Solar and Supernova neutrinos

Aldo Ianni

ISAPP 2023

27 Jun – 6 Jul Varenna, Italy

Outline of lectures

- solar neutrinos and historical remarks
- Brief digression on geo-neutrinos
- detection techniques for solar neutrinos
- solar neutrinos: results
- detection of neutrinos from core collapse supernovae

Email: aldo.ianni@lngs.infn.it

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

Observations of the sun and the solar energy paradigm

- Sometime around 300 B.C., Hellenistic scholars
- **1610** Galileo Galilei observes sunspots and determines the rotational velocity: 1st experimental study of the Sun
- William Herschel (1738-1822) believes the Sun has a solid surface with a shining atmosphere
- **1862**, Hermann von Helmholtz proposes the energy of the Sun is due to gravitation and makes an estimation for the age of 20×10^6 years
- **1868**, Jules Janssen and Joseph N. Lockyer, independently, discover a new element on the surface of the Sun. Lockyer names it helium after Helios.
- **1905**, Einstein $E = mc^2$
- **1920**, Arthur Eddington proposes hydrogen to helium fusion as the main source of energy in the Sun
- **1928**, George Gamow proposes the tunneling effect
- **1938**, Hans Bethe in "*Energy production in stars*" proposes the reaction chains to transform hydrogen into helium
- **1956**, the age of the Earth is established to be $(4.55\pm0.07)\times10^9$ years and ν observed

A few fundamental numbers

Solar luminosity: $L_{sun} = 3.8275\text{x}10^{26}$ W = $2.389\text{x}10^{39}$ MeV/s

Solar Mass: $M_{sun} = 2\text{x}10^{30}$ kg

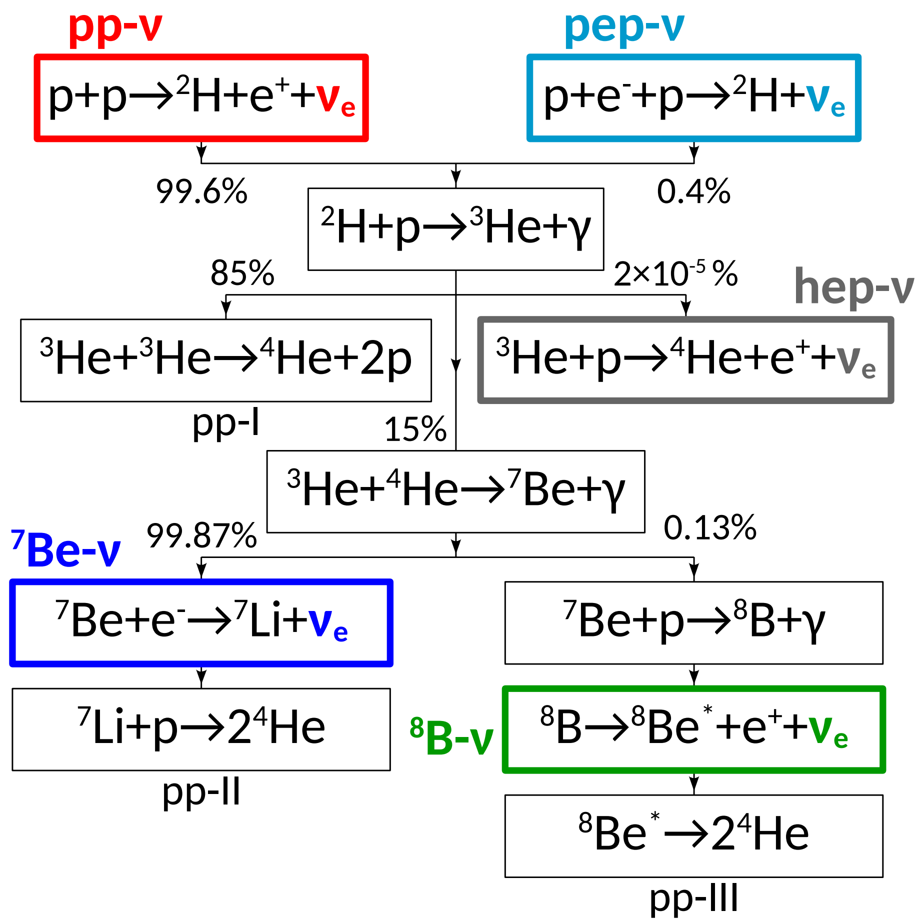
Solar radius: $R_{sun} = 6.957\text{x}10^{8}$ m

1 A.U. = $1.495978707\ 10^{11}$ m

Sun's fluence at Earth = $8.4946\text{x}10^{11}$ MeV/cm^2/s

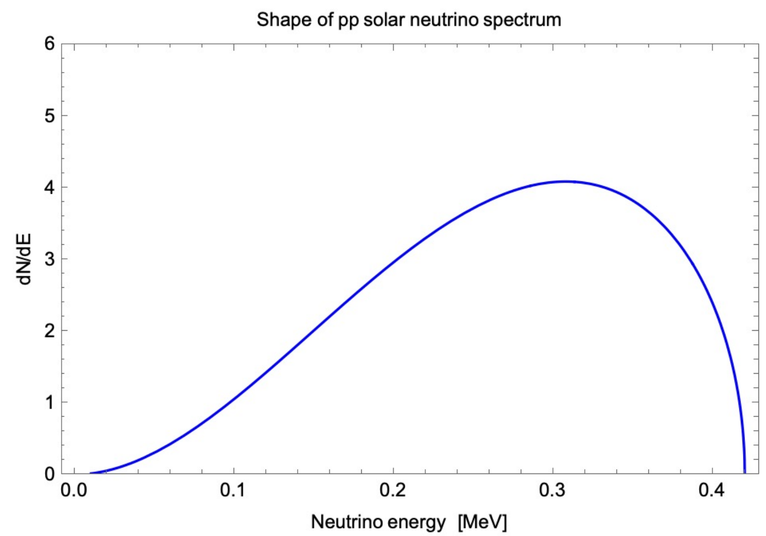
The pp-chain

- 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



Energy spectrum of pp solar neutrinos

- $p + p \dashrightarrow d + e^{+} + \nu_e + Q_{pp}$
- $Q_{pp} = 2m_p - m_d - 2m_e = 0.42$ MeV
- $\frac{d\Gamma}{dE_\nu} \propto E_\nu^2 (Q_{pp} - E_\nu + m_e c^2)\sqrt{(Q_{pp} - E_\nu + m_e c^2)^2 - m_e c^2}$
- $\langle E \rangle = 0.266$ MeV
- Fraction of energy carried by neutrinos: $\frac{2\ 0.27\ MeV}{26.74} \sim 0.02$
- Neutrino flux: $\phi_\nu = \frac{2\ L_{sun}}{4\pi\ AU^2 (26.74 MeV - 2\ 0.266 MeV)} = 6.5 \cdot 10^{10} cm^{-2} s^{-1}$



- Problem: determine the energy dependence of the pp solar neutrinos

Solar neutrino fluxes if pp-chain dominates

- pp-II side chain ($1\nu_{pp}$ + $1\nu_{Be}$) reduces pp flux by 0.15·0.5=7.5%

  - ✓ ϕ_{pp}~ $6.0\cdot10^{10}$ cm^{-2} s^{-1}
  - ✓ ϕ_{Be}~ $5.0\cdot10^{9}$ cm^{-2} s^{-1}
  - ✓ ϕ_{B} ~ $6\cdot10^{6}$ cm^{-2} s^{-1}

- A different hydrogen burning mechanism in 2^{nd} 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

- Slowest reaction from ^{14}N interaction since it has the highest Coulomb barrier
  - pp : $^{12}C(p,\gamma)$: $^{14}N(p,\gamma)$ = 1 : 3.5 : 4.2
- In addition (p,γ) slower than (p,α)
- Till 1950 CN cycle was considered the primary energy source in the sun
- Later it was understood that:
  - This cycle is not dominat in the sun
  - There exist additional cycles

Stellar interaction rates

- $\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}$ con $\eta = Z_1 Z_2 e^2/\hbar v \propto E^{-1/2}$
- Interaction rate = n$\langle\sigma v\rangle \propto \int_0^\infty dE\, S(E)\, e^{-b/\sqrt{E} - E/kT}$
- $\tau \sim \frac{1}{n\langle\sigma v\rangle}$
- Determine S(E) below 100 keV is a hard experimental work (T_{sun} ~ 1.4 keV)
- S(E≈0) depends on extrapolation and tail of high energy broad resonances
- $\langle\sigma v\rangle = 2.802 \times 10^{-16} \left(\frac{Z_1 Z_2}{A\, T_7^2}\right)^{\frac{1}{3}} S(0) f_e e^{-3E_0/kT}$ cm^3/s
  - f_e accounts for electron screening
  - E_0 is the Gamow peak energy (6-30) keV (for pp ν is about 6 keV)
- Timescale for $^{12}C(p,\gamma)$ and $^{14}N(p,\gamma)$ of order 10^7 and 10^{10} years at $T_\odot$

some thoughts

- Photons travelling to the surface of the sun
- How hot is the center of the sun?
- pp scattering vs pp fusion inside the sun
  - use $S(0) = 4.0\times10^{-22}$ keV barn

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 $2\text{x}10^3$
- ${}^{14}_{7}N$ produces ${}^{15}_{8}O$ and carbon again
- This branch
  - Negligible contribution to energy production
  - Important for nucleosynthesis of ^{16}O and ^{17}O

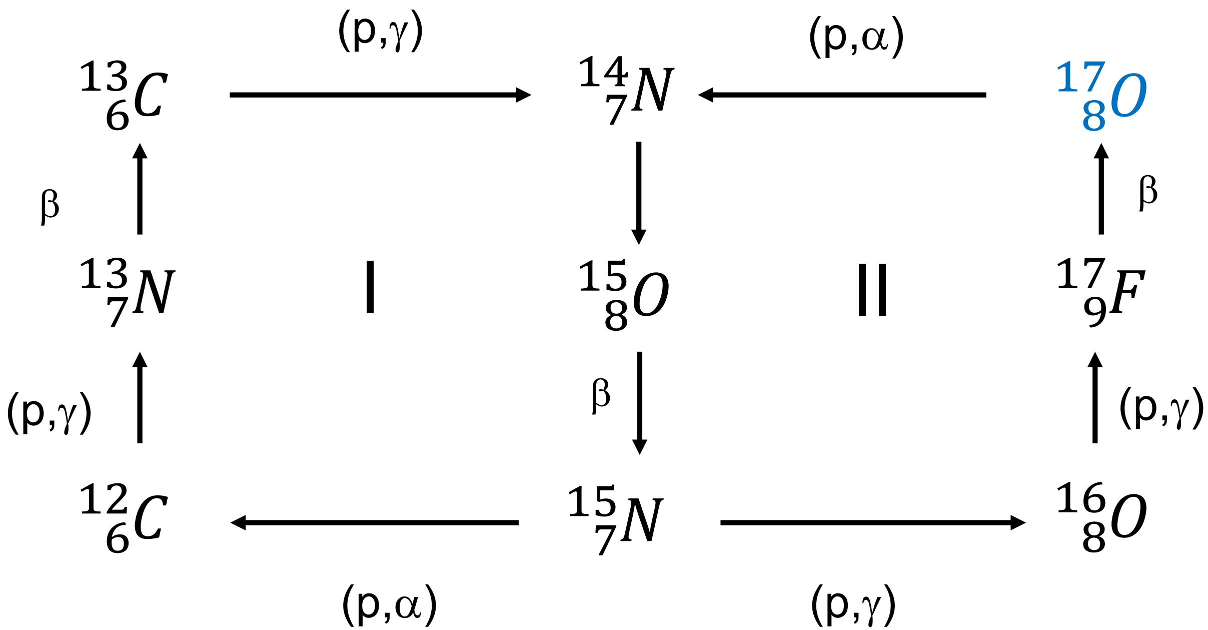
The CNO «cold» bi-cycle

$$
\begin{tikzcd}
{}^{13}_{6}C \arrow[r, "(p,\gamma)"] & {}^{14}_{7}N \arrow[d] & {}^{17}_{8}O \arrow[l, "(p,\alpha)"'] \\
{}^{13}_{7}N \arrow[u, "\beta"] \arrow[r, phantom, "\mathrm{I}"] & {}^{15}_{8}O \arrow[d, "\beta"'] \arrow[r, phantom, "\mathrm{II}"] & {}^{17}_{9}F \arrow[u, "\beta"'] \\
{}^{12}_{6}C \arrow[u, "(p,\gamma)"] & {}^{15}_{7}N \arrow[l, "(p,\alpha)"] \arrow[r, "(p,\gamma)"'] & {}^{16}_{8}O \arrow[u, "(p,\gamma)"']
\end{tikzcd}
$$

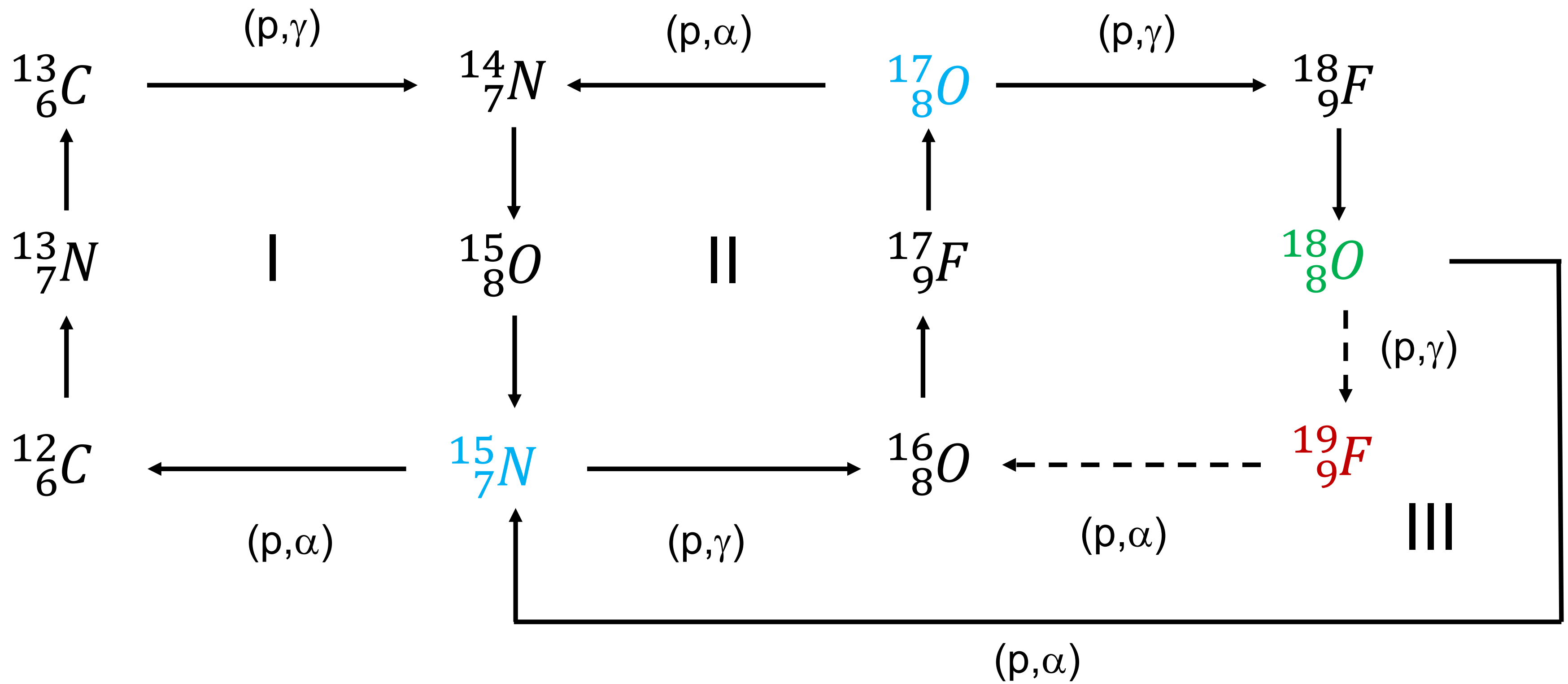
Additional cycles

- $p + {}^{17}_{8}O \rightarrow \begin{cases} {}^{14}_{7}N + \alpha \\ {}^{18}_{9}F + \gamma \end{cases}$
- ${}^{18}_{9}F \rightarrow {}^{18}_{8}O + e^{+} + \nu_e$
- $p + {}^{18}_{8}O \rightarrow {}^{15}_{7}N + \alpha$
- $p + {}^{15}_{7}N \rightarrow \begin{cases} {}^{12}_{6}C + \alpha \\ {}^{16}_{8}O + \gamma \end{cases}$

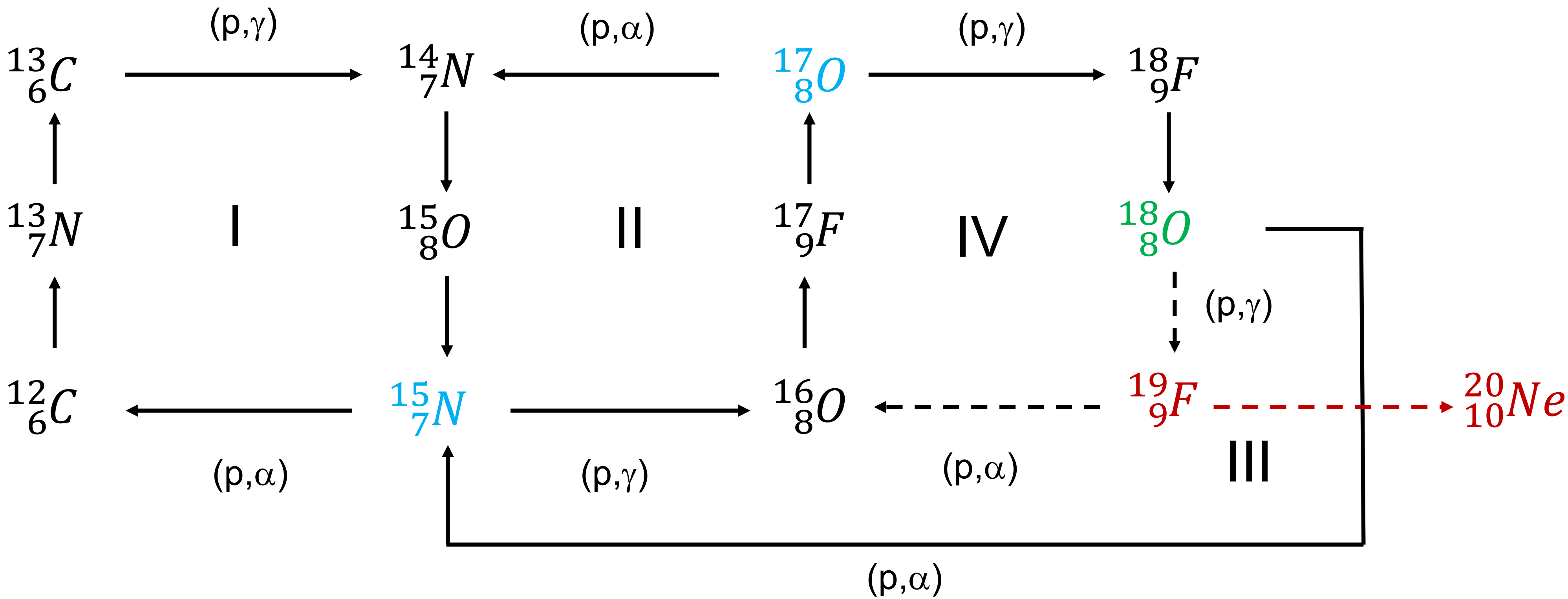
- The ratio of stellar reaction rates for ${}^{17}O(p,\alpha){}^{14}N$ and ${}^{17}O(p,\gamma){}^{18}F$ is ~ 1 for $T_6 < 25$ and $T_6 > 80$ [Ap J 194, 1974]
- The CNO cycle is **tri-cycling**



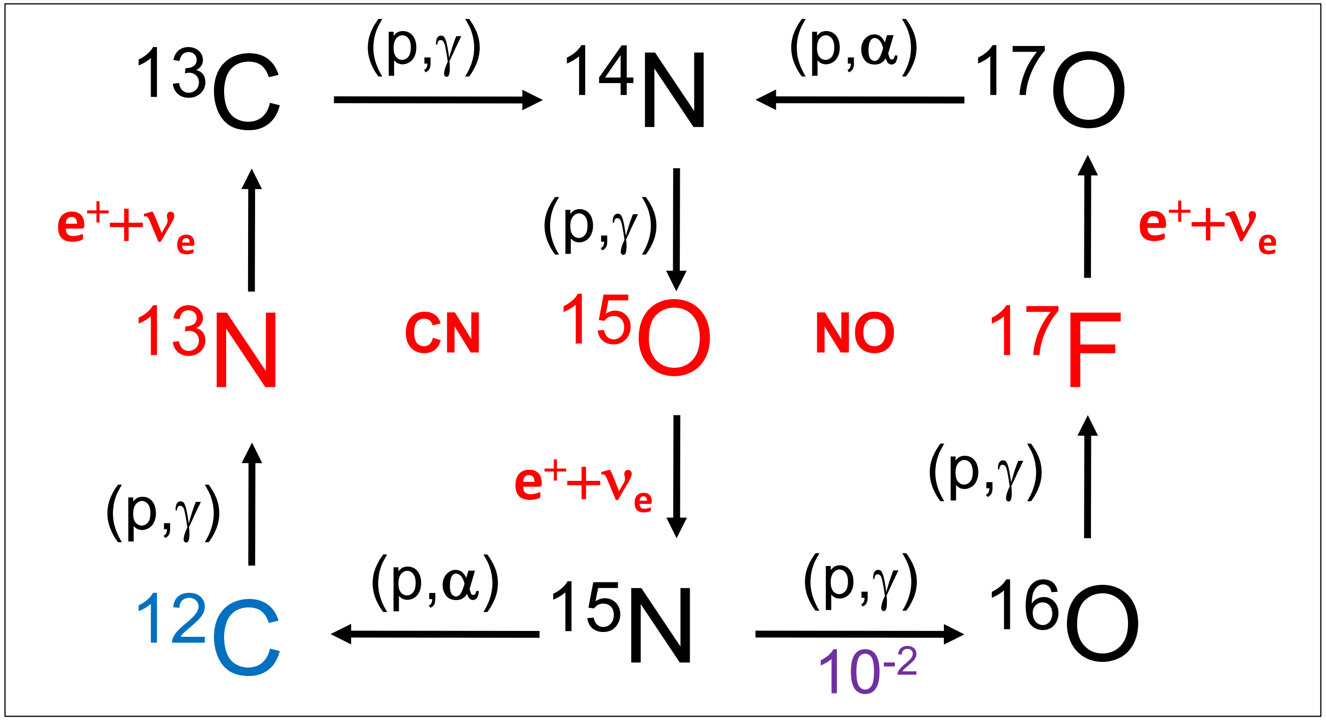
The CNO tri-cycle



The CNO four cycles



CNO bi-cycle H burning in the Sun



Solar neutrinos and energy production

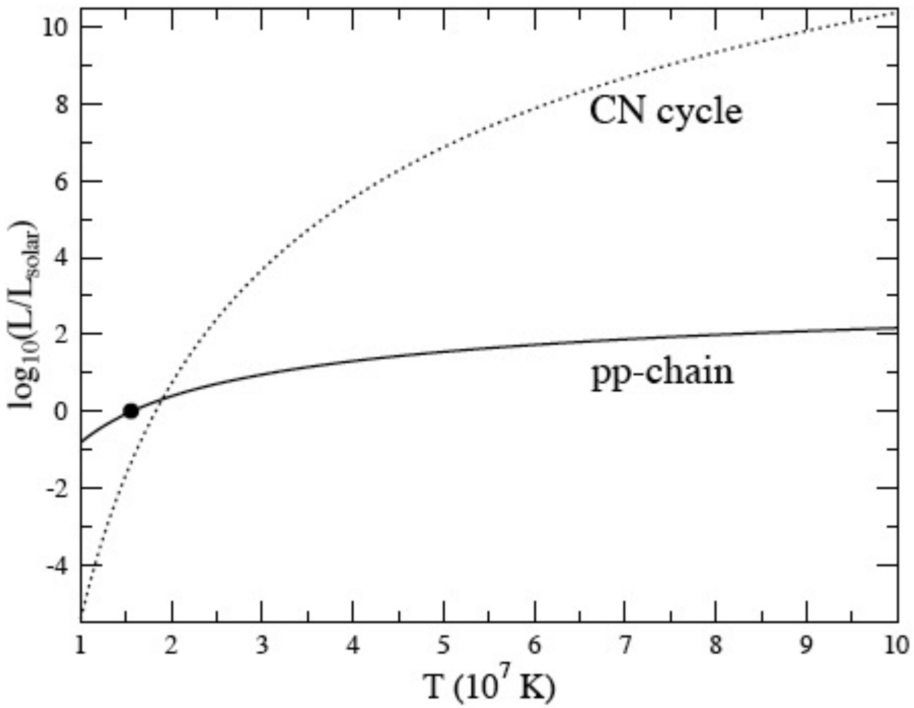
- *Energy conservation*

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

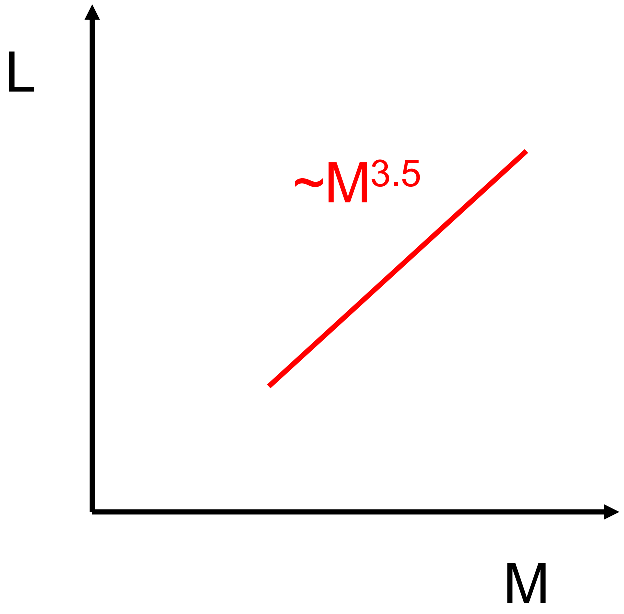
$L_\odot$=3.846±0.015 erg/s

At solar temperature

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

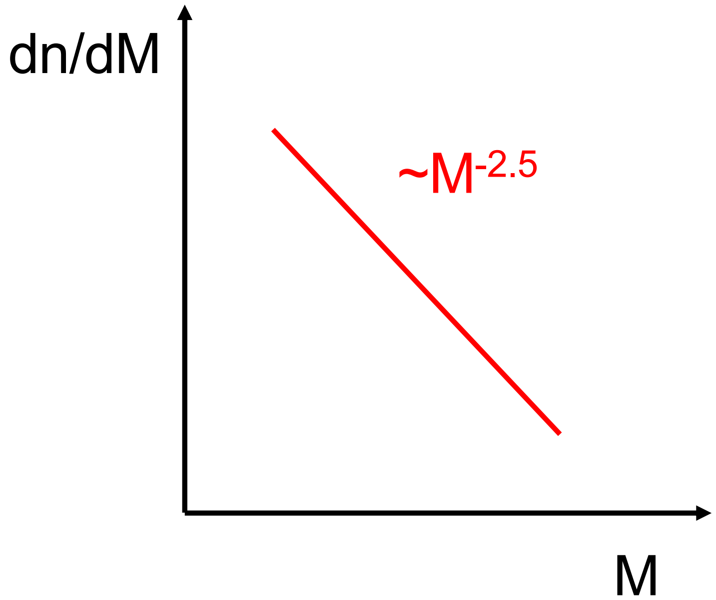


Stars mass-luminosity relationship



$$t_{nucl} \propto \frac{Mc^2}{M^{3.5}} \propto M^{-2.5}$$

Stars number density



Fundamental conjecture

Properties and evolutions of stars are fully determined by its initial mass and chemical composition

Application of this conjecture allows to determine stars observable parameters:

- surface temperature
- radius
- luminosity
- surface metal abundace

The Solar Standard Model (SSM)

- Assumptions of the SSM
  - Hydrostatic equilibrium
  - Energy generation by H burning
  - **Homogeneous zero-age Sun**: primordial core metal abundance equal to today's surface metal abundance
  - Boundary conditions: present luminosity, radius, $(Z/X)_{surf}$
  - Fixed parameters: age, mass
    - evolution should match age and mass

Output of SSM

- Neutrino production region, neutrino fluxes
- Depth of convection zone, $\mathbf{R_{CZ}}$
- Surface helium abundance, $\mathbf{Y_{surf}}$
- Profile of X(r), Y(r) and Z(r)
- density and sound speed profiles
- …

SSM solar neutrino fluxes predictions

Within the SSM solar neutrino fluxes are written as:

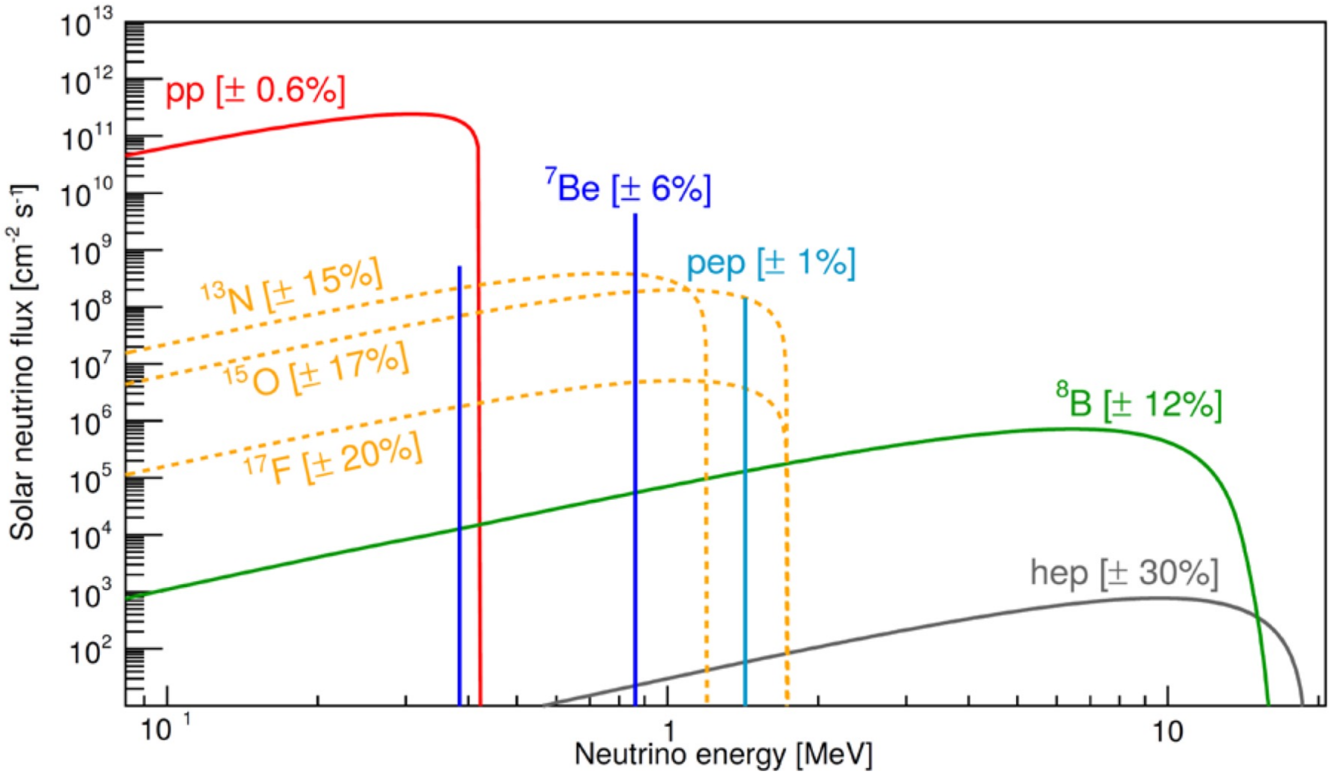
$$\phi_{\mathrm{pp}} \propto S_{11}{}^{+0.14} \cdot S_{33}{}^{+0.03} \cdot S_{34}{}^{-0.06} \cdot S_{1,14}{}^{-0.02} \cdot L_{\odot}{}^{+0.73} \cdot \tau_{\odot}{}^{-0.07} \cdot Op_{\odot}{}^{+0.14} \cdot (Z/X)^{-0.08},$$

$$\phi_{\mathrm{Be}} \propto S_{11}{}^{-0.97} \cdot S_{33}{}^{-0.44} \cdot S_{34}{}^{+0.88} \cdot L_{\odot}{}^{+3.56} \cdot \tau_{\odot}{}^{+0.69} \cdot Op_{\odot}{}^{-1.49} \cdot (Z/X)^{+0.59},$$

$$\phi_{\mathrm{B}} \propto S_{11}{}^{-2.59} \cdot S_{33}{}^{-0.40} \cdot S_{34}{}^{+0.81} \cdot L_{\odot}{}^{+6.76} \cdot \tau_{\odot}{}^{+1.28} \cdot Op_{\odot}{}^{-2.93} \cdot (Z/X)^{+1.36}.$$

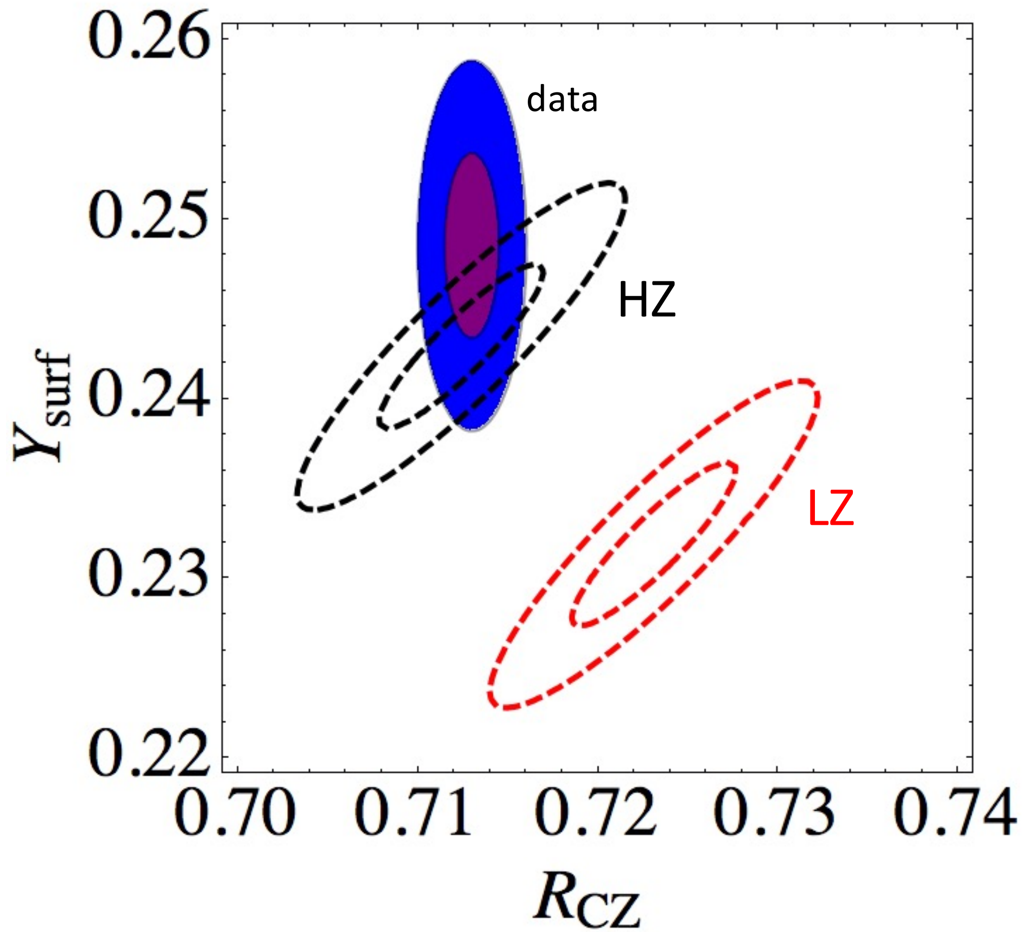
Solar neutrino spectra

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



The solar abundace problem

- Since 2005 best determination of surface metallicity gives a strong tension between data from helioseismology and SSM predictions
- CNO solar neutrino observation could shed light on this controversy



Solar neutrinos from SSM 2016

ν source	SSM-HZ SSM-LZ [cm^{-2} s^{-1}]
pp	$5.98(1\pm0.006)\times10^{10}$ $6.03(1\pm0.006)\times10^{10}$
pep	$1.44(1\pm0.01)\times10^{8}$ $1.46(1\pm0.01)\times10^{8}$
^{7}Be	$4.93(1\pm0.06)\times10^{9}$ $4.50(1\pm0.06)\times10^{9}$
^{8}B	$5.46(1\pm0.12)\times10^{6}$ $4.50(1\pm0.12)\times10^{6}$
hep	$7.98(1\pm0.30)\times10^{3}$ $8.25(1\pm0.30)\times10^{3}$
CNO	$4.88(1\pm0.16)\times10^{8}$ $3.51(1\pm0.14)\times10^{8}$

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

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

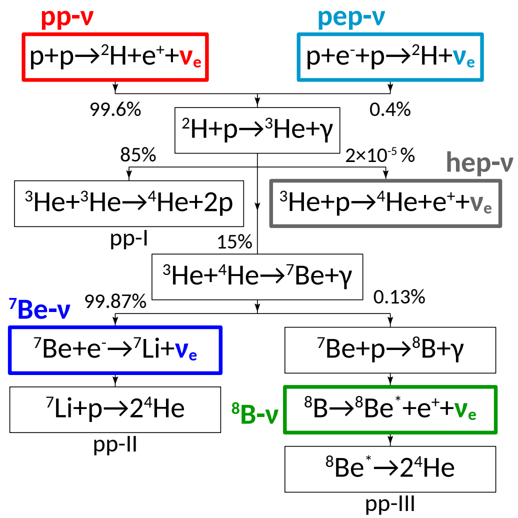
$^{2}H(p,\gamma)^{3}He$ and $^{3}He(^{3}He,2p)^{4}He$ have time scale of order 10^{-8} yr and 10^{5} yr, respectively

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

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

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

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



Detection of solar neutrinos

Experimental Search of Solar Neutrinos: early days

- **1946**, B. Pontecorvo proposes a method to measure neutrinos by $^{37}Cl(\nu,e)^{37}Ar$
- **1948**, H.R. Crane proposes the search of solar neutrinos
- **1949**, L. Alvarez proposes to make use of Pontecorvo's method to search for solar neutrinos
- **1963**, J. Bahcall determines the solar neutrino fluxes
- **1964**, J. Bahcall and R. Davis propose the Homestake experiment
- **1968**, the first experiment to search for solar neutrinos (Homestake) is in operation
- ….
- **1996**, SuperKamiokande stars data taking
- …
- **2002**, Nobel Prize to Homestake and Kamiokande
- ...
- **2005**, Solar Abundace Problem
- …
- **2007**, Borexino starts data taking
- …
- **2015**, Nobel Prize to SNO and SuperKamiokande
- **2020**, CNO solar neutrinos observation by Borexino

A proposed experimental test of the neutrino theory
Luis Alvarez, 1949

problem to be worked out in class: explain in details the proposal
goal: underline main difficulties in detecting low energy neutrinos

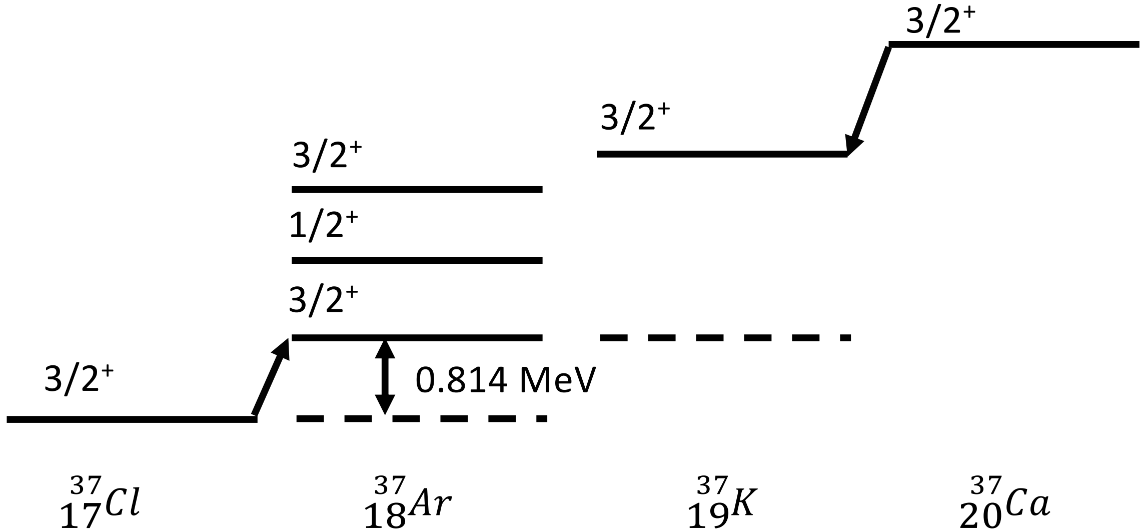
In Alvarez's proposal underlined all fundamental ideas to make the future first solar neutrino observation

- The radioactive isotope selected should decay mainly by emitting very short-range electrons
- It should exist in a gaseous molecule, preferably be a noble gas
- The substance from which it is produced by neutrino capture should be available in liquid form in large quantities
- The mass difference between initial and final state should be small
- The half-life should be long
- The decay rate should be well known
- Extraction technique feasible and established

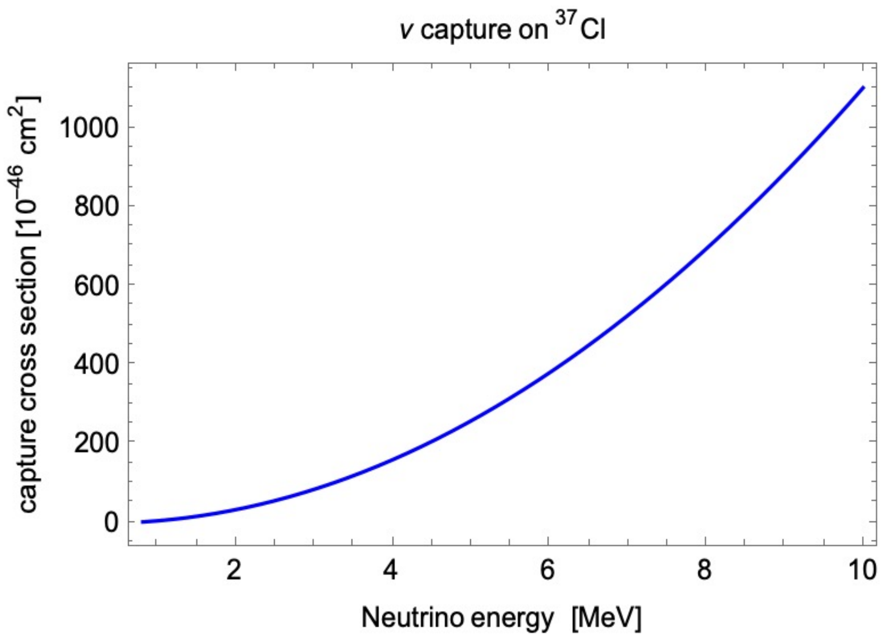
^{37}Ar is well justified as main choice to search for low energy ν

$^{37}Cl(\nu_e,e^-)^{37}Ar$

Neutrino capture on ^{37}Cl



- Cross section to ground state ~ 3.3×10^{-45} cm^2 at 2 MeV
- $\sigma_{gs} = \frac{2\pi^2 \, ln2 \, (\hbar c)^3}{f_t \, (m_e c^2)^5} \, E_e p_e F(Z, E_e) \, \frac{2J_f+1}{2J_i+1}$
- Log f_t = 5.1 for ^{37}Ar
- GT matrix elements to excited states from mirror beta decay of ^{37}Ca



Detecting Solar Neutrinos

- 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~$10^{-44}cm^2$)
  - 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

Detection of solar neutrinos

- $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ (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)

Geochemical detection of solar neutrinos

- $\boldsymbol{\nu_e + {}^{98}_{42}Mo \longrightarrow e^- + {}^{98}_{43}Tc}$ **, Q = 1.68 MeV abundance 24.3%** (also ^{97}Mo to ^{97}Tc, Q=0.32 keV, abundance = 9.6%))
    - ${}^{98}_{43}Tc \rightarrow {}^{98}_{42}Mo + e^+ + \nu_e$, $\tau \sim 6 \cdot 10^6\ yr$ ($\sim 3.8 \cdot 10^6\ yr$ for ^{97}Tc)
    - Proposal submitted in 1982 and crucial tests carried out in 1985-86
    - Identified a commercial site in Colorado with formation time about 25 My ago with depth of order 1-1.5km
    - 2600 tons of ore to extract 13 tons of MoS_2 which is turned to MoO_3
        - by floating separation 90 to 99% concentrate of MoS_2 can be produced
    - Available industrial processing at 50 tons/day to produce MoO_3
    - Chemical separation (ion exchange) to collect some 10^7 atoms to be detected by a mass spectrometer (10^6 atoms sensitivity)
        - In the chemical processing Tc forms volatile compound and can be separated
    - Test of stability of technetium in the ore is performed by demonstrating that ^{99}Tc is in secular equilibrium with uranium in MoS_2

- $\boldsymbol{\nu_e + {}^{205}_{81}Tl \longrightarrow e^- + {}^{205}_{82}Pb}$ **, Q = 0.05 MeV**
    - ${}^{205}_{82}Pb \rightarrow {}^{205}_{81}Tl + e^+ + \nu_e$, $\tau \sim 2.5 \cdot 10^{10}\ yr$

- Need geological stability of ore
- Sensitivity to average neutrino flux over millions of years
    - Sensitivity to solar energy production stability

Geochemical experiment on ^{205}Tl

problem to be worked out in class
determine the capture rate to the 1st excited state in ^{205}Pb
goal: underline main difficulties in capture cross section calculation and detection in such type of experiments

Classification of radio-isotopes

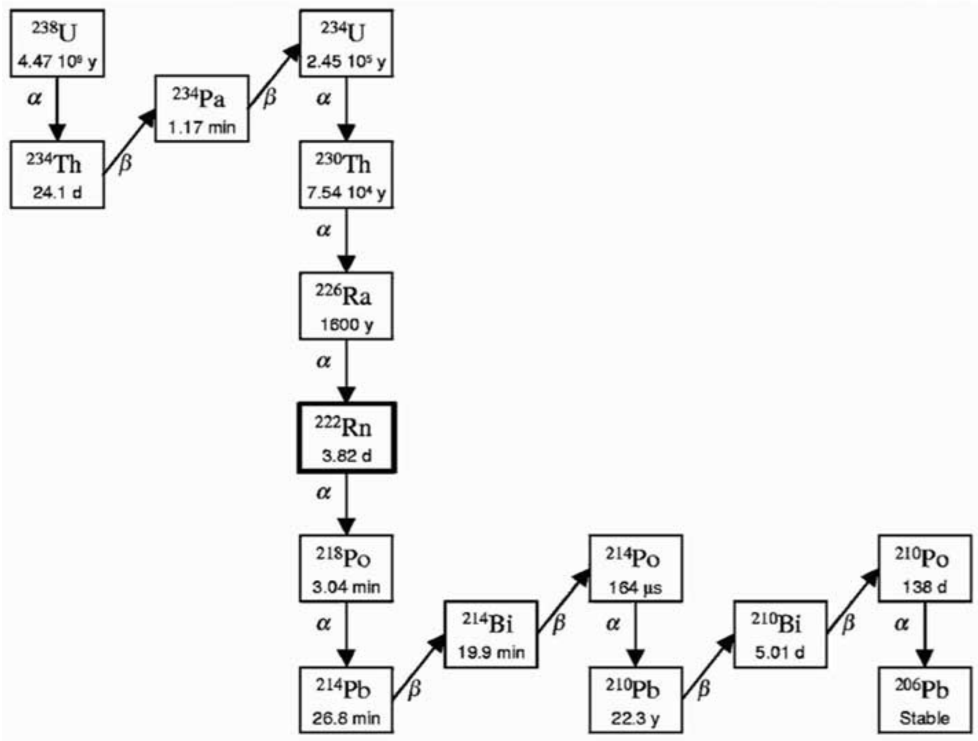
- Primordial: longlived, ^{238}U, ^{87}Rb, ^{40}K, ^{232}Th…

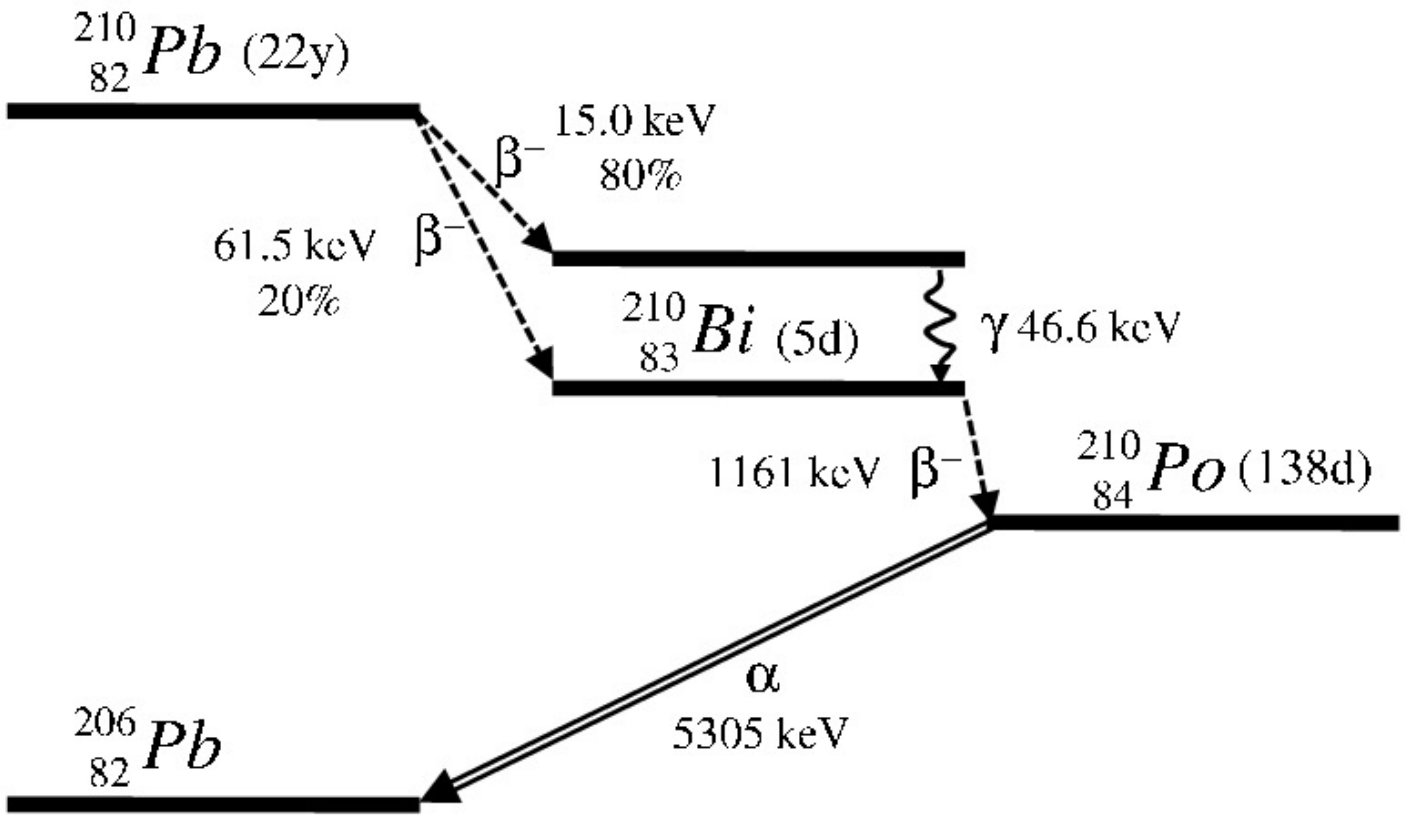
- Cosmogenic: produced by cosmic rays (primary and secondary) interactions, ^{14}C, ^{3}H, ^{7}Be, ^{11}C, ^{39}Ar, …

- 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)

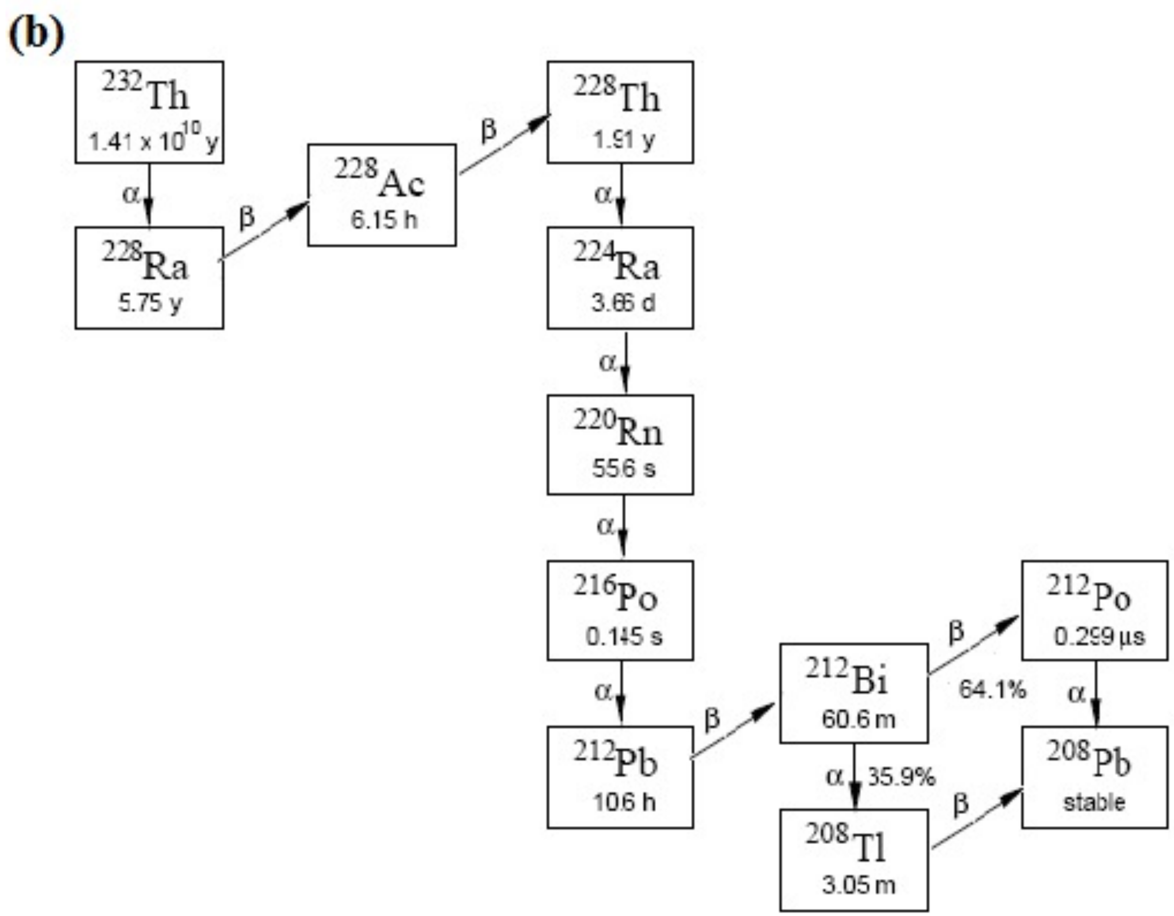




$^{210}_{82}Pb$ (22y)
β⁻ 15.0 keV
80%
61.5 keV β⁻
20%
$^{210}_{83}Bi$ (5d)
γ 46.6 keV
1161 keV β⁻
$^{210}_{84}Po$ (138d)
α
5305 keV
$^{206}_{82}Pb$

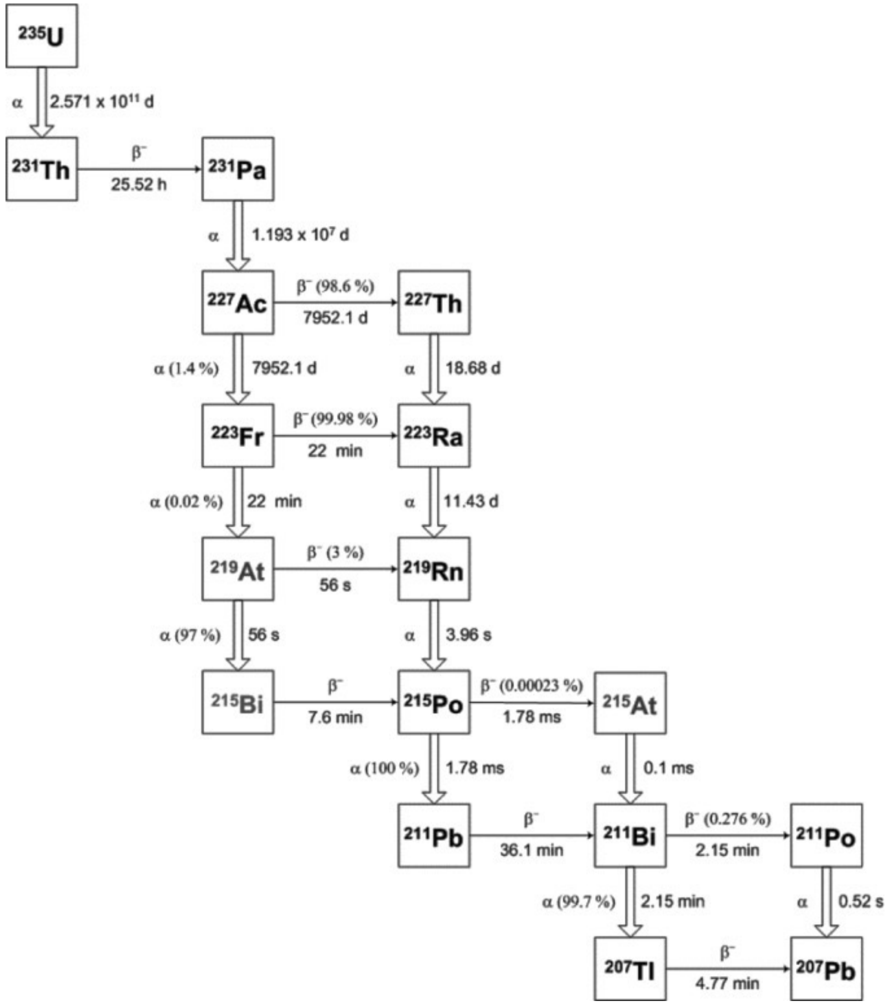
^{232}Th radioactive chain

- ^{232}Th is another of the long-lived radioactive elements on Earth
- $T_{1/2} = 14 \times 10^9$ 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)



^{235}U radioactive chain

$T_{1/2} = 7.04 \times 10^8$ anni



Radiogenic heat from the Earth

- **How much of the heat released by the Earth is radiogenic?**
- Geo-neutrinos can answer this question
- Geo-neutrinos are electron anti-neutrinos emitted by ^{238}U, ^{232}Th, and ^{40}K within the Earth (radiogenic elements)

Decay	$T_{1/2}$ [10^9 yr]	$E_{\rm max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [kg^{-1}s^{-1}]	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

$^{40}K + e^- \to {}^{40}Ar + \nu_e$ + 1.505MeV (10.7%)

A worked out example with uranium

- $^{238}U \rightarrow ^{206}Pb + 8\alpha + 6\beta + 6\bar{\nu}_e + 51.7 MeV$

- $A_U = 0.9927(N_A/238)(1/6.45x10^9 y)=1.23x10^4 Bq/g(U)$
- $L_\nu = 6 \times A_U = 7.4x10^4$ Bq/g(U)
- Heat = 51.7MeV – (average ν energy) = 51.02 MeV
- H_U = Heat x $1.23x10^4$Bq/g(U) $=1.0x10^{-7}$ W/g(U)

Geo-neutrinos as a unique probe for the interior of the Earth

- Geo-neutrinos offer a new and unique method to probe the interior of the Earth
  - Determine abundance and distribution (in the crust and mantle) of Heat Pproducing Elements
  - Determine radiogenic heat

Geo-neutrino history

- The idea of geo-neutrinos was conceived in 1953 by George Gamow while Reines and Cowan were attempting to measure anti-neutrinos from a reactor
  - A possible source of background
- In 1966 and 1969 Eder and Marx wrote papers on geo-neutrinos
- In 1984 Kraus et al. published a comprehensive review on geo-neutrinos in Nature
- In 1998 R. Raghavan et al. and F. Calaprice et al. published two independent papers discussing about detection of geo-neutrinos in Borexino and KamLAND
- 2000-present pleanty of literature on geo-neutrinos flux calculation
  - Fiorentini et al. introduced the term TNU (SNU for solar neutrinos)
- In 2005 1st experimental investigation in KamLAND (25^{+19}_{-18})
- In 2010 1st observation of geo-neutrinos in Borexino

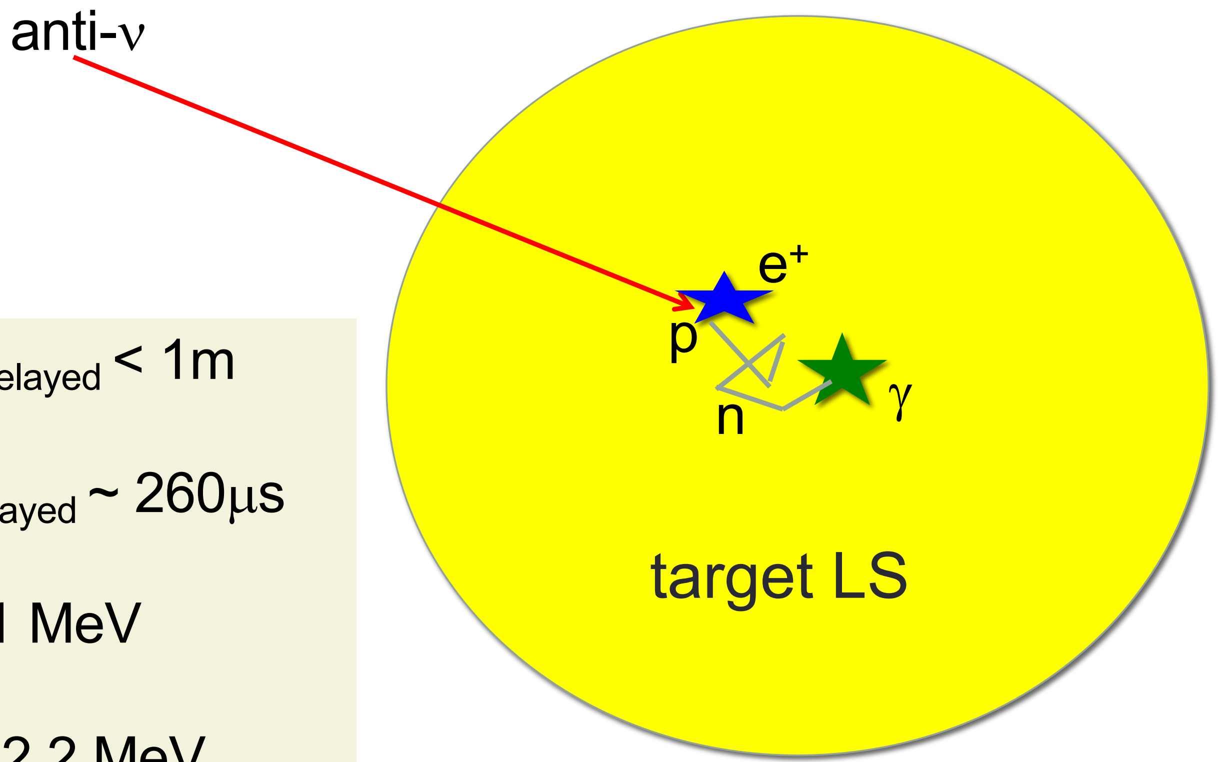
Detection of geo-neutrinos

- Electron anti-neutrinos can be detected by the inverse-beta decay reactions:

$$\bar{\nu}_e + p \rightarrow e^+ + n \ (E_{th}=1.806 \text{ MeV})$$

- Two signals:
  - **Prompt** from positron with
    $$E_{visible} = E_\nu - (m_n - m_p) - m_e c^2 + 2\, m_e c^2 = E_\nu - 0.782\text{MeV}$$
  - **Delayed** from neutron capture
    $$n + p \rightarrow d + \gamma \ (2.22\text{MeV})$$

Topology of an anti-ν event in LS



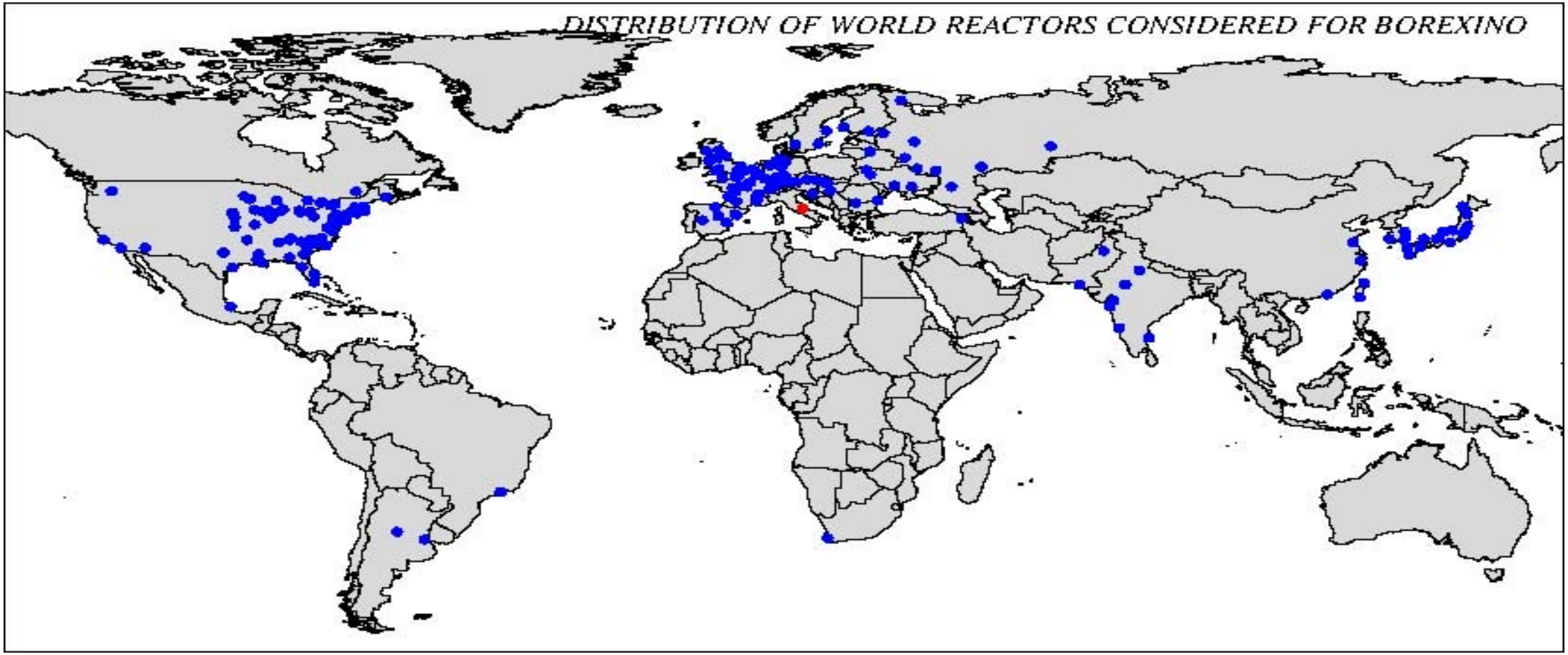
$\Delta R_{prompt\text{-}delayed} < 1m$

$\Delta t_{prompt\text{-}delayed} \sim 260\mu s$

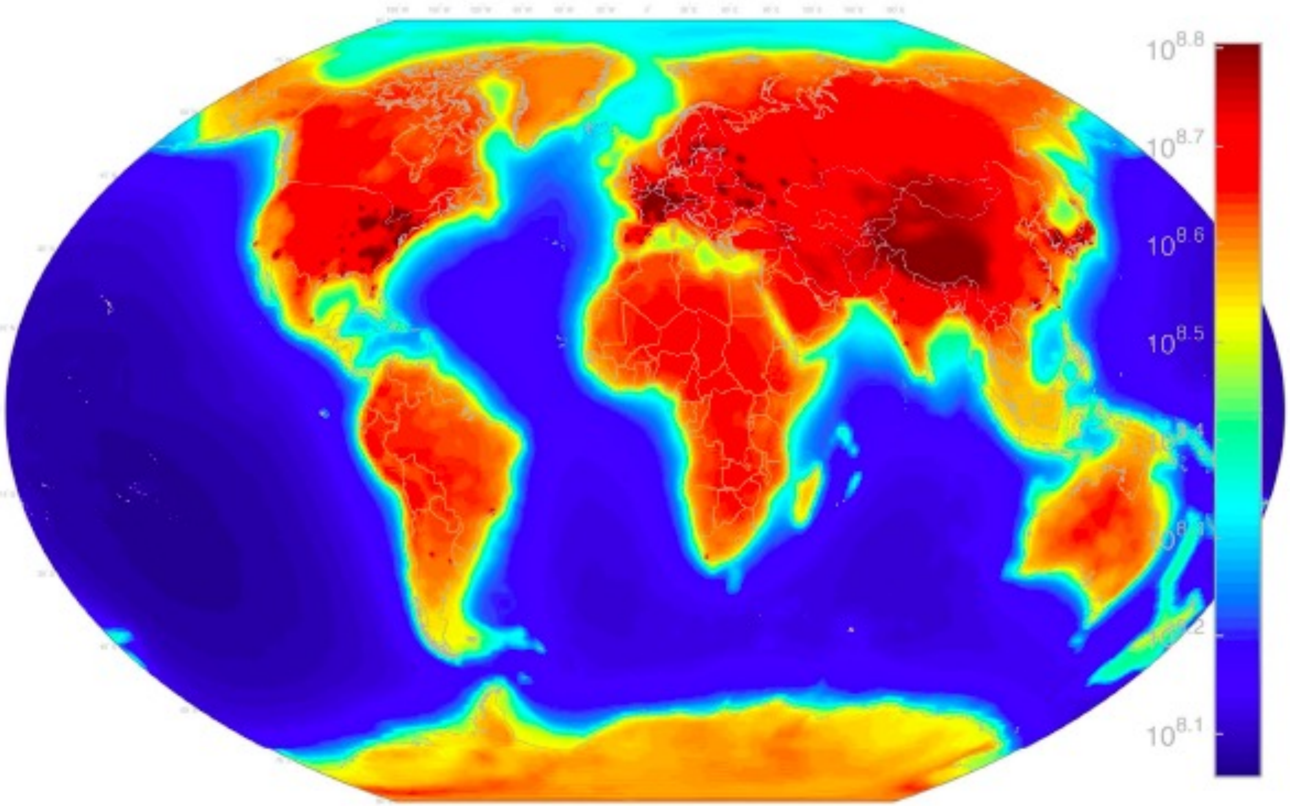
$E_{prompt} > 1$ MeV

$E_{delayed} \sim 2.2$ MeV

Reactors in the World

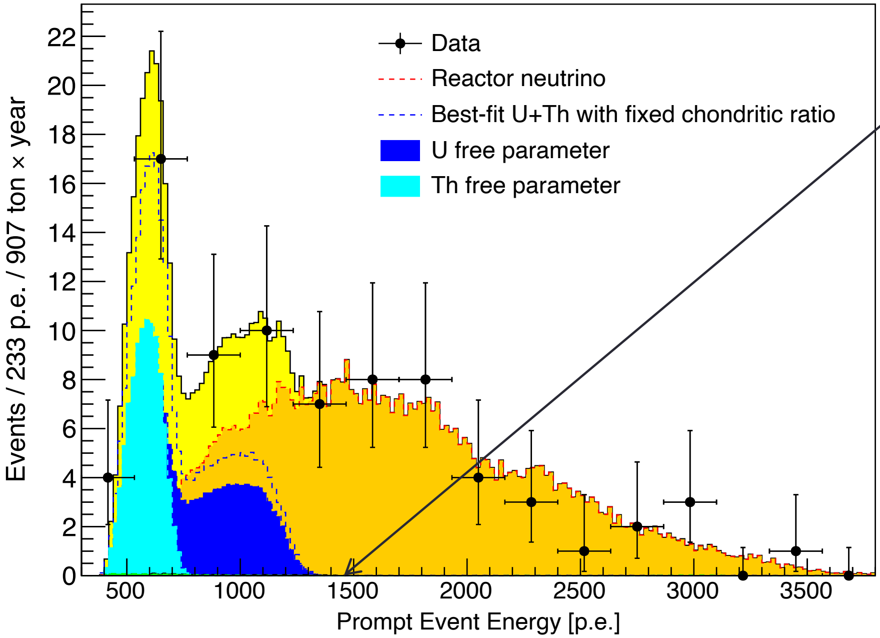


Total antineutrino flux from the Earth (U + Th + reactors)

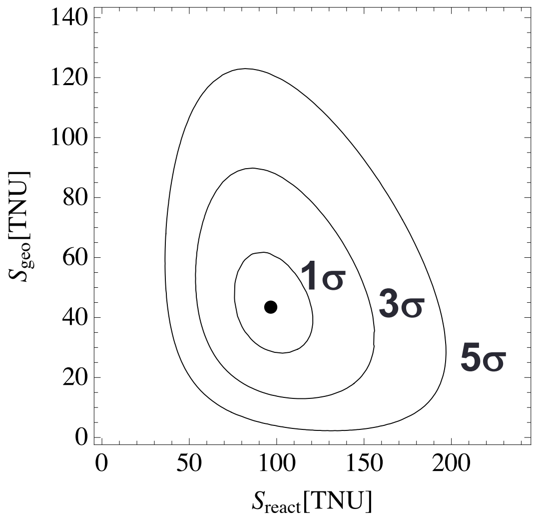


S.M. Usman, G.R. Jocher, S.T. Dye, W.F. McDonough & J.G. Learned
Scientific Reports, 1 September, 2015

1^{st} Borexino measurement of geo-ν



background



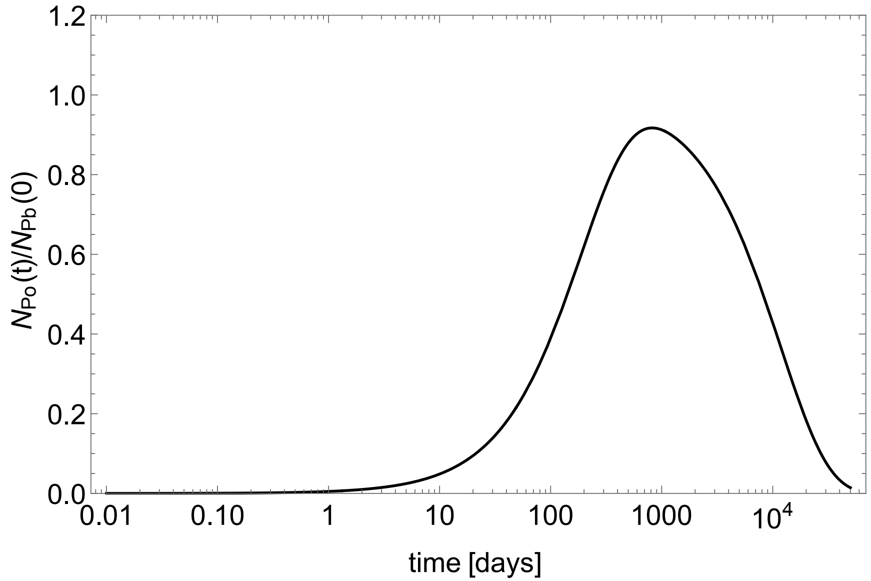
$N_{geo} = 23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$

$N_{react} = 52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(sys)$

Null hypothesis rejected at 3.6×10^{-9}

Secular equilibrium

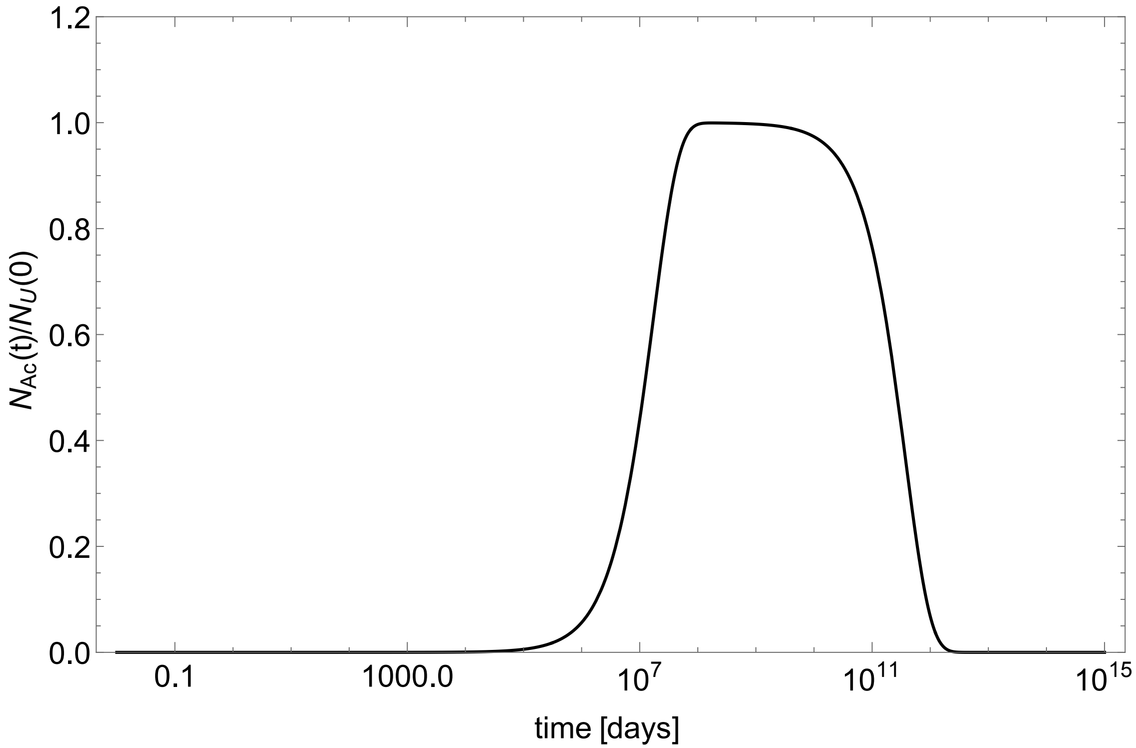
- A ➞ B ➞ C(stable)
    - if $\lambda_A \ll \lambda_B$ ($\tau_A \gg \tau_B$)
    - for $t \gtrsim \tau_B$ we have $A_A = A_B$



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

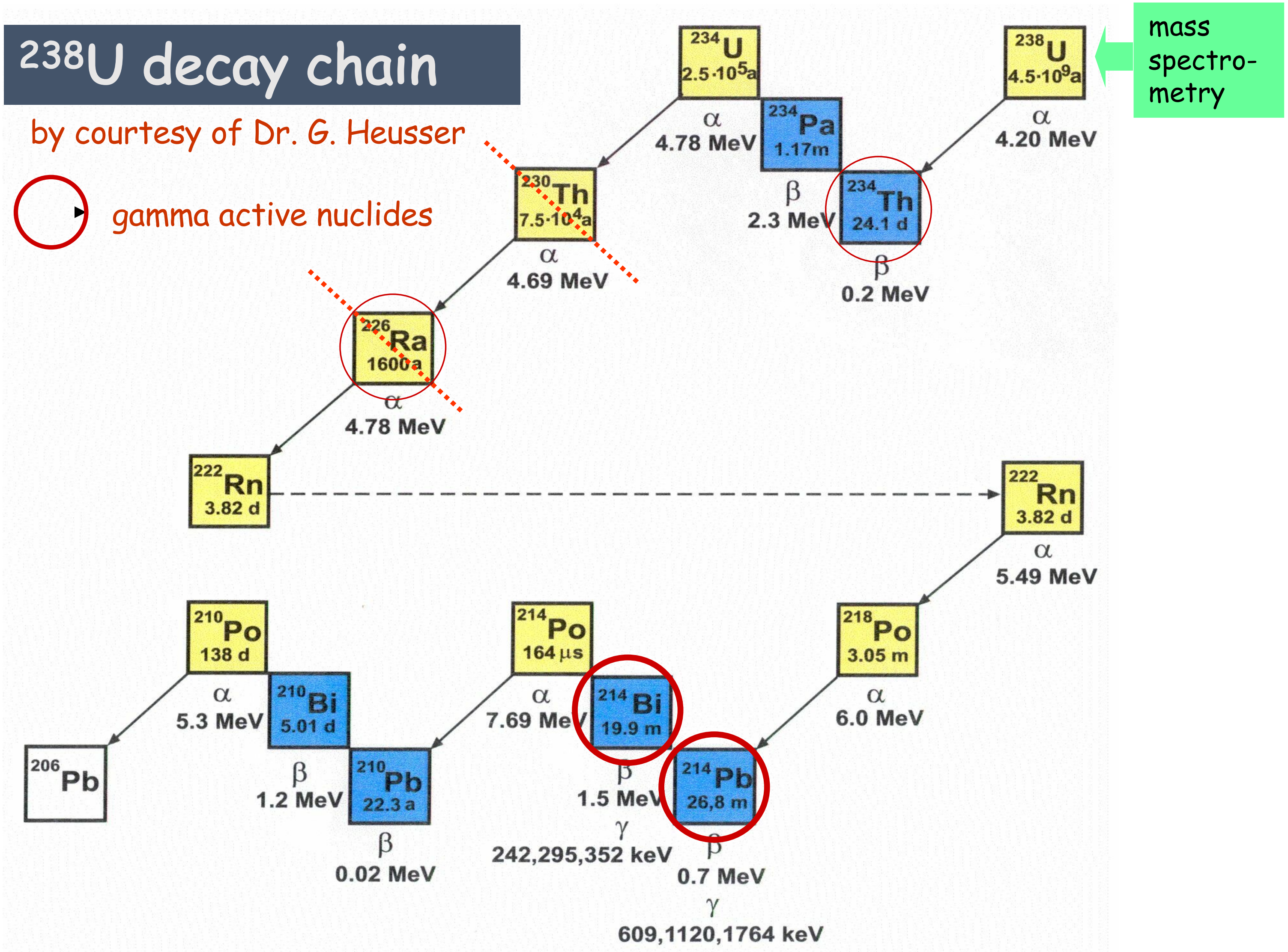
Secular equilibrium: ^{235}U

$$N_{Ac}(t) = N_U(0)e^{-\lambda_U t}\left(1 - e^{-\lambda_{Pa} t}\right)$$



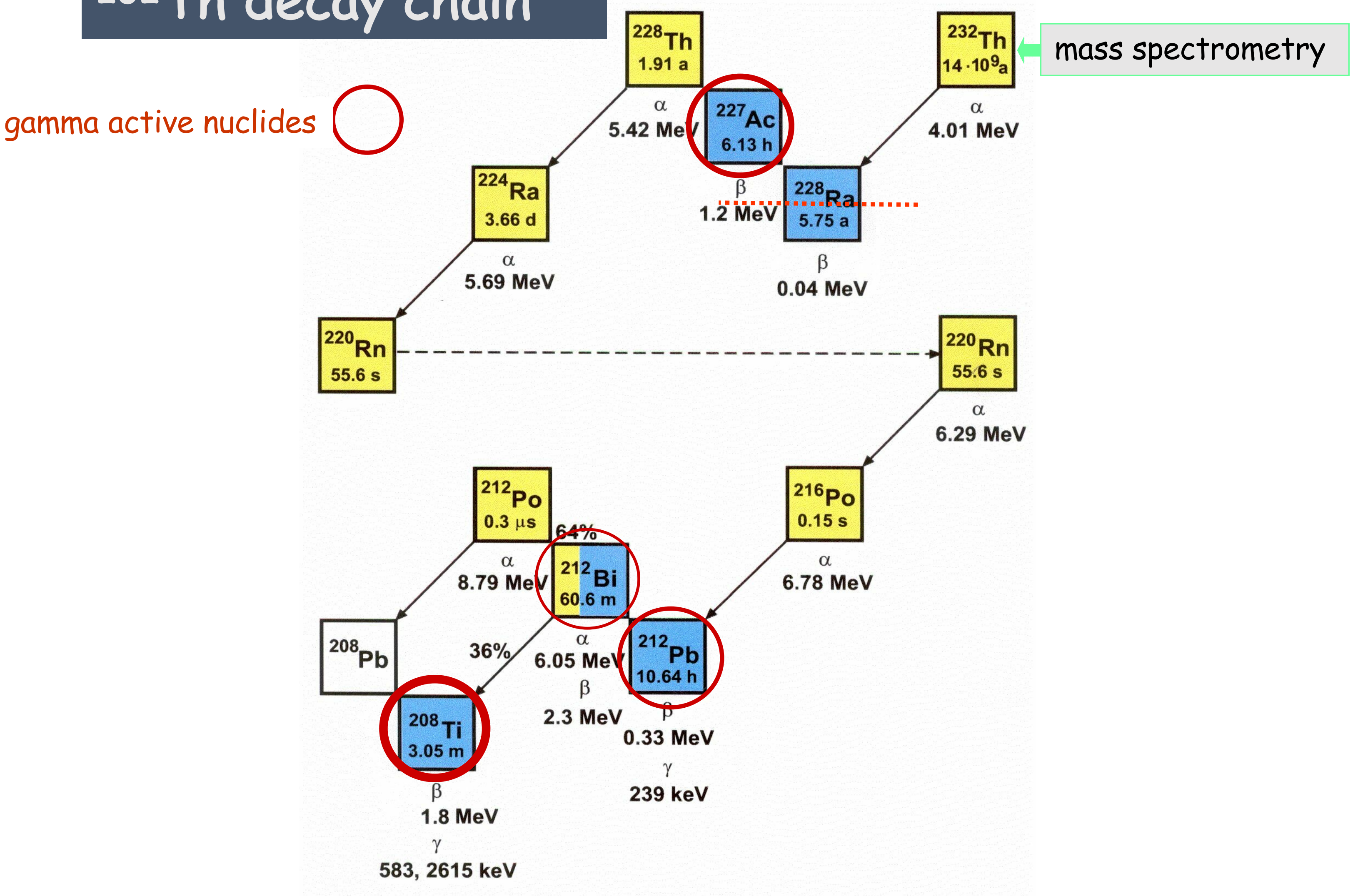
^{238}U decay chain

by courtesy of Dr. G. Heusser

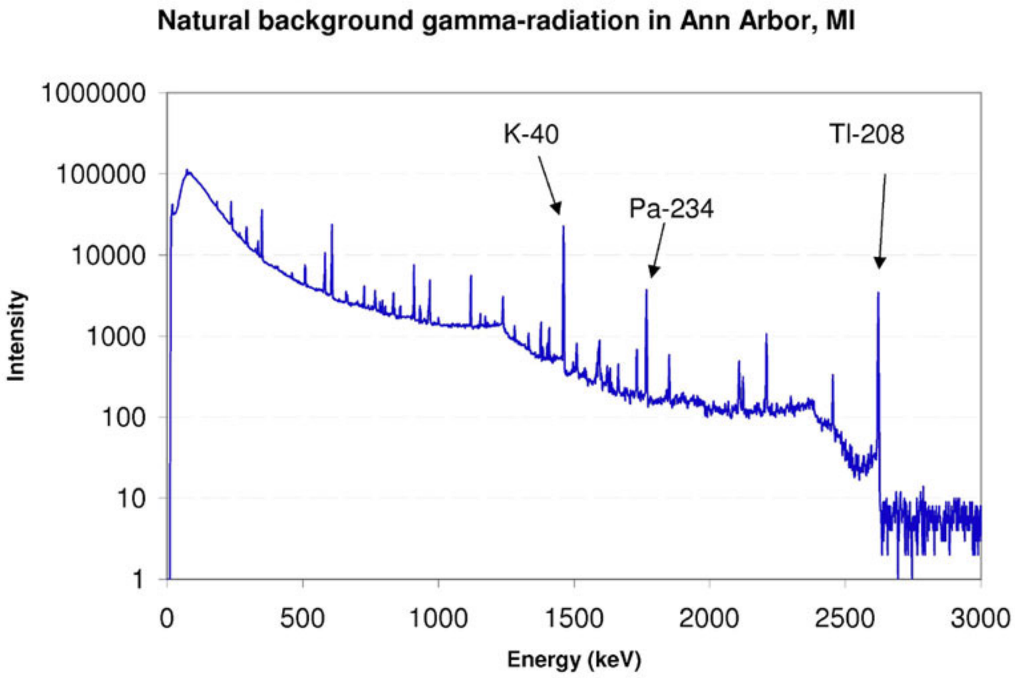


^{232}Th decay chain

by courtesy of Dr. G. Heusser



HPGe detector: gamma spectroscopy



Best sensitivity of order 10 μBq/kg

1ppt ^{238}U = 12.35 μBq/kg

1ppt ^{232}Th = 4.06 μBq/kg

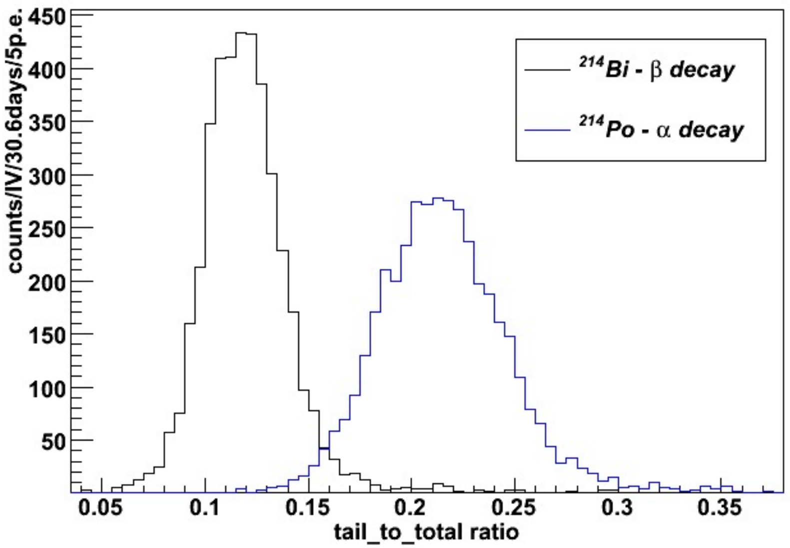
1ppb K_{nat} = 31 μBq/kg

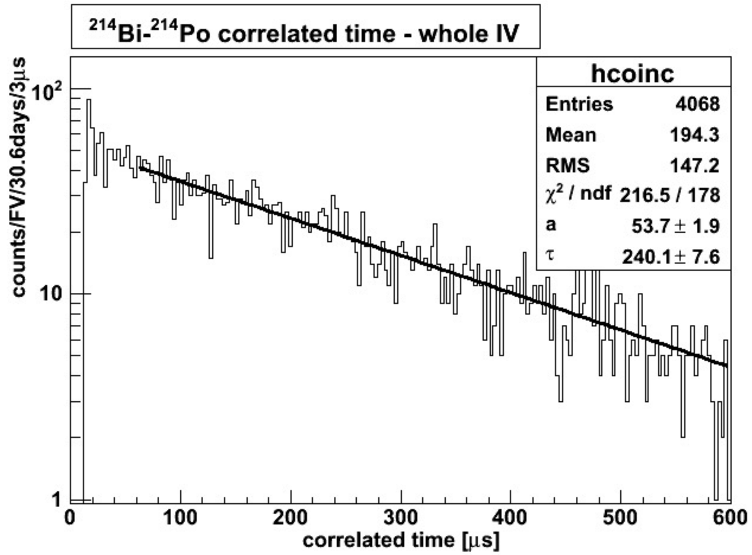
With ICP-MS one can probe fraction of ppt in U and Th (~ 1μBq/kg)

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: **$(7\pm2) \times 10^{-18}$ g/g**

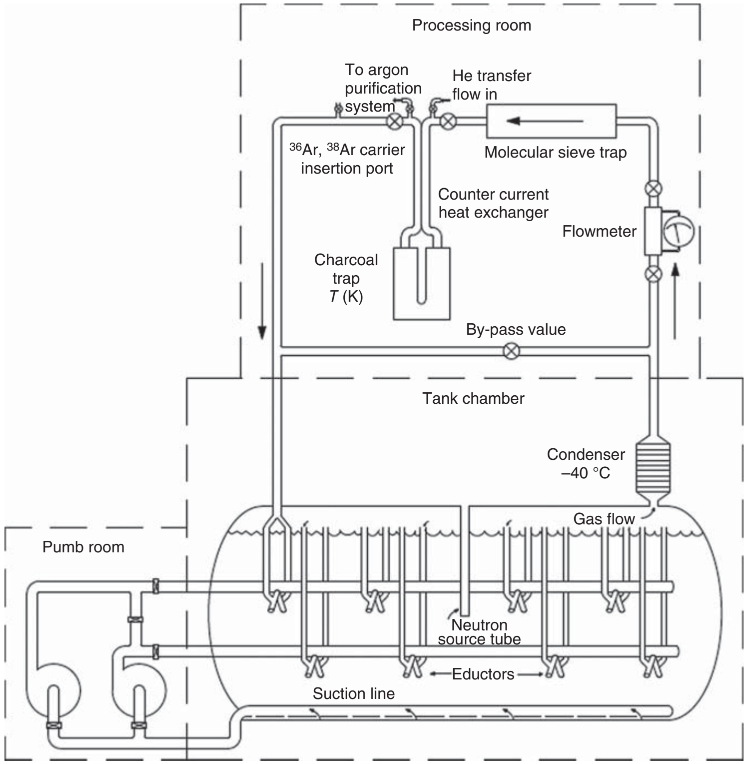




Homestake experiment

- $\nu_e + {}^{37}_{17}Cl \rightarrow e^- + {}^{37}_{18}Ar,\ Q = 0.814\ MeV$
- ^{37}Ar decays back to ^{37}Cl with $T_{1/2}$ = 35 days
- 615 tons of C_2Cl_4 (tetracloroethylene) in the Homestake mine (1500m depth) in South Dakota, USA
- 40 days exposure followed by ^{37}Ar extraction
- $N({}^{37}_{17}Cl)\sum_i \int_{0.814\ MeV}^{15\ MeV} dE_\nu \phi_i(E_\nu)\sigma(E_\nu) = \frac{\lambda N({}^{37}_{18}Ar, t_{run})}{\varepsilon_e \varepsilon_c (1 - e^{-\lambda t_{run}})} - b$
  - ✓ ε_e = extraction efficiency
  - ✓ ε_c = counting efficiency
  - ✓ b = Ar background rate
- Within the exposure time 41 atoms are expected in 2×10^{30}
  - ✓ this corresponds to 8 SNU (1 SNU = 10^{-36} captures/target nucleus/sec)

Background and operation for the Homestake experiment



- Cavity around the tank can be flooded with water for n shielding
- 0.2 cm^3 of ^{36}Ar / ^{38}Ar (~10^{19} atoms) added before each run
- 40 days exposure
- Purging with helium for 20h which carries gas to a condenser to freeze C_2Cl_4 vapors
- Gas is sent to a charcoal trap at 77K to adsorb argon (melting point 83.8K)
- Extraction of Ar from the charcoal (heating a 200C) and purification (exposure to hot metal surface for O and N)
- Remove heavy elements (Xe, Kr, Rn) by gas chromatography
- Gas into small charcoal trap to remove traces of helium by pumping off at 77K
- Gas into a 0.5 cm^3 proportional counter

Signal vs background in the Homestake experiment

- Extraction efficiency measured through ^{36}Ar, ~96%
- Counter looks for 2.8 keV Auger electrons with expected rate of 1cpd
  - ✓ background of counter ~ 1/month
  - ✓ counting efficiency 40%
- Capture cross section
  - ✓ use mirror process: ${}^{37}_{20}Ca \rightarrow {}^{37}_{19}K + e^{+} + \nu_e$
  - ✓ $\langle \sigma\phi \rangle = (1.14 \pm 0.03) \cdot 10^{-42}\ cm^2$
- Background mainly due to (α,p) and (p,n) reactions to make ^{37}Ar
- Capture rate = **0.478±0.030(stat)±0.029(sys) day^{-1}**

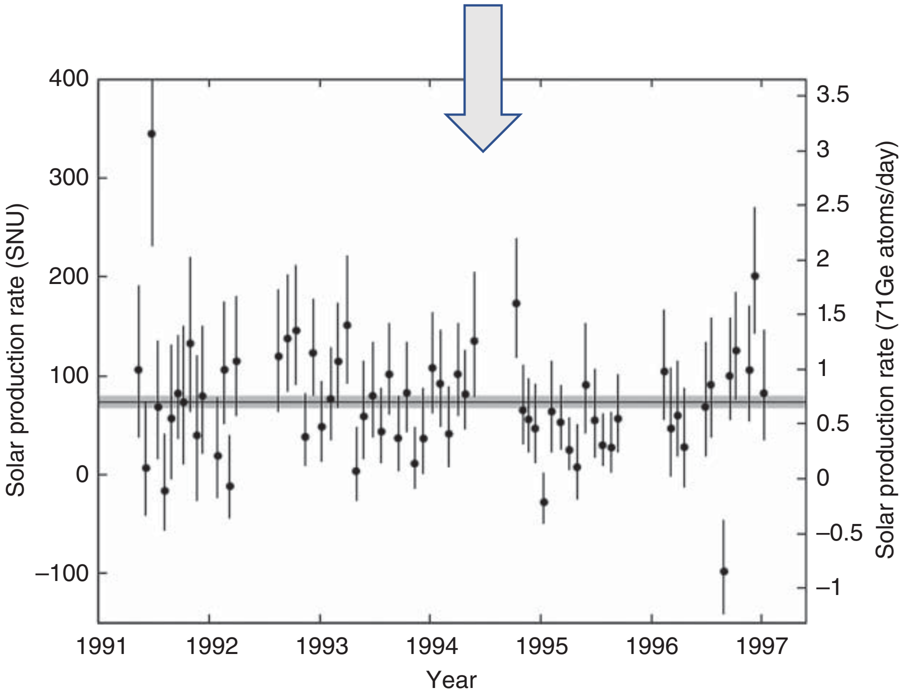
Background	^{37}Ar atoms/day
Cosmic rays	0.047 ± 0.013
Fast neutrons	0.03 ± 0.025
Radioactive contaminants in tank and in C_2Cl_4	< 0.017
Signal	^{37}Ar atoms/day
Expected solar neutrino rate	1.5 ± 0.2
Measurement	^{37}Ar atoms/day
	0.48 ± 0.04

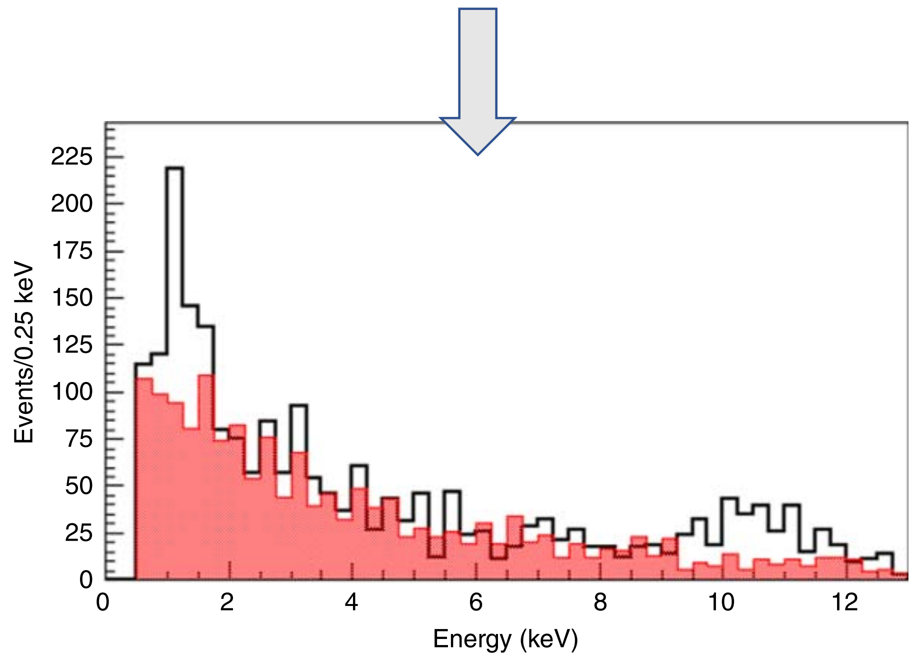
Gallium experiments

- $\nu_e + {}^{71}_{31}Ga \rightarrow e^- + {}^{71}_{32}Ge,\ Q = 0.233\ MeV$
  - ✓ threshold is below pp neutrinos maximum energy
  - ✓ ground-state transition well known; transition to 1st excited state gives only a minor contribution to pp rate
- ^{71}Ge decays back to ^{71}Ga with $T_{1/2}$ = 11 days
- Two experiments: GALLEX at LNGS and SAGE at Baksan
- Expected rate ~0.04 events/ton of Ga/day with 56% from pp neutrinos
- **Minimum** predicted **rate** due only to pp and pep neutrinos
  - This rate comes to be **80 SNU** larger than the «standard» rate due to the fact that only pp-I is taken into account
  - Any measurement below this value implies a physics modification of solar neutrino propagation to Earth
- In Gallex 100 tons of gallium chloride with 30.3 tons of Ga and 12 tons of ^{71}Ga
  - 16 atoms in 20 days exposure: 1 in 10^{29}
  - Main background source from $^{71}Ga(p,n)^{71}Ge$
- Ge produced is in the form $GeCl_4$ which is volatile and can be extracted by purging with nitrogen
  - A non-radioactive Ge isotope at 1 mg level is added before the run to determine the extraction efficiency
  - Extraction efficiency is 99.8%
- In 1998 GALLEX was upgraded to GNO (improved DAQ)
- Combined GALLEX + GNO result is **67±5 SNU**, which is significantly smaller than the minimum predicted rate based on solar luminosity

65 solar neutrino runs in GALLEX
Expected rate in detector ~ 0.5 event/day

- GNO energy specturm of selected ^{71}Ge events in counter
- The empy histogram shows counts occurring in first 50 days (3τ).
- L-peak at 1.2 keV and K-peak at 10.4 keV are visible.
- Filled histogram counts after first 50 days.

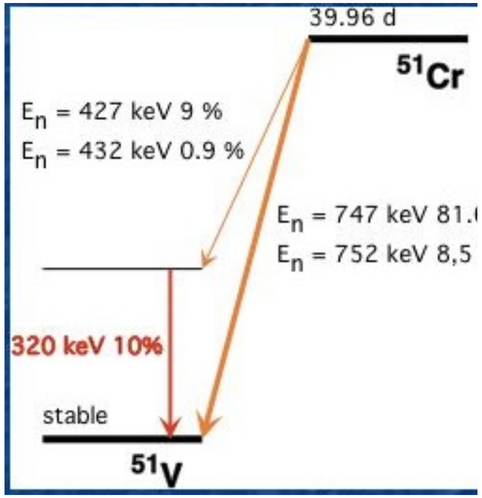


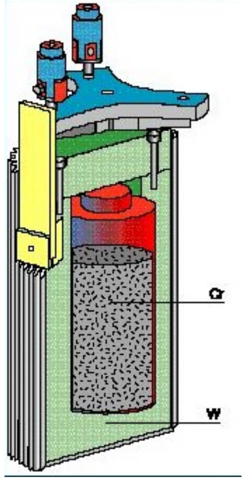


The GALLEX source experiment

- To very the extraction procedure a neutrino source experiment was carried out in GALLEX

- A ^{51}Cr neutrino source was was twice in 1994 and 1995
  - ^{51}Cr is produced by neutron activation on CrO_3 enriched in ^{50}Cr at 38.6% level
  - Neutron activation was done at Grenoble with a 35 MW reactor
  - ^{51}Cr decays with $T_{1/2}$ = 27.7 days emitting neutrinos at 746(81%)keV
  - The source activity was ~65 PBq
  - The source was located at the center of the detector in a special hole
  - Result: $\mathbf{A_{measured}/A_{predicted} = 0.882 \pm 0.078}$



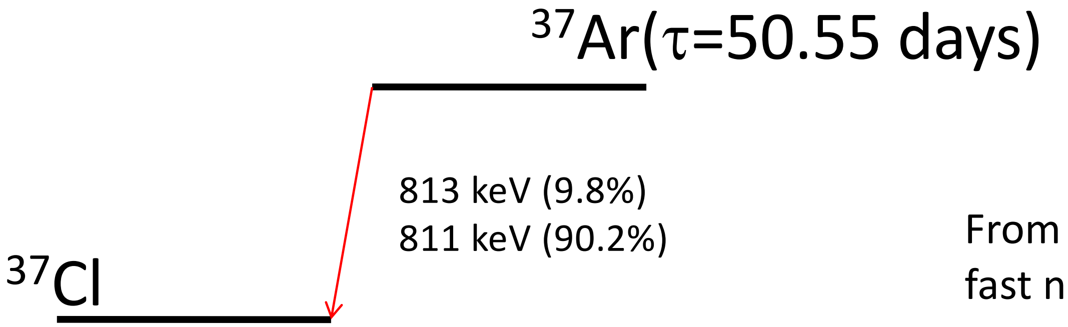


Gallex coll., PL B 420 (1998)
SAGE coll., PRC 59 (1999) 2246

The SAGE detector

- It made use of 30 tons of liquid metallic gallium in 4 containers holding 7 tons of target mass
- Metallic gallum is kept at 30C to remain molten
- A runs starts by adding 160 μg of stable Ge into each container
- After 3 weeks exposure hydlochloric acid solution is mixed with the metallic gallium
- Ge is extracted into aqueous phase and later vacuum evaporated
  - Extraction efficiency is ~95%
- GeH_4 is mixed with Xe and measured for six months in a proportional counter
- SAGE has also performed a calibration with a ^{51}Cr source of 19 PBq giving $A_{measured}/A_{predicted} = 0.95\pm0.12\pm0.03$
- Combined all gallium measurements give: 66.2±3.1 SNU

^{37}Ar calibration in SAGE



~16 W/MCi from 2.6 keV X-rays

From irradiation of CaO using fast neutrons ^{40}Ca(n,α)^{37}Ar

No gamma ray in the decay as in ^{51}Cr

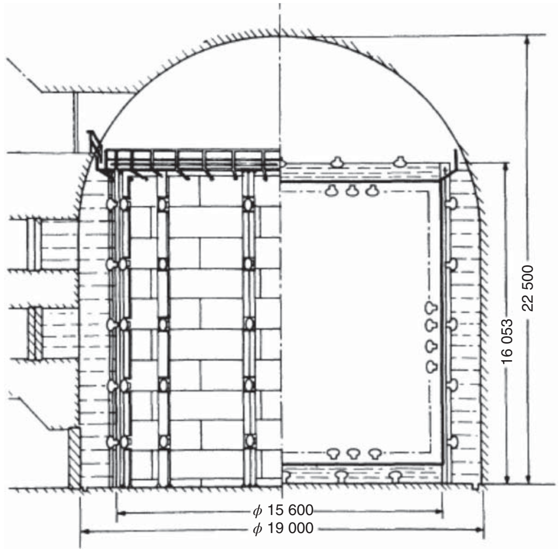
Used in SAGE with **~0.4 MCi**

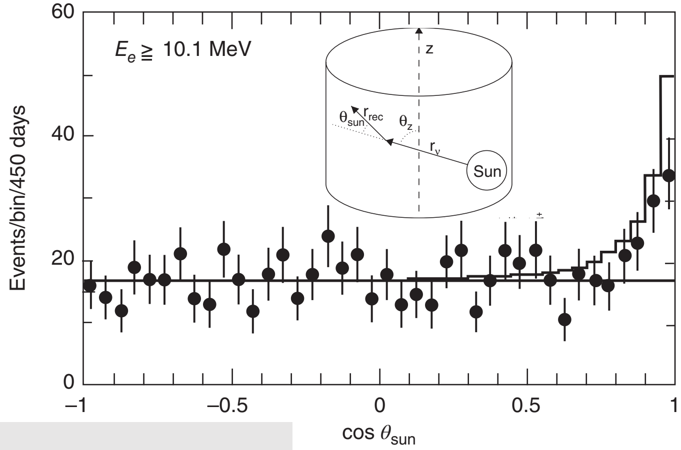
~80% extraction efficiency

SAGE coll., PRC 73 (2006) 045805

Kamiokande-II experiment

- Exploit neutrino-electron ES in a water Charenkov detector underground
- $R = A \int_{T_{th}}^{T_{max}(E_\nu)} dT\ \eta(T) \int_{E_{min}(T)}^{E_\nu^{max}} dE_\nu\ \phi(E_\nu) \frac{d\sigma}{dT}(E_\nu, T)$
- High radio-pure water required ~ 10^{-14} g/g
- Main backgrounds from ^{222}Rn and ^{208}Tl and from muon spallation on ^{16}O producing β decays from ^{8}B, ^{8}Li, ^{16}N, ^{12}B
  - ✓ Threshold > 7 MeV due to Radon background
- In water dN/dx ~ 210 photons/cm
- N_{phe} ~ (210ph/cm)L(cm)$e^{-l/\lambda}\eta Q_{PMT}C$ ~ 40 for 10 MeV electron
  - ✓ L = 5cm electron range for 10 MeV e^-
  - ✓ l = 10m detector size
  - ✓ η=0.9 collection efficiency for PMT
  - ✓ λ = 50m light attenuation length
  - ✓ Q_{PMT} = 0.25 PMT quantum efficiency
  - ✓ C = 0.2 PMT coverage
  - ✓ $\Delta E/E$ ~ 16% at 10 MeV

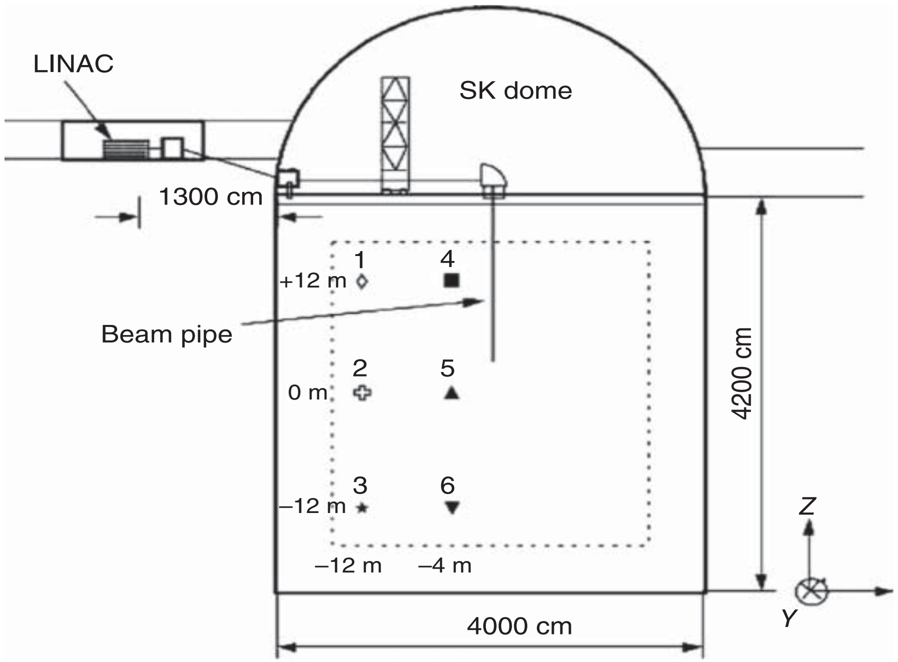


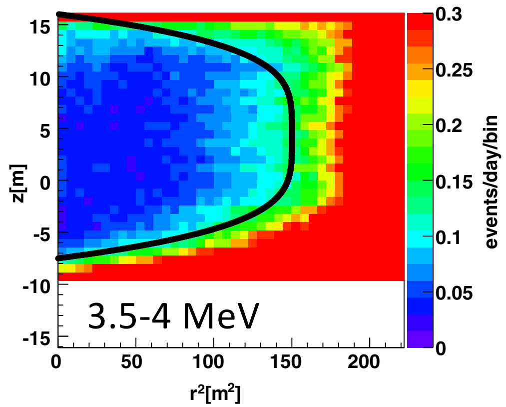


$$\frac{data}{theory} = 0.43 \pm 0.13(stat) \pm 0.08(syst)$$

The Super-Kamiokande experiment

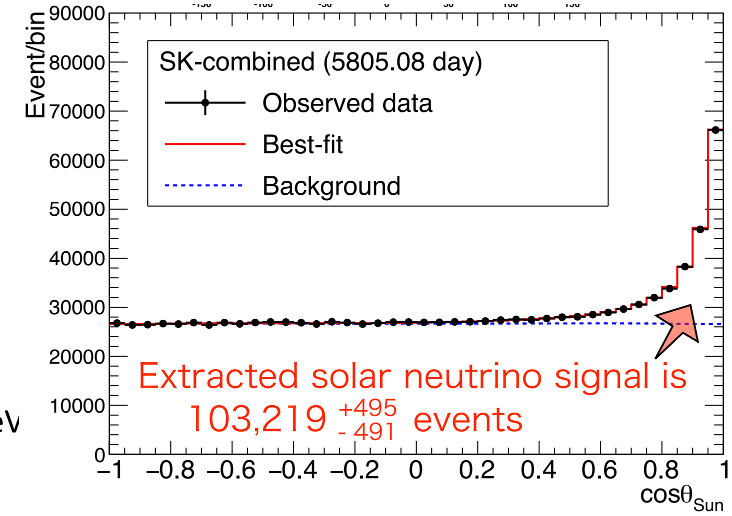
- World leading water Cherenkov detector
- 50 kton of water in total and 32 kton in inner detector
- 22.5kton Fiducial Volume
- 11,146 50cm PMTs with 40% coverage
- Outer detector with 3m water and 1885 20cm PMTs
- Energy scale, angular distribution, and vertex position calibrate by a LINAC, injecting 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

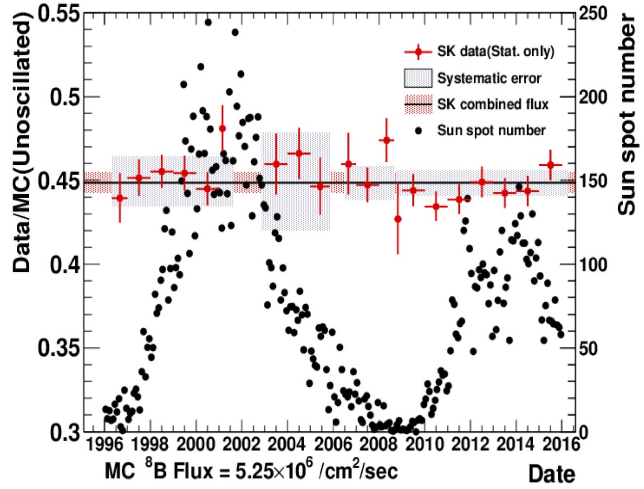




Expected events in Super-Kamiokande

- 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: $(N_A/18) \times 10 \times 22.5 \times 10^9 = 7.5 \times 10^{33}$
- ~ 150 cpd/FM

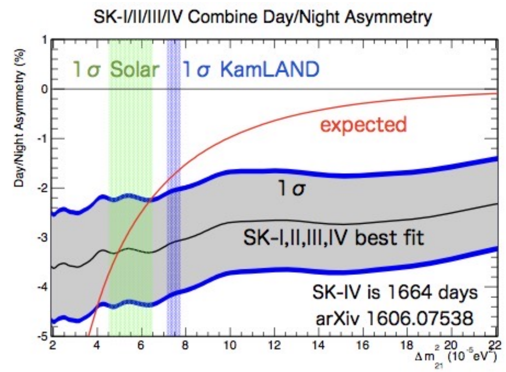


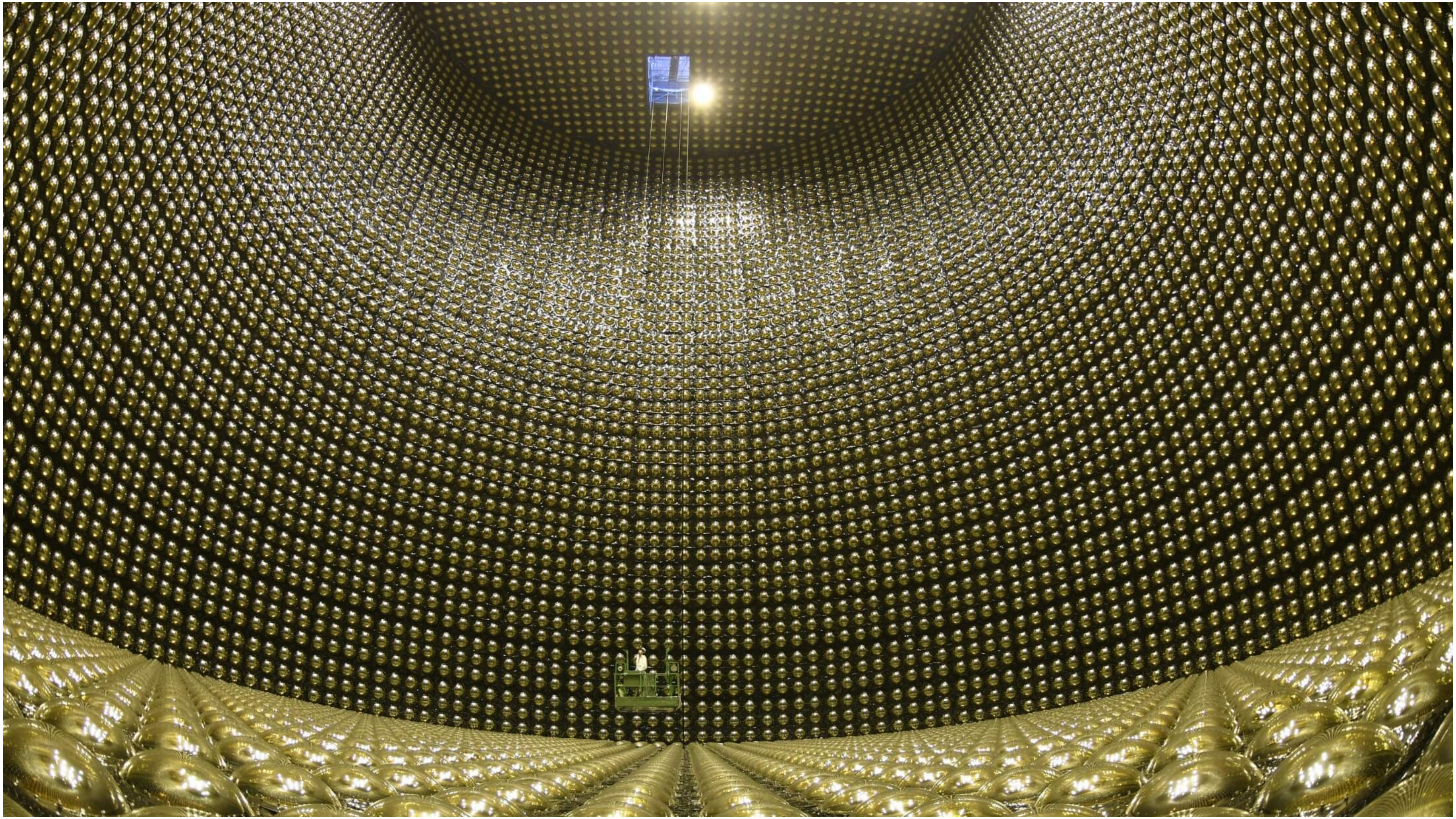


$$\frac{data}{theory} = 0.44486 \pm 0.0062$$

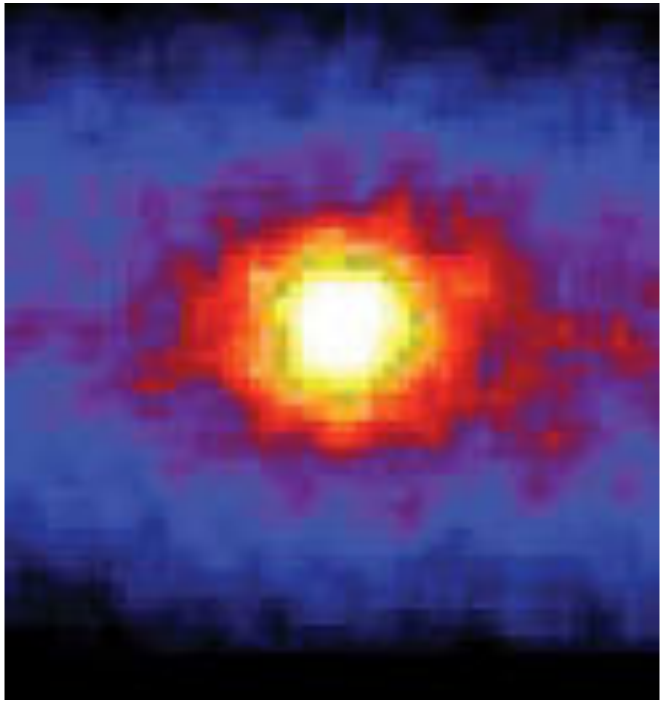
Most precise ^{8}B flux measurement, 1.4%

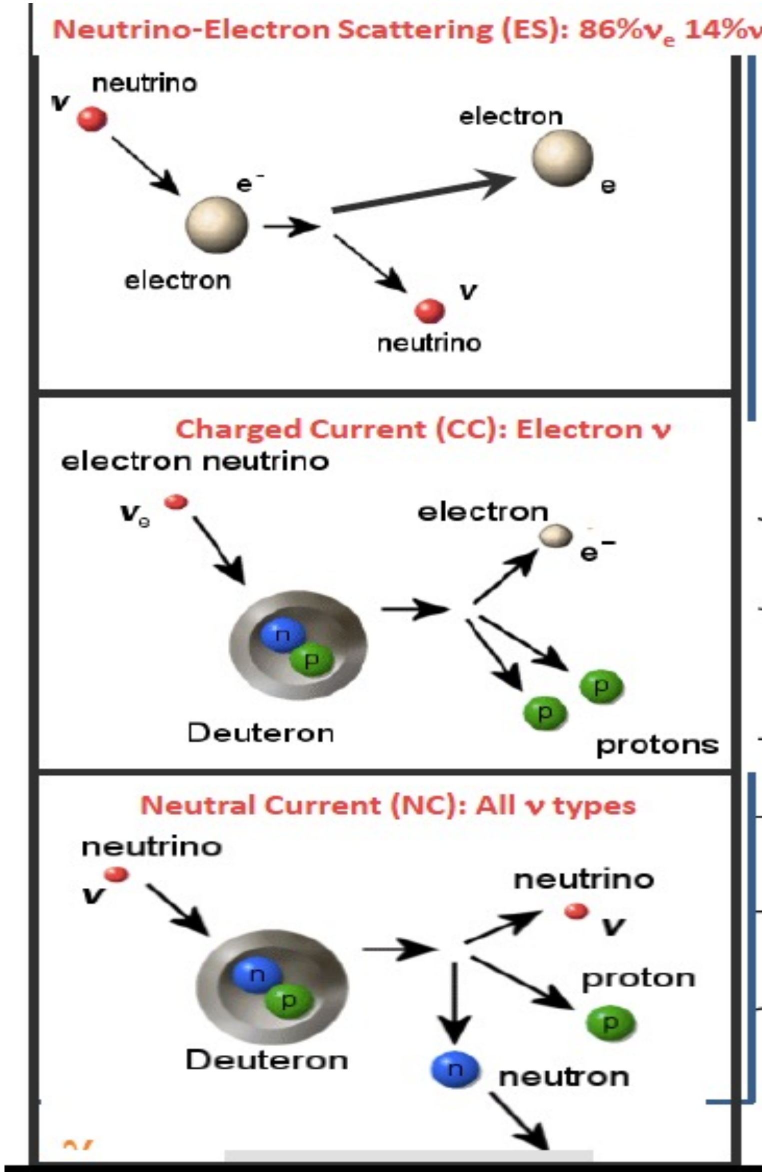
Day-Night asymmetry = -3.3±1.0±0.5 %



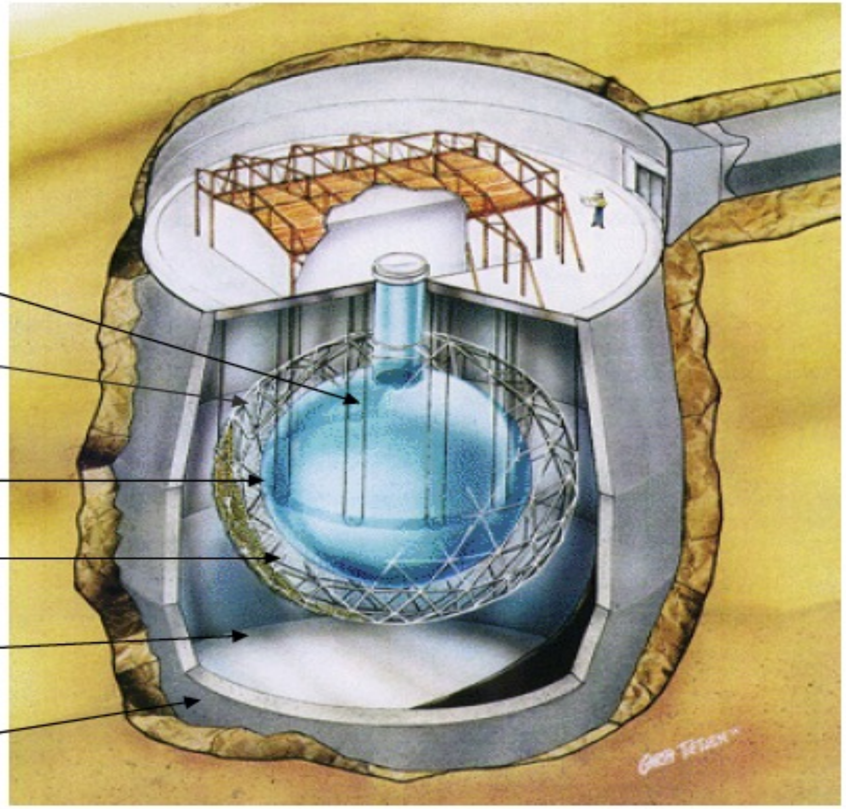


Sun through the neutrinos light from Super-Kamiokande





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

SNO Neutral Current Trilogy

Pure D_2O	Salt	^3He Counters
Nov 99 – May 01	**Jul 01 – Sep 03**	**Nov 04 – Nov 06**
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$	$n + {}^3He \rightarrow t + p$
(E_γ = 6.25 MeV)	($E_{\Sigma\gamma}$ = 8.6 MeV)	proportional counters σ = 5330 b
	enhanced NC rate and separation	event-by-event separation
PRL **87**, 071301 (2001) PRL **89**, 011301 (2002) PRL **89**, 011302 (2002)	PRL **92**, 181301 (2004)	
PRC **75**, 045502 (2007)	PRC **72**, 055502 (2005)	PRL **101**, 111301 (2008)

"long" archival papers with complete details

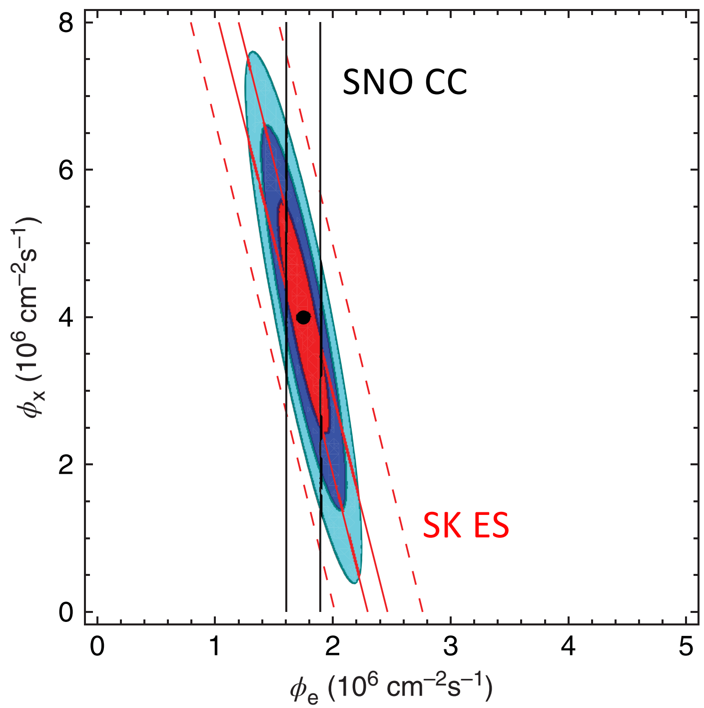
PRC **81**, 055504 (2010)
combined analysis with lower energy threshold

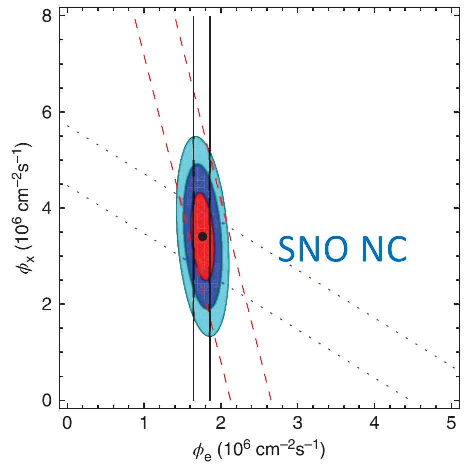
ARXIV: 1109.0763 (2011)
combined analysis of all three phases with pulse shape discrimination for ^3He counters

A few considerations on SNO

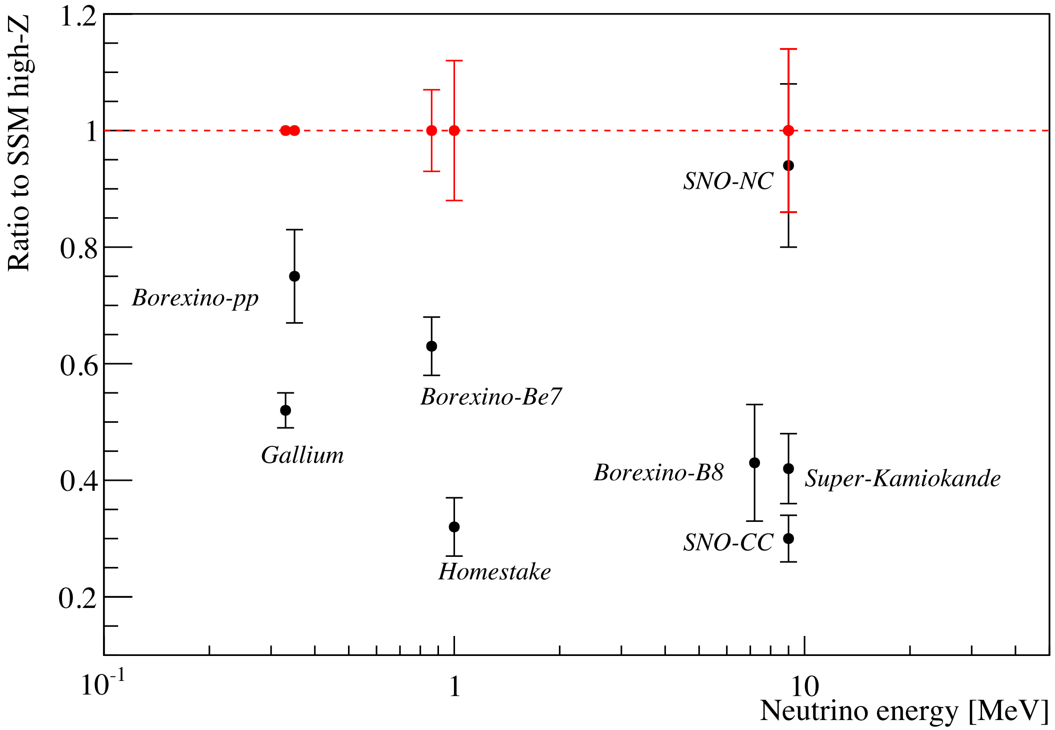
- Probe at the same time CC, ES, and NC
- $\phi_{\nu_e}^{CC} \leq \phi_{\nu_e}^{ES}$
- $\phi_{\nu_x}^{NC} \leq \phi_{\nu_e}^{SSM}$

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





Solar Neutrino Problem (SNP)



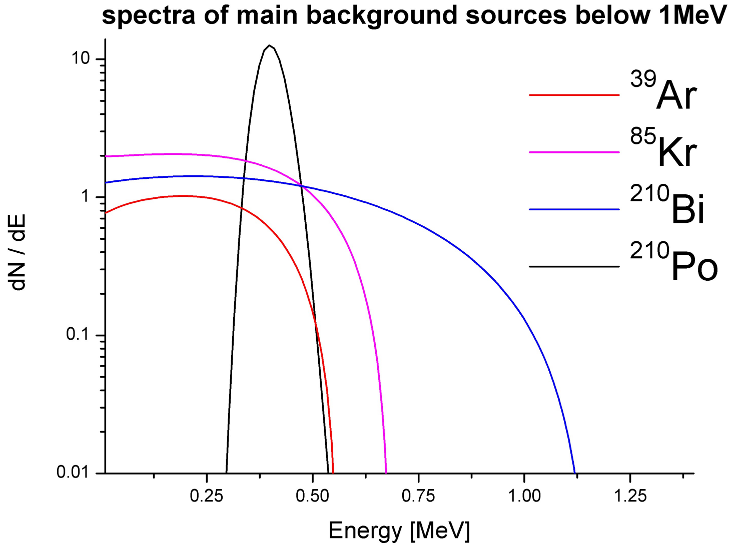
How to detect sub-MeV solar neutrinos in real time

- Make use of an organic liquid scintillator
- 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
  - $N_{p.e.}$~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 ^7Be solar neutrinos
- $\sigma \sim 5\times10^{-45}\ cm^2$ 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**

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



All spectra normalized to 1

Asking for 1 cpd/100tons

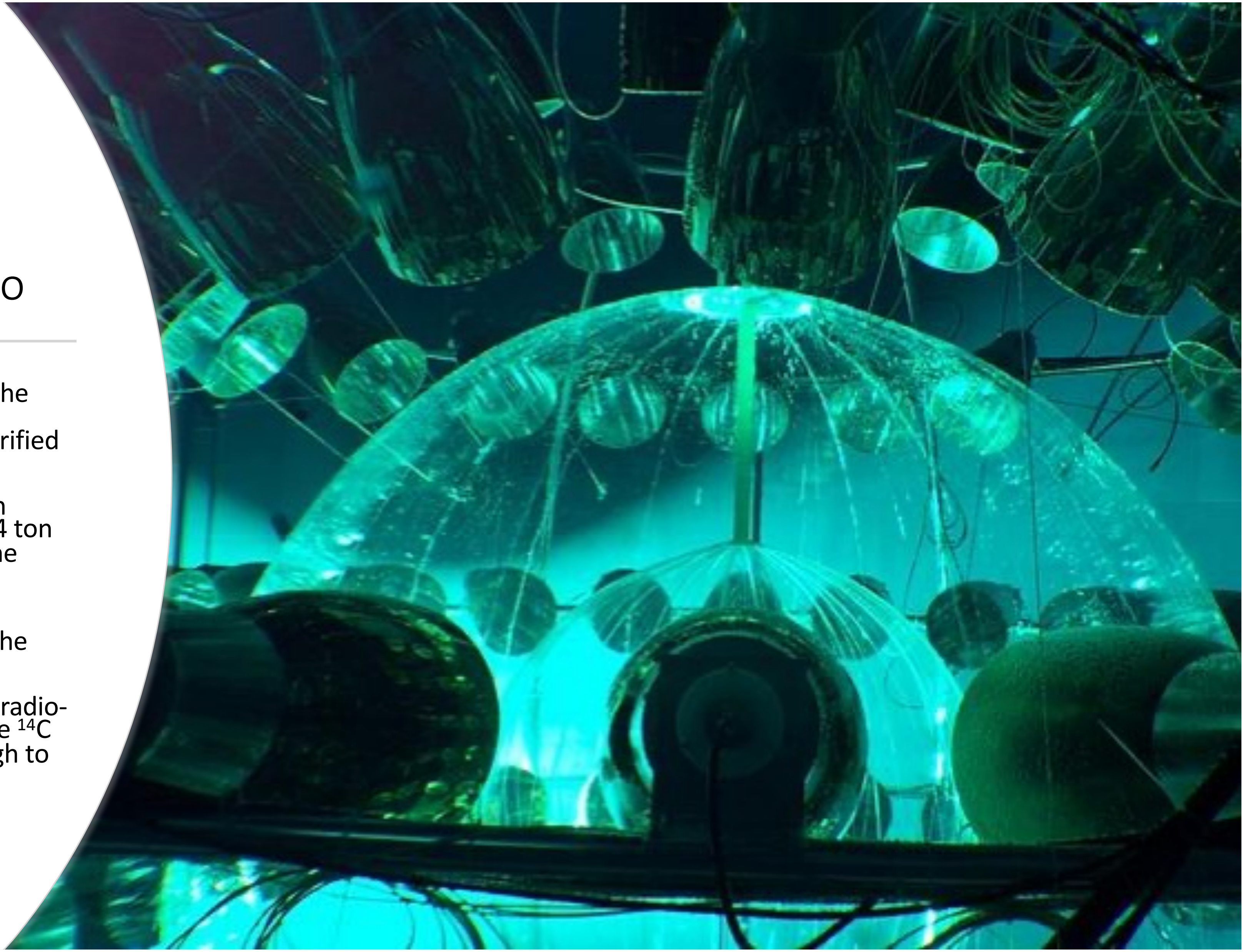
[0.1 μBq/m^3 in LS] it implies:

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

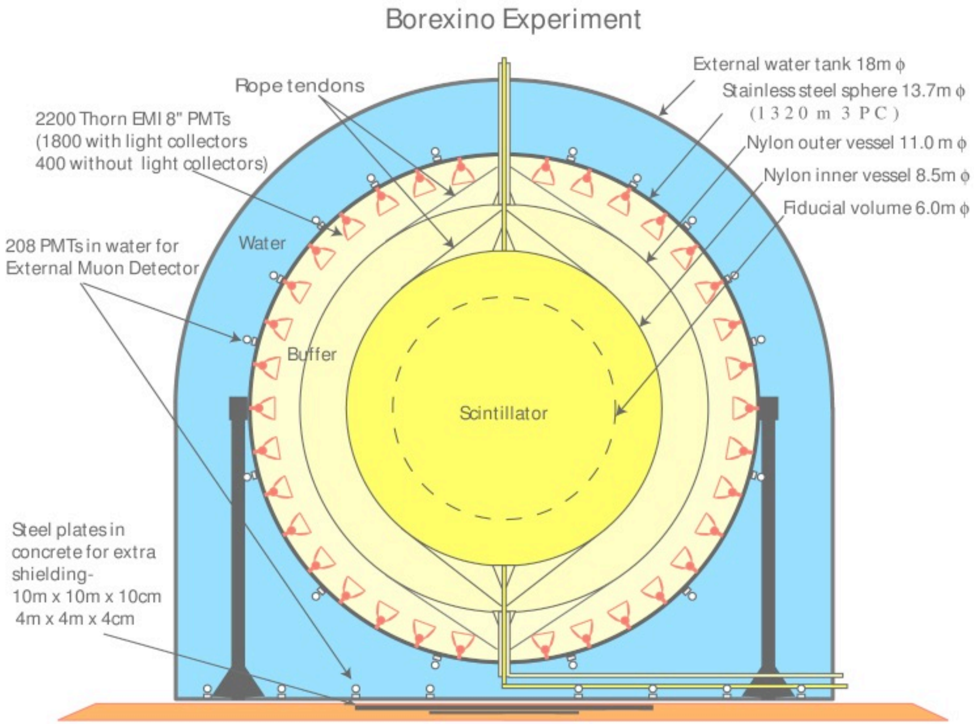
^{210}Pb and ^{210}Po are often found not in equlibrium due to a different chemistry

The idea of Borexino

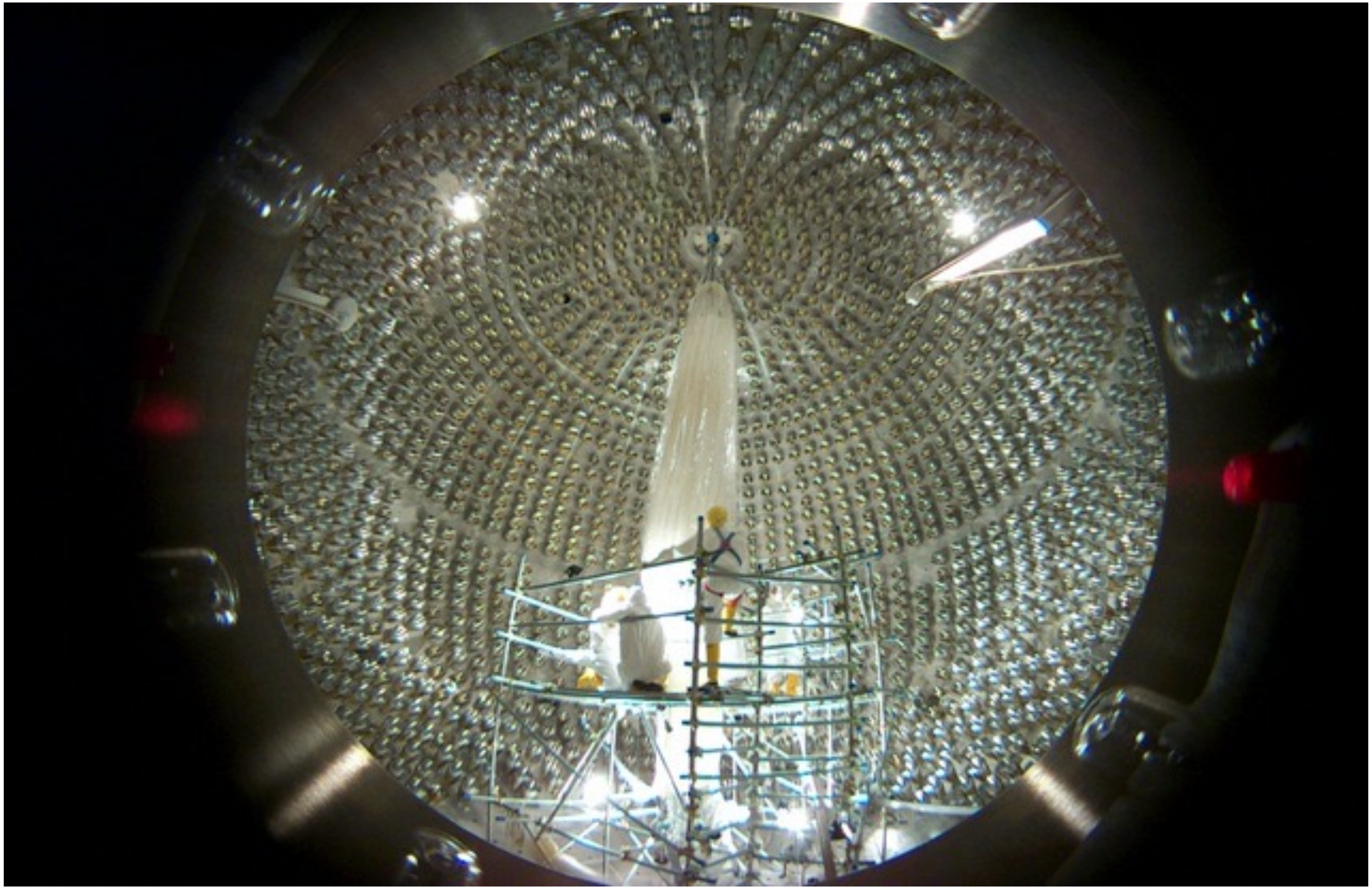
- In late 1980s it was proposed the idea that an organic liquid scintillator could have been purified to levels below 10^{-15} g/g
- This idea was put forward in an experimental effort running a 4 ton liquid scintillator detector at the Gran Sasso Laboratory: The Counting Test Facility (CTF)
- The success of the CTF paved the way to build Borexino
- The CTF showed that 10^{-16} g/g radio-purity was feasible and that the ^{14}C contaminations was low enough to set a threshold at 200 keV



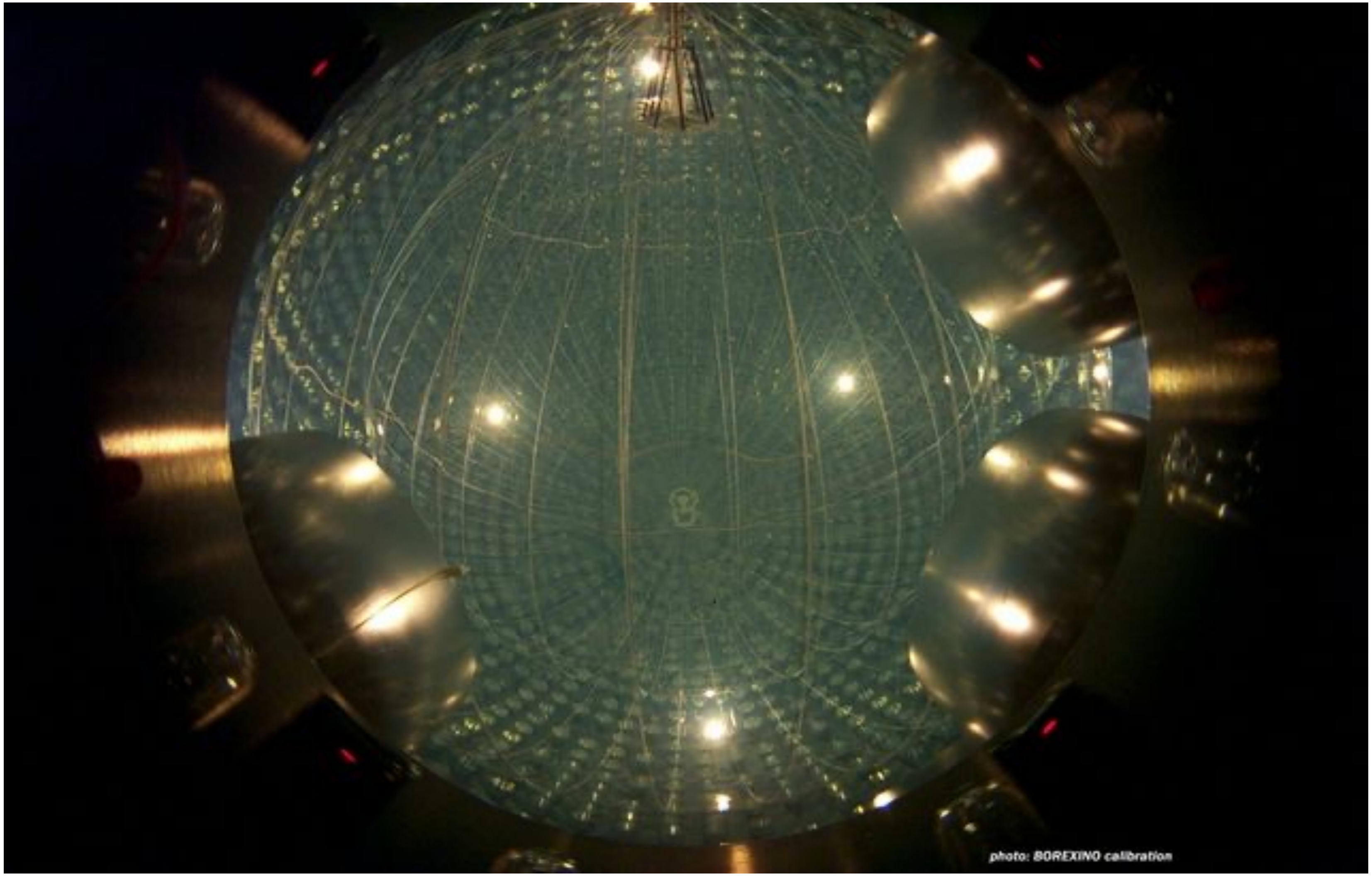
The BOREXINO detector



Borexino: nylon vessel installation

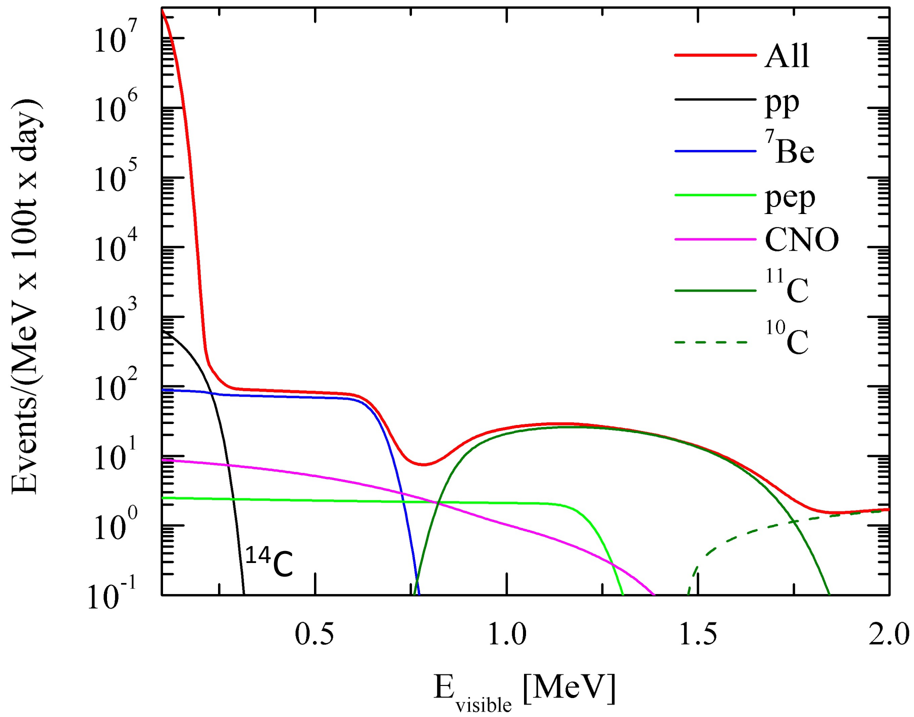


Borexino: liquid scintillator filling



Borexino Expected Solar ν Spectrum

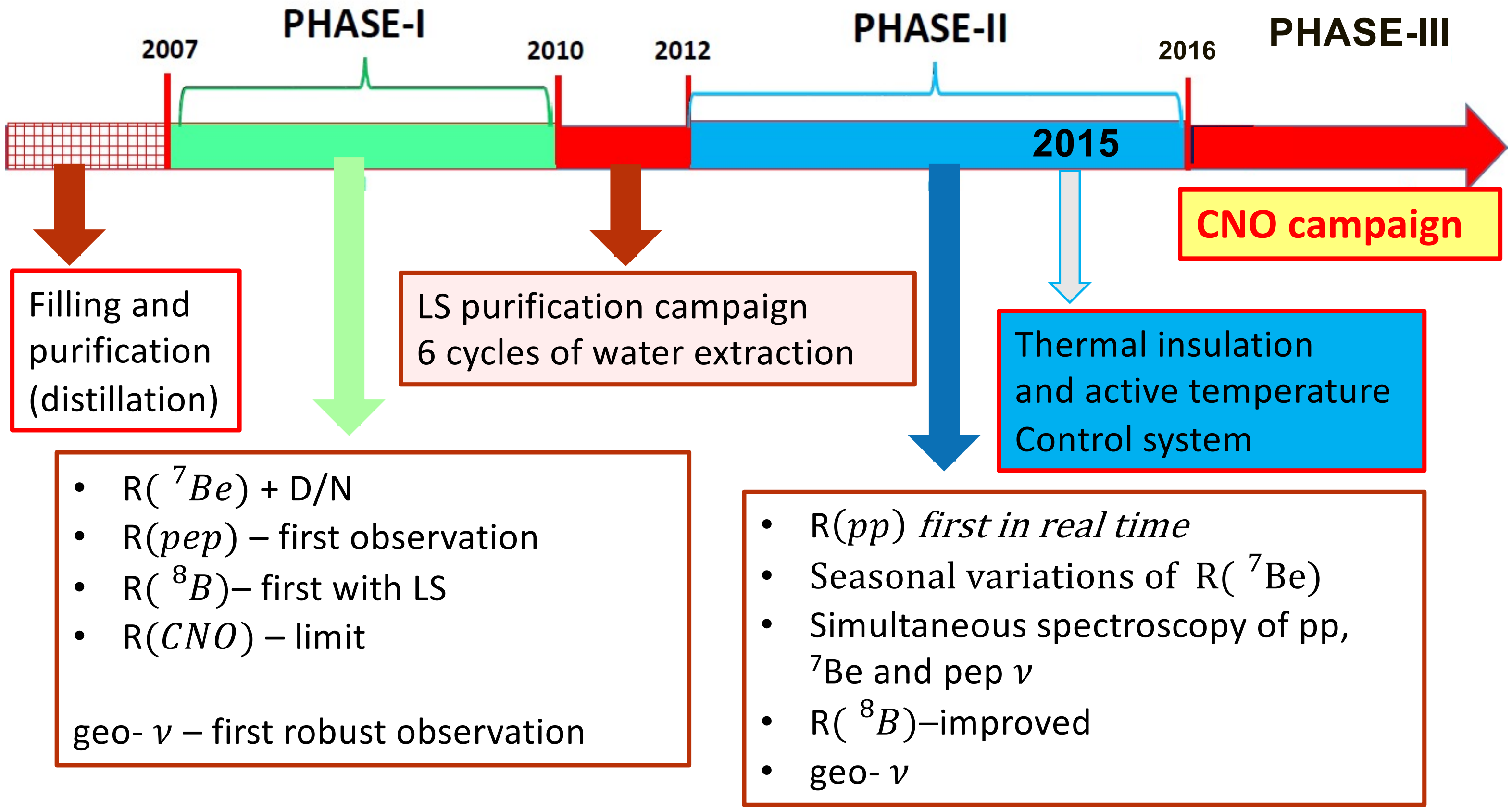
Spectrum with irreducible backgrounds



Borexino strategy

- Careful cleaning of as-built systems
- Purification of the liquid scintillator
- Use of the CTF detector to assess good performance of the proposed strategy:
  - test cleanlinesss
  - test purification and filling strategy

Borexino operations and achievements



Background in Phase-II

After 6 cycles of Water Extraction purification (May 2010 – August 2011)

- ^{85} Kr reduced below sensitivity (Kr-Rb tagging)
- ^{210}Bi reduced to 20 cpd/100ton from about 100 cpd/100ton
- ^{238}U (from ^{214}BiPo tagging) < 1.2×10^{-19} g/g at 95% CL
- ^{232}Th (from ^{212}BiPo tagging) < 1.2×10^{-18} g/g at 95% CL (2 events in 600 days)
- ^{222}Rn $(5.8\pm1.2)\times10^{-2}$ cpd/100ton (< 1 atom in 100 tons)
  - ✓ Rn is not the source of ^{210}Pb

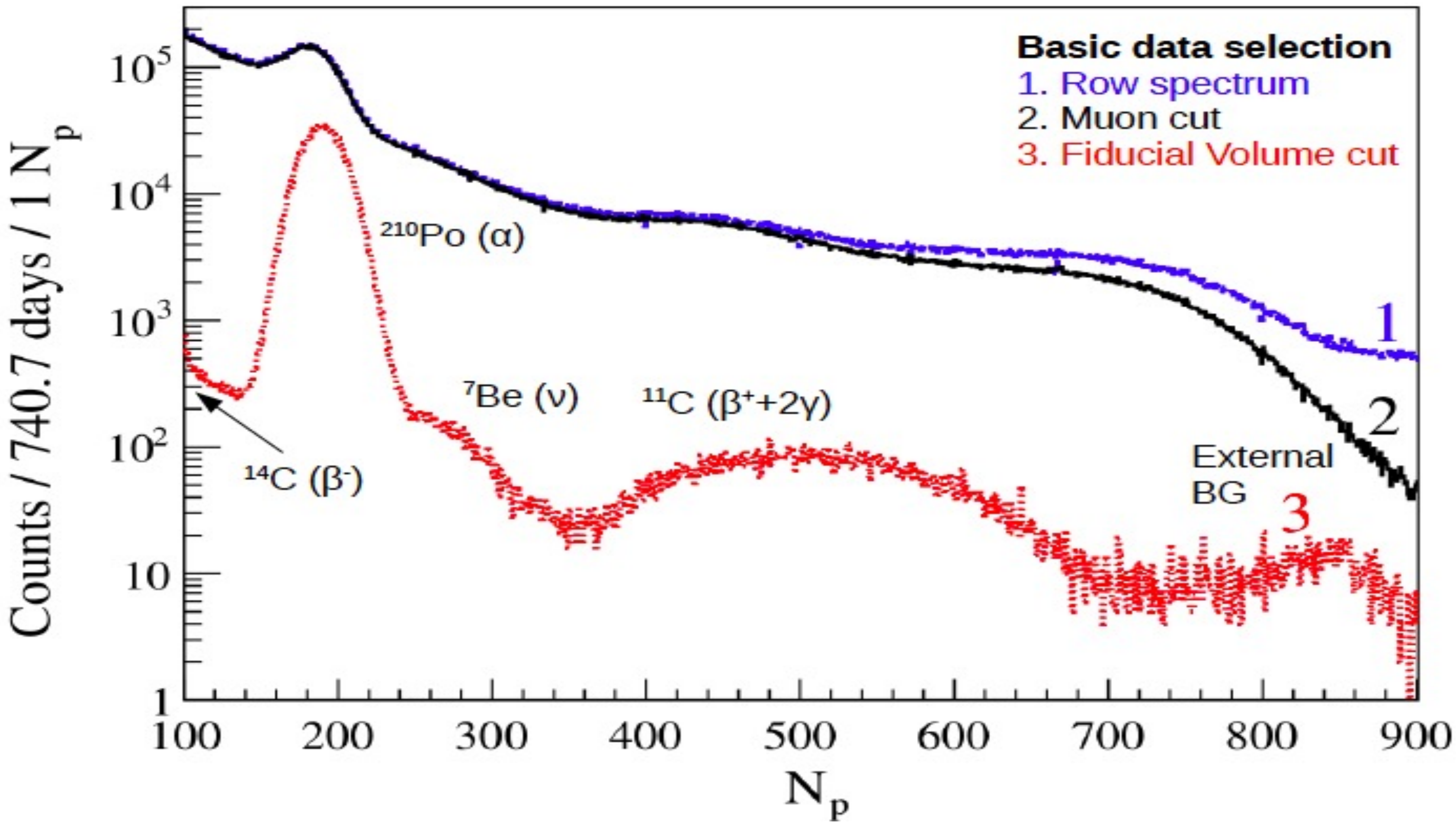
Borexino radio-purity

Isotope	Spec. in LS	After filling	After purification
^{238}U	$\leq 10^{-16}$ g/g	$(5.3\pm0.3)\ 10^{-18}$ g/g	$\leq 9.4\ 10^{-20}$ g/g
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8\pm0.8)\ 10^{-18}$ g/g	$< 5.7\ 10^{-19}$ g/g
$^{14}C/^{12}C$	$\leq 10^{-18}$	$(2.7\pm0.1)\ 10^{-18}$ 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

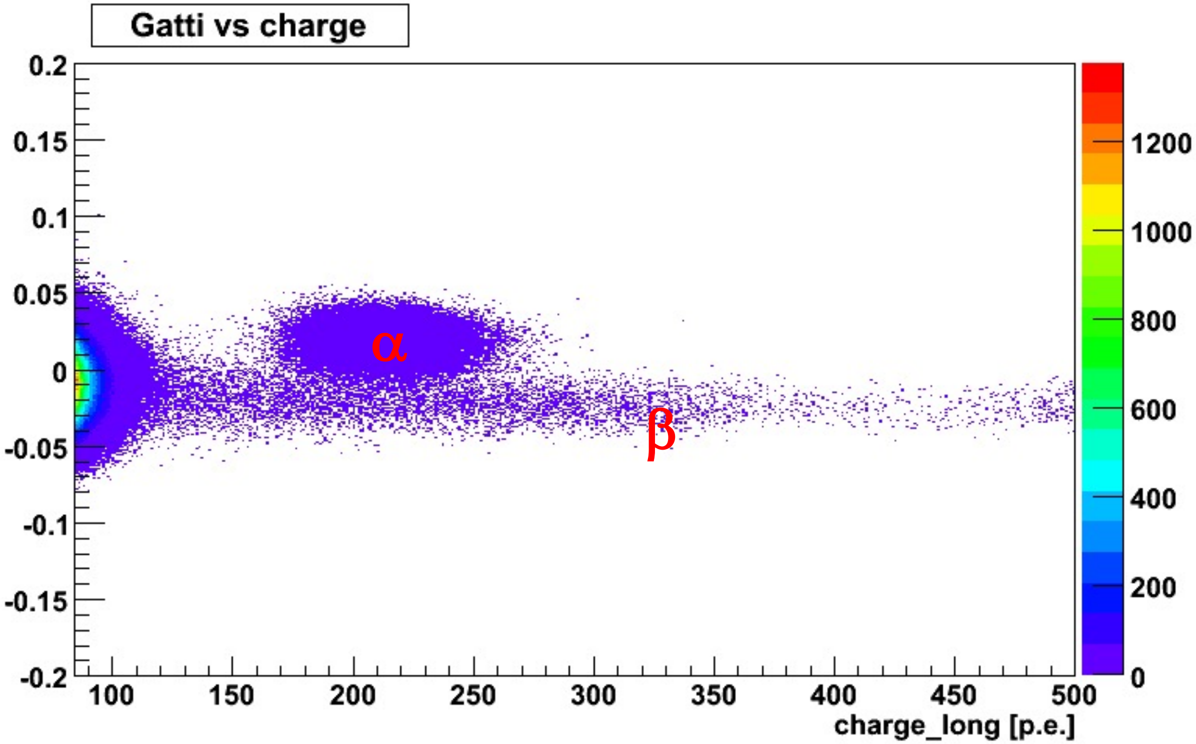
A_{BX} ~ 40 cpd/100ton in ^{7}Be ROI

A_{BX} ~ 5×10^{-9} Bq/kg

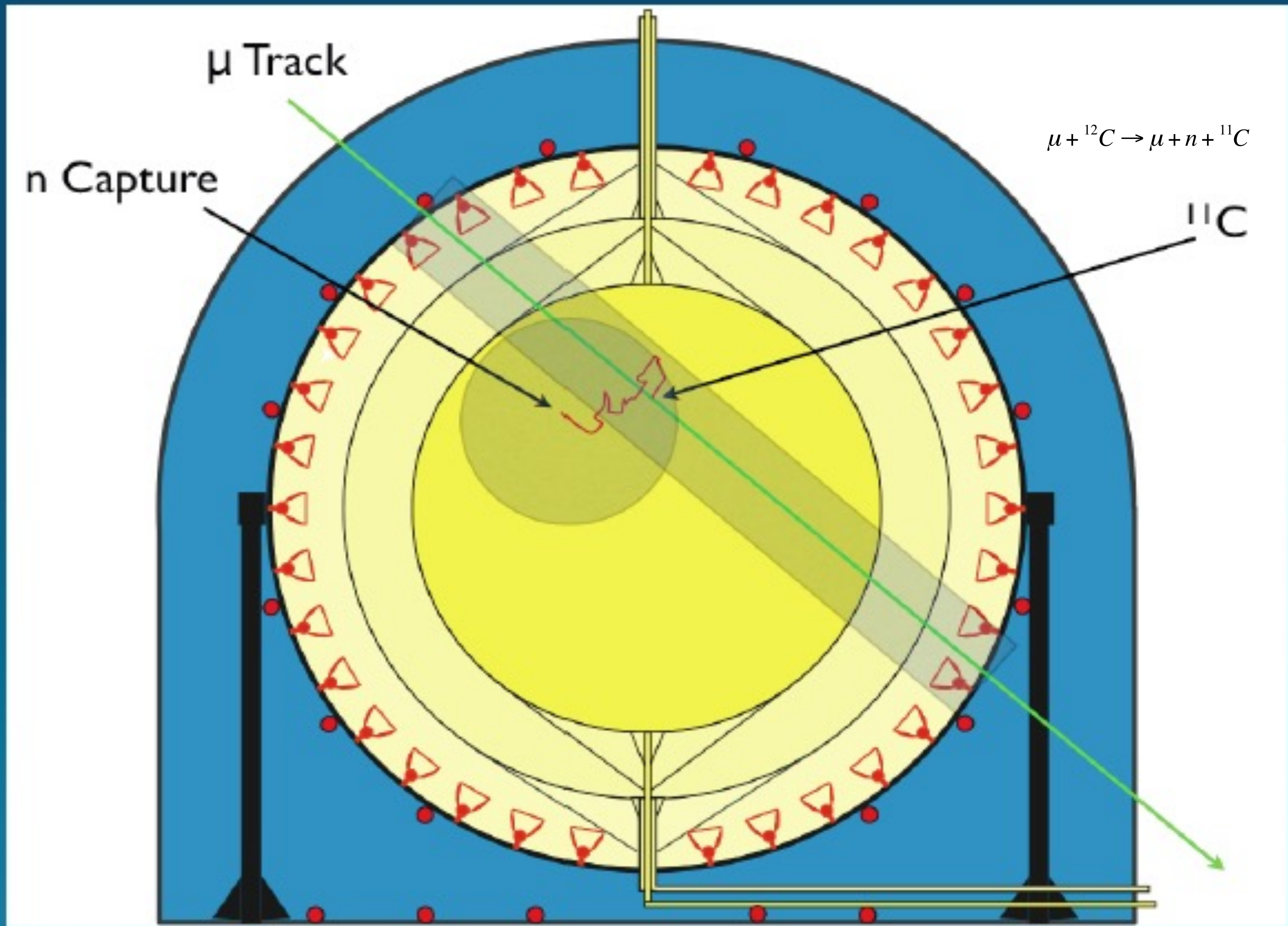
The β-like energy spectrum



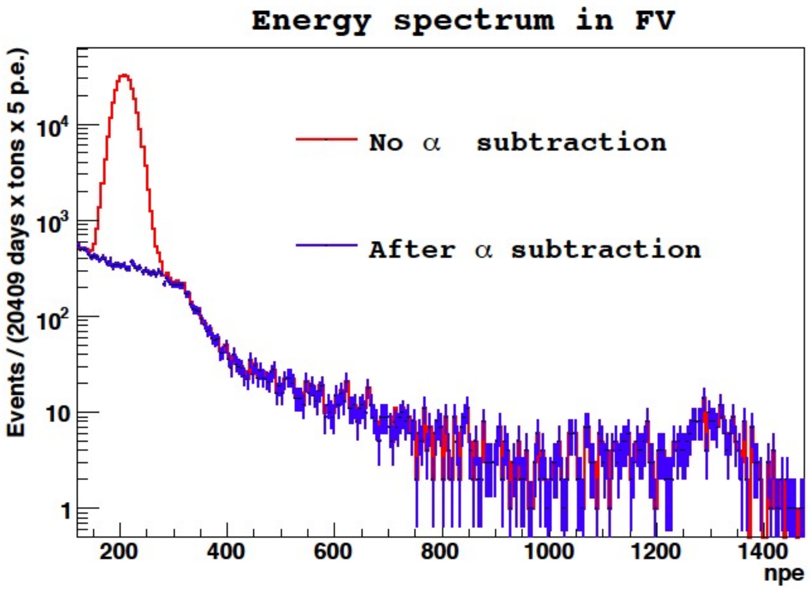
Pulse Shape Discrimination

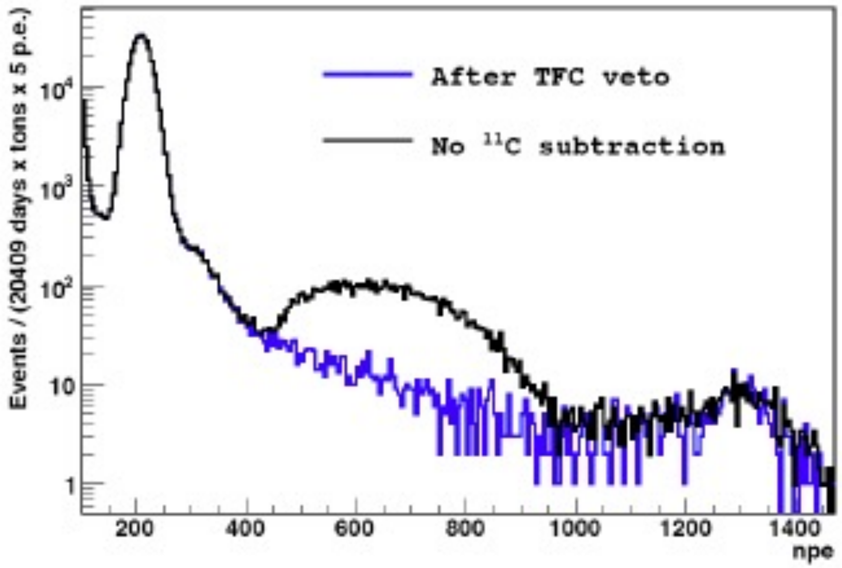


Tagging and removing ^{11}C cosmogenic background



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





Background from nylon vessel

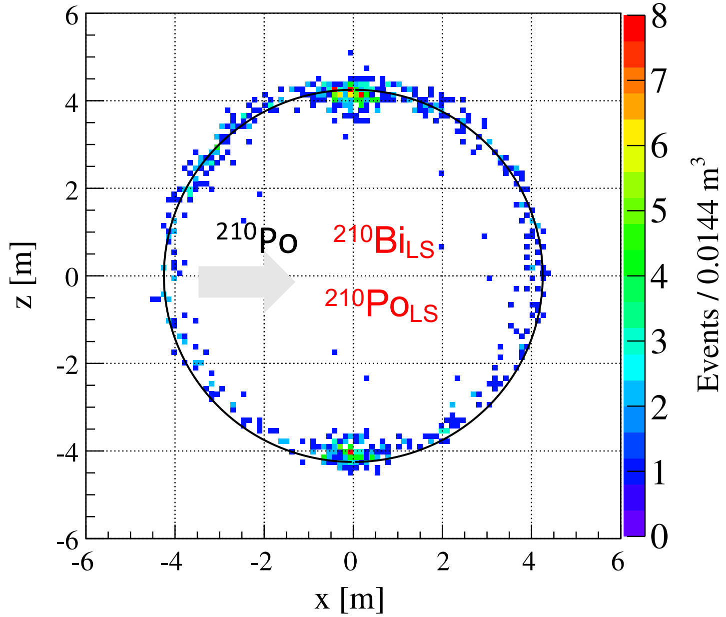
Convective currents can carry radioactive isotopes from the nylon vessel into the Fiducial Mass

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

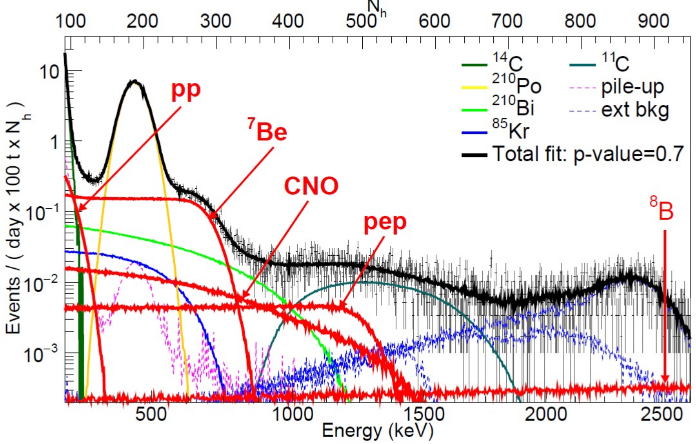
^{210}Po in LS has two components:

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

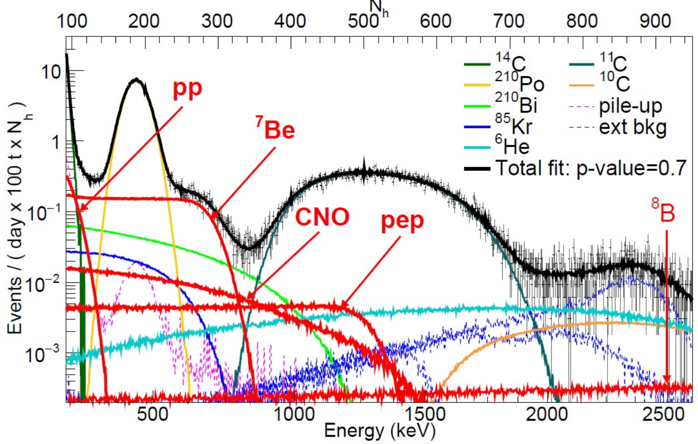


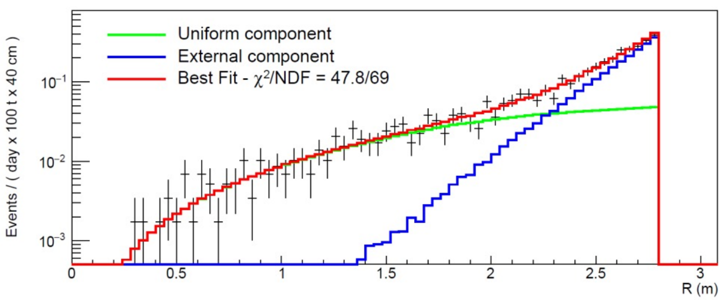
Multivariate fit example

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

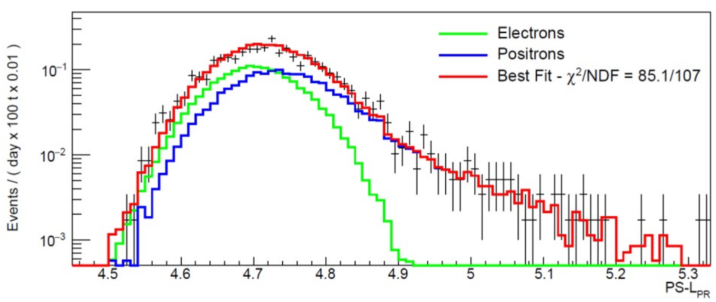


L($^{11}C_{tag}$)





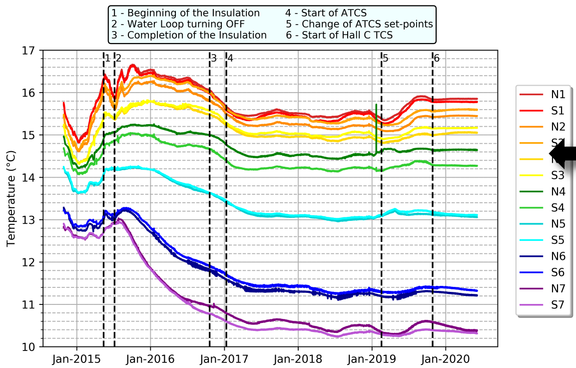
L(Rad)



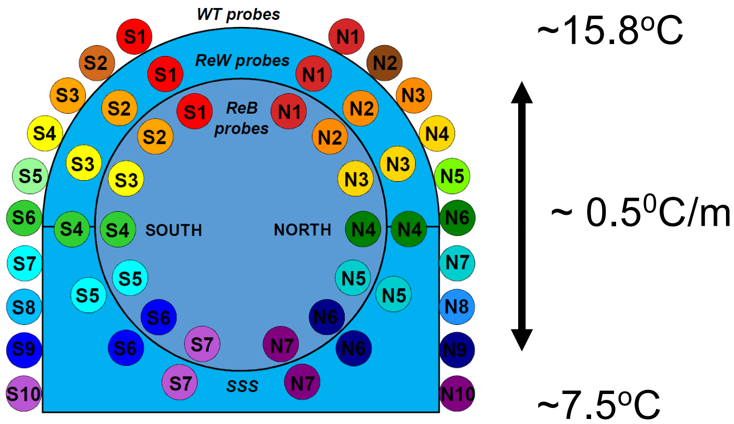
L(PS)

Thermal insulation and temperature control

Borexino Water Tank with insulation



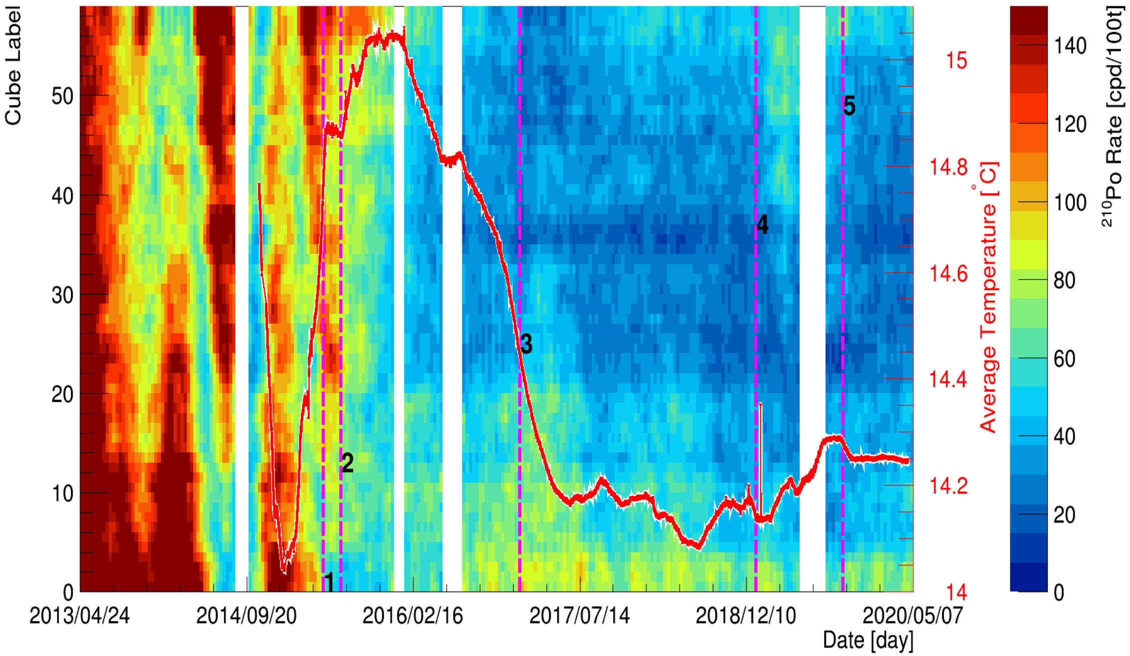
Deployment of T probes



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



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

- ^{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

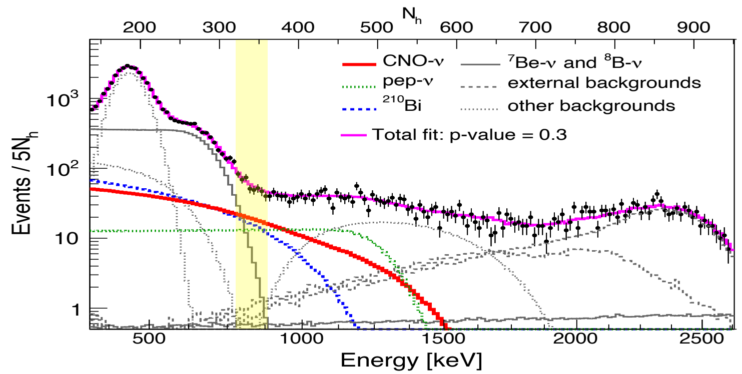
CNO solar neutrinos

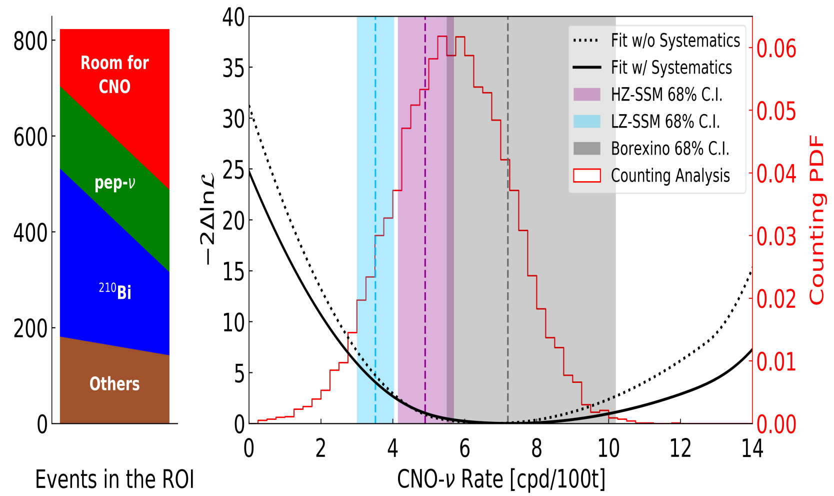
- Expected CNO rate: 3 – 5 cpd/100ton
- main background ^{210}Bi
  - constraint from ^{210}Po
  - study uniformity and stability
  - **R(^{210}Bi)≤11.5±1.3 cpd/100ton**

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

- Expected S/B ~ 0.2 – 0.3

$\phi_{CNO} = 6.6^{+2.0}_{-0.9} \times 10^{8}\ \mathrm{cm^{-2}s^{-1}}$





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)	$4.88(1\pm0.11)\times10^{8}$	$3.51(1\pm0.10)\times10^{8}$	$6.6^{+2.0}_{-0.9}\times10^{8}$
p-value (pp, Be, B)	0.96	0.43	

CNO luminosity from Borexino

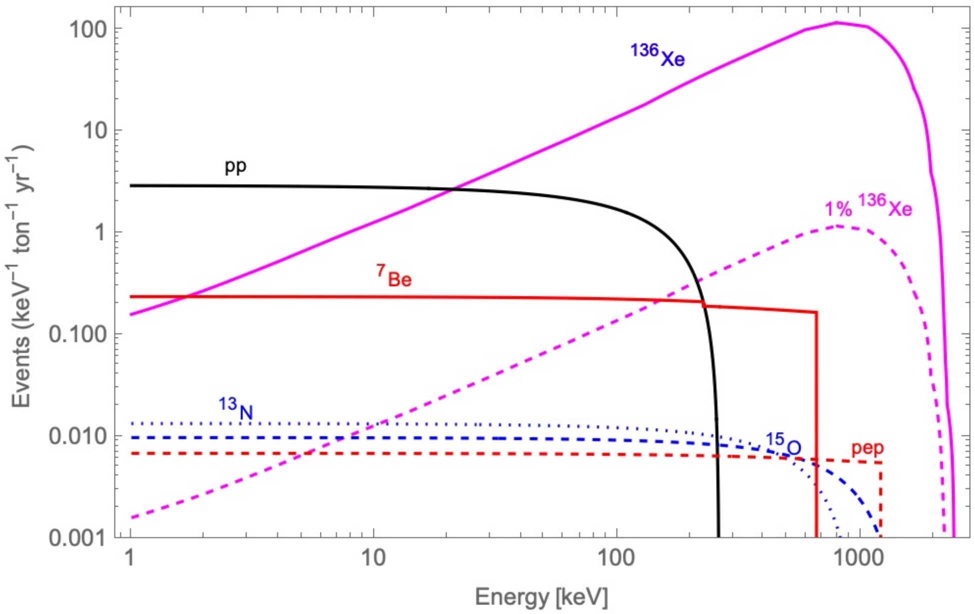
- Luminosity constraint: $\frac{L_{\odot}}{4\pi A.U.^2} = \sum_i \alpha_i \phi_i$
- In the assumption of luminosity constraint:

$$\frac{L_{CNO}}{L_{\odot}} = \phi_{CNO}^{BX} \sum_{i=\{N,O,F\}} \alpha_i f_i = 1.0^{+0.4}_{-0.3}\ \%$$

- α_i taken from F. Vissani, 2020

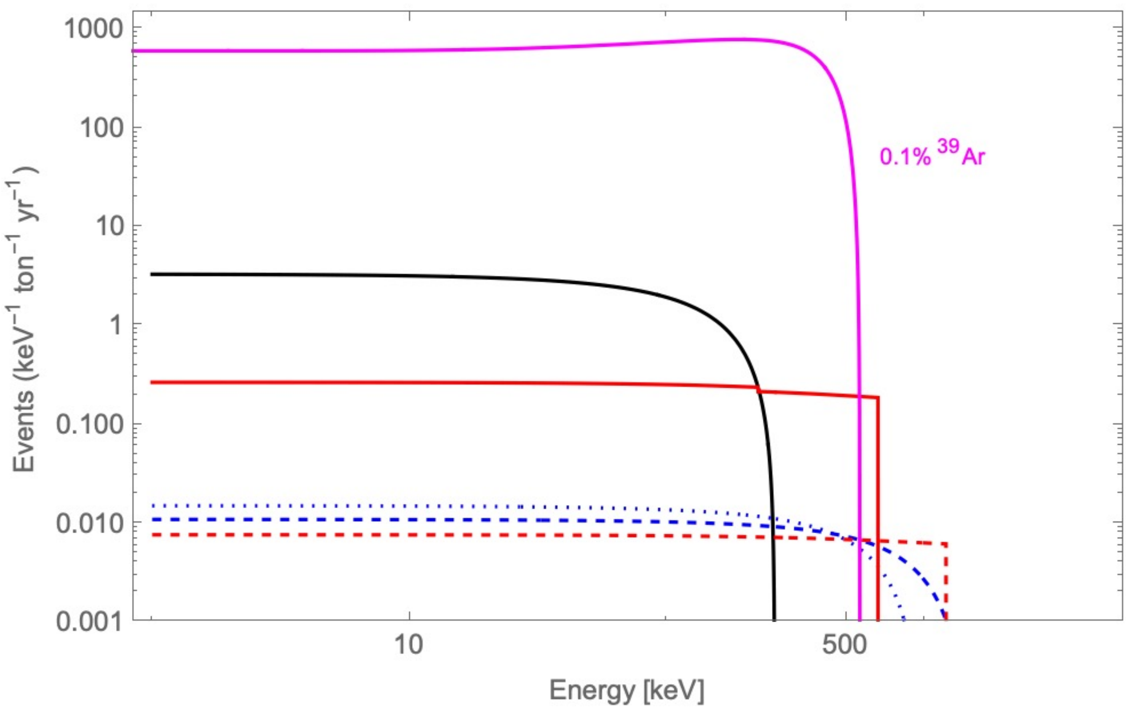
- Borexino has proven CNO is at work in the Sun as predicted by SSM, only metallicity is still unknown

Solar neutrinos in LXe



- pp neutrinos in [1,10] keV ~ 26/ton/yr
- ~2% stat in 100 ton x year
- Sensitivity to CNO and pep neutrinos limited by ^{136}Xe
- Possible 3σ CNO neutrinos measurement with x1000 reduction of ^{136}Xe and 1000 ton x year
- In LAr ^{39}Ar plays a role similar to ^{136}Xe but at low energy, Q_β = 0.565 MeV

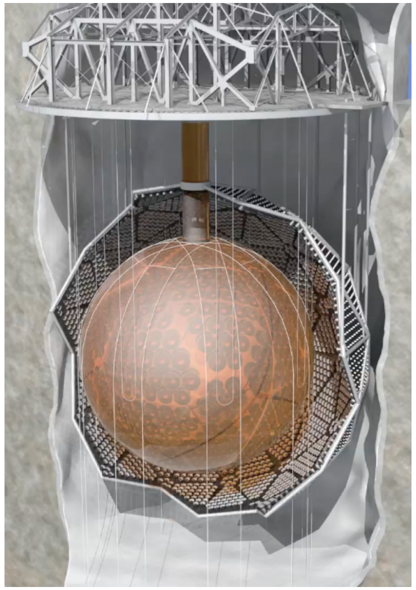
Solar neutrinos in LAr



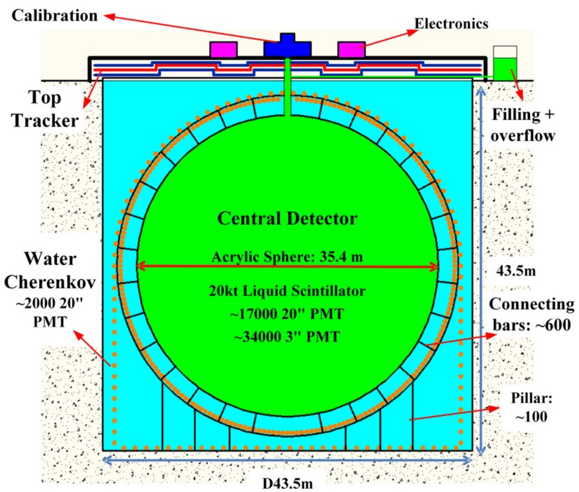
For E > Q_β pep ~ 5% and CNO ~6% stat in 100 ton x year

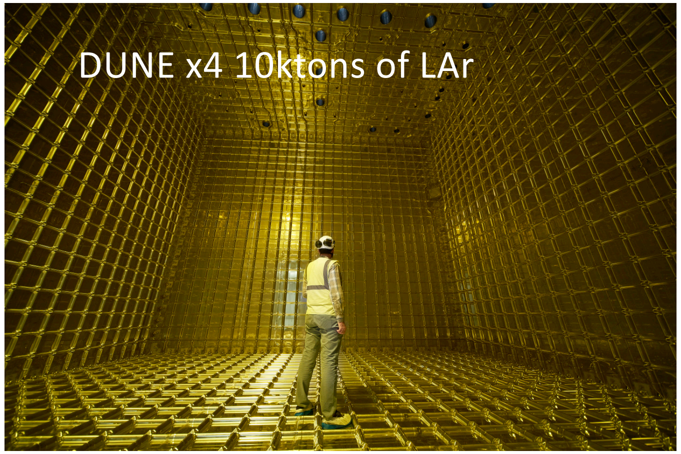
Next future for solar neutrino detection

SNO+ 780 tons of LAB

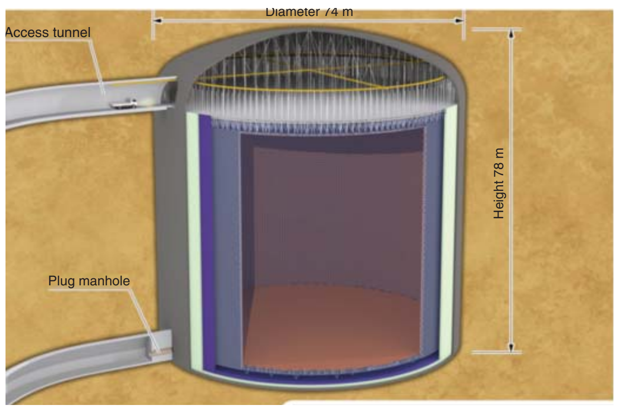


JUNO 20 ktons of LAB



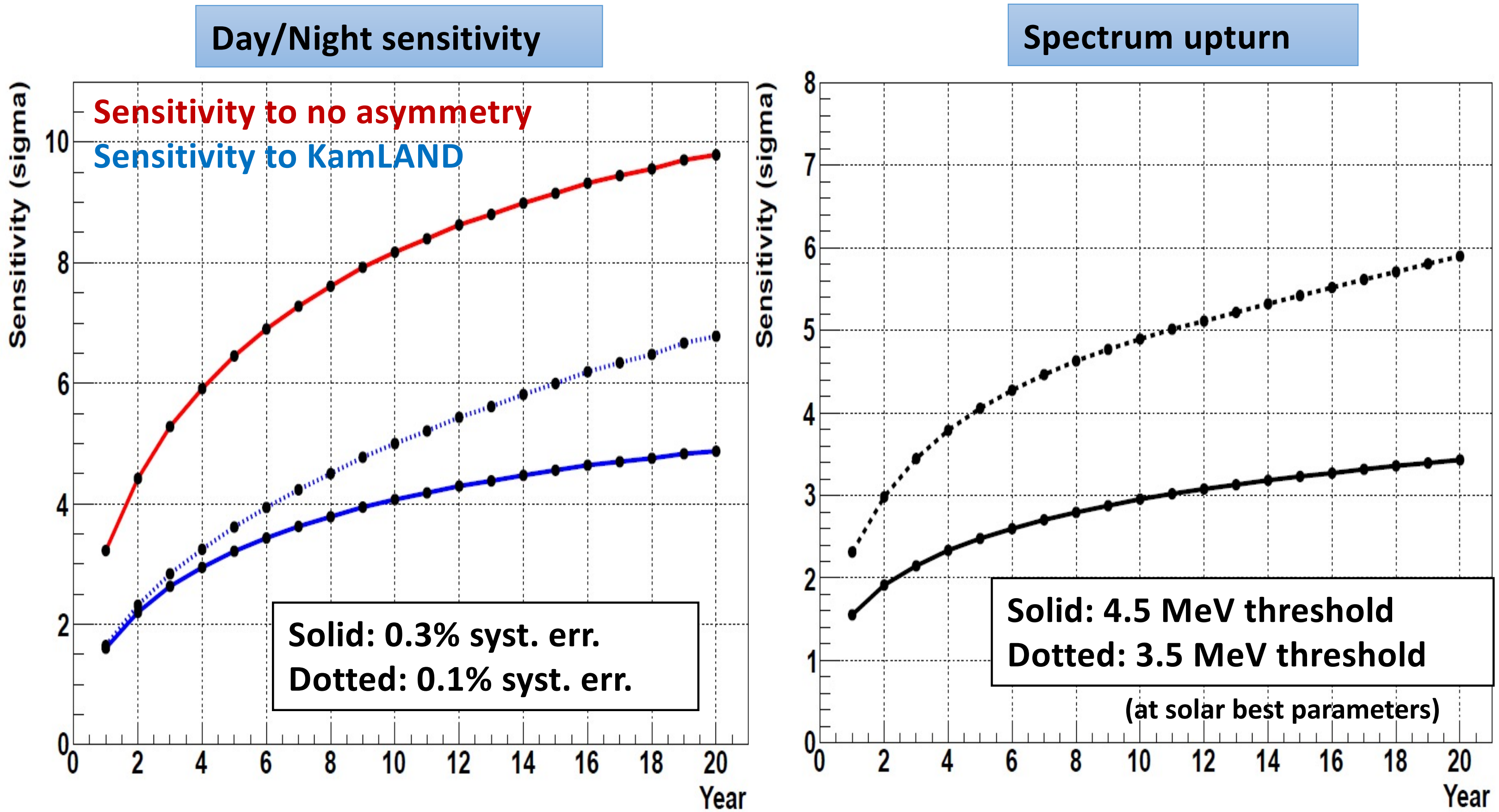

DUNE x4 10ktons of LAr

HyperKamiokande 187kton H_2O FM



$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$$

Solar neutrino measurements in HK

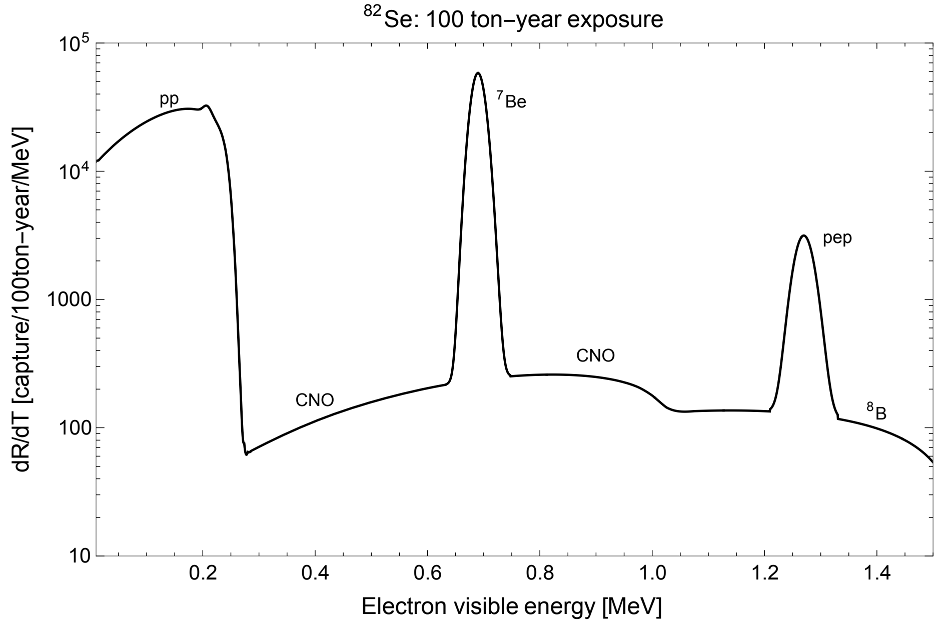


- Day/Night (solar vs reactor): 4~5 sigma in 10 years
- Spectrum upturn: ~3 sigma in 10 years

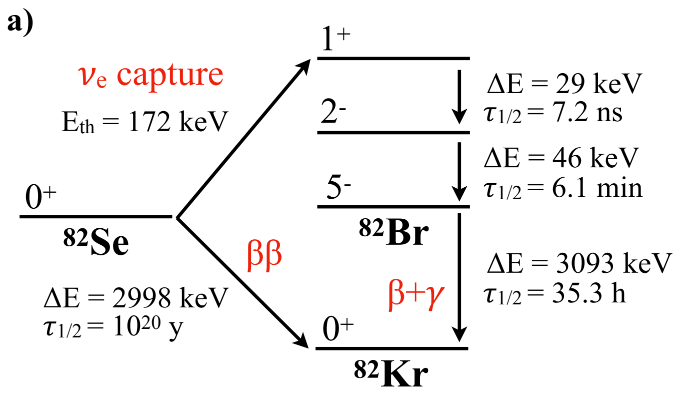
Adapted from M. Shizowa

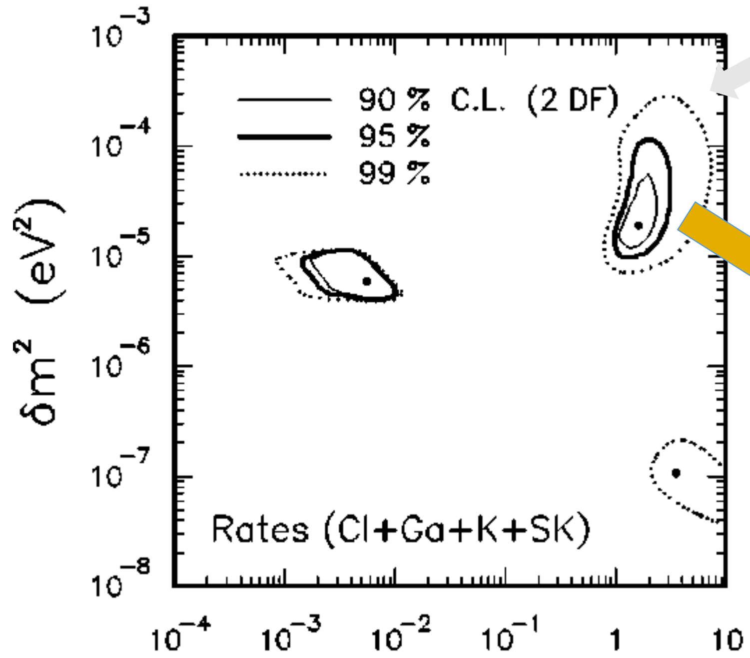
The Selena proposal

Selenium deposited on a CMOS active pixel charge sensor



Species	E range [keV]	N in 100 ton-year	$1/\sqrt{N}$
pp	29–278	5359	1.4%
^{7}Be	665–775	1814	2.3%
pep	1230–1360	130	8.8%
CNO	278–655, 785–1220	136	8.6%
^{8}B	$(1.5\text{-}15)\times10^3$	209	6.9%



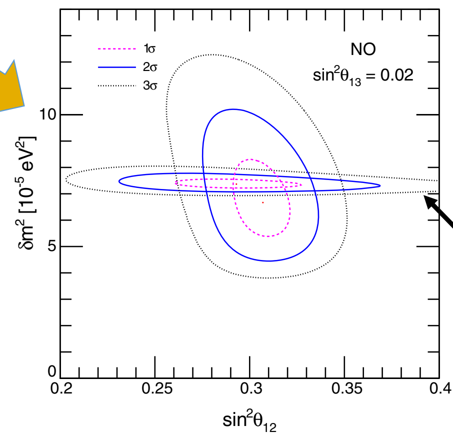


PRD 62.013002(2000)

SuperKamiokande: since 1996

SNO from 1999 to 2006

21 years later



KamLAND

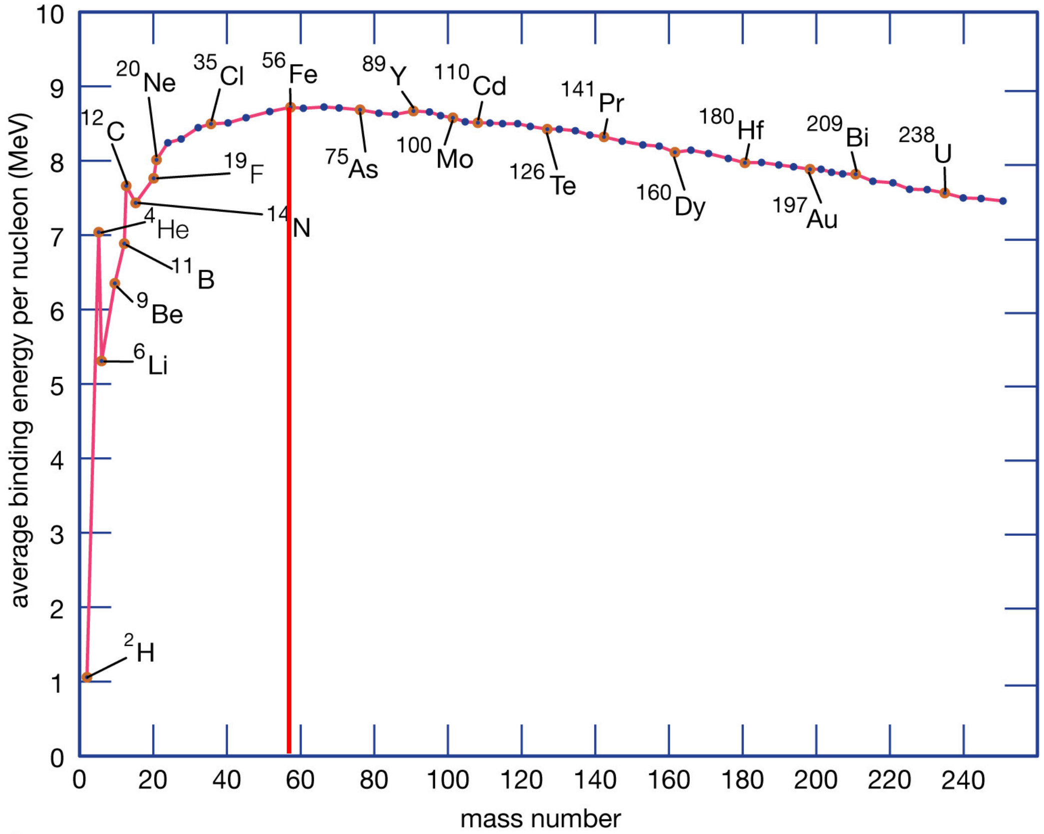
PRD 104.083031(2021)

Detection of neutrinos from a core collapse supernova

Nucleon binding energy

- On average $\varepsilon_N \sim 8$ MeV/nucleon
- Maximum for ^{56}Fe
- Short range interaction
  - Binding energy ~ 8A
  - Not ~ A(A-1) ~ A^2

- A massive start (>$10M_{sun}$) burns silicon at T~$4x10^9$ K (0.3 MeV) and make iron
- No other fusion process is possible
- When the iron core exceeds $1.4M_{sun}$ gravity is no longer sustained by internal pressure

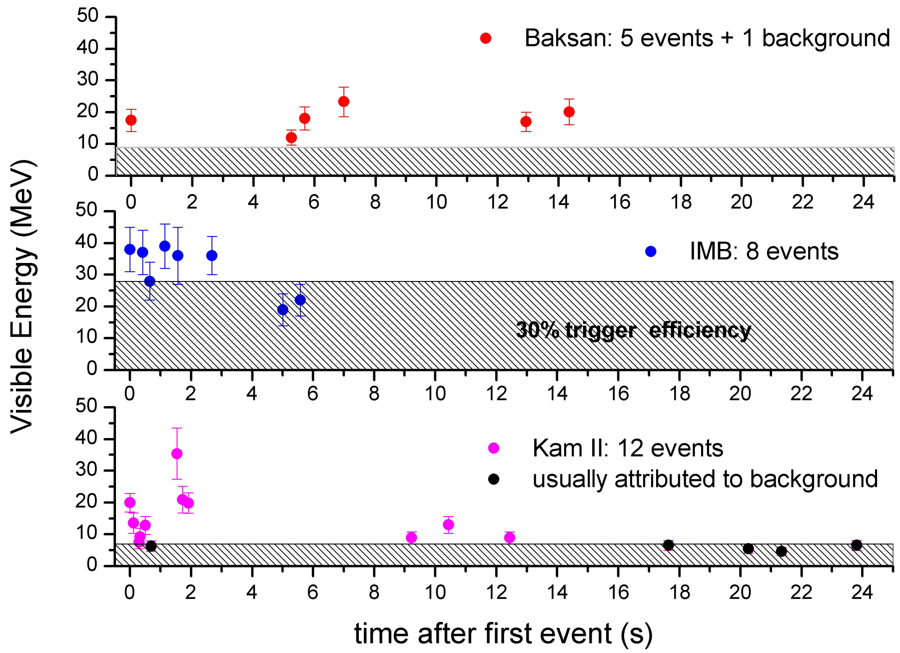


General picture

- Internal pressure cannot balance gravity, the core shrinks and becomes hotter
- Whent the temperature reaches 10^{10}K, photons in the tail of the distributin have enough energy to rip nuclei apart
  - The fusion nucleosynthesis is undone
- Photodisintegration of iron nuclei takes a lot of energy and boost the collapse
- At the onset of the gravitational collapse neutrinos are produced through: $e^- + p \rightarrow \nu_e + n$
  - This process follows the photodisintegration of Fe, reduces the number of e^-, reducing the electron pressure and boosting the collapse
  - When $\rho > 10^{11}$ g/cm^3 neutrinos are trapped in the so-called neutrino sphere (NS)
  - When the inner core reaches 3×10^{14} g/cm^3 and falling matter bounce back propagating through the NS increasing e+p capture and ν_e production (deleptonisation burst)
  - The NS sphere heated by the shock wave emits a neutrino burst from $\gamma \leftrightarrow e^- + e^+ \leftrightarrow \bar{\nu} + \nu$
- Free-fall time from 10^9 g/cm^3 < 0.1 s
- The collapse is supposed to end to a neutron start with M ~ $1.5M_{sun}$ and R~15km
- The energy is released by neutrinos streaming away
- Electron neutrinos and electron anti-neutrinos have larger opacity due to CC interactions: $\nu_e + n \rightarrow e^- + p$, $\bar{\nu}_e + p \rightarrow e^+ + n$
- We expect: $\langle E_{\nu_e} \rangle \leq \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_x} \rangle$
- Neutrino diffusion time ~ 1sec with $\lambda \sim 2$m due neutrino-nucleon interaction

SN1987A: 1st SN ν observation

- 23rd Feb 1987
- ~ 50 kpc
- Only 29 events
  - 16 Kamiokande (Cherenkov)
  - 8 IMB (Cherenkov)
  - 5 Baksan (LS)



Neutrino energy and luminosity

- Neutrino emission time: τ ~ 10 sec
- SN binding energy: $E_b = \frac{3}{5} G \frac{M^2}{R} = 1.6 \cdot 10^{53} erg \left(\frac{M}{M_{sun}}\right)^2 \left(\frac{10km}{R}\right)$
- Considering a mass at $\rho > 10^{11}$ g/cm^3 where neutrinos are trapped (neutrino sphere): energy/time = $4\pi R^2 \sigma T^4 (7/8)(g_\nu/2) \sim 2.4\text{x}10^{52}$ erg
- T = $6\text{x}10^{10}$K and E_ν=3.15T = 16 MeV
- $L_\nu = \frac{E_b}{E_\nu} \sim 10^{57}$ s^{-1}
- Compare with solar neutrino luminosity = $2\text{x}10^{38}$ s^{-1}

Estimation of the binding energy and neutrino energy from SN1987A

- Consider:
  - 12 neutrino observed in Kamiokande in 10^3 tons of water
  - $<E_\nu>$ ~ 10 MeV

$$12 = N_{\text{target}} \cdot F_\nu \cdot \sigma$$

$$\sigma \approx 9.3 \cdot 10^{-42}\ \text{cm}^2$$

$$N_{\text{target}} = 6.7 \cdot 10^{31}$$

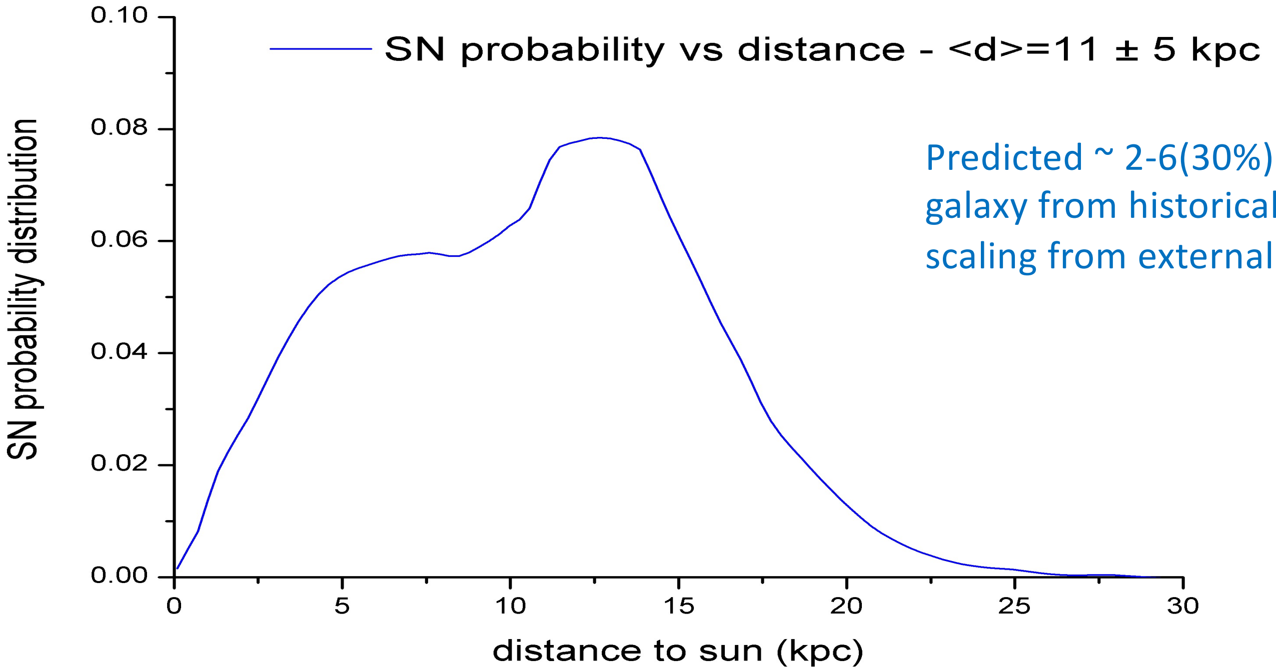
$$N_\nu = F_\nu \left(4\pi D^2\right) = 5.7 \cdot 10^{57}\ \bar{\nu}_e$$

$$E_b = \langle E_\nu \rangle N_\nu = 5.7 \cdot 10^{58}\ \text{MeV} \approx 10^{53}\ \text{ergs for } \bar{\nu}_e$$

Expected

$$\boxed{E_B \equiv \Delta E \approx \frac{3}{5} G \frac{M_{NS}^2}{R_{NS}} \sim 2 \cdot 10^{53} erg \left(\frac{M_{NS}}{M_{Sun}}\right)^2 \left(\frac{10 km}{R_{NS}}\right)}$$

Probability of a galactic SN vs distance to the Sun



Predicted ~ 2-6(30%) SN/100yr in our MW galaxy from historical galactic SN and scaling from external galaxies

Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006)

The SuperNova model

$$F^0_{\nu_i}(E_\nu) = \frac{Es}{4\pi d^2}\left(\frac{E_\nu}{E_{0,i}}\right)^\alpha \frac{(\alpha+1)^{\alpha+2}}{E_{0,i}^2}\frac{e^{-(\alpha+1)E/E_{0,i}}}{\Gamma(\alpha+2)}\ \mathrm{cm}^{-2}\mathrm{MeV}^{-1}$$

$$E_{0,i} = T_i(\alpha+1)$$

$$\alpha = 3$$

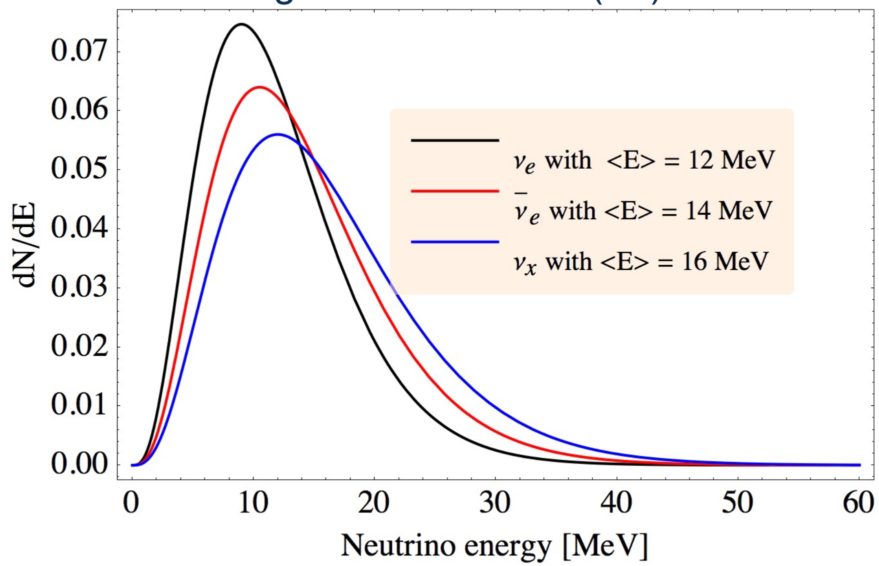
$$d = 10\ \mathrm{kpc}$$

$$\sum_i 4\pi d^2 \int dE_\nu E_\nu F_{\nu_i}(E_\nu) = 3\cdot 10^{53}\ \mathrm{erg}$$

$$\mathrm{N}_{\nu,i} = 4\pi d^2 \int dE_\nu F_{\nu_i}(E_\nu) = \begin{array}{l} N_{\nu_e} = 2.6\cdot 10^{57} \\ N_{\bar{\nu}_e} = 2.2\cdot 10^{57} \\ N_{\nu_x} = 7.8\cdot 10^{57} \end{array}$$

$$F_\nu^{Tot} = 1.1\cdot 10^{12}\ \mathrm{cm}^{-2}$$

SN Signal duration ~ O(10) s



Average energy expected to change as:

ν_e : ~12-14 MeV

bar-ν_e : ~14-16 MeV

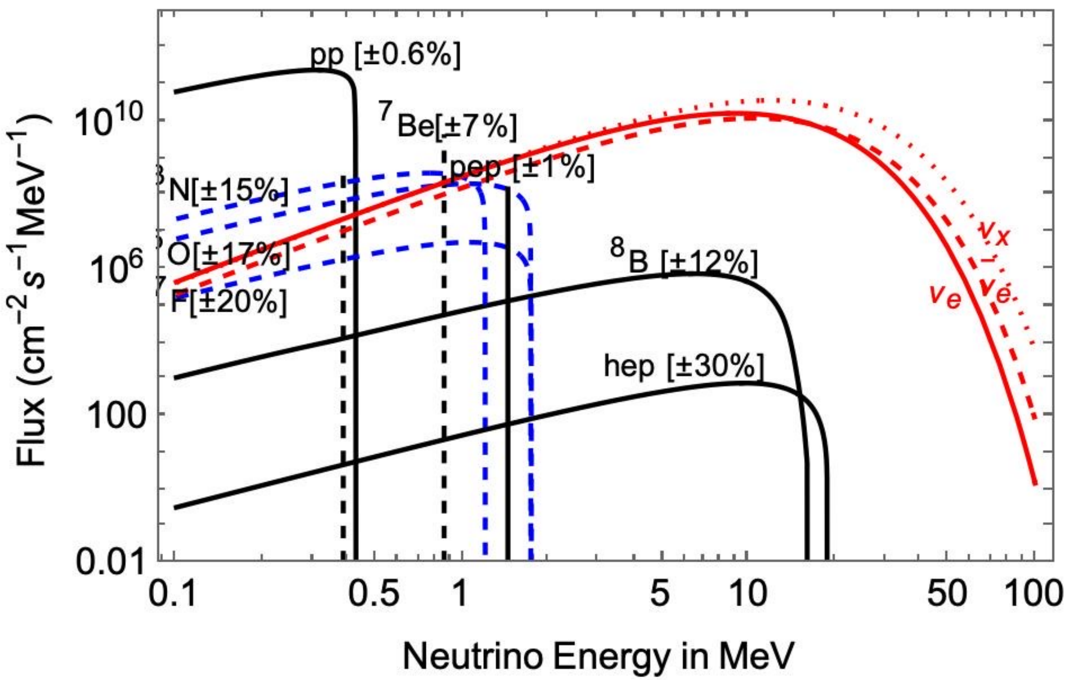
ν_x : ~14-16 MeV

A. Summa et al. Astrophys. J 825 (2016)

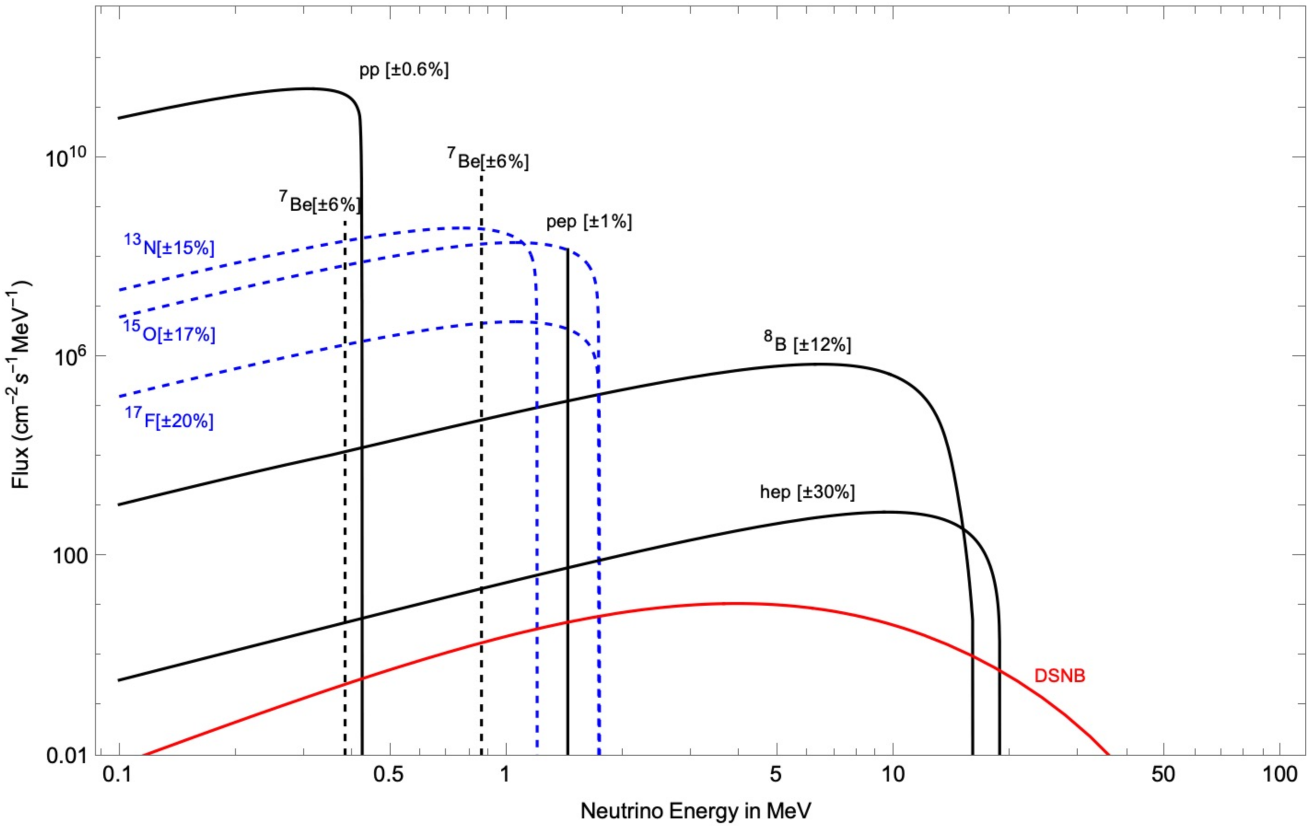
Expected signal

- Suppose a SN at 10 kpc
- Total fluence 10^{12} ν/cm^2
- Detector = 1kton water Cherenkov
- Detection channel: IBD and ES
- Expected events:
  - ES: $6\text{x}10^{32}$ $1.4\text{x}10^{-43}$ $4\text{x}10^{11}$+ $6\text{x}10^{32}$ $0.2\text{x}10^{-43}$ $6.5\text{x}10^{11}$ ~ 40
  - IBD: $6.7\text{x}10^{31}$ $1.6\text{x}10^{-41}$ $1.7\text{x}10^{11}$ ~ 180
- For SuperKamiokande FM of 22.5 kton implies order of 900 ES and 4000 IBD

10 sec snapshot



Neutrinos <100 MeV from outside the Earth



Effect of neutrino oscillations

- $\phi_{\nu_e} = P_{ee}\, \phi^0_{\nu_e} + (1 - P_{ee})\phi^0_{\nu_x}$
- $2\phi_{\nu_x} = (1 - P_{ee})\phi^0_{\nu_e} + (1 + P_{ee})\phi^0_{\nu_x}$
- $2\phi_{\nu_x} + \phi_{\nu_e} = 2\phi^0_{\nu_x} + \phi^0_{\nu_e}$

- Normal Ordering P_{ee} ~ 0.68 for electron anti-neutrinos, P_{ee} ~ 0.02 for electron neutrinos

Neutrino arrival time on Earth

A massive neutrino will experience a delay in the arrival time

$$\Delta t = \frac{D}{2c}\left(\frac{m_\nu c^2}{E_\nu}\right)^2 = 5.1ms\,\left(\frac{m_\nu c^2}{1\ eV}\right)^2\left(\frac{10\ MeV}{E_\nu}\right)^2$$

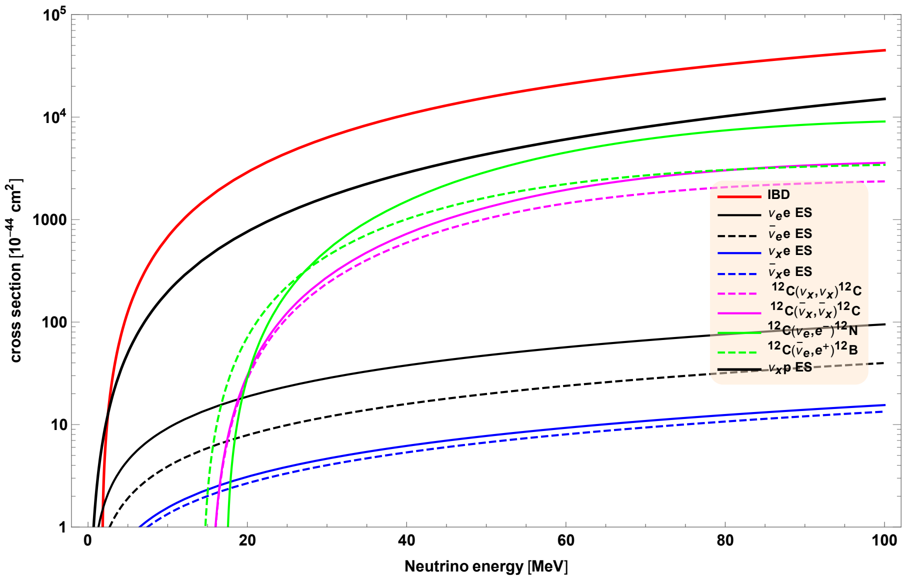
Looking at the arrival times of neutrinos with different energy one can establish a limit on the neutrino mass of order 20 eV

SN ν detection in liquid scintillator detectors

Interaction channels

- Neutrino-electron ES
- IBD above 1.806 MeV
- $^{2}C(\nu_x, \nu_x)^{12}C^*$, E_{th} = 15.11 MeV, all flavors
- $^{12}C(\text{anti-}\nu_e, e^+)^{12}B$, E_{th} = 14.39 MeV
- $^{12}C(\nu_e, e^-)^{12}N$, E_{th} = 17.34 MeV
- $\boldsymbol{\nu_x + p \rightarrow \nu_x + p}$, no threshold, all flavors

Interaction channel	Detection Threshold [MeV]	Expected average energy [MeV]	Number of events per kton w/o oscillations	Number of events per kton w/ oscillations
IDB	1.02	~20	193	202
ES	0.2	~7.5	16	16
$^{12}C(\text{anti-}n_e,e^+)^{12}B$	1.02	15	4.5	5.2
$^{12}C(n_e,e^-)^{12}N$	0.2	12	2.2	7.3
$^{12}C(n_x, n_x)^{12}C$	15.1	15.1	19	19
$n_x + p \rightarrow n_x + p$	0.2	0.4	90	90



Geochemical detection of SN neutrinos

- Haxton and Johnson in 1988 (Nature 333 (1988) 325–329
  - Recently re-considered in arXiv:0901.0581

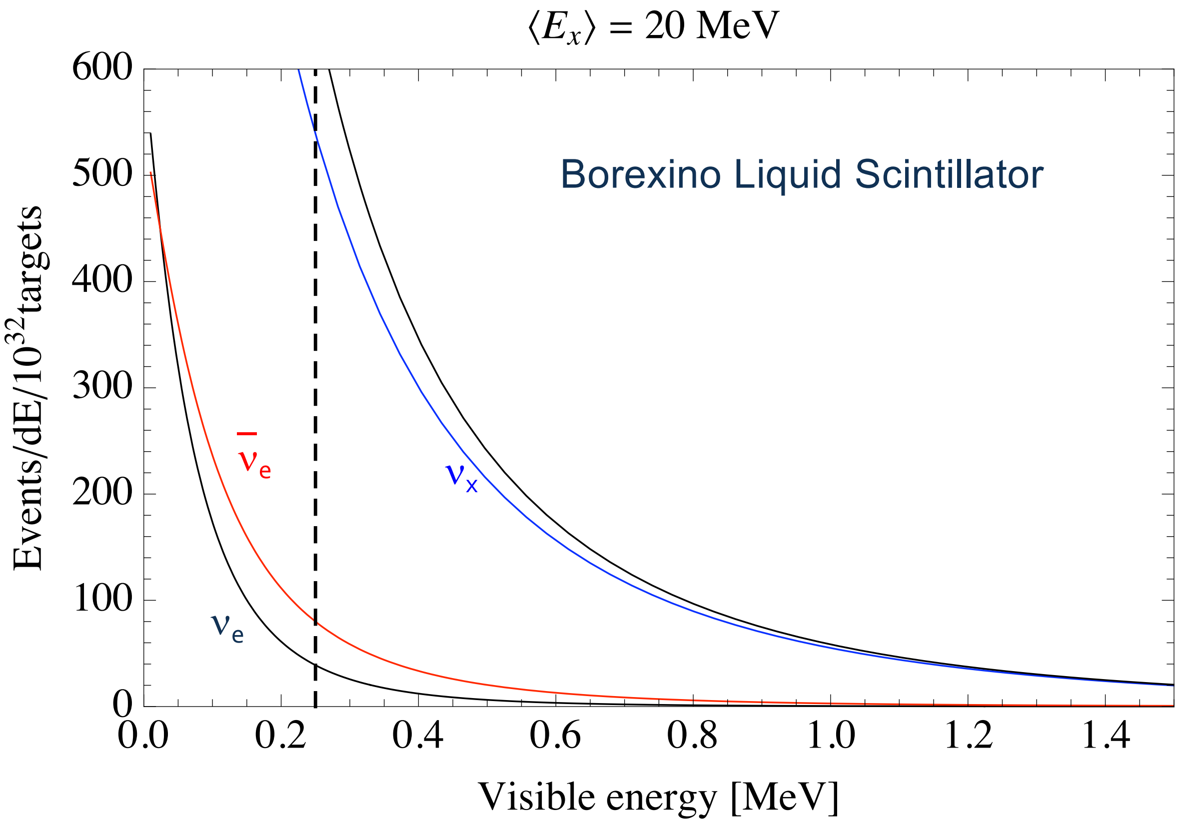
- Use ^{98}Mo and ^{97}Mo to detect SN neutrinos collected in a ore underground

- Half-lifes ~10^6 years eliminate the possibility of priomordial formation

- Any ^{98}Tc or ^{97}Tc found in the ore above the expected contrbution of solar neutrinos and cosmic rays is due to SN neutrinos

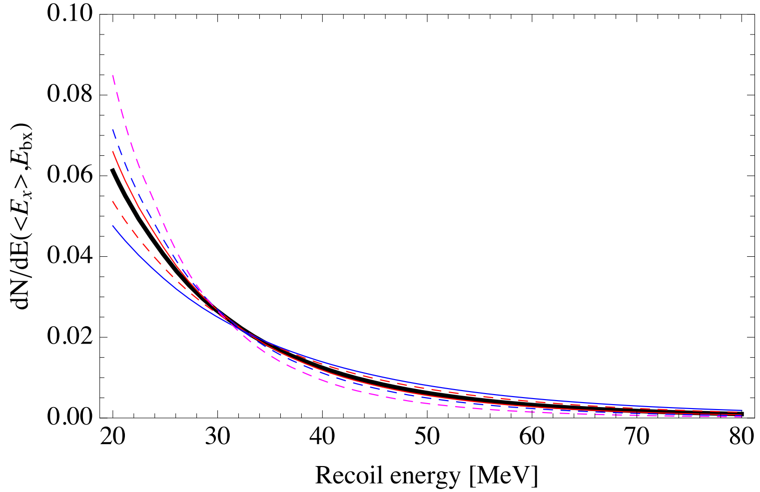
- Archeological signature from past galactic supernovae

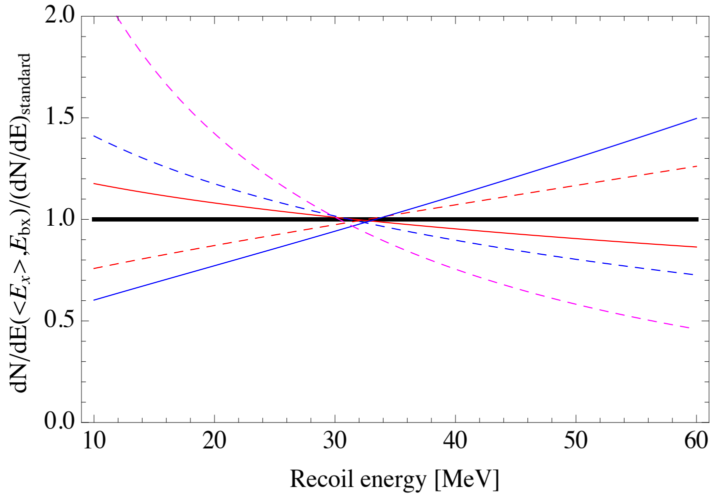
The SN neutrino spectrum in a Borexino-like detector for ν-p scattering



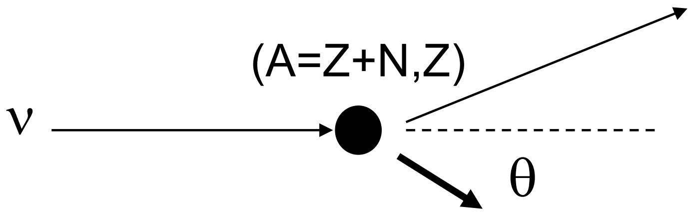
Breaking <E_x> and $E_{binding\_x}$ degeneracy

Reference SN: E_x=16 MeV; E_{b-x}=0.5x10^{52}erg (total energy is 10^{53} erg)
LAr with ROI = [20,80] keVr
Select different E_x and E_{bx} to give the same number of events above threshold
E_x changing from 12 to 20 MeV





Coherent neutrino-nucleus scattering



$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{ME_r}{2E_\nu^2}\right) F^2\left(Q^2\right)$$

$$Q^2 = 2E_\nu^2\left(1 - \cos\theta\right)$$

$$Q_W = \left(1 - 4\sin^2\theta_W\right) Z - N$$

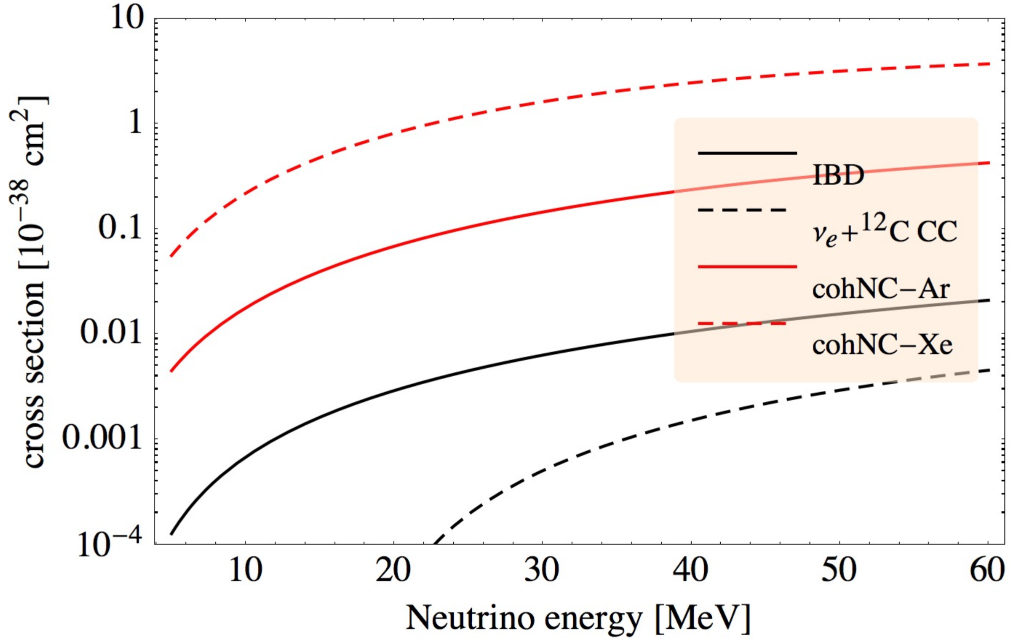
$$\sigma = \frac{G_F^2}{4\pi} Q_W^2 E_\nu^2 \approx 4.215\times10^{-45} Q_W^2 \left(\frac{E_\nu}{\mathrm{MeV}}\right)^2 \mathrm{cm}^2 \approx 4.215\times10^{-45} N^2 \left(\frac{E_\nu}{\mathrm{MeV}}\right)^2 \mathrm{cm}^2$$

Condition of coherence

$$Q\left(E_\nu\right)\cdot\left(r_0 A^{1/3}\right) \le 1$$

Supernova neutrinos in Dark Matter detectors for WIMPs

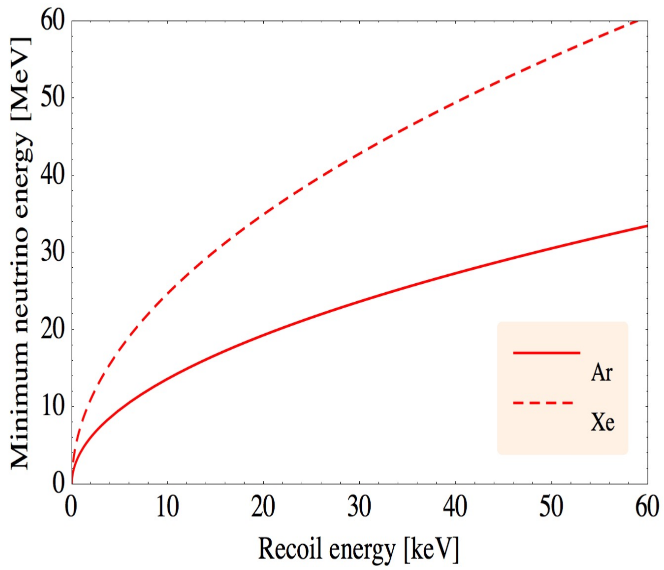
- ✓ Detectors designed
  - to detect low energy nuclear recoils (< 100 keV)
  - to have high discrimination power between Electron Recoils (ER) and Nuclear Recoils (NR)
  - to have intrinsic low background due to the radio-purity of selected detector components
  - To have good fiducial mass determination
- ✓ Look ideal for cohNS measurement and SN neutrino observation



SN signal in Ar and Xe

$$\frac{dN}{dE_r} = C \int_{E_{\min}(E_r)}^{\infty} dE_r \frac{d\sigma}{dE_r}(E_\nu, E_r) \sum_{i=\nu_e,\bar{\nu}_e,4\nu_x} F^0_{\nu_i}(E_\nu)$$

Threshold [keV]	Ar [events/ton]	Xe [events/ton]
0	7.4 ±20%	26.2 ±20%
5	3.9	4.0
10	2.3	1.0
20	1.0	0.09



Why solar neutrinos in the future?

- **Particle physics**
  - Measurement of expected matter-vacuum upturn
  - Measurement of day-night asymmetry

- **Astrophysics**
  - Solve the *solar abundance problem* by detecting CNO neutrinos
  - Use solar neutrinos to better understand the Sun (*inverse problem*)

Conclusions

- 55 years of solar neutrino observations
- Fundamental results on neutrino physics and astrophysics
- More to come with SuperKamiokande
- Future observations with SNO+, HyperKamiokande, DUNE, and JUNO
- Observation of solar neutrinos with dark matter detectors

Thank you!