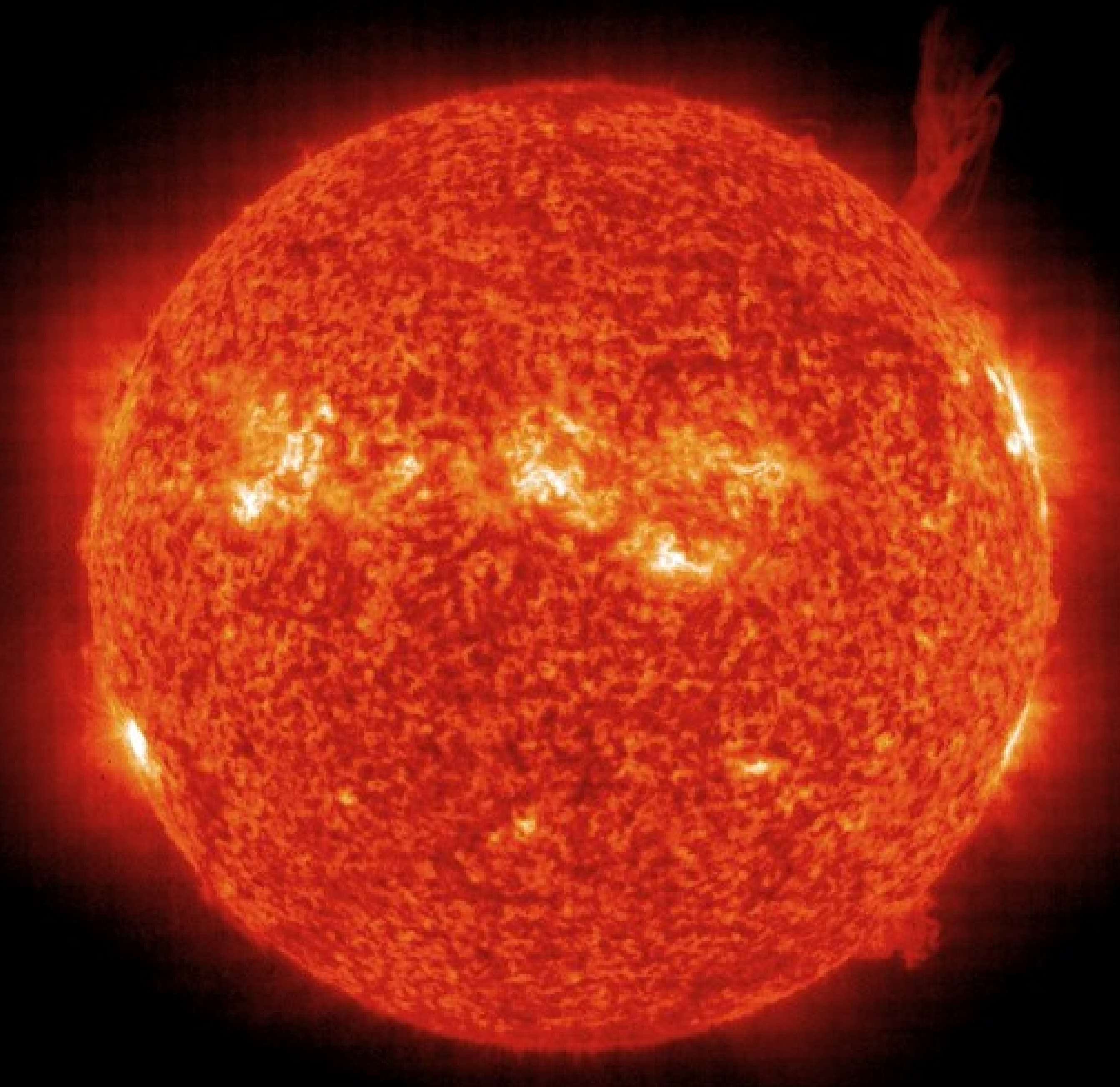
Solar Neutrino Spectroscopy: New results from BOREXINO

Stefano Davini, Genova University
On behalf of the
Borexino Collaboration

How does the Sun work?



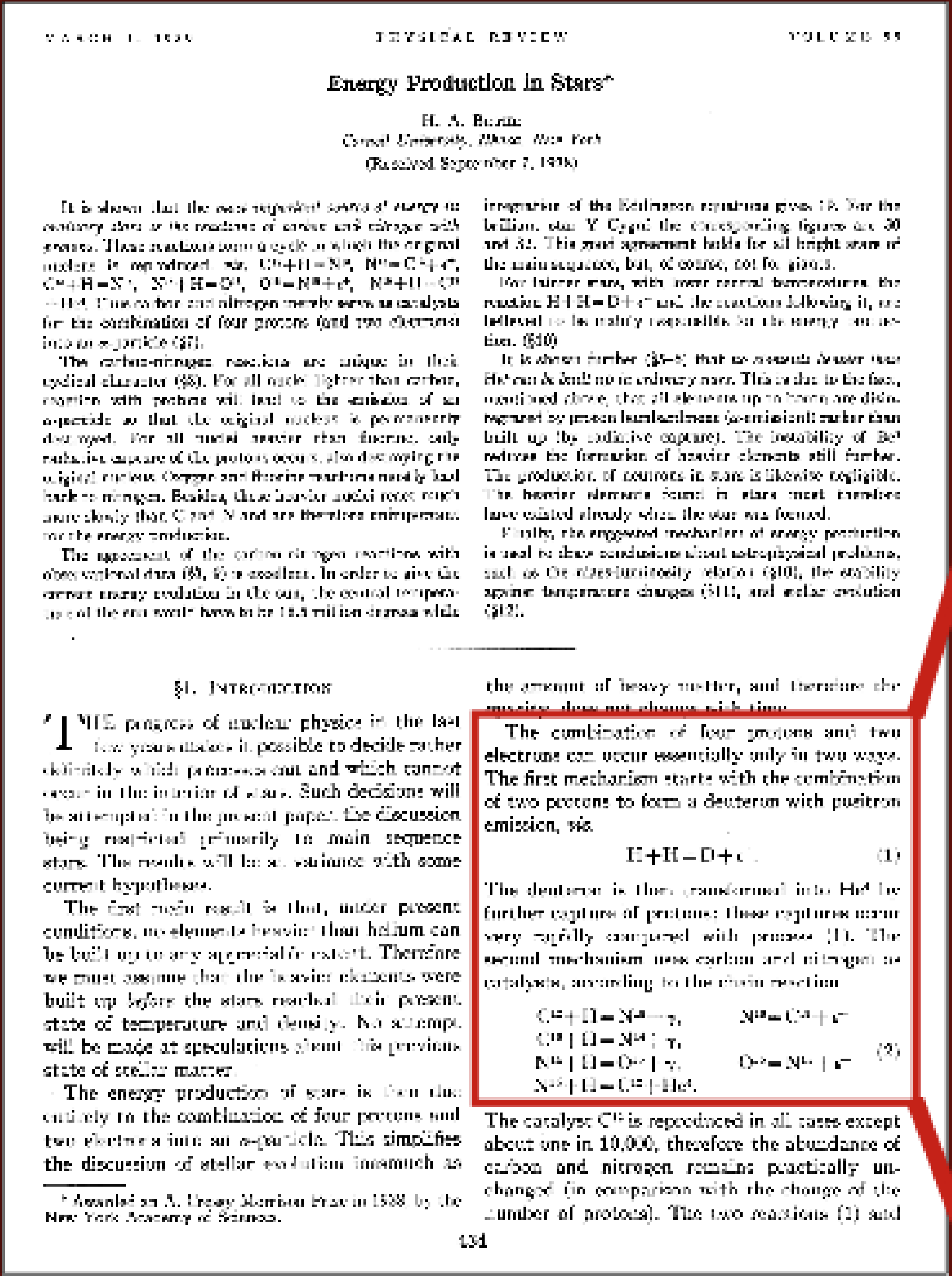
http://sohowww.nascom.nasa.gov/data/realtime-update.html

How does the Sun work?

The Sun is a god fueled by human sacrifice

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

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

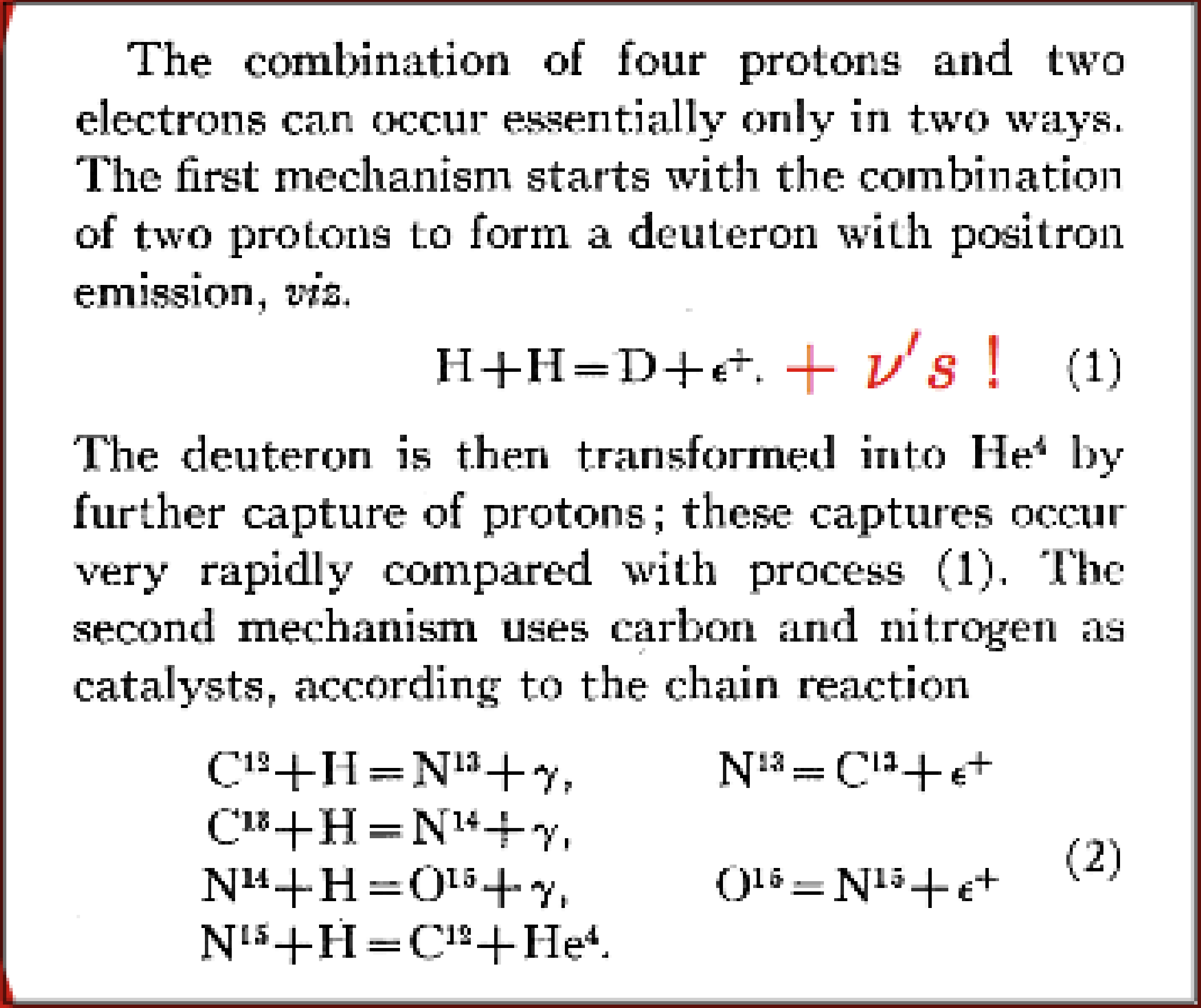


Energy Production in Stars*

H. A. Bethe

Cornell University, Ithaca, New York

(Received September 7, 1938)

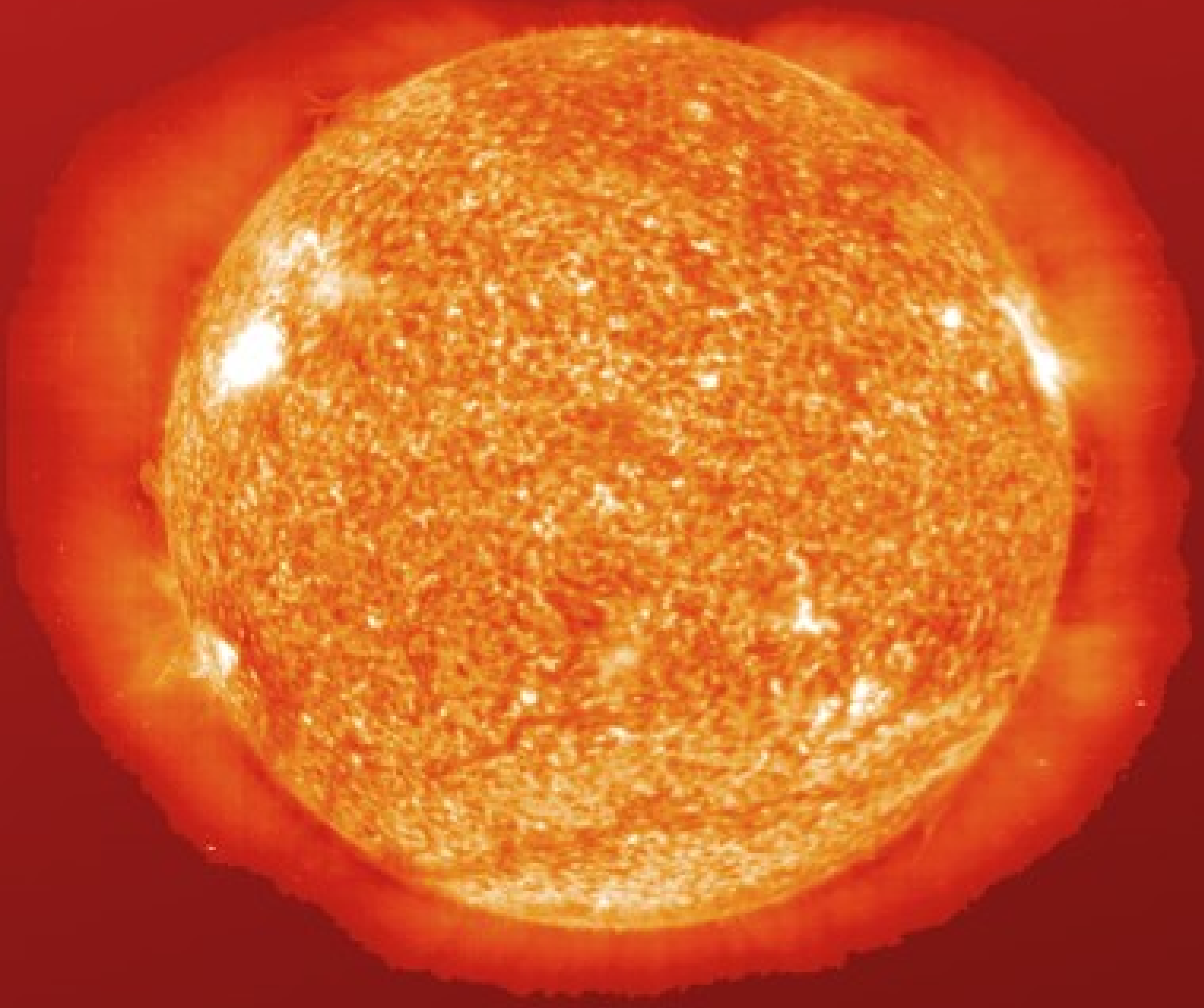


The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$\mathrm{H}+\mathrm{H}=\mathrm{D}+\epsilon^{+}. \; + \nu's\ ! \qquad (1)$$

The deuteron is then transformed into He⁴ 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

$$\begin{aligned} &\mathrm{C}^{12}+\mathrm{H}=\mathrm{N}^{13}+\gamma, && \mathrm{N}^{13}=\mathrm{C}^{13}+\epsilon^{+} \\ &\mathrm{C}^{13}+\mathrm{H}=\mathrm{N}^{14}+\gamma, && \\ &\mathrm{N}^{14}+\mathrm{H}=\mathrm{O}^{15}+\gamma, && \mathrm{O}^{15}=\mathrm{N}^{15}+\epsilon^{+} \\ &\mathrm{N}^{15}+\mathrm{H}=\mathrm{C}^{12}+\mathrm{He}^{4}. && \end{aligned} \qquad (2)$$



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.

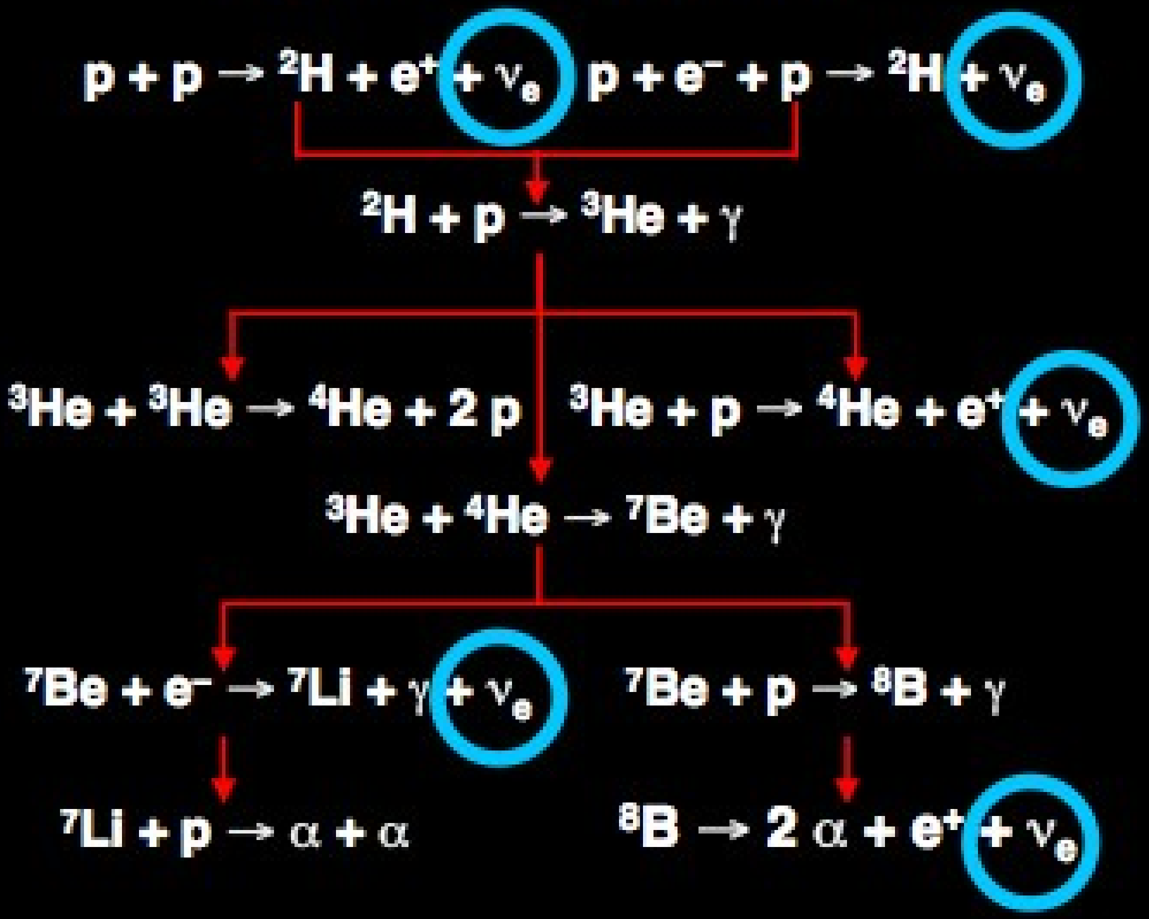
(3) Primary energy generation is nuclear fusion.

(4) Elemental abundance determined solely from fusion reactions.

John Bahcall
1934 - 2005

Solar Neutrinos

p-p Solar Fusion Chain



$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

${}^2H + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2\,p$ $\quad$ ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

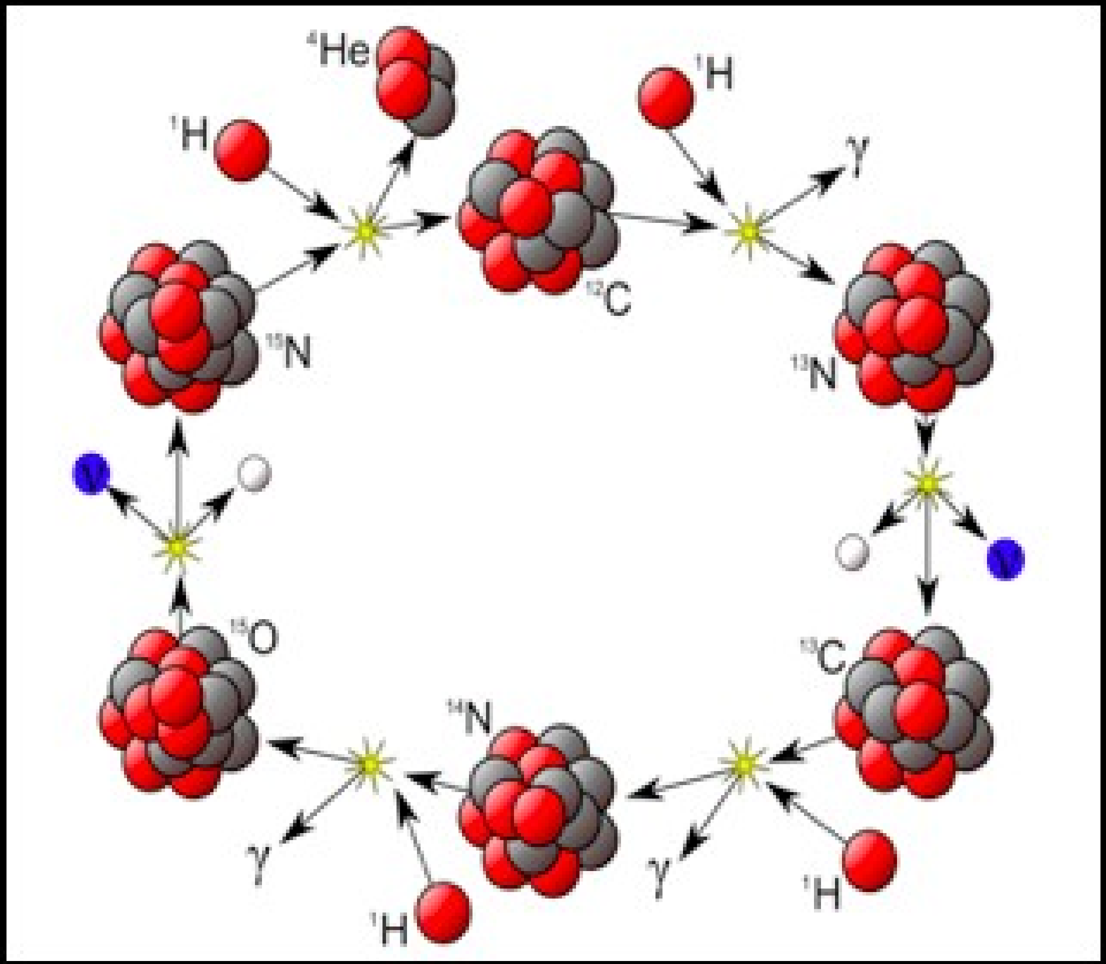
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\,\alpha + e^+ + \nu_e$

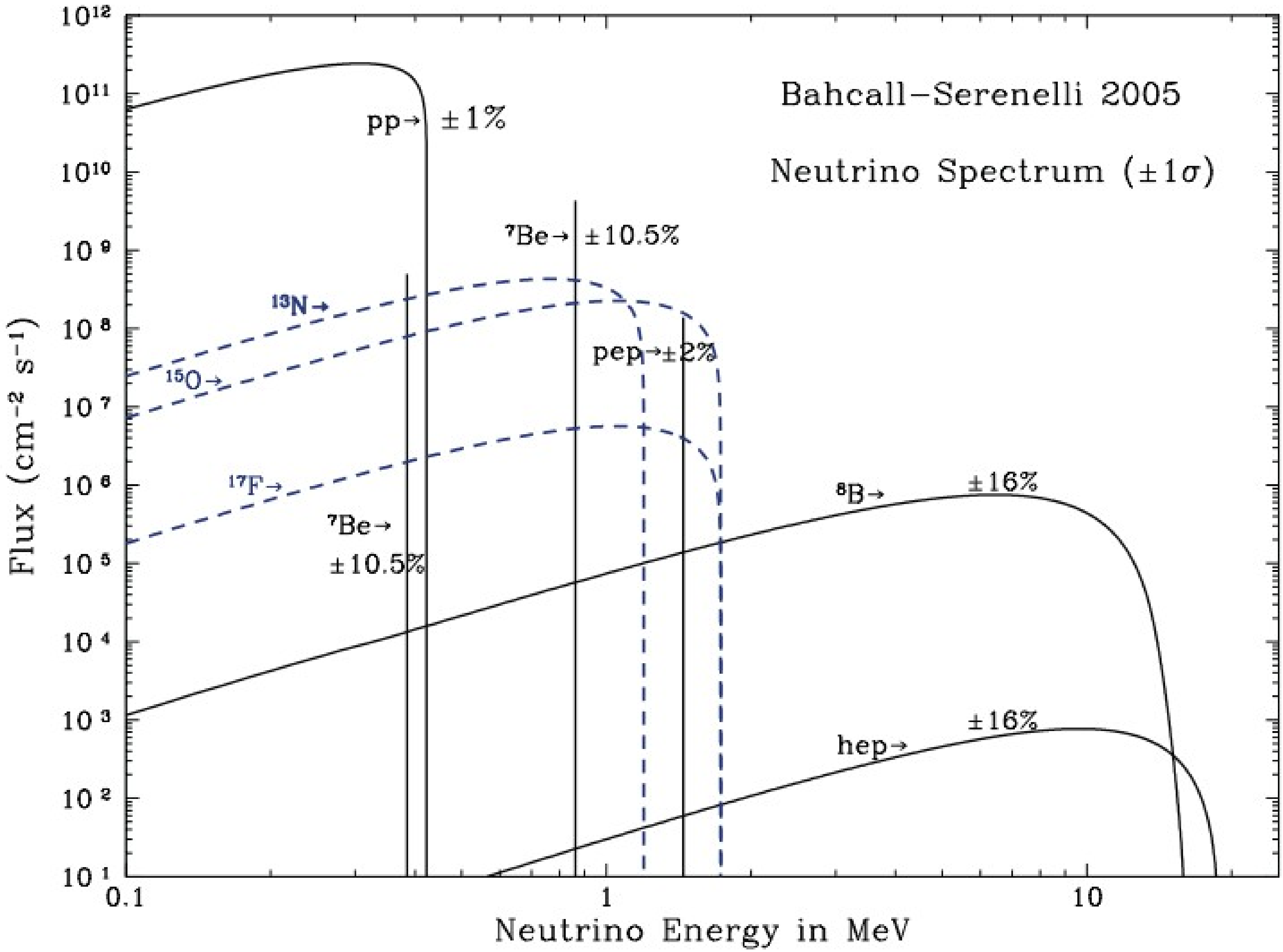
Dominant fusion mechanism in the Sun

CNO Cycle



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

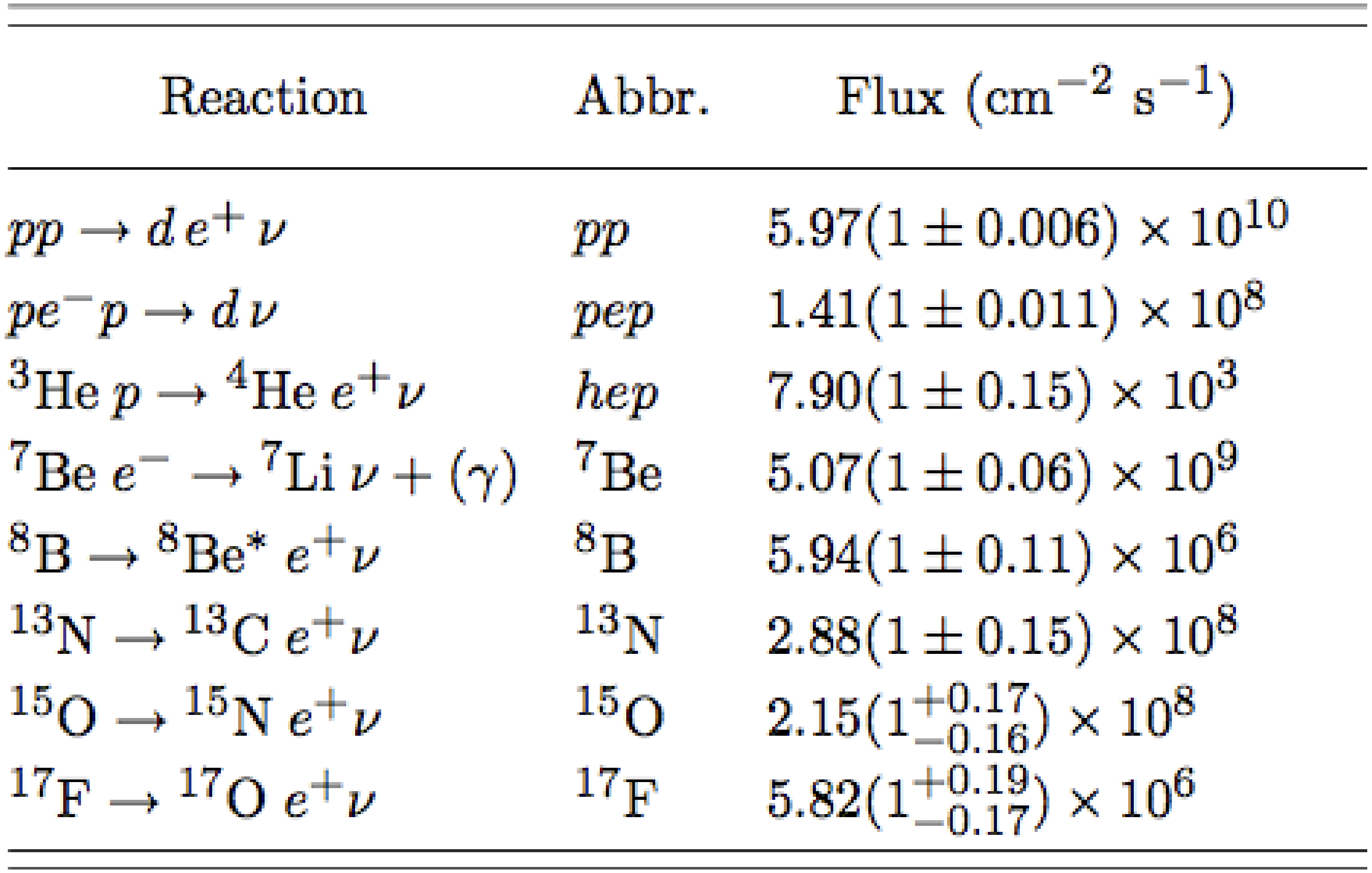
Solar Neutrinos



Solar **S**tandard **M**odels predict spectra, fluxes of solar ν

Solar Neutrino experiments can test SSM

Solar Standard Model predicted ν fluxes



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

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

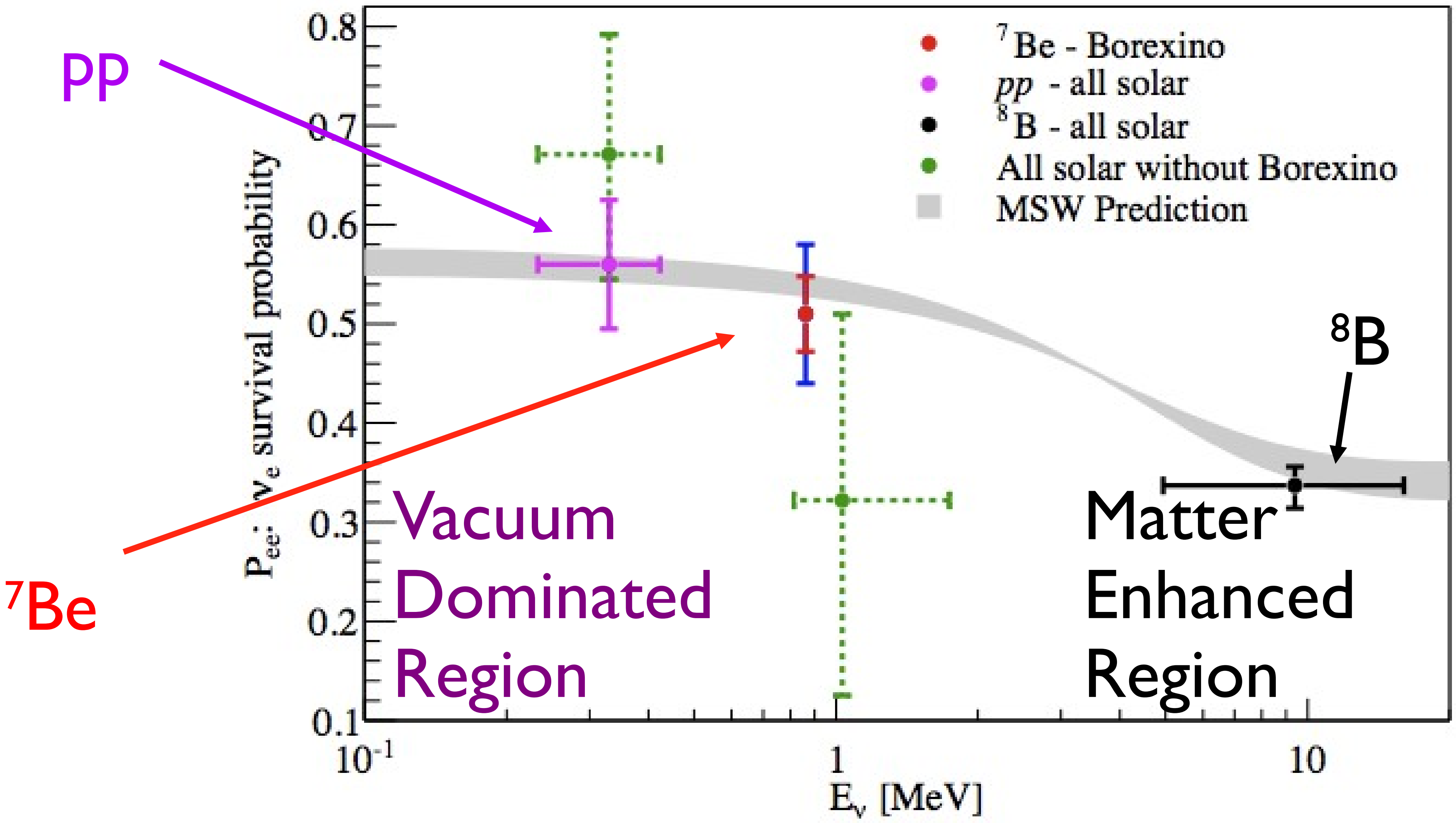
In **vacuum**:

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

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

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

Solar Neutrino Propagation



MSW-LMA scenario: coherent scattering in matter enhances oscillation probability → **Energy dependent Pee**

Large **M**ixing **A**ngle

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 ^{8}B neutrinos (1980s).
- **But** detected ν_e flux ~1/3 of expected: "The Solar Neutrino Problem"
- SNO measured (2000) the total ν_e and ν_x flux from ^{8}B neutrinos demonstrating neutrino oscillations.

The present: Solar Neutrino and Astrophysics wish list

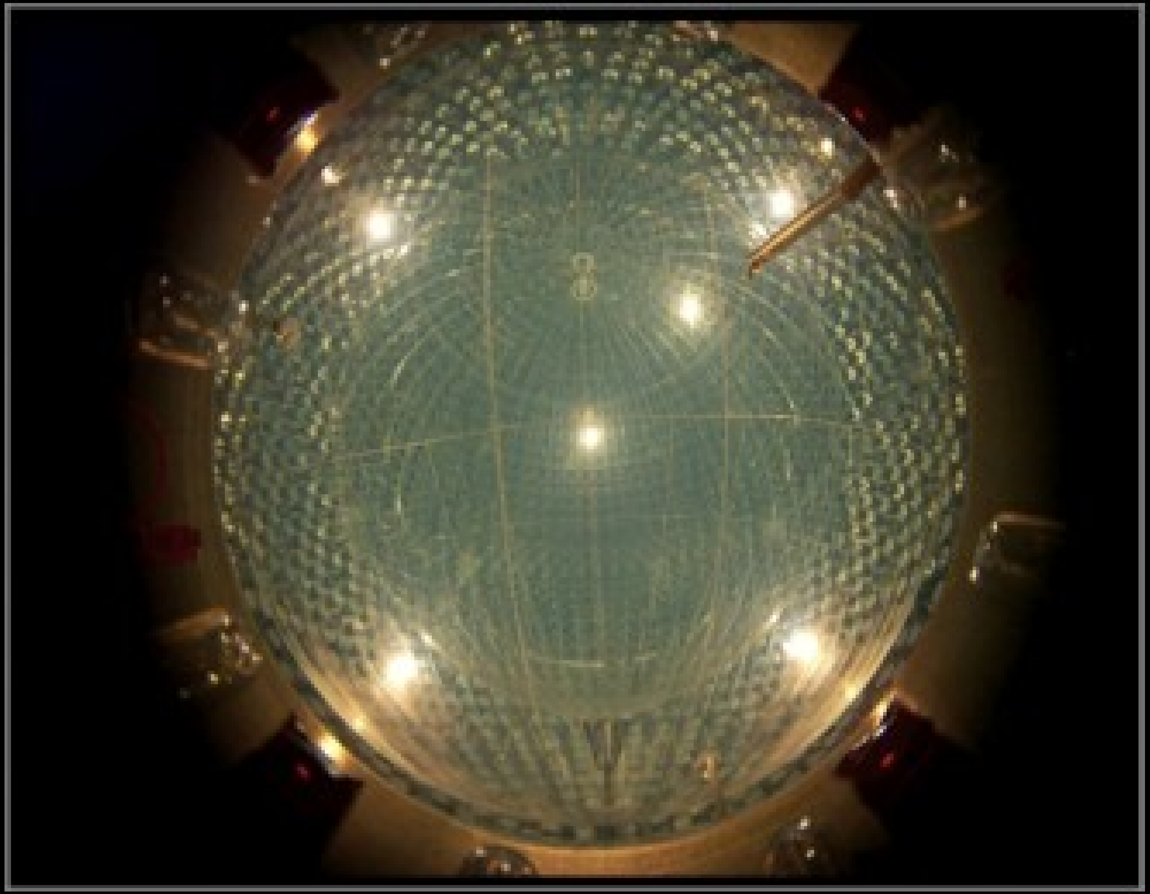
- Particle physics:
  - Test **MSW-LMA** P_{ee} with high accuracy
  - Probe the **P_{ee}** in the **transition region**, sensitive to Physics beyond Standard Model
- Solar Astrophysics:
  - Test SSM predictions, prove **CNO** cycle in Sun
  - Test two competing models of **SSM**: **High** and **Low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

Borexino Detector

Gran Sasso National Laboratory
(Under Apennine Mountains)

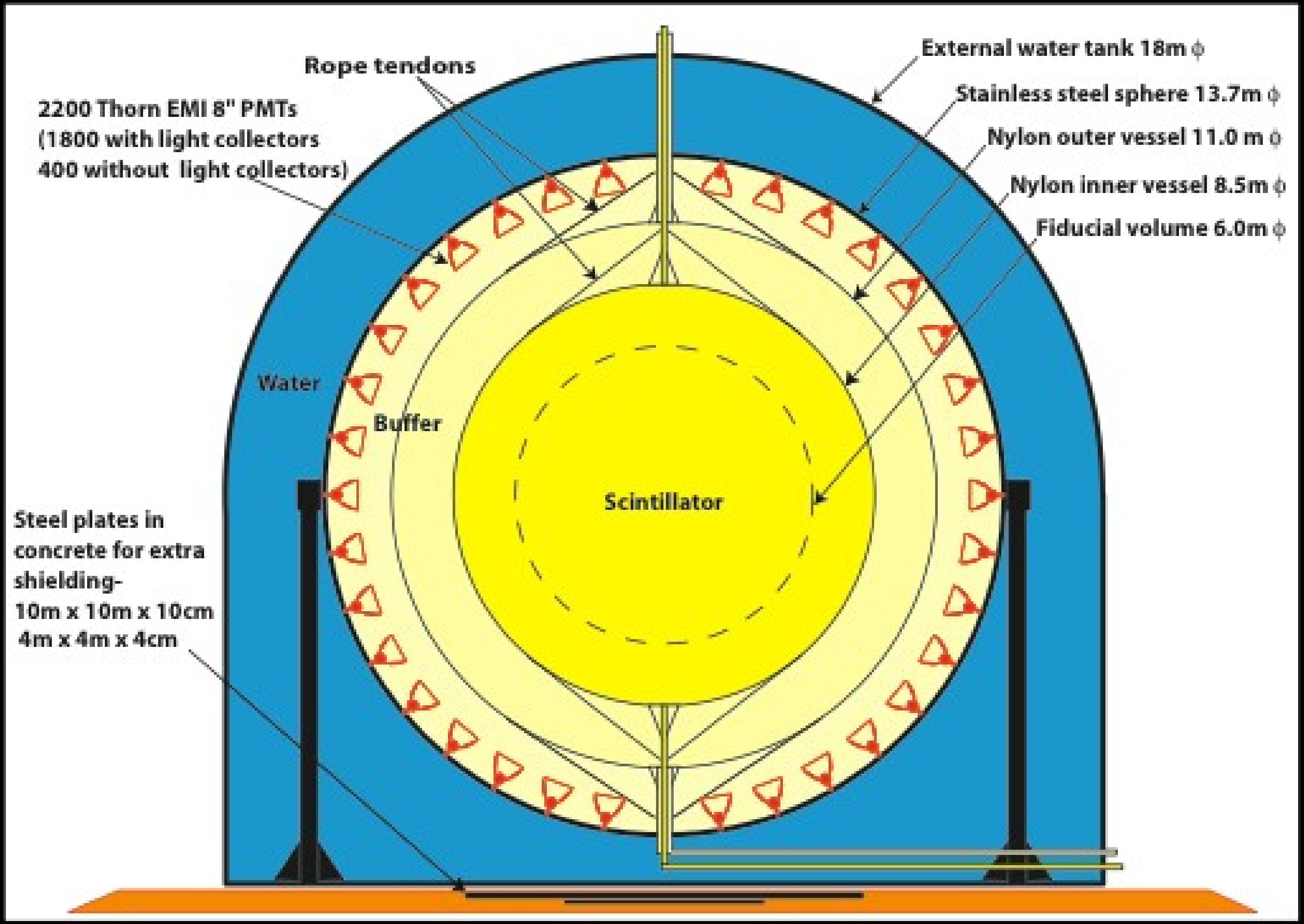
Rock Shielding
~ 1400m (3500 m.w.e)

Cosmic Muon Flux
~ 1/m^2/hr
(4300/day through detector)



Borexino Detector

Design based on principle of graded shielding



Exterior instrumented water tank (Cherenkov detector)

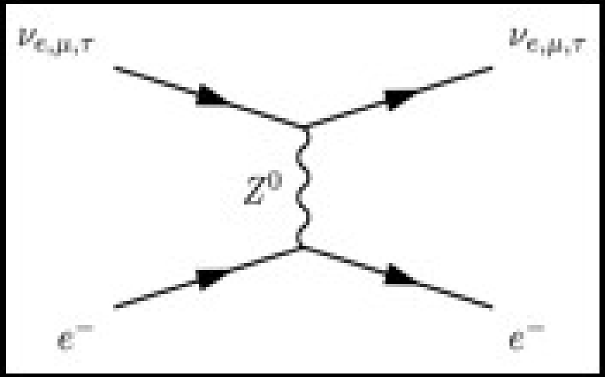
Stainless Steel Sphere with ~2200 PMTs

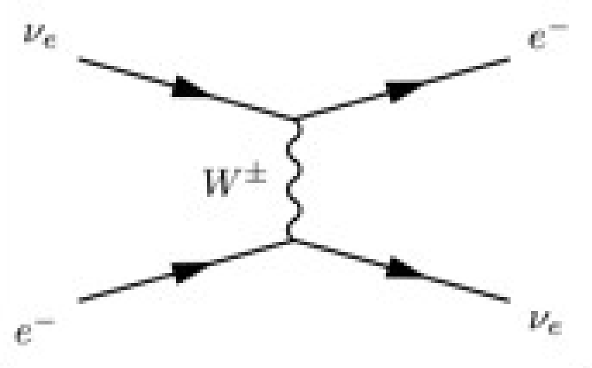
898 tons of quenched scintillator as buffer

278 tons of active scintillator

Fiducial Mass ~ 75 tons

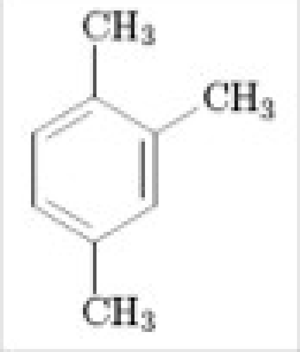
Borexino Detector

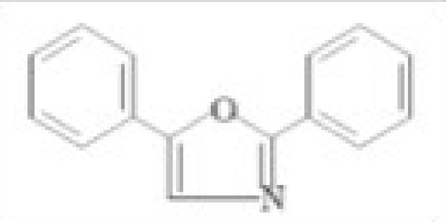




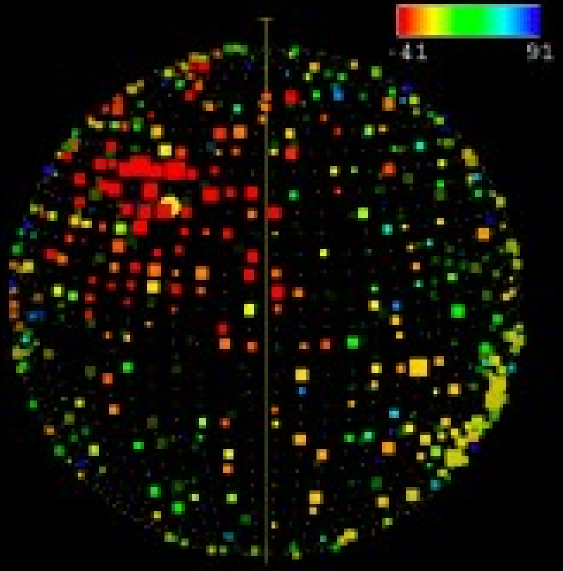
Neutrinos are detected through elastic scattering on electrons

Recoiling electrons excite scintillator molecules which emit light

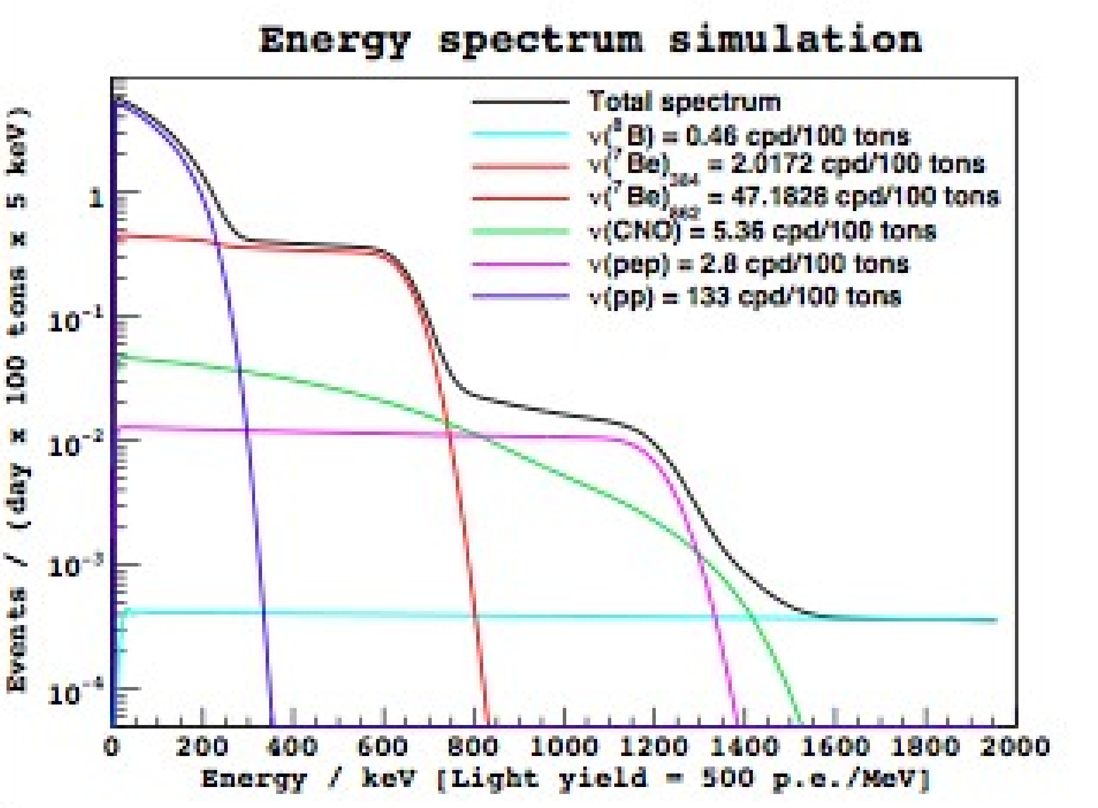




PC + 1.5g/l PPO



Scintillation light is detected by photomultiplier tubes



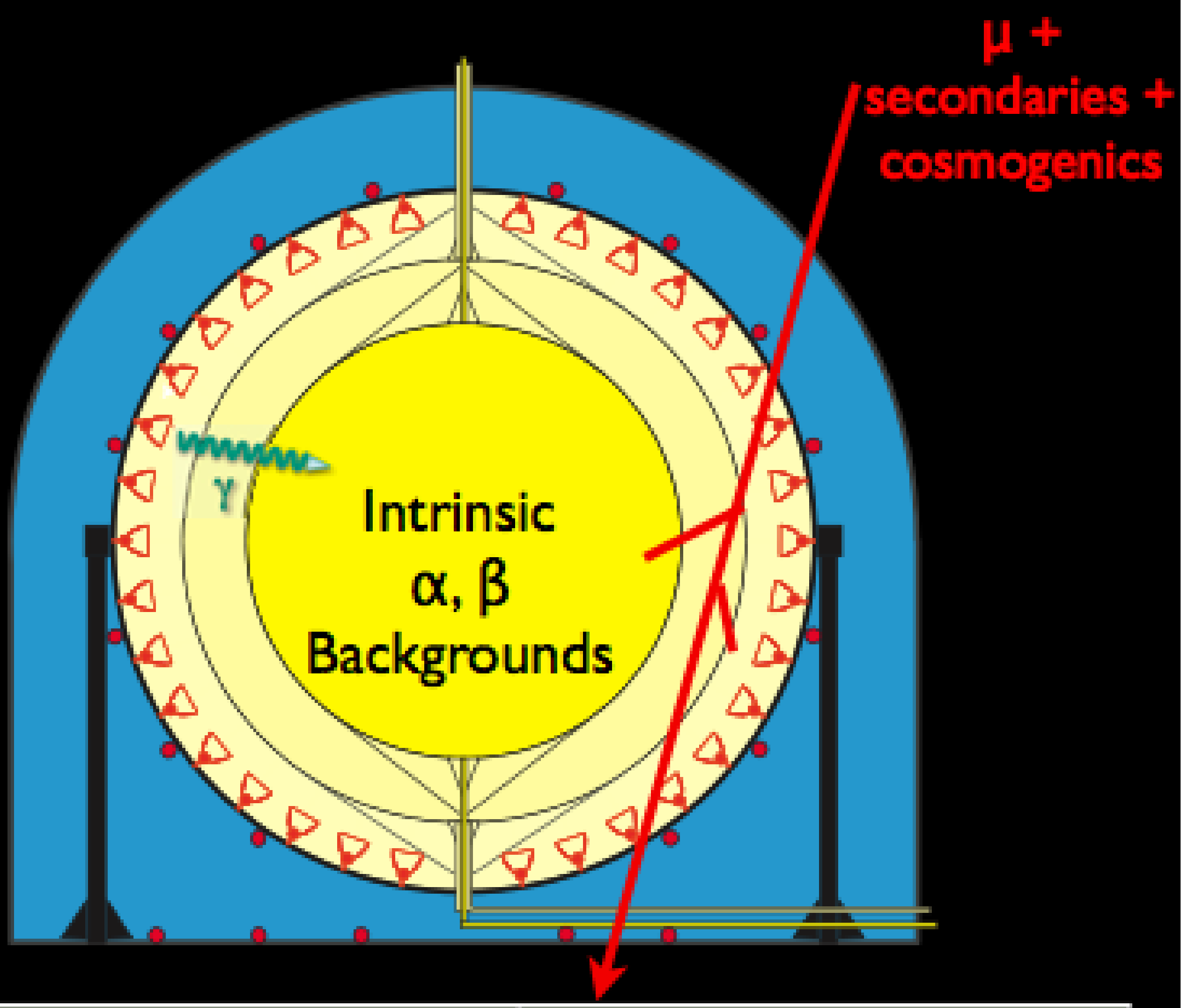
Amount and timing of light give energy and position information

Backgrounds

No directional information from scintillation light

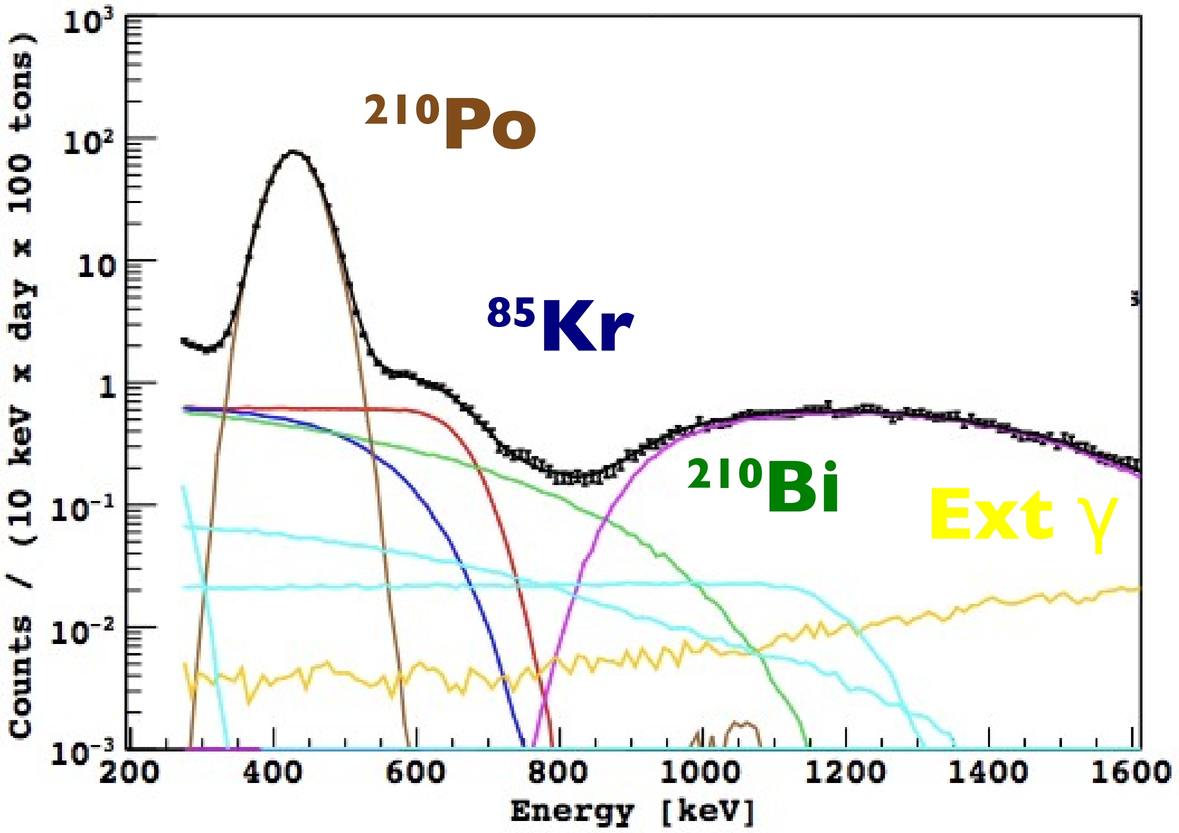
Cannot discriminate between electron recoils and β/γ backgrounds

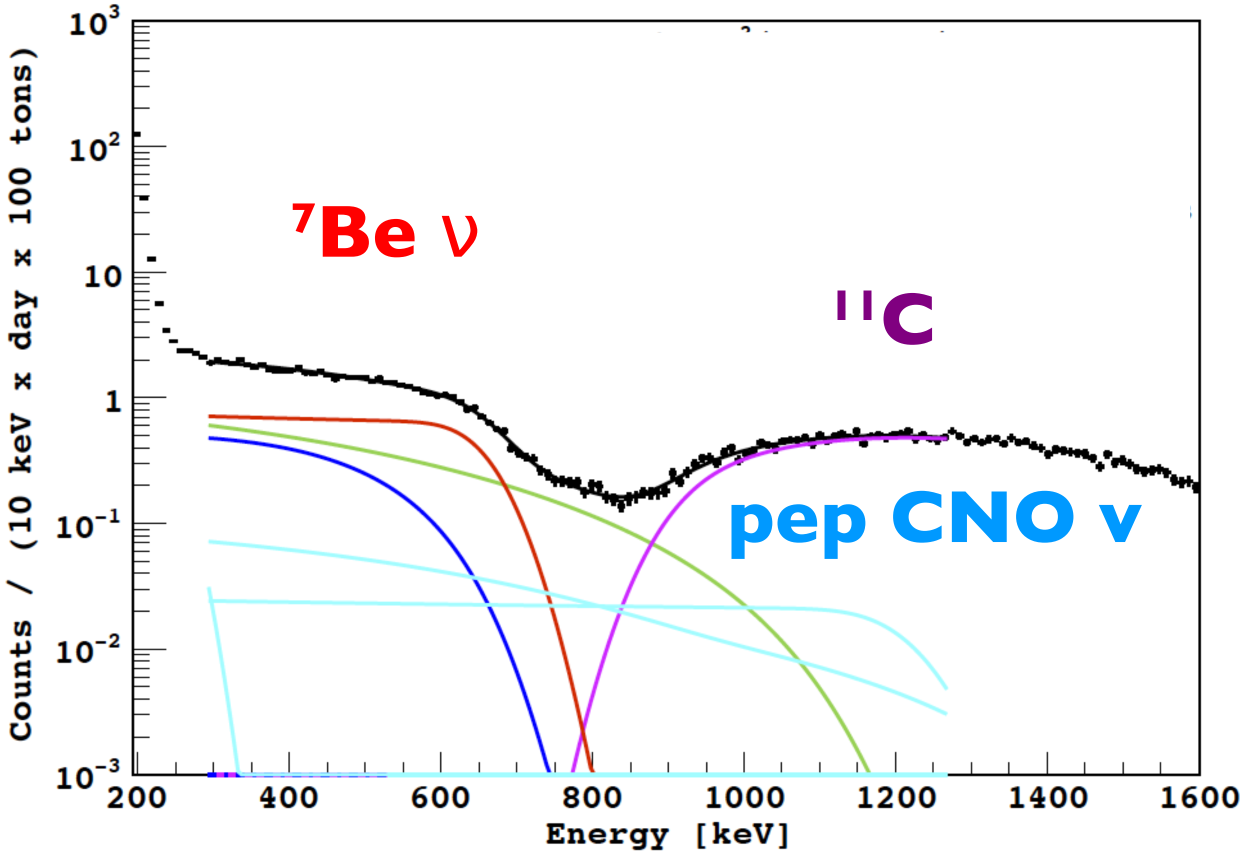
Need unprecedented low levels of background



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

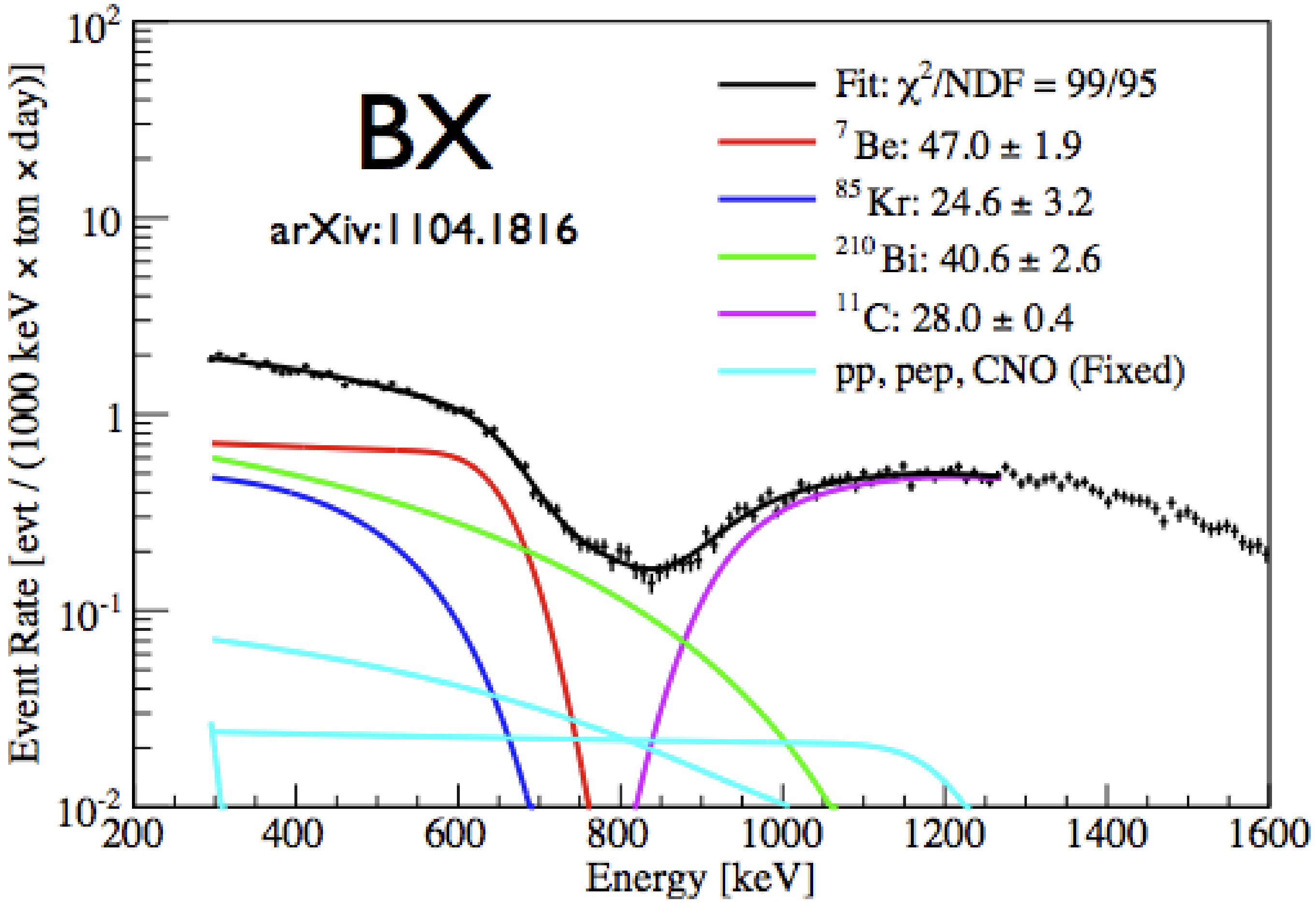
Purification → Low background rates

High Light Yield → High Energy Resolution

Calibration → Detector response understood

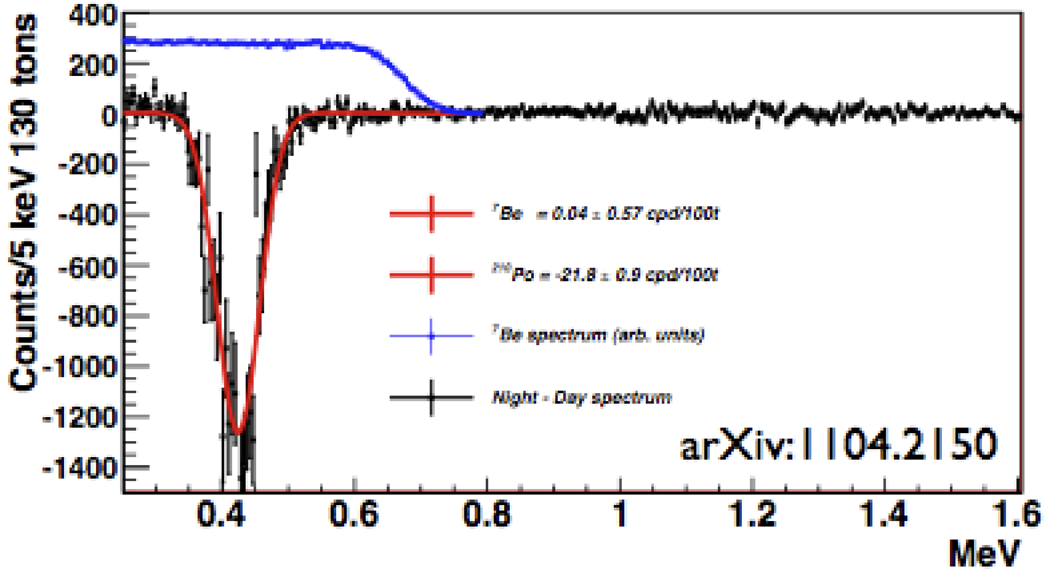
^{7}Be neutrinos

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



arXiv:1104.1816

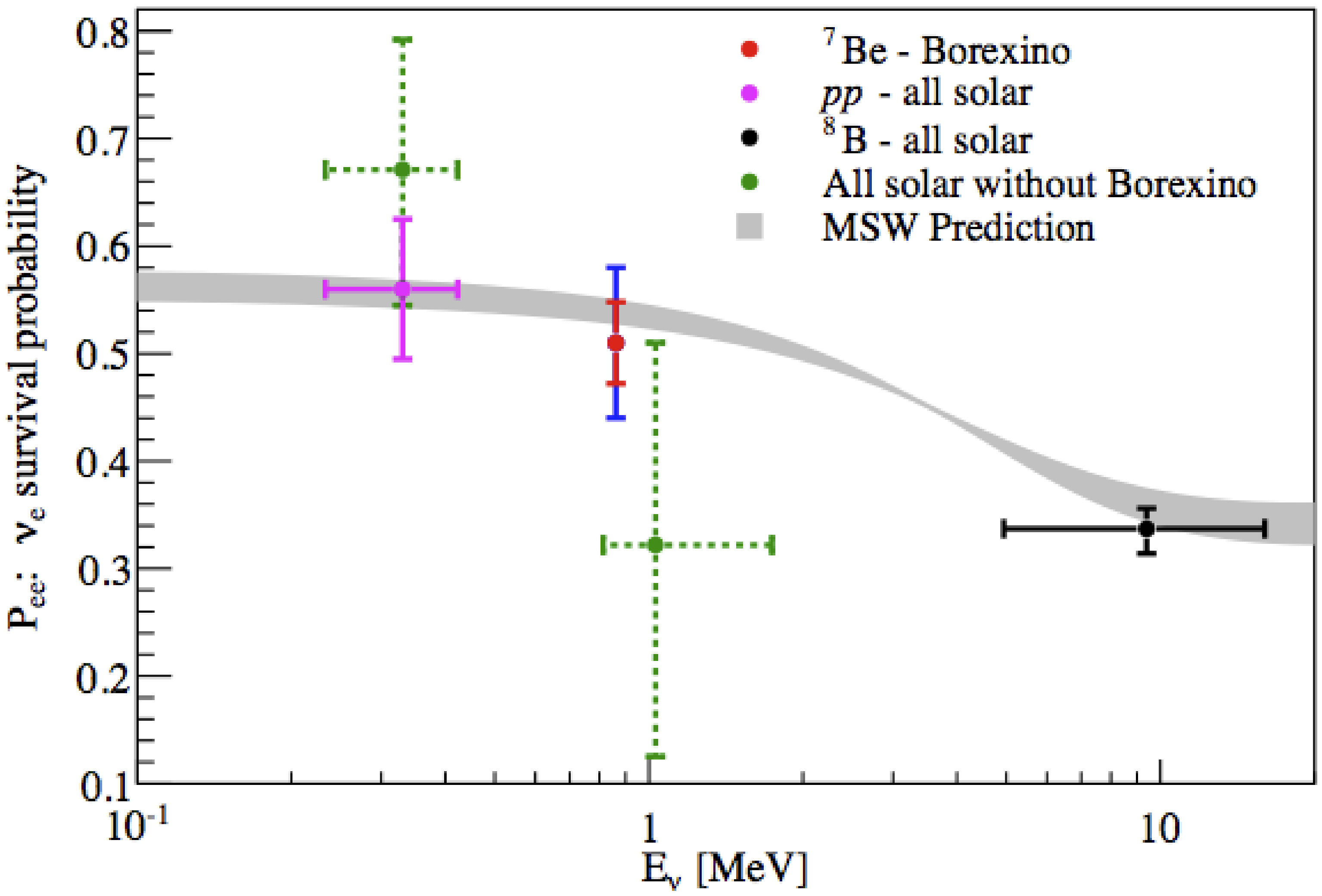
Day/Night Asymmetry



arXiv:1104.2150

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

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



+ Global solar analysis
Total fluxes

pp flux:
$(6.06^{+0.02}_{-0.06})\times10^{10}$ $cm^{-2}s^{-1}$

CNO flux:
$<1.3\times10^{9}$ $cm^{-2}s^{-1}$

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

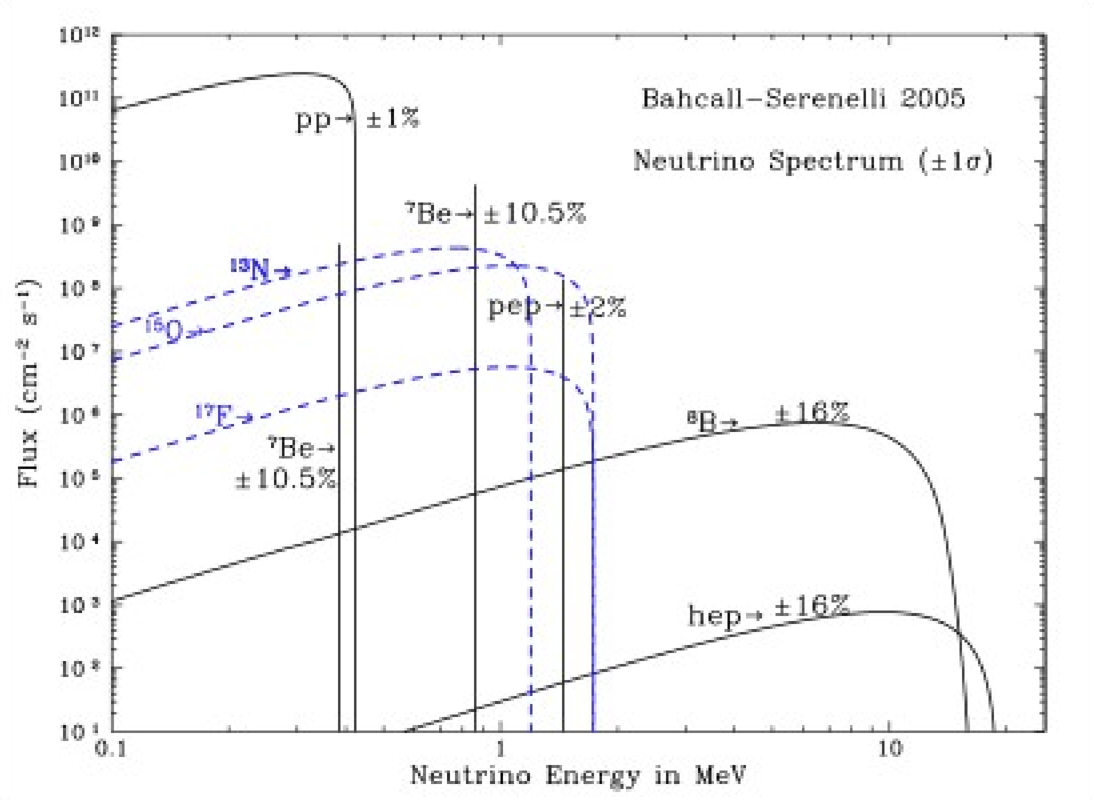
Measured rate uncertainty smaller than flux uncertainty

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

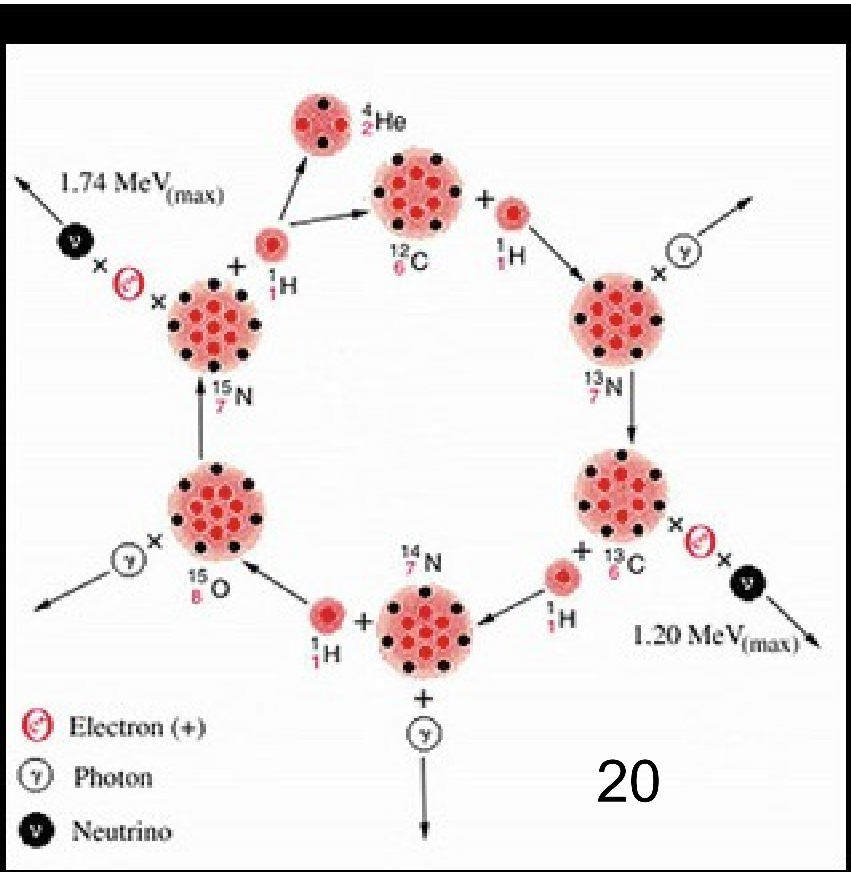
Solar pep and CNO νs



<u>pep reaction</u>, part of the proton-proton chain, at a rate ~1/400 of pp reaction:

$$p + e^- + p \longrightarrow d + \nu \text{ (1.44 MeV)}$$

$$\boxed{\sim 3 \text{ cpd/100 tons}}$$



<u>CNO cycle</u>, alternate energy production mechanism in the Sun

ν from ^{13}N (E_{max} = 1.20 MeV)

ν from ^{15}O (E_{max} = 1.74 MeV)

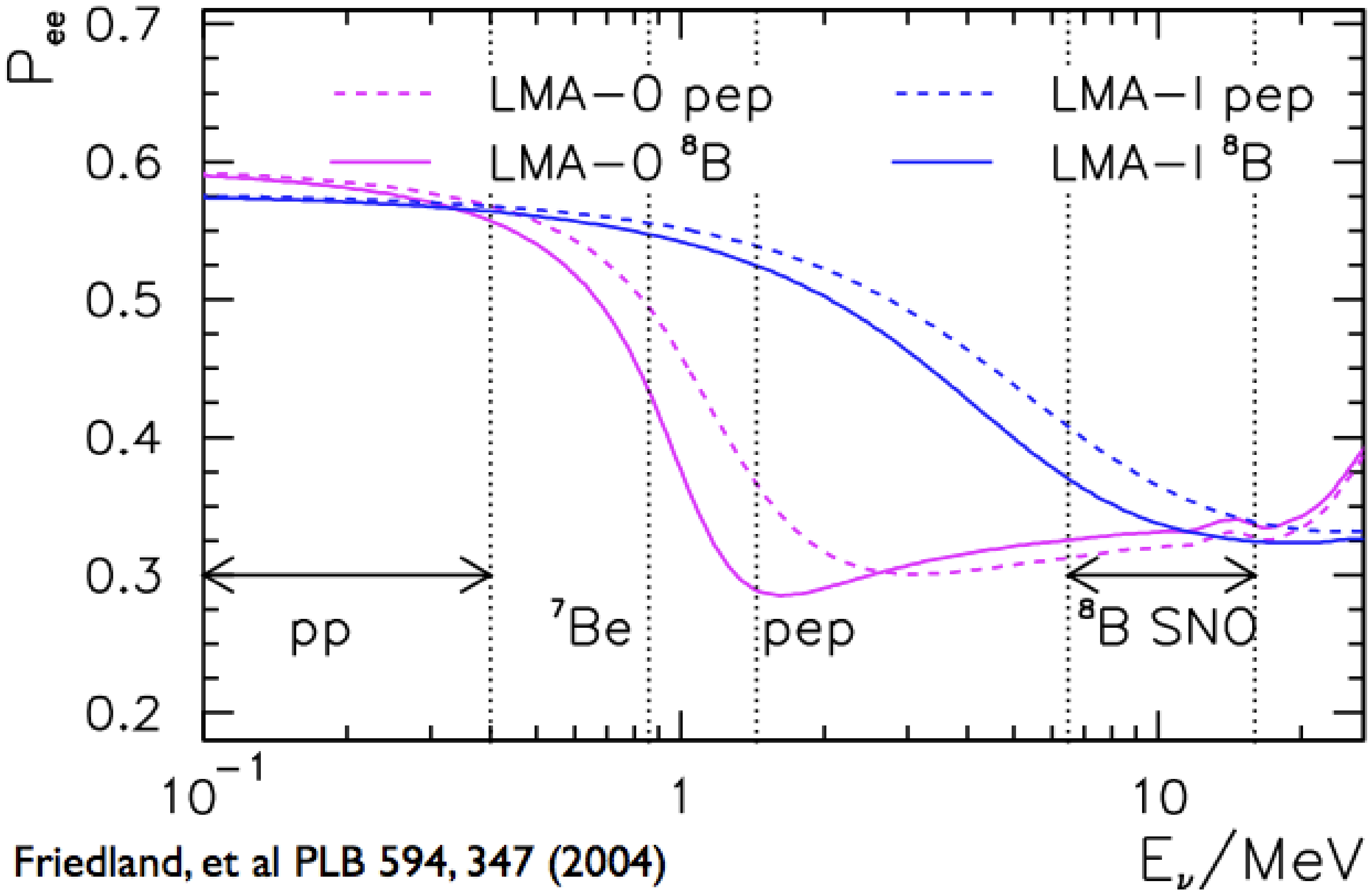
$$\boxed{\sim 3 - 5 \text{ cpd/100 tons}}$$

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 beyons Standard Model

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



Friedland, et al PLB 594, 347 (2004)

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 cm^{-2} s^{-1})
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
ΔΦ	28%

pep and CNO neutrino measurement in Borexino

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

Cosmogenic ^{11}C

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

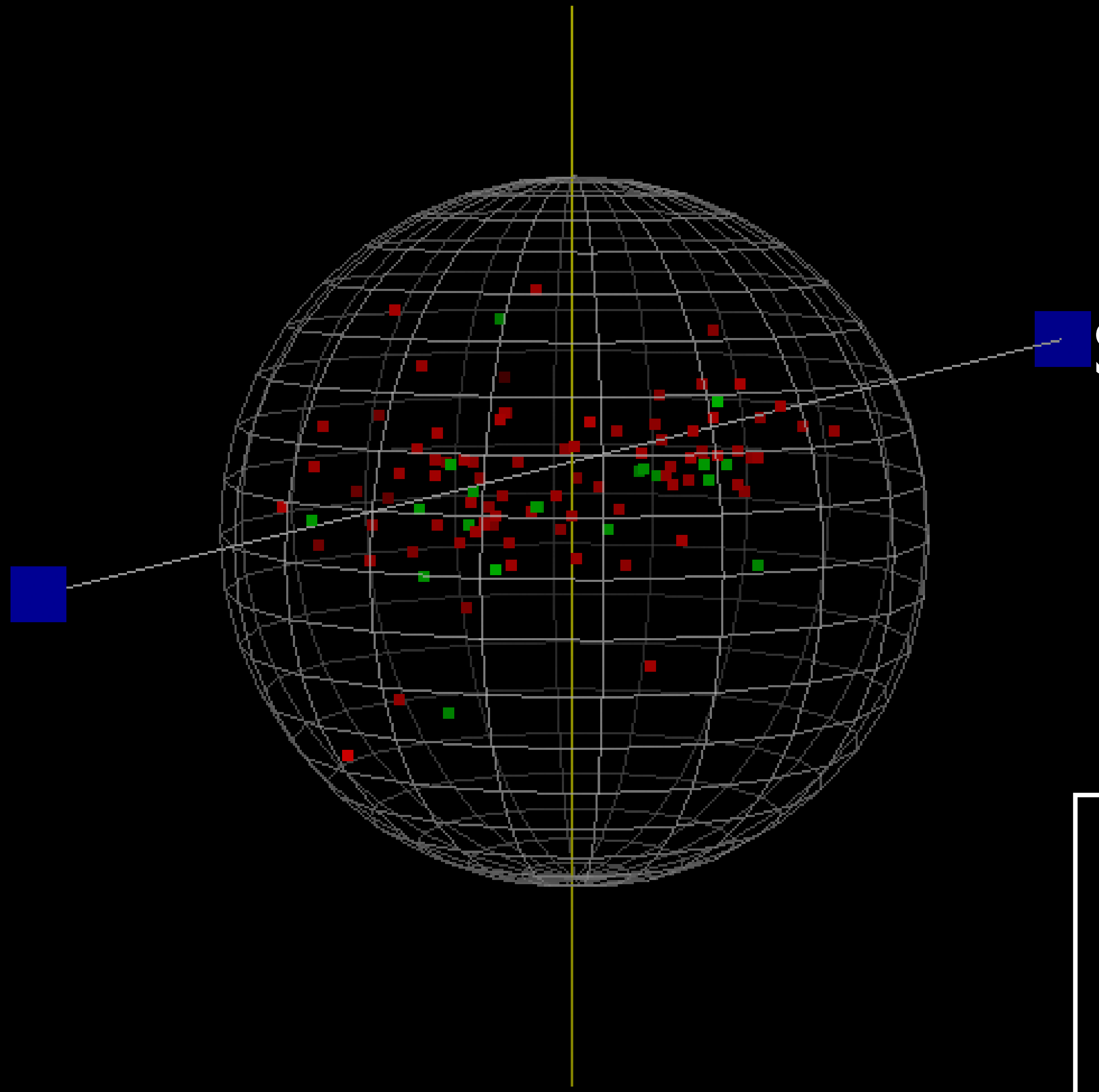
4200 μ/day

Spallation neutron in 95% cases

n captured in scintillator

^{11}C rate 27 cpd/100ton

Lifetime: 29.4 min



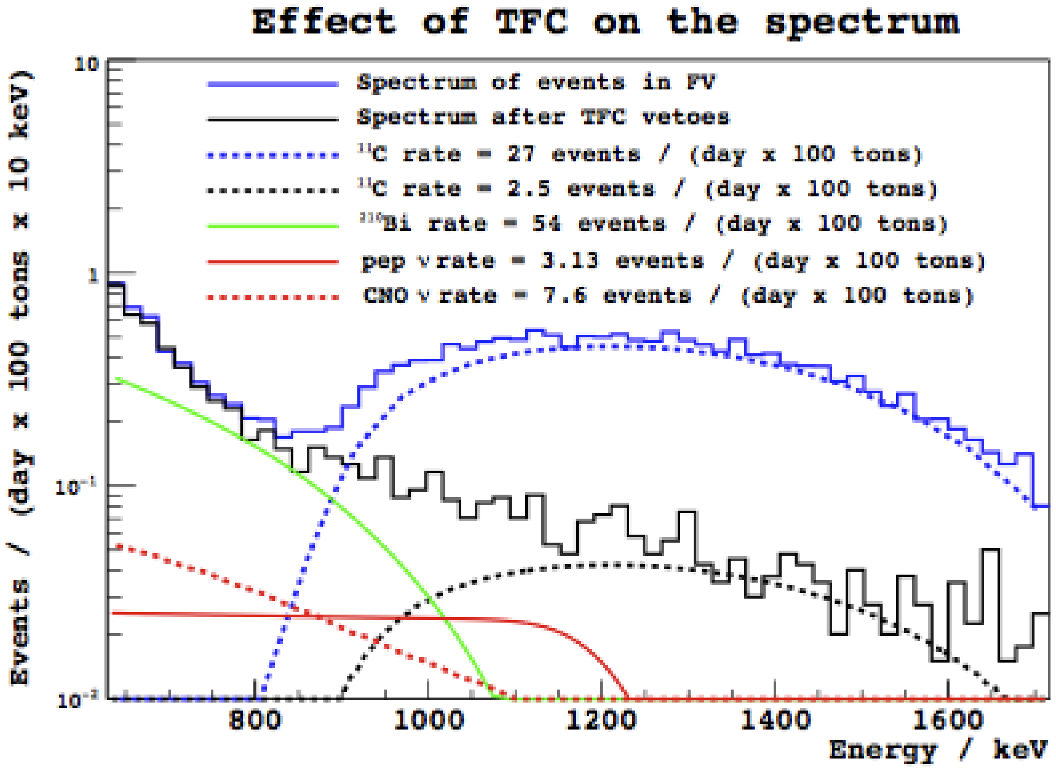
🟦 Reconstructed μ entry/exit points

🟥 Reconstructed position of neutron

🟩 Reconstructed position of ^{11}C

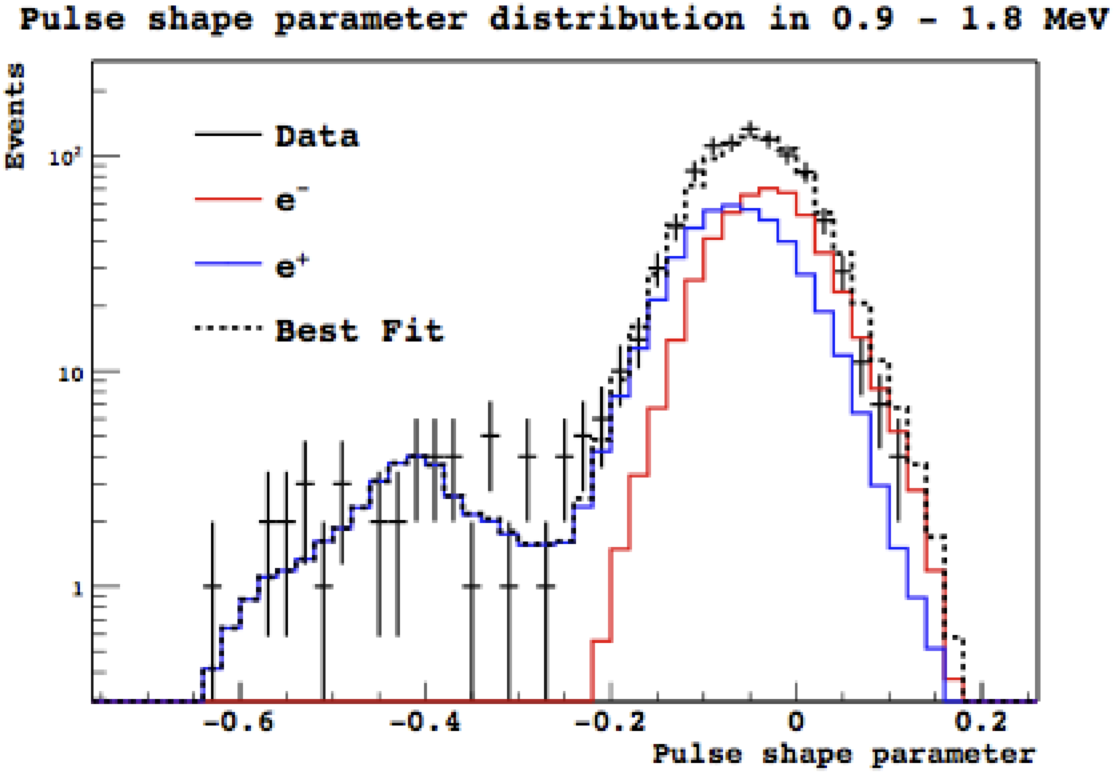
Can use space + time correlation with μ + n to veto regions of the detector with higher ^{11}C background: Three-fold coincidence (TFC) technique

^{11}C suppression in Borexino



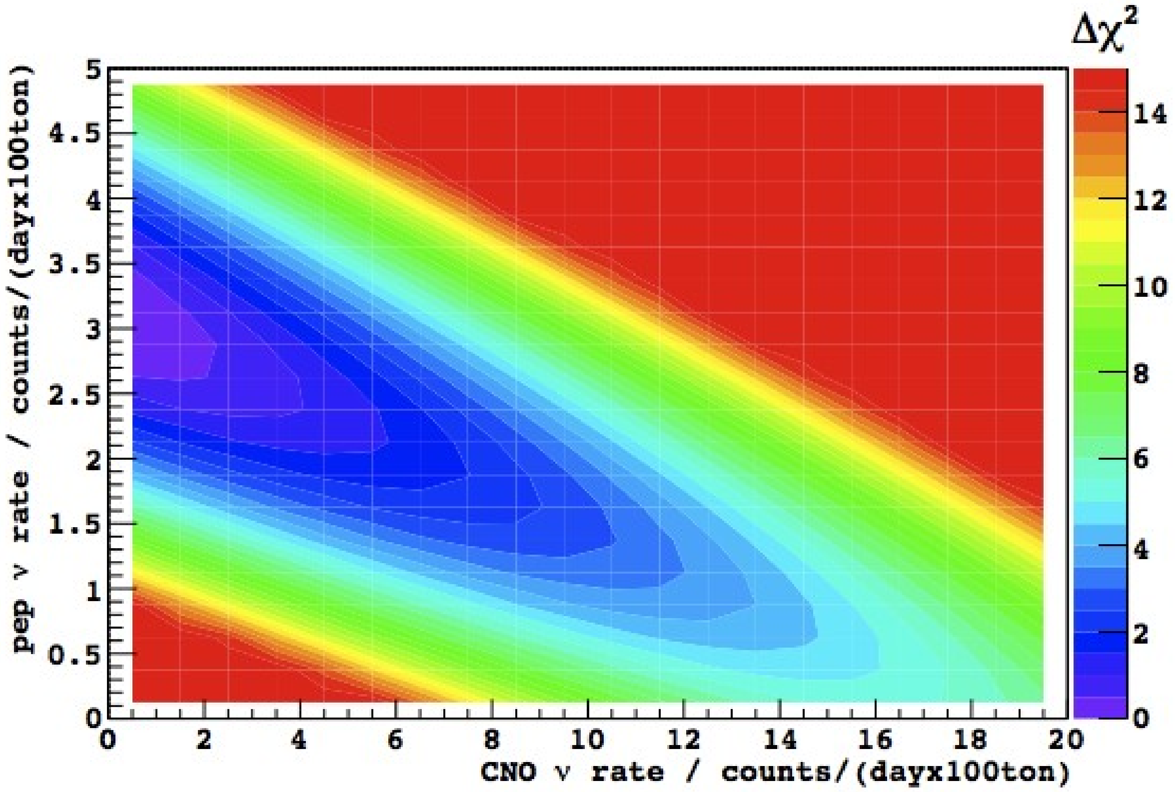
TFC decreases ^{11}C rate to ~10% of its original value with ~50% loss of exposure.

Limiting background is now internal ^{210}Bi.



β-/β+ Pulse Shape discrimination

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

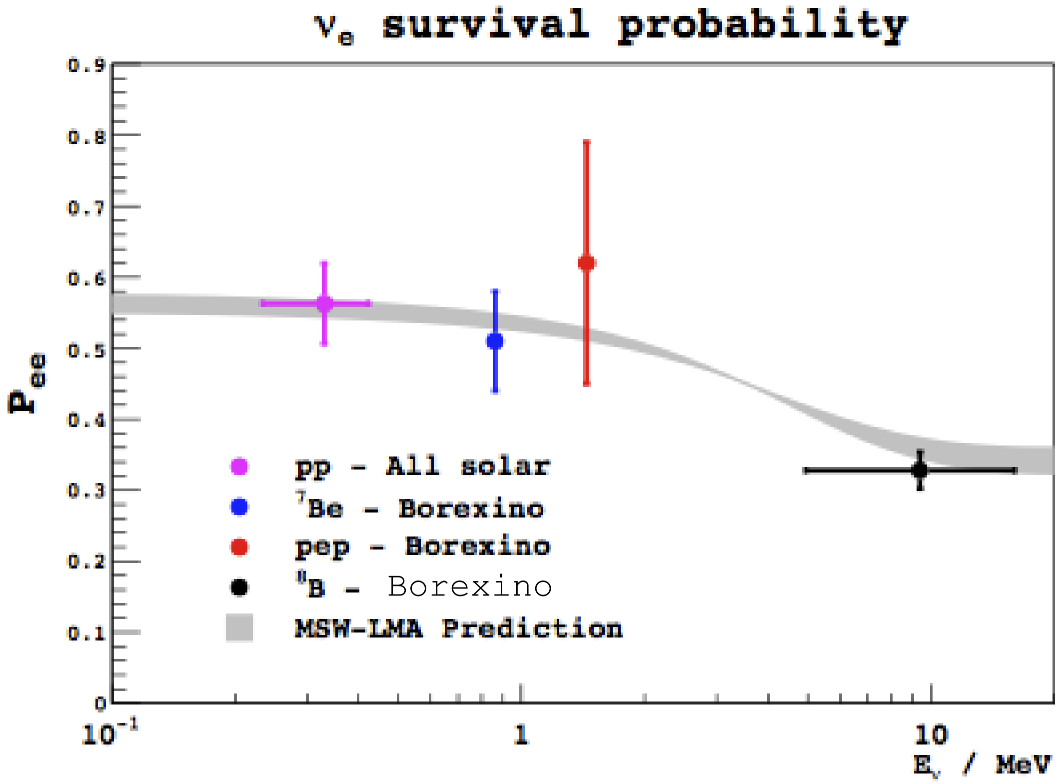


Statistical significance of pep measurement 97% C.L.

Total fluxes from direct measurement

pep flux: $(1.6\pm0.3)\times10^8$ cm^{-2}s^{-1}

CNO flux: $<7.4\times10^8$ cm^{-2}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}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

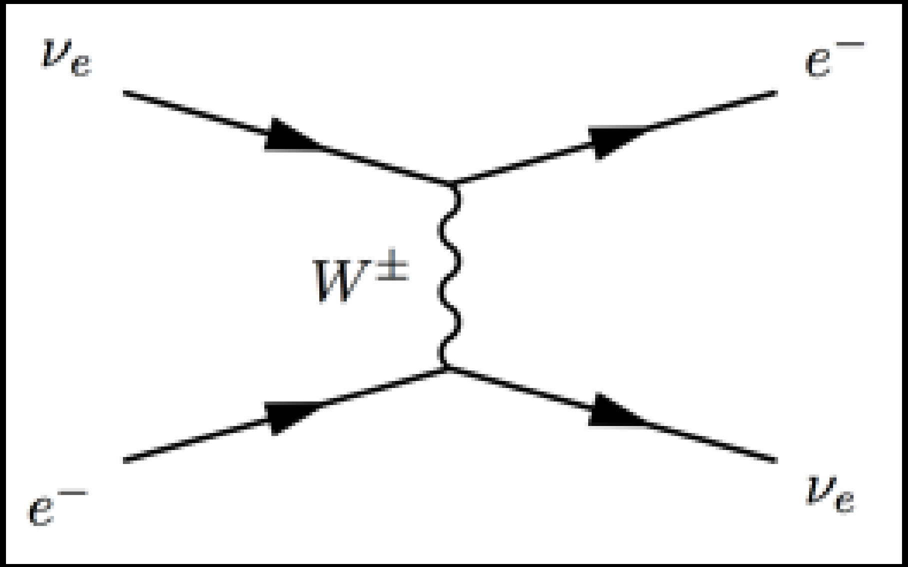
THE END

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)

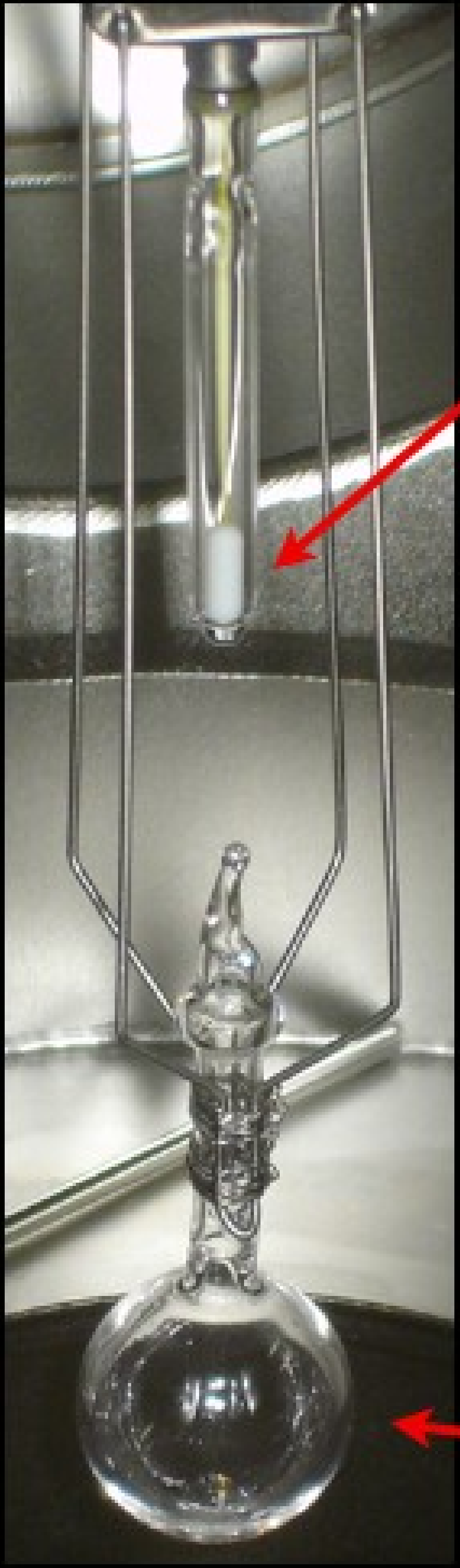


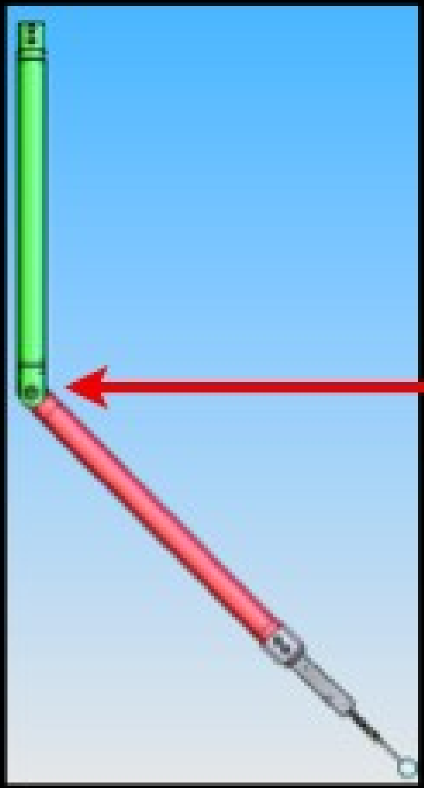
Charged current interaction of electron neutrinos introduces new term to mass matrix:

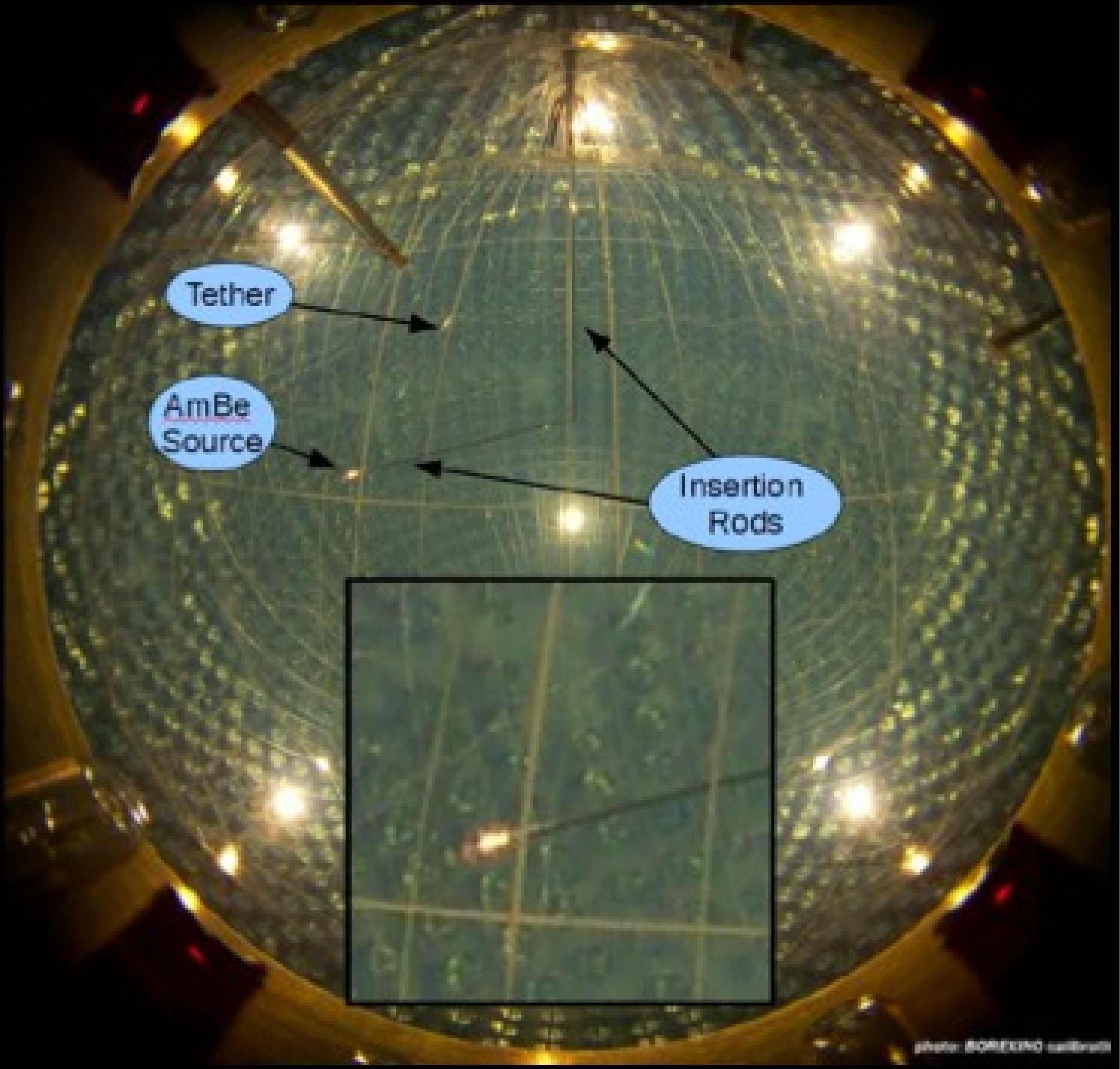
$$\begin{bmatrix} -\frac{\Delta m_{12}^2}{4E}\cos(2\theta_{12}) + \boxed{\sqrt{2}\mathrm{G}_F\mathrm{N}_e} & \frac{\Delta m_{12}^2}{4E}\sin(2\theta_{12}) \\ \frac{\Delta m_{12}^2}{4E}\sin(2\theta_{12}) & \frac{\Delta m_{12}^2}{4E}\cos(2\theta_{12}) \end{bmatrix}$$

Detector Calibration

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







Steve Hardy (Thesis)

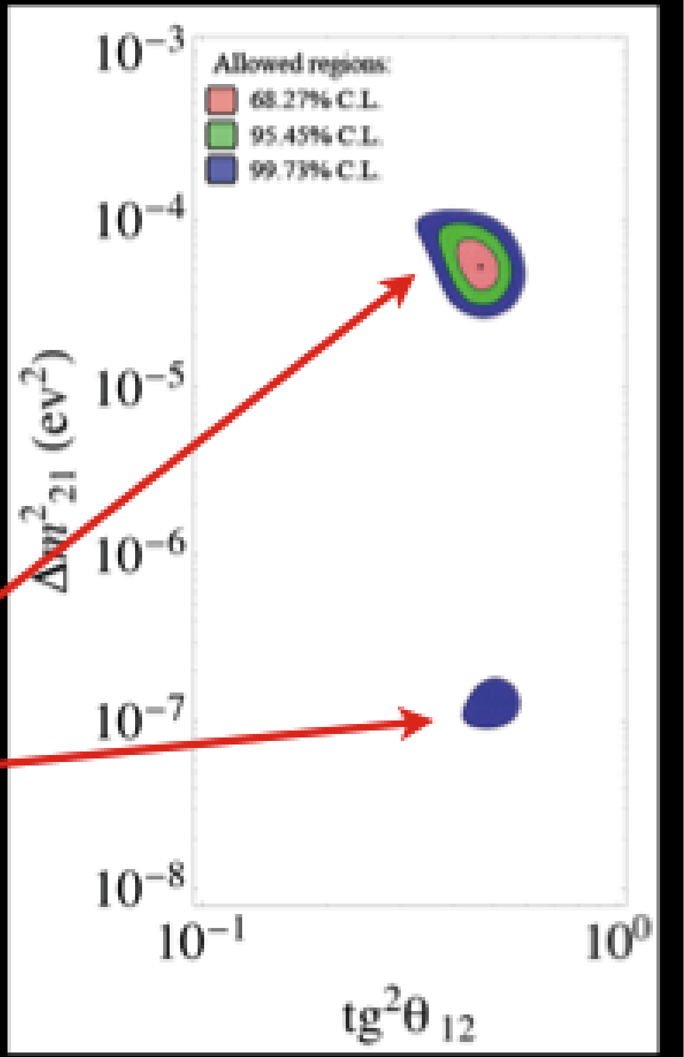
Day-Night Asymmetry

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

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

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

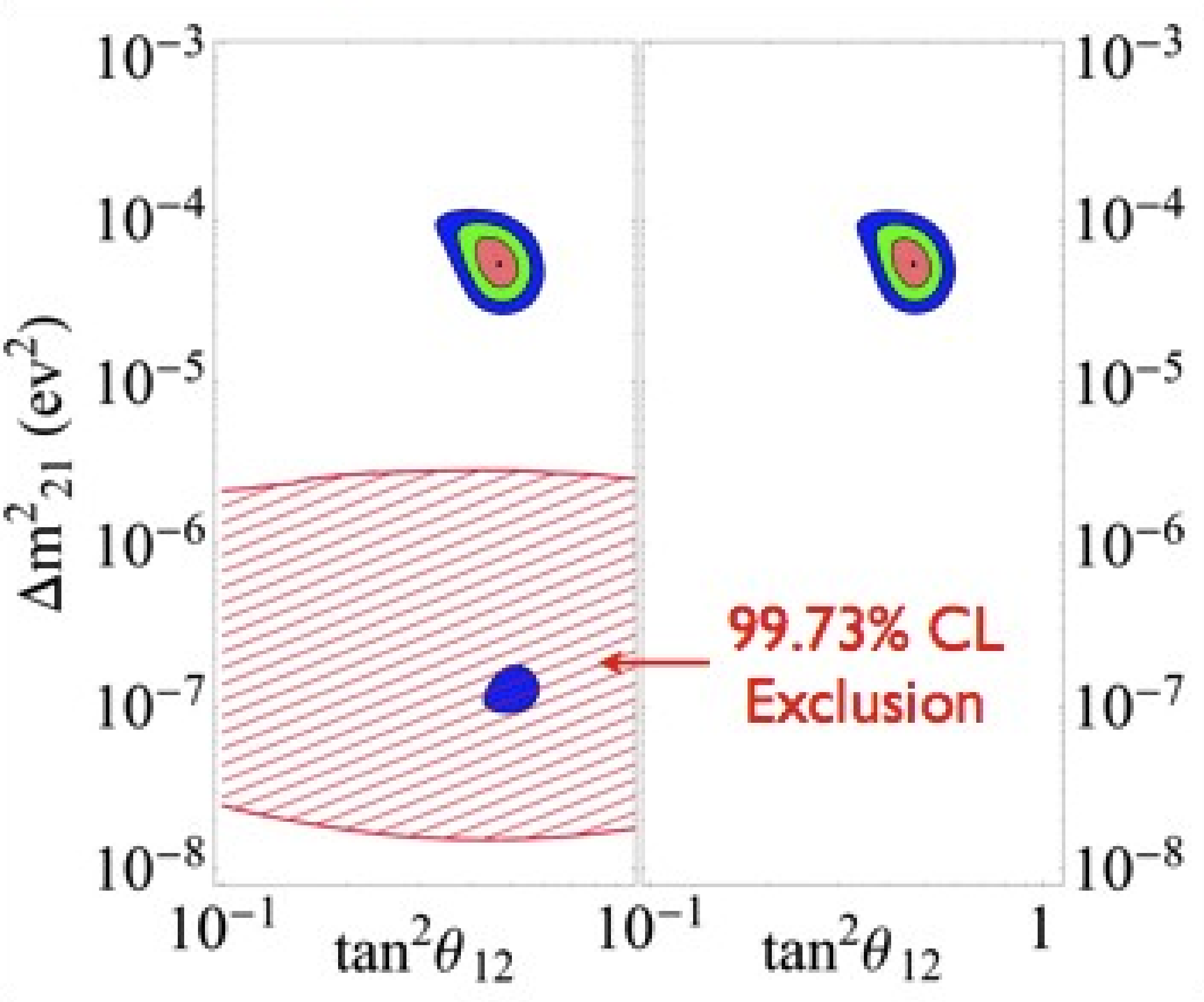

Global Solar - Borexino

Implications

Day-Night Asymmetry

A_{dn} = 0.001 +/- 0.012(stat) +/- 0.007(sys)

Rules out LOW solution at > 8σ



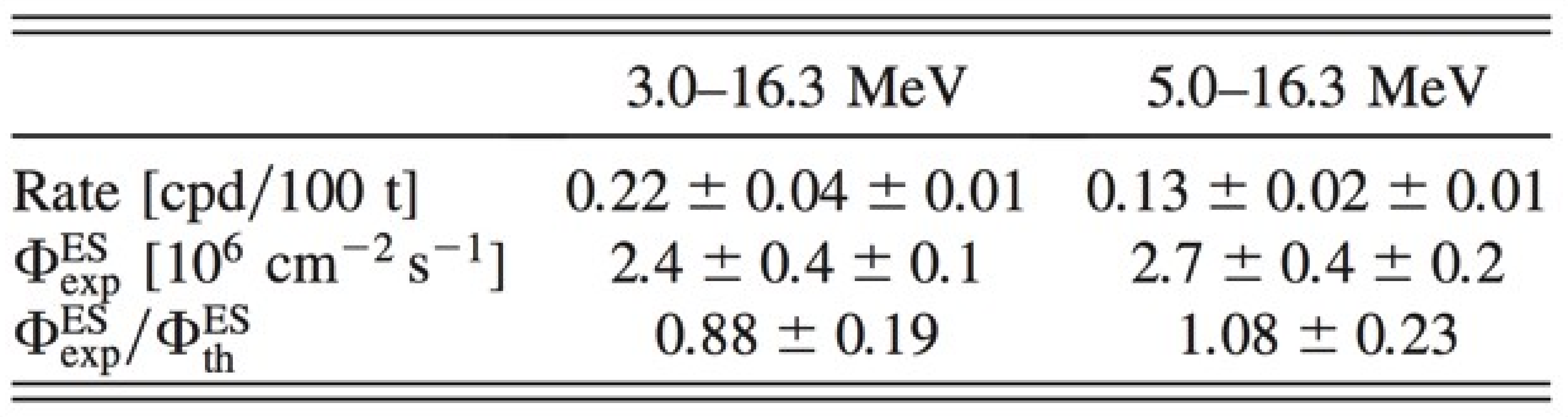
99.73% CL
Exclusion

Global Best Fit (All Solar Data)
$\Delta m^2 = 5.3 \times 10^{-5}$ eV^2
$\tan^2\theta_{12} = 0.46$

^{8}B Measurement

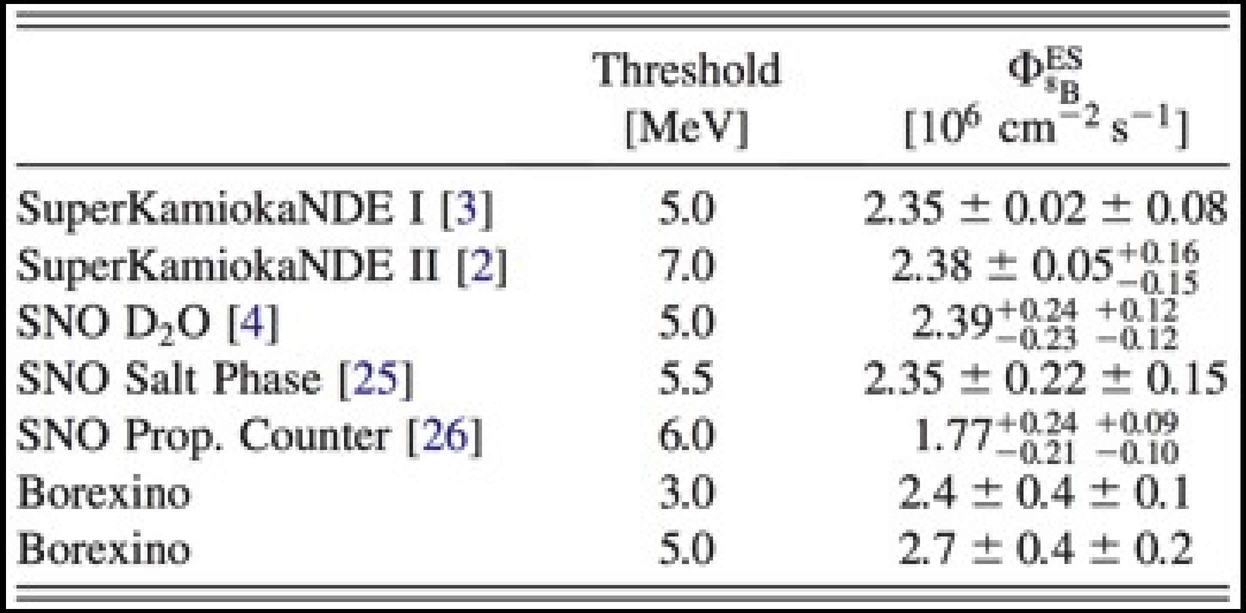
Physical Review D 82, 03306 (2010)

Final Result:

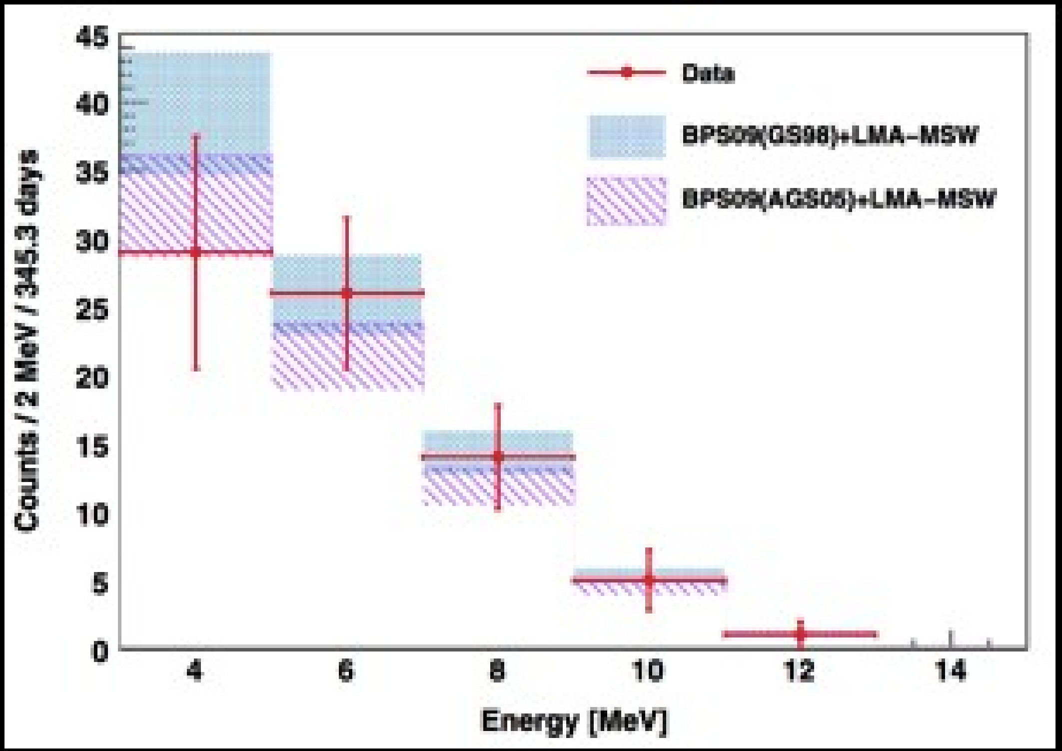


	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	$0.22 \pm 0.04 \pm 0.01$	$0.13 \pm 0.02 \pm 0.01$
Φ^{ES}_{exp} [10^6 cm^{-2} s^{-1}]	$2.4 \pm 0.4 \pm 0.1$	$2.7 \pm 0.4 \pm 0.2$
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88 ± 0.19	1.08 ± 0.23

Result consistent with other experiments / SSM predictions



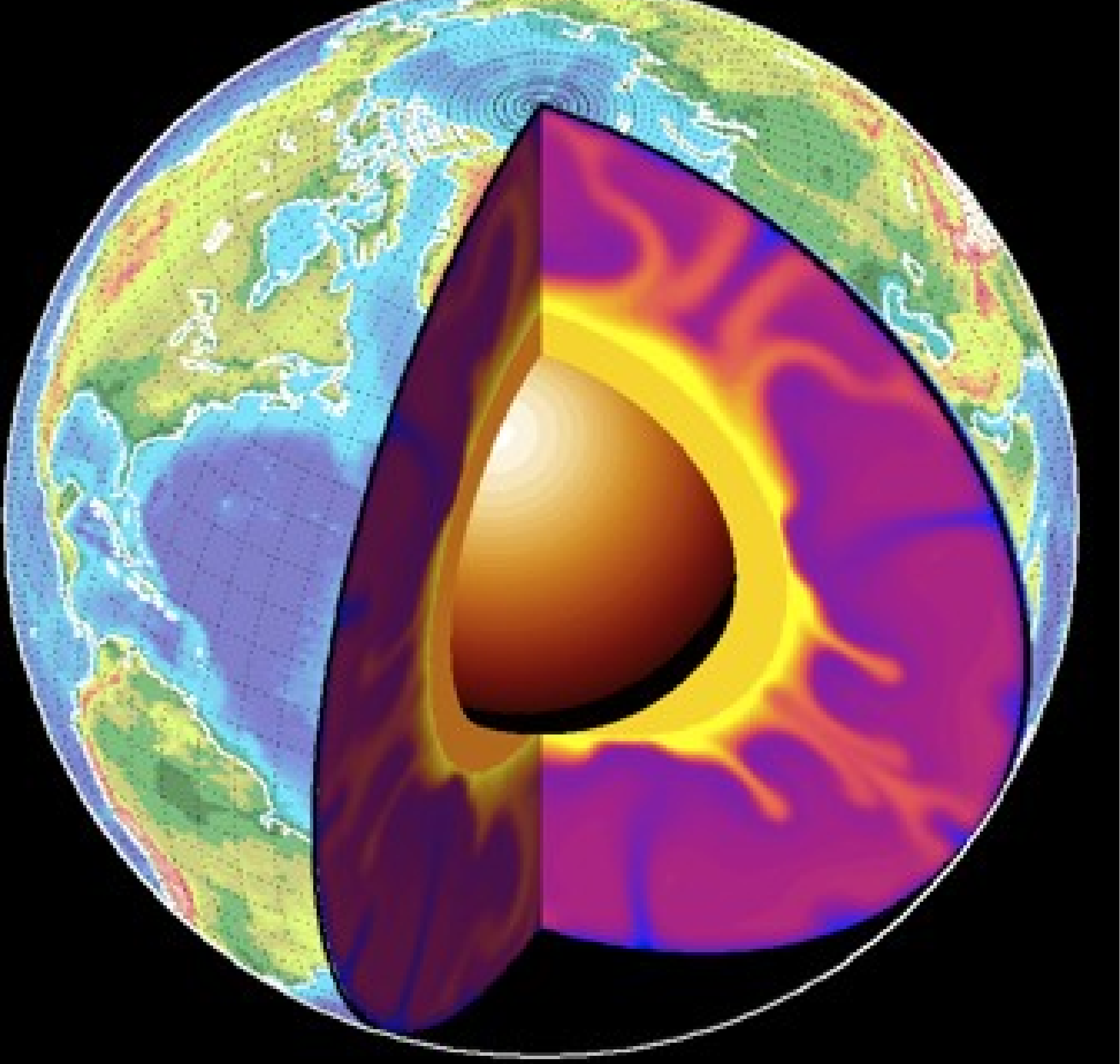
	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [3]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [4]	5.0	$2.39^{+0.24}_{-0.23}\ ^{+0.12}_{-0.12}$
SNO Salt Phase [25]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [26]	6.0	$1.77^{+0.24}_{-0.21}\ ^{+0.09}_{-0.10}$
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)?

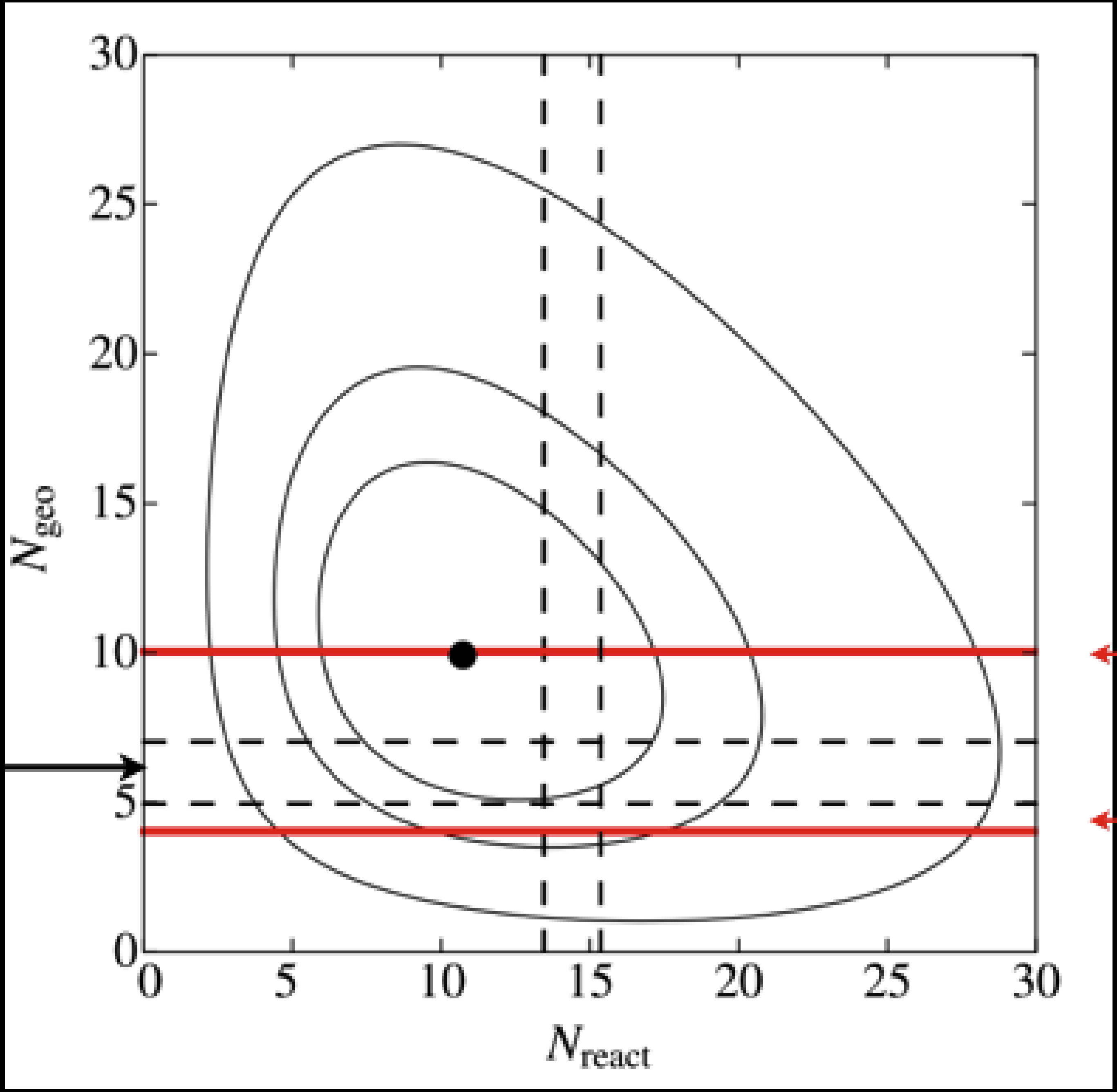
How much U/Th is there in the mantle / crust ?

Geo-Neutrinos provide valuable information about the composition of the Earths interior

Geo-Neutrinos

Physical Letters B 687 (2010) 299-304

First detection of geo-neutrinos at >3σ C.L.



Max. Radiogenic

BSE Predicted Range

Min. Radiogenic