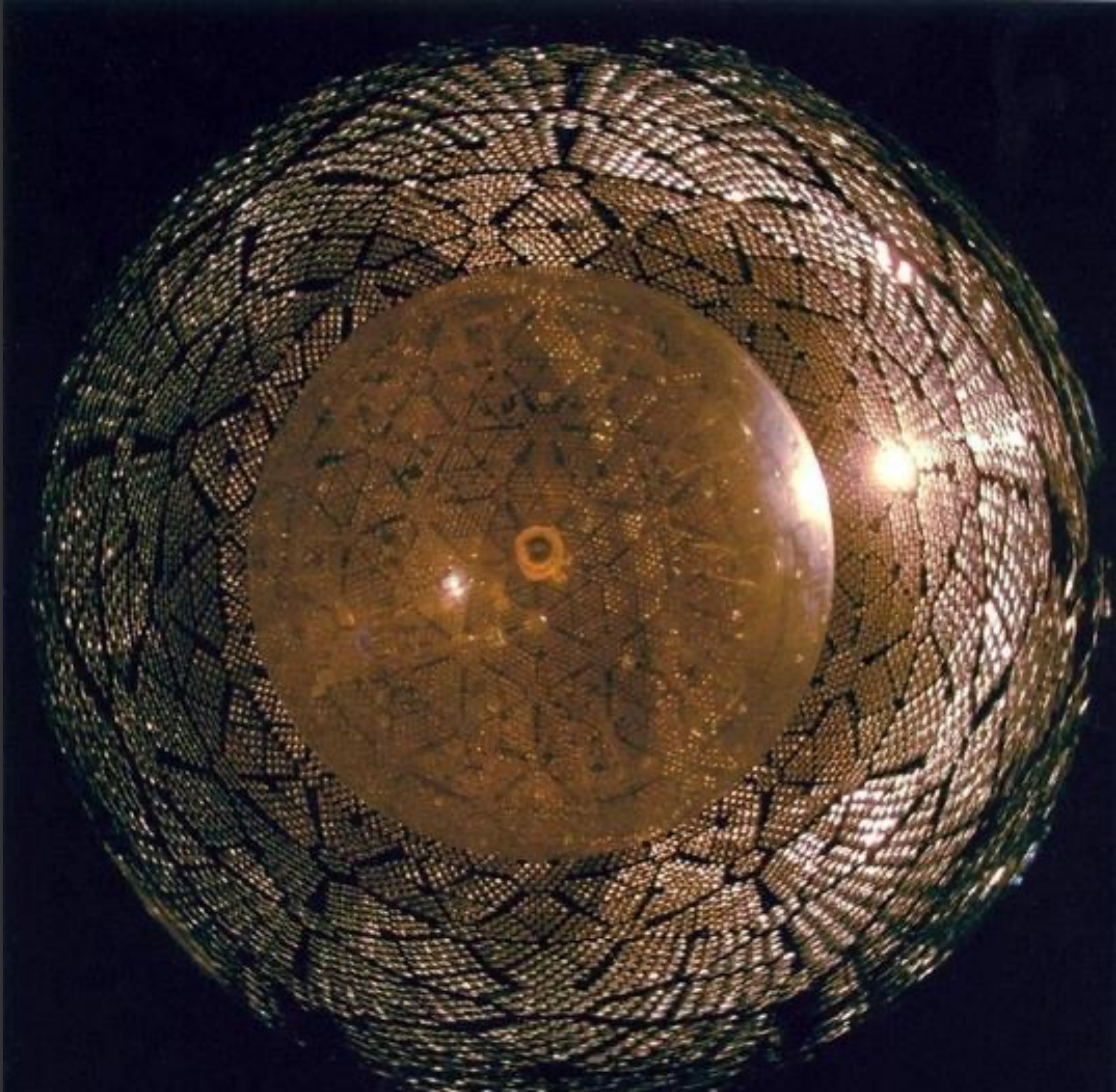
The Solar Neutrino Puzzle

Art McDonald, Gray Chair Emeritus, Queen’s University

John Learned’s 85th Birthday

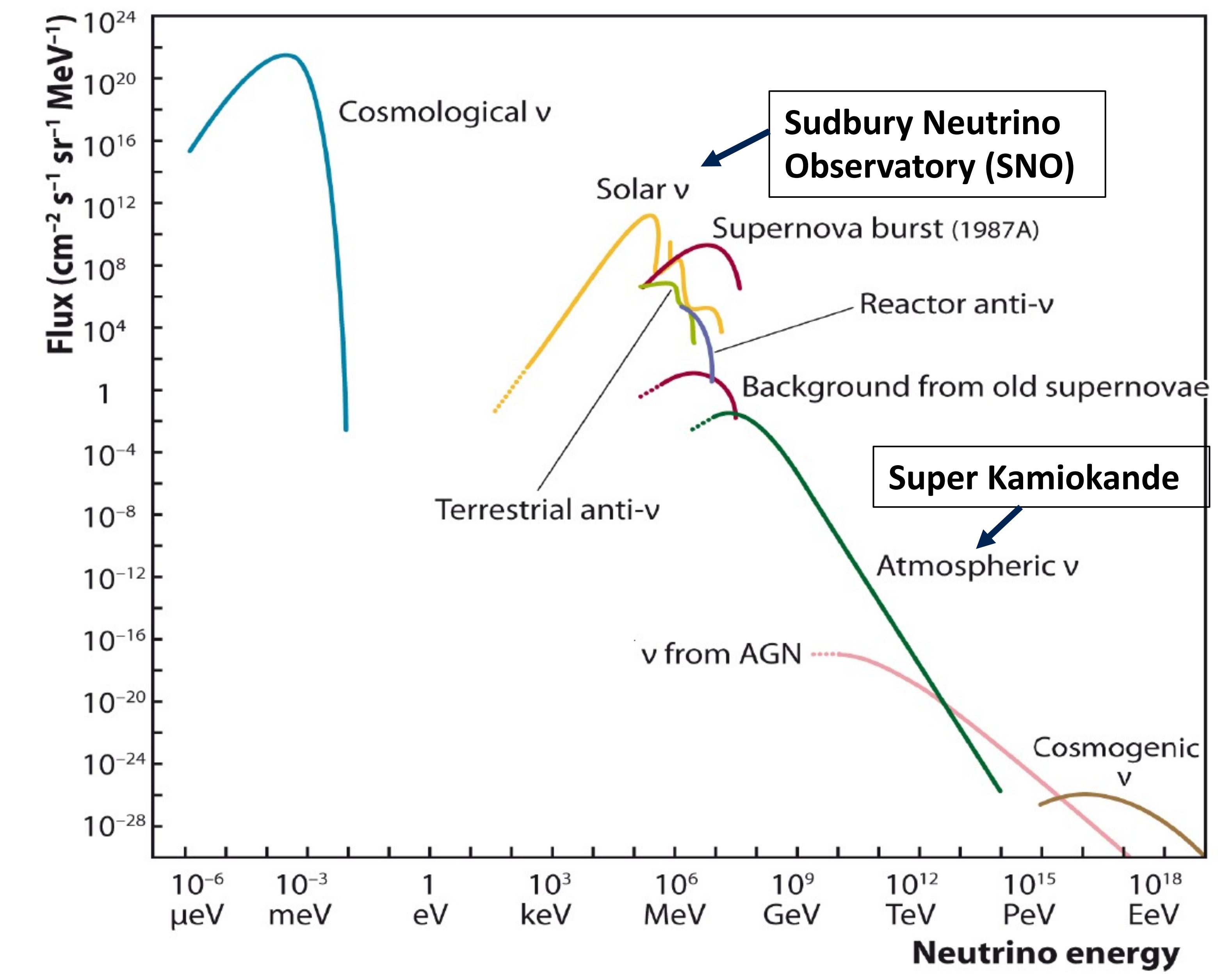
University of Hawaii

April 29, 2025



Nobel Week in Stockholm with our good friends Professor John Learned and his wife Colleen.

Neutrinos reaching the Earth



Homestake Gold Mine

100,000 gallons of cleaning fluid C_2Cl_4

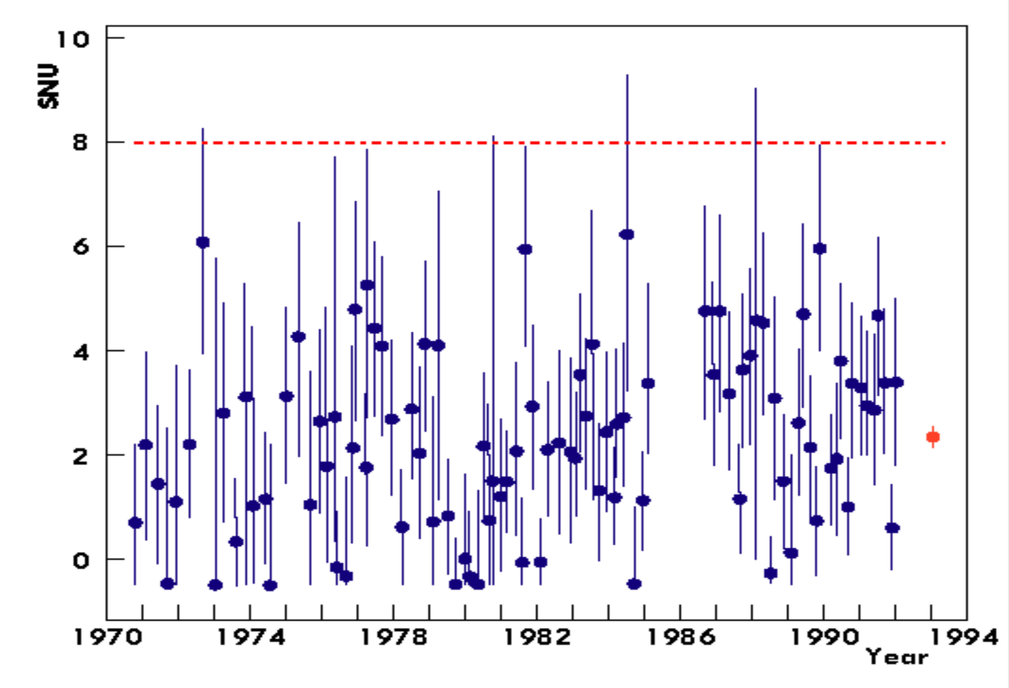
Expected 1.5 interactions per day
Measured 0.5 interactions per day

Sensitive to ^{8}B solar neutrinos only

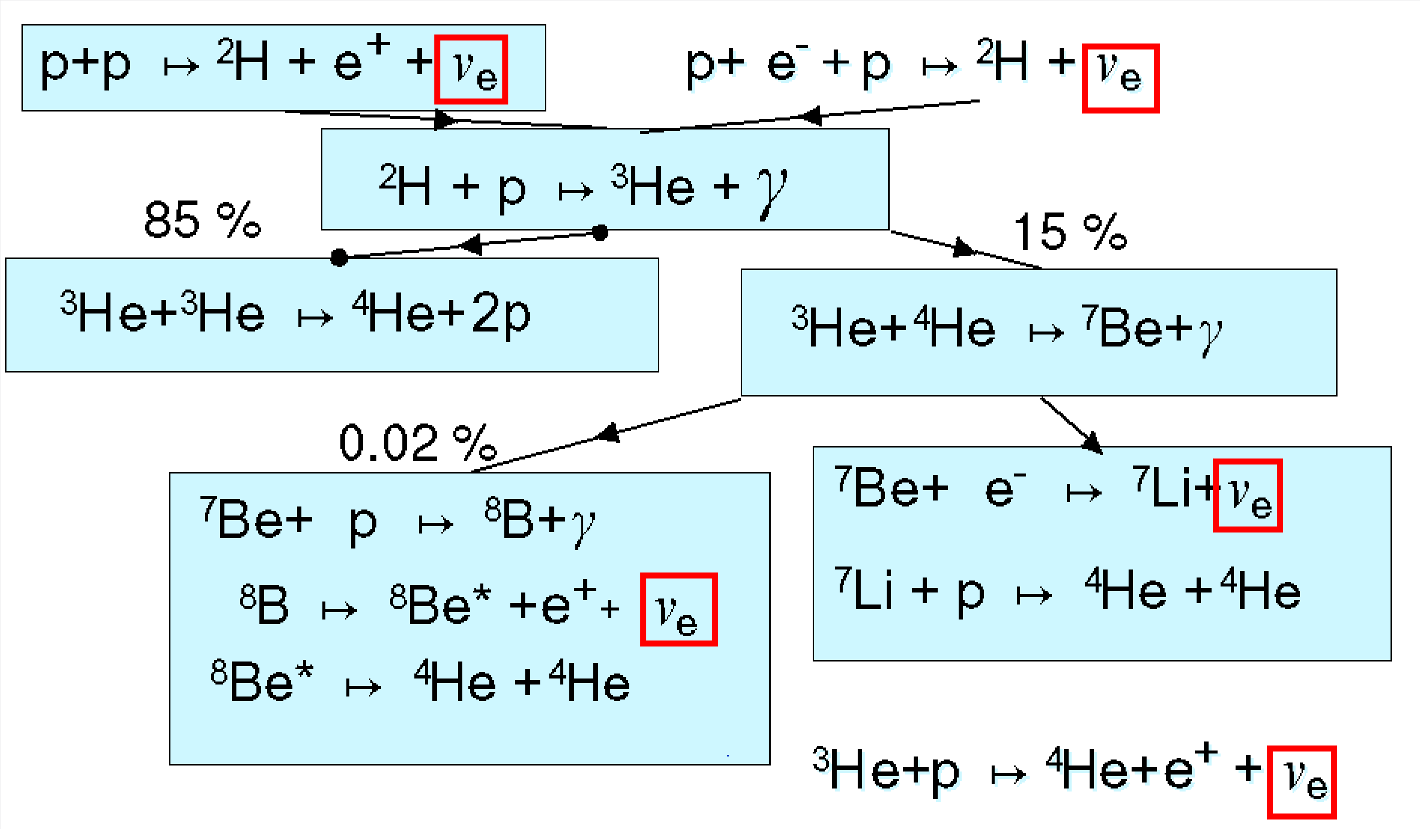
1968!

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

Slide From Learned and Pakvasa lecture course

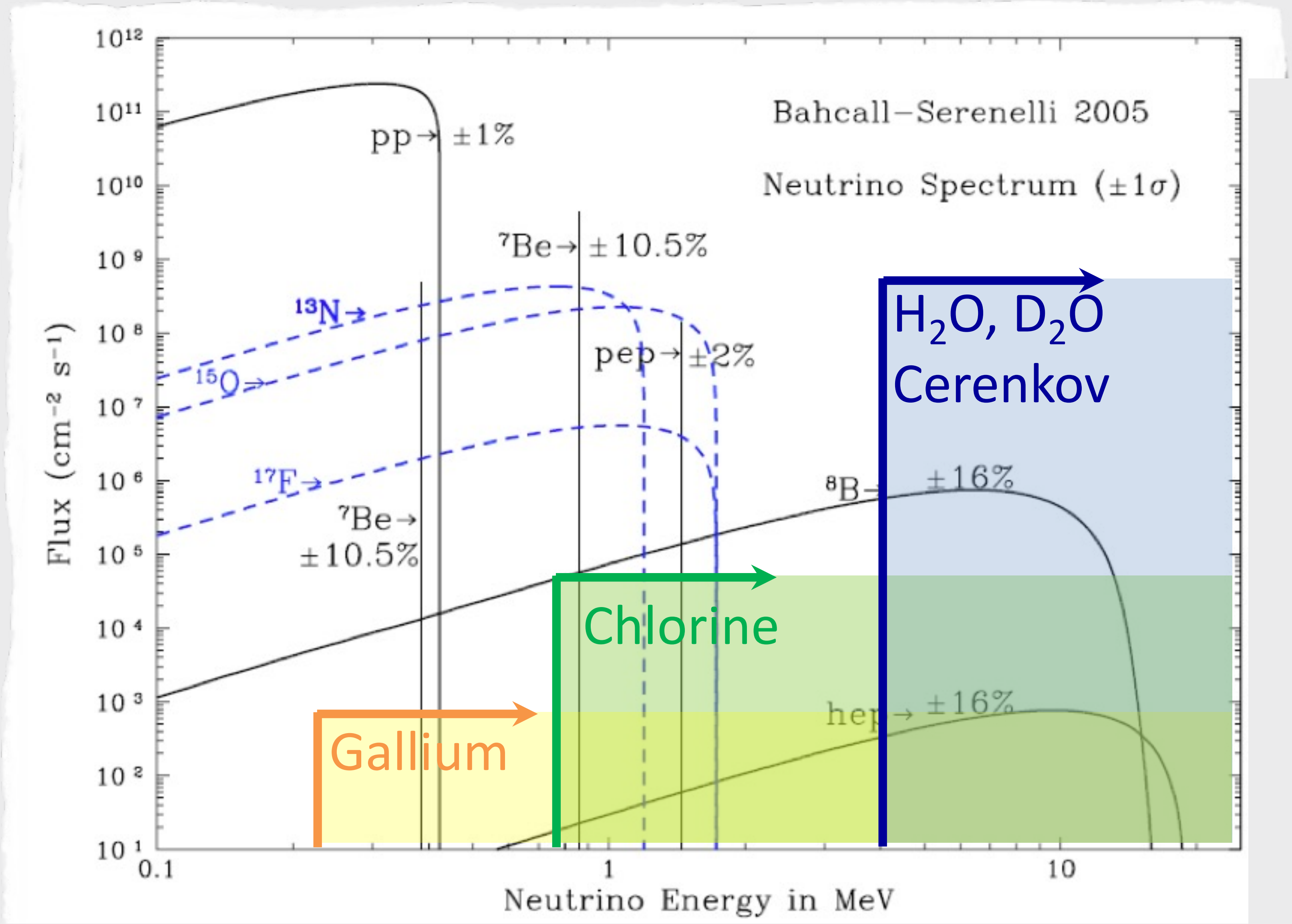


SOLAR FUSION CHAIN

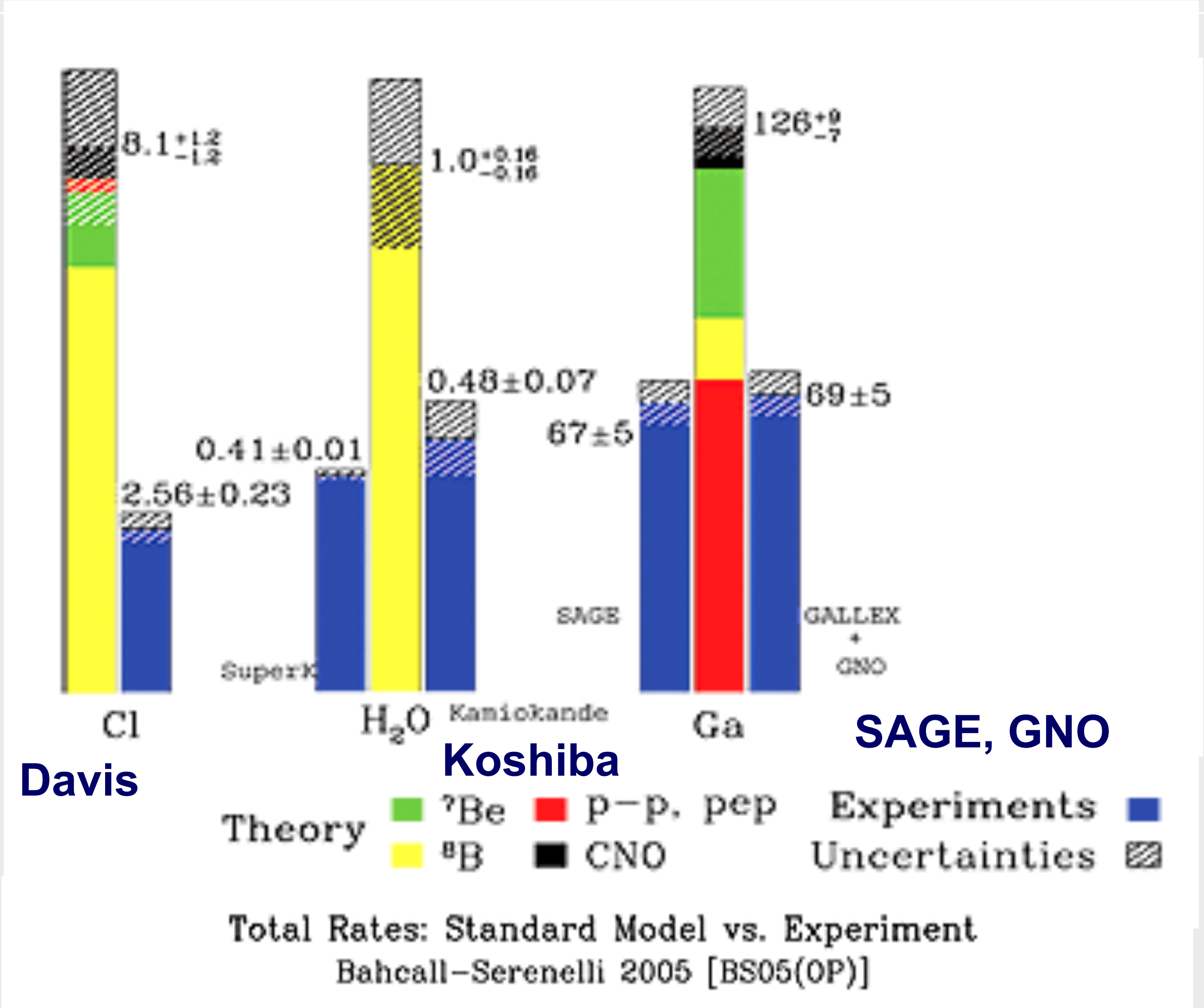


The detection of neutrinos from the Sun is a very direct way to verify models of the Sun and the energy generation reactions.

Solar ν Energy Spectra



Experiments sensitive primarily or exclusively to Electron Neutrinos saw too few neutrinos compared to Solar Models. Was this solar physics or neutrino physics?



"Solar Neutrino Puzzle"

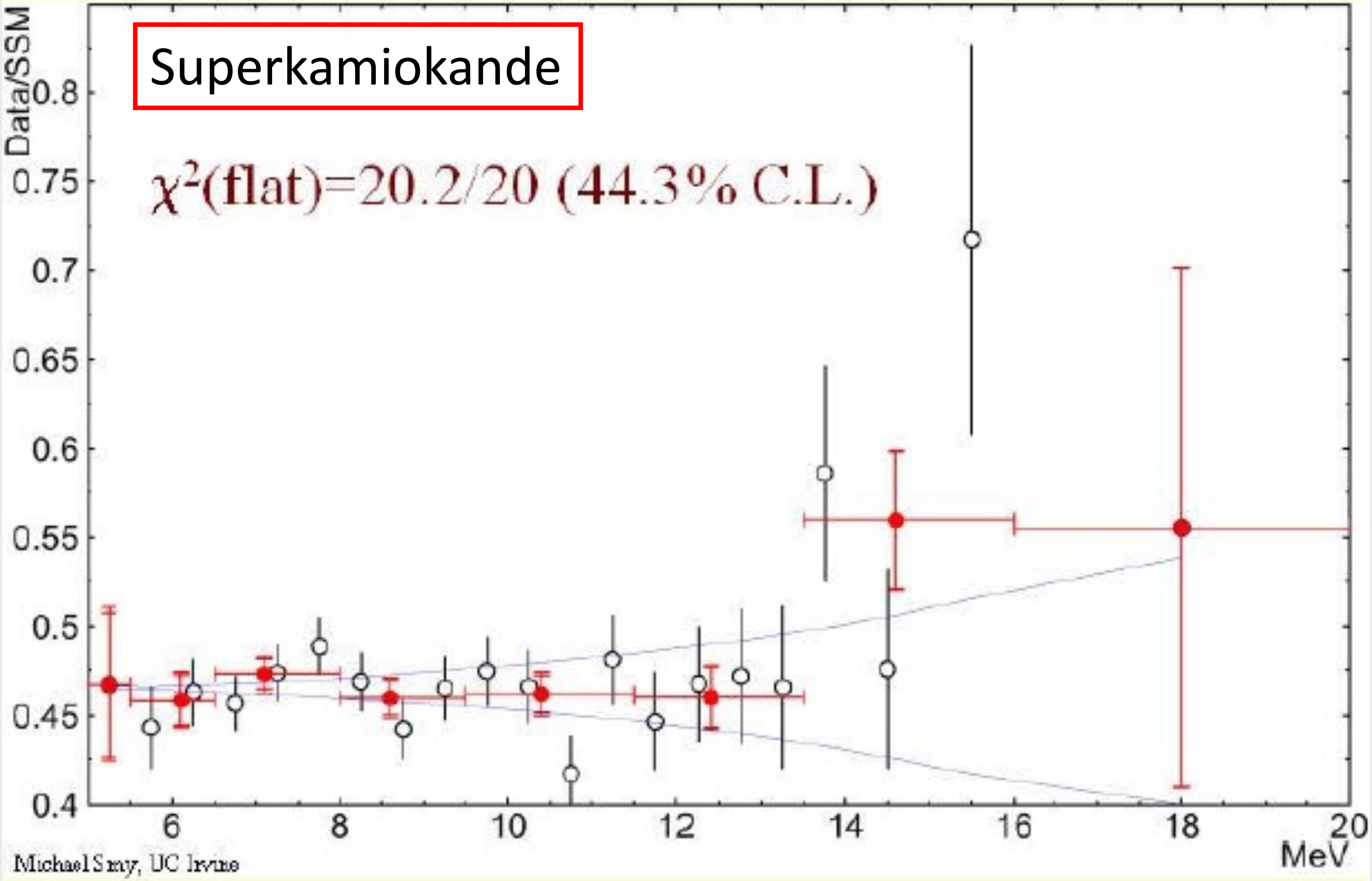
1967 - 2001

Solar Model Independent Measurements: SuperKamiokande, (Using elastic scattering from electrons in ^{8}B Solar Neutrinos)

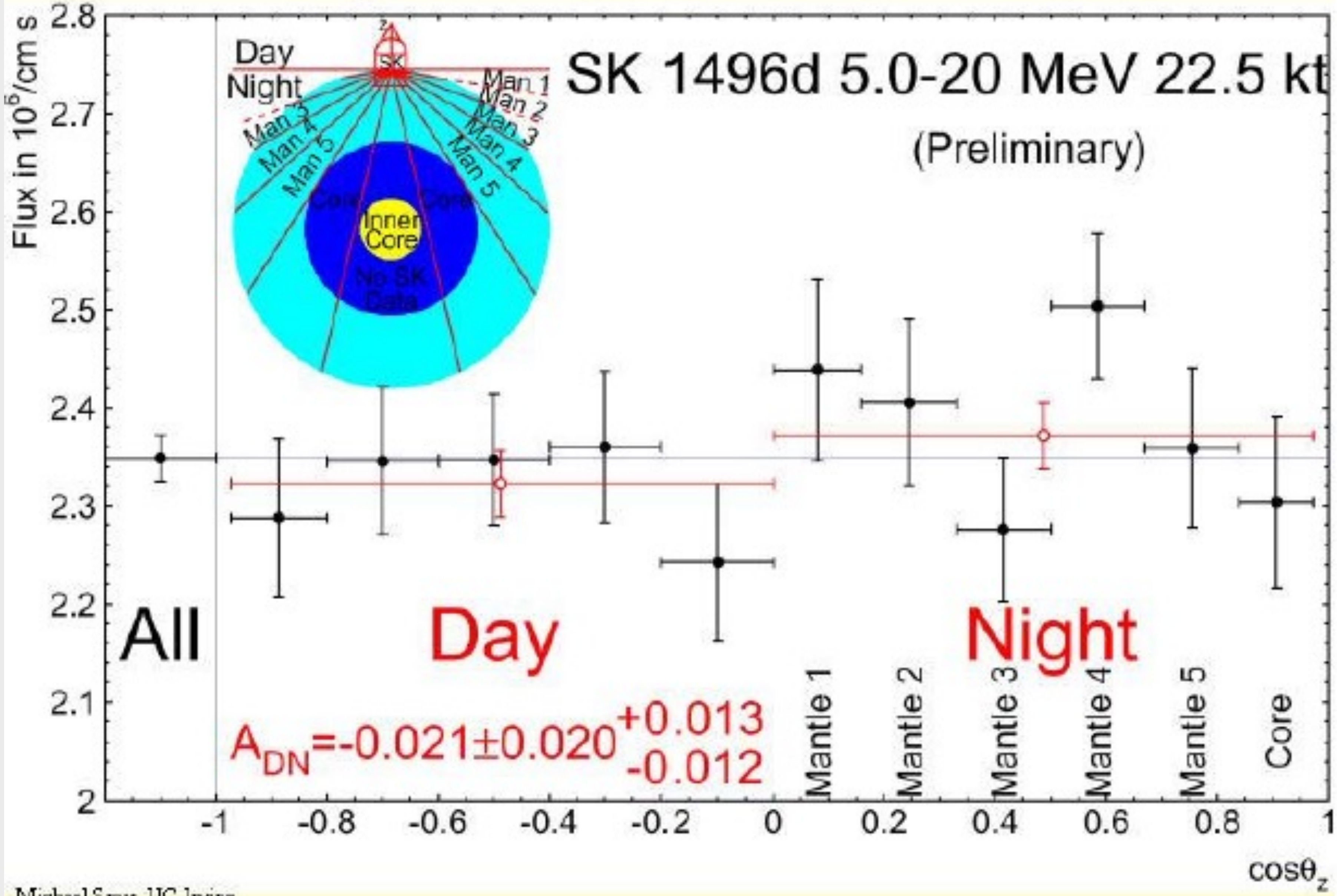
- **MSW Effects**
  - Distortion of the spectrum
  - Regeneration in the Earth (Day/Night Effects)

- **Other Time Dependent Effects**
  - Seasonal effects (Earth-Sun Distance, Neutrino Magnetic Moments ..)
  - Long Term: Solar cycle … (Neutrino Magnetic Moments …)

Recoil Electron Spectrum



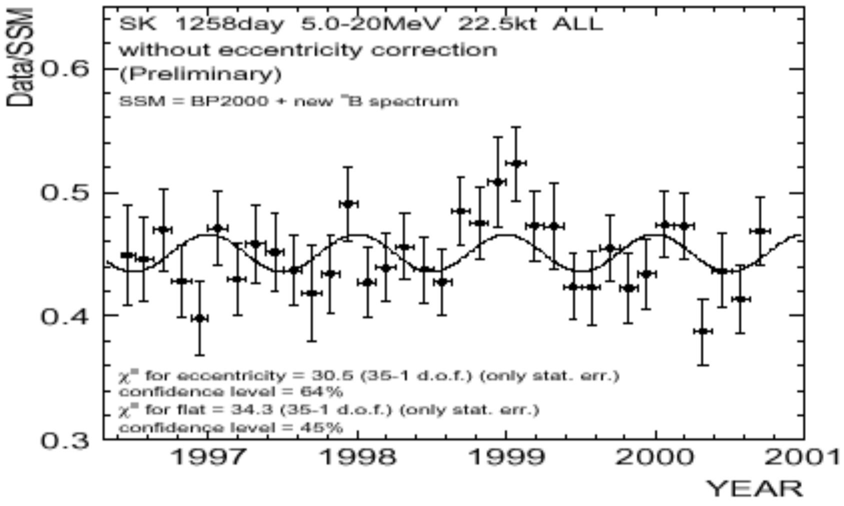
Daily Variation of SK Rate

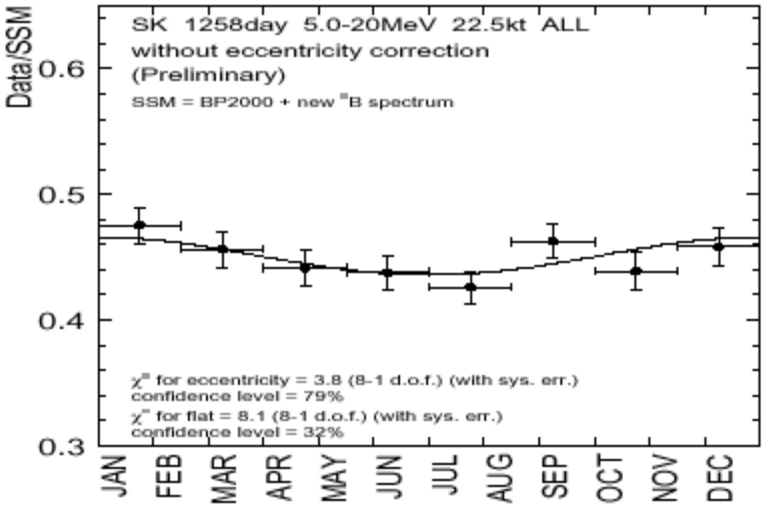


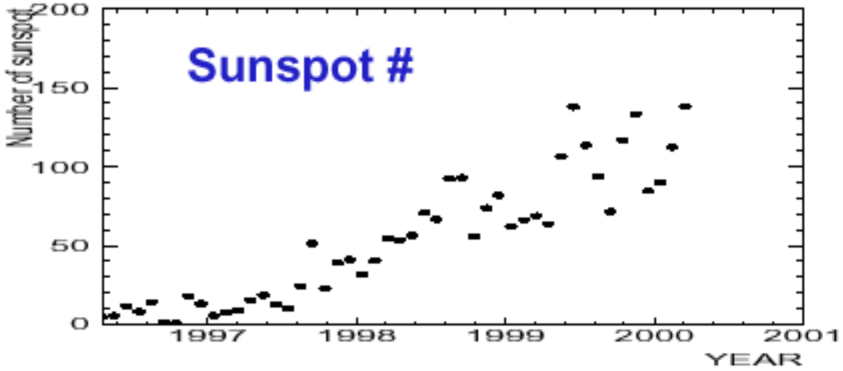
Michael Smy, UC Irvine

Time variation of the flux, seasonal

Superkamiokande



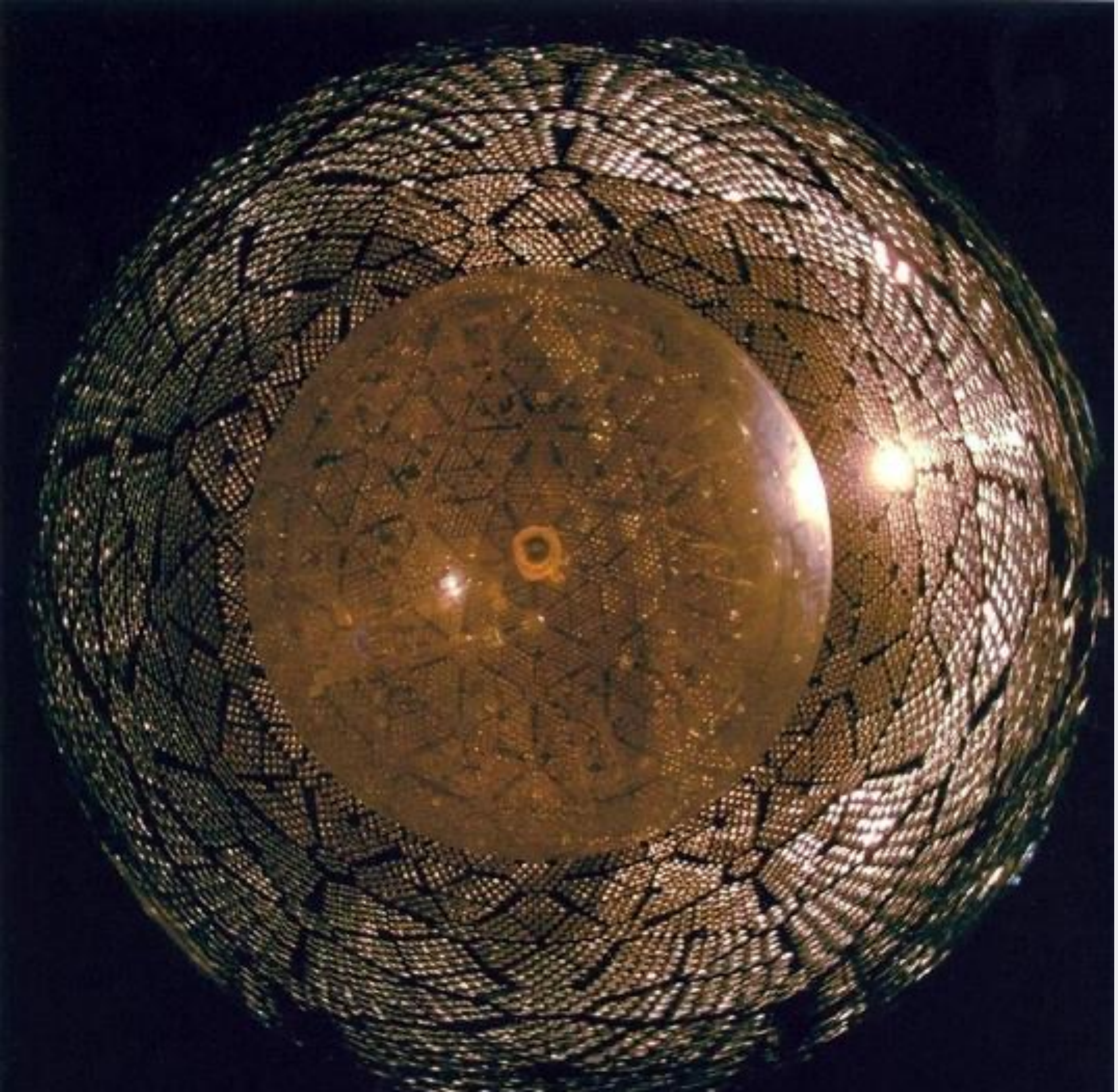




χ^2 for eccentricity:
3.9 / 7 d.o.f. (79% C.L.)

(χ^2 for flat: 8.1 / 7 d.o.f.
(32% C.L.))

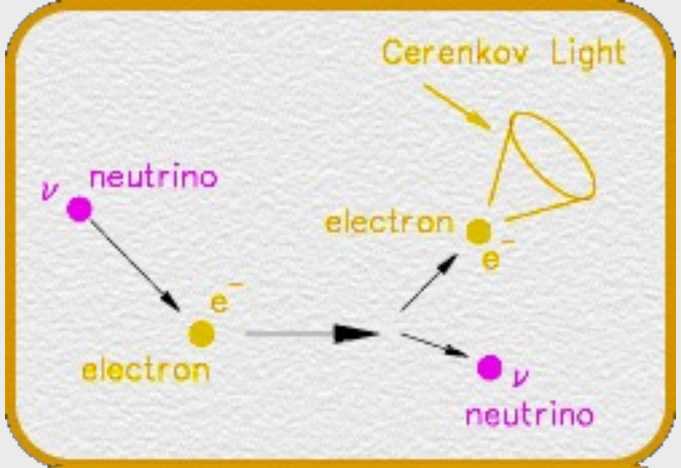
Also: Limit on Anti-electron neutrinos: few % of Standard Solar Model



The Sudbury Neutrino Observatory (SNO)

D_2O and H_2O

Scattering from electrons

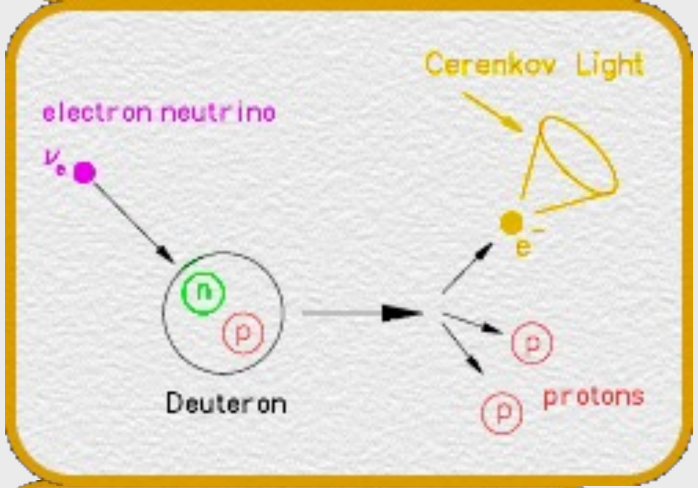


1) Neutrino Electron Elastic Scattering
Sensitive: ~86 % ν_e and ~14% ν_μ , ν_τ
As also observed by SuperKamiokande

First: SNO-SK comparison with lower sensitivity to ν_μ , ν_τ
First result: flavor change: 3.3 σ (2001)

D_2O

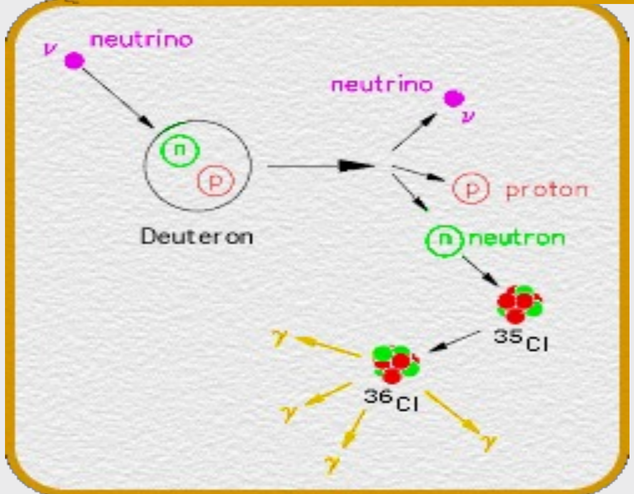
Interactions with Deuterium



2) Charged Current Interaction on Deuterium
100 % ν_e

Second: SNO-only comparison with high sensitivity to ν_μ , ν_τ
Second result: flavor change: 5.3 σ (2002)

D_2O



3) Neutral Current Interaction on Deuterium
Equal sensitivity for ν_e , ν_μ , ν_τ

Neutrons are detected by capture in 1) Deuterium, 2) Chlorine in dissolved salt and 3) ^3He in a detector array during the three phases of the experiment.

Gamma radioactivity must be very low to avoid neutron background from photodisintegration

The Sudbury Neutrino Observatory: SNO

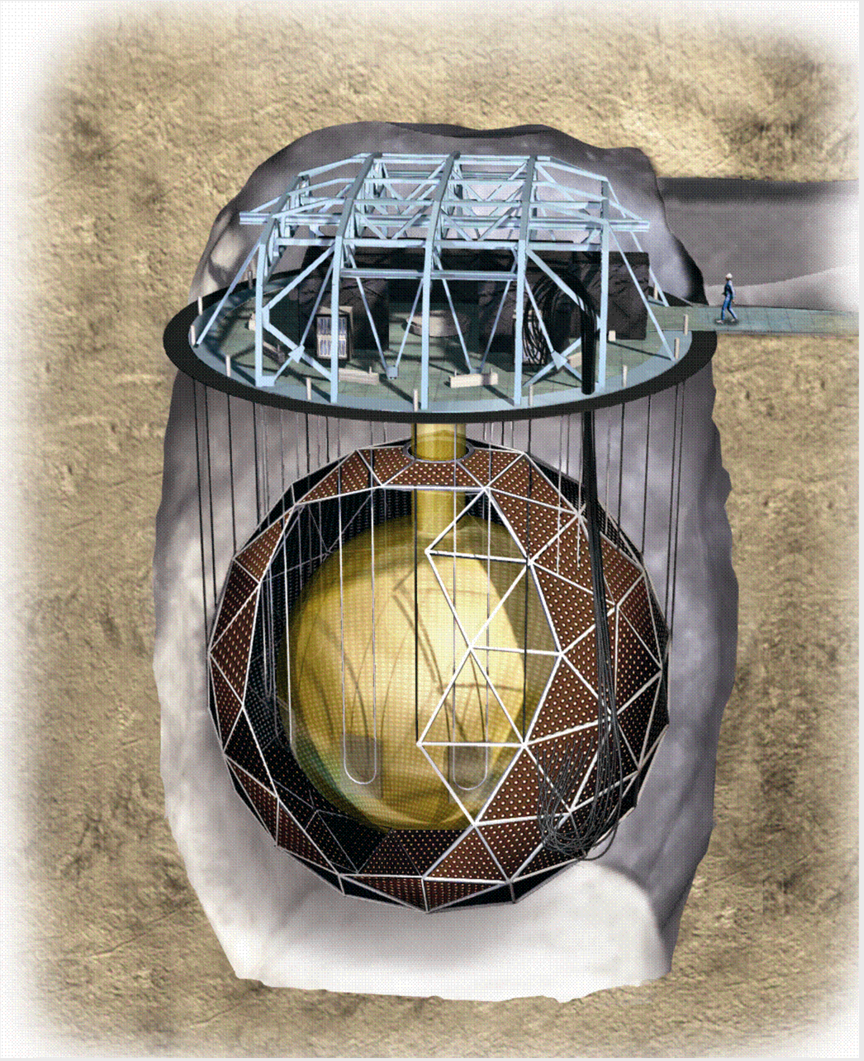
Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O
($300 million)
On loan for $1 (Canadian)

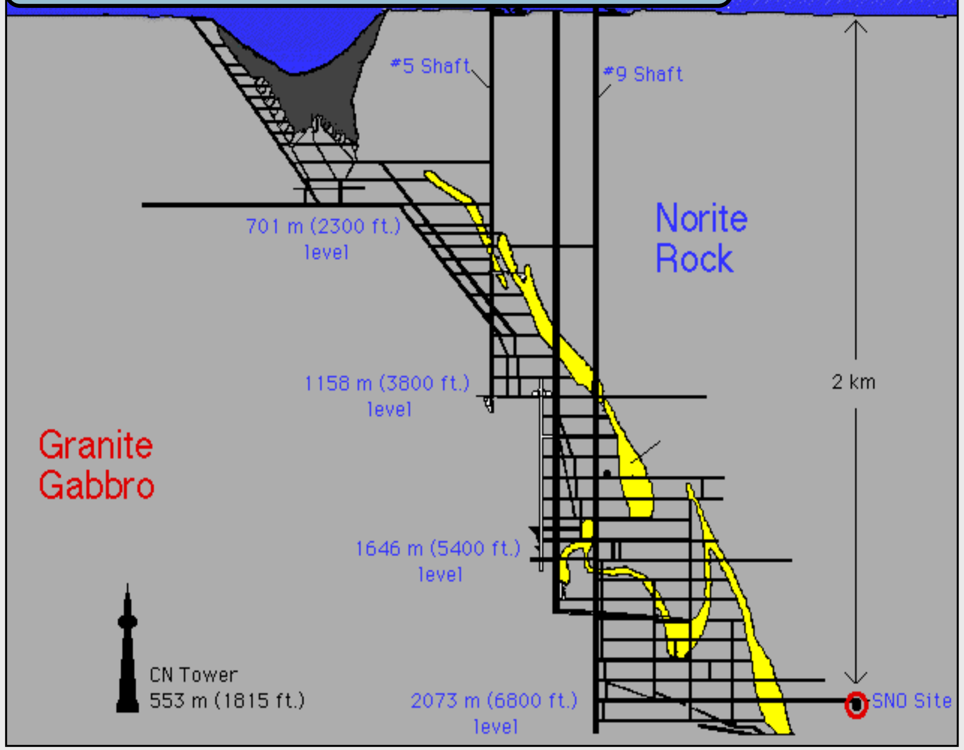
1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
outer shielding

~9500 PMT's

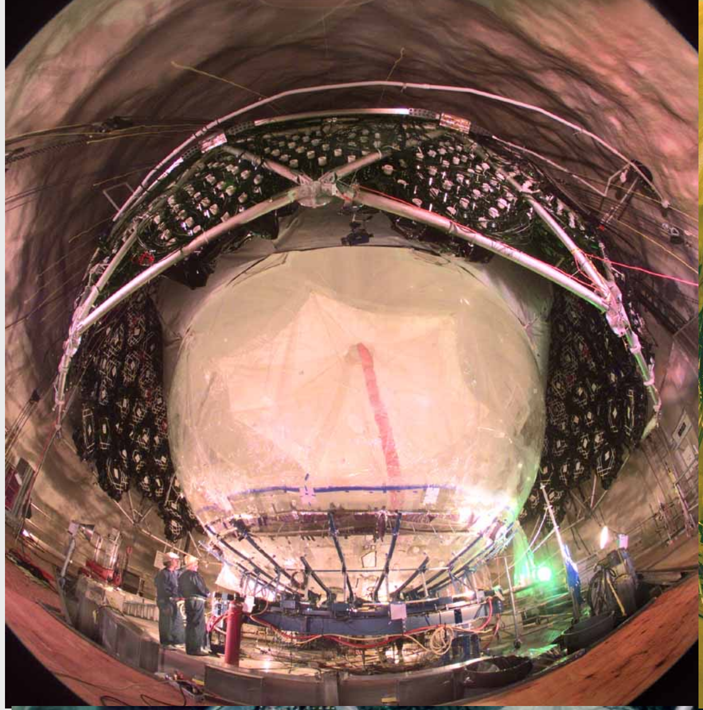


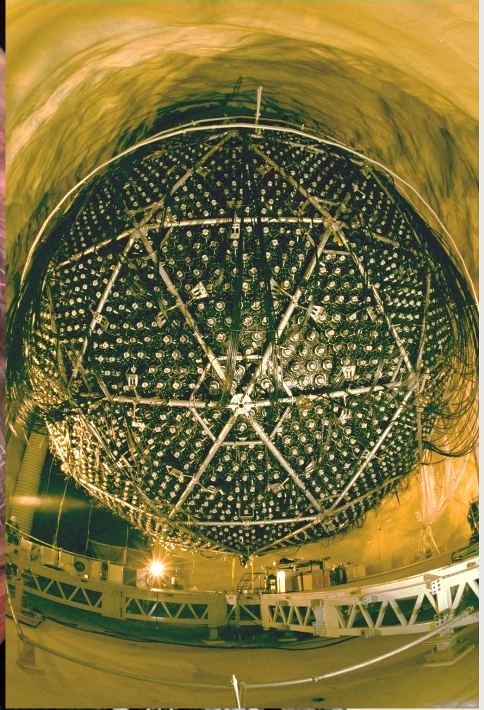
6800 feet (~2km) underground



Creighton mine
Sudbury, CA

- Entire detector
Built as a Class 2000
Clean room
- Low Radioactivity
Detector materials

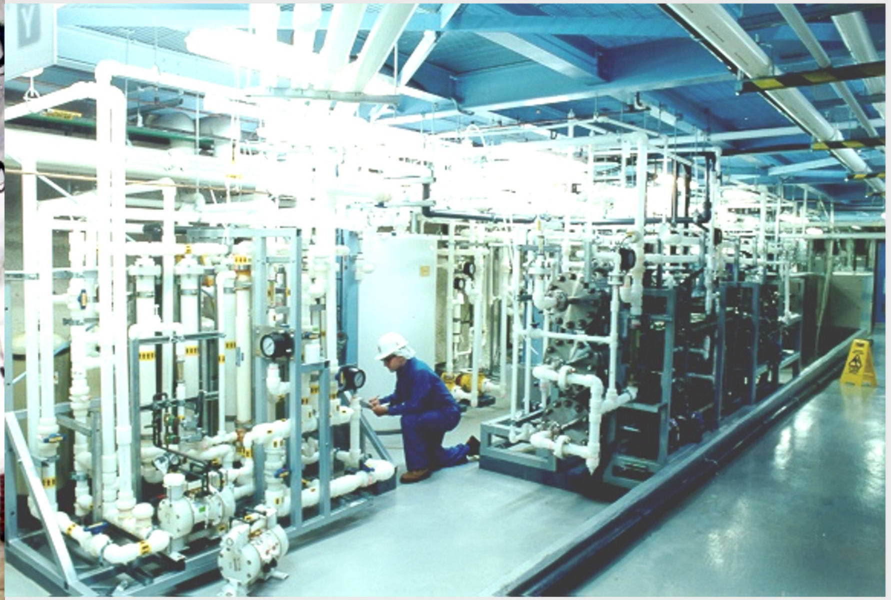




One million pieces transported down in the 10 foot square mine cage and re-assembled under ultra-clean conditions.

More than 70,000 showers.

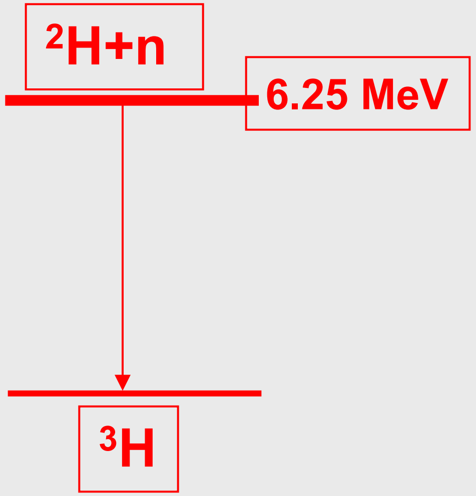
Ultra-pure water systems.



SNO: 3 neutron detection methods for ν_{all} reaction.

Phase I (D_2O)
Nov. 99 - May 01

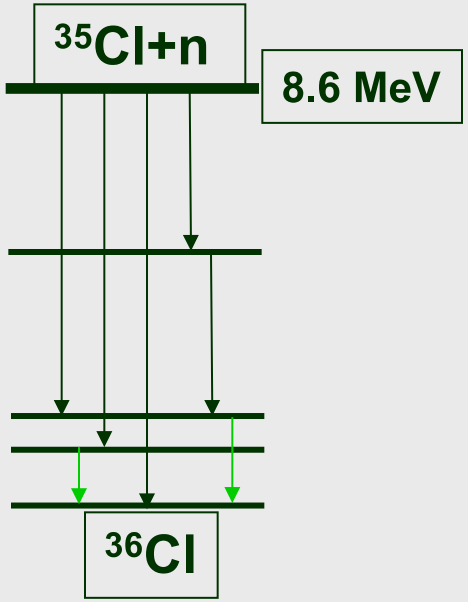
n captures on deuterium
Effciency ~14.4%
ν_{all} and ν_e
Separation difficult



Demonstrate Neutrino Flavor Change clearly

Phase II (salt)
July 01 - Sep. 03

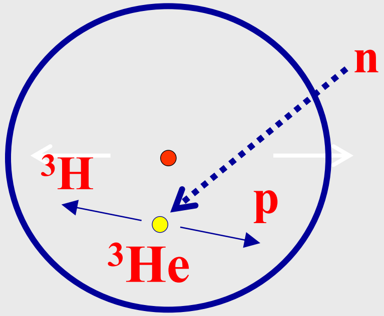
Add 2 tons NaCl
n captures on chlorine
Effc. ~40%
ν_{all} and ν_e separation by event isotropy



Measure Total Flux of all Neutrino types (ν_{all}), Compare with solar models.

Phase III (^{3}He)
Nov. 04-Dec. 06

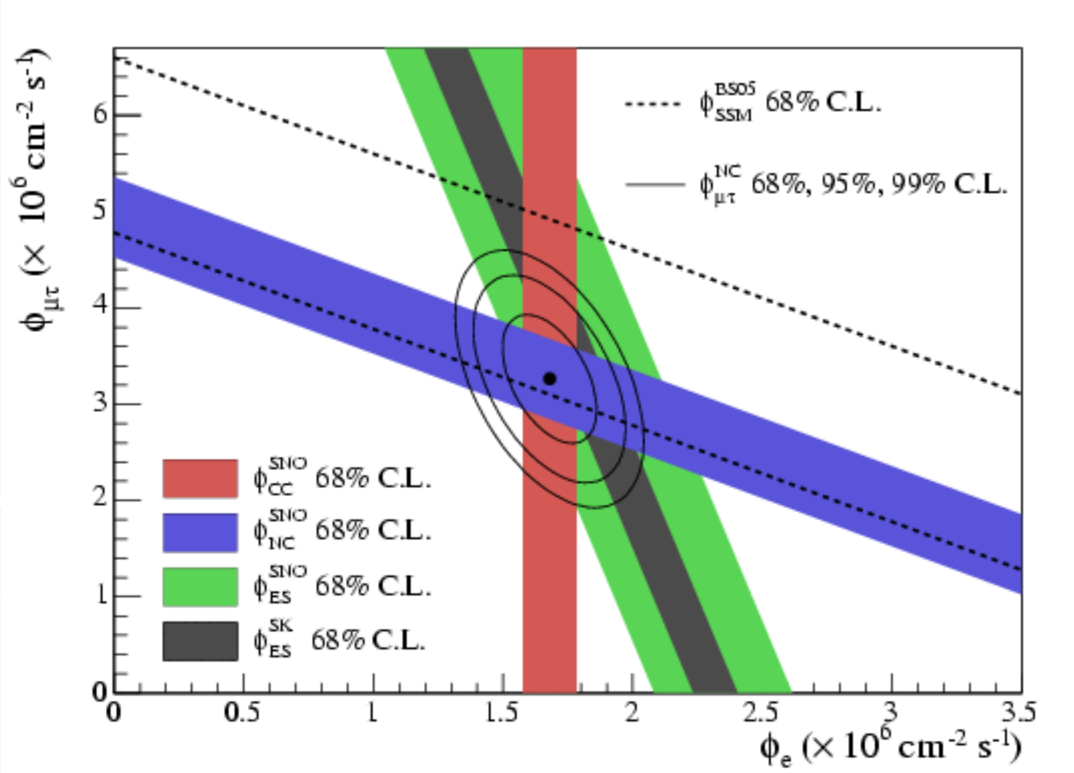
Remove salt, add 400 m of proportional counters 5 cm diameter.
Neutron Effc. ~ 30%



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

Measure ν_{all} rate with Independent system.
Paper in June 2008.

Final ν_e / ν_{all} ratio Measured to < 7 %



SNO Salt Phase

CC, NC FLUXES MEASURED INDEPENDENTLY

Fluxes

$$\phi_{CC} = 1.68 \ {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \ {}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35 \ {}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

$$(\text{In units of } 10^6 \text{cm}^{-2}\text{s}^{-1})$$

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031} \approx \sin^2\theta_{12}$$

Improved accuracy for θ_{12}.

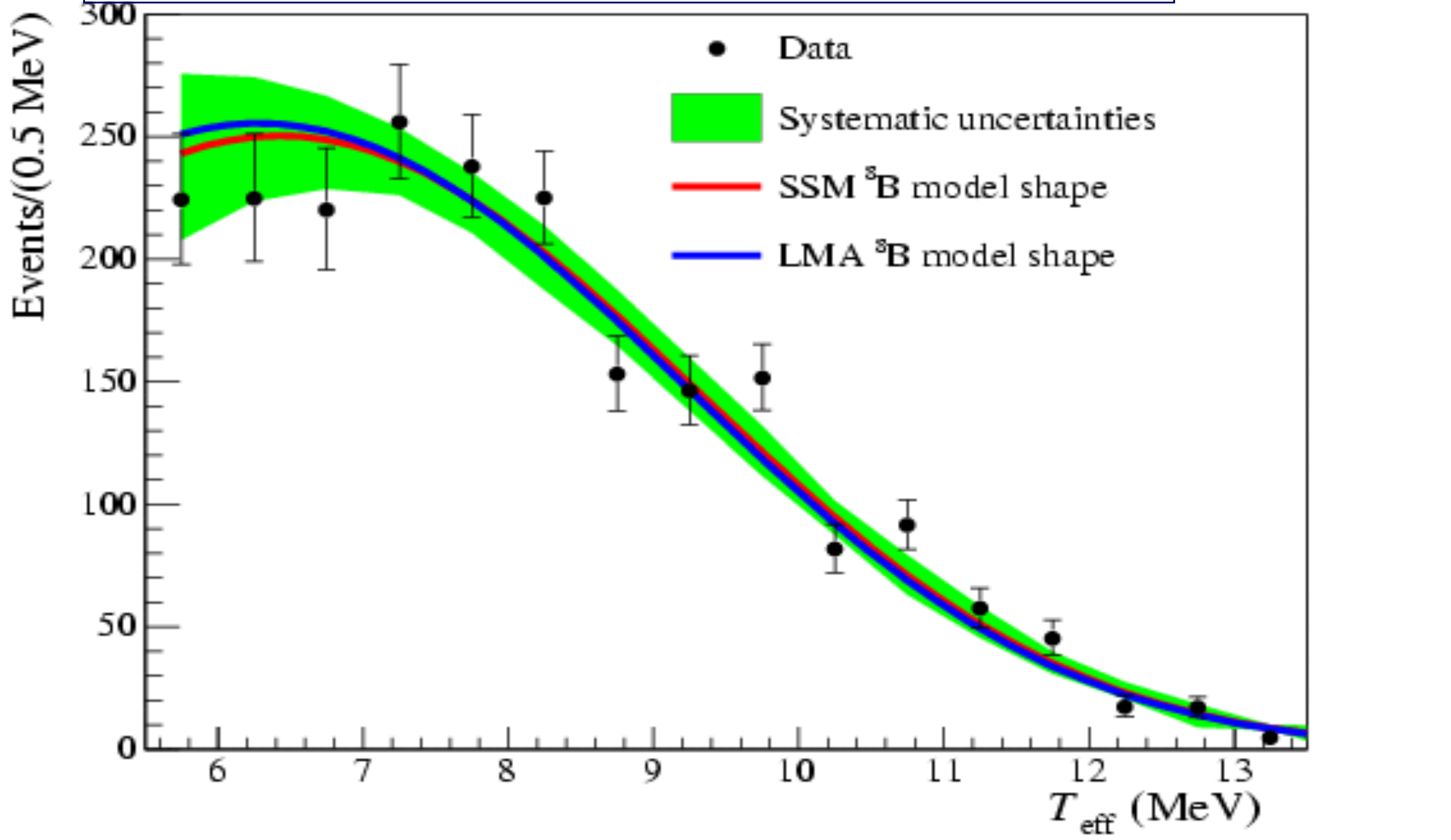
Flavor change is determined with > 7 σ

Data from Experiments in Operation

SNO data: 391 live days with salt

hep-ex/0502021 March 2005

New Information: Charged Current Energy Spectrum



Day-Night Asymmetry assuming A_{NC}=0

$$A_{salt + D_2O} = 0.037 \pm 0.040$$

SNO Phase III (NCD Phase)

- ^{3}He Proportional Counters ("NC Detectors")

40 Strings on 1-m grid

440 m total active length

Detection Principle

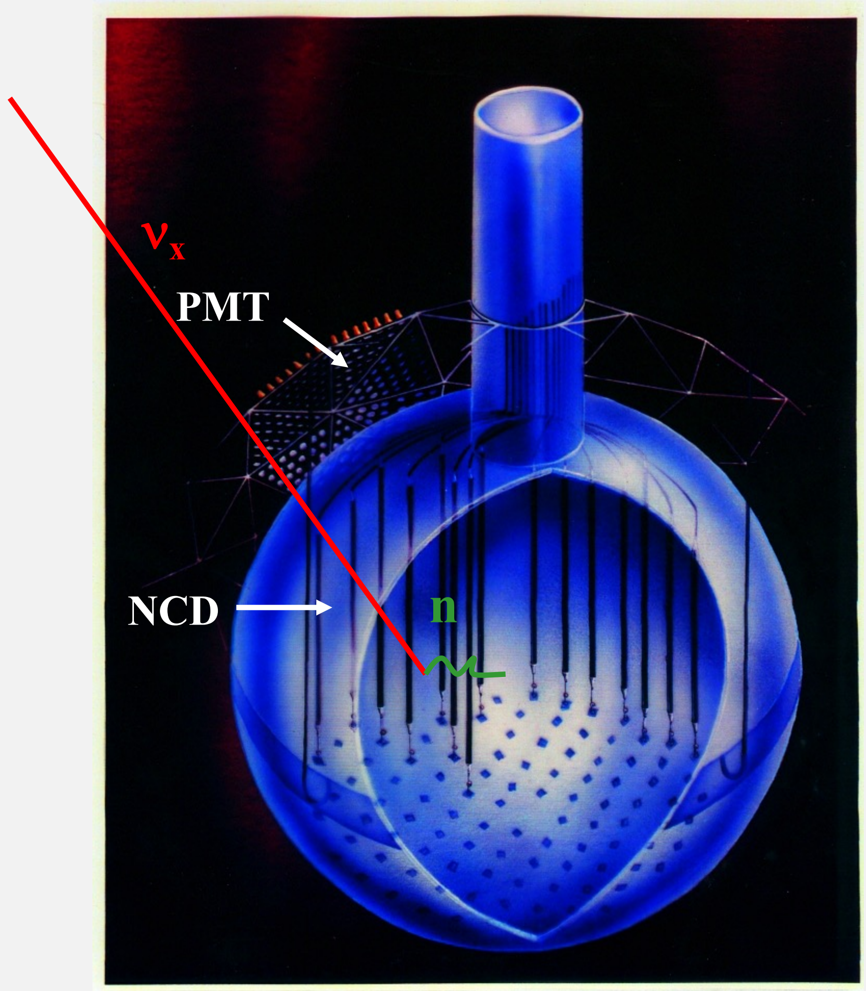
$$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22\ \text{MeV} \qquad \text{(NC)}$$

$$^3He + n \rightarrow p + {}^3H + 0.76\ \text{MeV}$$

Physics Motivation

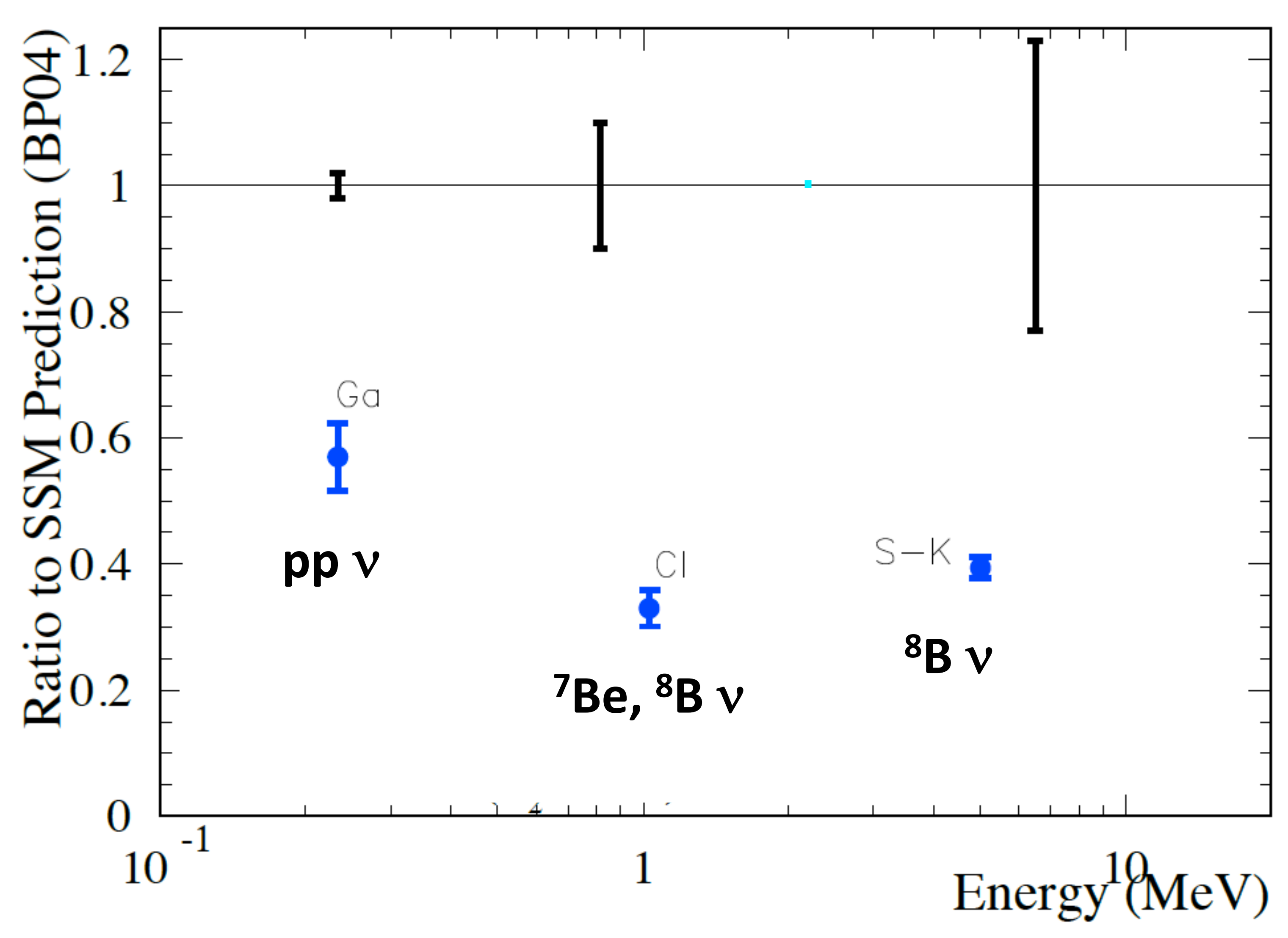
Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

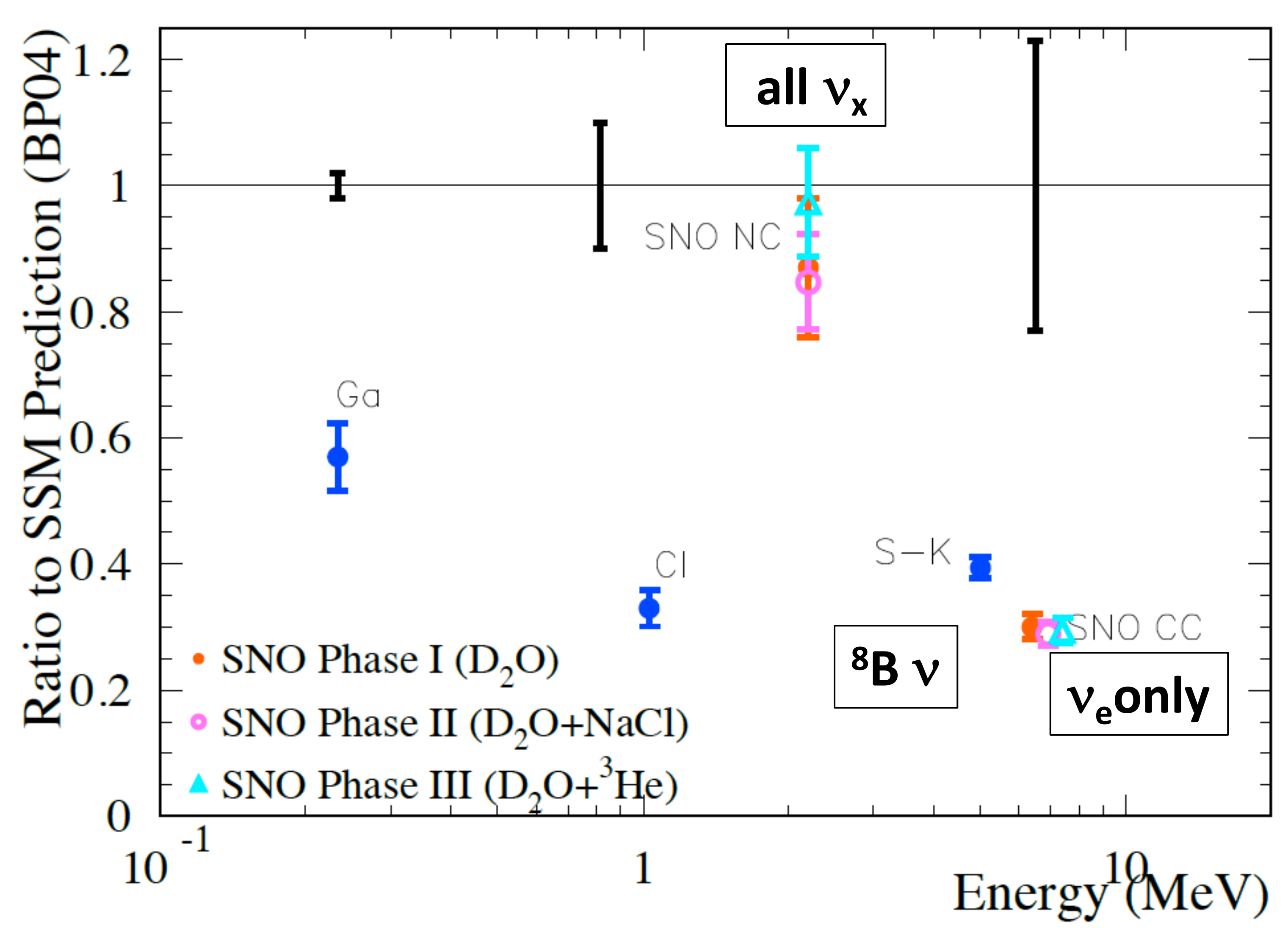


Solar Neutrino Problem

Pre 2001



Solar Neutrino Problem Resolved



Neutrino Properties to Date

Using the oscillation framework:

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix

(Double β decay only)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✓ **Solar,Reactor** ✓ **Atmospheric** ? **CP Violating Phase** ✓ **Reactor,LBL** ? **Majorana Phases**

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

✓ **Range defined for Δm_{12}, Δm_{23}**

For two neutrino oscillation in a vacuum: (valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \left(1.27 \boxed{\frac{\Delta m^2 L}{E}}\right)$$

Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenstein)

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

The extra term arises because solar ν_e have an extra interaction via W exchange with electrons in the Sun or Earth.

In the oscillation formula:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

Fits to solar neutrino data indicate that electron neutrinos interact with electrons in the sun via MSW and emerge as a mass 2 state with nearly equal parts electron, mu, tau neutrinos. These matter interactions define the mass hierarchy (m_2>m_1). The MSW effect produces an energy spectrum distortion and flavor regeneration in Earth giving a Day-night effect of about 3% as measured by SuperK.

SUMMARY OF OSCILLATION RESULTS FOR THREE ACTIVE ν TYPES

Particle Data Group

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2(\theta_{23}) = 0.539 \pm 0.022 \quad (S = 1.1) \quad$ (Inverted order)

$\sin^2(\theta_{23}) = 0.546 \pm 0.021 \quad$ (Normal order)

$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Inverted order)

$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2 \quad$ (Normal order)

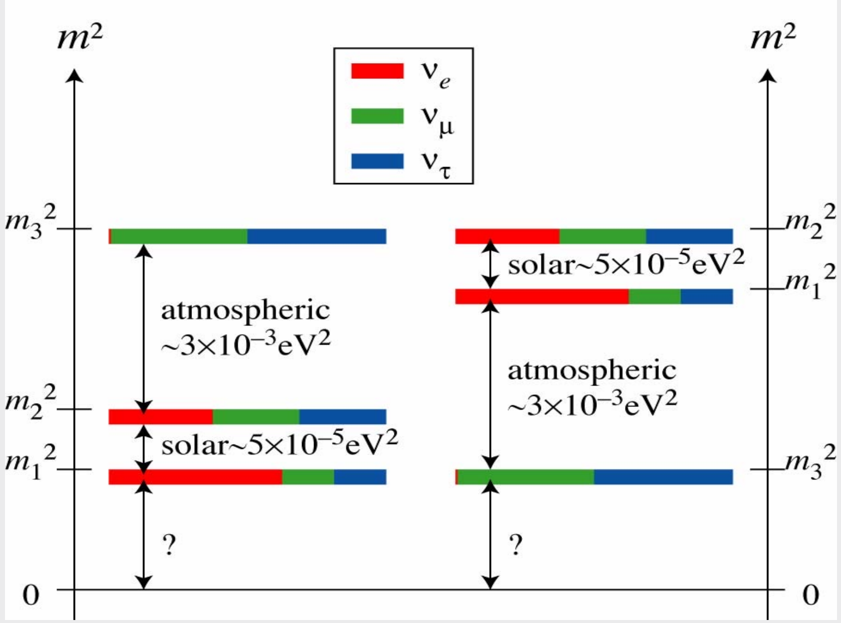
$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

Solar, Reactor

Atmospheric,Accelerator

Reactor, Accelerator

Mass Hierarchies



Normal Inverted

Future objectives:

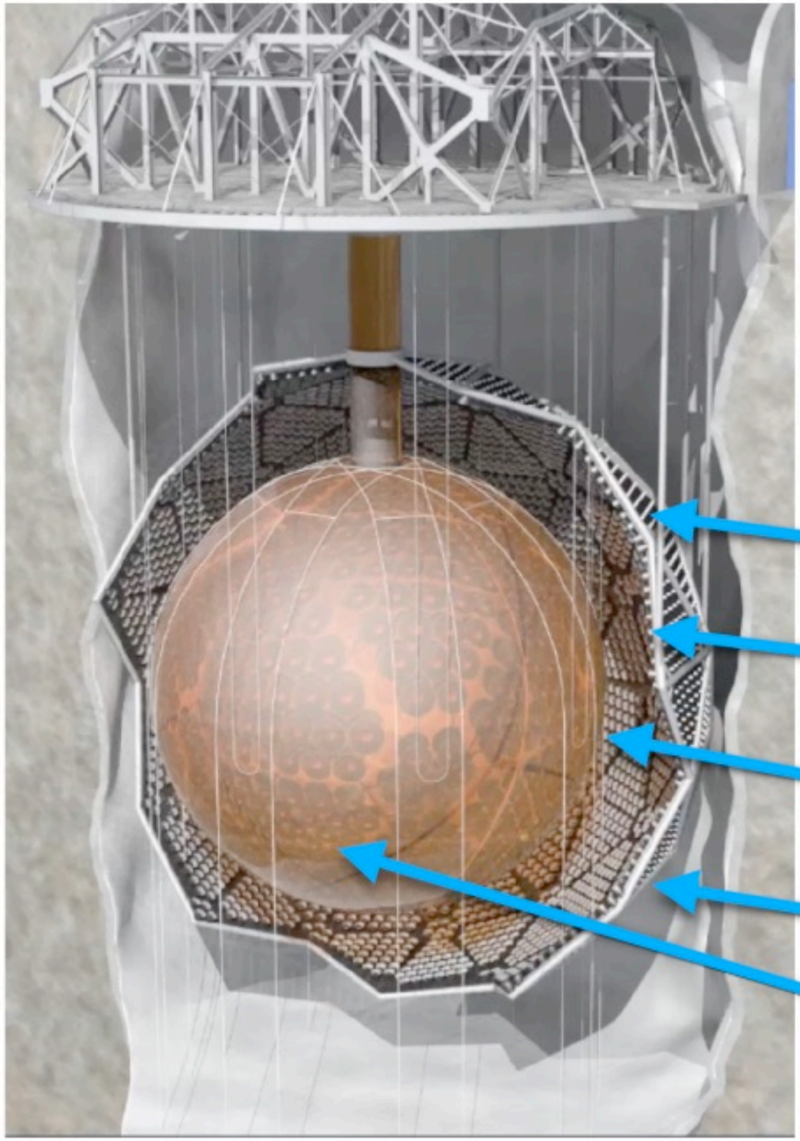
- δ_{CP}
- θ_{23} max?
- Hierarchy?
- Majorana ν?
- Absolute mass
- Sterile ν?

Accelerator,Reactor, Atmospheric

$0\nu\beta\beta$, Cosmology, Electron spectrometers,

Accelerator,Reactor, Atmospheric

The SNO+ Experiment



- **2km** underground in **SNOLAB**, Canada
- Infrastructure repurposed from **SNO**:
  - New calibration systems
  - Upgraded DAQ and electronics
  - New hold-down ropes
  - Scintillator Plant + Tellurium synthesis and purification

~9300 PMTs

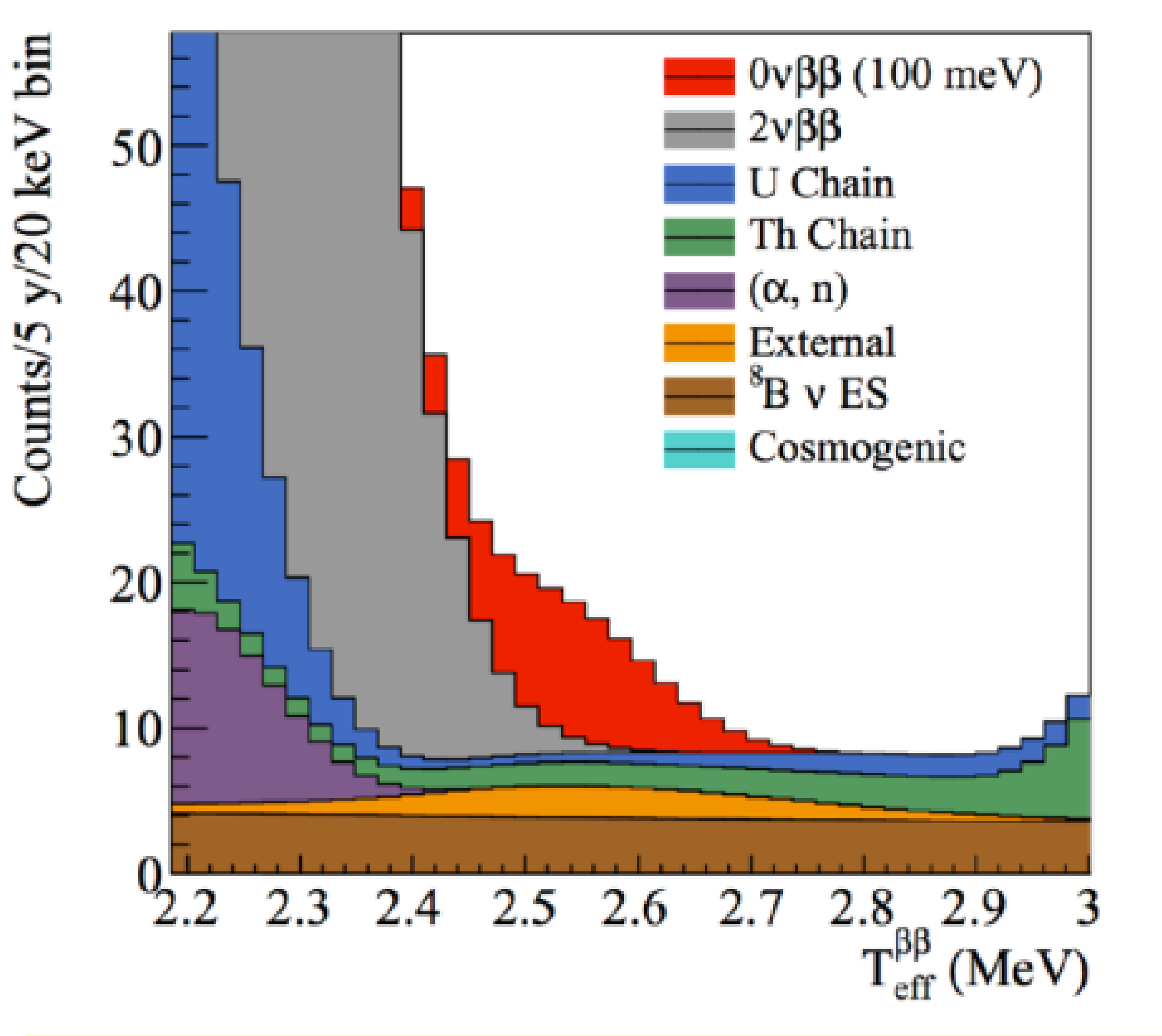
18m diameter PMT Support Structure

12m diameter Acrylic Vessel

7kt ultra pure water shielding

780t Liquid Scintillator to be loaded with 0.5% Te in 2026

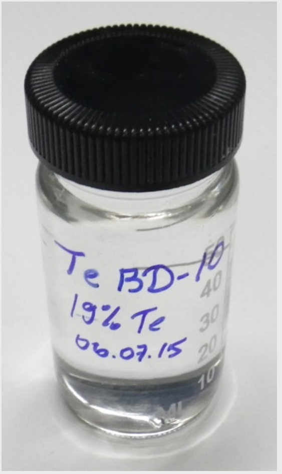
Increase to 1.5% planned for future



SNO+
5 years at 0.5% Te Loading:
1300 kg ^{130}Te

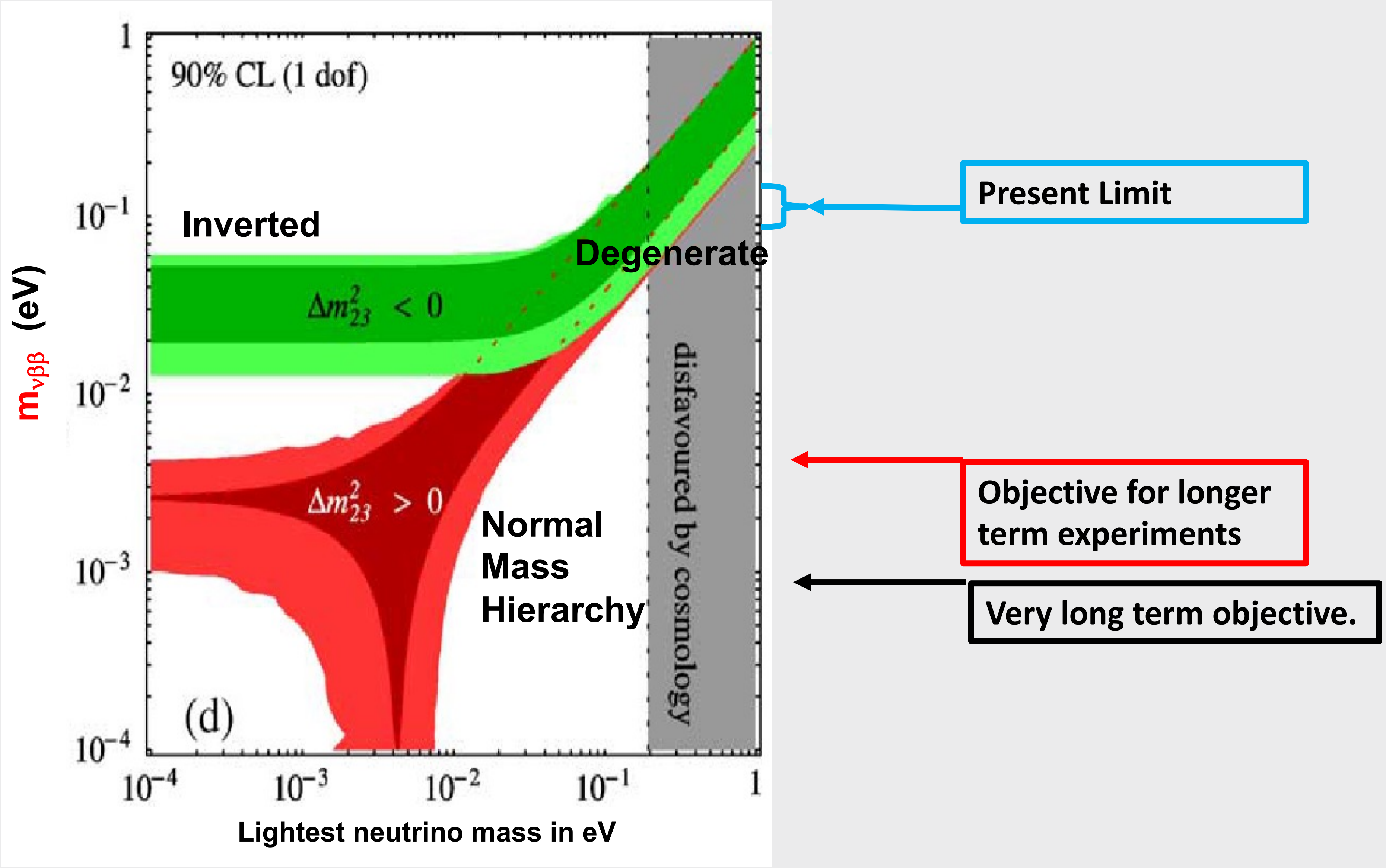
$m_{\beta\beta}$ < 30-130 meV
(99.7% CL)

Phase II
1.5% ^{130}Te
$m_{\beta\beta}$ < 17-80 meV

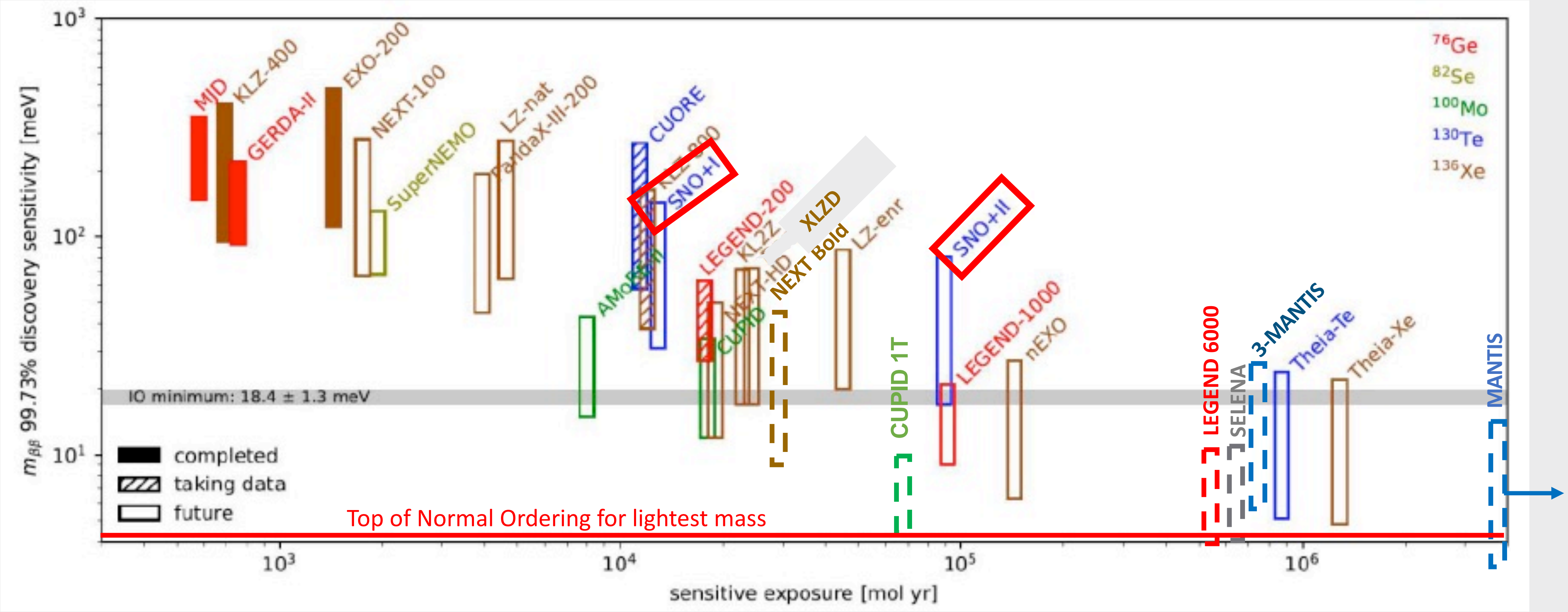


Presently running with liquid scintillator for other physics and evaluating backgrounds. Te projected for 2026

Variation of $m_{\beta\beta}$ vs Lightest ν mass



Summary plot from NSAC LRP White Paper (Augmented) (Values provided by experiments)



From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

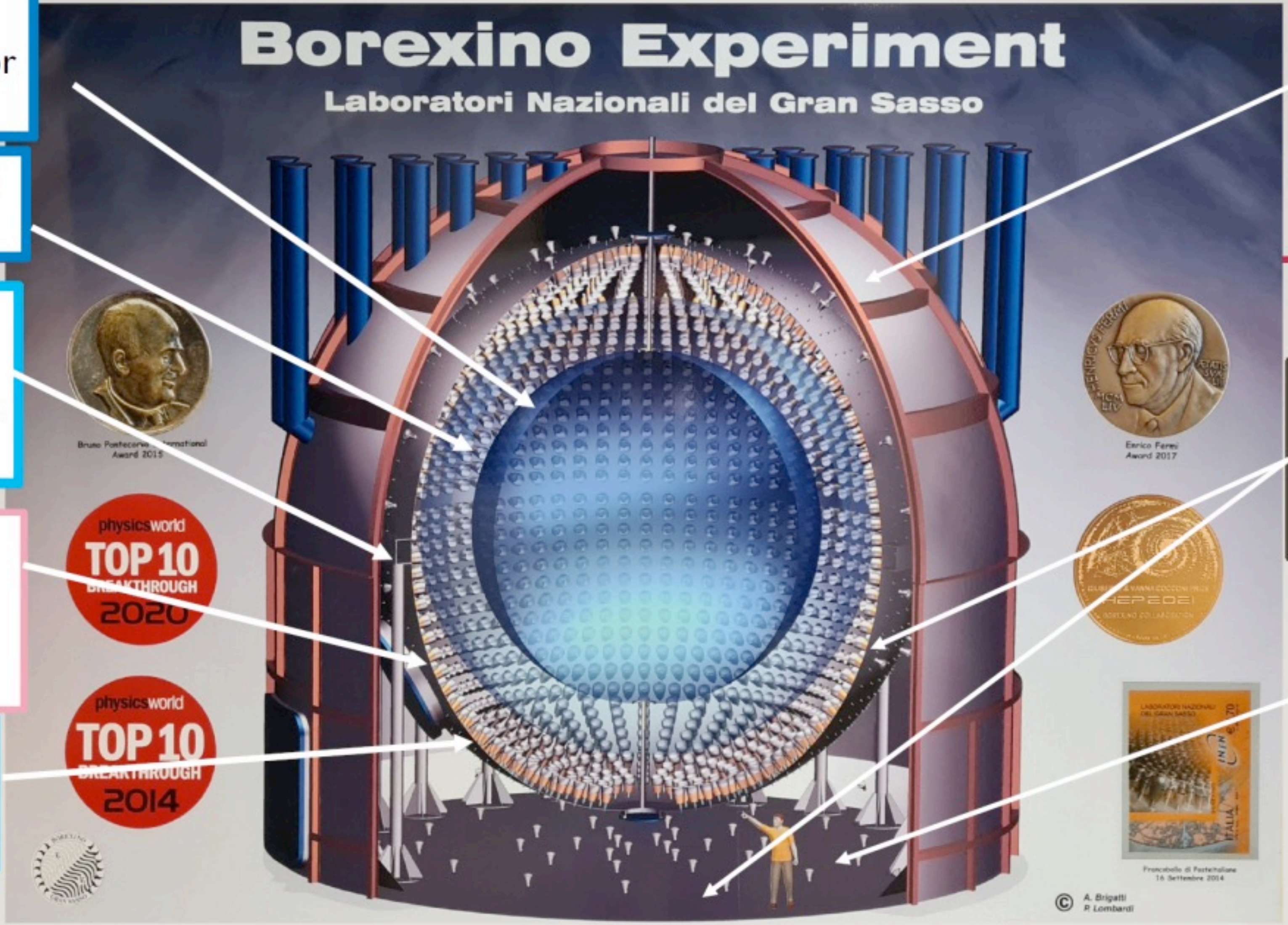
278 tons of liquid scintillator PC+PPO

IV-125 μm thick ultrapure nylon

OV 2nd nylon Vessel- barrier against emission PMT and SSS

SSS (6.85 m radius), supports 2212 8” PMTs

Buffer liquid 600 t PC+ DMP (3.5 g/l)



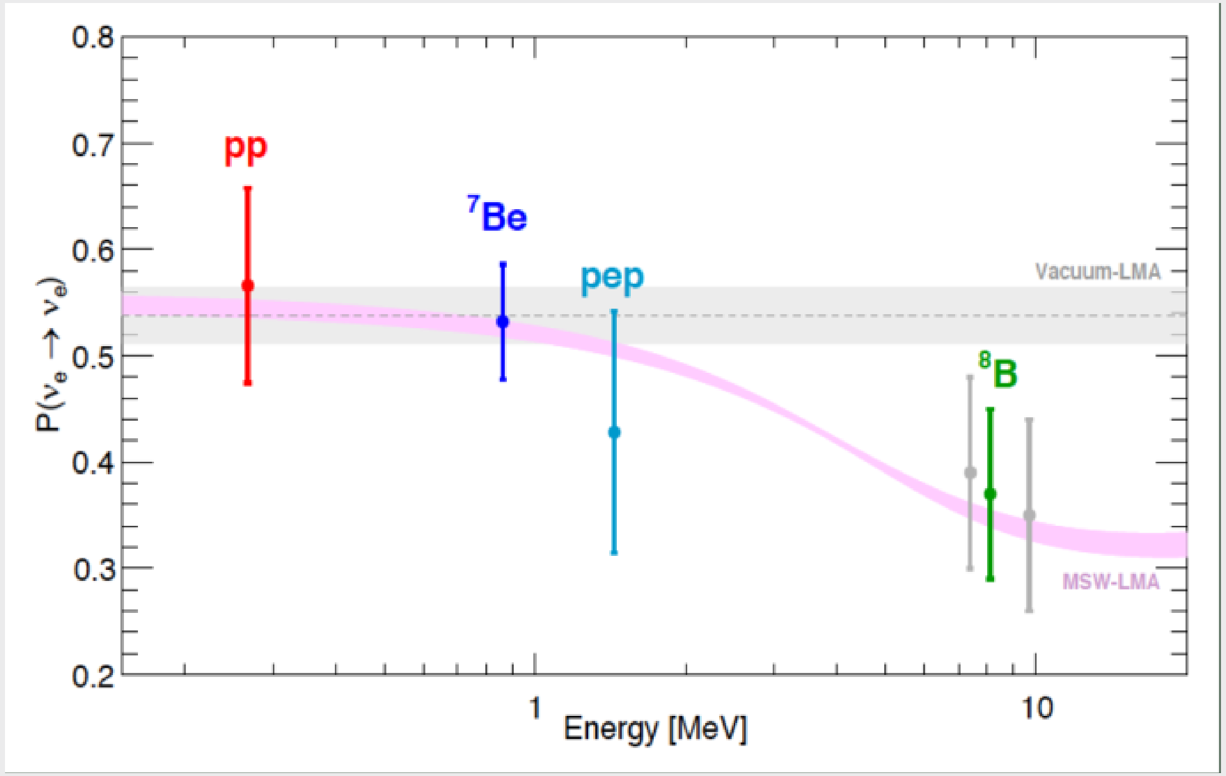
WT, 16.9 m high and 9.0 m of radius; 2400 t ultrapure water.

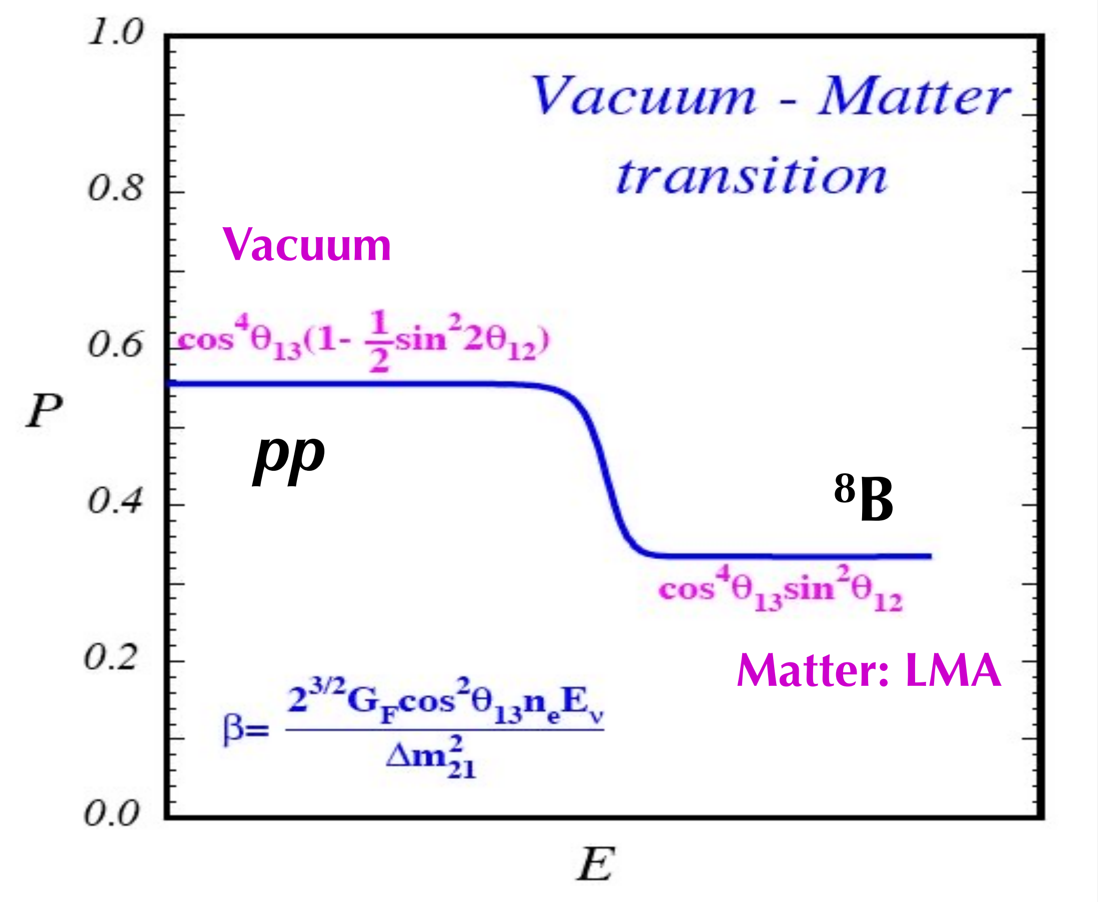
TYVEK to enhance light collection on the SSS outer wall and the WT inner walls

200 PMTs- muon veto

A remarkable set of measurements to understand solar neutrino reactions in the pp and CNO cycles
Bellini, Calaprice and the Borexino collaboration

BOREXINO RESULTS





Bahcall & Pena-Garay
hep-ph/0305159

^{210}Po rate from the Low Polonium Field : $R_{min} = 11.5 \pm 1.3 \frac{cpd}{100t}$

$R(^{210}Bi) \leq 11.5 \pm 1.3$ cpd/100t

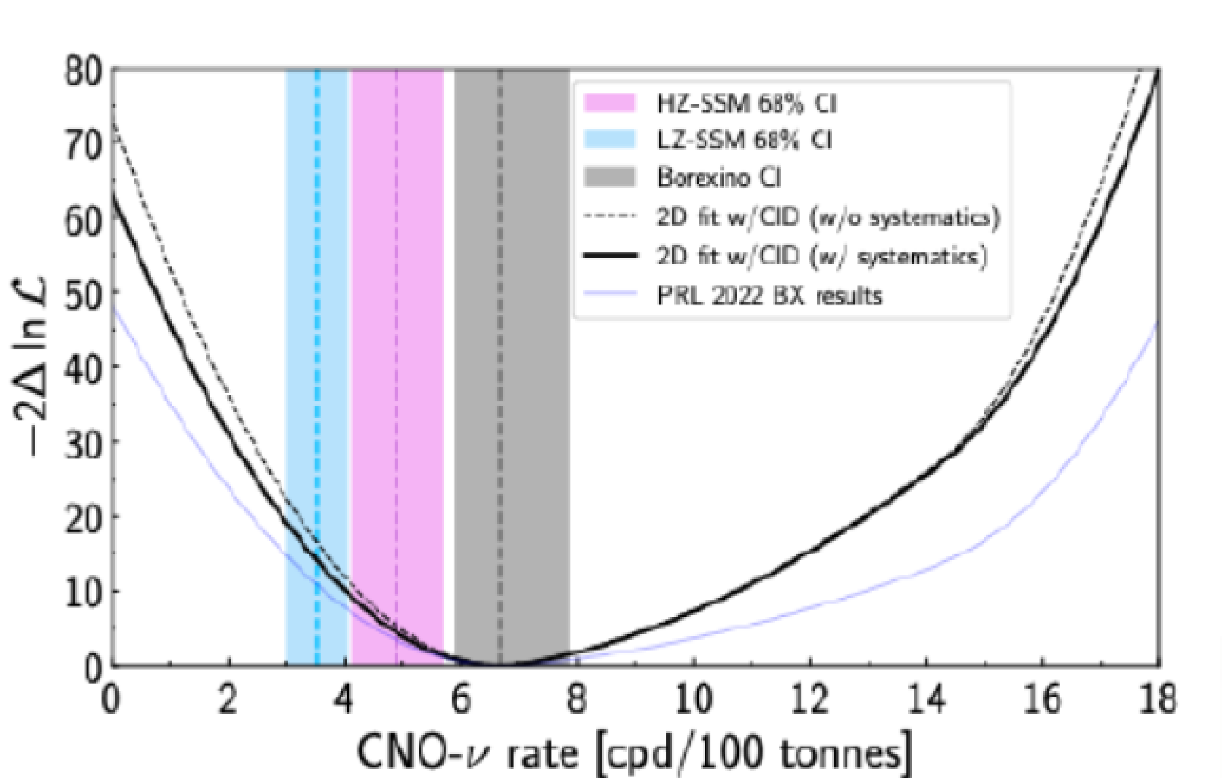
we cannot exclude in principle that residual ^{210}Po from the vessel surface would be present

Fit with pep and ^{210}Bi constrained

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

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

No CNO-excluded at 7σ C.L.



HAPPY BIRTHDAY JOHN!!!