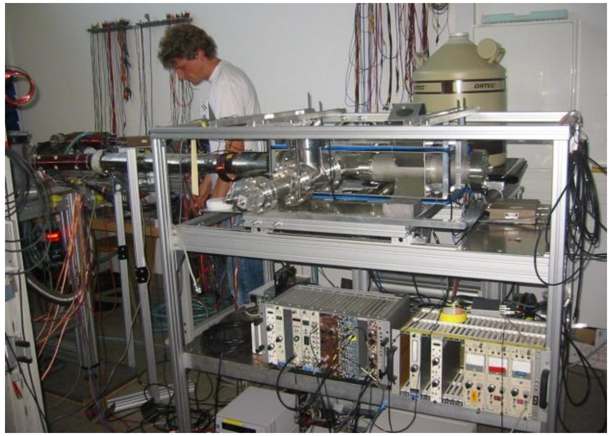
Understanding the Universe through Neutrinos

(and how nuclear physics helps us understand neutrinos)

EBSS 2022 - Notre Dame University

Thomas Brunner
McGill University
June 8, 2022

My Career Path



Studied Physics at the Technical University Munich (2001 – 2011)

- Undergraduate research project
- Diploma thesis (MSc equivalent)
  - Investigation of positronium formation on cold surfaces
- PhD project, stationed at TRIUMF, Vancouver
  - In-trap decay spectroscopy with the TITAN EBIT

Post doctoral research fellow at Stanford (2011 – 2015)

- EXO-200, nEXO, and Ba-tagging

Assistant professor at McGill (2015 – 2020)

- EXO-200, nEXO, Ba-tagging, and in-trap decay spectroscopy

Associate professor at McGill (2020 – now)

- nEXO, Ba-tagging, and in-trap decay spectroscopy

(Condensed matter physics)

↓

Atomic physics

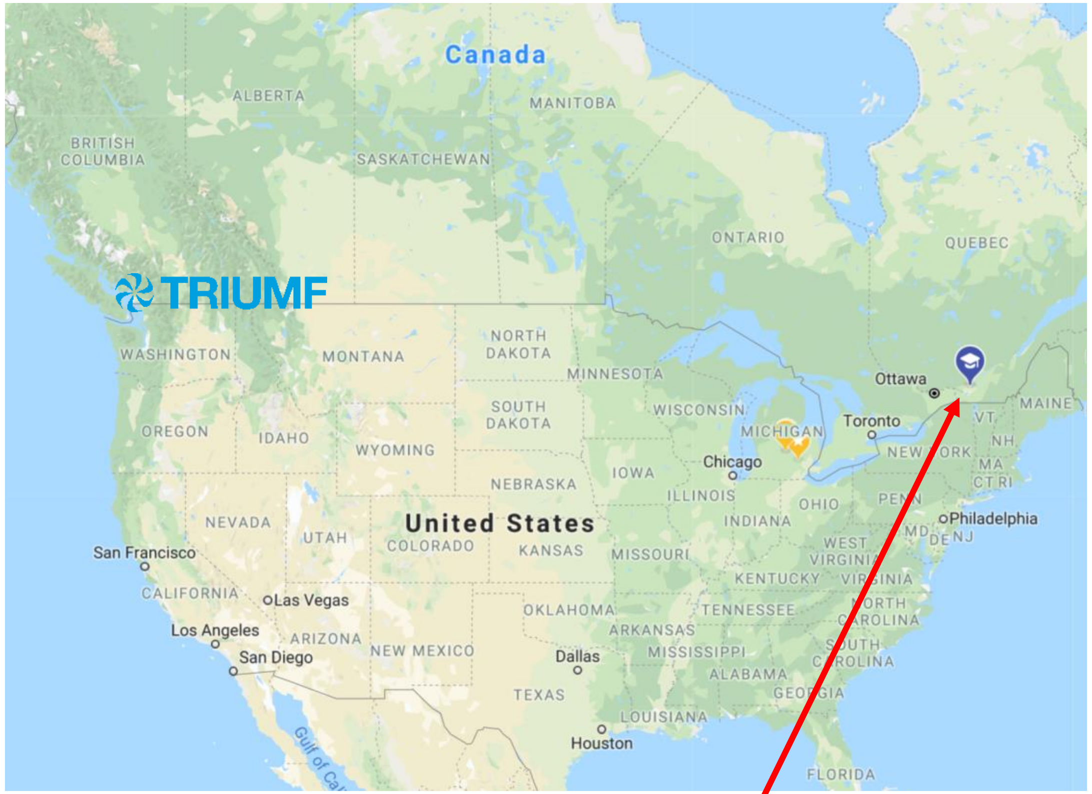
↓

Nuclear physics
(decay spectroscopy and
mass measurements)

↓

Particle/neutrino/nuclear physics

McGill University in Montreal



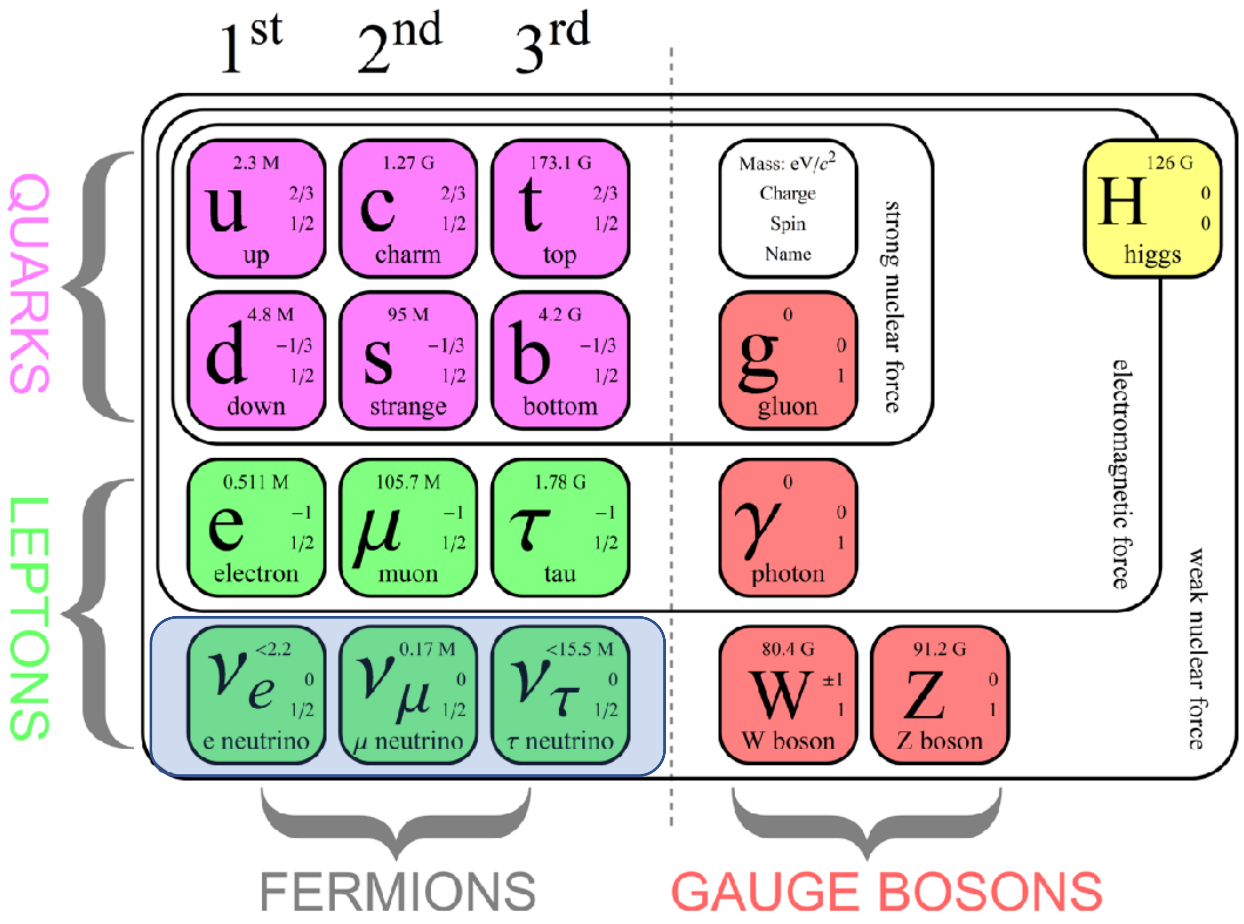
McGill

Outline

- The Standard Model of Particle Physics and why we think there is more out there.
- A very short history about neutrinos.
- The neutrino as a candidate for a Majorana particle.
- Neutrinoless double-beta decay to probe Majorana nature of neutrinos.
- Introduction to the nEXO experiment.

Neutrinos in the Standard Model

- Neutrinos in the SM:
  - Fundamental Spin ½ particle
  - Are Leptons
  - Only interact via the weak force
  - Electrically neutral
  - Most abundant particles with mass in the universe, yet we do not even know their mass
  - 60 billion solar neutrinos penetrate us per cm^2 every second
- The Standard Model has been extremely successful in describing particle physics experiments and even predicting the existence of particles.



Some of the Big Questions in Cosmology and Particle Physics

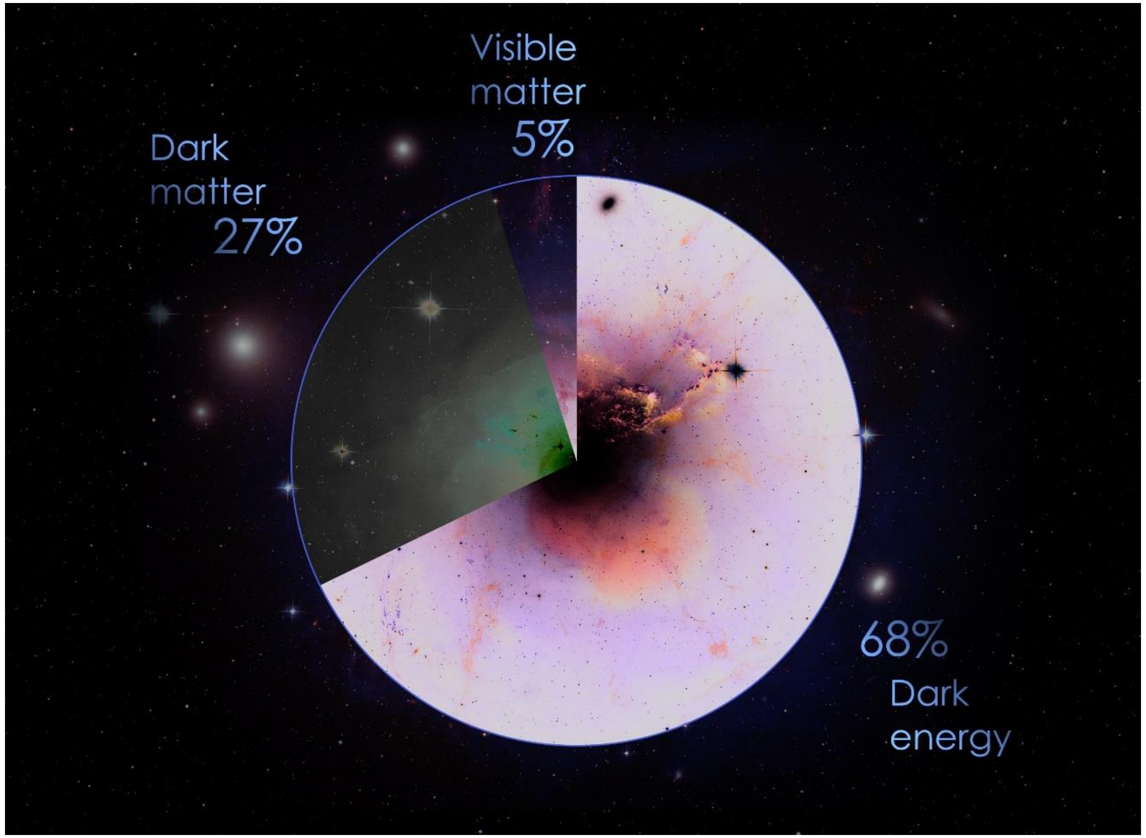


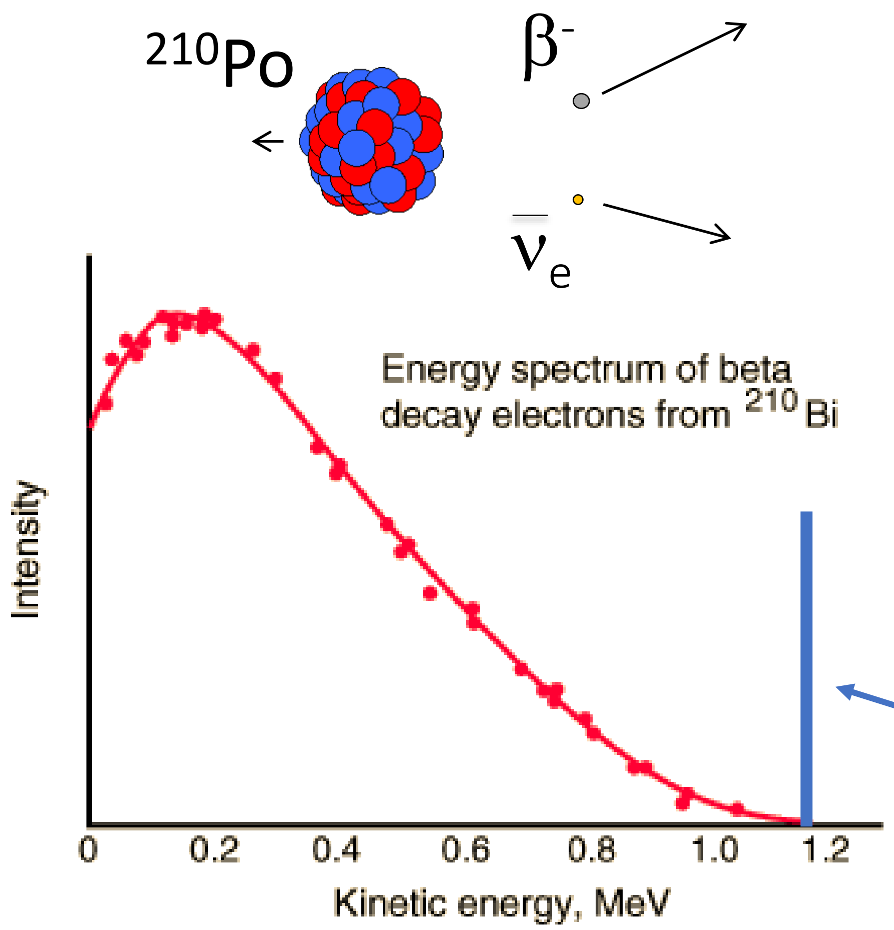
Figure: NASA

- 95% of the mass/energy density of the Universe is of as yet unknow composition
- What is Dark Energy?
- What is Dark Matter?
- Why is matter so abundant? (and dominant over anti-matter)?
- Why is gravity so weak?
- Why are neutrinos so light?

Neutrinos may hold the key to answering some of these questions.

How it all started

Energy and angular momentum conservation



G. J. Neary, Roy. Phys. Soc. (London), A175, 71 (1940).

Spin = 1/2

$$^{210}Bi \rightarrow {}^{210}Po + e^-(+\bar{\nu})$$

(1$^-$) (0$^+$)

A two-body decay would result in a peak at the Q-value

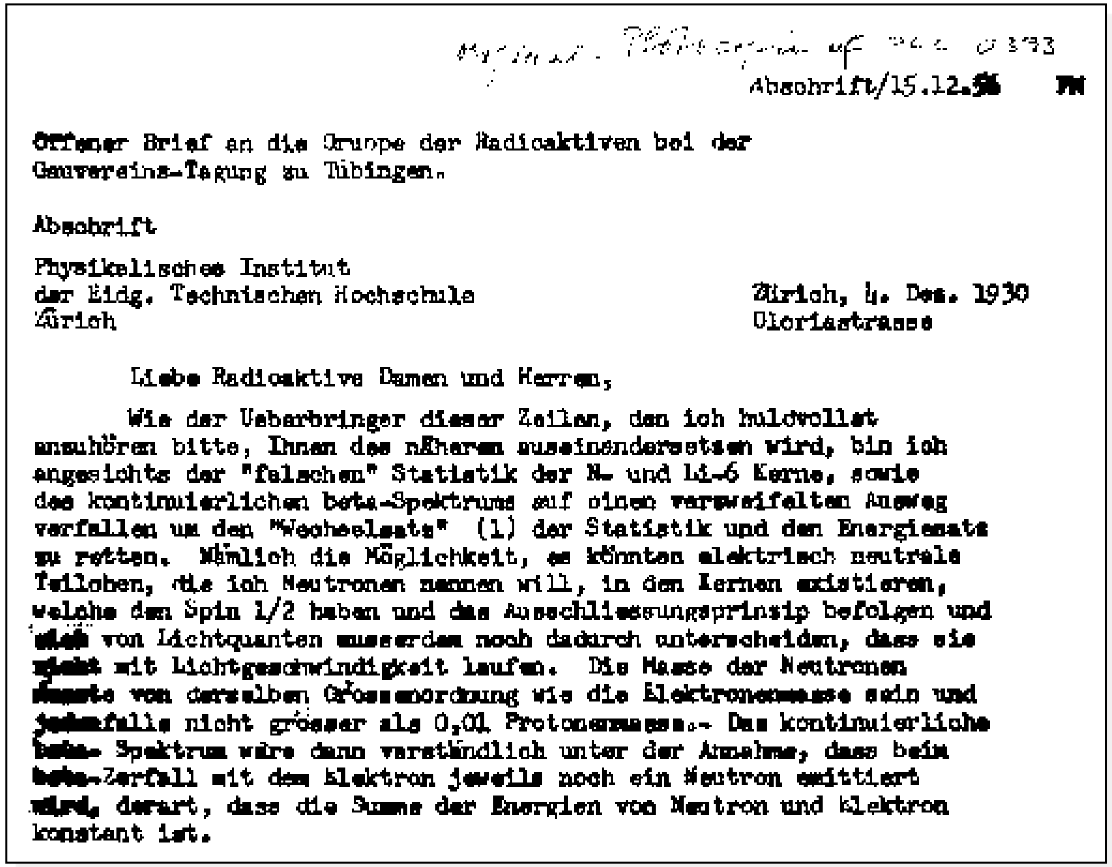
Pauli invents neutrinos 1930 to explain nuclear β decay

Dear Radioactive Ladies and Gentlemen,

... I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy [in β decay].

Pauli proposes a particle that

- Is **electrically neutral**
- Is a **spin ½** particle
- **Differs from light** and does not travel with *c*
- Has mass not exceeding 0.01 proton mass



Abschrift/15.12.56 PM

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 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.

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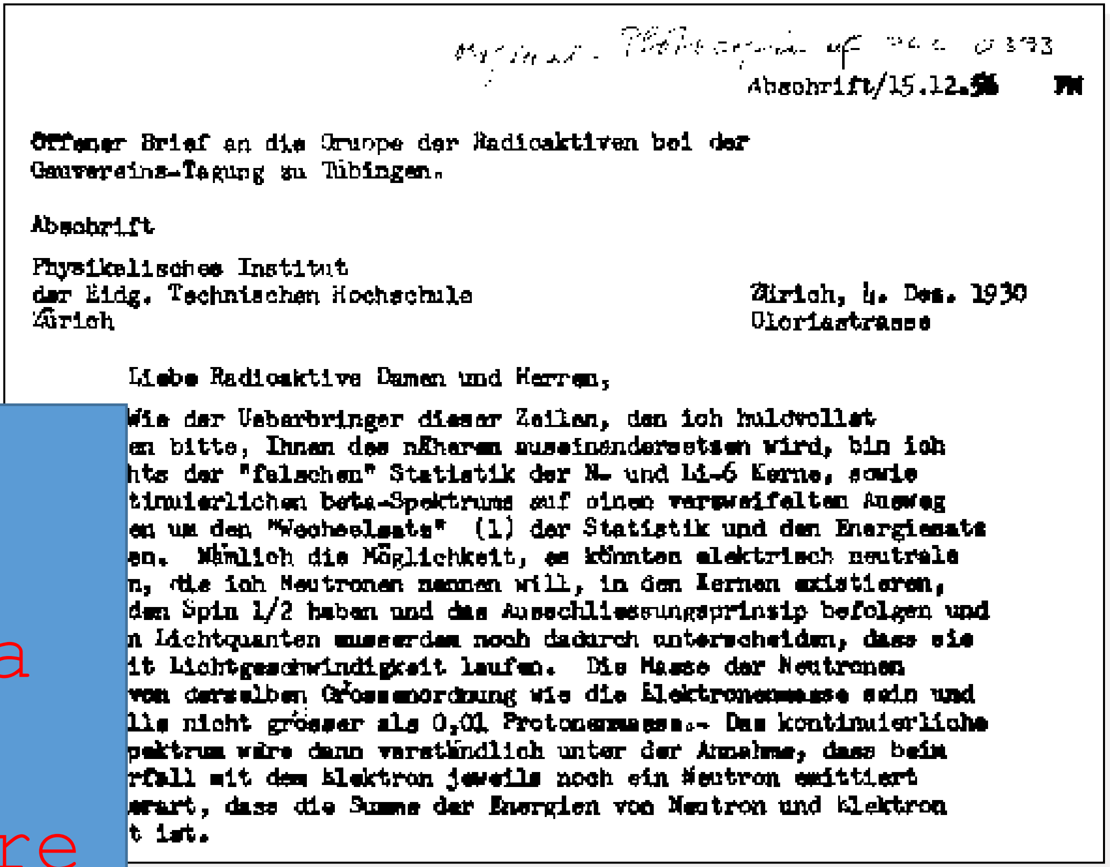

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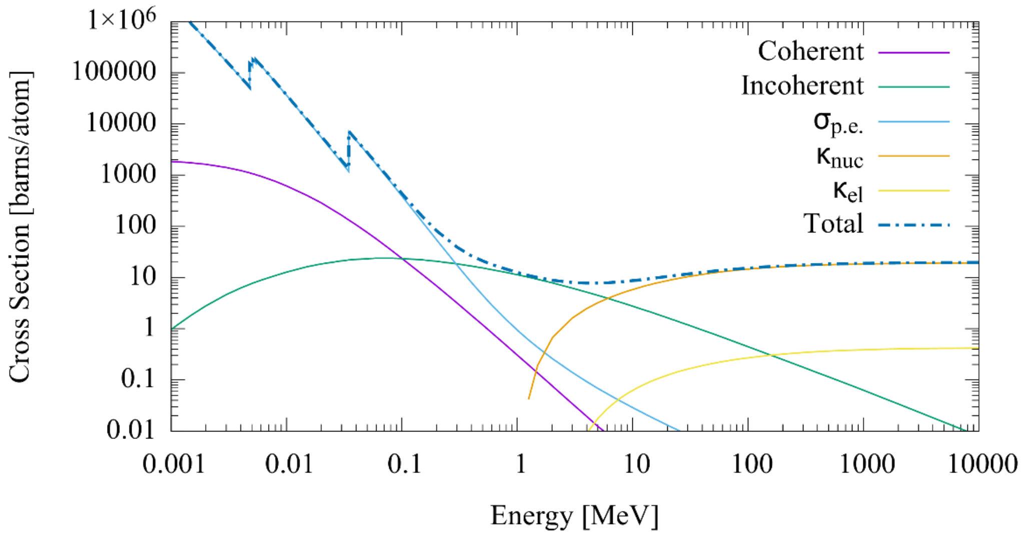
@pauli

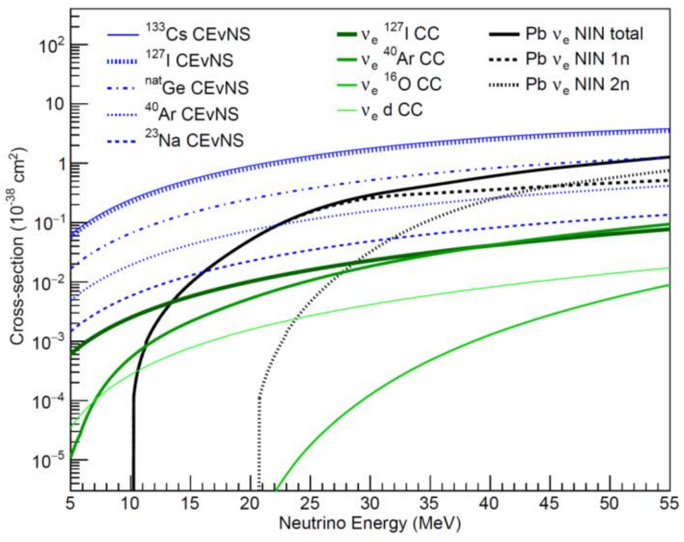
I have done a terrible thing. I have postulated a particle that cannot be detected. #Desperate-measure

Neutrino detection not impossible – only challenging

Photon-Matter Cross Section

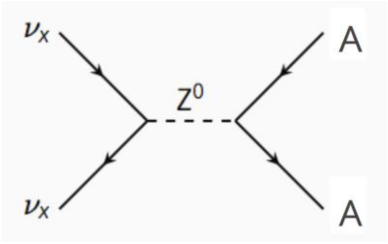


Neutrino-Matter Cross Section



Source: Pershey, NEUTRINO2022

CEvNS: Coherent Elastic ν Nucleon Scattering (see e.g. D. Akimov et al, Science 357 (2017))



CC: Charged Current interaction

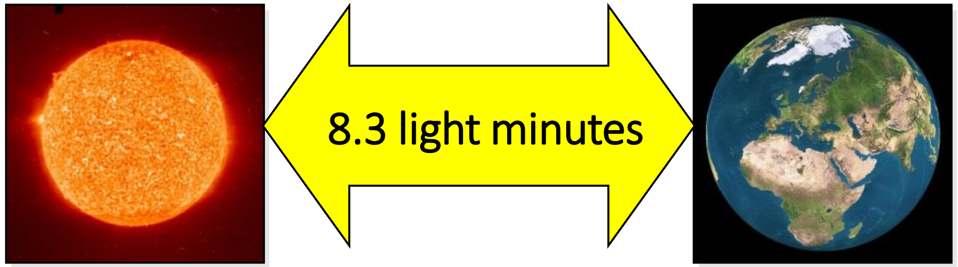
Cross section of order ~10^{-24} cm^2

Orders of magnitude smaller cross section

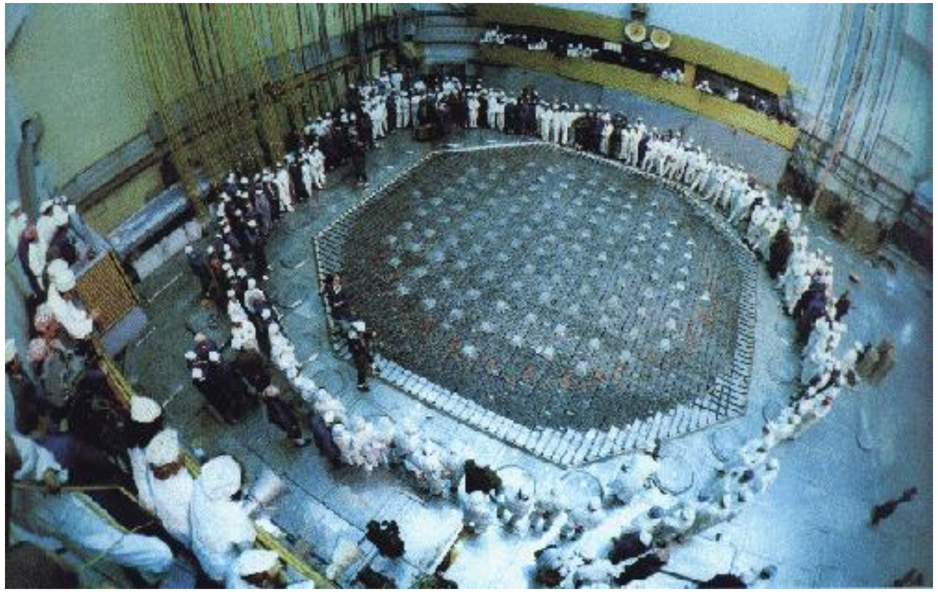
Cross section of order ~10^{-38} cm^2

Radioprotection from neutrinos ?

- **Mean free path of neutrinos from a reactor in lead is ~ 0.3 light years !**



- **A big nuclear reactor makes 6 x 10^{20} neutrinos/s: at 20 meter distance (just outside the building) only one neutrino every 3 sec interacts with our body !**



<u>Bethe & Peierls 1934:</u>
"… this implies that one evidently never will be able to detect Neutrinos."

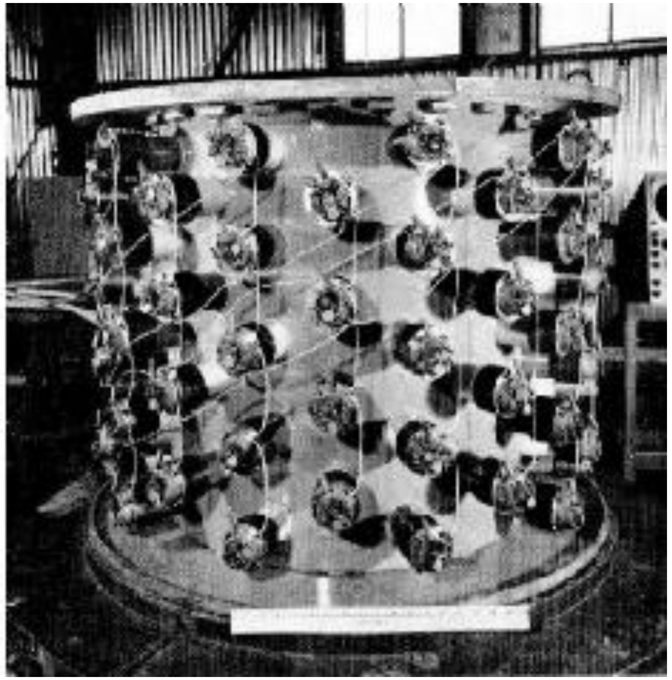
1956: Cowan and Reines detects neutrinos

Detection through inverse β decay

$$\bar{\nu}_e + p \rightarrow n + e^+ \longrightarrow$$ Annihilates with e^- into (two) γ

From reactor

$$n + {}^{113}Cd \rightarrow {}^{114}Cd^* \rightarrow {}^{114}Cd + \gamma$$

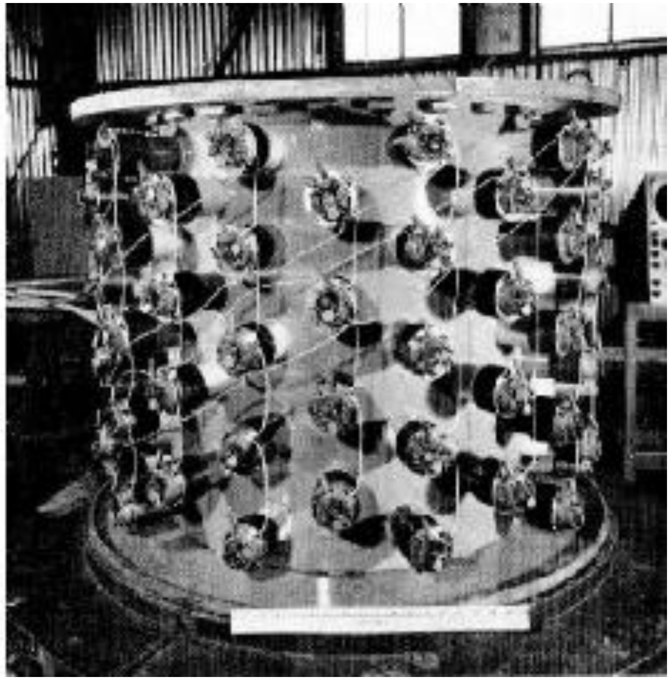
1956: Cowan and Reines detects neutrinos

Detection through inverse β decay

~ 2.9 events/hour were observed in ~200 l water (~40 kg CdCl)!

(or about 1 in 10^{20} antineutrinos produced)

The signal went away when the Reactor power was turned down.



Nobel Price 1995
F. Reines

1956: Cowan and Reines detects neutrinos

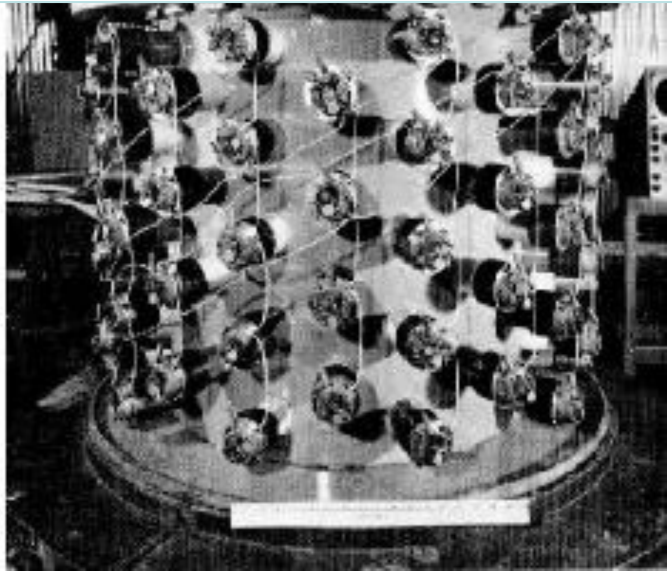
Detection through inverse β decay

"[Prof. Pauli], we are happy to inform you that we have definitely **detected neutrinos** from fission fragments by observing inverse beta decay of protons."

- F. Reines and C. Cowan (1956)

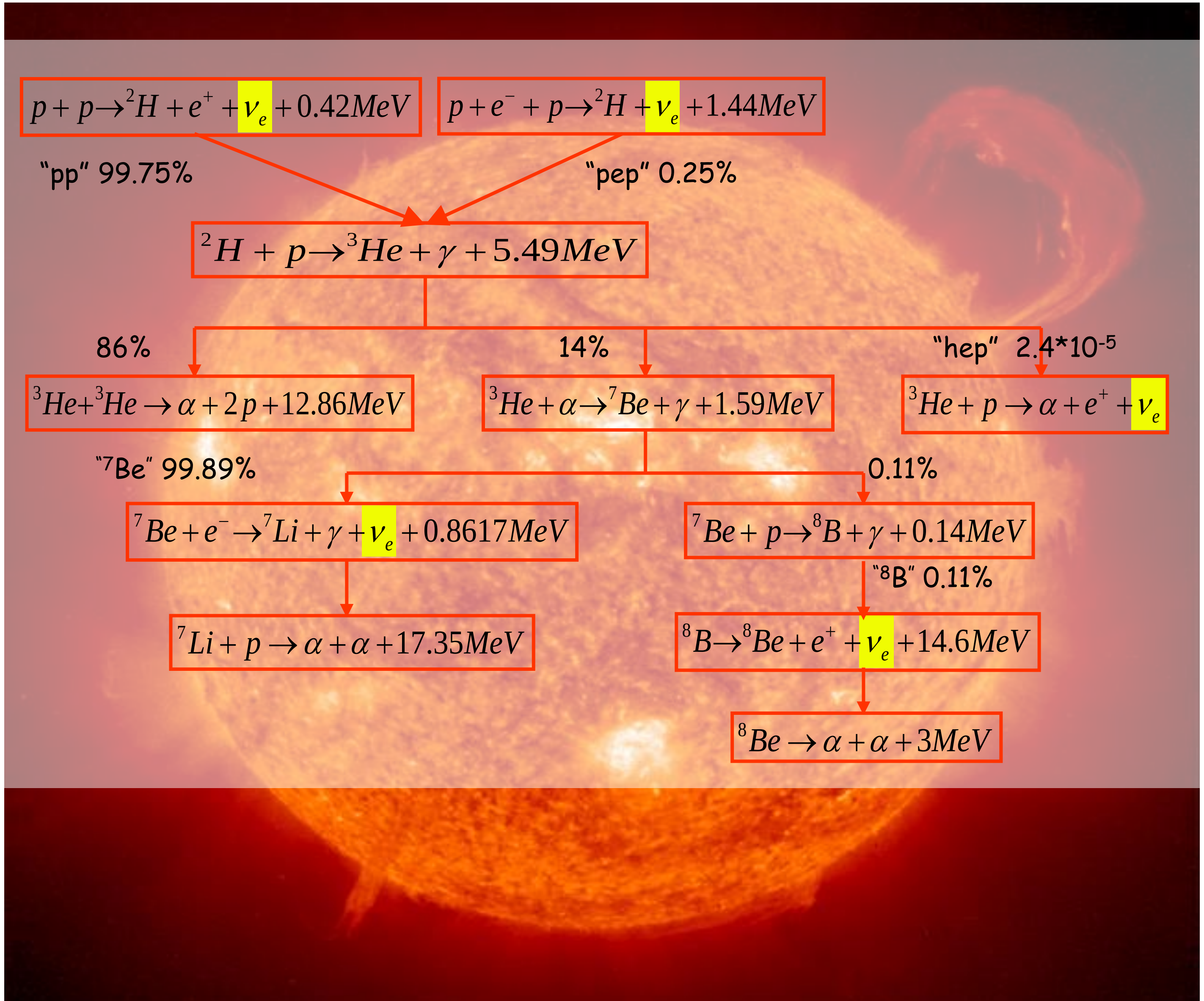
"Everything comes to him who knows how to wait."

- W. Pauli (1956)



Nobel Price 1995
F. Reines

Detecting Neutrinos from the Sun



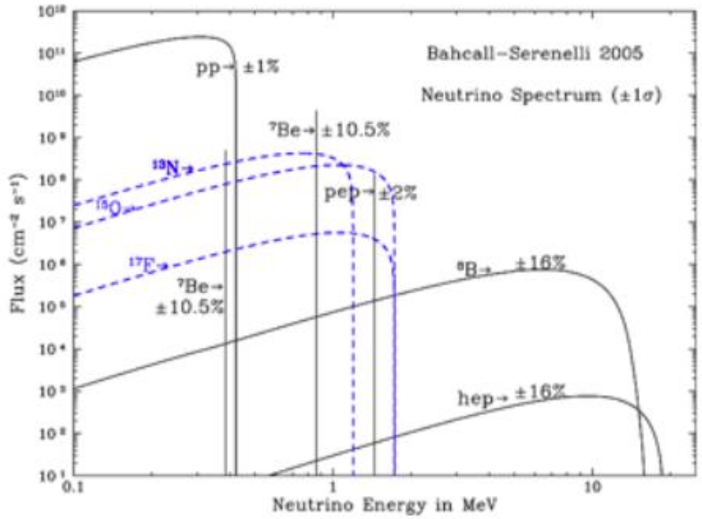
Complex fusion reactions take place inside the sun.

Detecting Neutrinos from the Sun

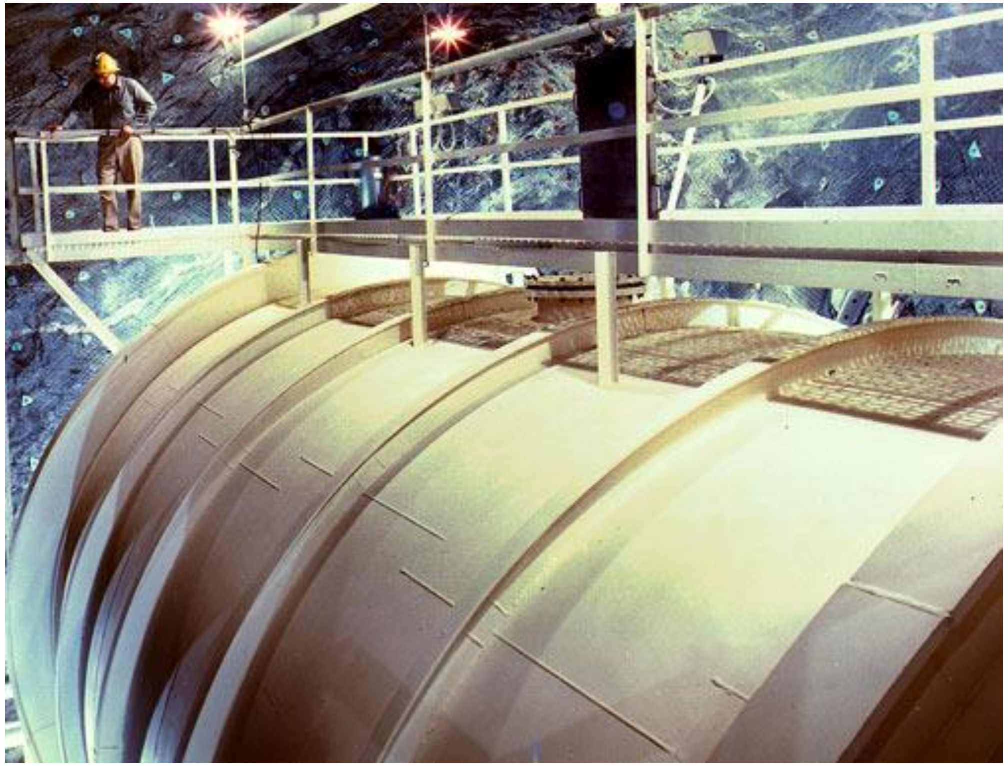
$^{37}Cl + \nu_e = {}^{37}Ar + e^-$

600 tons of dry clean fluid

Produced at only 15 atoms per month !



The Homestake detector was built by Ray Davis (Nobel Prize 2002) to test John Bahcall's Standard Solar Model.



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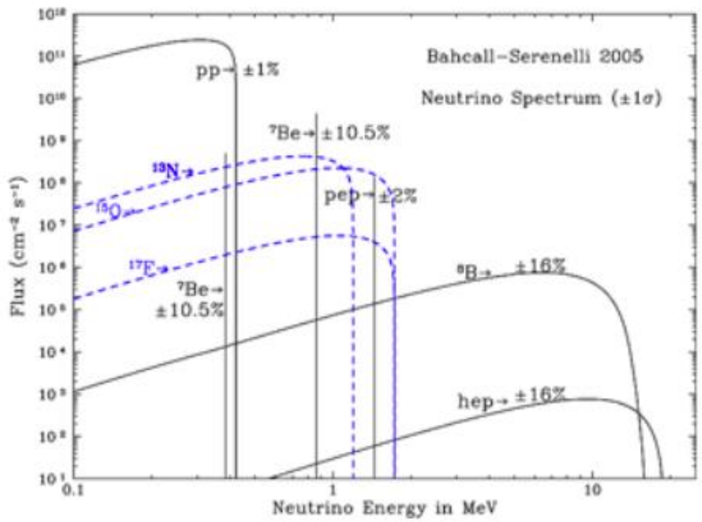

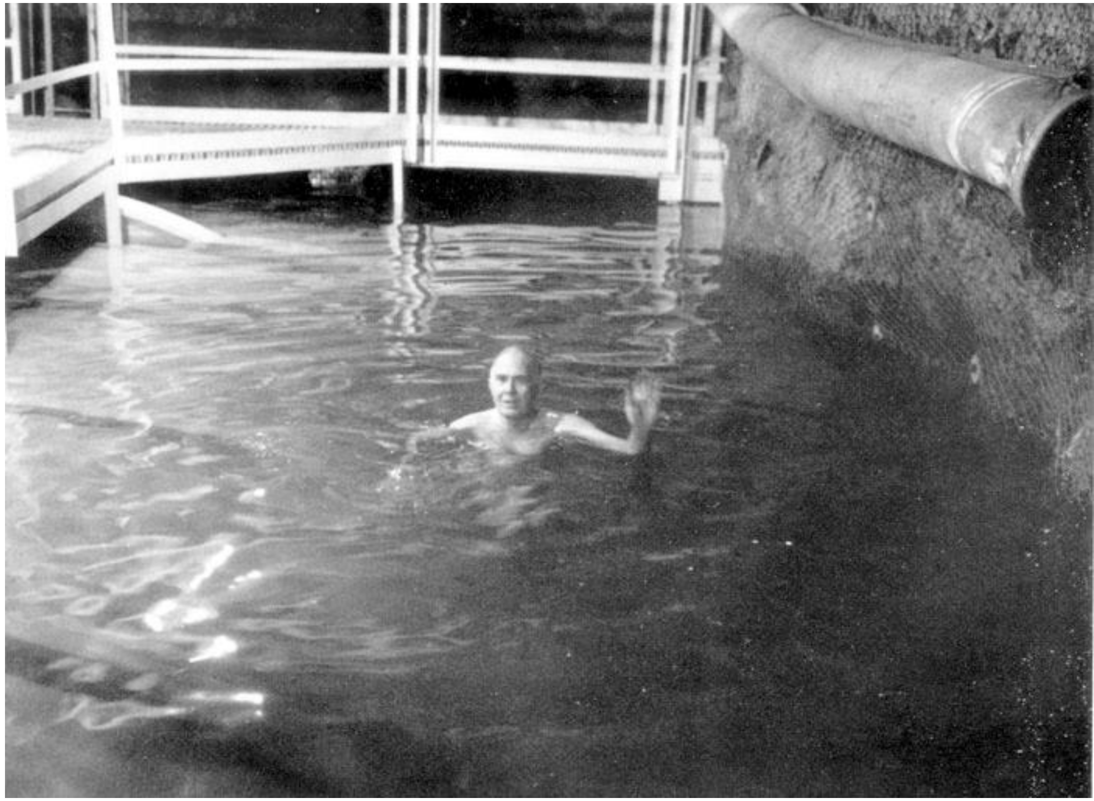

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Solar Neutrino Puzzle

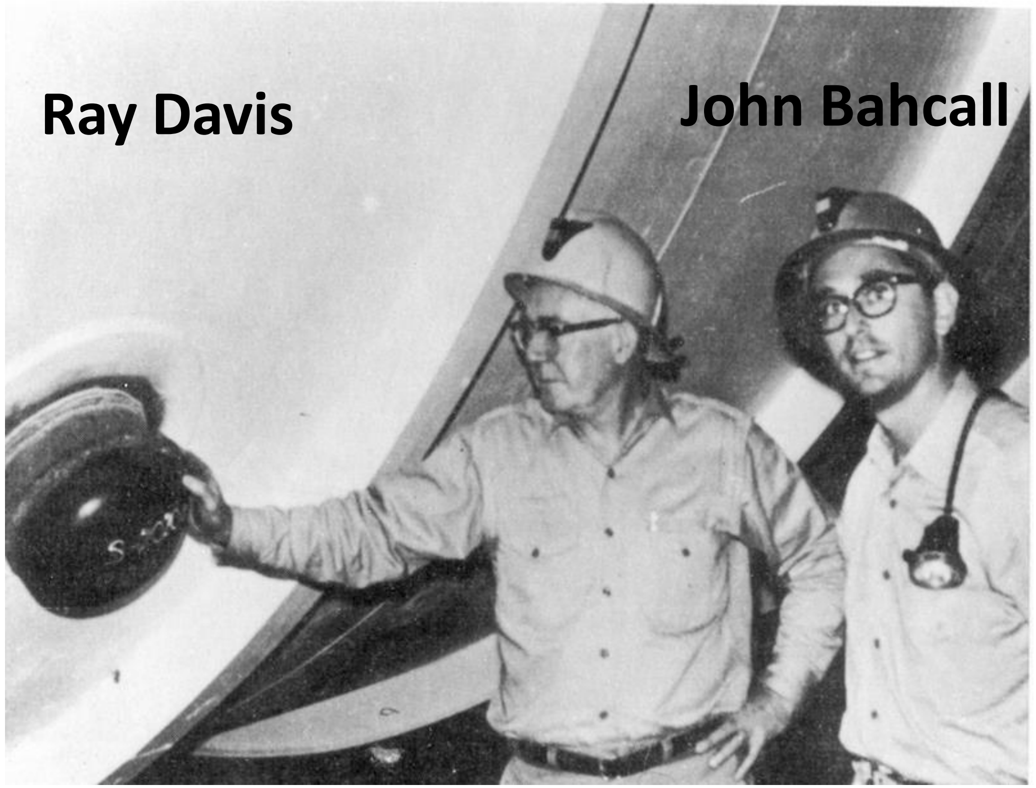
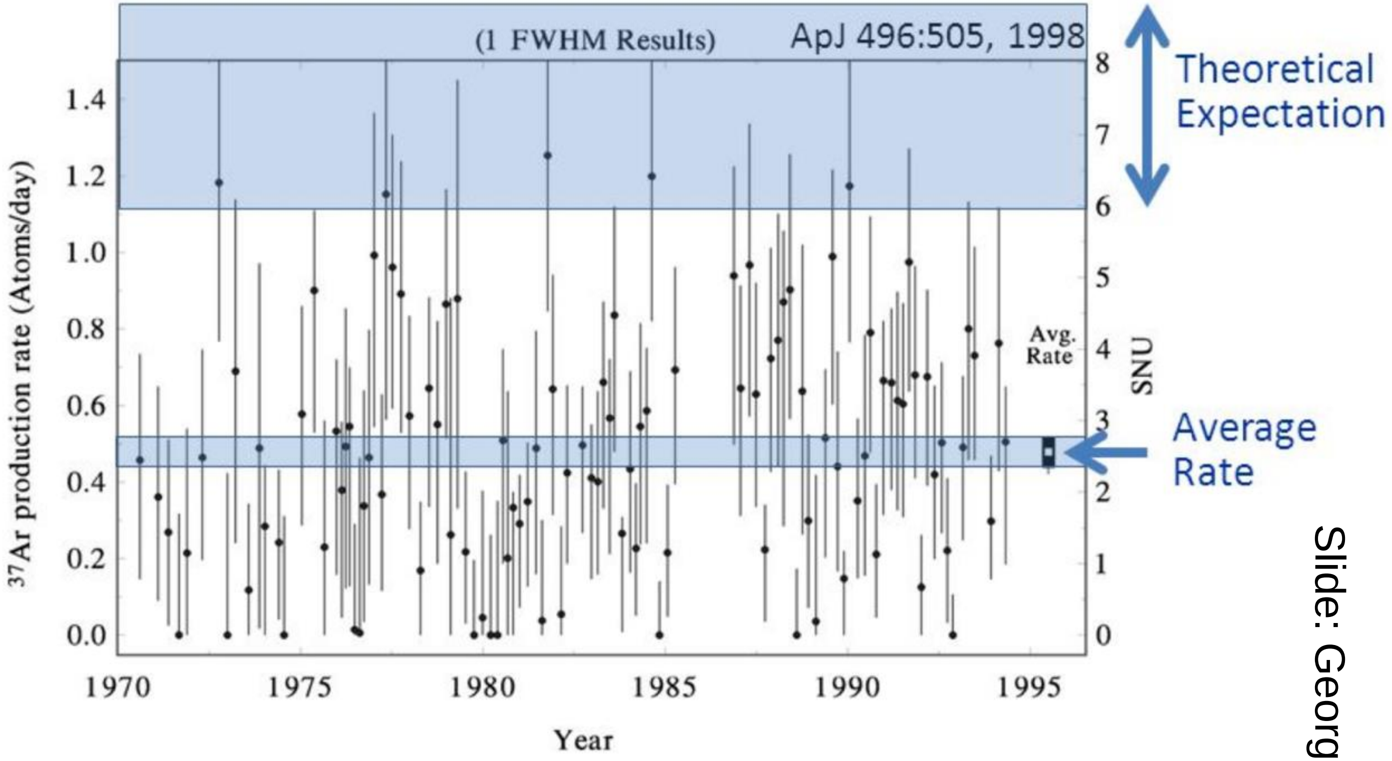


Photo: Courtesy of Raymond Davis, Jr. and John Bahcall



Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

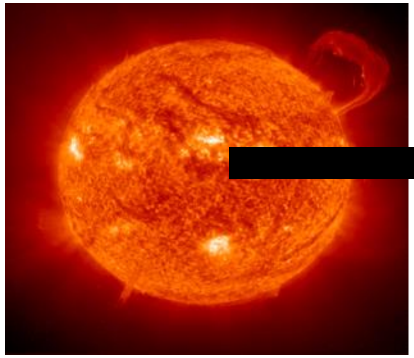
Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

Slide: Georg Raffelt

Far too few (~1/3) solar neutrinos were seen compared to predicted solar production !

Where are the missing neutrinos?



ν_e ν_e ν_e

ν_e ν_μ ν_τ

Astrophysics Wrong?

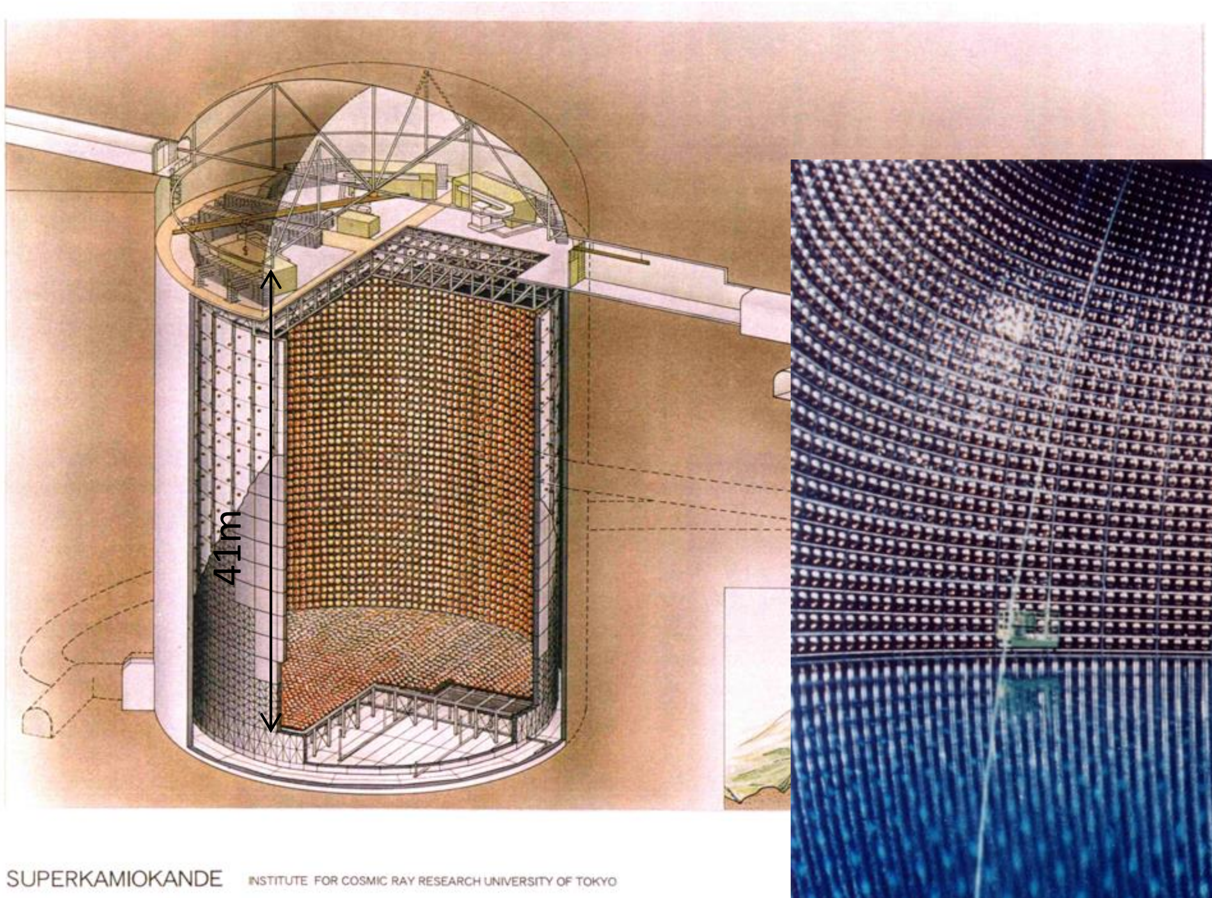
Experiment Wrong?

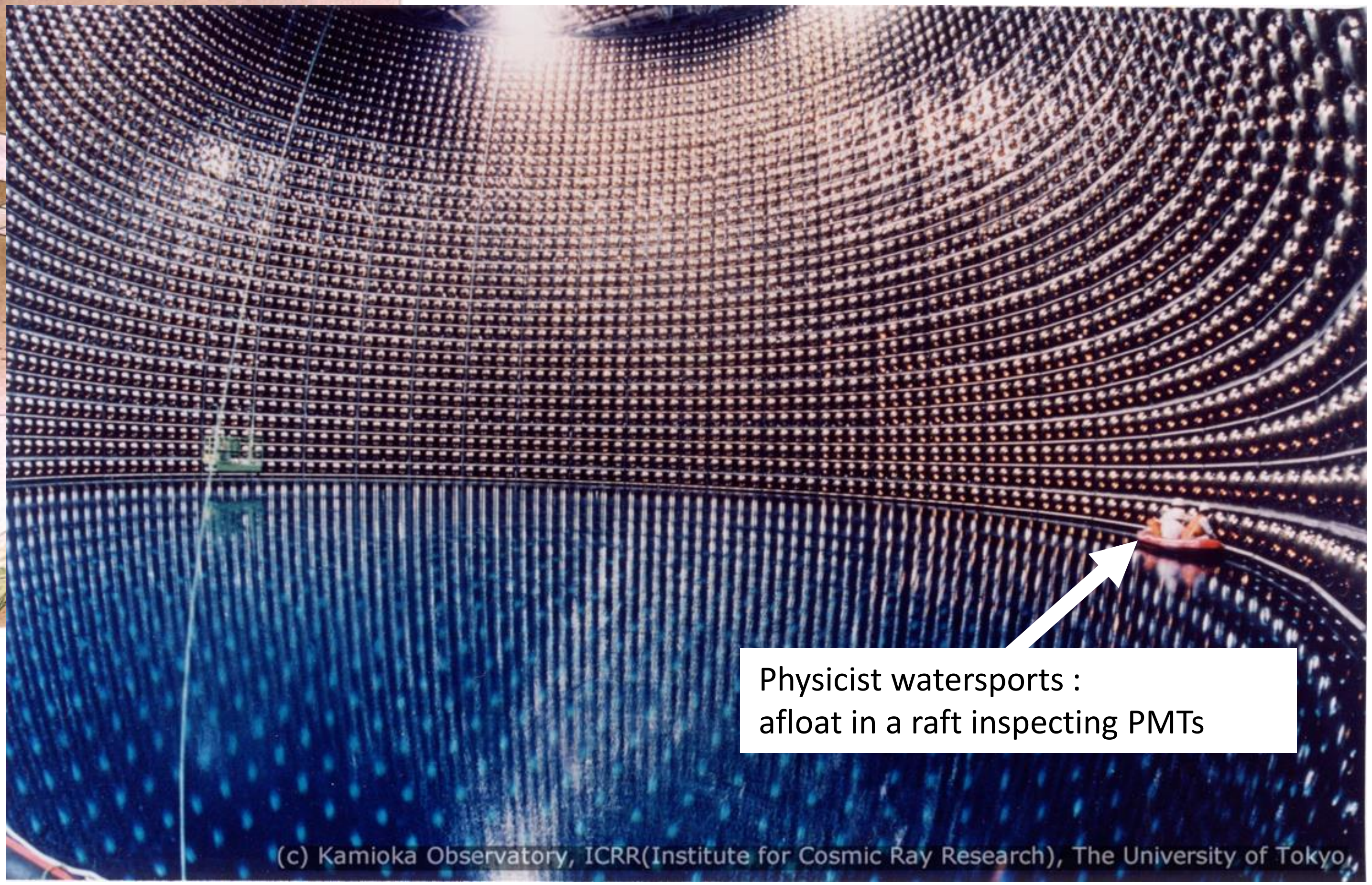
Bruno Pontecorvo

Neutrino Change Flavors?

The Super-Kamiokande Detector

Super K can identify the direction of neutrinos

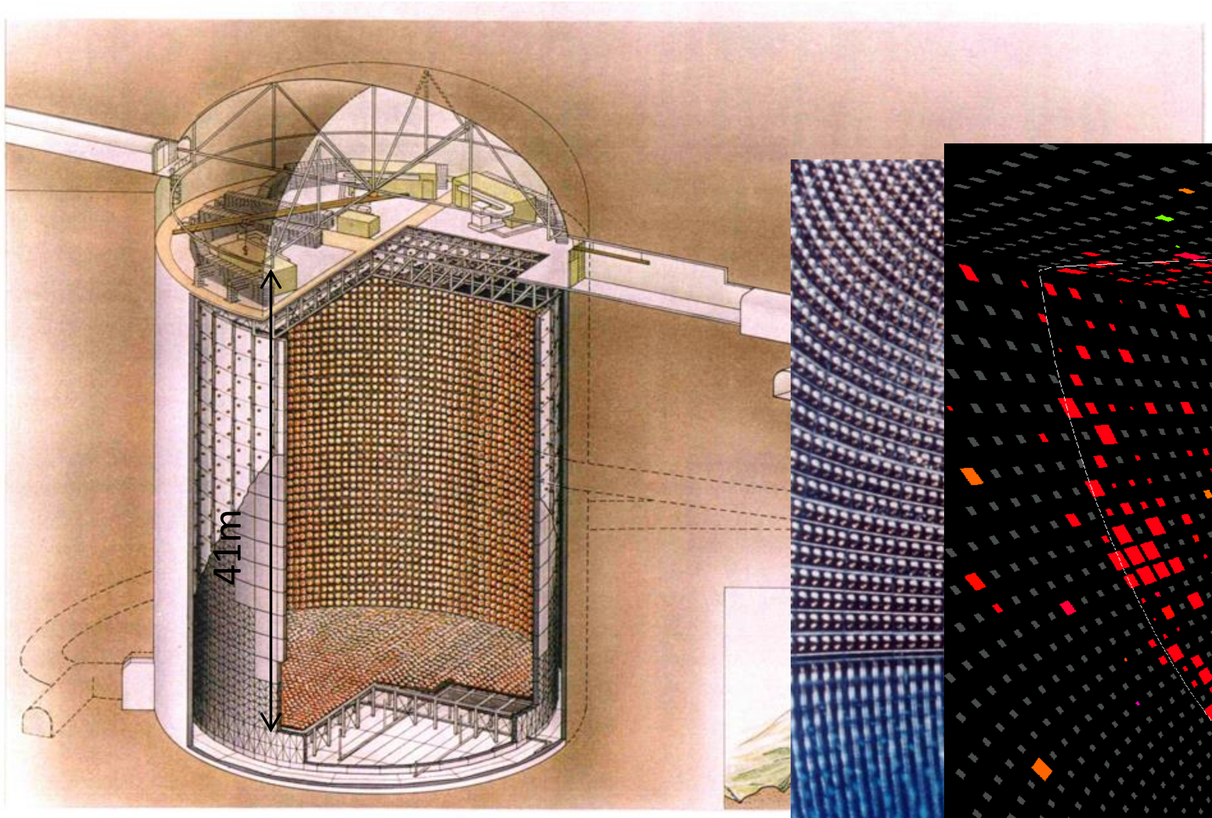




50,000 tonnes of ultra clean water (20 times larger mass than Kamiokande)

11,200 photomultiplier tubes

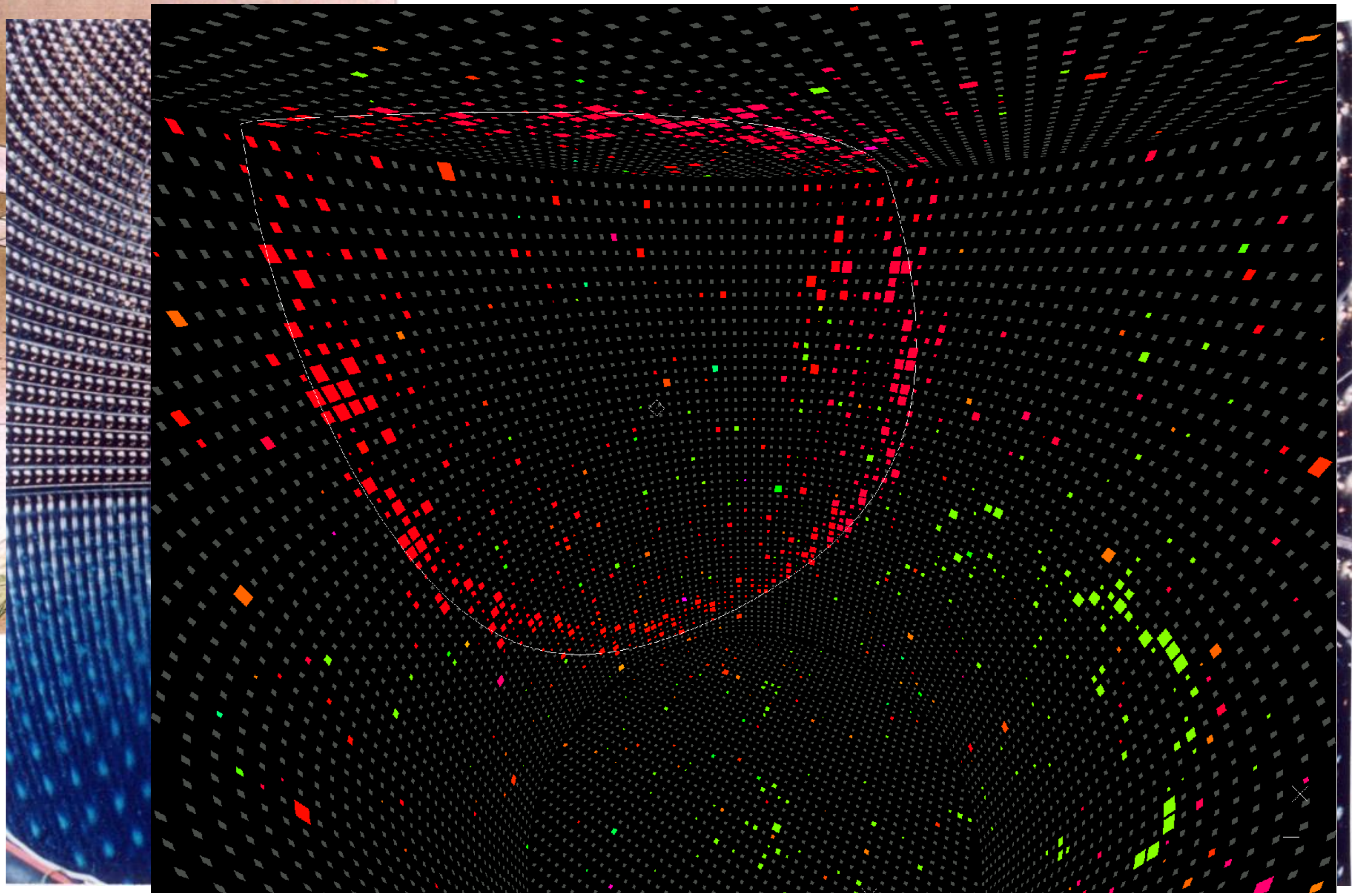
The Super-Kamiokande Detector



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

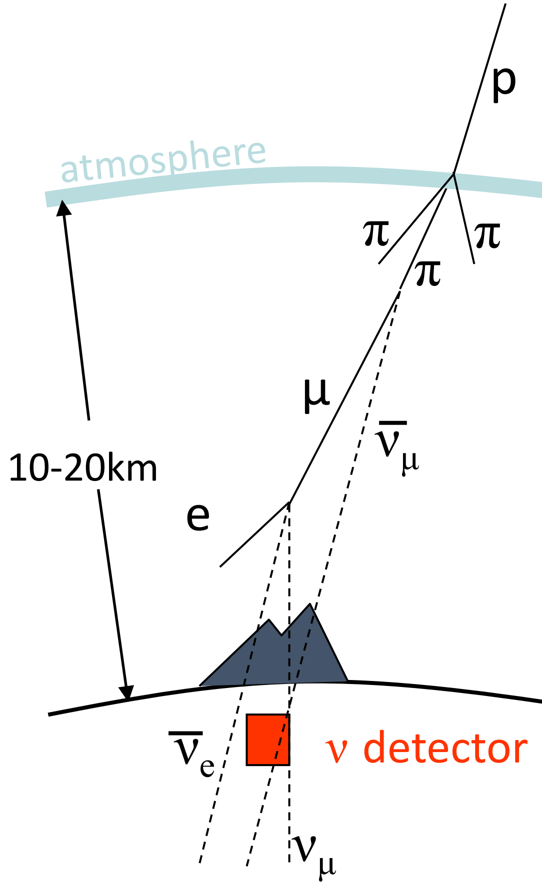
50,000 tonnes of ultra clean water (20 times larger mass than Kamiokande)

Super K can identify the direction of neutrinos



Atmospheric Neutrino

Graphics: SuperK



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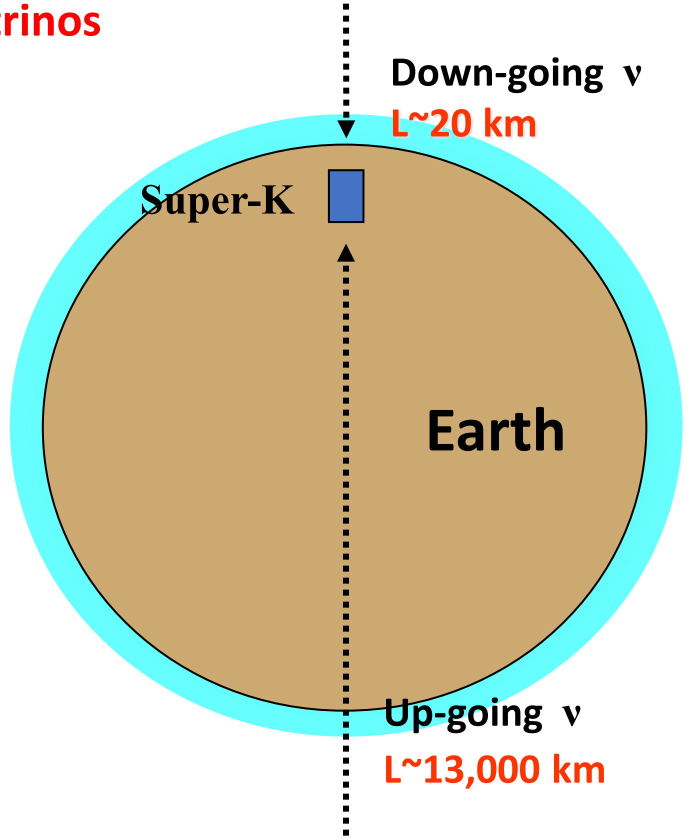
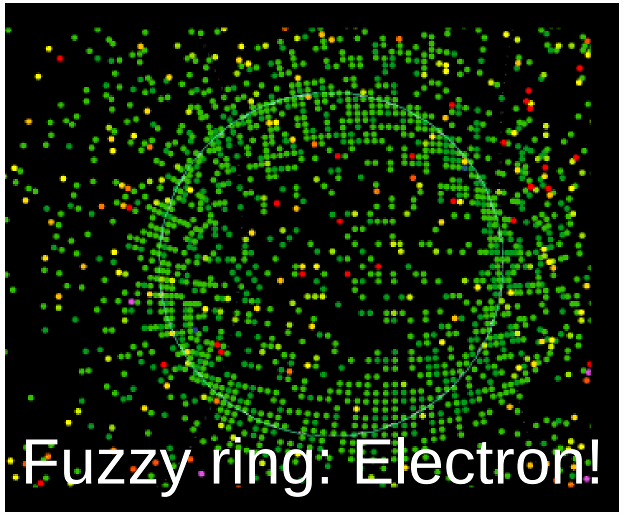
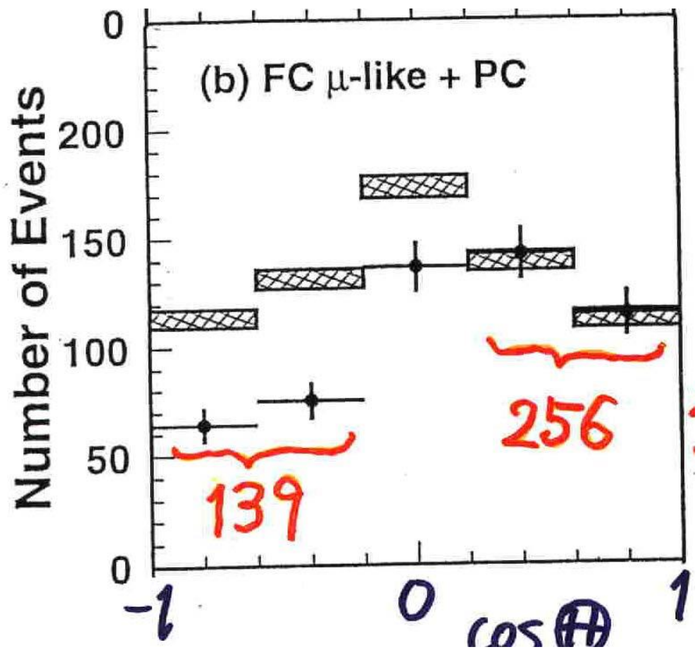




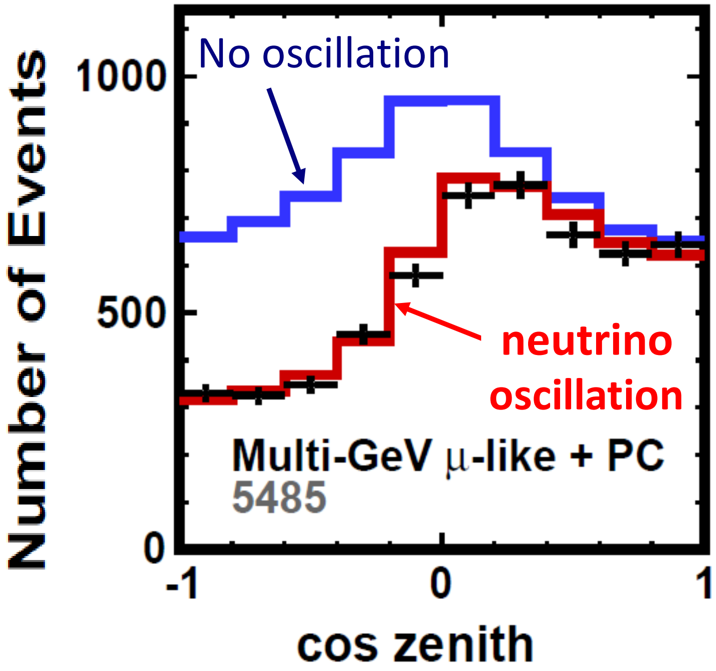
SuperK results

Takaaki Kajita
Nobel Prize 2015

Super-K @Neutrino98



Super-K (2015)



Takaaki Kajita, Nobel Prize Lecture, 2015

Number of events plotted:

<u>531 events</u>

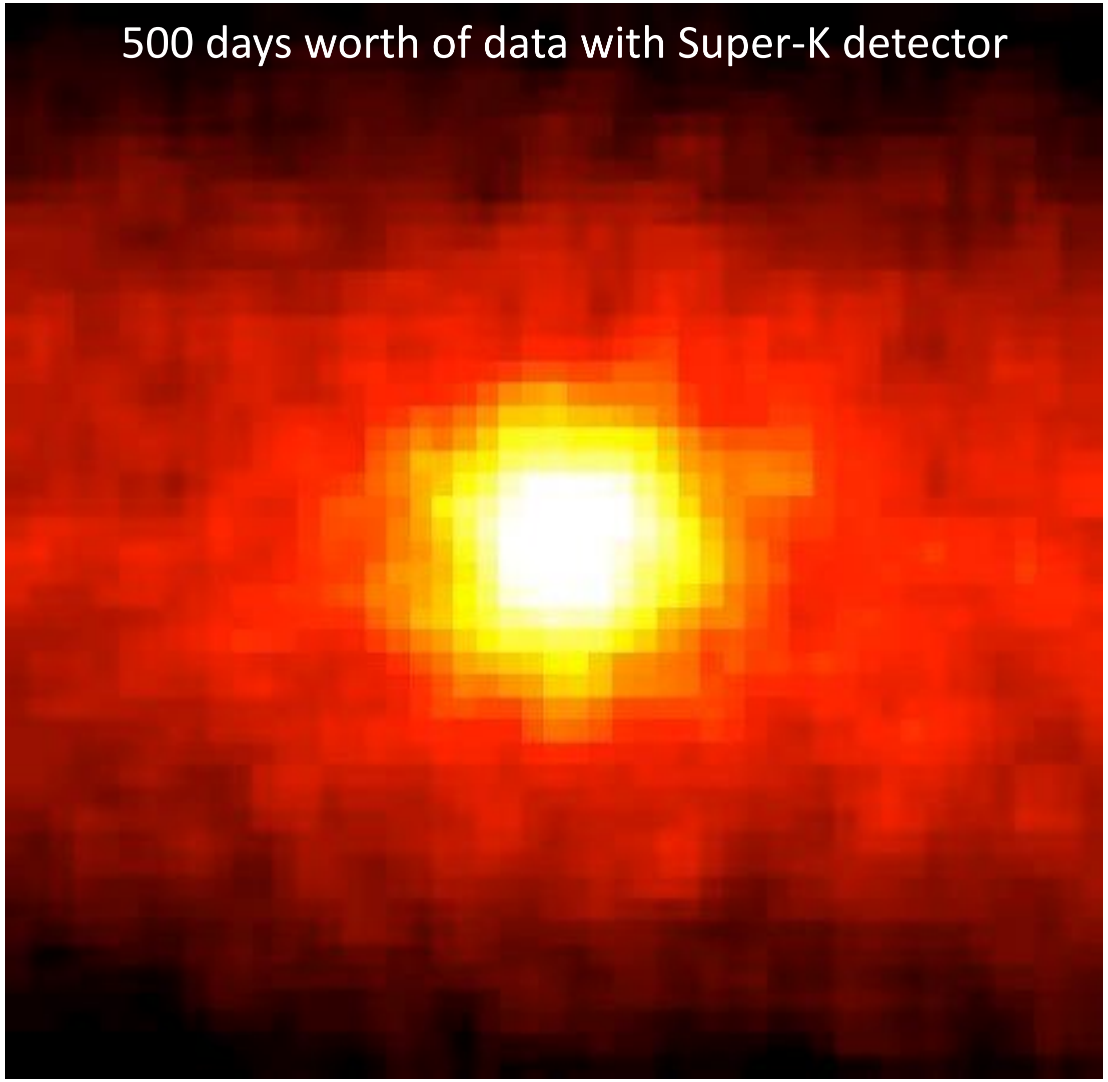
<u>5485 events</u>

The Sun imaged with neutrinos!

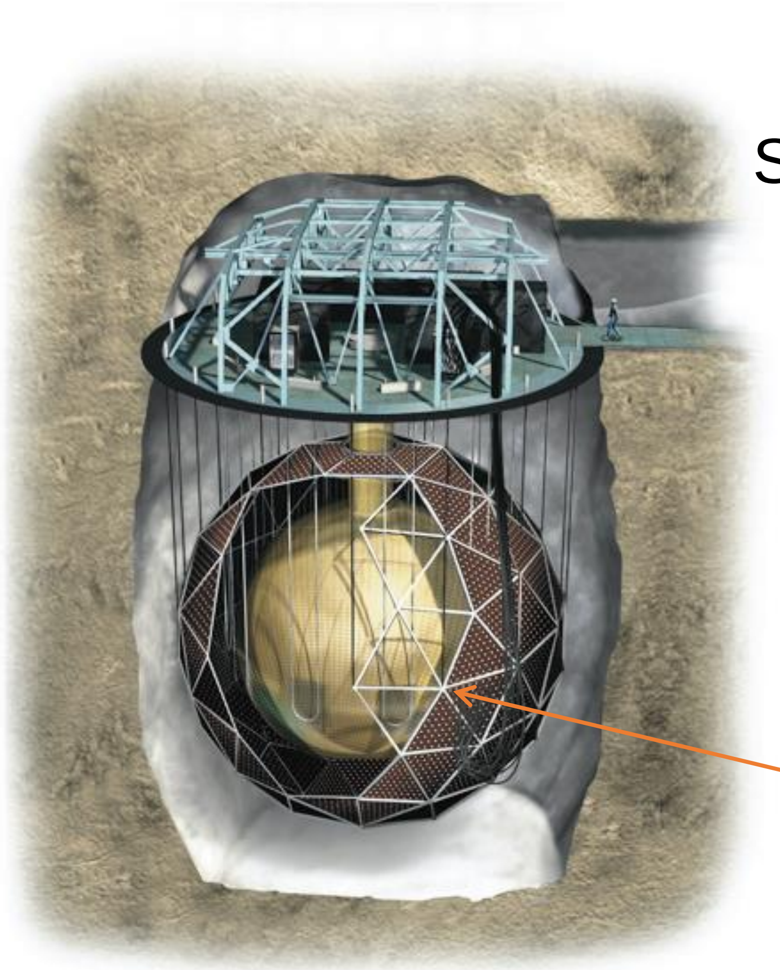
SuperK cannot provide solution to the missing ν_e from the sun, but…

While sunlight takes about 30,000 years to work its way out from the center to the surface of the Sun, neutrinos take just two seconds

→ Neutrinos can be used as probes for nuclear processes



Sudbury Neutrino Observatory (SNO)



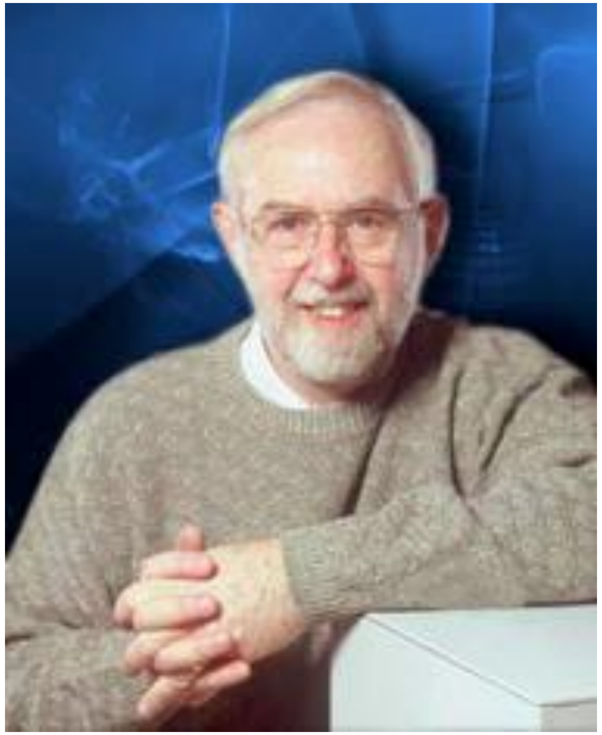
Sudbury Neutrino Observatory

Sudbury Neutrino Observatory: combine CC, NC sensitivity

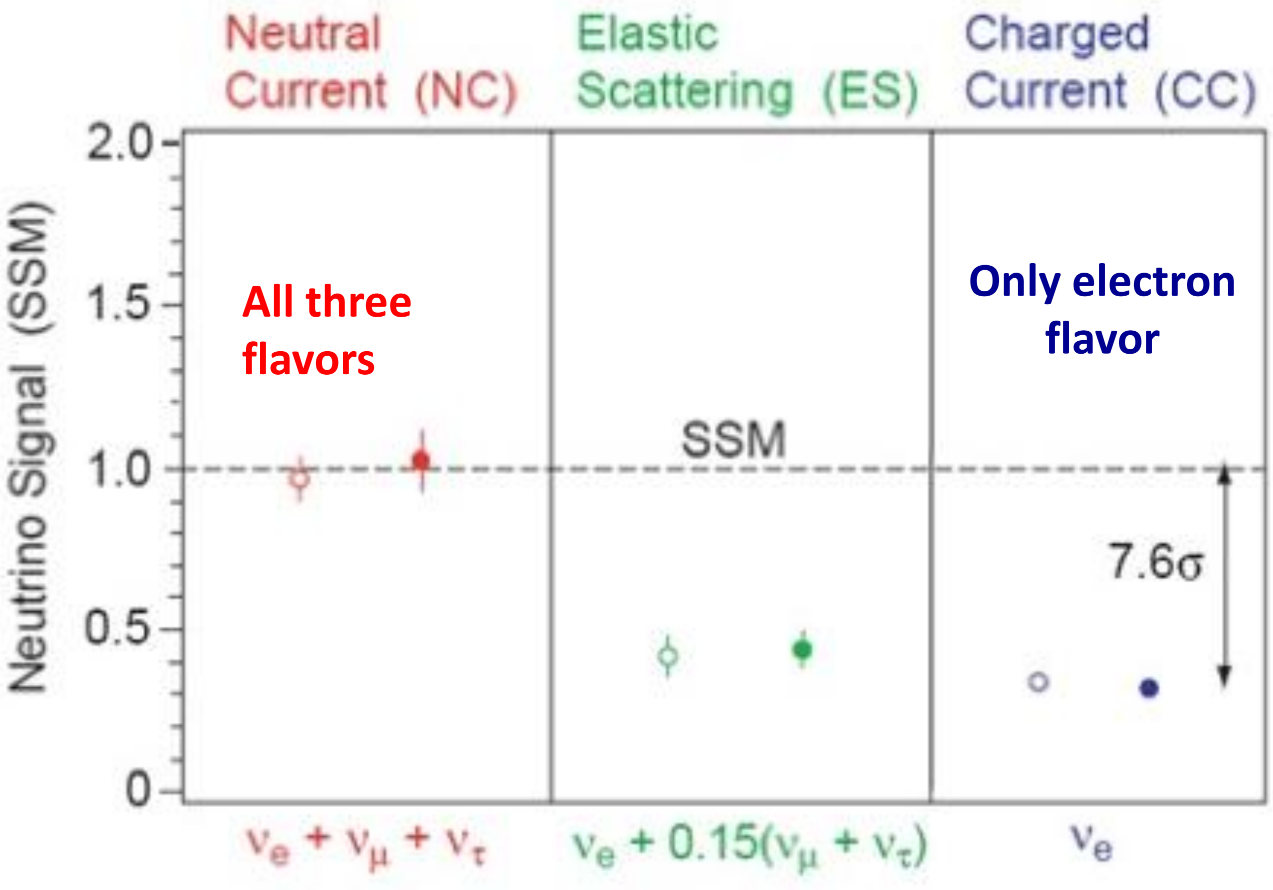
- Measure both ν_e disappearance AND total ν_X flux
- Confirm where missing electron neutrinos went

1000 tonnes of ultra-pure heavy water (D_2O) housed in a clear acrylic vessel 12 m in diameter, located a mile underground in a nickel mine in Sudbury, Ontario, Canada.

Solving the solar neutrino problem (2002)



Art MacDonald
Nobel Prize (2015)



Missing neutrinos changed into other flavors!

Neutrino mixing, mass, and 0νββ

In Quantum Mechanics there are 2 representations for our neutrinos if $m_\nu \neq 0$:

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

$$\nu_{m1}(t) = e^{-i(\boxed{E_1 t} - p_1 L)} \nu_{m1}$$
$$\nu_{m2}(t) = e^{-i(\boxed{E_2 t} - p_2 L)} \nu_{m2}$$
$$\nu_{m3}(t) = e^{-i(\boxed{E_3 t} - p_3 L)} \nu_{m3}$$

$E_i=m_i c^2$
Evolve in time with m_i & E

"Weak interaction eigenstate"

this is the state of definite flavor:

interactions couple to this state

"Mass eigenstate"

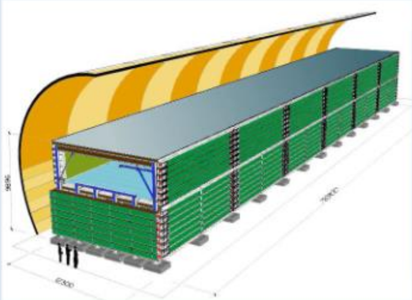
this is the state of definite energy:

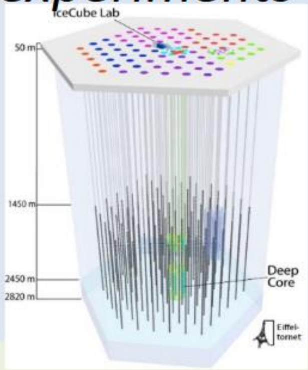
propagation happens in this state

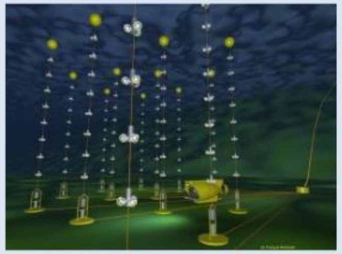
- The elements of the MNSP matrix are determined in oscillation experiments.
- Oscillation experiments can only determine Δm_{ij}^2, the squared mass difference between two eigenstates.

Many exciting results in neutrino oscillations (partial list)

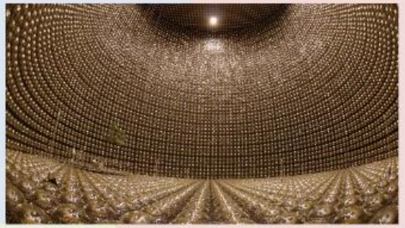
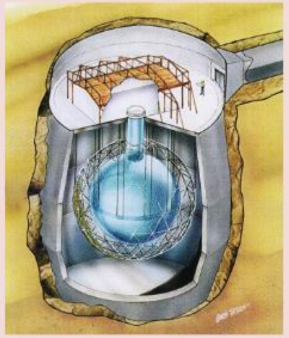
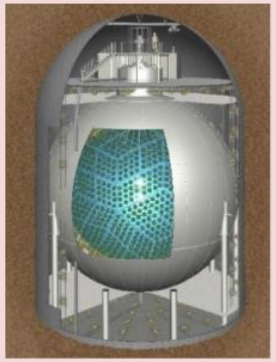
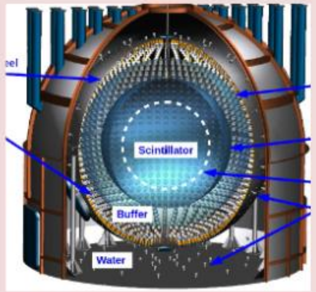
Atmospheric neutrino oscillation experiments



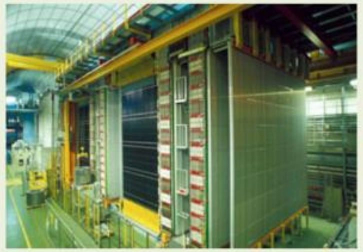




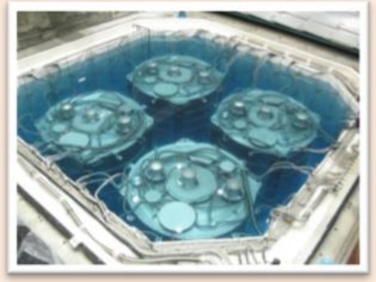
Solar neutrino oscillation experiments

Accelerator based neutrino oscillation experiments



3 flavor(type) neutrino oscillation experiments



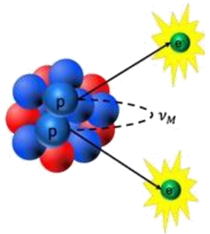
Slide from Takaaki Kajita, NEUTRINO 2022

Measuring Neutrino Masses

Effective ββ mass

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

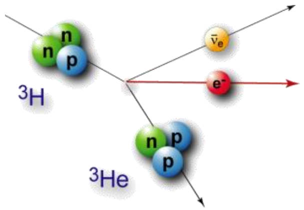
virtual ν exchange



- Majorana nature
- Upper limit: ~0.05 – 0.2 eV
- GERDA, KamLAND-ZEN, MAJORANA, LEGEND, nEXO, CUORE, CUPID, NEXT, …

m of ν_e from β endpoint

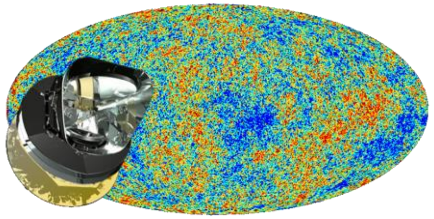
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i}$$



- Direct measurement
- Upper limit: 0.8 eV [Nature 2022]
- KATRIN, Project8, ECHo, HOLMES

Observational Cosmology

$$\sum = \sum m_i$$

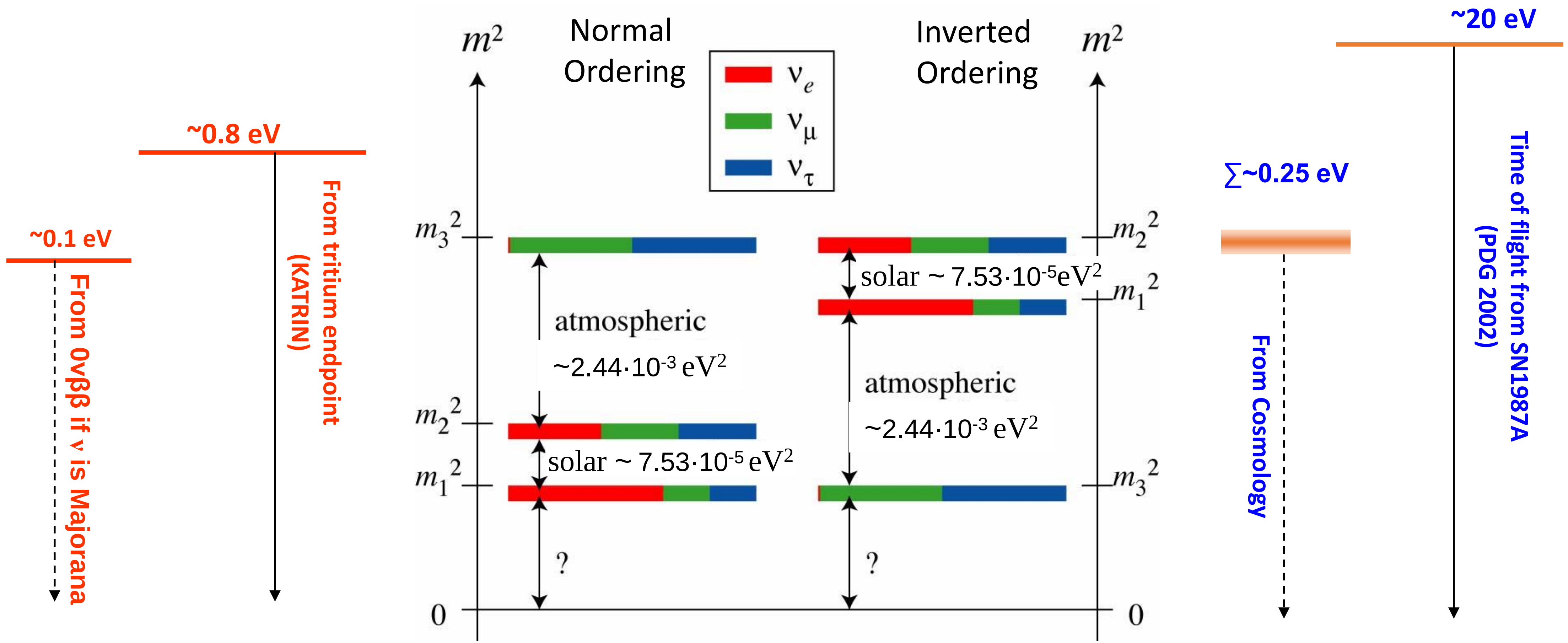


- Multi-parameter cosmological model
- Upper limit: ~0.11 – 0.54 eV*
- Planck satelite

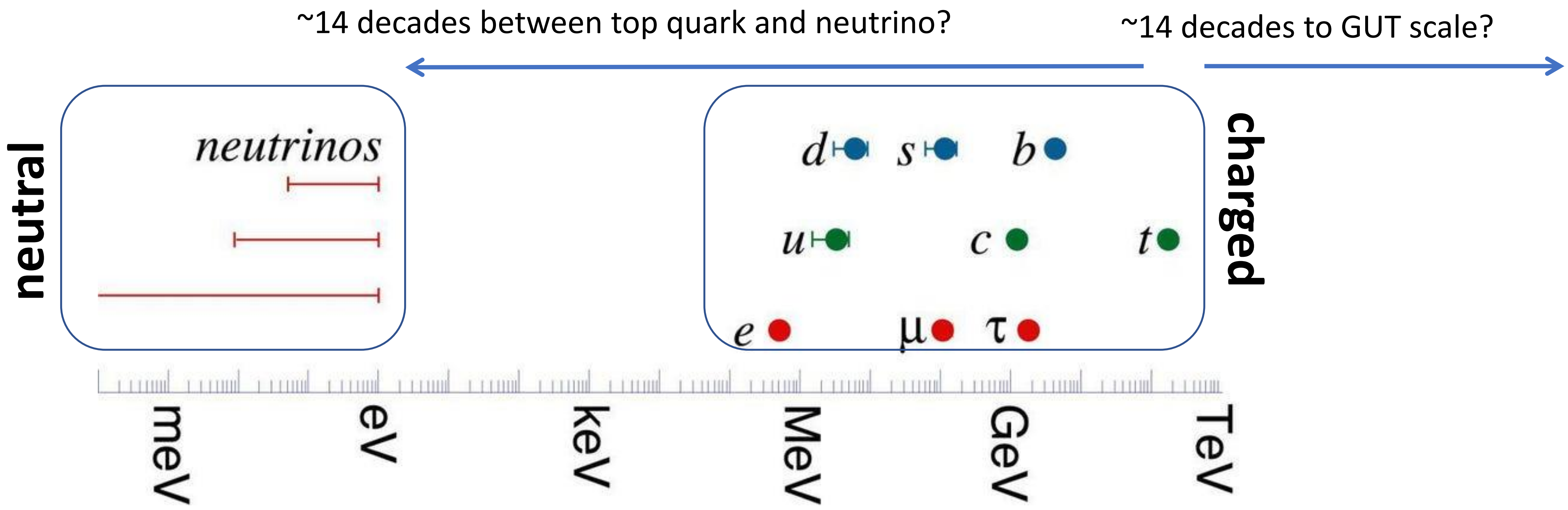
*source: PDG 2020: Neutrinos in Cosmology

See https://neutrino2022.org for any question about neutrinos.

What we know about neutrinos



Spin ½ Fermion Mass spectrum



Adopted from: Hitoshi

- Neutrinos are 6 orders of magnitude lighter than the next heavy particle.
- What determines the mass scale hierarchy of elementary particles?
- Is the Higgs mechanism responsible for neutrino mass?
- Perhaps neutrinos are very different from other fermions, such as a Majorana particle?

Electrically neutral neutrinos

Generation

Charge	**1^{st}**	**2^{nd}**	**3^{rd}**
1	e^+	μ^+	τ^+
2/3	u	c	t
1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
0	ν_e	ν_μ	ν_τ
-1/3	d	s	b
-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
-1	e^-	μ^-	τ^-

Neutrinos do not carry charge

What about lepton number?

Could it be that the mass and charge peculiarities are somehow related?

Say that for neutrinos $\bar{\nu} = \nu$, since they have no charge…

But… isn't there a lepton number to conserve?

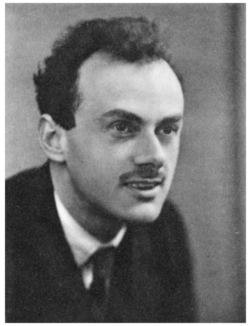
No worries: lepton number conservation is not as "serious" as -say- energy conservation

Lepton number conservation is just an empirical notion.

Basically, lepton number is conserved "because", experimentally, $\bar{\nu} \neq \nu$. But the distinction could derive from the different helicity states.

Quantum Nature of the Neutrino

"Dirac" neutrinos $\nu \neq \bar{\nu}$



$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$

"Majorana" neutrinos $\nu = \bar{\nu}$

Could help explain the origin of matter!

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Which way Nature chose to proceed is an open experimental question, although Majorana neutrinos are favored by theory.

The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

Matter-Antimatter Asymmetry

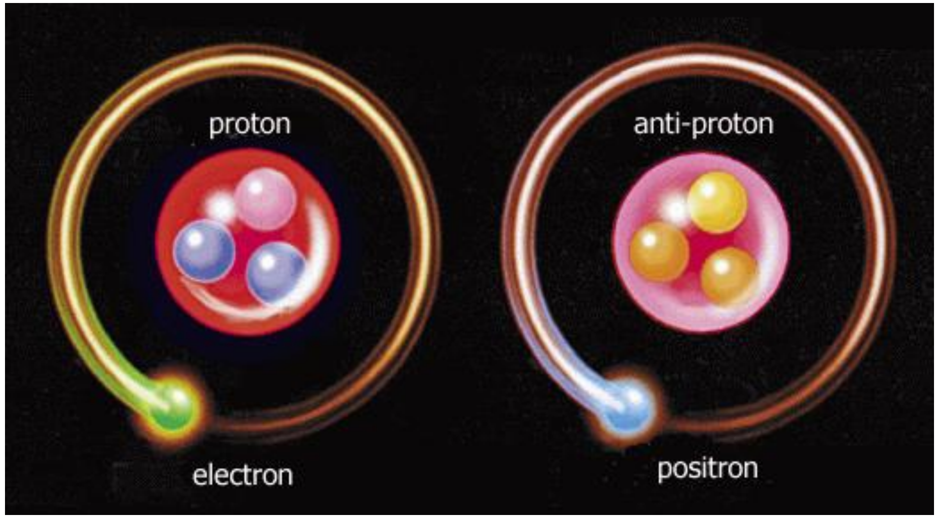
Nothing in our theory tells us why there seems to be so much more matter than antimatter in the Universe.

This is a pretty big **asymmetry**, so we should look for symmetry violations.

Neutrinos could be the key!

Source: https://www.spacetelescope.org/

The matter-antimatter asymmetry



"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery." [NSAC 2015]

How do we generate a matter-antimatter asymmetry?

Sakharov (1967) conditions for baryogenesis:

1. Baryon number violation
2. C and CP violation
3. Out of thermal equilibrium

Instead of starting with a baryon number violating process (baryogensis), leptogenesis relies on violating **lepton number**, *then* converting *L* into *B*.

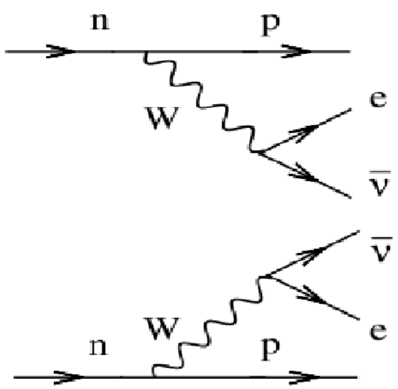
Neutrinos could be the key to explaining the matter-antimatter asymmetry in the universe…

How can we determine if $\nu = \bar{\nu}$?

The answer may be neutrinoless $\beta\beta$ decay

Double Beta Decay

Maria Goeppert Mayer



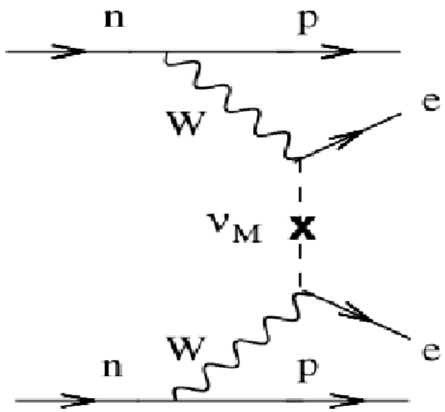
Two neutrino double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay

1987 first direct observation in ^{82}Se by M. Moe

Ettore Majorana



Neutrinoless double beta decay

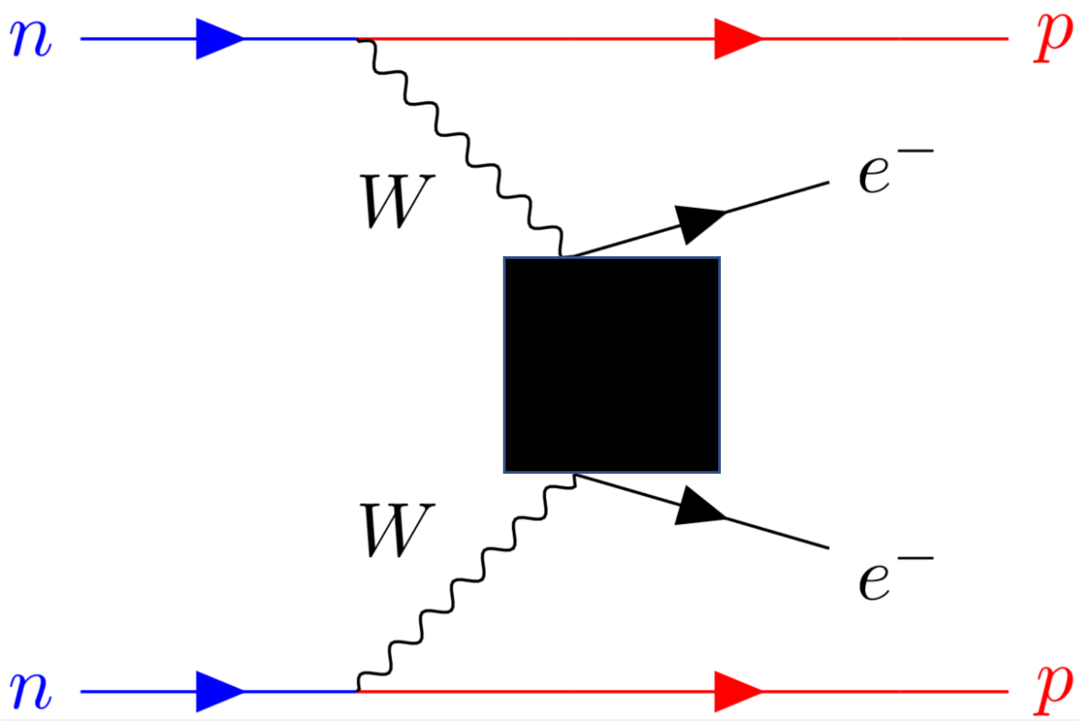
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-}$$

1937 Ettore Majorana proposed the theory of Majorana fermions

1939 Wendell Furry proposed neutrino less double beta decay

Black Box Theorem

- "Black box" theorem*: Observation of 0νββ always implies **new physics**:
  - Majorana neutrinos
  - Lepton number violation
  - Help explain observed cosmic baryon asymmetry → leptogenesis

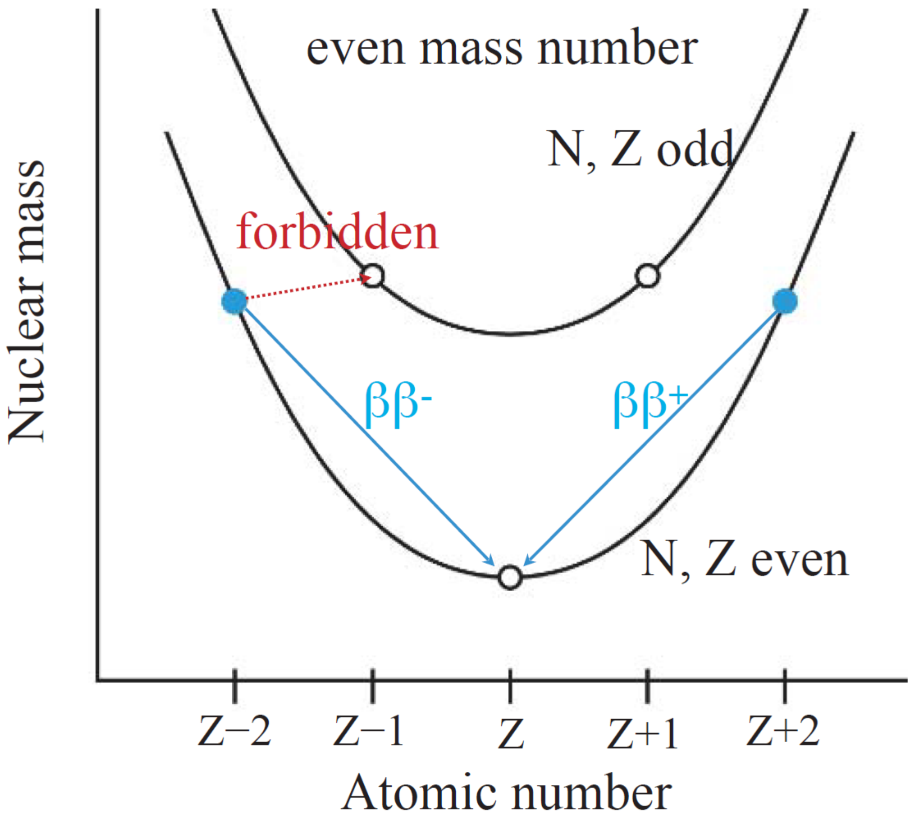


*J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982)

2ν Double Beta Decay

- Second-order weak nuclear process
- First-order beta decay is forbidden energetically or by spin → ββ is detectable

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



35 2νββ nuclei found

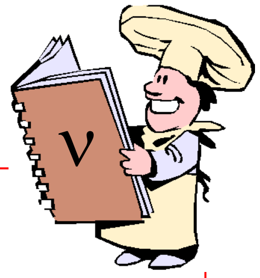
ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Ru$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.8
$^{130}Te \rightarrow {}^{130}Xe$	2.528	34.2
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

EXO-200 and nEXO

Challenges of double-β decay experiments

Sensitivity on $$T_{1/2} \propto \varepsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

ε	detection efficiency
A	isotopic abundance
M	active mass
T	exposure
b	background rate
ΔE	energy resolution



$T_{1/2}^{0\nu} > 10^{25}$ years !!

→Need:

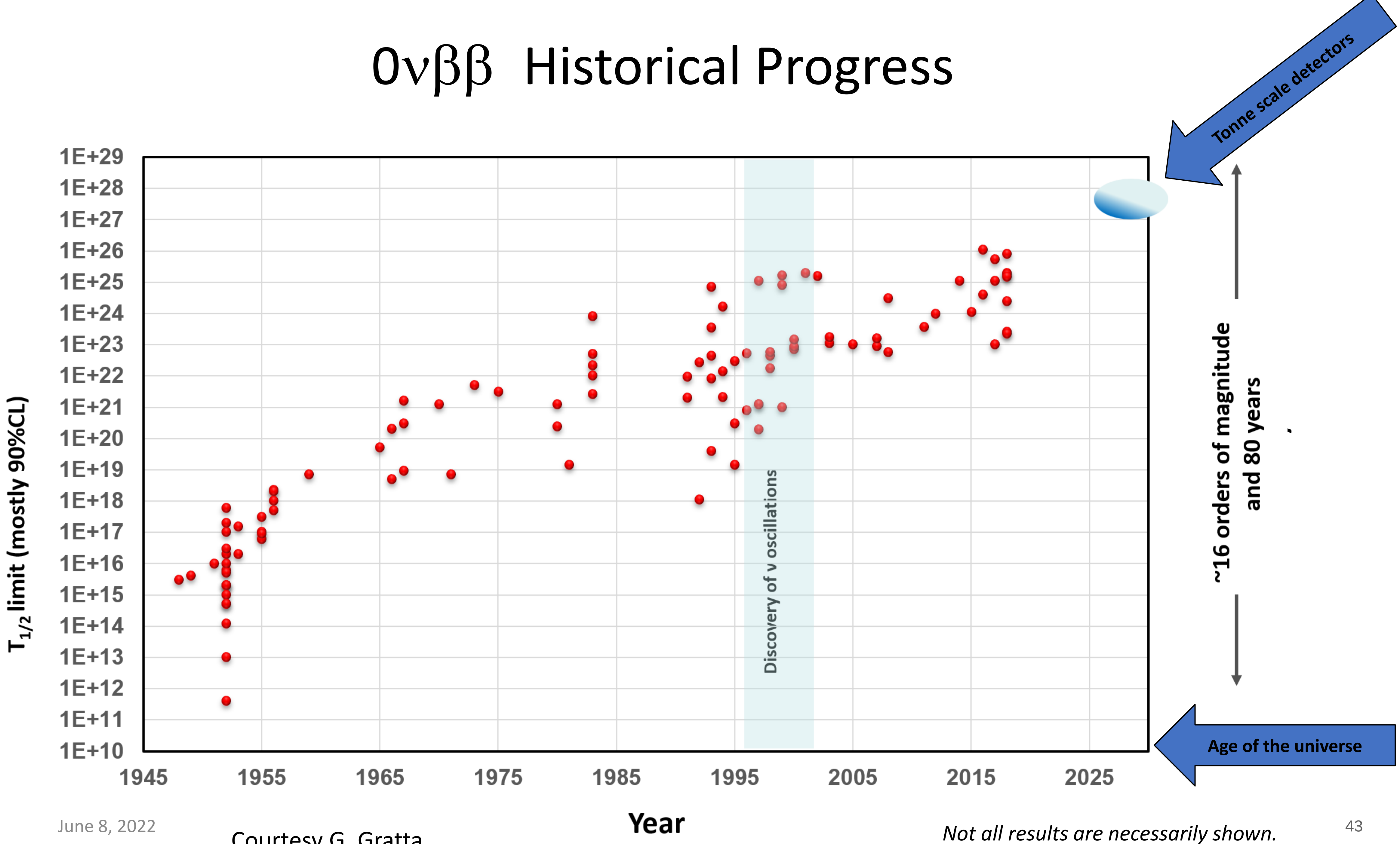
- high target mass
- high exposure
- low background rate
- good energy resolution

<u>Natural radiation decay rates</u>

A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

0νββ decay	>10,000 x rarer than 2νββ
Age of universe	1.4 x 10^{10} years

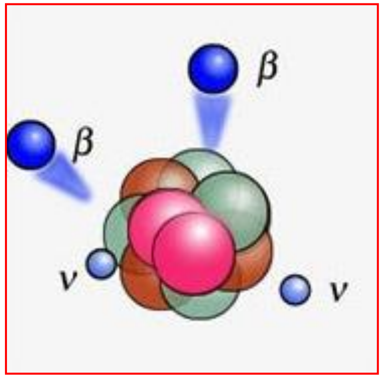
$0\nu\beta\beta$ Historical Progress



Courtesy G. Gratta

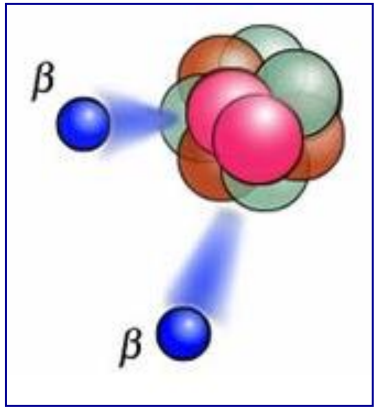
Not all results are necessarily shown.

Double Beta Decay



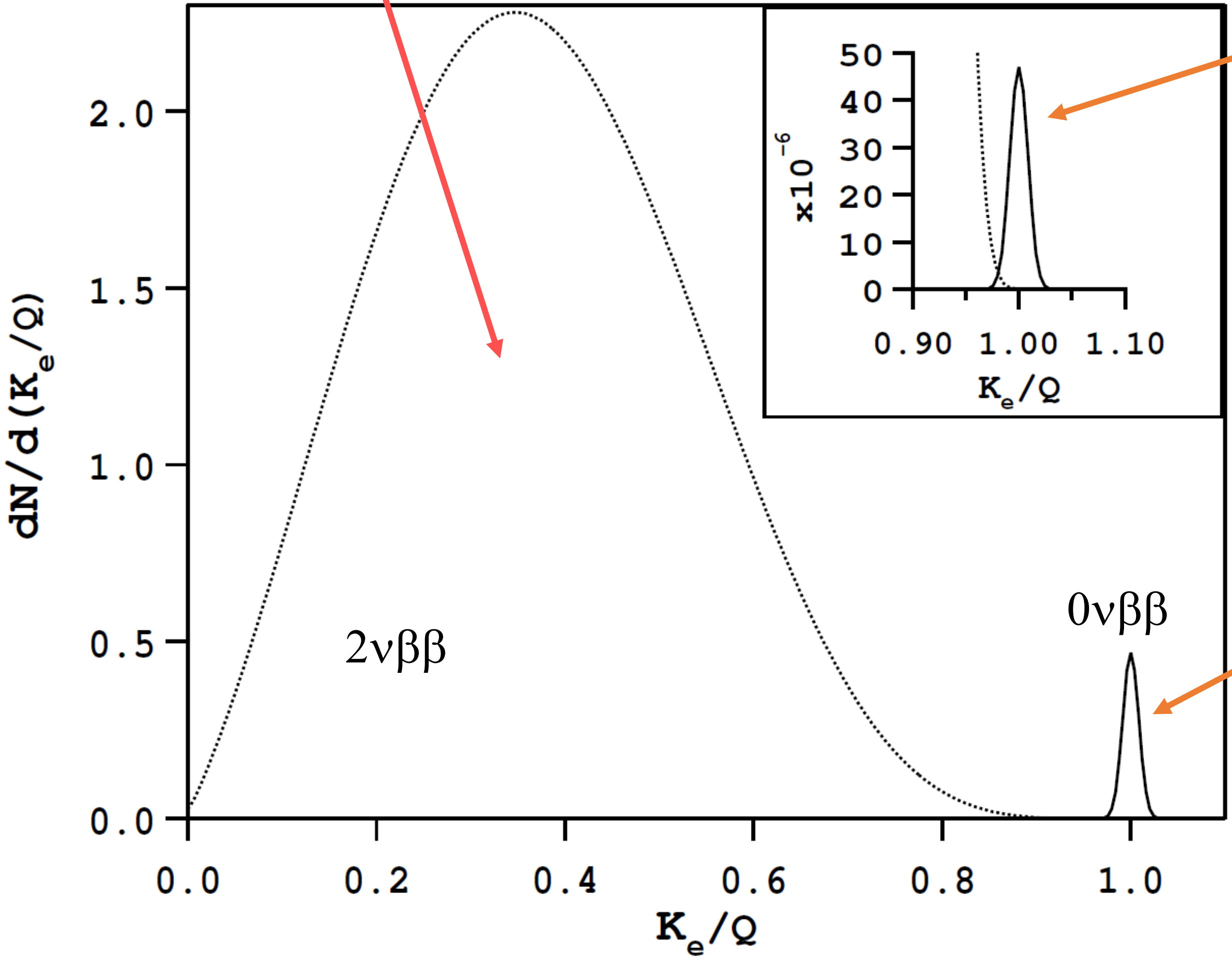
2νββ

$T_{1/2} \approx 10^{20}$ y



2νββ spectrum
(normalized to 1)

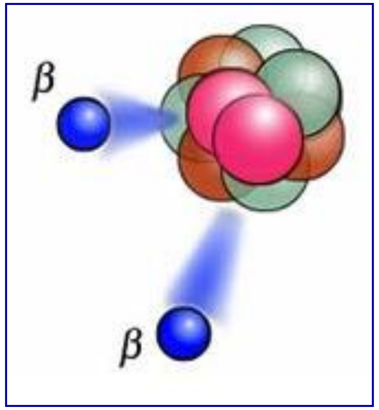
[arXiv:hep-ph/0611243]



0νββ peak
(normalized to 10^{-6})

0νββ peak
(normalized to 10^{-2})

$0\nu\beta\beta$ – Can only happen for Majorana neutrinos! $T_{1/2} > 10^{25}$ y!



0νββ and Neutrino Mass

Nuclear physics input

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\boxed{G^{0\nu} g_A^4 |M^{0\nu}|^2}$$

Phase space factor

Axial vector coupling, $g_A = 1.27$

Nuclear Matrix Element

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

Mixing matrix

mass eigenvalues

Majorana phase

Effective Majorana mass is a coherent sum of neutrino mass eigenvalues, therefore cancellations are possible…

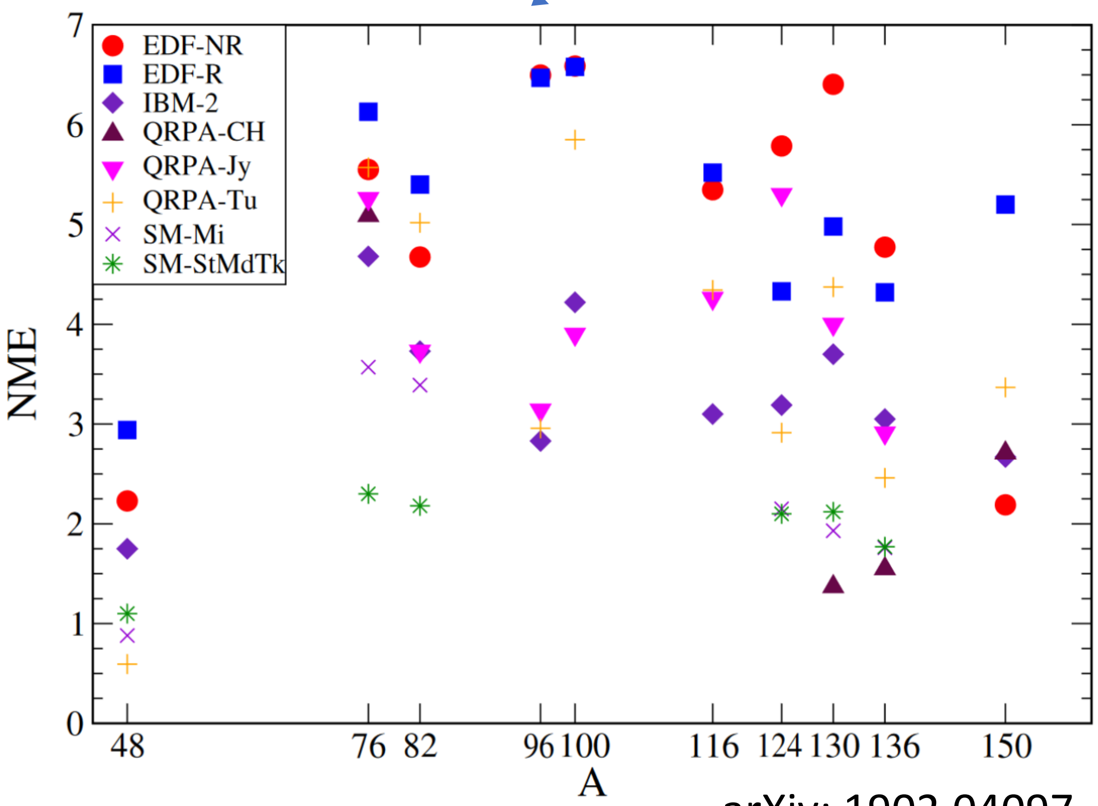
Three Caveats:

- Neutrino is a Majorana particle
- Light Majorana neutrino being the dominate decay mechanism
- Reliable calculation of matrix elements

Nuclear Matrix Element Situation

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

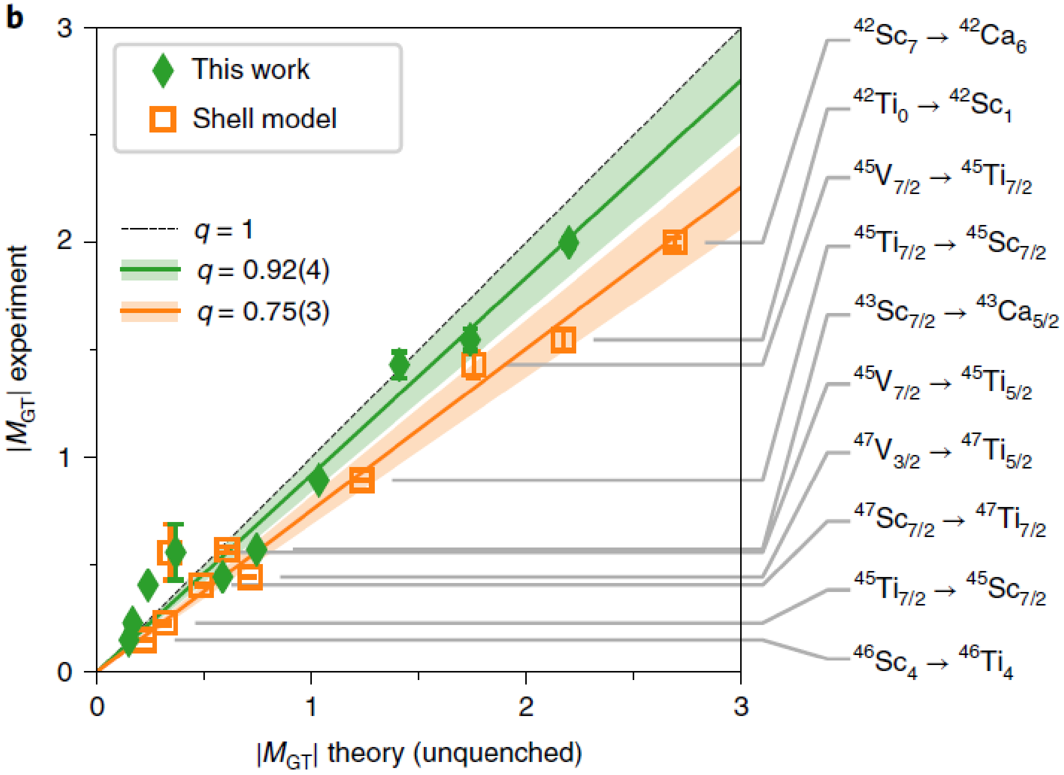
- Matrix element calculation is very difficult, in particular for big nuclei, which most of the $0\nu\beta\beta$ candidates are.
- Recent theoretical progress has narrowed the difference between models, but significant spread remains, difficult to estimate uncertainty.
- As a result, a particular half life results in a spread of calculated $\langle m_{\beta\beta}\rangle$.



arXiv: 1902.04097

Nuclear Physics Situation: is g_A quenched?

g_A^{free} = 1.27 being the free-nucleon axial-vector coupling measured in neutron beta decay.
$g_A^{eff} = q \times g_A^{free}$ with quenching factor q.



[…] observed β-decay rates in nuclei have been found to be systematically smaller than for free neutrons: […] by a factor of about 0.75 […] we demonstrate that **this quenching arises to a large extent from the coupling of the weak force to two nucleons** as well as from strong correlations in the nucleus. […] state-of-the-art computations of β-decays from light- and medium mass nuclei to ^{100}Sn by **combining effective field theories** of the strong and weak forces **with powerful quantum many-body techniques**. […] have **implications for […] the neutrino-less double-β-decay, where an analogous quenching puzzle is a source of uncertainty in extracting the neutrino mass scale.**

[Nature Physics, 15(2019)428]

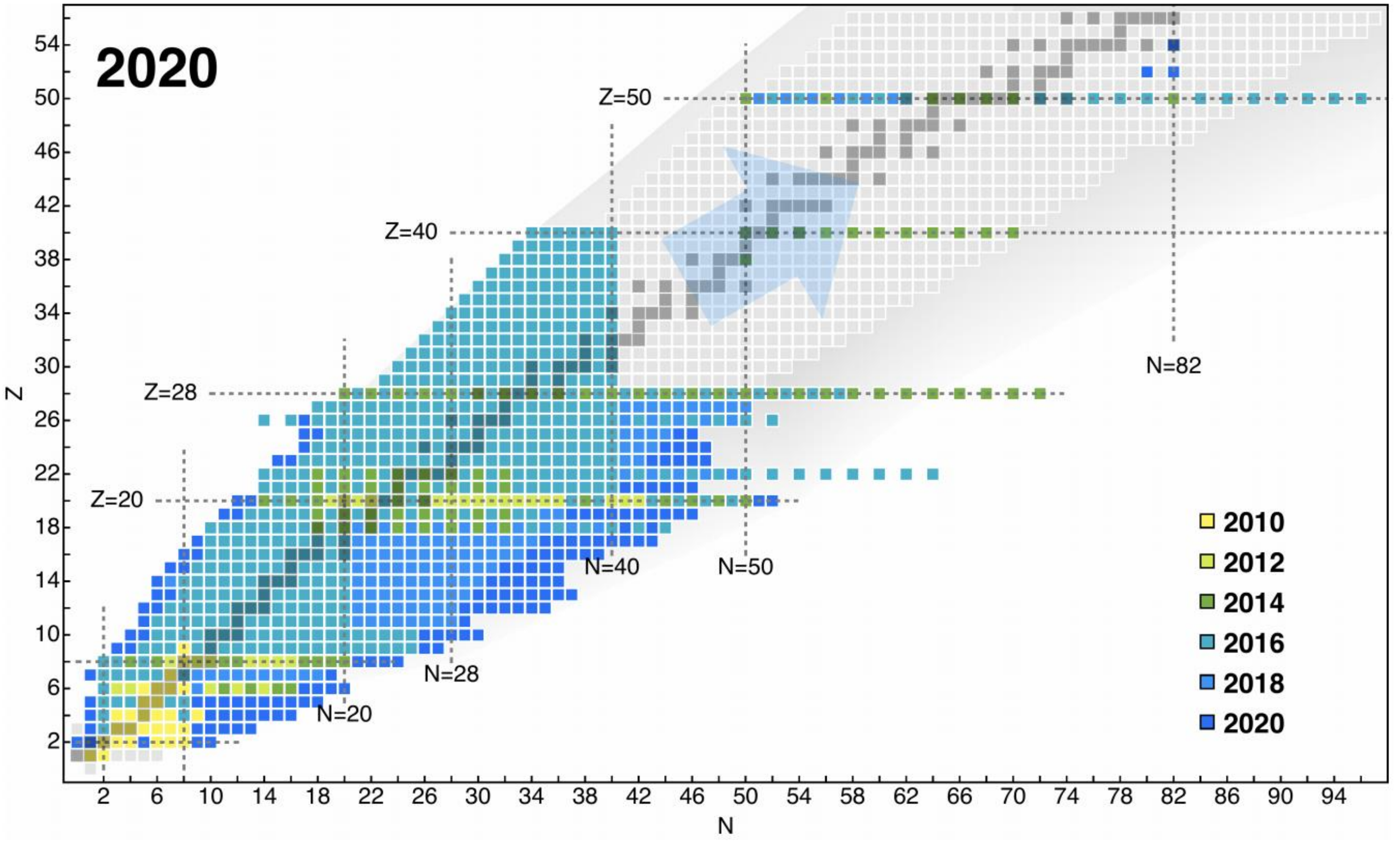
Progress in Nuclear Structure Theory

- Huge advances in nuclear theory
  - Quality and reach of *Ab initio* calculations
  - Refined chiral effective field theories and phenomenological calculations
- Hugh predictive power
  - Need to validate under extreme conditions
    (outskirts of the nuclear chart)

  →**Need of high-quality nuclear data from experiments at radioactive ion beam facilities!**
  (decay properties, masses, etc.)
- Refined NMEs anticipated

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} \boxed{g_A^4 |M^{0\nu}|^2}$$

Progress in *ab initio* nuclear structure calculations over the past decade



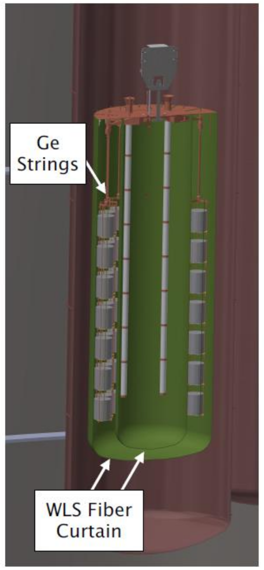
H. Hergert, Frontiers in Physics 8 (2020) 379

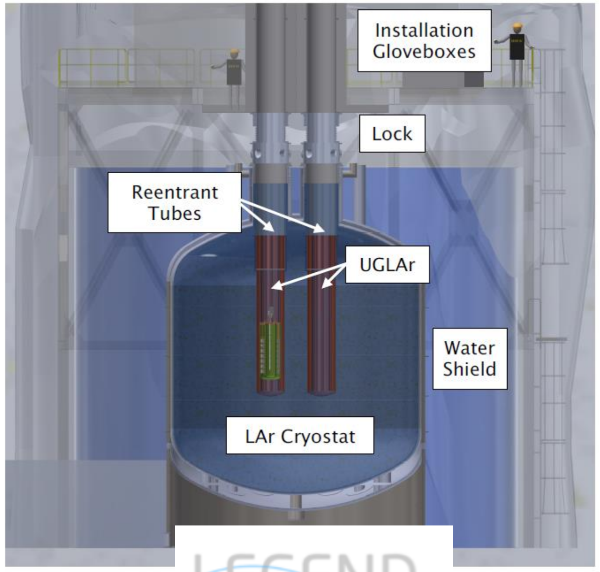
Proposed next-generation $0\nu\beta\beta$ experiments

Disclaimer: These are two of several next-generation experiments that I consider most exciting!

LEGEND-1000

- 1T Ge enriched at 90 % ^{76}Ge
- arXiv:2107.11462
- Technology demonstrated with GERDA, MAJORANA, LEGEND-200

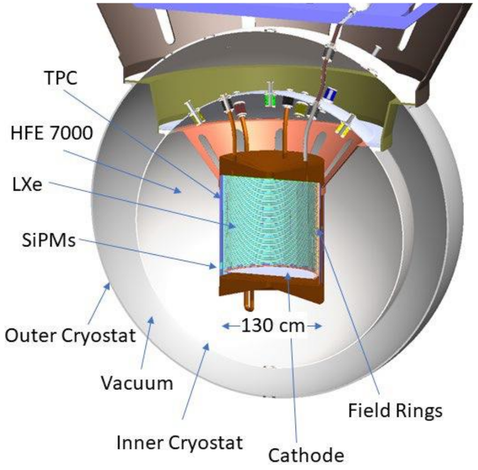


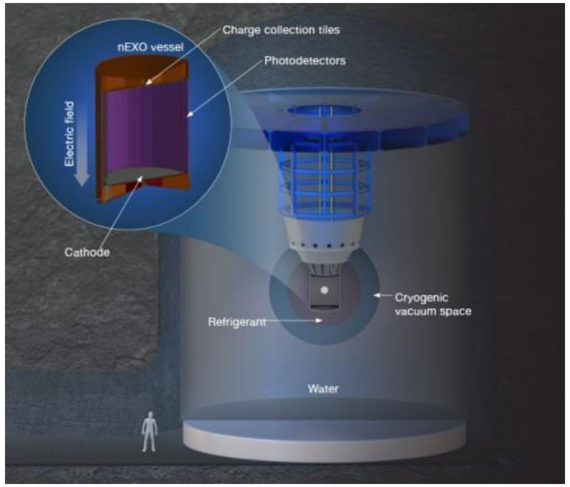


LEGEND

nEXO

- 5T Xe enriched at 90 % ^{136}Xe
- arXiv:1805.11142
- Technology demonstrated with EXO-200

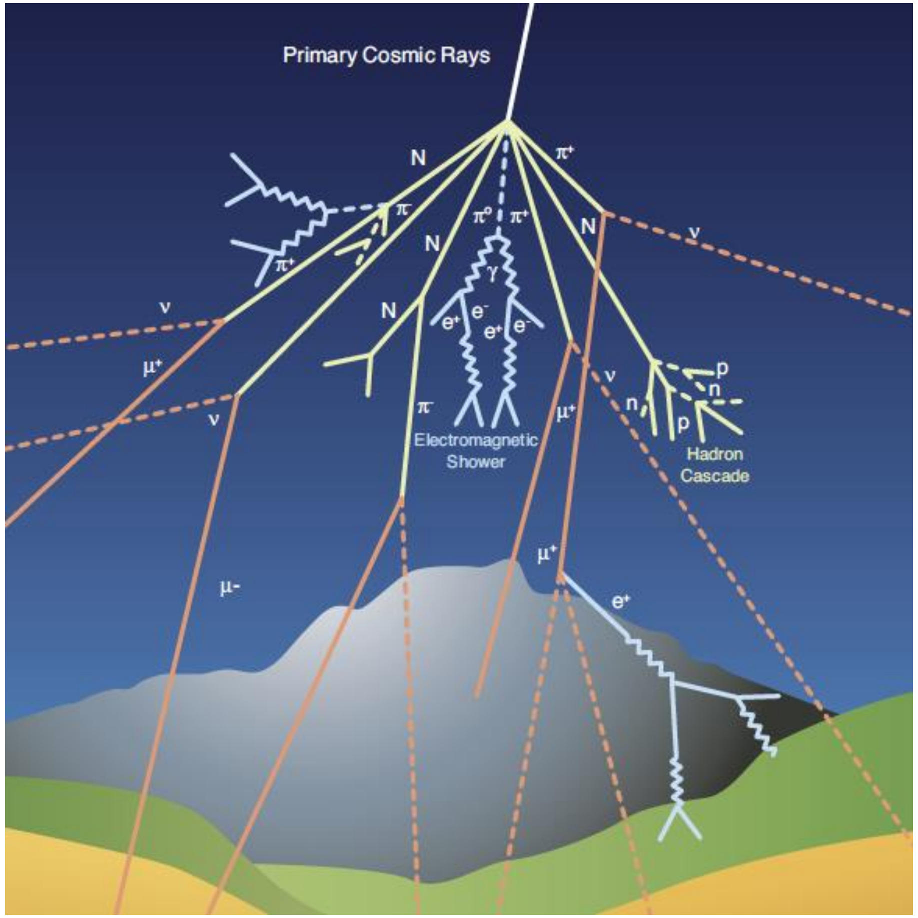




nEXO

A healthy neutrinoless double-beta decay program requires more than one isotope!

Cosmic Ray Background



Source: CERN

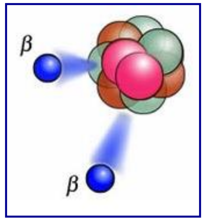
- Cosmic rays striking the upper atmosphere will create a shower of subatomic particles, including energetic muons.

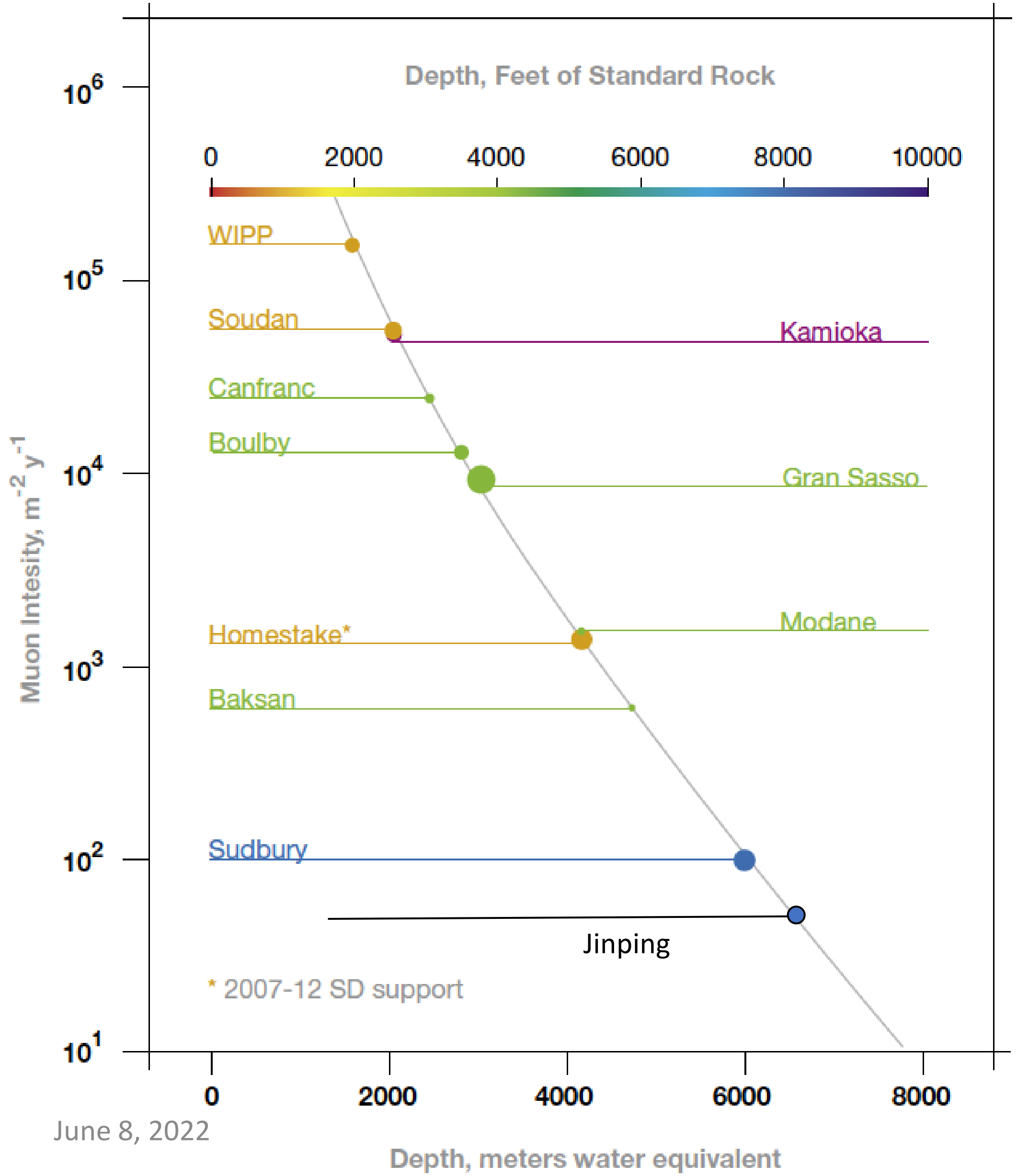
- Cosmic muons can create radioactive isotopes via spallation, neutron activation and other nuclear processes.

- When muon goes through a detector, it can produce radioactive isotopes directly inside the detector.

- Muon can also produce secondary particles in material outside the detector such as fast neutrons, which later interact with the detector material.

Going Underground….

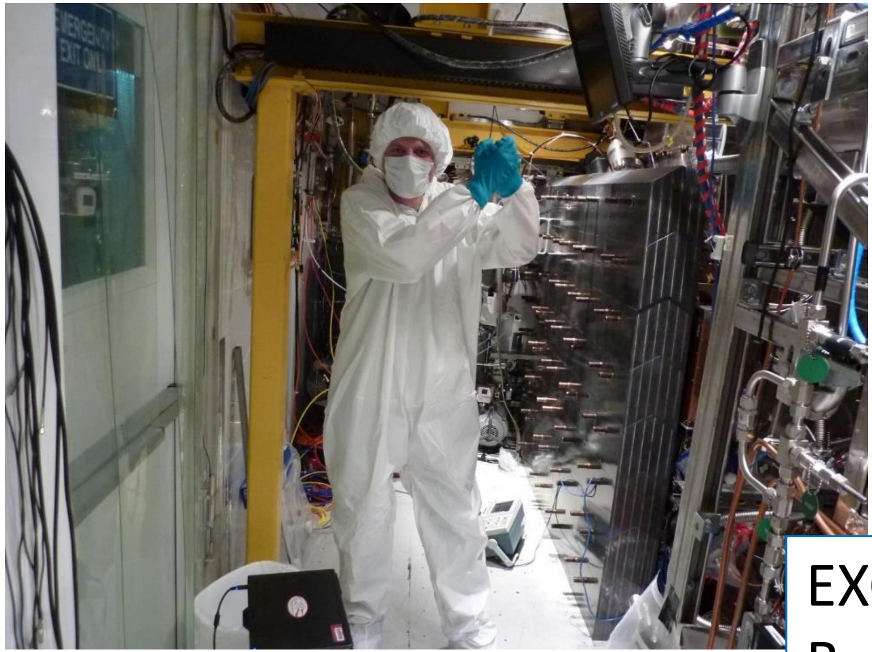




- By going to deeper underground lab, one can effectively shield against cosmic muons.

- At 6600 m.w.e., Jinping lab in Sichuan, China is the deepest underground lab, with a muon flux of ~50/m^2/yr, 9 order of magnitude reduction compared to sea level

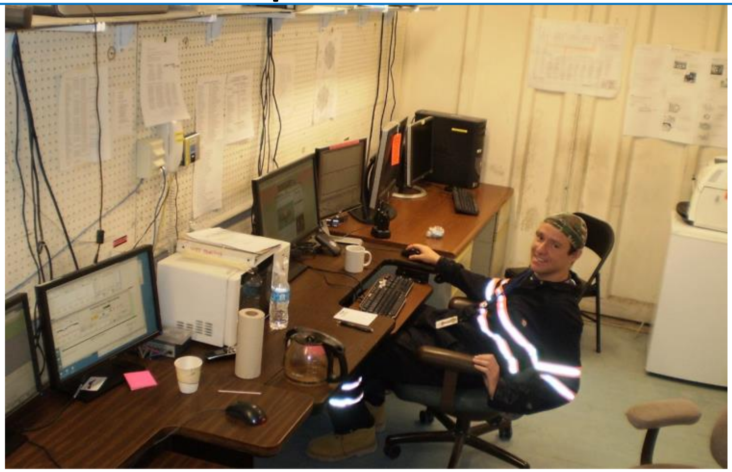
- The muon angular and energy distribution depends on the depth, so Monte Carlo simulation is needed to understand the full background from the cosmic ray.



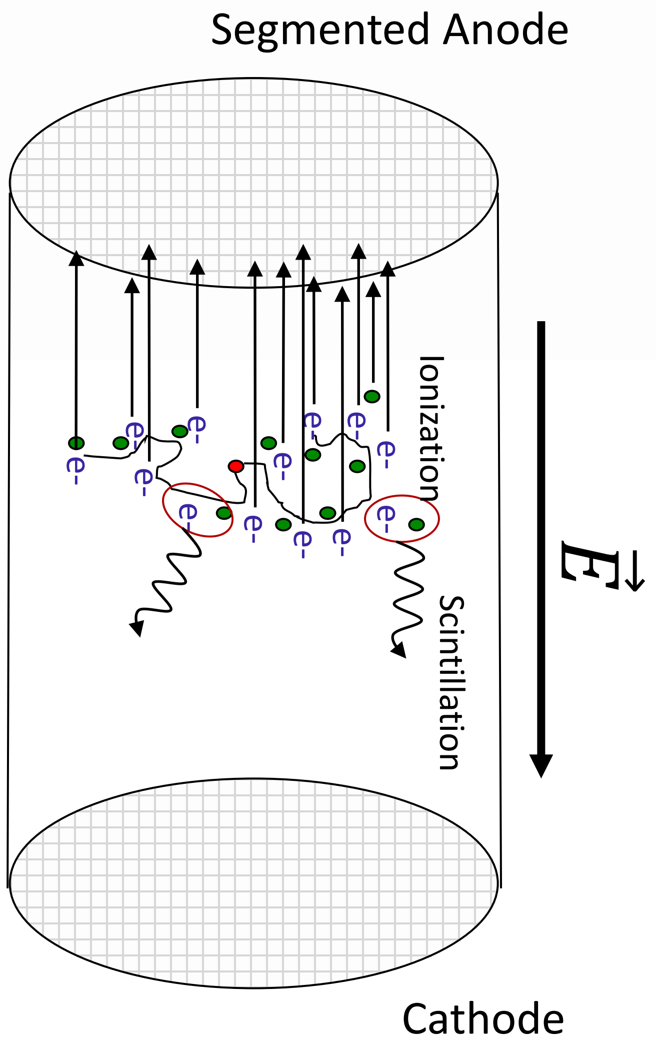
EXO-200 @ WIPP mine

Being on shift can be a very special experience

nEXO is anticipated at SNOLAB



EXO's search for $0\nu\beta\beta$ in ^{136}Xe with liquid Xe TPC

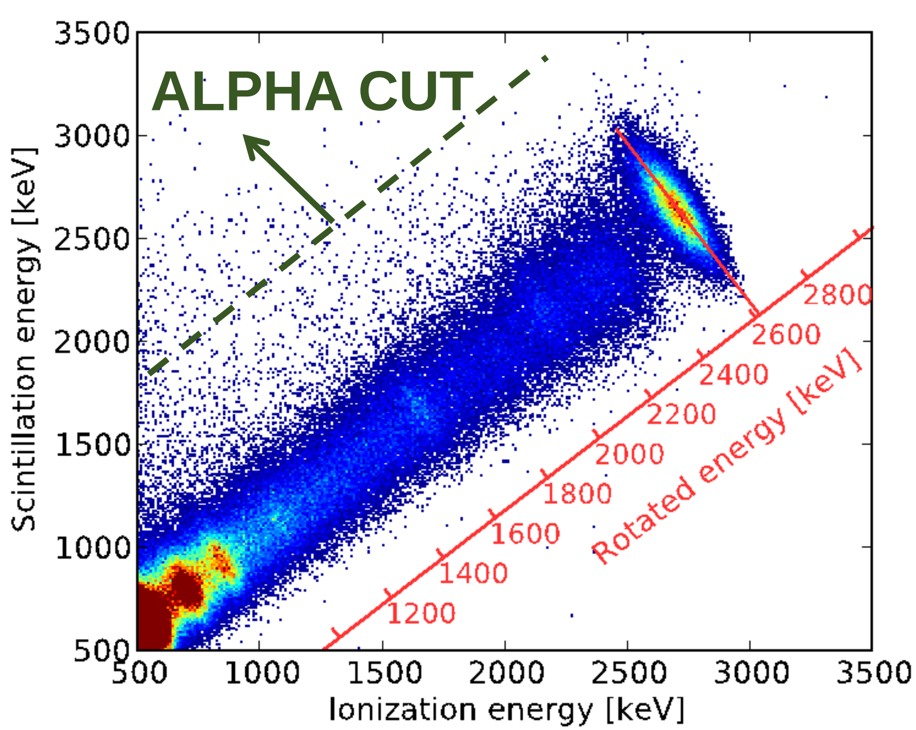


Liquid-Xe Time Projection Chamber (TPC)

- Xe is used both as the source and detection medium.
- LXe is continuously recirculated and purified.
- No long-lived cosmogenically activated Xe isotopes
- LXe TPC are well understood.
- Monolithic detector structure enables excellent background rejection capabilities.
- Multiparameter measurement from detection of scintillation light and ionization signal:
    1. Energy from combined scintillation/ionization
    2. Topology, e.g., single-site or multi-site
    3. Position distribution from 3D event reconstruction
    4. Particle identification from scintillation/ionization ratio

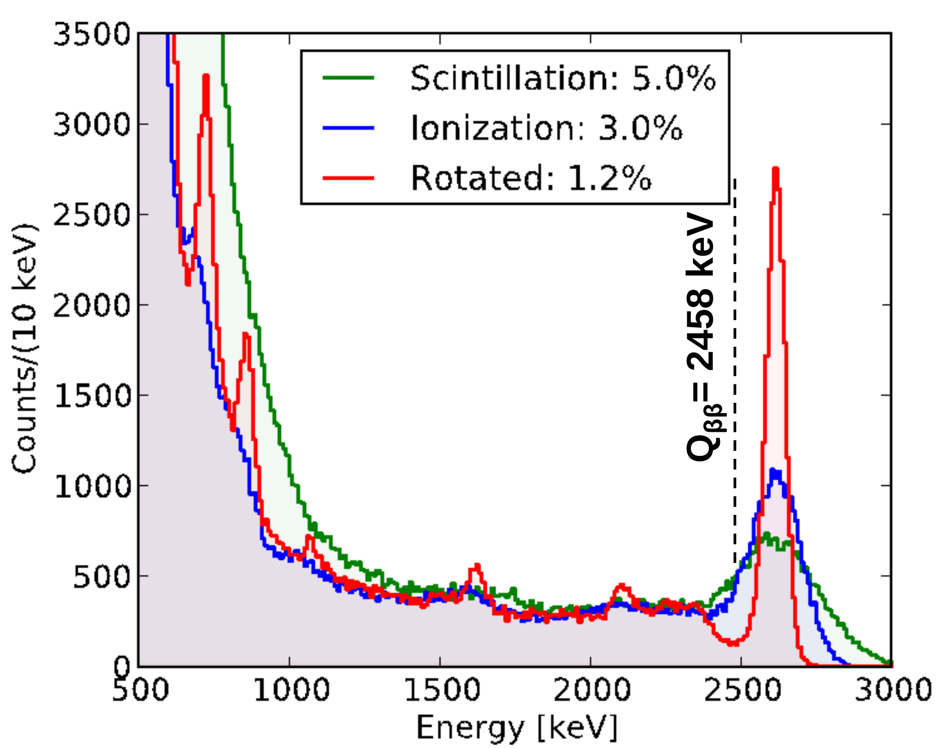
Energy measurement (EXO-200 data)

Scintillation vs. ionization, ^{228}Th calibration:



Rotation angle chosen to optimize energy resolution at 2615 keV

Reconstructed energy, ^{228}Th calibration:

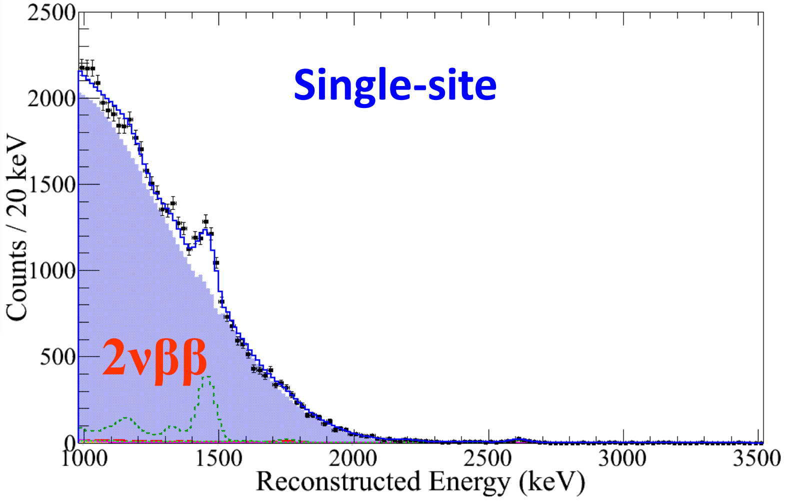


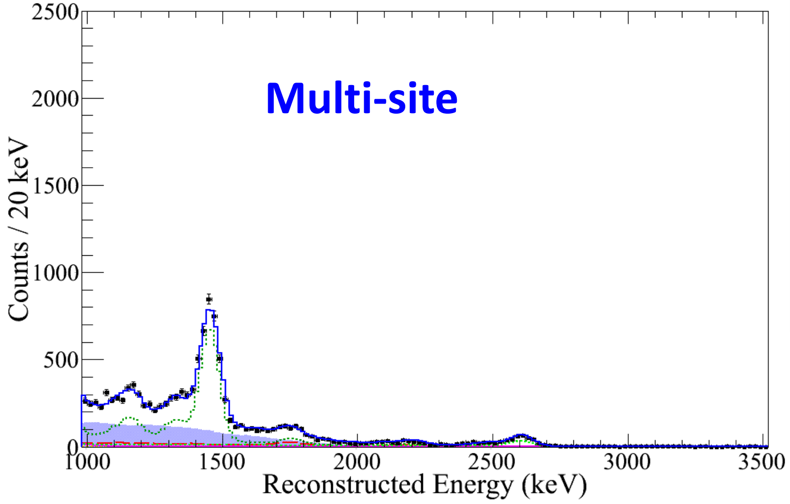
- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D and now standard in LXe detectors [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.15% (arxiv:1906.02723) energy resolution at the double-beta decay Q value in Phase II

Event Position and Multiplicity

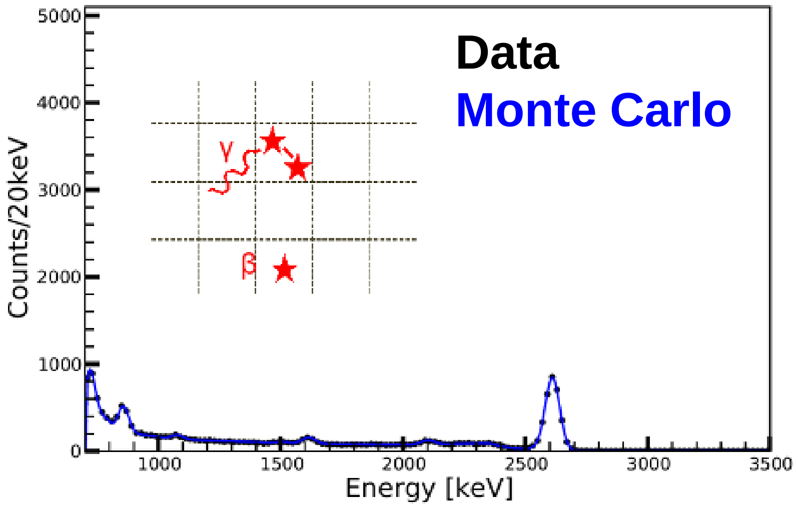
EXO-200 data

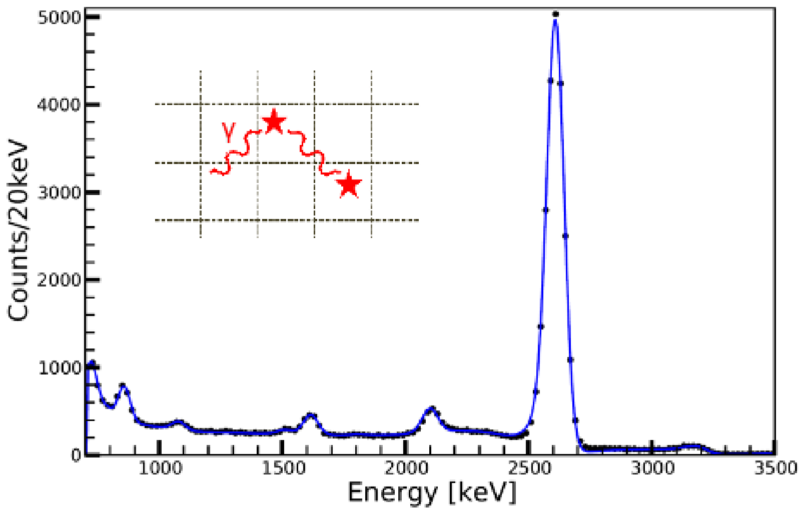
Low background data





^{228}Th calibration source





Allows for background measurement and reduction

Events with **> 1** charge cluster: multi-site events (MS)

Events with **1** charge cluster: single-site events (SS)

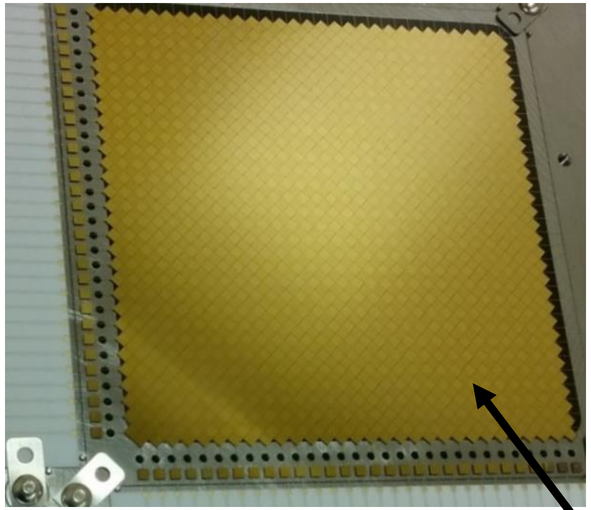
EXO-200 simulations:

$0\nu\beta\beta$: ~90% SS

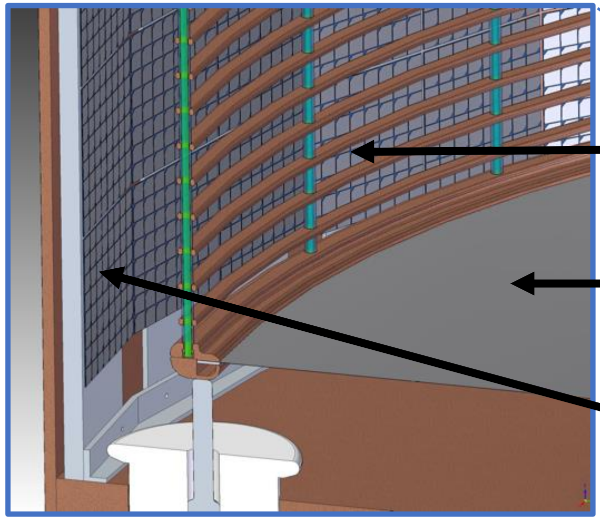
γ-rays: ~15% SS at $0\nu\beta\beta$ Q-value

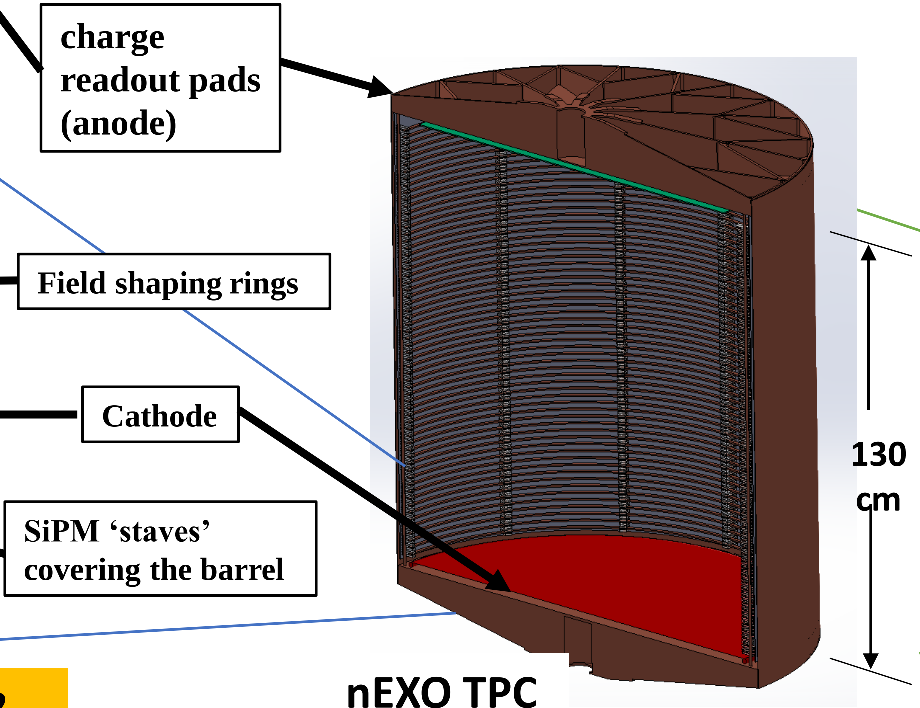
The nEXO detector

- 5 t liquid xenon TPC similar to EXO-200 (~30x the volume).
- SiPM for 175nm scintillation light detection, ~4.5m^2 SiPM array in LXe.
- Tiles for charge read out in LXe.
- Cold electronics inside TPC in liquid Xe.
- 3D event reconstruction.
- Combine charge and light readout. Goal → σ/E of <1% at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.

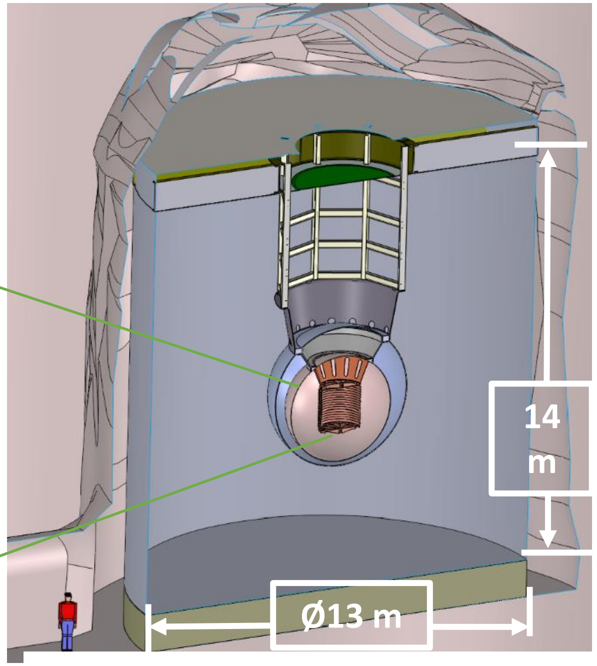


Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.





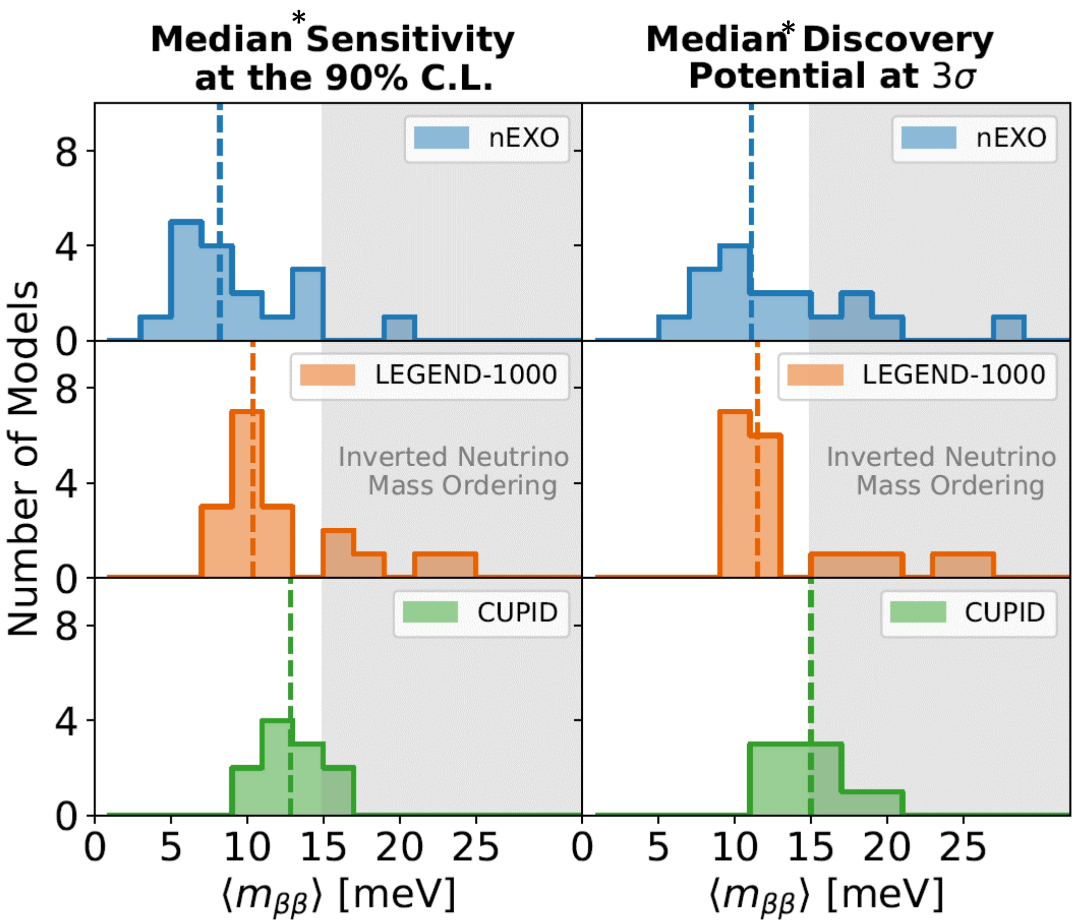
nEXO TPC



nEXO at the SNOLAB Cryopit

nEXO pre-CDR, arXiv:1805.11142

Proposed next-generation 0νββ experiments



← Deeper Physics Reach →

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor — Axial coupling, $g_A = 1.27$ — NME

- 3σ discovery potential for most NME reaching beyond inverted ordering further into normal ordering

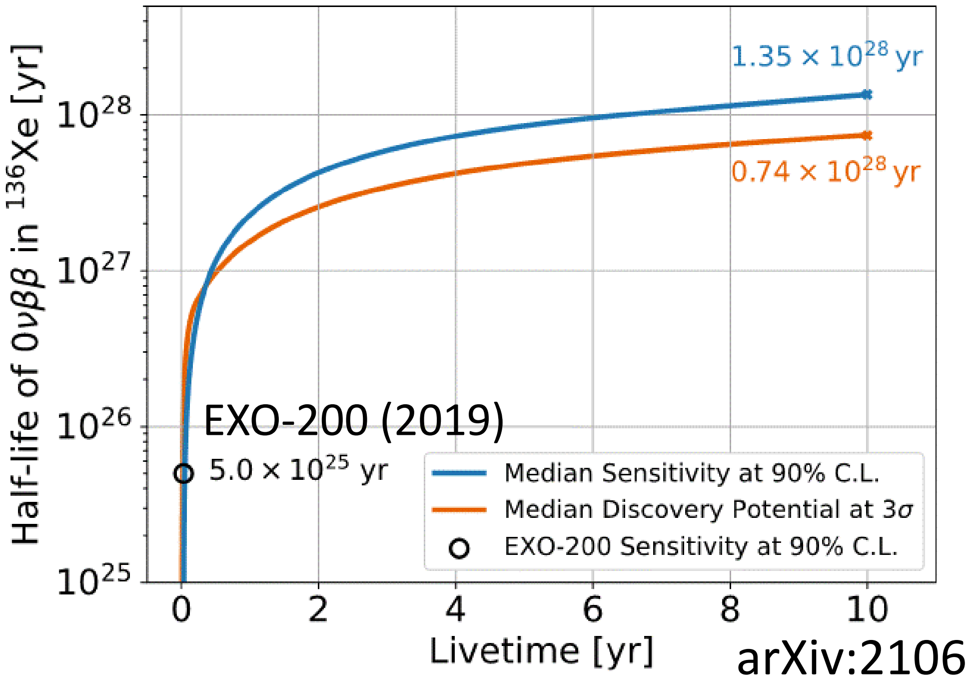
	$m_{\beta\beta}$ [meV], *(median* NME)*	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

*$T_{1/2}$ values used [$\times 10^{28}$ yr]:
nEXO: 1.35 (90% sens.), 0.74 (3σ discov.) [1]
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.) [2]
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]

[1] nEXO collaboration, arXiv:2106.16243
[2] LEGEND pCDR, arXiv: 2107.11462
[3] CUPID pCDR, arXiv:1907.09376

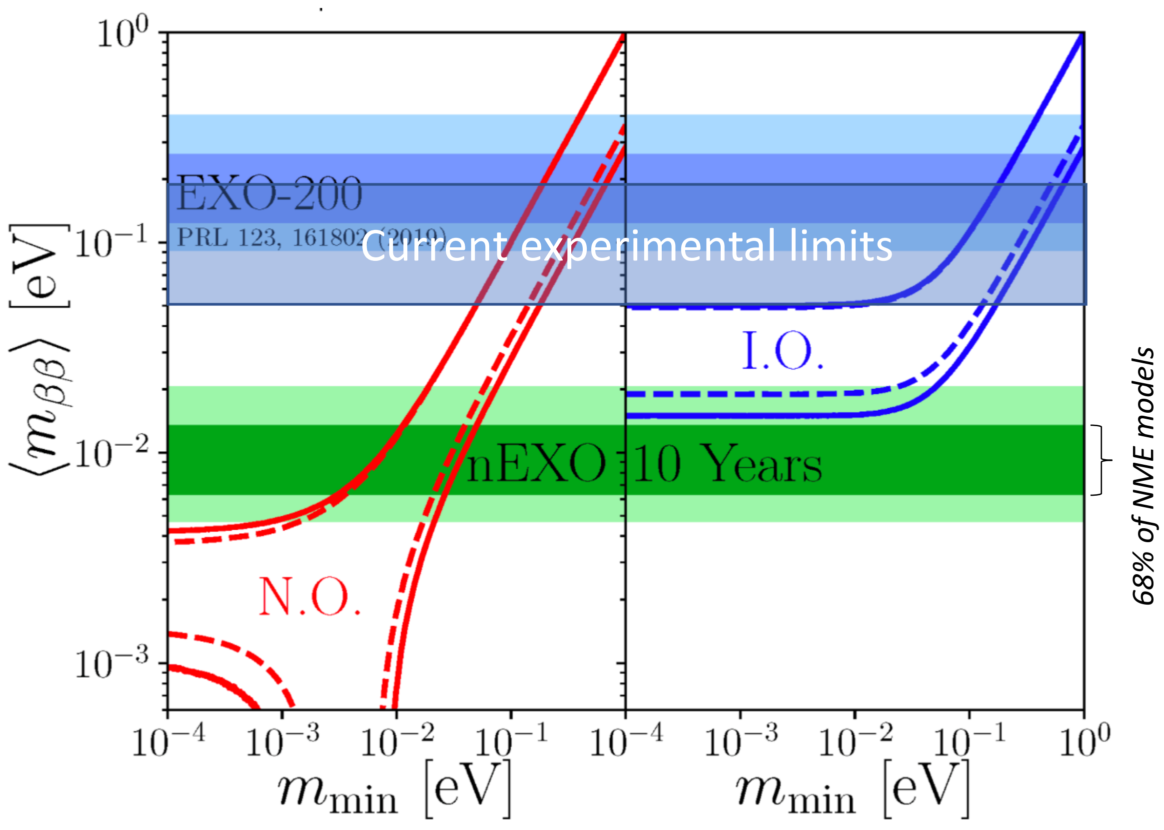
*Median shown to guide the eye; NME is not a statistical value → There is only one correct NME.

nEXO Projected Sensitivity



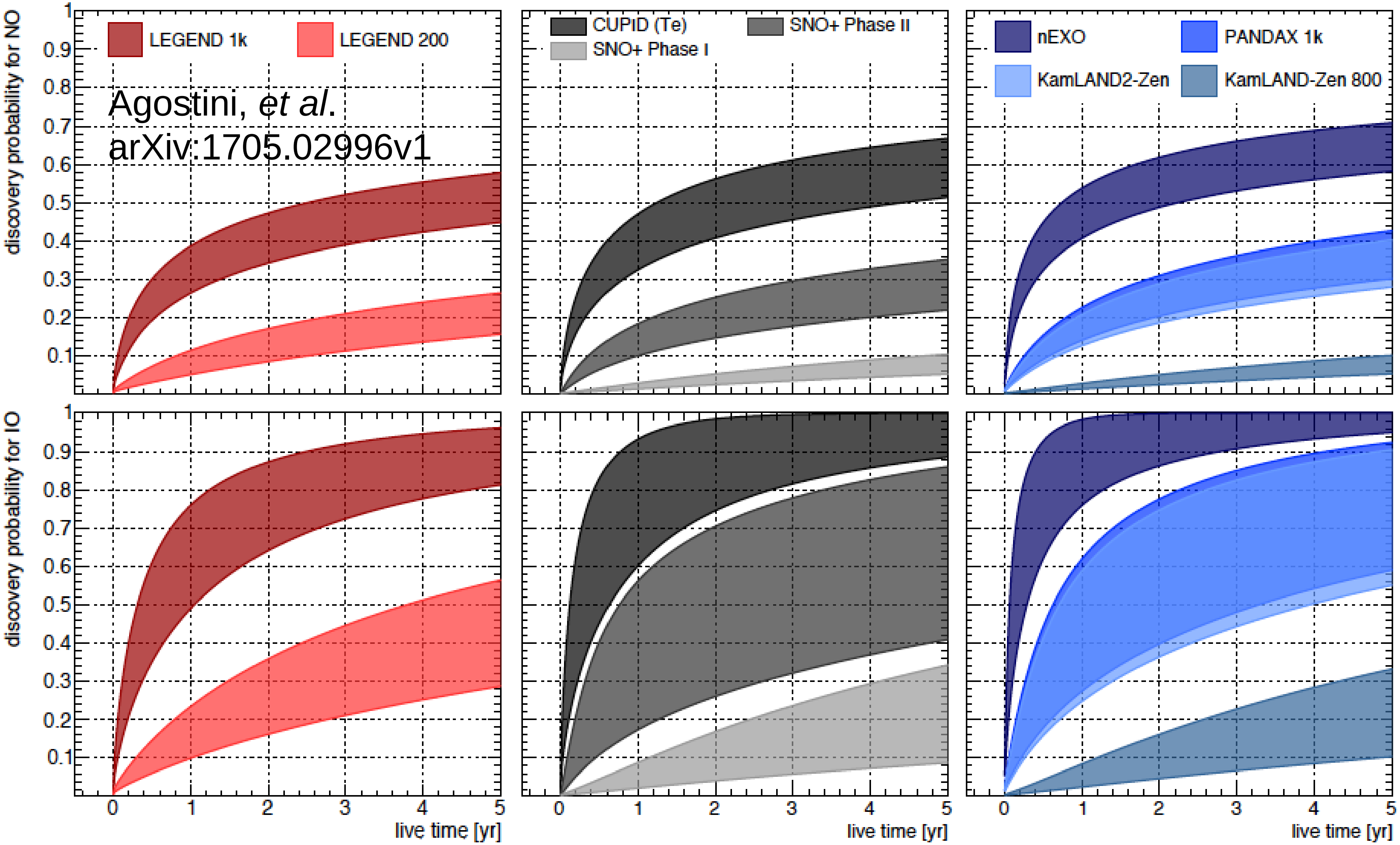
arXiv:2106.16243

Allowed parameter space and nEXO exclusion sensitivity (90% CL):



- Proposed next-generation experiments will significantly increase the sensitivity to 0νββ.
- Projected sensitivities of these experiments are beyond 10^{28} years.

$0\nu\beta\beta$ Discovery Potential



$0\nu\beta\beta$ is the most practical way to test the Majorana nature of neutrinos.

An observation of $0\nu\beta\beta$ always implies 'new' physics!

Summary

- Neutrino physics has delivered many surprising discoveries
- The search for $0\nu\beta\beta$ is the most promising approach to determine the quantum nature of neutrinos: Dirac versus Majorana
- An observation of neutrinoless double beta decay could help explain the observed matter-antimatter asymmetry in the universe
- Next-generation $0\nu\beta\beta$ are being designed to reach sensitivities beyond 10^{28} years (this is 10^{18} times the age of the Universe!)
- An observation of $0\nu\beta\beta$ always implies physics beyond the Standard Model, independent of the underlying process!

Neutrinos, these ghostly particles will continue to surprise us!

Please contact me if you have any questions:
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