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Neutrinos - An Introduction

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Université Laurentienne



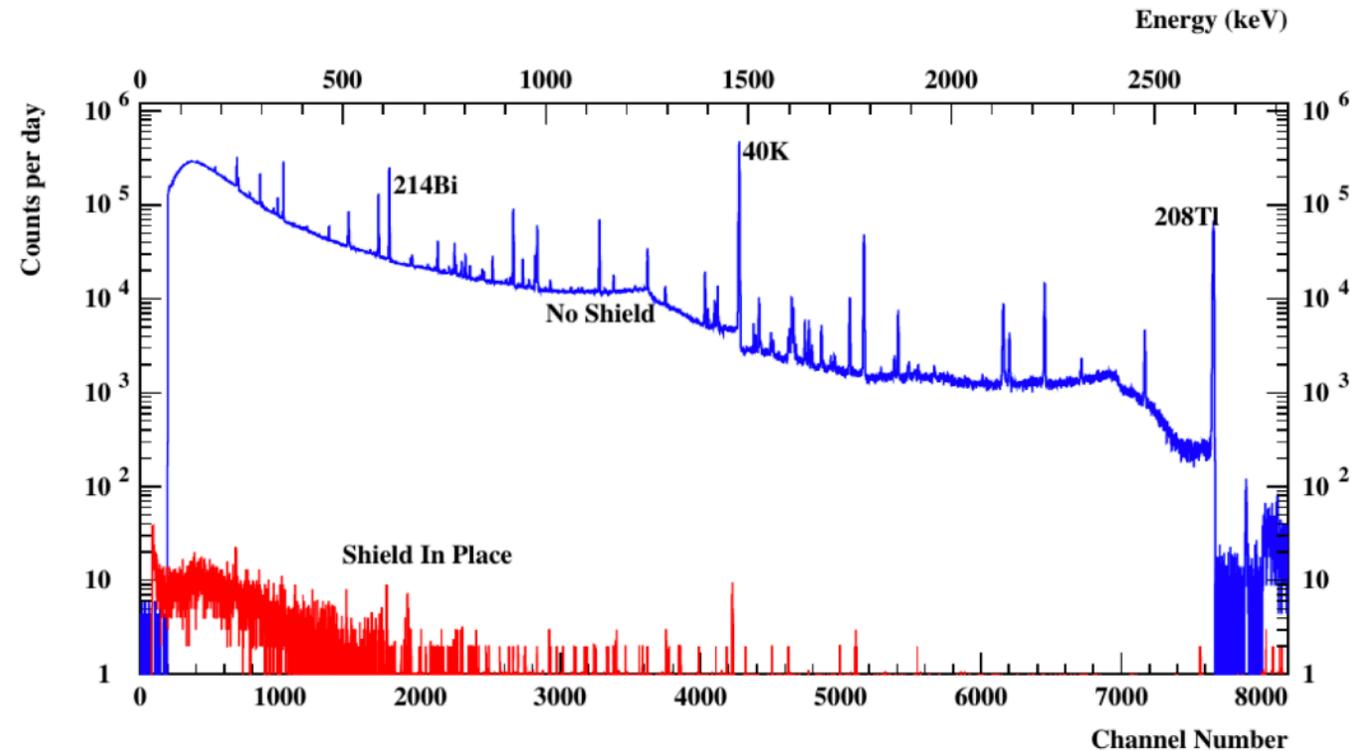
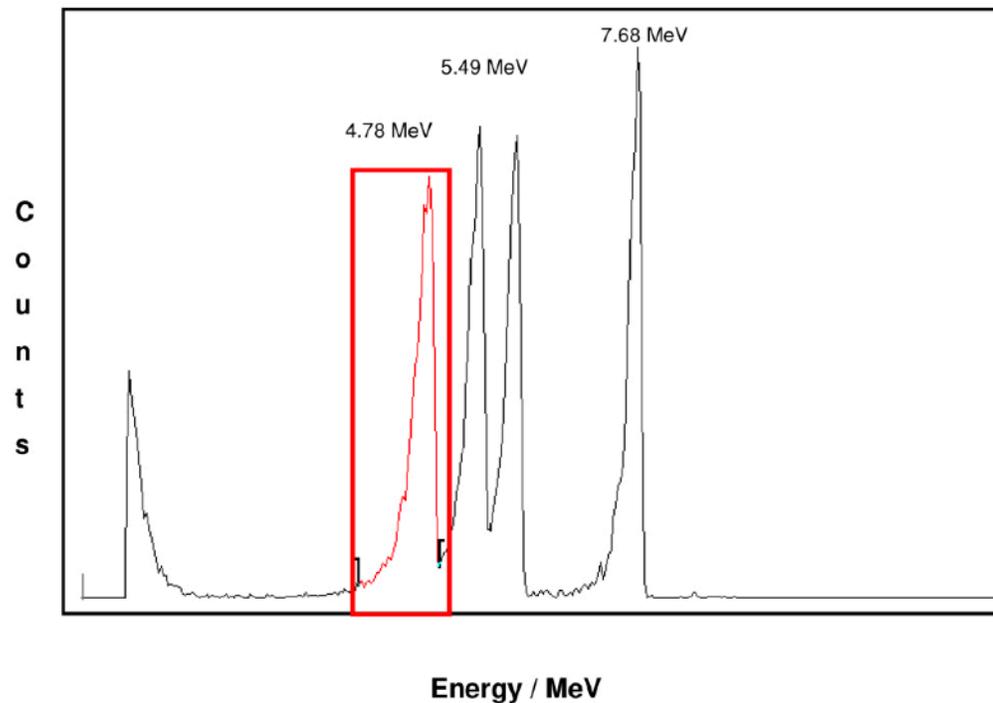
McGill
UNIVERSITY



First some History

1930: Beta Spectrum Problem

- ▶ Early particle physicists studied the energy spectra of collisions
- ▶ Alphas (left) and gammas (right) had sharp recognizable peaks



1930: Beta Spectrum Problem

- ▶ Betas had broad spectra, which seemed to violate conservation of energy
- ▶ Reactions also violated conservation of momentum

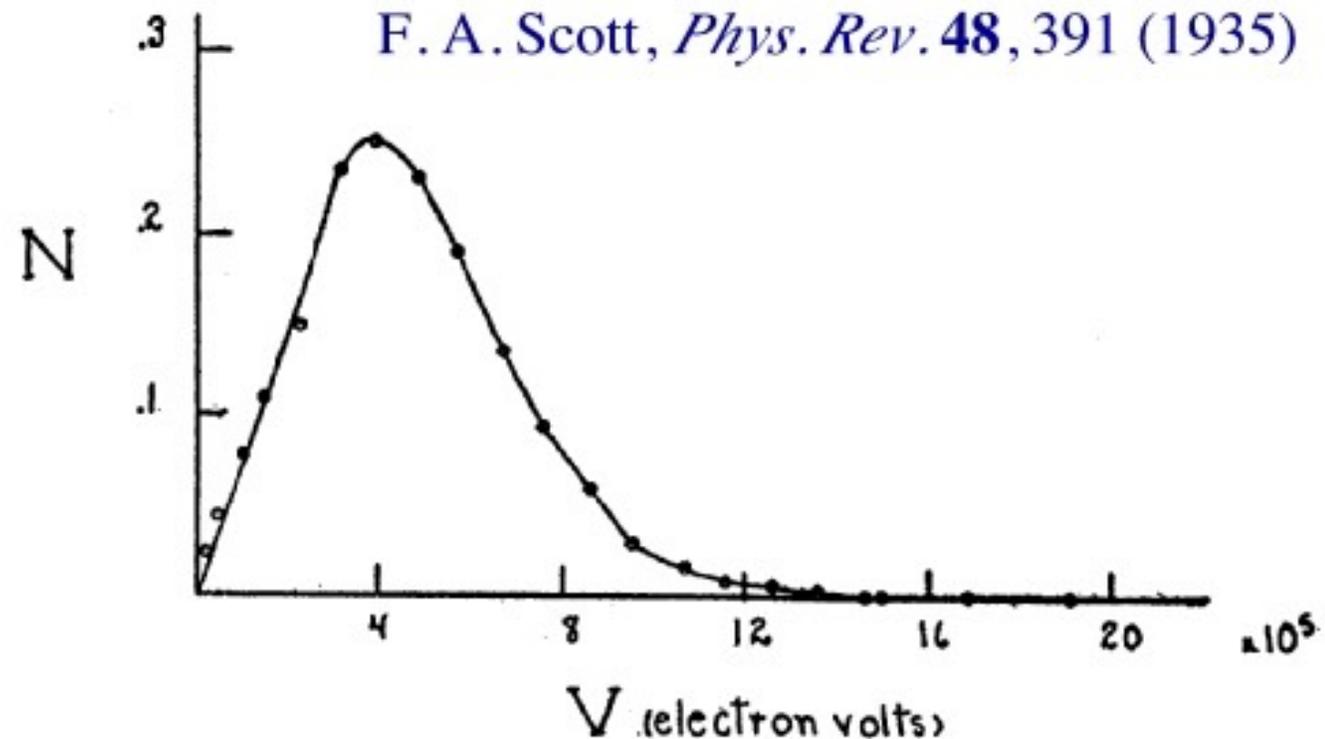
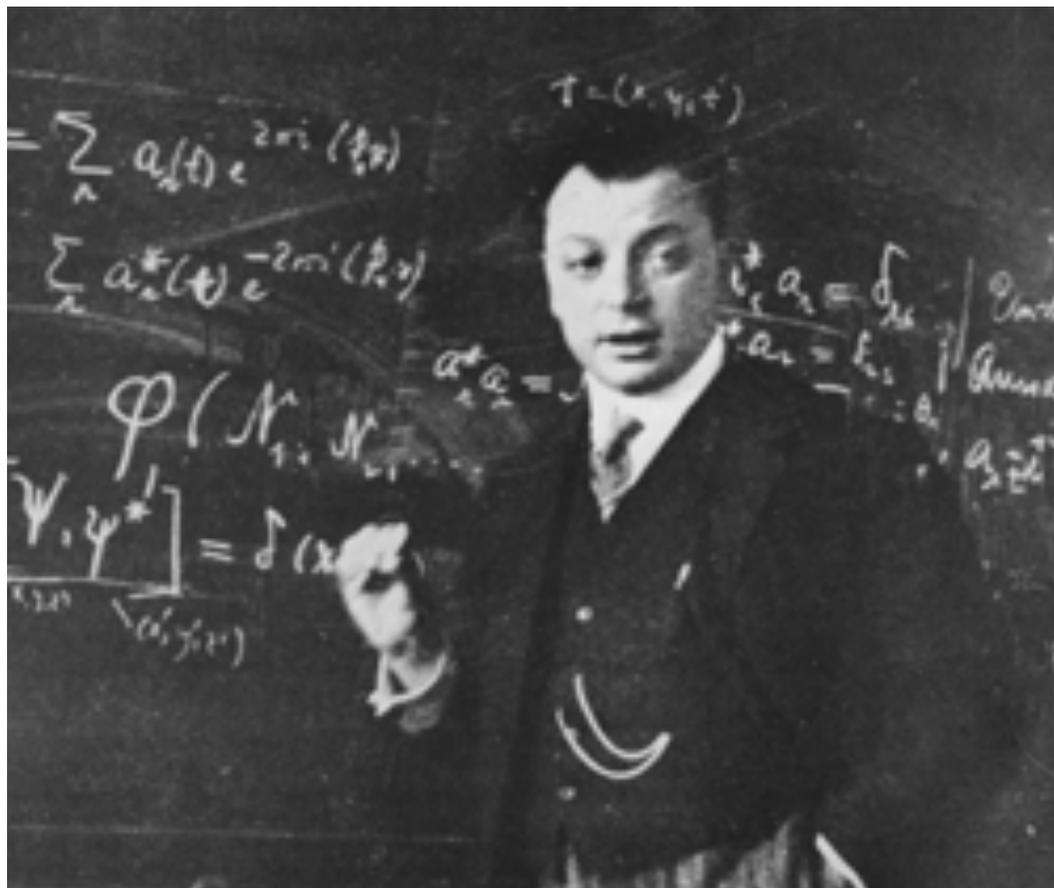


FIG. 5. Energy distribution curve of the beta-rays.

1930: Beta Spectrum Problem



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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
ansuhören 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
wäre von derselben Grössenordnung 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 M ist. Die Experimente
verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons
nicht grösser sein kann, als die eines gamma-Strahls und darf dann
 M wohl nicht grösser sein als $e \cdot (10^{-13} \text{ cm})$.

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,
gesteht und der Ernst der Situation beim kontinuierlichen beta-Spektrum
wird durch einen Ausspruch meines verehrten Vorgängers im Amt,
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. Des. in Zürich stattfindenden Balles hier unabkömmlich
bin.- Mit vielen Grüßen an Euch, sowie an Herrn Baek, Euer
untertänigster Diener

ges. W. Pauli

1953–1956: Project Poltergeist

- ▶ In 1951, Reines had the idea to detect neutrinos from the explosions of atomic bombs!
- ▶ 1 T detector needed, 10^3 bigger than anything tried before.
- ▶ Scintillator detector - new technology then

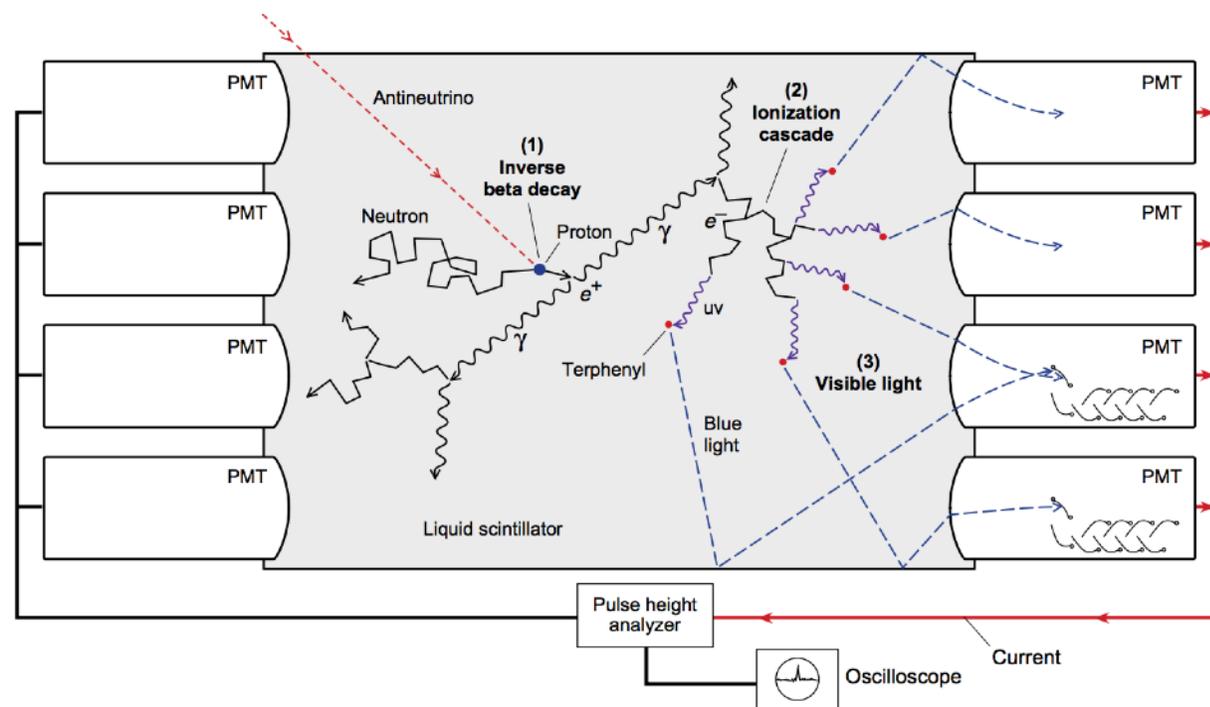
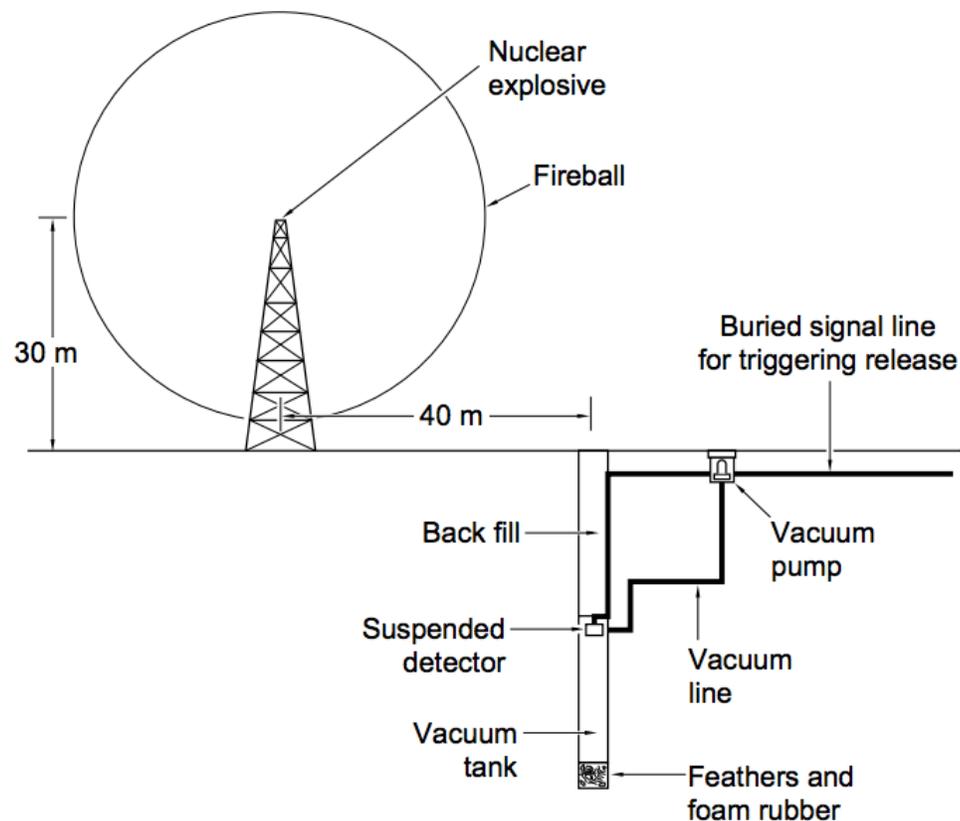
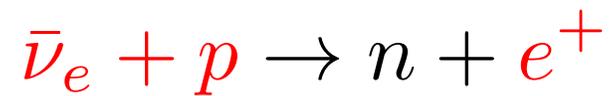


Fred Reines

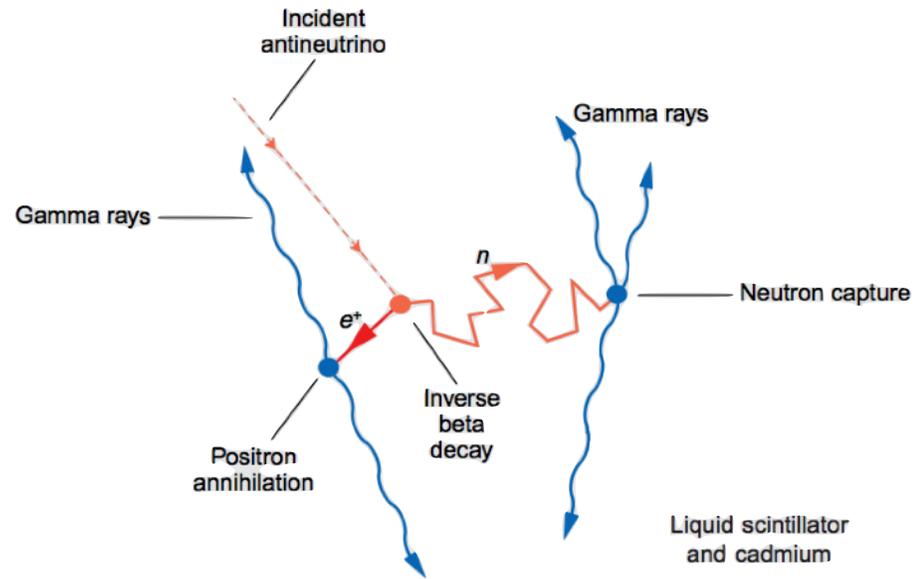


Clyde Cowan

Original Reines-Cowan Experiment



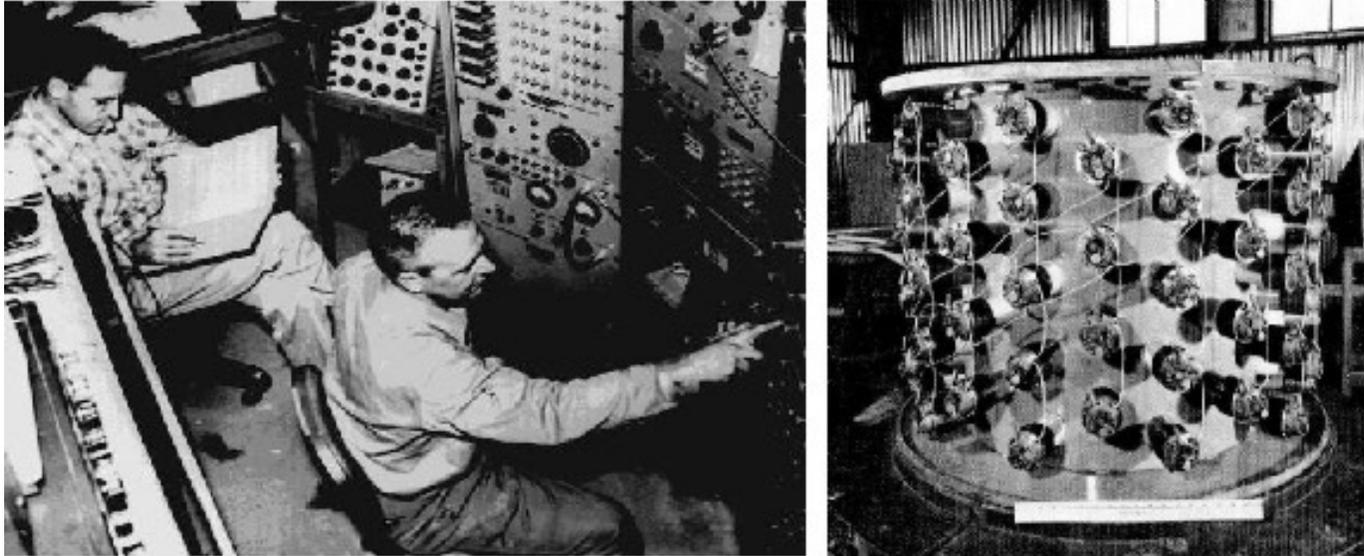
Inverse Beta Decay



- ▶ Electronic circuits could be designed to detect this “delayed-coincidence” signature, two well defined flashes of light separated by microseconds provide a powerful means to discriminate the signature of inverse beta decay from background noise.

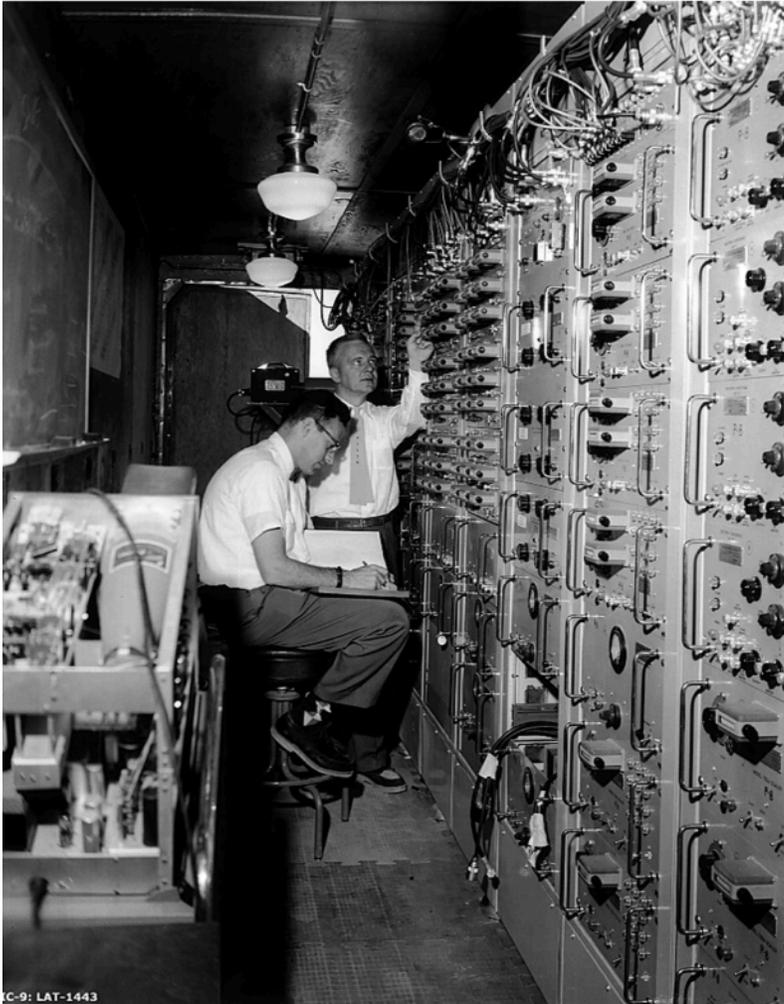
	σ [b]	E [MeV]
H	0.33	2.2
^{113}Cd	19820	9

1953: Hanford Reactor



- ▶ For several months, the team stacked shielding and used various recipes for the liquid scintillator
- ▶ The delayed-coincidence background was about 5 counts per minute, much higher than the expected signal rate.
- ▶ Reines and Cowan reported a small increase in the number of delayed coincidences when the reactor was on versus when it was off
 - ▶ increase was consistent with the number expected from the estimated flux of reactor neutrinos.
- ▶ Tantalizing result but insufficient evidence that neutrino events were being detected.

1956: Savannah River Reactor



Experimentalists check their signal! Reconfigured detector at different reactor site.

- ▶ Are coincidences from positron annihilation and neutron capture, rather than other processes?
 - ▶ Dissolve ^{64}Co in the water to understand what positrons look like
 - ▶ Doubled Cd_2Cl_4 in the water to watch the coincidence time decrease
- ▶ Does signal strength vary with number of protons?
 - ▶ Filled half of tanks with heavy water, decreased IBD cross section on deuterium
- ▶ Is signal really cosmic rays & reactor backgrounds?
 - ▶ varied the thickness and type of shielding

This and all other tests confirmed that the signal was indeed inverse beta decay of reactor antineutrinos!

1956: Discovery!



RADIO-SCHWITZ S.A. **RADIOGRAMM - RADIOGRAMME** RADIO-SUISSE S.A.

SBZ1311 ZHV UW1844 FM BZJ116 MH CHICAGO DILL 56 14 1310
PLC 00253

Erhalten - Rece **VIA RADIO-SUISSE** Bulletin - Transmis

von - de **NEWYORK** NAME - NOM

Brieftelegramm 74 15.11.56 -1 10

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NACHLASS
PROF. W. PAULI

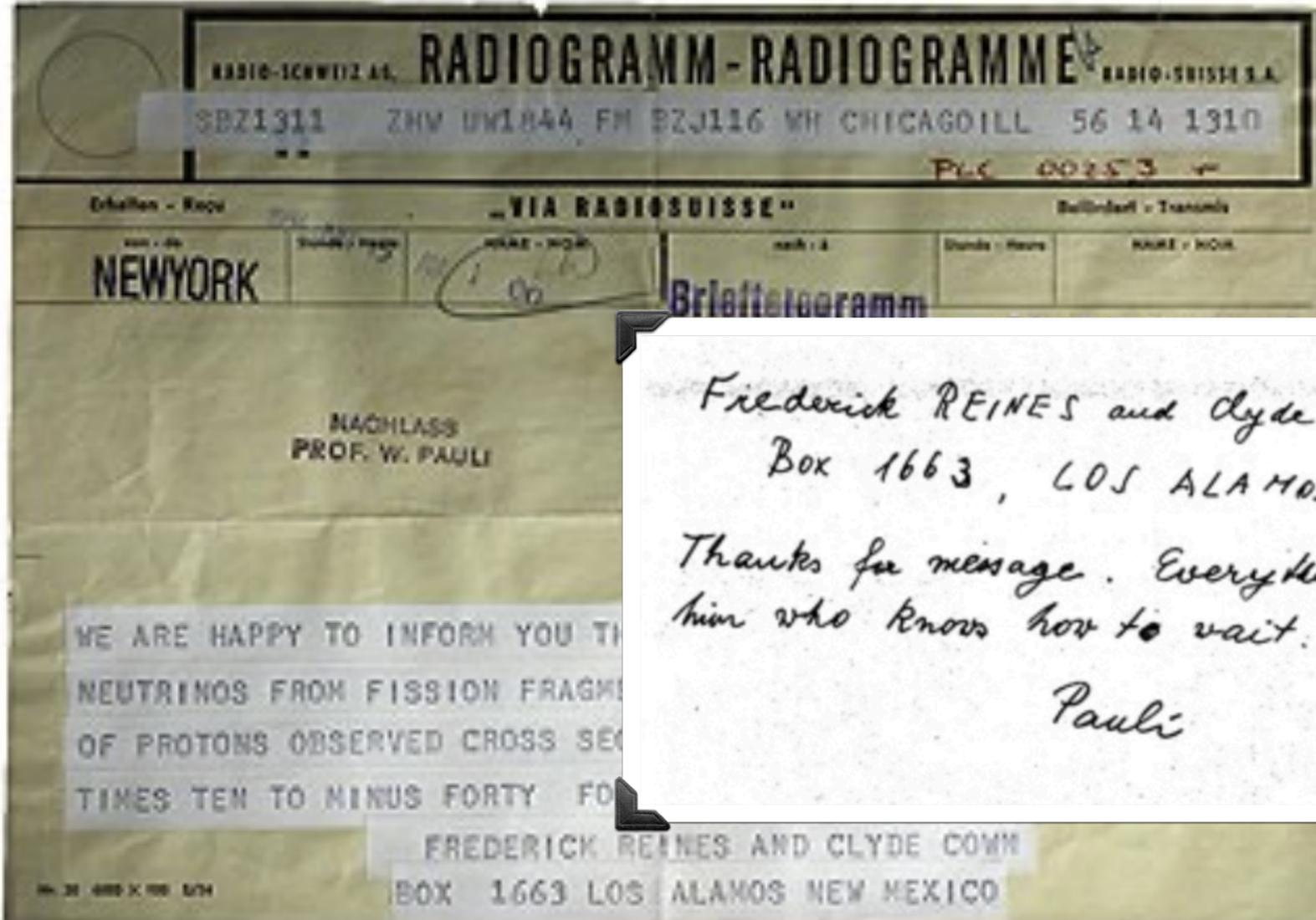
PROFESSOR W PAULI *Per Post*
ZURICH UNIVERSITY ZURICH ①

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED
NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY
OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX
TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWEN
BOX 1663 LOS ALAMOS NEW MEXICO

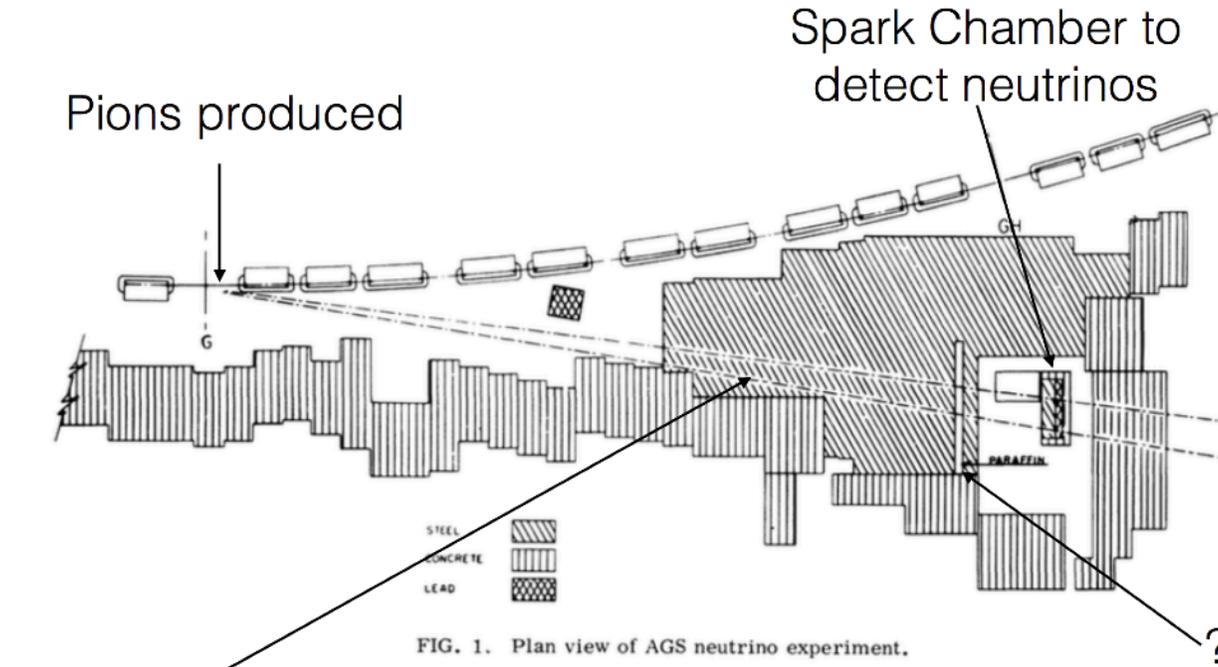
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1956: Discovery!



Muon Neutrino Discovery

- ▶ In 1962, Lederman, Steinberger, & Schwartz's group discovered the muon neutrino



Steel shield stops strongly interacting particles

- ▶ 34 muon tracks, 6 electrons showers
- ▶ They're different particles!

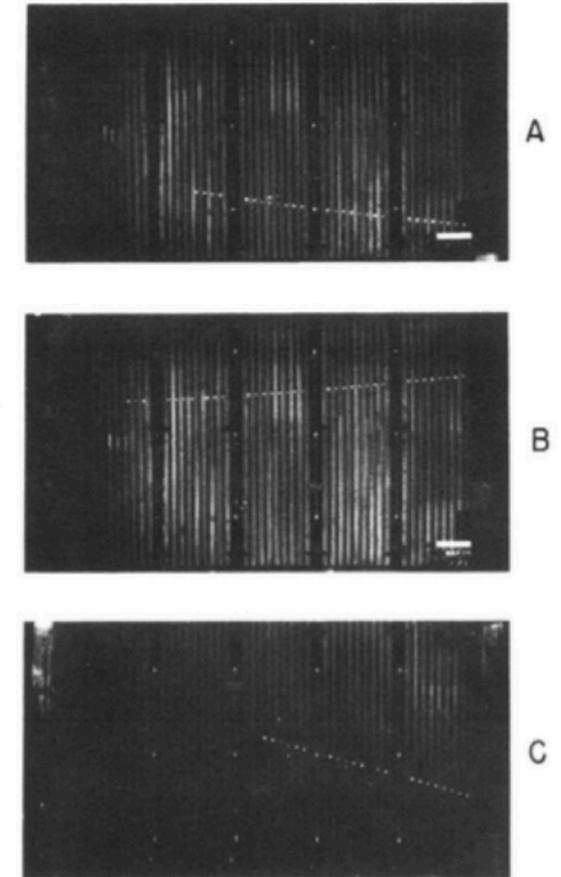
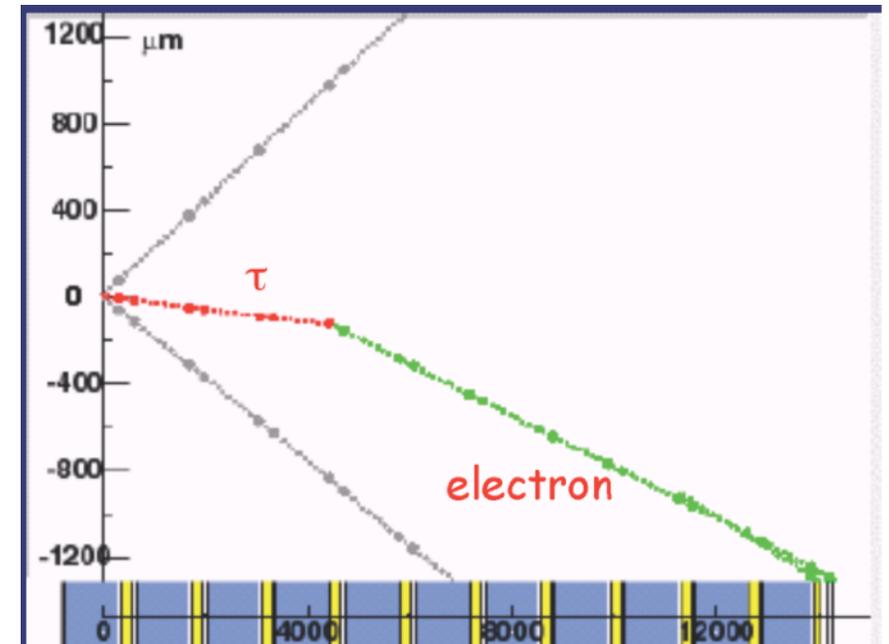
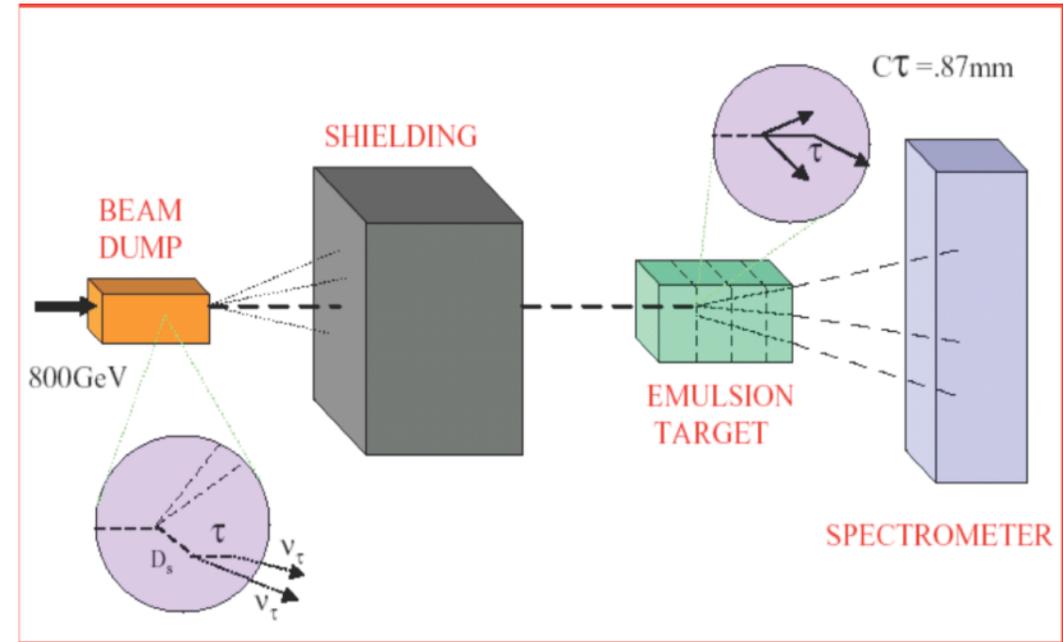


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

Tau Neutrino Discovery

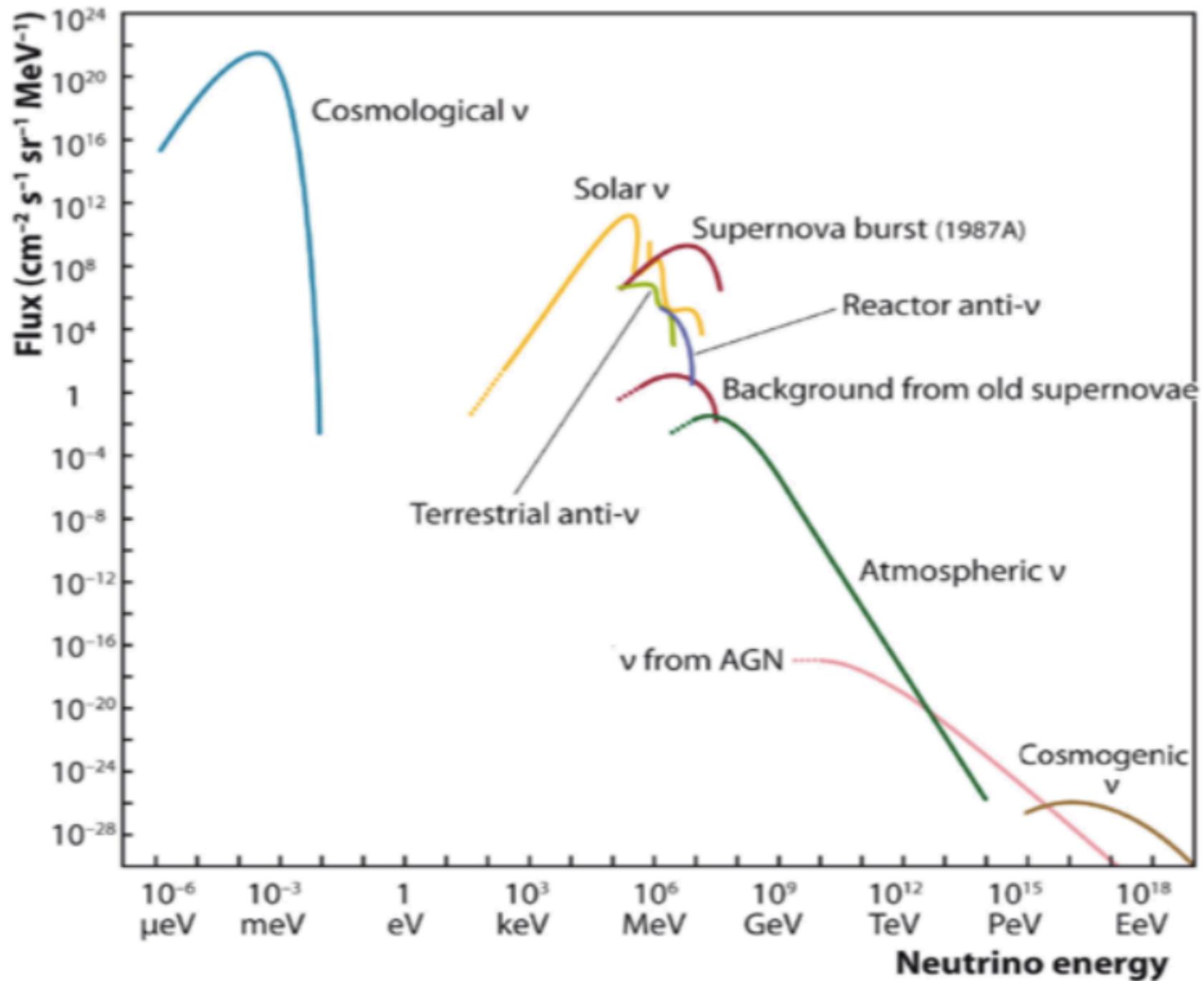
- ▶ In 1975 Martin Perl et al. observed events at SLAC in e^+e^- collisions which suggested the existence of a third charged lepton, christened the tau (τ).
- ▶ In 2000 the DOnuT collaboration discovered the tau neutrino
- ▶ The neutrino source was the tungsten beam dump behind the Tevatron.
- ▶ Only 36 feet from source to target.
 - ▶ This did not allow enough time for flavour oscillations.
- ▶ The target was made of emulsion sheets, which was used as an electromagnetic calorimeter in some cases.
- ▶ 4 Tracks observed! (bkg < 0.2)



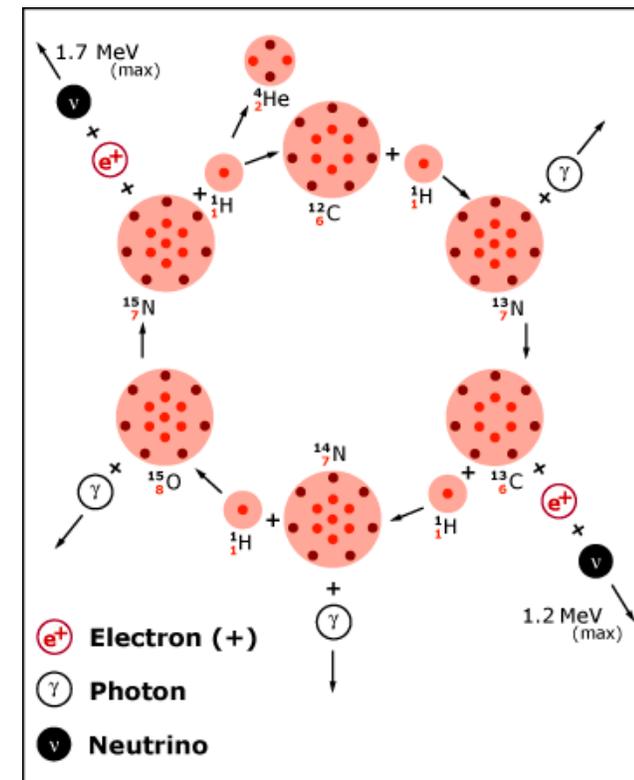
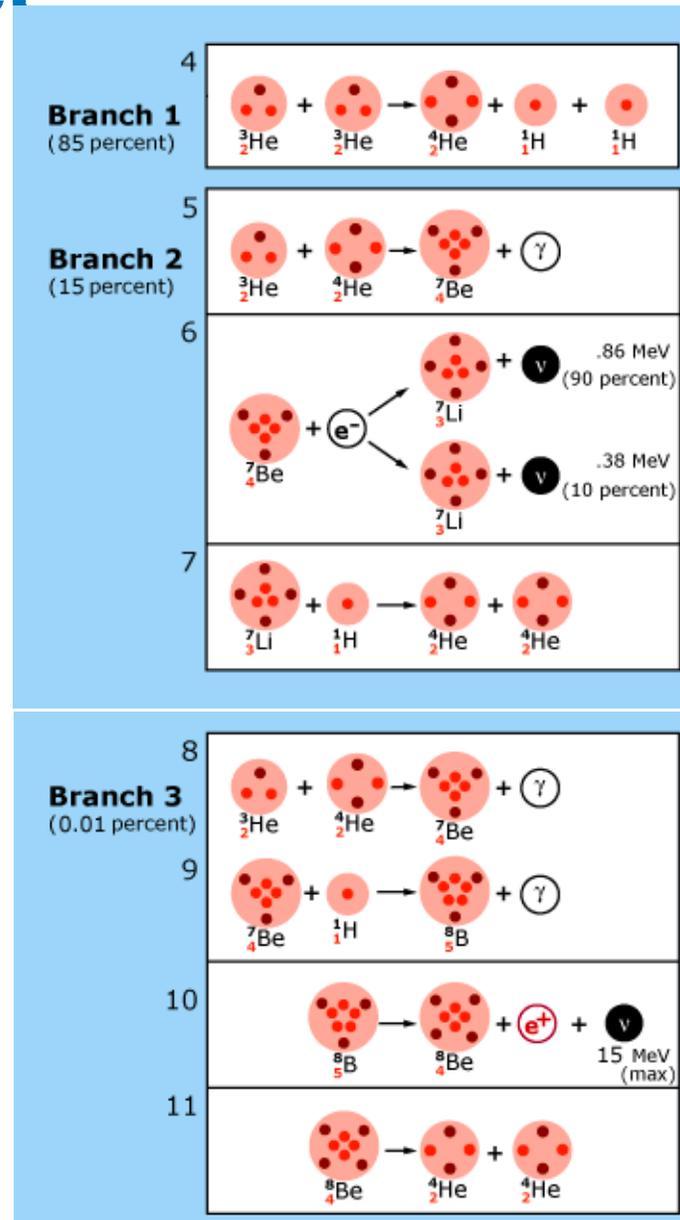
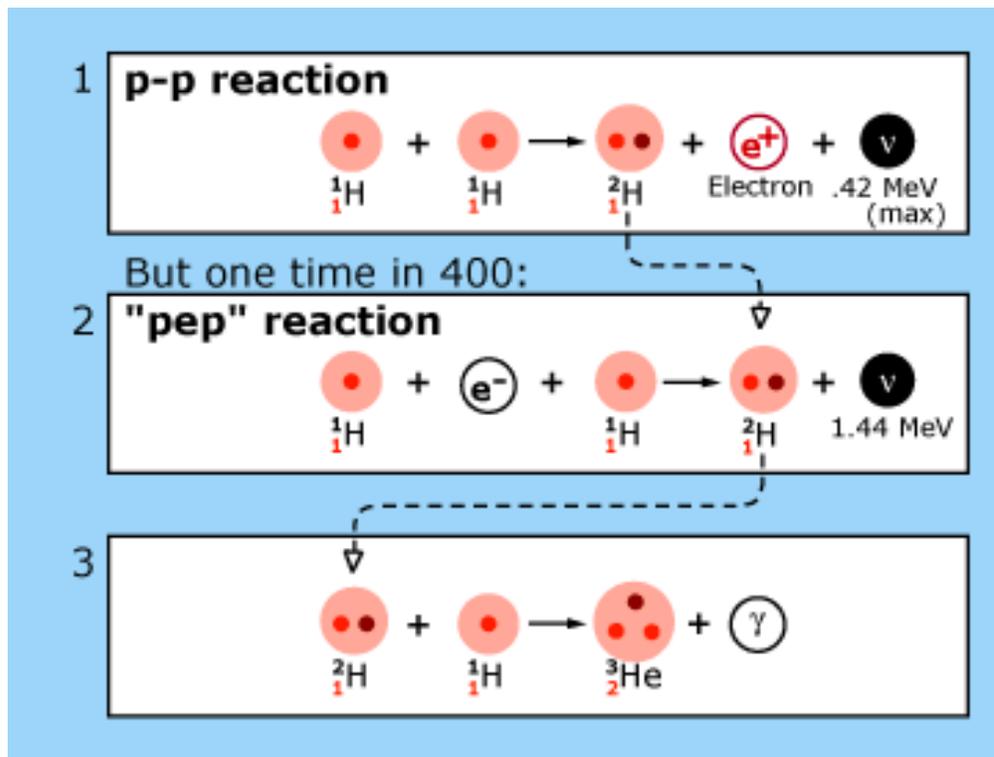
The Standard Model

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	d down	s strange	b bottom	γ photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	0	0	0	$80.4 \text{ GeV}/c^2$	
	$1/2$	$1/2$	$1/2$	± 1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

Where do Neutrinos come from?

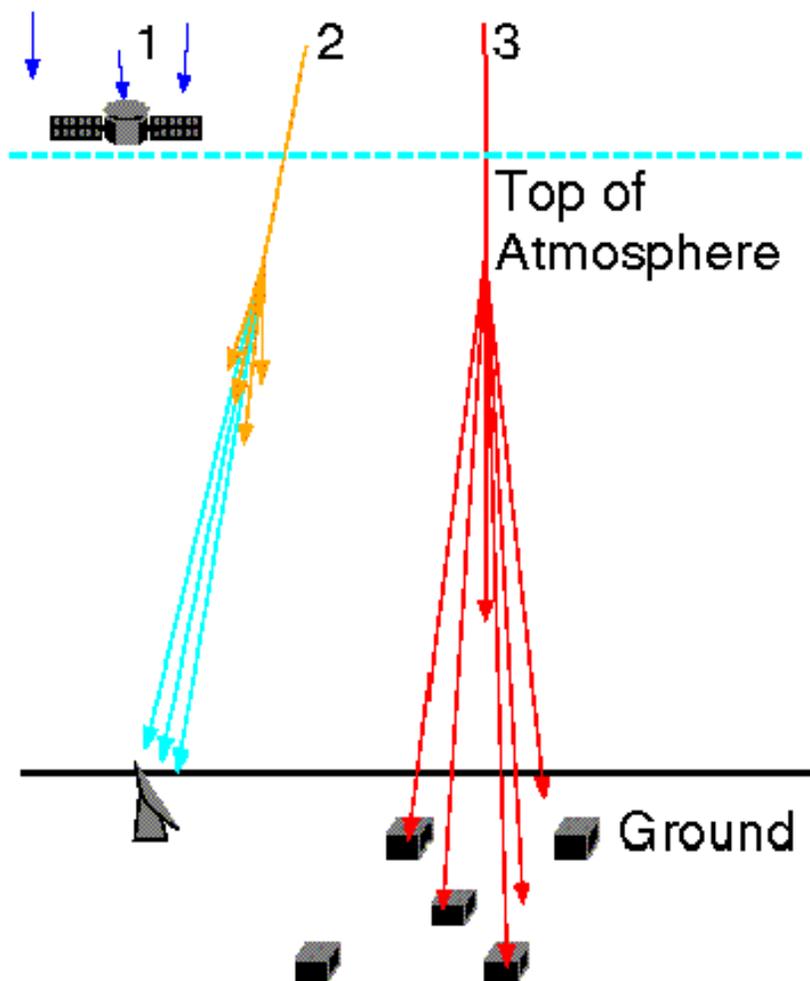


The Standard Solar Model

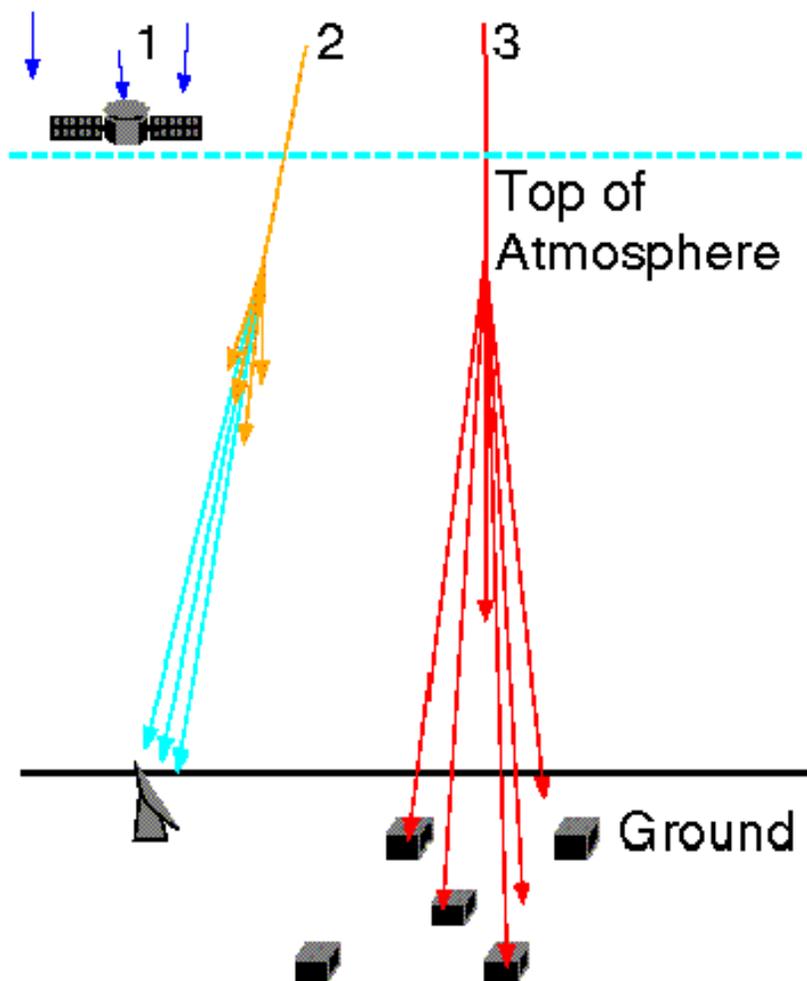


$$\Phi_{\nu_e} = 10^{11} / \text{cm}^2 / \text{s}$$

Solar Neutrino Experiments need to be:

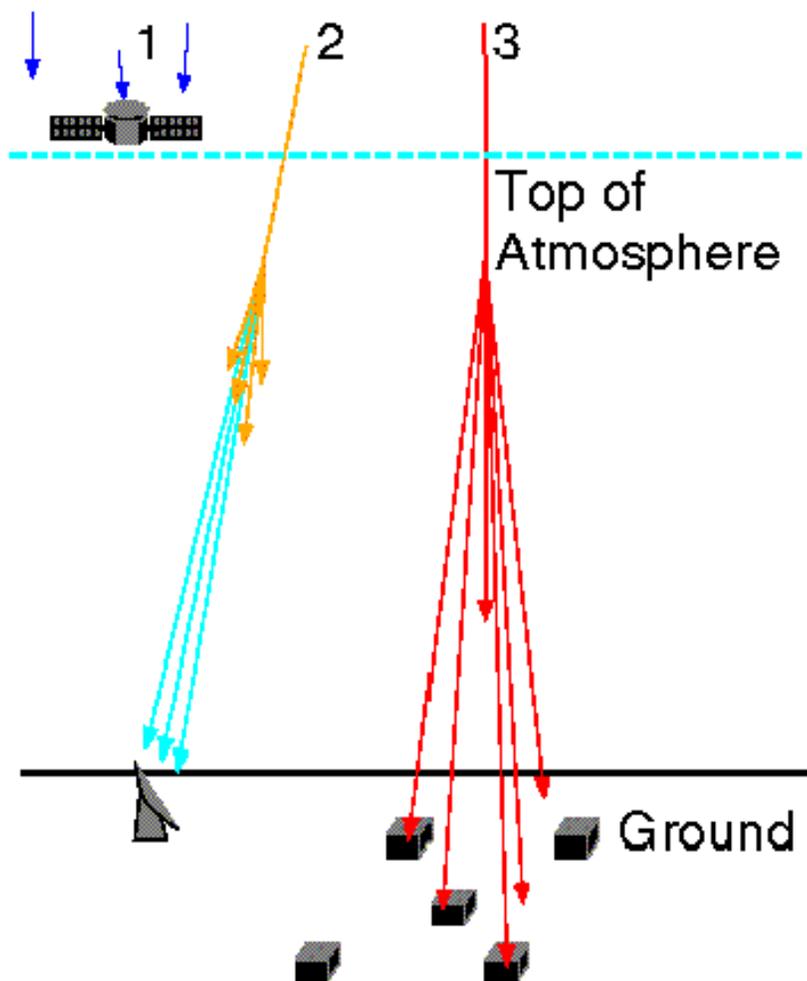


Solar Neutrino Experiments need to be:



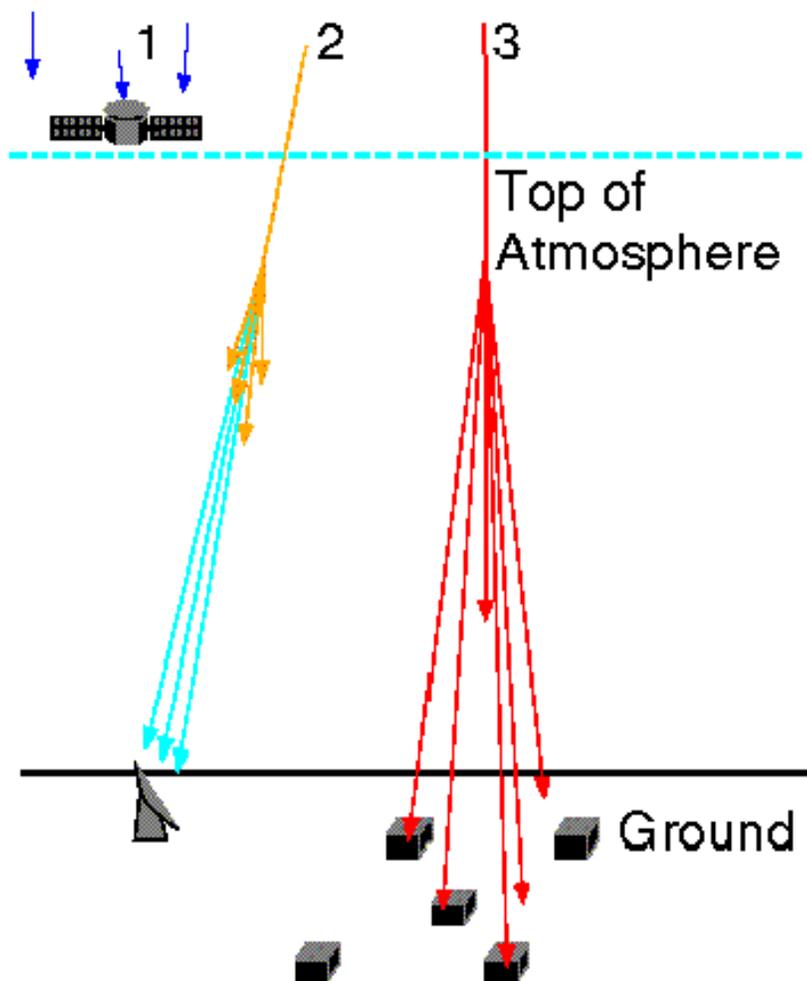
- ▶ BIG -> to detect weakly interacting ν 's

Solar Neutrino Experiments need to be:



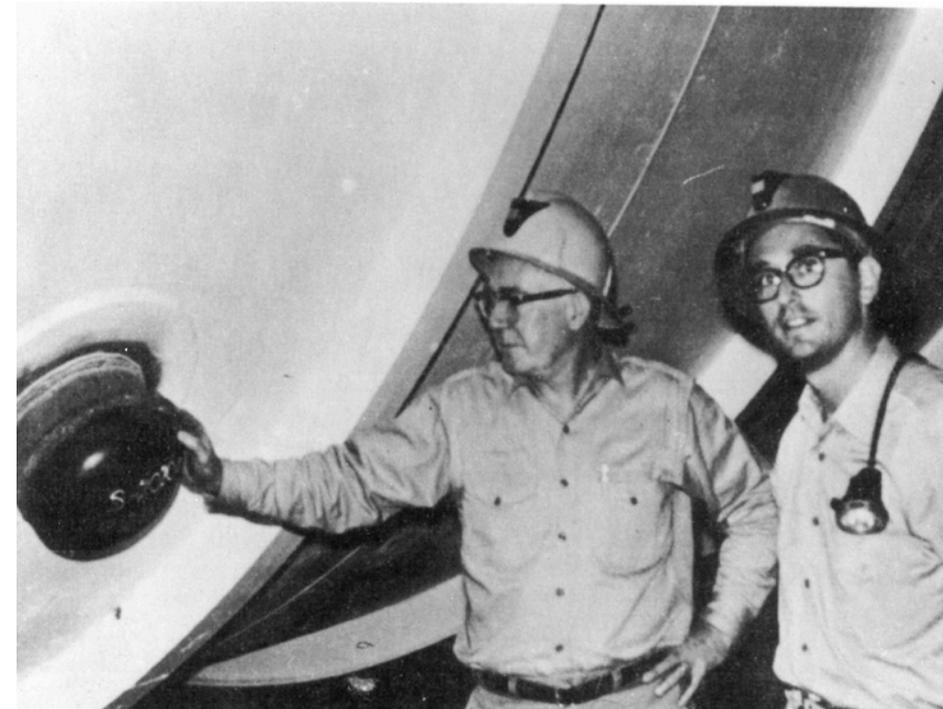
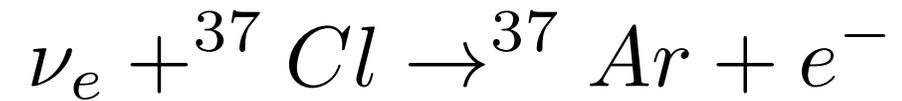
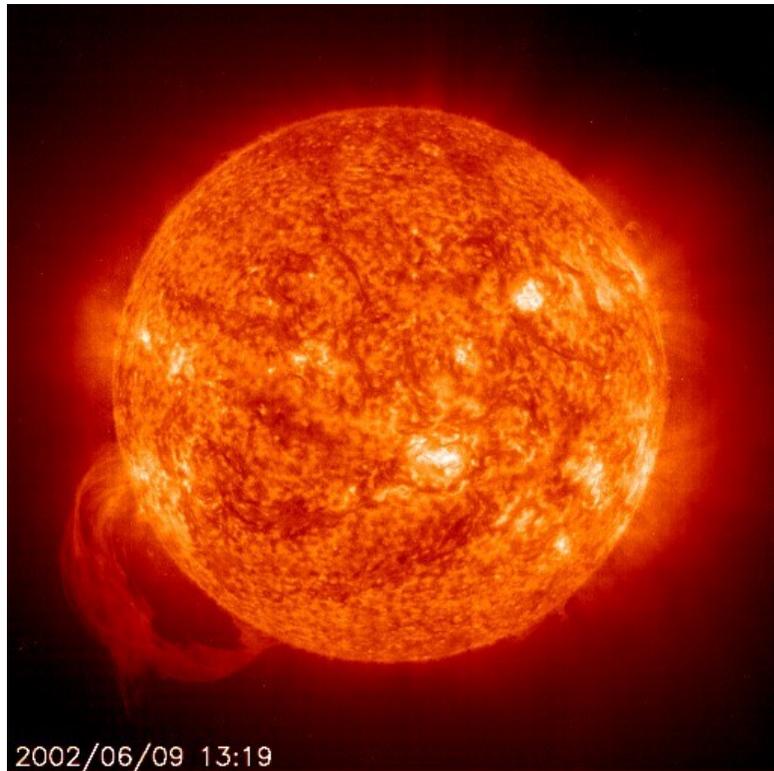
- ▶ BIG -> to detect weakly interacting ν 's
- ▶ DEEP -> to get away from cosmic rays

Solar Neutrino Experiments need to be:



- ▶ BIG -> to detect weakly interacting ν 's
- ▶ DEEP -> to get away from cosmic rays
- ▶ CLEAN -> to reduce radioactivity

Searching for Solar Neutrinos



$$\Phi_{\nu_e} = 10^{11} / \text{cm}^2 / \text{s}$$

Ray Davis and John Bahcall
378 tonnes of C_2Cl_4
 ${}^{37}\text{Cl}$ is 25% of nat Cl



Homestake Experiment



- ▶ The ^{37}Ar formed by neutrino capture is then removed from the bulk of the liquid by bubbling 280 lpm of helium gas through the system.
- ▶ After the sample of argon is purified chemically it is placed in a small counter holding about .5 ml of gas.
- ▶ The ^{37}Ar is unstable and reverts to ^{37}Cl by capturing one of its own orbital electrons. The decay releases a low-energy electron from the Ar, which is detected

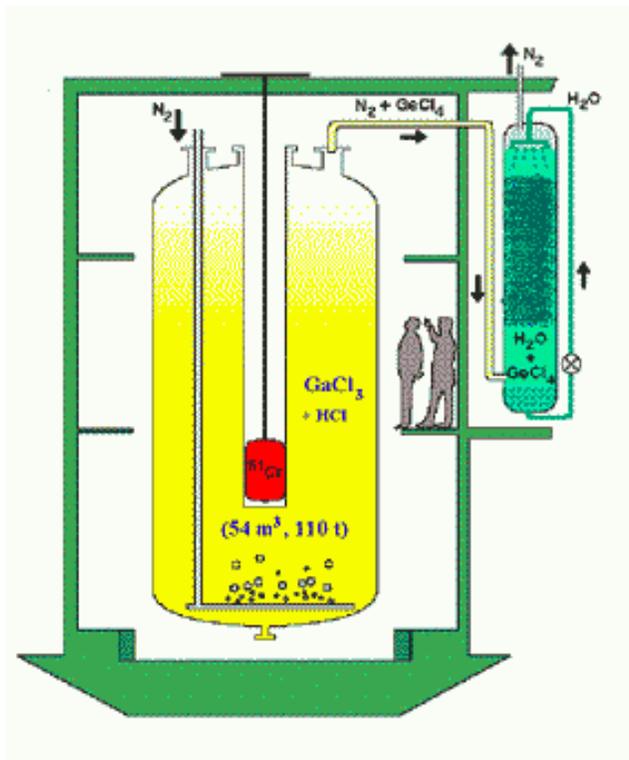
Homestake Experiment



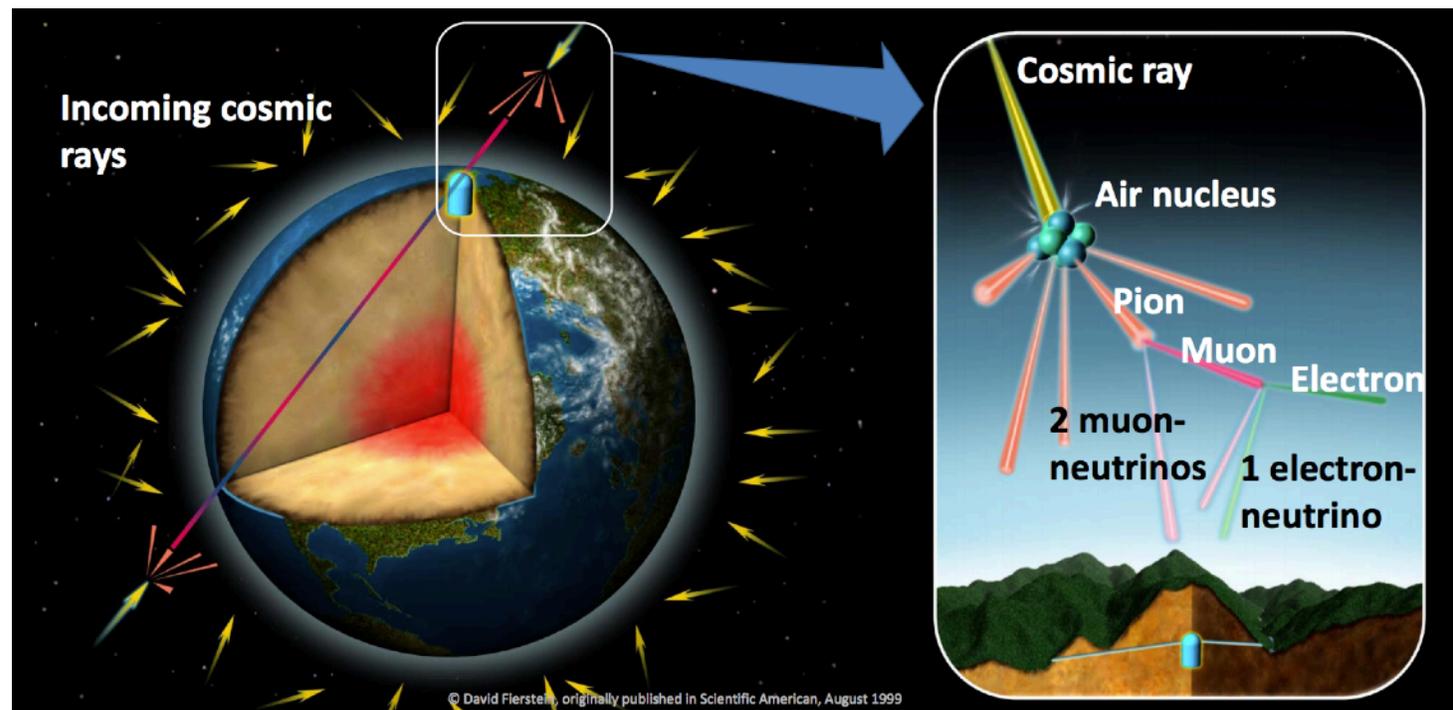
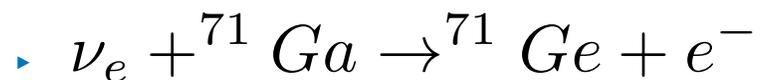
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Only detected 1/3 of predicted flux

Neutrino Anomaly?

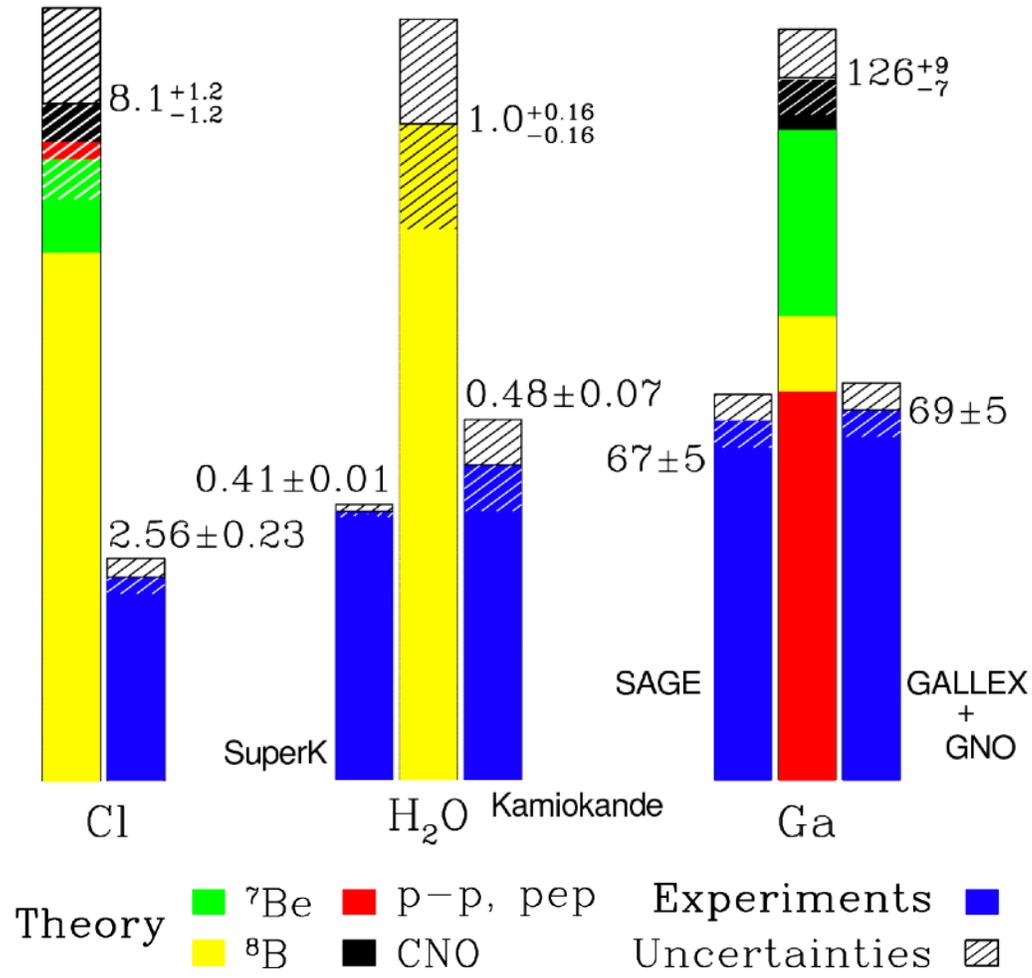


- ▶ Gallium Radiochemical Experiments (SAGE, GNO, GALLEX) looking for lower energy solar vs

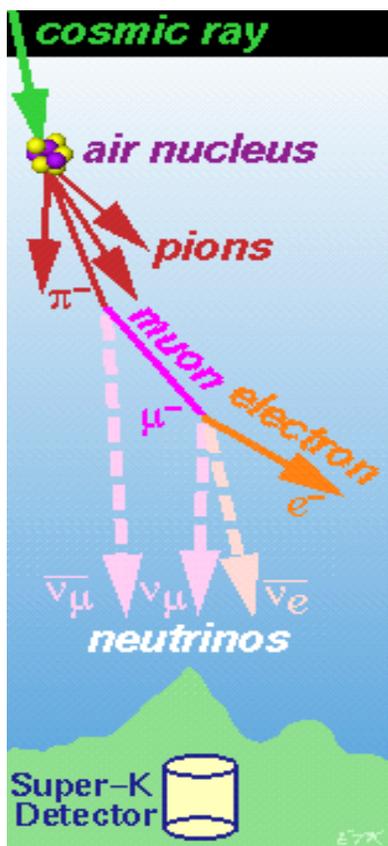


- ▶ KamiokaNDE, MACRO, IMB looking for nucleon decay, observed atmospheric nus
- ▶ Saw half of expected rate

Standard Model Rates vs Experimental Results



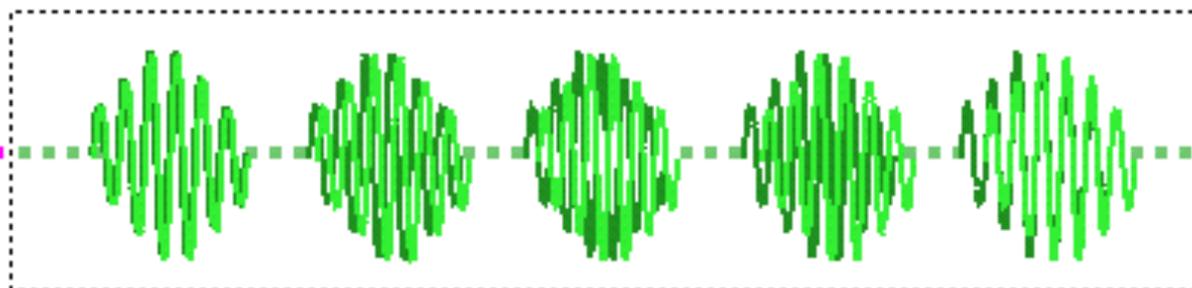
Neutrino Oscillations



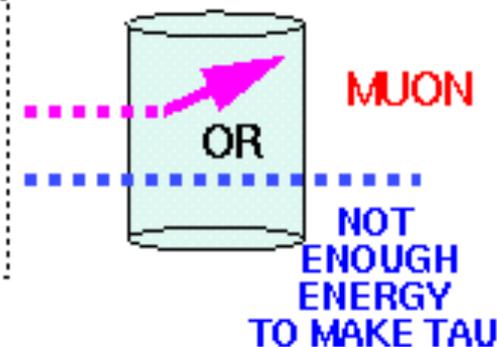
MUON NEUTRINO
CREATED IN THE
UPPER ATMOSPHERE

TWO WAVE PACKETS OF
DIFFERENT MASS TRAVEL
AT DIFFERENT VELOCITIES

WHICH FLAVOR IS
DETECTED DEPENDS
ON THE INTERFERENCE
PATTERN AT SUPER-K

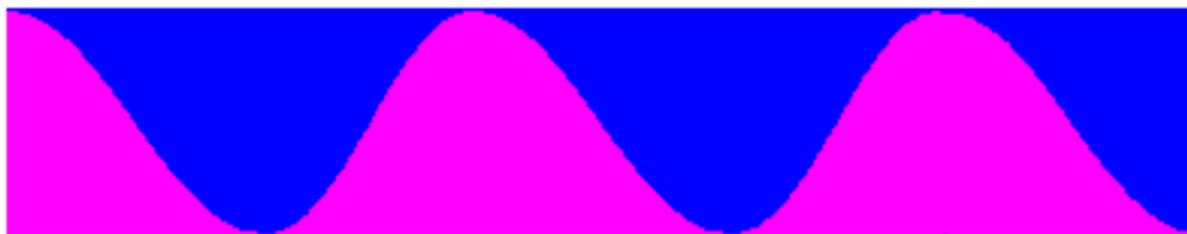


INTERFERENCE PATTERN OF WAVE PACKETS DETERMINES
PROBABILITY OF THE NEUTRINO FLAVOR



100% MUON
NEUTRINO

0% TAU
NEUTRINO



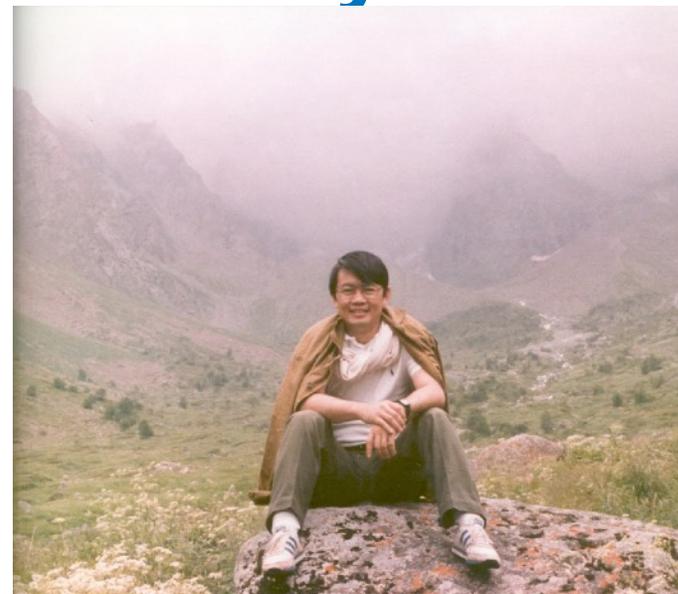
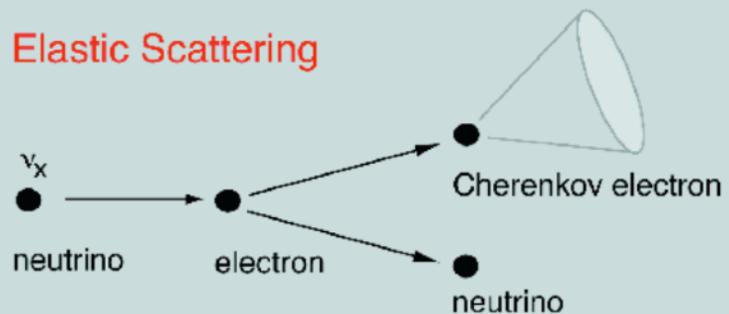
100% TAU
NEUTRINO

0% MUON
NEUTRINO

Herb Chen's Idea (1984): Use Heavy Water

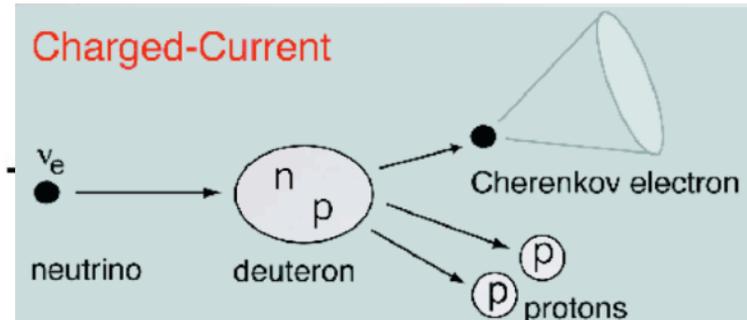
Neutrino-electron scattering

Elastic Scattering



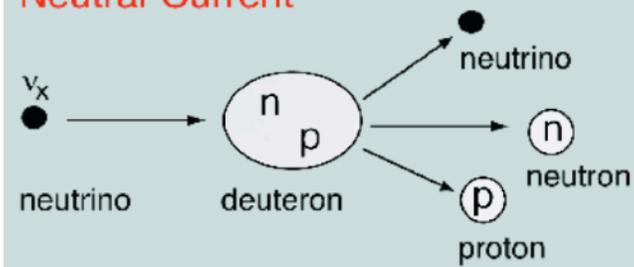
Neutrino absorption by deuteron

Charged-Current

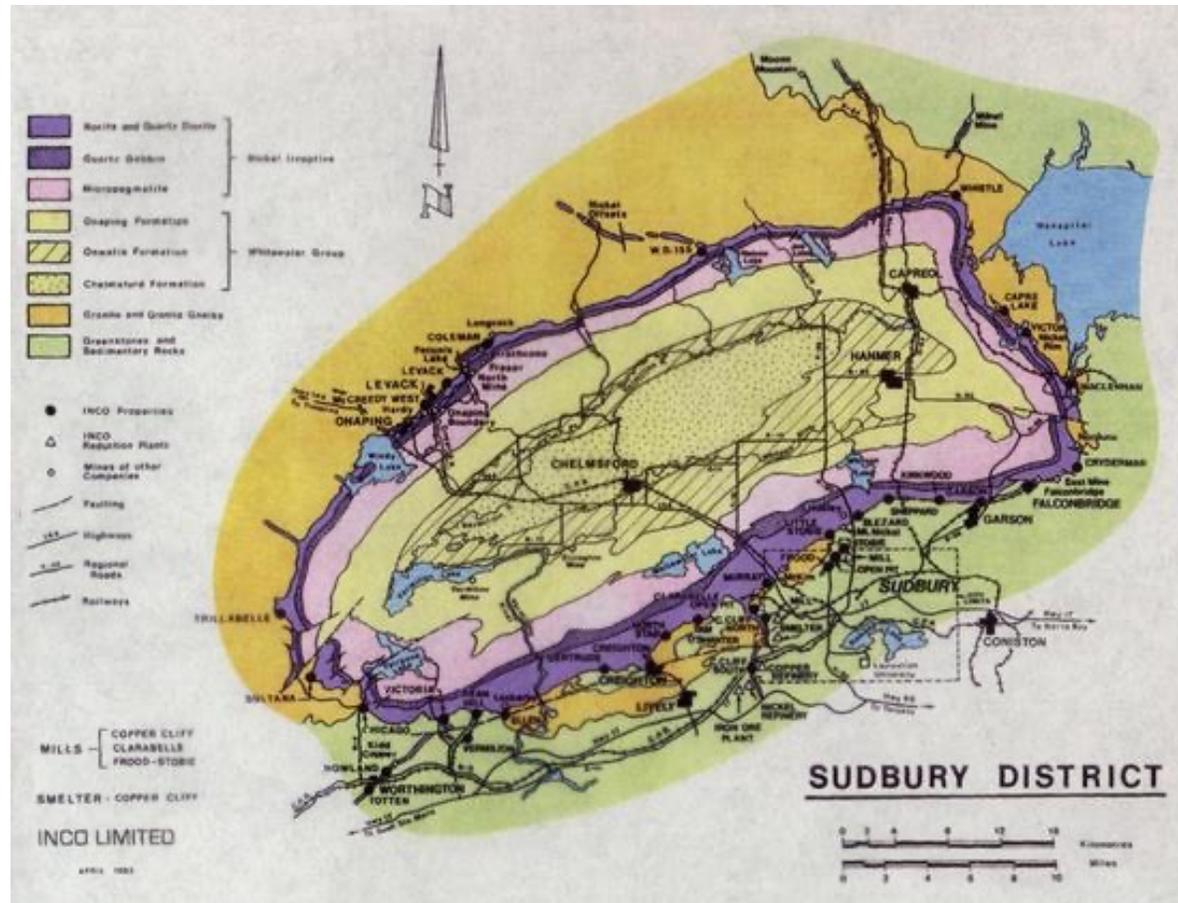


Neutrino breakup of deuteron

Neutral-Current



Where to put it?



Sudbury Neutrino Observatory

1000 tonnes D_2O

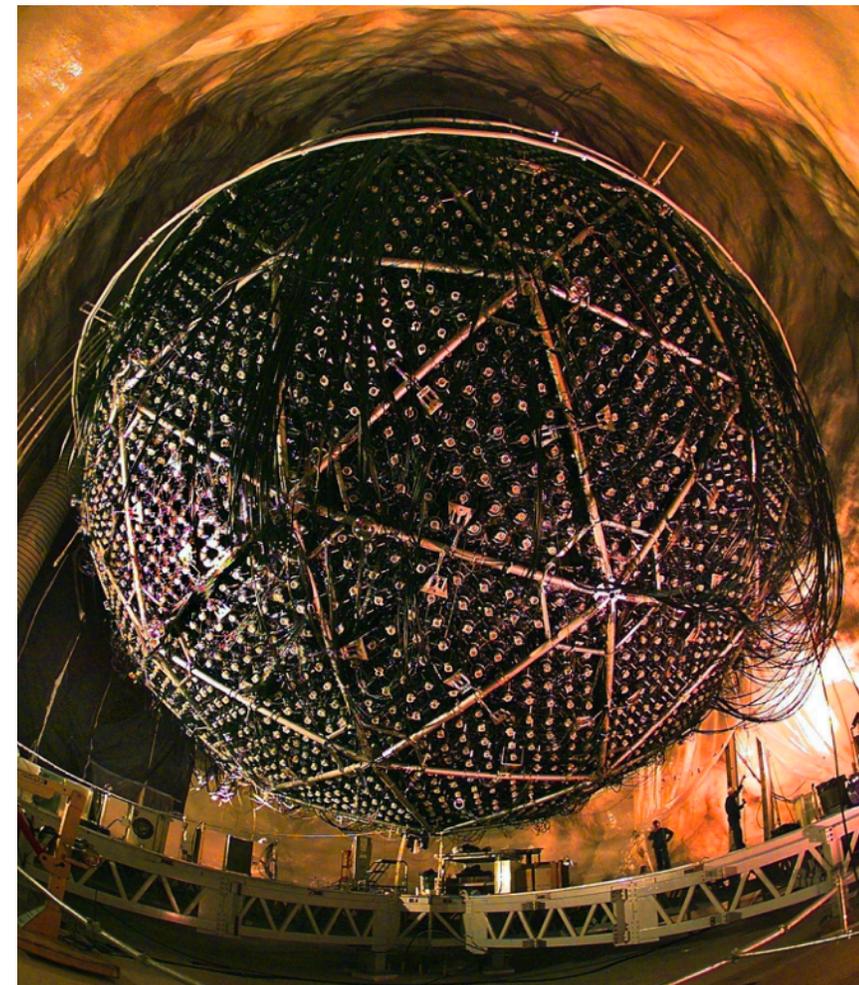
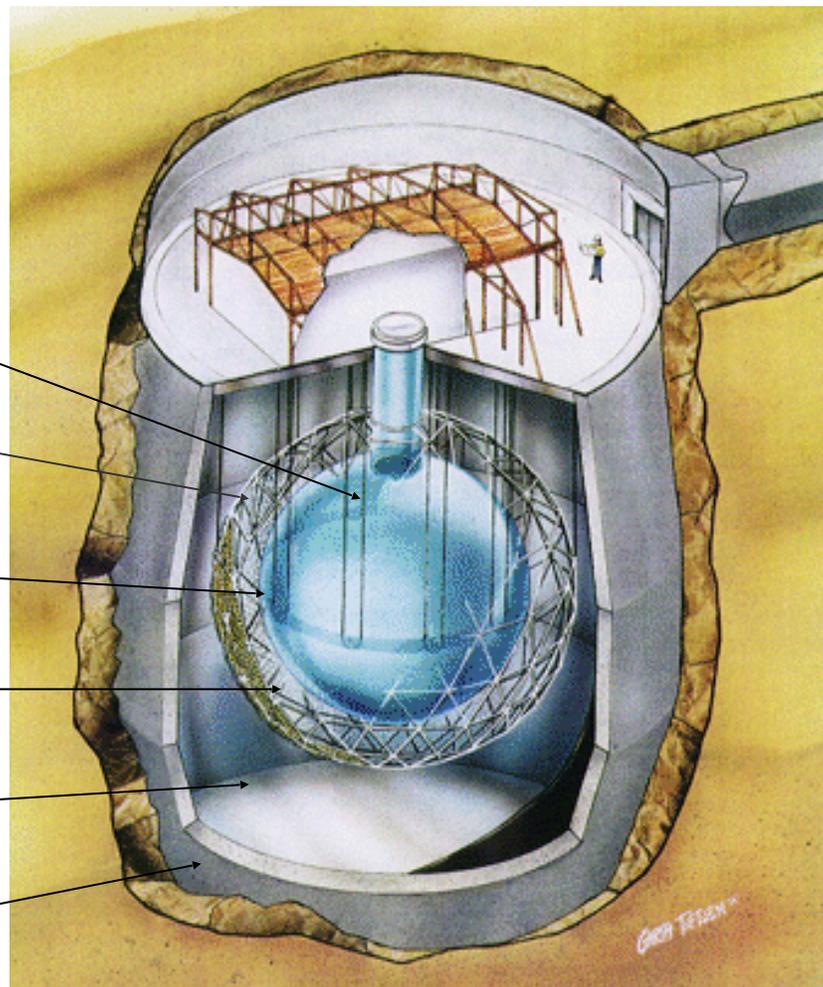
Support Structure
for 9500 PMTs,
60% coverage

12 m Diameter
Acrylic Vessel

1700 tons Inner
Shielding H_2O

5300 tons Outer
Shield H_2O

Urylon Liner and
Radon Seal



SNO Signal Extraction: Flux Measurements

$$\phi_{CC}^{\text{SNO}} = 1.76_{-0.05}^{+0.06}(\text{stat.})_{-0.09}^{+0.09}(\text{syst.})$$

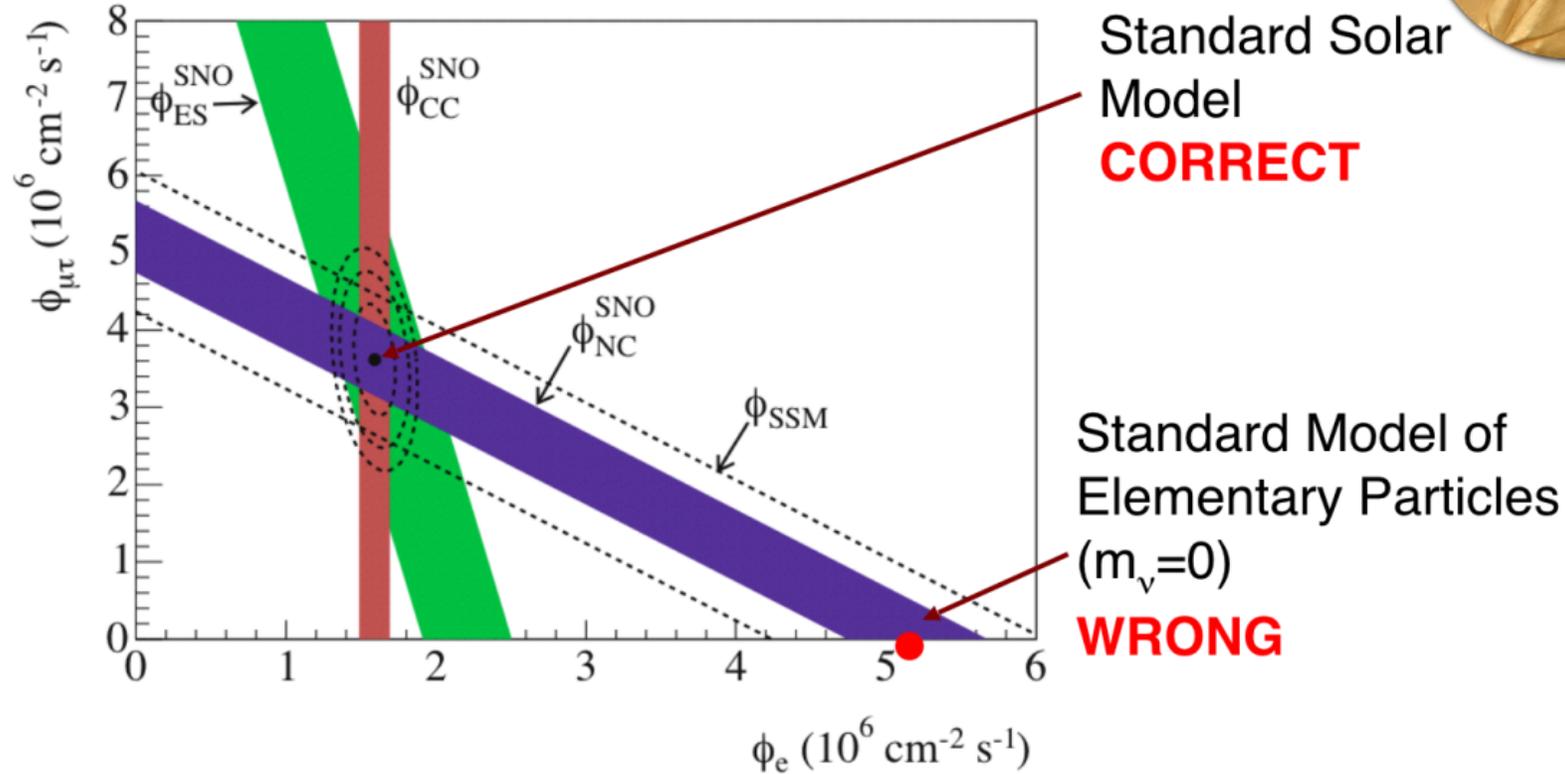
$$\phi_{ES}^{\text{SNO}} = 2.39_{-0.23}^{+0.24}(\text{stat.})_{-0.12}^{+0.12}(\text{syst.})$$

$$\phi_{NC}^{\text{SNO}} = 5.09_{-0.43}^{+0.44}(\text{stat.})_{-0.43}^{+0.46}(\text{syst.})$$

SNO measurements: (units $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

Total number of neutrinos much bigger than ν_e 's!

Sudbury Neutrino Observatory (SNO)

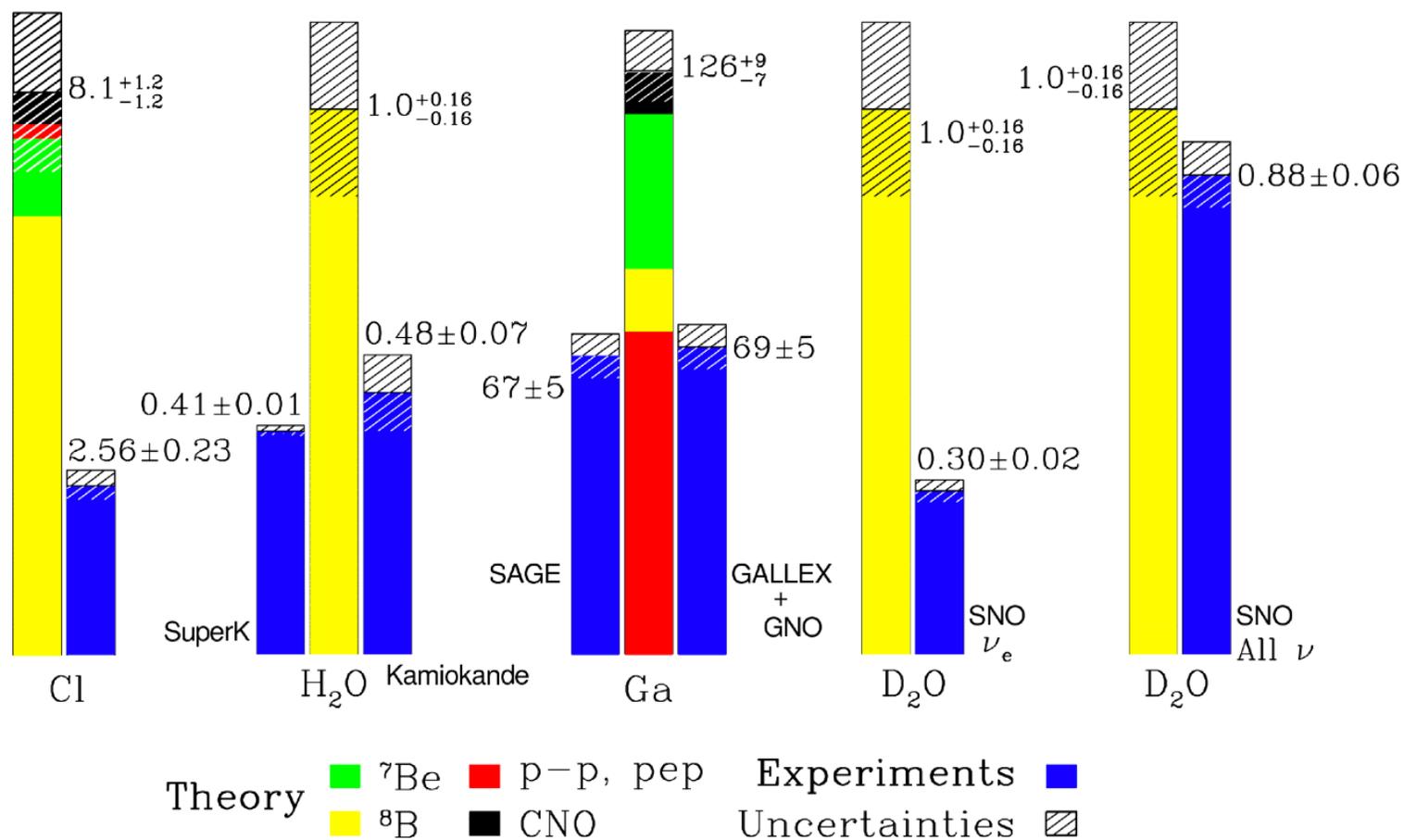


~2/3 of the ν_e produced in the Sun have transformed into ν_μ or ν_τ

SNO provided the first direct observation of neutrino flavor transformation (which requires neutrinos to be massive)

Standard Model Rates vs Expt

Bahcall–Serenelli 2005 [BS05(OP)]



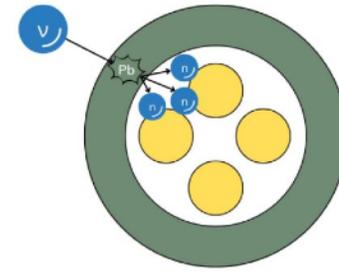
SNOLAB Neutrino Experiments

Supernova neutrinos

- ▶ Most of the energy released in a supernova explosion comes in the form of neutrinos
- ▶ Neutrinos are great messengers – they don't interact much
- ▶ They reach us much faster than light
- ▶ Looking for “bursts”

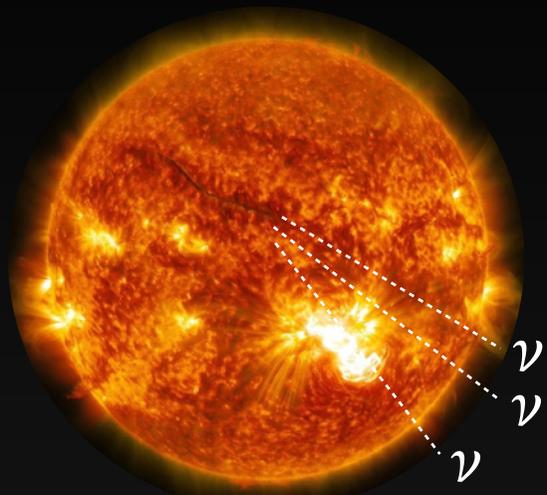
Image credit: NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.)

HALO: Helium and Lead Observatory

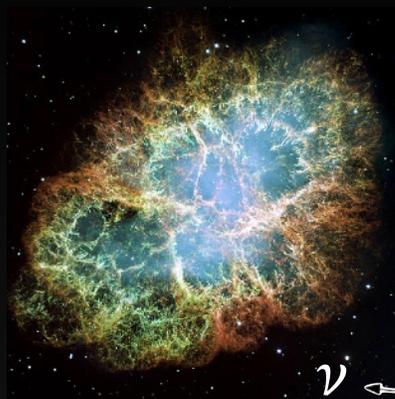


- ▶ 79 tonnes of recycled lead and 128 recycled SNO neutral current detectors
- ▶ Can detect all three neutrino flavours
- ▶ > 99% uptime, sensitive to supernova within 10 kpc
- ▶ Connected to Supernova Early Warning System

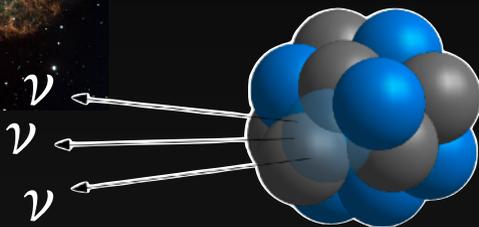
SNO+ Physics Program



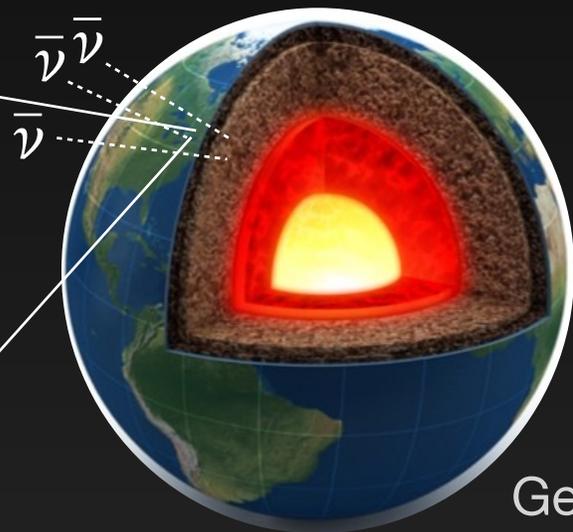
Solar Neutrinos



Supernovae & Exotic Processes



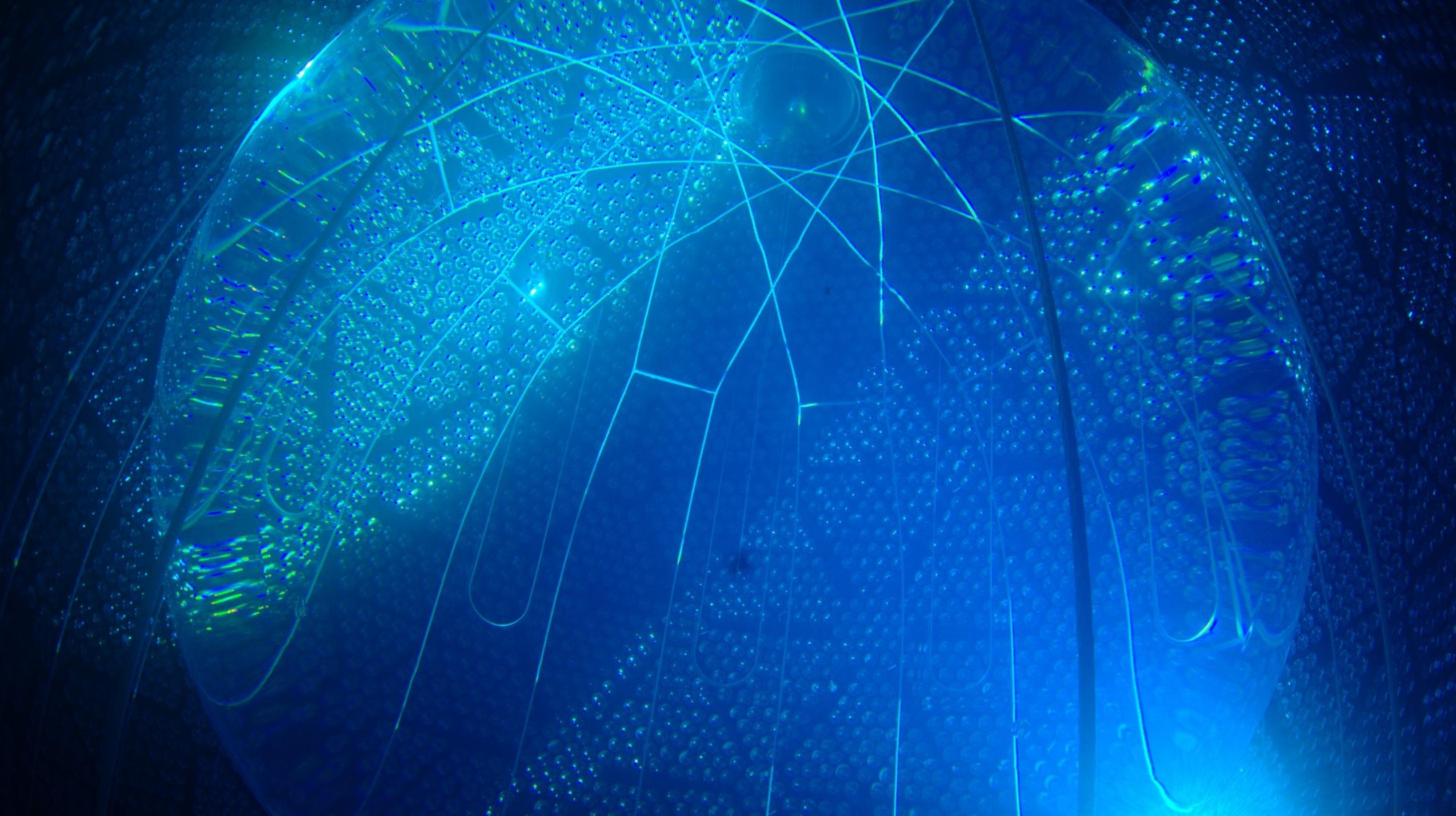
Reactor Anti-Neutrinos



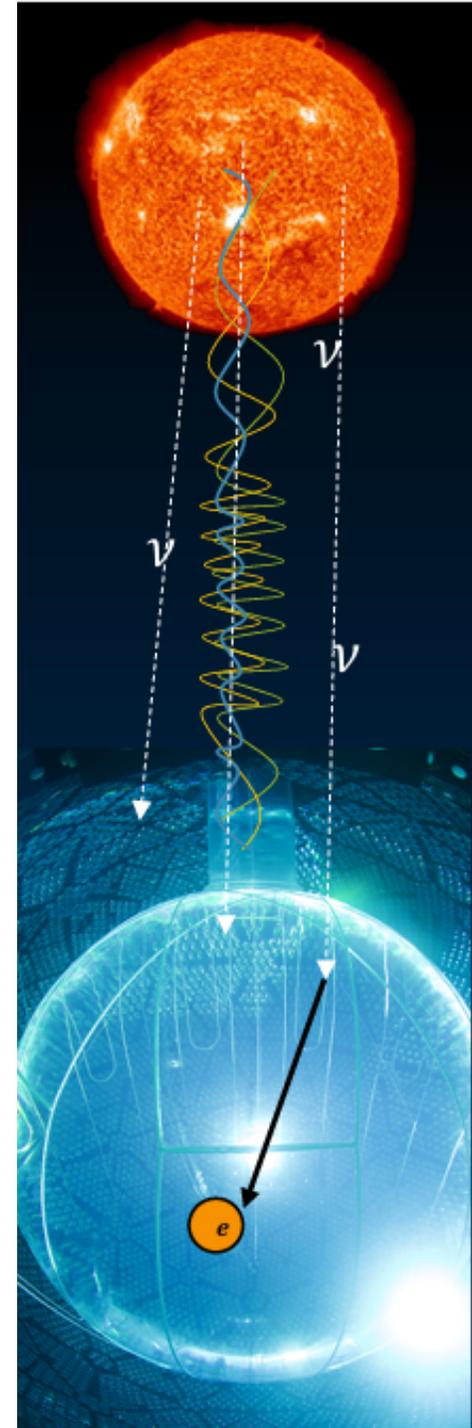
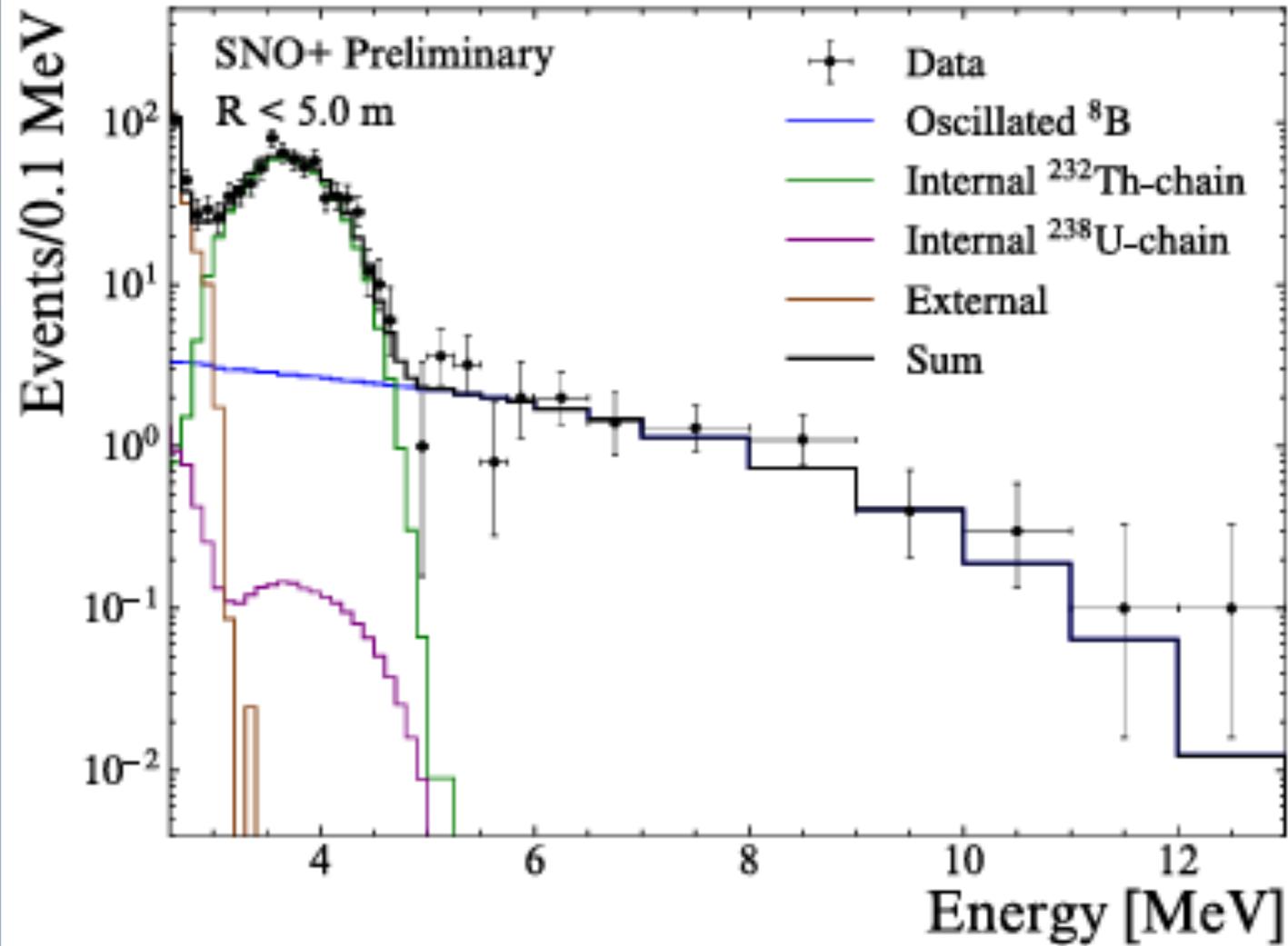
Geo-Neutrinos



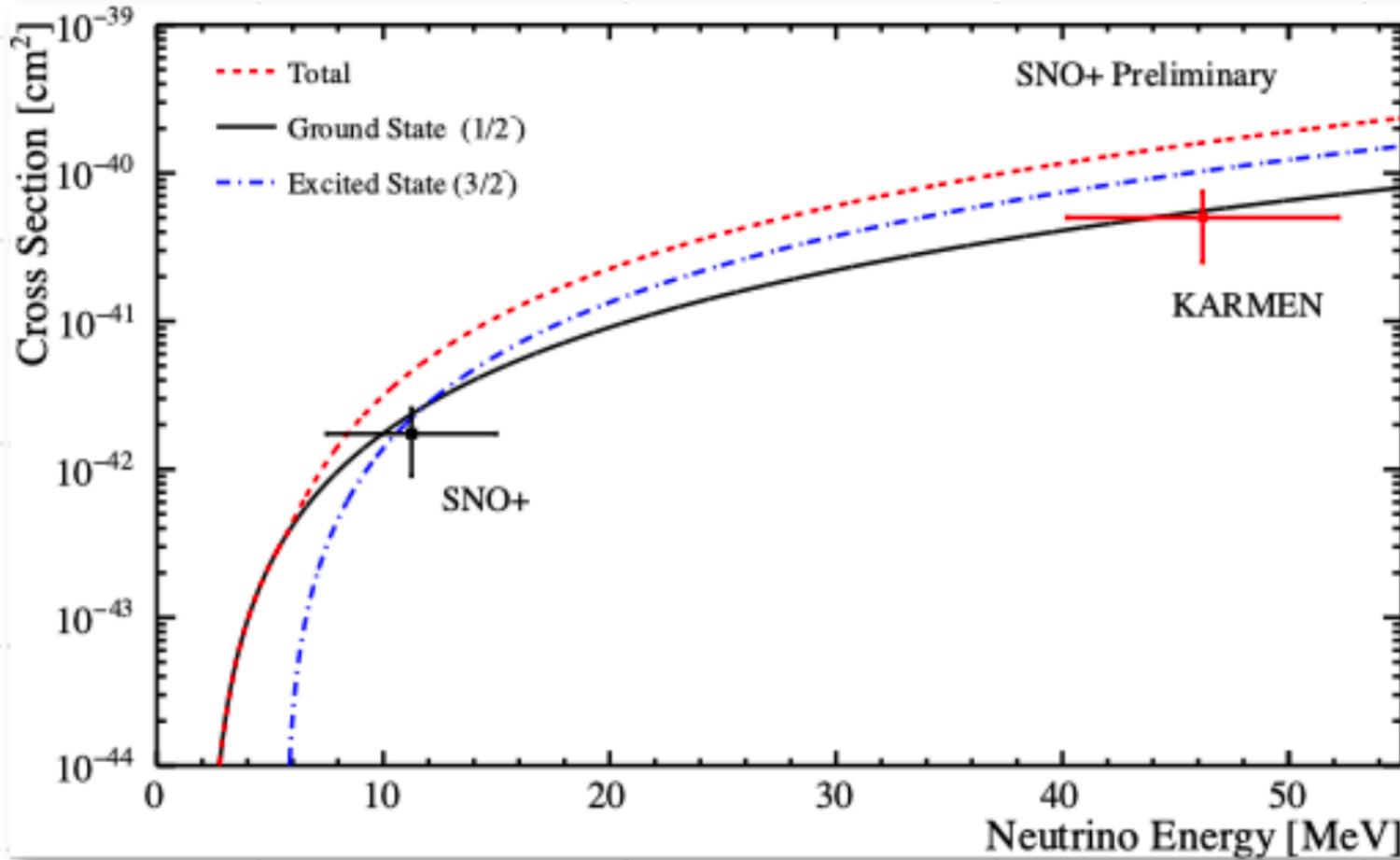
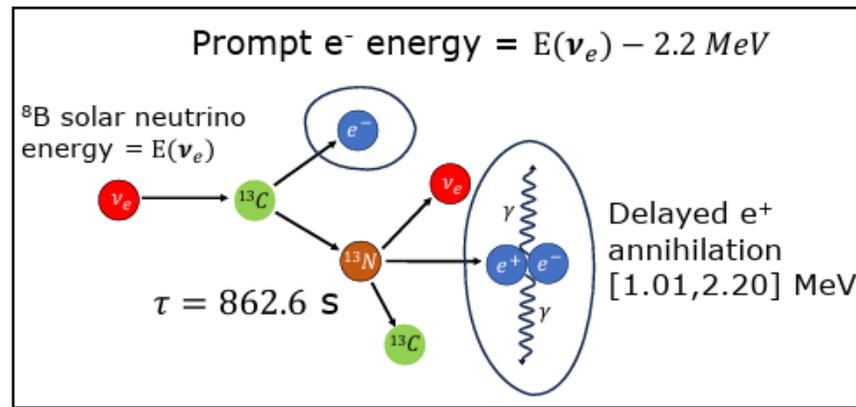
Neutrinoless
Double Beta
Decay



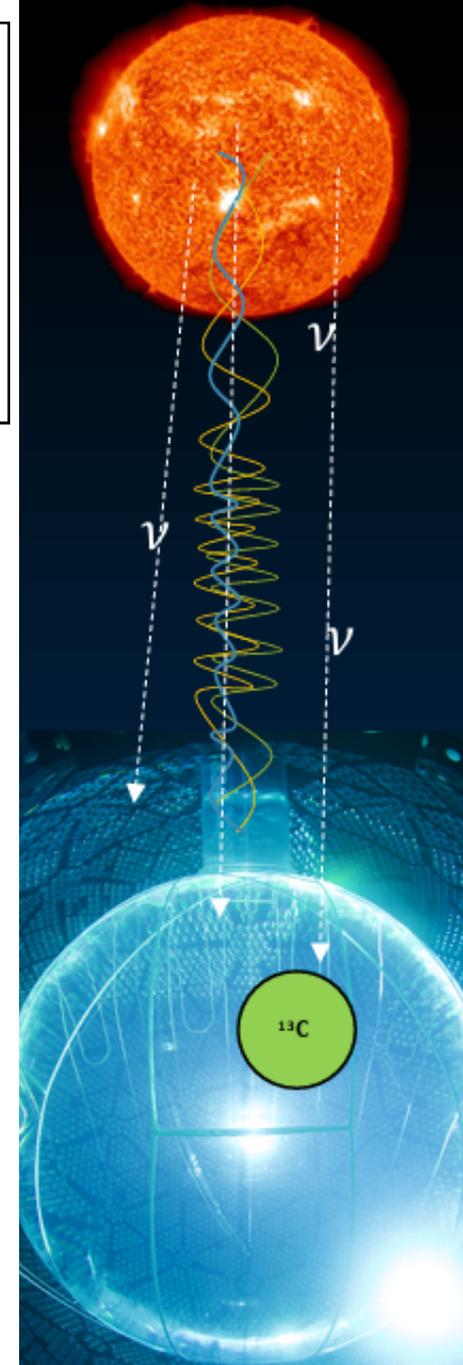
Solar Neutrinos in SNO+



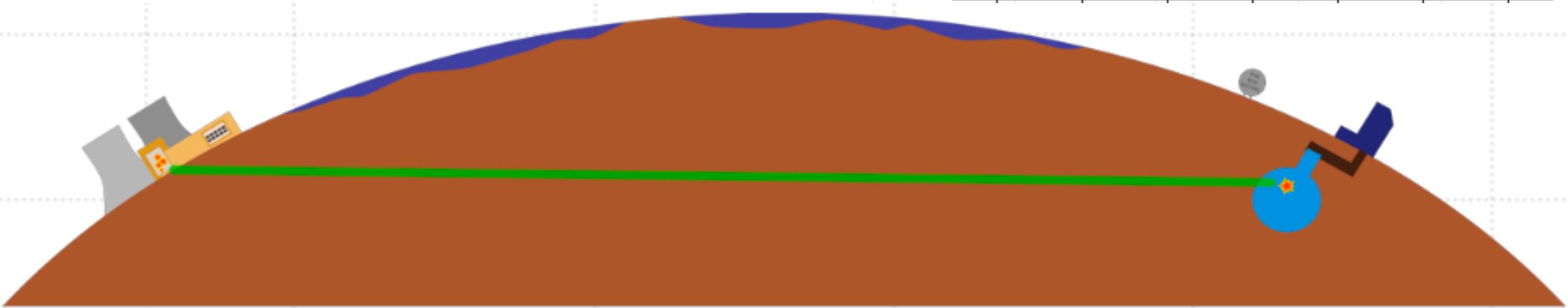
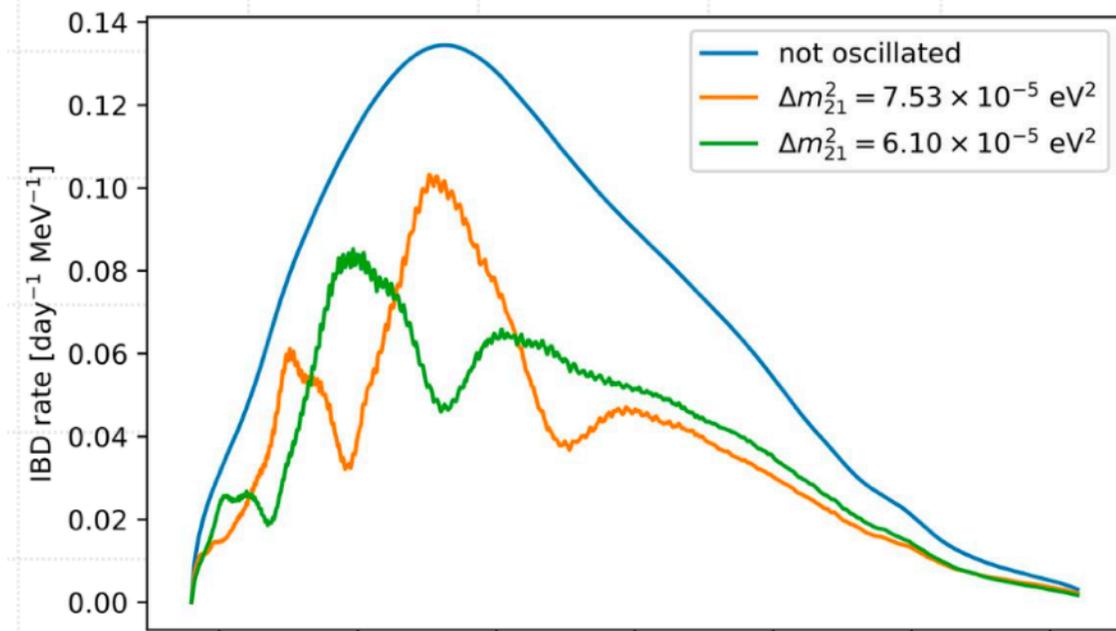
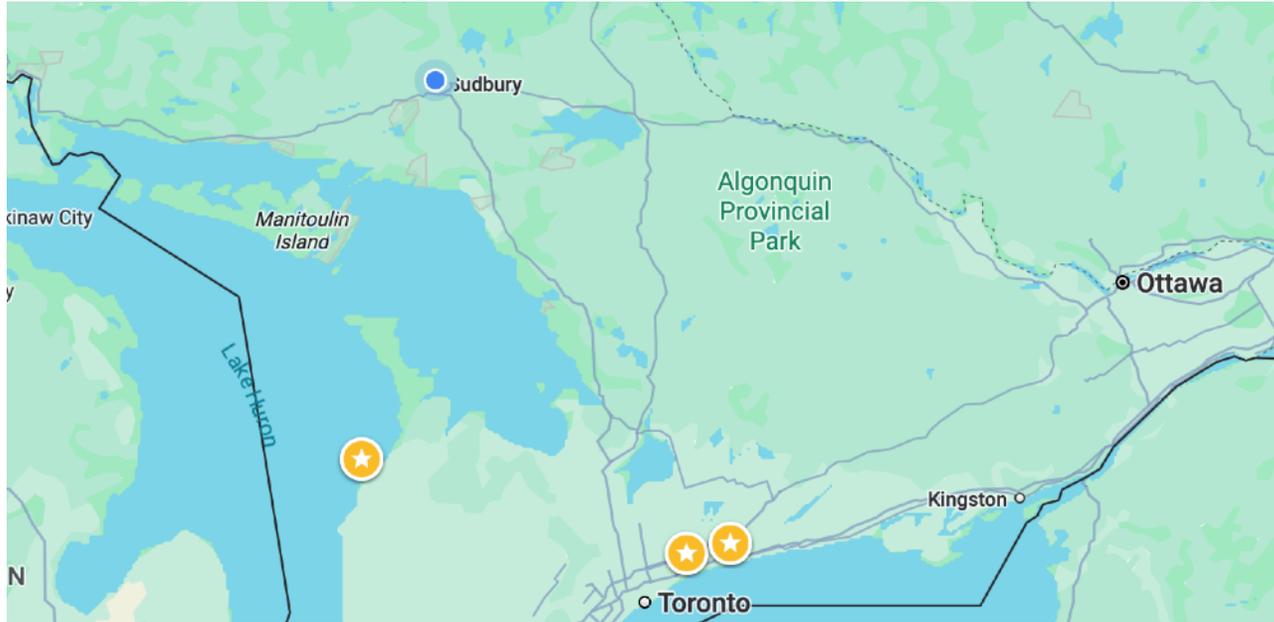
Solar Neutrinos in SNO+



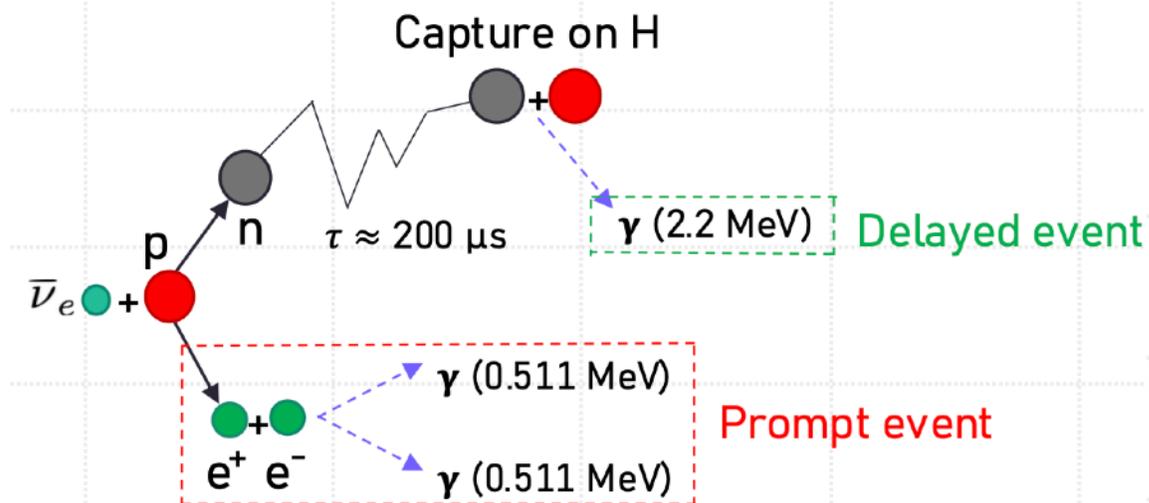
- ▶ 4 signal-like events detected in 225 days of data!



Reactor Anti-Neutrinos



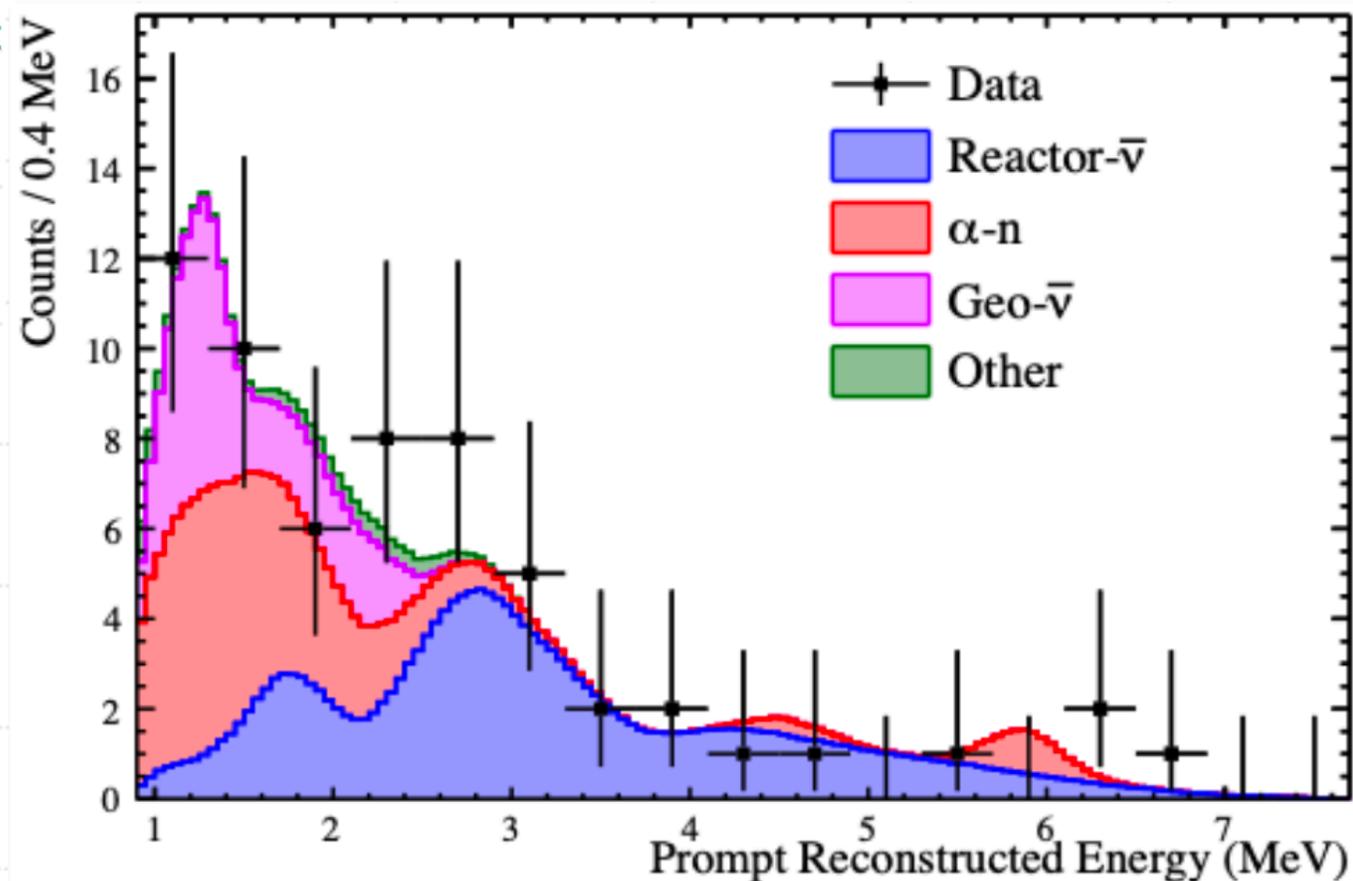
Reactor Anti-Neutrinos



$$\Delta m_{21}^2 = 7.96_{-0.42}^{+0.48} \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{12} = 0.62_{-0.40}^{+0.16}$$

$$\Phi_{\text{geo-}\bar{\nu}} = 73_{-43}^{+47} \text{ TNU}$$



..... Slight Tangent

How are we here?



- ▶ Why do we live in a matter dominated universe?
- ▶ Big Bang means energy created matter, should have created equal parts of matter and anti-matter.
Should have re-collided and all turned back to energy
- ▶ But somewhere along the line, there is more matter than anti-matter, else we wouldn't be here

More Neutrino History



- ▶ P. Dirac
- ▶ $\nu \neq \bar{\nu}$
- ▶ Proc. Royal Society,
112 762 (1926)

More Neutrino History



- ▶ P. Dirac
 - ▶ $\nu \neq \bar{\nu}$
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- ▶ M. Goeppert-Mayer
 - ▶ Double Beta Decay
 - ▶ Phys. Rev **48**, 512 (1935)

More Neutrino History

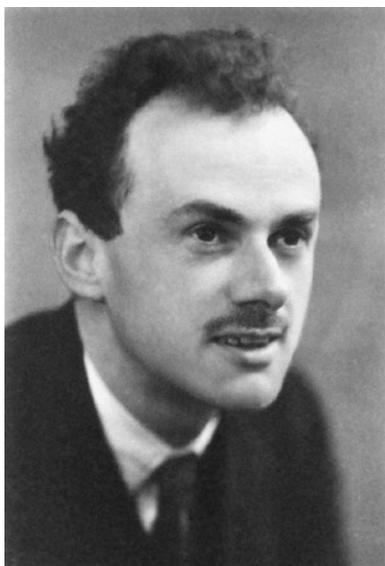


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- ▶ Double Beta Decay
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More Neutrino History



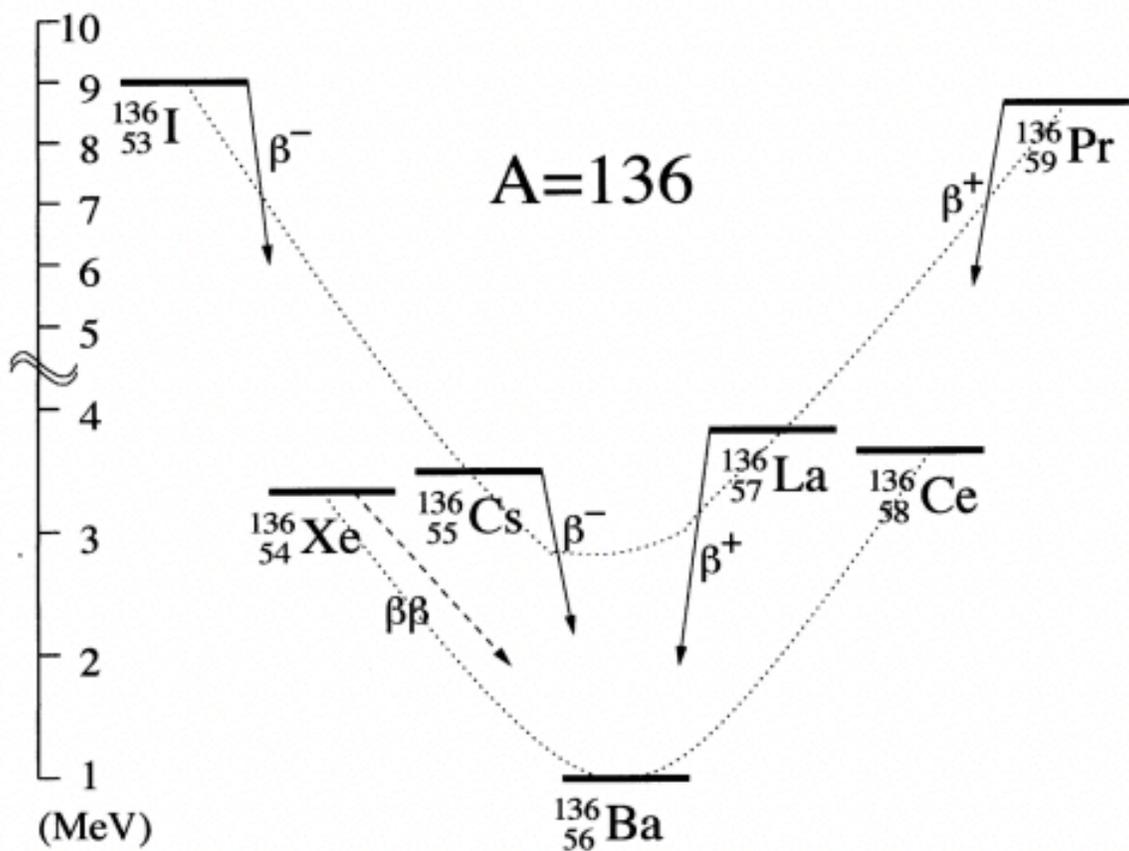
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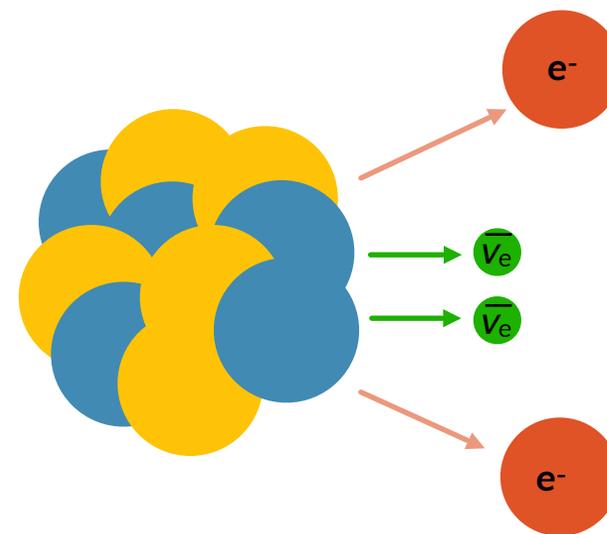
- ▶ E. Majorana
- ▶ $\nu \equiv \bar{\nu}$
- ▶ Nuovo Cimento **14**, 171 (1937)

- ▶ W. H. Furry
- ▶ Double beta decay **without** neutrinos
- ▶ Phys. Rev. **56**, 1184 (1939)

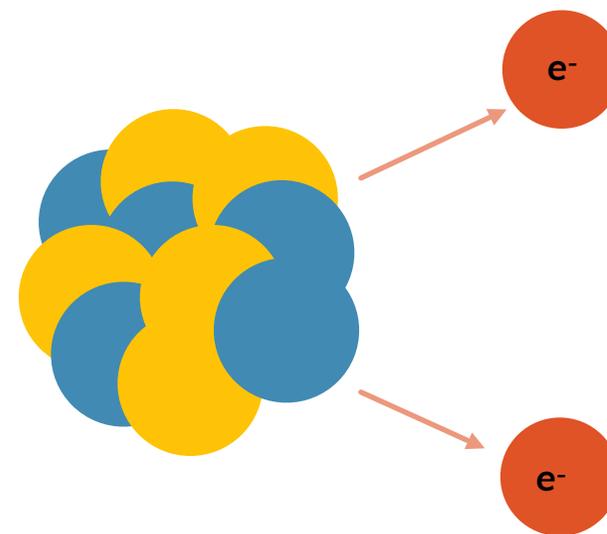
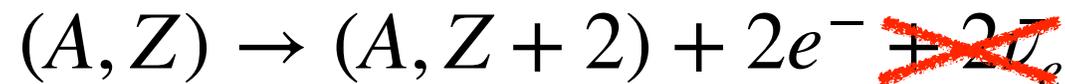
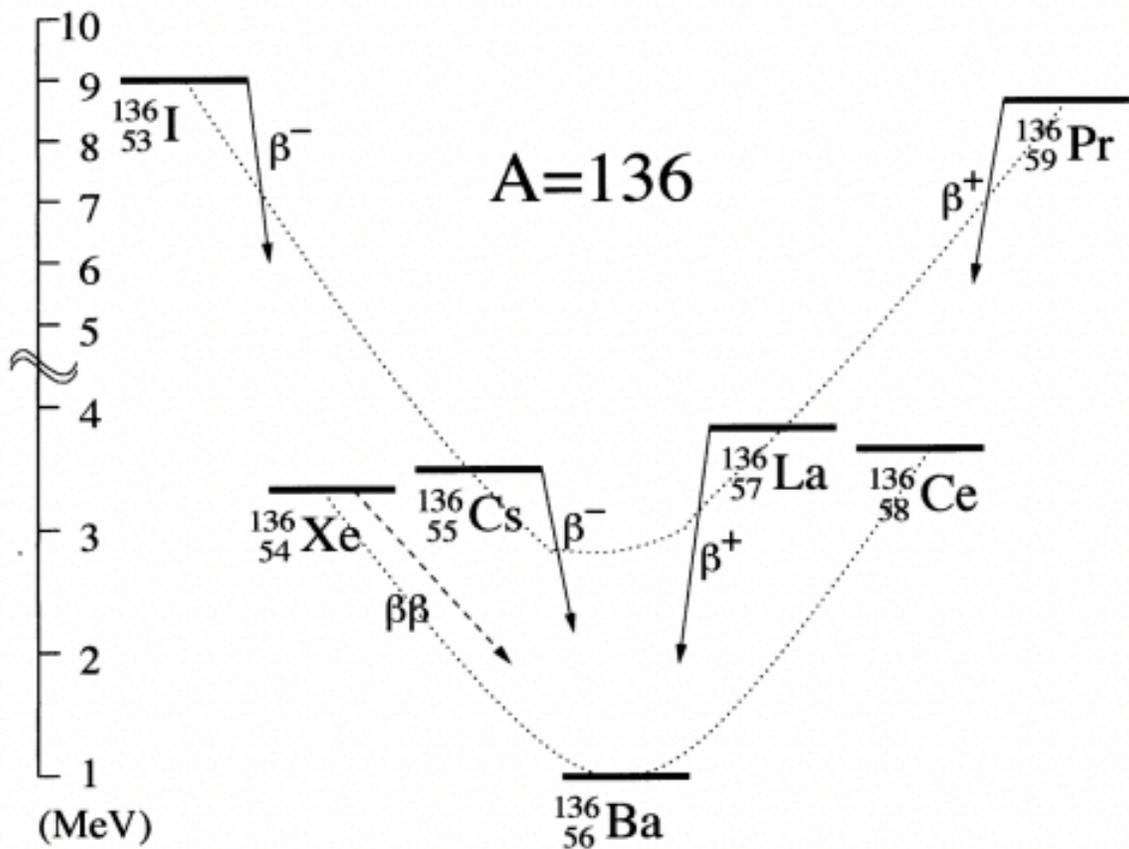
Double Beta Decay



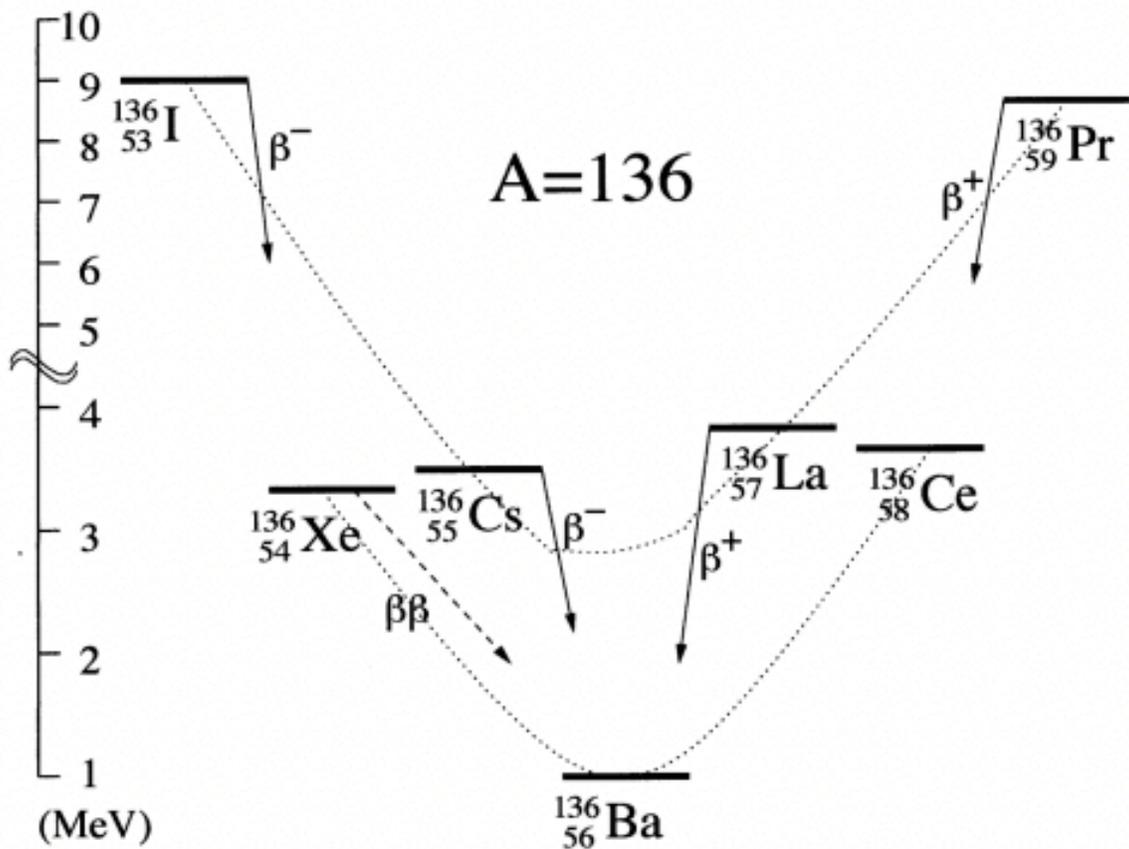
$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$$



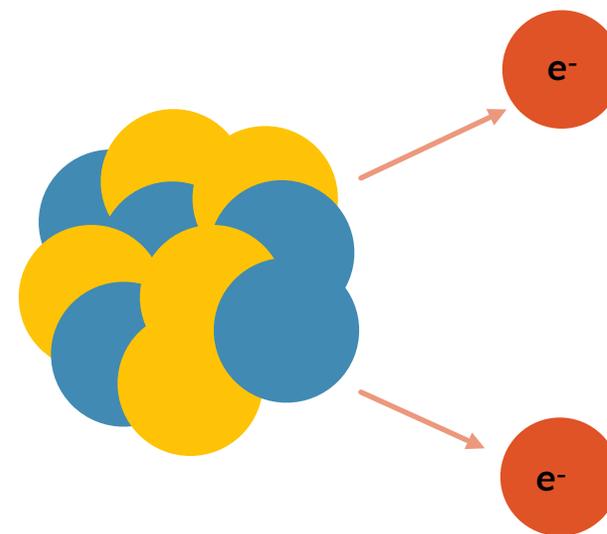
Double Beta Decay



Double Beta Decay



$$(A, Z) \rightarrow (A, Z + 2) + 2e^- \neq 2\bar{\nu}_e$$

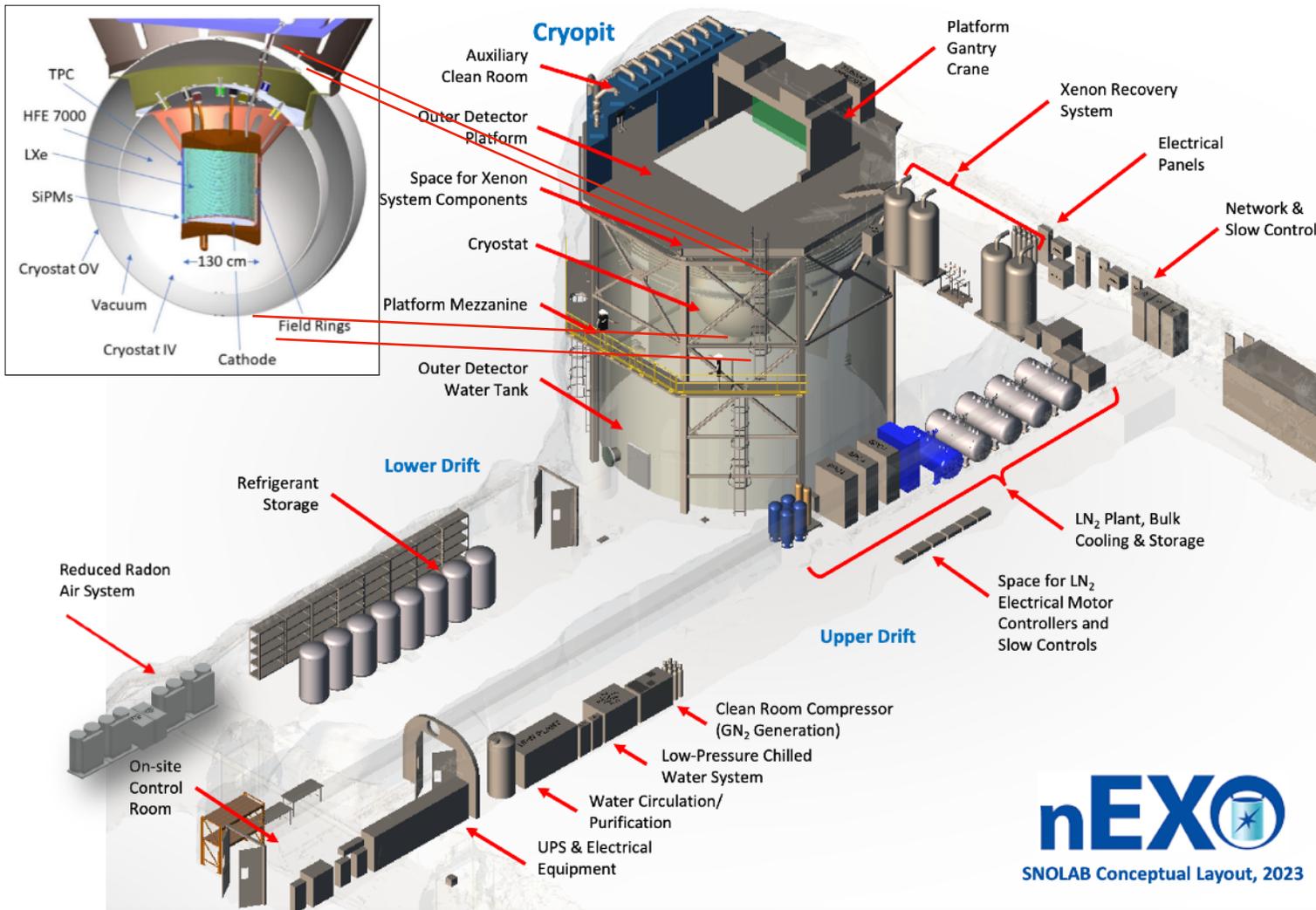


This is Matter Creation!
Violation of Lepton Number Conservation!!!

SNO+: Te-130



Next-Generation $0\nu\beta\beta$ nEXO: (Xe-136)



- Time Projection Chamber with 5000 kg of 90% enriched ^{136}Xe ($Q_{\beta\beta}=2457$ keV)
- Encased in Cryostat filled with refrigerant
- House in Instrumented Water Tank
- Signal: Light and charge detection, multi parameter analysis

Summary

Neutrinos Have been mystifying us for almost 100 years

Come from many interesting sources

Still trying to understand all their properties

Not covered:

Mass, mass hierarchy, long baseline experiment, CP violation, many other topics

Neutrino Experiments at SNOLAB: HALO, SNO+, nEXO (future)