Solar Neutrinos
A Path to Discovery

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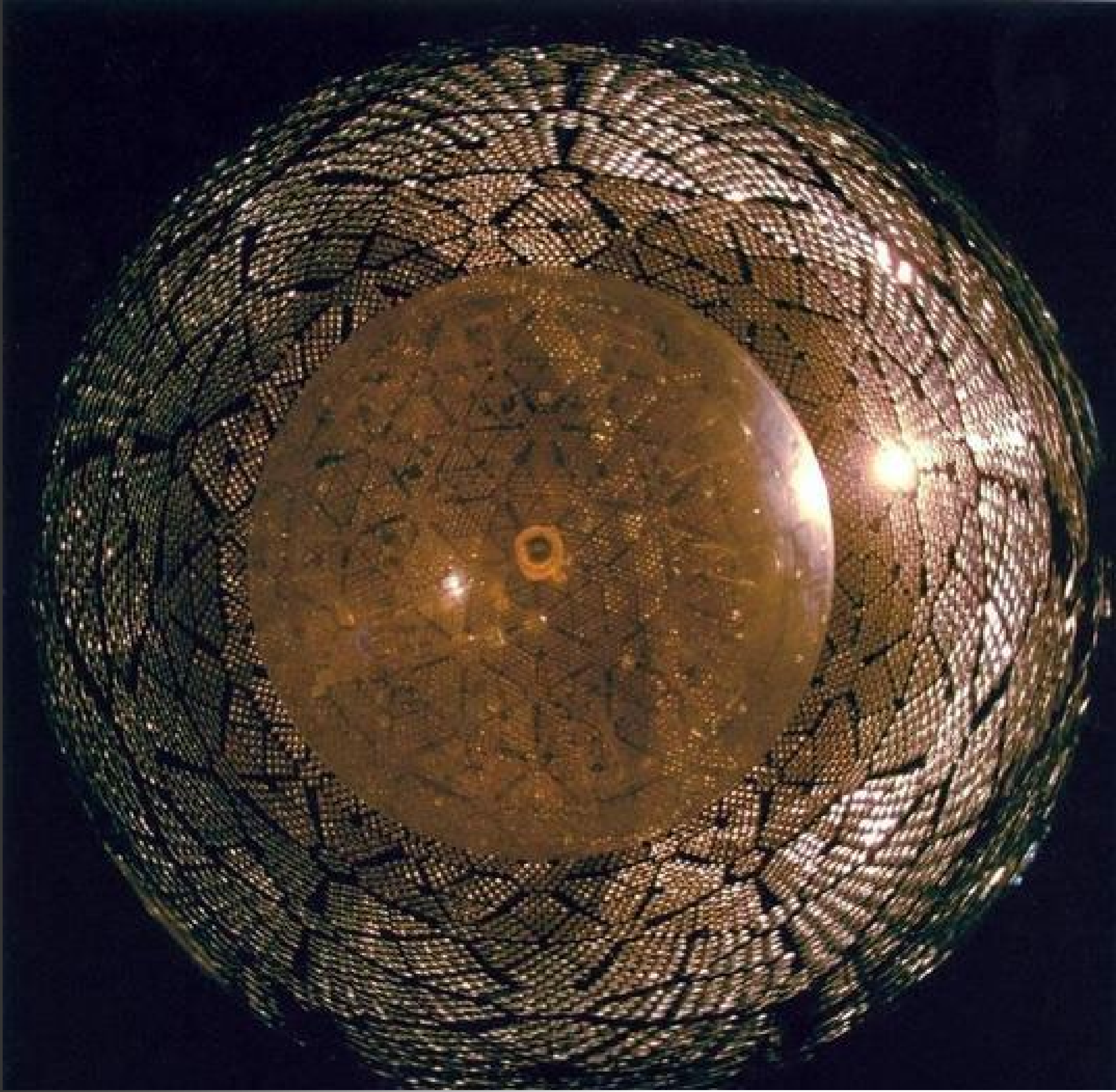
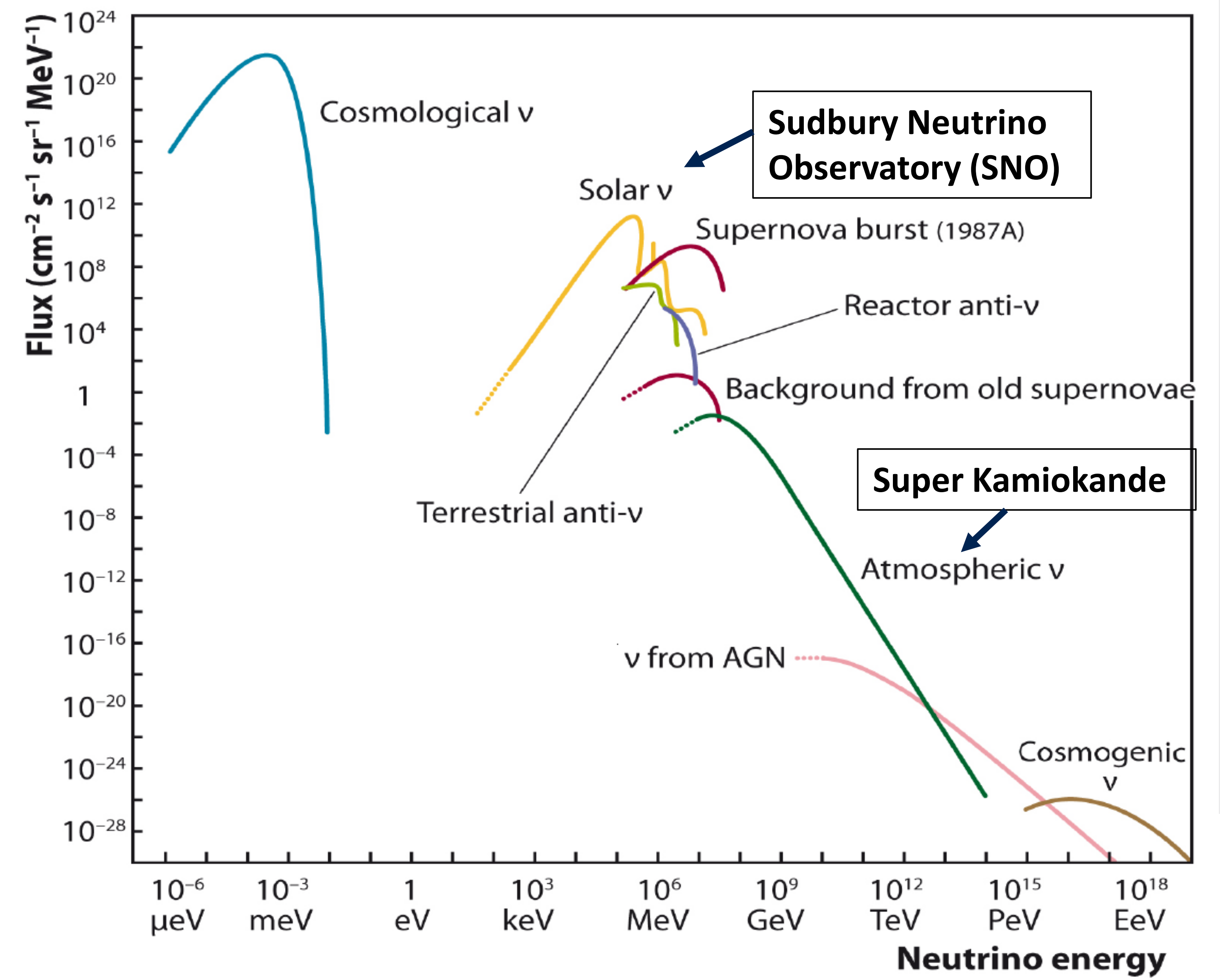
Paris

May 5, 2025



Neutrinos reaching the Earth

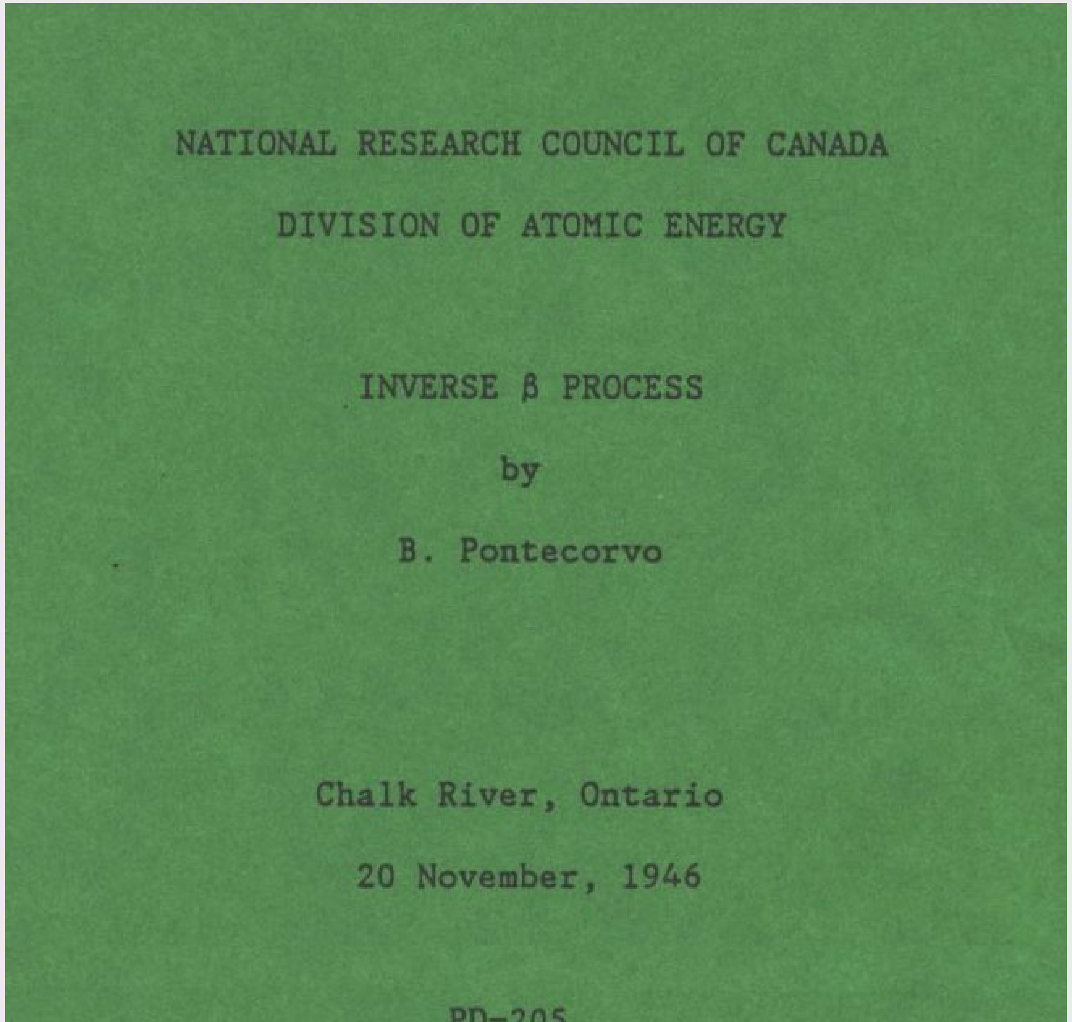


Sudbury Neutrino Observatory (SNO)

Super Kamiokande

Many Connections Between Bruno Pontecorvo and Solar Neutrinos

- **Science:**
  - He proposed chlorine as a detection medium for reactor and solar neutrinos: 1946
  - Developed proportional counters – used by Davis and SNO ^{3}He detectors: 1949
  - Proposed neutrino oscillations: 1957
  - Proposed oscillations as the explanation for the solar neutrino problem: 1968



NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF ATOMIC ENERGY

INVERSE β PROCESS

by

B. Pontecorvo

Chalk River, Ontario

20 November, 1946

PD-205

Бруно Понтекорво

1968: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible outcome of measurements of solar neutrinos.

Homestake Gold Mine

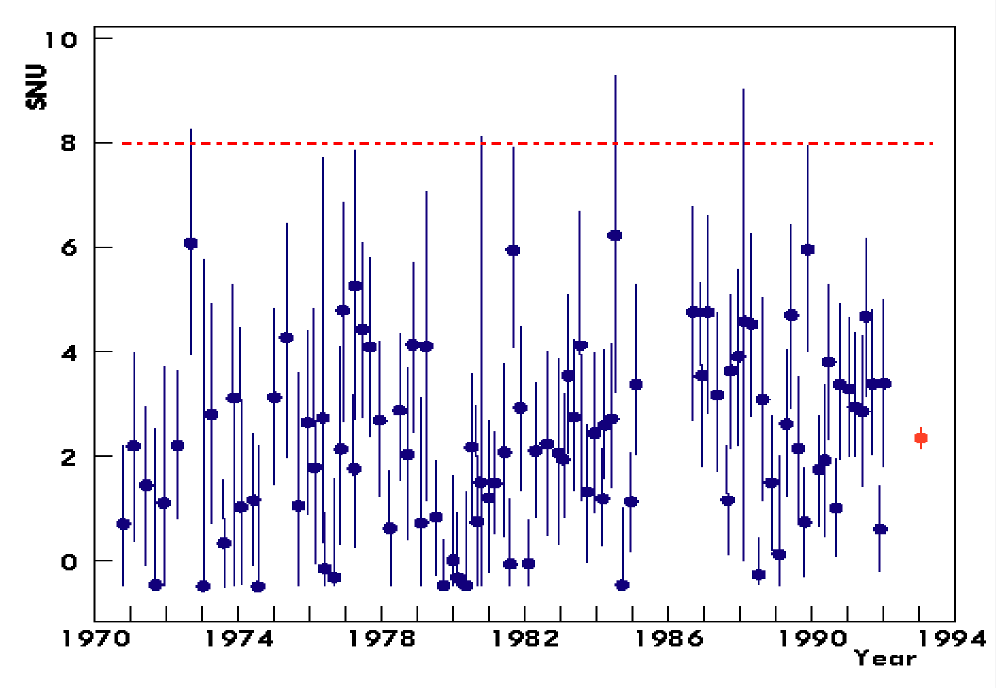
100,000 gallons of cleaning fluid C_2Cl_4

Expected 1.5 interactions per day
Measured 0.5 interactions per day

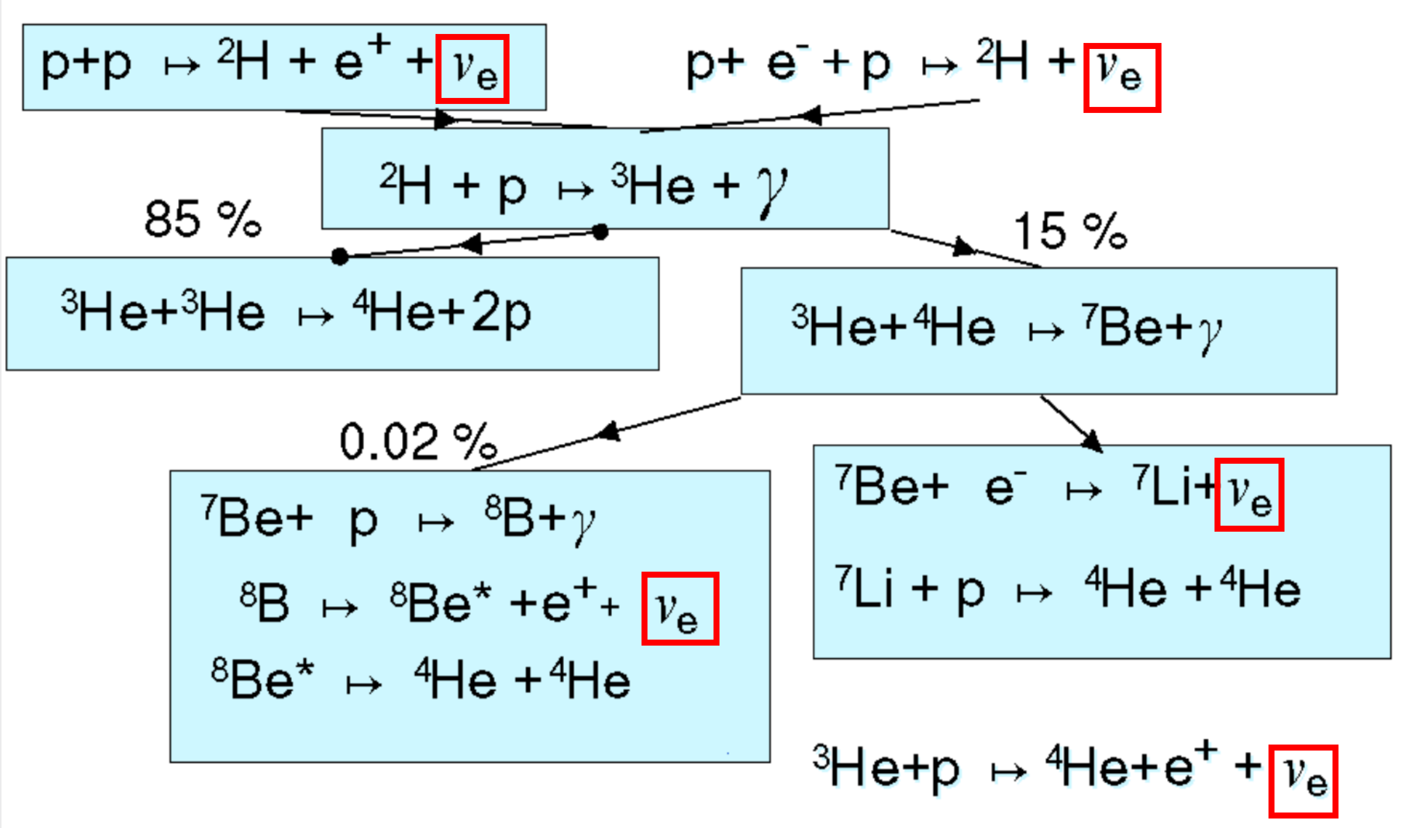
1968!

Sensitive to ^{8}B solar neutrinos only

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



SOLAR FUSION CHAIN



$p+p \mapsto {}^{2}H + e^{+} + \boxed{\nu_e}$

$p+ e^{-} + p \mapsto {}^{2}H + \boxed{\nu_e}$

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

85 %

${}^{3}He+{}^{3}He \mapsto {}^{4}He+2p$

15 %

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

0.02 %

${}^{7}Be+ p \mapsto {}^{8}B+\gamma$

${}^{8}B \mapsto {}^{8}Be^{*} + e^{+} + \boxed{\nu_e}$

${}^{8}Be^{*} \mapsto {}^{4}He + {}^{4}He$

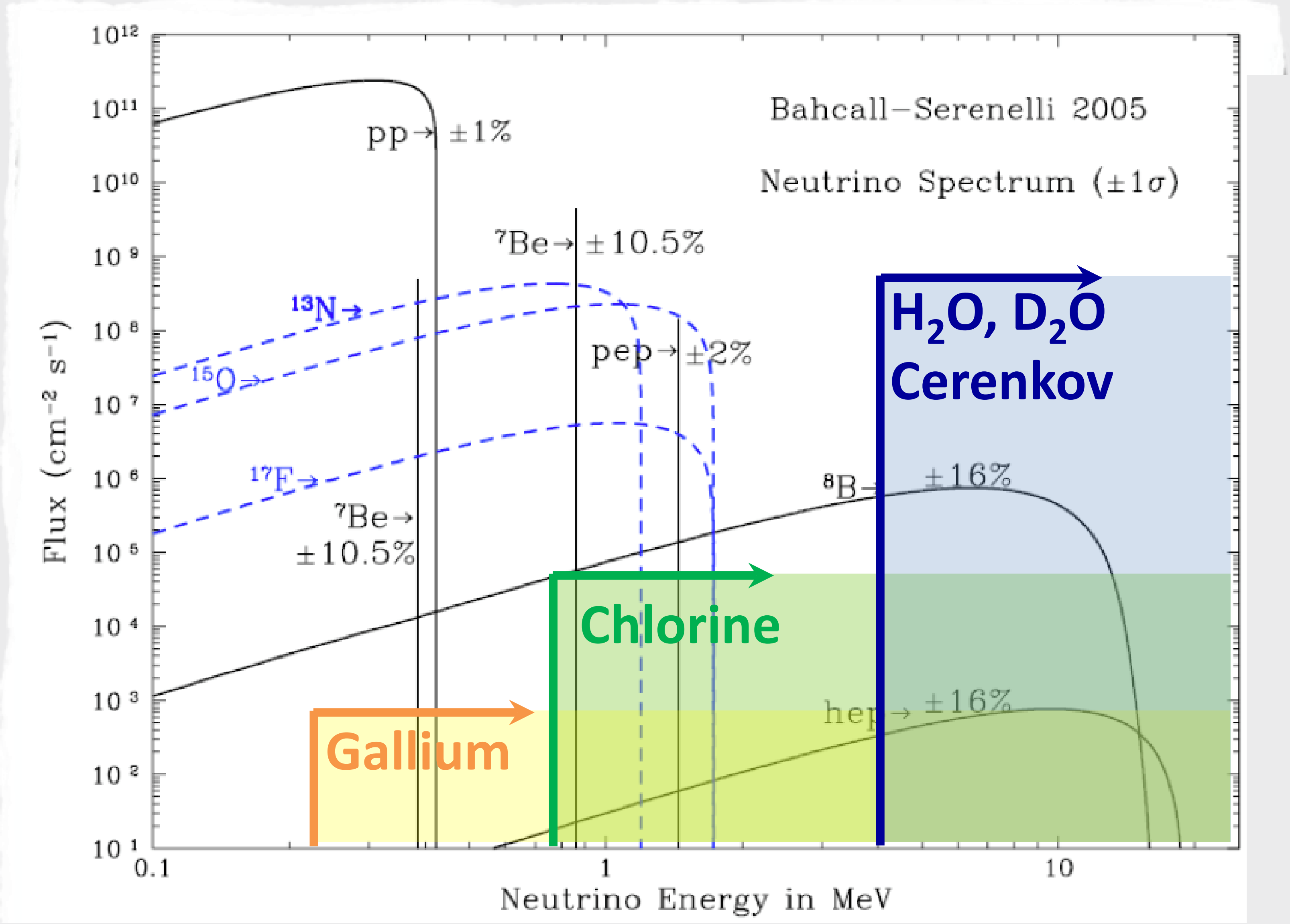
${}^{7}Be+ e^{-} \mapsto {}^{7}Li+\boxed{\nu_e}$

${}^{7}Li + p \mapsto {}^{4}He + {}^{4}He$

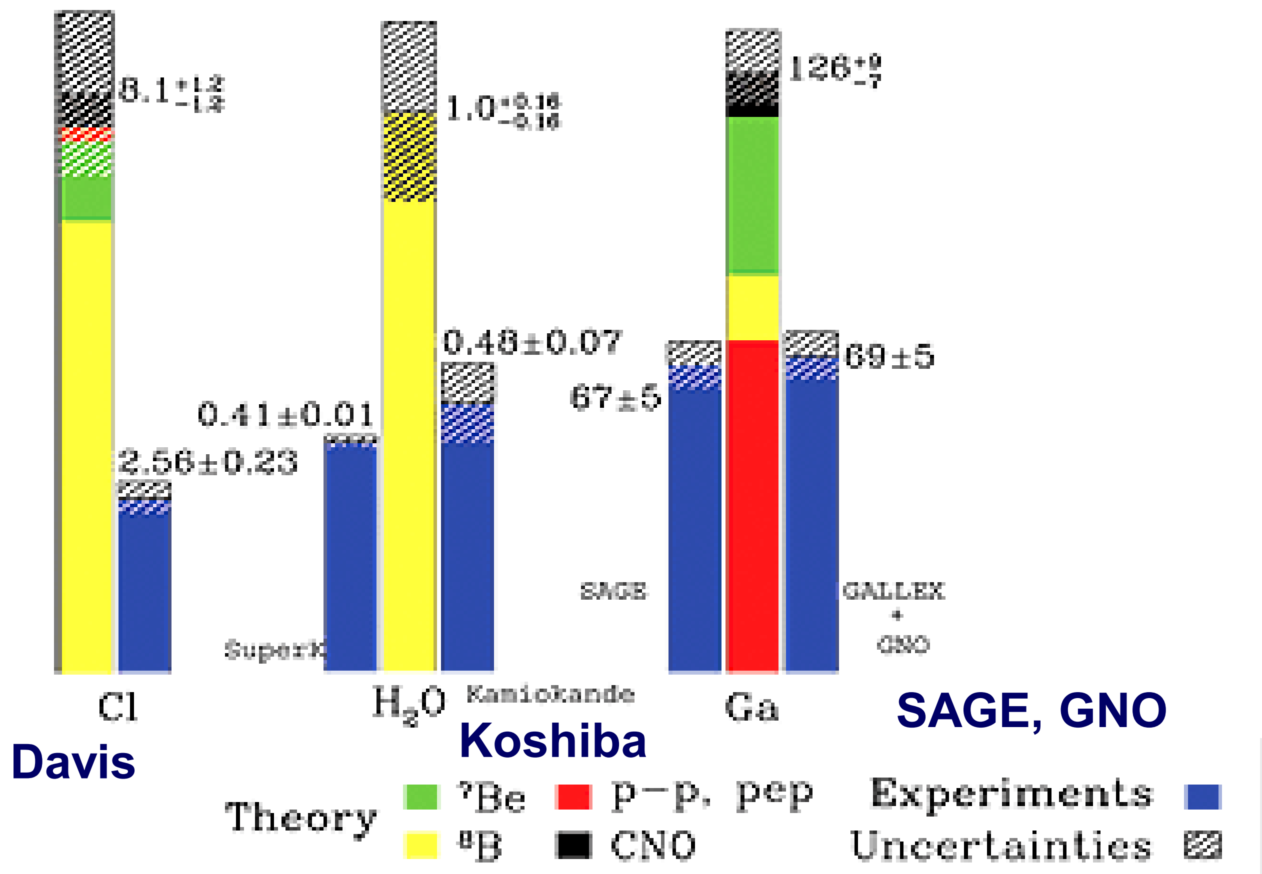
${}^{3}He+p \mapsto {}^{4}He+e^{+} + \boxed{\nu_e}$

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?



Davis

Koshiba

SAGE, GNO

Total Rates: Standard Model vs. Experiment
Bahcall−Serenelli 2005 [BS05(OP)]

“Solar Neutrino Puzzle”

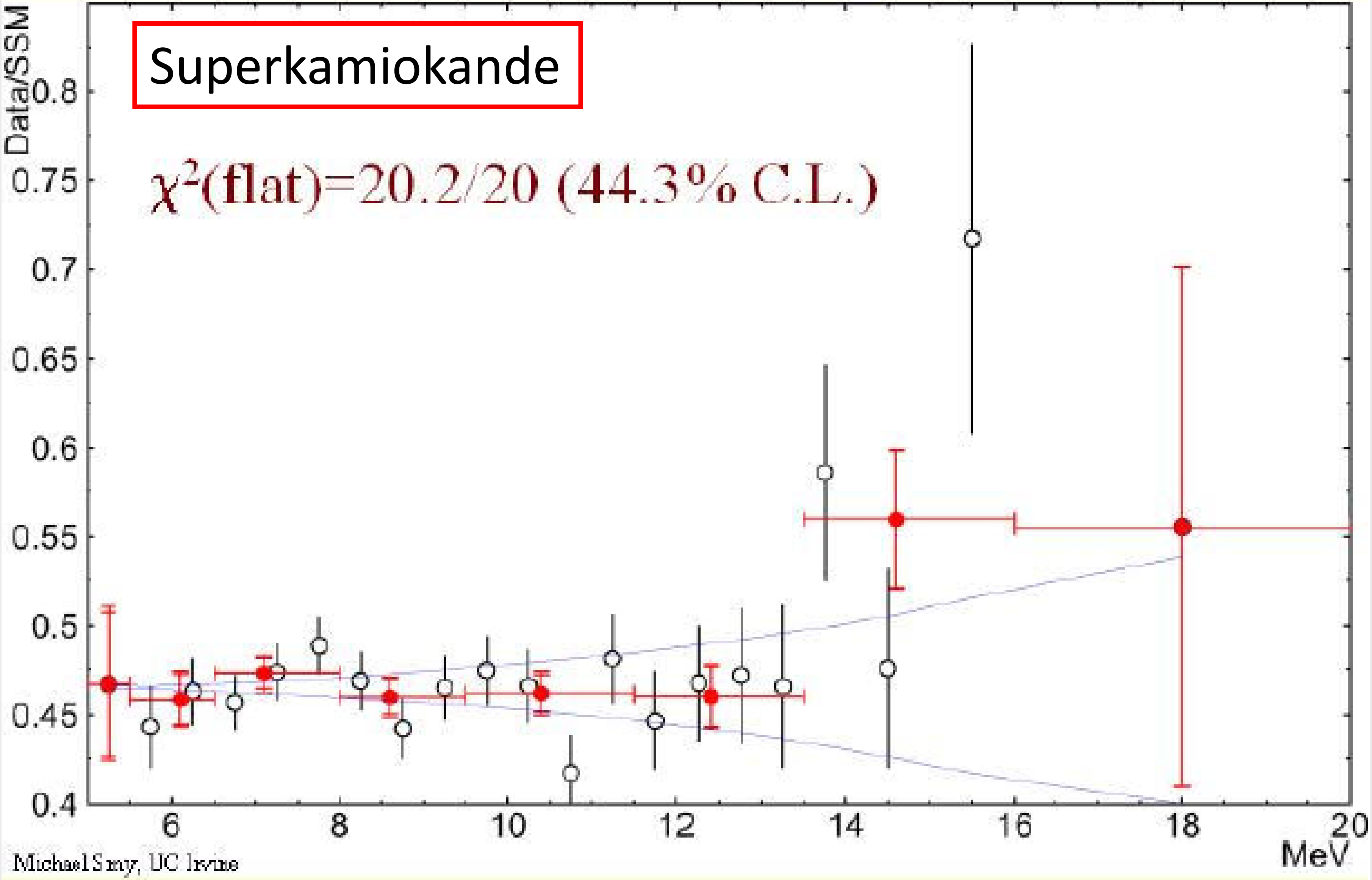
1967 - 2001

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

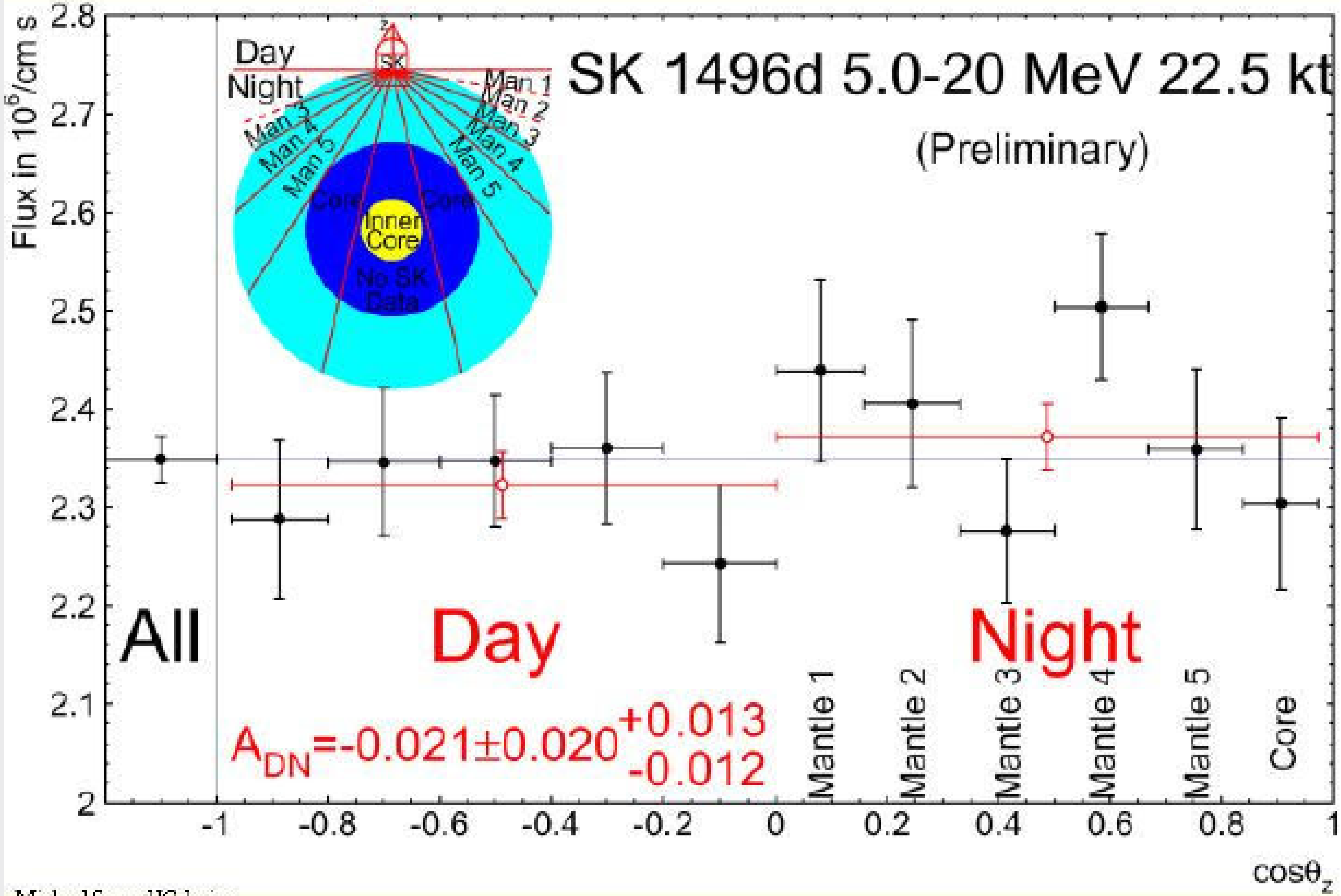


Superkamiokande

$\chi^2(\text{flat})=20.2/20$ (44.3% C.L.)

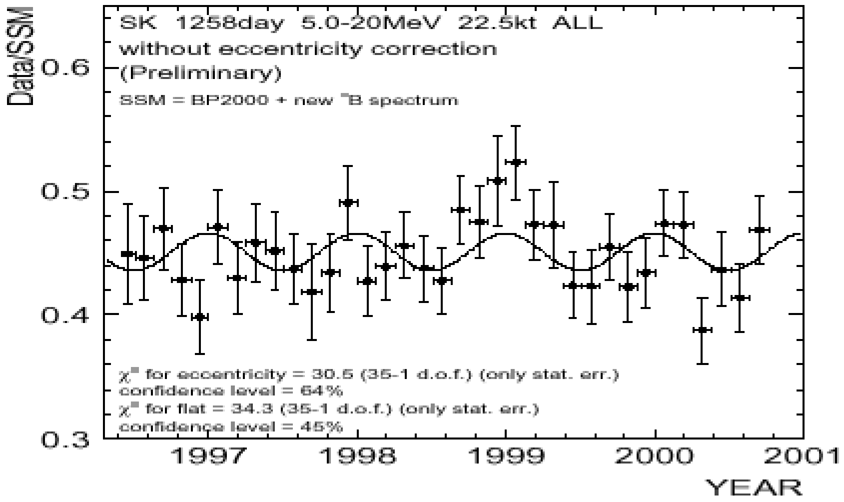
Michael Smy, UC Irvine

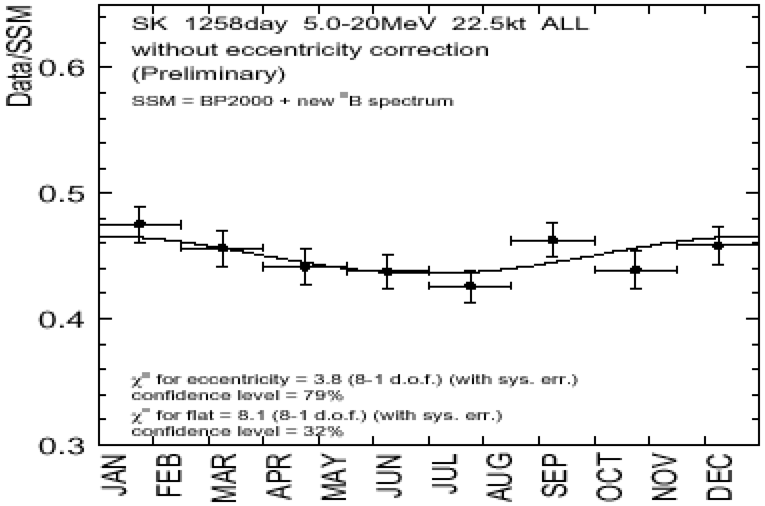
Daily Variation of SK Rate

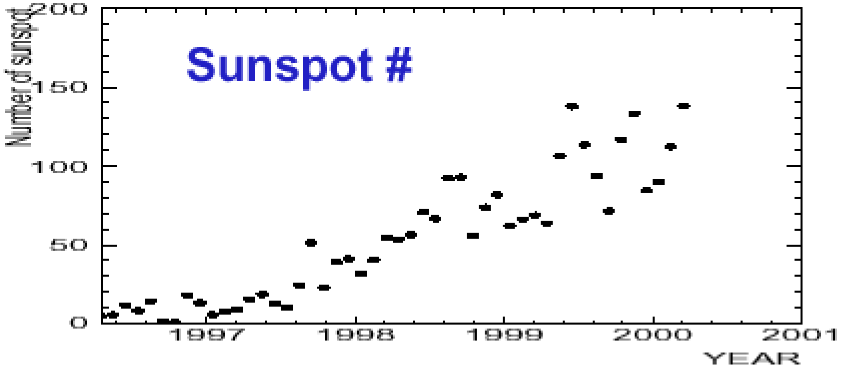


Time variation of the flux, seasonal

Superkamiokande





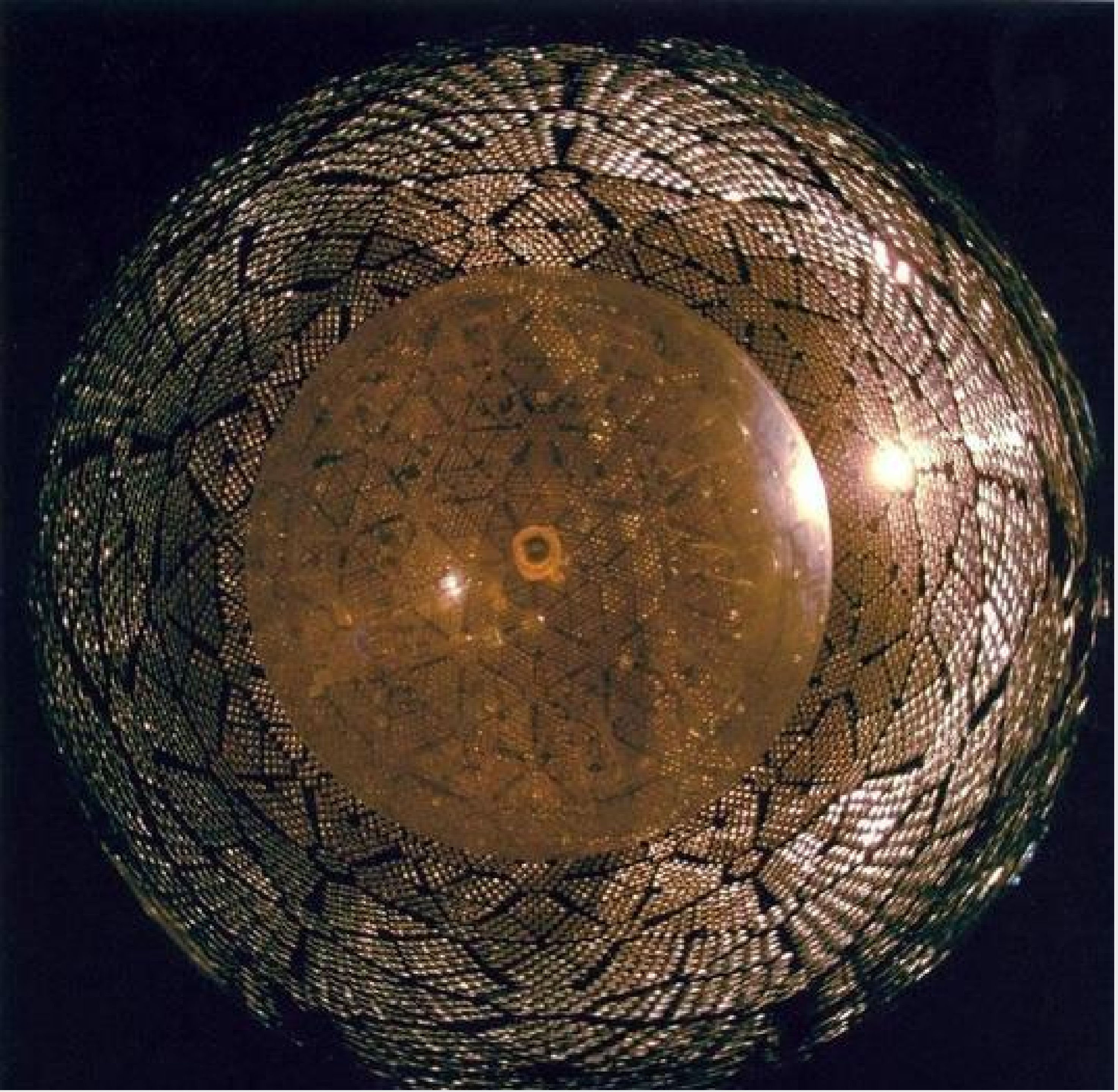


χ^2 for eccentricity:
3.9 / 7 d.o.f. (79% C.L.)

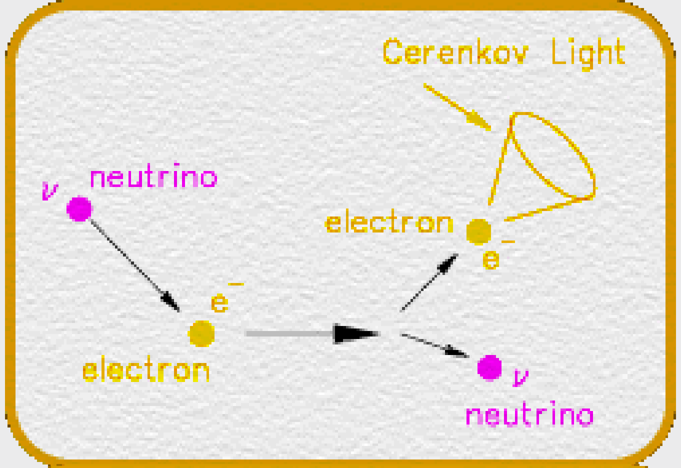
(χ^2 for flat: 8.1 / 7 d.o.f.

(32% C.L.))

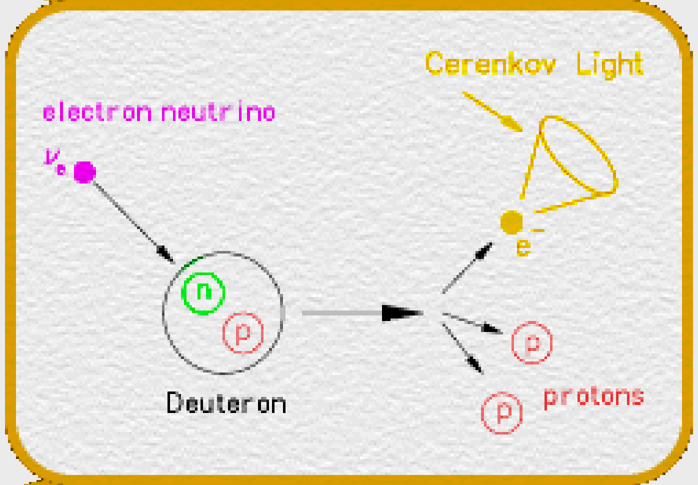
Also: Limit on Anti-electron neutrinos: few % of Standard Solar Model

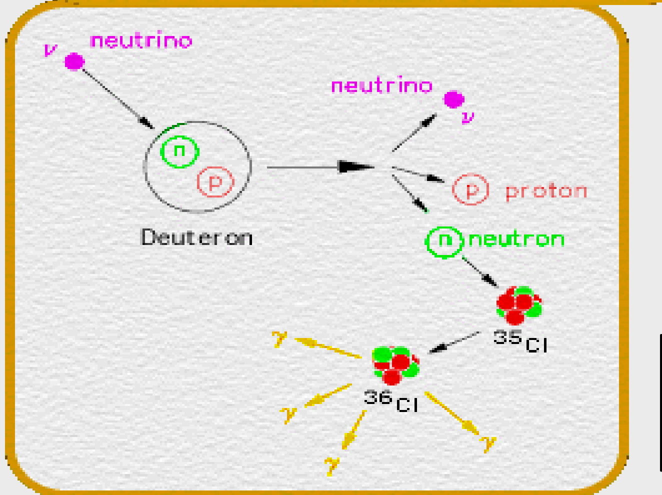


The Sudbury Neutrino Observatory (SNO)



D_2O





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

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

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)

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) ^{3}He 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

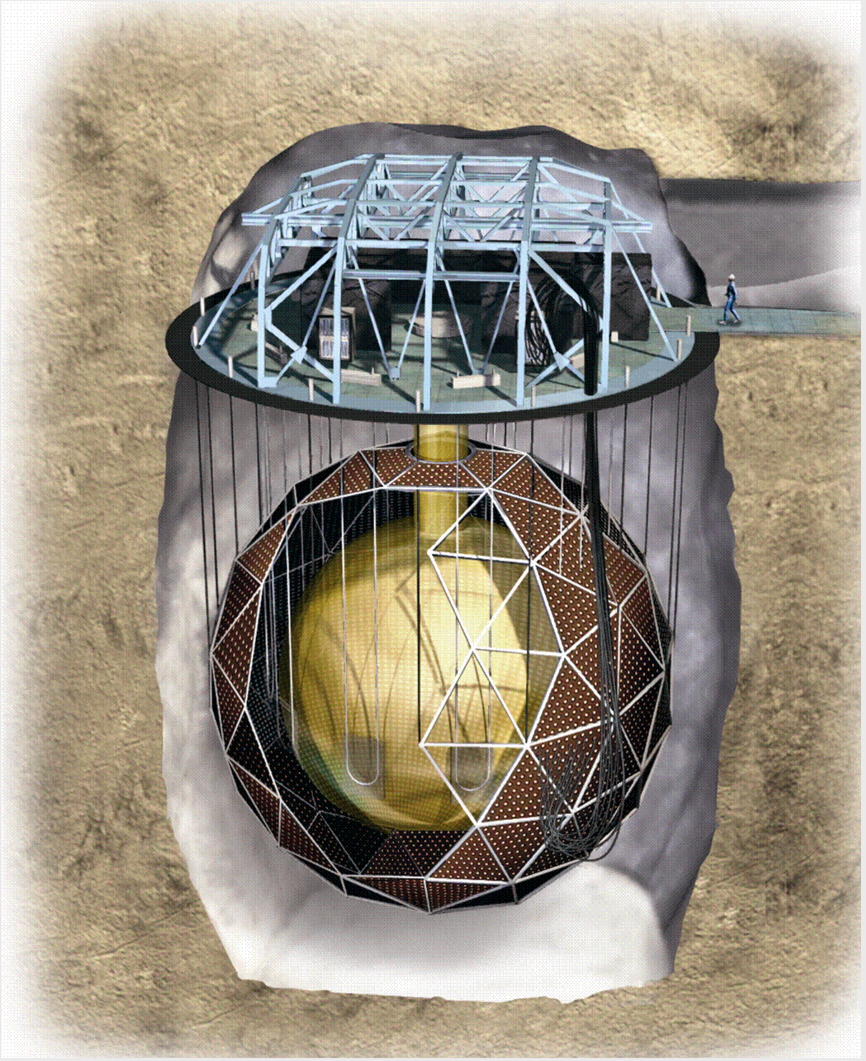
Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O
(\$300 million)

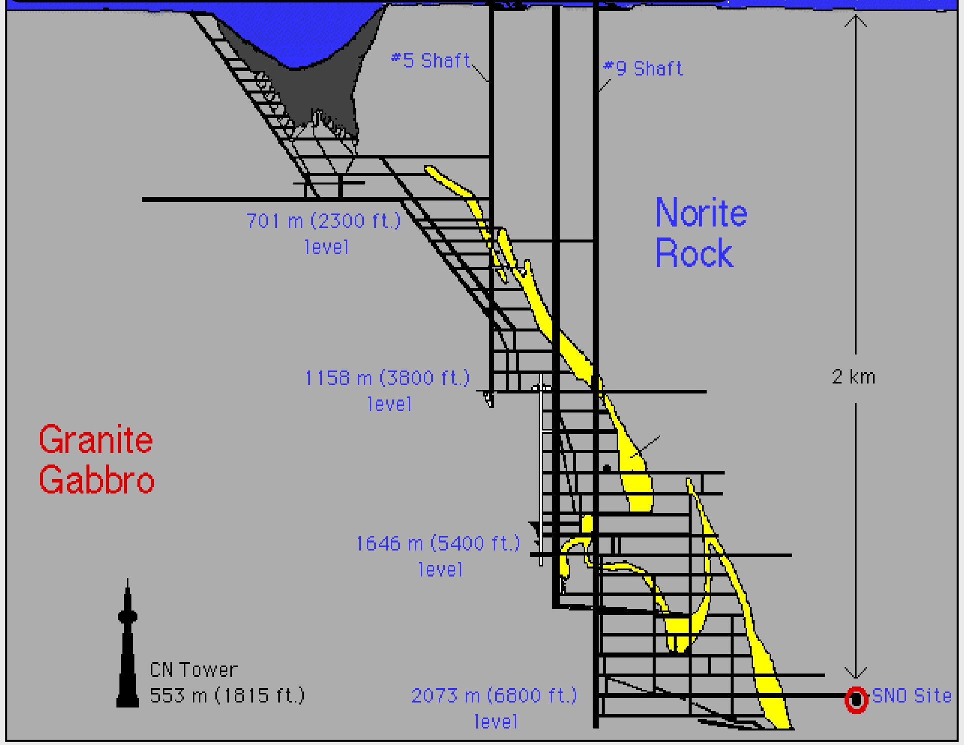
1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
outer shielding

~9500 PMT's

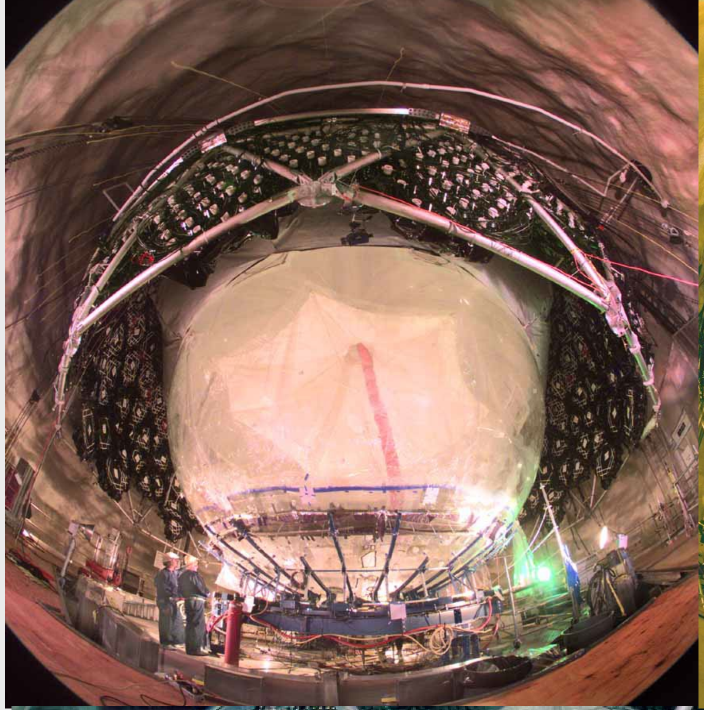


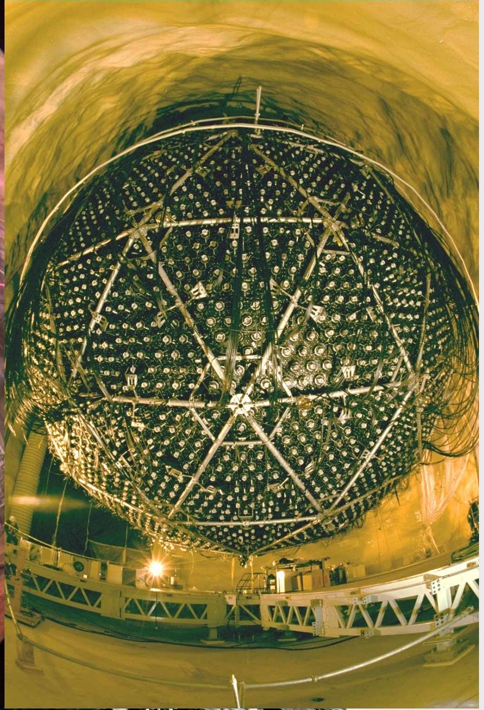
6800 feet (~2km) underground



Creighton mine
Sudbury, CA

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

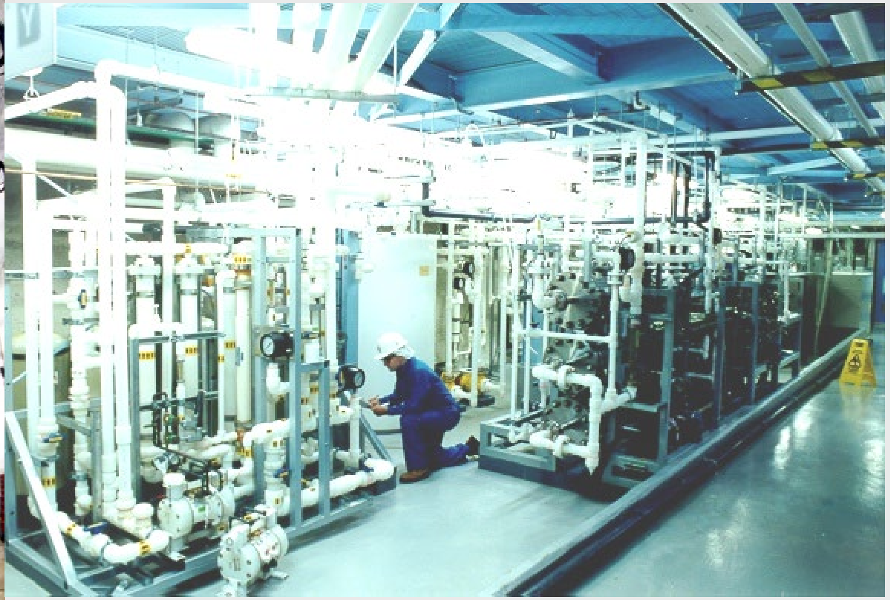




One million pieces
transported down in the
10 foot square mine
cage and re-assembled under
ultra-clean conditions.

More than 70,000 showers.

Ultra-pure water systems.

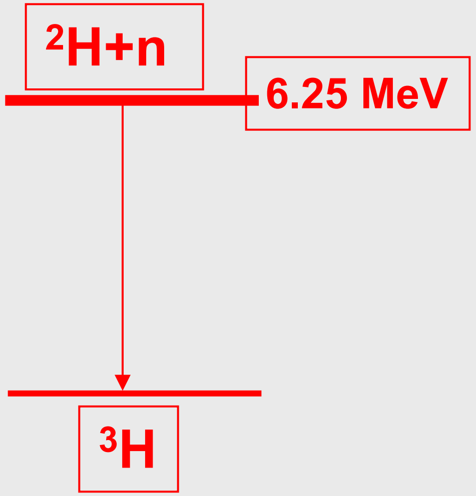


SNO: 3 neutron detection methods for ν_{all} reaction.

Phase I (D_2O)

Nov. 99 - May 01

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

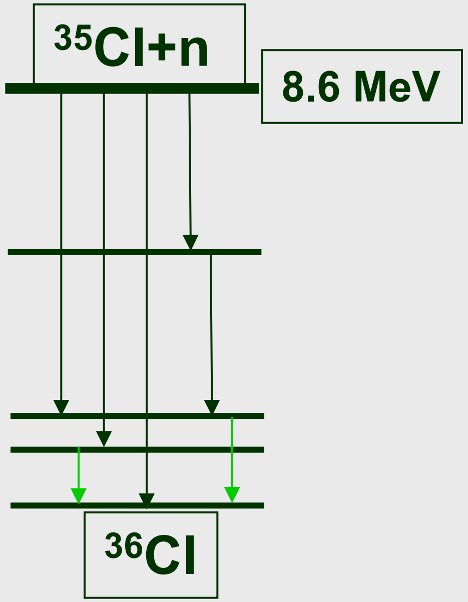


Demonstrate Neutrino
Flavor Change clearly

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

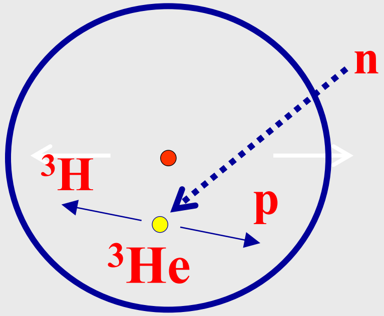


Measure Total Flux
of all Neutrino types (ν_{all}),
Compare with solar models.

Phase III (^3He)

Nov. 04-Dec. 06

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



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

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

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

Measuring U/Th Content

Ex-situ

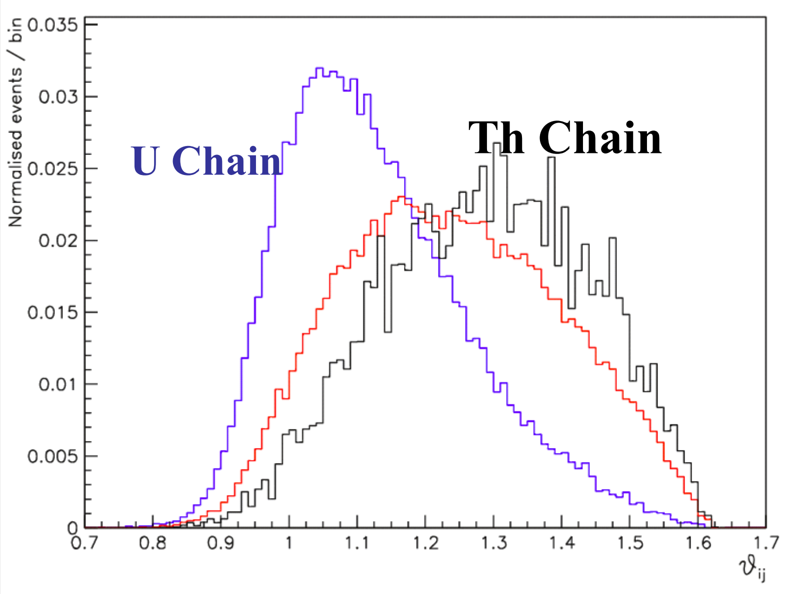
- Ion exchange (^{224}Ra, ^{226}Ra)
- Membrane Degassing (^{222}Rn)

count daughter product decays

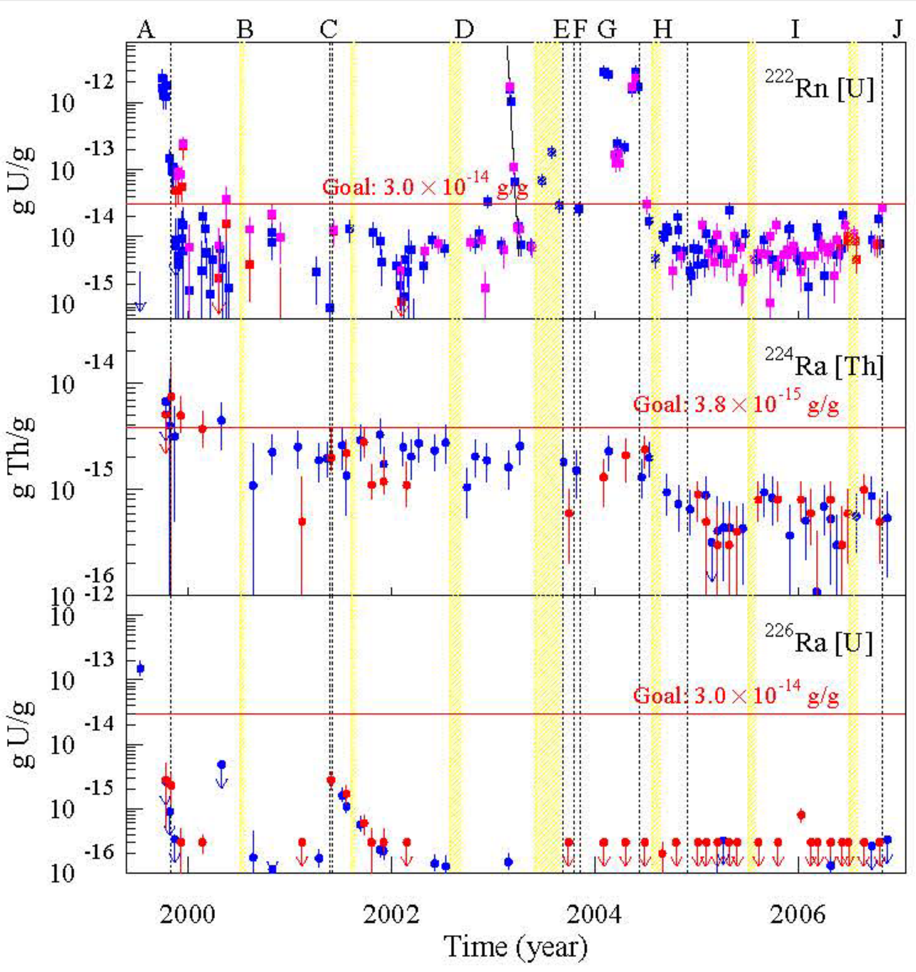
In-situ

- Low energy data analysis
- Separate U and Th Chains

Using Event isotropy



Isotropy

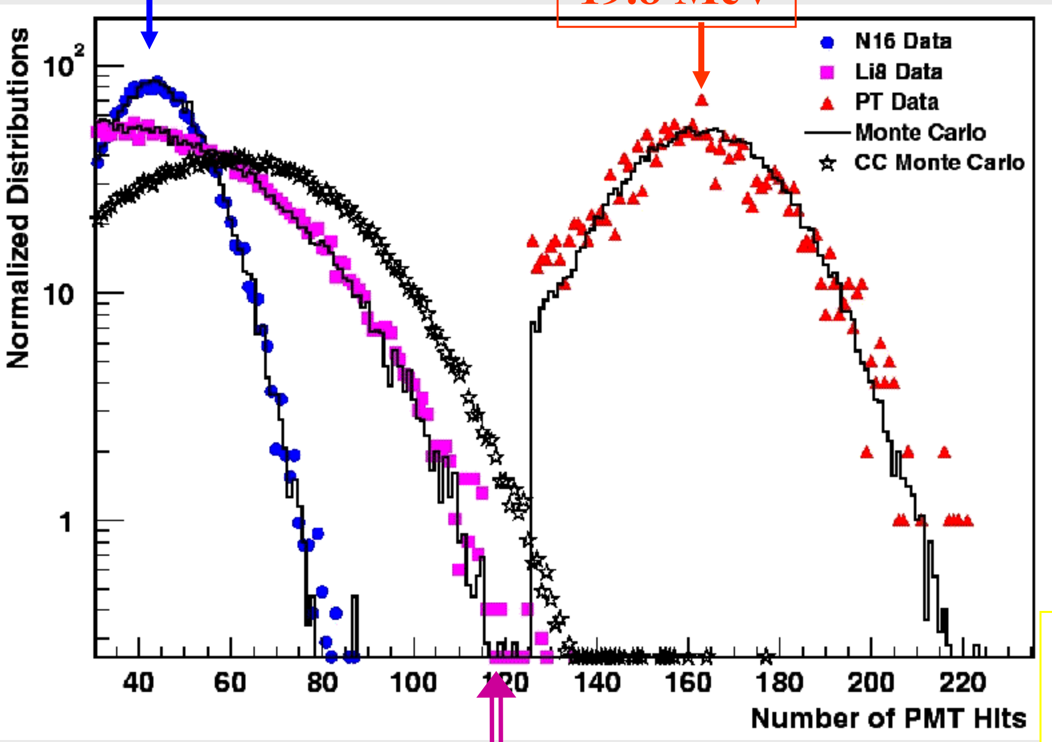


Objective met and measured: Less than one radioactive decay per day per tonne of heavy water

SNO Energy Calibrations

6.13 MeV

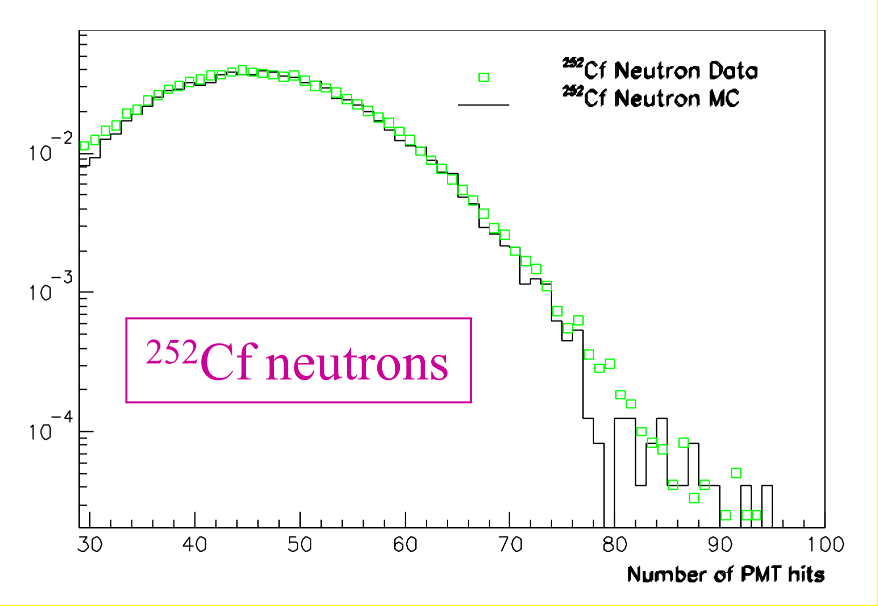
19.8 MeV



Detailed Detector Mapping with LaserBall, ^{16}N, ^{252}Cf, ^{238}U, ^{232}Th

β's from ^{8}Li
γ's from ^{16}N and t(p,γ)^{4}He

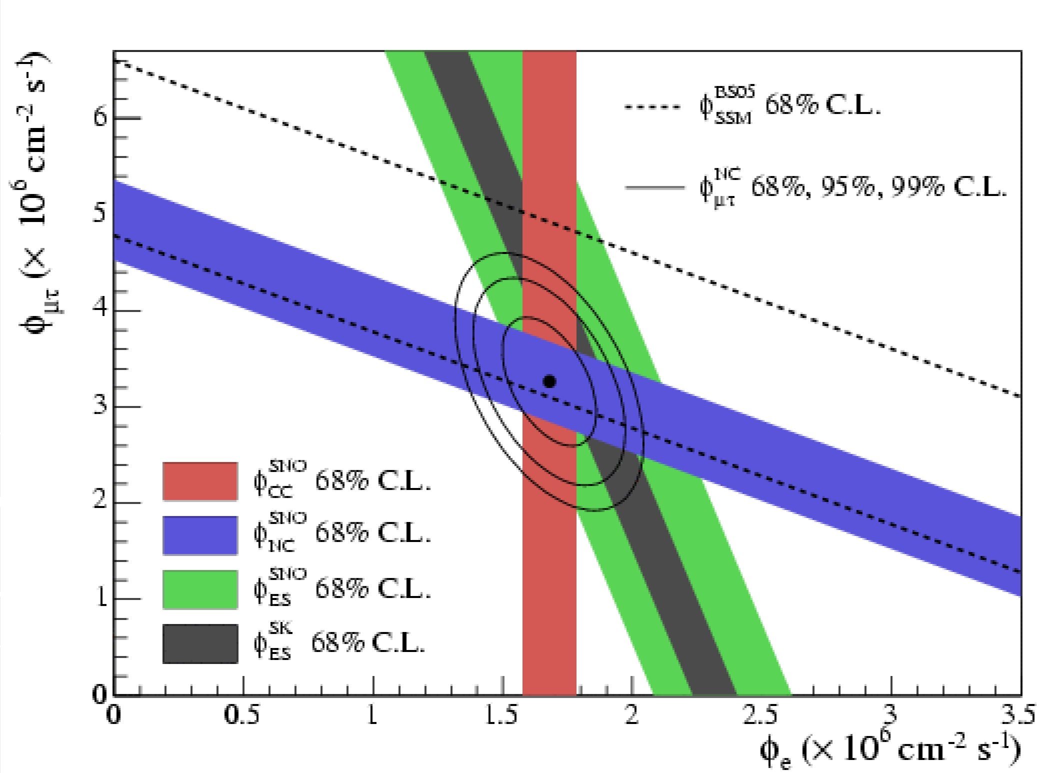
Radioactivity: Rn and encapsulated U and Th



^{252}Cf neutrons

SNO Salt Phase

CC, NC FLUXES MEASURED INDEPENDENTLY



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)

Fluxes

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

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

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

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

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

Improved accuracy for θ_{12}.

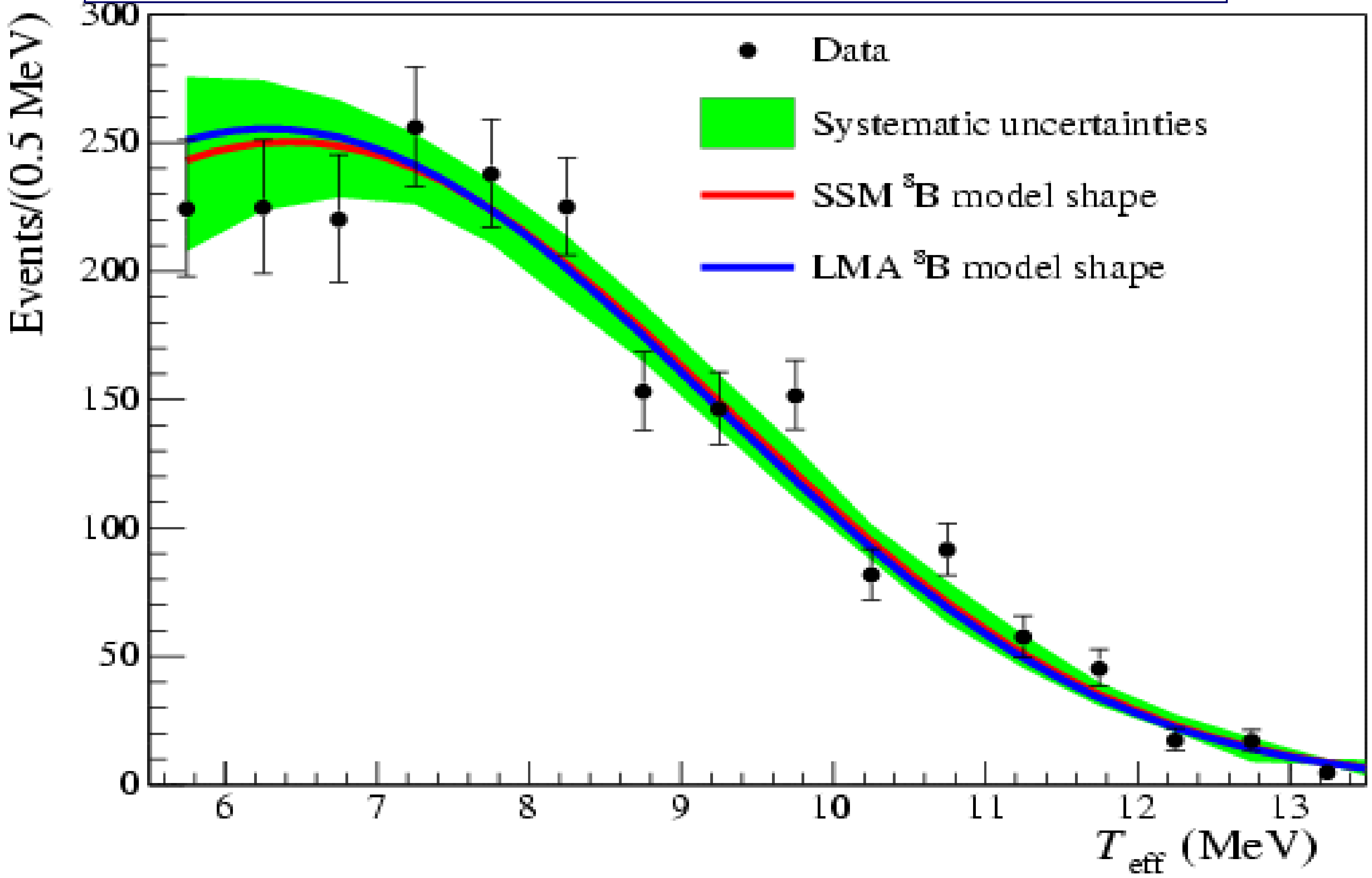
Flavor change is determined with > 7 σ

Data from Experiments in Operation

The latest 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

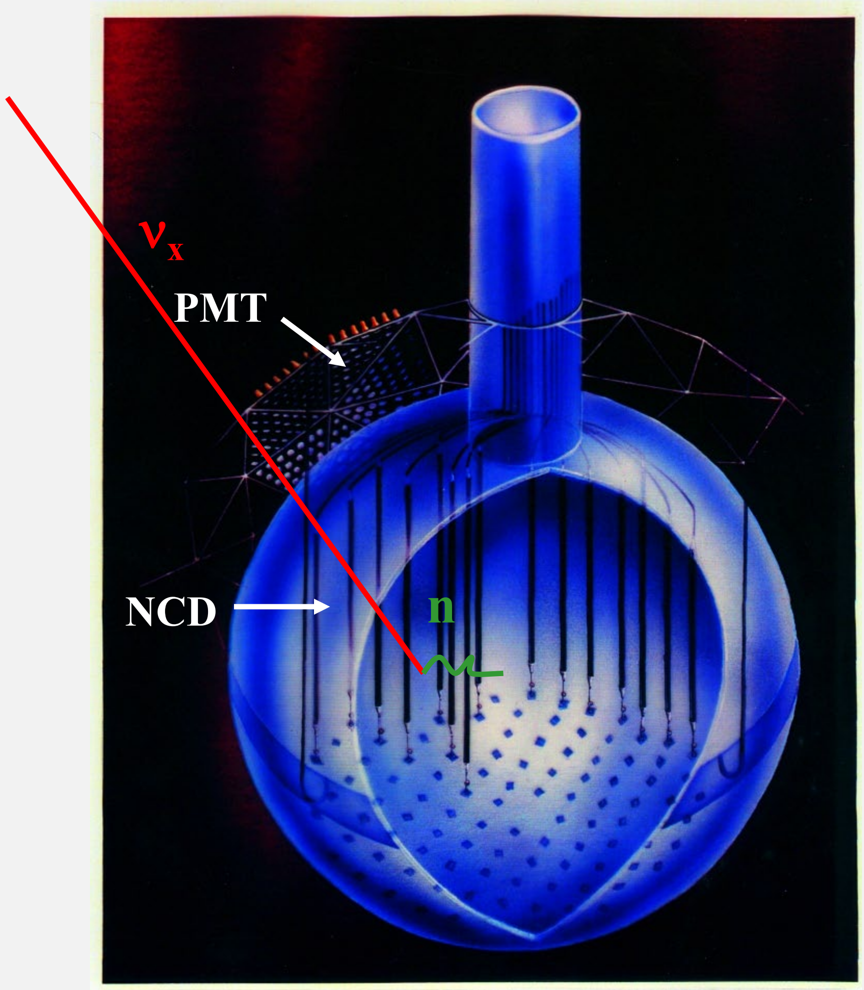
$$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22\ \text{MeV} \qquad \text{(NC)}$$

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

Physics Motivation

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

Different systematic uncertainties than neutron capture on NaCl.

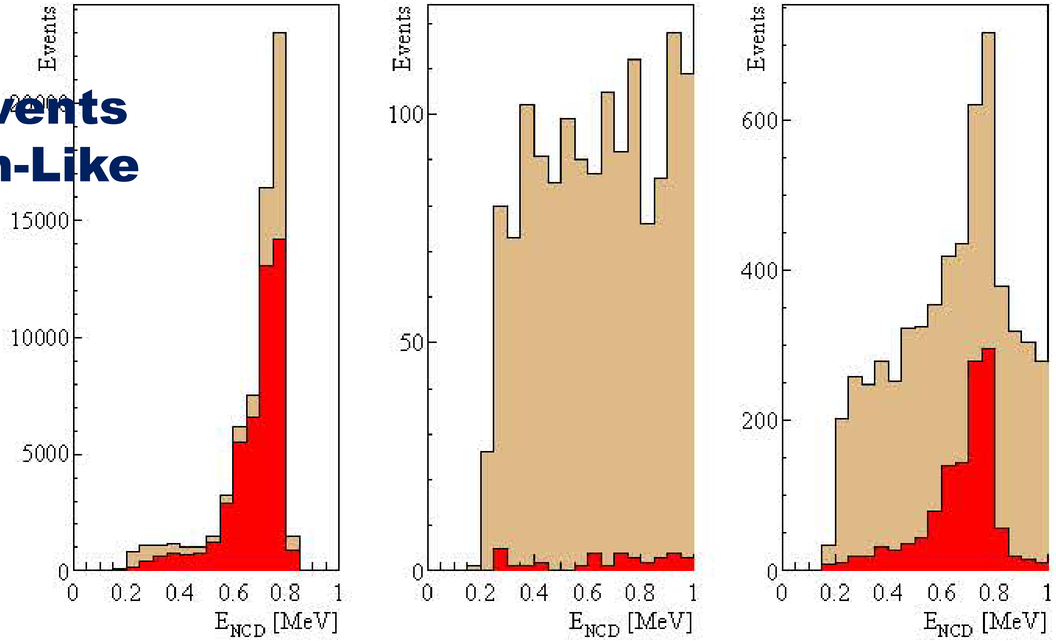


Final Complete Analysis of SNO solar data

Presented at TAUP2011 in Munich Sept. 5, 2011: arXiv:1109.0763v1

NCD pulse shape analysis to identify neutron events

Brown: All events
Red: Neutron-Like



^{3}He detectors: neutron source

^{4}He detectors: alpha backgnd

^{3}He detectors: neutrino data

$$CC/NC = 0.317 \pm 0.016(stat) \pm 0.009(syst)$$

implies flavor change at far more than 7 σ

Full joint analysis of solar data from all three phases provides best sensitivity with all correlations, backgrounds, systematic uncertainties included.

S. Habib thesis(Alberta)

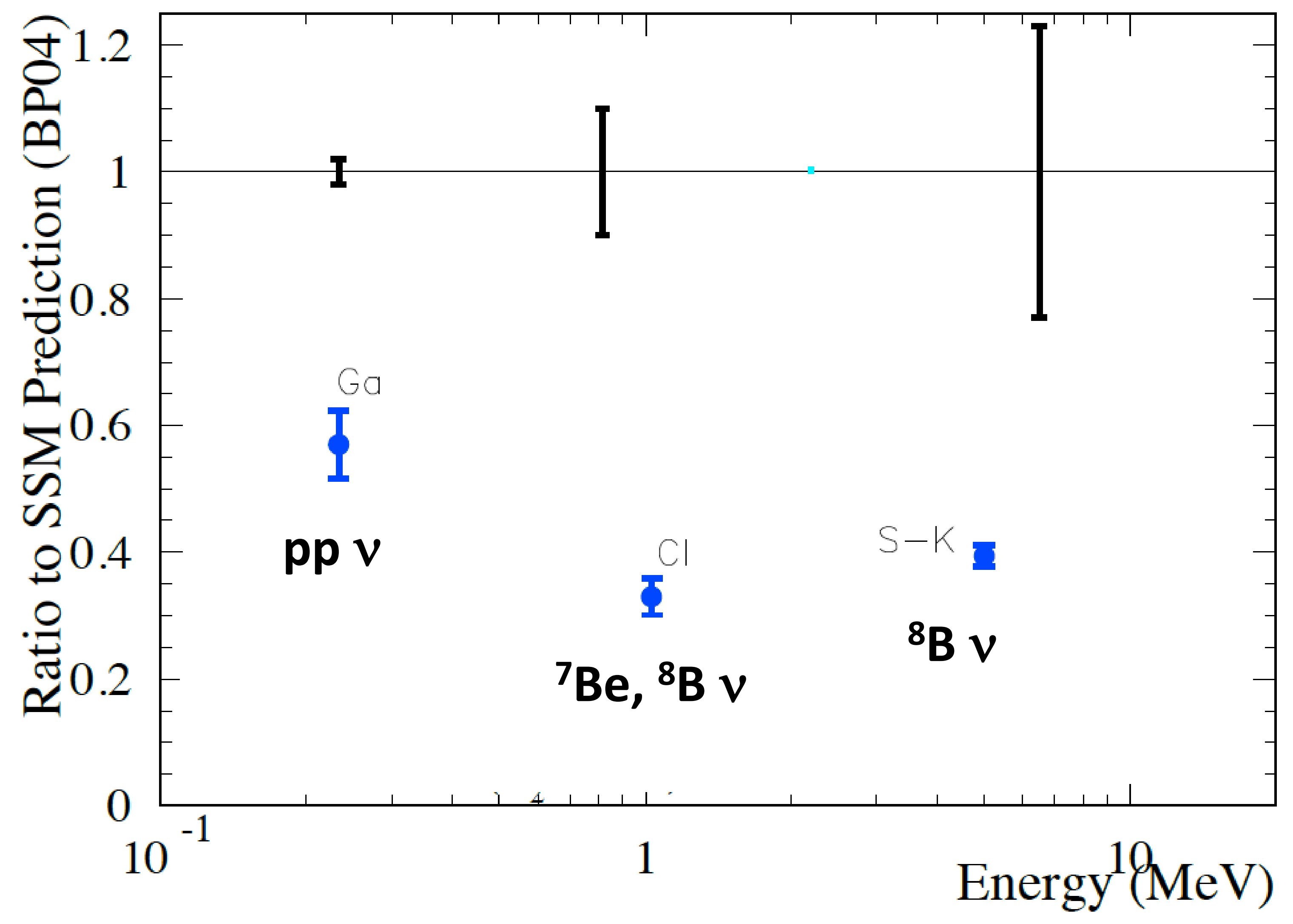
Individual results from all three phases are very consistent within uncertainties

$$\Phi_{^8B} = 5.25 \pm 0.16 \begin{array}{l} +0.11 \\ -0.13 \end{array}$$

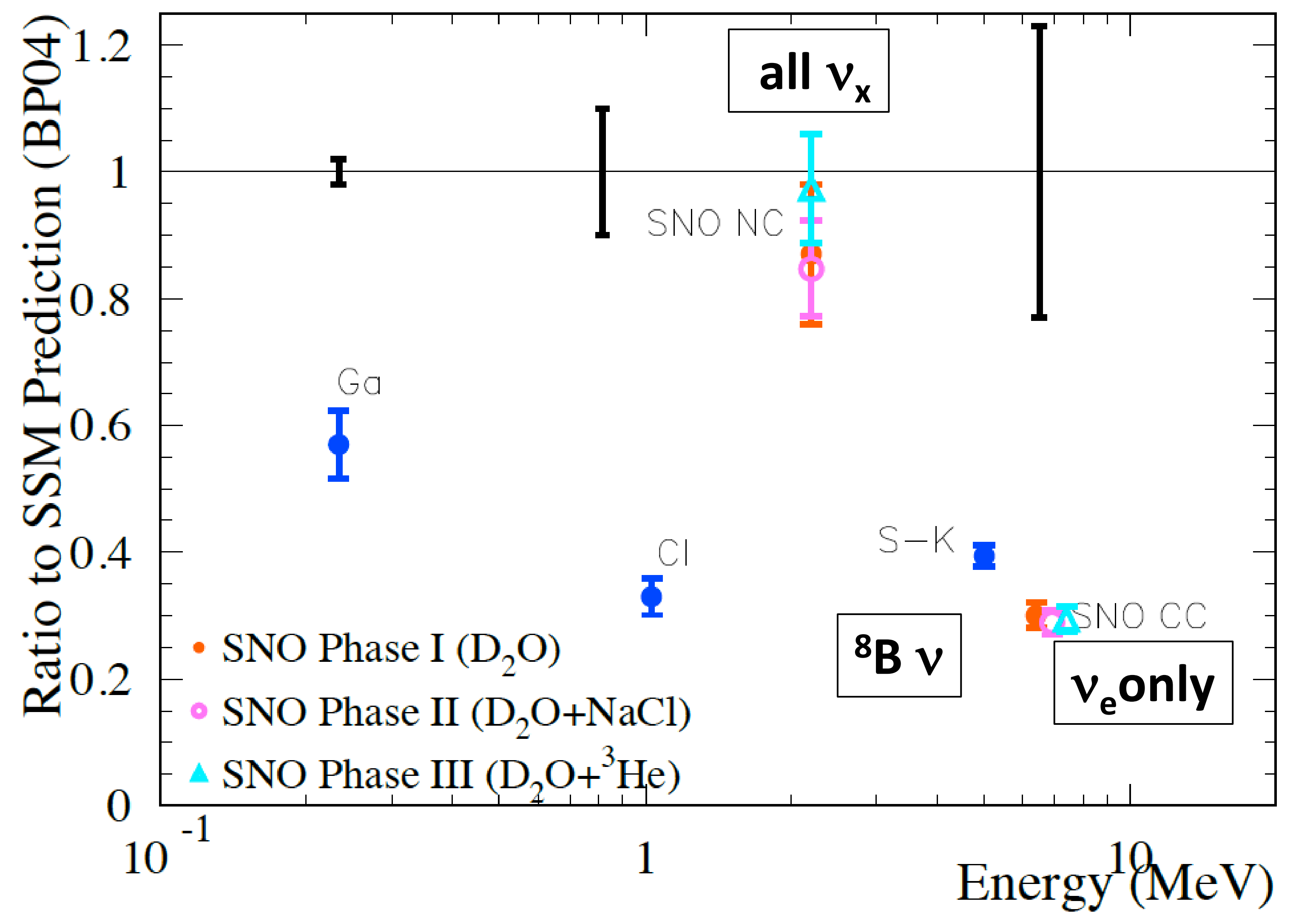
More accurate than current solar models and lying between the fluxes predicted for two values of metallicity in the sun

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**

Range defined for Δm_{12}, Δm_{23} ✓

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

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

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

Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenstein)

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

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

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:

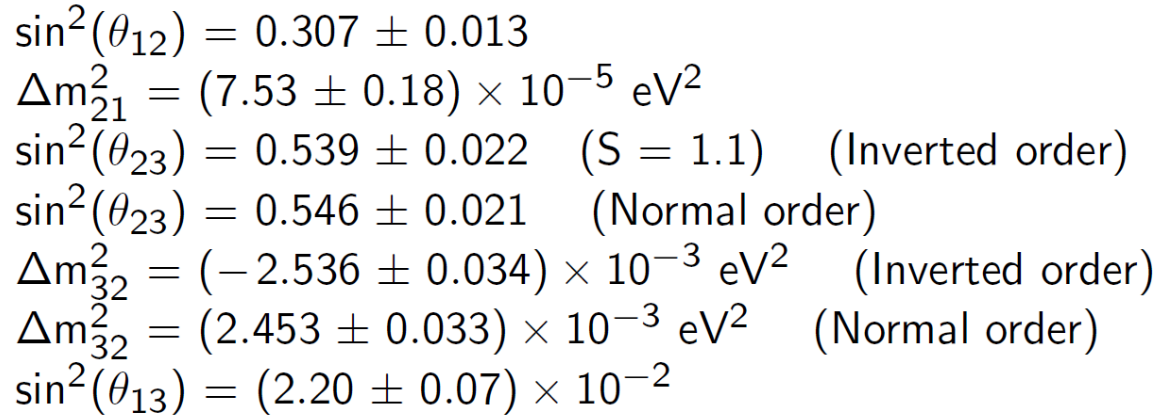
$$\sin^2 2\theta_m=\frac{\sin^2 2\theta}{(\omega-\cos 2\theta)^2+\sin^2 2\theta}$$

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

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)

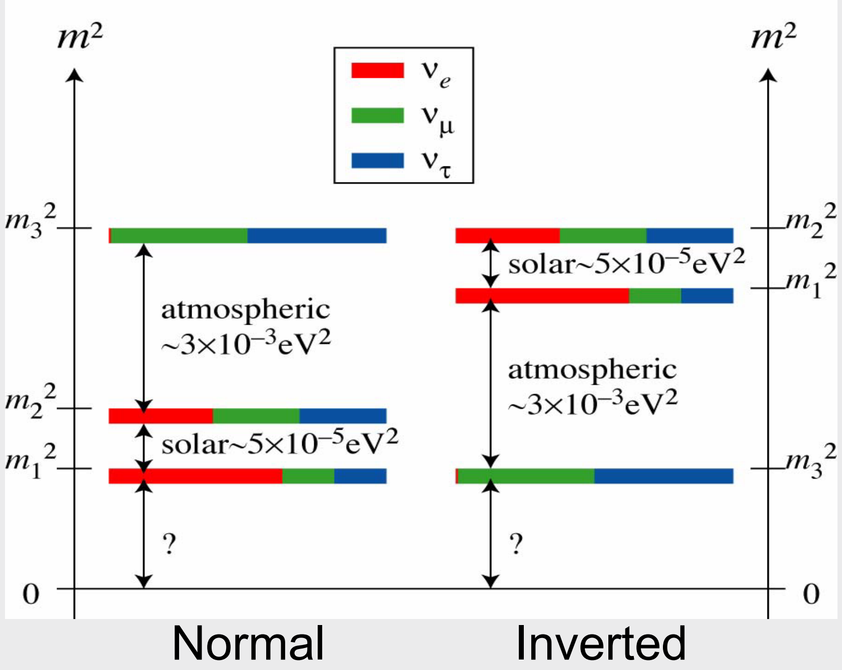
$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

Solar, Reactor

Atmospheric,Accelerator

Reactor, Accelerator

Mass Hierarchies

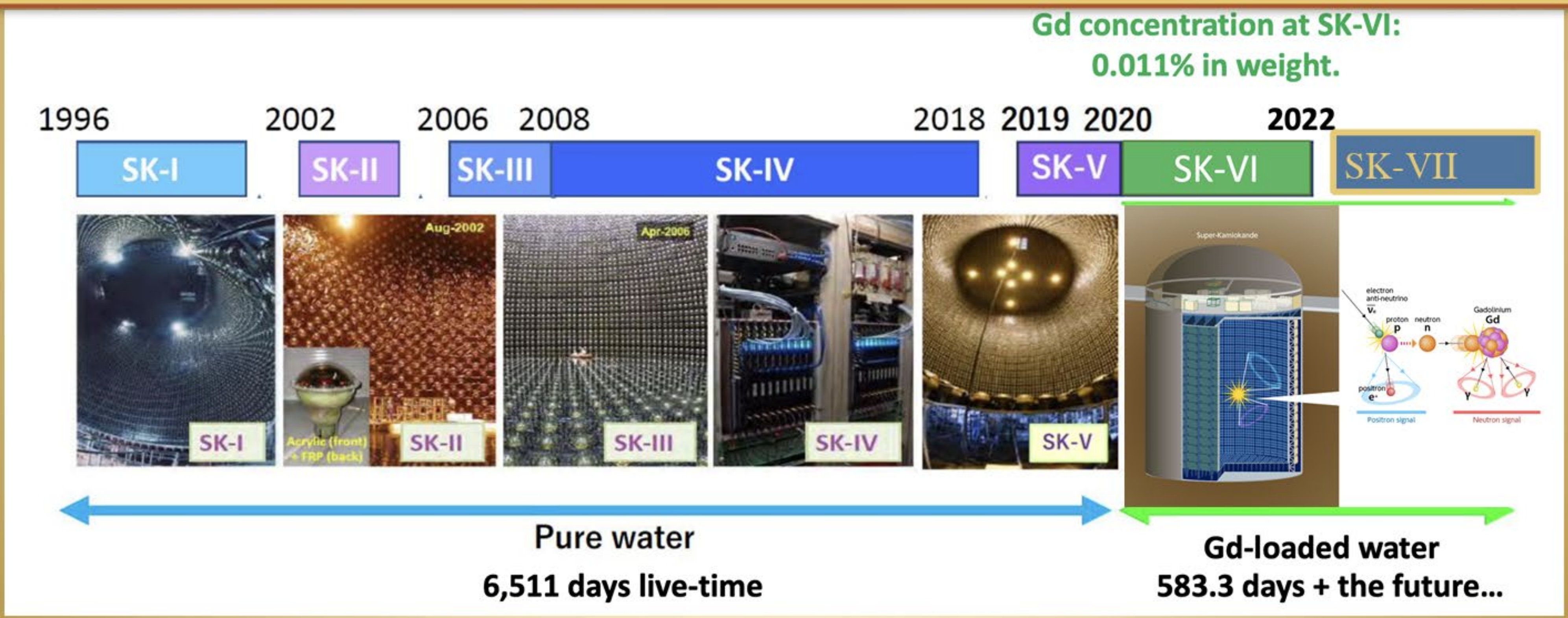


Future objectives:

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

The Super-Kamiokande experiment

- Super-Kamiokande has been taking data since 1996 and has come through seven run periods
- Densely packed PMTs (40% / 20% for SK-II) and good water quality provide excellent sensitivity for various physics targets.
- In 2020 we have added Gd sulfate to the water in order to increase the sensitivity for neutron capture.



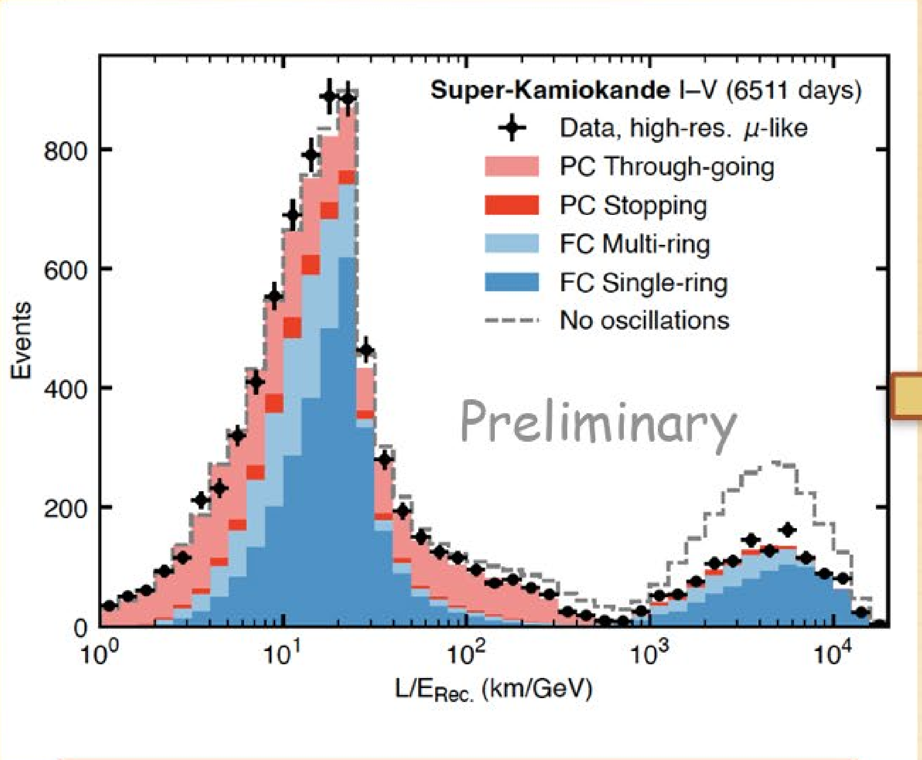
Gd concentration at SK-VI: 0.011% in weight.

Pure water
6,511 days live-time

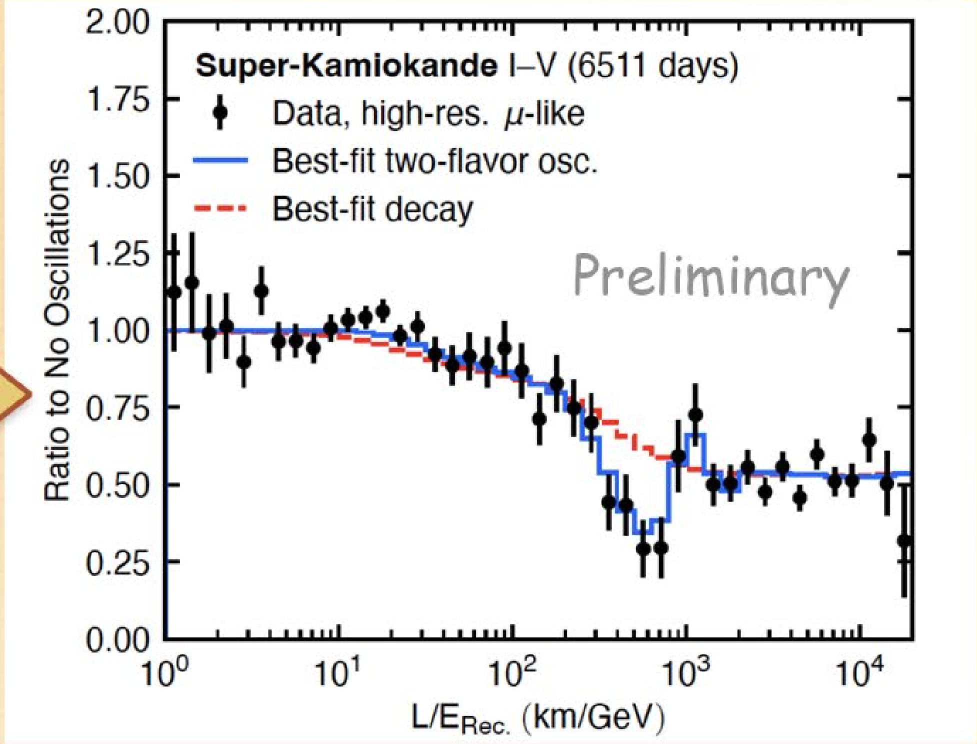
Gd-loaded water
583.3 days + the future...

L/E analysis @ Super - Kamiokande

- Atmospheric neutrinos at SK span ~4 orders of magnitude in L/E, possible to see a complete oscillation of ν_μ **survival probability**
- Updates since the last published results in **2004 Phys. Rev. Lett. 93, 101801, SK1**:
  - Full SK pure water phases (SK-I~V data - 6511 days- $\sqrt{(}\Delta\chi^2$(decay, 2 fl. osc.) $= 6.0\sigma$))
  - New L/E estimator, high- and low-resolution samples

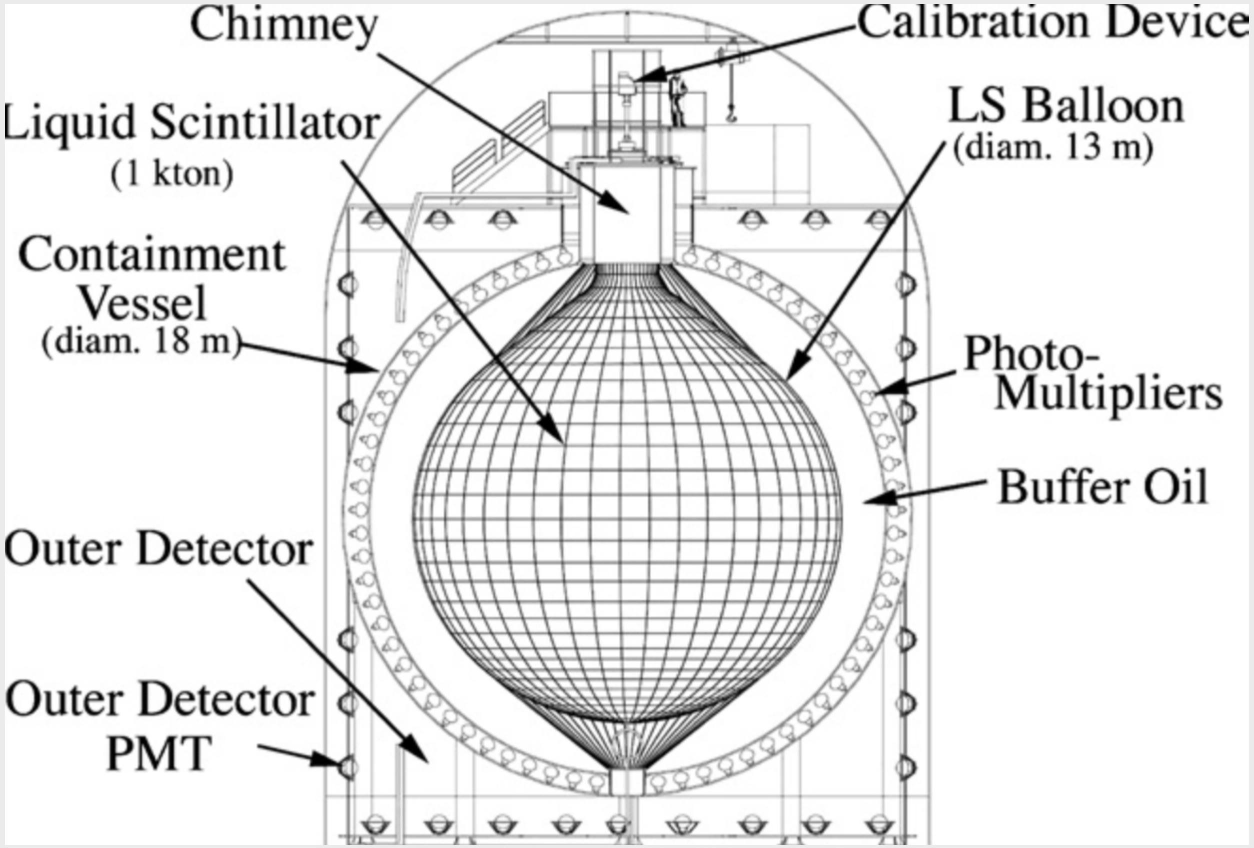


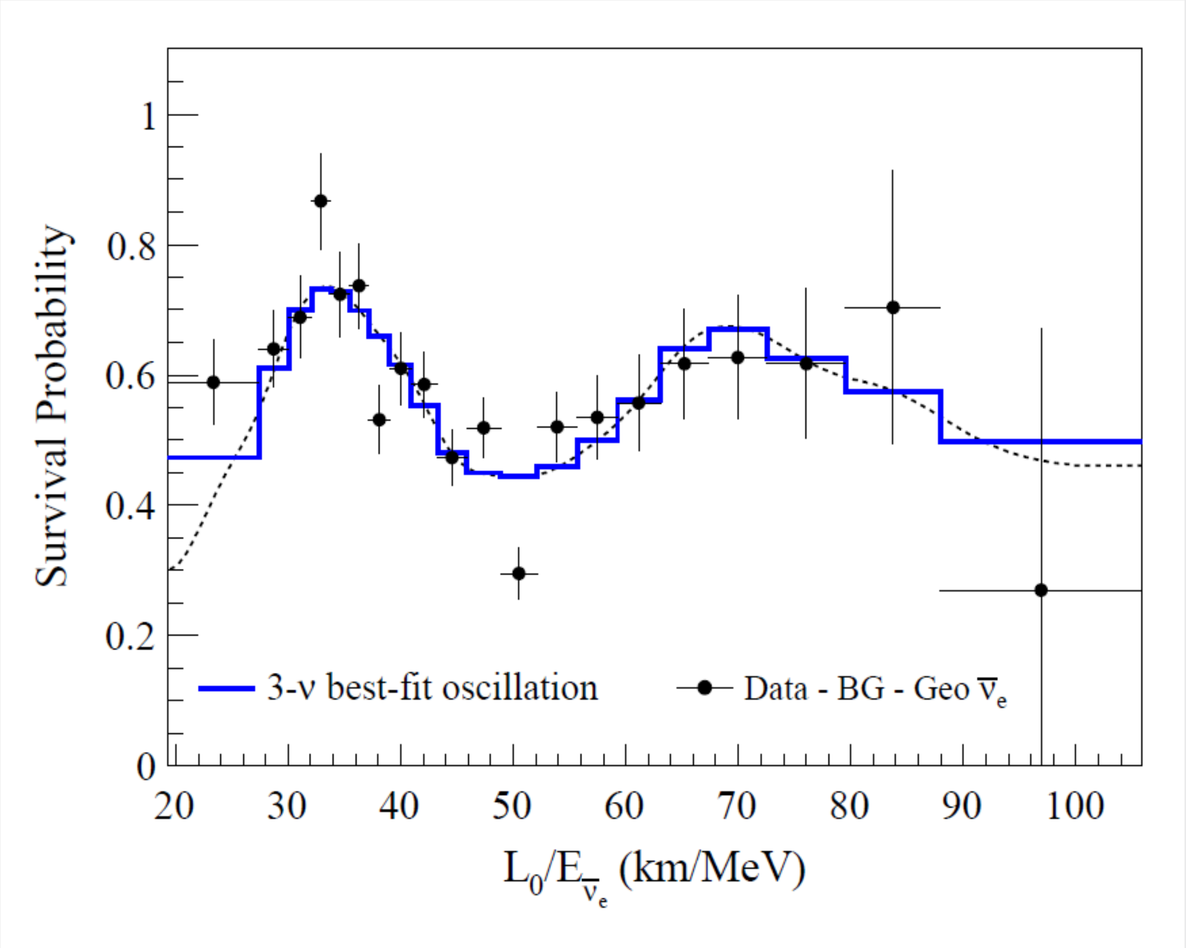
High - resolution data/MC sample



High resolution data: best fit for two flavour oscillations vs. neutrino decay

Kamland



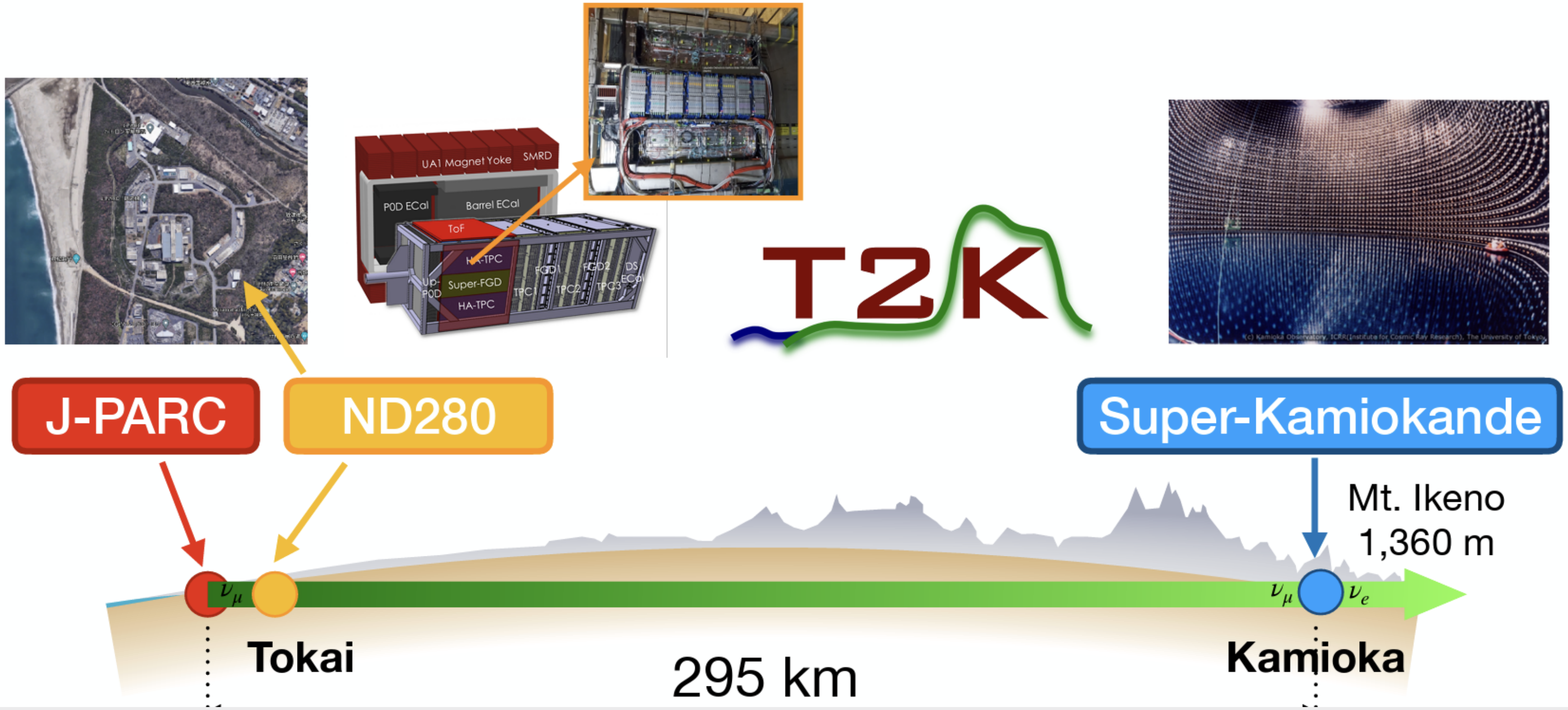


- Conversion of Kamioka to liquid scintillator. First results in 2002.
- Oscillation of electron anti-neutrinos from Japanese reactors at an average distance of 180 km.
- Oscillation parameters very similar to those observed for solar neutrinos (Θ_{12} and Δm^2)

$$\Delta m^2_{21} = 7.59 \pm 0.21 \cdot 10^{-5}\ \mathrm{eV}^2,\ \tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

T2K experiment

- High intensity ~600 MeV ν_μ or $\bar{\nu}_\mu$ beam produced at J-PARC (Tokai)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande)
  - ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$



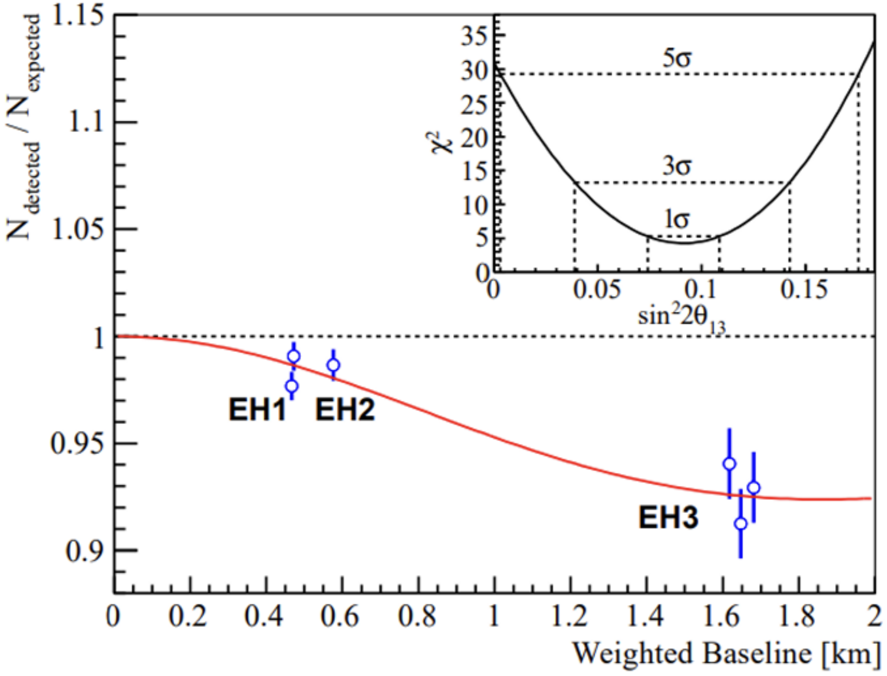
2012: $\theta_{13} \neq 0$! It's relatively large!

Nature is kind to us! **Reactor electron anti-neutrino Experiments Medium Baseline**

We will be able to know the neutrino mass ordering and δ_{CP} in 2030s

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

March 2012, 5.2σ for non-zero $\sin^2 2\theta_{13}$

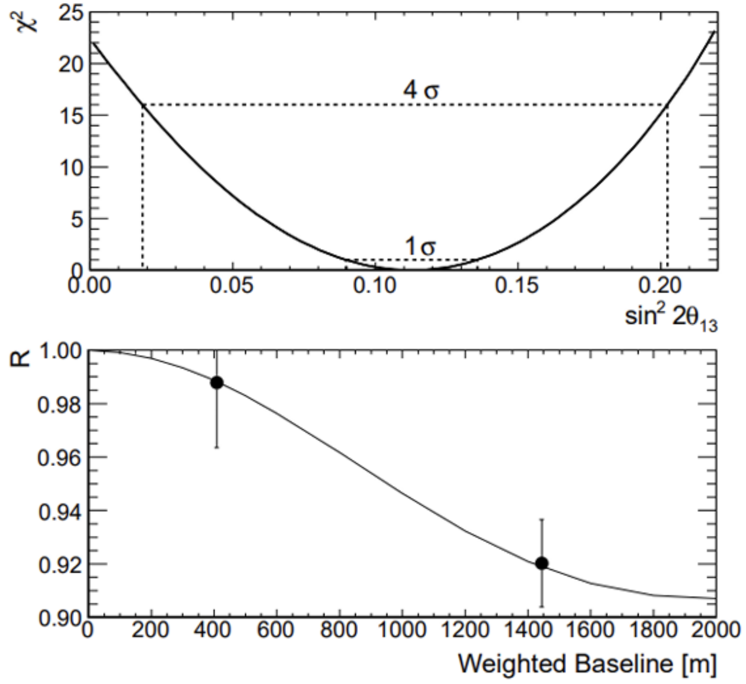


Daya Bay

Phys.Rev.Lett. 108 (2012) 171803

$0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$

April 2012, 4.9σ

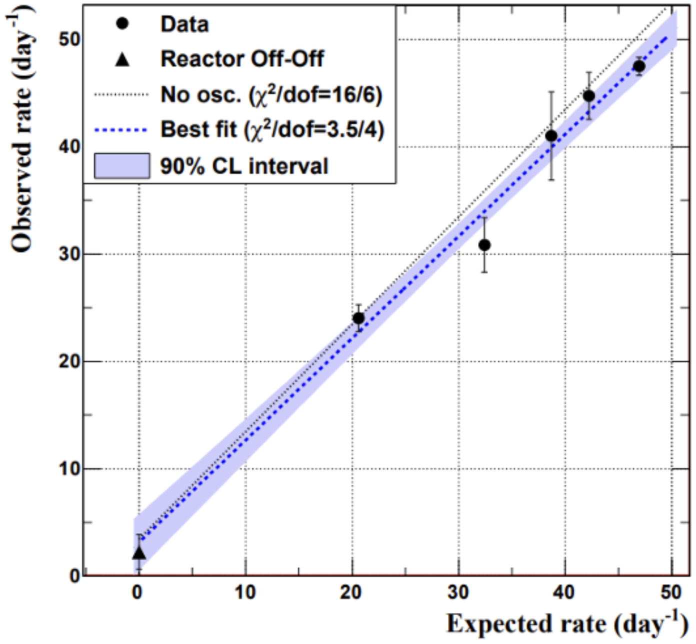


RENO

Phys.Rev.Lett. 108 (2012) 191802

$0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$

Nov. 2011, 94.6% C.L.

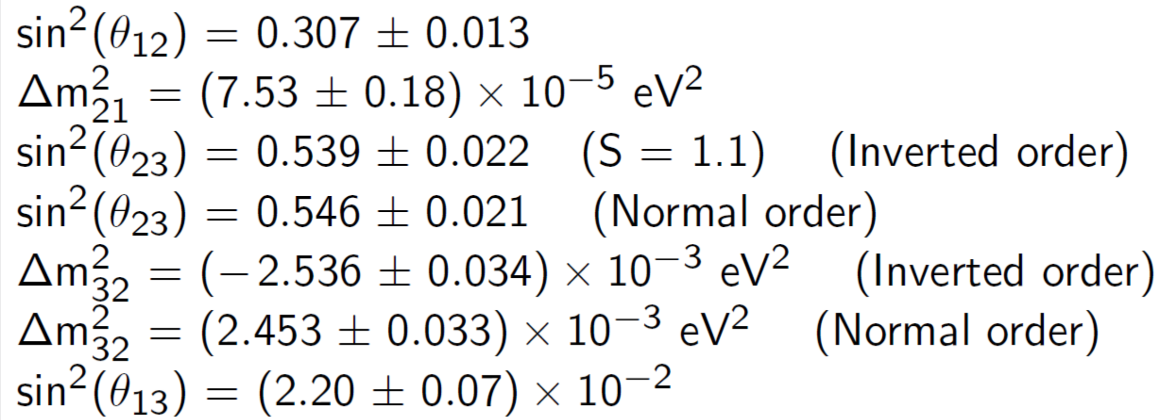


Double Chooz far detector

Phys.Rev.Lett. 108 (2012) 131801

SUMMARY OF OSCILLATION RESULTS FOR THREE ACTIVE ν TYPES

Particle Data Group



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

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

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

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

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

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

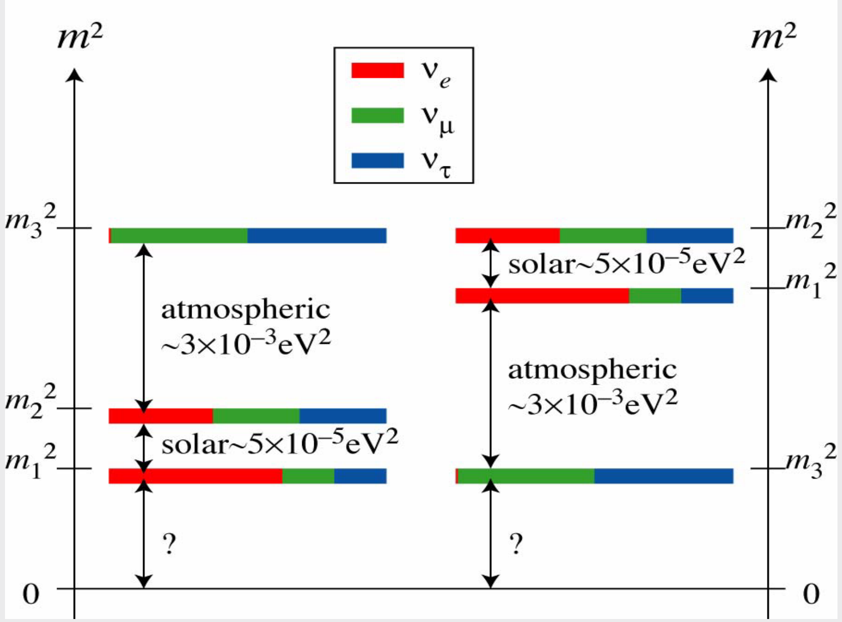
$$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$$

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

0νββ, Cosmology, Electron spectrometers,

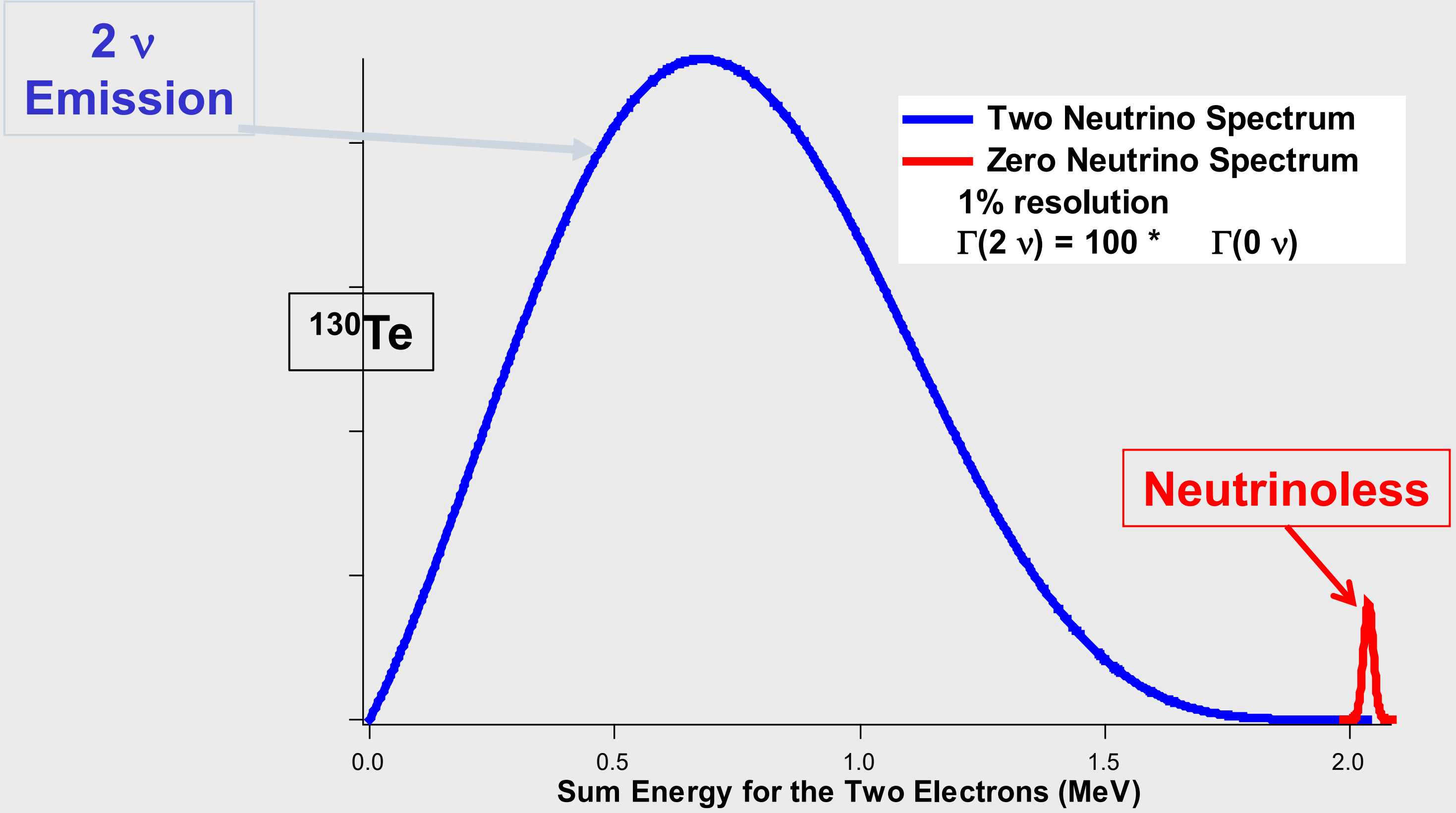
Accelerator,Reactor, Atmospheric

ν-less Double Beta Decay: Measuring Effective ν Mass

$$\boxed{(T_{1/2})^{-1} = F(Q_{\beta\beta},Z)\,|M^{0\nu}|^2 <m_{\nu\beta\beta}>^2}$$

Additional phases

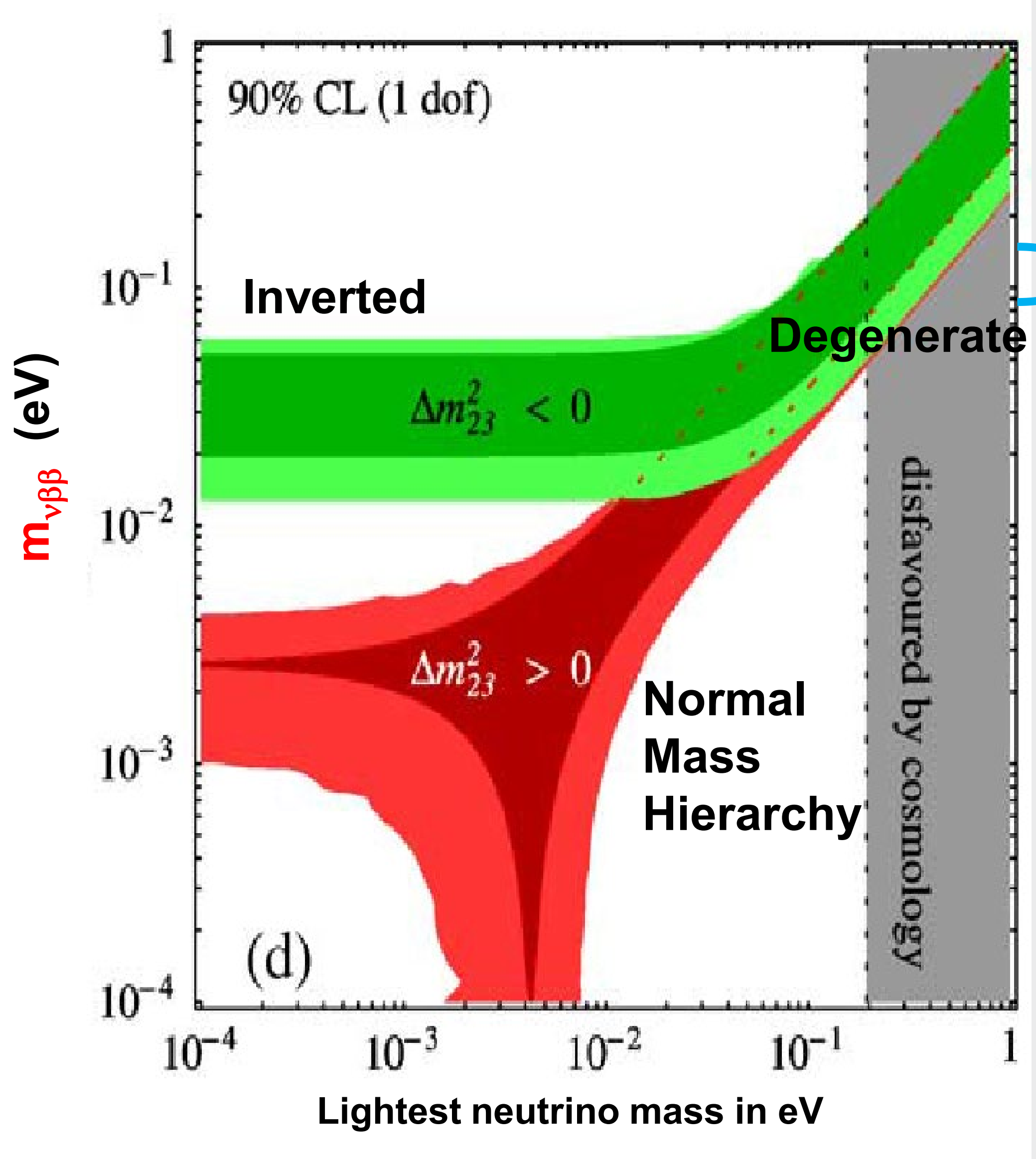
$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta} \sin^2\theta_{13}|$$



Requires: Neutrinos to be their own antiparticle (Majorana particles)

- **Finite ν mass: Lifetimes > ~10^{26} years imply ν mass < 0.1 eV**

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



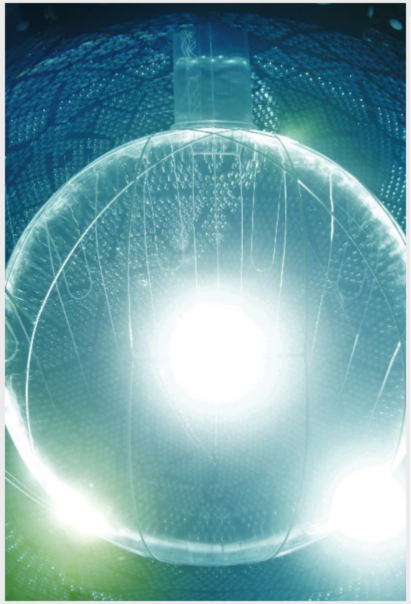
Present Limit

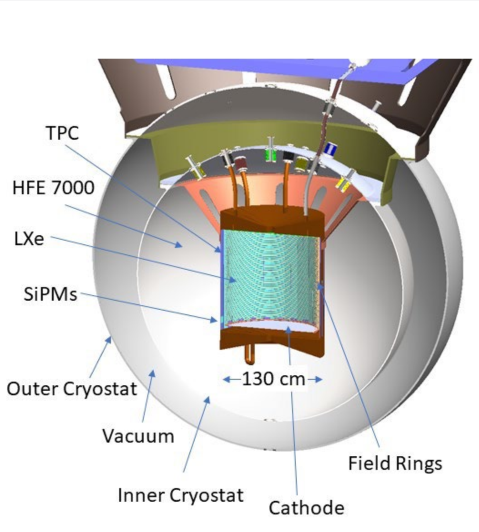
Objective for nearer term experiments

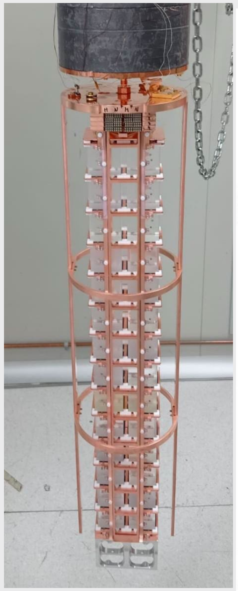
Objective for longer term experiments

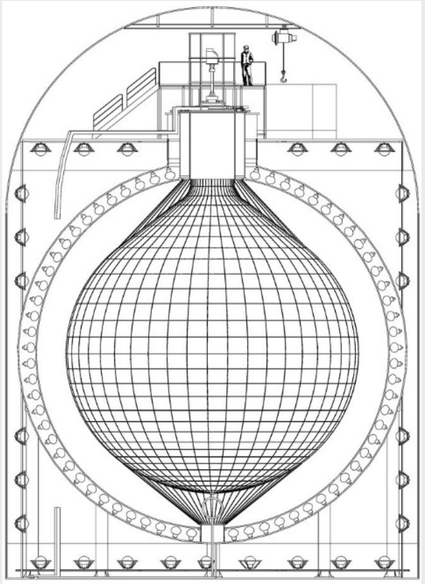
Very long term objective.

Neutrino-less Double Beta Decay









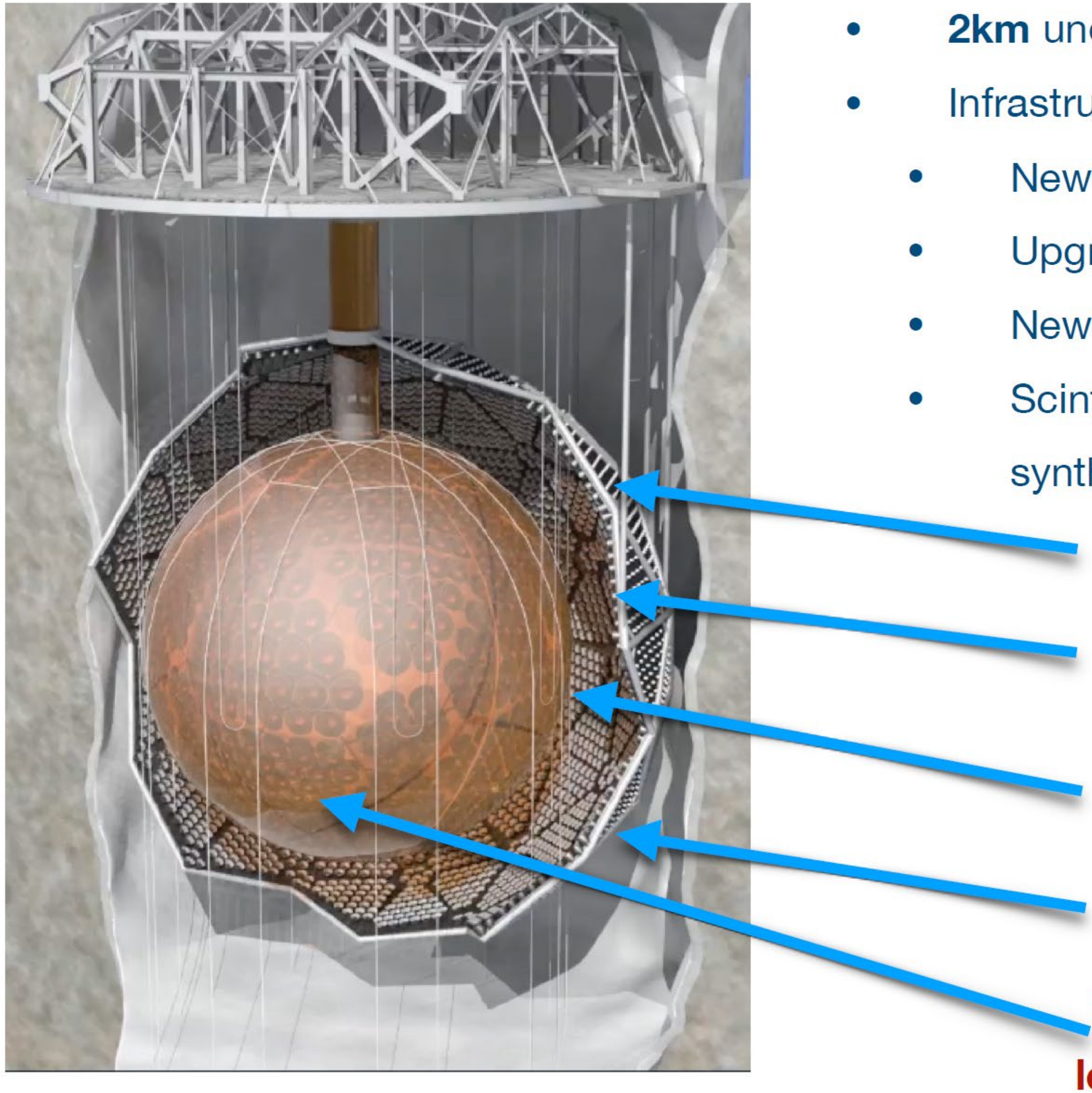
SNO+ (Te) **nEXO (Xe)** **LEGEND (Ge)** **CUPID (Mo)** **KAM-ZEN (Xe)**

- There are a number of experiments in operation and others in development with several different isotopes. This will be an advantage in the advent of a discovery

- Detailed nuclear theory calculations are needed to interpret these measurements and are an important part of the field.
- There is a question of quenching of g_A that could reduce the sensitivity of these experiments to effective neutrino mass by a factor of 2 to 4.

SNO+ 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

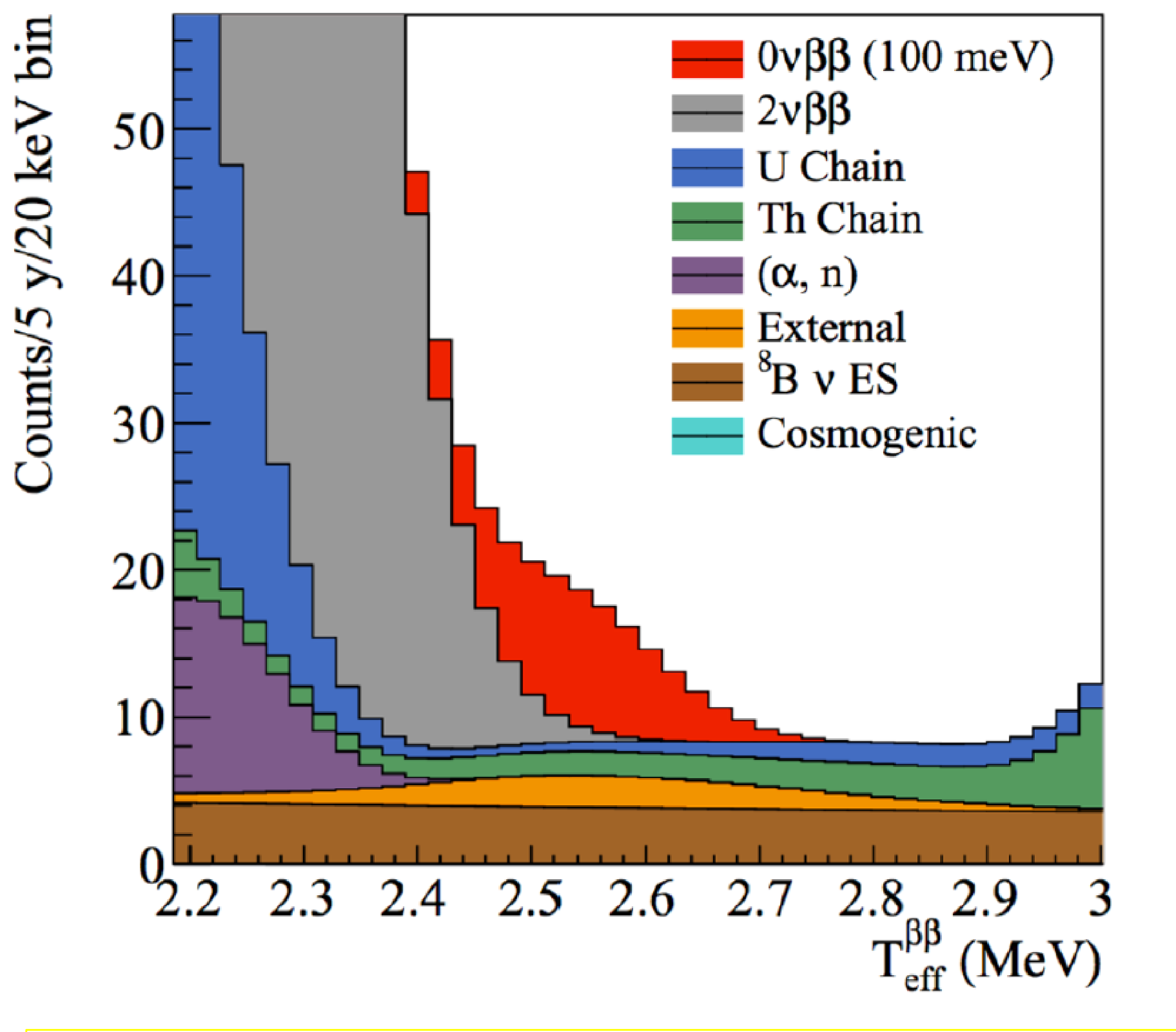
18m diameter PMT Support Structure

12m diameter Acrylic Vessel

7kt ultra pure water shielding

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

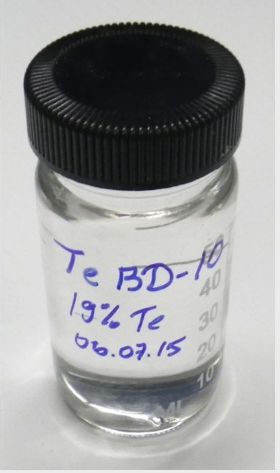
Increase to 1.5% planned for future



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

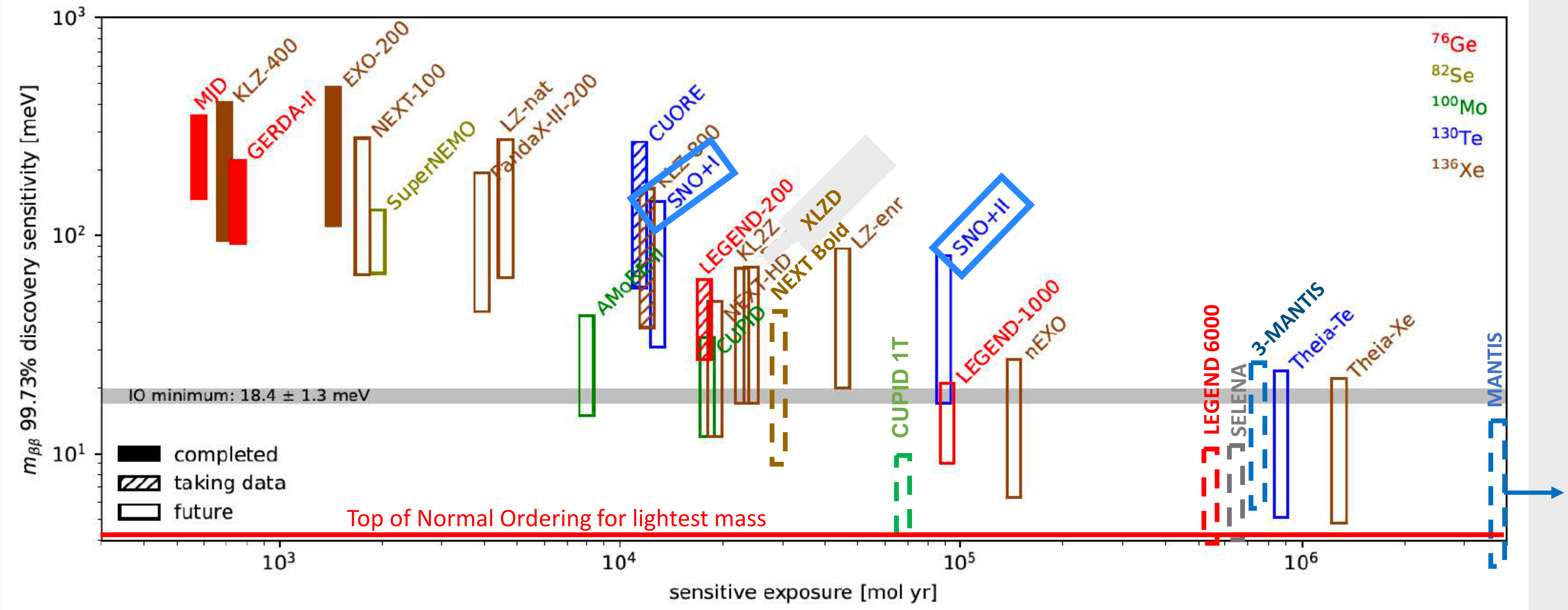
$m_{\beta\beta}$ < 30-130 meV
(99.7% CL)

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

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

Neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

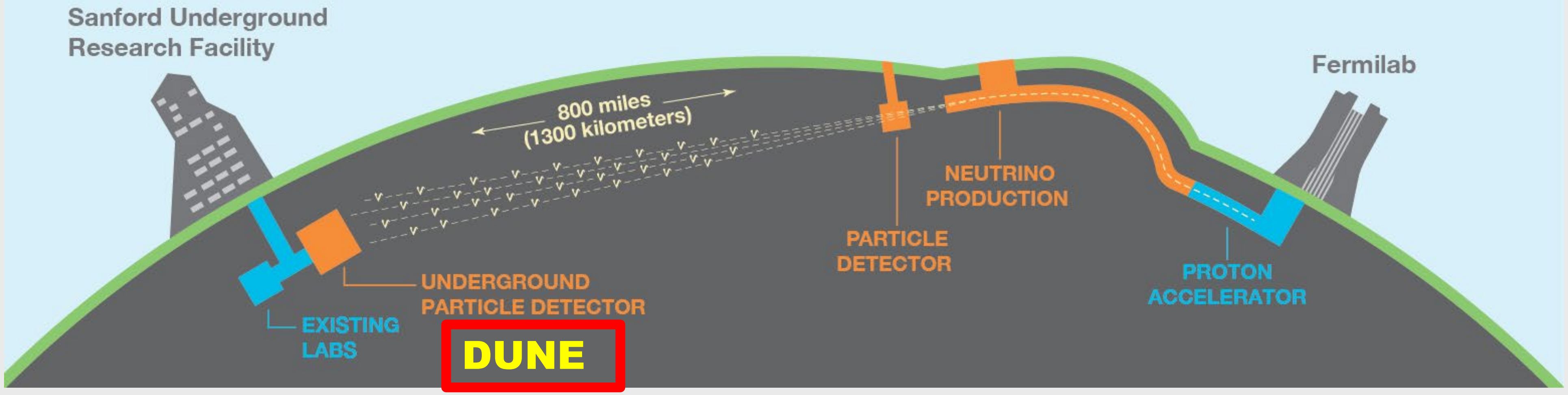
Atmospherics and LBL
$\theta_{23} \sim 45°$
$|\Delta m^2_{32}| \sim 2.5\text{x}10^{-3}$ eV^2

Reactors
$\theta_{13} \sim 10°$
LBL
θ_{13} and δ_{CP}

Solar and reactors
$\theta_{12} \sim 35°$
$\Delta m^2_{21} \sim 7.5\text{x}10^{-5}$ eV^2

- Long baseline (LBL) experiments sensitive to 5 of the PMNS parameters
  - θ_{23}, $|\Delta m^2_{32}|$ → LBL provides the most precise measurements of these parameters
  - θ_{13} → dominated by reactor experiments
  - δ_{CP} and sign of Δm^2_{32} (normal or inverted ordering) → still unknown and accessible to LBL

In progress: Next-Gen Long-Baseline experiments: Different neutrino interactions in the earth. Combined analysis will be valuable.



- **DUNE in the US and Hyper-Kamiokande in Japan**

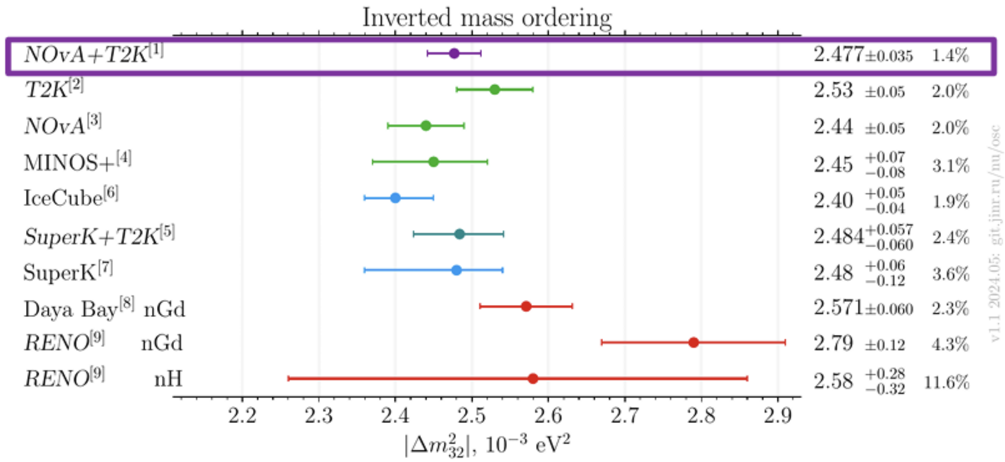
Compare neutrino oscillations initiated by muon neutrinos and their anti-particles.

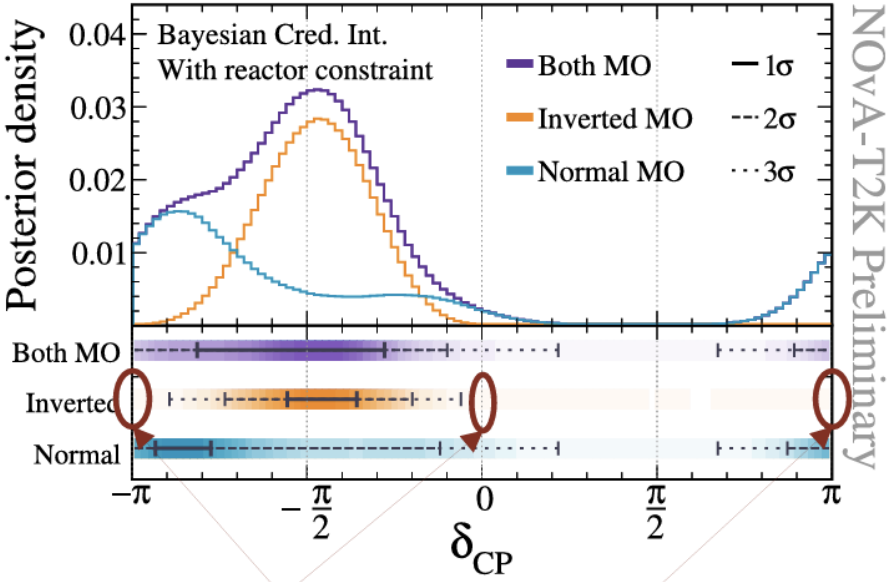
δ_{CP}, θ_{23} max?, Hierarchy?

NOvA-T2K joint fit: takeaways

Advancing the precision frontier on $|\Delta m^2_{32}|$

<2% measurement!





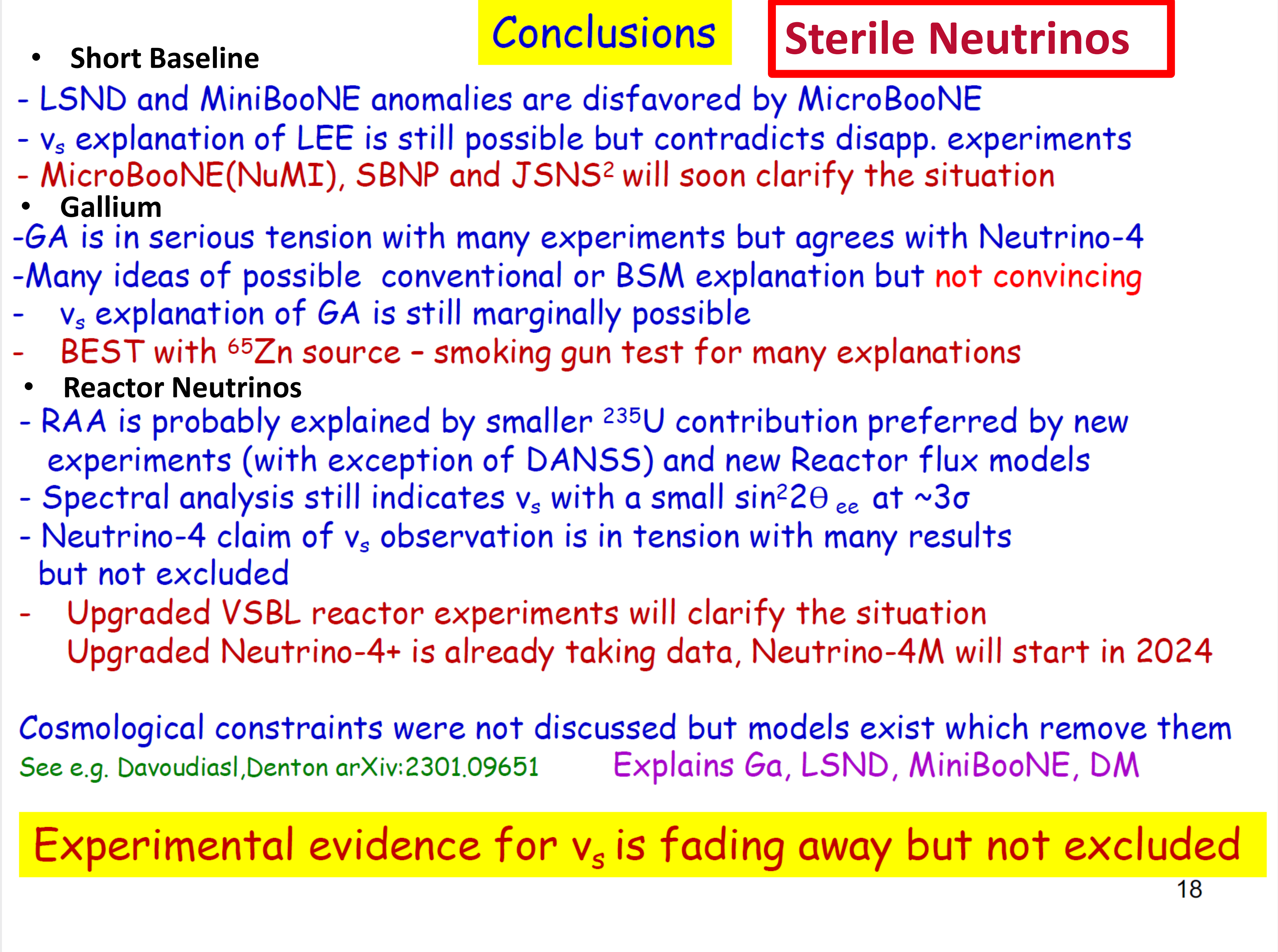
Mild preference for Inverted Ordering but **influenced by θ_{13} constraint**

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

[1] KEK IPNS seminar, FNAL JETP seminar
[2] Eur. Phys. J. C83, 782 (2023)
[3] Phys. Rev. D106, 032004 (2022)
[4] Phys. Rev. Lett. 125, 131802 (2020)
[5] arXiv:2405.12488
[6] arXiv:2405.02163
[7] Phys. Rev. D109, 072014 (2024)
[8] Phys. Rev. Lett. 130, 161802 (2023)
[9] RENO @ Neutrino 2020 [10.5281/zenodo.3959697]



Conclusions

Sterile Neutrinos

- **Short Baseline**

- LSND and MiniBooNE anomalies are disfavored by MicroBooNE
- ν_s explanation of LEE is still possible but contradicts disapp. experiments
- MicroBooNE(NuMI), SBNP and $JSNS^2$ will soon clarify the situation

- **Gallium**

-GA is in serious tension with many experiments but agrees with Neutrino-4
-Many ideas of possible conventional or BSM explanation but not convincing
- ν_s explanation of GA is still marginally possible
- BEST with ^{65}Zn source – smoking gun test for many explanations

- **Reactor Neutrinos**

- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\Theta_{ee}$ at $\sim 3\sigma$
- Neutrino-4 claim of ν_s observation is in tension with many results but not excluded
- Upgraded VSBL reactor experiments will clarify the situation
  Upgraded Neutrino-4+ is already taking data, Neutrino-4M will start in 2024

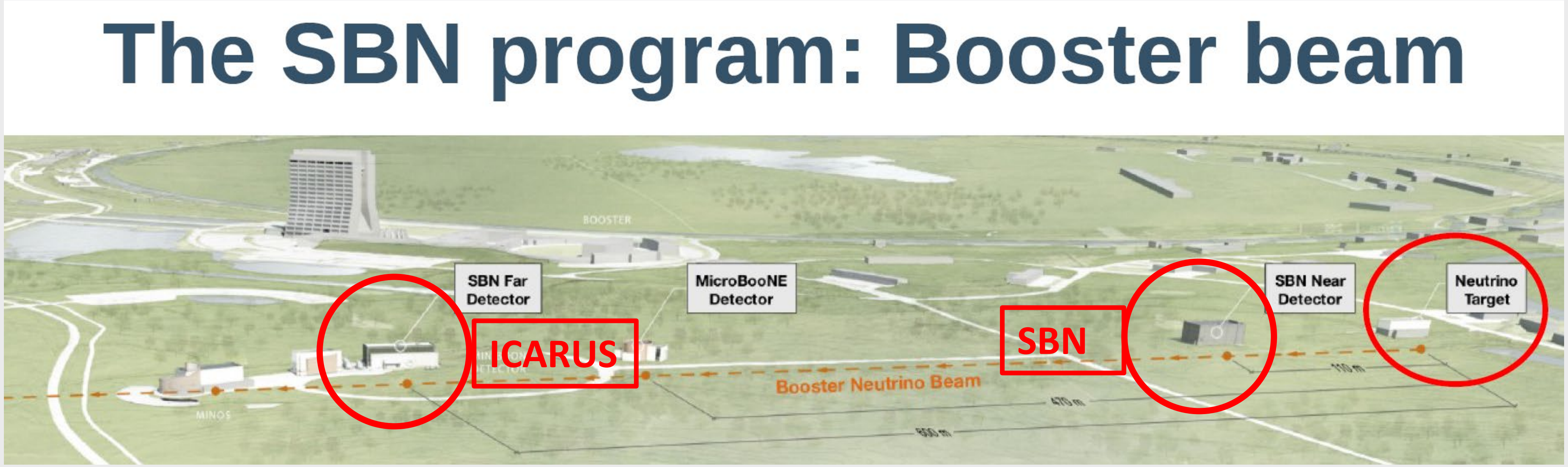
Cosmological constraints were not discussed but models exist which remove them

See e.g. Davoudiasl,Denton arXiv:2301.09651 Explains Ga, LSND, MiniBooNE, DM

Experimental evidence for ν_s is fading away but not excluded

Sterile Neutrino Summary by Danilov at Moriond 2024

FERMILAB



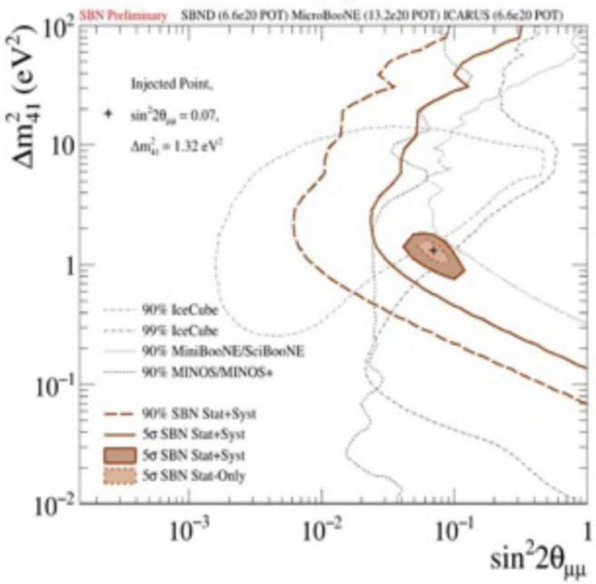
The SBN program: Booster beam

- Two similar Liquid Argon Detectors
- Search for neutrino oscillations at O(Δm2) ~ 0.1-10 eV^2
- Measure ν-Ar interactions
- Search for physics beyond the Standard Model

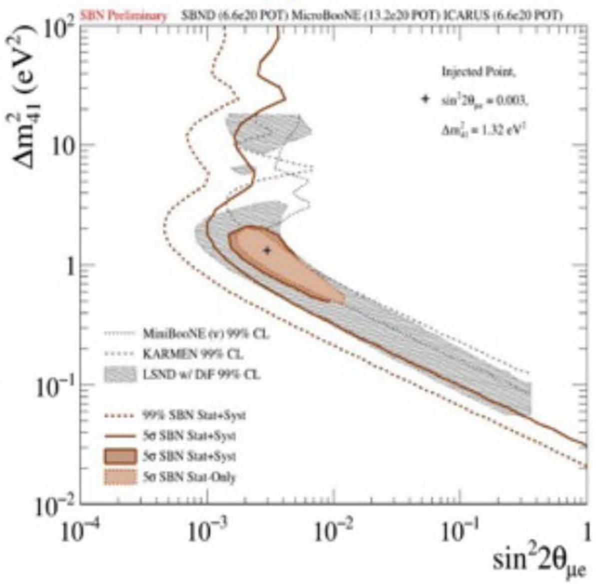
SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} PoT)

- Combined analysis of events collected far by ICARUS at far site and by SBND at near using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPCs rejecting NC event background;
  - "Initial" BNB beam composition and spectrum provided by SBND detector.

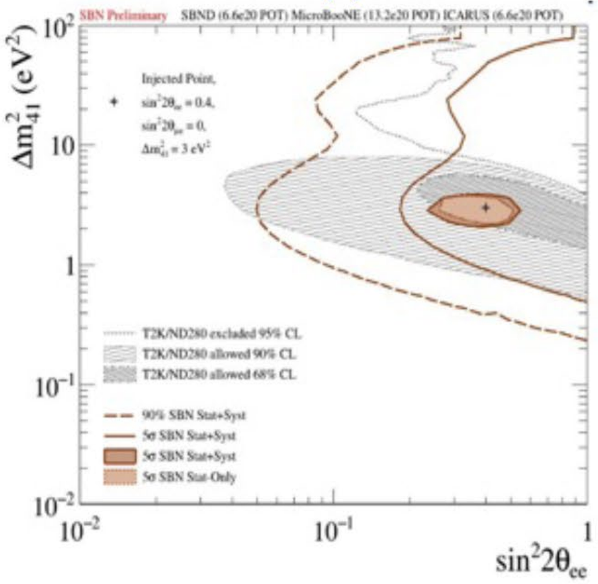
νμ disappearance



νe appearance



νe disappearance



5σ coverage of the parameter area relevant to LSND anomaly

Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study neutrino appearance and disappearance simultaneously

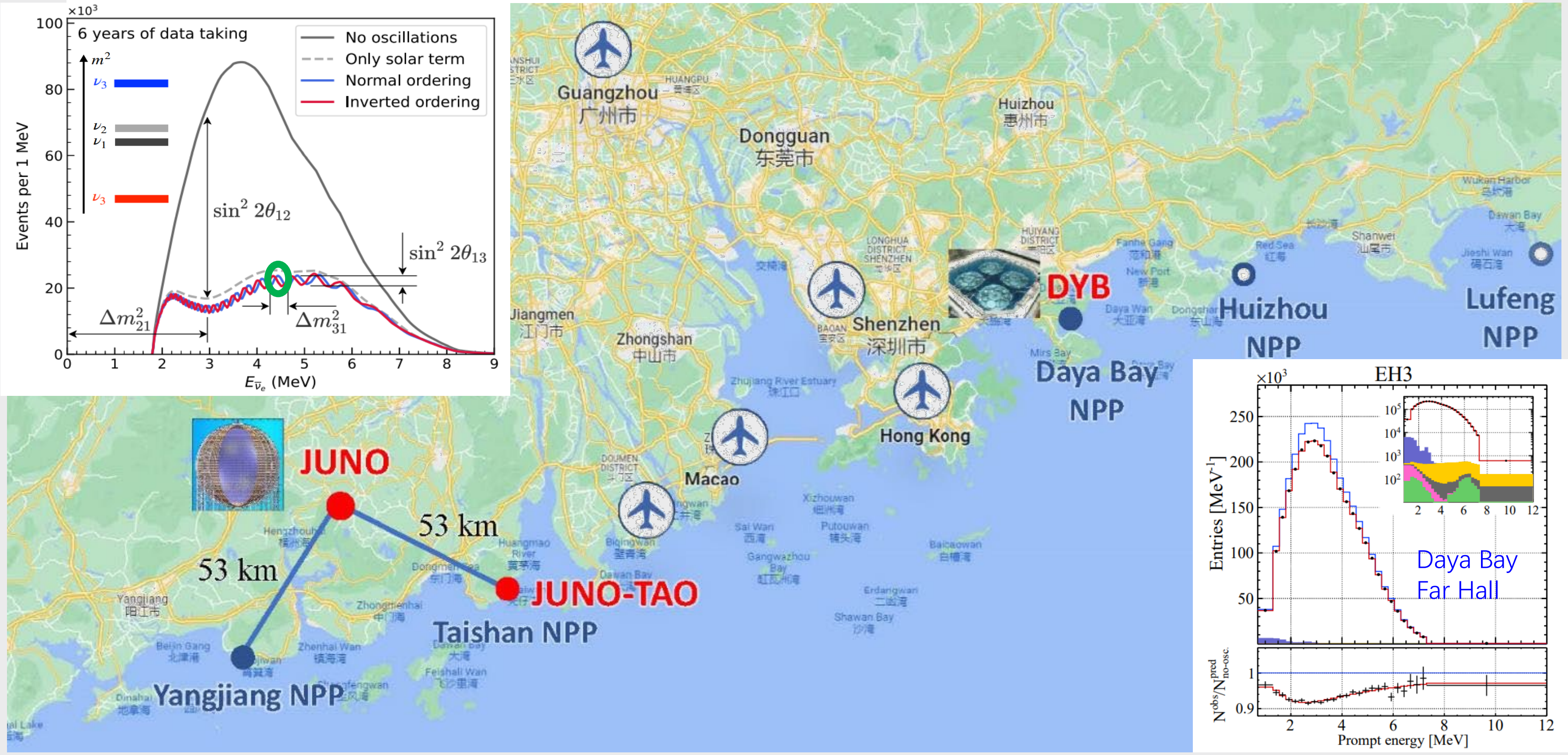
Jiangmen Underground Neutrino Observatory

$$
\begin{aligned}
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 &- \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E} \\
&- \frac{1}{2} \underline{\sin^2 2\theta_{13}} \left[\sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \frac{\Delta m^2_{32} L}{4E} \right] \\
&- \frac{1}{2} \cos 2\theta_{12} \underline{\sin^2 2\theta_{13}} \sin \frac{\Delta m^2_{21} L}{4E} \sin \frac{(\Delta m^2_{31} + \Delta m^2_{32}) L}{4E}
\end{aligned}
$$

Leading term at JUNO

Leading term at Daya Bay

Sensitive to mass ordering



Key for NMO:

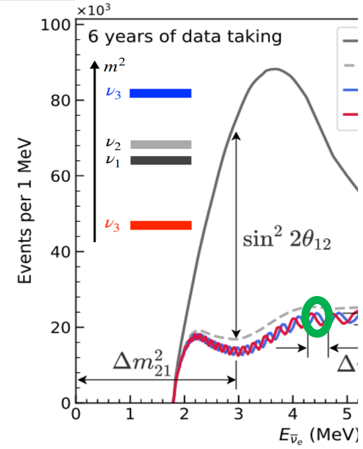
1、20 kton liquid scintillator detector

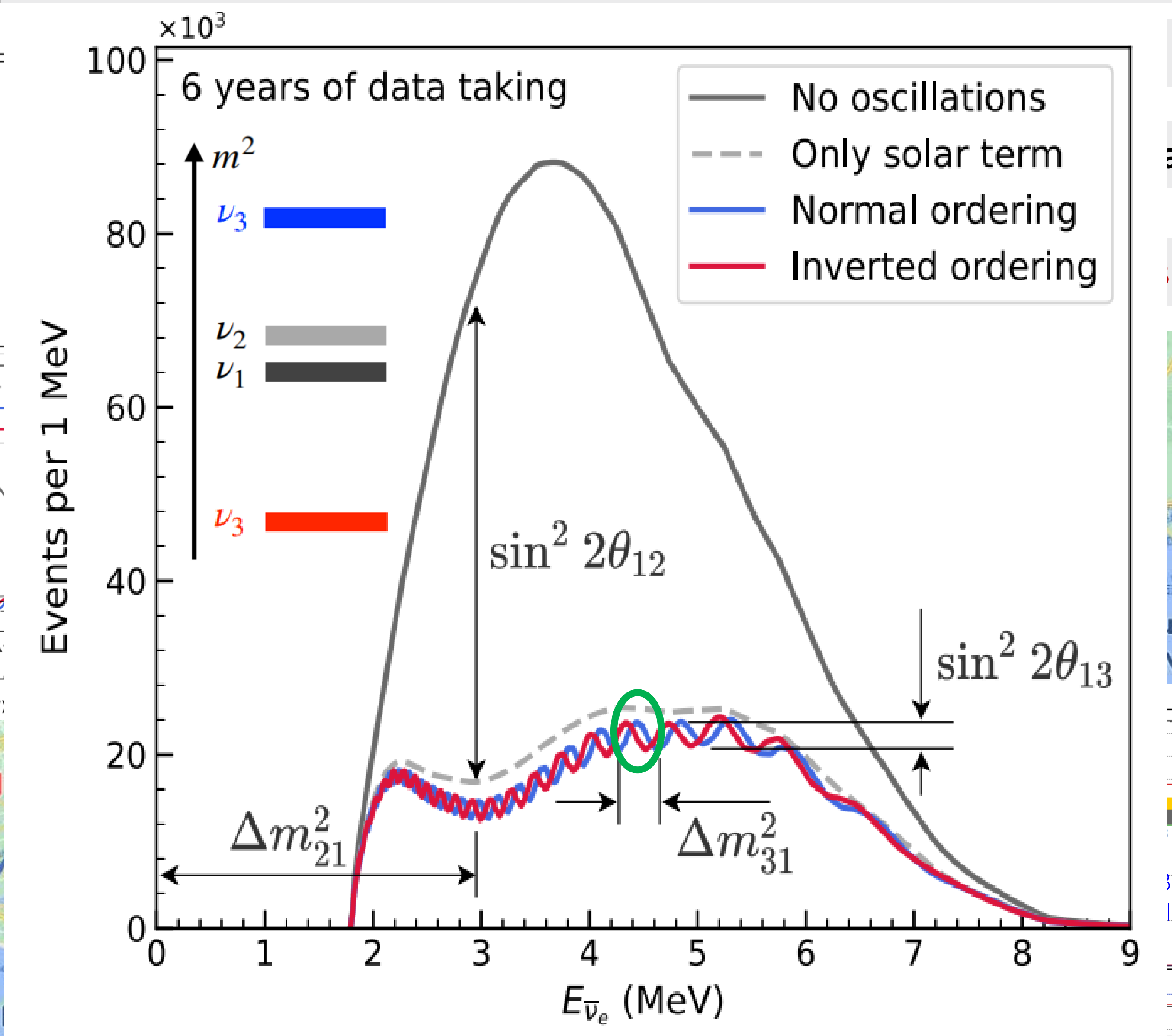
2、3% energy resolution at 1 MeV energy deposit

3、low background

Jiangmen **U**nderground **N**eutrino **O**bservatory

$P(\bar{\nu}_e \to \bar{\nu}_e)$ =





at **Daya Bay**

itive to mass ordering

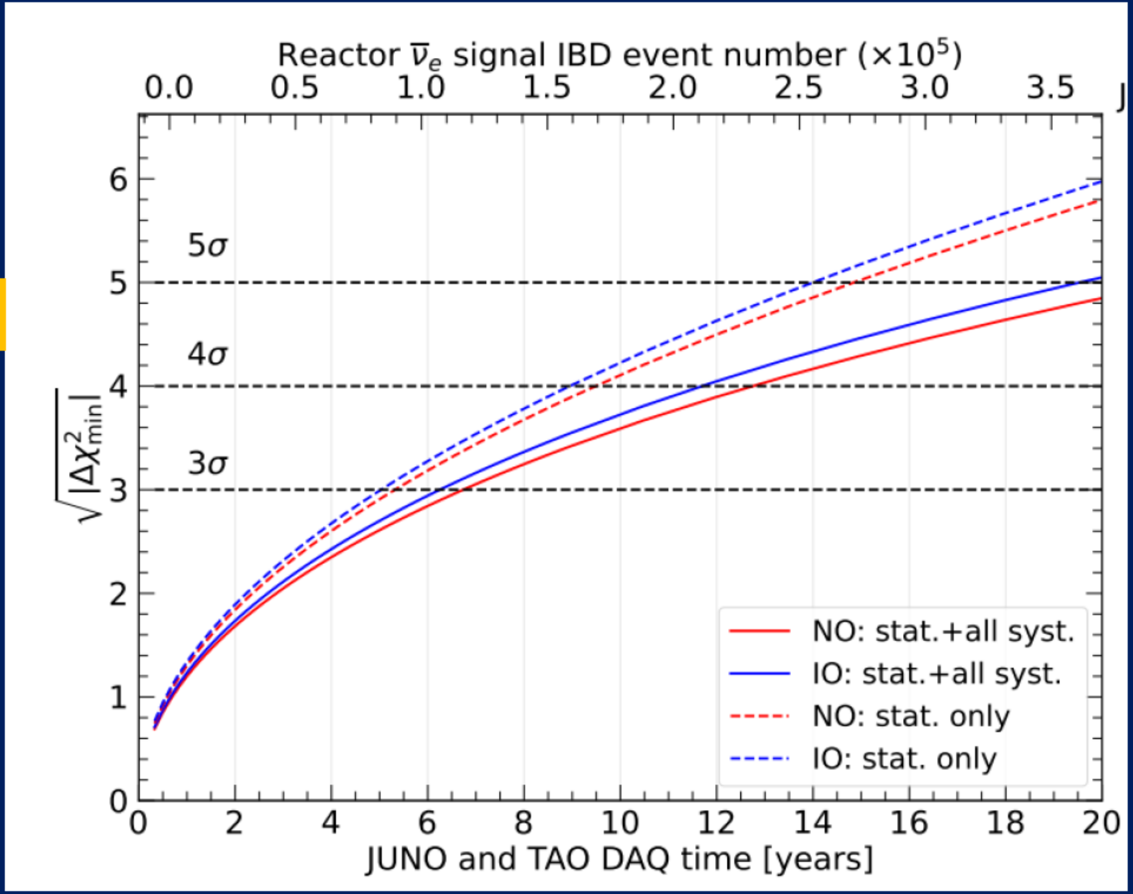
Key for NMO:

1、20 kton liquid scintillator detector

2、3% energy resolution at 1 MeV energy deposit

3、low background

Neutrino Mass Ordering

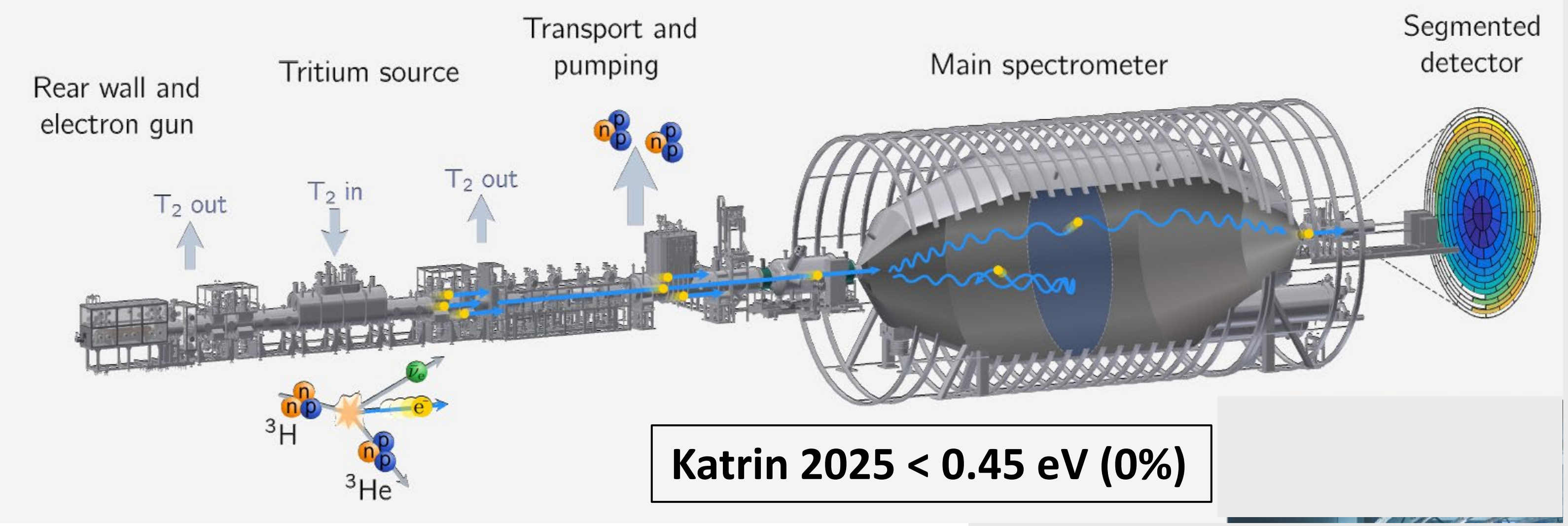


Preliminary

JUNO NMO median sensitivity: **3σ (reactors only) @ ~6 yrs * 26.6 GW$_{\text{th}}$ exposure**

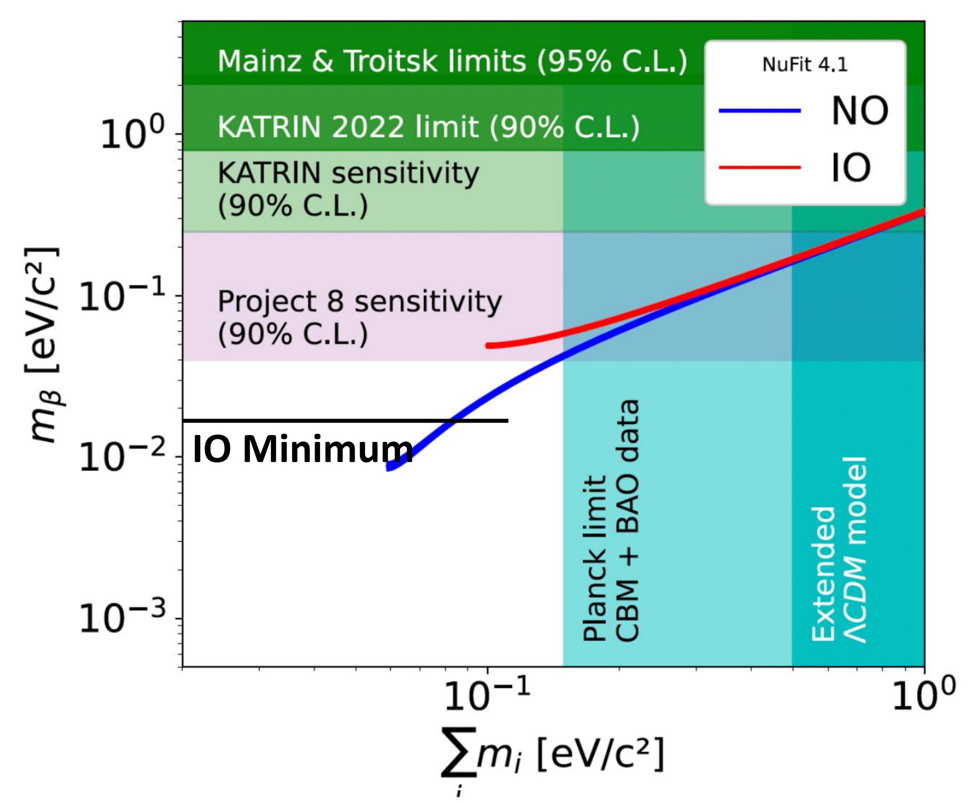
Combined reactor+atmospheric neutrino analysis in progress: further improve the Neutrino Mass Ordering sensitivity

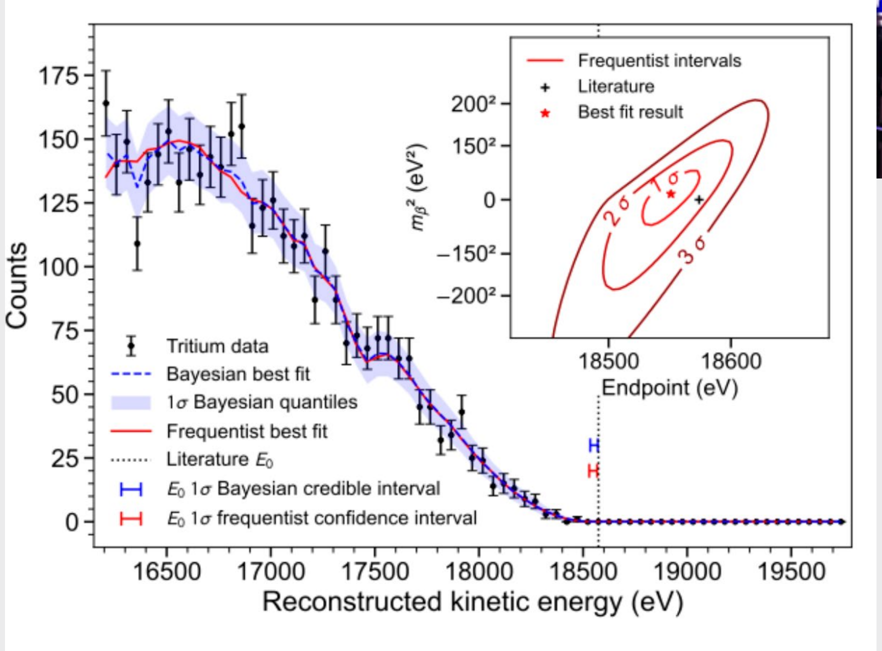
Neutrino Mass from Tritium Beta decay



Katrin 2025 < 0.45 eV (0%)

Both Projects will also search for kinks in the spectra at lower energy to look for sterile neutrinos: KATRIN Next Phase





Phys.Rev.Lett. 131 (2023) 10, 102502

Project 8

Cyclotron Radiation Emission Spectrometry (CRES)
Published result:
Neutrino Mass < 150 ev/c^2
Future: Atomic Tritium, greater statistics:
Projected reach: ~ 0.040 ev/c^2

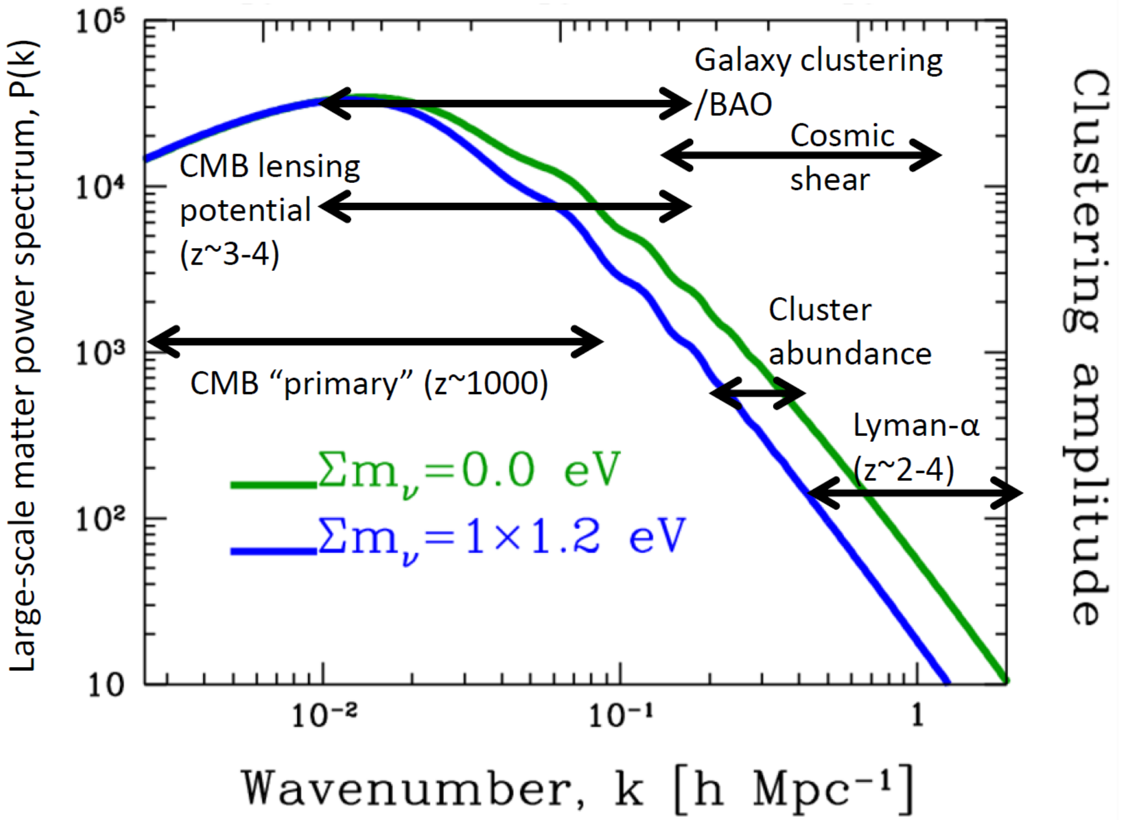
Prospects for the measurement of the absolute neutrino mass in cosmology

Yvonne Y. Y. Wong

UNSW Sydney

International Symposium on Neutrino Physics and Beyond, HKUST,
February 19 – 21, 2024

Studies of the Large-scale Matter Power Spectrum are sensitive to the sum of ν masses



- ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

Planck 2018 TT+TE+EE+ lowE+lensing+BAO

$$\sum m_\nu < 0.121 \text{ eV}$$ Degenerate

$$\sum m_\nu < 0.146 \text{ eV}$$ Normal hierarchy

$$\sum m_\nu < 0.172 \text{ eV}$$ Inverted hierarchy

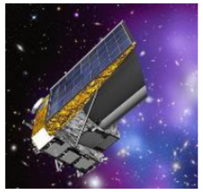
Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

Roy Choudhury & Hannestad 2019

Future Measurements will improve this sensitivity

What to expect in the future?

Galaxies,
cosmic shear,
clusters, etc.

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to N_{eff}
	**ESA Euclid**	Launched 2023	$0.011 - 0.02$ eV	0.05
	**LSST**	202X	0.015 eV	0.05

These numbers mean, if the true neutrino mass sum is $\sum m_\nu = 0.06$ eV, then it is possible to measure it with $(3-5)\sigma$ significance.

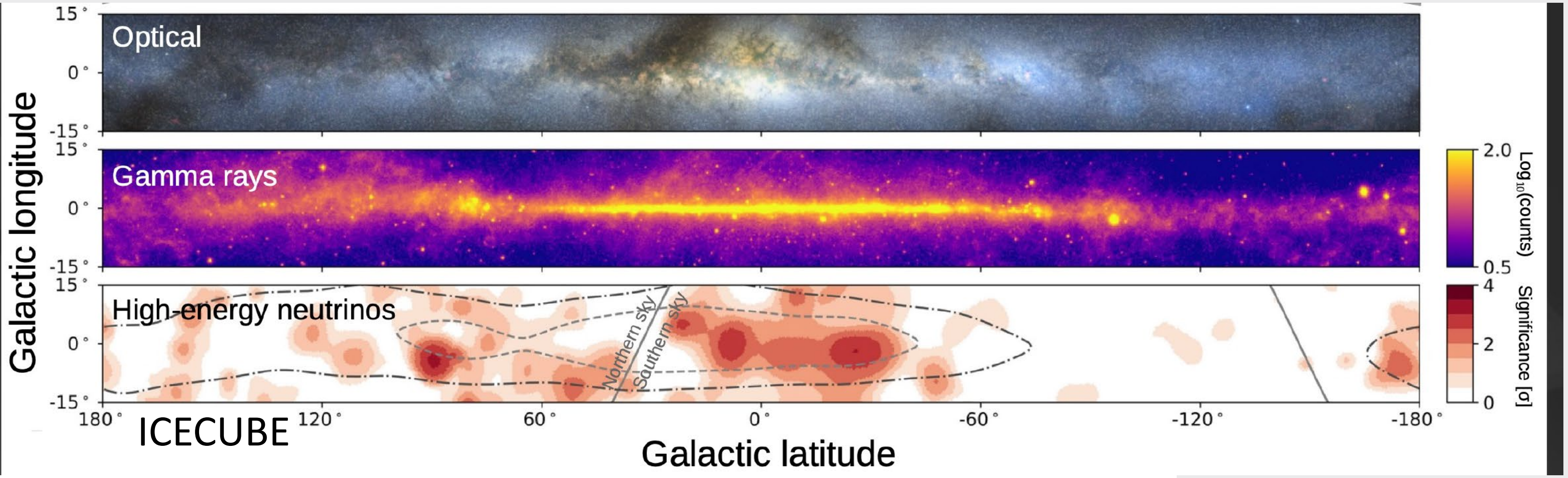
Summary…

Yvonne Y. Y. Wong
UNSW Sydney

These is no doubt that neutrino masses induce some non-trivial effects on cosmological observables.

- You can even turn this around and use cosmological observables to "measure" the neutrino mass.
- But please please please don't over-interpret bounds or forecasted sensitivities. They are best treated as ballpark figures.
- Until **multiple observations** have measured the same neutrino mass sum value, take all "measurements" *cum grano salis*.

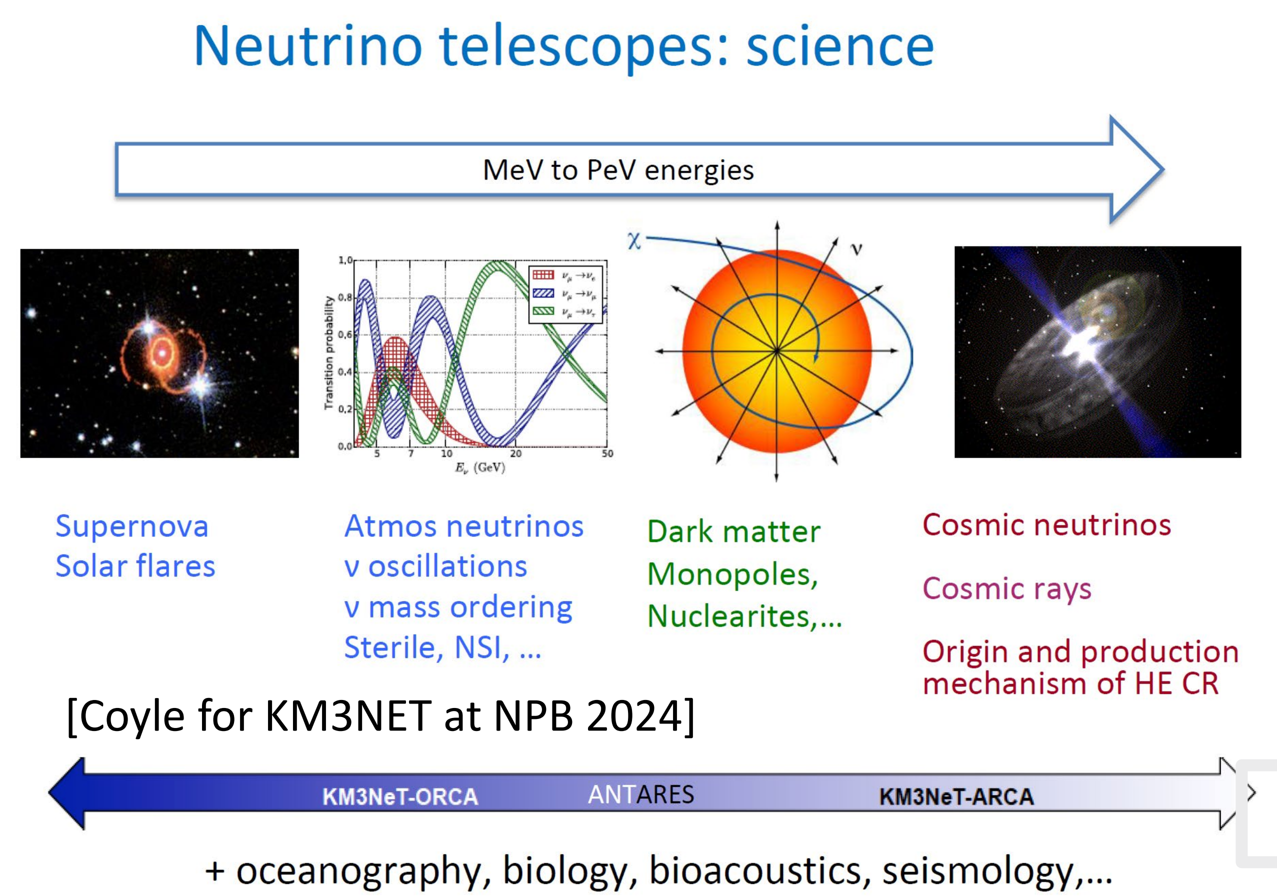
Also summarised in Antel et al., Feebly Interacting Particles: FIPs 2022 workshop report, *Eur.Phys.J.C* 83 (2023) 1122 [arXiv:2305.01715 [hep-ph]].



ICECUBE

Galactic Plane

← **ICECUBE**



Neutrino telescopes: science

MeV to PeV energies

Supernova
Solar flares

Atmos neutrinos
ν oscillations
ν mass ordering
Sterile, NSI, …

Dark matter
Monopoles,
Nuclearites,…

Cosmic neutrinos

Cosmic rays

Origin and production mechanism of HE CR

[Coyle for KM3NET at NPB 2024]

KM3NeT-ORCA ANTARES KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

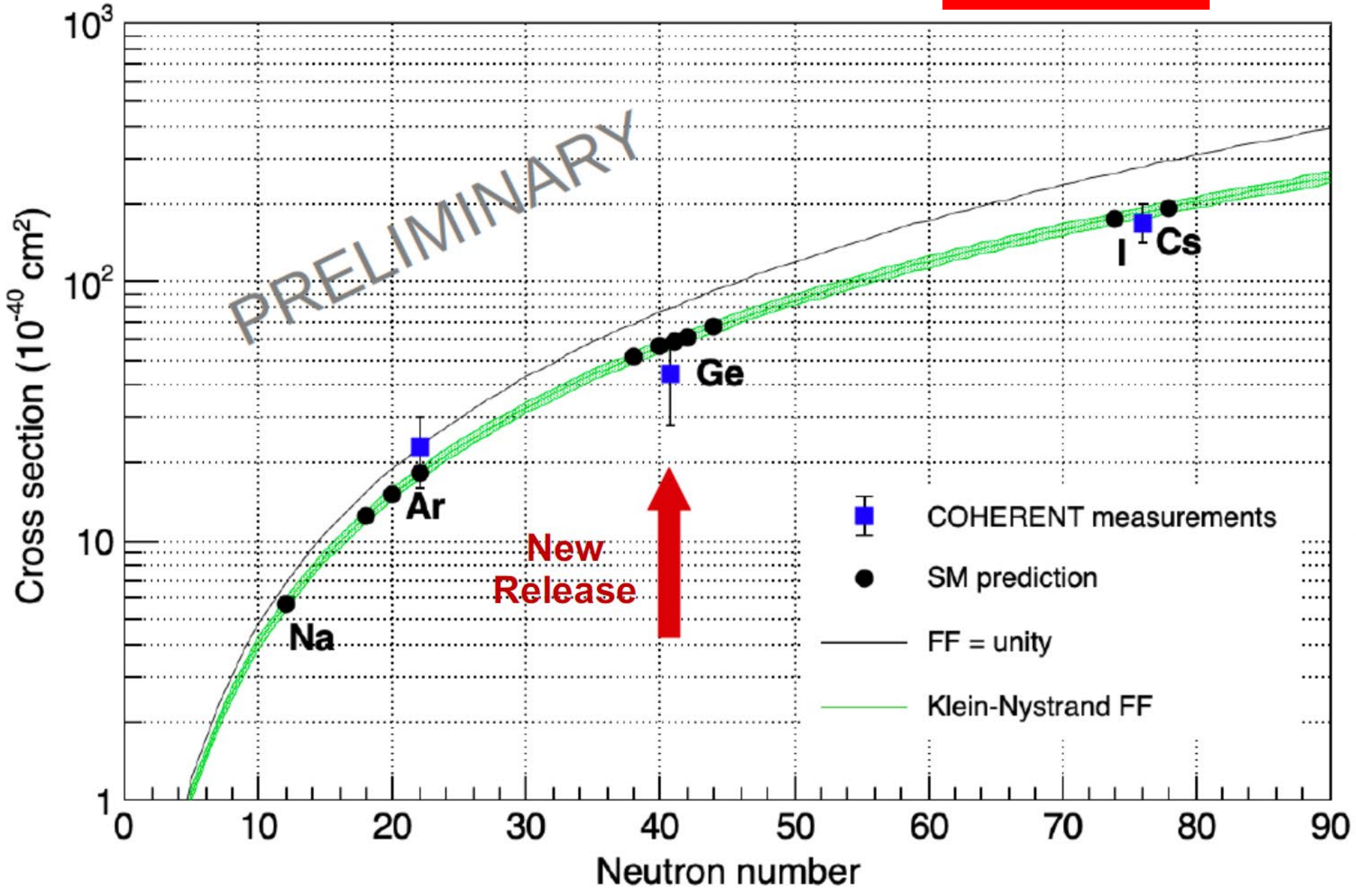
High-Energy Neutrinos and Multi-messenger Astronomy

ICECUBE: Potential correlation between active galaxy NGC 1068 and neutrino hot spot (with 79 +22 -21 events). Significance 4.2 sigma. [Halzen at NPB 2024 Hong Kong]

KM3NET: Remarkable 120 PeV event!!

Future P-ONE? In Ocean off Vancouver Island

Collaboration Published Detection of CEvNS on Three Targets



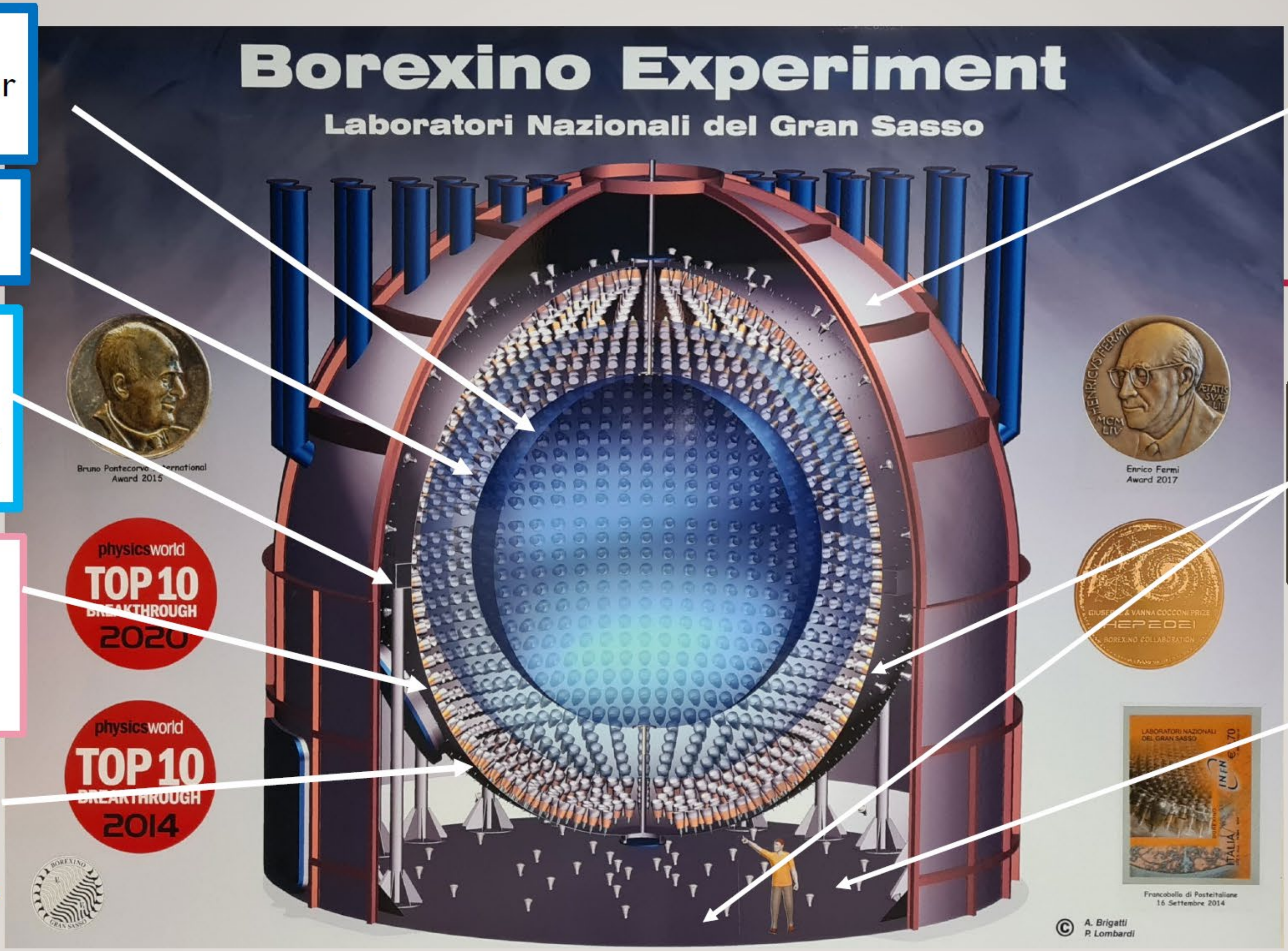
COHERENT Collaboration

All three individual results agree with the Standard Model within one sigma

However, accuracy is limited so far

Dominant source of uncertainty is the knowledge of Neutrino Flux at the SNS
Which we believe is known within 10% accuracy. Phys. Rev. D, 106(3):032003, 2022, 2109.11049.

Efremenko at NPB 2024



278 tons of liquid scintillator PC+PPO

IV-125 μm thick ultrapure nylon

OV 2^{nd} 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)

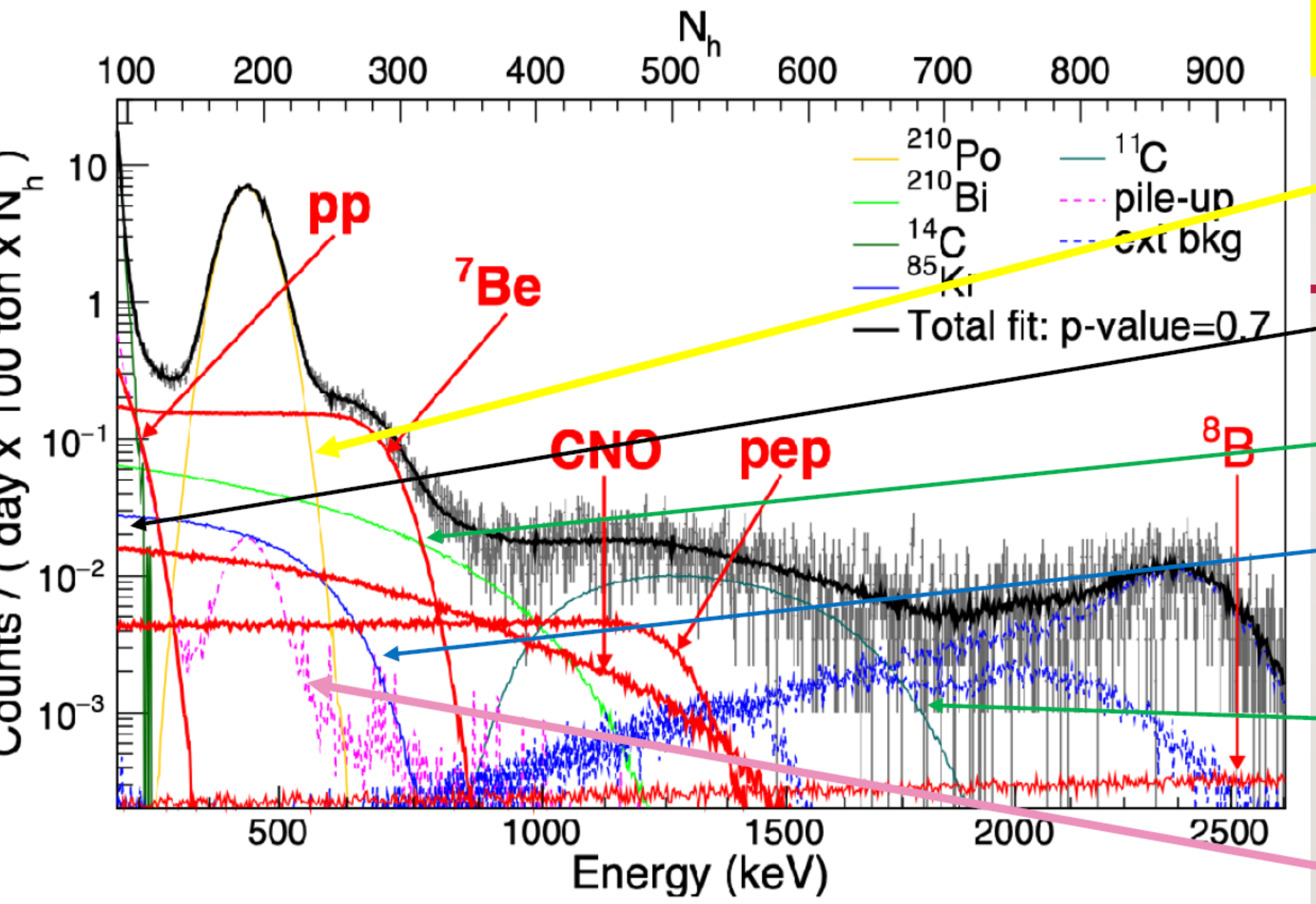
WT, 16.9 m high and 9.0 m of radius; 2400 t ultrapure water.

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

First spectroscopy of pp,^{7}Be and pep



^{210} Po

^{14}C

^{210} Bi

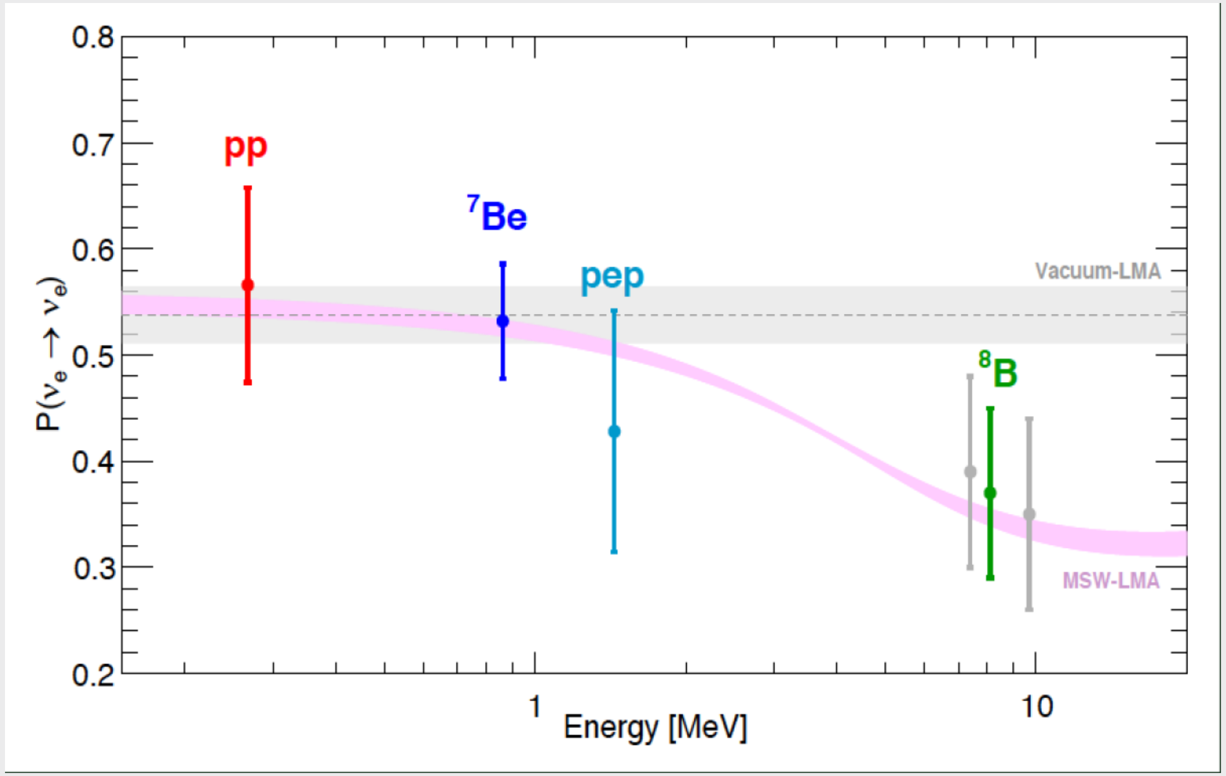
^{85}Kr

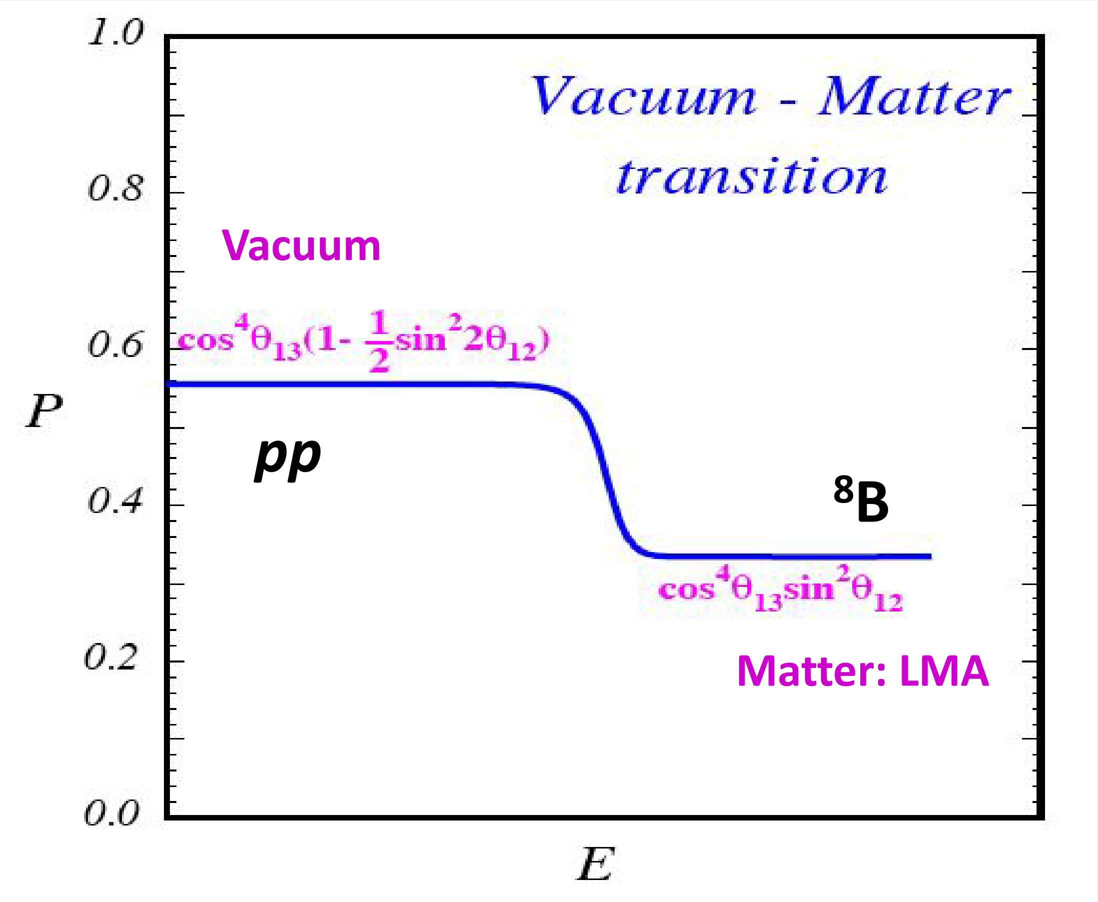
Residue despite the very high radiopurity

Cosmogenic ^{11}C

Pile-up due to the ^{14}C rate

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) ≤ 11.5 ± 1.3 cpd/100t

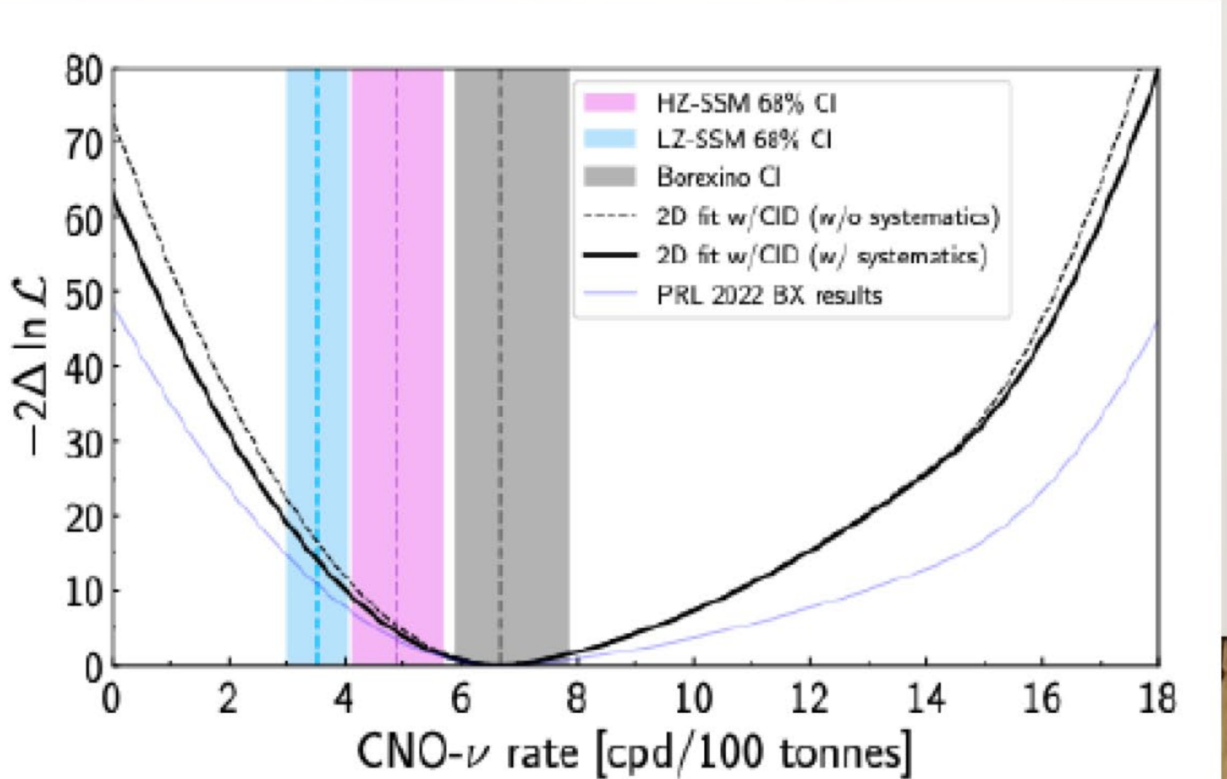
we cannot exclude in principle that residual ^{210}Po from the vessel surface would be present

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.



Thank You