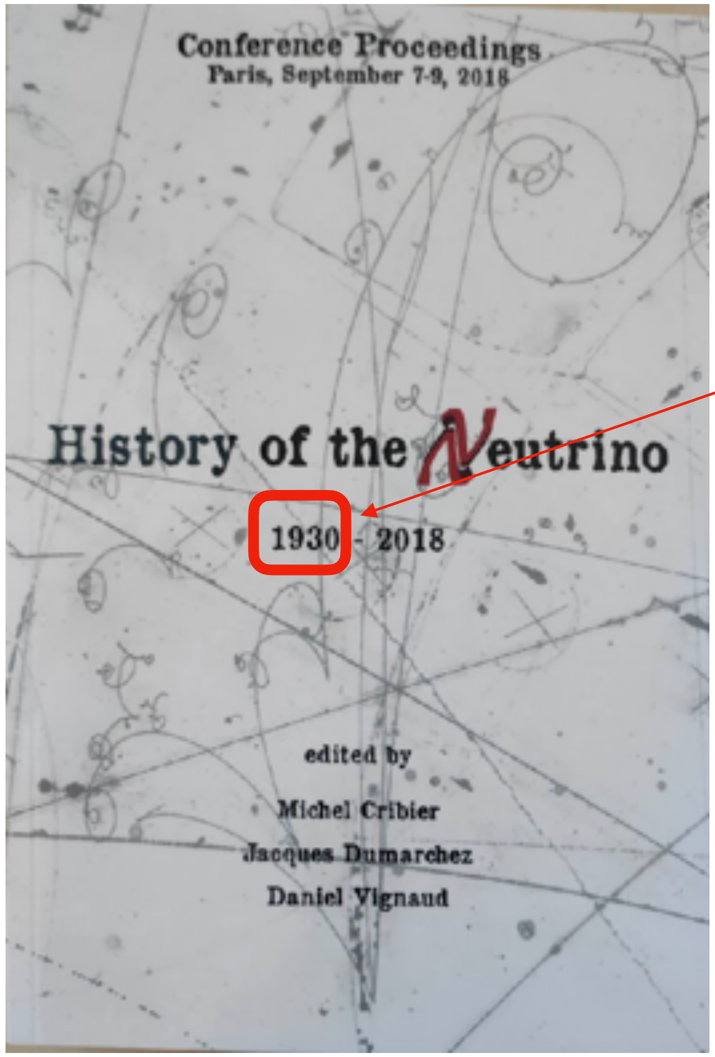
Solar Neutrinos

Davide Franco, APC

A short recap

1914 James Chadwick and others showed experimentally that electron spectrum from ^{210}Bi beta decay is continuous and not mono energetic like with alphas and gammas. Energy-momentum not conserved in beta-decays?



1928 new problem related to the integer spin (= 1) measured for the nitrogen nucleus but 14 protons + 7 electrons corresponds to an odd number of fermions.

1930 Pauli proposed the existence of an unknown neutral particle of spin 1/2 within the nucleus, which he called neutron:

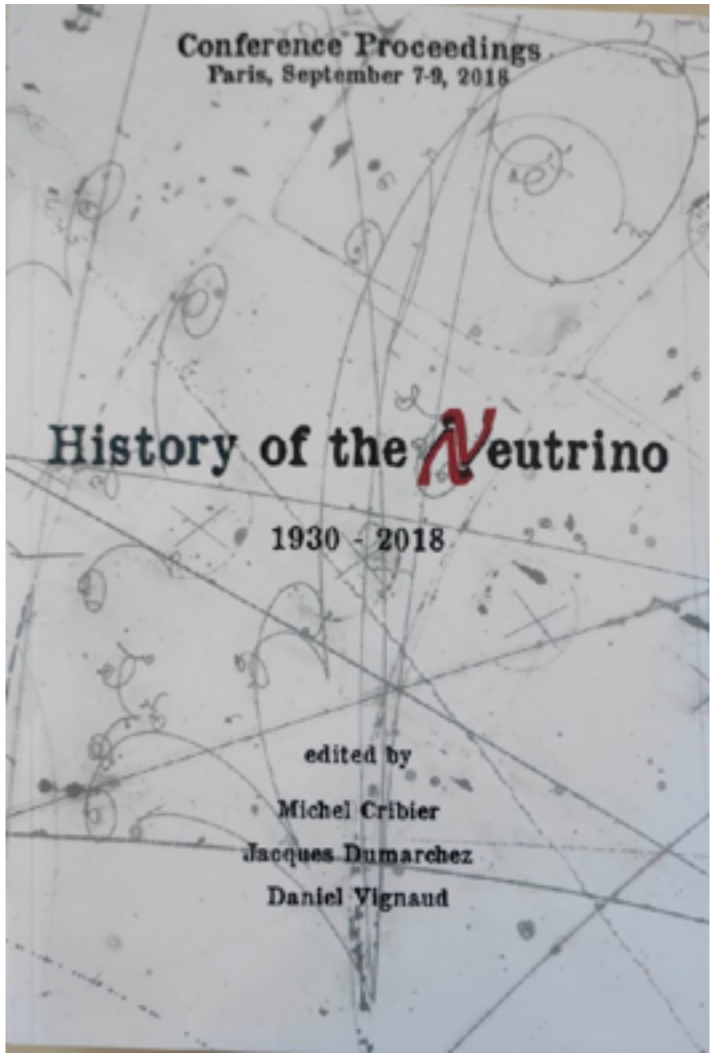
- (7 protons + 7 "neutrons") x 1/2 = possible integer
- "neutron" is emitted together with electron in the beta decays = continuous spectrum

1932 Chadwick observes experimentally the true neutron, much more massive than the electron (Nobel Prize 1935)

1933 Fermi proposes a theory of the beta decay and he calls neutrino the Pauli particle

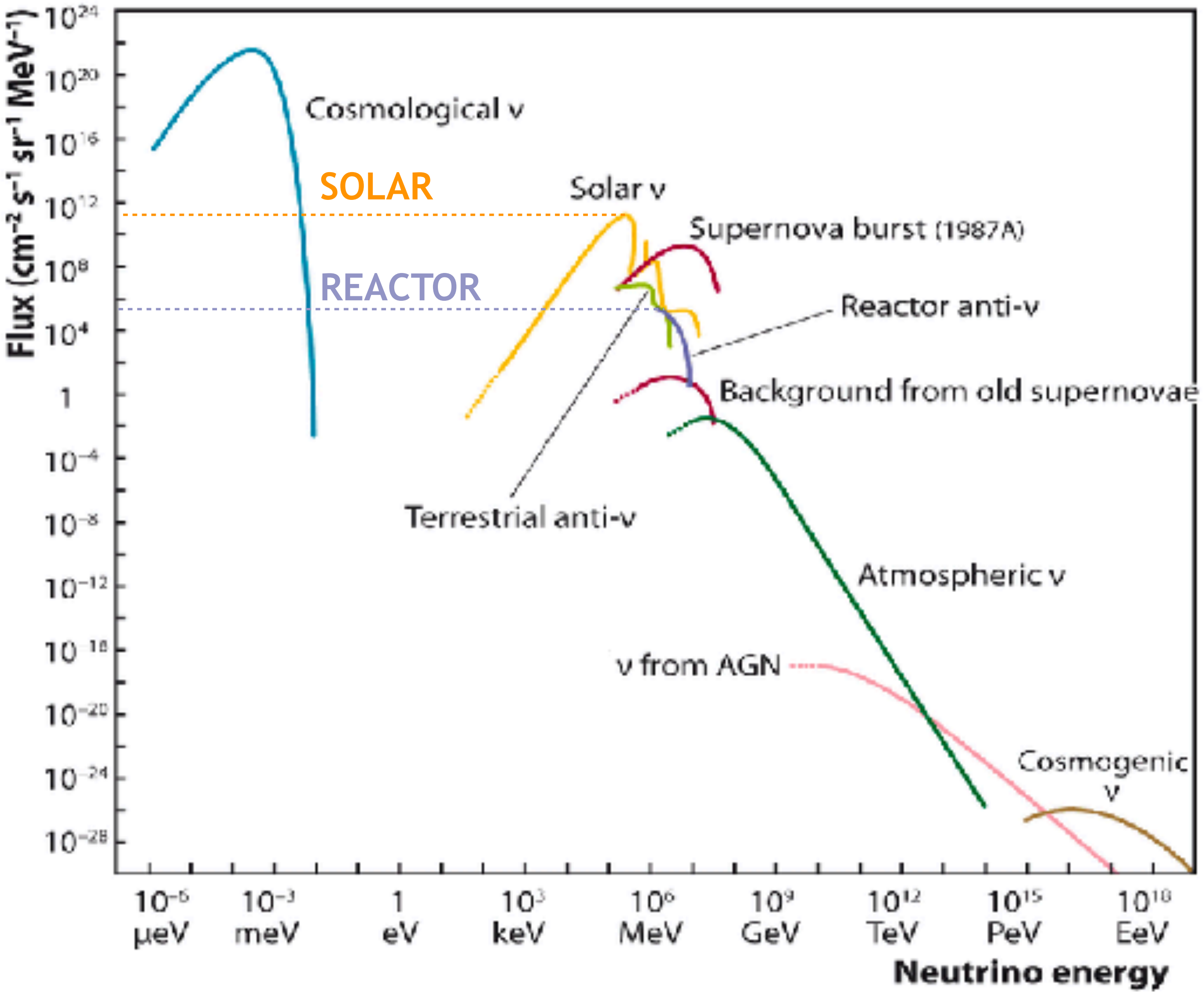
1934 Hans Bethe and Rudolf Peierls calculated the cross-section for the inverse reaction in which a neutrino is absorbed, but when they found a value of about 10^{-44} cm^2. **They concluded that no one would be able to detect neutrinos**

Reactor and Solar Neutrinos



First detection with reactor neutrinos by Cowan and Reines in 1956

First deficit observed with solar neutrinos with the Ray Davis' experiment in the late 1960s



B. Pontecorvo, Inverse beta processes Chalk River Report, Pd-205,1946

Pontecorvo proposes to detect neutrinos via inverse beta decay with a radiochemical approach

For completeness, we will mention also some inverse β processes produced by other particles than a neutrino; an inverse β process, more generally, can be defined as the transformation of a neutron into a proton, or vice versa, produced artificially by bombardment with neutrinos, electrons, or γ-rays. These processes are:

(b) Absorption of a neutrino with emission of a β particle

$$\nu + Z \rightarrow \beta^- + (Z+1) \qquad \nu + Z \rightarrow \beta^+ + (Z-1).$$

Pontecorvo considered the following reaction

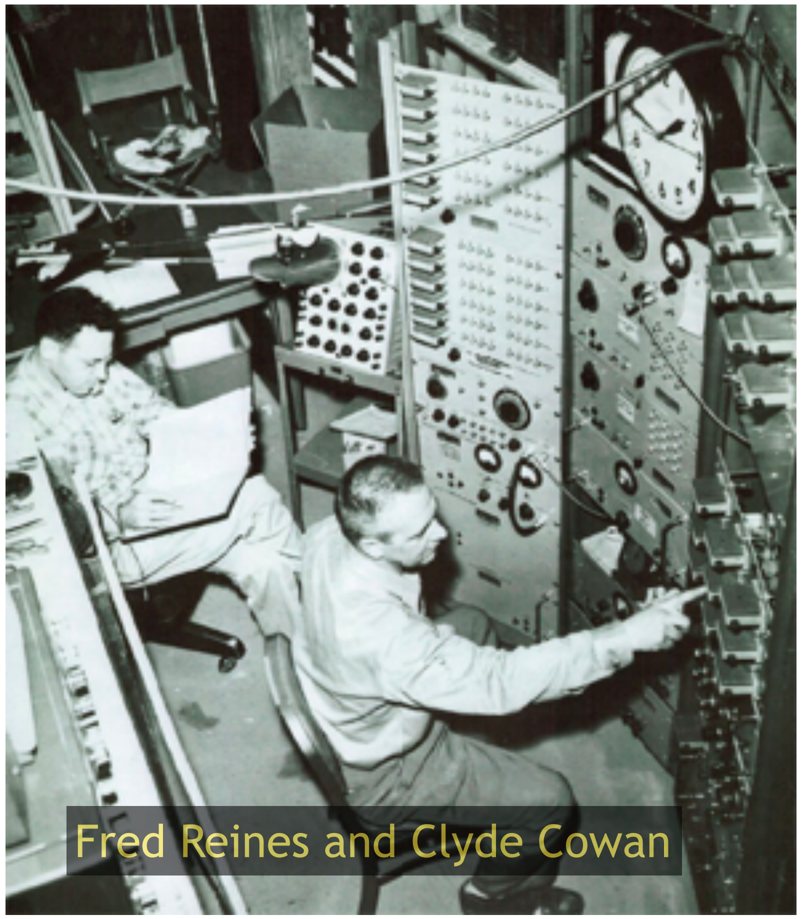
$$\nu + {}^{37}\mathrm{Cl} \longrightarrow e^- + {}^{37}\mathrm{Ar}$$

(i) C_2Cl_4 is a cheap, nonflammable liquid.

(ii) ^{37}Ar nuclei are unstable (K-capture) with a half-life of 34.8 days

(iii) A few atoms of ^{37}Ar (rare gas), produced during the exposition time, can be extracted from a large detector with high efficiency

1956 - Cowan and Reines



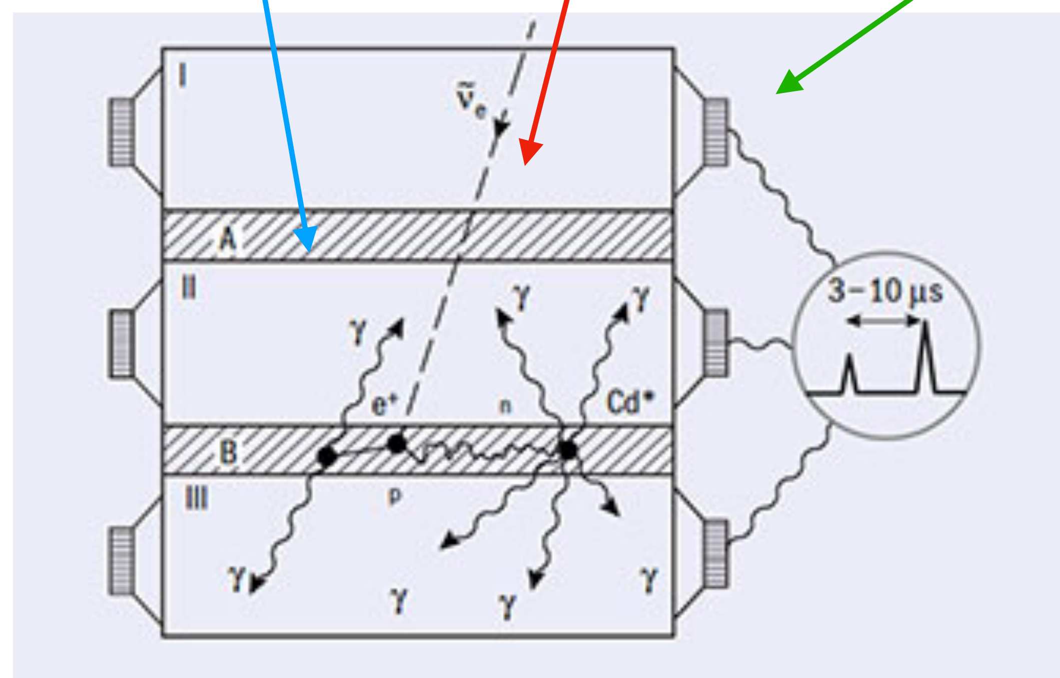
Fred Reines and Clyde Cowan

The first neutrino detection exploiting a **reactor** at the Savannah River Plant (South Carolina)

200 litre-tank of water doped with cadmium

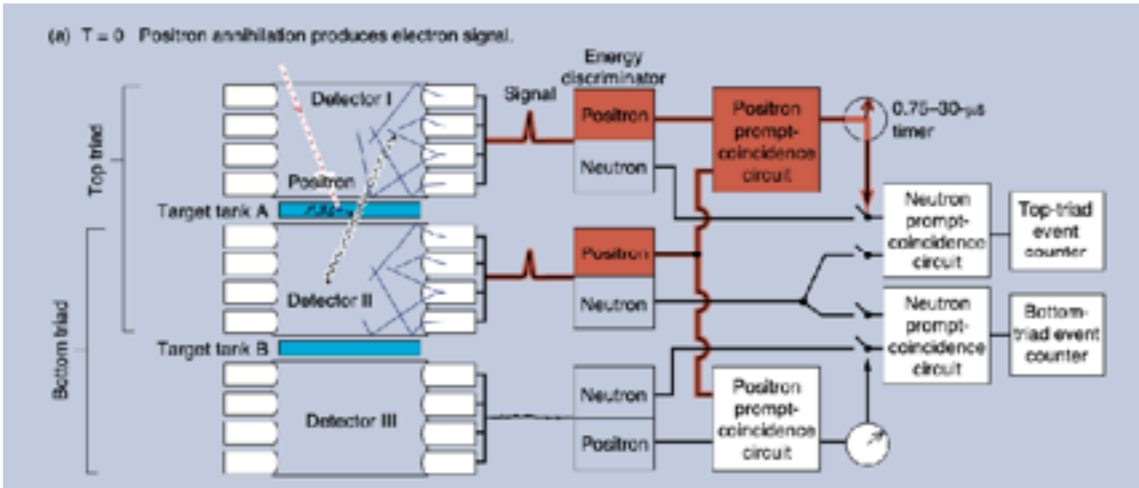
1400-litre tank of liquid scintillator

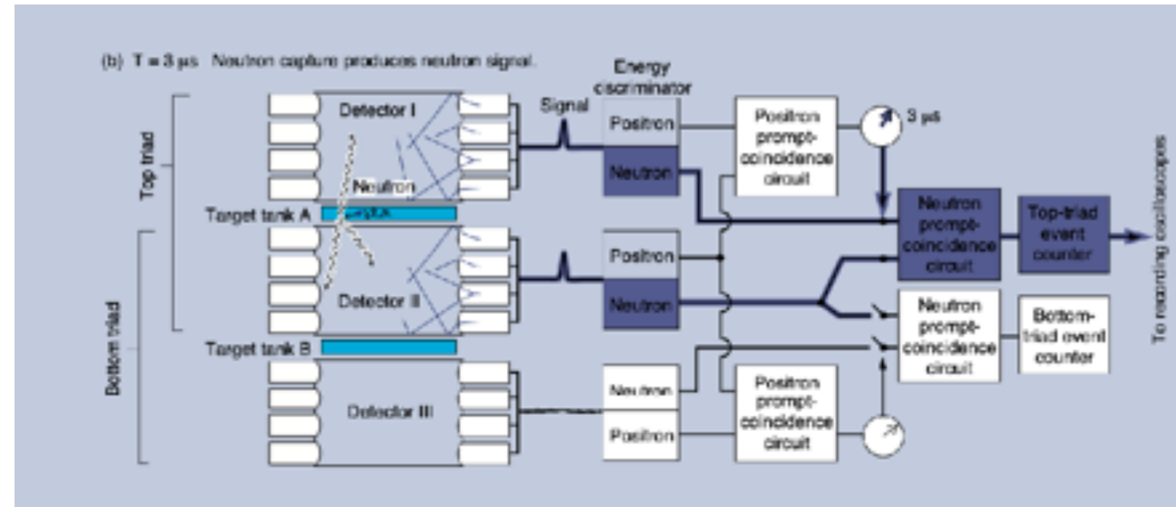
100 phototubes

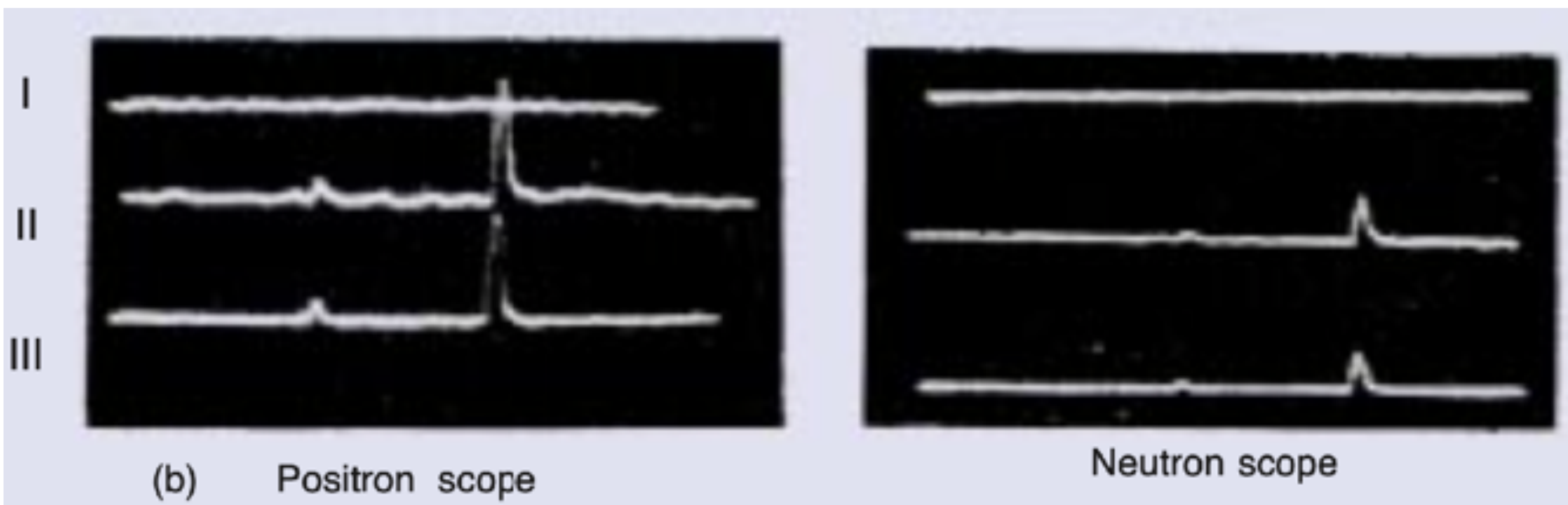


11 m from the reactor and 12 m underground

average rate of 3 neutrino events per hour



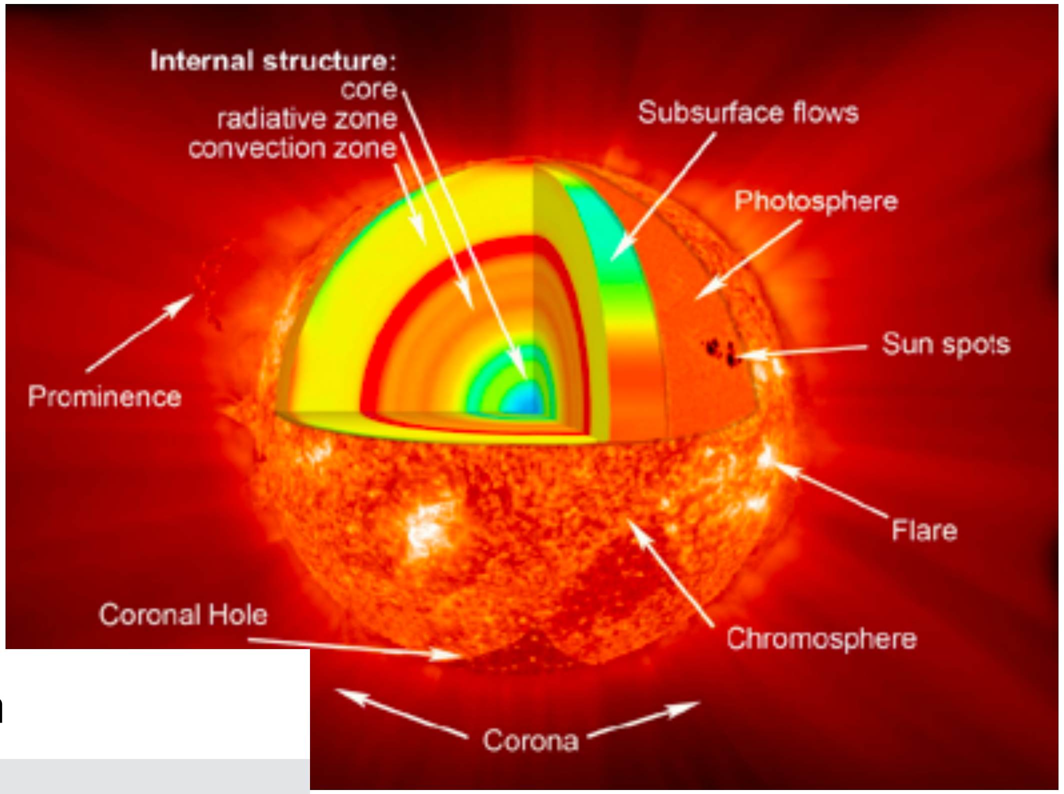




On June 14, 1956, Reines and Cowan sent a telegram to Pauli at CERN: “We are happy to inform you that we have definitely detect neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected 6x10^{-44} cm^2”.

The theoretically predicted cross section for inverse beta decay on protons is 6.3x10^{-44} cm^2 with an uncertainty of about 25 percent arising from the uncertainty of the energy spectrum for the reactor neutrinos.

The Sun



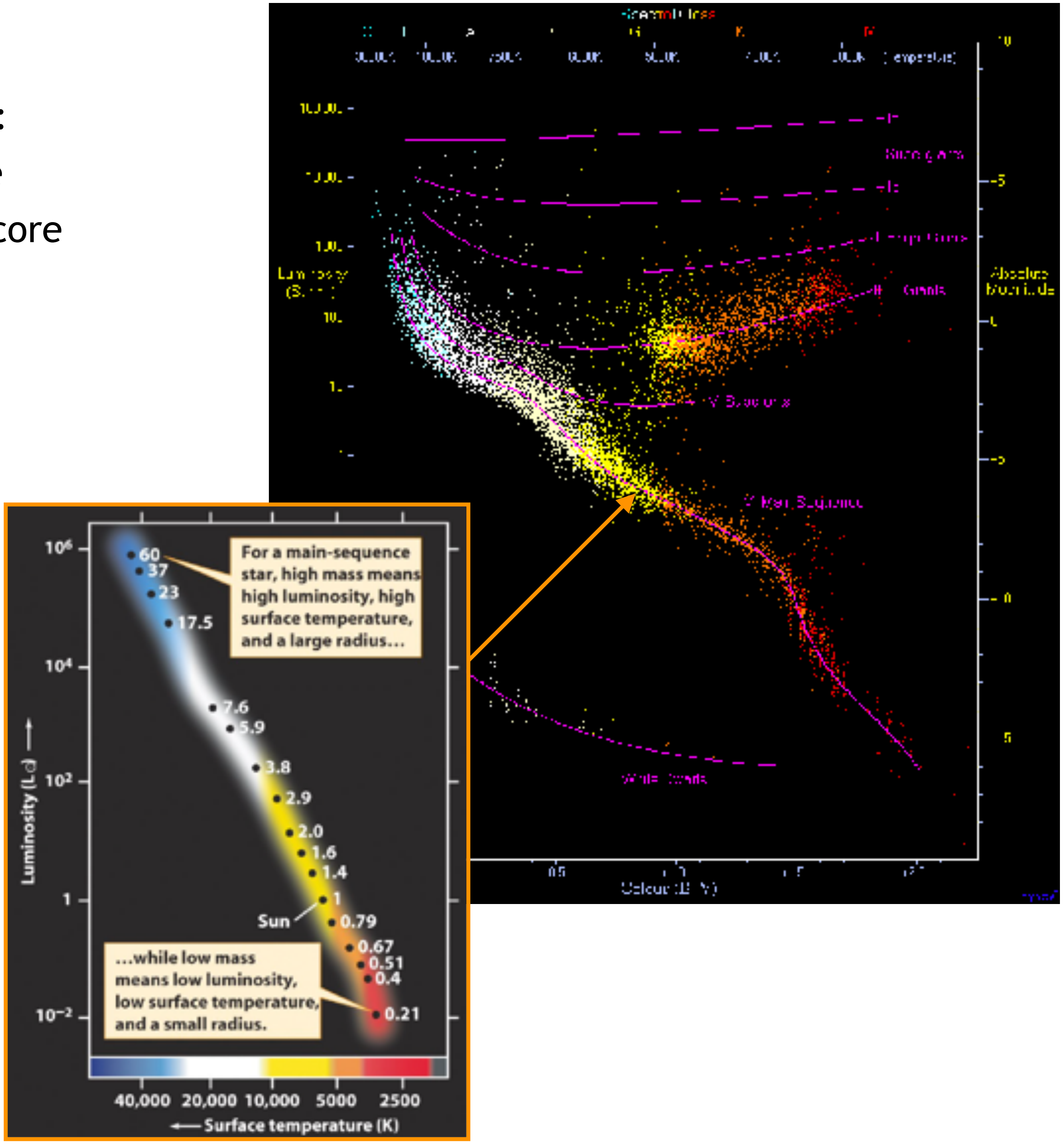
Distance from the Earth	~150,000,000 km
Light travel time to the Earth	~8 min
Radius	696,000 km
Mass	~2 x 10^{30} kg
Composition by mass	74% H, 25% He, 1% others
Composition by # of atoms	92.1% H, 7.8% He, 0.1% others
Mean density	1.4 g / cm^3 (150 g / cm^3 in the core)
Mean temperature	Surface: 5,800 K, Center: $1.55x10^7$ K
Luminosity	$3.86x10^{26}$ W

The Sun

The Sun is an average "**main sequence**" star:

- same chemical composition: 75% H, 25% He
- fuelled by thermonuclear reactions in the core
- lies in the Hertzsprung-Russell diagram

$$L = 4\pi R^2 \sigma T^4$$

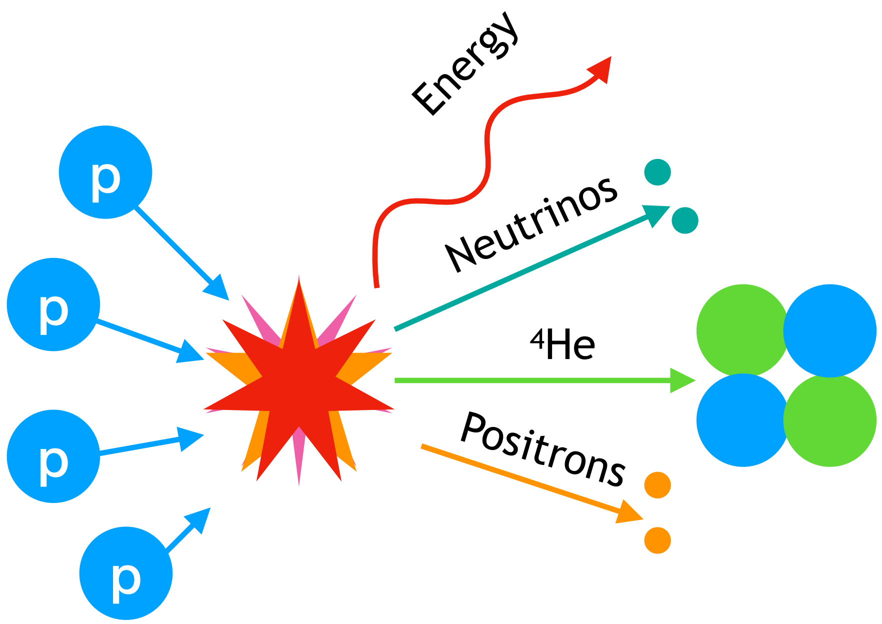


Kelvin-Helmholtz contraction and chemical reactions **do not produce enough energy** to maintain solar brightness for billions of years

Energy is generated by **thermonuclear reactions in its core**, where temperature, density and pressure are tremendously high to push light atoms to fuse into heavy ones, e.g., hydrogen fusion.

The energy production in the Sun

$$\Delta m = 4m_H - m_{He}$$
$$= 4 \times 1.67353 \times 10^{-27}\,kg - 6.64648 \times 10^{-27}\,kg$$
$$= 4.76578 \times 10^{-29}\,kg = 0.7\%(4m_H)$$



$$E = \Delta mc^2 = 4.29 \times 10^{-12}\,J \sim 26.8\,MeV$$

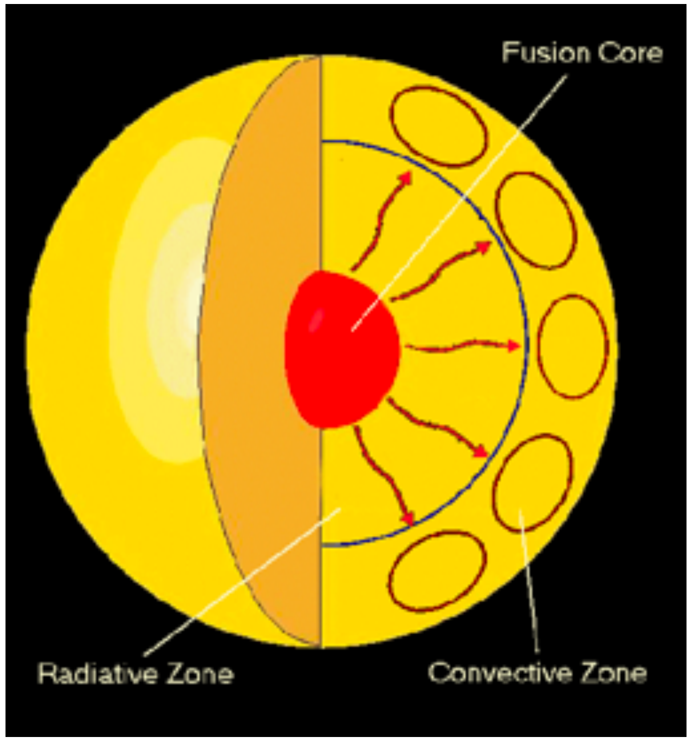
Net energy input:
nuclear fusion energy

Net energy output:
radiation

The energy release by **1g of hydrogen** through fusion is

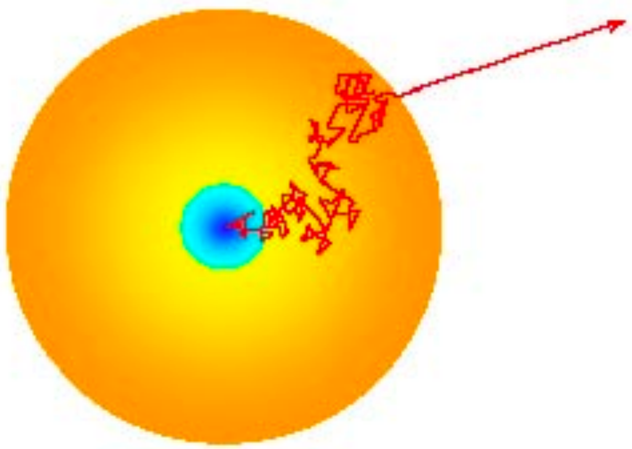
$$E = 4.29 \times 10^{-12}\,J \times 1g/(4 \times 1.67353 \times 10^{-27}) = 6.39 \times 10^{11}\,J \sim 4 \times 10^{27}\,MeV$$

Equilibrium and energy transfer



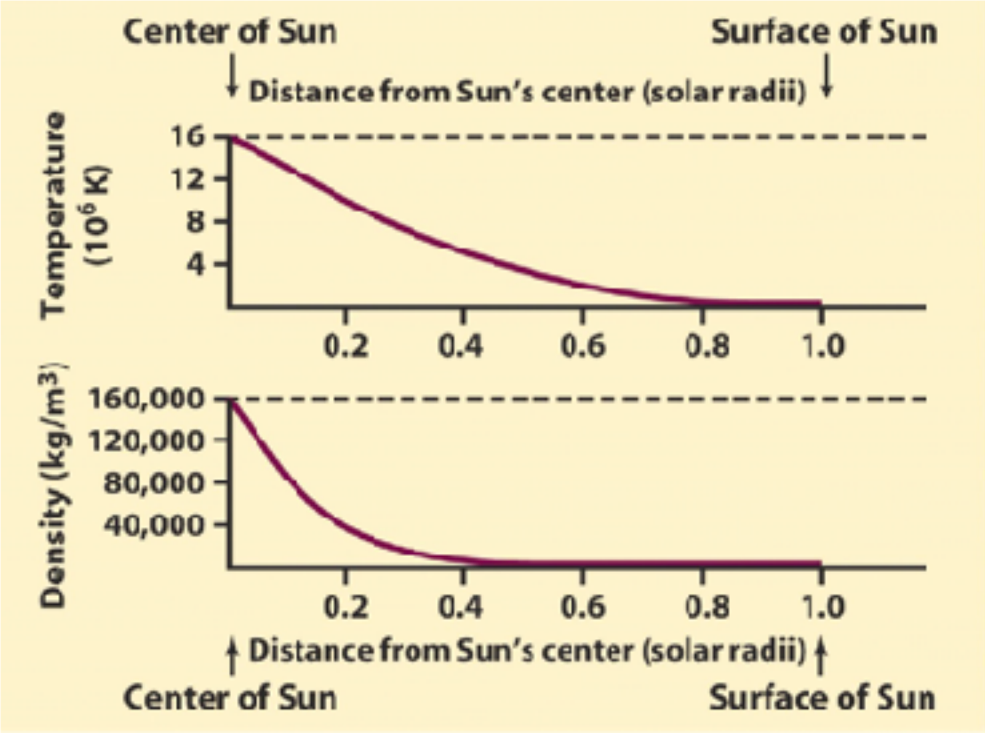
- **Hydrostatic equilibrium** is a force balance: gas pressure and radiation pressure work against gravity
- **Thermal equilibrium** is an energy balance: the same amount of energy enters and leaves a layer
- **Energy transfer** inside the Sun (stars) by radiation and convection: by radiation, energy is carried away in photons with temperature gradient; by convection, energy is transported by gas flows

Photons take O(10^5) years to escape the Sun



The Sun's energy is transported from the 15 MK center outward by radiation in the radiative zone and then convection in the convective zone.

The interior of the Sun can be "observed" by its oscillations in brightness, size, and velocity on surface



The Standard Solar Model

Ingredients

Conservation laws and material dependent equations

- Mass conservation
- Hydrostatic equilibrium
- Energy conservation
- Energy transport
- Equation of state
- Expression for entropy
- Nuclear reaction networks and reaction rates
- Energy production
- **Opacity**

This quantity describes the coupling between radiation and matter in the hot dense interior of the Sun

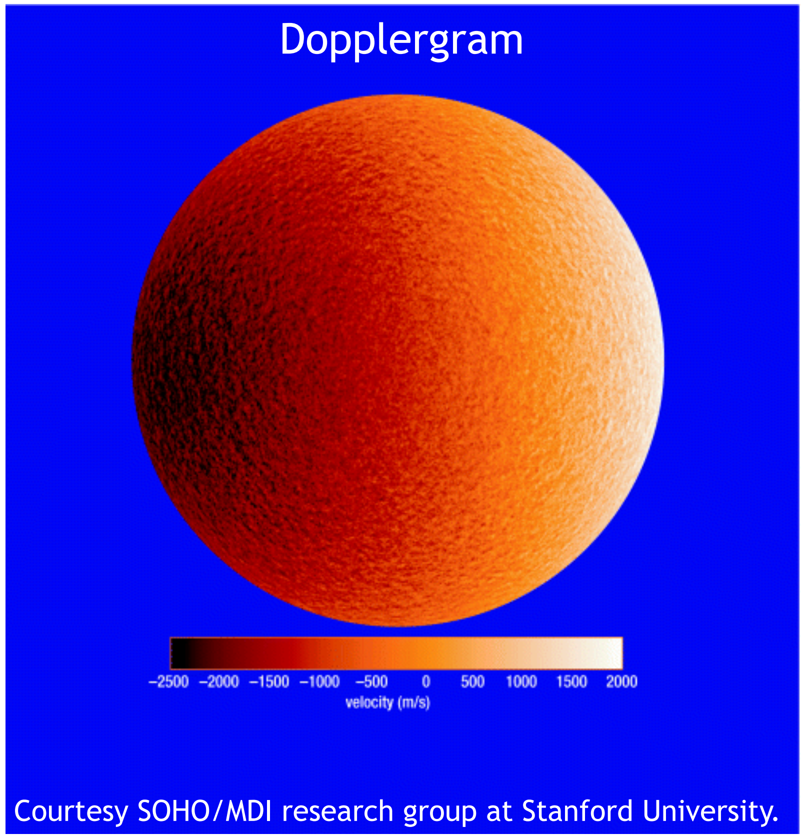
Impacted by "**metallicity**", the abundance of metals, id est, elements heavier than He

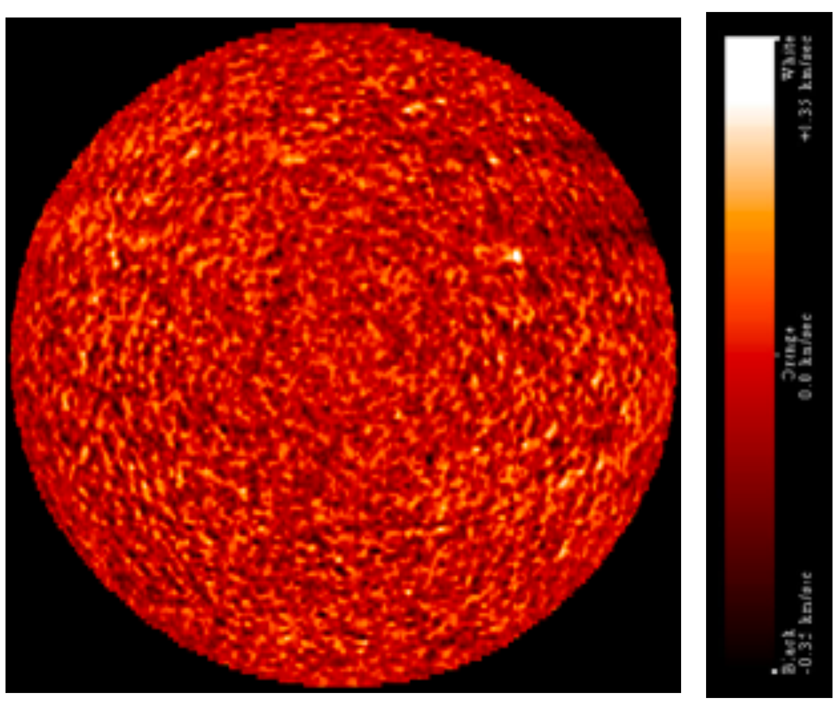
Assumptions

- no mixing in core or in radiative zone
- hydrostatic equilibrium, i.e. model passes through a stage of equilibria
- the only time dependence is introduced by reduction of H and build up of He in core

How is the Sun inspected?

Helioseismology is the study of the structure and dynamics of the Sun through its oscillations

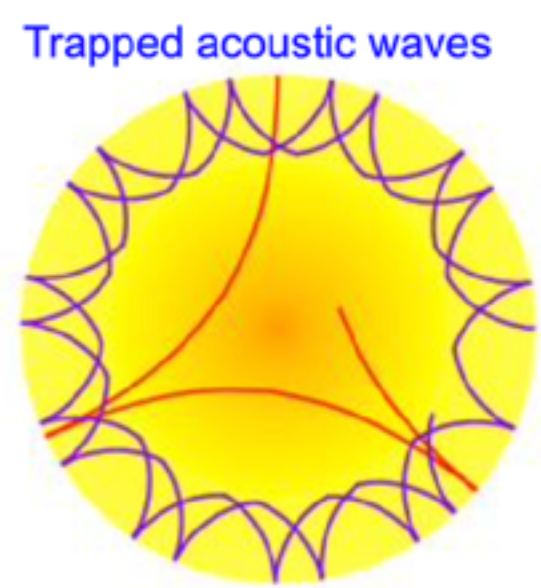




Doppler image of the Sun taken by the MDI instrument on board the SOHO satellite

- ranging from roughly −2 km s^{-1} (dark tones) to +2 km s^{-1} (light tones)
- The dominant grading is due to the Sun's rotation
- The residual when this and other large-scale motions are corrected for reveals the Sun's resonant-mode oscillations

Trapped acoustic waves, or pressure P mode waves, refracted in the interior by increased temperature and reflected below the surface by low density



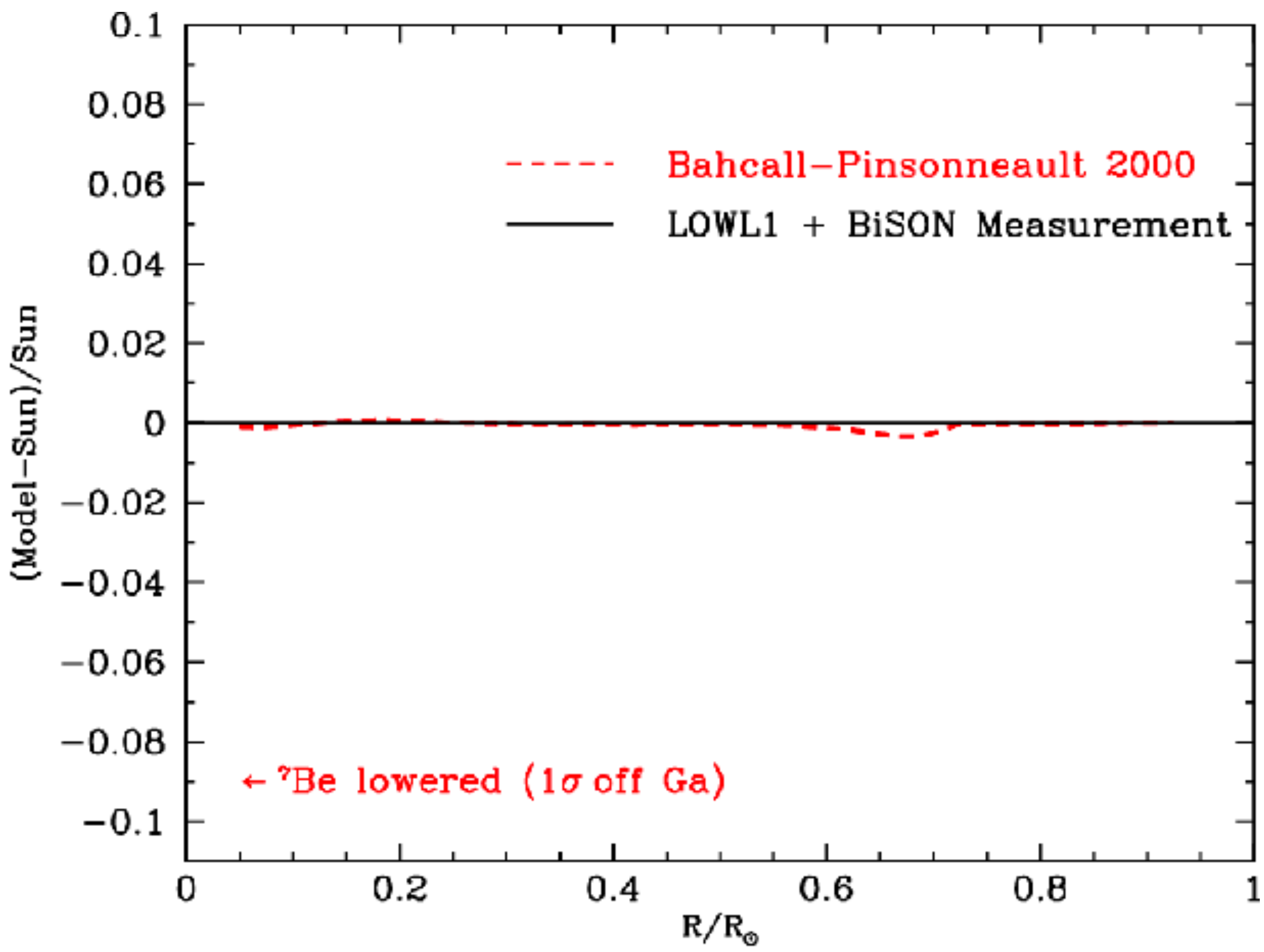
- they produce a quasi-sinusoidal radial variation in the velocity field with an amplitude of a few hundred m/s and period of 5 min

- long wavelength waves travel deeper into the sun.

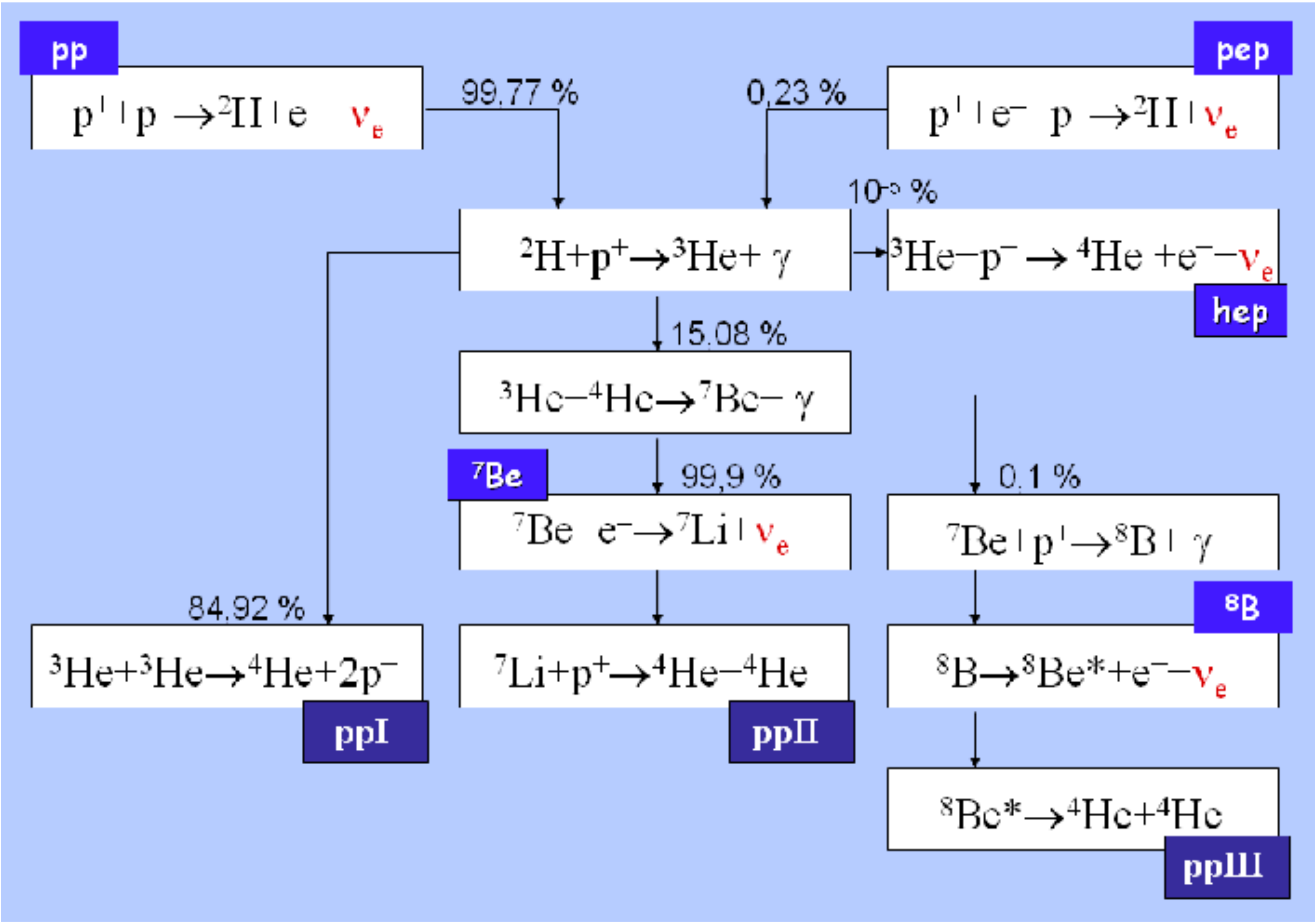
Helioseismology and the SSM

Excellent agreement (up to 2009!)

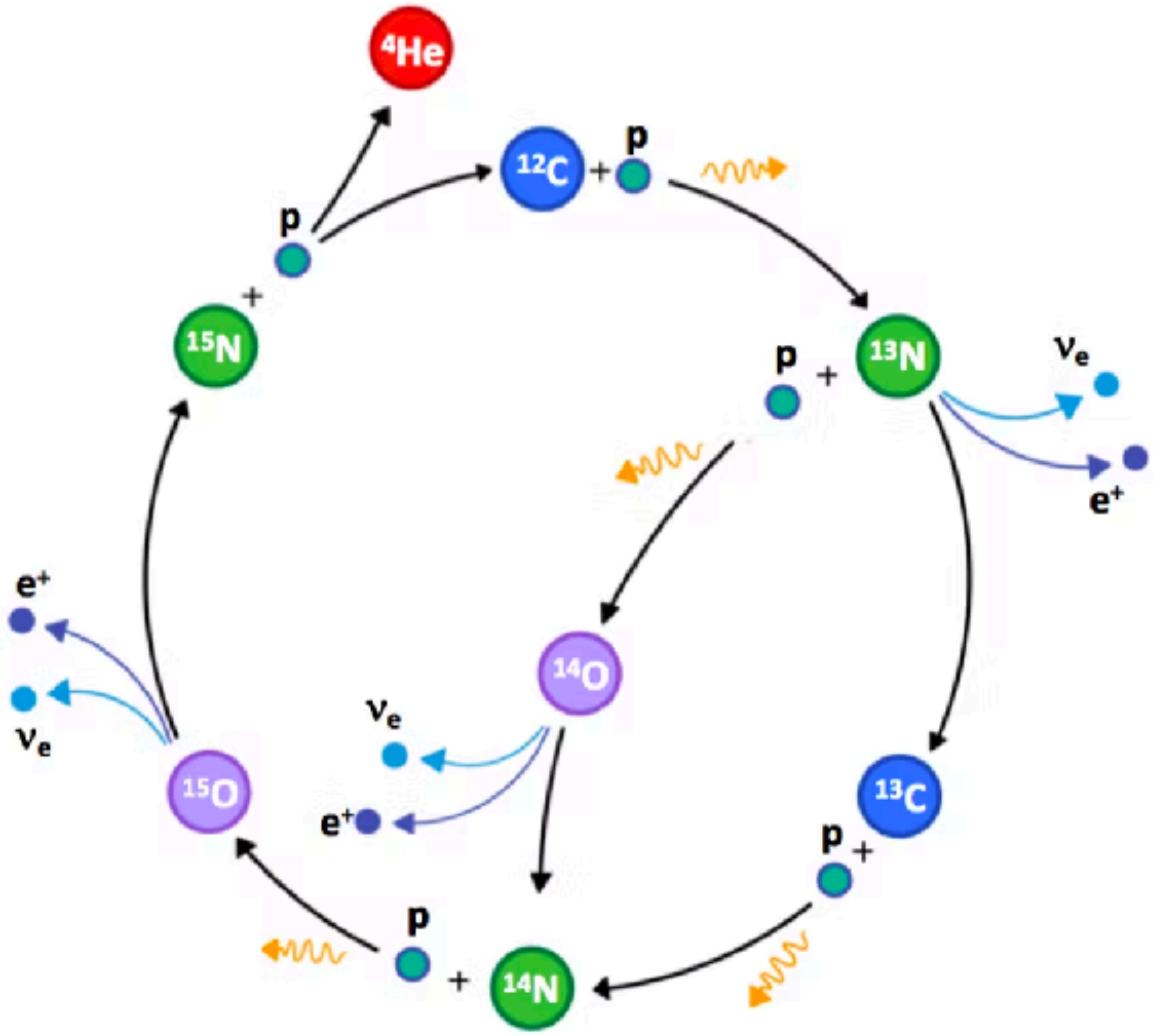
Sound Speed



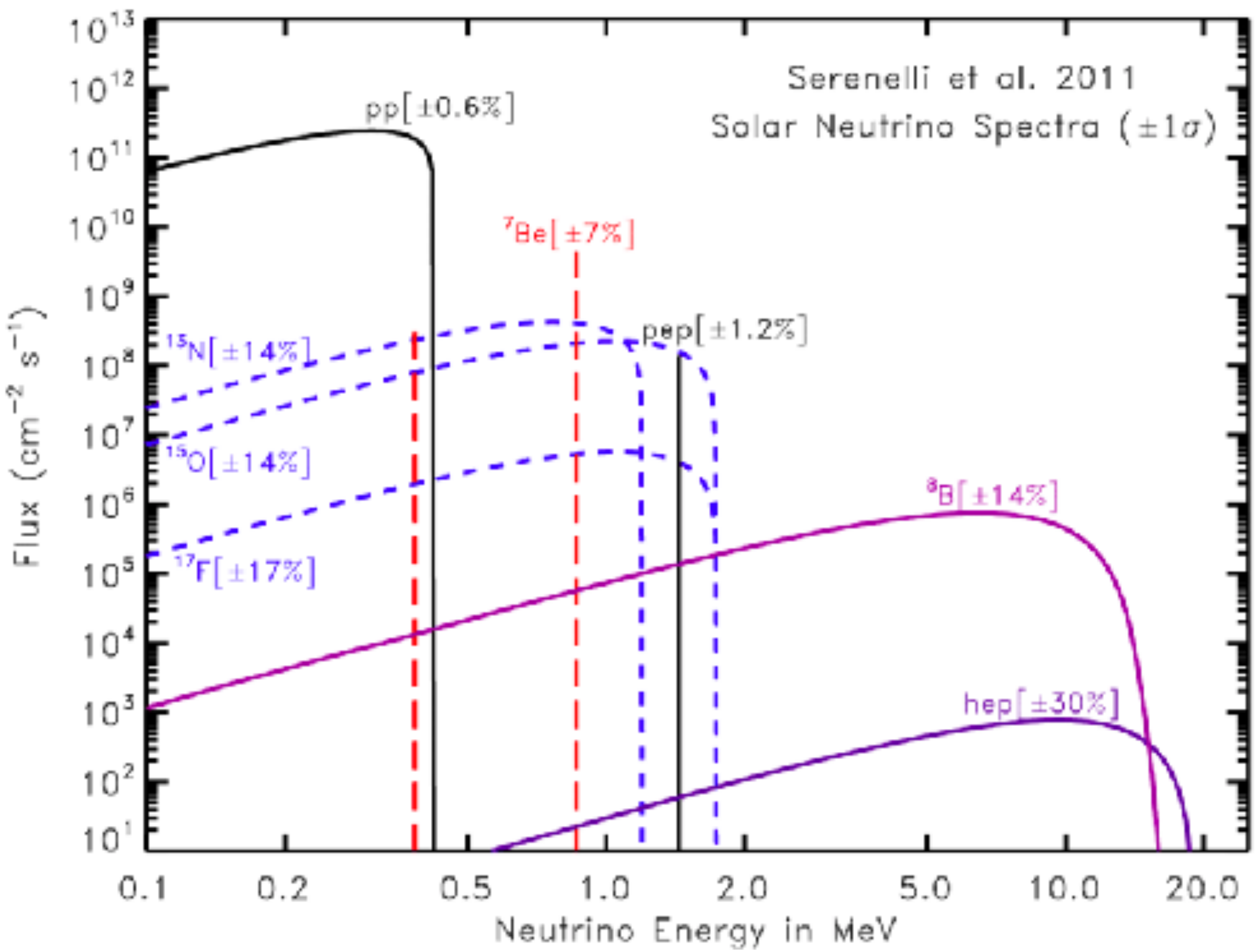
The proton-proton chain

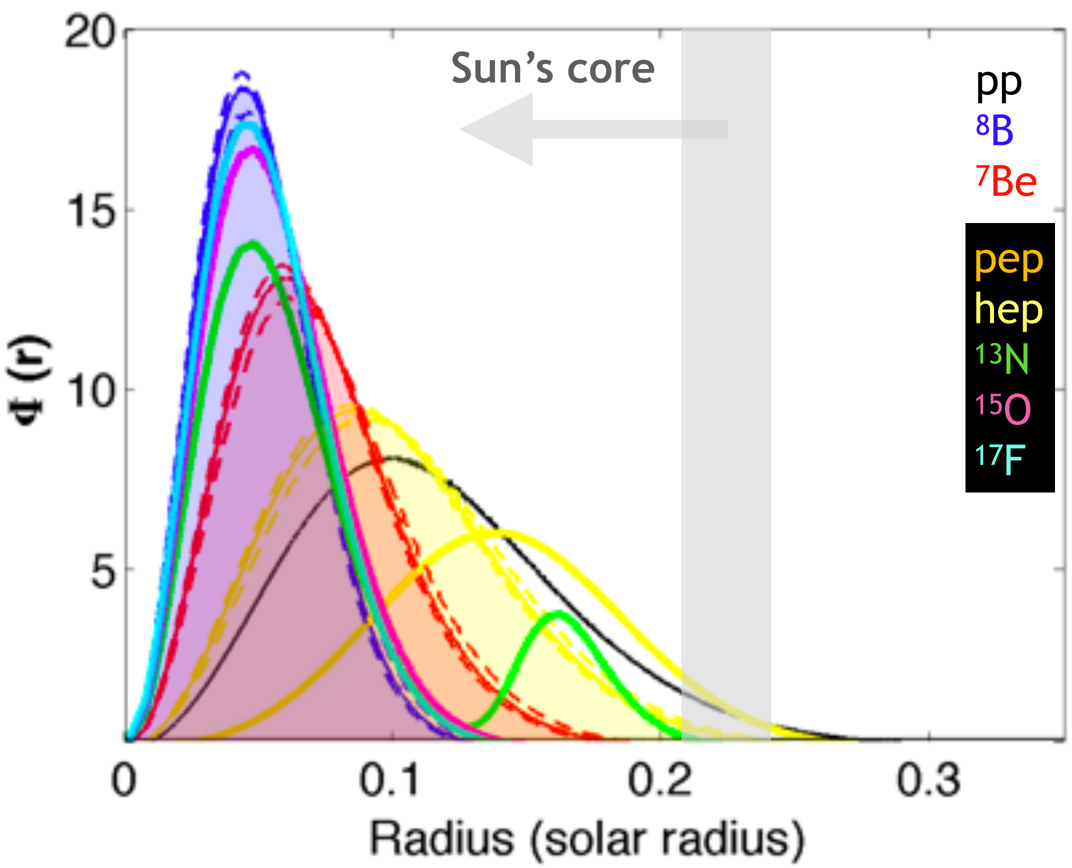


The CNO cycle

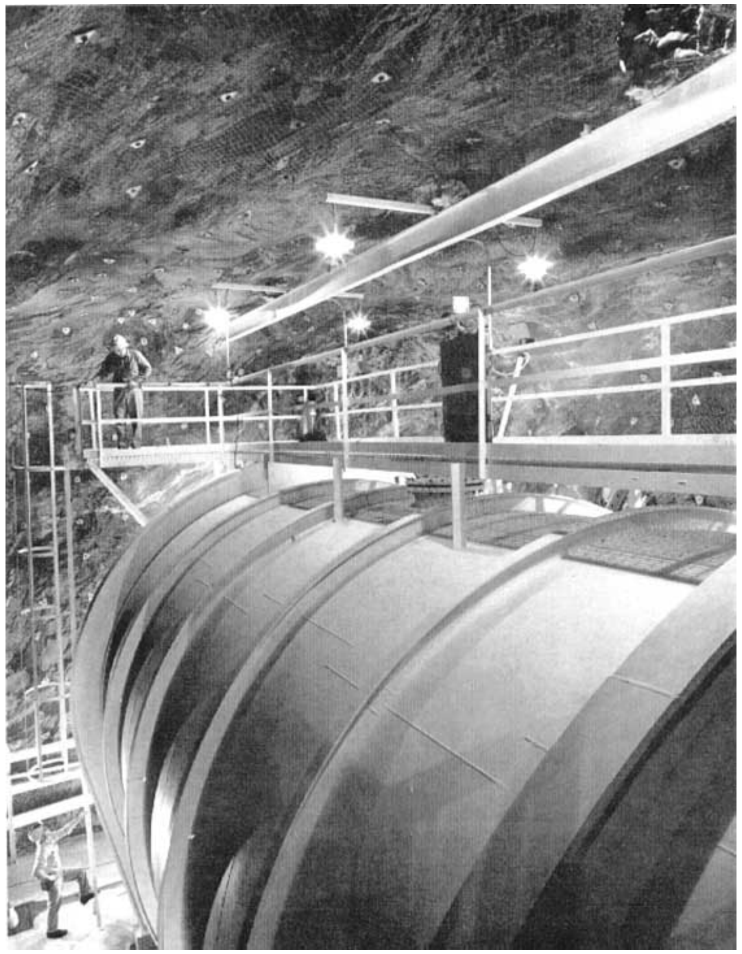


Solar Neutrinos





Homestake



1964 John Bahcall and Ray Davis have the idea to detect solar neutrinos using the reaction

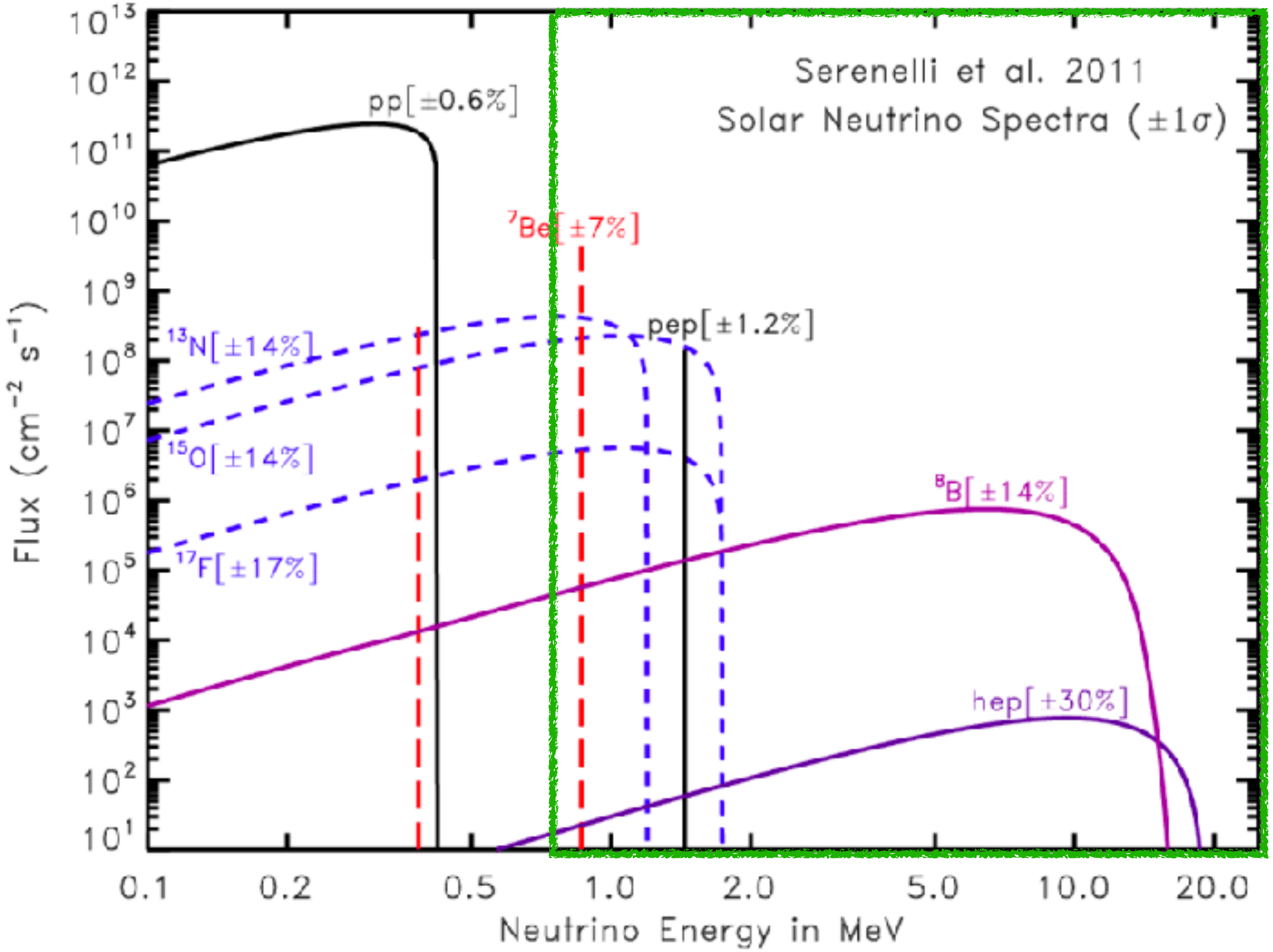
$$^{37}Cl + \nu_e \longrightarrow {}^{37}Ar + e^-$$

Bahcall's demonstration that transitions to excited states in ^{37}Ar, particularly the superallowed transition to the analog state at 4.99 MeV, **increased the ^{8}B cross section by a factor of 40**. This suggested that Davis's detector would have the requisite sensitivity to detect ^{8}B neutrinos, thereby accurately determining the central temperature of the Sun

1967 Homestake experiment starts taking data

- 0.61 kiloton of perchloroethylene (C2Cl4)
- 1500 m (4900 m.w.e.) underground
- ^{37}Ar extracted chemically every few months (single atoms!) and decay counted in counting station (35 days half-life)
- event rate: ~1 neutrino capture per day !

814 keV threshold for exciting the ^{37}Ar ground state



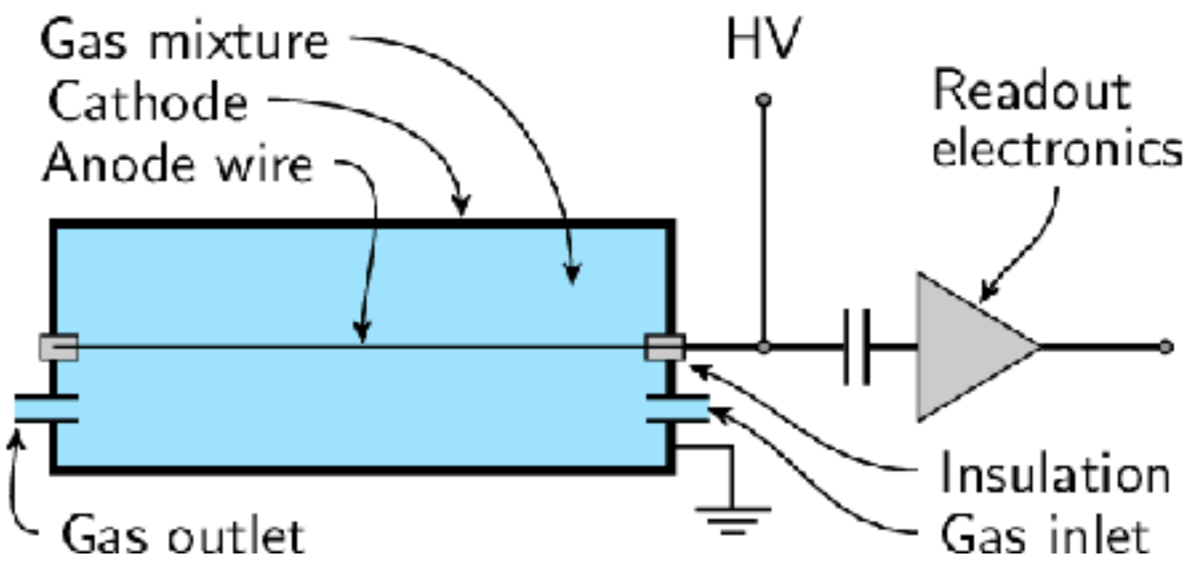
Extraction. ^{37}Ar, as a noble gas, can be removed readily from perchloroethylene by a **helium purge**

Circulation and trapping. Argon is circulated through a condensor, a molecular sieve, and a charcoal trap cooled to the temperature of liquid nitrogen. Typically ~**95% of the argon in the tank is captured** in the trap.

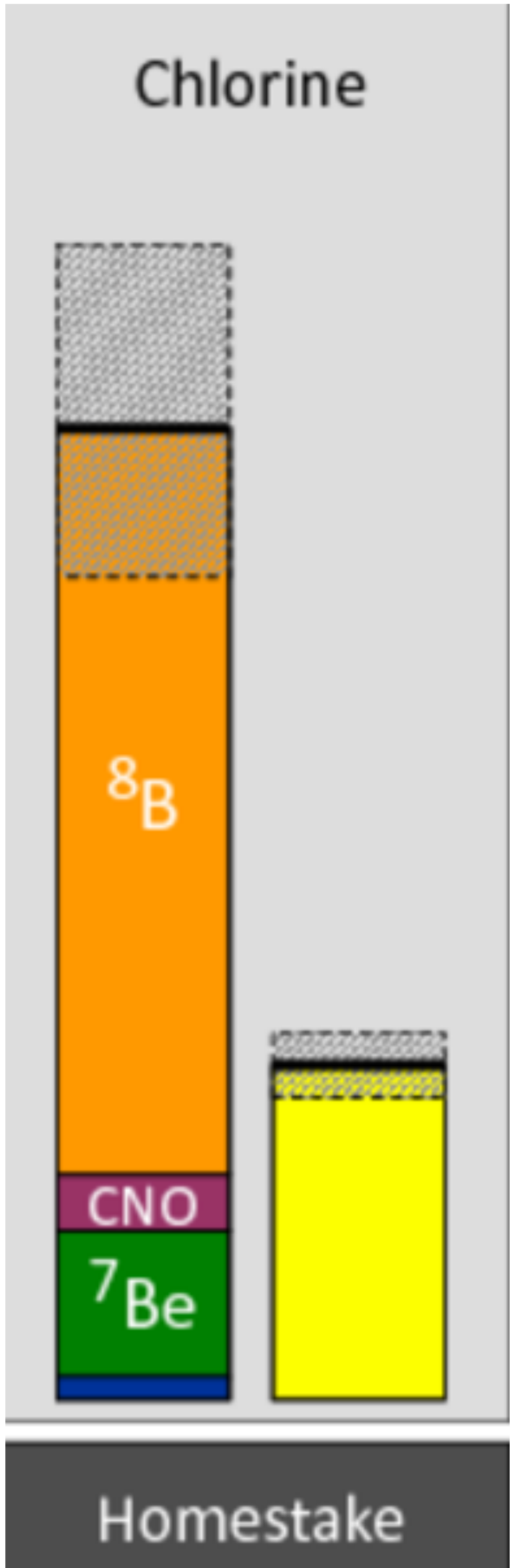
Efficiency monitoring. The efficiency is determined each run from the recovery results for a **known amount of carrier gas, ^{36}Ar or ^{38}Ar**, introduced into the tank at the start of the run. When the extraction is completed, the trap is heated and swept by He.

Purification. The extracted gas is passed through a hot titanium **filter** to remove reactive gases, and then other noble gases are separated by gas **chromatography**.

Counting. The purified argon is loaded into a small **proportional counter** along with tritium-free methane, which serves as a counting gas. Signal: 2.82 keV Auger electron from electron capture decay of ^{37}Ar. The counting of the gas typically continues for about one year (~10 half lives).



Homestake



The measured **cosmic ray-induced background** in the Homestake detector is 0.06 **^{37}Ar atoms/day**

Neutron-induced backgrounds are estimated to be <0.03 **atoms/day.**

A **signal** of 0.48 ± 0.04 atoms/day is expected from solar neutrinos. Taking into account of detector efficiencies, 37Ar decays occurring in the tank, etc., **the number of ^{37}Ar atoms counted is about** **25/year**

1968 First results with only 34% of predicted neutrino flux:

$$\boxed{\langle\sigma\phi\rangle_{^{37}Cl} = 2.55 \pm 0.17 \pm 0.18 \ \ \text{SNU}}$$

1 SNU = the neutrino flux producing 10^{-36} captures per target atom per second

To be compared to the BP and TCL SSM **predictions of 8.0±1.0 SNU and 6.4±1.4 SNU**, respectively, all with 1σ errors

Solar neutrino problem is born - for next 20 years no other detector!

Homestake

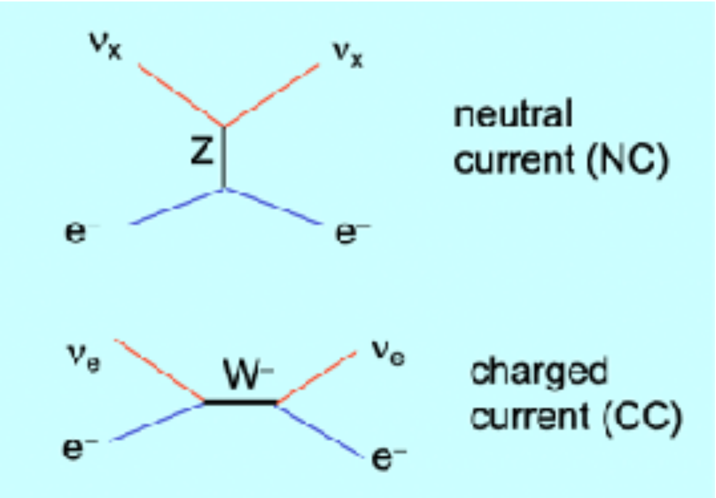
At first, the scientific community thought the experiment must be wrong, but Davis insisted he was right. “The solar neutrino problem caused great consternation among physicists and astrophysicists”, Davis wrote. “My opinion in the early years was that something was wrong with the standard solar model; many physicists thought there was something wrong with my experiment.”

The Kamiokande Experiment

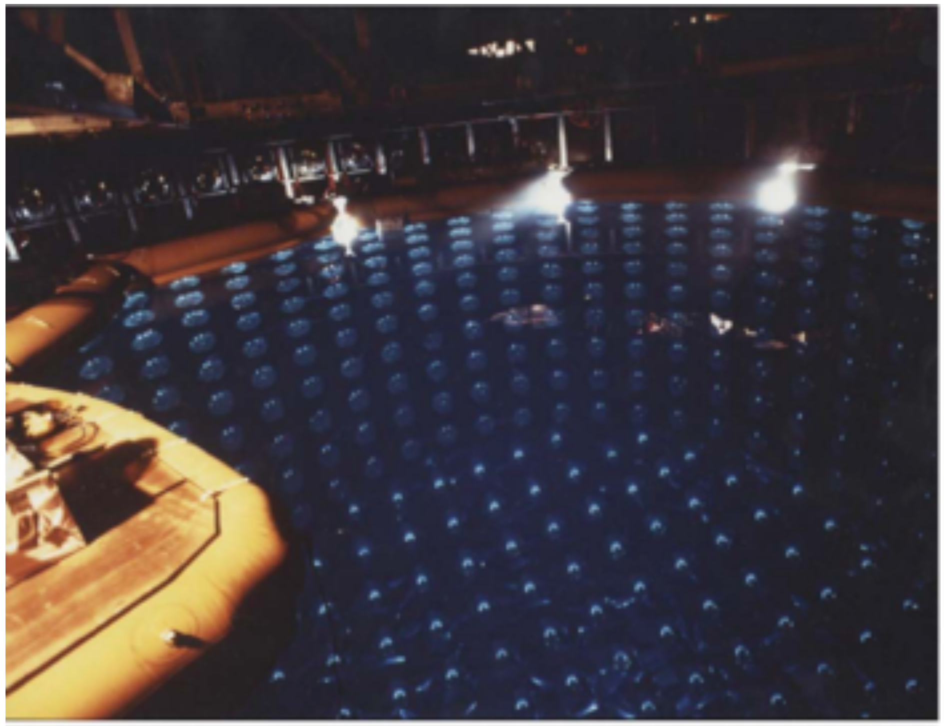
4.5 kiloton cylindrical imaging water Cerenkov detector

Designed for proton decay searches and later re-instrumented to detect low energy neutrinos.

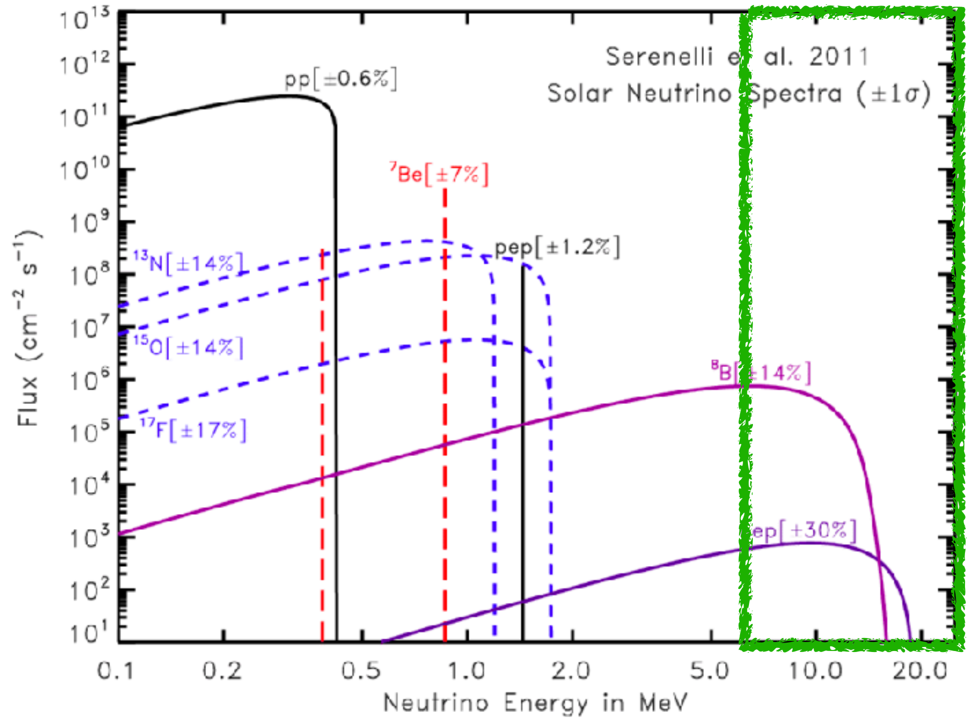
It detects recoiling electrons from the elastic scattering reaction, **7 times more sensitive to electron neutrinos than to muon and tau ones**



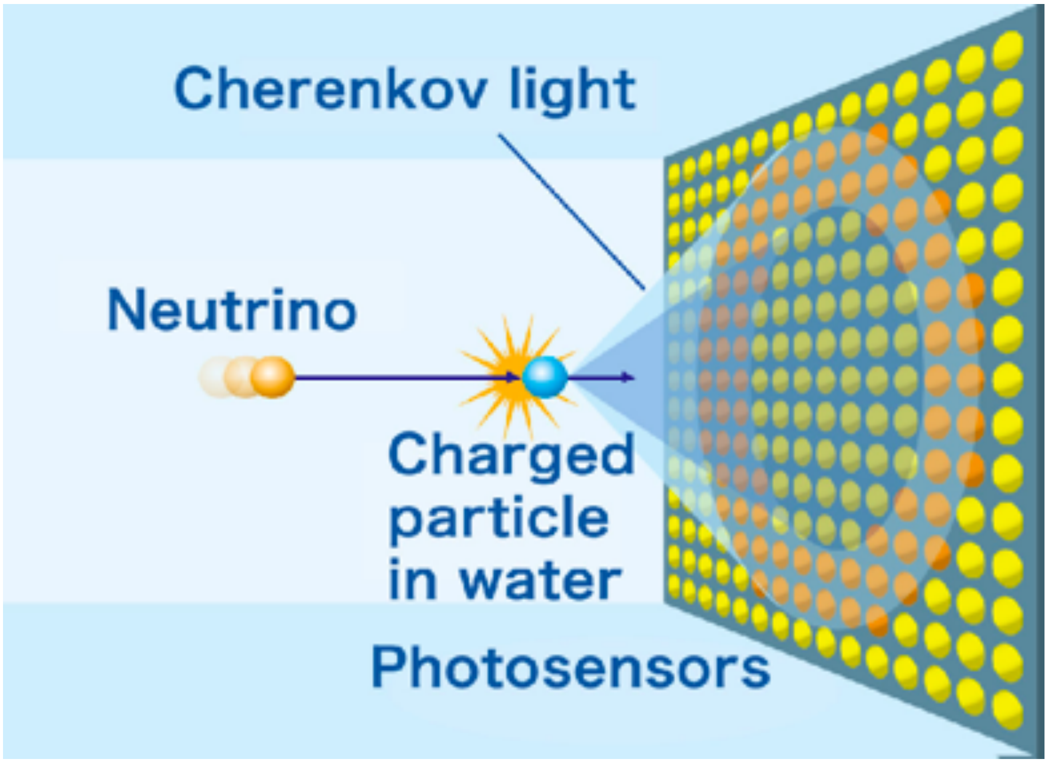
$$\nu_x + e \rightarrow \nu_x' + e'.$$

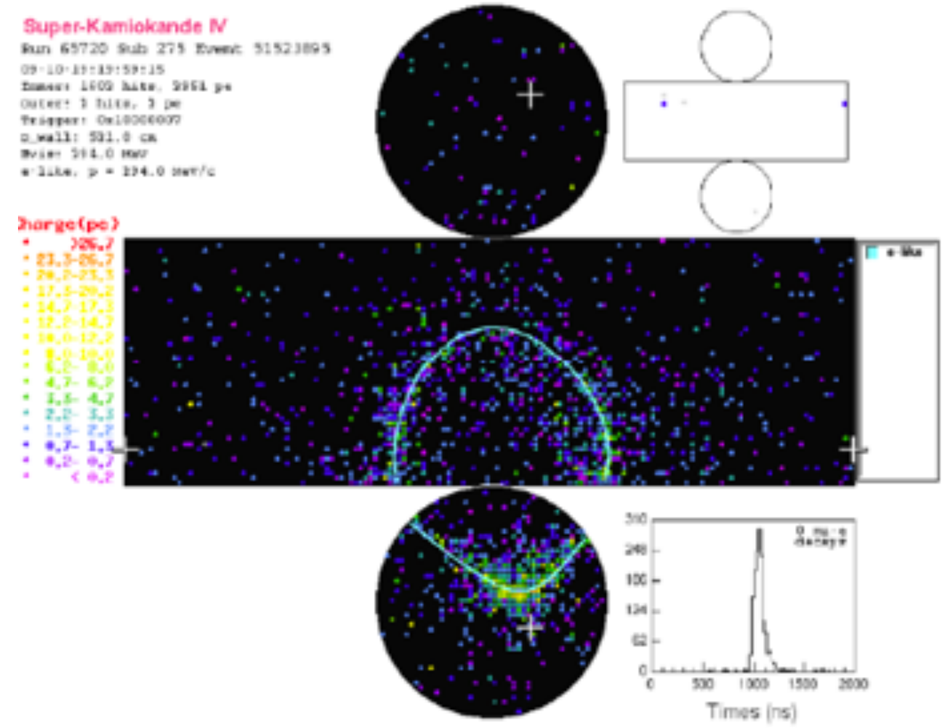


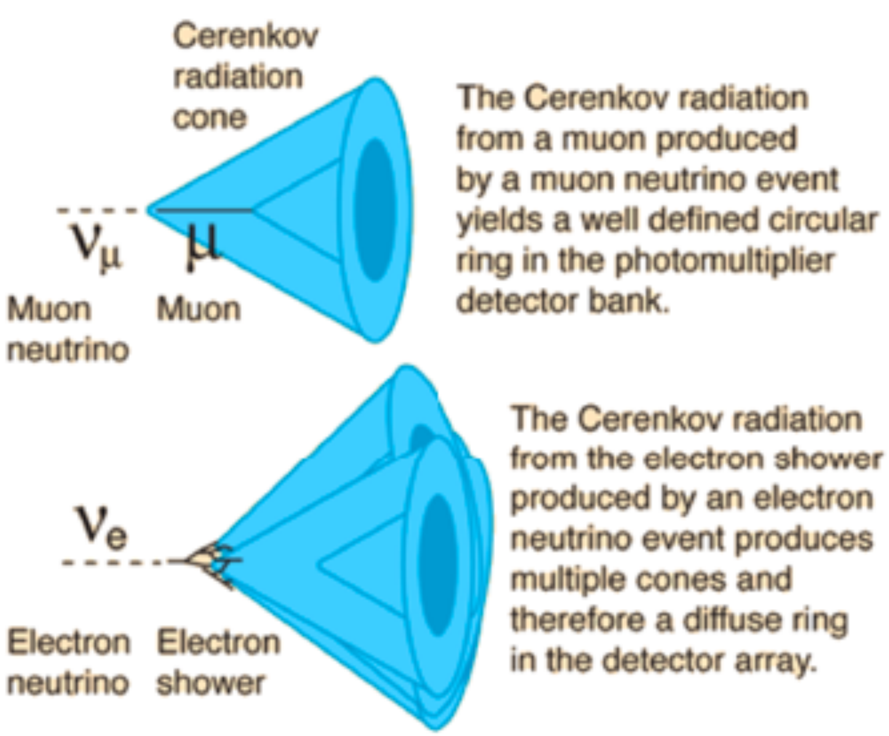
Threshold at 7.5 MeV neutrino energy

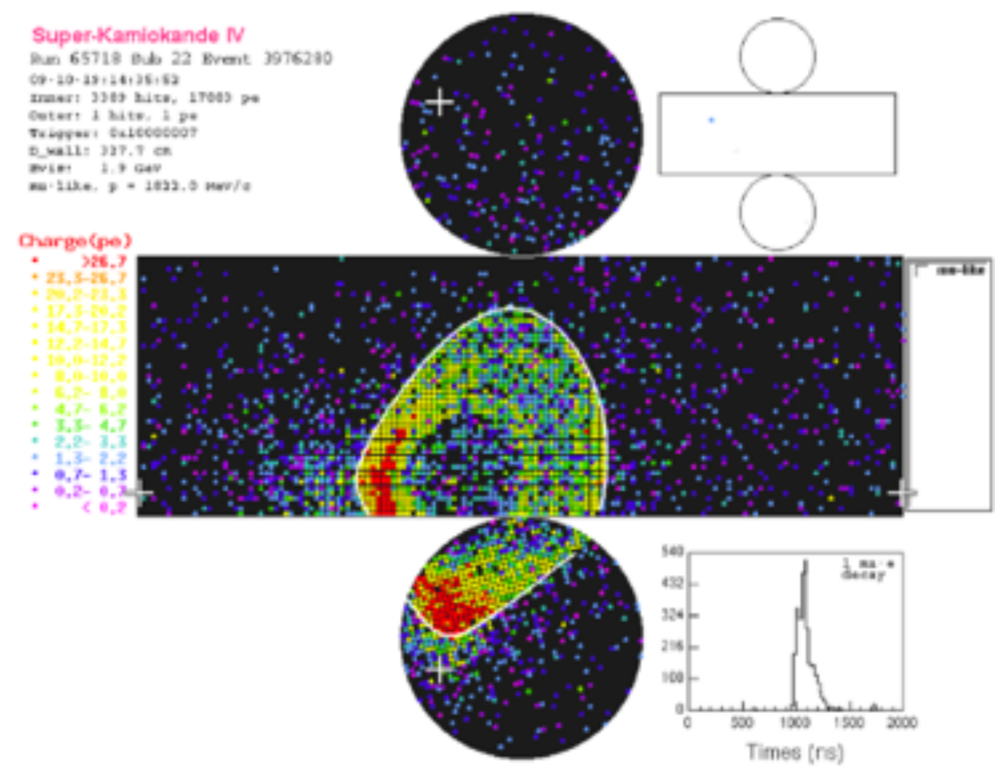


Detection with Cherenkov light

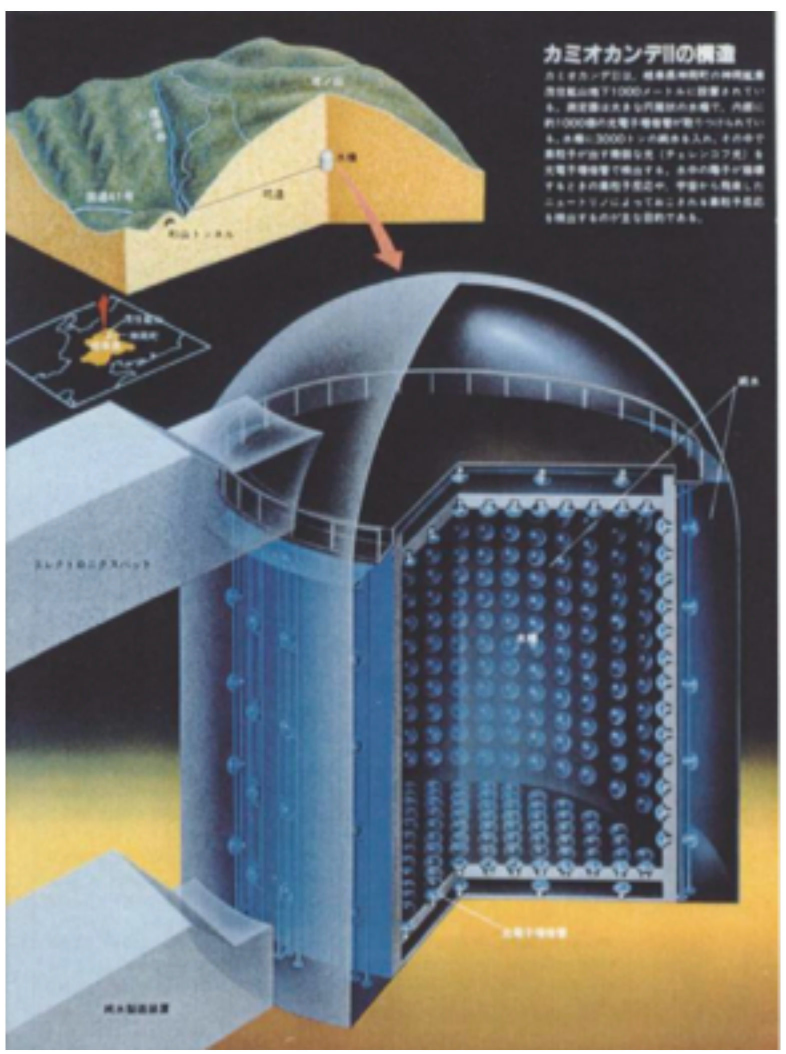


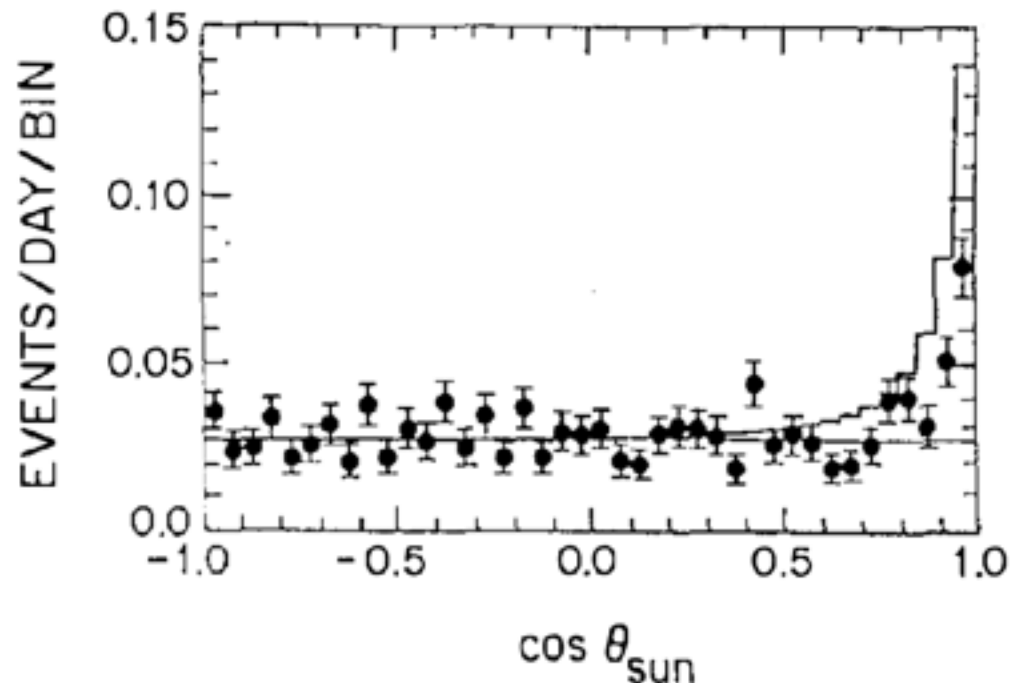


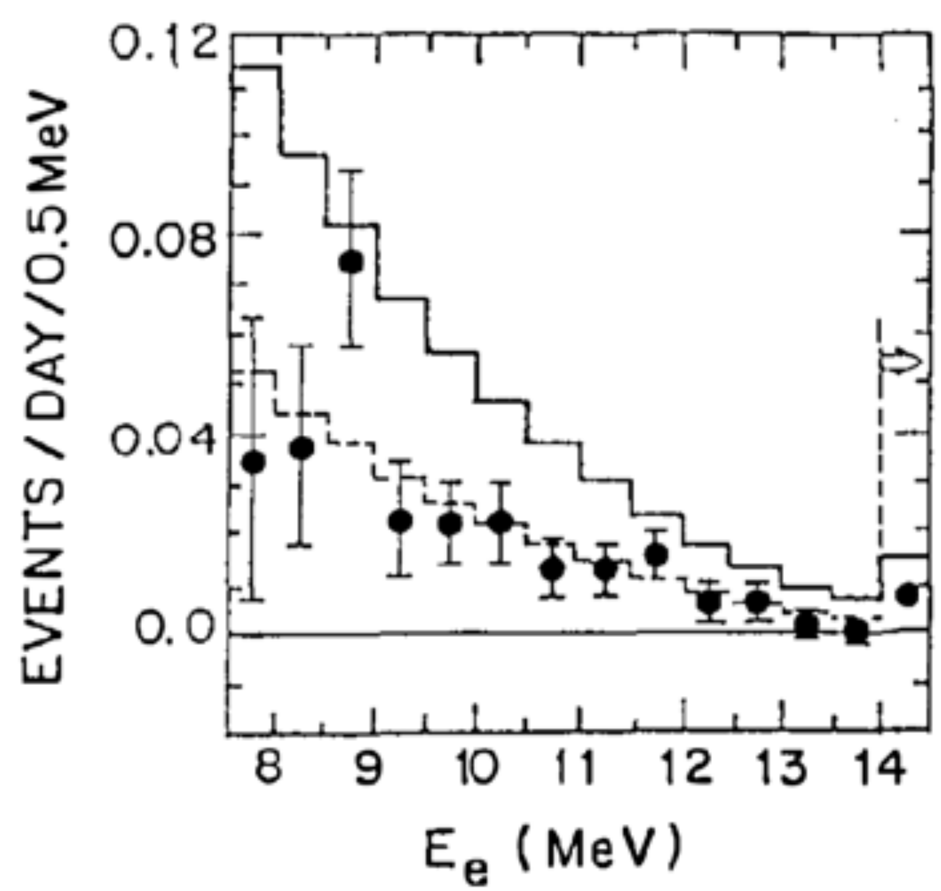




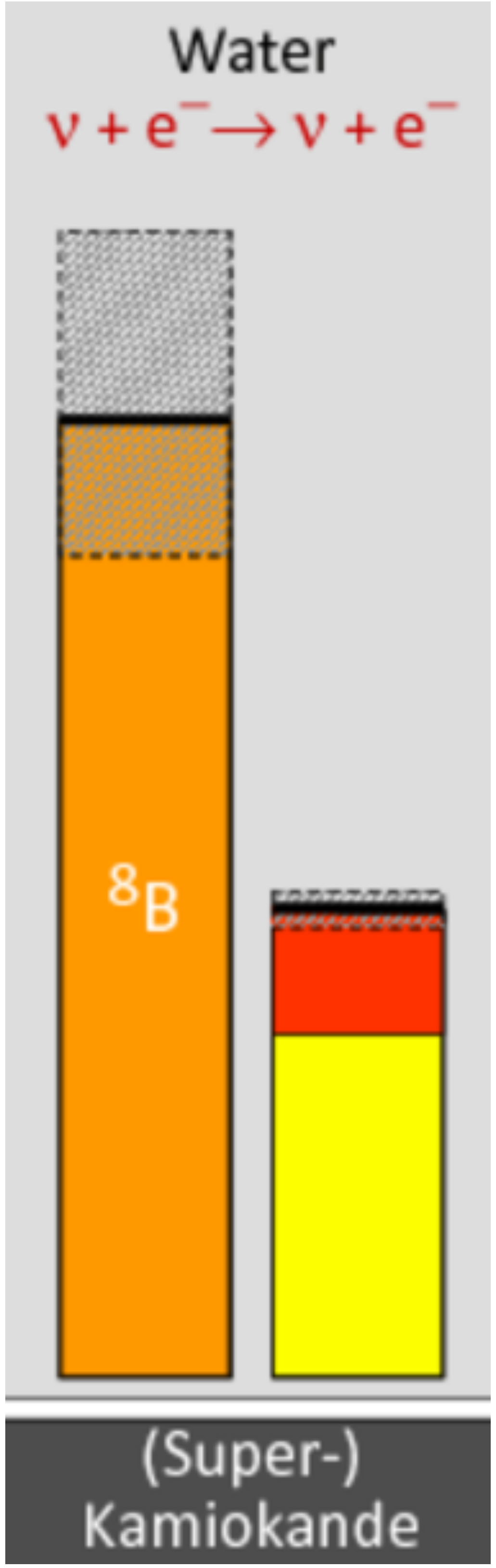
- Active volume: 2.14 kt
- Fiducial volume: 0.68 kt
- 948 Hamamatsu 20” PMTs (20% optical coverage)
- Veto: 1.5 m thick water surrounding the active volume equipped with 123 PMTs
- Shielded by 2700 m.w.e. of rock at the Kamioka mine







The Kamiokande Experiment



The result from the combined Kamiokande II/III data set is

$$\phi_{\nu_e}(^8\mathrm{B}) = (2.91 \pm 0.08 \pm 0.12) \cdot 10^6/cm^2s \qquad (1\sigma)$$

corresponding to 51% of the BP SSM prediction. The total number of detected solar neutrino events is 476^{+36}_{-34}

Remarks

It is the first detector to measure solar neutrinos in **real time**

Angular allows the experimenters to separate solar neutrino events from isotropic background.

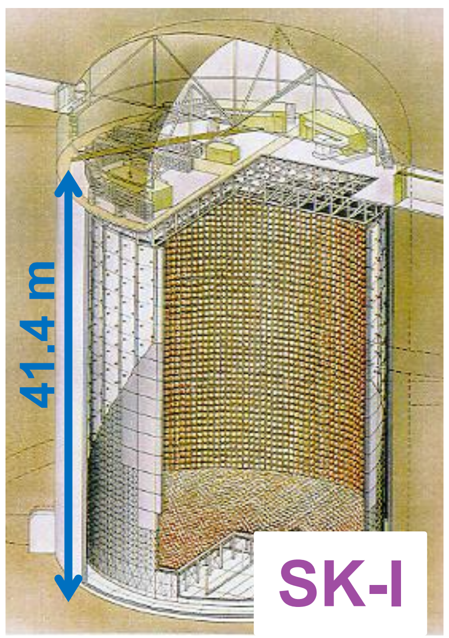
First **direct demonstration that the Sun produces neutrinos** as a byproduct of fusion.

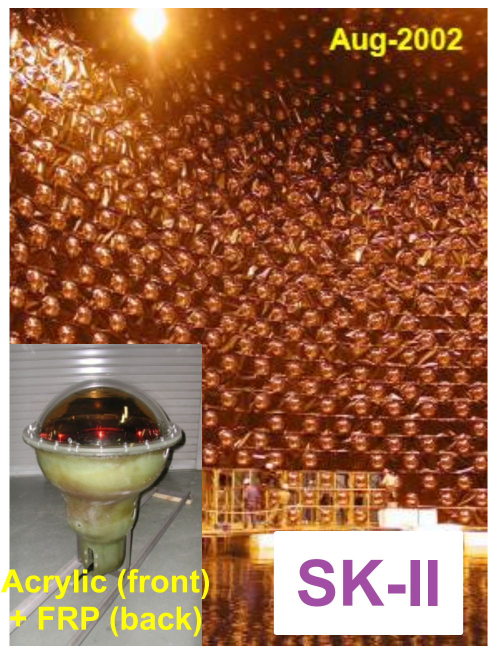
Recoil spectrum is reduced in amplitude but **not distorted in shape** with respect to predictions

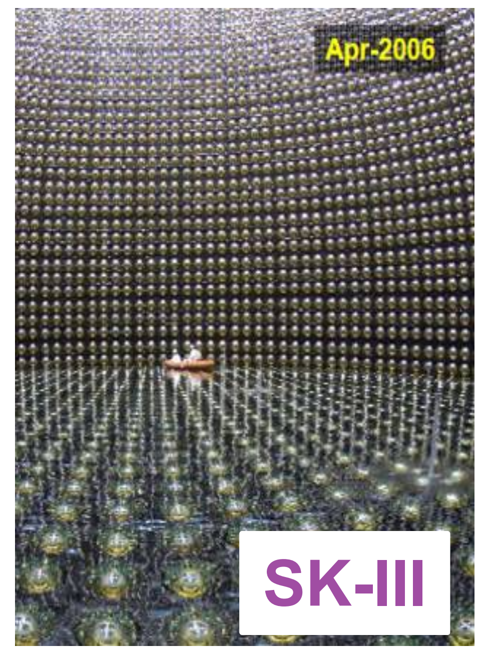
SuperKamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I SK-II SK-III SK-IV

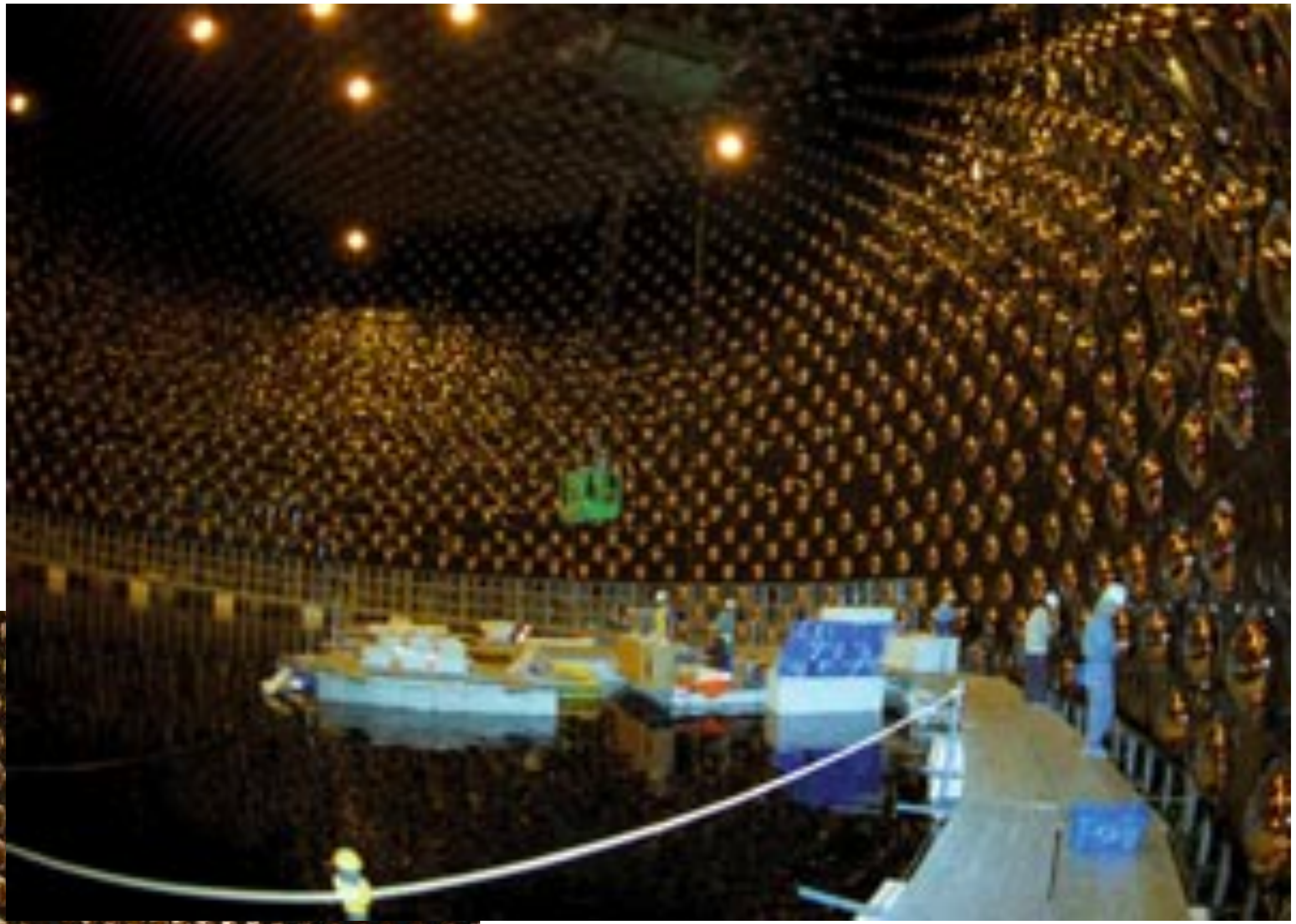


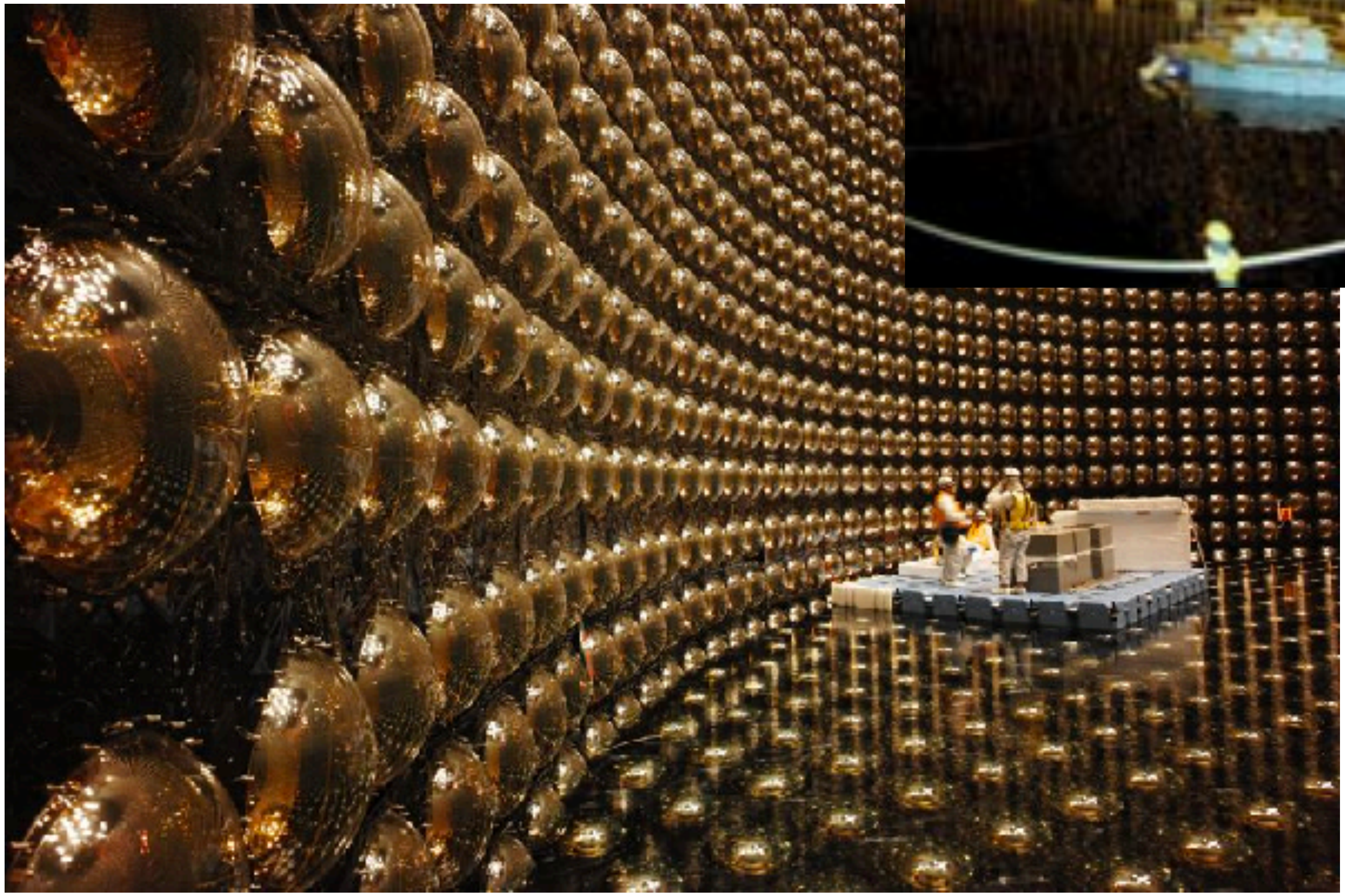




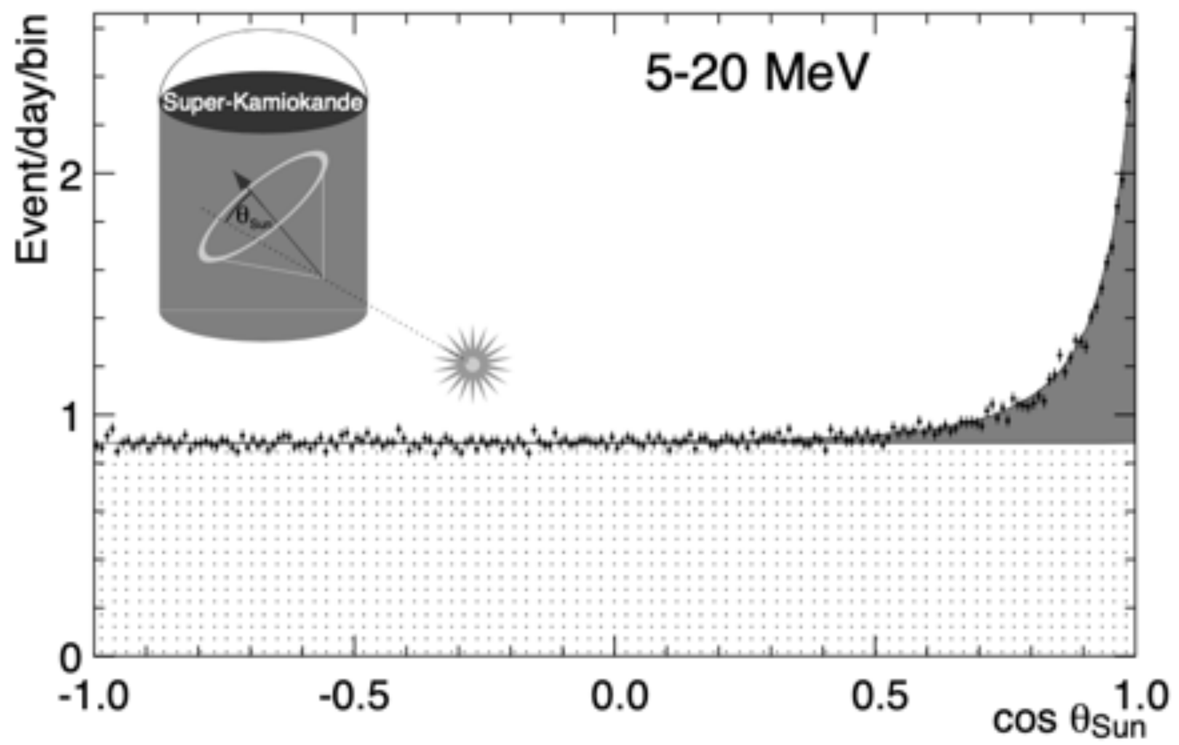
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
			Current	Target
5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV

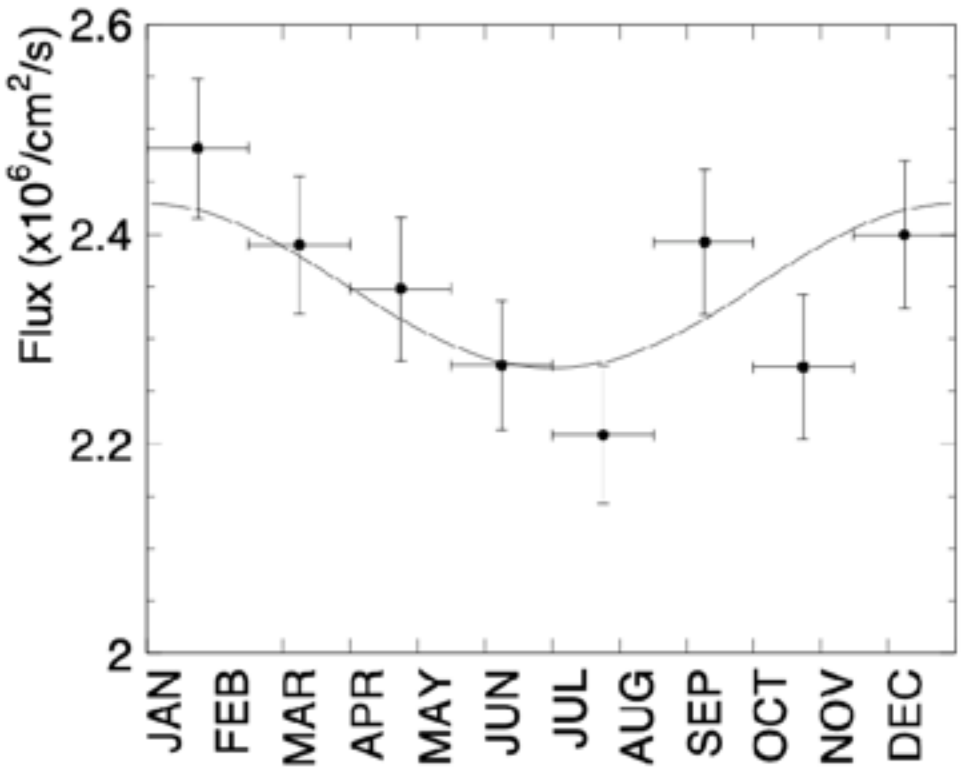
SuperKamiokande

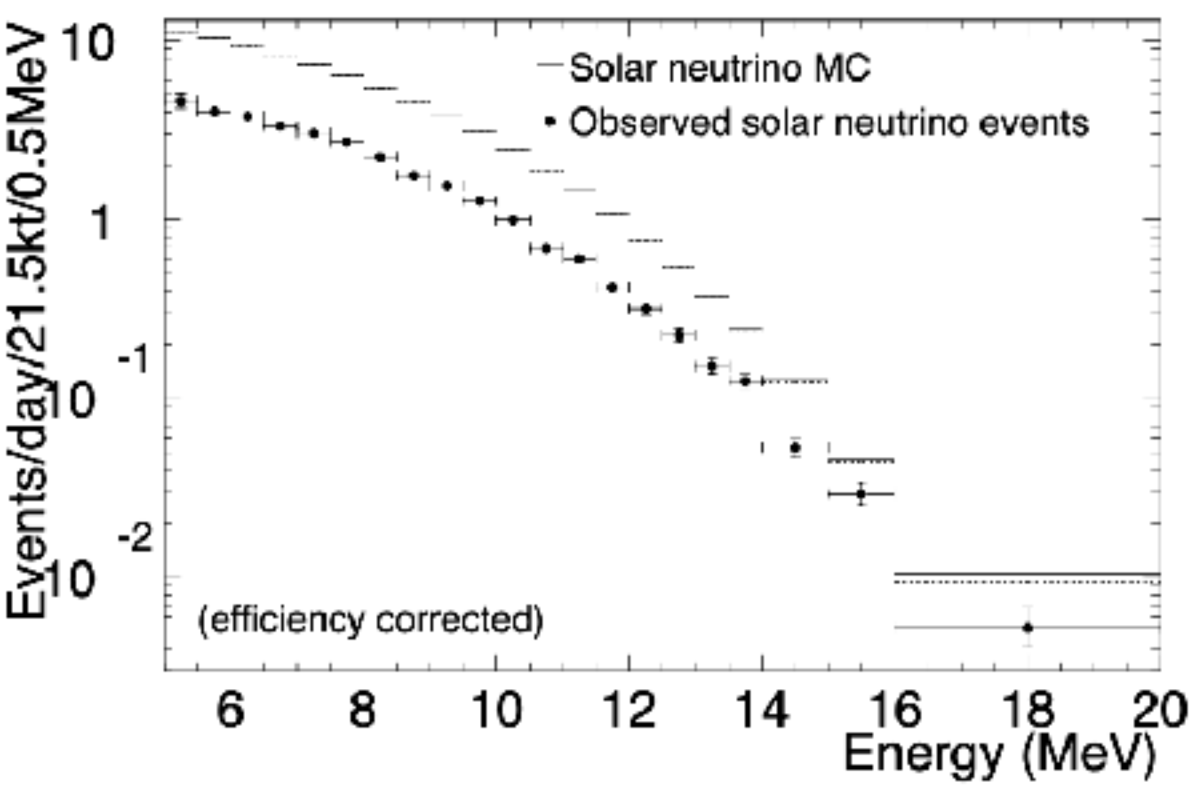




SuperKamiokande

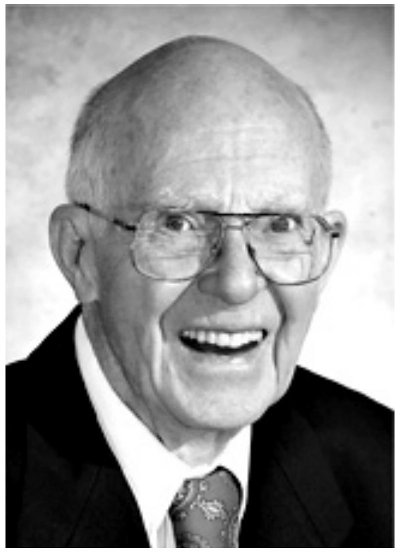






Nobel Prize 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



Raymond Davis Jr.

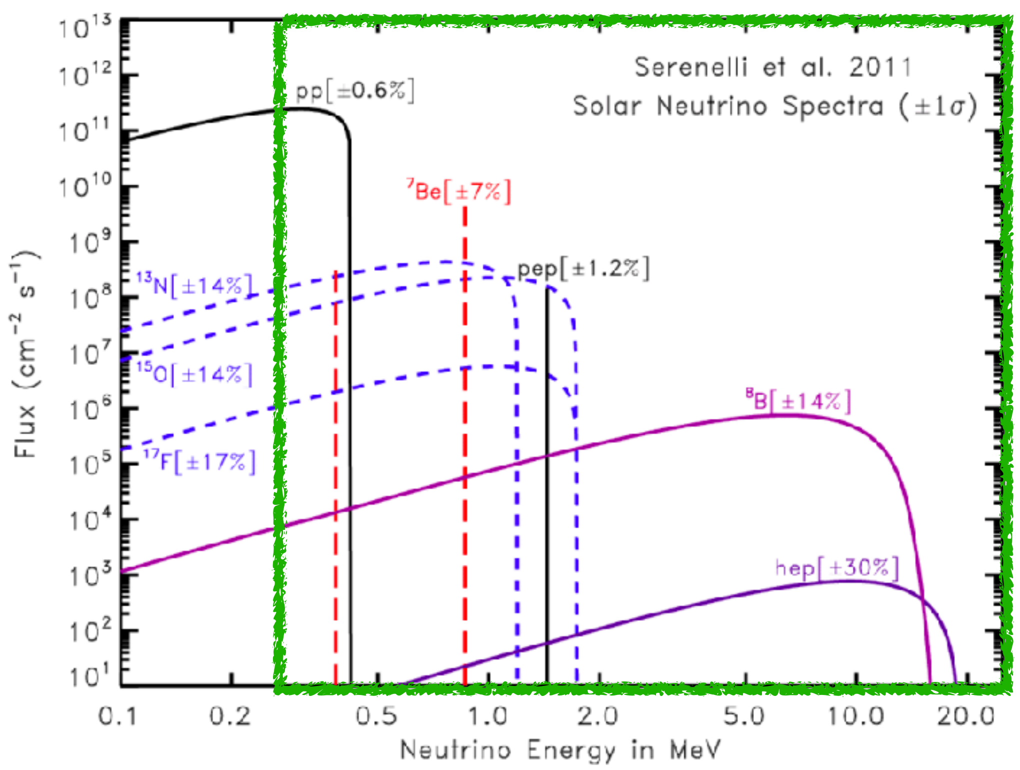
Masatoshi Koshiba

The SAGE and GALLEX Experiments

Lowering the energy threshold down to **233 keV**:
sensitive to **pp** neutrinos!

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

11.4 days half life



SAGE: Soviet-American Gallium Experiment

- Baksan Neutrino Observatory, northern Caucasus
- 50 tons of metallic 71Ga
- 2000 m deep, 4700 m.w.e. => $\Phi\mu$ ~ 2.6 m^{-2} day^{-1}

GALLEX / G.N.O. : GALLium EXperiment

- Gran Sasso Underground Laboratory, Italy,
- 30.3 tons of gallium in 101 tons of gallium chloride ($GaCl_3$ –HCl) solution
- 1400 m deep, 3300 m.w.e.=> $\Phi\mu$ ~ 30 m^{-2} day^{-1}

The SAGE and GALLEX Experiments

SAGE

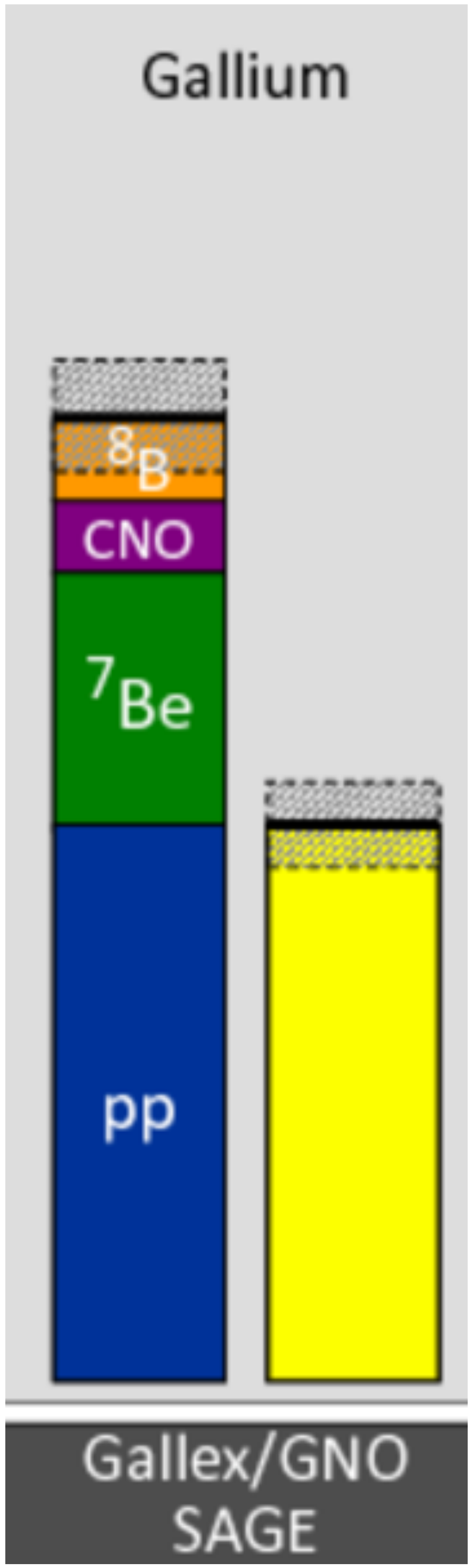
1. Metallic gallium as a target
2. 71Ge is separated by vigorously mixing into the gallium a mixture of hydrogen peroxide and dilute hydrochloric acid.
3. This produces an emulsion, with the Ge migrating to the surface of the emulsion droplets where it is oxidized and dissolved by hydrochloric acid.
4. The Ge is extracted as GeCl4, purified and concentrated, synthesized into GeH4, and further purified by gas chromatography. The overall efficiency is typically 80%.
5. The GeH4 is inserted into miniaturized gas proportional counters, carefully designed for their radiopurity Ge counted as it decays back to Ga ($\tau 1/2 = 11.43$ d)

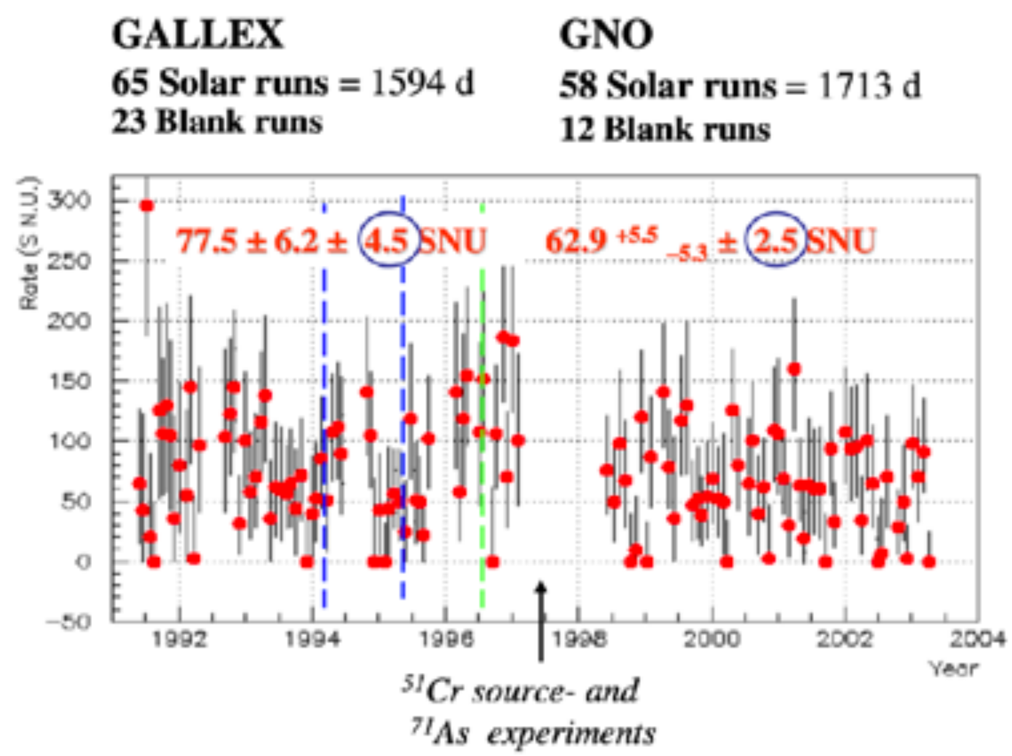
GALLEX / GNO

1. Solution of GaCl3 in hydrochloric acid as a target
2. Ge is recovered as GeCl4 by bubbling nitrogen through the solution and then scrubbing the gas through a water absorber.
3. The Ge is further concentrated and purified
4. Converted into GeH4, mixed with Xe, and extracted with 99% efficiency
5. The GeH4 is inserted into miniaturized gas proportional counters, carefully designed for their radiopurity Ge counted as it decays back to Ga ($\tau 1/2 = 11.43$ d)

Exposures of about three weeks

The SAGE and GALLEX Experiments

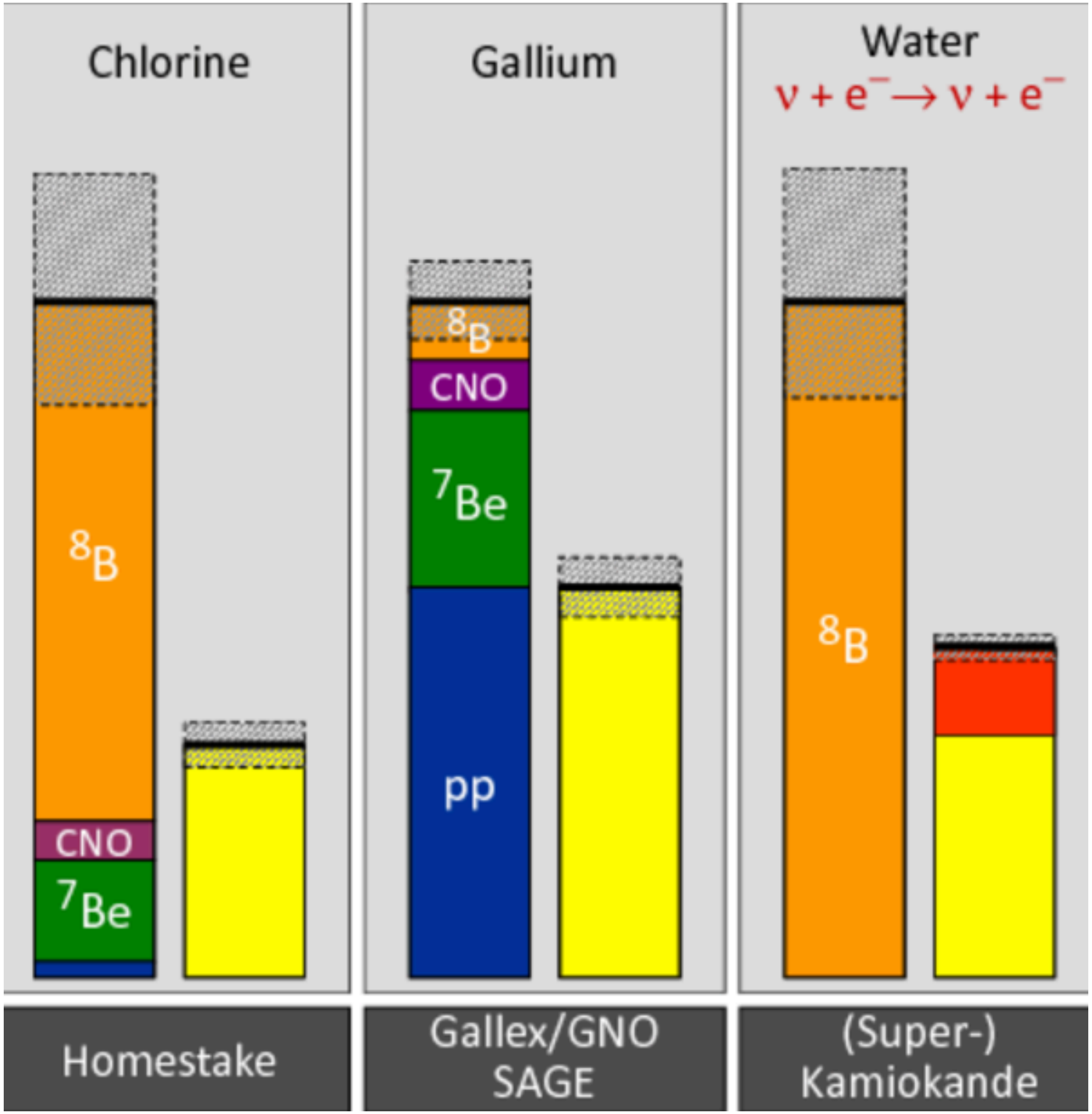




Expected: 122 – 131 SNU

GNO	$62.9 \pm^{6.0}_{5.9}$ **SNU**
GALLEX	$77.5 \pm^{7.6}_{7.8}$ **SNU**
GALLEX+GNO	69.3 ± 5.5 **SNU**
SAGE	$66.9 \pm^{5.3}_{5.0}$ **SNU**

The SAGE and GALLEX Experiments



The Solar Neutrino Problem(s)

Problem 1. **Calculated versus Observed Absolute Rate**

- **Deficit** observed at the Chlorine experiment with respect to the SSM prediction

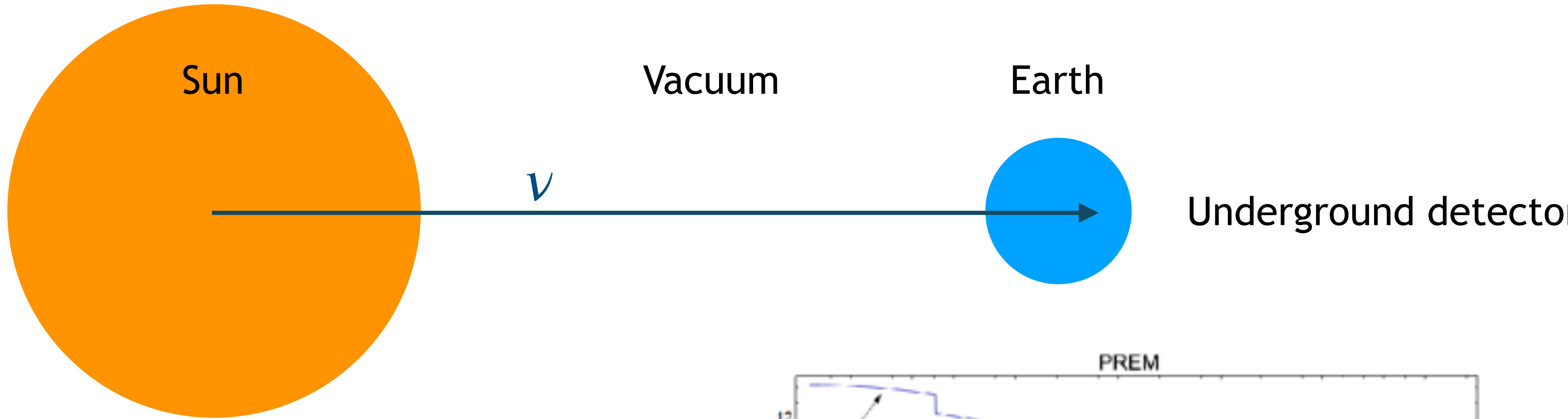
Problem 2. **Incompatibility of Chlorine and Water (Kamiokande) Experiments**

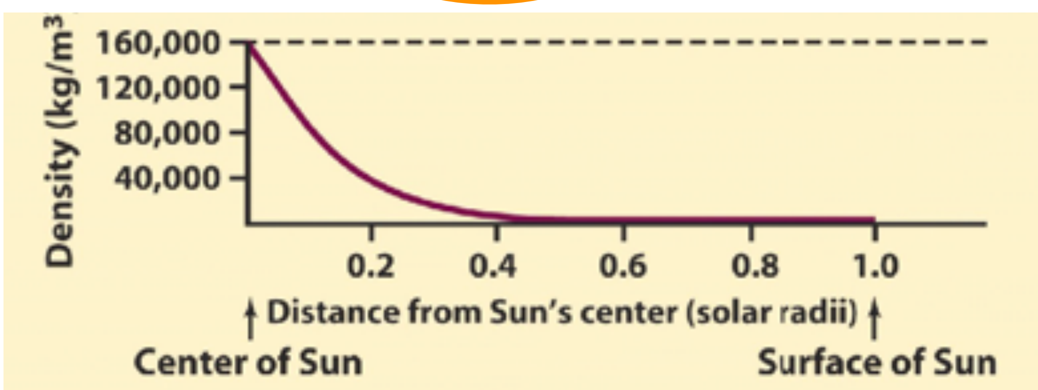
- ^{8}B spectral shape in Kamiokande agrees with expectations. Rescaling the rate to the Homestake energy threshold, the chlorine experiment should observe **3.2 ± 0.45 SNU** **from 8B** neutrinos only, which exceeds the **total** observed chlorine rate of **2.55 ± 0.25** SNU.

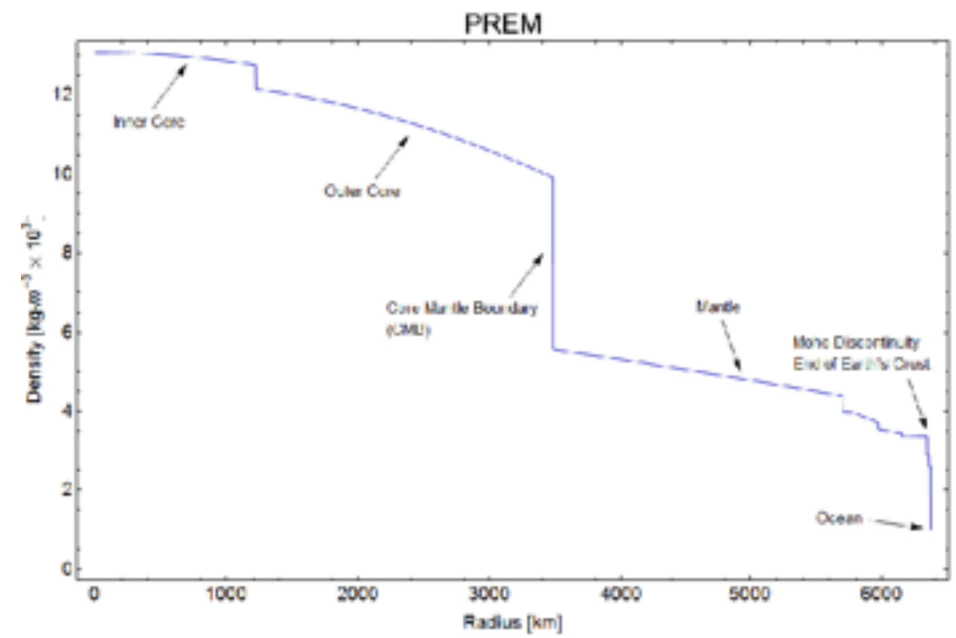
Problem 3. **Gallium Experiments: No Room for ^{7}Be Neutrinos**

- GALLEX and SAGE observed rate is **70.5±7 SNU**
- To be compared with **73 SNU** from pp + pep neutrinos from the model (known at 1% accuracy thanks to the luminosity constraint) **+ 7 SNU** from 8B as rescaled from Kamiokande + **34 ± 4 SNU** expected from 7Be => ~**134 SNU**
- **No room for ^{7}Be neutrinos**

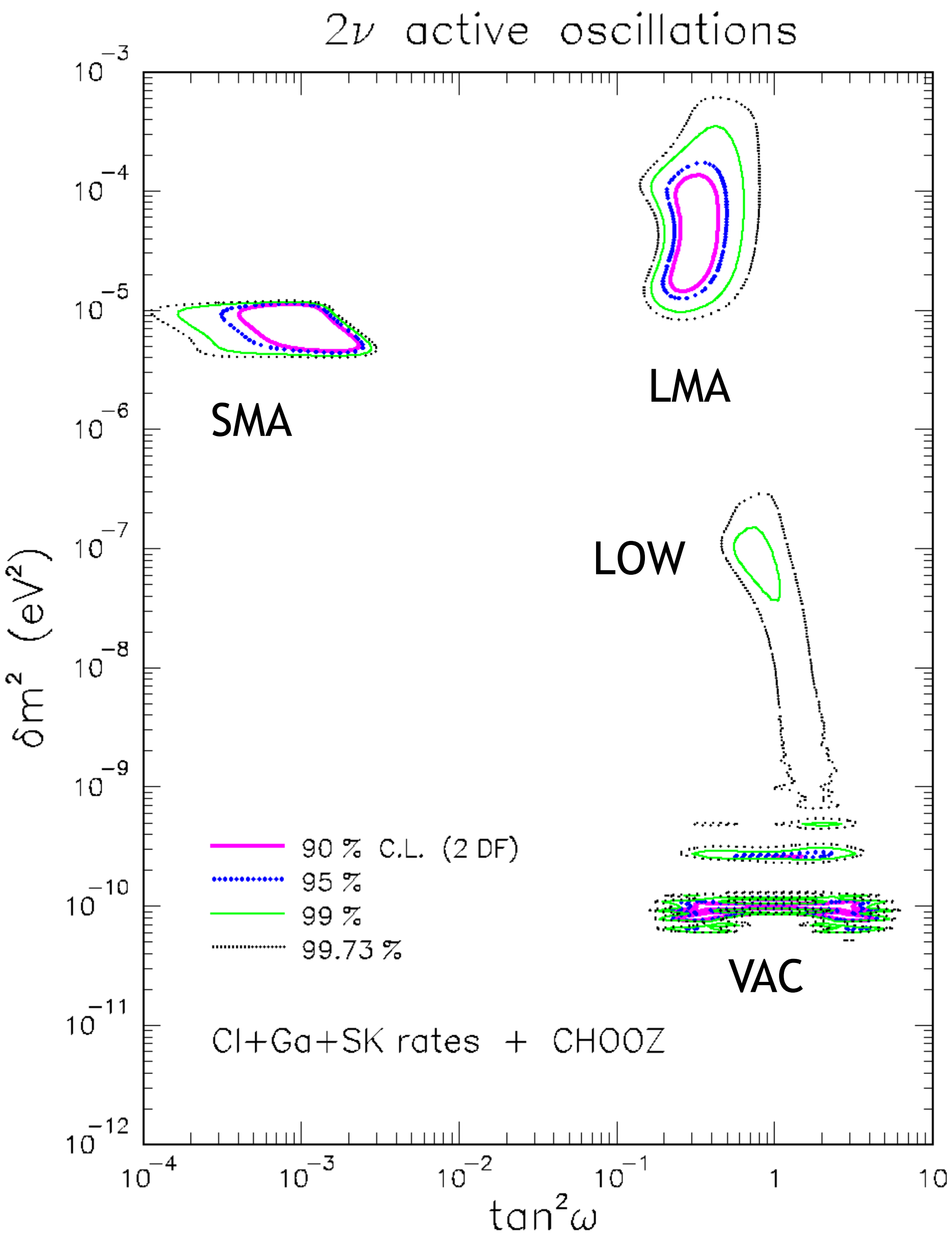
Neutrino mixing



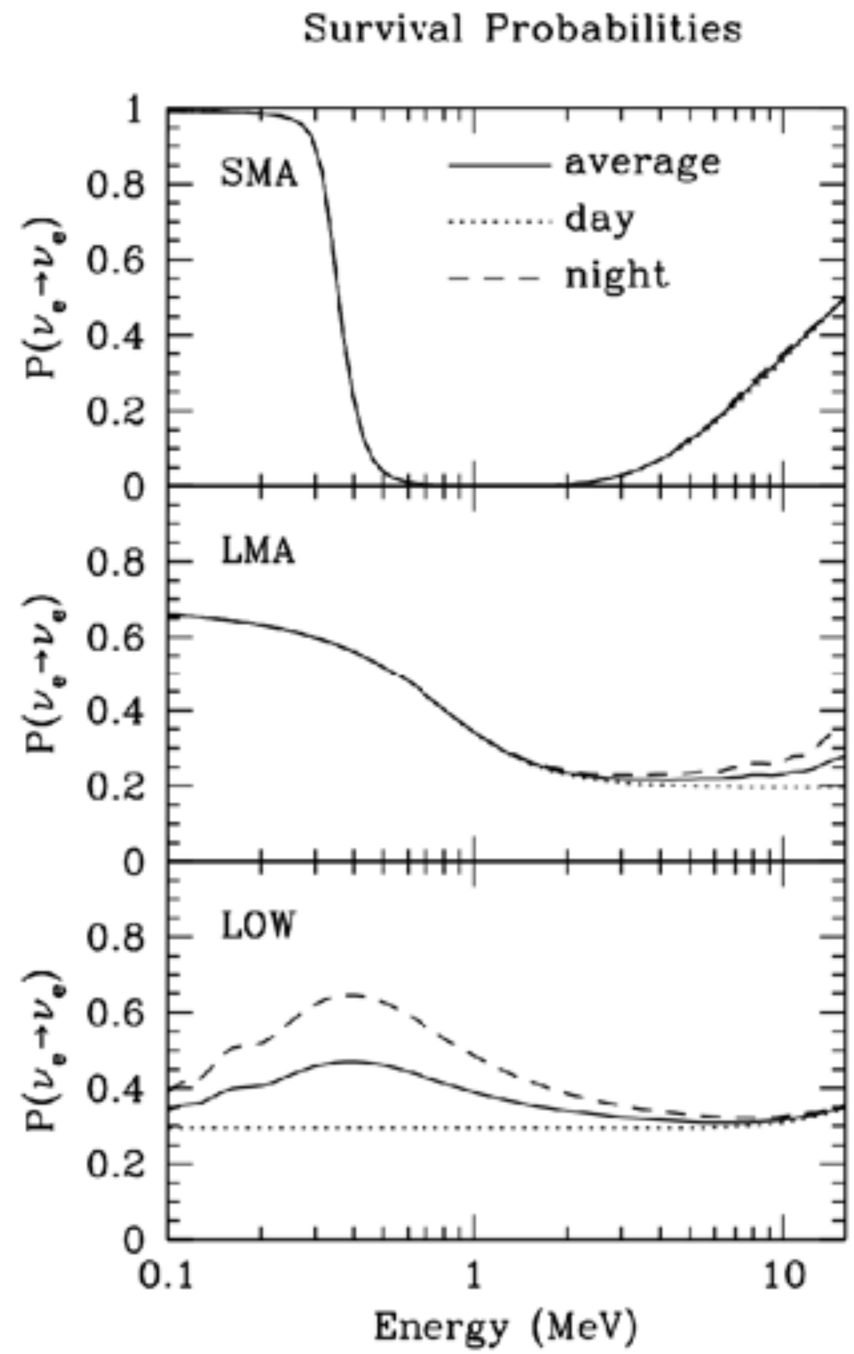




The Mikheyev-Smirnov-Wolfenstein Mechanism: the density dependence of the neutrino effective mass could greatly enhance oscillation probabilities: a ν_e is adiabatically transformed into a ν_μ as it traverses a critical density within the Sun.



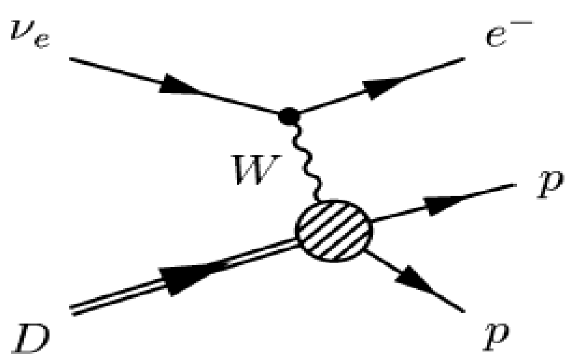
2ν active oscillations
SMA
LMA
LOW
VAC
90 % C.L. (2 DF)
95 %
99 %
99.73 %
Cl+Ga+SK rates + CHOOZ
δm² (eV²)
tan²ω



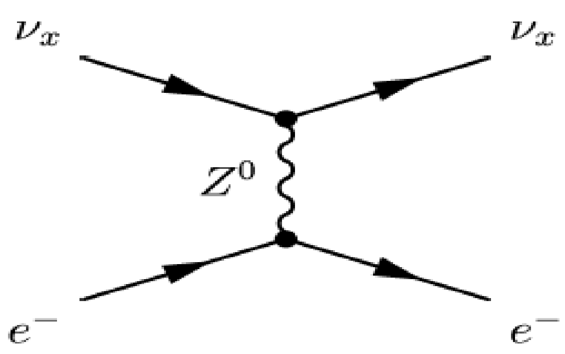
Survival Probabilities
SMA
LMA
LOW
average
day
night
P(νe→νe)
Energy (MeV)

SNO

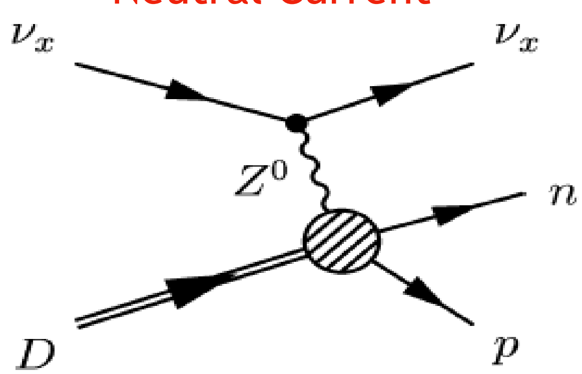
Charged Current



Elastic Scattering



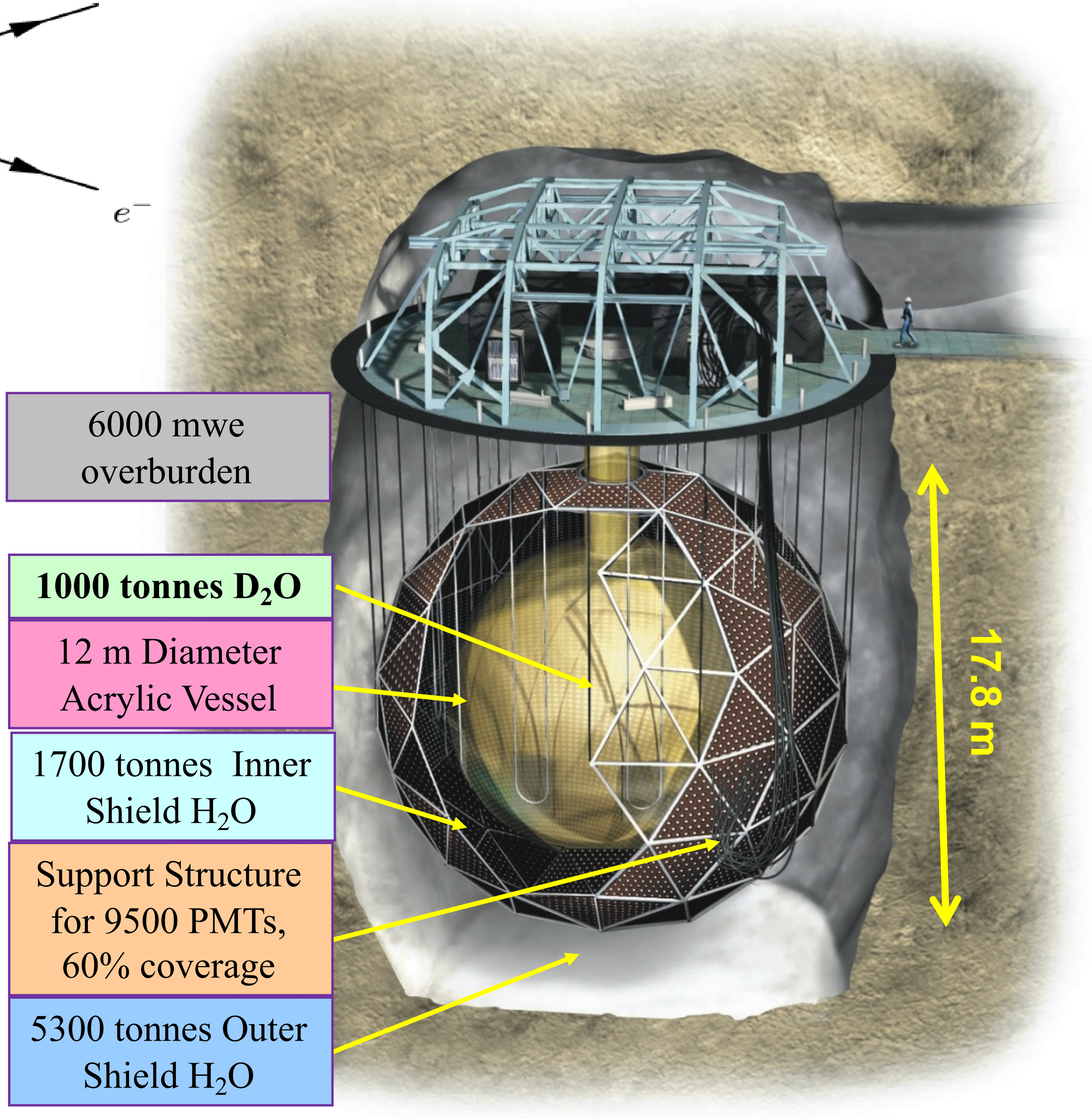
Neutral Current

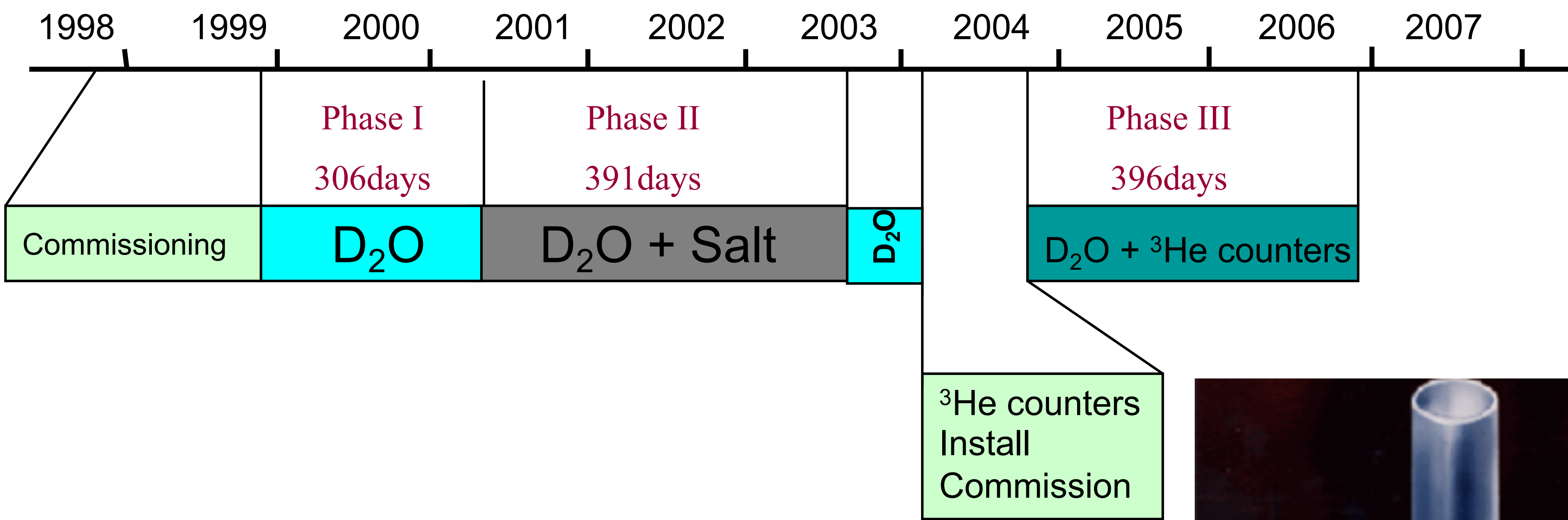


$$\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

Image courtesy National Geographic





Phase-I

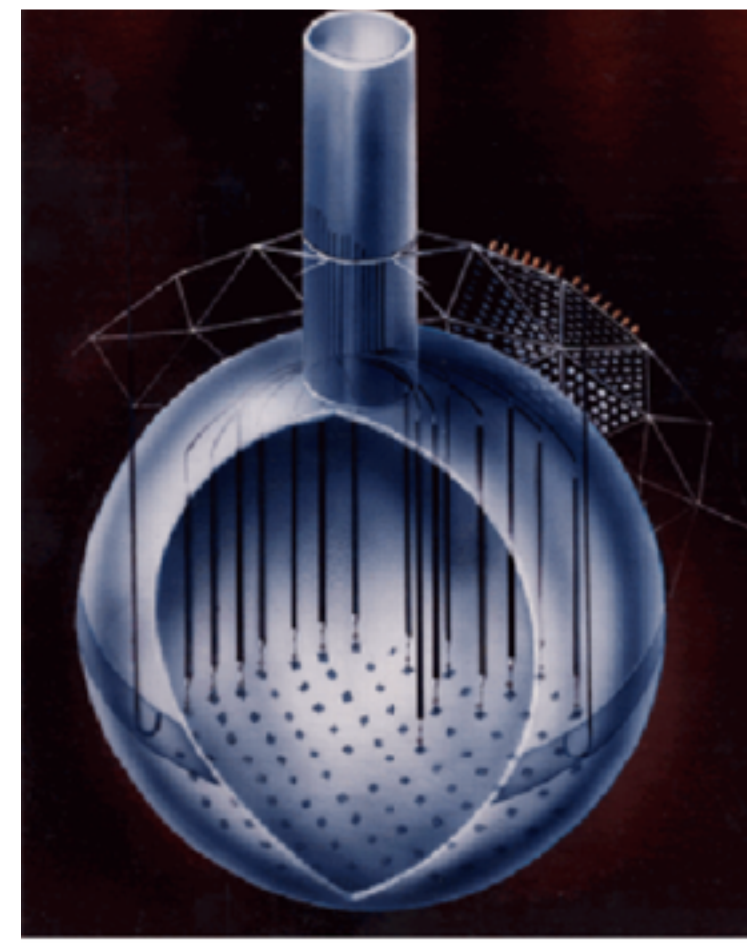
- n captures on Deuterium
- $^2H(n,\gamma)^3H$
- σ = 0.0005b
- 6.25 MeV single γ
- PMT array readout

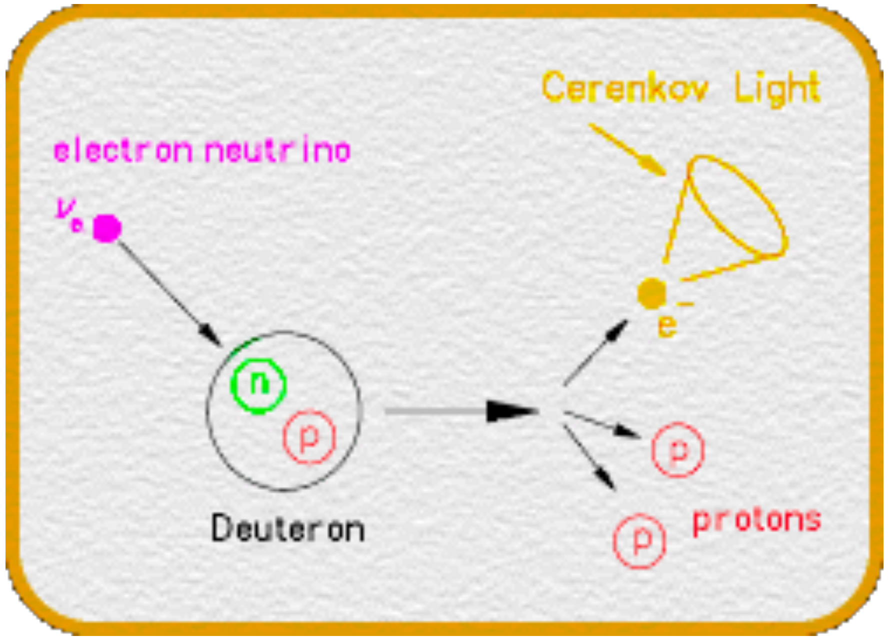
Phase-II

- 2 tons of NaCl added
- n captures on Chlorine
- $^{35}Cl(n,\gamma's)^{36}Cl$
- σ = 44b
- 8.6 MeV multiple γs
- PMT array readout

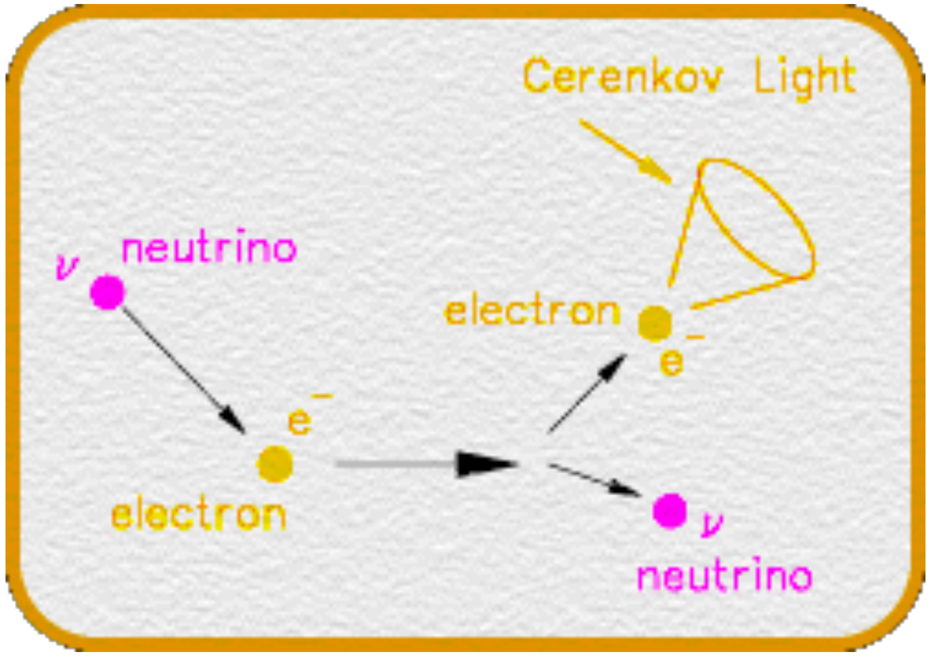
Phase-III

- n captures on 3He
- $^3He(n,p)^3H$
- σ = 5330b
- 0.764 MeV(p,3H)
- NCD readout

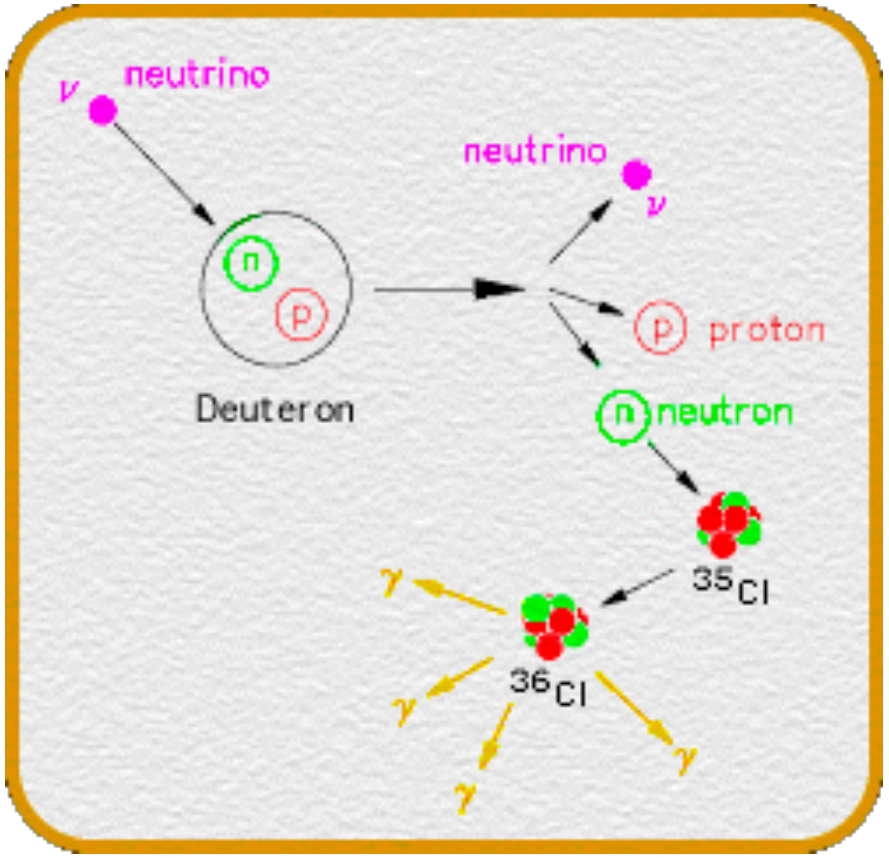




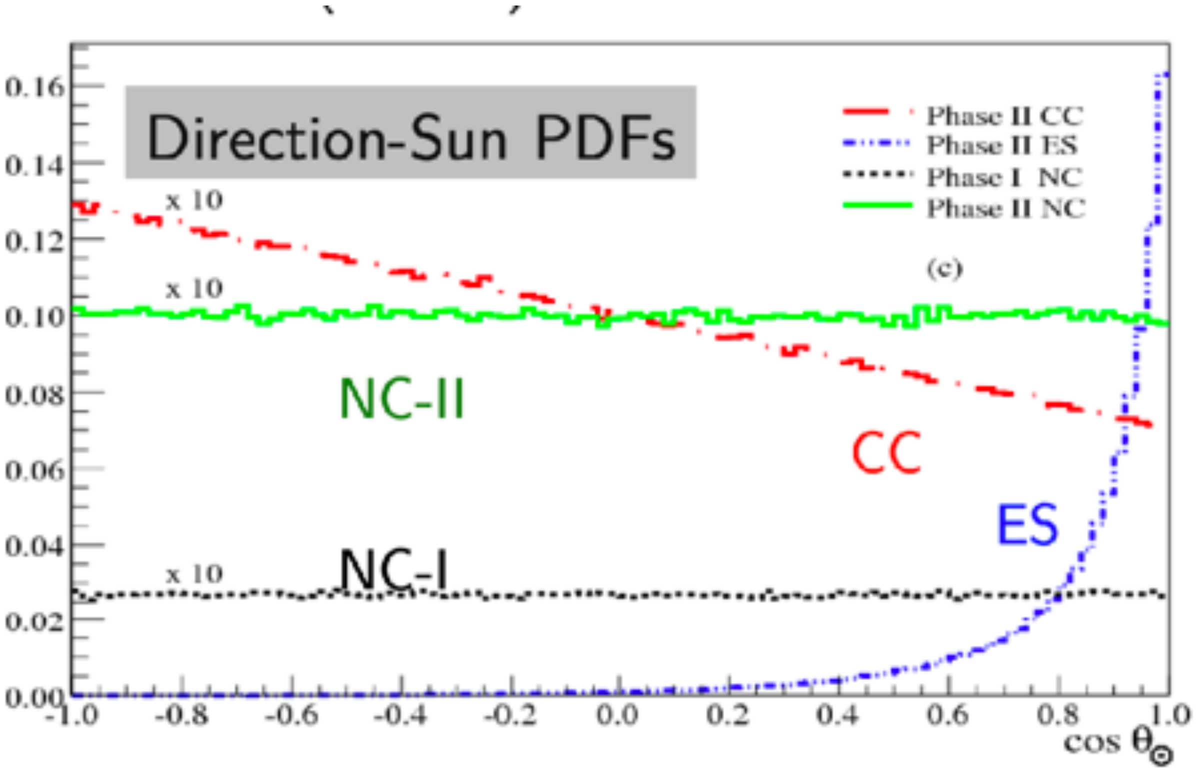
Cerenkov Light
electron neutrino
ν_e
n
p
Deuteron
e⁻
p
p
protons



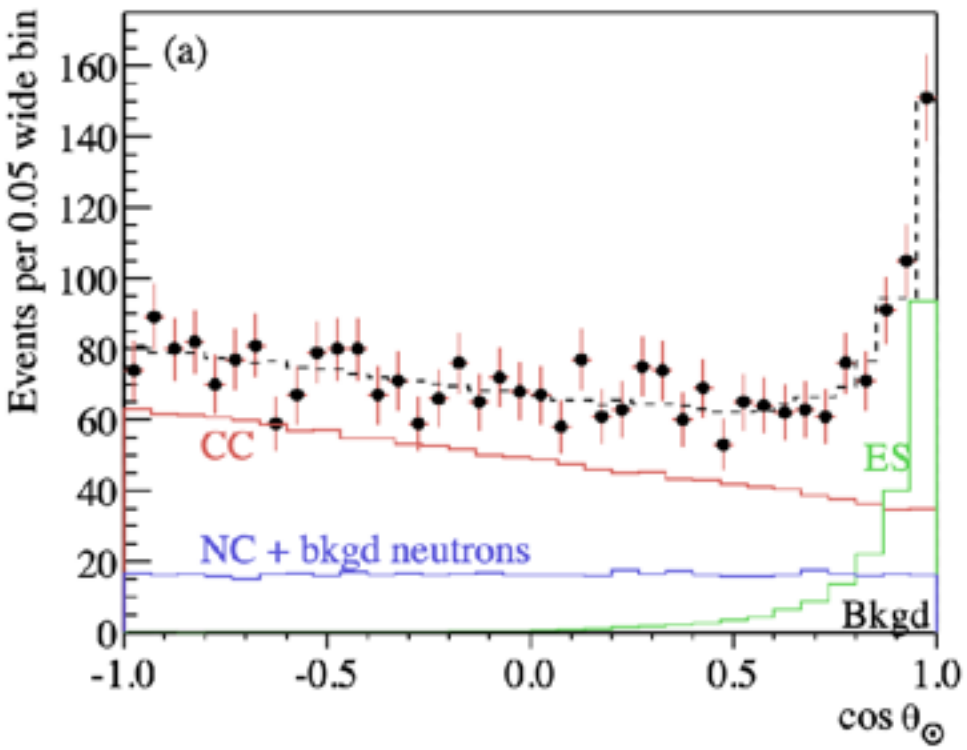
Cerenkov Light
ν
neutrino
electron
e⁻
e⁻
electron
ν
neutrino

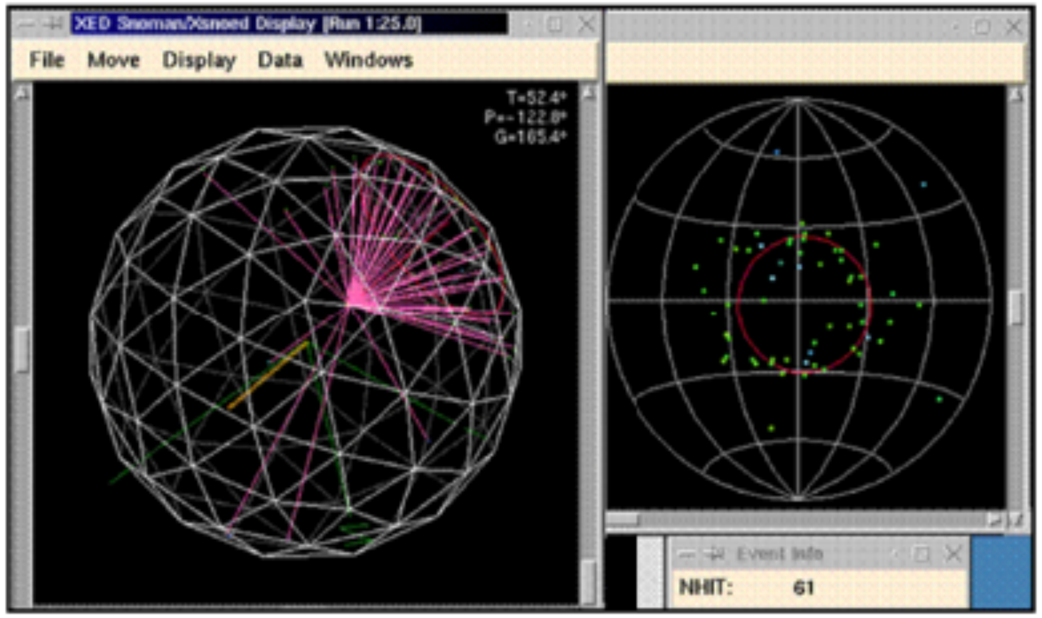


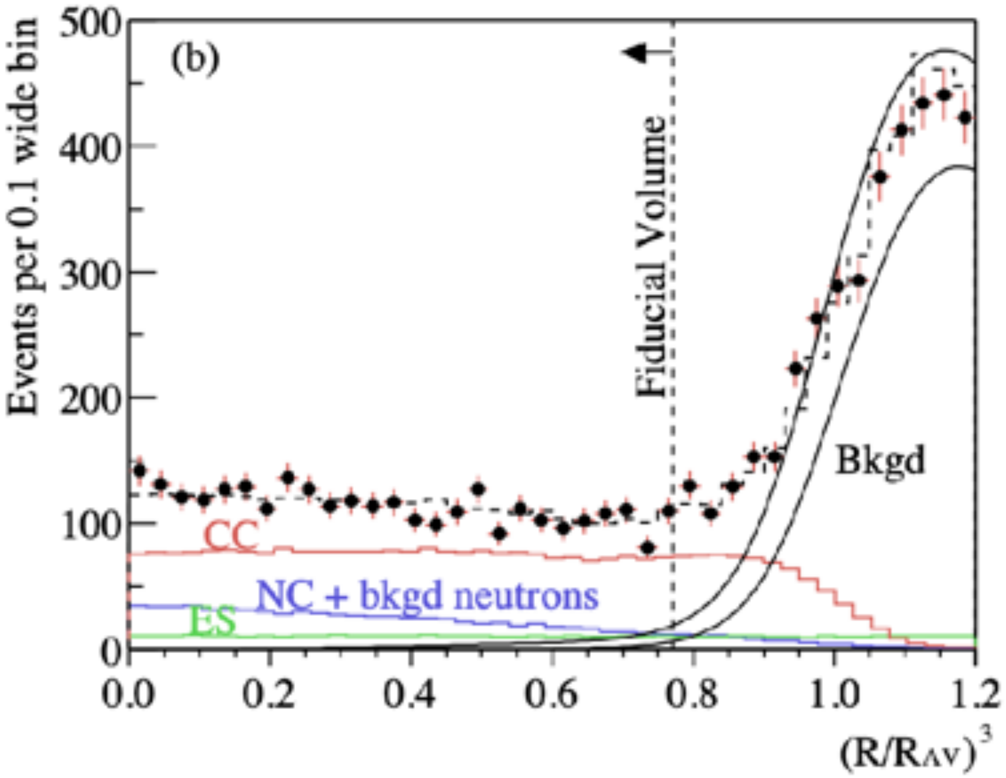
ν
neutrino
neutrino
ν
n
p
Deuteron
p
proton
n
neutron
^{35}Cl
^{36}Cl
γ

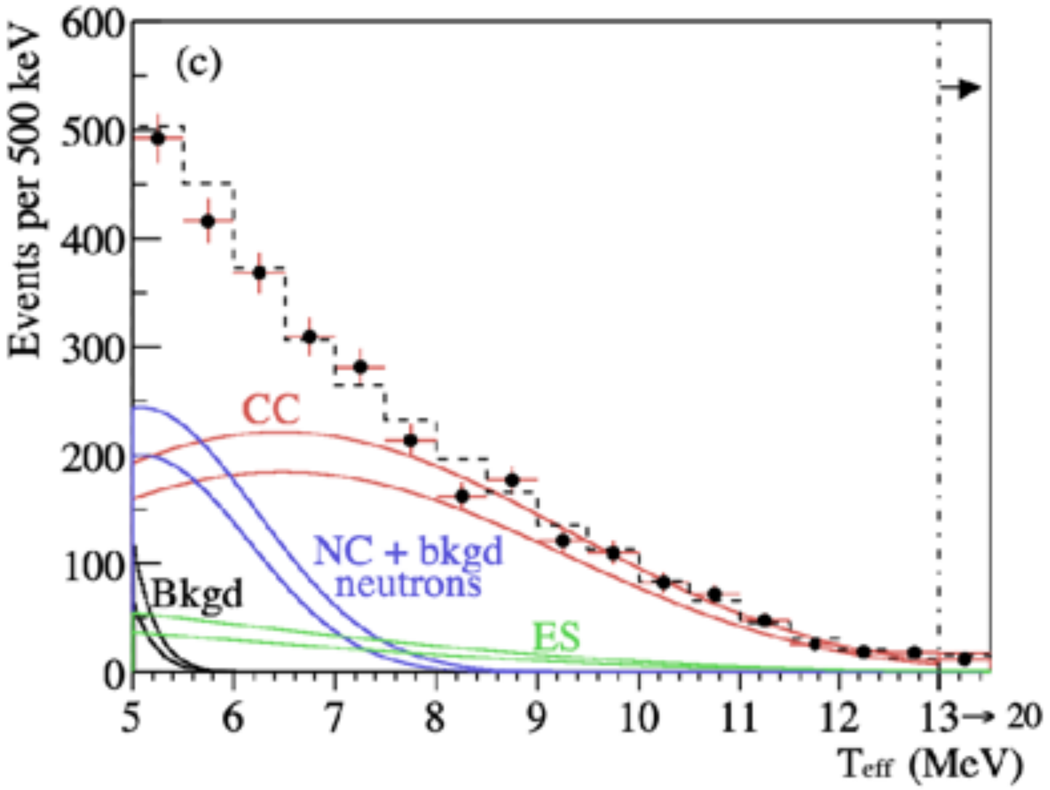


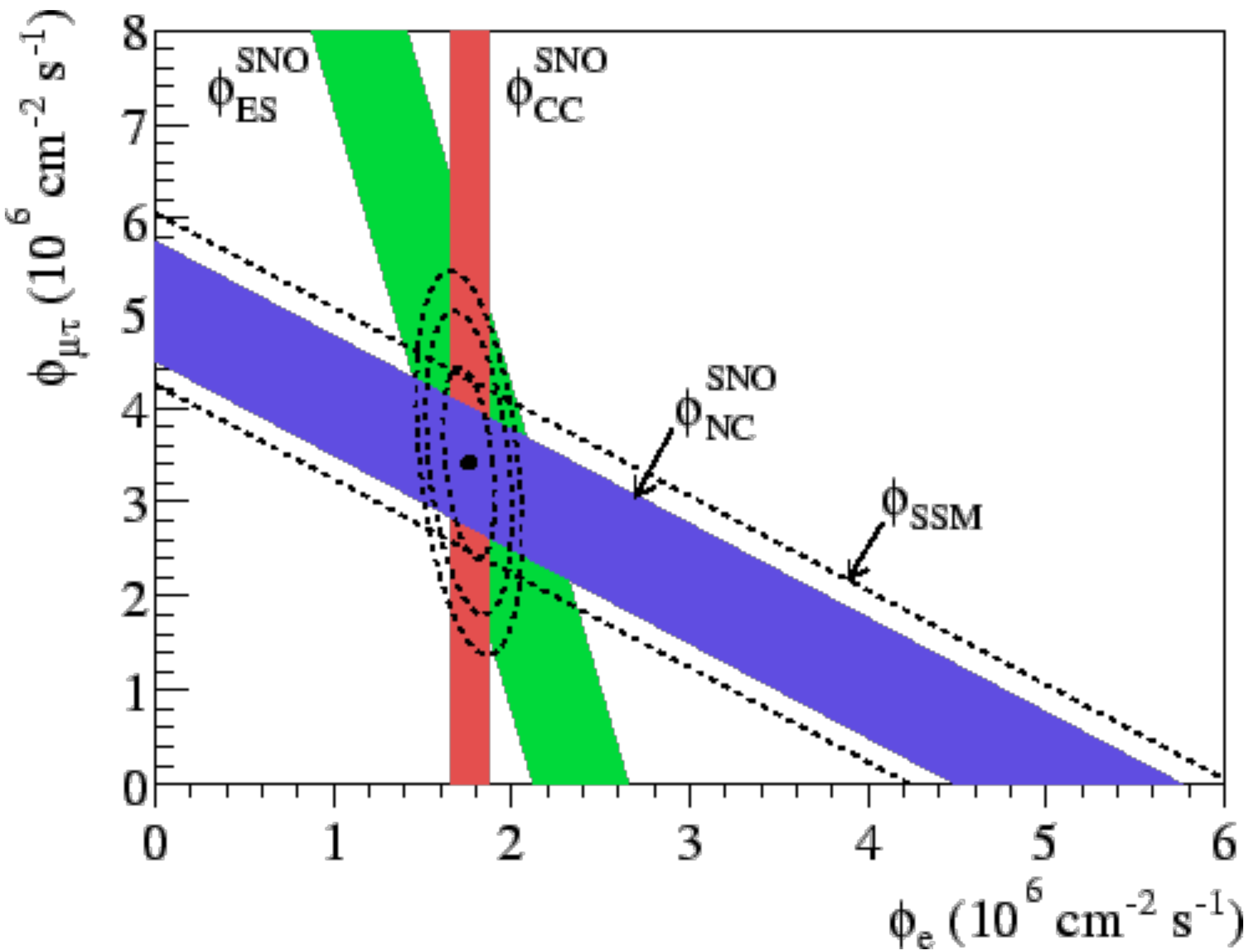
Direction-Sun PDFs
Phase II CC
Phase II ES
Phase I NC
Phase II NC
(c)
x 10
x 10
x 10
NC-II
CC
ES
NC-I
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\cos\theta_\odot$


(a)
Events per 0.05 wide bin
CC
ES
NC + bkgd neutrons
Bkgd
cos θ⊙


XED Snoman/Xsnoed Display [Run 1:25.0]
File Move Display Data Windows
NHIT: 61


(b)
Events per 0.1 wide bin
Fiducial Volume
CC
NC + bkgd neutrons
ES
Bkgd
(R/RAV)3


(c)
Events per 500 keV
CC
NC + bkgd
neutrons
Bkgd
ES
Teff (MeV)



ϕ_{ES}^{SNO}
ϕ_{CC}^{SNO}
ϕ_{NC}^{SNO}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

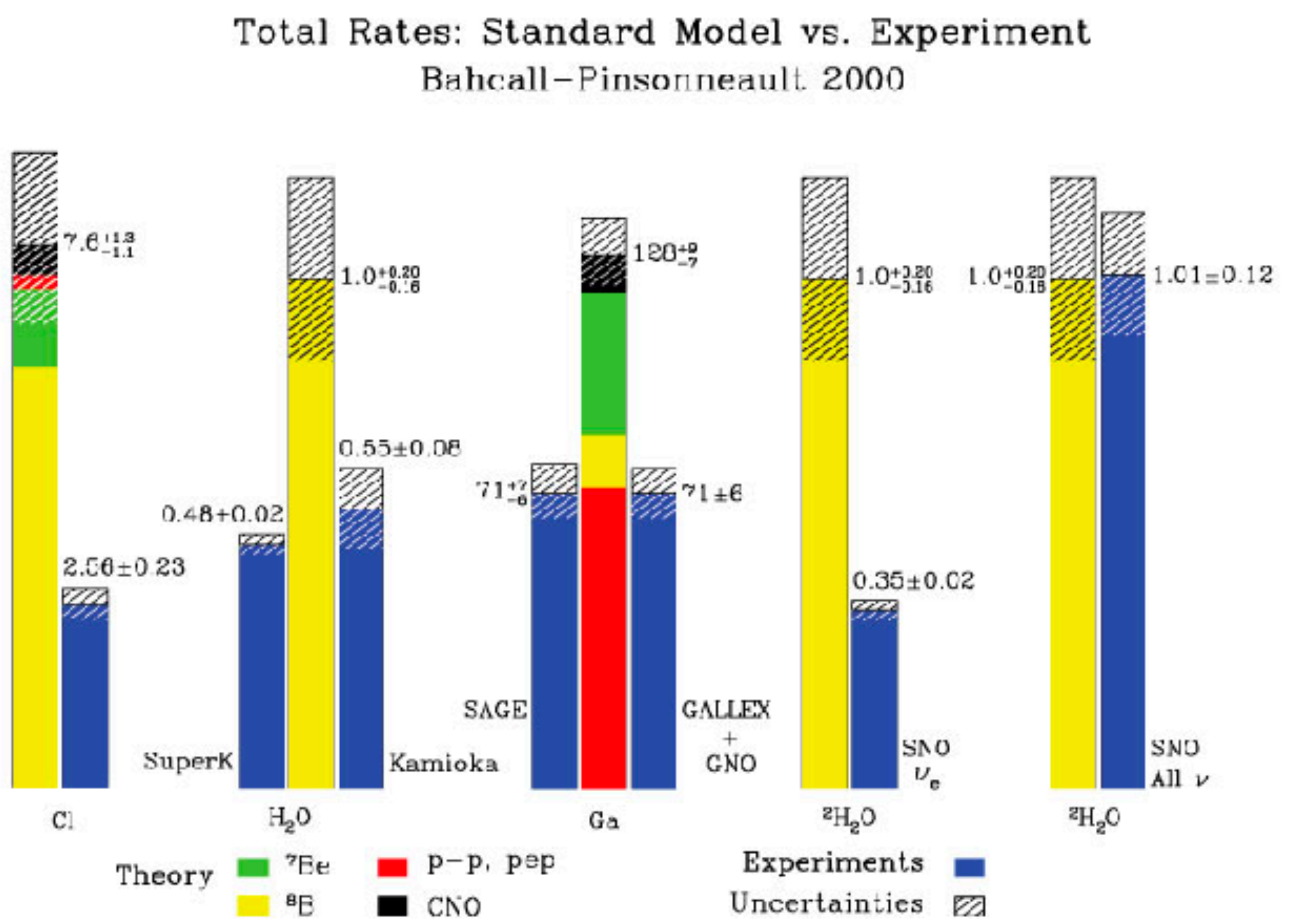
Nobel Prize 2015

for the discovery of neutrino oscillations, which shows that neutrinos have mass

Takaaki Kajita

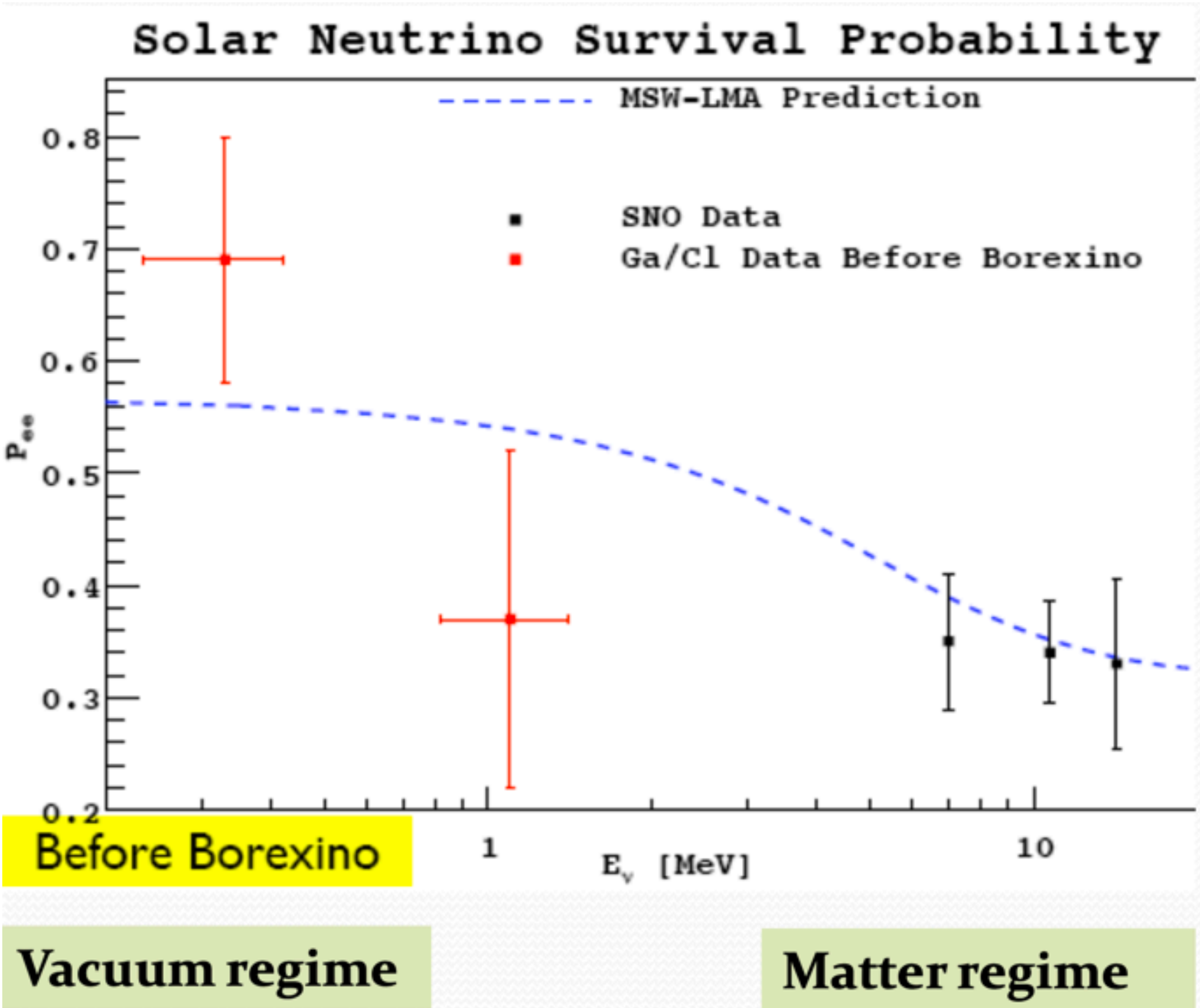
Arthur B. McDonald

SNO



The puzzle is going to be solved… but only a small fraction of 8B neutrinos were observed in real time.
In total less than 1% of the entire solar neutrino flux was detected

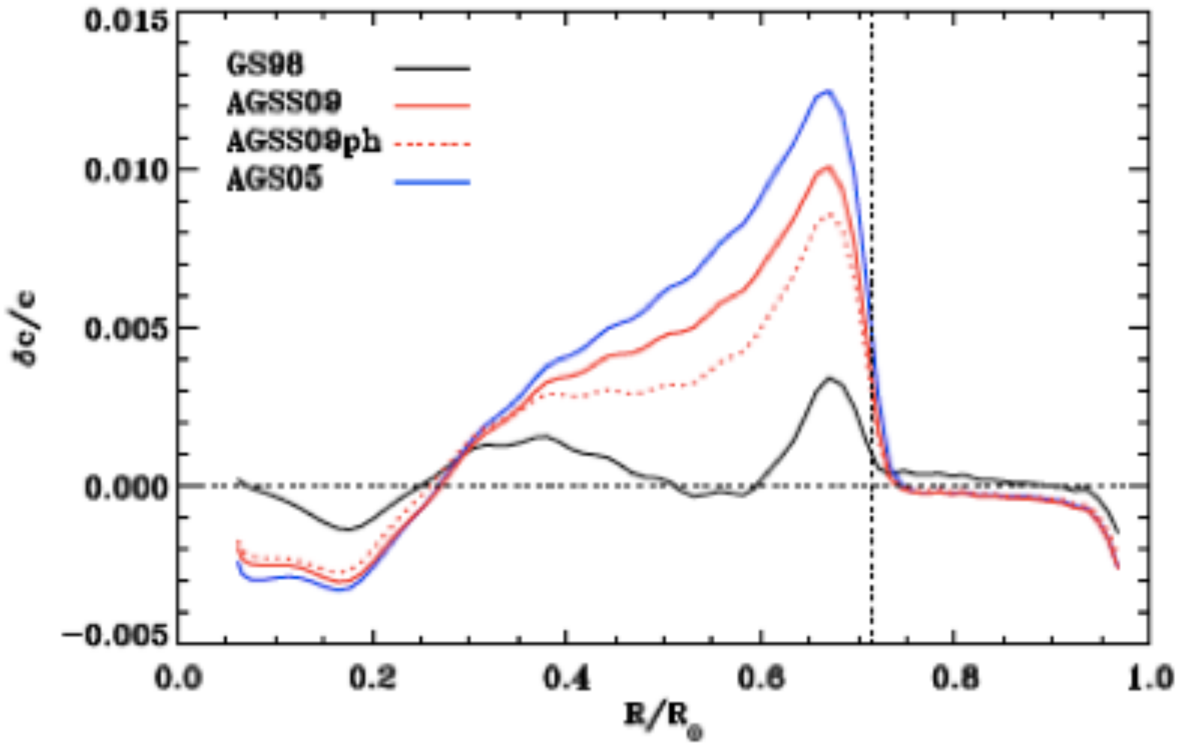
Before Borexino



New issues with the SSM

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.



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

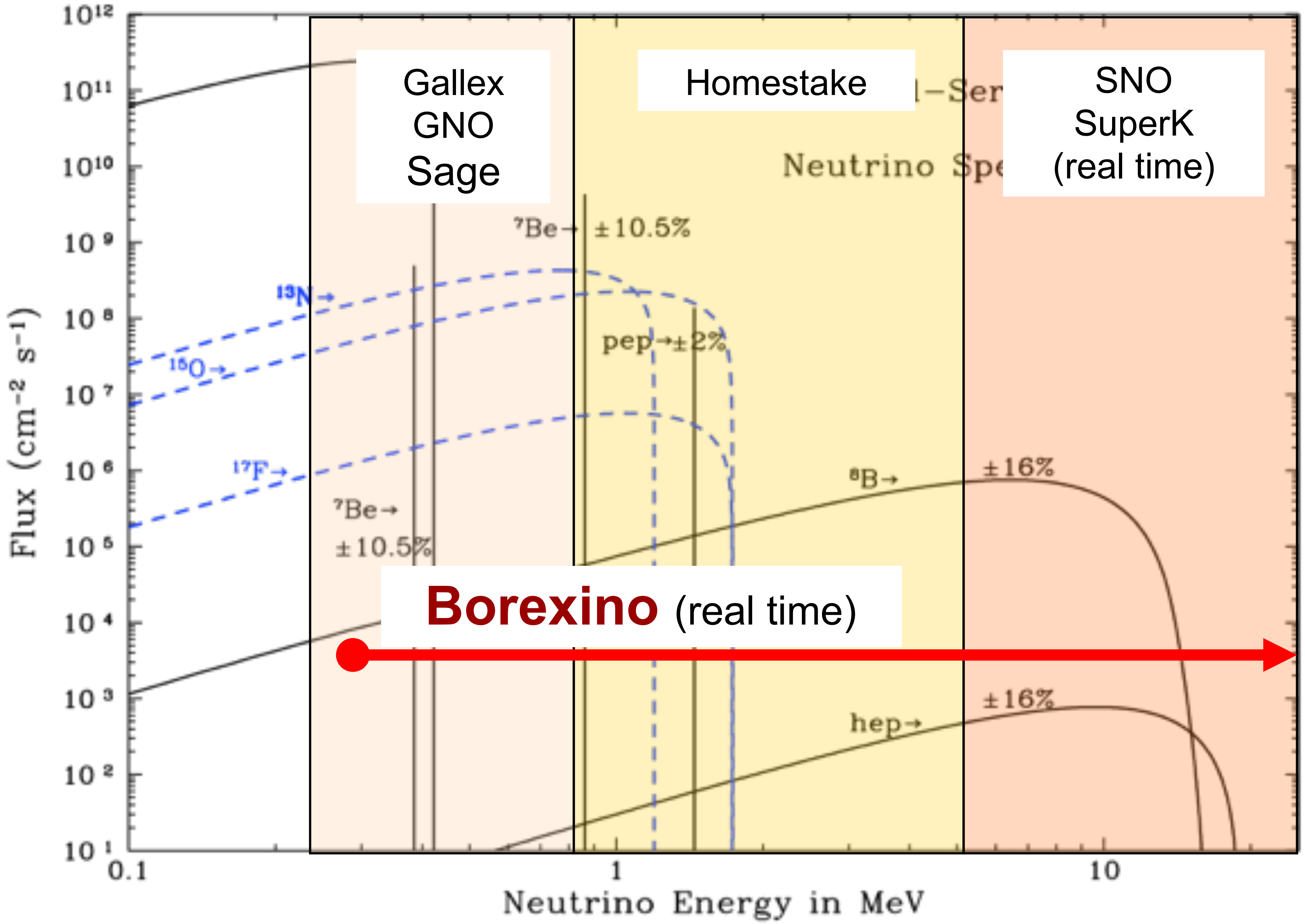
Revised model in 2009 by Serenelli, Basu, Ferguson, Asplund (Astrophys.J.705:L123-L127,2009) slightly reduced the discrepancy.

New issues with the SSM

What about neutrinos?

$[cm^{-2}\ s^{-1}]$	pp (10^{10})	pep (10^{10})	hep (10^{3})	^{7}Be (10^{9})	^{8}B (10^{6})	^{13}N (10^{8})	^{15}O (10^{8})	^{17}F (10^{6})
GS 98	5.97	1.41	7.91	5.08	5.88	2.82	2.09	5.65
AGS 09	6.03	1.44	8.18	4.64	4.85	2.07	1.47	3.48
Δ	-1 %	-2 %	-3 %	-9 %	-18 %	-27 %	-30 %	-38 %

Real time detection, via elastic scattering, from 200 keV

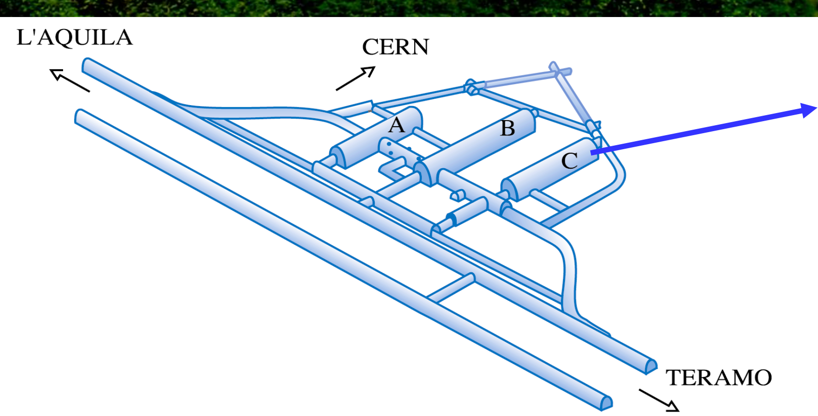


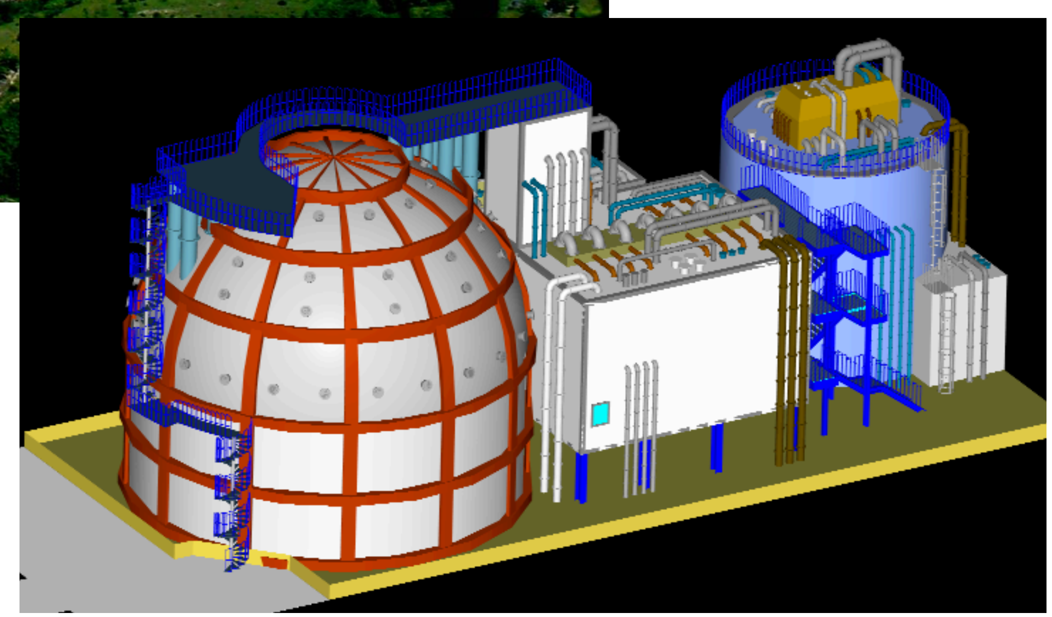
Borexino

Laboratori Nazionali del Gran Sasso

Assergi (AQ) Italy

~3500 m.w.e

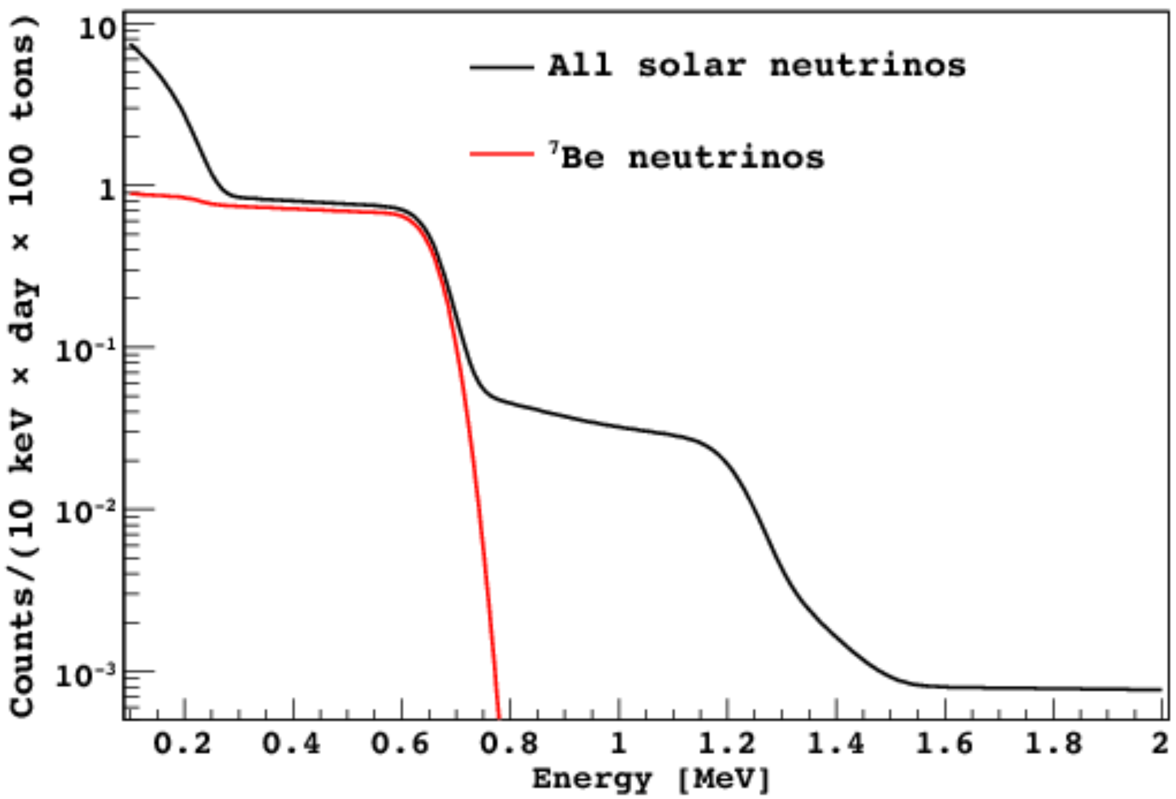




- Borexino detects solar ν via their **elastic scattering off electrons** in a volume of **highly purified liquid scintillator**
  - Mono-energetic **0.862 MeV ^{7}Be ν** are the main target, and the only considered so far
  - Mono-energetic pep ν , CNO ν and possibly pp ν will be studied in the future

- Detection via scintillation light:
  - Very low energy threshold
  - Good position reconstruction
  - Good energy resolution

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



- **Extreme radiopurity of the scintillator is a must!**

Expected solar neutrino rate in 100 tons of scintillator ~ 50 counts/day (**~ 5 10^{-9} Bq/kg**)

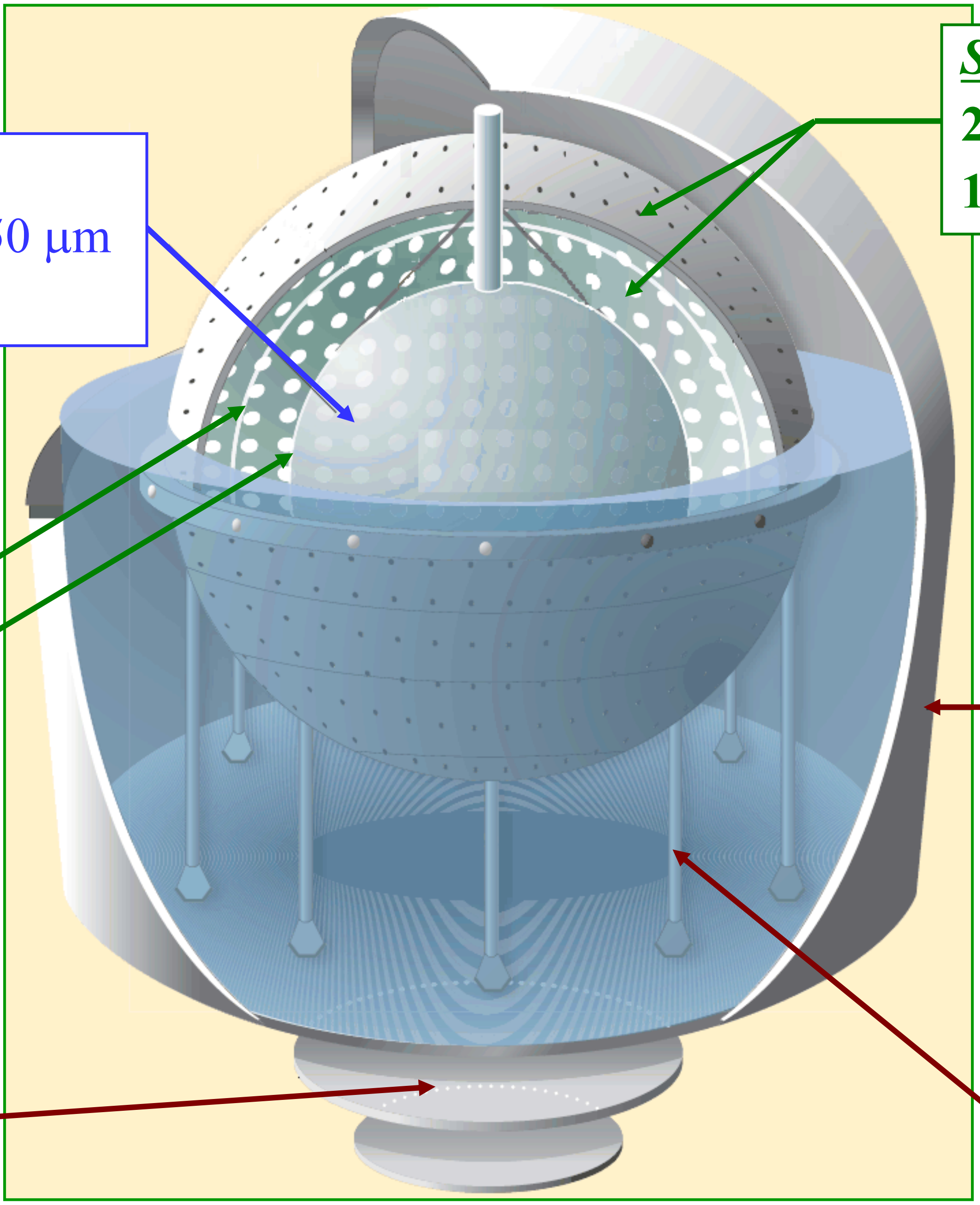
Just for comparison:

Natural water	~ 10 Bq/kg in ^{238}U, ^{232}Th and ^{40}K
Air	~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}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 (^{7}Be)
- Underground **purification plant** to distill scintillator components.
- **Gas stripping** of scintlllator with special nitrogen free of radioactive ^{85}Kr and ^{39}Ar from air
- All materials **electropolished SS or teflon**, precision cleaned with a dedicated cleaning module

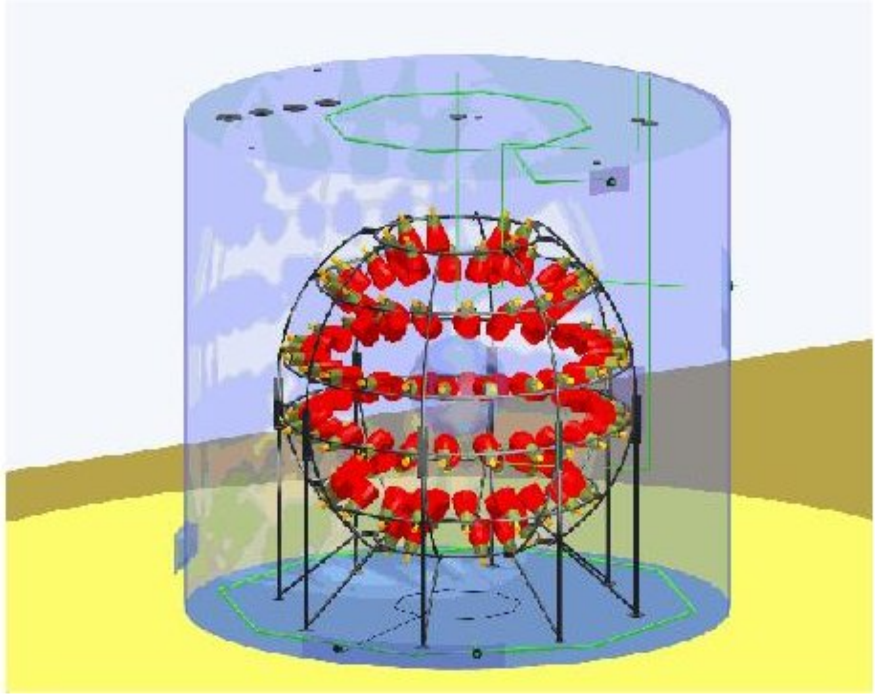
Borexino

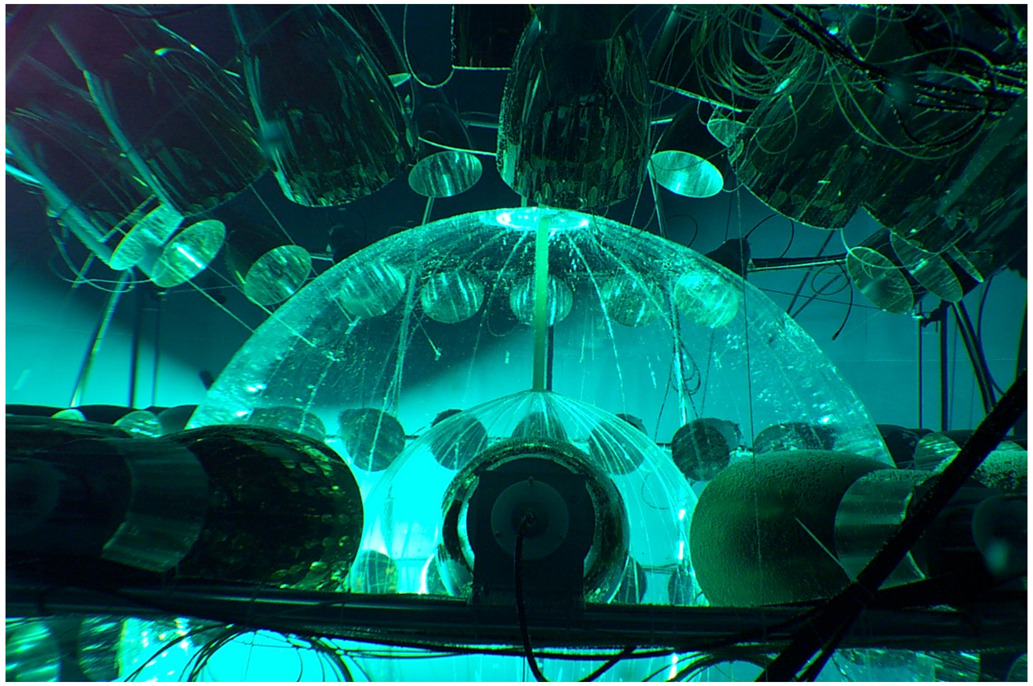


Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel
Stainless Steel Sphere:
2212 PMTs
1350 m^3
Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3
Carbon steel plates
20 legs

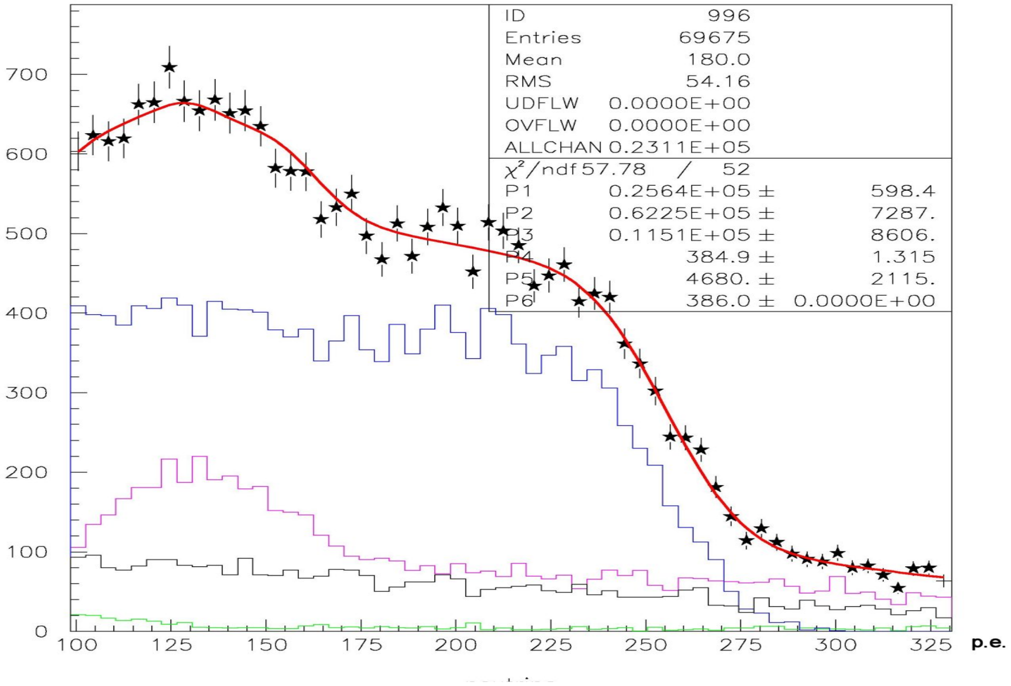
Counting Test Facility

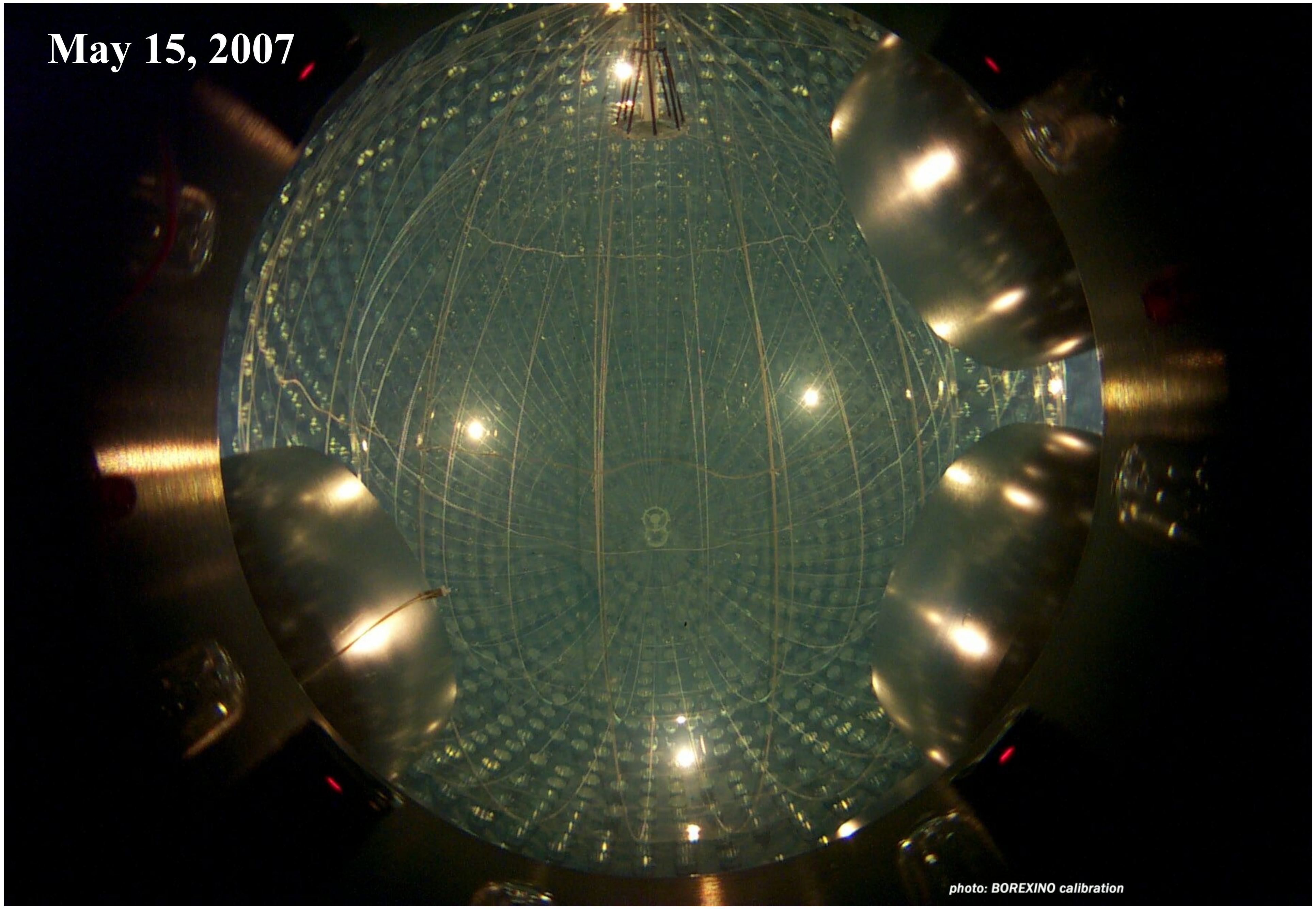
✓CTF is a small scale prototype of Borexino:
✓ ~ 4 tons of scintillator
✓ 100 PMTs
✓ Buffer of water
✓ Muon veto
✓ Vessel radius: 1 m





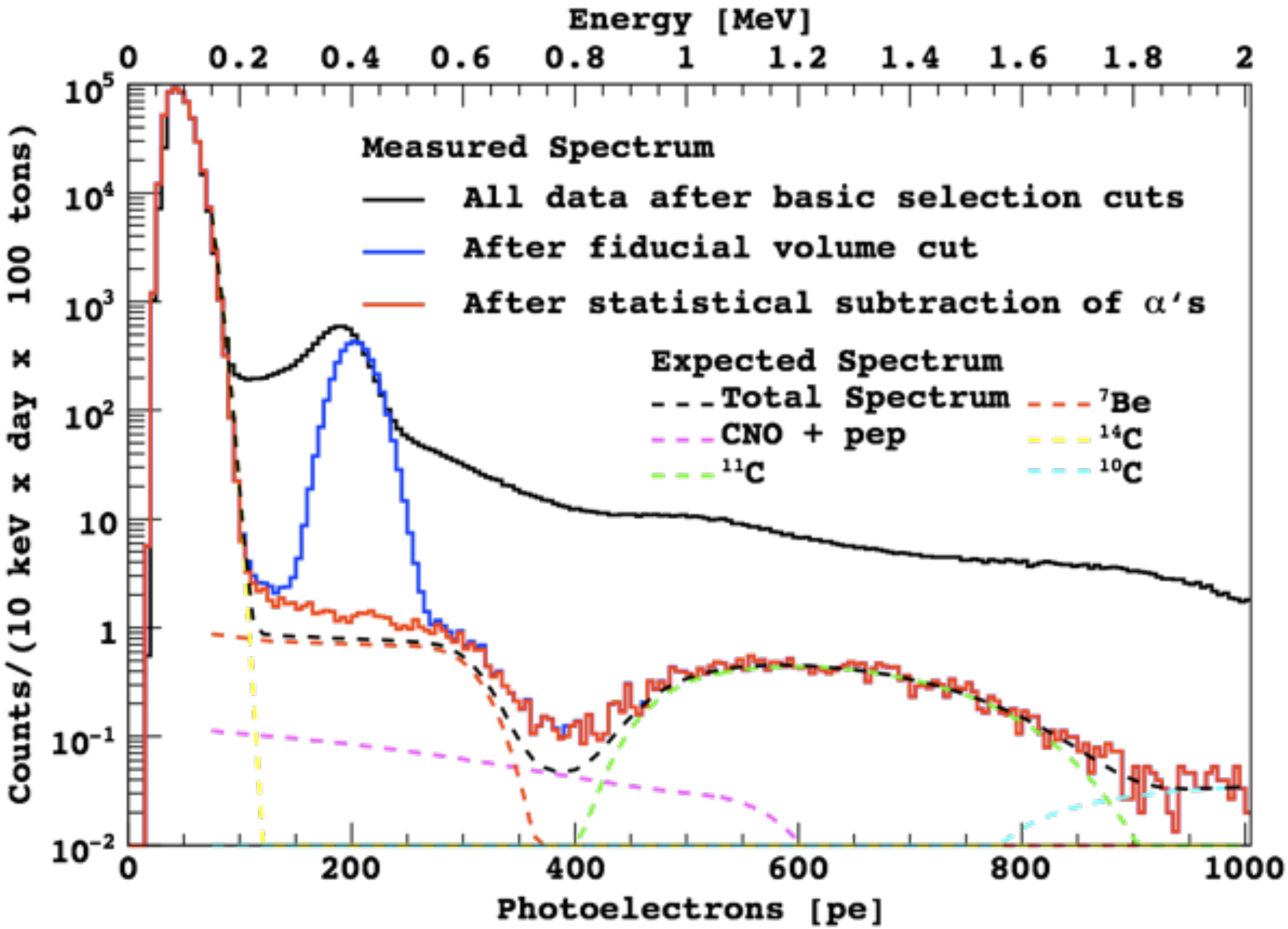
CTF demonstrates the Borexino feasibility




May 15, 2007
photo: BOREXINO calibration

RadioIsotope		Concentration or Flux		Strategy for Reduction		
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	**Achieved**
μ	cosmic	~200 s^{-1} m^{-2} at sea level	~ 10^{-10}	Underground Cherenkov detector	Cherenkov signal PS analysis	$<10^{-10}$ (overall)
Ext. γ	rock			Water Tank shielding	Fiducial Volume	negligible
Int. γ	PMTs, SSS Water, Vessels			Material Selection Clean constr. and handling	Fiducial Volume	negligible
^{14}C	Intrinsic PC/PPO	~ 10^{-12}	~ 10^{-18}	Old Oil, check in CTF	Threshold cut	~ 10^{-18}
^{238}U ^{232}Th	Dust Organometallic (?)	~ 10^{-5}-10^{-6} g/g (dust)	< 10^{-16} g/g (in scintillator)	Distillation, Water Extraction Filtration, cleanliness		~ 2 10^{-17} ~ 7 10^{-18}
^{7}Be	Cosmogenic (^{12}C)	~ 3 10^{-2} Bq/t	< 10^{-6} Bq/ton	Fast procurement, distillation	Not yet measurable	?
^{40}K	Dust, PPO	~ 2 10^{-6} g/g (dust)	< 10^{-14} g/g scin. < 10^{-11} g/g PPO	Water Extraction Distillation	Not yet measurable	?
^{210}Pb	Surface contam. from ^{222}Rn decay			Cleanliness, distillation	Not yet measurable (NOT in eq. with ^{210}Po)	?
^{210}Po	Surface contam. from ^{222}Rn decay			Cleanliness, distillation	Spectral analysis α/β stat. subtraction	~ 14 ~ 0.01 c/d/t
^{222}Rn	air, emanation from materials, vessels	~ 10 Bq/l (air) ~100 Bq/l (water)	< 1 c/d/100 t (scintillator)	Water and PC N_2 stripping, cleanliness, material selection	Delayed coincidence	< 0.02 c/d/t
^{39}Ar	Air (nitrogen)	~17 mBq/m^3 (air)	< 1 c/d/100 t	Select vendor, leak tightness	Not yet measurable	?
^{85}Kr	Air (nitrogen)	~ 1 Bq/m^3 in air	< 1 c/d/100 t	Select vendor, leak tightness (learn how to measure it)	Spectral fit fast coincidence	= 25±3 = 29±14

Borexino



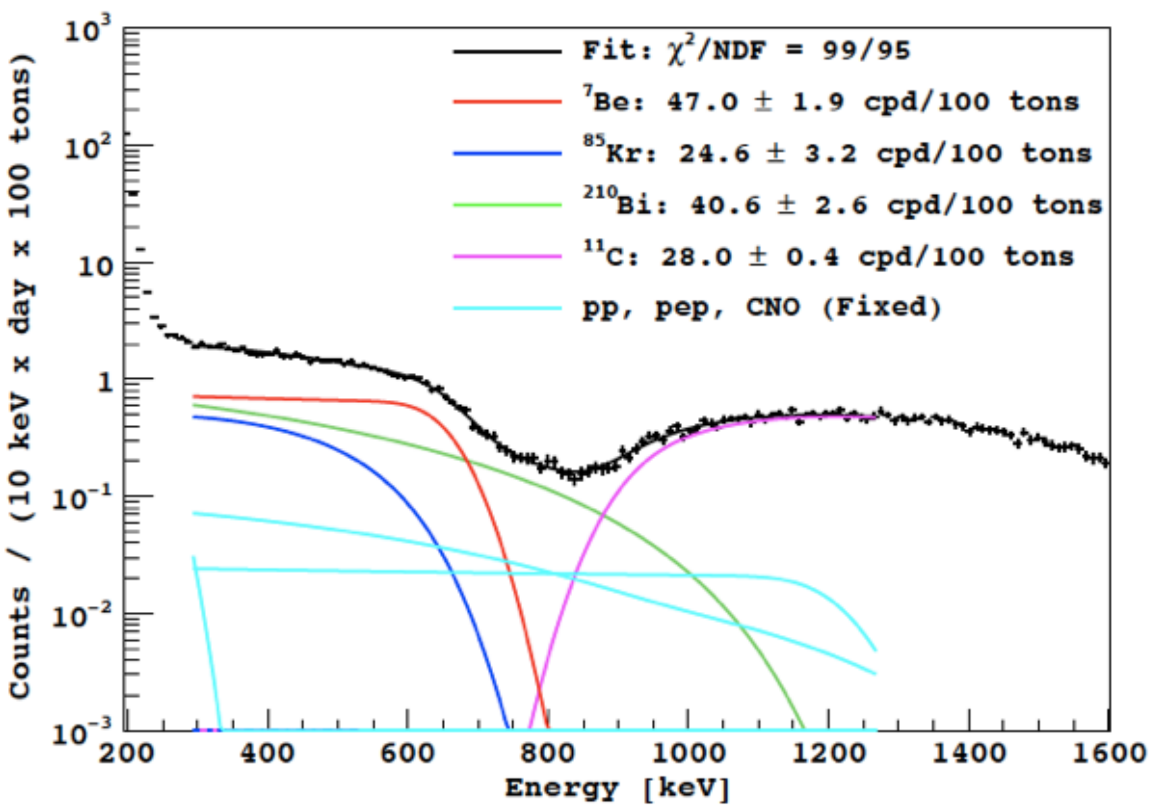
Energy [MeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Measured Spectrum
All data after basic selection cuts
After fiducial volume cut
After statistical subtraction of α's
Expected Spectrum
Total Spectrum
^{7}Be
CNO + pep
^{14}C
^{11}C
^{10}C
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
Counts/(10 keV x day x 100 tons)
0
200
400
600
800
1000
Photoelectrons [pe]

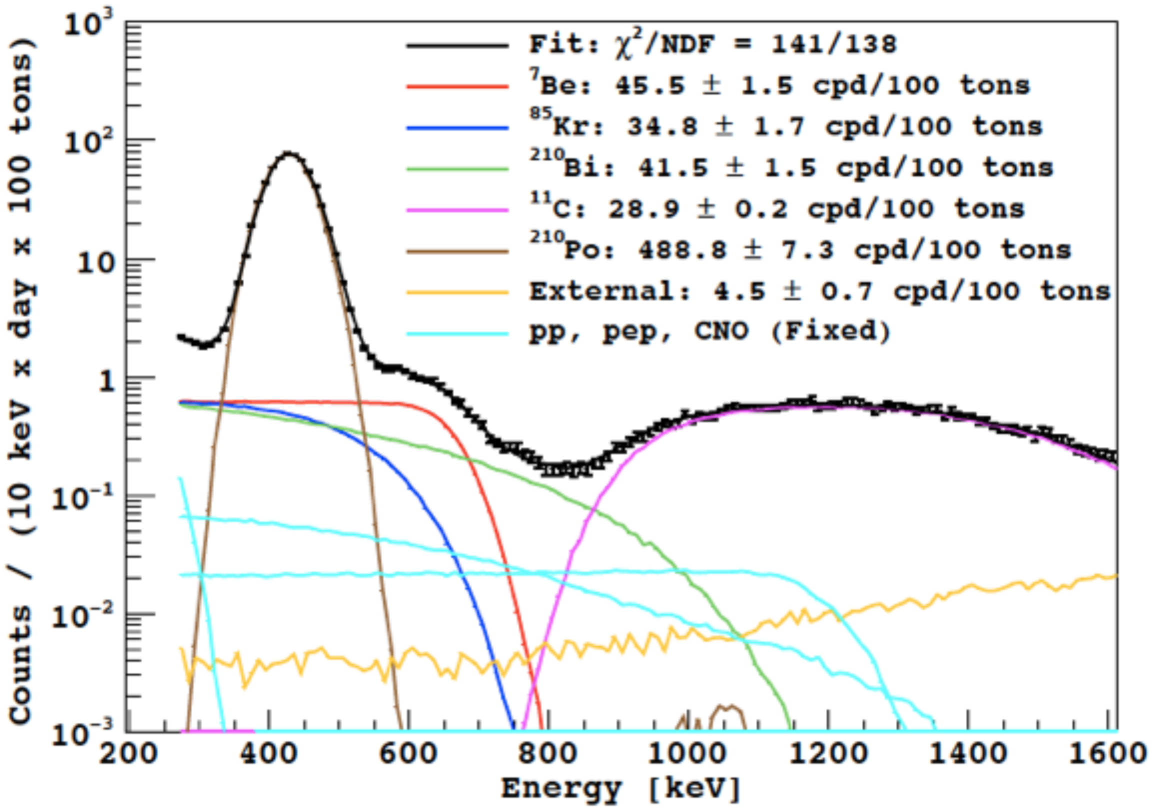
Borexino: ^{7}Be neutrinos

First results with 740 days livetime

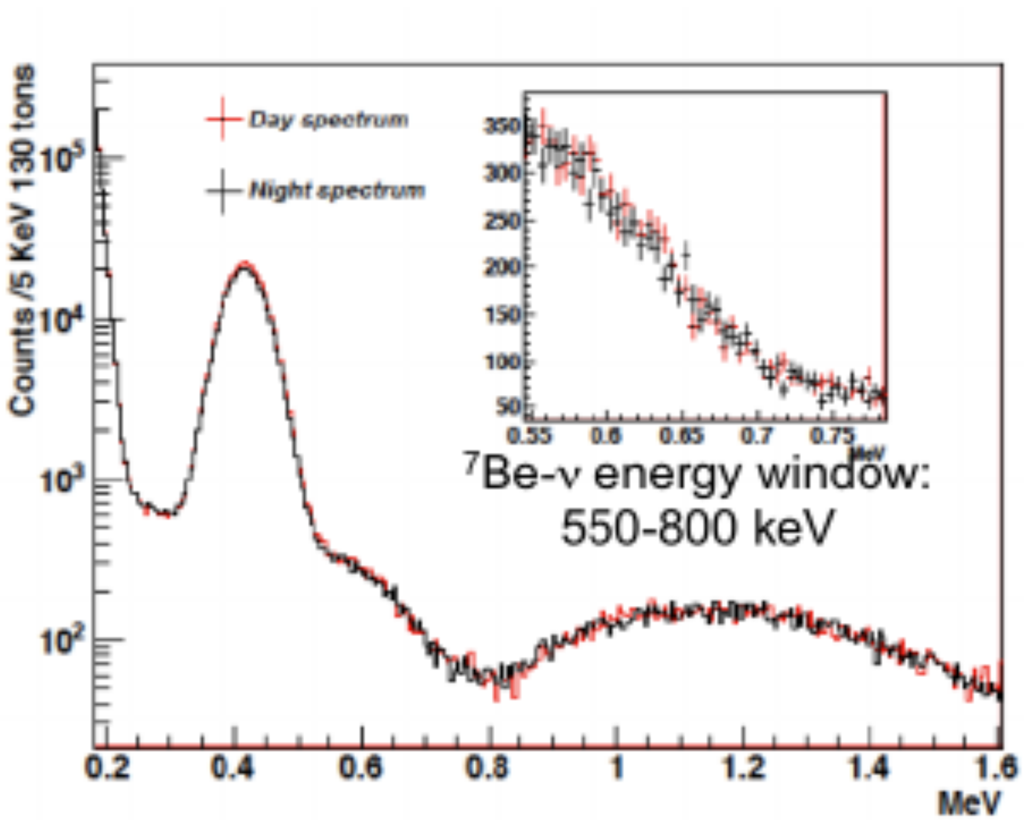
7Be Rate: 46.0±1.5stat+1.6-1.5 syst cpd/100 tons

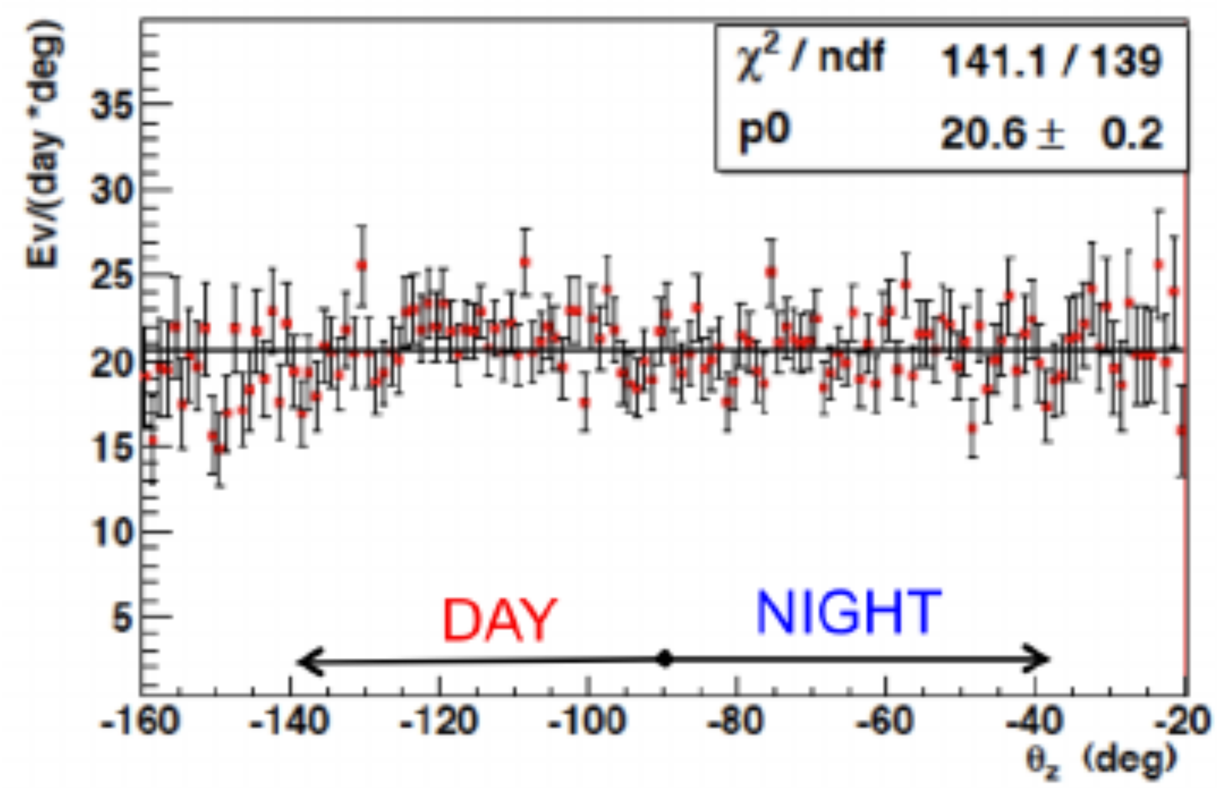
fBe = 0.97 ± 0.05





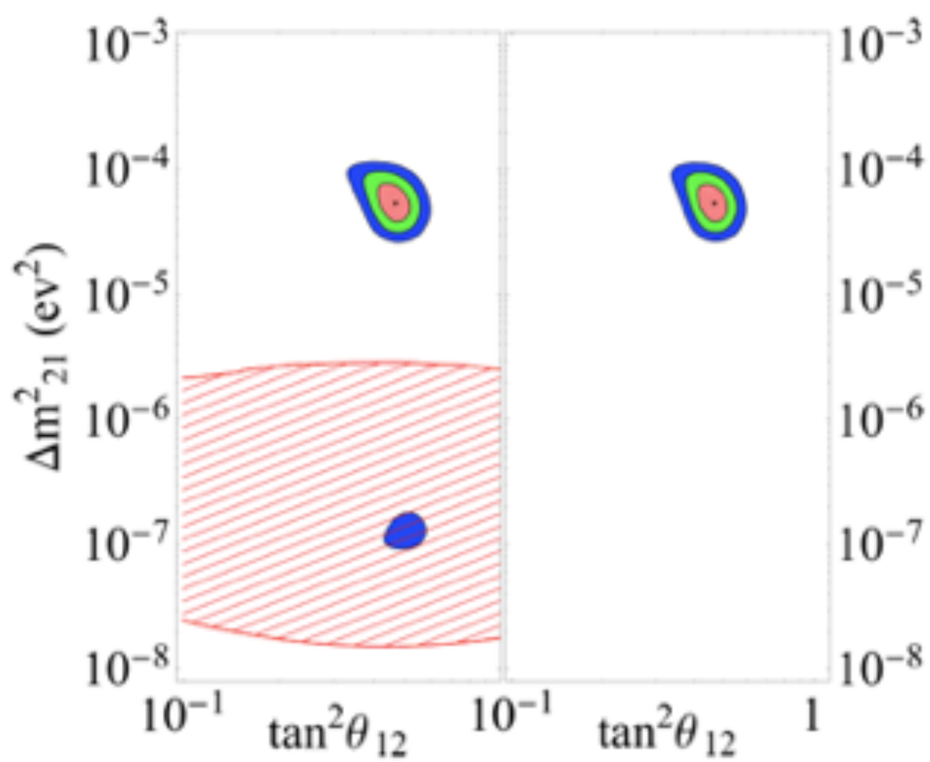
Borexino



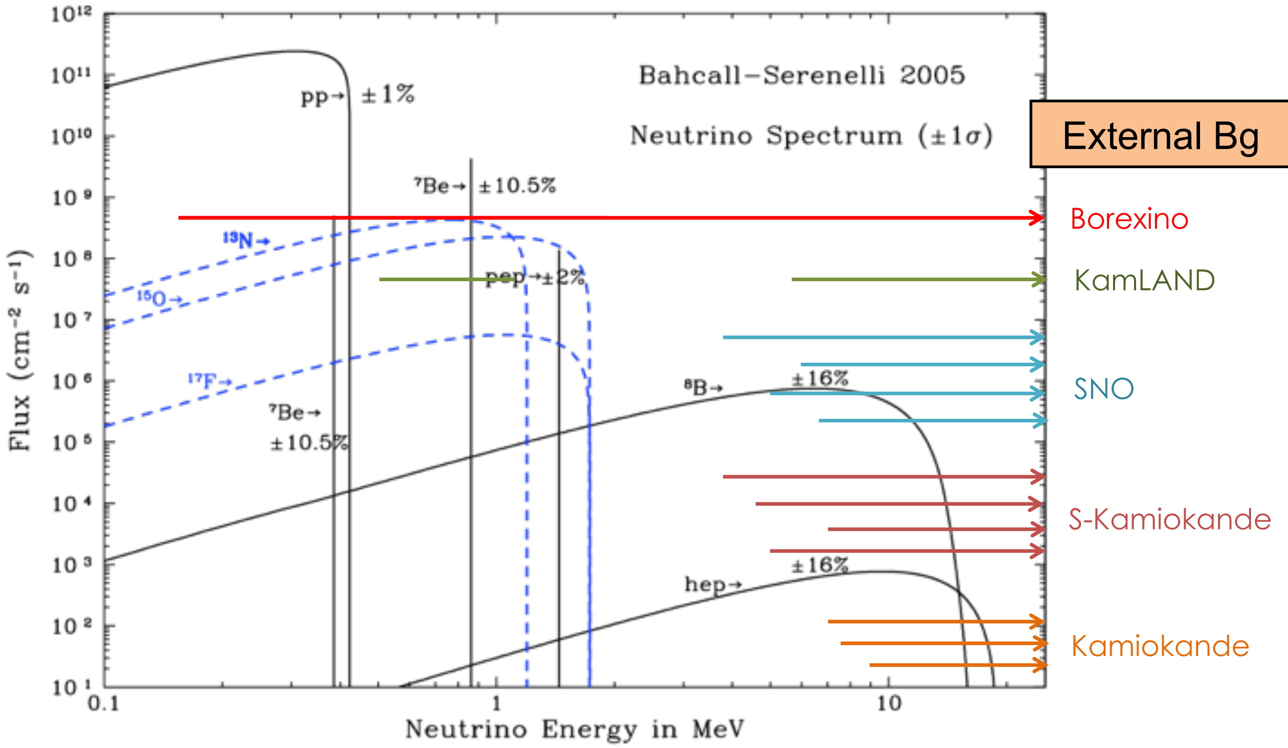


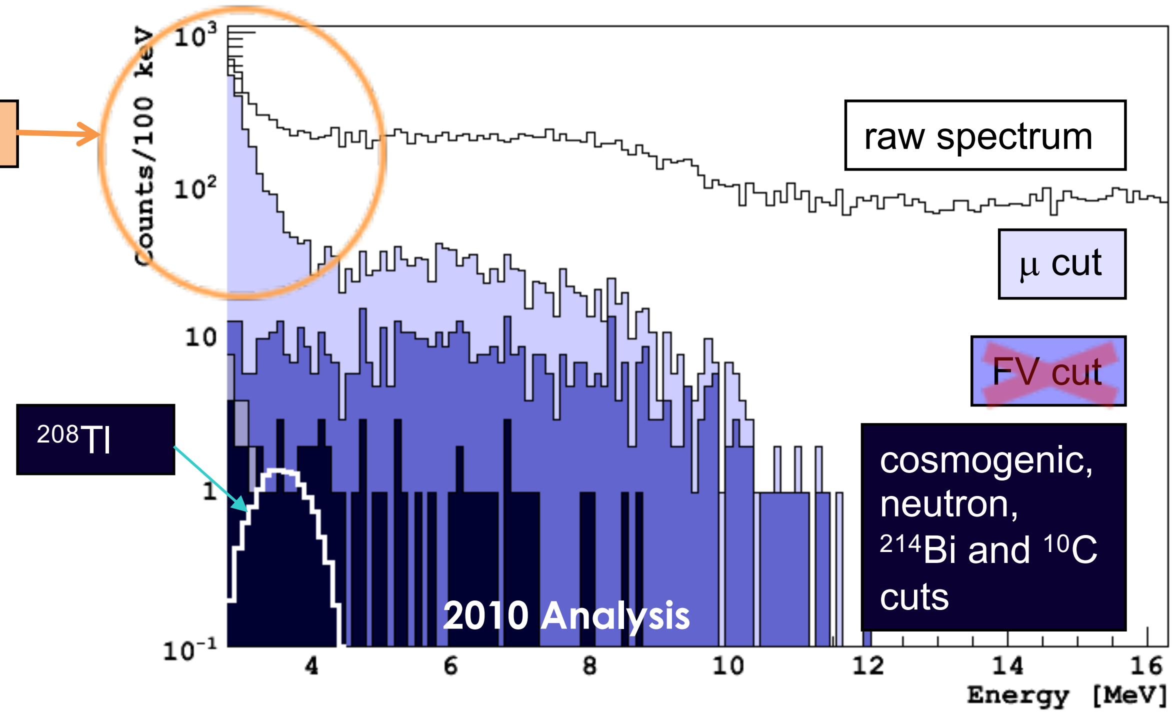
$$A_{dn} = 2\,\frac{R_N - R_D}{R_N + R_D}$$

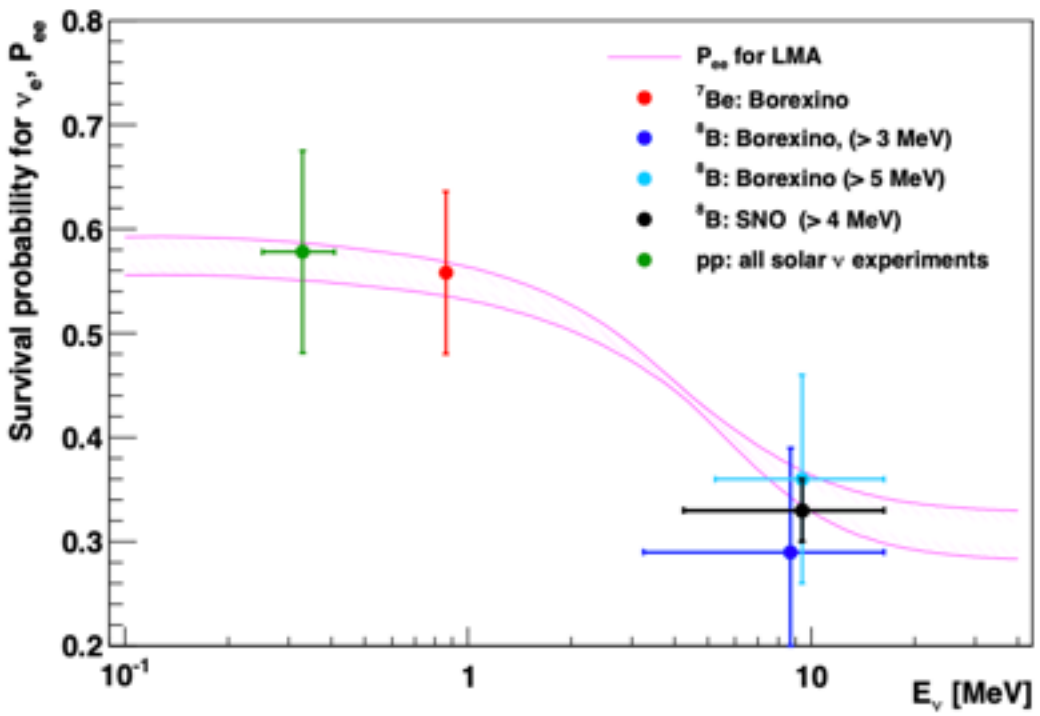
A_{dn} = 0.001 +-0.012 (stat) +- 0.007 (syst)

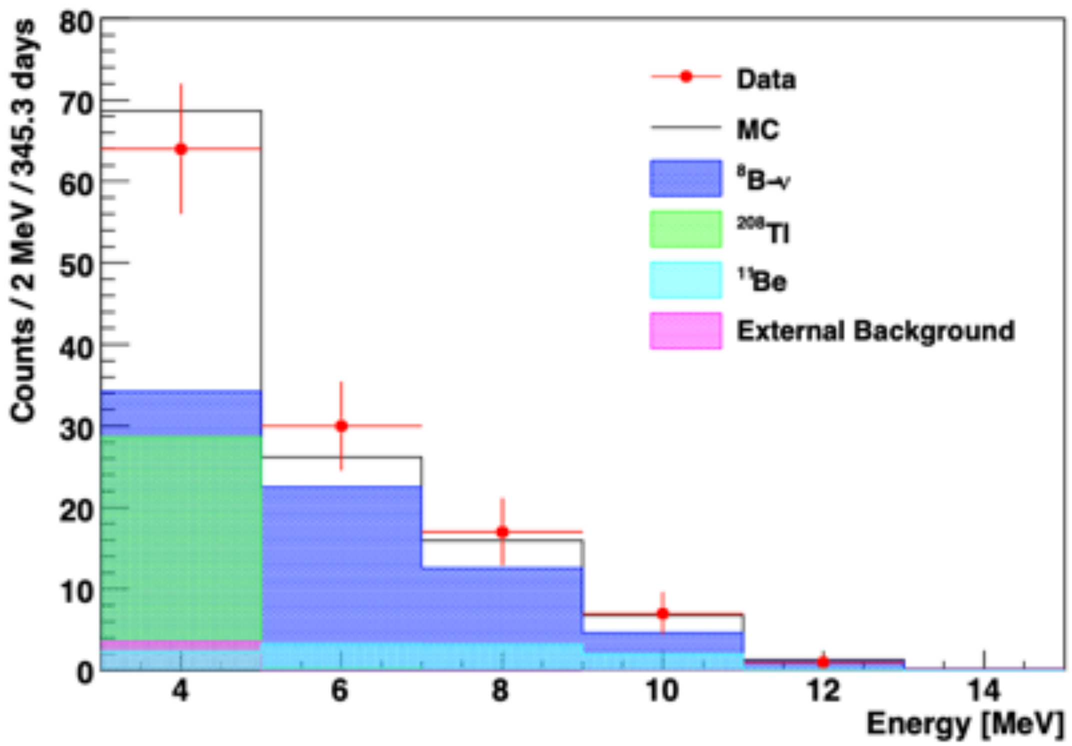


Borexino: ^{8}B neutrinos







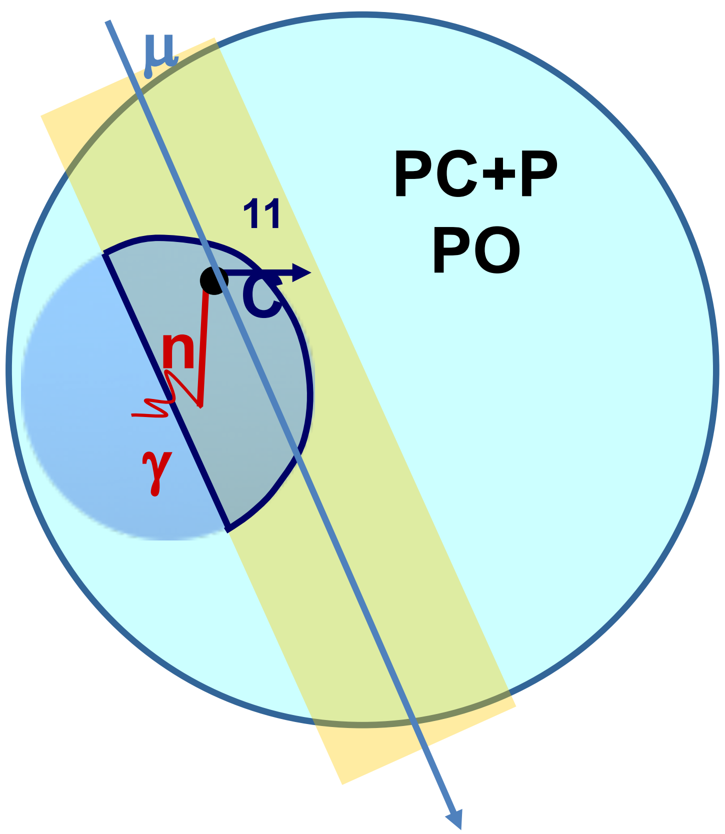


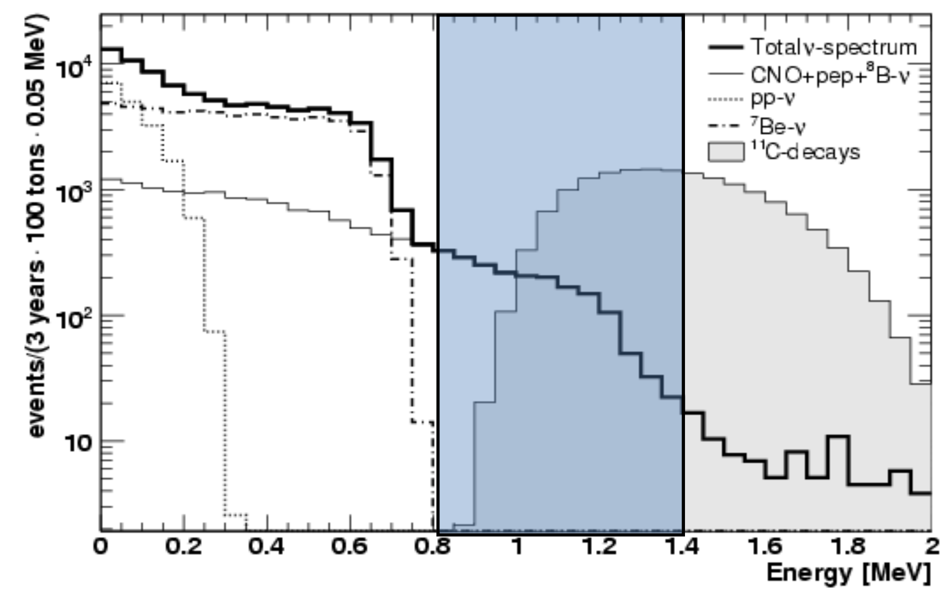
Borexino: the pep and CNO range

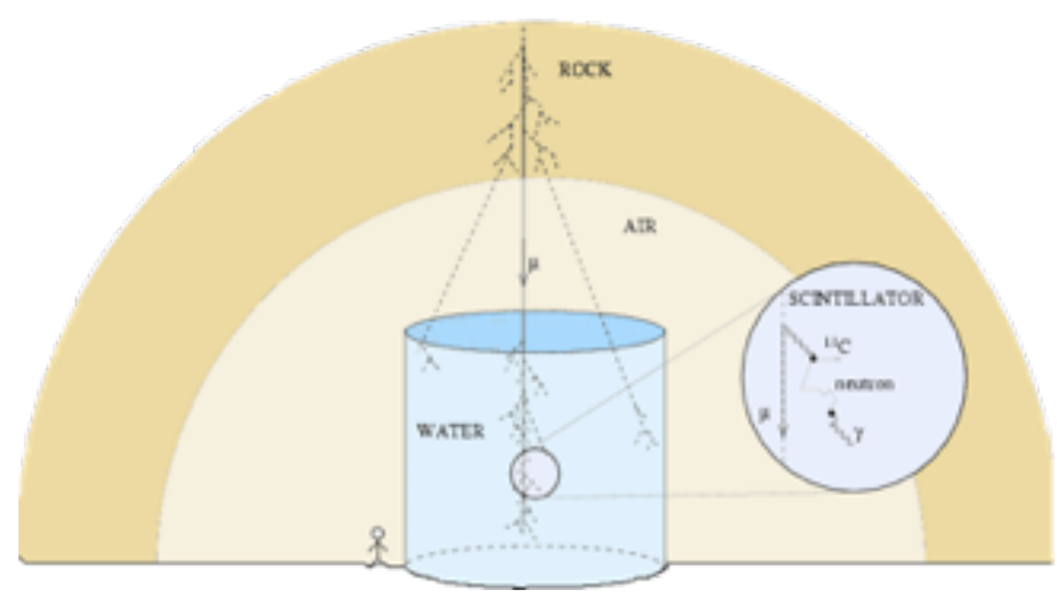
μ (+ secondaries) + $^{12}C \rightarrow \mu$ (+ secondaries) + ^{11}C + n

n + p $\rightarrow$ d + γ

$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$







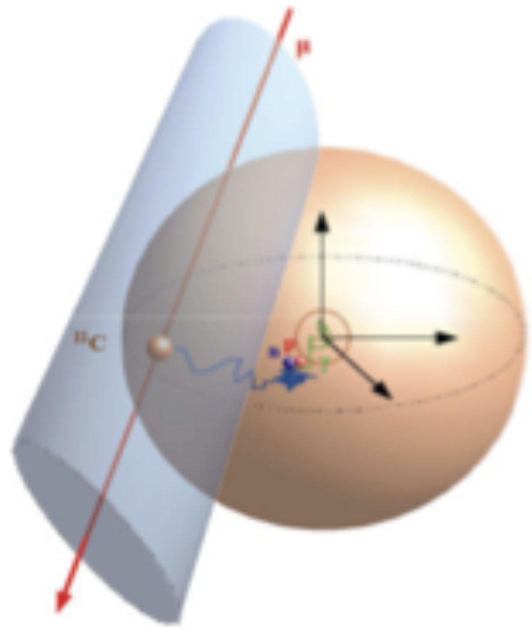
Borexino: the pep and CNO range

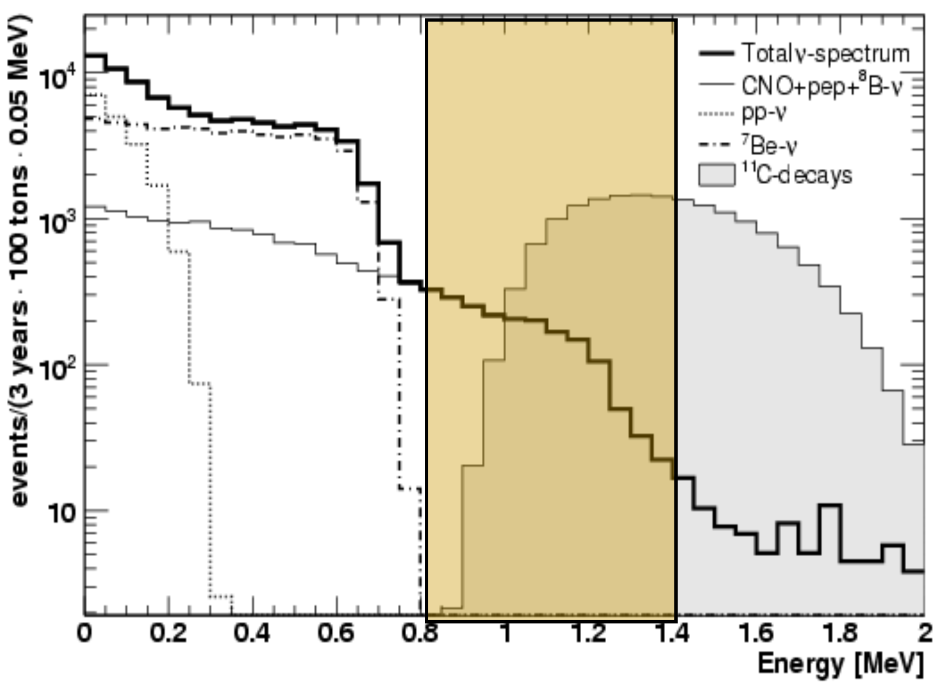
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

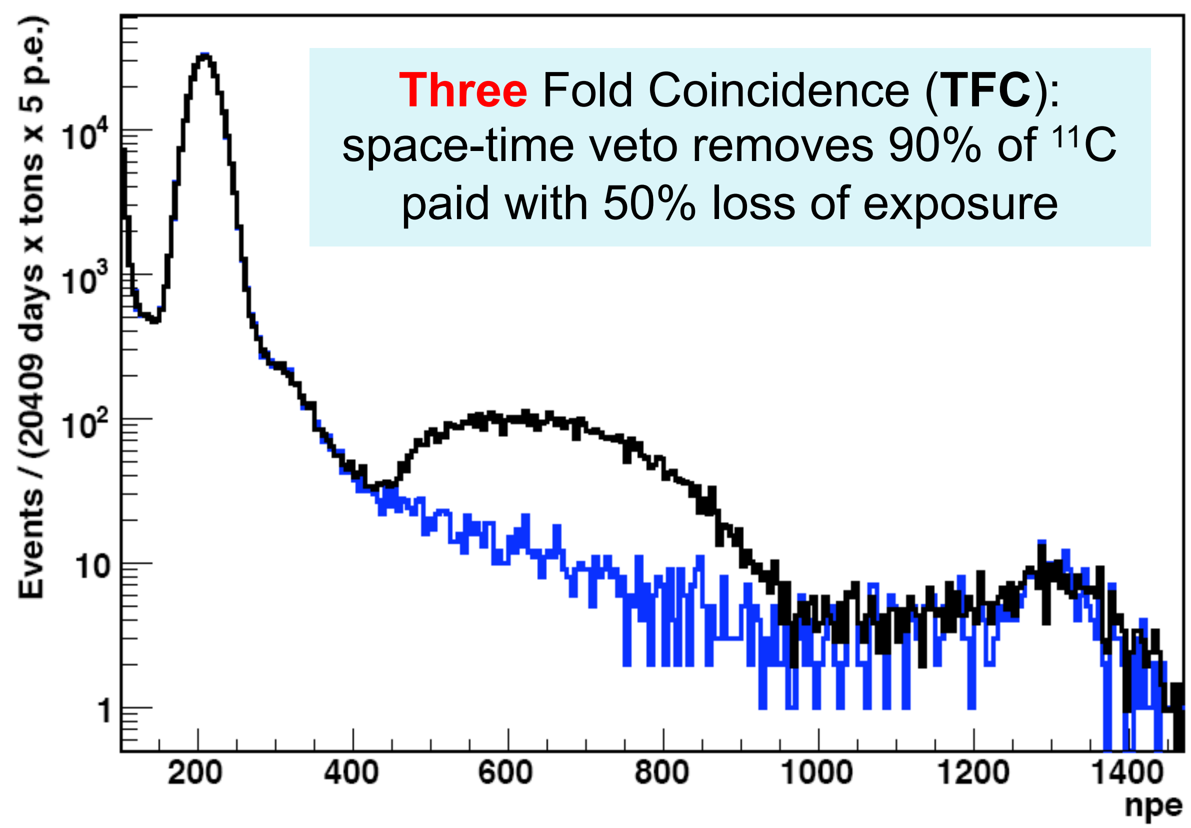
$$\hookrightarrow + p \rightarrow d + \gamma$$

$$\rightarrow {}^{11}B + e^{+} + \nu_e$$

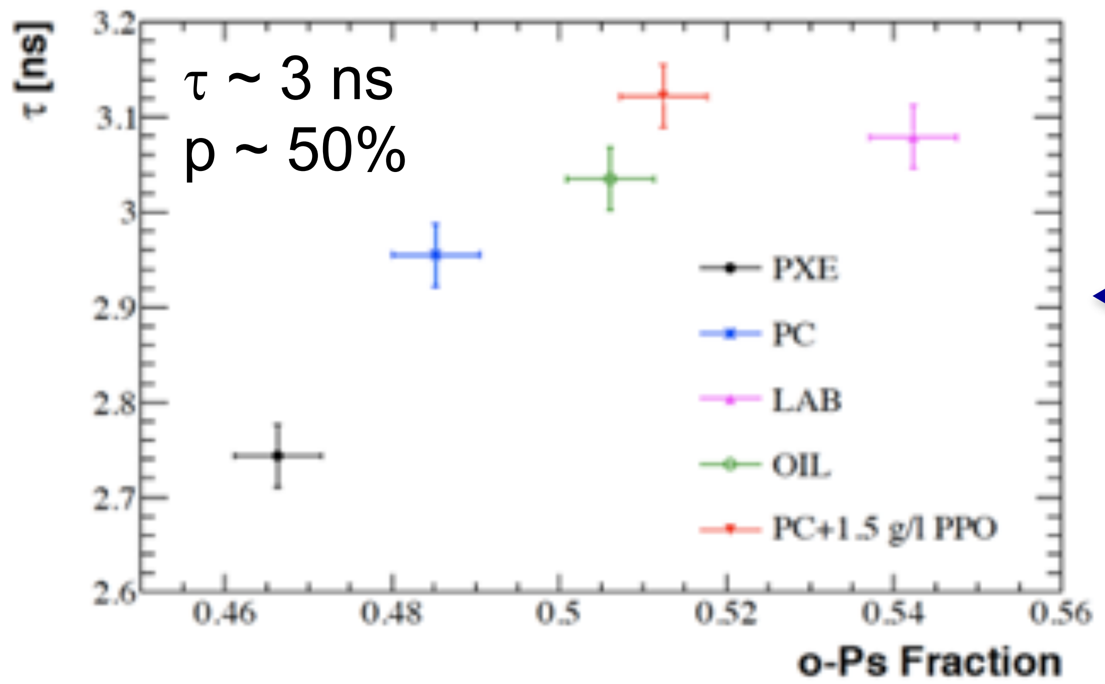
$\boxed{{}^{11}C\ \tau \sim 30\ \text{min}}$





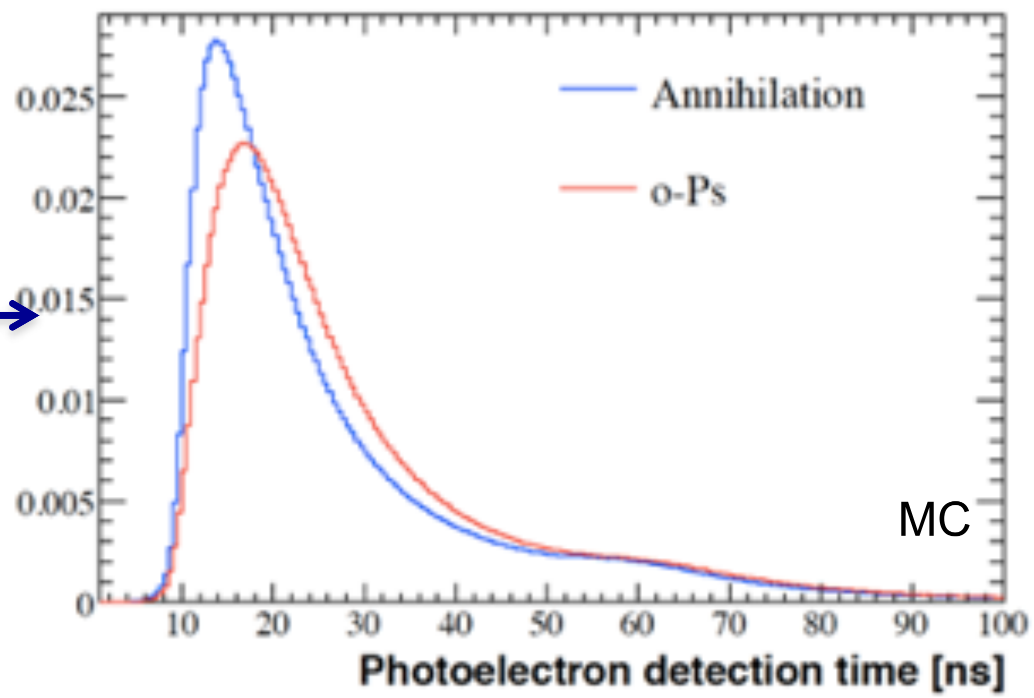


Three Fold Coincidence (**TFC**):
space-time veto removes 90% of ^{11}C
paid with 50% loss of exposure

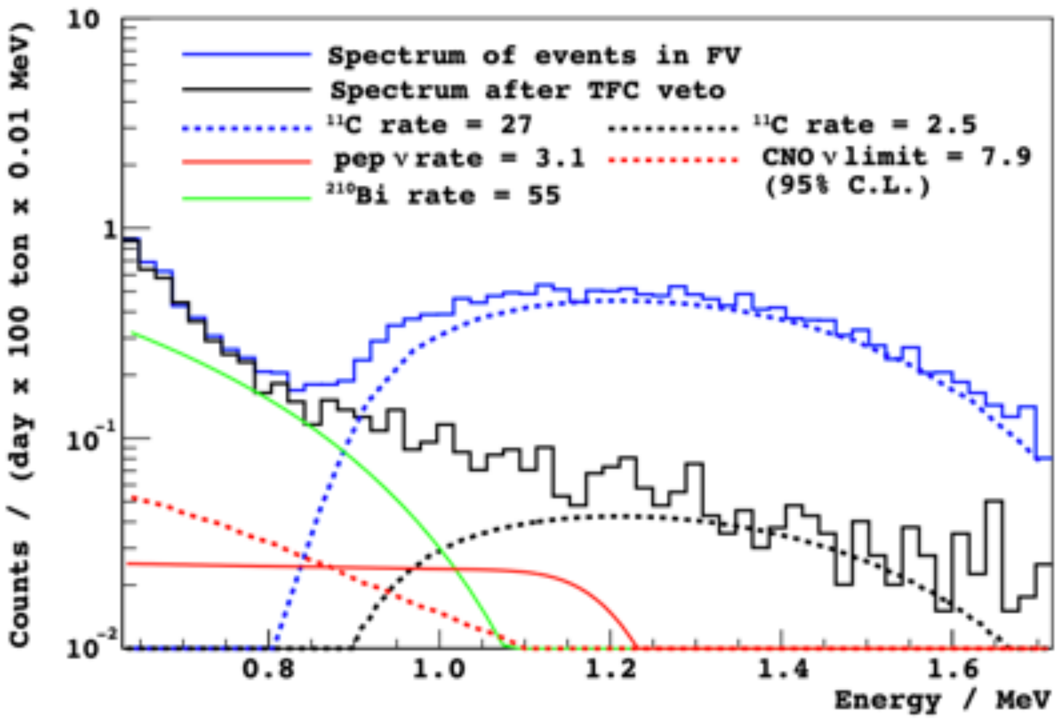


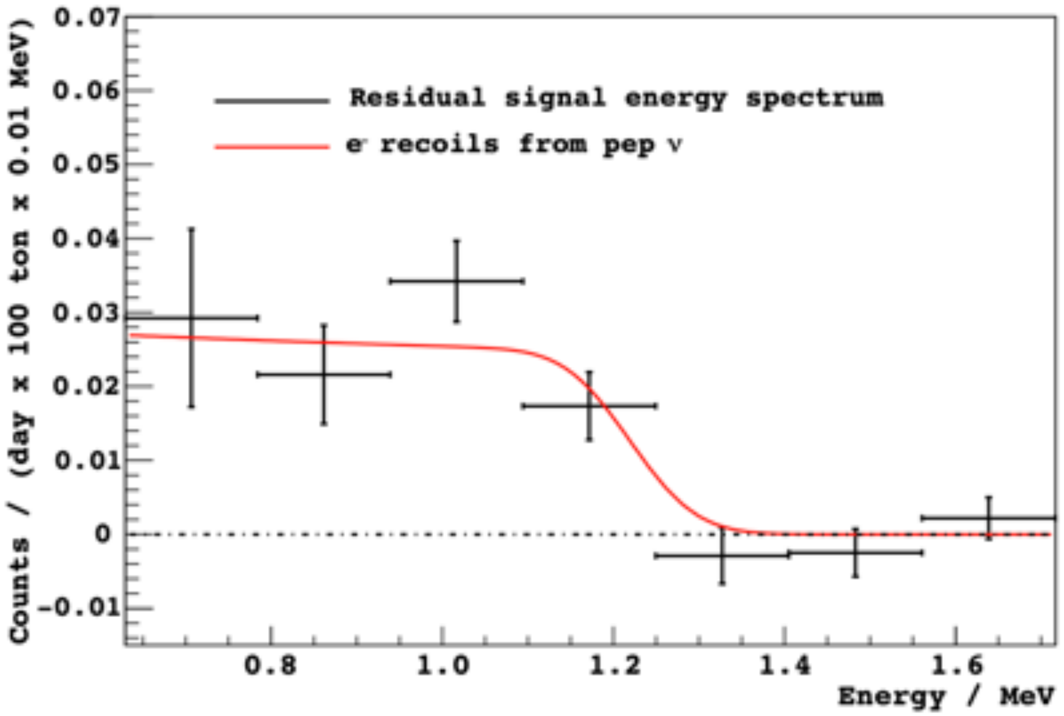
Measurements of the o-Ps mean-life and formation probability in scintillators with the PALS technique

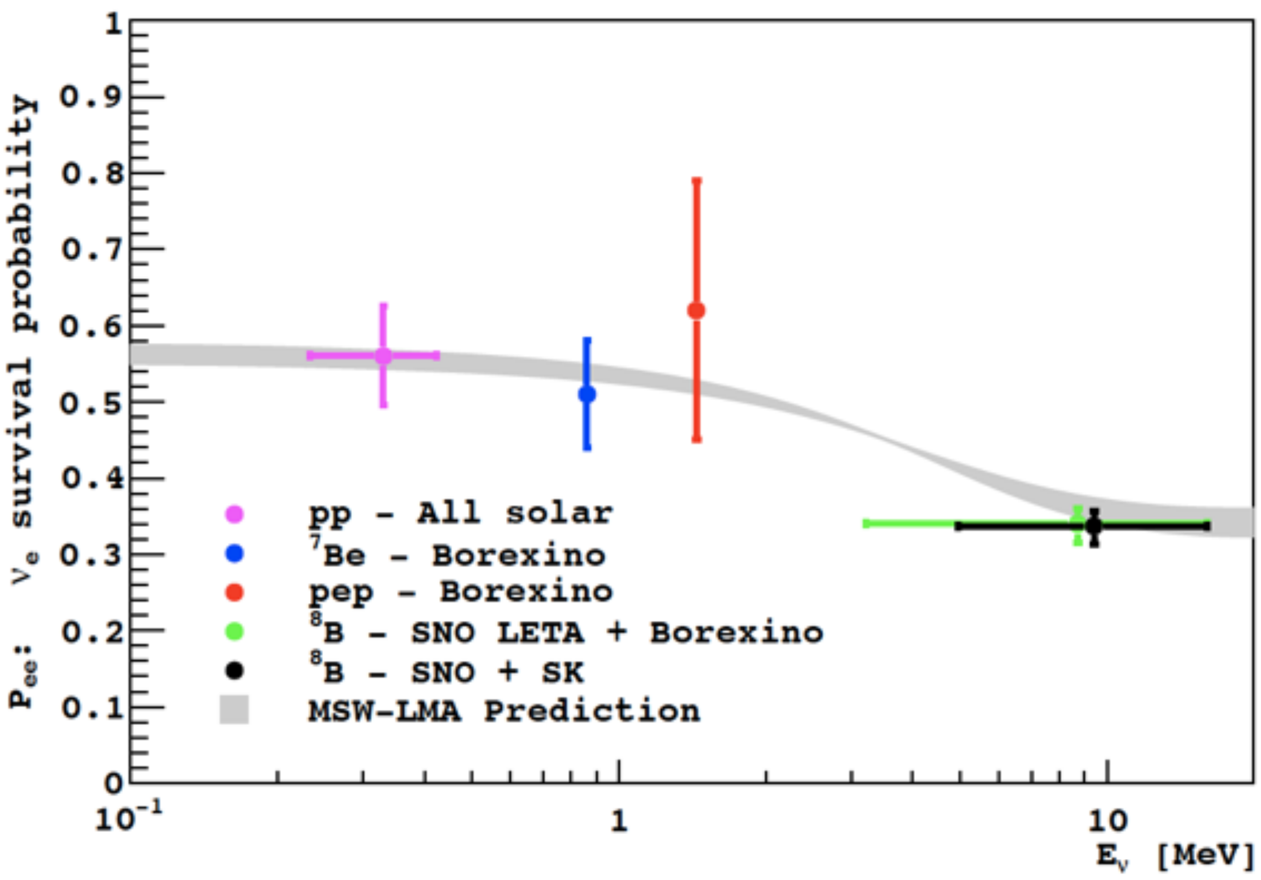
Pulse shape induced distortion



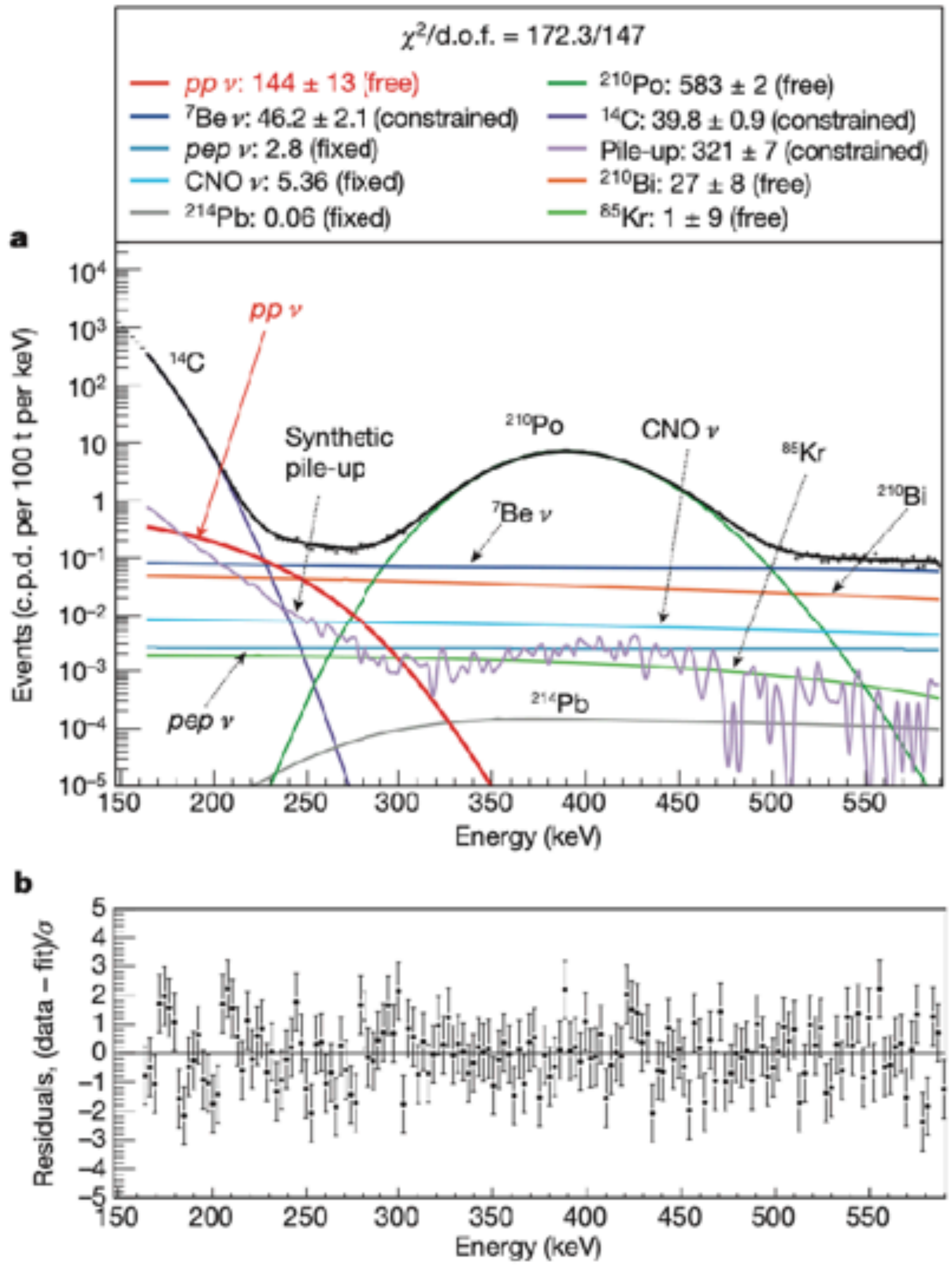
Borexino: *pep* neutrinos

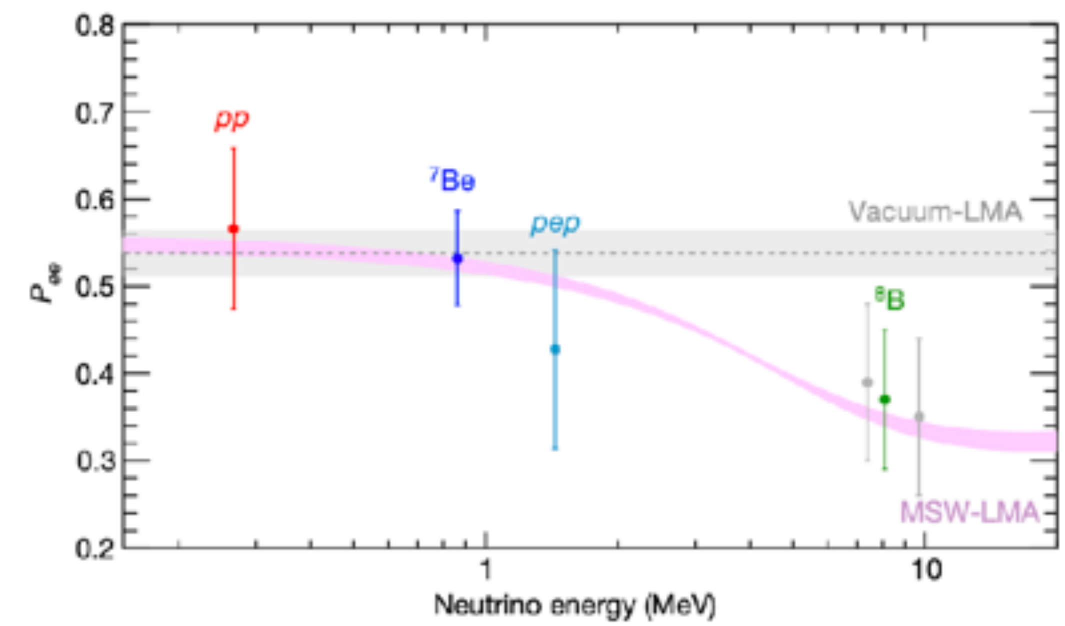


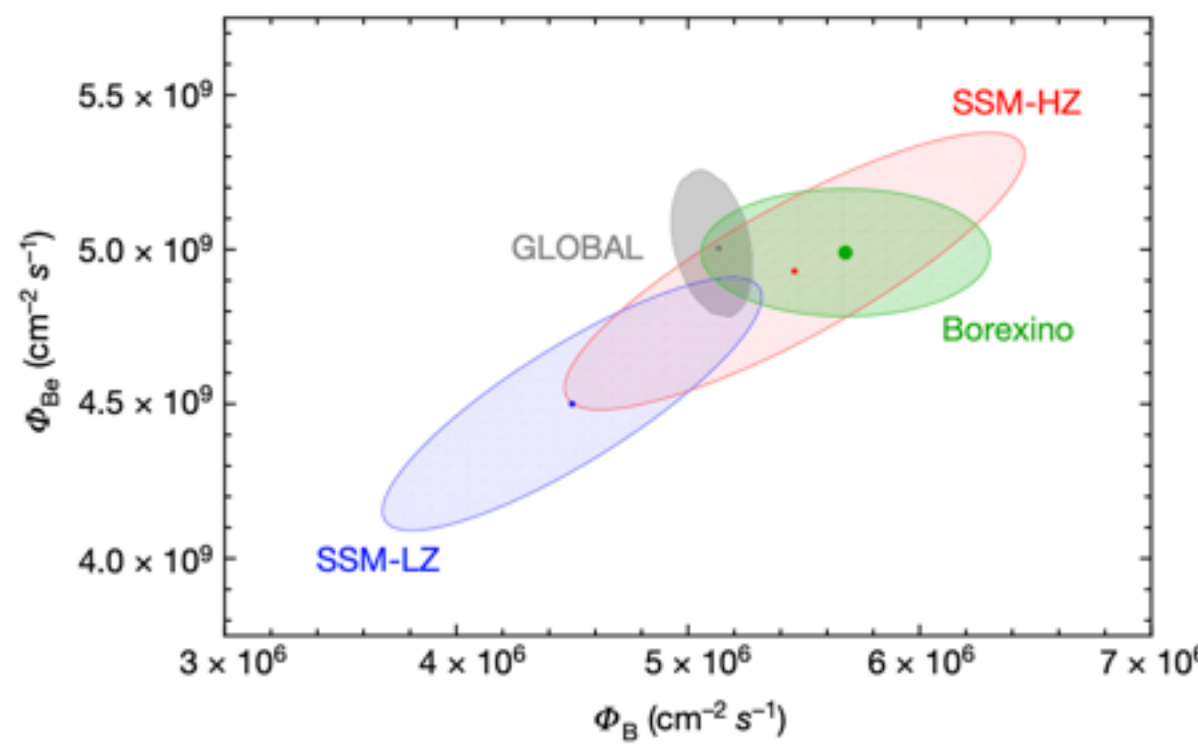




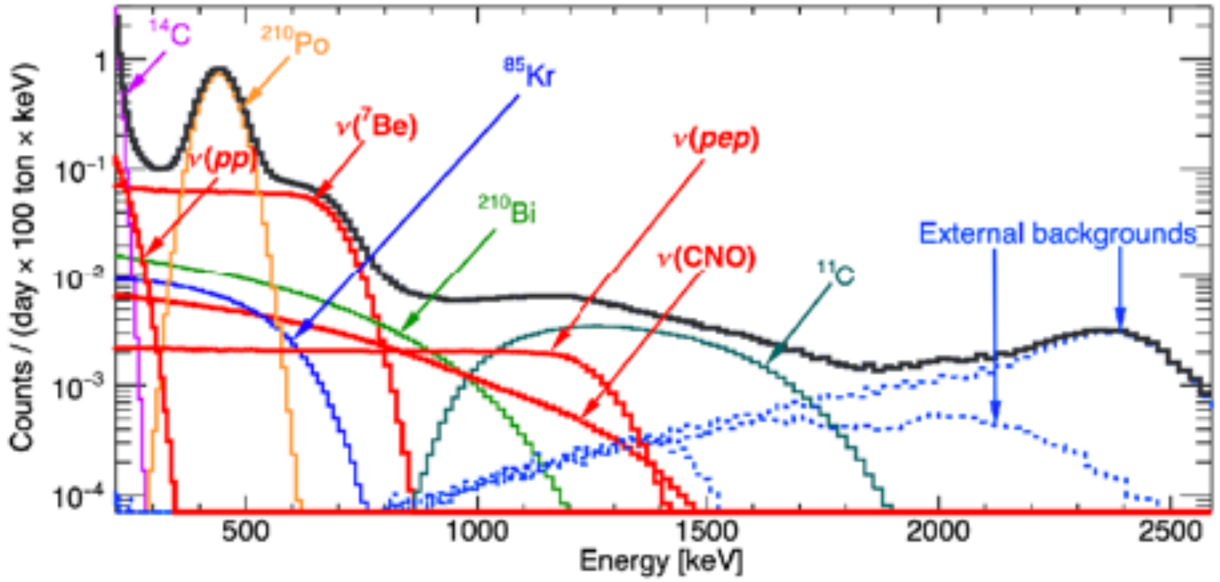
Borexino: *pp* neutrinos

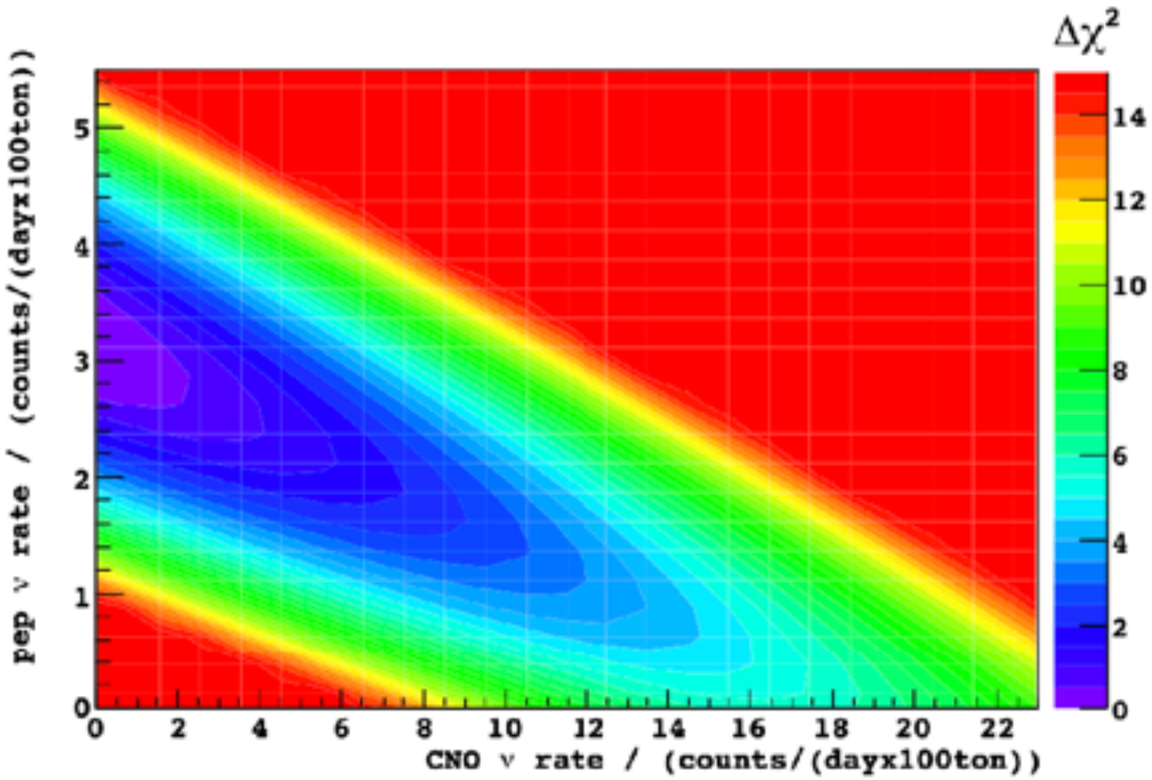


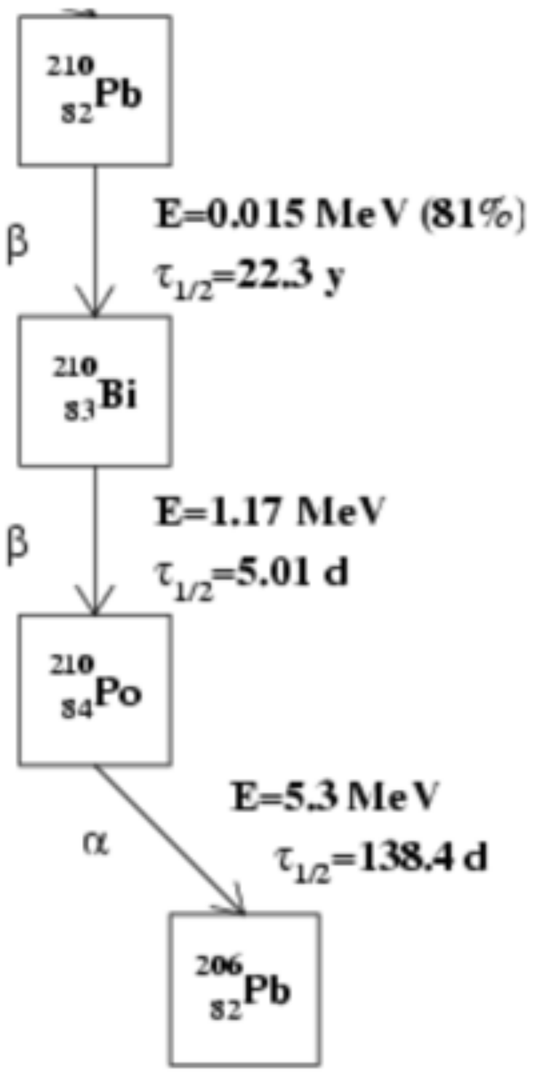




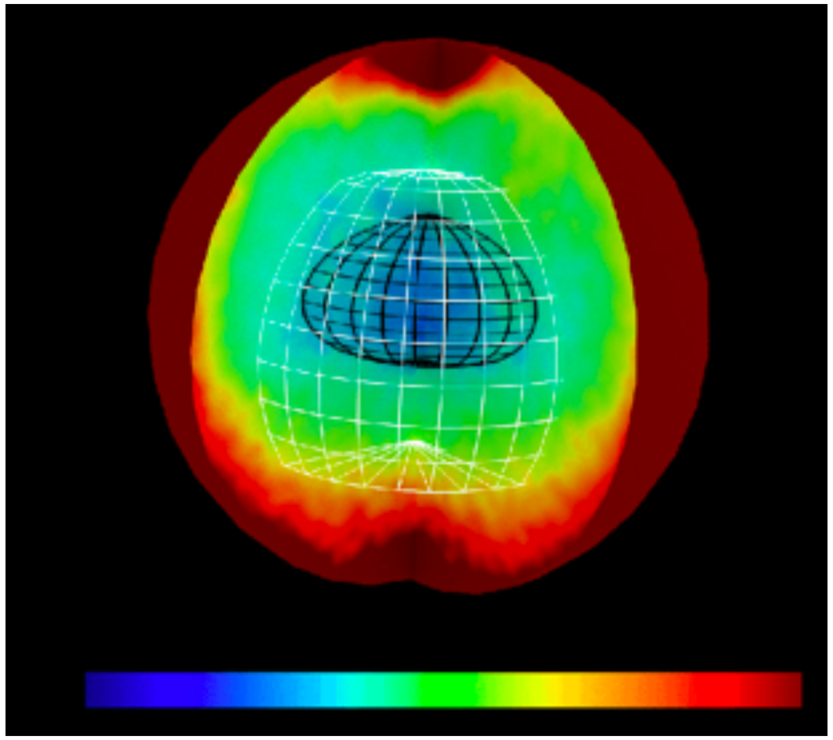
Borexino: CNO neutrinos

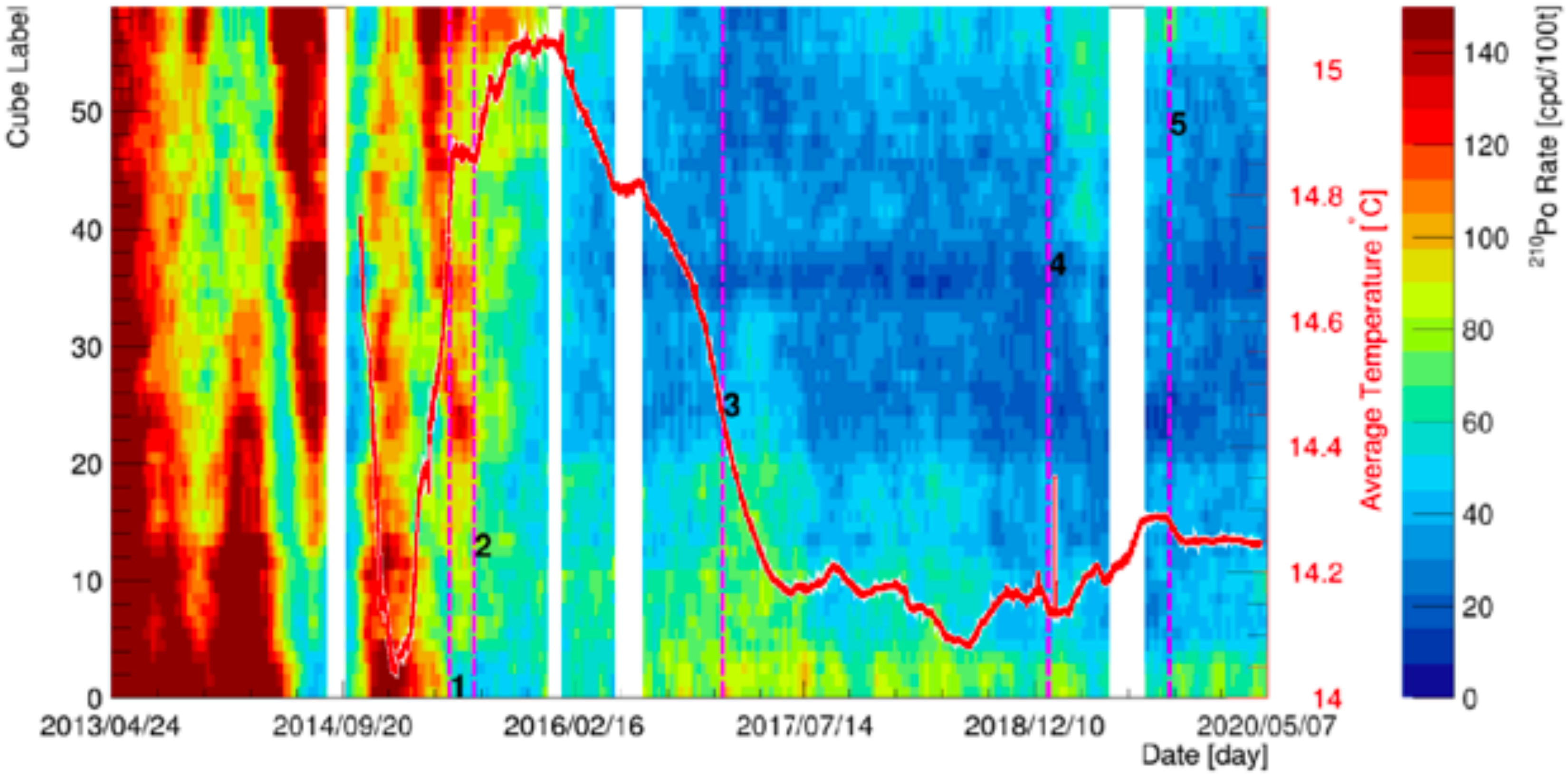


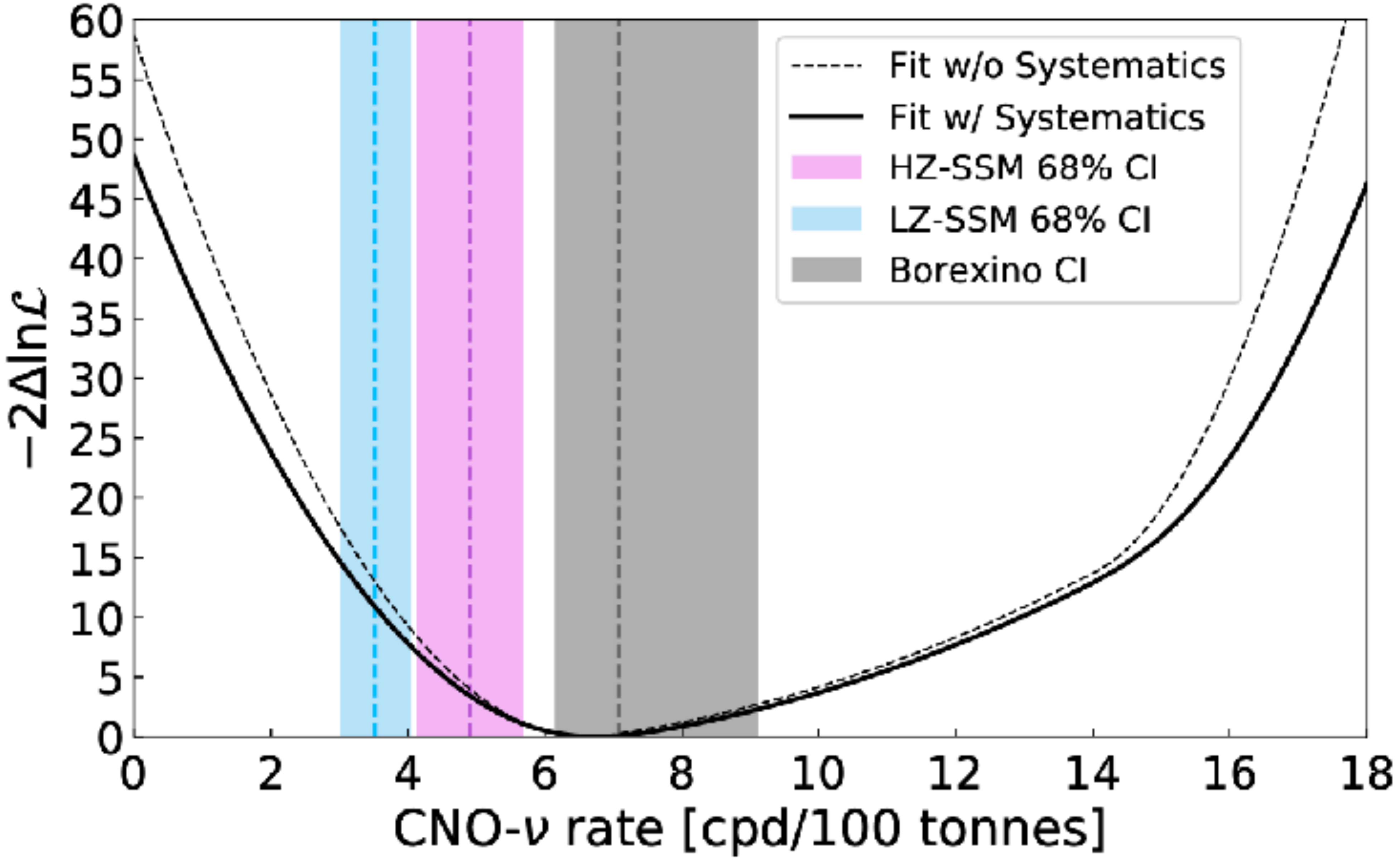




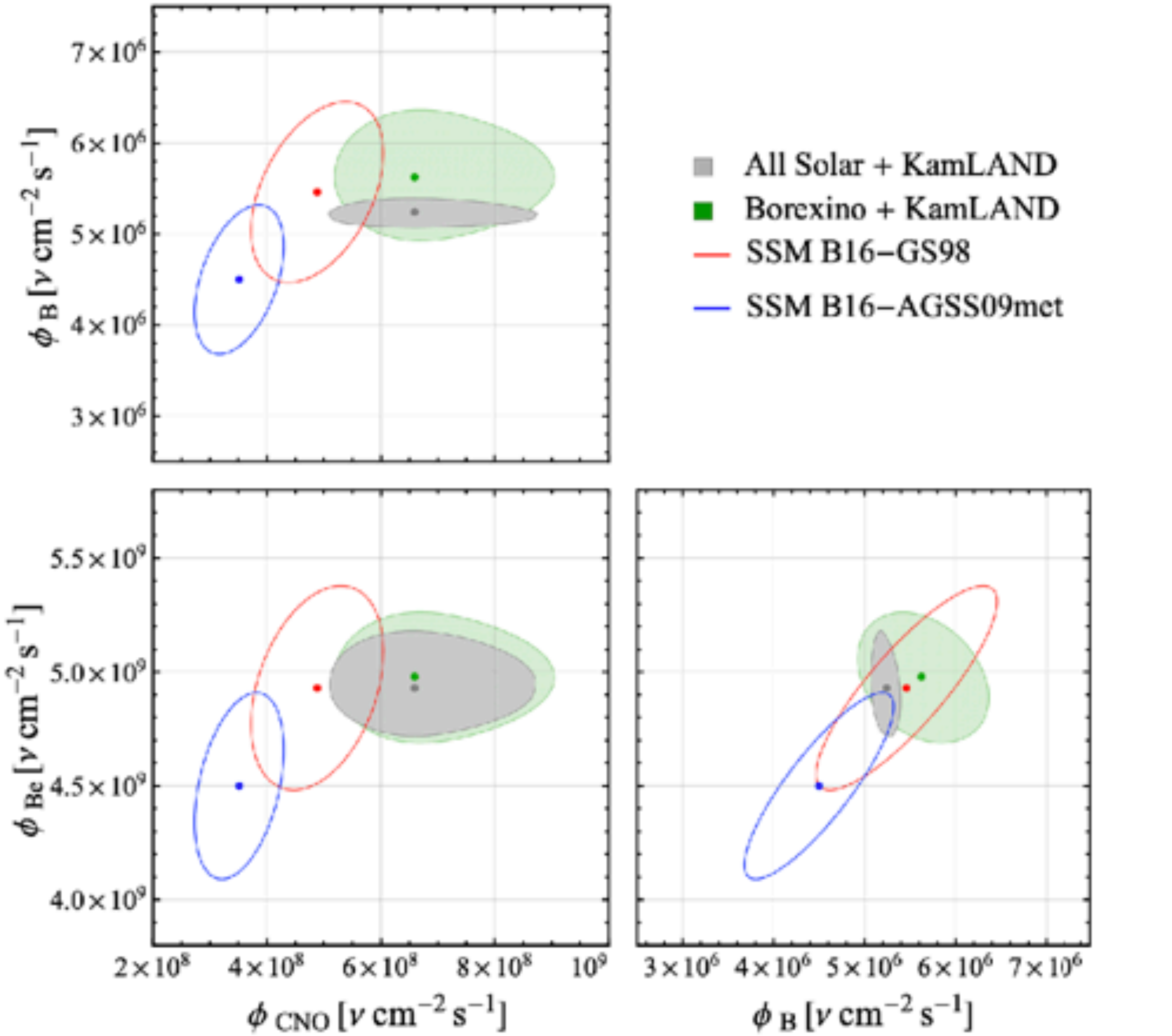
Borexino: CNO neutrinos

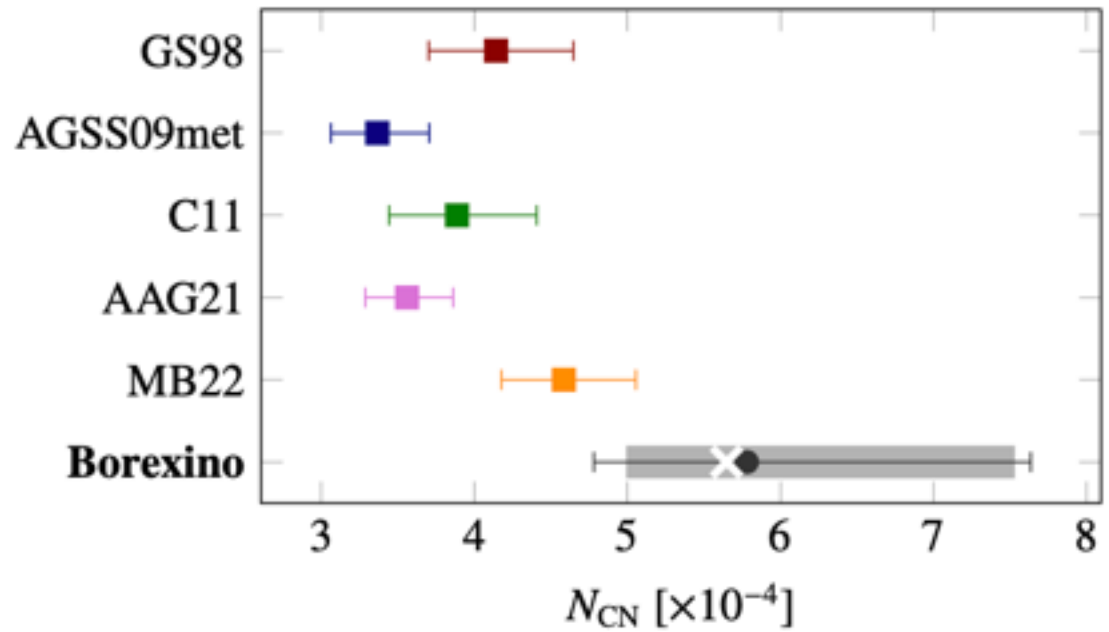





Fit w/o Systematics
Fit w/ Systematics
HZ-SSM 68% CI
LZ-SSM 68% CI
Borexino CI
$-2\Delta\ln\mathcal{L}$
0 5 10 15 20 25 30 35 40 45 50 55 60
0 2 4 6 8 10 12 14 16 18
CNO-ν rate [cpd/100 tonnes]

Borexino: CNO neutrinos





KAMLAND: solar neutrinos

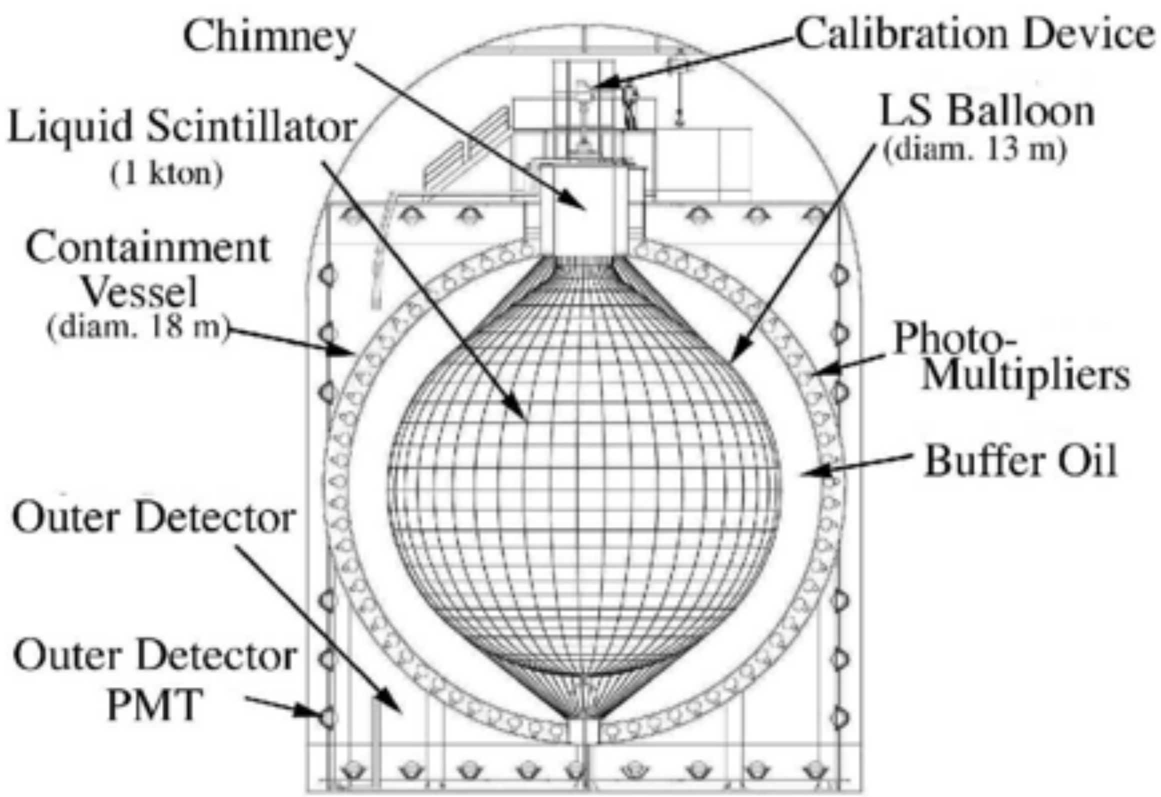
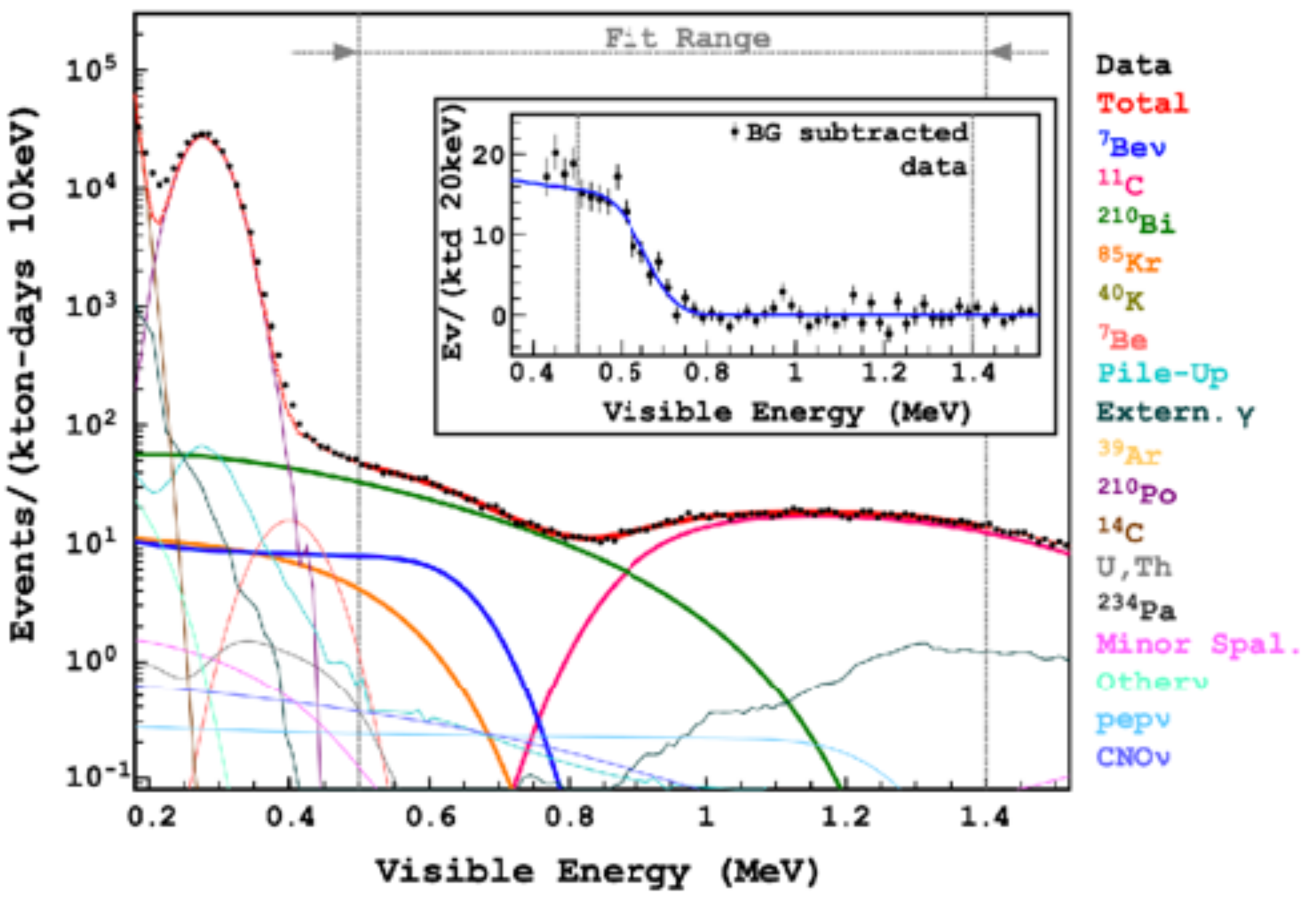
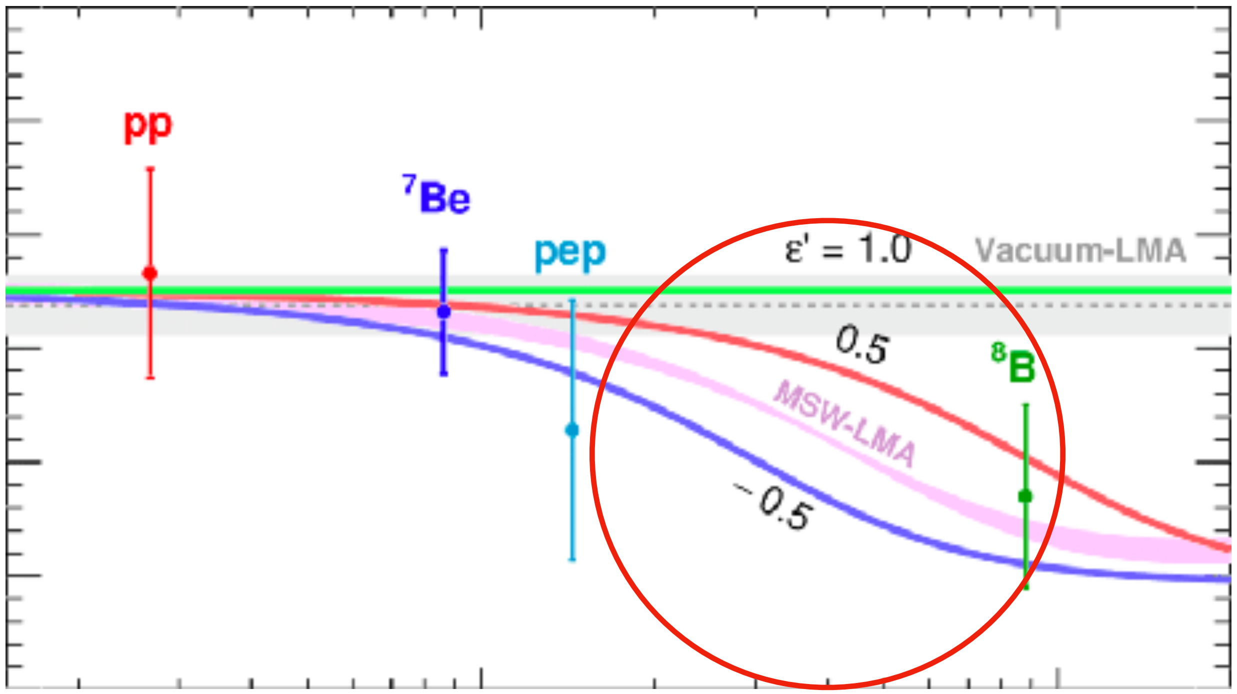


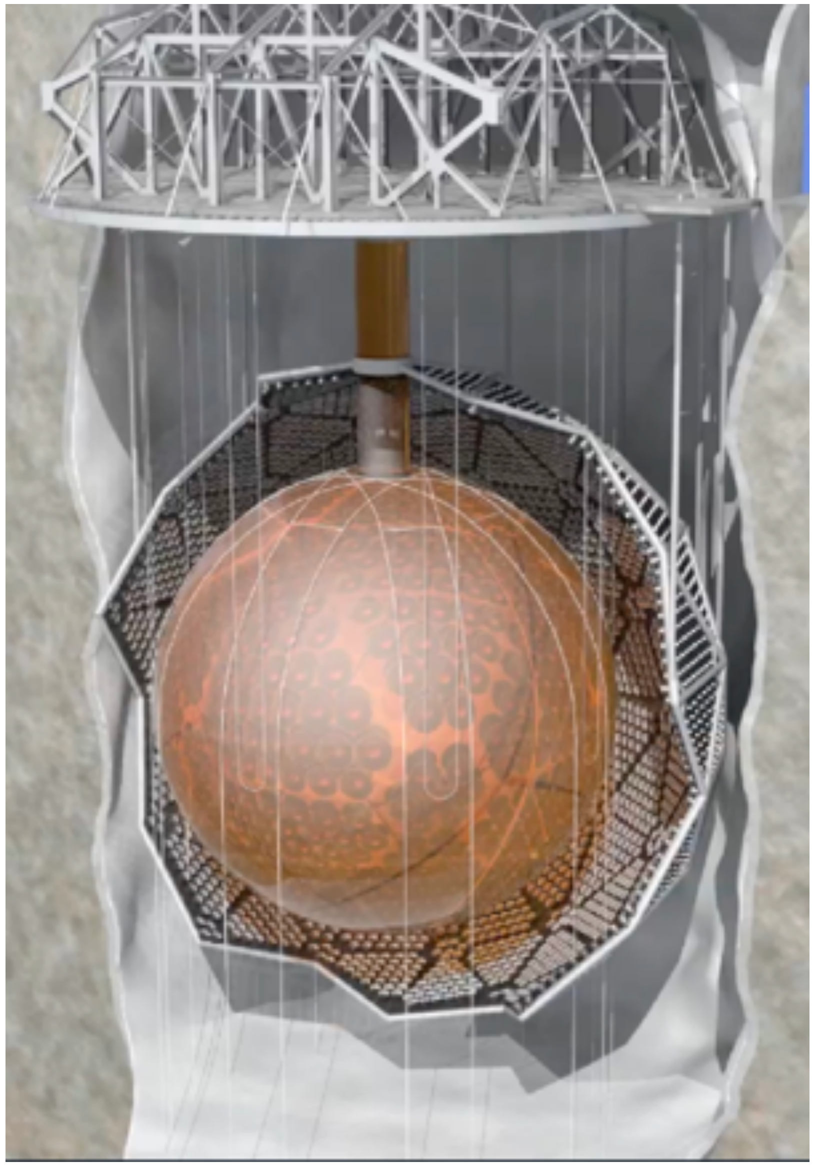
FIG. 1: Schematic diagram of the KamLAND detector.

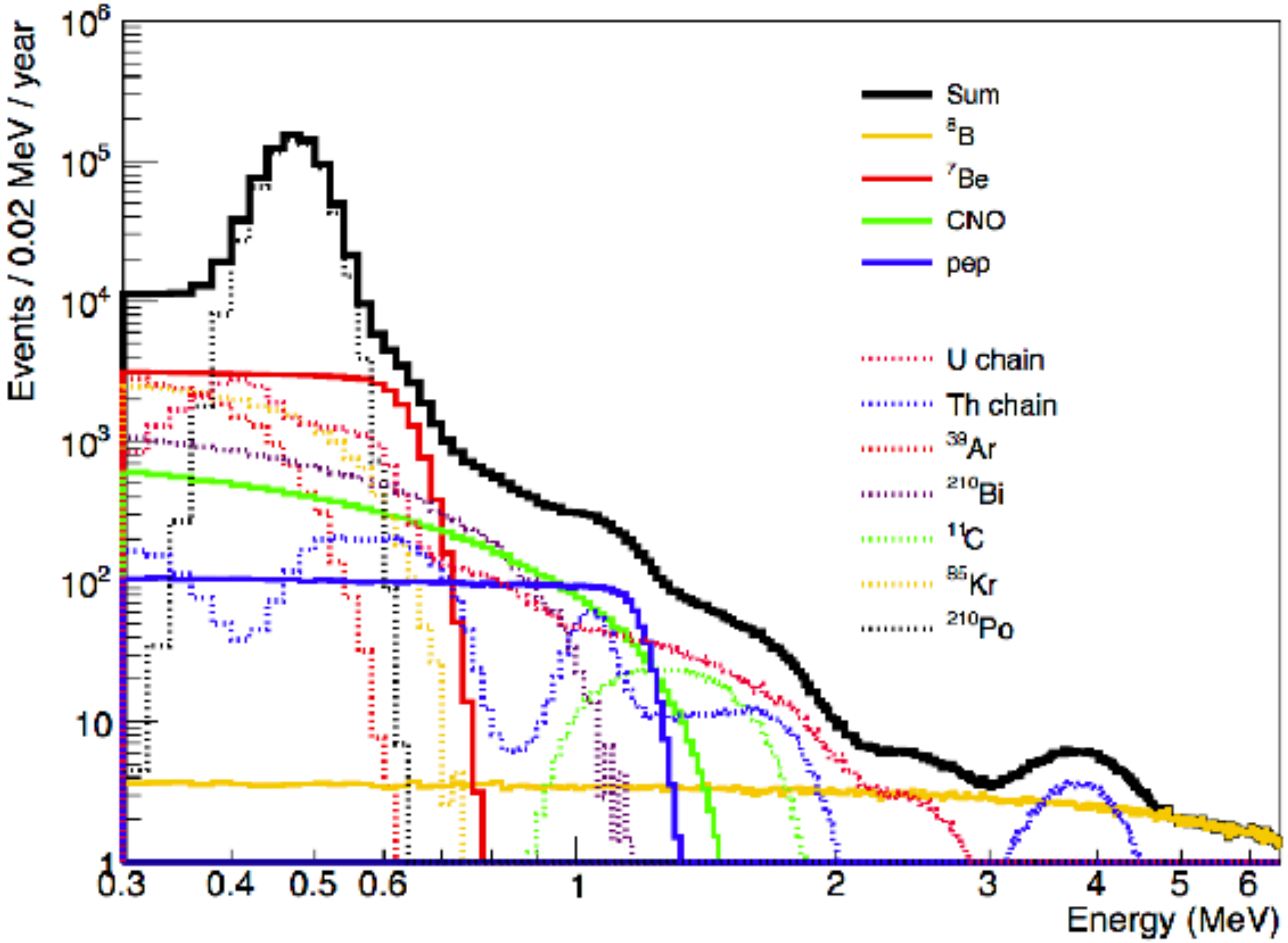


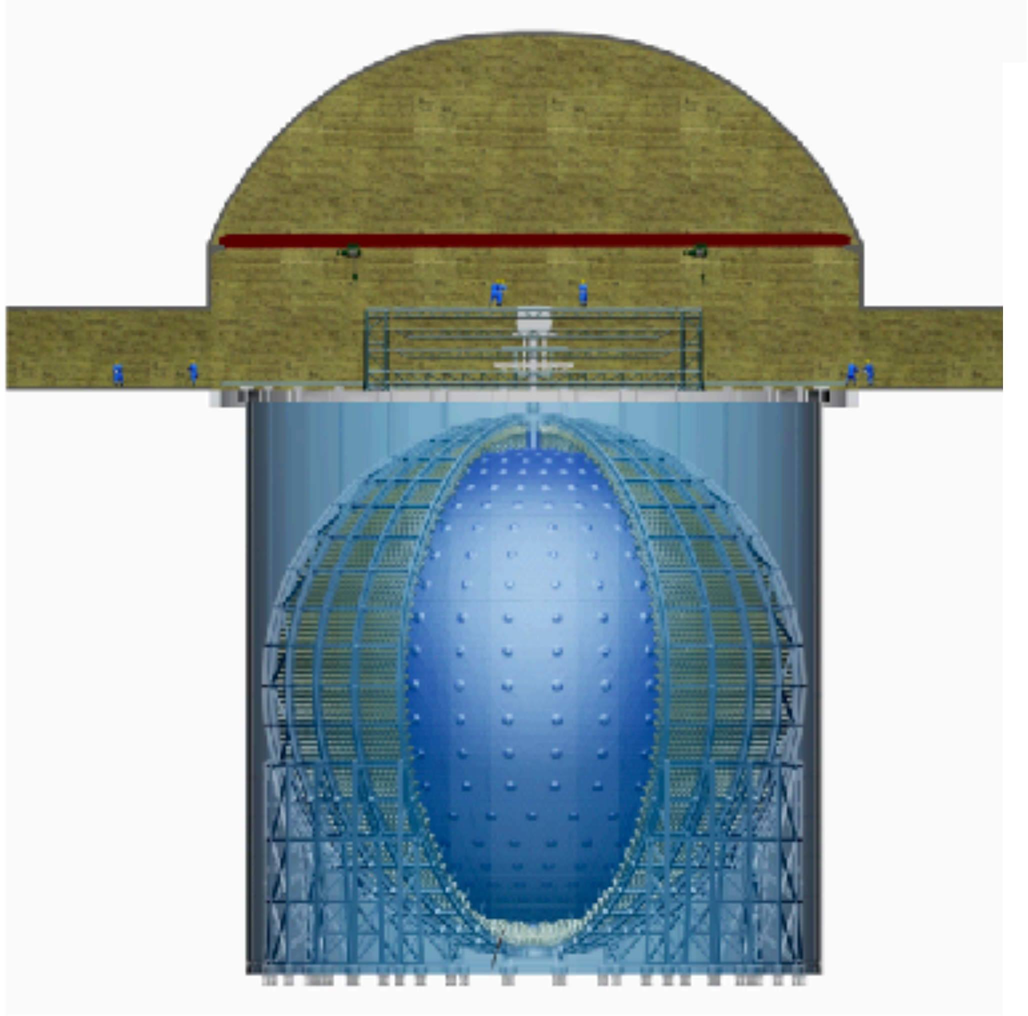
Is the end of the saga?

Non-standard interactions?
Sterile neutrinos?
Metallicity?






Events / 0.02 MeV / year
Energy (MeV)
Sum
^{8}B
^{7}Be
CNO
pep
U chain
Th chain
^{39}Ar
^{210}Bi
^{11}C
^{85}Kr
^{210}Po



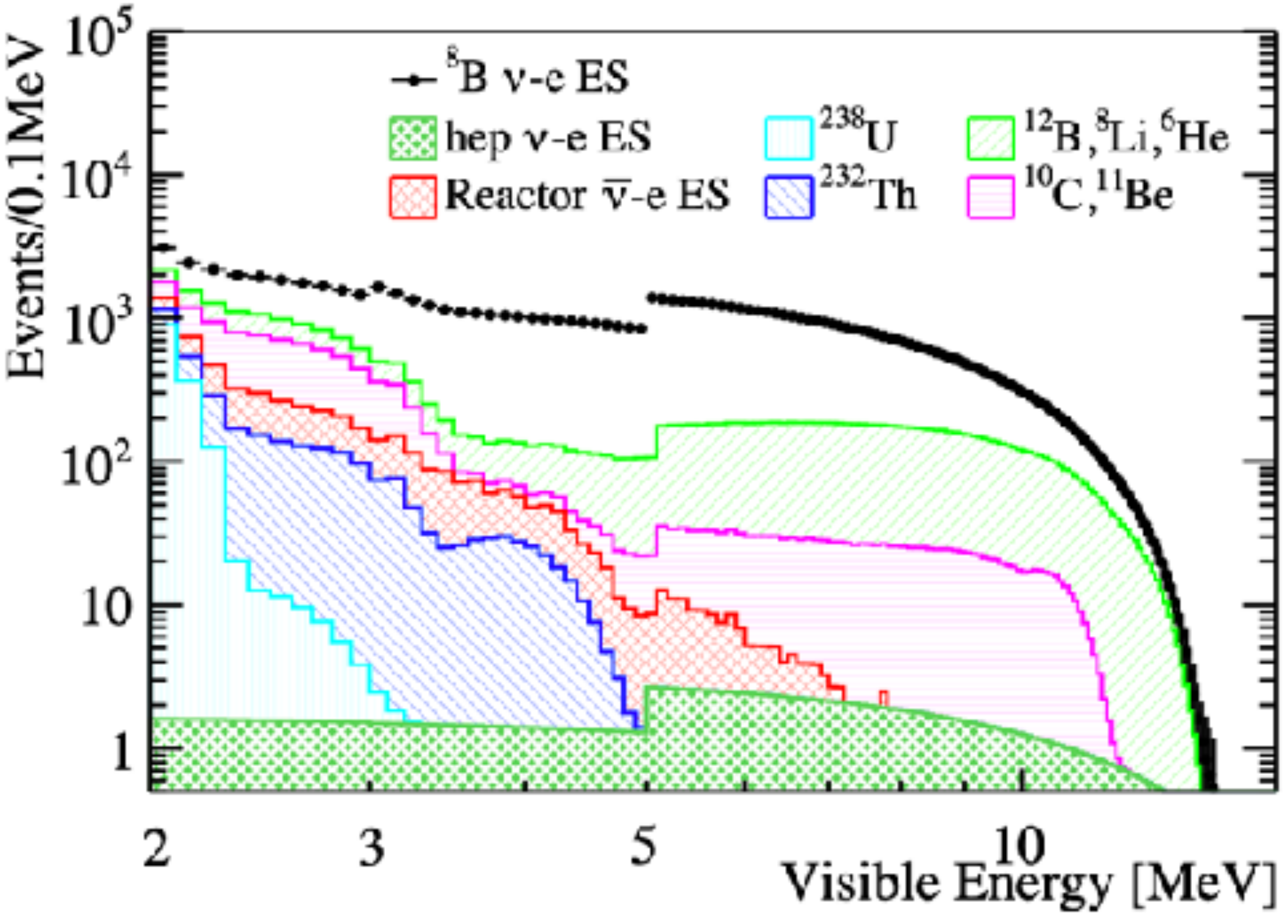
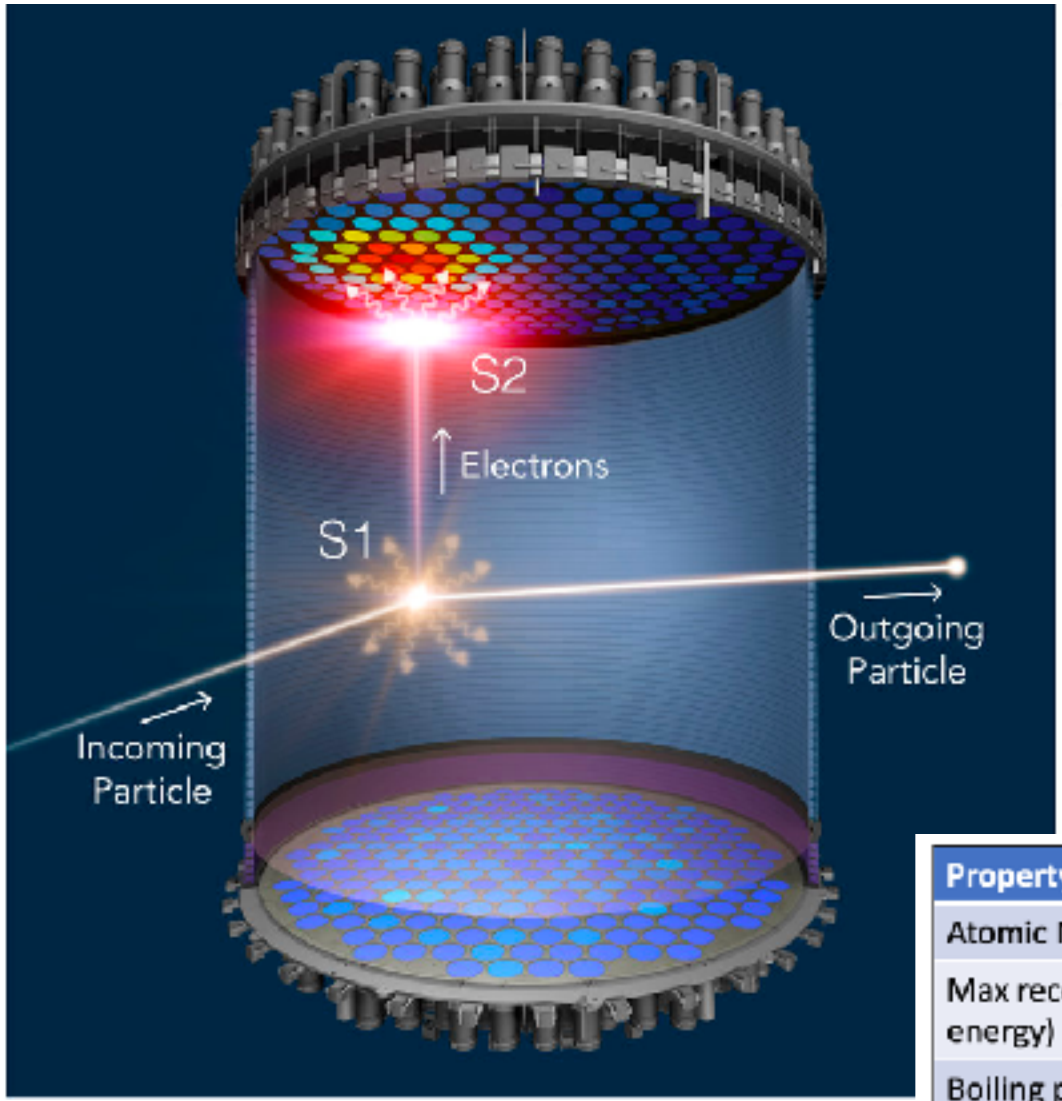
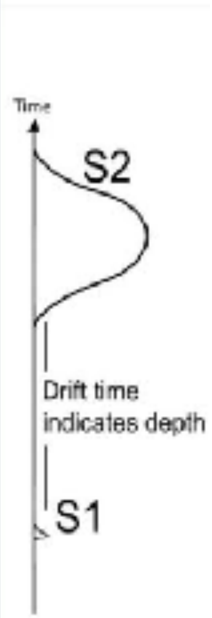


Figure 6: Diagram of the JUNO detector. The 20 kt LS is contained in a spherical acrylic vessel with an inner diameter of 35.4 m, and the vessel is supported by stainless steel latticed shell and the shell also holds about 18,000 pieces of 20-inch PMTs and 25,000 pieces of 3-inch PMTs.

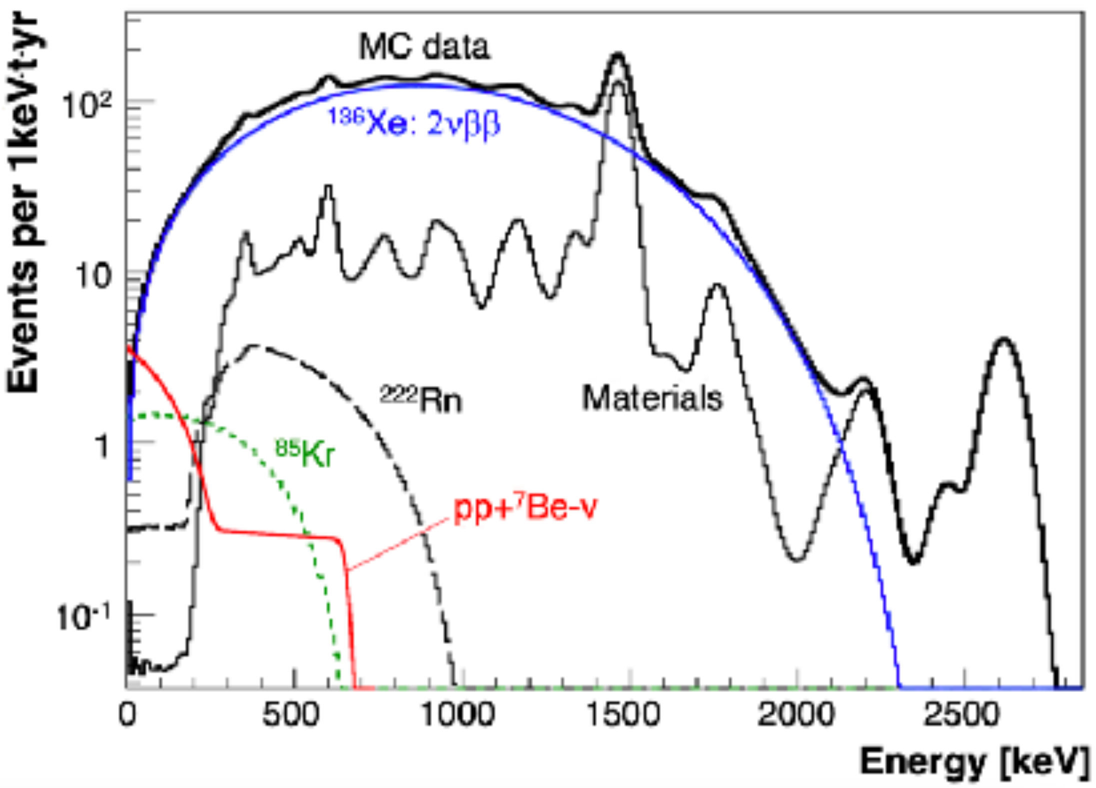
Dual-Phase Noble Liquid TPC



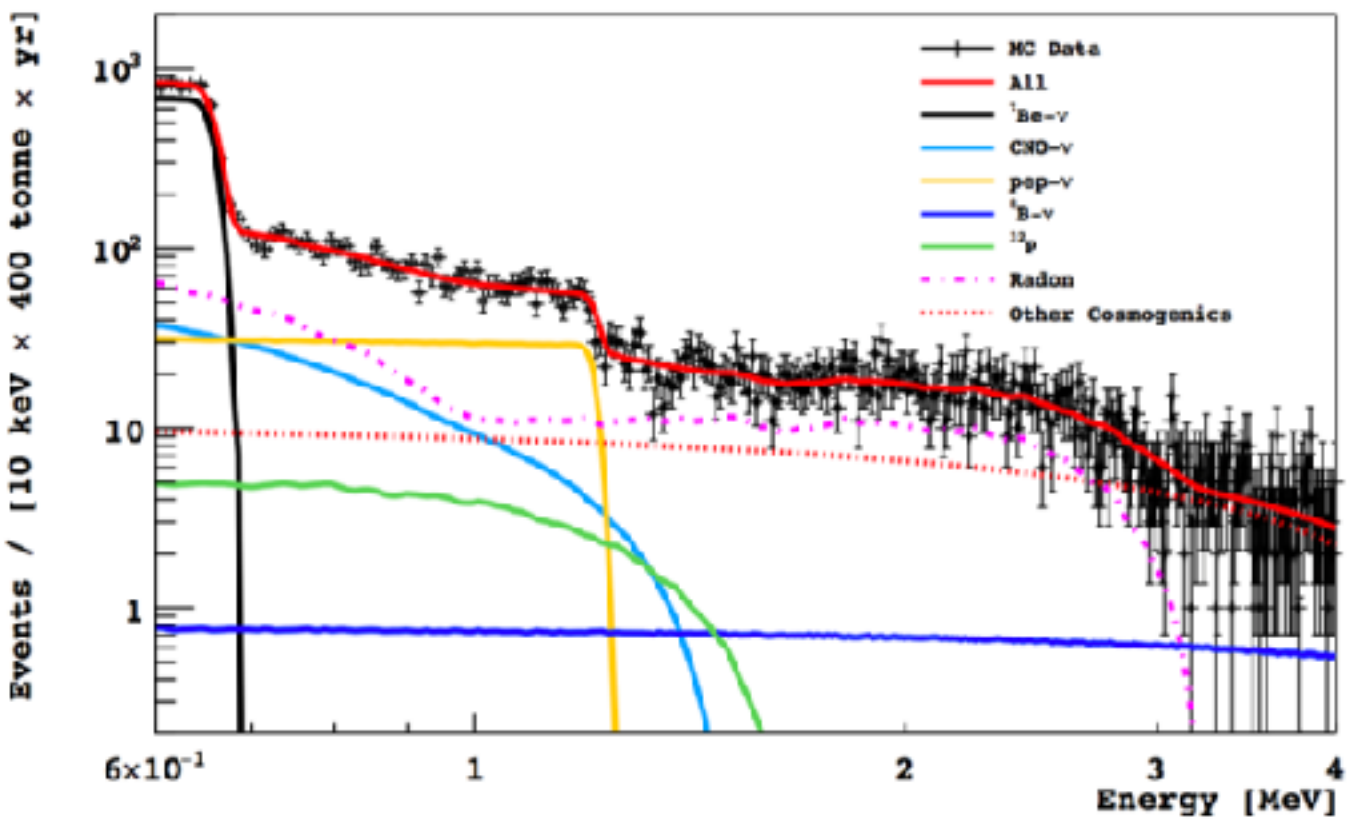


Property	Argon	Xenon
Atomic No. (Z)	18	54
Max recoil energy (% of incident n energy)	9.5	3.0
Boiling point	87.3	165
Density (g/cc)	1.4	3.0
Electron mobility (cm2/v*s)	400	2200
Ion drift velocity at 1kV/cm (mm/μs)	2.2	2.4
Energy resolution (FWHM@ 662 keV) scint. only (%)	8%	8%
Scintillation wavelength (nm)	128 (WLS /doping) also NIR	175 (UV quartz PMT window)
Scintillation yield (photons/MeV)	40000	42000
Fast decay time (ns)	7 (25% light)	4.3
Slow decay time (ns)	1500 (75% light)	22 (100% in ≤ 22 nm)

Xenon


MC data
^{136}Xe: 2νββ
^{222}Rn
Materials
^{85}Kr
pp+^{7}Be-ν
Events per 1keV·t·yr
10^2
10
1
10^{-1}
0
500
1000
1500
2000
2500
Energy [keV]

Argon


MC Data
All
^{7}Be-ν
CNO-ν
pep-ν
^{8}B-ν
^{32}P
Radon
Other Cosmogenics
Events / [10 keV × 400 tonne × yr]
10^3
10^2
10
1
6×10^{-1}
1
2
3
4
Energy [MeV]