Nobel neutrinos

Simon JM Peeters

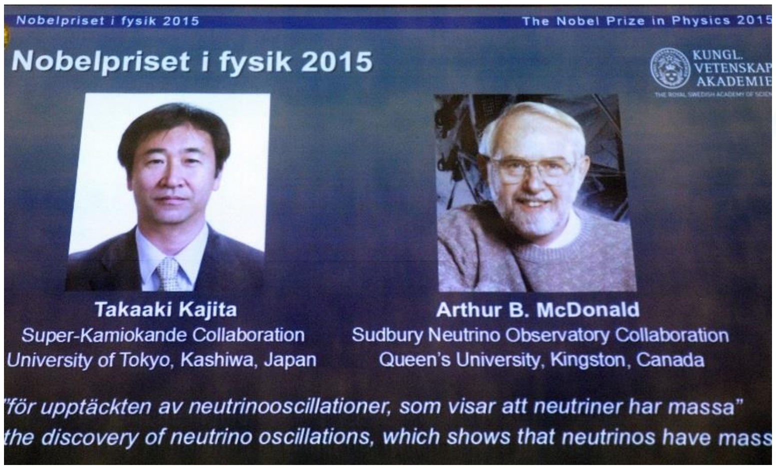
Physics & Astronomy
University of Sussex

14 Dec 2015

University of Sussex
Physics & Astronomy

Happy ν Year

Nobel prize



Tuesday 6th October

Breakthrough prize

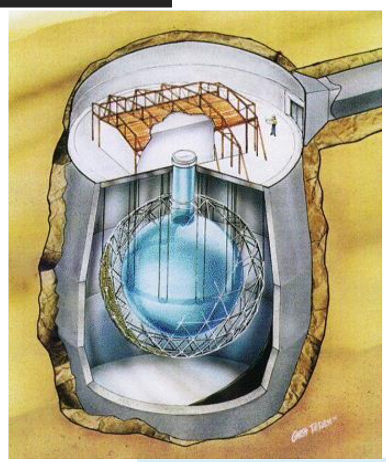
Daya Bay, K2K & T2K, KamLAND, SNO, SuperK

Sunday 8th November

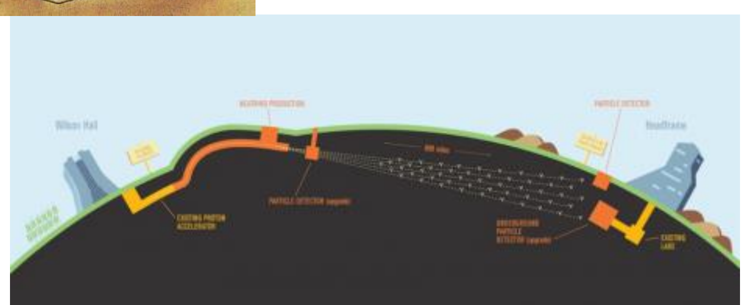
Thursday 10th Dec

The story of neutrinos – to SNO and beyond

Historic perspective



Fascinating neutrinos



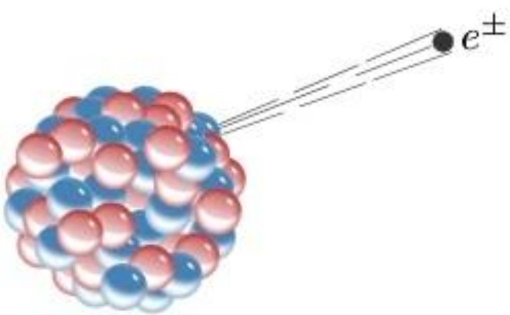
Future horizons

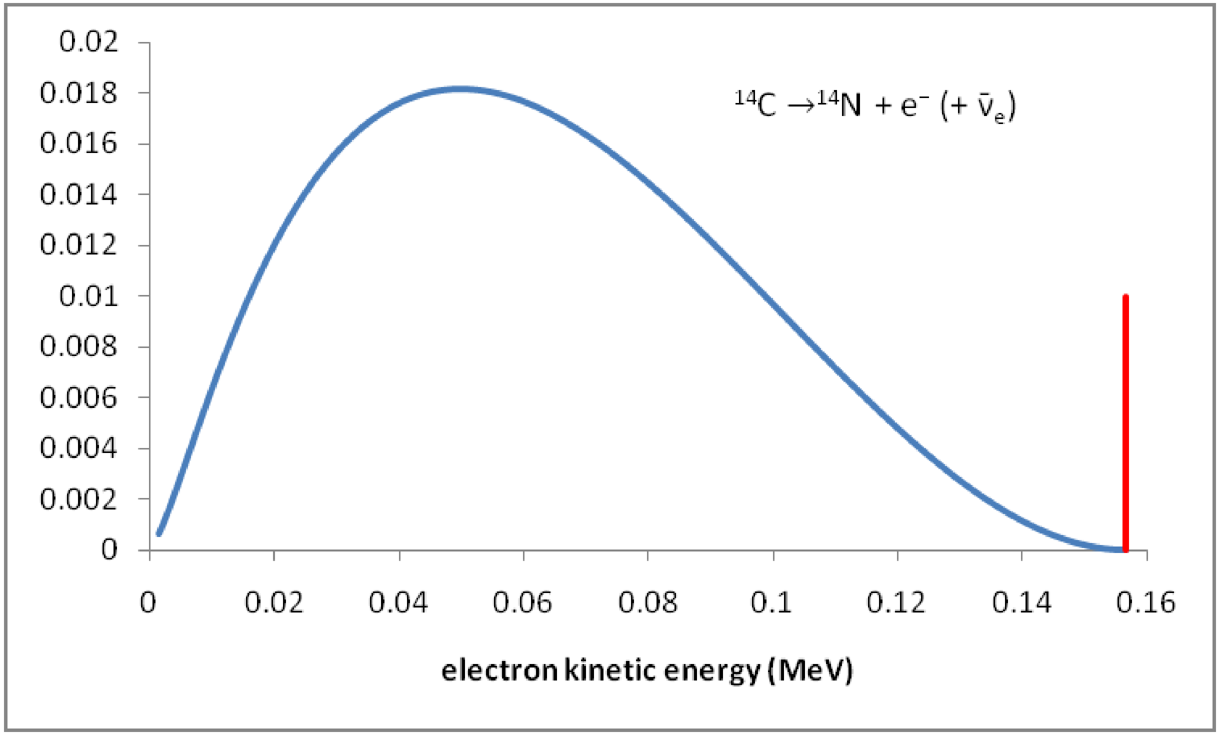
Historic perspective

Chadwick (1914)

The Nobel Prize in Physics 1935 was awarded to James Chadwick "for the discovery of the neutron“

… not the neutrino ….



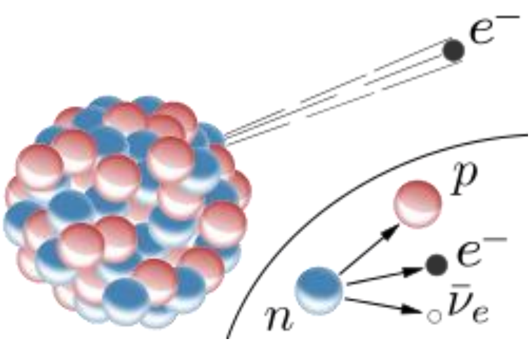


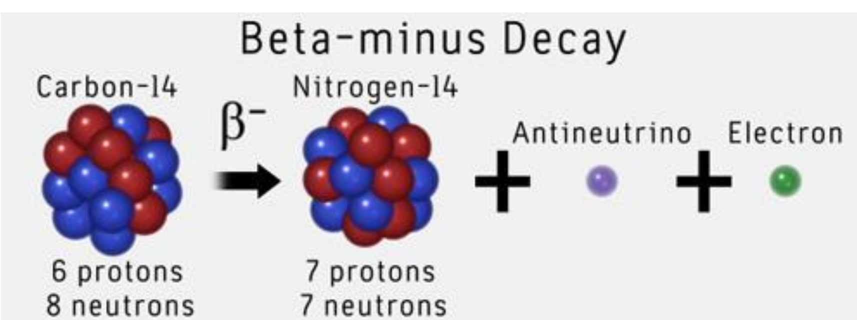
Bohr vs Pauli

Pauli (1930)

The Nobel Prize in Physics 1945 was awarded to Wolfgang Pauli "for the discovery of the Exclusion Principle, also called the Pauli Principle".

... not the neutrino ...





Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

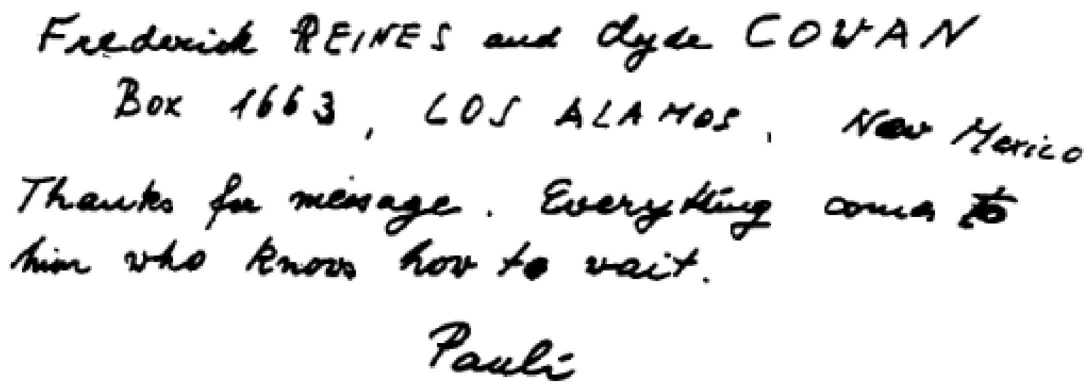
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

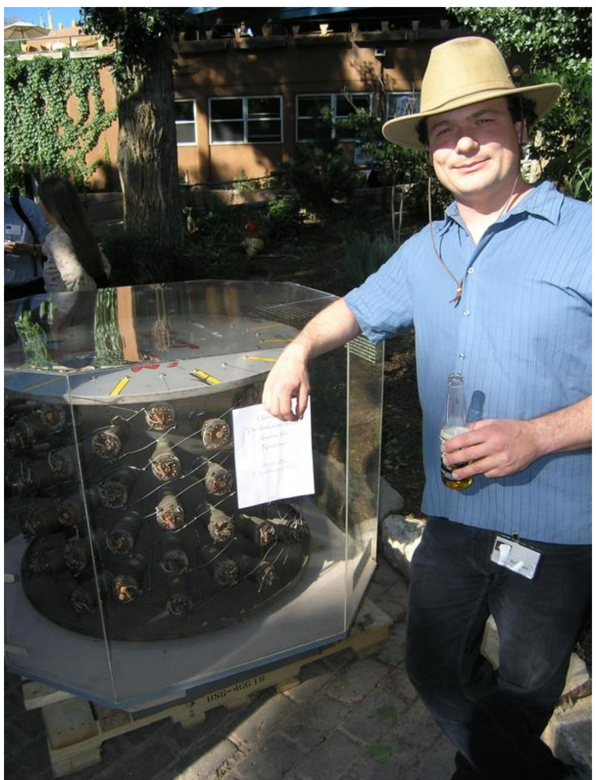
…. much later *(1956)*….

The Nobel Prize in Physics 1995 was Frederic Reines (Cowan had passed away by then) and Martin Perl 'for pioneering contributions to lepton physics'.


Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

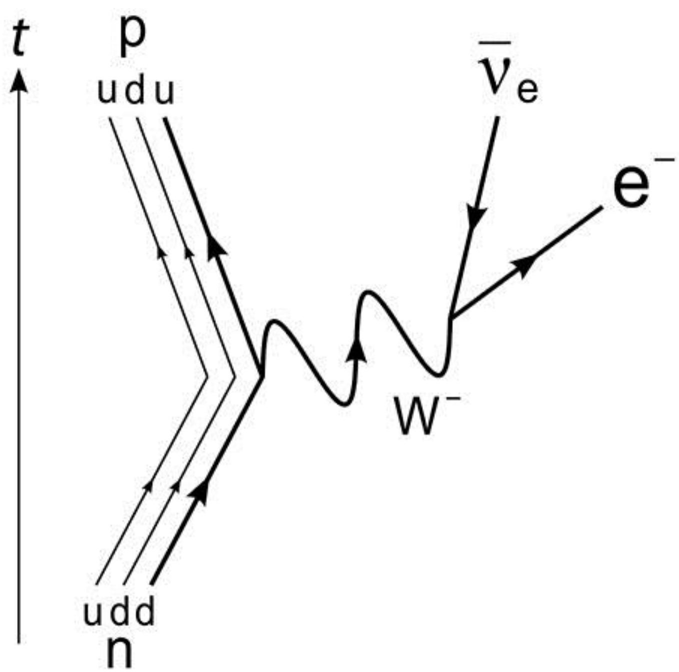
Thanks for message. Everything comes to him who knows how to wait.

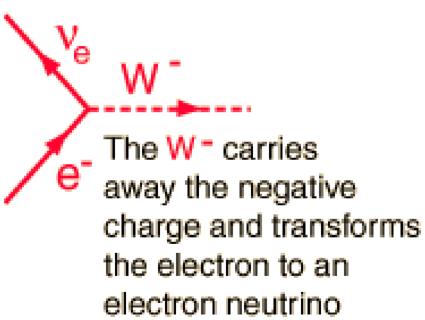
Pauli



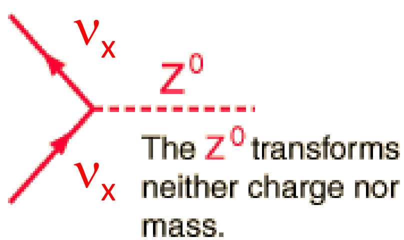
Neutrinos 2006 – Santa Fe

Weak interaction (1957)





Charged Current (CC)

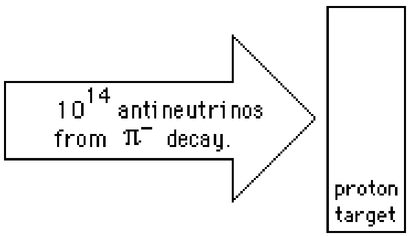


Neutral Current (NC)

Robert Marshak & George Sudarshan, later Richard Feynman (Nobel 1965) and Murray Gell-man (Nobel 1969) proposed 'V-A'

The Nobel Prize in Physics 1979 was awarded to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".

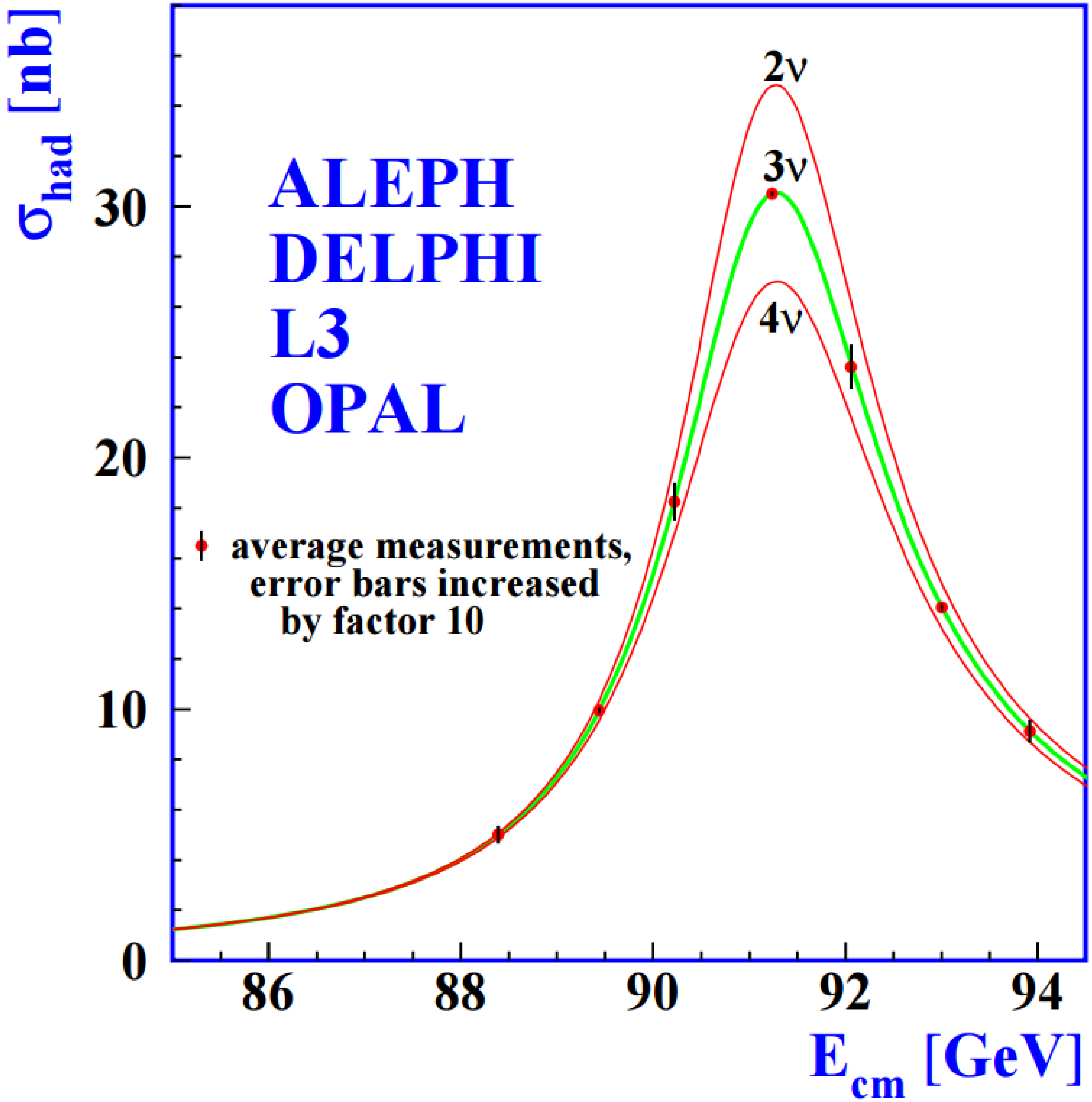
Neutrino flavour (1962)



Reaction	Number observed
$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n$	29
$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n$	0

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz (pictured) *and Jack Steinberger "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".*

Only three (light) neutrinos



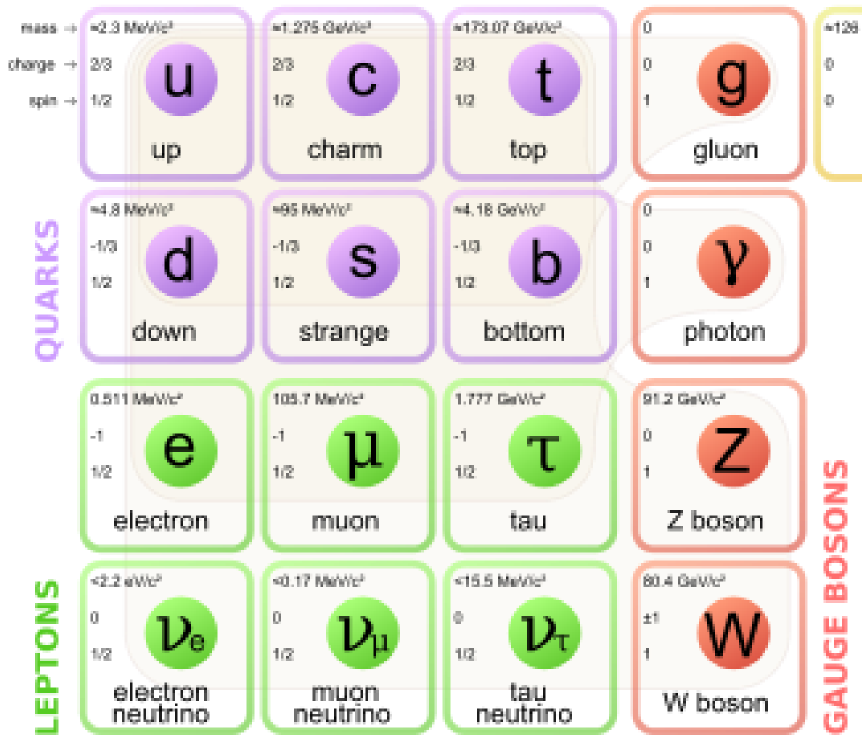
Phys.Rept.427:257-454,2006

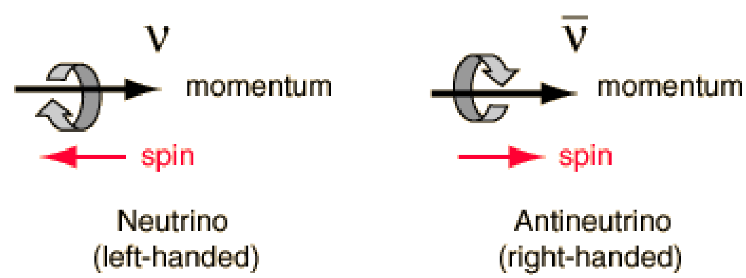
So what did we know about neutrinos?

Neutrinos come in three flavours

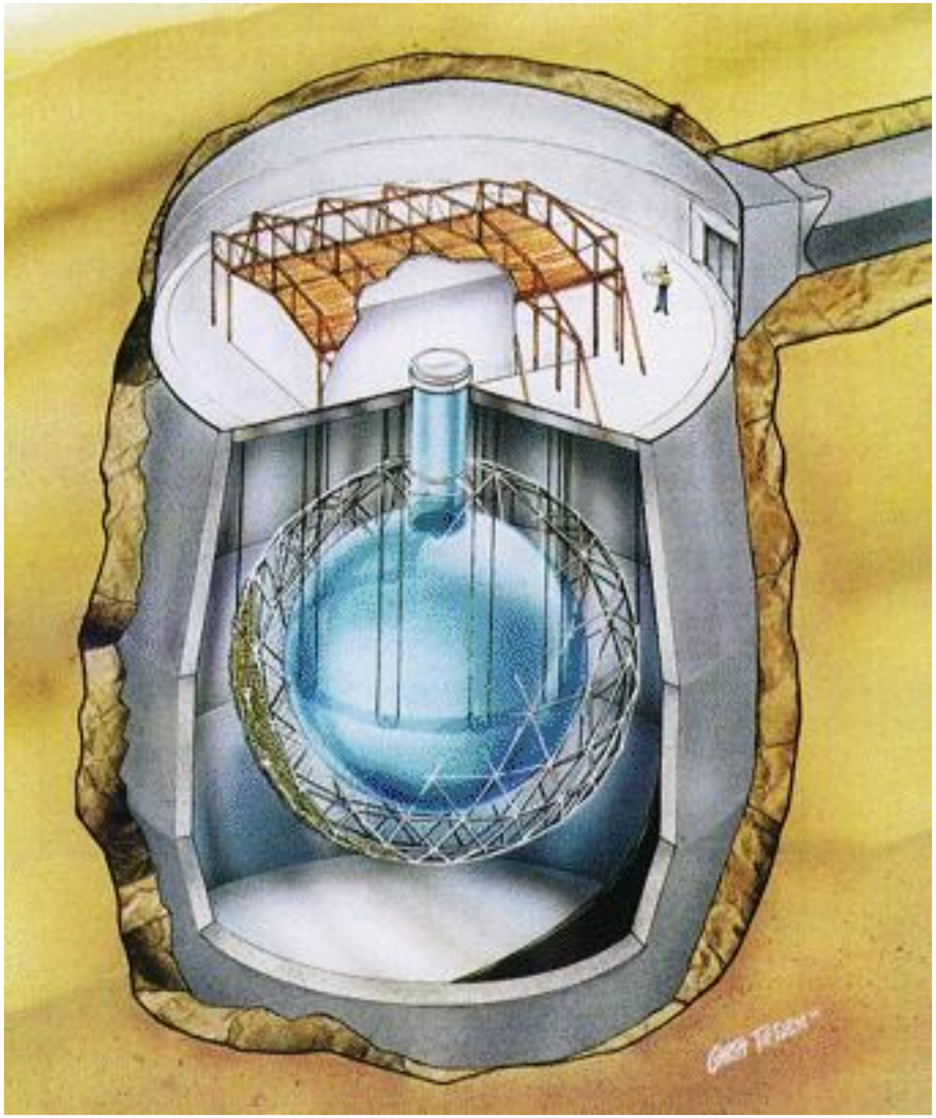
Neutrinos interact weakly only

Neutrinos are massless

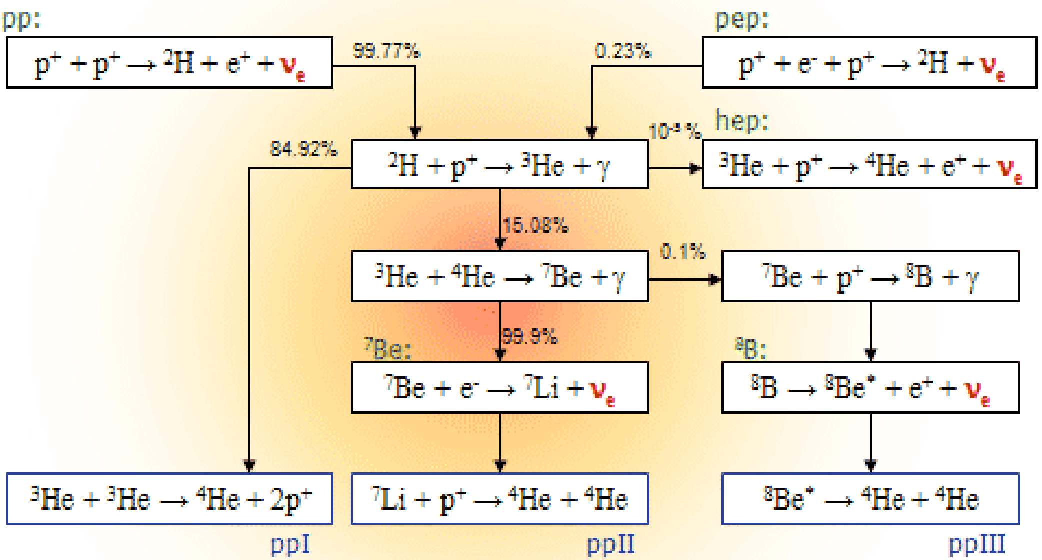


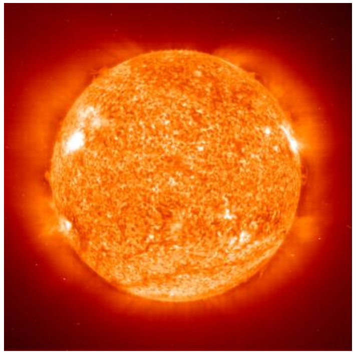


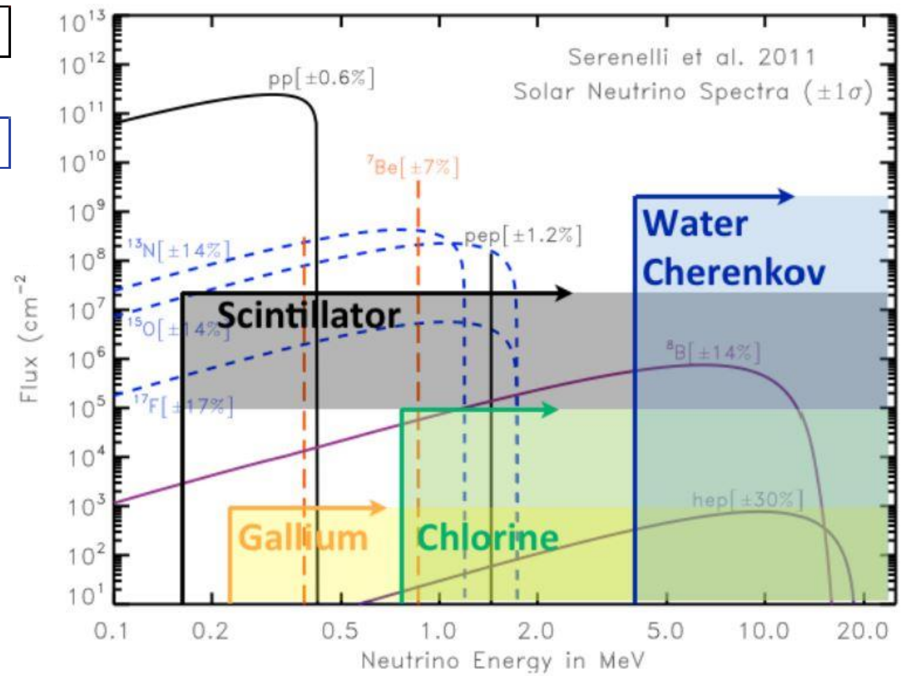
The truly fascinating behaviour of neutrinos



Standard Solar Model: exact flux prediction







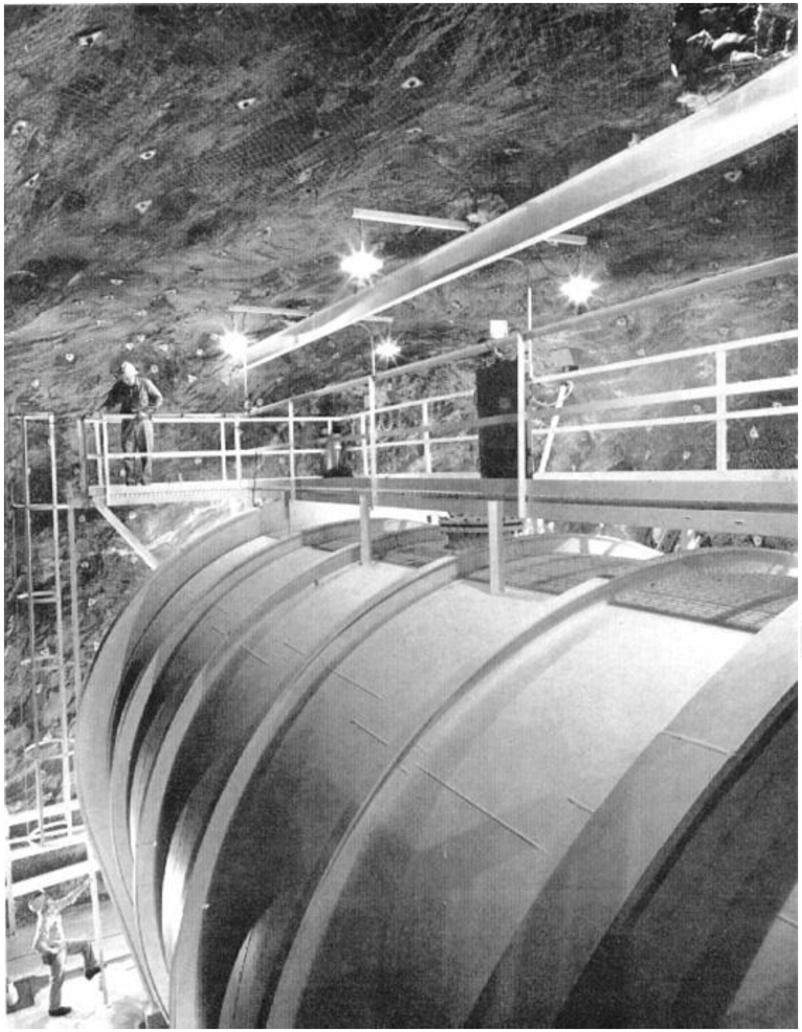
Championed by John F Bahcall,
sadly passed away in 2005.
… no Nobel prize …

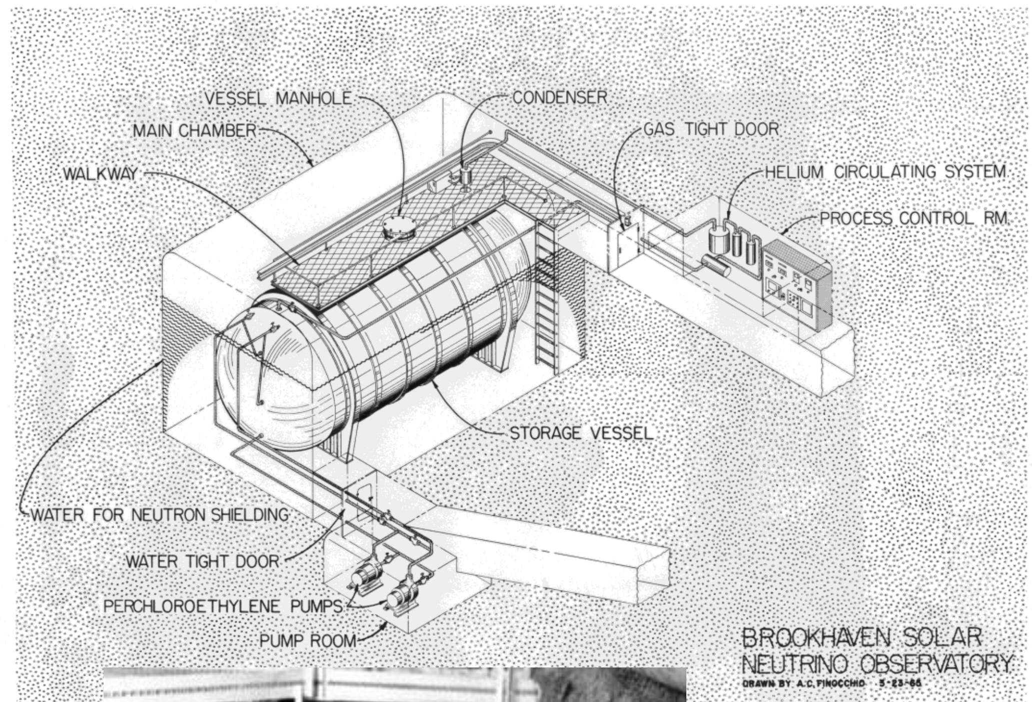
Ray Davis' Chlorine Experiments*

Proposed by Bruno Pontecorve (1946):

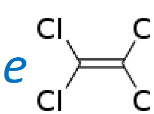
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

** Tried Savanah and Brookhaven reactors first.*
We know now that this does not work for anti-neutrinos (right handed)

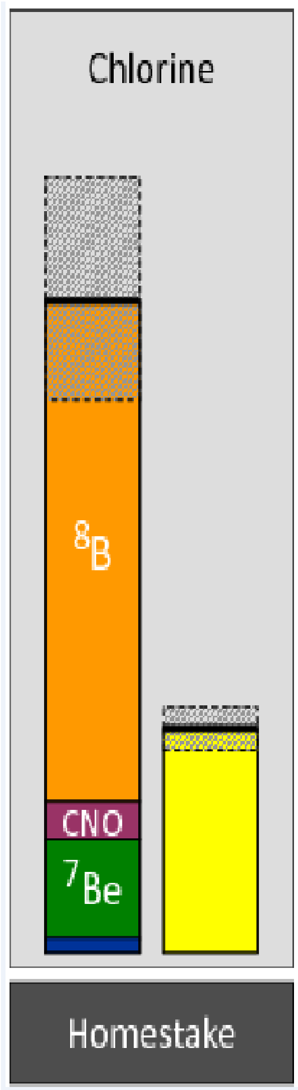




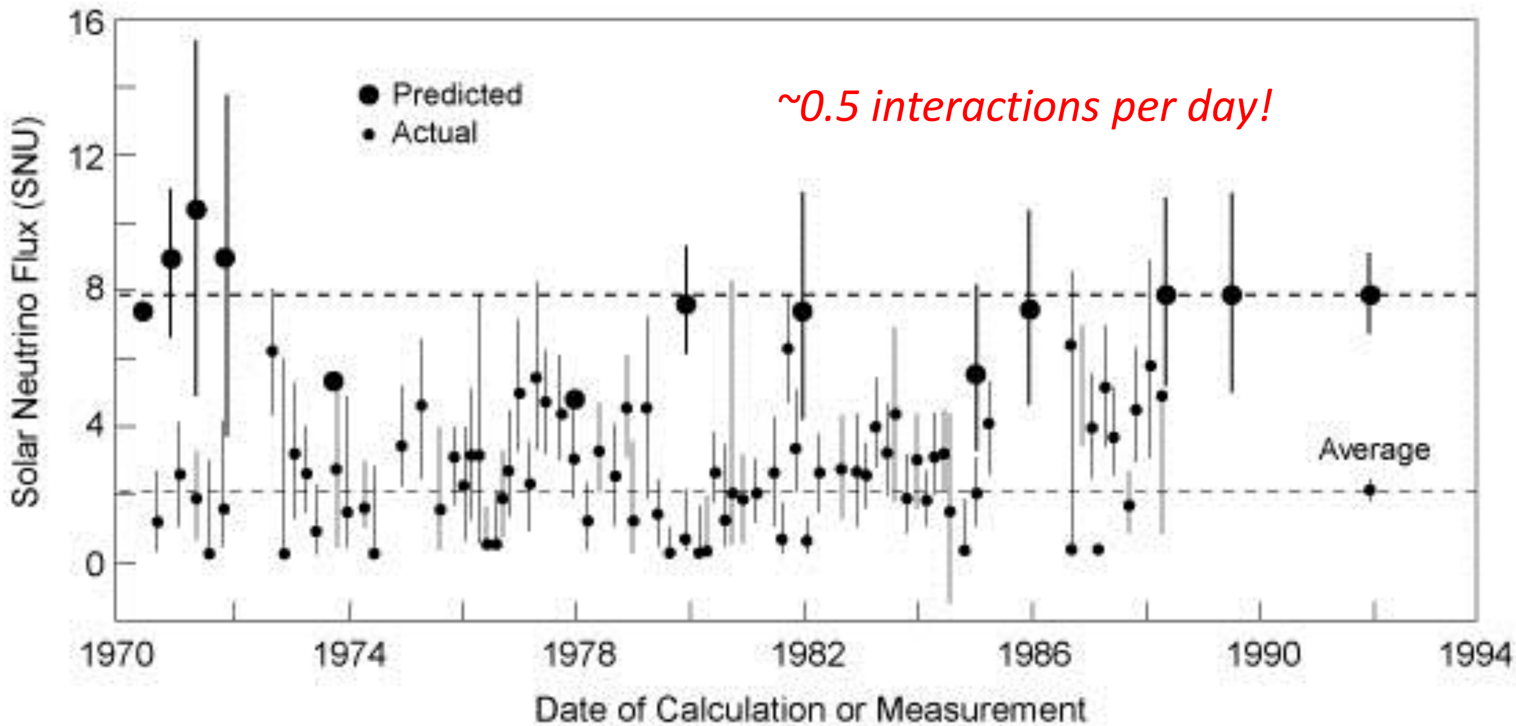
Homestake Gold Mine (South Dakota, US), 1.5 km UG, 380 m^3 perchlorethylene



Raymond Davis' result: solar neutrino problem



The Nobel Prize in Physics 2002 (just after SNO's first results) was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos".

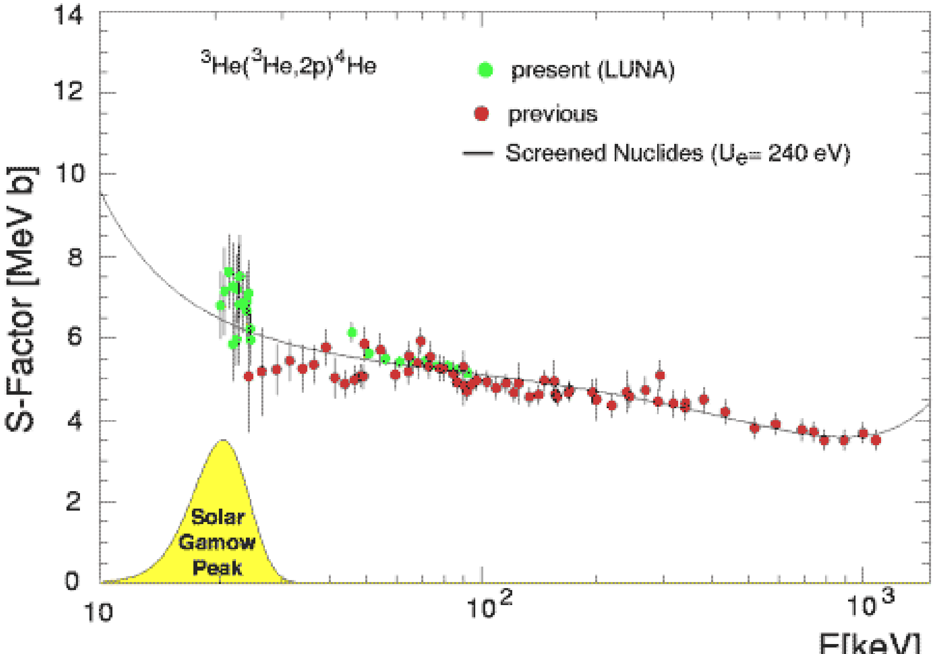


So what was happening?

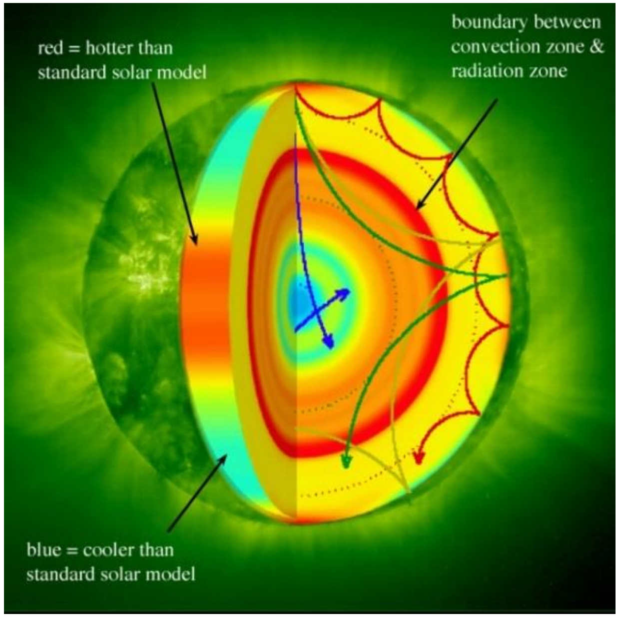
- Is the Standard Solar Model wrong?
- Is our nuclear physics wrong?
- Is the experiment wrong?
- Is our understanding of neutrinos wrong?

SAGE

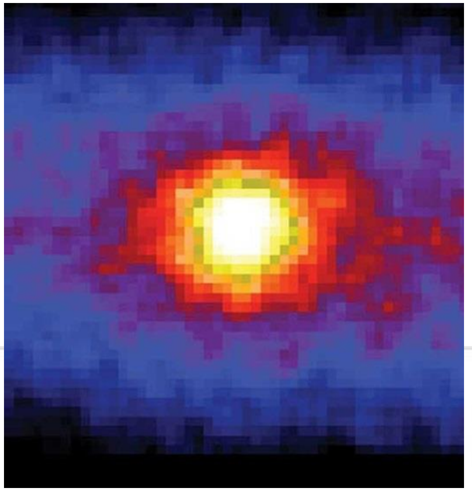
LUNA

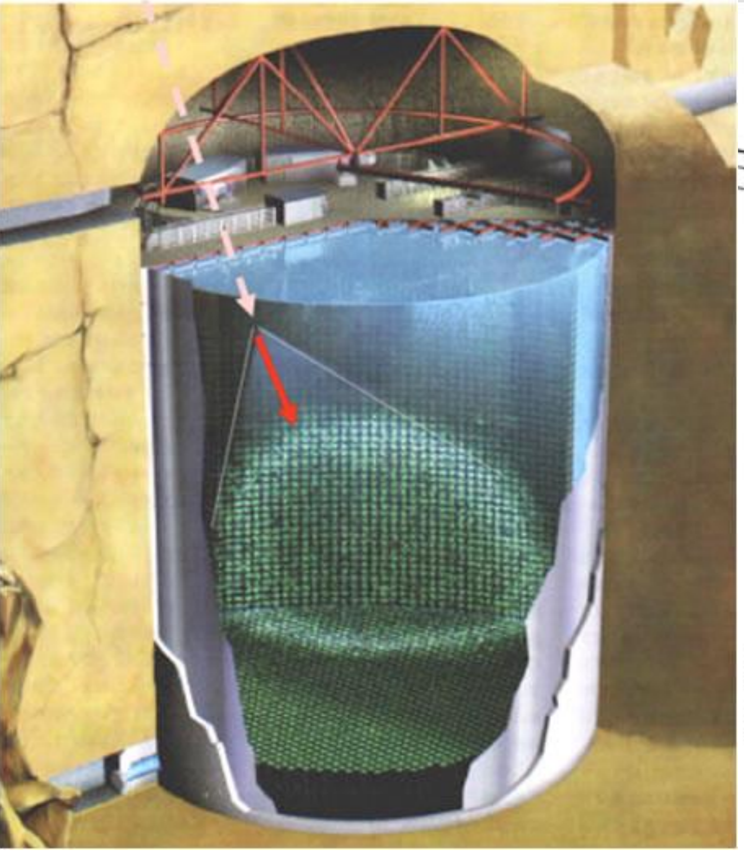


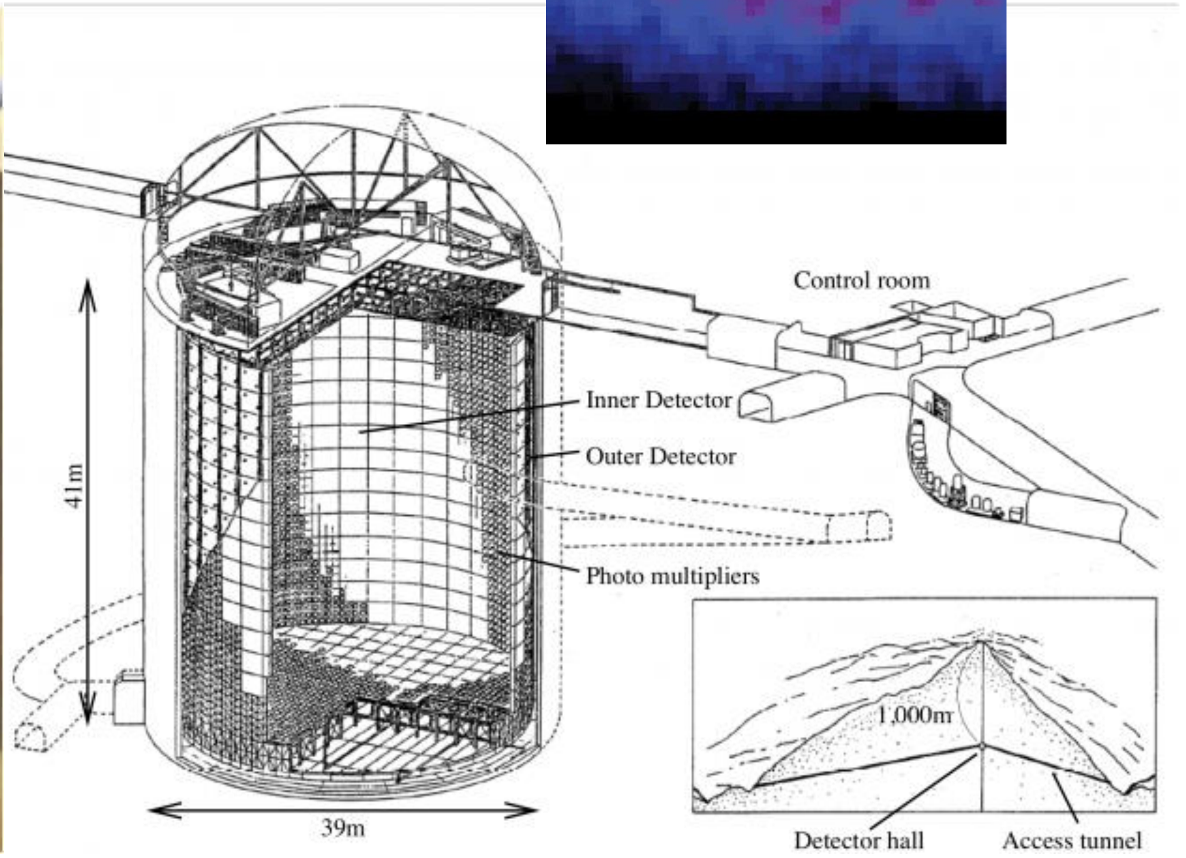
BiSON



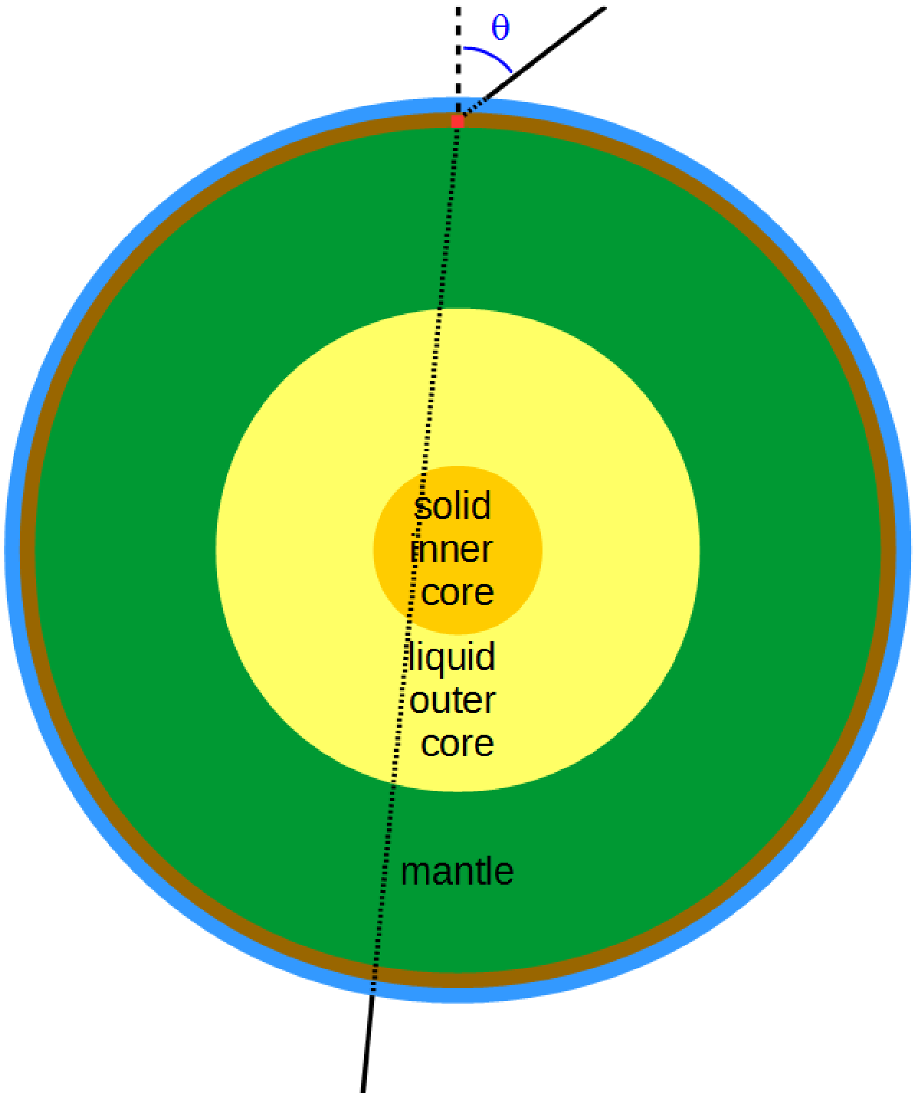
Super Kamiokande (Japan)

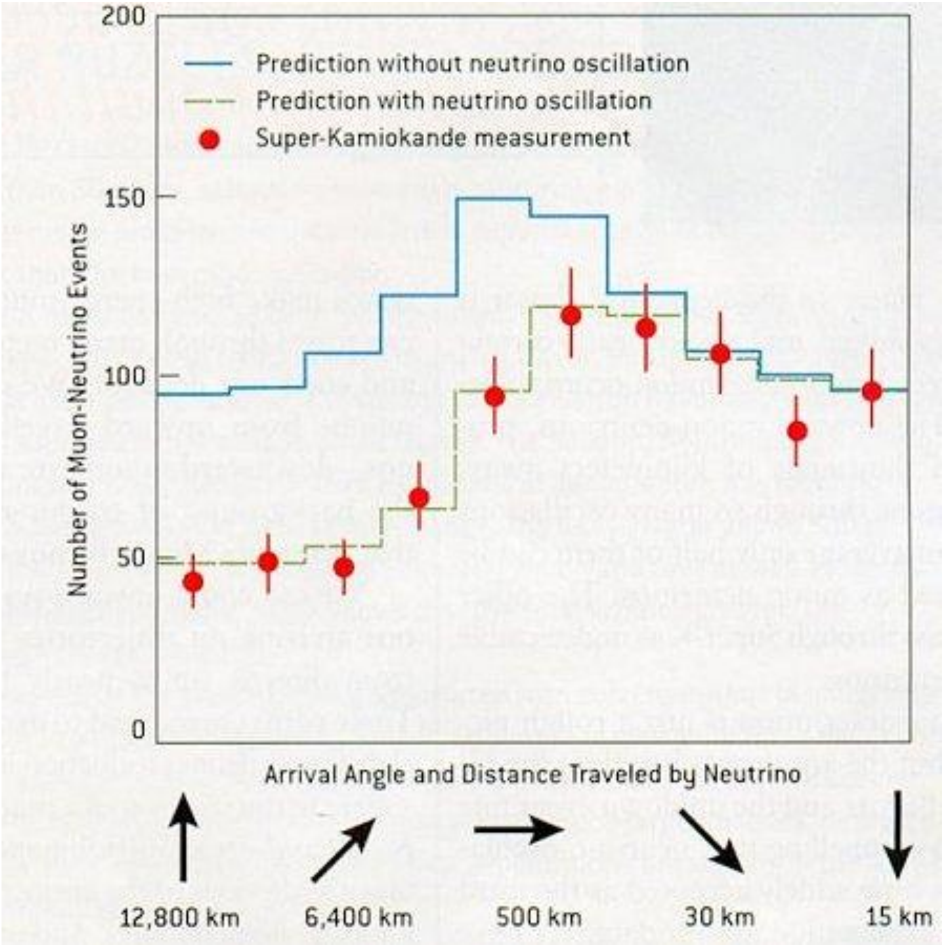






Super Kamiokande observation in 1998





Herb Chen's brilliant idea (1985)

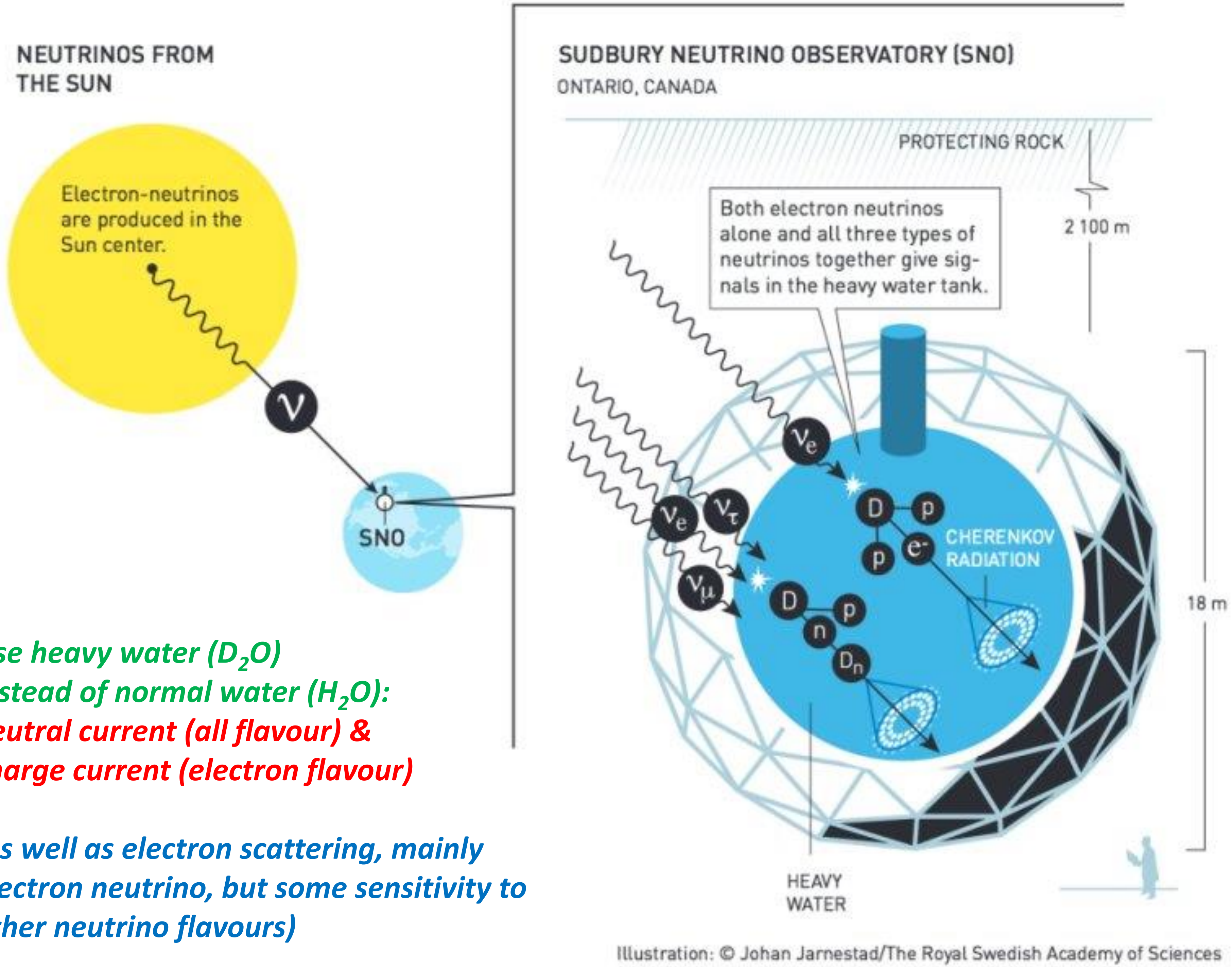
VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh



Use heavy water (D_2O)
instead of normal water (H_2O):
neutral current (all flavour) &
charge current (electron flavour)

(as well as electron scattering, mainly Electron neutrino, but some sensitivity to other neutrino flavours)

Birth of the Sudbury Neutrino Observatory

ELECTRONIC DETECTORS FOR THE STUDY OF

^{8}B SOLAR NEUTRINOS *+

(with sensitivity to energy and direction)

Herbert H. Chen

Dept. of Physics, University of California, Irvine, CA 92717

ABSTRACT

The statistical requirement for any directional ^{8}B solar neutrino experiment with an initially large background to signal ratio (about 1000) indicates the need for extremely large detectors. However, this detector scale can be decreased substantially if the detector mass can be made radioactively clean so that only external backgrounds remain. Then the detector can be operated in a self-shielding mode. Among a number of detector options, the water Cherenkov approach being used in the search for proton decay satisfies these requirements. With the neutrino deuteron reaction via the use of heavy water rather than light water, the background to signal ratio can be further improved and one can demonstrate observation of the ^{8}B solar neutrino much before one can demonstrate its directionality.

I. INTRODUCTION

The solar neutrino "problem", i.e. that there are fewer neutrinos from the sun as observed in the chlorine/argon radio-chemical experiment of Davis et al. [1] than that predicted by the "standard" solar model [2], has prompted a variety of solutions ranging from neutrino oscillations [3], neutrino decay [4], to a very large variety of non-standard solar models [5]. These have been discussed widely over the past decade, and the discussions continue here at this conference. The new radio-chemical experiments: ^{71}Ga [6], sensitive to neutrinos from the pp reaction in the sun; ^{81}Br [7], sensitive to the ^{7}Be neutrino; and the geo-chemical experiment: ^{98}Mo [8], sensitive to the ^{8}B flux averaged over the last several million years; will add greatly to our knowledge when they are carried out.

It is clear, however, that radio-chemical and geo-chemical experiments need to be complemented by direct-counting experiments, particularly those sensitive to neutrino direction as well as to energy. With sensitivity to direction and to energy, direct-counting experiments can demonstrate unambiguously

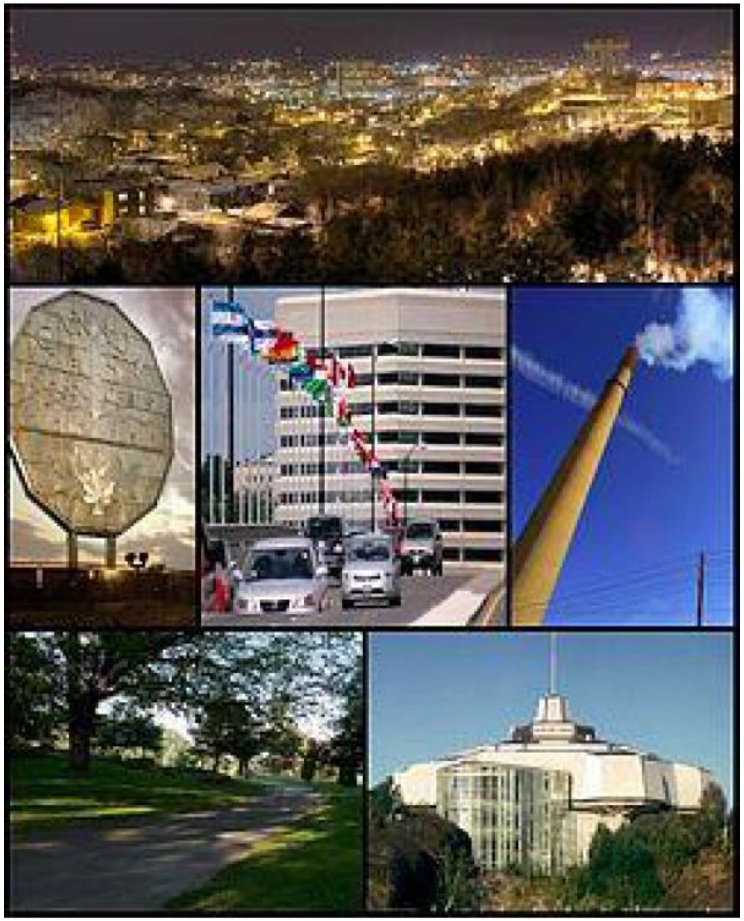
* Research supported in part by the National Science Foundation.
+ Research supported in part by the U.S. Department of Energy.

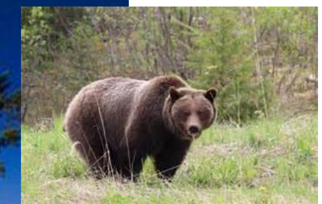
First SNO collaboration meeting, Chalk River 1986

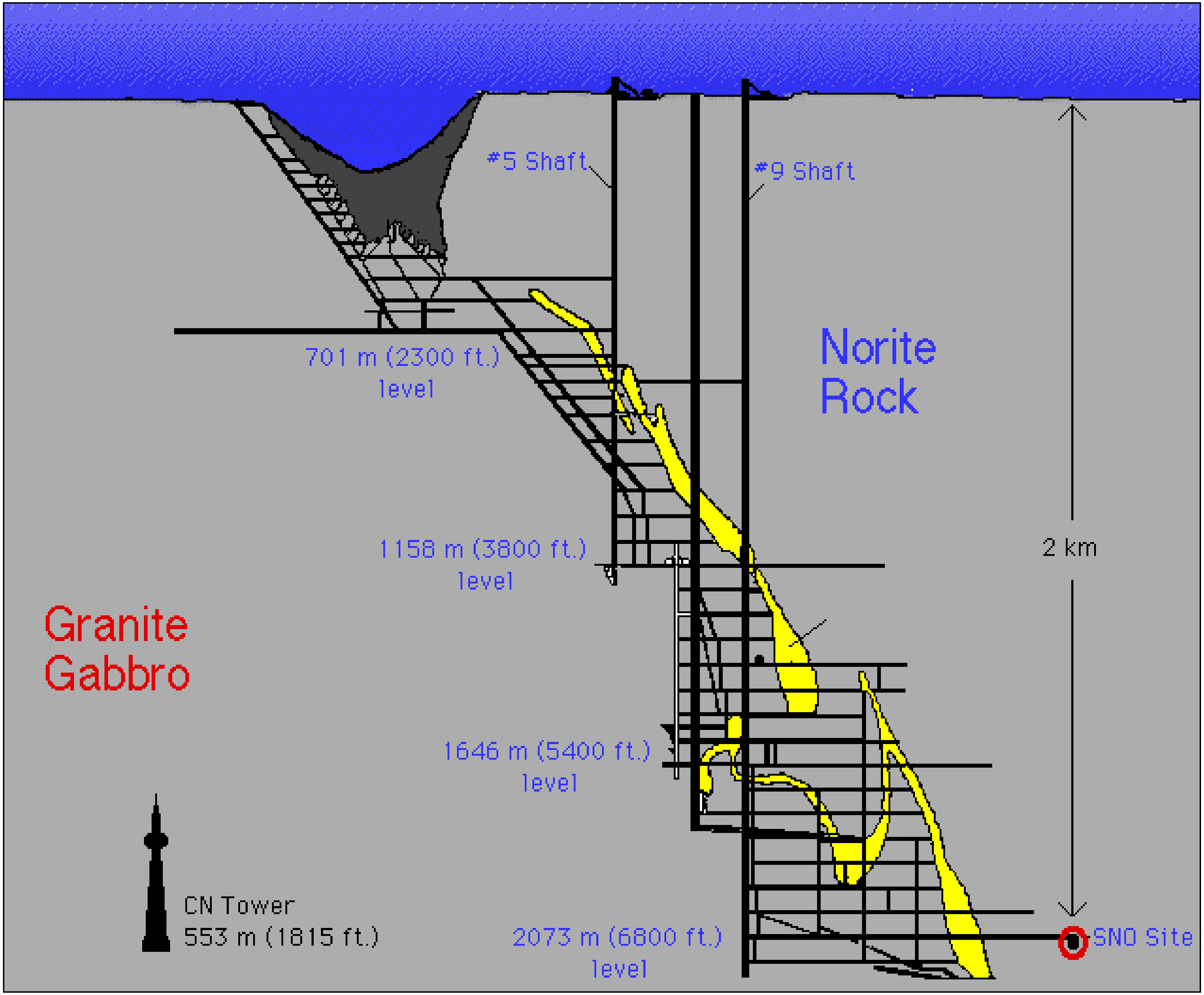
Official SNO Proposal: 1987

ON
QC
Moosonee
Thunder Bay
Timmins
Lake Superior
Sault Ste. Marie
Sudbury
North Bay
Quebec City
Duluth
MI
Ottawa
Montreal
Lake Huron
WI
Lake Michigan
Toronto
Lake Ontario
400 KM (250 miles)
Milwaukee
Buffalo
Sarnia
Niagara Falls
Detroit
Windsor
Lake Erie
Chicago
New York
PA
Columbus
Philadelphia
Indianapolis
800 KM (500 miles)
St. Louis

Sudbury in Northern Ontario, Canada

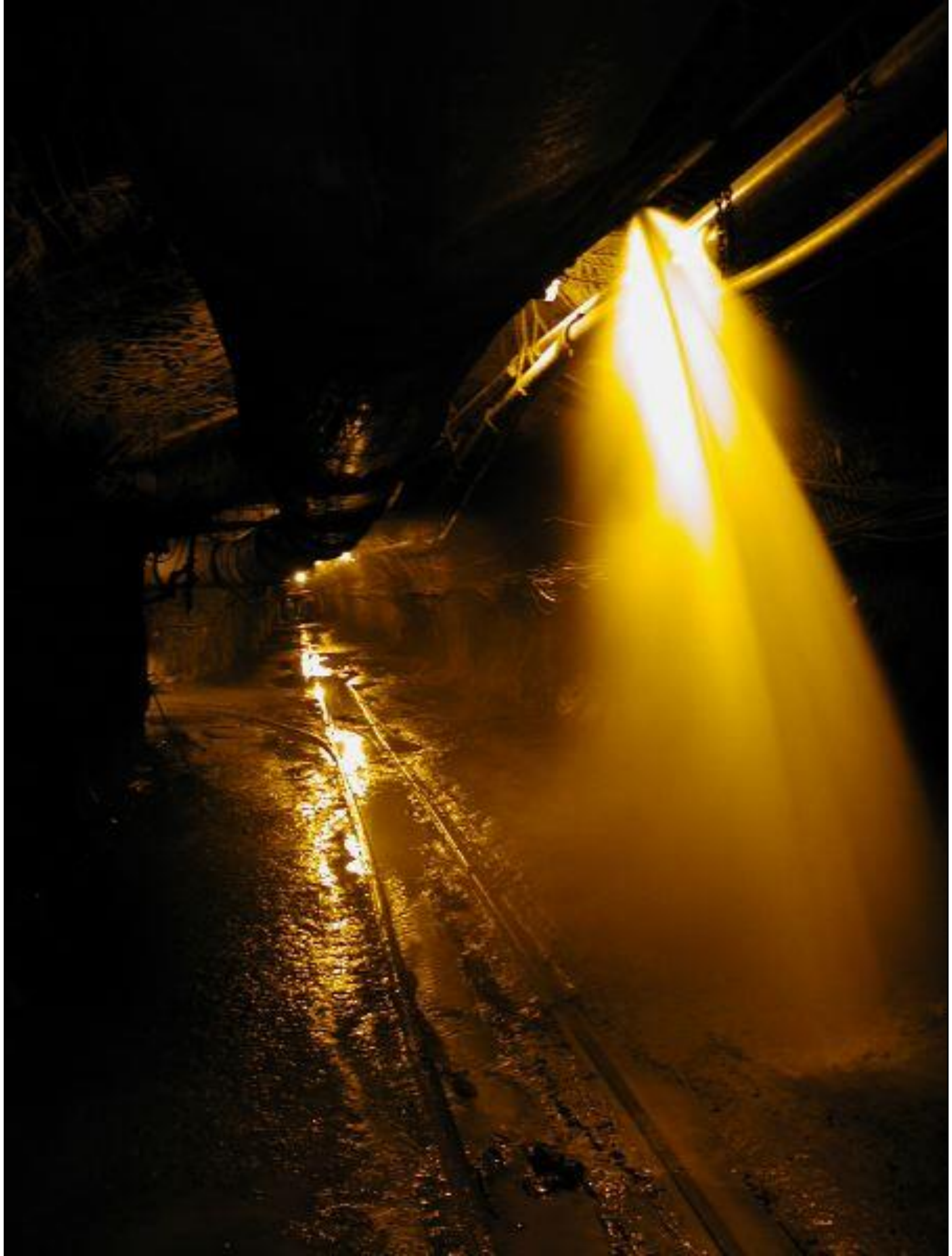


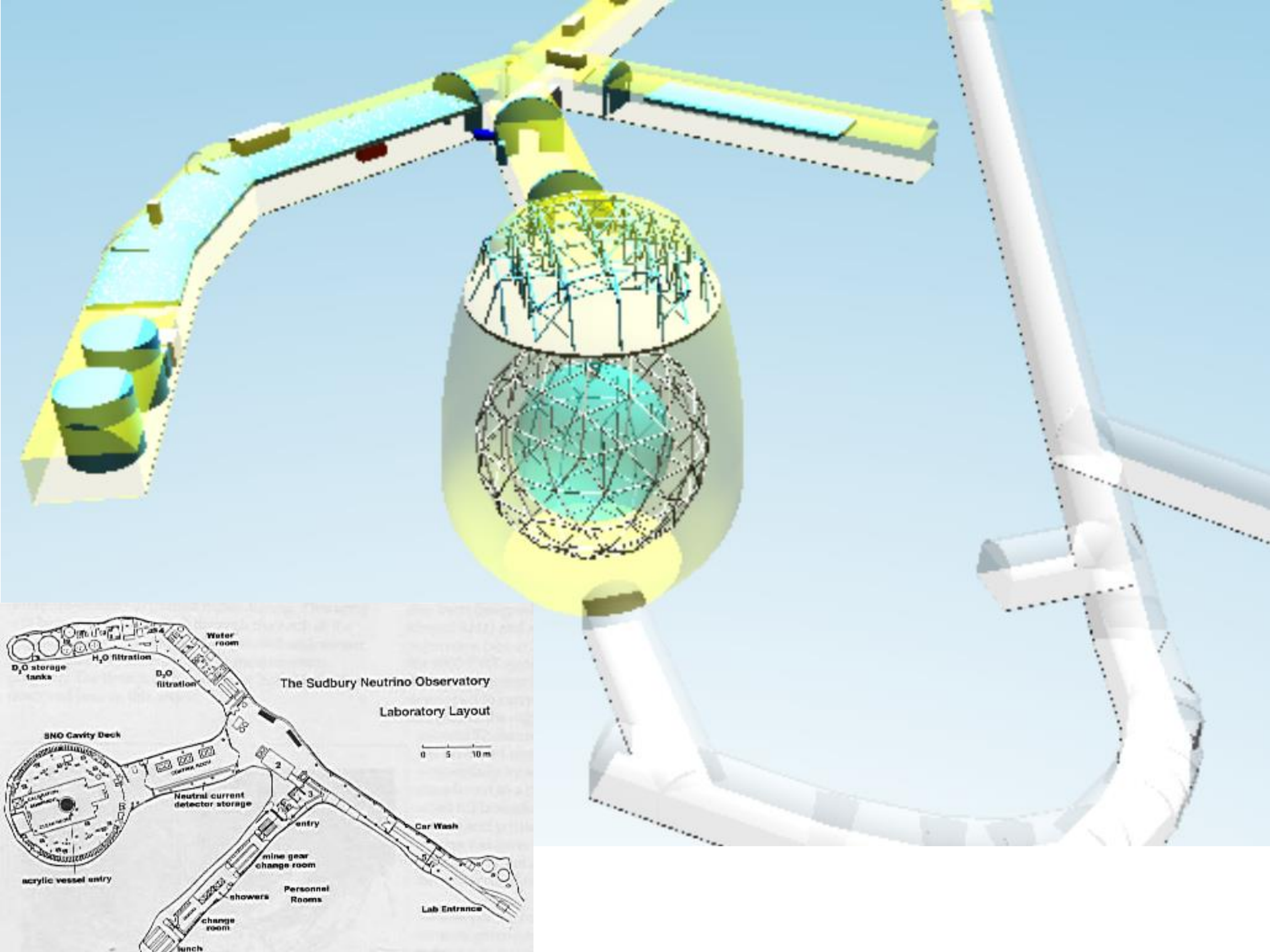


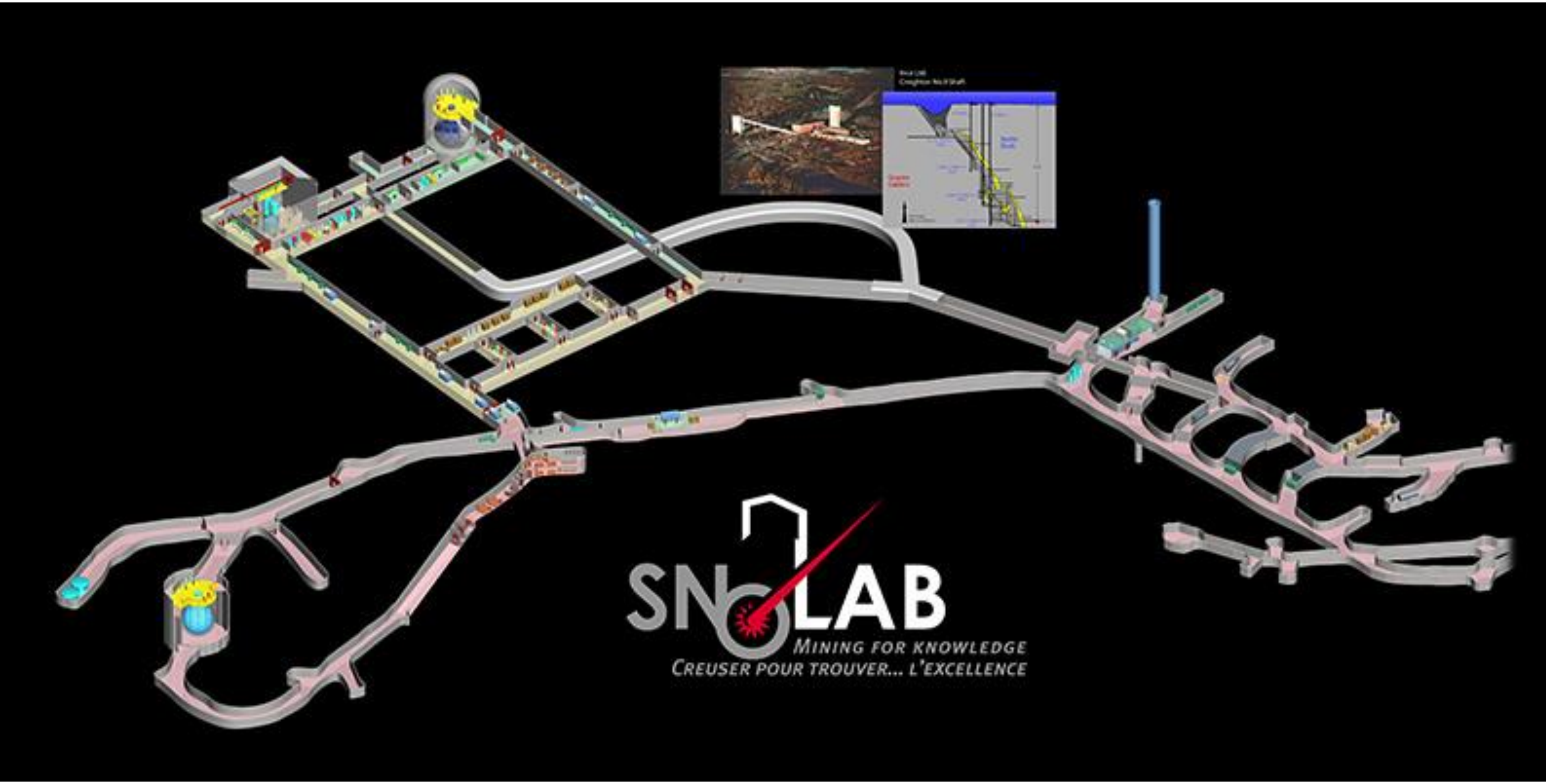


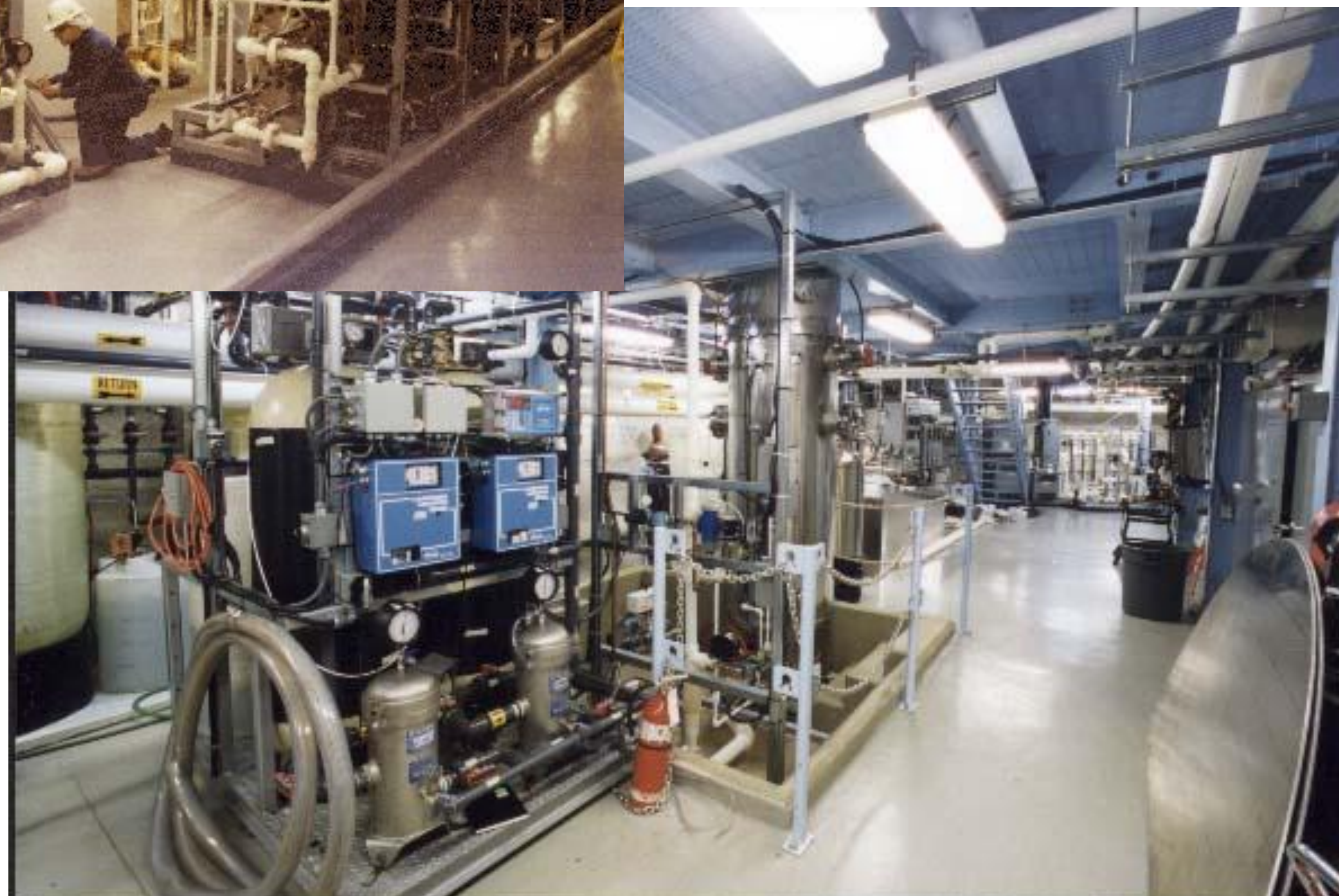
#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site

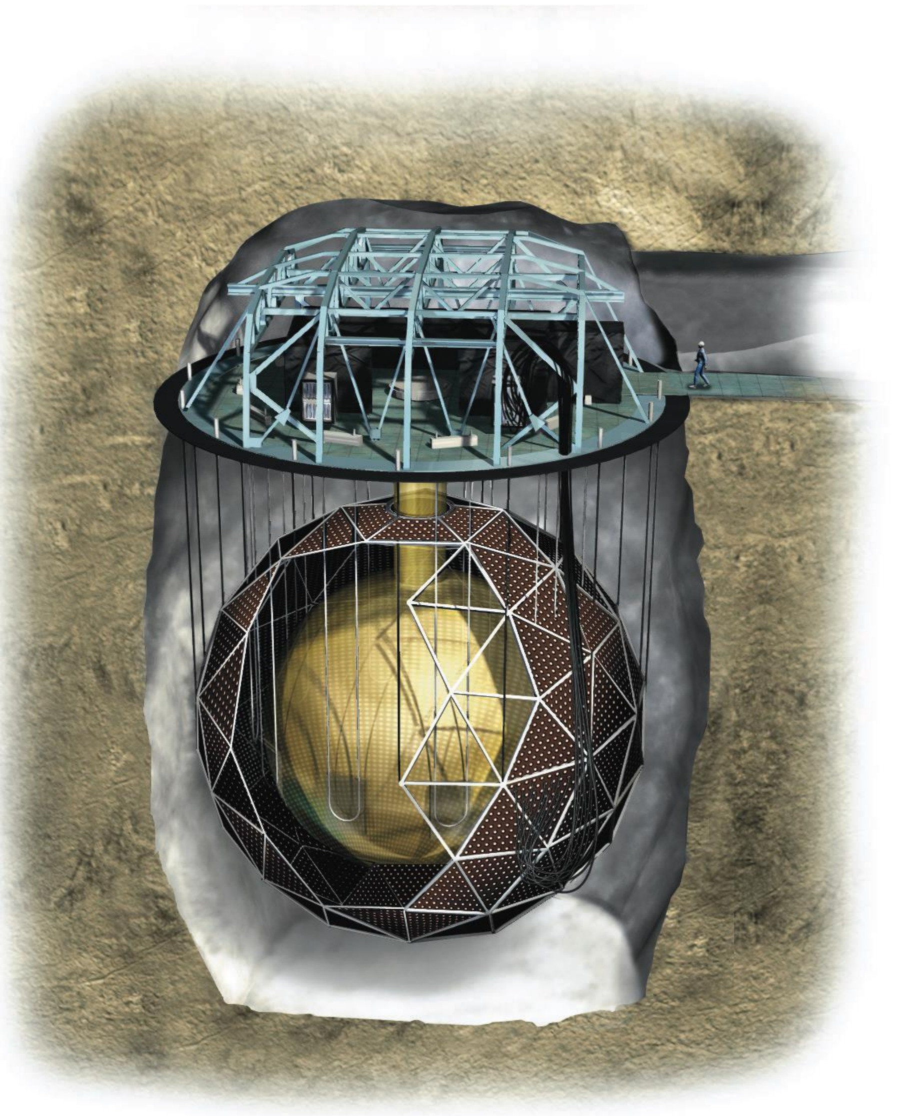

AG IN BOARD



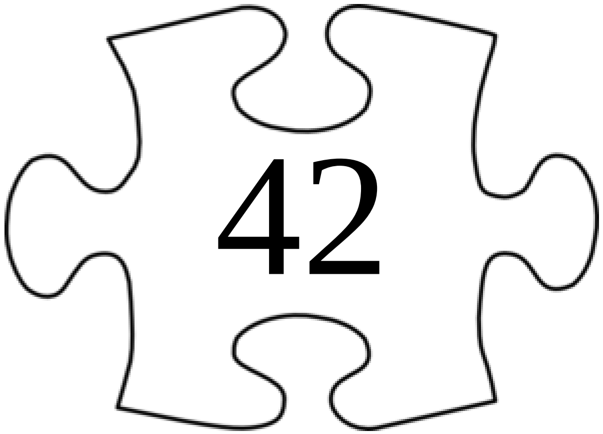

The Sudbury Neutrino Observatory
Laboratory Layout
Water room
H_2O filtration
D_2O storage tanks
D_2O filtration
SNO Cavity Deck
0 5 10 m
Neutral current detector storage
2
3
entry
Car Wash
mine gear change room
acrylic vessel entry
Personnel Rooms
showers
Lab Entrance
change room
lunch


SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE





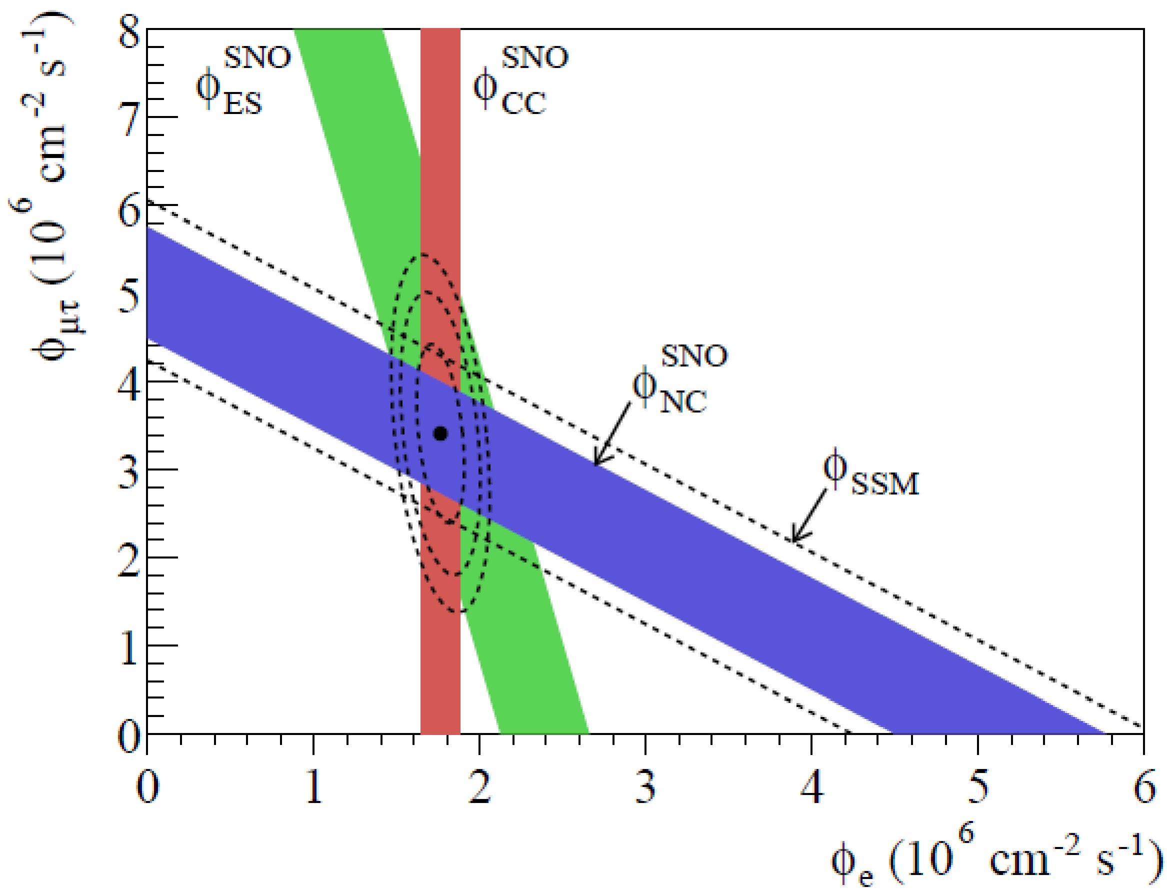
SNO's answer was:



electron flavour neutrinos per square milli-furlongs per nano-minute*

and a total neutrino flux of about three times that many!

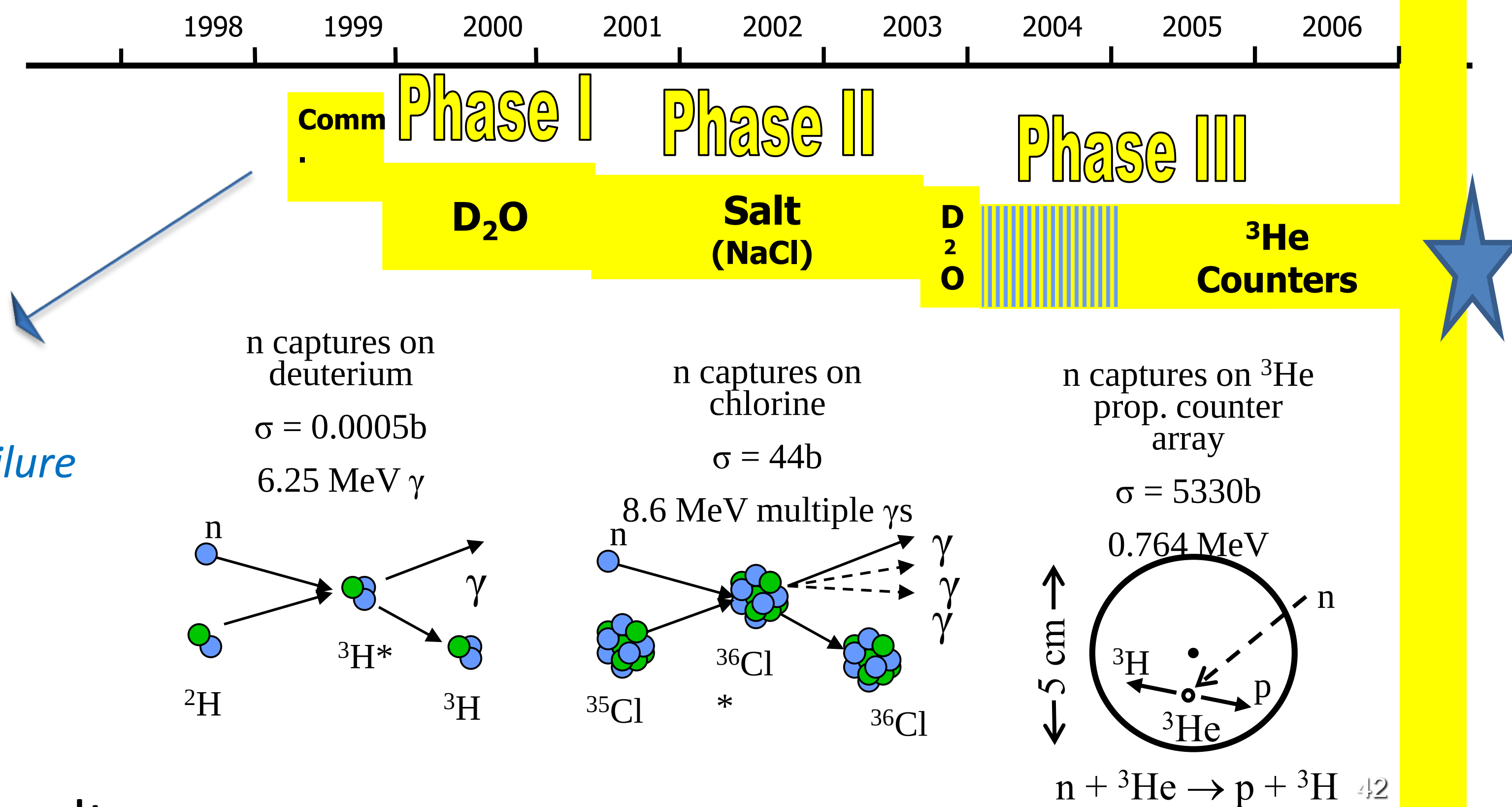
Solar neutrino puzzle solved:
Neutrinos change their flavour between the Sun and Earth!



Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

Q.R. Ahmad,[17] R.C. Allen,[4] T.C. Andersen,[6] J.D. Anglin,[10] J.C. Barton,[11,*] E.W. Beier,[12] M. Bercovitch,[10] J. Bigu,[7] S.D. Biller,[11] R.A. Black,[11] I. Blevis,[5] R.J. Boardman,[11] J. Boger,[3] E. Bonvin,[14] M.G. Boulay,[9,14] M.G. Bowler,[11] T.J. Bowles,[9] S.J. Brice,[9,11] M.C. Browne,[17,9] T.V. Bullard,[17] G. Bühler,[4] J. Cameron,[11]

SNO programme



Difference between success and failure can be small…

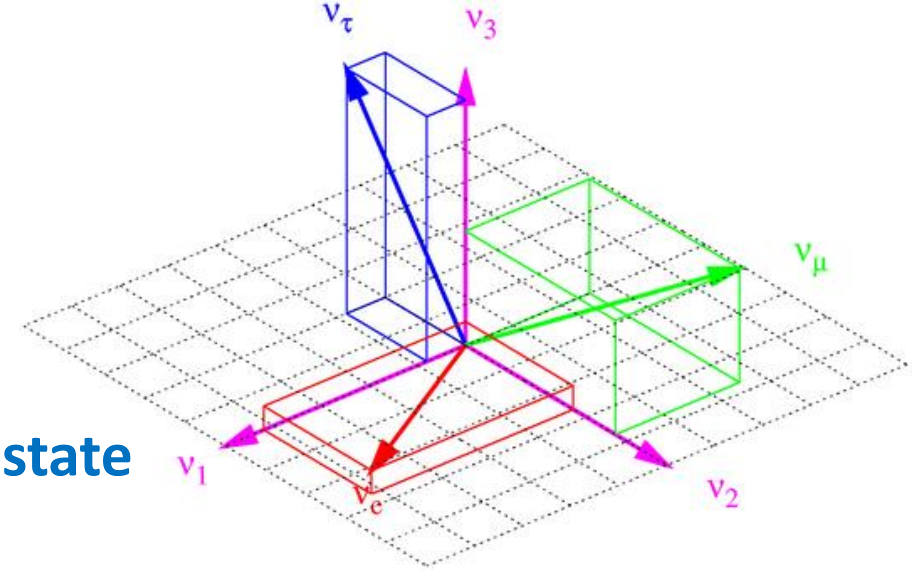
SNO main results:

- Neutrinos change flavour and thus have mass: BSM
- Neutrino oscillation parameters
- More precise measurement of solar neutrino flux (factor 2) than theoretical prediction
- Energy dependent survival probability for ^8B

Final SNO collaboration meeting, summer 2008

Analysis of SNO data now continued, using 2/3 of the Breakthrough prize

Neutrino oscillations

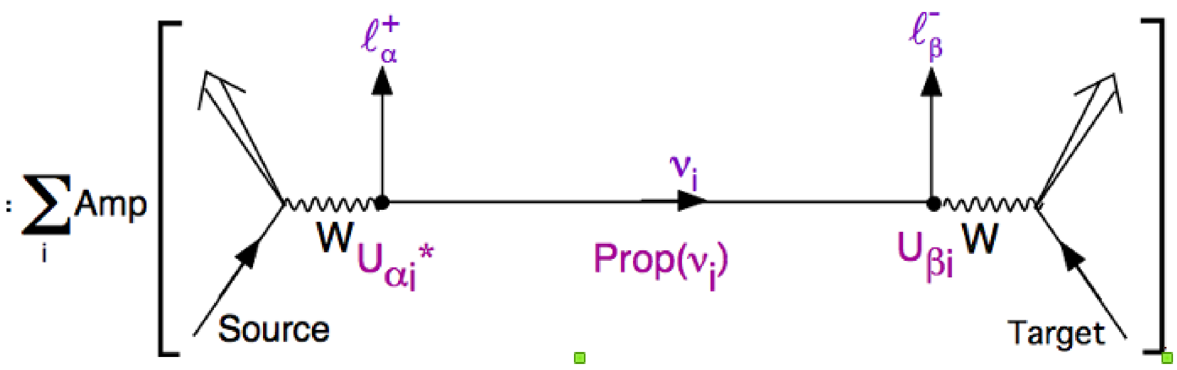


Neutrinos have mass,
and
their mass eigenstate ≠ flavour eigenstate

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

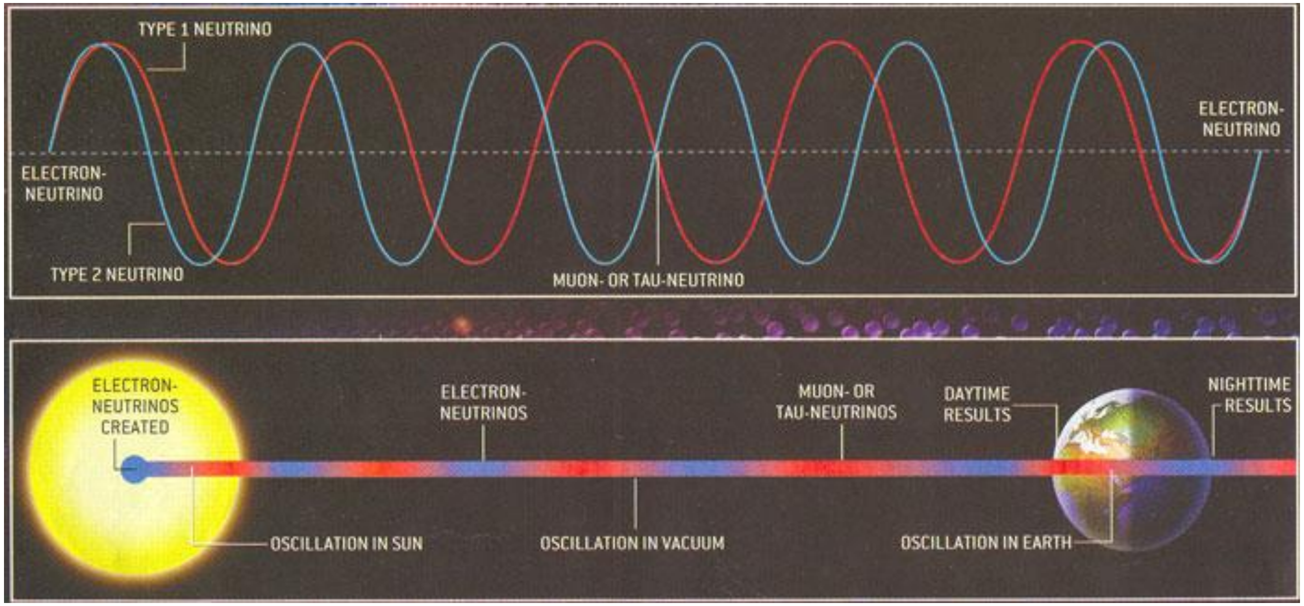
Pontecorvo–Maki–Nakagawa–Sakata matrix (**PMNS matrix**)

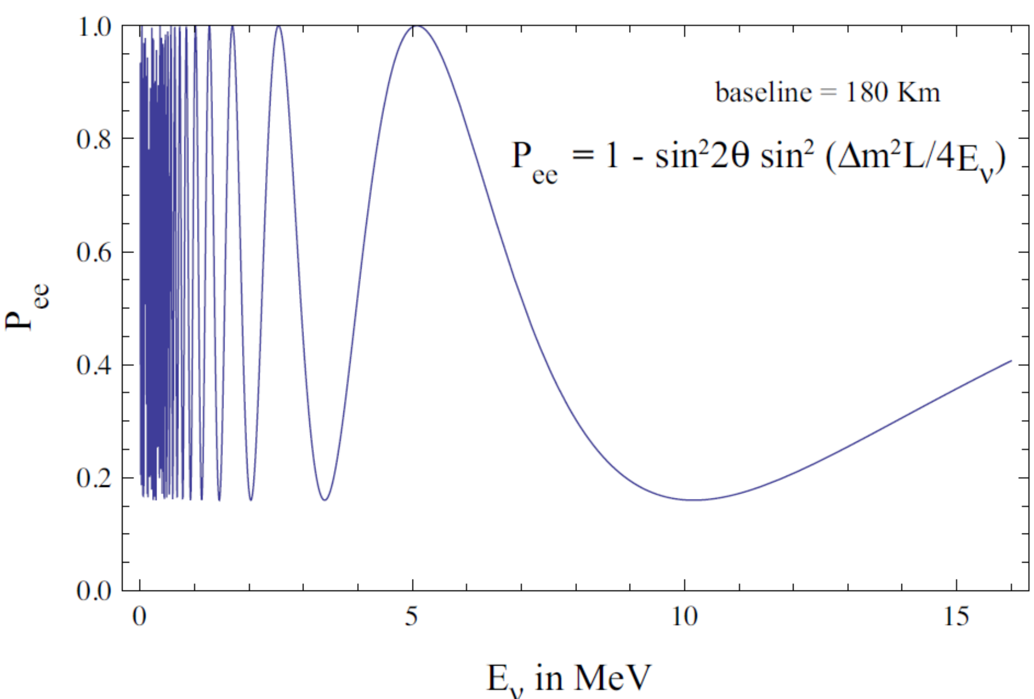
$s_{ij} = \sin\theta_{ij}$; $c_{ij} = \cos\theta_{ij}$



Neutrino oscillations

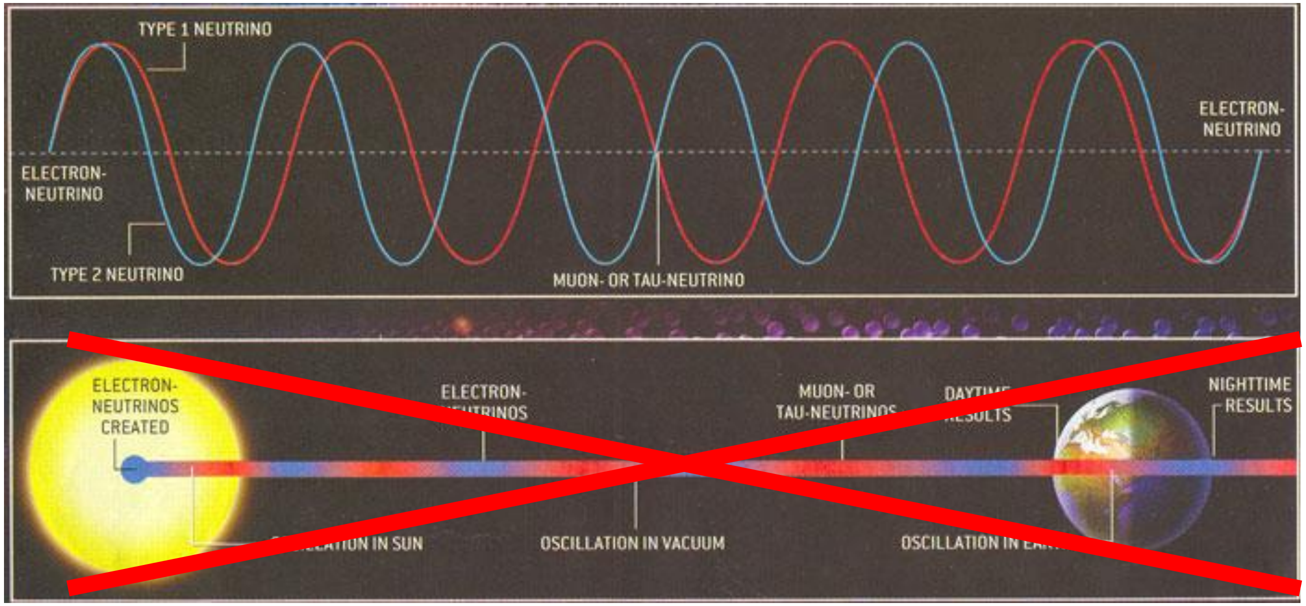
Two neutrino case

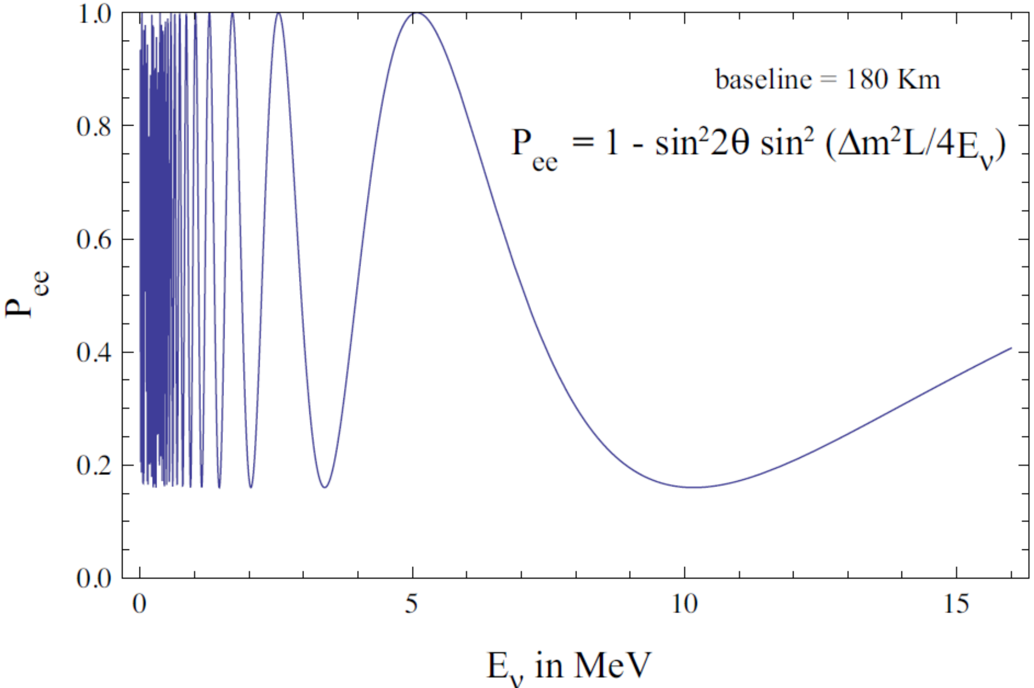




Neutrino oscillations

Two neutrino case

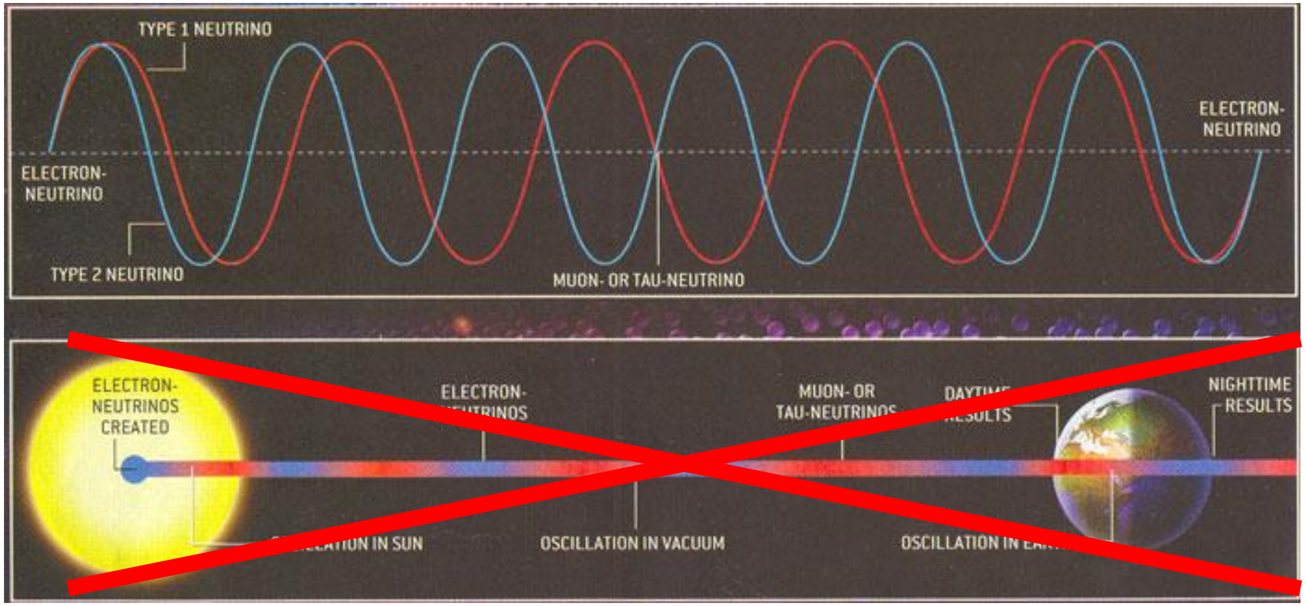


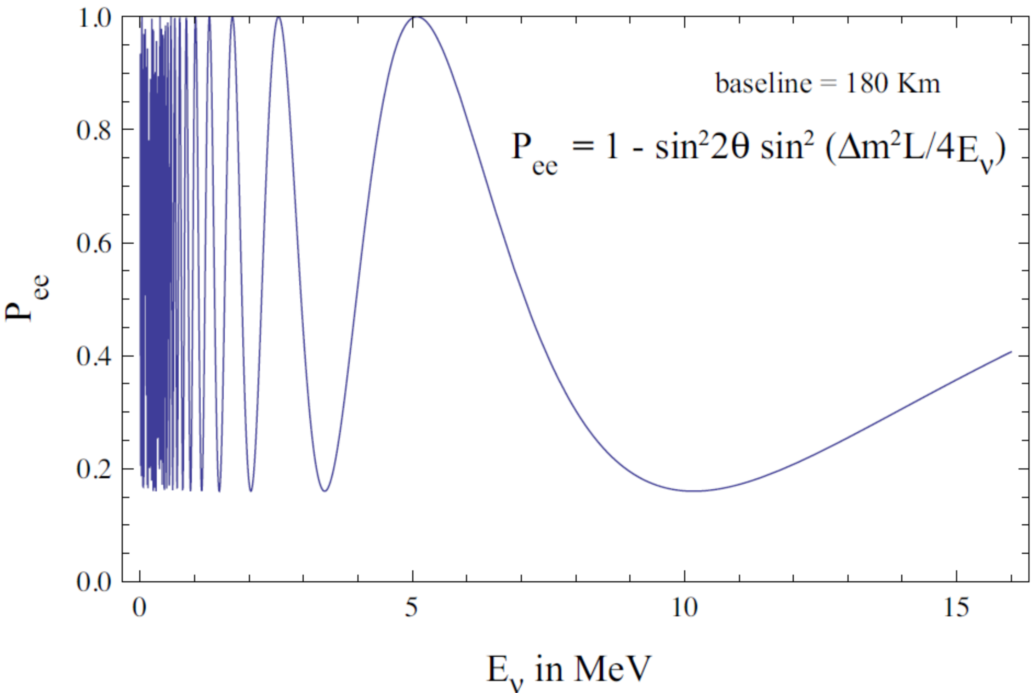


$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta = \frac{1}{2}(1 + \cos^2 2\theta) > \frac{1}{2}$$

Neutrino oscillations

Two neutrino case





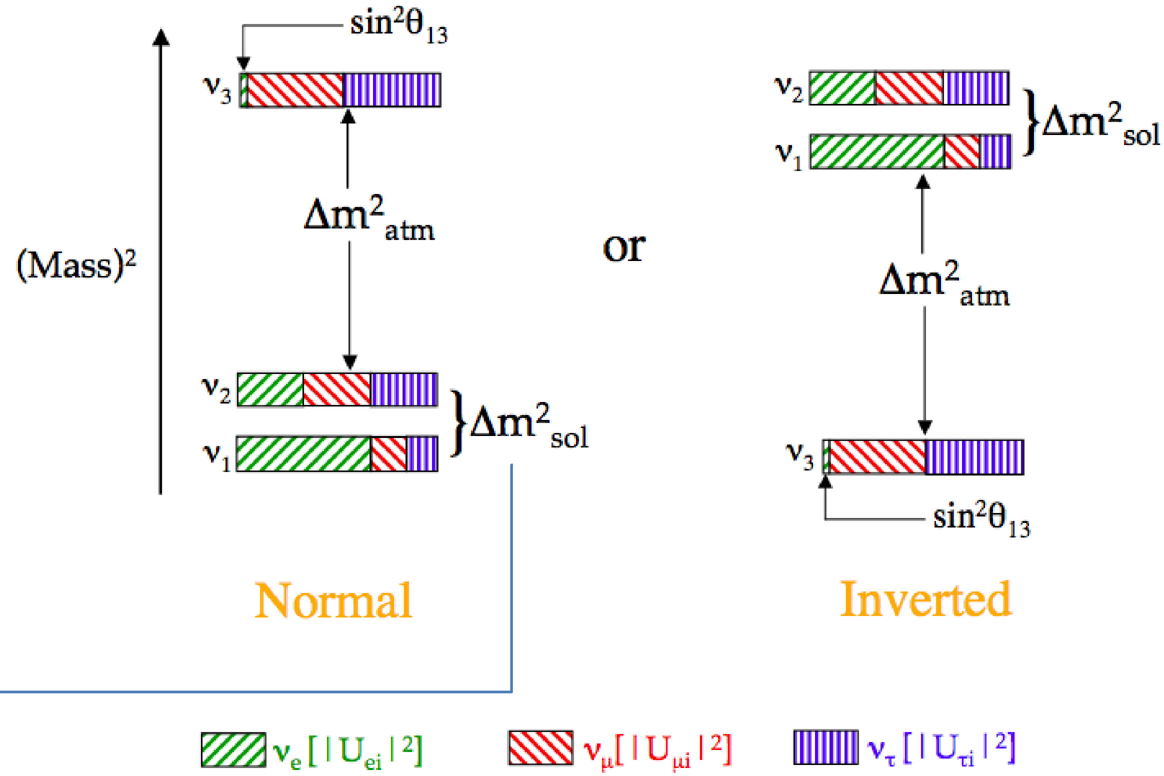
$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta = \frac{1}{2}(1 + \cos^2 2\theta) > \frac{1}{2}$$

With matter effects, this can be smaller than ½:

$$P_{ee} = \frac{1}{2}(1 + \cos 2\theta\, cos2\theta_m)$$

Neutrino oscillations

Three neutrino case



Known due to matter effects in the Sun (MSW)

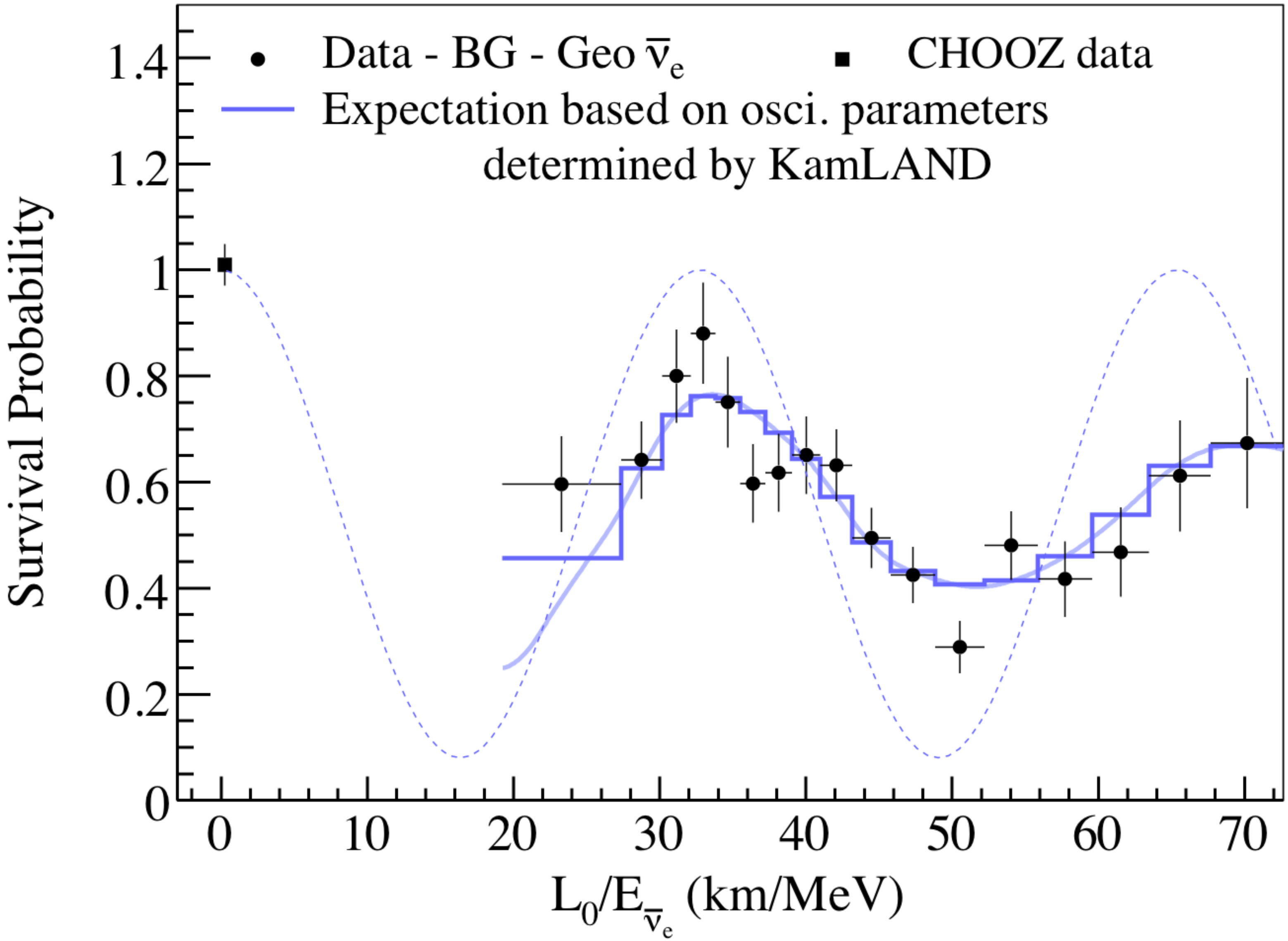
Reactor anti (electron) neutrinos (without CP)

$$P(\nu_e \rightarrow \nu_e) = 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2(1.27\Delta m^2_{12}\,\frac{L}{E}) - \sin^2(2\theta_{13})\sin^2(1.27\Delta m^2_{23}\,\frac{L}{E})$$

Long baseline (muon) neutrino beam …

Correlations between CP phase, matter effects, hierarchy: go to long enough baseline to break those

KamLAND



Phys.Rev.Lett. 100 (2008) 221803, KamLAND webpage

Neutrino oscillations are well established now

K2K, KamLAND, Daya Bay, T2K experiments recognised in the Breakthrough Prize for fundamental physics 2015.

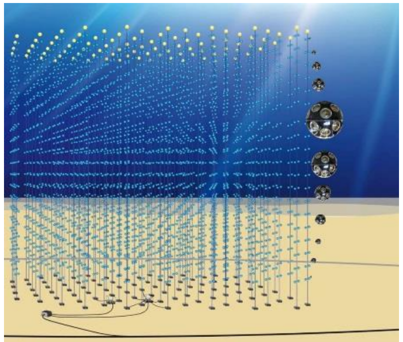
(As well as SuperK and SNO)

Many open questions however remain:

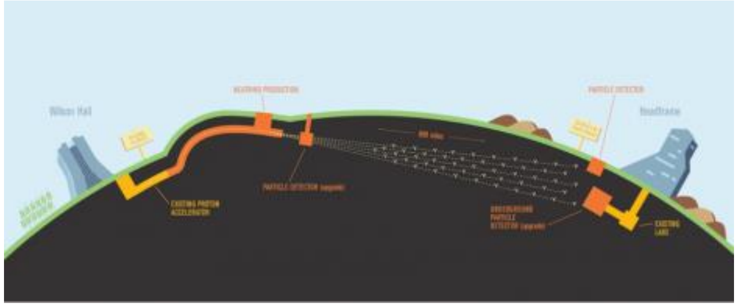
- Why is the neutrino so much lighter than all other particles?
- Is the neutrino Majorana
  (particle and anti-particle essentially the same)?
- What is the mass hierarchy?
- What is the value of the CP violating phase δ (non-zero)?

…

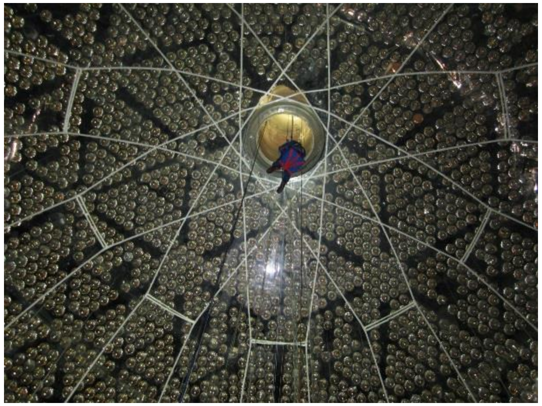
(Some of the things) coming up next …



Mass hierarchy

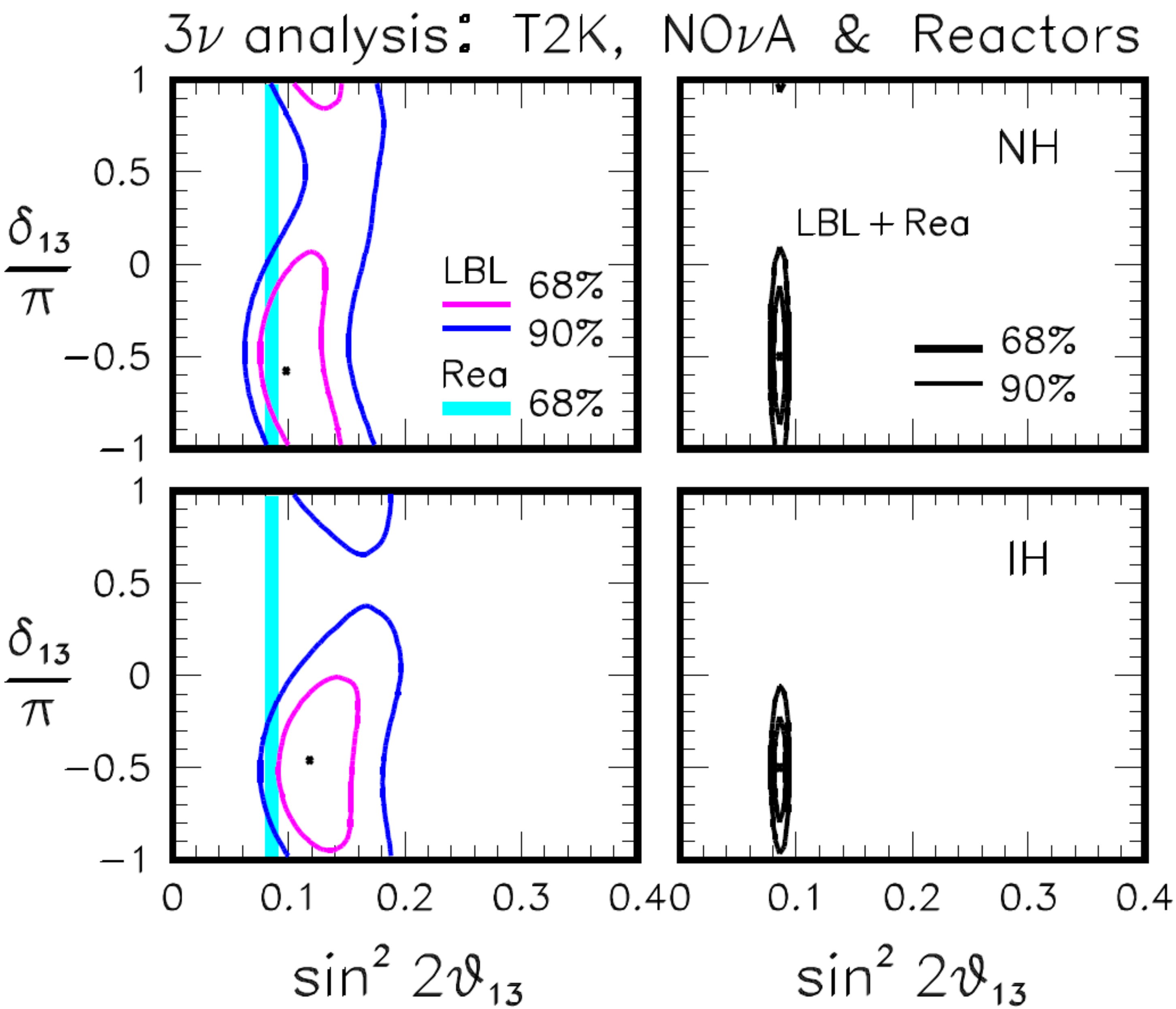


CP violation



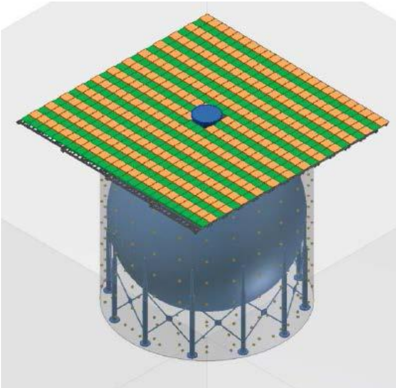
Neutrino nature

T2K and reactor (Daya Bay), and recent NOvA results

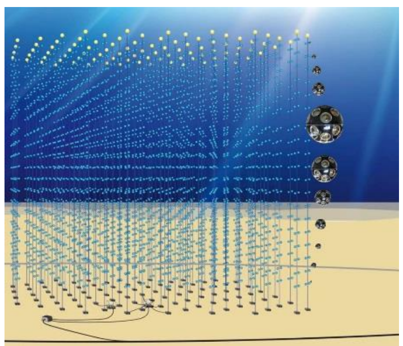


Palazzo, Arxiv:1509.03148

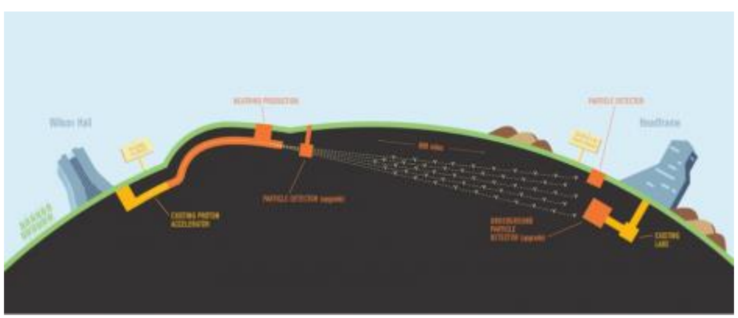
Mass hierarchy: 3 methods are being pursuit



Reactor experiments
(JUNO, RENO-50)

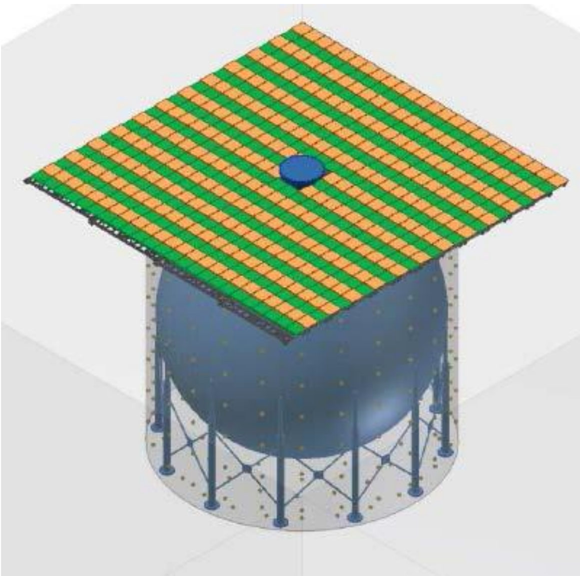


Atmospheric neutrinos
(PINGU, ORCA)



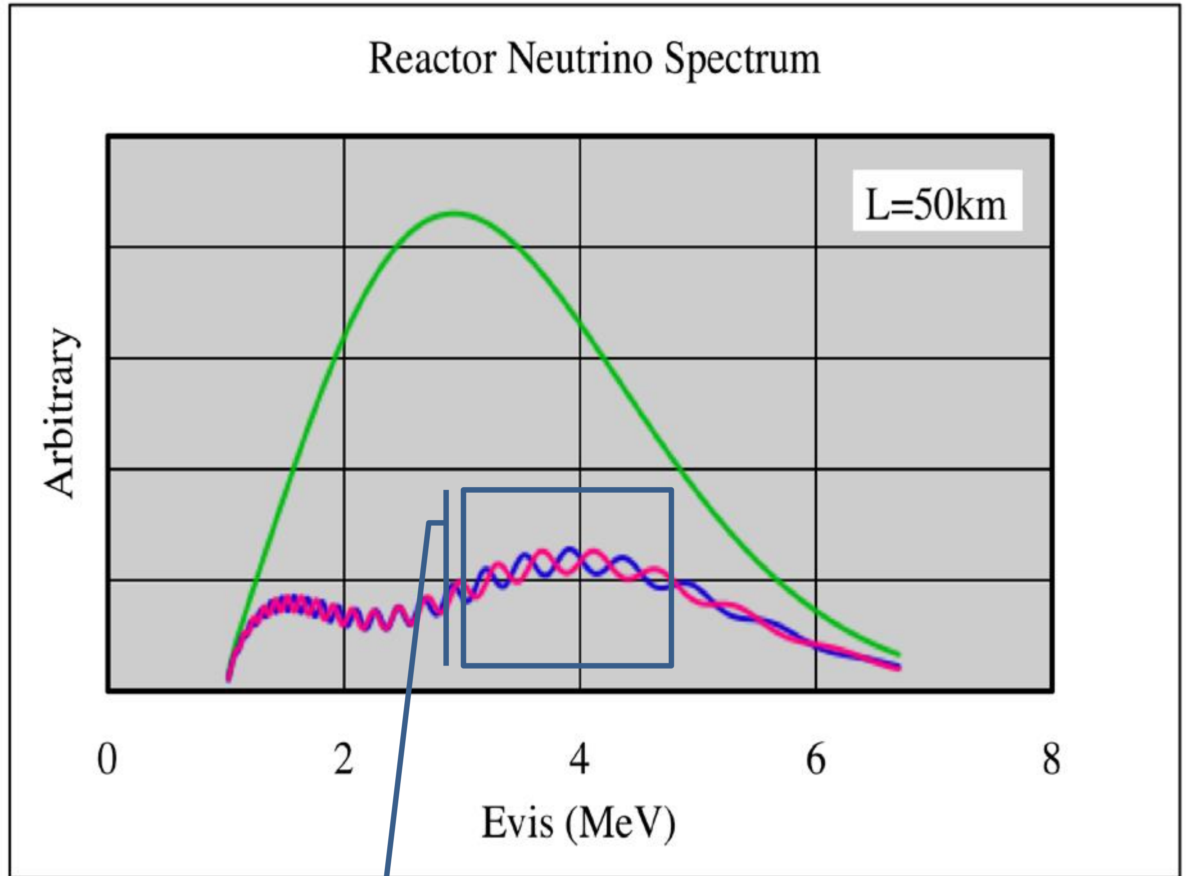
Long baseline neutrino experiments
(INO, HyperK, DUNE)

Reactor neutrinos



JUNO
- Approved & funded
- Data taking expected in 2020

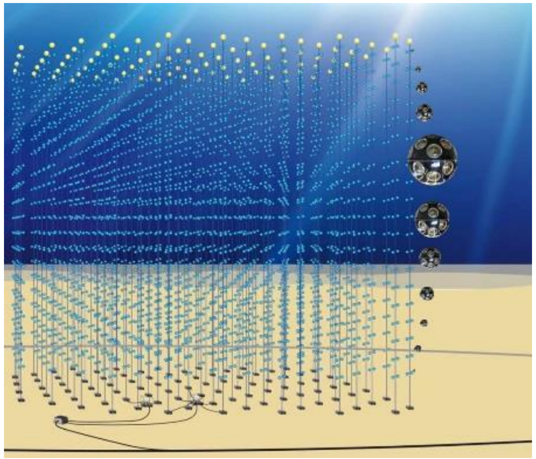
RENO-50
- Site identified
- R&D funding

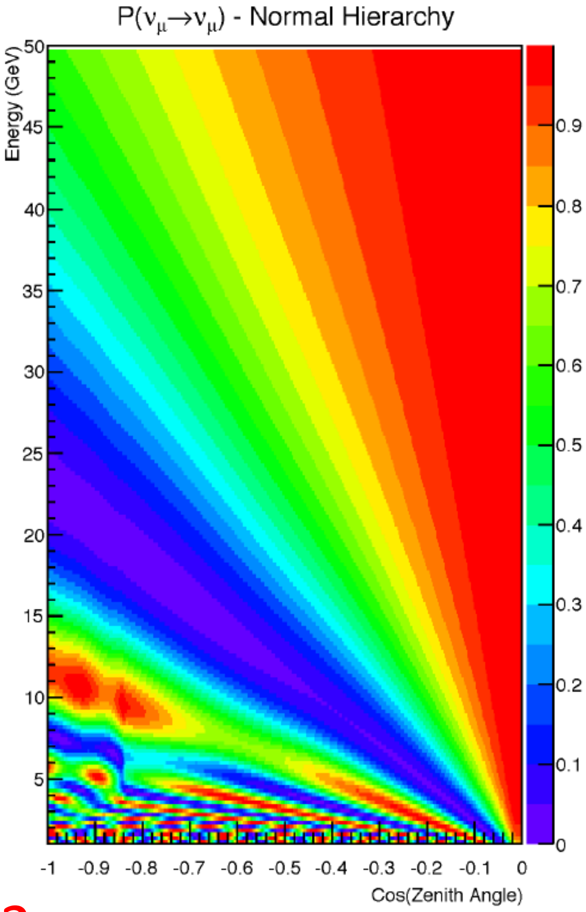


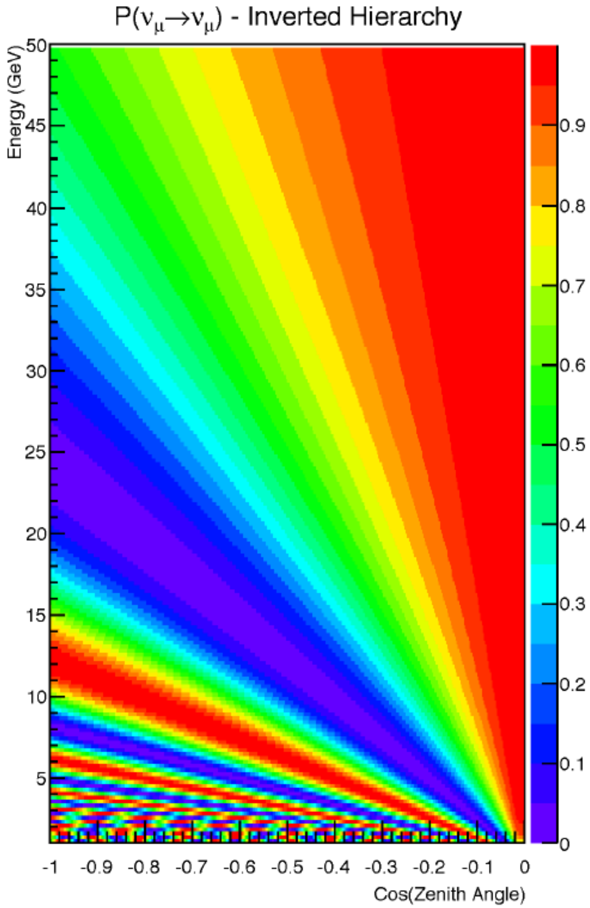
Large (20 ktonne LS) detector,
Excellent energy resolution (<3%)

More info: neutrino telescope 2015

Atmospheric neutrinos







PINGU

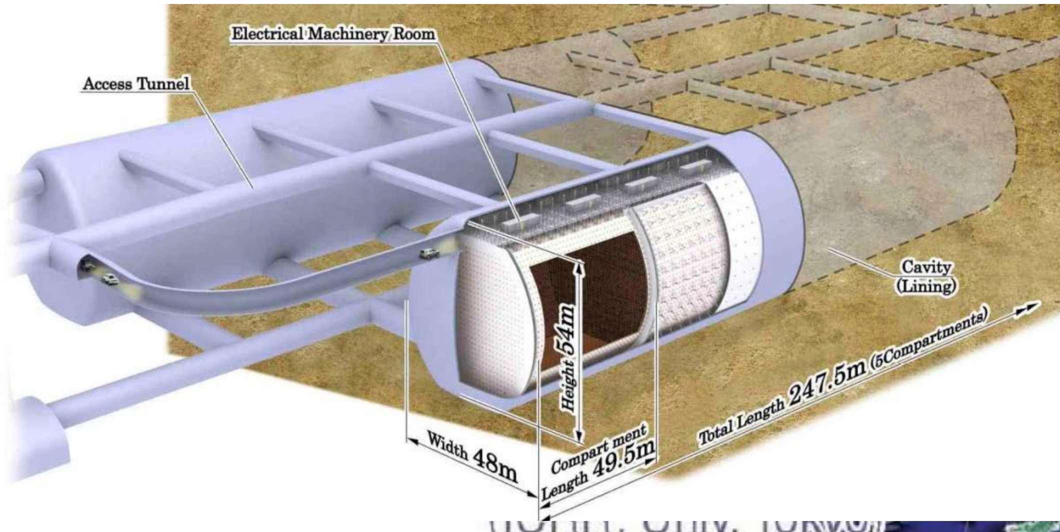
- Well understood
- 20 strings / season , 40 total
- Completion 2021/2022

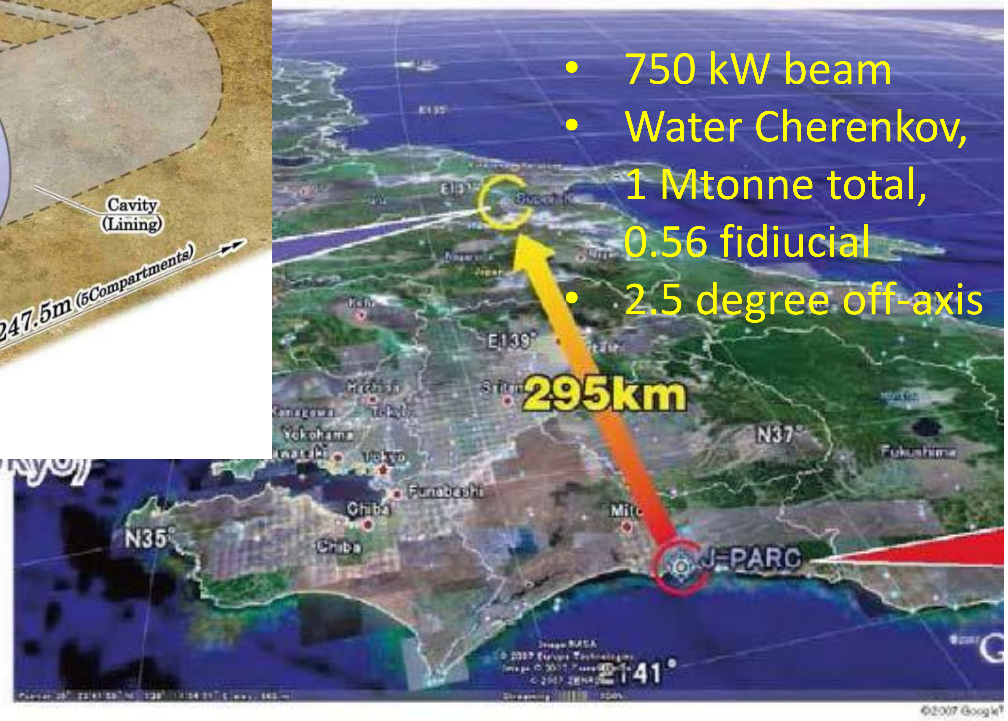
ORCA

- 6 strings deployed and operation end 2016
- Completion possible 2020

More info: neutrino telescope 2015

Long-base line experiments: HyperK

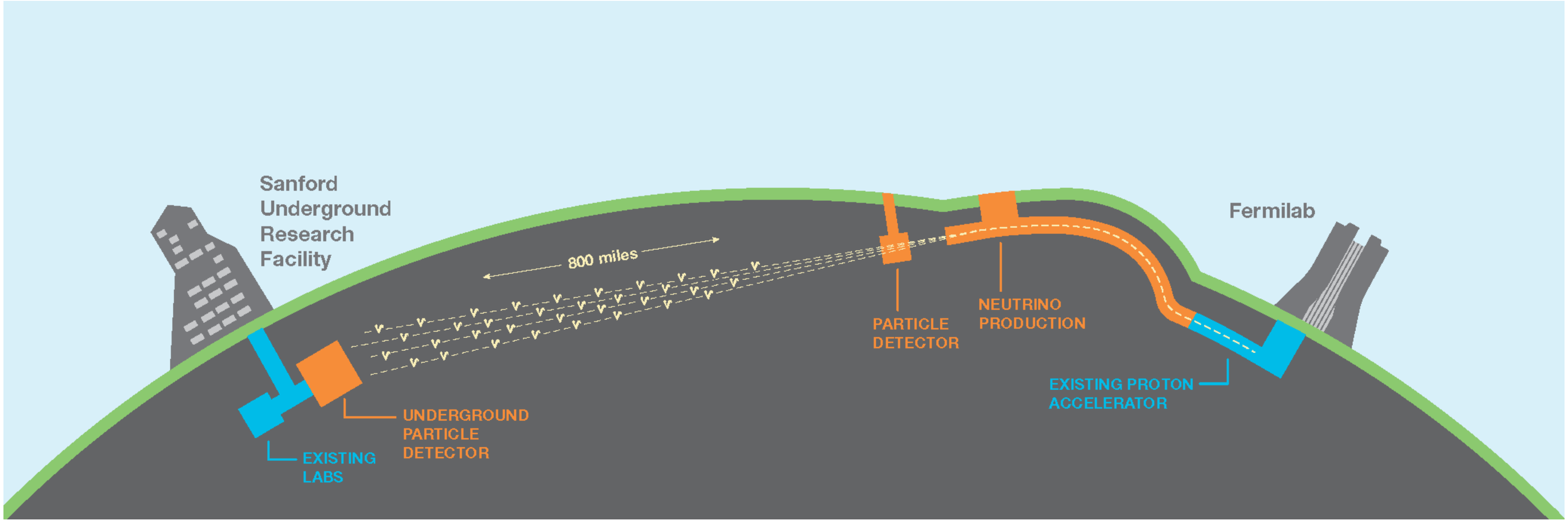




- proto-collaboration
- 240 people, 13 countries
- R&D funds granted
- Selected as one of the 25 top priority future projects by Science Council of Japan in 2014
- Not included in the MEXT (Japanese funding agency) roadmap in 2014, next round (2017)
- If the construction begins in 2018, experiment ~2025

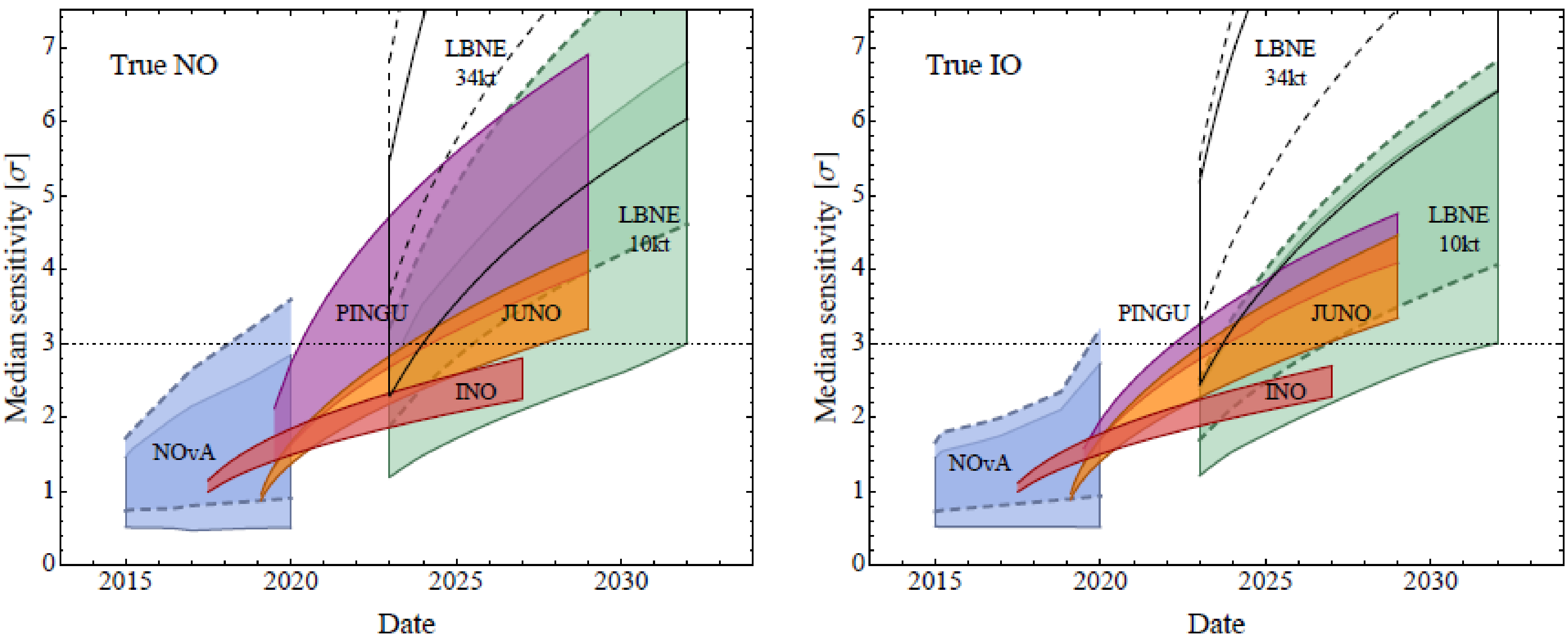
Kajita, Invisibles 2015 workshop

Long-base line experiments: DUNE



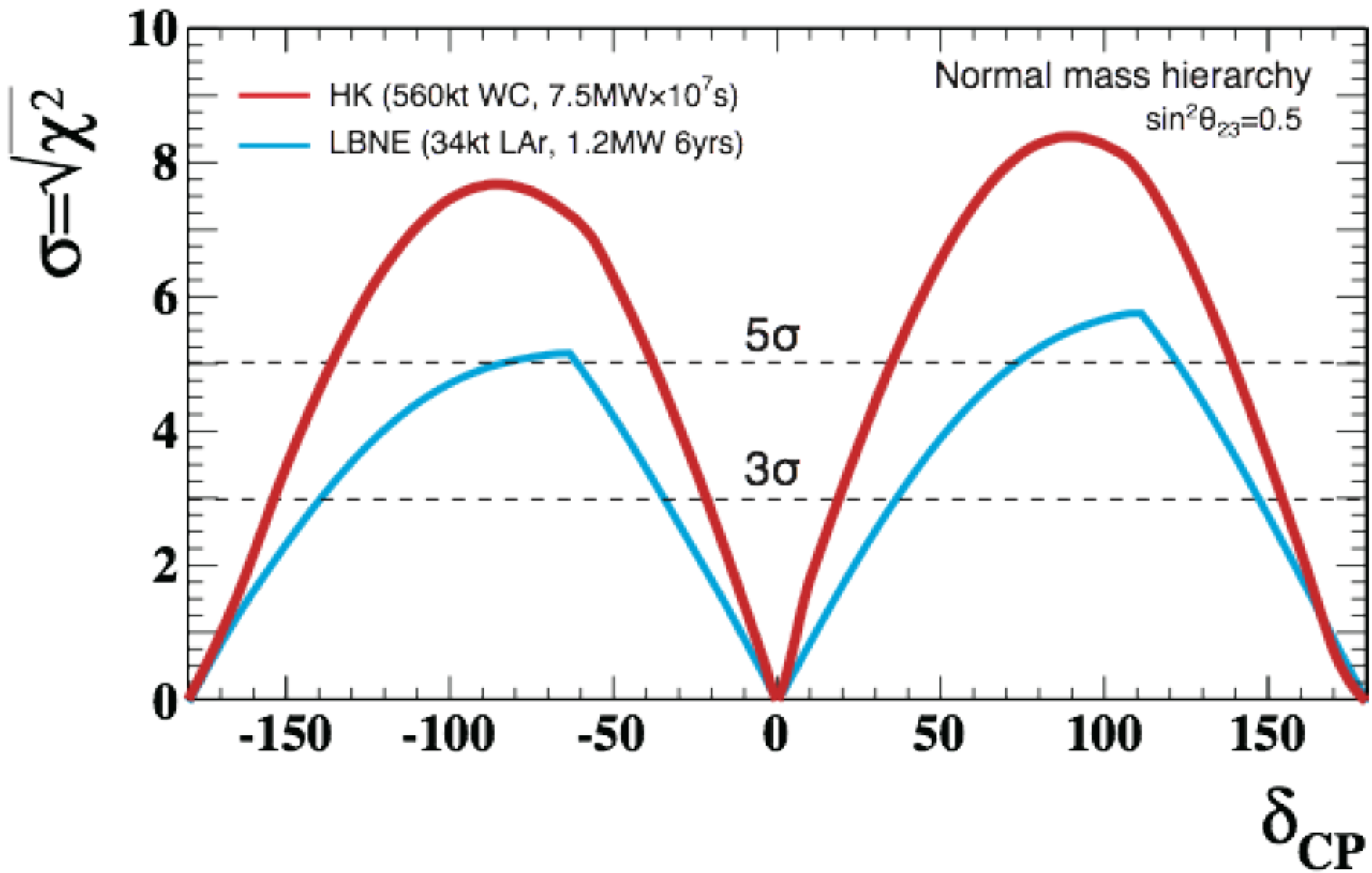
- DUNE collaboration: liquid argon TPC
- 800 people, 25 countries
- Development of first 10 ktonne detector by 2021
- Followed by expansion to 34 ktonne soon thereafter
- LBNF: 1.2 MW of power by 2024,
  up to 2.4 MW of beam power by 2030
- CERN neutrino platform / LArTPC BNB Fermilab

Mass hierarchy summary

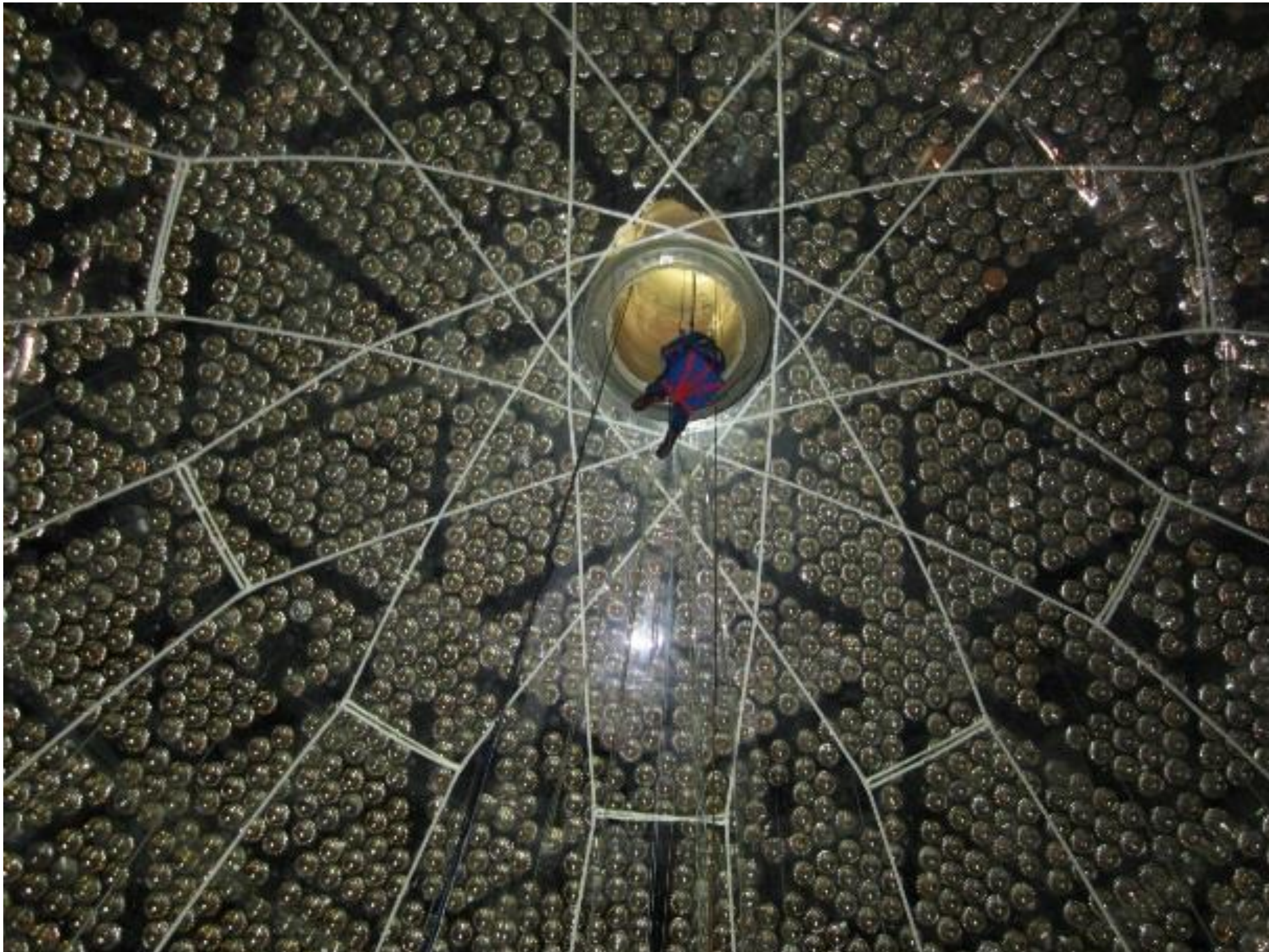


arXiv: 1311.1822

CP violation

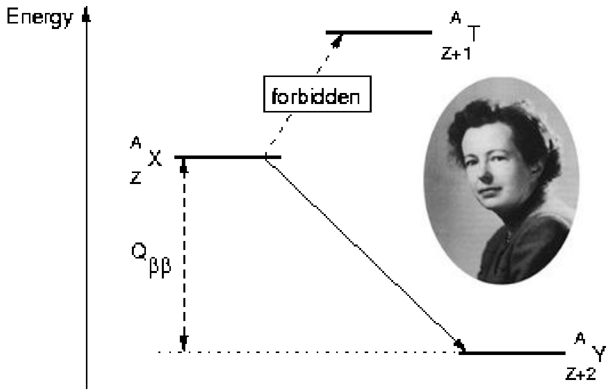


Neutrino nature

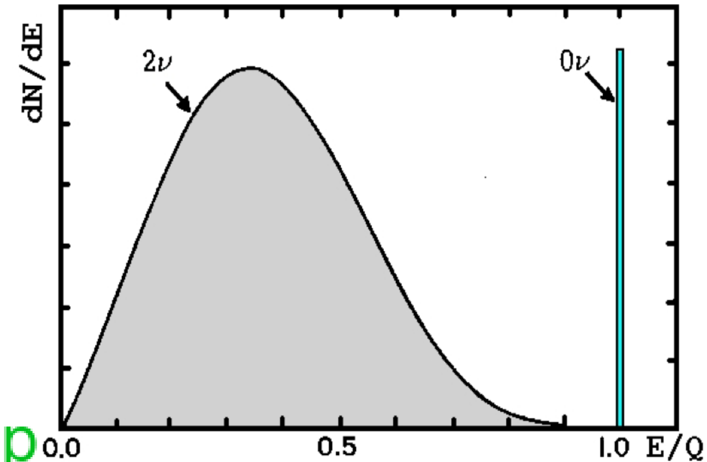


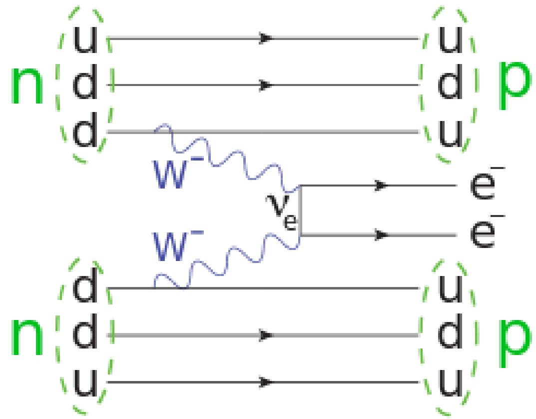
Neutrinoless double-beta decay

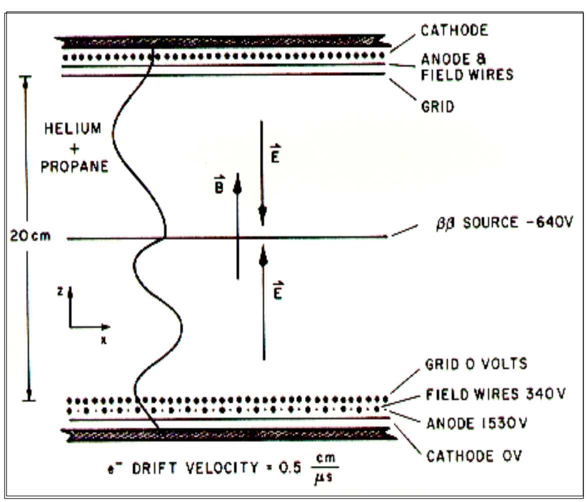
$$Q = E_{\text{parent}} - E_{\text{progeny}} - 2m_e$$



Maria Goeppert-Mayer (1935)







Elliott, Hahn & Moe 1988 (^{82}Se)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

Phase factor

Matrix element

Effective neutrino mass

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

Neutrino oscillation matrix element

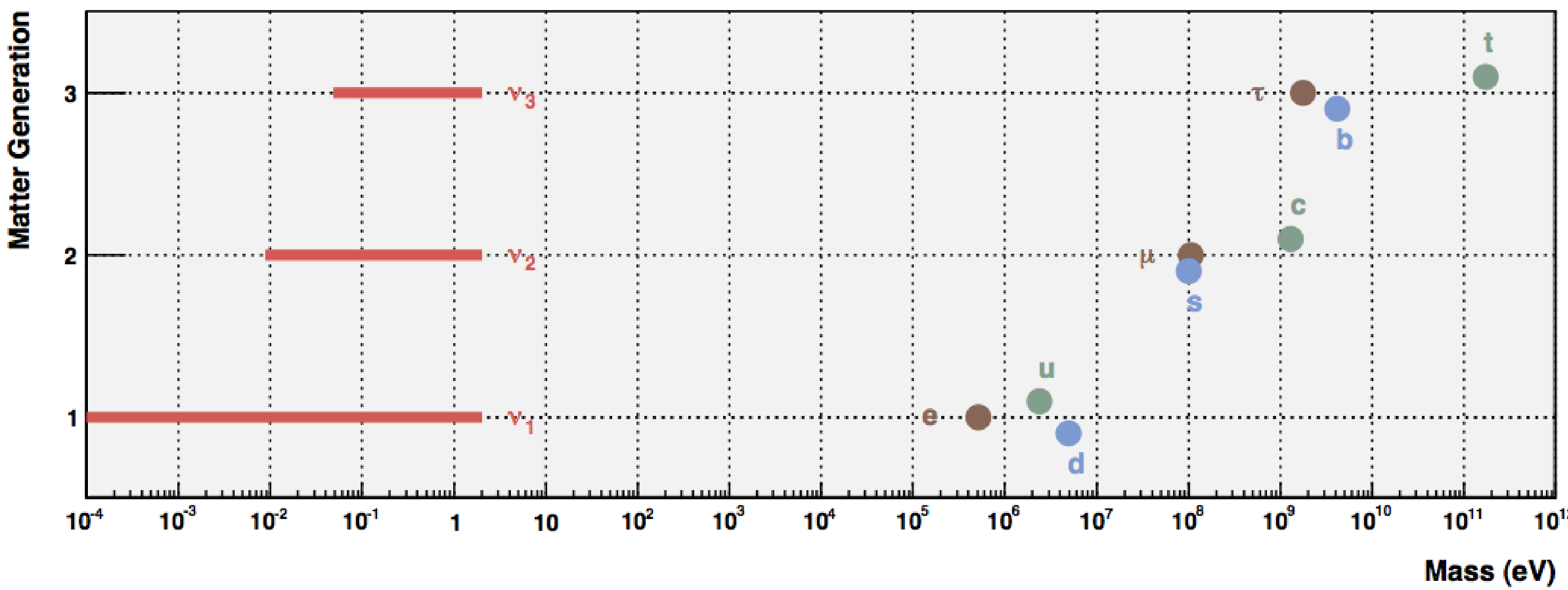
Neutrinoless double-beta decay

Observation of this process implies:

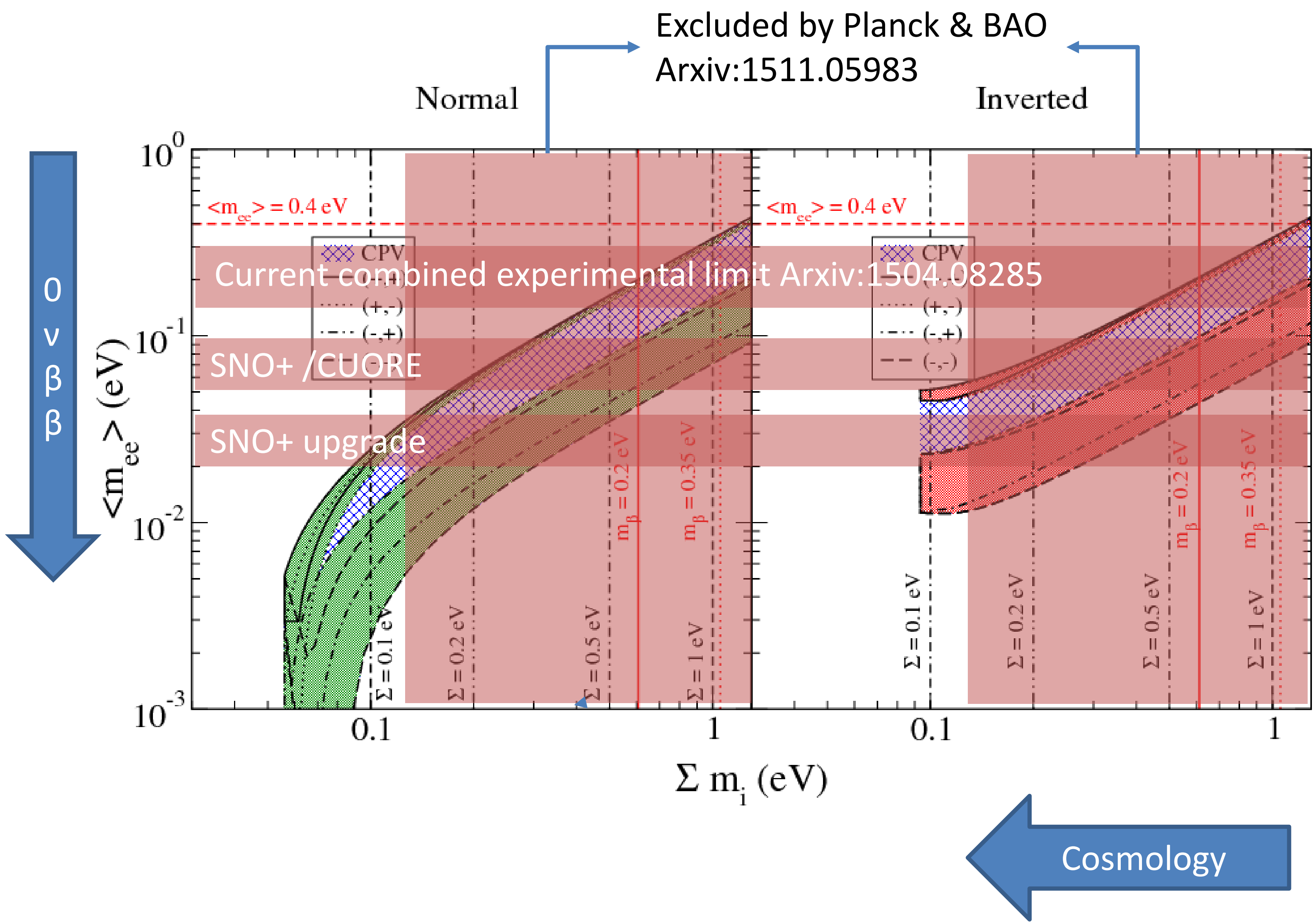
- *Violation of lepton number (by 2!)*
- *Neutrinos have Majorana masses (different than quarks and leptons, Schlechter and Valle, 1982)*
- *Neutrinos are their own anti-particles*

It would give information about:

- *The seesaw model and why neutrinos are so much lighter than other particles*
- *Leptogenesis, a possible origin of the baryon-antibaryon assymmetry in the Universe*
- *Neutrino absolute mass scale*



Current status



More information: see NSAC report November 2015

CUORE vs SNO+

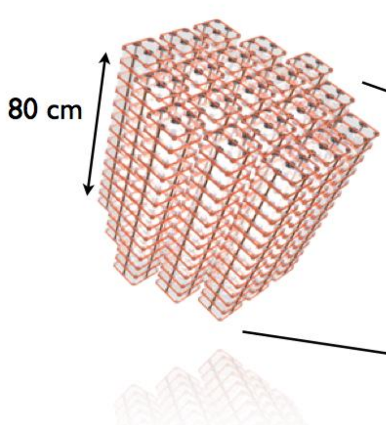
NSAC review (US) Nov 2015:

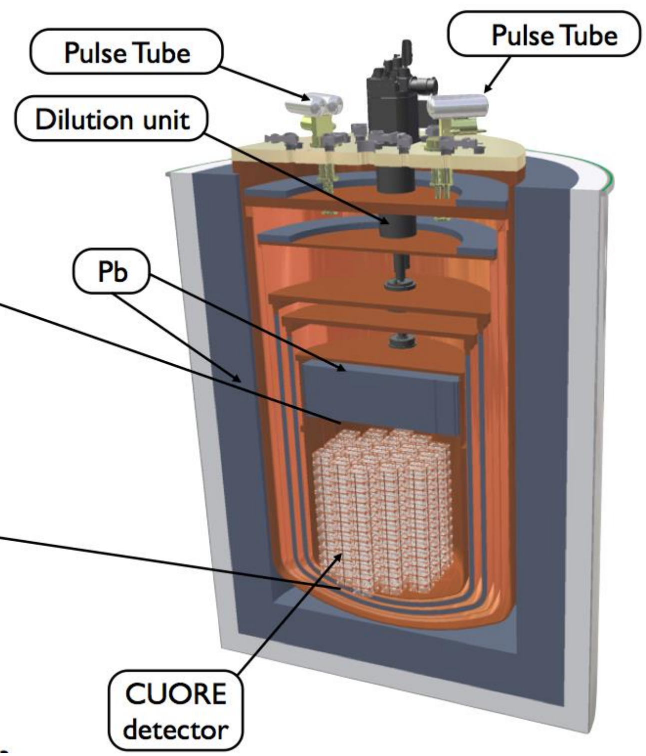
The modular and monolithic approaches both offer advantages and disadvantages. However, it is not possible to firmly conclude which approach will be optimal at this point and it is certainly prudent to pursue both approaches in this R&D phase of the subject. This is certainly the case at present, and will likely continue to be the situation for at least a few more years.

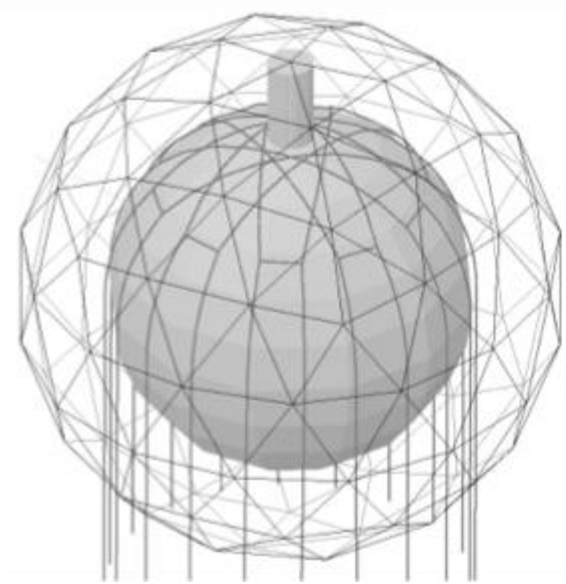
Candidate for Double beta Decays

	Q (MeV)	Abund.(%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Array of 988 detectors. 19 CUORICINO-like towers M = 0.741 ton of TeO_2 (~200 kg ^{130}Te) to measure 0ν-DBD of ^{130}Te with bolometric detector.







Sensitivity (5 y): $T_{1/2} = 1.6 \times 10^{26}$ y

$m_{\beta\beta}$ = 41-95 meV

NME from F.Simkovic et al. Phys.Rev. C77 - J.Suhonen et al. Int.Jou.Mod.Phys. E17 - J.Menendez et al. Nucl. Phys.A818 - J.Barea et al. Phys. Rev. C79

Sensitivity – improving limits is difficult

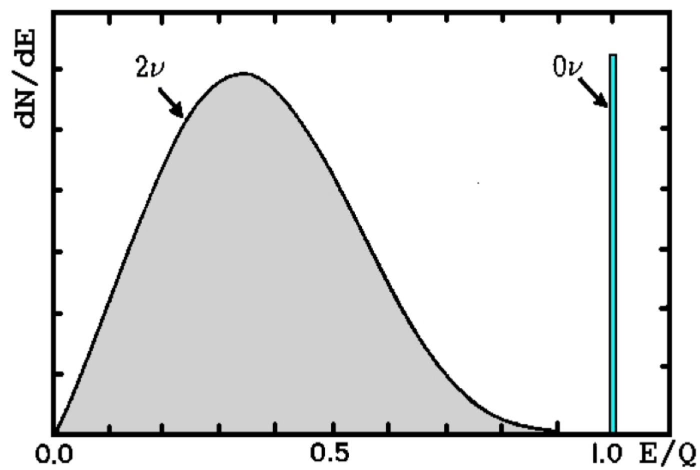
$$T_{1/2} \propto m_{\beta\beta}^{-2}$$

$$R_{\text{obs}} = \frac{ln(2)}{T_{1/2}} N \propto m_{\beta\beta}^{2}$$

$$B_i = a_i + b_i M$$

Experimental Sensitivity:

$$\frac{S}{\sqrt{B}} \propto \frac{Mt}{\sqrt{B_i \Delta E t}} = \frac{Mt}{\sqrt{(a_i + b_i M)\Delta E t}}$$



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta} \rangle^2$$

Sensitivity – improving limits is difficult

$$T_{1/2} \propto m_{\beta\beta}^{-2}$$

$$R_{\text{obs}} = \frac{ln(2)}{T_{1/2}} N \propto m_{\beta\beta}^2$$

$$B_i = a_i + b_i M$$

Experimental Sensitivity:

$$\frac{S}{\sqrt{B}} \propto \frac{Mt}{\sqrt{B_i \Delta E t}} = \frac{Mt}{\sqrt{(a_i + b_i M)\Delta E t}}$$

Background scales with mass (b_i dominant):

$m_{\beta\beta}$ sensitivity scales with $M^{1/4}$

Sensitivity – improving limits is difficult

$$T_{1/2} \propto m_{\beta\beta}^{-2}$$

$$R_{\text{obs}} = \frac{ln(2)}{T_{1/2}} N \propto m_{\beta\beta}^2$$

$$B_i = a_i + b_i M$$

Experimental Sensitivity:

$$\frac{S}{\sqrt{B}} \propto \frac{Mt}{\sqrt{B_i \Delta E t}} = \frac{Mt}{\sqrt{(a_i + b_i M)\Delta E t}}$$

Background scales with mass

(b_i dominant):

$m_{\beta\beta}$ sensitivity scales with $M^{1/4}$

Background does not scale with mass

(a_i dominant):

$m_{\beta\beta}$ sensitivity scales with $M^{1/2}$

Sensitivity – improving limits is difficult

$$T_{1/2} \propto m_{\beta\beta}^{-2}$$

$$R_{\text{obs}} = \frac{ln(2)}{T_{1/2}} N \propto m_{\beta\beta}^2$$

$$B_i = a_i + b_i M$$

Experimental Sensitivity:

$$\frac{S}{\sqrt{B}} \propto \frac{Mt}{\sqrt{B_i \Delta E t}} = \frac{Mt}{\sqrt{(a_i + b_i M)\Delta E t}}$$

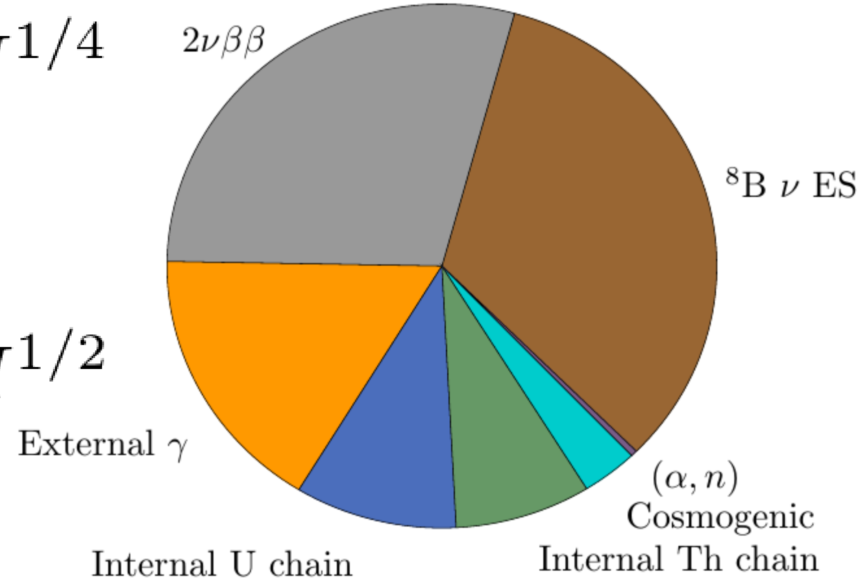
Background scales with mass (b_i dominant):

$m_{\beta\beta}$ sensitivity scales with $M^{1/4}$

Background scales with mass (a_i dominant):

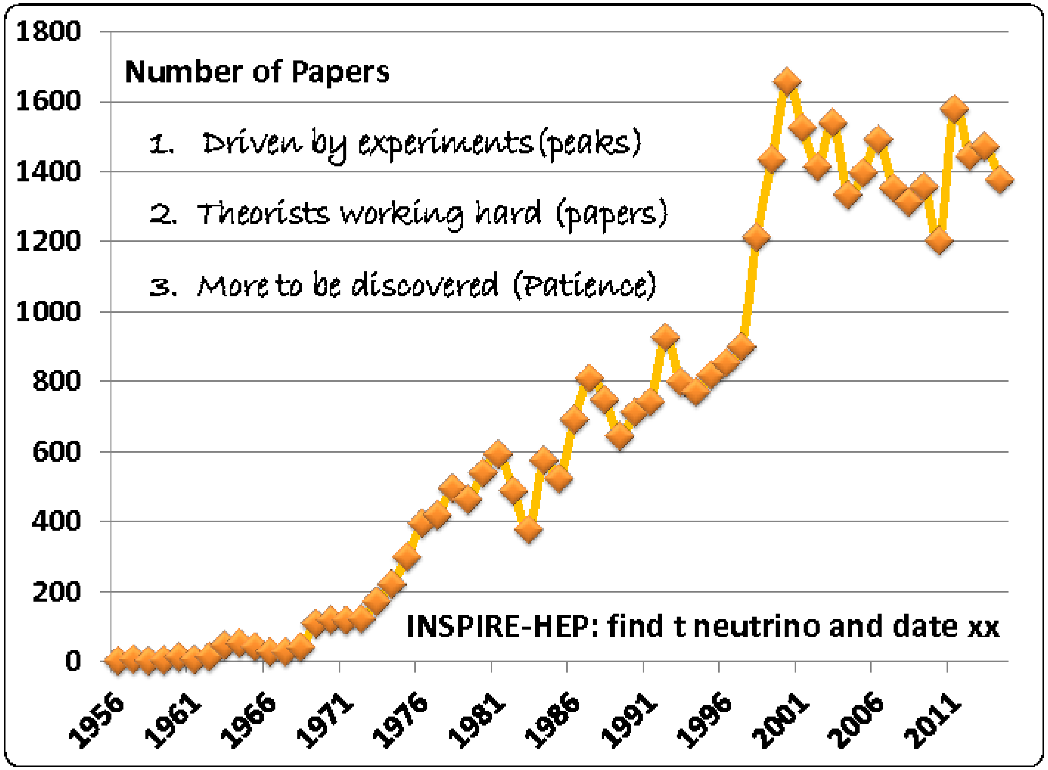
$m_{\beta\beta}$ sensitivity scales with $M^{1/2}$

SNO+



To summarise

SuperK & SNO showed that neutrinos change mass,
creating a step-change
in neutrino physics.



Many intriguing questions are still open:

- Lightness of the neutrino
- Is the neutrino Majorana?
- What is the mass hierarchy?
- CP violating phase δ?

and more …

Neutrino physics is an active field pursuing the answers to these fundamentally important questions.

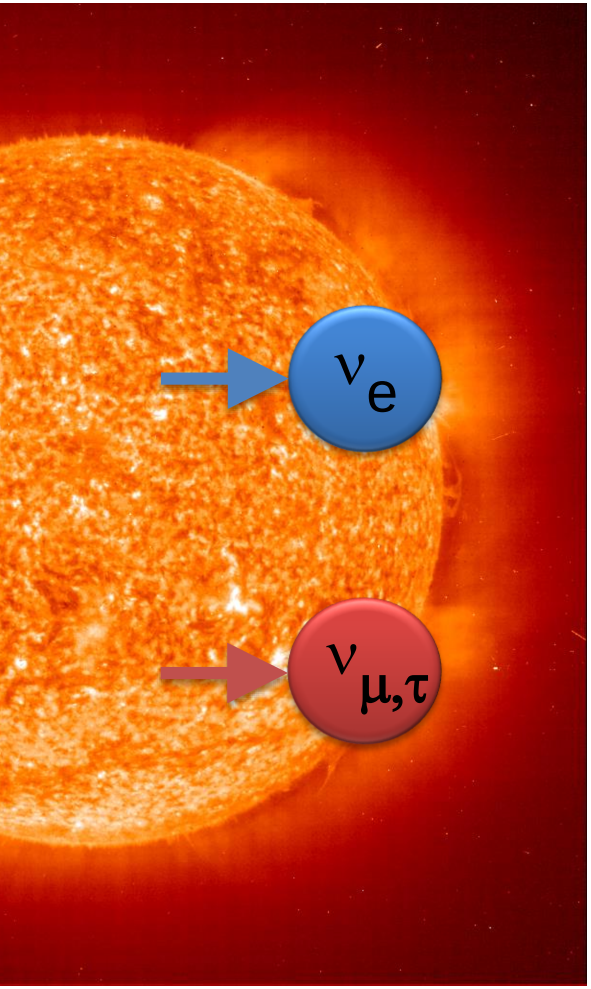
Watch this space:

More neutrino prizes to follow!

Sudbury is Southern

MSW effect

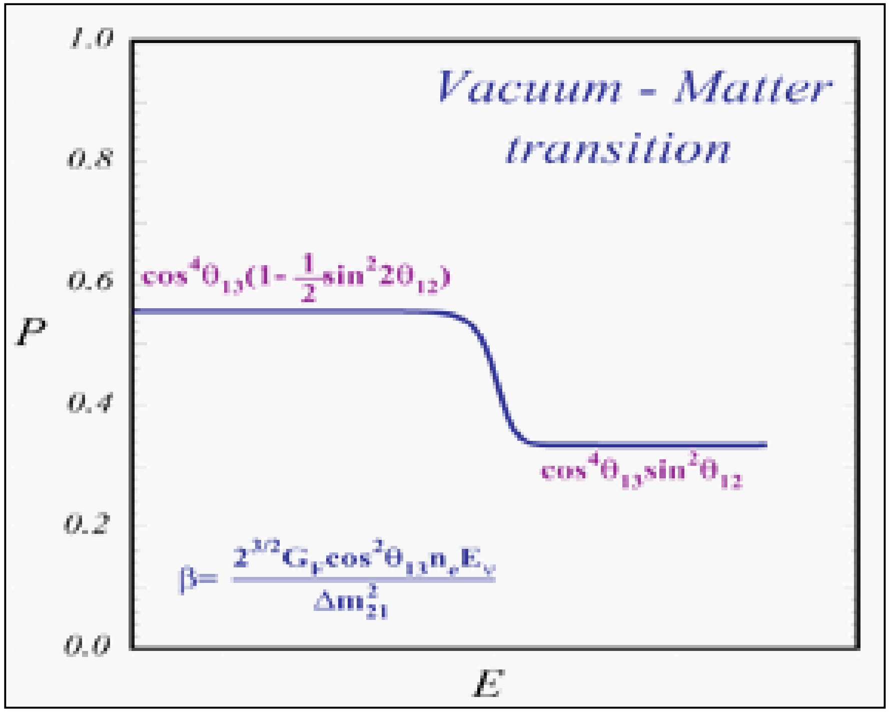
Mikhaev, Smirnov, Wolfenstein



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

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

$$P(\nu_e \rightarrow \nu_e) = ½\,(1 + \cos 2\theta_m \cos 2\theta)$$



Neutrinoless double beta decay rate

$$\Gamma = (T_{1/2})^{-1} = G^{0\nu} \left| M'^{0\nu} \right|^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2$$

Phase space factor
Well defined

Nuclear Matrix Element
Not so calculable

Effective
Neutrino Mass

$$M'^{0\nu} = \left(\frac{g_A^{eff}}{g_A} \right)^2 M^{0\nu}$$

Phenomenological correction
Accounts for use of nuclear models
to estimate NME
Taken from single-β decay
Some controversy over value

Probes absolute neutrino mass scale
Also sensitive to mass hierarchy

$$m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 \right|$$

$$= \cos^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{i\beta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3$$

0νββ Sensitivity (Phase I)

Top physics priority for SNO+ is a 0νββ using ^{130}Te loaded into the scintillator

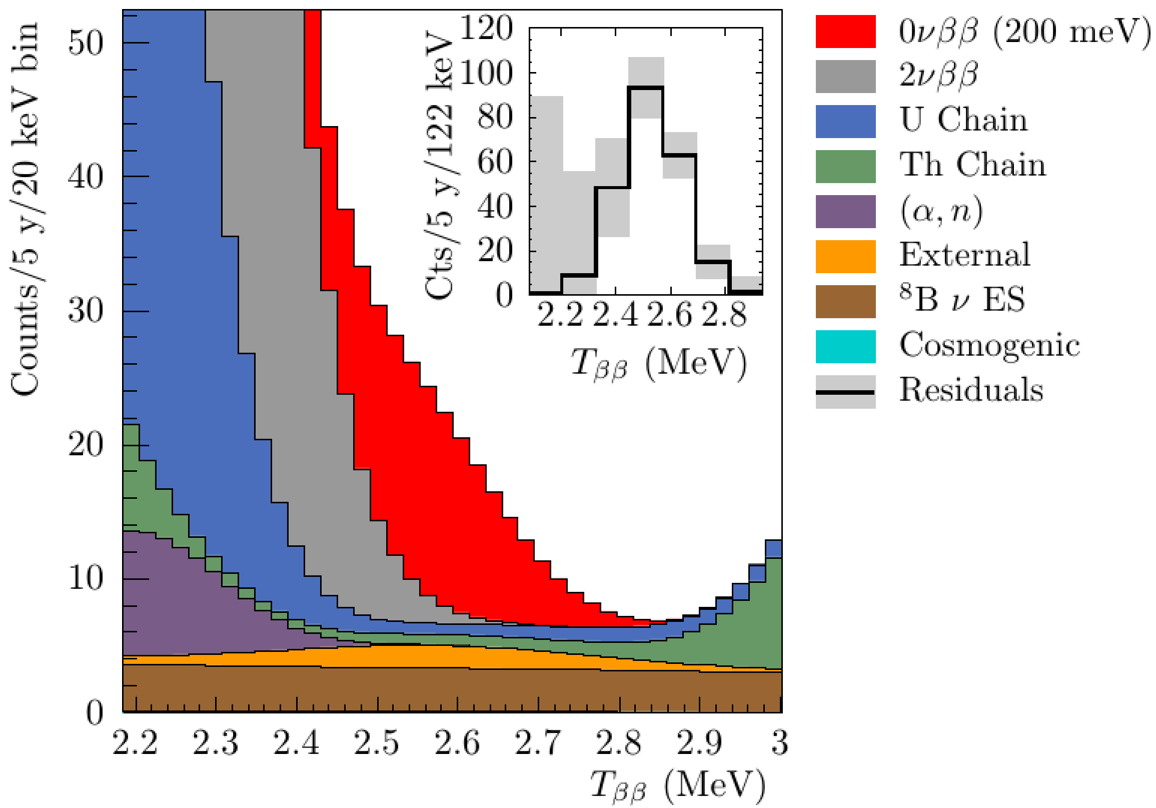
Expected spectrum for 5 years assuming:

- 0.3% ^{nat}Te loading
- Fiducial radius of 3.5 m
- 99.99% rejection of ^{214}BiPo
- 98% of ^{212}BiPo
- Light yield of 200 Nhits/MeV

SNO+ can set a lower bound of:

$$T_{1/2}^{0\nu\beta\beta} > 9 \times 10^{25}\ \text{yr}\ \ (90\%\ \ \text{CL})$$

Assuming a phase space factor $G=3.69\times10^{-14}\ yr^{-1}$ and $g_A=1.269$, this corresponds to an $m_{\beta\beta}$ of 55-133 meV



Understanding Backgrounds

2νββ:

- Sharply falling with energy
- Assymetric ROI about 0νββ signal
- Limited by energy resolution

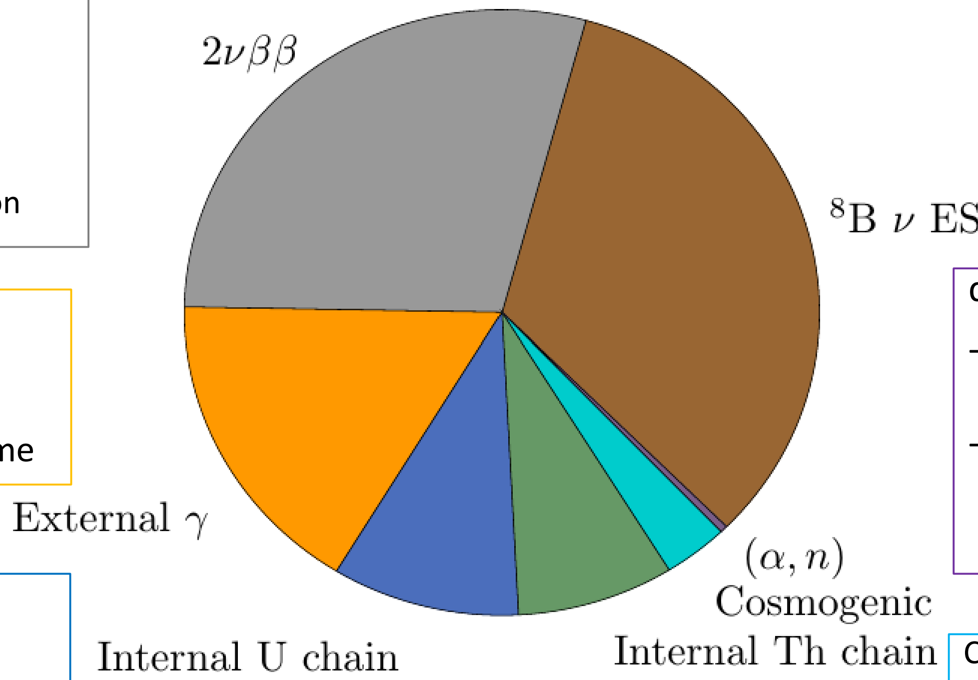
External BGs:

- From AV, ropes, PMTs, …
- Reduced by fiducial volume

Internal U/Th Chains:

-β from ^{214}BiPo and ^{212}BiPo

-Tag using time-coincidence of α follower



Solar ^{8}B:

- Flat spectrum
- Constrained by SNO/SK
- Limited by energy resolution

α-n:

- Absorption of α produces neutron
- Tagged using time-coincidence between prompt light and neutron capture gamma

Cosmogenics:

- ^{60}Co, ^{110}Ag, ^{88}Y, ^{22}Na
- Reduced UG cool down period and purification

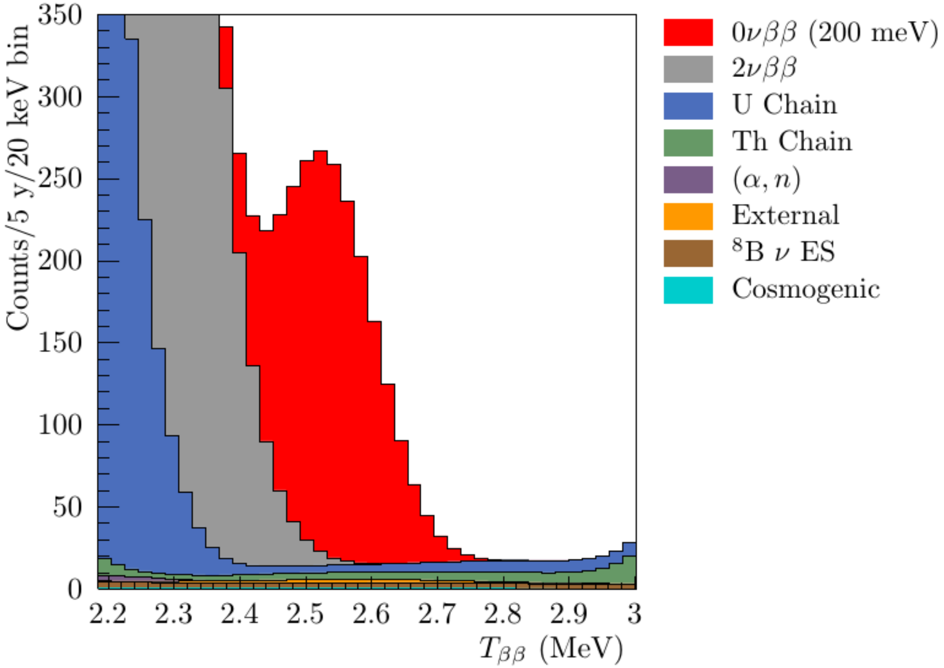
0νββ Sensitivity (Phase II)

R&D efforts have shown that 3% loading can be achieved with ~150 Nhits/MeV

This could be compensated for by replacing PMTs with high QE PMTs and new concentrators, expected to triple light yield

Assumptions:

- 3% loading of ^{nat}Te
- Fiducial radius of 3.5 m
- Light yield of 450 Nhits/MeV



Preliminary studies suggest a sensitivity at 3% and after 5 years running of:

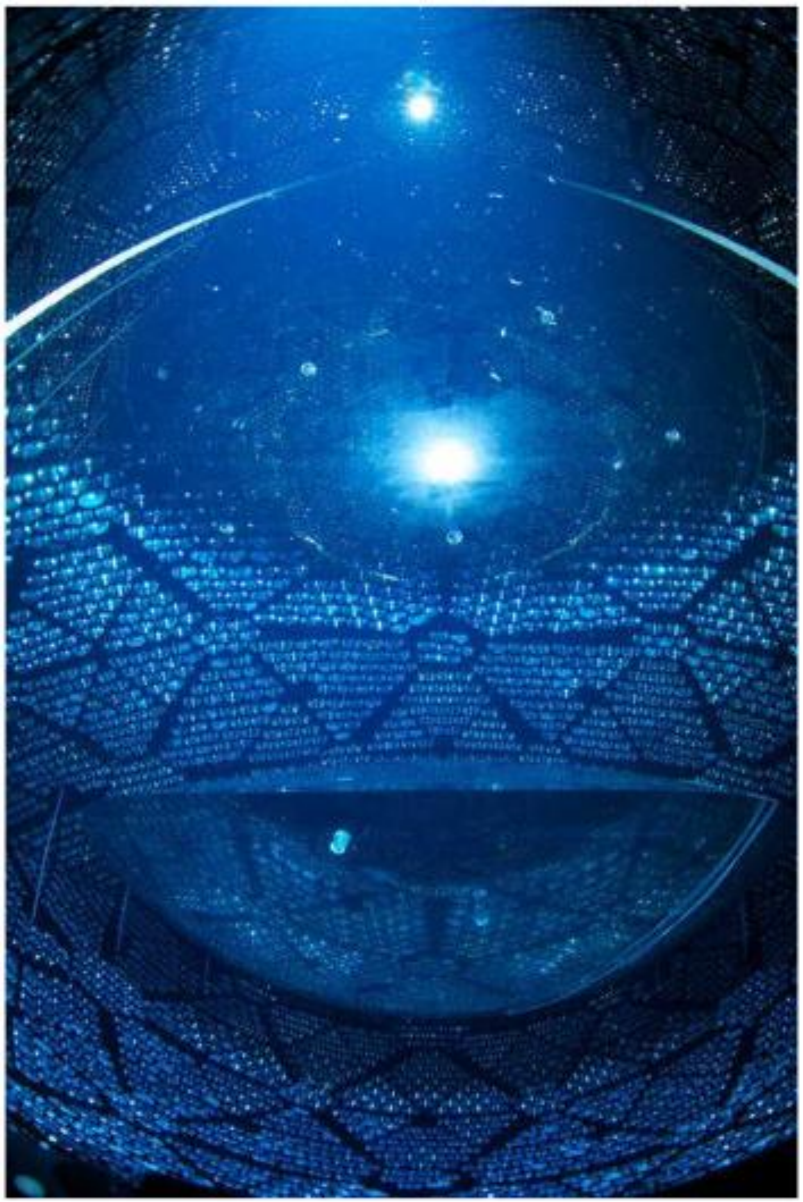
$$T_{1/2}^{0\nu\beta\beta} > 7 \times 10^{26} \text{ years (90\% C.L.)}$$

and $m_{\beta\beta}$ of 19-46 meV

SNO+ collaboration

Arxiv:1508.05759
"Current Status and Future Prospects of the SNO+ Experiment"

Refurbishing



Filling with water!