Experimental observations of solar neutrinos:
from the pp chain to the CNO cycle

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Neutrino Frontiers

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Solar Neutrinos

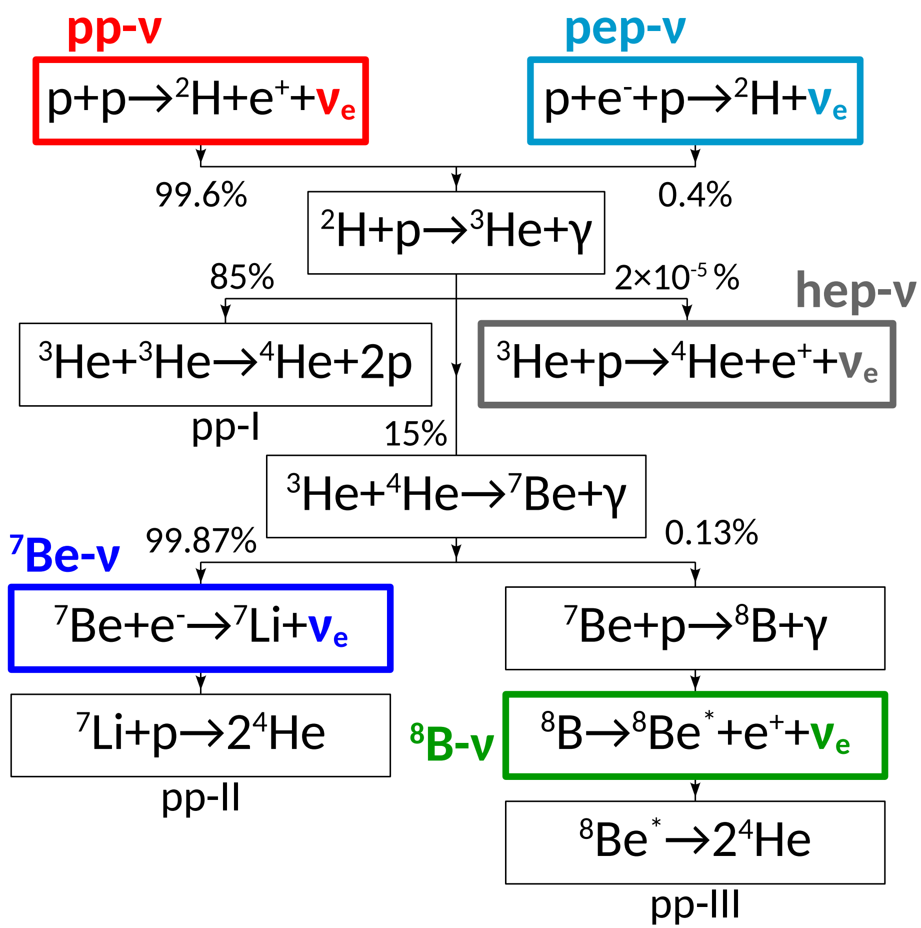
Fundamental paradigm:
The source of energy in the sun makes neutrinos:

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e} + (24.69 + 2 \cdot 1.022)MeV$$

Hydrogen burning works through:
- pp-chain reactions
- CNO bi-cycle

The pp-chain

- 26.2 MeV effective thermal energy/termination (pp-I)
- 9.2×10^{37} hydrogen/sec
- 612×10^{6} ton/sec of H into He
- assuming 10% of solar mass involved in energy production: **timescale ~ 10^{10} years**
- Dominant in 1st generation stars
- 2nd generation stars might have a different mechanism at work



- A different hydrogen burning mechanism in 2nd generation stars may involve light elements such as carbon and nitrogen

- This idea was originally introduced independently by von Weizsaker and Bethe between 1937 and 1939

- Idea based on the fact that second or third generation stars contain some «heavy» elements such as ^{12}C

- ^{12}C can indirectly induce fusion of 4 protons to form helium

- The total energy released is the same as for the pp-chain

The CN cycle

- $p + {}^{12}_{6}C \rightarrow {}^{13}_{7}N + \gamma$
- ${}^{13}_{7}N \rightarrow {}^{13}_{6}C + e^{+} + \nu_e$ $(\leq 1.199\ MeV, \tau \sim 860\ s)$
- $p + {}^{13}_{6}C \rightarrow {}^{14}_{7}N + \gamma$
- $p + {}^{14}_{7}N \rightarrow {}^{15}_{8}O + \gamma$
- ${}^{15}_{8}O \rightarrow {}^{15}_{7}N + e^{+} + \nu_e$ $(\leq 1.732\ MeV, \tau \sim 180\ s)$
- $p + {}^{15}_{7}N \rightarrow \begin{cases} {}^{12}_{6}C + \alpha \\ {}^{16}_{8}O + \gamma \end{cases}$

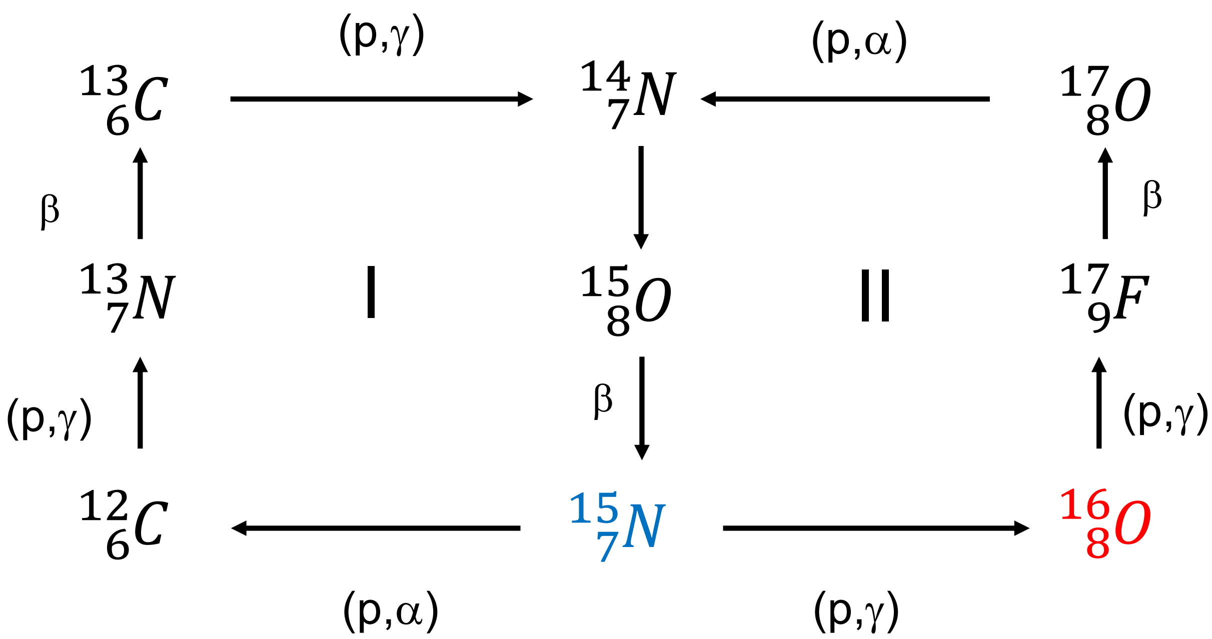
- This cycle consumes only hydrogen
- It starts and ends with ^{12}C which is used as a catalyst
- It transforms 4p into helium producing the same energy as from the pp-chain
- It produces two electron neutrinos
- More efficient at higher internal energy

The CNO bi-cycle

- $p + {}^{15}_{7}N \rightarrow \begin{cases} {}^{12}_{6}C + \alpha \\ {}^{16}_{8}O + \gamma \end{cases}$
- $p + {}^{16}_{8}O \rightarrow {}^{17}_{9}F + \gamma$
- ${}^{17}_{9}F \rightarrow {}^{17}_{8}O + e^{+} + \nu_e \; (\leq 1.740\ MeV, \tau \sim 90\ s)$
- $p + {}^{17}_{8}O \rightarrow \begin{cases} {}^{14}_{7}N + \alpha \\ {}^{18}_{9}F + \gamma \end{cases}$

- The relative probability of (p,α) to (p,γ) in the sun is of order 2×10^3
- ${}^{14}_{7}N$ produces ${}^{15}_{8}O$ and carbon again
- This branch
  - Negligible contribution to energy production
  - Important for nucleosynthesis of ^{16}O and ^{17}O

The CNO «cold» bi-cycle



Solar neutrinos and energy production: fundamental paradigm

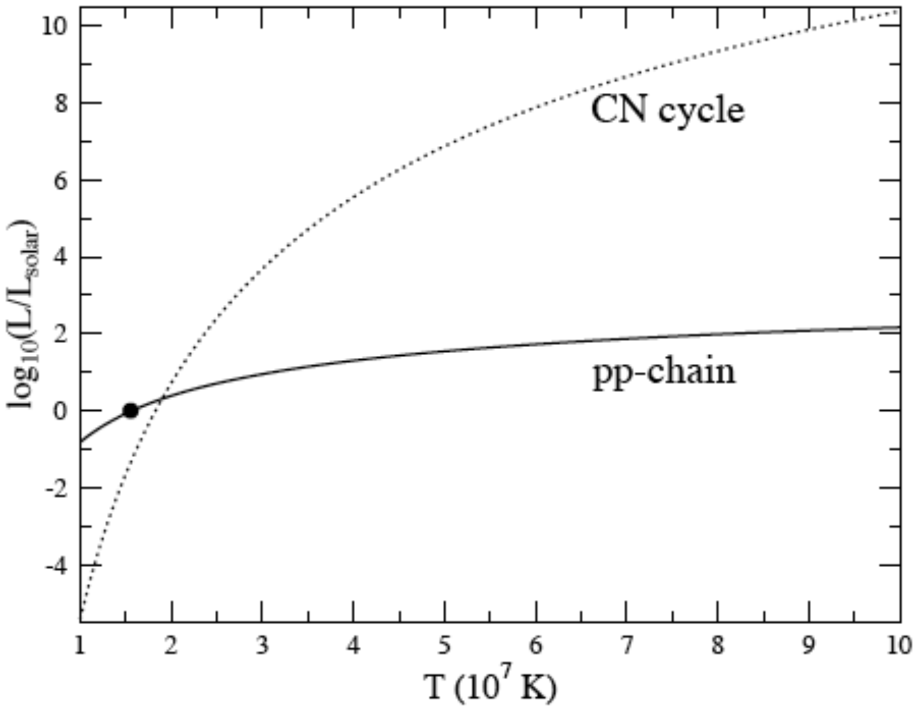
- *Energy conservation*

$$\frac{L_{\odot}}{4\pi(A.U.)^2} = \sum_i a_i \phi_i^{\nu}$$

$L_{\odot}$=3.846±0.015 erg/s

At solar temperature

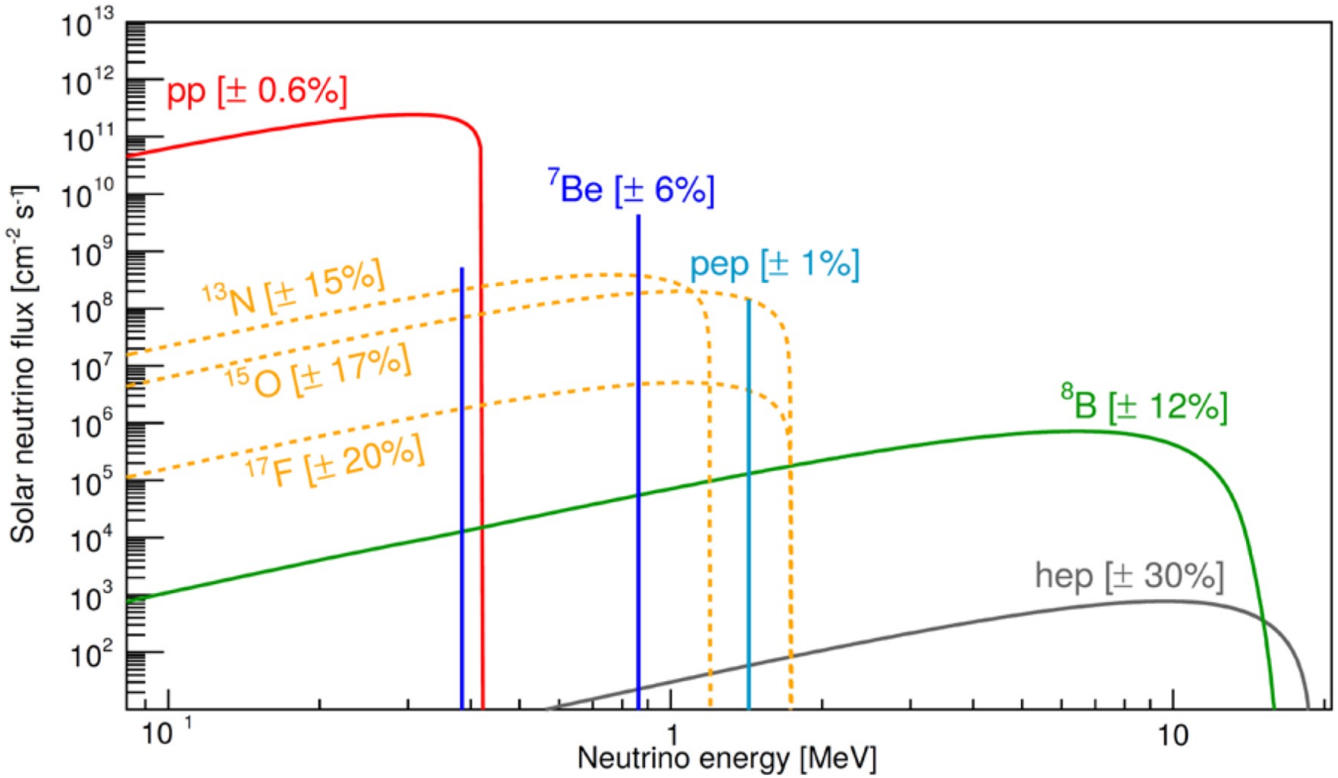
- $\epsilon_{pp} \propto T^4$
- $\epsilon_{CNO} \propto T^{18}$



Can we probe this idea through solar neutrino observations ?

Solar neutrino spectra

A. Serenelli et al, **Astrophys.J. 835 (2017) no.2, 202**



See Francesco Villante at this meeting for further details

Detecting Solar Neutrinos: interaction channels

- Electron capture: ν_e+(A,Z-1)$\rightarrow$(A,Z)+e^- (σ~$10^{-42}cm^2$)
  - charged-current interaction
  - can be associated with a correlated delayed event from the produced (A,Z) nucleus

- Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ (σ~$10^{-44}cm^2$)
  - charged/neutral-current interaction
  - Specific signature for monenergetic neutrinos

- $\nu_e + d \rightarrow e^- + p + p$ ($E_\nu \geq 1.44$ MeV) (σ~$10^{-42}cm^2$)
- $\nu_x + d \rightarrow \nu_x + p + n$ ($E_\nu \geq 2.74$ MeV)
  - Associated with n+d$\rightarrow$^{3}H+γ(6.25 MeV) or n+^{35}Cl$\rightarrow$^{36}Cl+$\sum\gamma$(8.6 MeV)

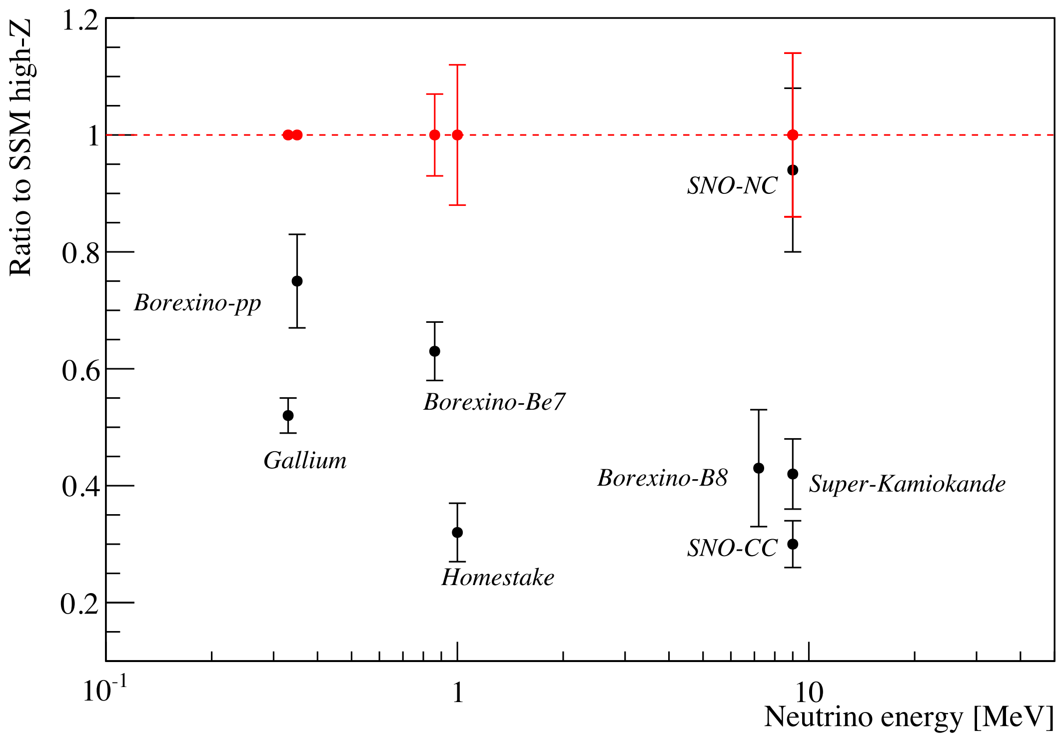
Solar Neutrino Experiments: past and present

Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1967-1994
Kamiokande II/III	3kton H_2O	9/7.5 / 7.0	1986-1995
SAGE	50tons molted metal Ga	0.233	1990-2007
GALLEX	30.3tons $GaCl_3$-HCl	0.233	1991-1997
GNO	30.3tons $GaCl_3$-HCl	0.233	1998-2003
Super-Kamiokande	22.5ktons	5 7 4.5 3.5 3.5 Gd loading 0.01% Gd loading 0.03%	1996-2001 2003-2005 2006-2008 2008-2018 2019-2020 2020-2022 **2022-present**
SNO	1kton D_2O	6.75/5/6/3.5	1999-2006
Borexino	300ton C_9H_{12}	0.2 MeV	2007-2019
SNO+	780 tons of LAB	0.2 MeV	**2023-present**

Detection of solar neutrinos: exploited reactions

- $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ (E_{th} = 0.814 MeV)
- $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ (E_{th} = 0.233 MeV)
- $\nu_x + e^- \rightarrow \nu_x + e^-$ $(\sigma_{\nu_e e} \sim 9 \cdot 10^{-45} cm^2 \frac{E_\nu}{MeV} \sim 6\, \sigma_{\nu_{\mu,\tau} e})$
- $\nu_e + d \rightarrow e^- + p + p$ (E_{th} = 1.442 MeV)
- $\nu_x + d \rightarrow \nu_x + n + p$ (E_{th} = 2.224 MeV)
- $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$ (E_{th} = 2.22 MeV)

Solar Neutrino Problem (SNP)

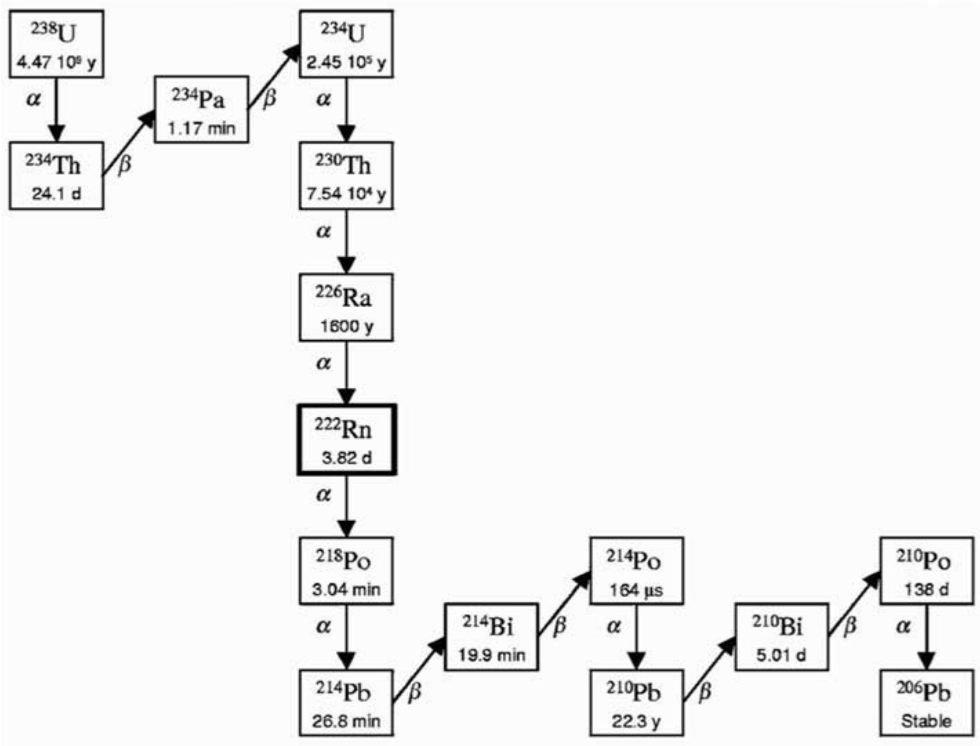


Backgrounds:
classification of radio-isotopes

- Primordial: longlived, ^{238}U, ^{87}Rb, ^{40}K, ^{232}Th…
- Cosmogenic: produced by cosmic rays (primary and secondary) interactions, ^{14}C, ^{3}H, ^{7}Be, ^{11}C, ^{39}Ar, …
- Antropogenic: produced by nuclear tests, ^{85}Kr, ^{90}Sr, ^{131}I, ^{137}Cs…

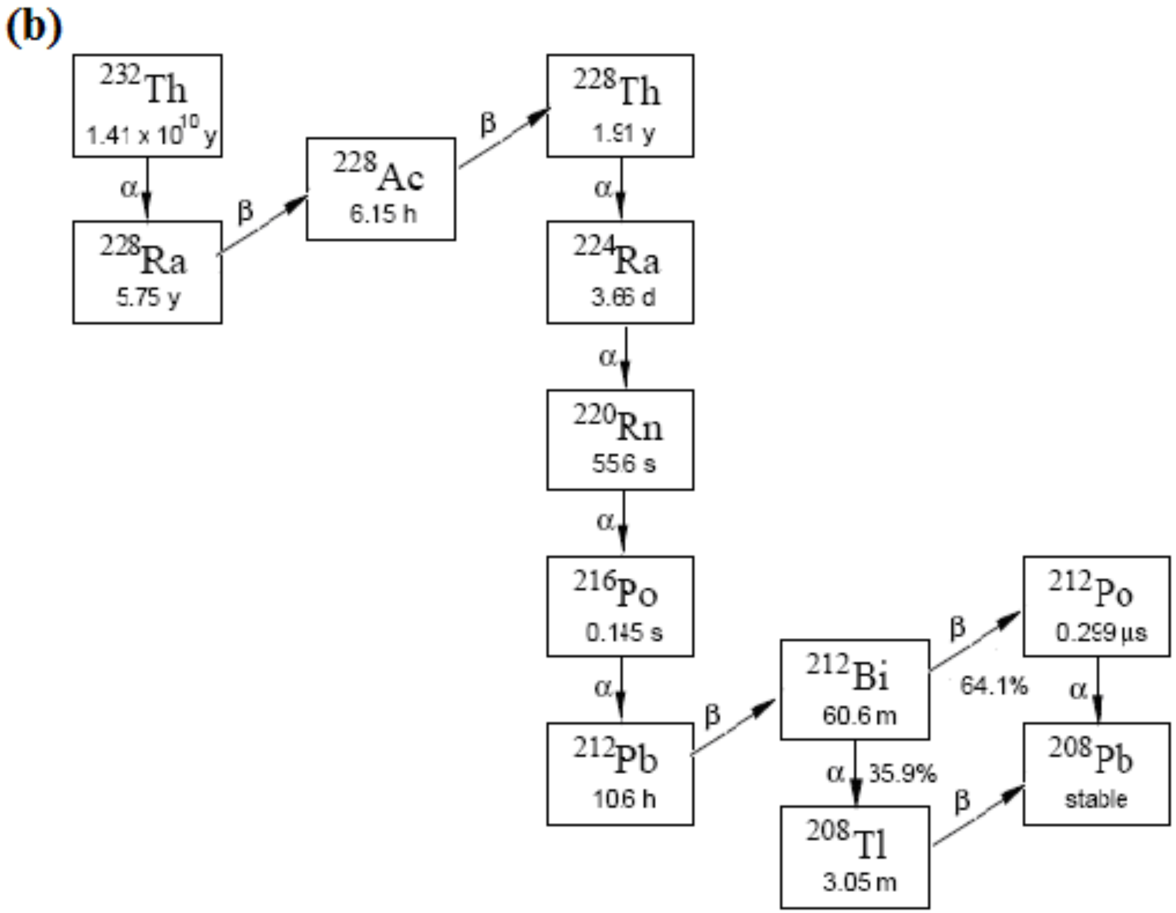
^{238}U radioactive chain

- ^{238}U is one of the longlived radioactive elements on Earth
- $T_{1/2} = 4.47 \times 10^9$ anni
- $^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6\beta + 51.7$MeV
- **^{222}Rn** (noble gas) -> **^{214}Bi** (3.2MeV β with many γ-rays)



^{232}Th radioactive chain

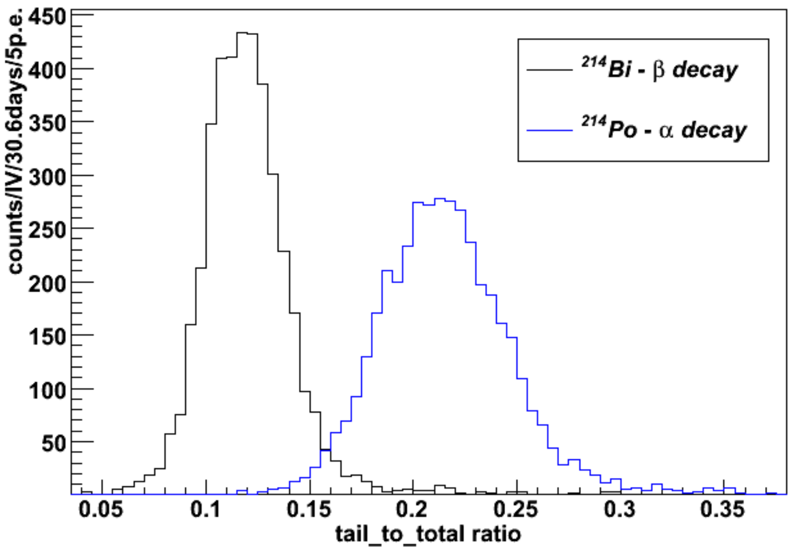
- ^{232}Th is another of the long-lived radioactive elements on Earth
- $T_{1/2}$ = 14x10^{9} years
- ^{232}Th--> ^{208}Pb+6α+4β+42.8MeV
- ^{232}Th -> **^{208}Tl** (2.6 MeV γ-ray largest in natural radioactivity 5 MeV β)

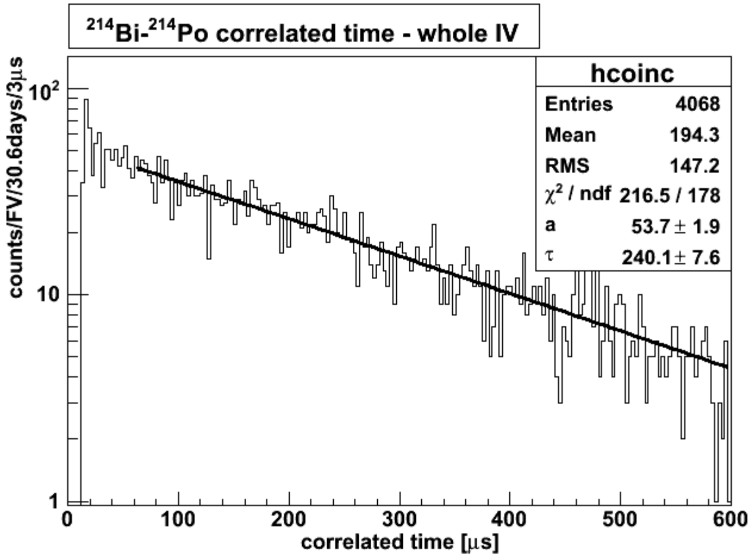


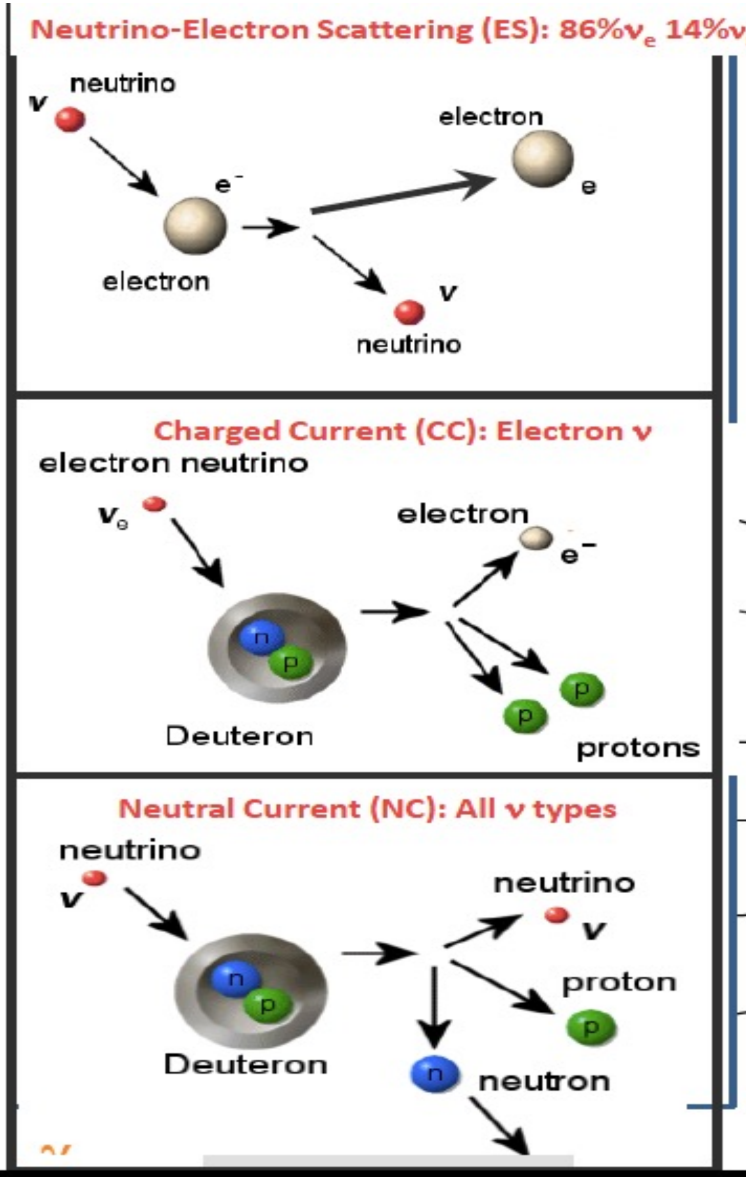
Bi-Po tagging

- Exploit β–α decay sequence to infer ^{238}U and ^{232}Th contamination to very low levels (~ 10^{-6} μBq/kg) assuming secular equilibrium

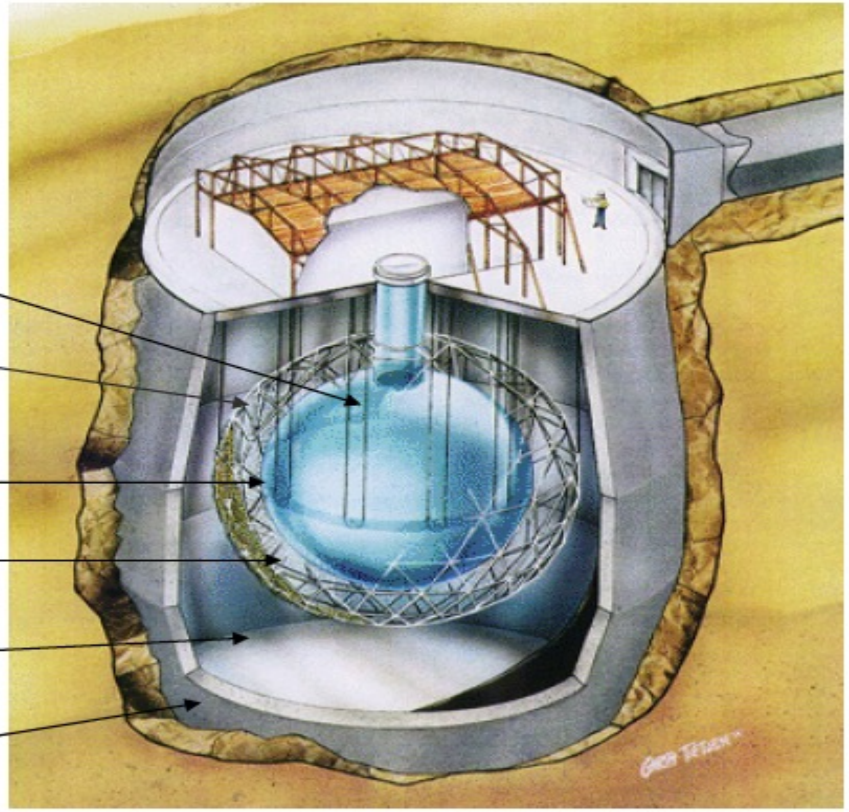
An example from Borexino: ^{238}U from ^{214}Bi-^{214}Po correlated events: **(7±2) × 10^{-18} g/g**







Sudbury Neutrino Observatory

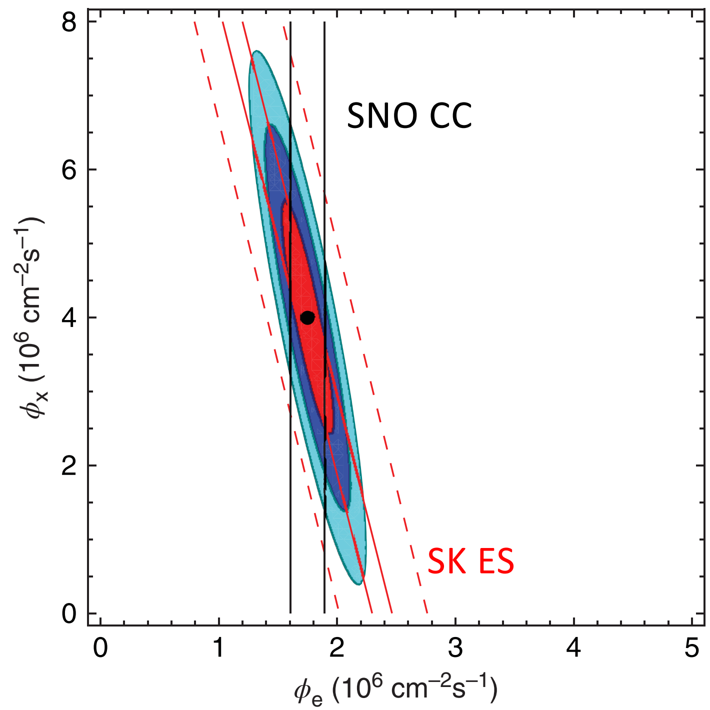


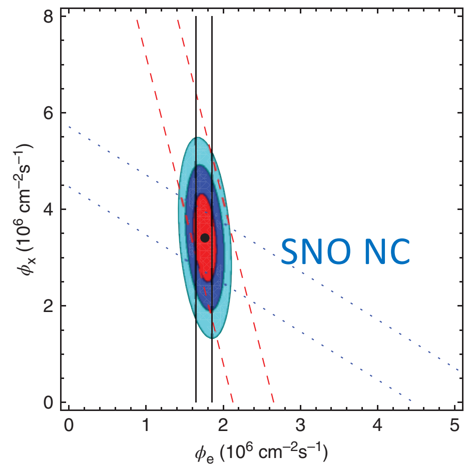
- Build at 6000 m.w.e.
- 1kton D_2O in 12m acrylic vessel
- 9456 20cm PMTs
- 55% coverage
- 7kton H_2O shielding with 91 PMTs
- 3 phases
  - Pure D_2O
  - Salt
  - 40 vertical Neutral Current Detectors

A few considerations on SNO

- Probe at the same time CC, ES, and NC
- $\phi_{\nu_e}^{CC} \leq \phi_{\nu_e}^{ES}$
- $\phi_{\nu_x}^{NC} \leq \phi_{\nu_e}^{SSM}$

In 2001 combining SK and SNO data it was possible to establish a flavor change in solar neutrino propagation





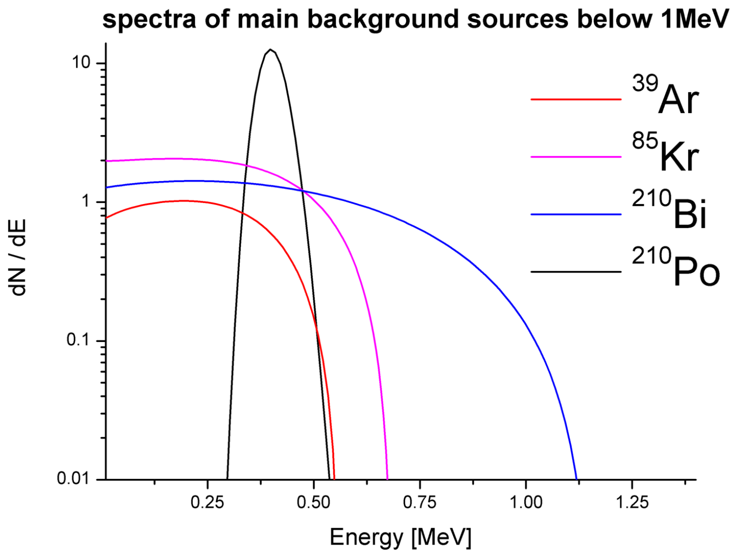
How to detect sub-MeV solar neutrinos in real time

- Due to radioactivity in high purity water (~ 10^{-15-14} g(U,Th)/g) in Cherenkov detector it is not possible to measure neutrinos below 3.5 MeV
- Make use of an organic liquid scintillator
  - ✓ 1998: start idea within Borexino collaboration
- Material reach in hydrogen and electrons
  - Good for neutrino-electron ES and inverse-beta decay
- Scintillator = solvent(bulk) + solute
  - Solvent needs to be transparent (low light quenching), high radio-purity
- Light yield ~ 10^4 photons/MeV
  - $N_{p.e.} \sim 10^4 e^{-6/10}$ 0.25 0.9 0.3 = 370 p.e./MeV
  - Energy resolution ~ $0.05/\sqrt{T_e}$

What level of radio-purity ?

- **Goa**l: observe ^{7}Be solar neutrinos (energy ~ 0.86 MeV)
- $\sigma \sim 5\times10^{-45}$ cm^2 and $\phi \sim 5\times10^{9}$ cm^{-2}s^{-1}
- Use 100 tons of C_9H_{12} with 4.2×10^{31} electrons
- Expected events ~ 70 cpd
- With 100% PSD and 10^{-16} g/g of ^{238}U and ^{232}Th: ~76 cpd
- **S/B ~ 1 requires extreme radio-purity level**
  - ✓ **≤ 10^{-16} g(U,Th)/g which means order of ≤ 10^{-4} μBq/kg**

Beyond U and Th: ^{39}Ar, ^{85}Kr, ^{210}Pb, ^{222}Rn



All spectra normalized to 1

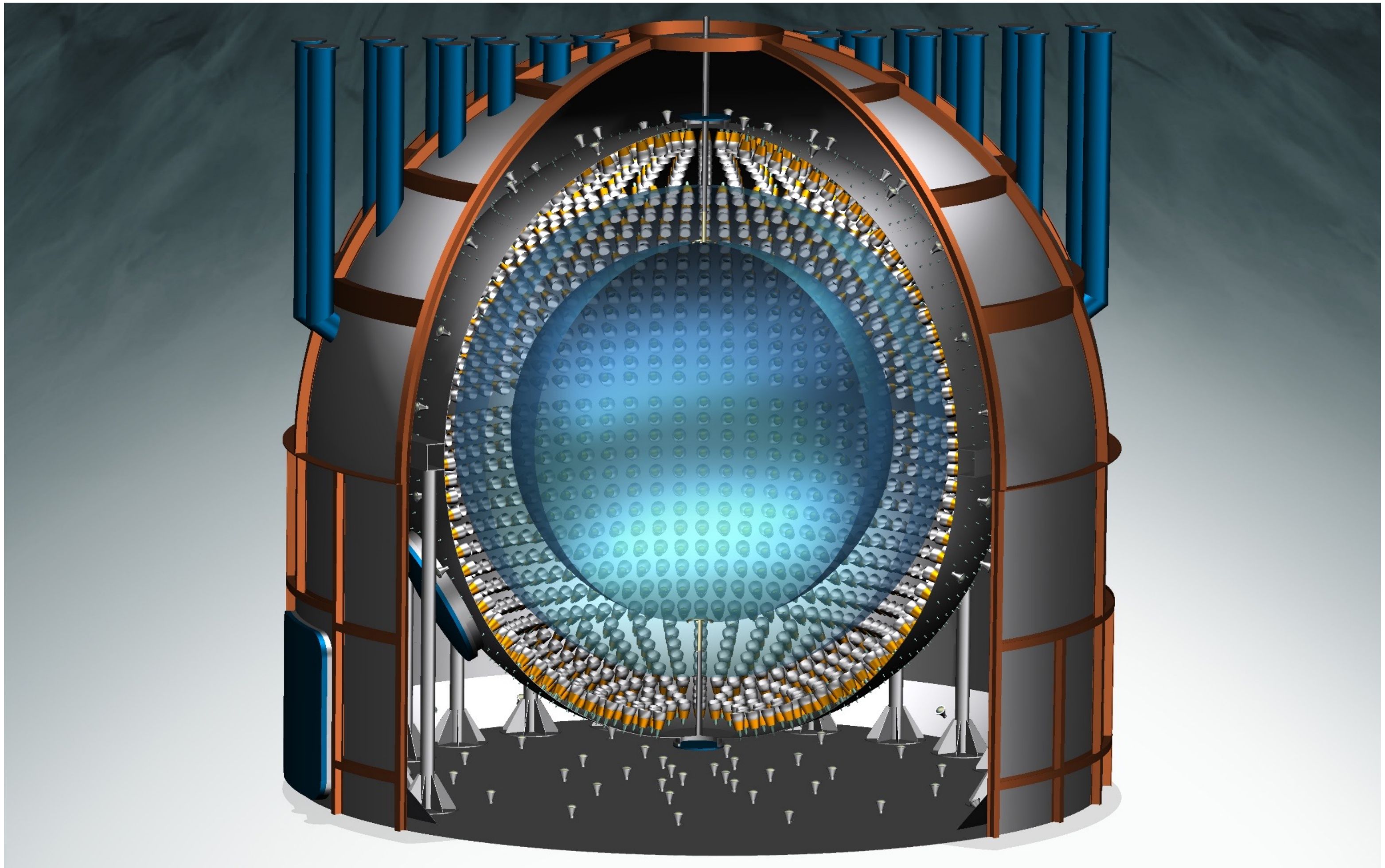
Asking for 1cpd/100tons

[0.1 μBq/m^3 in LS] it implies:

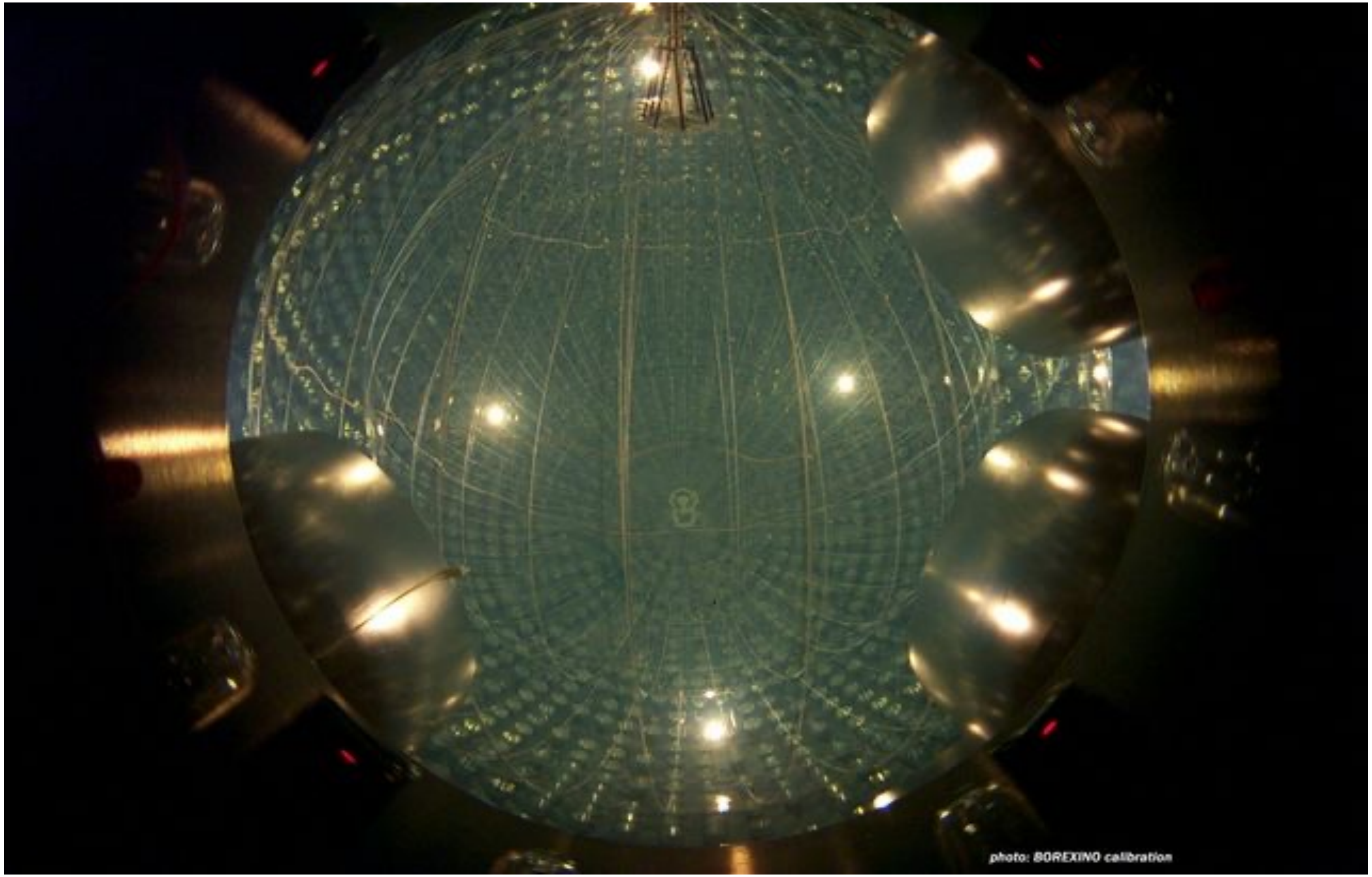
1. System sealed against ^{222}Rn ~10^{-4} Bq/ton
2. 0.4 ppm ^{39}Ar in N_2
3. 0.2 ppt ^{85}Kr in N_2

^{210}Pb and ^{210}Po are
often found not in equlibrium
due to a different chemistry

Borexino experiment overview

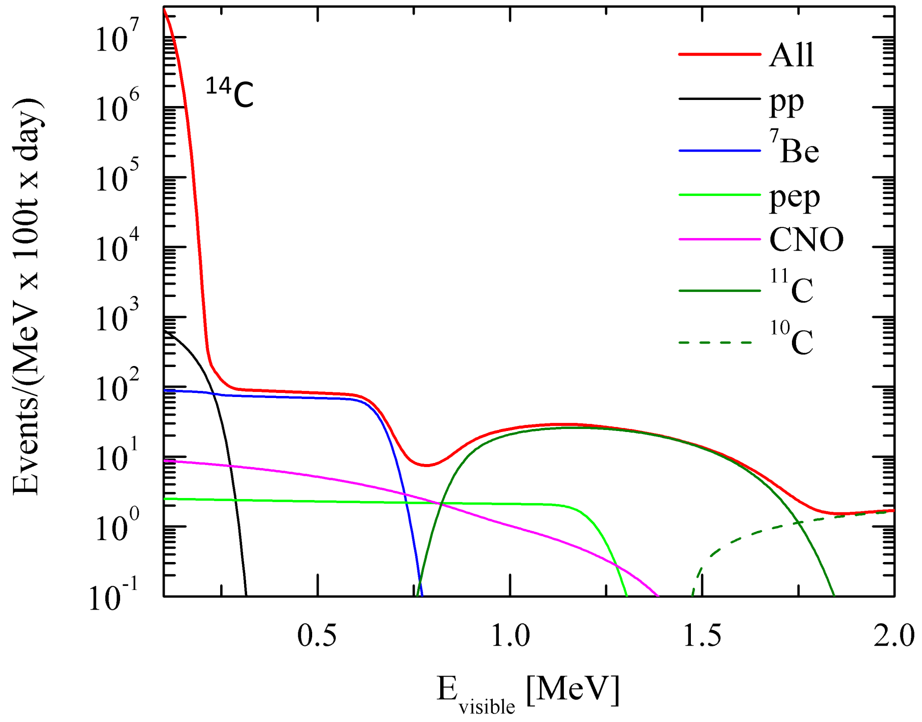


Borexino: liquid scintillator filling

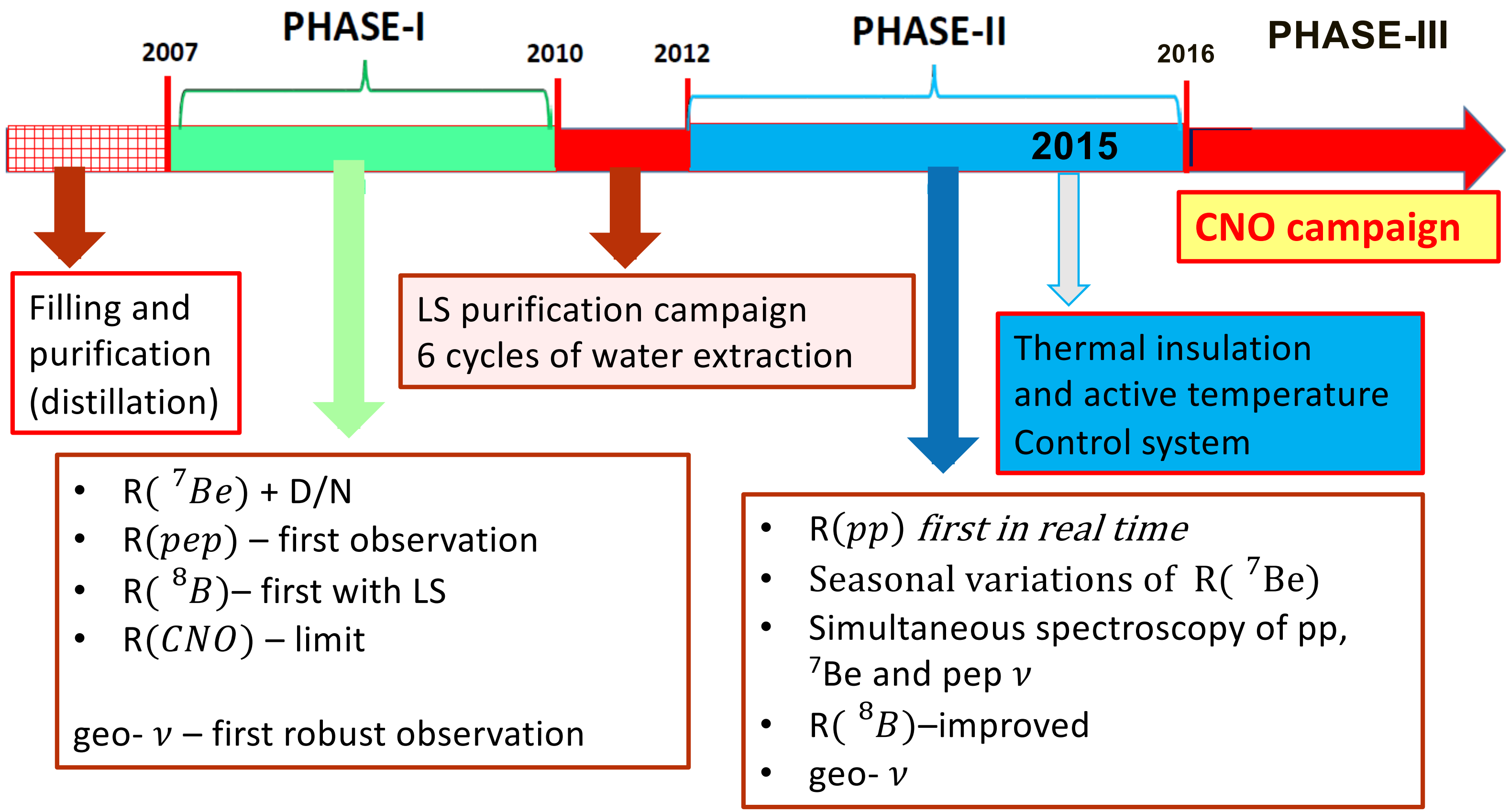


Borexino Expected Solar ν Spectrum

Spectrum with irreducible backgrounds



Borexino operations and achievements



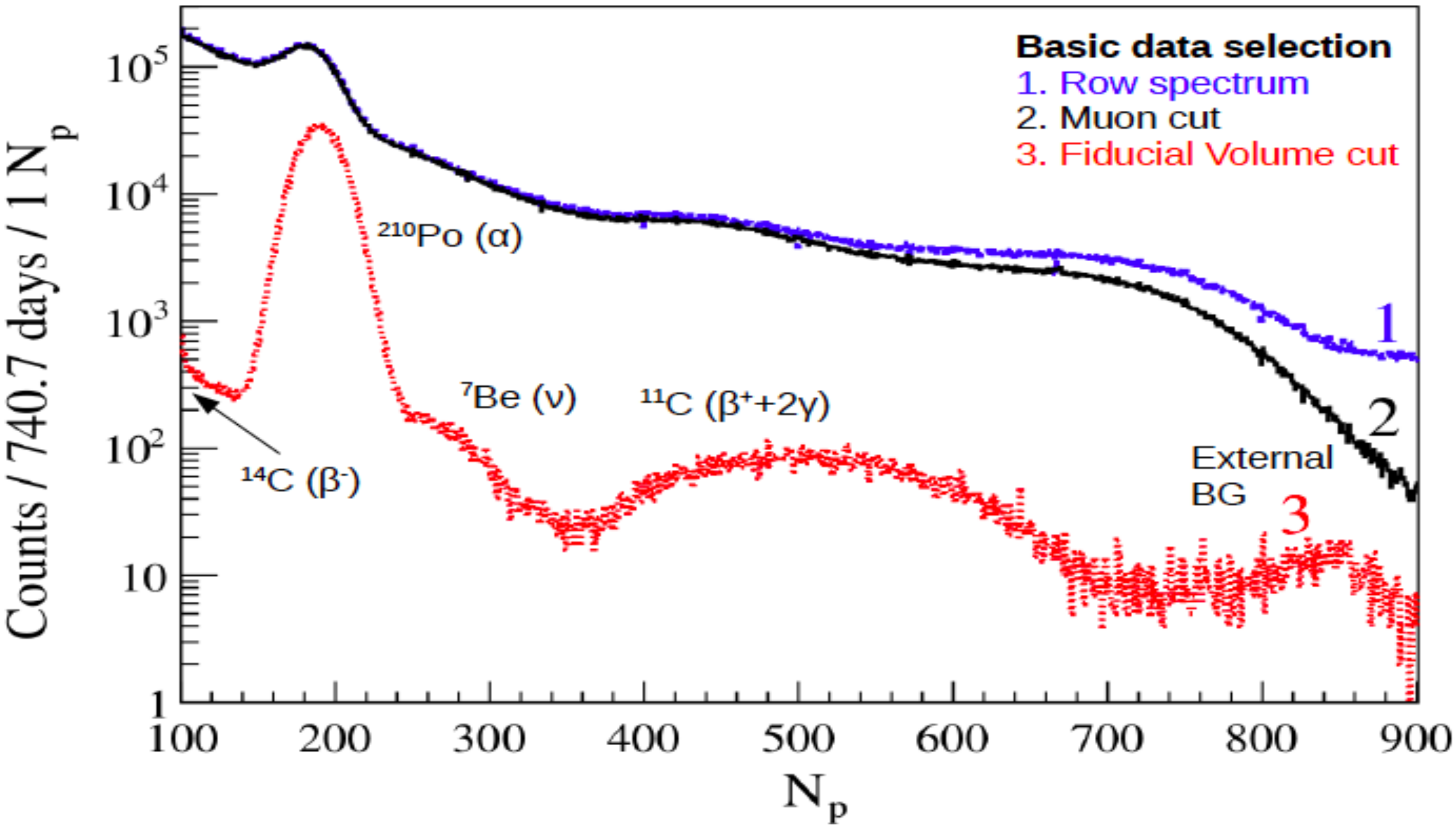
Borexino radio-purity

Isotope	Spec. in LS	After filling	After purification
^{238}U	$\leq 10^{-16}$ g/g	(5.3±0.3) 10^{-18} g/g	$\leq 9.4\ 10^{-20}$ g/g
^{232}Th	$\leq 10^{-16}$ g/g	(3.8±0.8) 10^{-18} g/g	$< 5.7\ 10^{-19}$ g/g
$^{14}C/^{12}C$	$\leq 10^{-18}$	(2.7±0.1) 10^{-18} g/g	no change
^{40}K	$\leq 10^{-18}$ g/g	$\leq 0.4\ 10^{-18}$ g/g	
^{85}Kr	≤ 1 cpd/100ton	30± 5 cpd/100ton	≤ 5 cpd/100ton
^{39}Ar	≤ 1 cpd/100ton	<< ^{85}Kr	<< ^{85}Kr
^{210}Po	not specified	~ 8000 cpd/100ton	no change
^{210}Bi	not specified	~ 20-70 cpd/100ton	20±5 cpd/100ton

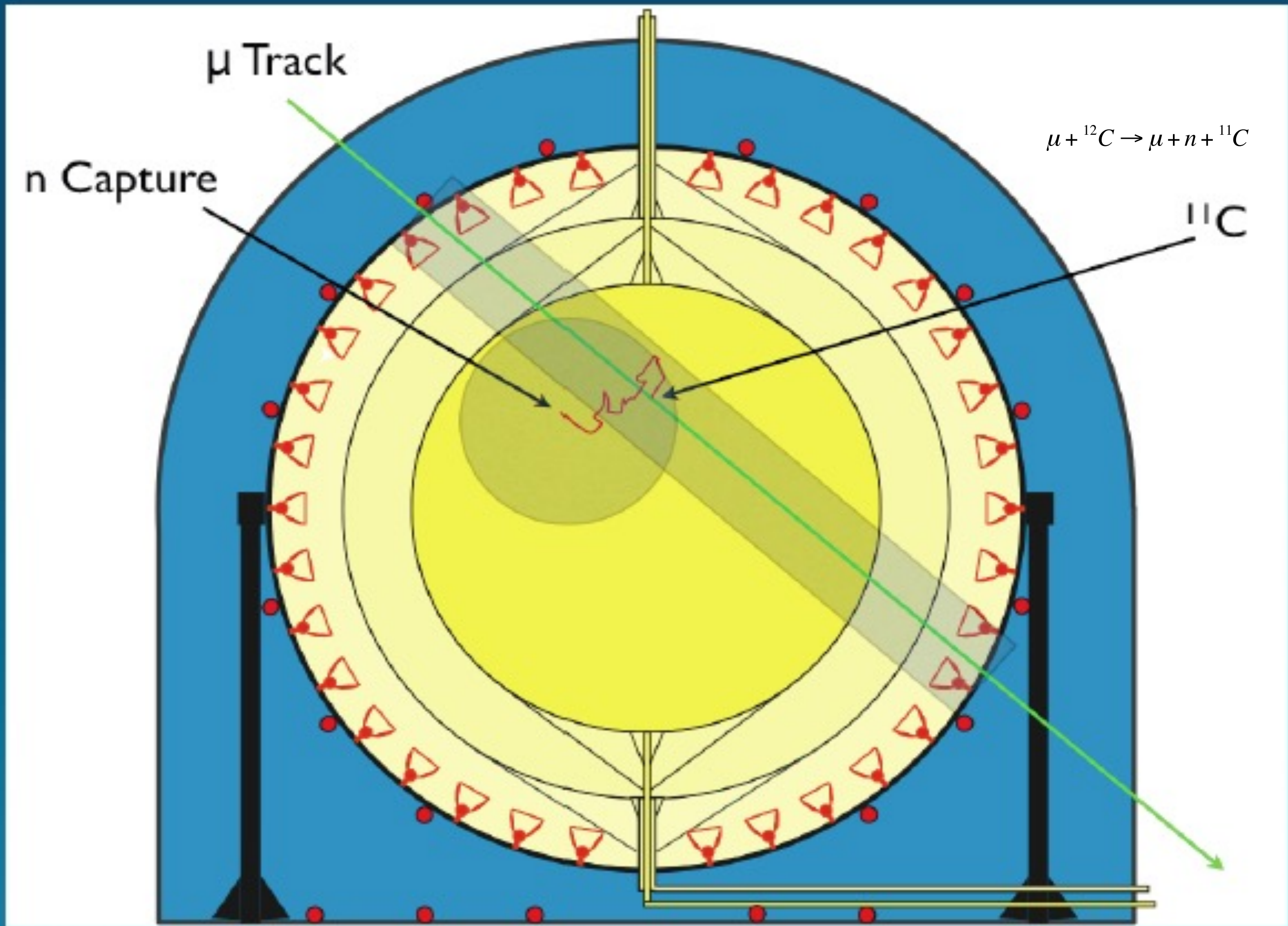
A_{BX} ~ 40 cpd/100ton in ^{7}Be ROI

A_{BX} ~ 5×10^{-9} Bq/kg

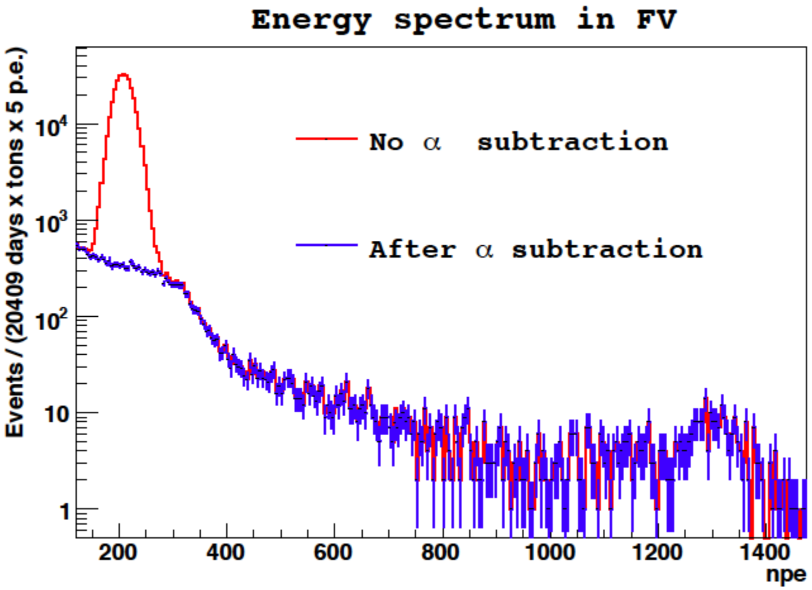
The β-like energy spectrum

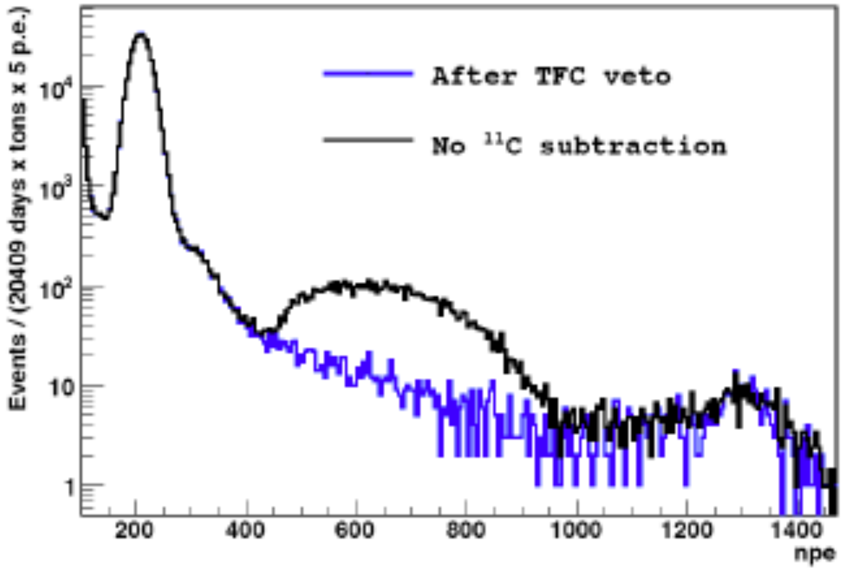


Tagging and removing ^{11}C cosmogenic background



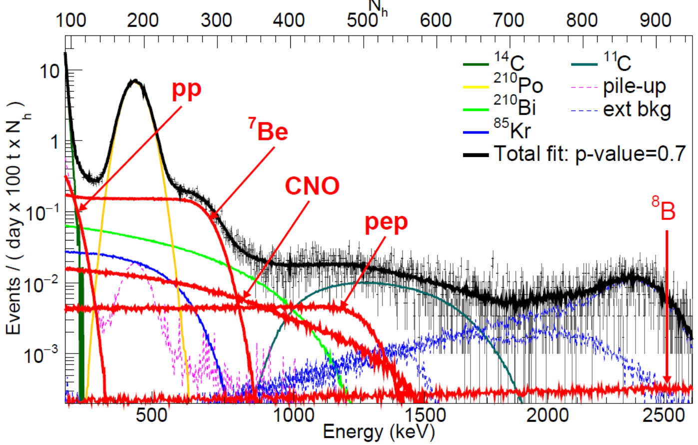
Remove ^{11}C and ^{210}Po



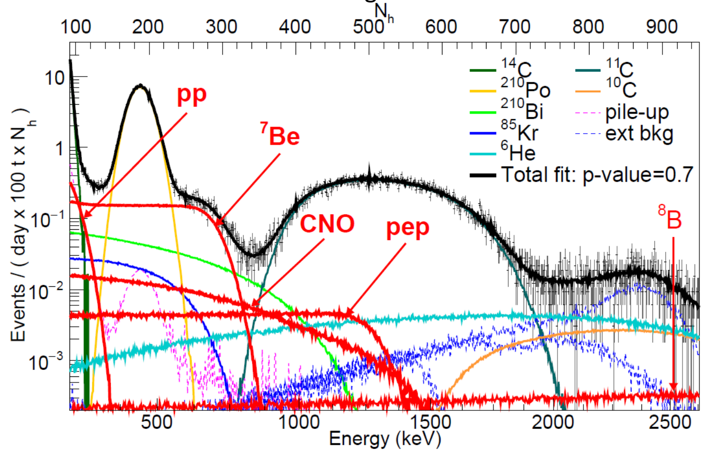


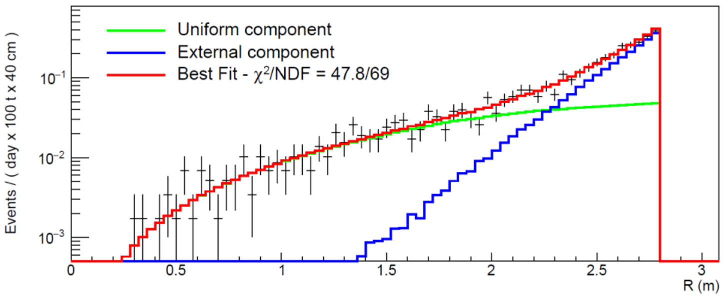
Multivariate fit example: simultaneous fit of pp, 7Be and pep

$L(^{11}C_{sub})$

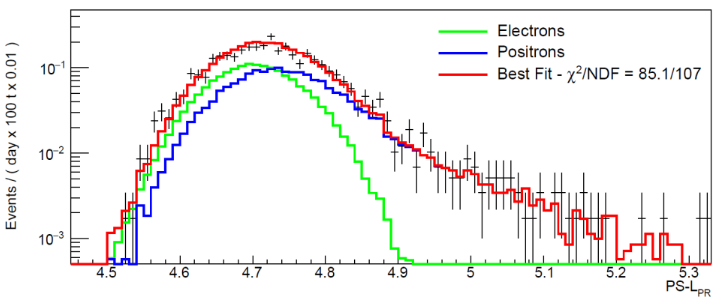


$L(^{11}C_{tag})$



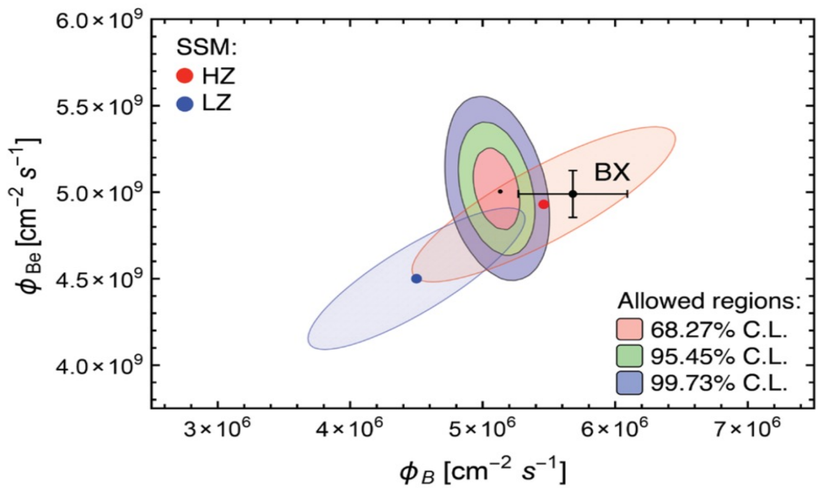


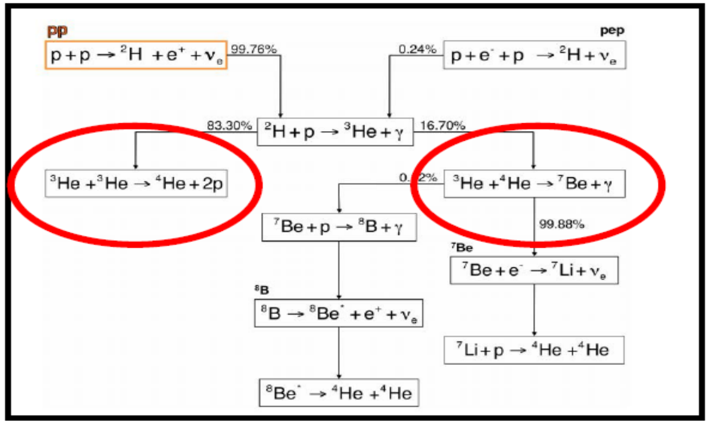
L(Rad)



L(PS)

Borexino vs Solar Standard Model





$$R \equiv \frac{<{}^3\mathrm{He} + {}^4\mathrm{He}>}{<{}^3\mathrm{He} + {}^3\mathrm{He}>} = \frac{2\phi({}^7\mathrm{Be})}{\phi(\mathrm{pp}) - \phi({}^7\mathrm{Be})}$$

$$f_{\mathrm{Be}} = \frac{\Phi(\mathrm{Be})}{\Phi(\mathrm{Be})_{\mathrm{HZ}}} = 1.01 \pm 0.03$$

$$f_B = \frac{\Phi(\mathrm{B})}{\Phi(\mathrm{B})_{\mathrm{HZ}}} = 0.93 \pm 0.02$$

R(HZ)=0.180±0.011
R(LZ)=0.161±0.010

From the pp and ^{7}Be fluxes measurement

$R(BX)=0.178^{+0.027}_{-0.023}$

See Francesco Villante at this meeting for further considerations

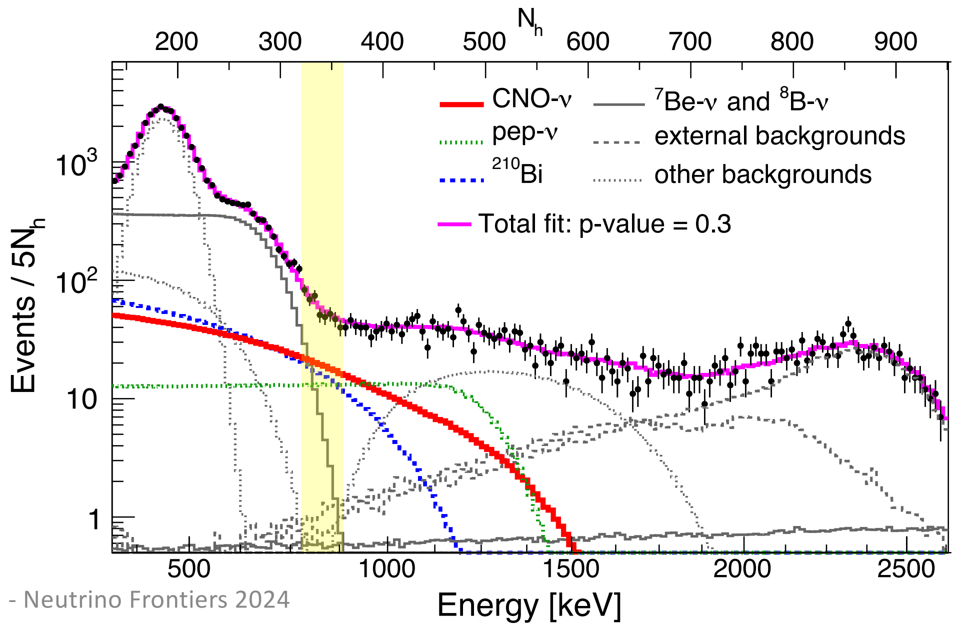
Challenge for CNO solar neutrino observation in Borexino

- Expected signal rate: 3 – 5 cpd/100ton
- Main background: ^{210}Bi

$$^{210}\mathrm{Pb} \xrightarrow[22.3\,\mathrm{years}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\,\mathrm{days}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}$$

- Strong correlation between CNO, pep, and ^{210}Bi
- Expected S/B ~ 0.2 – 0.3

Initial considerations on 210Po and 210Bi for CNO observation in liquid scintillators: *Phys.Lett.B* 701 (2011) 336-341



Towards CNO neutrinos observations: ackground from nylon vessel

Convective currents can carry radioactive isotopes from the nylon vessel into the Fiducial Mass

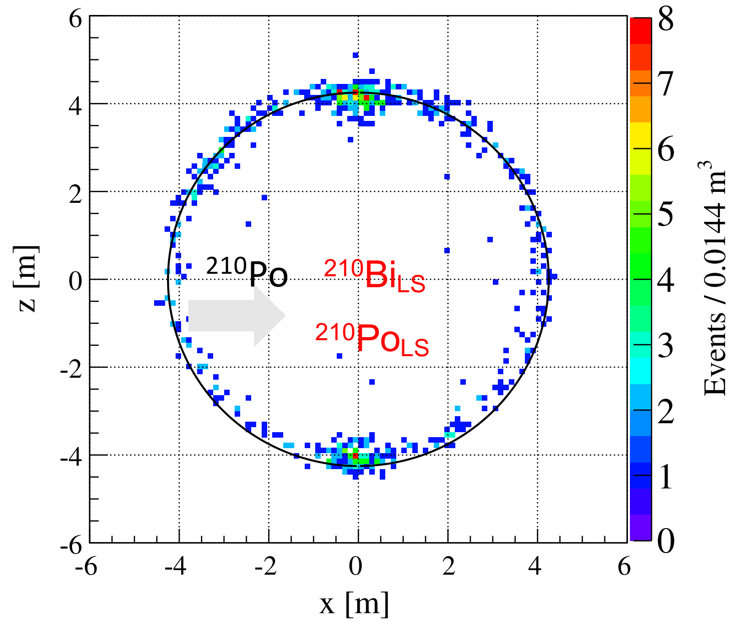
$$^{210}\text{Pb} \xrightarrow[22.3\,\text{years}]{\beta^-} {}^{210}\text{Bi} \xrightarrow[5\,\text{days}]{\beta^-} {}^{210}\text{Po} \xrightarrow[138.4\,\text{days}]{\alpha} {}^{206}\text{Pb}$$

Nylon vessel has ppt level of U, Th plus out-of-equilibrium ^{210}Pb and surface ^{210}Po contamination

Some isotopes can leach off the surface and move to the FM

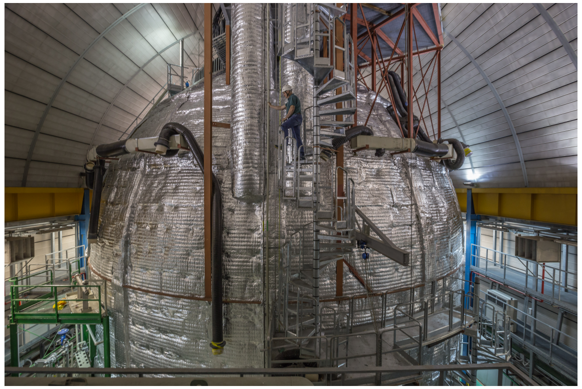
^{210}Po in LS has two components:

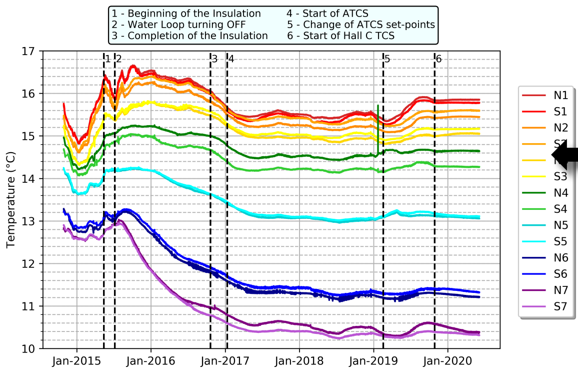
1. Intrinsic (supported by ^{210}Pb)
2. Due to convection



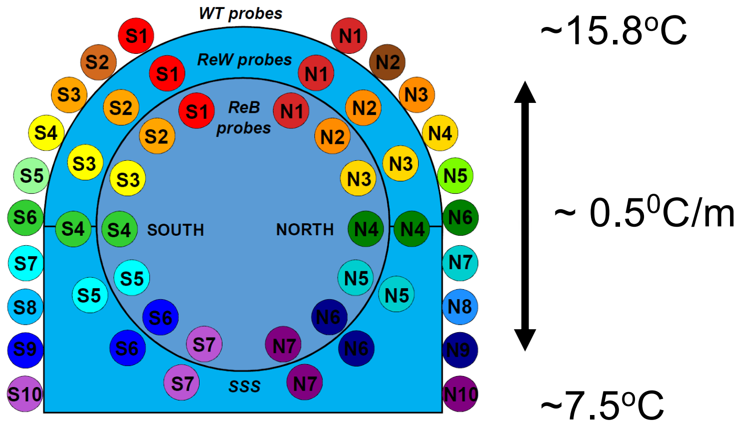
Thermal insulation and temperature control

Borexino Water Tank with insulation





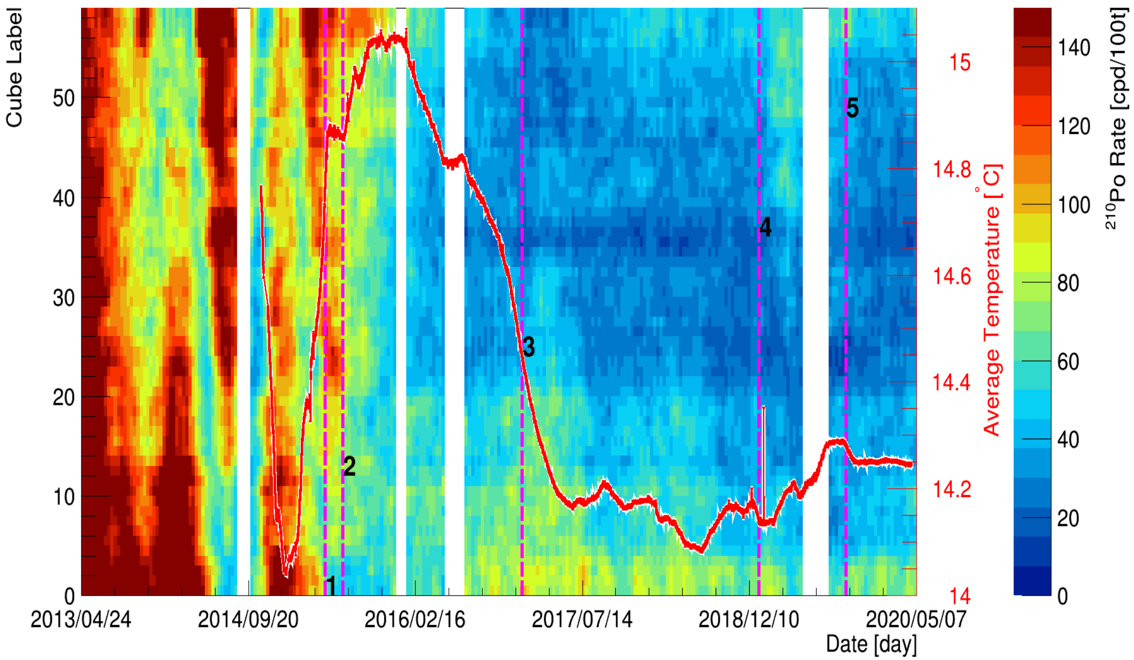
Deployment of T probes



Temperature as a function of time in different volumes of the detector

Goal: reduce seasonal and external activity effects to avoid convective currents

^{210}Po background in Borexino



- ^{210}Po rate in Borexino in cpd/100tons from bottom to top
- 3 tons cubes within 3m sphere

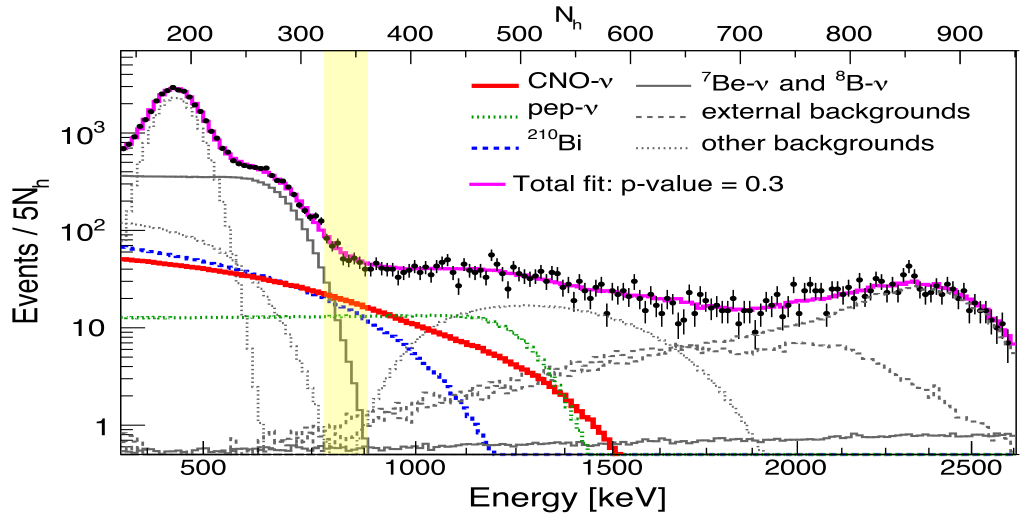
1. Beginning of thermal insulation
2. Water re-circulation loop in Water Tank off
3. Active temperature control system on
4. Change set point in the active control system
5. Air temperature control system in underground Hall

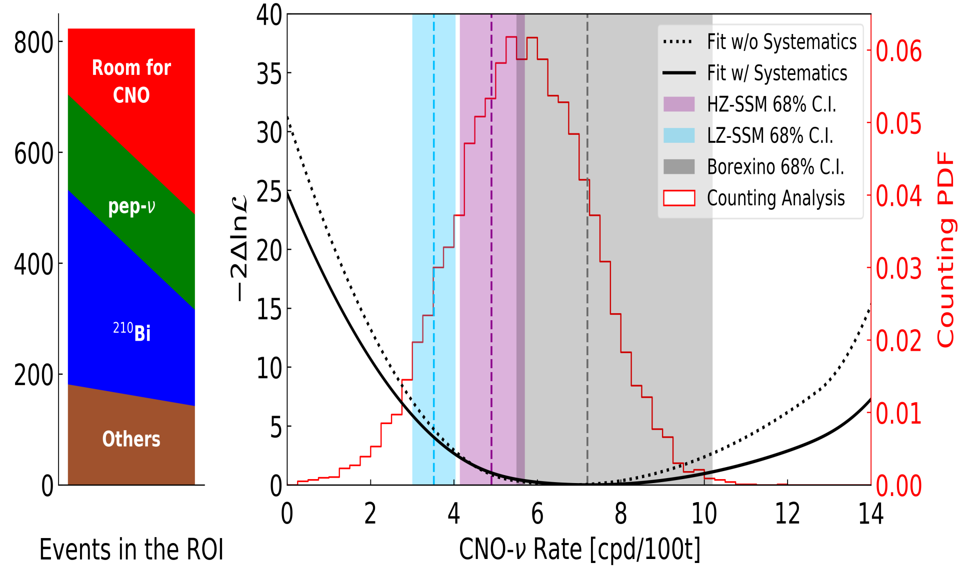
$R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po^{Vessel})$

^{210}Bi constrained ≤ 11.5±1.3 cpd/100ton

CNO solar neutrinos

- Energy window: 0.32-2.64 MeV
- Fit energy spectrum and radial distribution
- Free pars: CNO, ^{85}Kr, ^{11}C, ^{40}K, ^{208}Tl, ^{214}Bi, ^{7}Be
- pep constrained to 2.74±0.04 cpd/100ton
- **^{210}Bi constrained ≤ 11.5±1.3 cpd/100ton**
- Data set July 2016 – Feb 2020
- 1072 days of livetime
- Selection cuts:
    - Muon and muon daughters
    - FV (R < 2.8 m && -1.8m<z<2.2m)
    - TFC (remove ^{11}C)





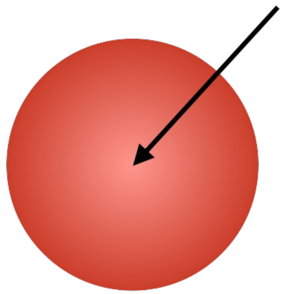
R(CNO) = 7.2 $^{+2.9}_{-1.7}$ cpd/100ton
Null hypothesis (CNO=0) rejected at 5.1σ

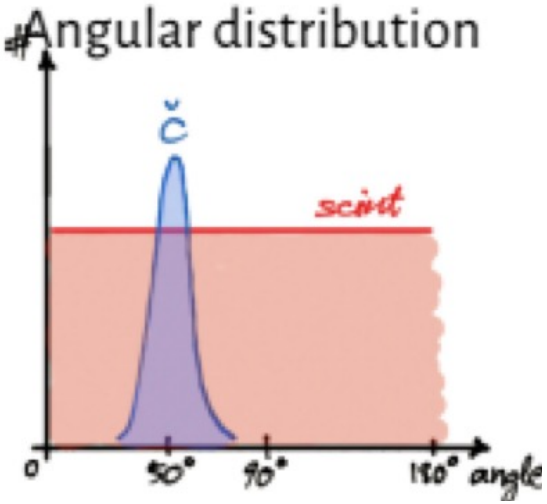
Nature 587 (2020) 577-582

Cherenkov vs Scintillation in a LS

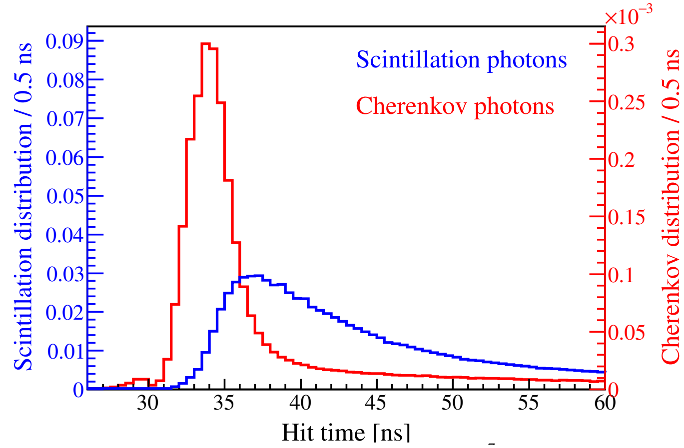
Cherenkov

Scintillation

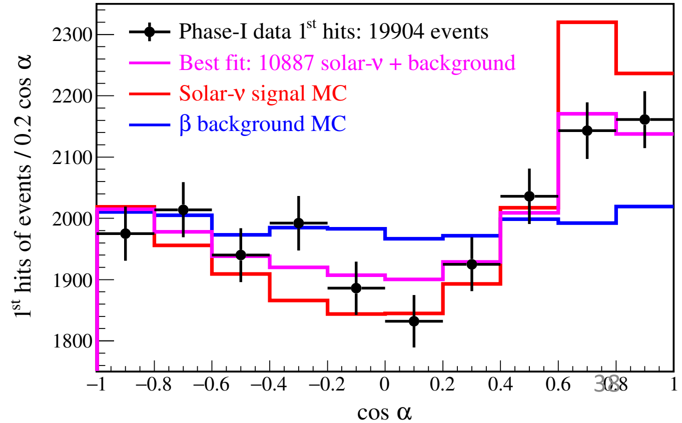




^{7}Be MC

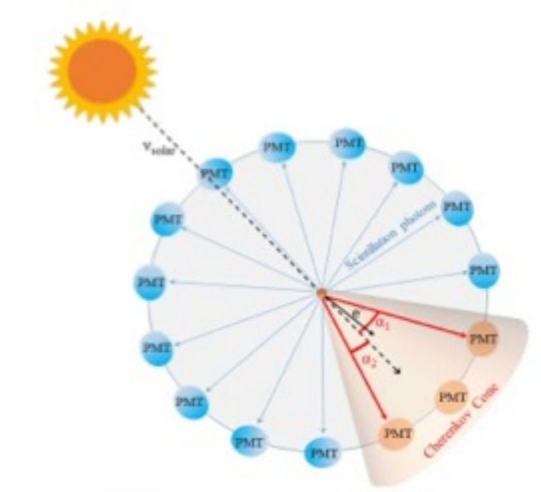


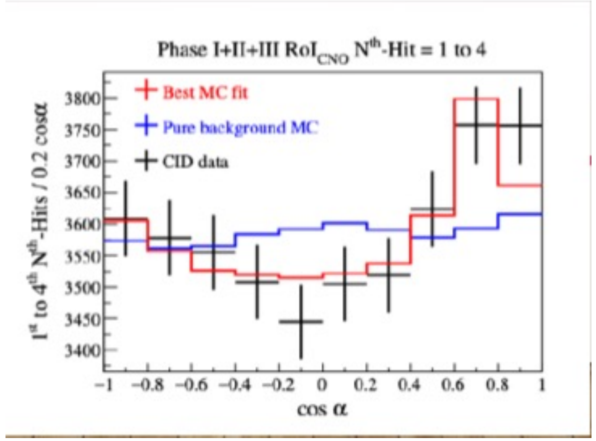
MC generated pdf for signal and background

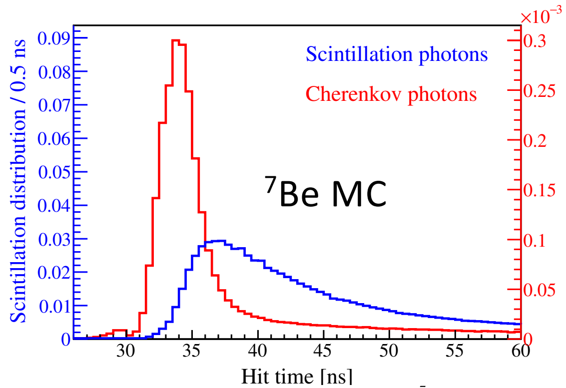


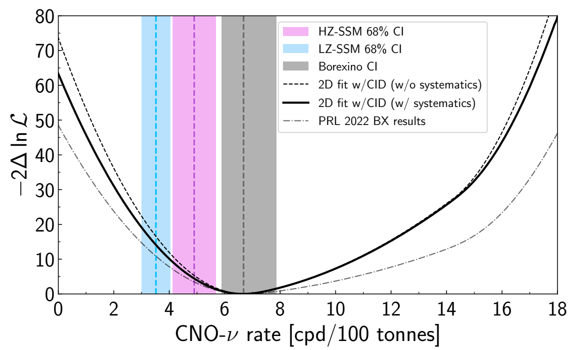
CNO with directionality

- *Phys.Rev.Lett.* 128 (2022) 9, 091803, *Phys.Rev.D* 108 (2023) 10, 102005
- Detected PMT-hit pattern of selected event with position of the sun
- CID (Correlated Integrated Directionality) method
- CID can be used with **full Borexino statistics data set**









CNO rate
$\mathbf{7.2^{+2.5+1.2}_{-2.5-0.9}}$ cpd/100t (**stat.+syst**)

CNO neutrinos from Borexino

^{214}Bi constraint

CNO rate $\mathbf{6.7^{+2.0}_{-0.8}}$ cpd/100t (stat+sys)

Flux: $\mathbf{6.7^{+2.0}_{-0.9}}$ x 10^8 cm^{-2} s^{-1}

Directionality

CNO rate

$\mathbf{7.2^{+2.5+1.2}_{-2.5-0.9}}$ cpd/100t (**stat. +syst**)

Combined
No CNO excluded at 8σ

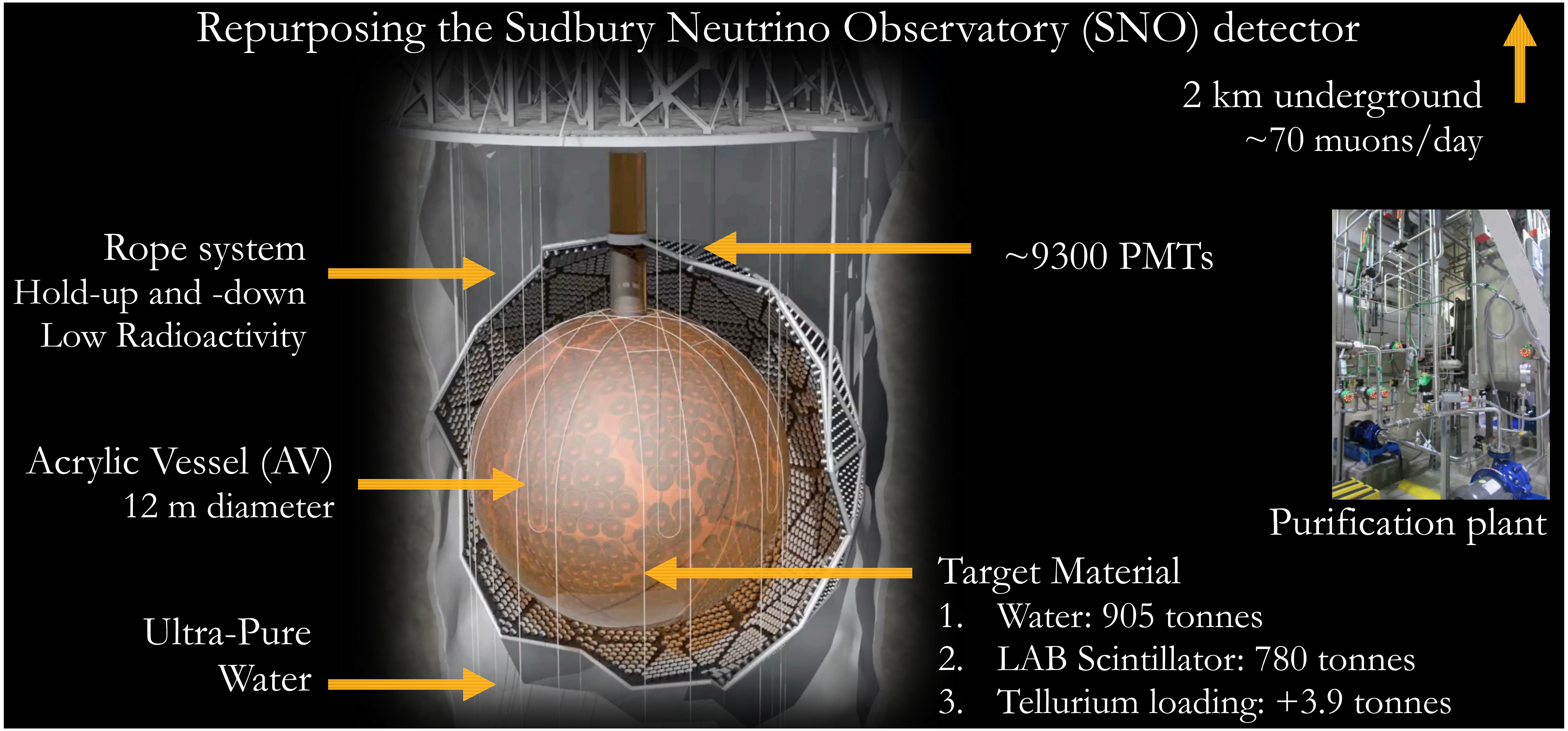
CNO rate $\mathbf{6.7^{+1.2}_{-0.7}}$ cpd/100 tons

Flux: $\mathbf{6.7^{+1.2}_{-0.8}}$ × 10^8 cm^{-2} s^{-1}

Solar neutrinos: observations vs theory

Sorgente	Flusso [$cm^{-2}s^{-1}$] SSM-HZ	Flusso [$cm^{-2}s^{-1}$] SSM-LZ	Flusso [$cm^{-2}s^{-1}$] Data
pp (BX)	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.005)\times10^{10}$	$6.1(1\pm0.10)\times10^{10}$ w/o luminosity constraint
pep (BX)	$1.44(1\pm0.009)\times10^{8}$	$1.46(1\pm0.009)\times10^{8}$	$1.27(1\pm0.17)\times10^{8}$ (HZ CNO) $1.39(1\pm0.15)\times10^{8}$ (LZ CNO)
^{7}Be (BX)	$4.93(1\pm0.06)\times10^{9}$	$4.50(1\pm0.06)\times10^{9}$	$4.99(1\pm0.03)\times10^{9}$
^{8}B (SK+SNO)	$5.46(1\pm0.12)\times10^{6}$	$4.50(1\pm0.12)\times10^{6}$	$5.35(1\pm0.03)\times10^{6}$
CNO (BX)	$4.88(1\pm0.11)\times10^{8}$	$3.51(1\pm0.10)\times10^{8}$	$6.7^{+1.2}_{-0.7}\times10^{8}$
p-value (pp, Be, B)	0.96	0.43	

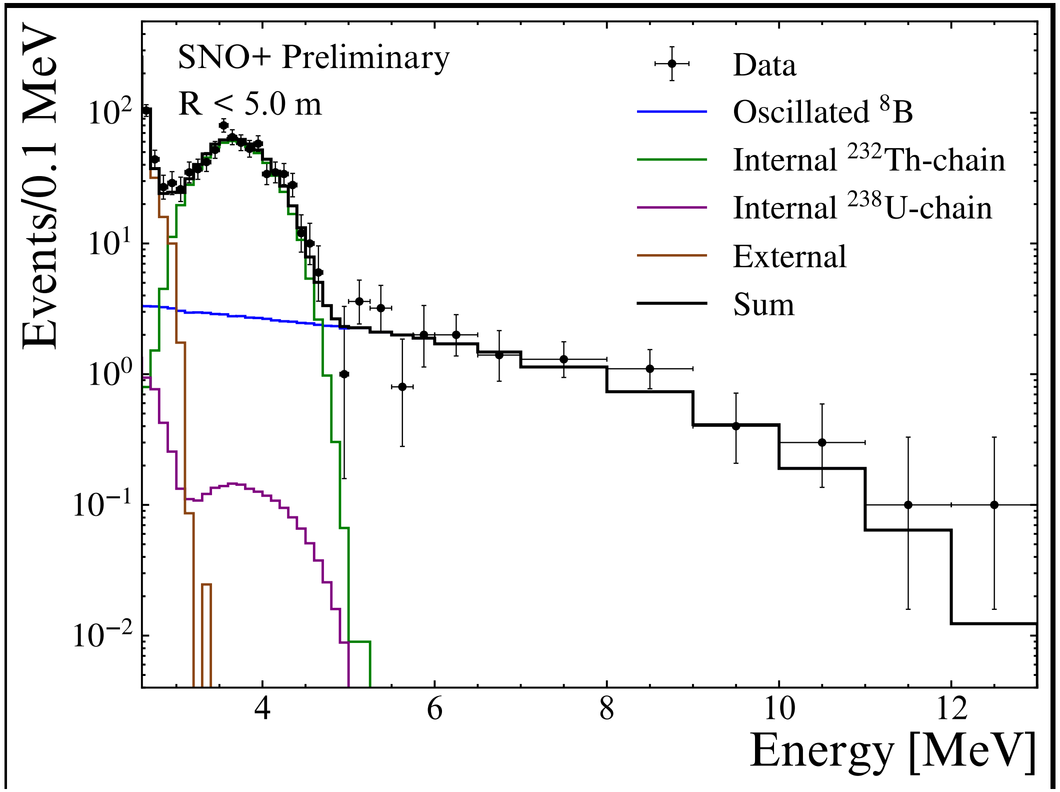
SNO+



From J. Maneira at Neutrino 2024

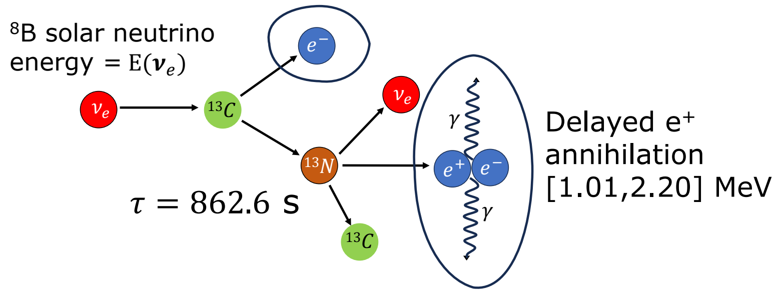
8B neutrinos from ES and CC in SNO+

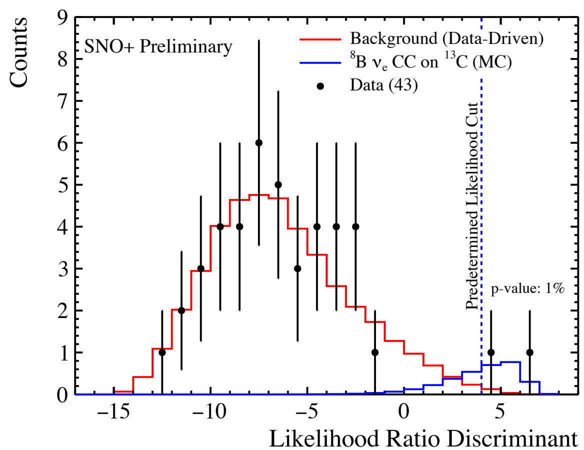
ES



Ianni, Montanino, Villante, *Phys.Lett.B* 627 (2005) 38-48

Prompt e⁻ energy = $E(\boldsymbol{\nu}_e) - 2.2\ MeV$





Conclusions

- 56 years of solar neutrino observations
- Fundamental results on neutrino physics and astrophysics
- More to come with SuperKamiokande and SNO+
- Future observations with HyperKamiokande, DUNE, and JUNO
- Observation of solar neutrinos with dark matter detectors already started through neutrino-nucleus coherent scattering (see IDM 2024)

Thank you!

Added material

Paradigm of the Luminosity Constraint

Spiro and Vignaud, 1990

$$4p \rightarrow \begin{cases} {}^4_2He + 2\nu_{pp} + 26.20\ MeV \\ {}^4_2He + \nu_{pp} + \nu_{Be} + 25.60\ MeV \\ {}^4_2He + \nu_{pp} + \nu_B + 19.70\ MeV \end{cases}$$

$$\frac{L_{sun}}{4\pi\, d^2} = 8.4946 \cdot 10^{11}\, \frac{MeV}{cm^2 s} = \sum_i a_i \phi_i = 19.7\ MeV\ \phi_B + 25.6\ MeV\,\phi_{Be} + \frac{26.2\ MeV}{2}\left(\phi_{pp} - \phi_{Be} - \phi_B\right)$$

$1 = 0.922\ f_{pp} + 0.07\ f_{Be} + 0.00004\ f_B$ with $f_i = \phi_i / \phi_{SSM}$

Luminosity constraints and CNO neutrinos

$$ {}^{12}_{6}C\ (p,\gamma)\ {}^{13}_{7}N $$

$$ M({}^{12}_{6}C) + M({}^{1}_{1}H) - M({}^{13}_{7}N) = 1.944\ MeV $$

$$ {}^{13}_{7}N \rightarrow {}^{13}_{6}C + e^{+} + \nu_e $$

$$ M({}^{13}_{7}N) - M({}^{13}_{6}C) - \langle E_\nu \rangle = 2.22\ MeV - 0.707\ MeV = 1.513\ MeV $$

$$ a_N = 3.457\ MeV $$

$$ {}^{13}_{6}C\ (p,\gamma)\ {}^{14}_{7}N $$

$$ M({}^{13}_{6}C) + M({}^{1}_{1}H) - M({}^{14}_{7}N) = 7.551\ MeV $$

$$ {}^{14}_{7}N\ (p,\gamma)\ {}^{15}_{8}O $$

$$ M({}^{14}_{7}N) + M({}^{1}_{1}H) - M\left({}^{15}_{8}O\right) = 7.297\ MeV $$

$$ {}^{15}_{8}O \rightarrow {}^{15}_{7}N + e^{+} + \nu_e $$

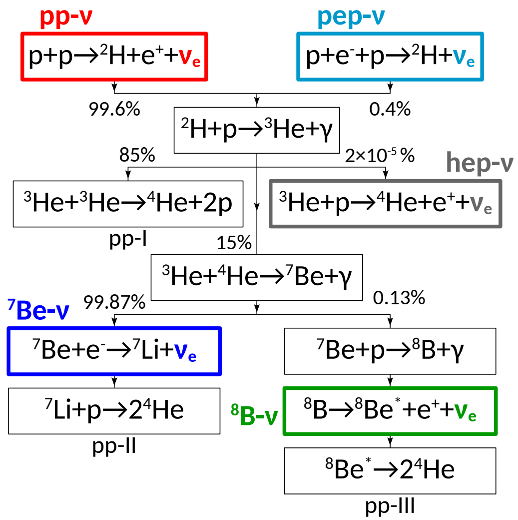
$$ M\left({}^{15}_{8}O\right) - M\left({}^{15}_{7}N\right) - \langle E_\nu \rangle = 2.754\ MeV - 0.996\ MeV = 1.758\ MeV $$

$$ {}^{15}_{7}N\ (p,\alpha)\ {}^{12}_{6}C $$

$$ M\left({}^{15}_{7}N\right) + M({}^{1}_{1}H) - M({}^{4}_{2}He) - M({}^{12}_{6}C) = 4.966\ MeV $$

$$ a_O = 21.571\ MeV $$

Luminosity constraint refined



Bahcall, 2002; Vissani et al 2020

$^1H(p,e^+\nu_e)^2H$ and $^1H(p\ e^-,\nu_e)^2H$ have time scale of order 10^{10} yr and 10^{12} yr, respectively

$^2H(p,\gamma)^3He$ and $^3He(^3He,2p)^4He$ have time scale of order 10^{-8} yr and 10^5 yr, respectively

So both ^2H and ^3He are in kinetic equilibrium, dn/dt = 0. This implies that:

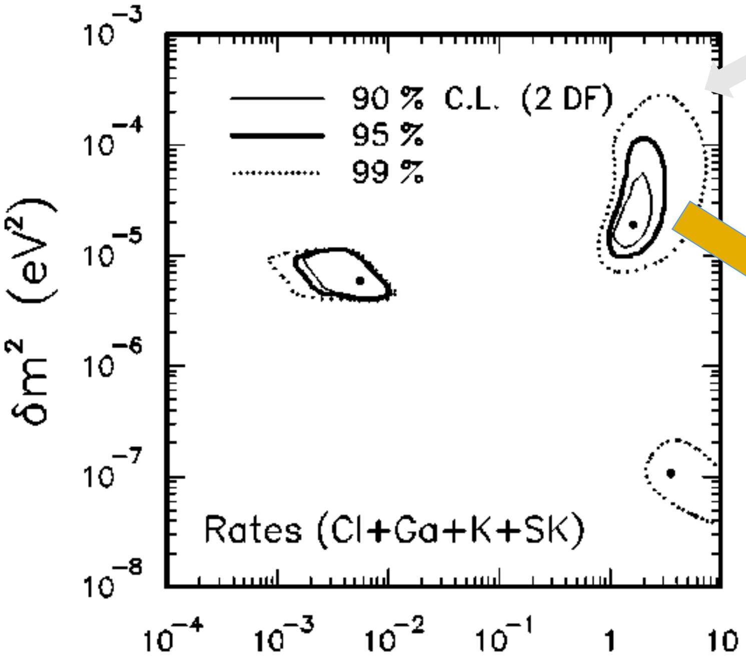
$$R_{pp} + R_{pep} = R_{33} + R_{34} + R_{31} \quad with \ \ R_{ij} = \frac{\langle\sigma\, v\rangle_{ij} n(i) n(j)}{1+\delta_{ij}} \quad the\ reaction\ rate$$

$$\frac{L_{sun}}{4\pi\, d^2} = a_{pp}\phi_{pp} + a_{pep}\phi_{pep} + \frac{a_{33}}{2}\left(\phi_{pp} + \phi_{pp} - \phi_{hep} - \phi_{Be} - \phi_B\right) + a_{hep}\phi_{hep} + (a_{34} + a_{e7})\phi_{Be} + (a_{34} + a_{17})\phi_B + a_N\phi_N + a_O\phi_O$$

$$1 = 0.922 f_{pp} + 0.002 f_{pep} + 0.073 f_{Be} + 0.00004 f_B + 0.0011 f_N + 0.0052 f_O$$

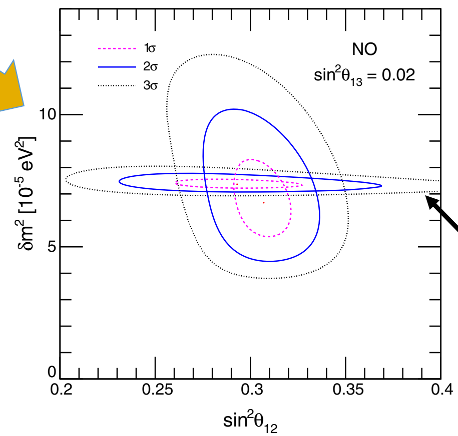
SuperKamiokande: since 1996

SNO from 1999 to 2006



PRD 62.013002(2000)

21 years later

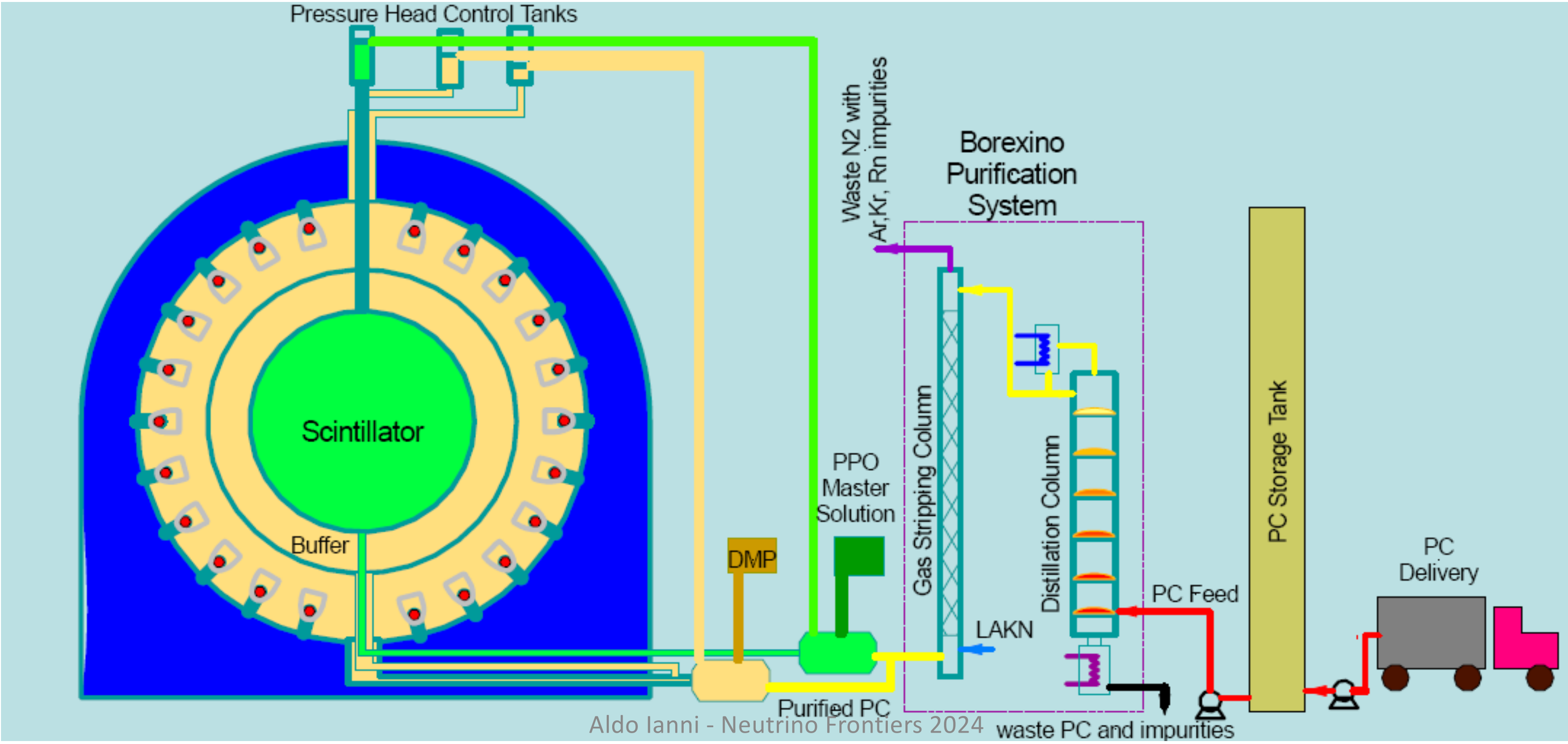


KamLAND

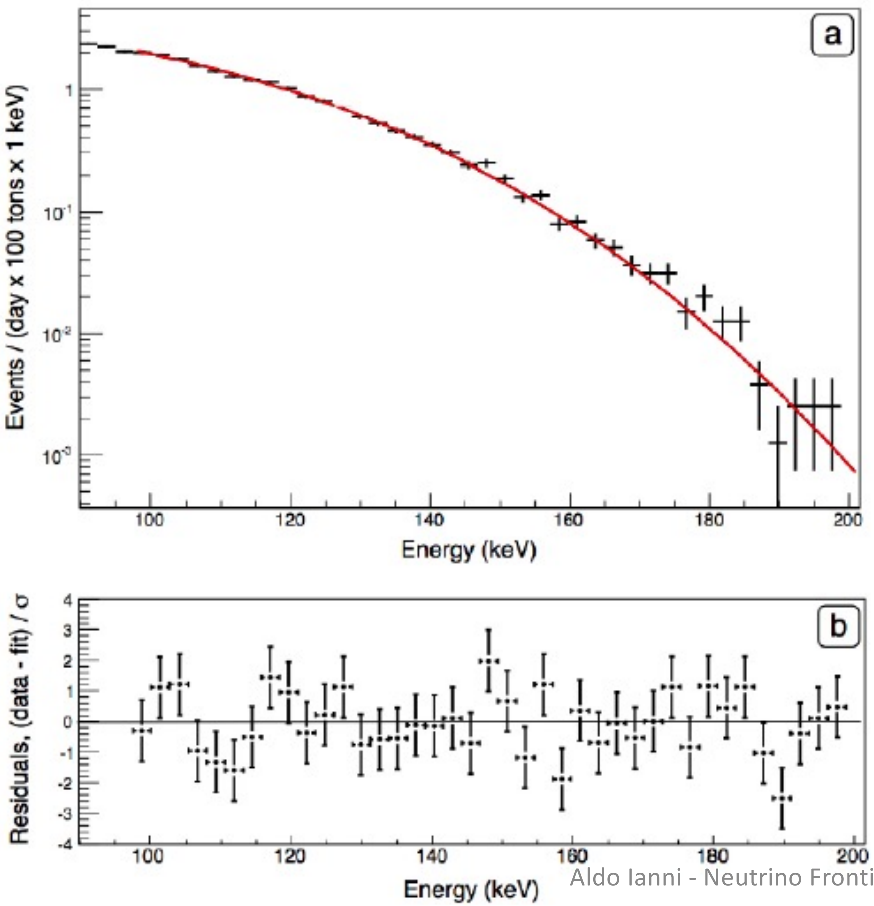
PRD 104.083031(2021)

Purification of the liquid scintillator

Borexino makes use of three methods to remove impurities from the liquid scintillator (U, Th, K, ^{210}Po, ^{210}Bi, ^{85}Kr, ^{222}Rn)



^{14}C activity estimation



From 2nd cluster events > 8μs to avoid afterpulses from PMTs

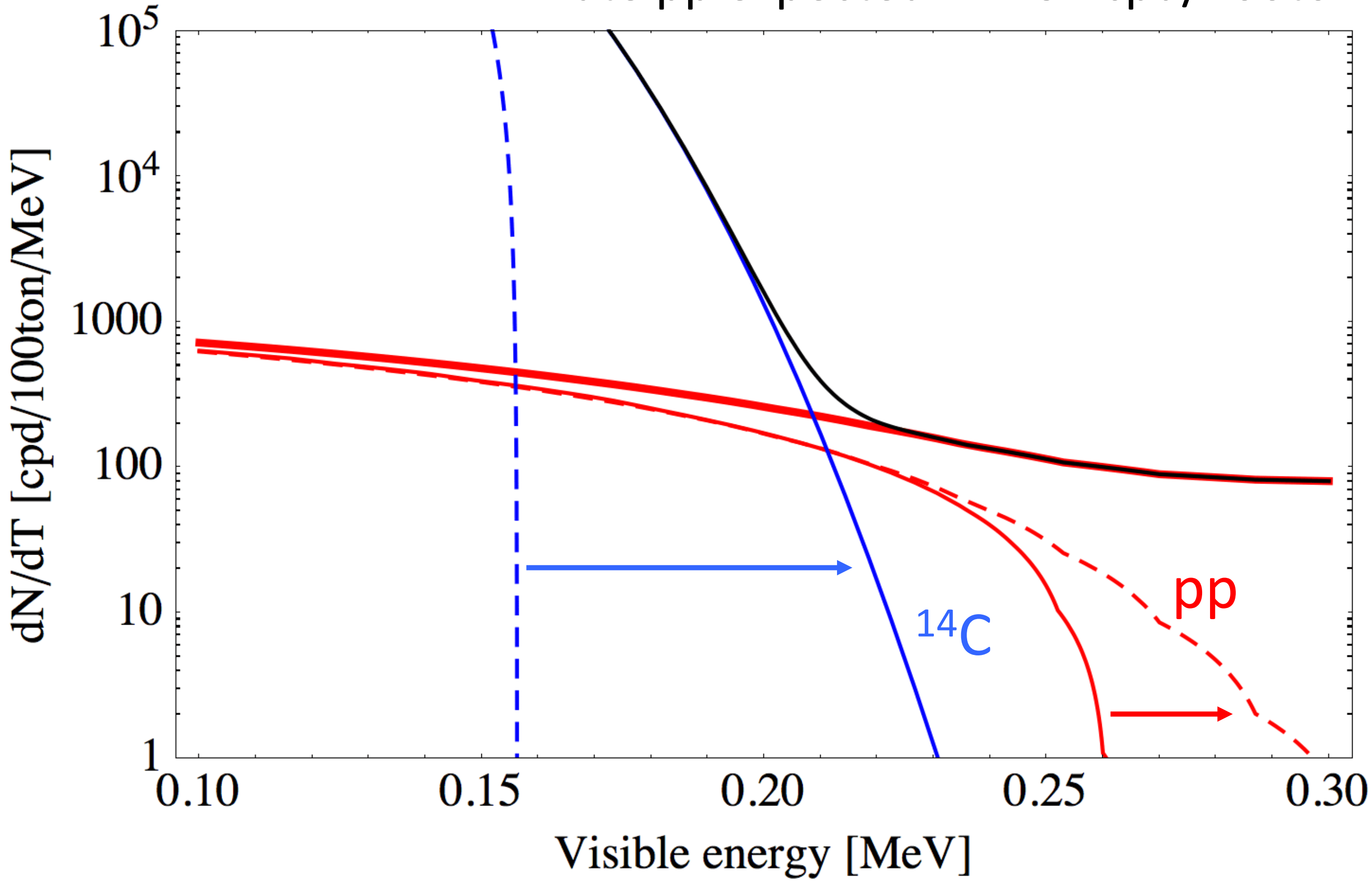
40 ± 1 Bq

$^{14}C/^{12}C = (2.7\pm0.1) \times 10^{-18}$

Beta spectrum with shape factor: $1+1.24(Q_\beta\text{-}T)$

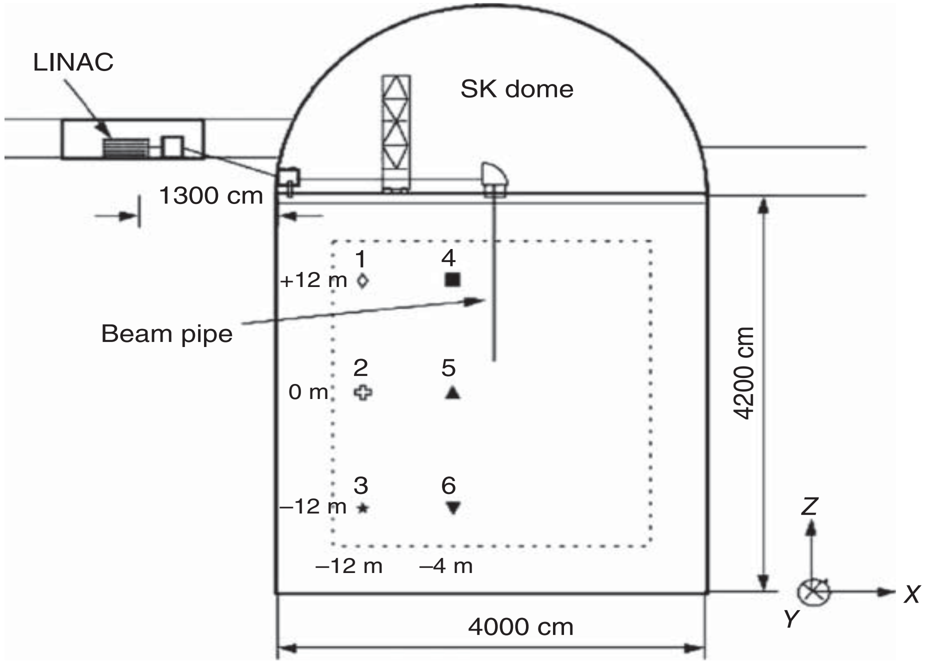
Spectral measurement of pp neutrinos

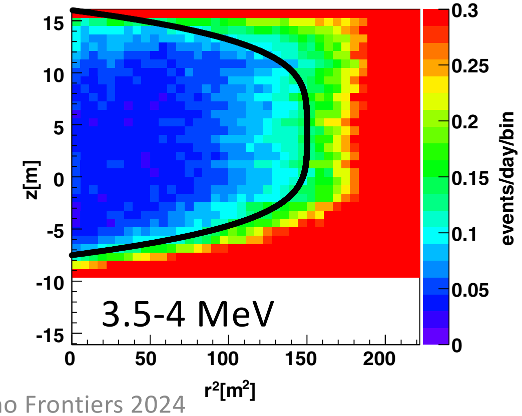
Rate pp expected : ~ 131 cpd/100ton



The Super-Kamiokande experiment

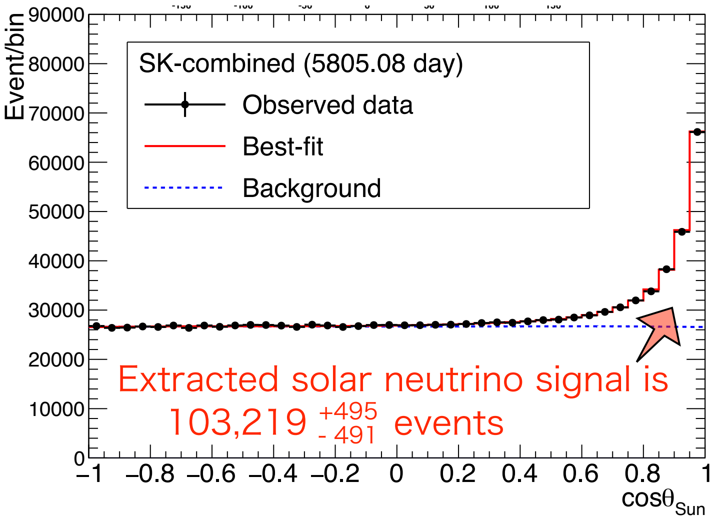
- World leading water Cherenkov detector
- 50 kton of water in total and 32 kton in inner detector
- 22.5kton Fiducial Volume
- 11,146 50cm PMTs with 40% coverage
- Outer detector with 3m water and 1885 20cm PMTs
- Energy scale, angular distribution, and vertex position calibrate by a LINAC, injecting e^- from 5 to 16 MeV
- $^{16}O(n,p)^{16}N$ and ^{16}N decay (Q_β=10.4 MeV) used for energy calibration
- Initial threshold at 5 MeV was reduced to 4 MeV by removing convection currents in inner detector, reducing Radon propagation
- In 2020 detector loaded with $Gd_2(SO_3)_3$ at 0.01% wt

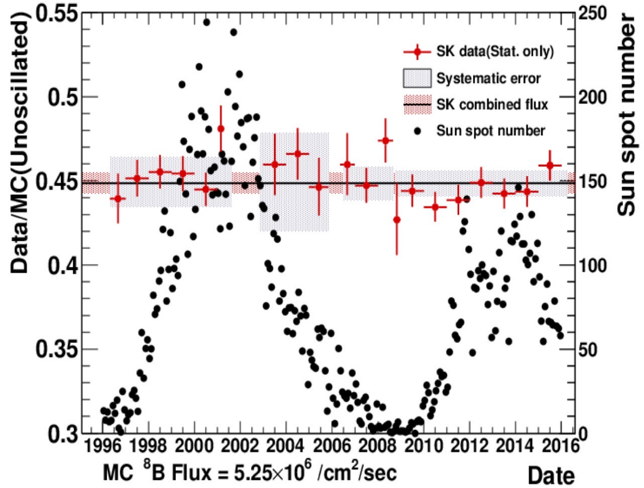




Expected events in Super-Kamiokande

- Rate = Flux(E) × Cross-Section × Target
- For Super-K: 22.5 kton of water
- 8B neutrinos on average ~ 7.6 MeV above 5 MeV
- Flux ~ 5×10^{6} cm^{2}/s, fraction above 5 MeV = 0.7
- Cross-section ~ 6.8×10^{-44} cm^{2} @ 7.6 MeV
- Target electrons: $(N_A/18)\times10\times22.5\times10^{9}=7.5\times10^{33}$
- ~ 150 cpd/FM

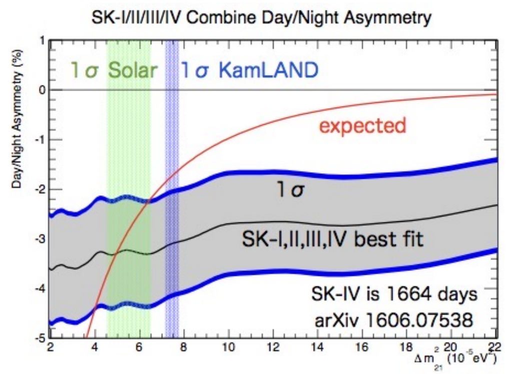


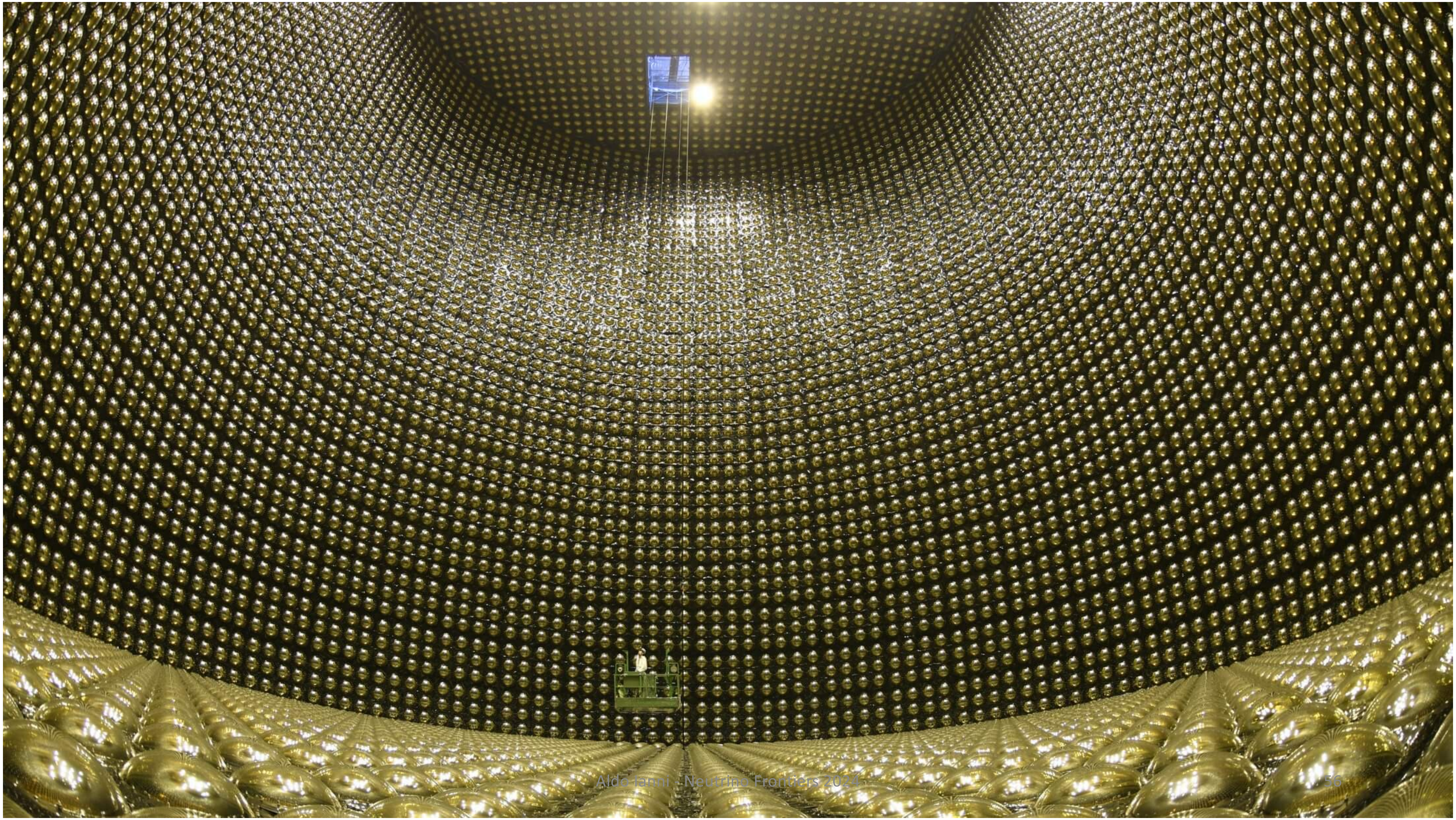


$$\frac{data}{theory} = 0.44486 \pm 0.0062$$

Most precise ^{8}B flux measurement, 1.4%

Day-Night asymmetry = -3.3±1.0±0.5 %





SNO Neutral Current Trilogy

Pure D_2O

Nov 99 – May 01

$n + d \rightarrow t + \gamma$

$(E_\gamma = 6.25\ \text{MeV})$

PRL **87**, 071301 (2001)

PRL **89**, 011301 (2002)

PRL **89**, 011302 (2002)

PRC **75**, 045502 (2007)

Salt

Jul 01 – Sep 03

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$

$(E_{\Sigma\gamma} = 8.6\ \text{MeV})$

enhanced NC rate and separation

PRL **92**, 181301 (2004)

PRC **72**, 055502 (2005)

"long" archival papers with complete details

^{3}He Counters

Nov 04 – Nov 06

$n + {}^3He \rightarrow t + p$

proportional counters
$\sigma = 5330$ b

event-by-event separation

PRL **101**, 111301 (2008)

PRC **81**, 055504 (2010)
combined analysis with lower energy threshold

ARXIV: 1109.0763 (2011)
combined analysis of all three phases with pulse shape discrimination for ^{3}He counters

Pulse Shape Discrimination