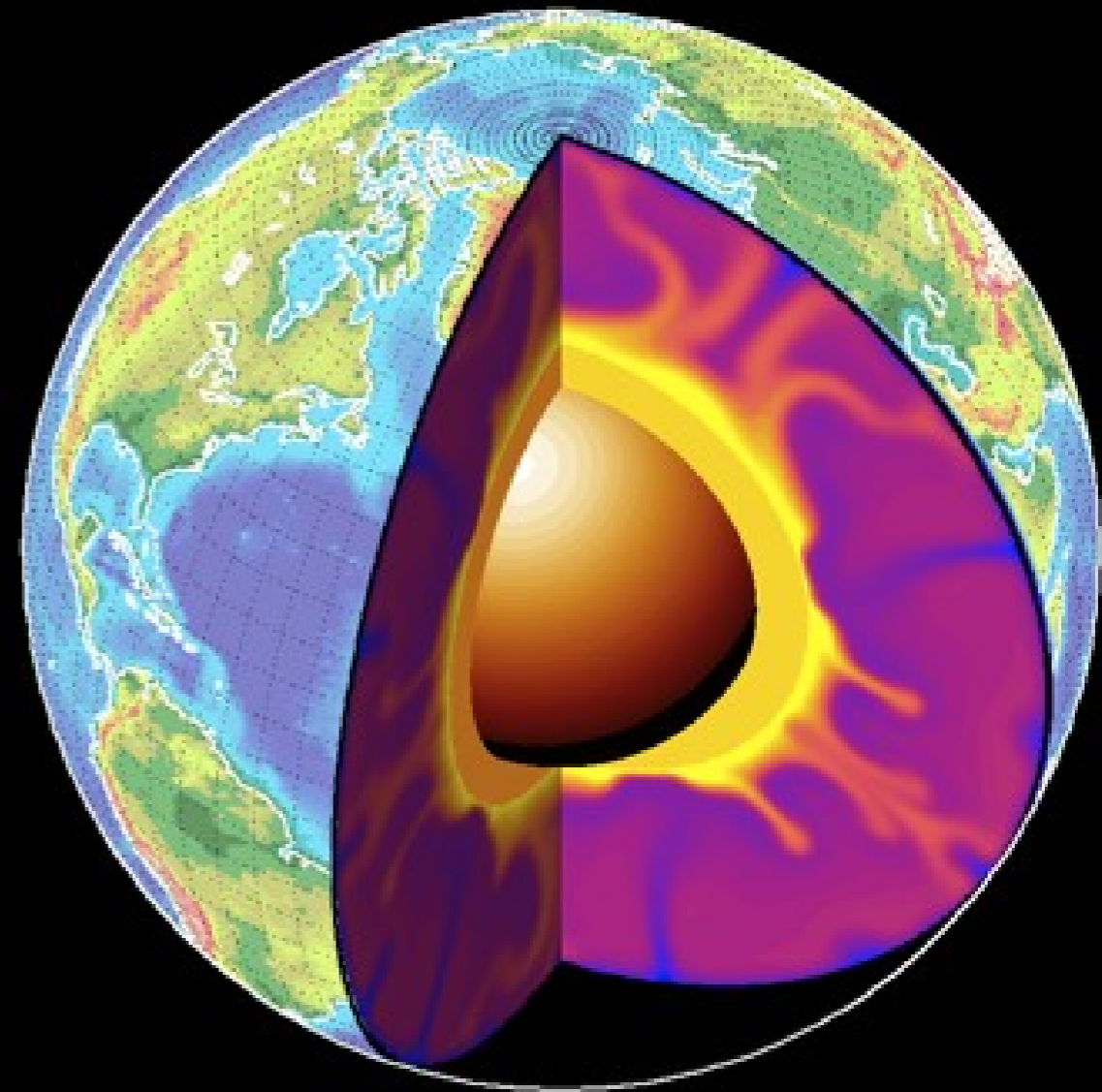
Geo-Neutrinos

Physical Letters B 687 (2010) 299-304

Open questions in GeoPhysics:

What fraction of the terrestrial heat production comes from radioactive decay (U, Th, K)?

How much U/Th is there in the mantle / crust ?

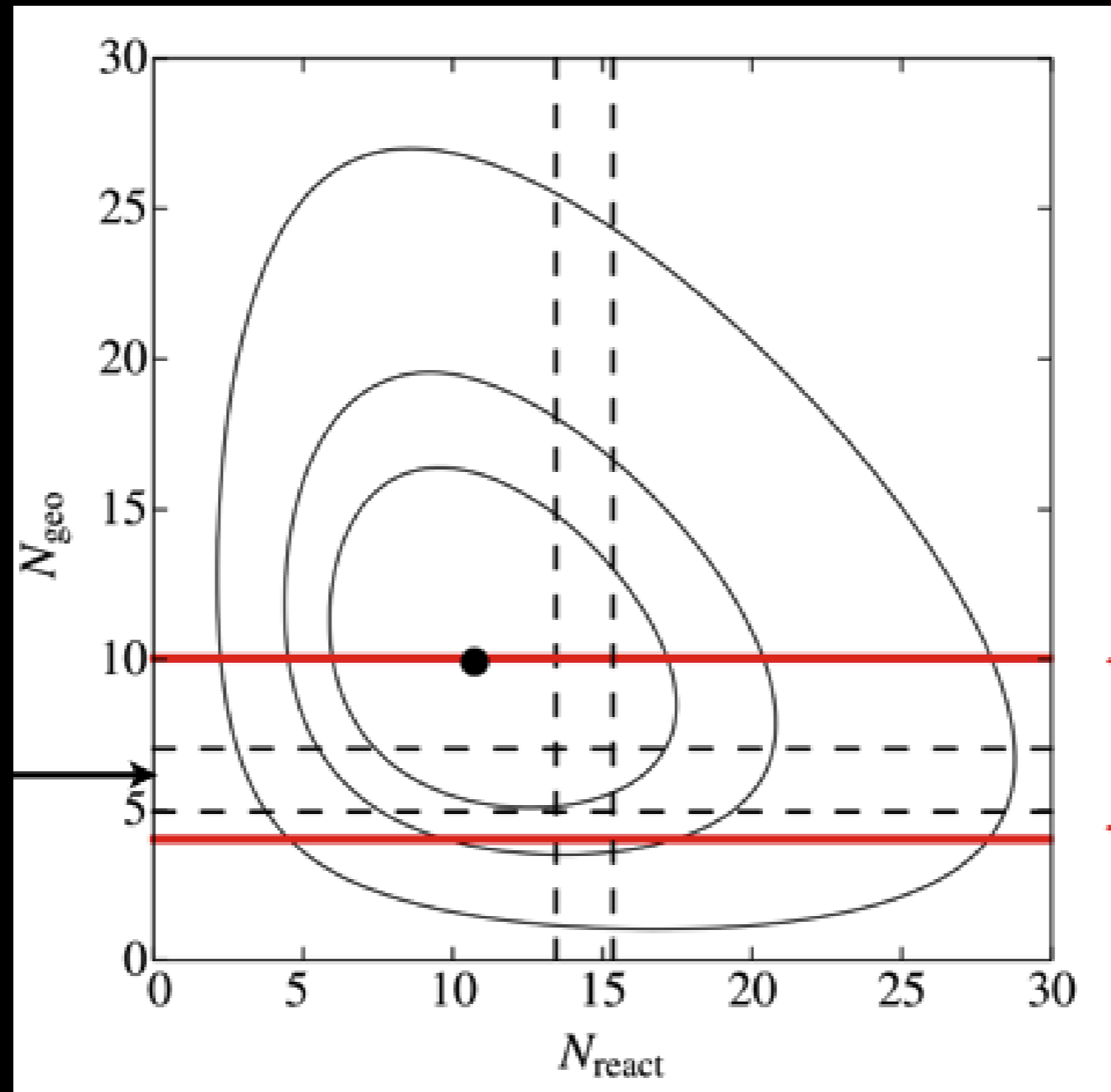


Geo-Neutrinos provide valuable information about the composition of the Earth's interior

Geo-Neutrinos

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First detection of geo-neutrinos at $>3\sigma$ C.L.



BSE Predicted Range

Max. Radiogenic

Min. Radiogenic