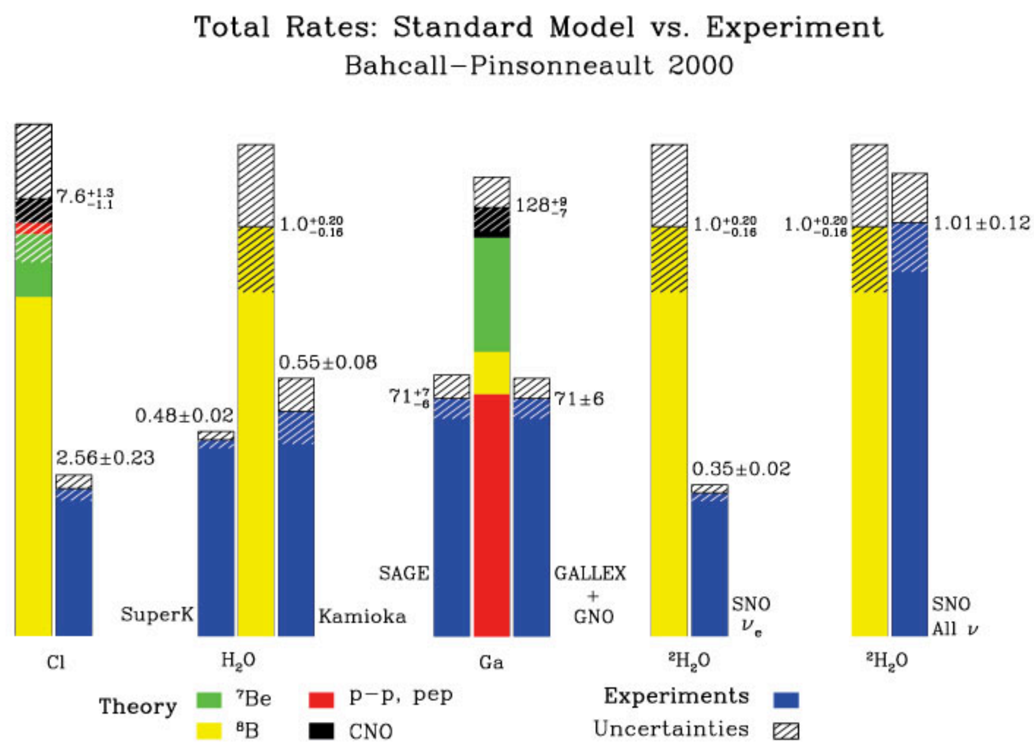
Neutrinos

- Oscillation
- CP violation
- Mass
- Majorana vs. Dirac
- Sterile Neutrinos
- Other fun neutrino experiments…
  - Ice Cube

Neutrinos DISAPPEAR!

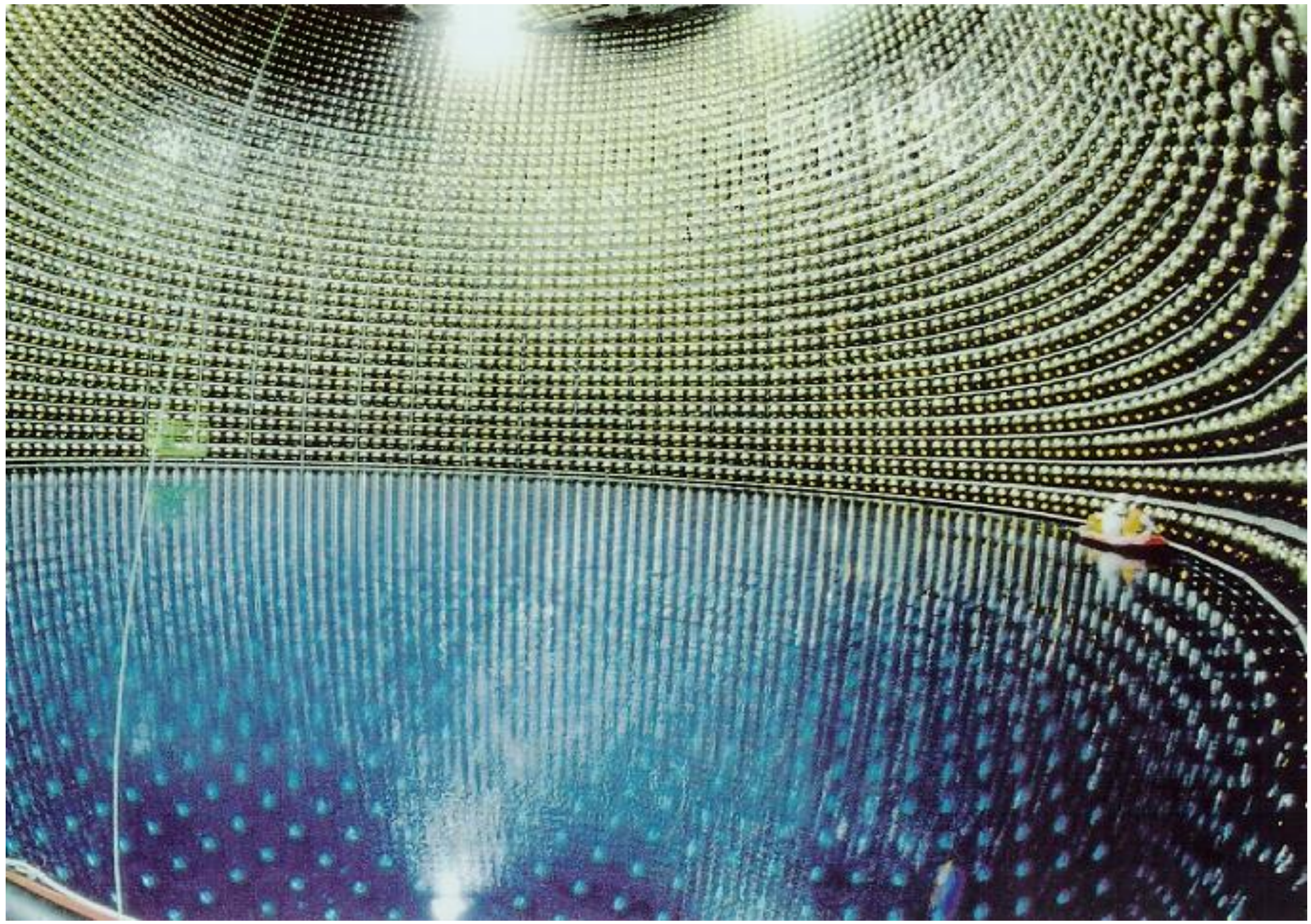
- Originally discovered by Ray Davis: there are too few neutrinos coming from the sun

- Original experiment in Homestead Mine (Cl): Only 1/3 of expected flux
- Confirmed by Sage, Gallex, Super-K, SNO, …
- Confirmed with reactors: Bugey, Chooz, KamLand,… and accelerator neutrinos (T2K, NOνA,…)
- Also found disappearance of μ-neutrinos in atmosphere: Super-K.



Kamiokande, Super-K

- Detect neutrinos from sun and atmospheric neutrinos
- Only 50% of solar νs
- Detection via Cherenkov Light



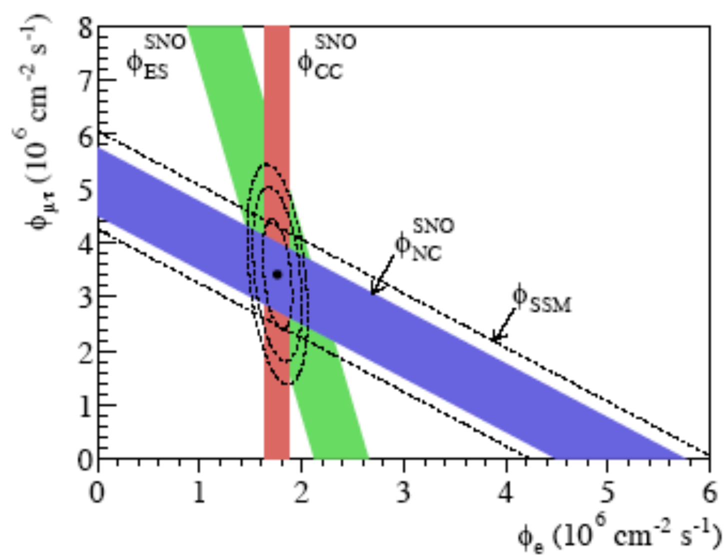
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

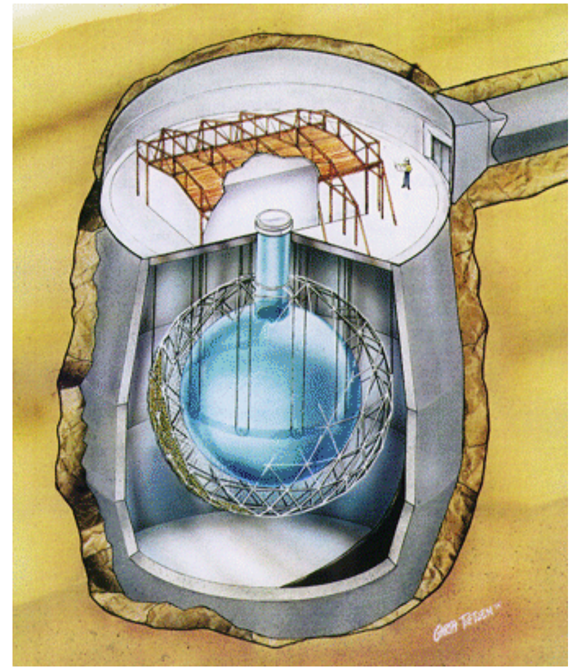
SNO

- Heavy Water Cherenkov detector
- Sensitive to all 3 types of ν's with different observables:

  $d + \nu_e \rightarrow p + p + e^-$;

  $d + \nu_\mu \rightarrow p + n + \nu_\mu$
- First unambiguous confirmation that total number of ν's from sun is as expected - only flavor changes





The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

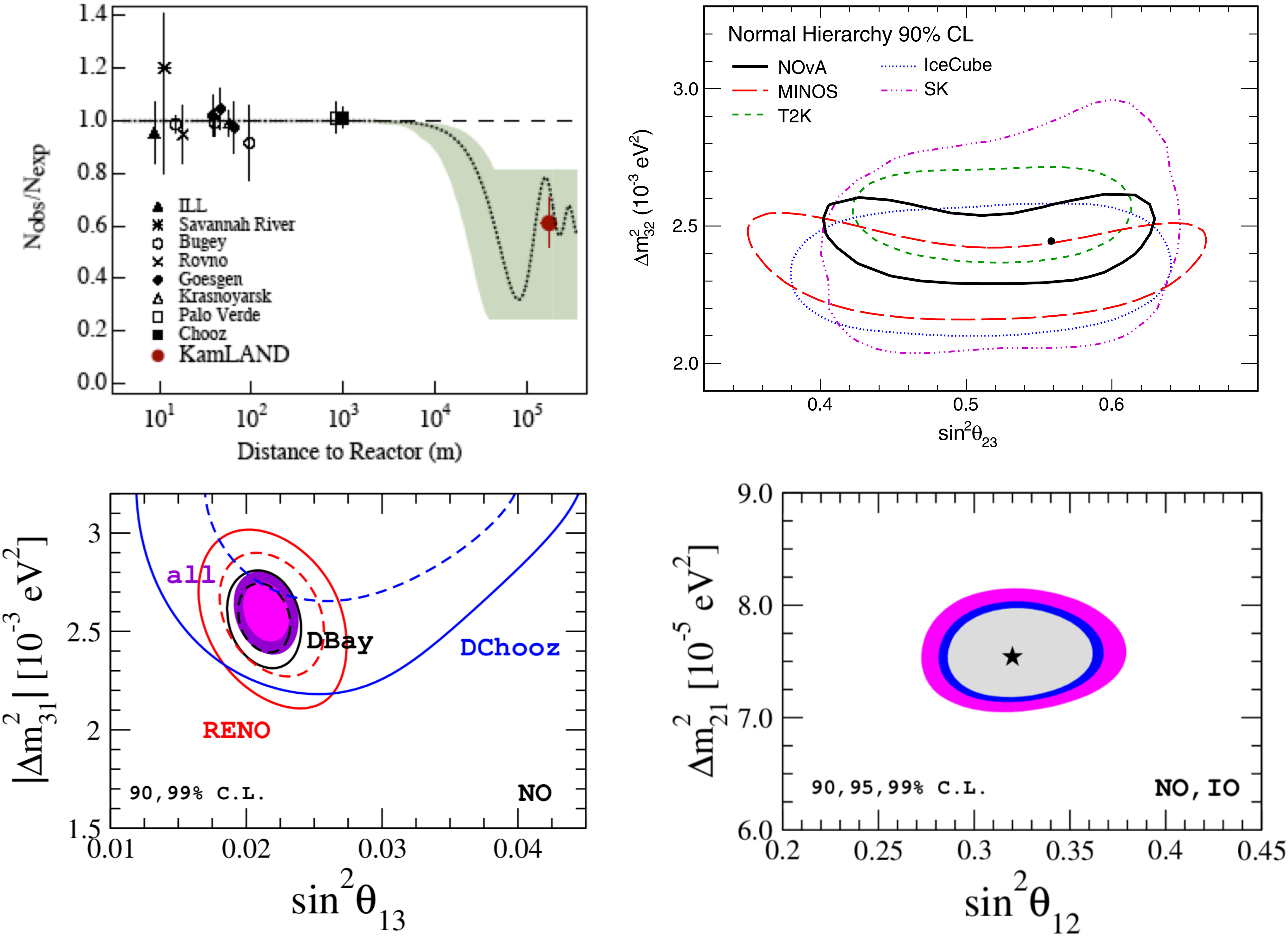
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Explanation: 2 –neutrino model

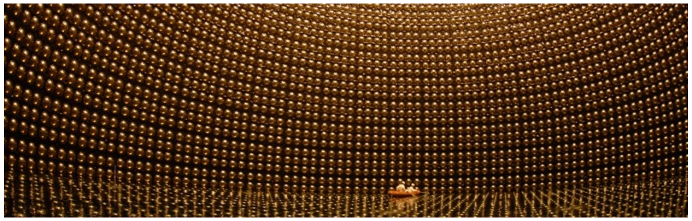
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \text{(natural units)}.$$

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right).$$

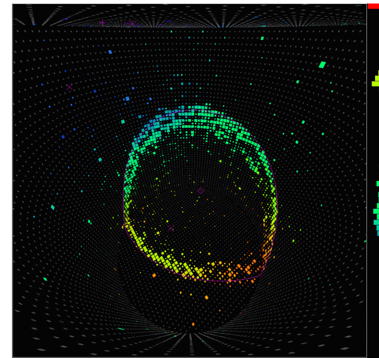
- The mass differences, Δm^2, are known to be on the order of 1×10^{-4} eV^2
- Oscillation distances, L, in modern experiments are on the order of kilometers
- Neutrino energies, E, in modern experiments are typically on order of MeV or GeV.

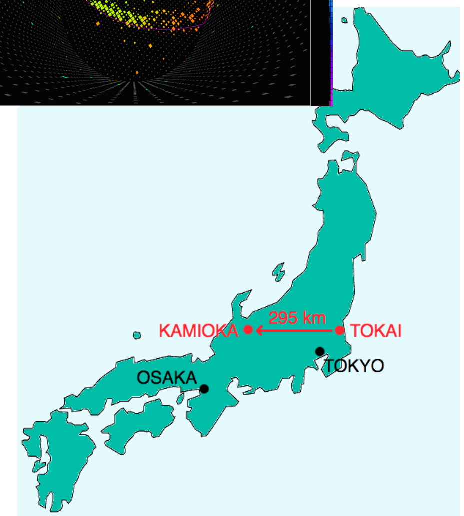


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N_{obs}/N_{exp}
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)
Normal Hierarchy 90% CL
NOvA
MINOS
T2K
IceCube
SK
3.0
2.5
2.0
Δm^2_{32} (10^{-3} eV^2)
0.4
0.5
0.6
$\sin^2\theta_{23}$
3
2.5
2
1.5
$|\Delta m^2_{31}|$ [10^{-3} eV^2]
all
DBay
DChooz
RENO
90,99% C.L.
NO
0.01
0.02
0.03
0.04
$\sin^2\theta_{13}$
9.0
8.0
7.0
6.0
Δm^2_{21} [10^{-5} eV^2]
90,95,99% C.L.
NO,IO
0.2
0.25
0.3
0.35
0.4
0.45
$\sin^2\theta_{12}$

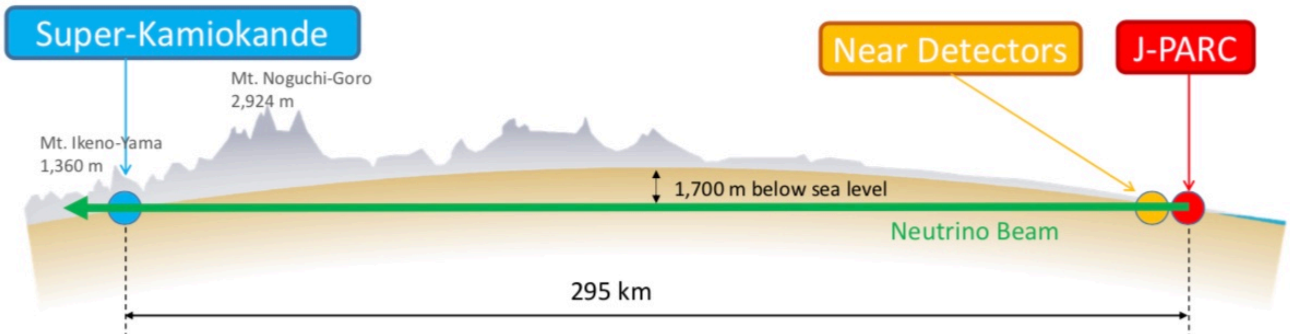


CP violation

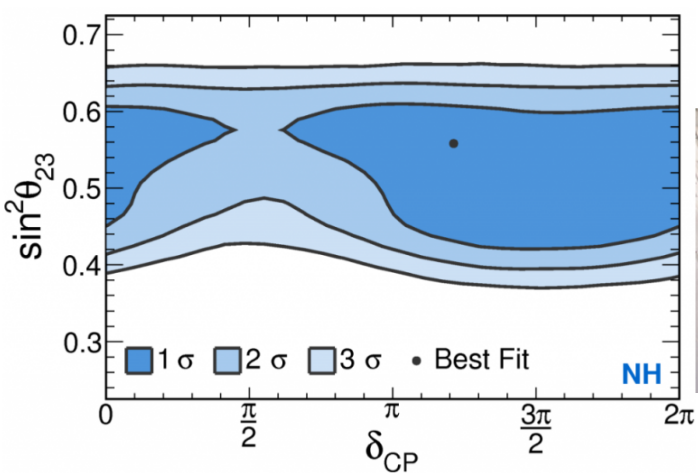




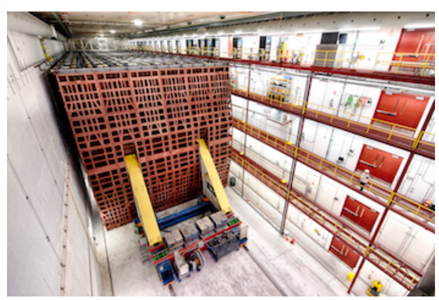
Due to a mixing in the PMNS matrix describing neutrino mixing

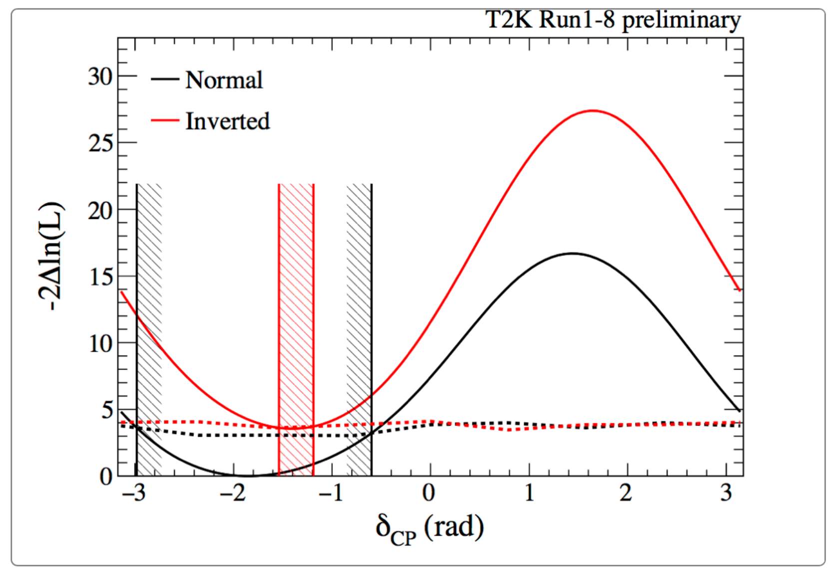


Result from NOvA: A joint fit to the data for ν_μ disappearance and ν_e appearance gives the best fit point as normal mass hierarchy, $\Delta m^2_{32} = 2.44\times10^{-3}$ eV^2/c^4, $\sin^2\theta_{23} = 0.56$, and $\delta_{CP} = 1.21\pi$. The 68.3% confidence intervals in the normal mass hierarchy are $\Delta m^2_{32} \in [2.37,2.52]\times10^{-3}$eV^2/c^4, $\sin^2\theta_{23} \in [0.43,0.51] \cup [0.52,0.60]$, and $\delta_{CP} \in [0,0.12\pi] \cup [0.91\pi,2\pi]$. The inverted mass hierarchy is disfavored at the 95% confidence level for all choices of the other oscillation parameters.



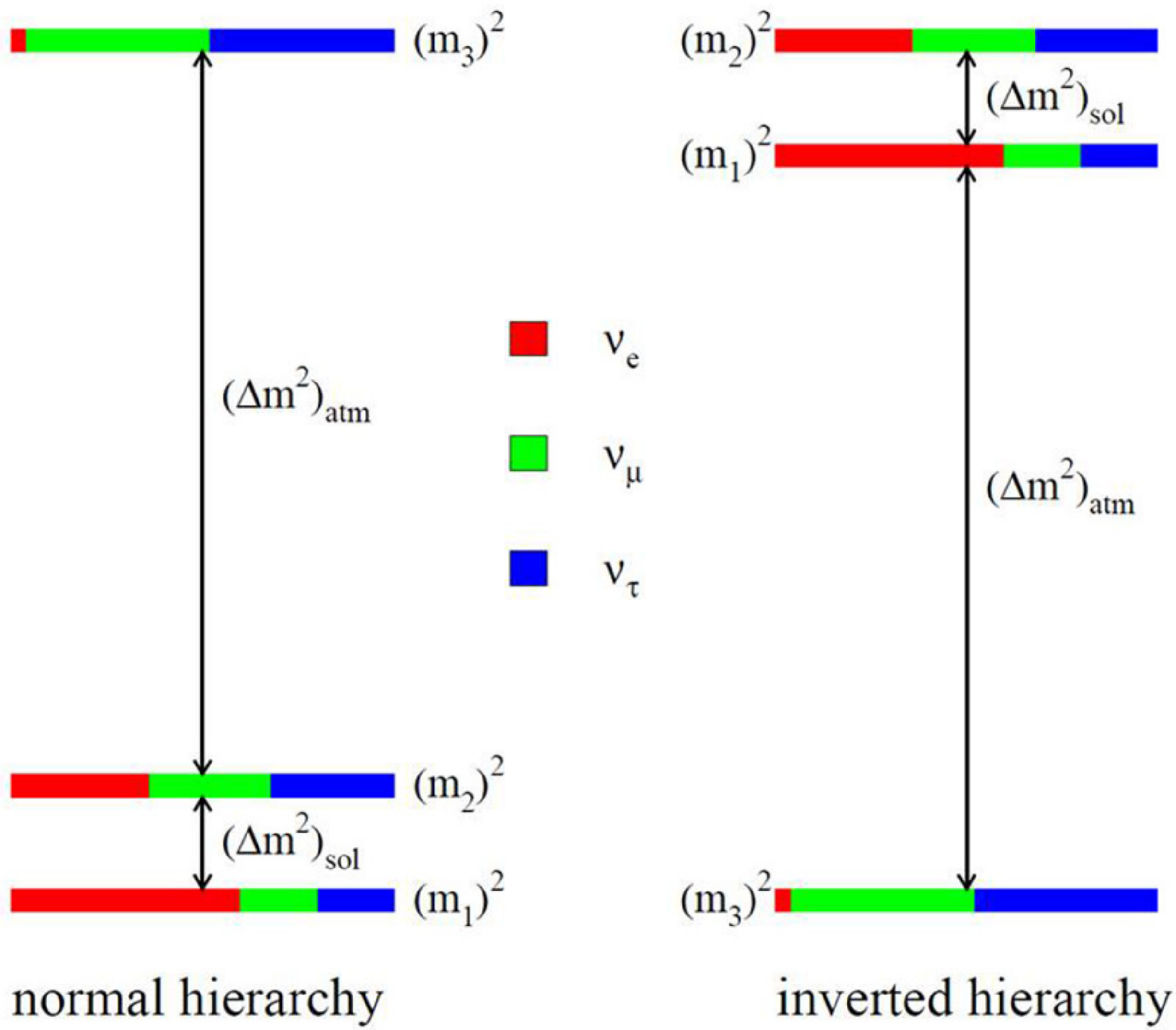
Fermilab-Minnesota





$-2\Delta\ln L$ (equivalent of $\Delta\chi^2$) as a function of δ_{CP} for the normal (black) and inverted (red) mass ordering. The vertical lines show the corresponding allowed 95% confidence interval, calculated using the Feldman-Cousins method.

Neutrino Masses



Absolute Neutrino Mass

KATRIN spectrometer

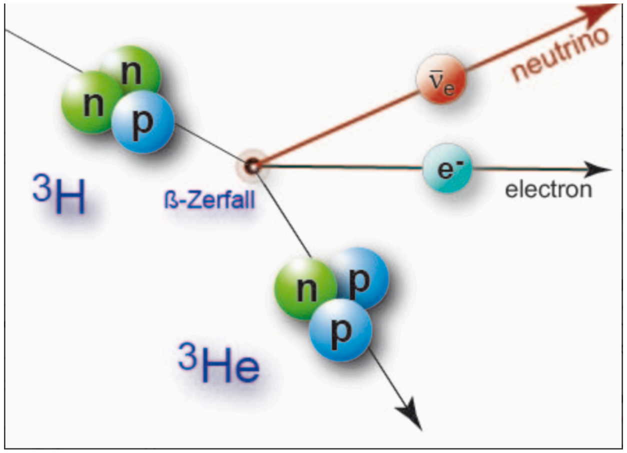
Intense T_2 source
(10^{11} decays/second)

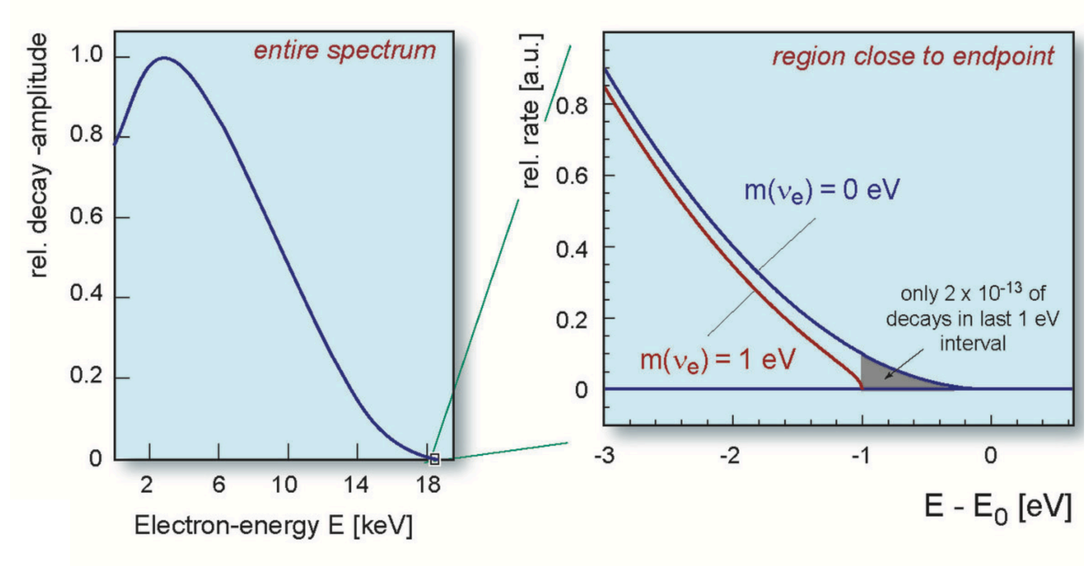
Spectrum analysis with electromagnetic filter

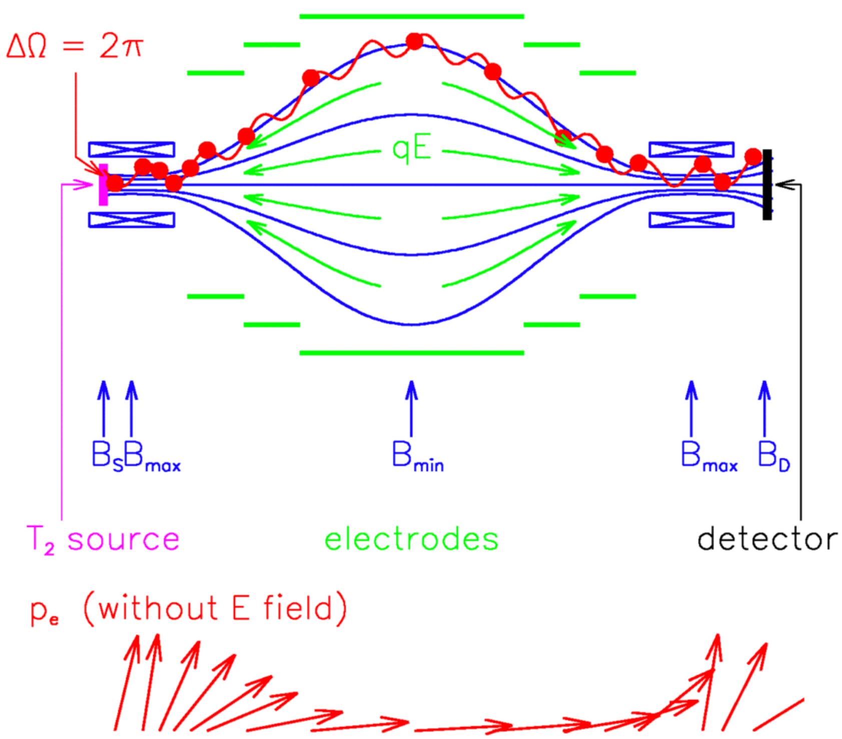
Design resolution: **0.93eV**

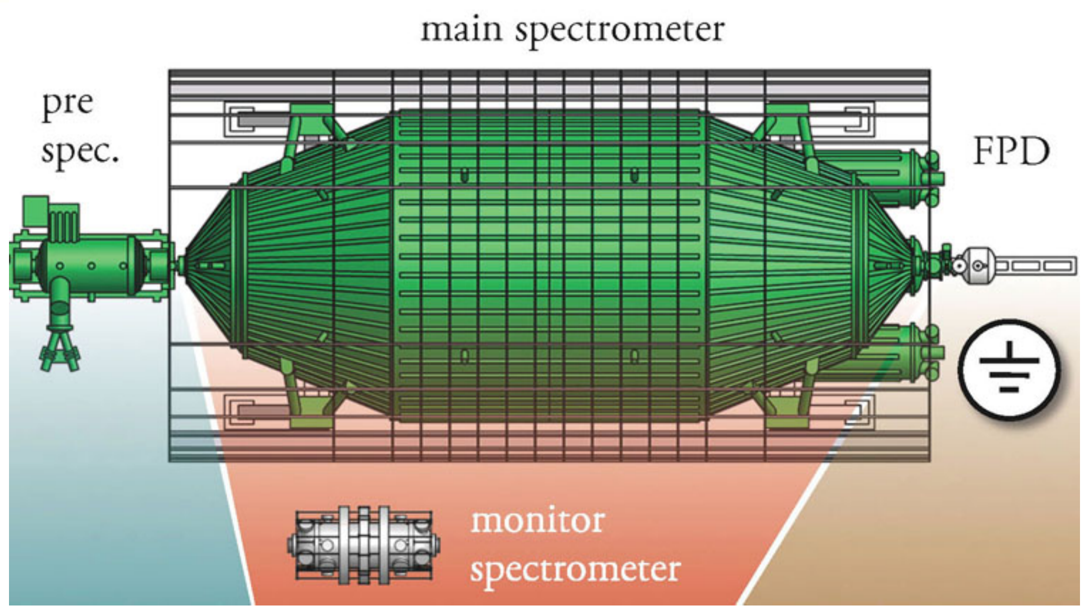
Design $m_{\nu\beta}$ sensitivity: **0.2eV** (90%CL)

How does it work?

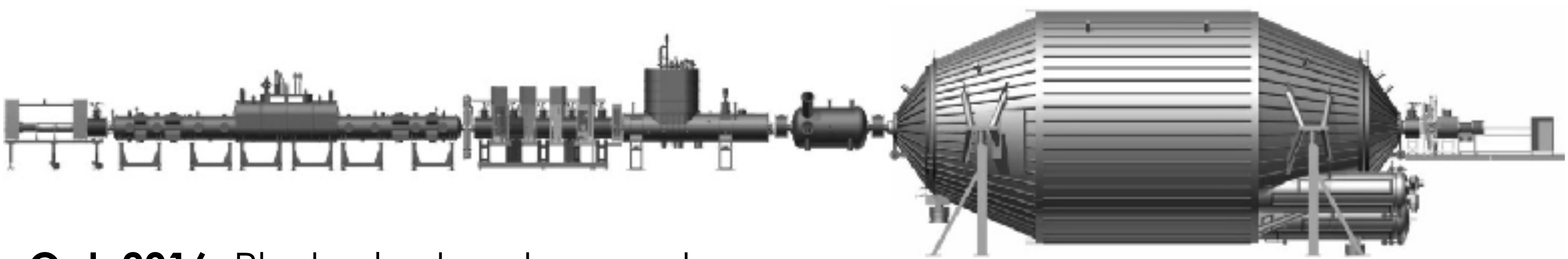




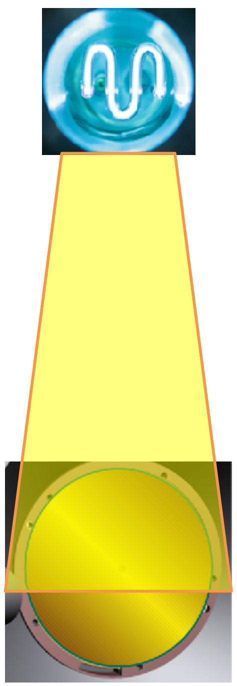




Recent KATRIN Progress



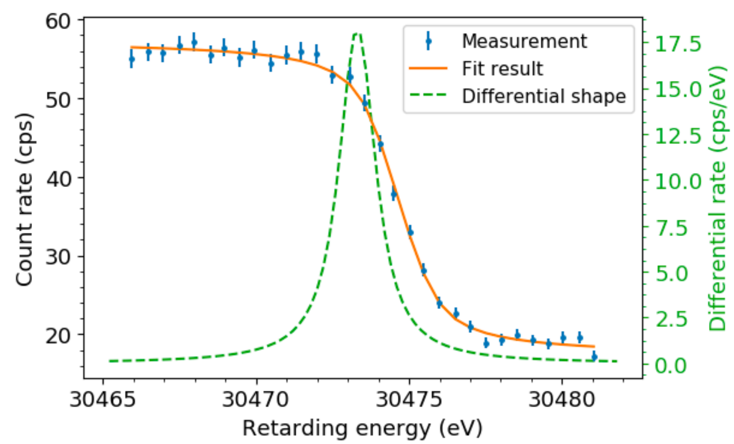
Oct. 2016: Photoelectron transport over full 70m apparatus.



- Illuminate rear wall
- Magnetically guide photoelectrons along beamline
- First all-KATRIN commissioning

Summer 2017: Gaseous and condensed ^{83m}Kr source measurements.

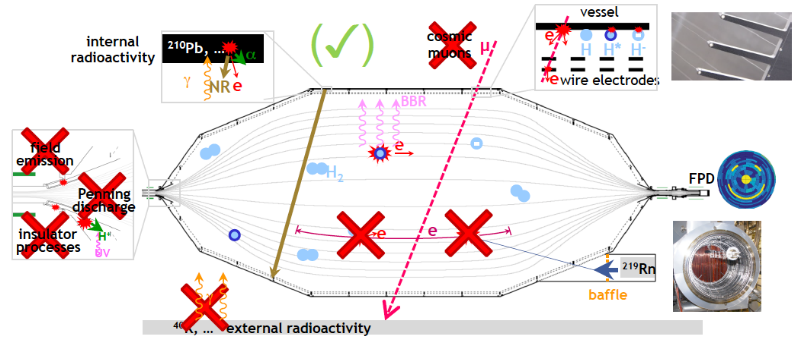
- calibration
- alignment
- systematics

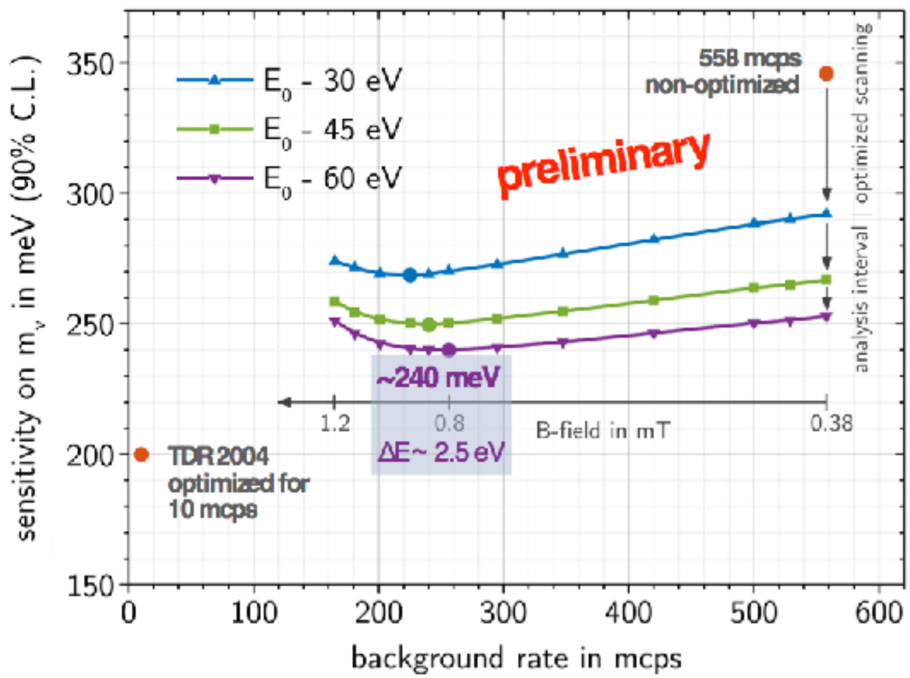


KATRIN - Status and Next 3 Years

Status:

- All major components on-site
- Unexpected background from ^{210}Po decay in/on walls. Background rate ~ 50 times larger then design value (10 mcps), due to ionization of Rydberg atoms by black body radiation
- With revised measurement plan, should reach sensitivity of ~240 meV.
- Implementing major revision of Electronics/FPGA/DAQ to optimize mass sensitivity and sterile neutrinos searches (support much higher data rates, ~ MHz per channel).
- Successful gaseous and condensed Kr commissioning measurements.





Spring 2018: System commissioning with H_2, D_2,

Mid 2018: First tritium data

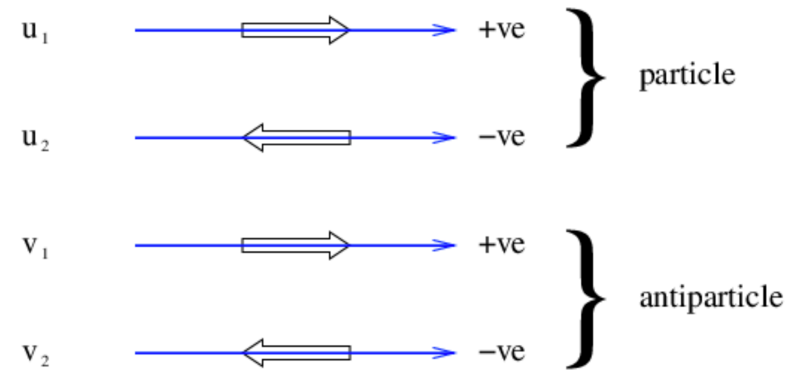
2018-2020:

- First mass results (final sensitivity: 3 beam-yrs)
- Sterile neutrino searches
- Searches for beyond-the-standard-model physics

Neutrinos beyond the Standard Model

- Majorana vs. Dirac
  - What is a Majorana Particle?
  - Could neutrinos be majorana particles?
  - Double beta decay
  - Neutrinoless double beta decay
- Sterile Neutrinos?

What is a Majorana Particle?



- Basic definition:
  A fermion that is its own antiparticle
- Cannot be true for charged particles (electrons, muons, tauons and quarks) – have 4 distinctive dof:
  (Left-handed - right handed) x (particle – antiparticle)
- If neutrinos had NO mass, they would ONLY participate in the weak interaction => only 2 dof: left-handed neutrinos and right-handed (anti)neutrinos
- Mass term in Dirac-equation couples LH to RH -> massive neutrinos must be Dirac-Fermions… or must they?
- Mass eigenstates COULD be linear combinations of neutrinos and antineutrinos
- Another possibility: one heavy (sterile) Majorana neutrino coupling to 3 light and 3 heavy Majorana neutrinos
- Consequence: Lepton number violation

Dirac equation

For a moving particle, $\vec{p} \neq 0$ the Dirac equation becomes (using (5.13) and (5.17)):

$$(\gamma^\mu p_\mu - m)\begin{pmatrix} u_A & u_B \end{pmatrix} = \begin{pmatrix} E-m & -\vec{\sigma}\cdot\vec{p} \\ \vec{\sigma}\cdot\vec{p} & -E-m \end{pmatrix}\begin{pmatrix} u_A \\ u_B \end{pmatrix} = 0 \tag{5.27}$$

where u_A and u_B denote the 1×2 upper and lower components of u respectively. The equations for u_A and u_B are coupled:

$$u_A = \frac{\vec{\sigma}\cdot\vec{p}}{E-m}u_B \qquad u_B = \frac{\vec{\sigma}\cdot\vec{p}}{E+m}u_A \tag{5.28}$$

$$u^1 = \begin{pmatrix} 1 \\ 0 \\ p_z/(E+m) \\ (p_x+ip_y)/(E+m) \end{pmatrix} \quad u^2 = \begin{pmatrix} 0 \\ 1 \\ (p_x-ip_y)/(E+m) \\ -p_z/(E+m) \end{pmatrix}$$

$$u^3 = \begin{pmatrix} -p_z/(-E+m) \\ (-p_x-ip_y)/(-E+m) \\ 1 \\ 0 \end{pmatrix} \quad u^4 = \begin{pmatrix} (-p_x+ip_y)/(-E+m) \\ p_z/(-E+m) \\ 0 \\ 1 \end{pmatrix}$$

Setting $m = 0$ and $p = p_z = E$ in the highly relativistic limit $\beta \to 1$:

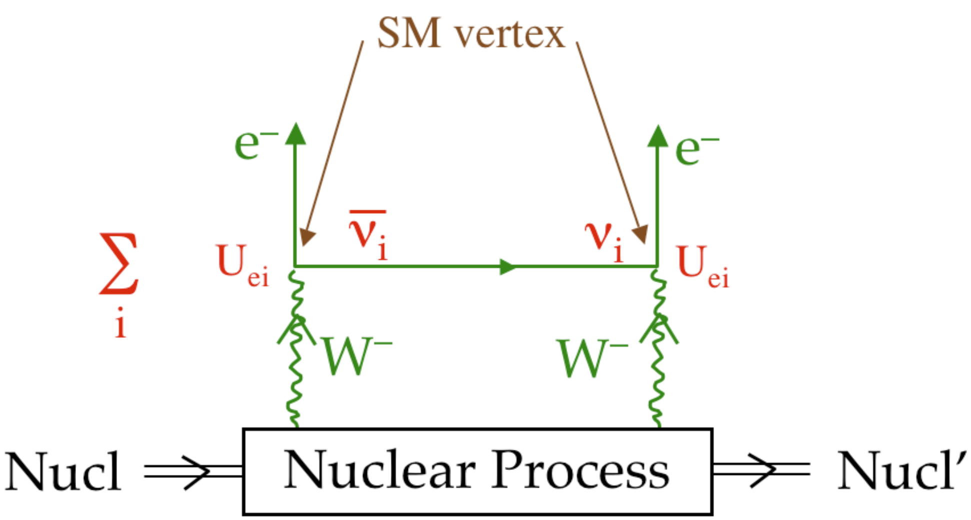
$$u^1 = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad u^2 = \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix} \quad v^2 = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad v^1 = \begin{pmatrix} 0 \\ -1 \\ 0 \\ 1 \end{pmatrix}$$

What is a Majorana Particle?

Left-handed Majorana Mass Term: $\mathcal{L}_L = m_L \overline{\nu_L} \nu_L{}^c$, which absorbs a $(\bar{\nu})_R$ and creates a ν_L

=> Mass eigenstates: $\nu_i = \nu_L + \nu_L{}^c$

Consequence: Lepton-number violating neutrinoless double-beta decay



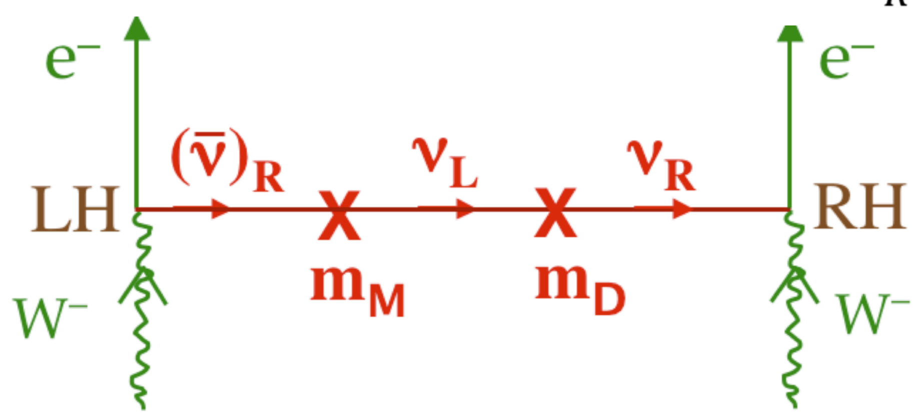
Decay rate is proportional to

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

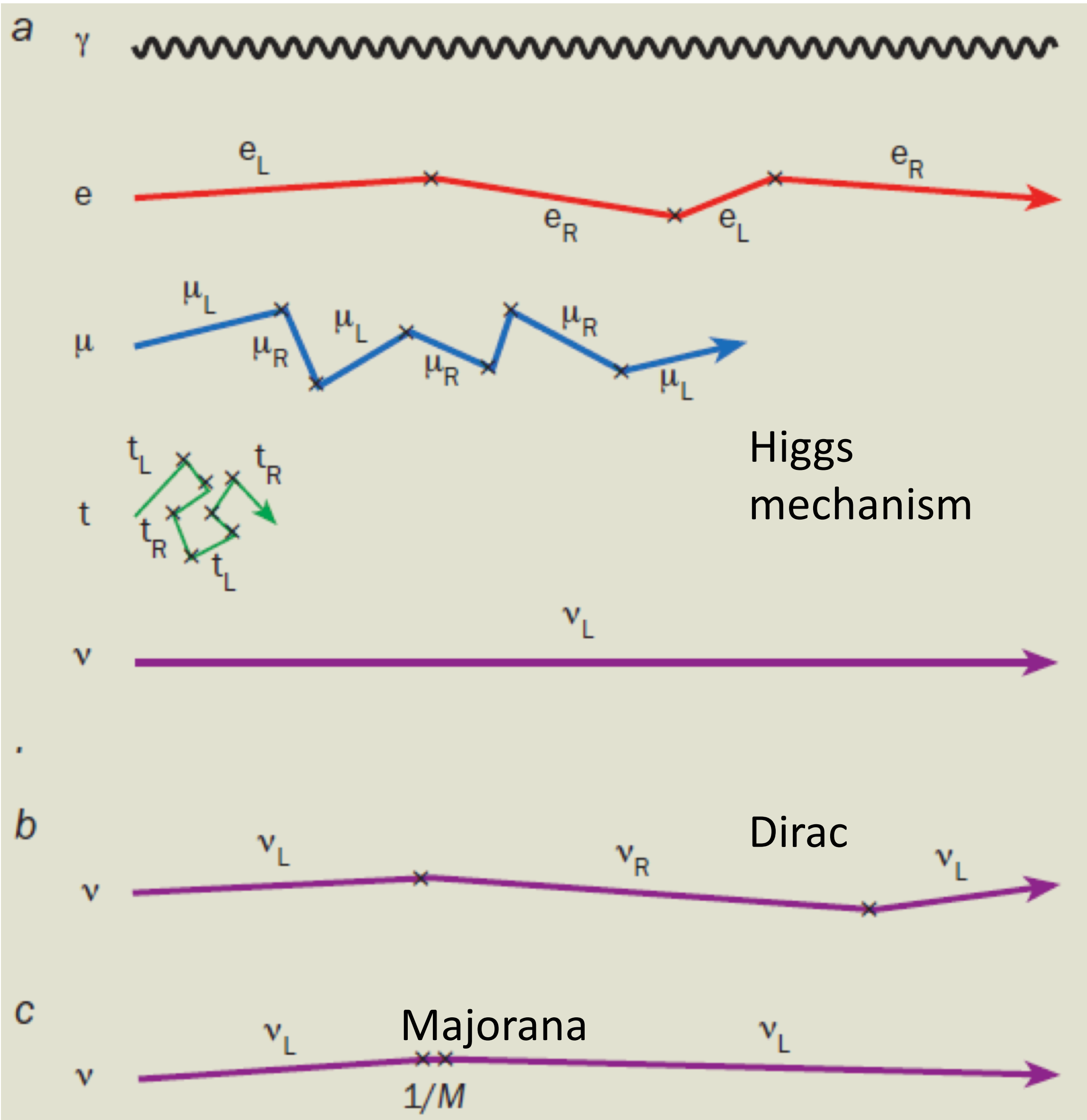
More general (+RH heavy Majorana ν):

$$\mathcal{L}_m \sim m_D\,[\,\bar{\psi}_L \psi_R + \ldots] + \,[m_L \bar{\psi}_L^c\, \psi_L + m_R \bar{\psi}_R^c\, \psi_R + h.c.]$$

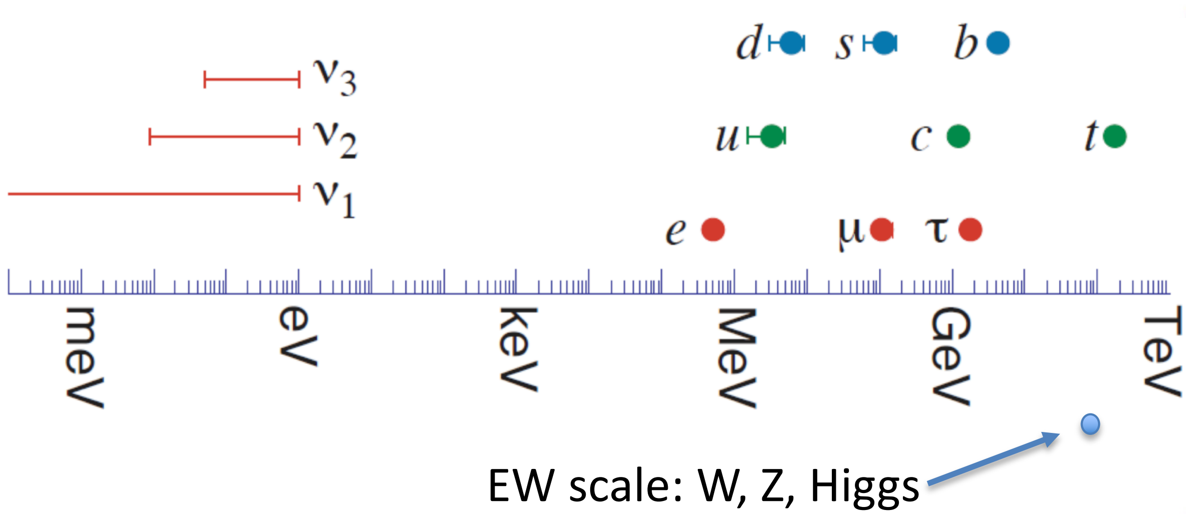
See-saw mechanism: $m_\nu \sim m_D \left(\frac{m_D}{m_R}\right)$

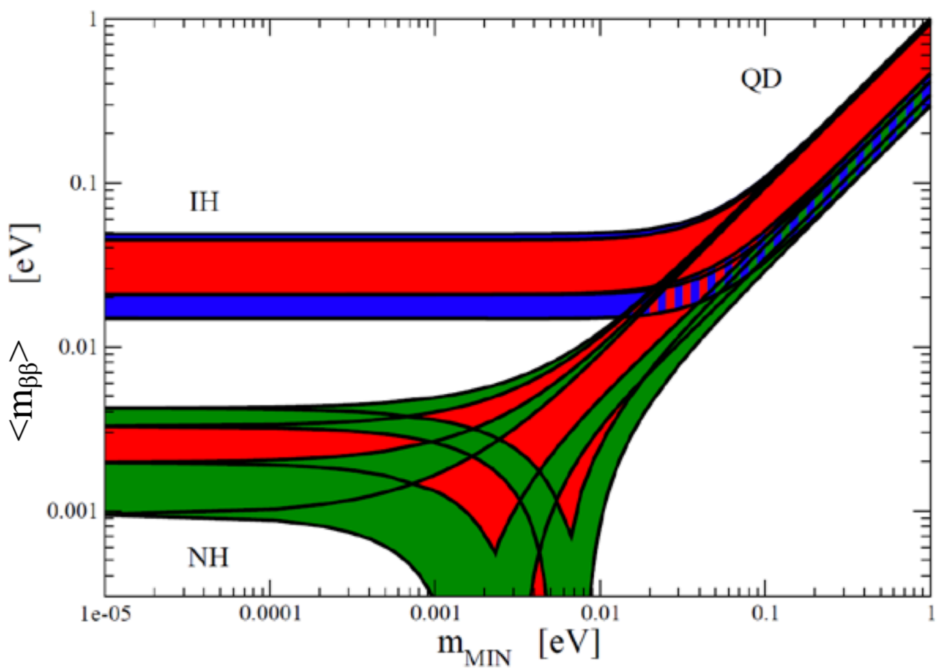


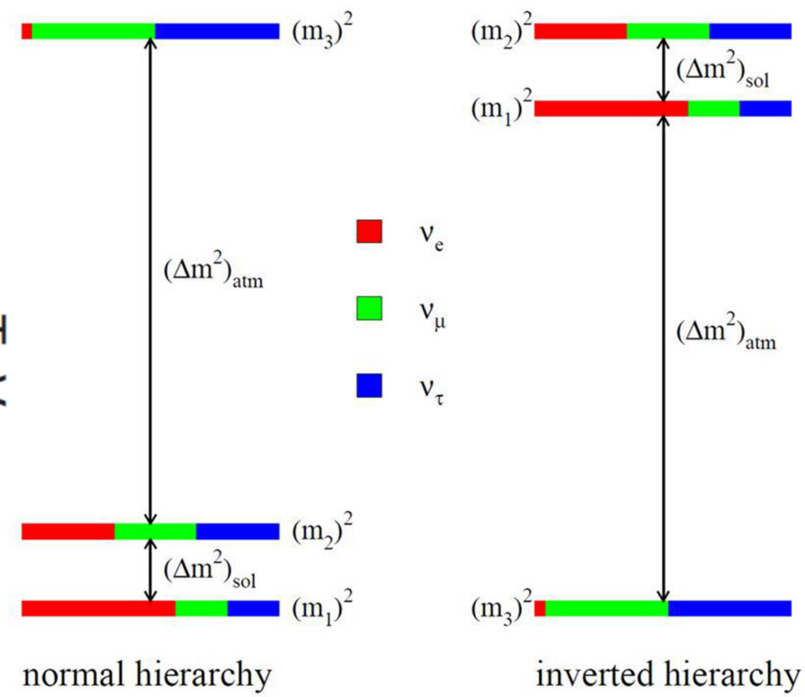
Mass generation



Reminder: neutrino masses







Cosmological bounds:

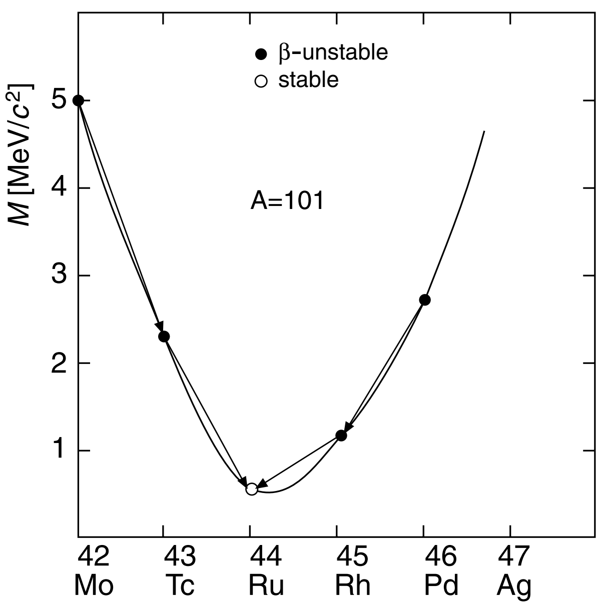
Present: $\Sigma m < 0.25$ eV

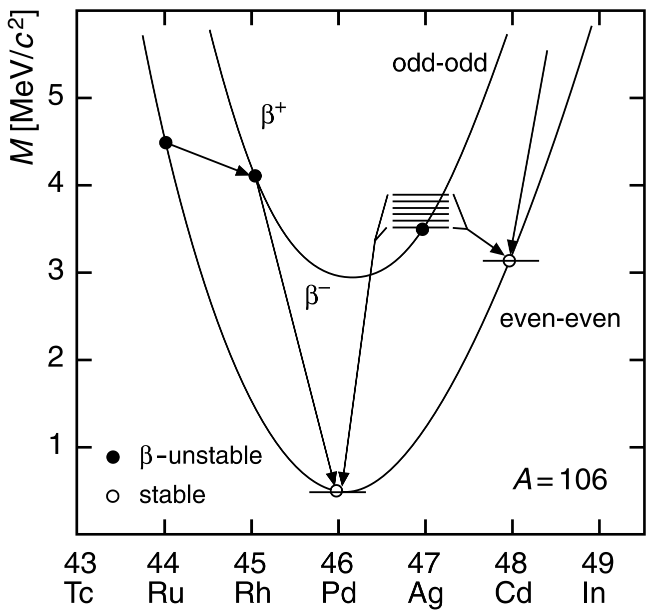
Future: push to 0.01 eV

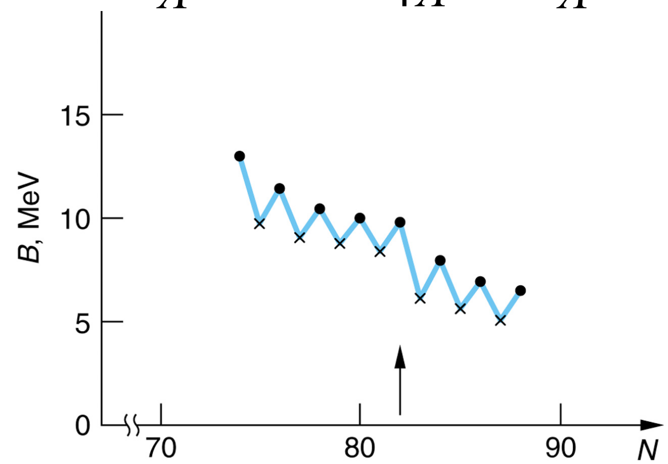
Nuclear Beta Decay

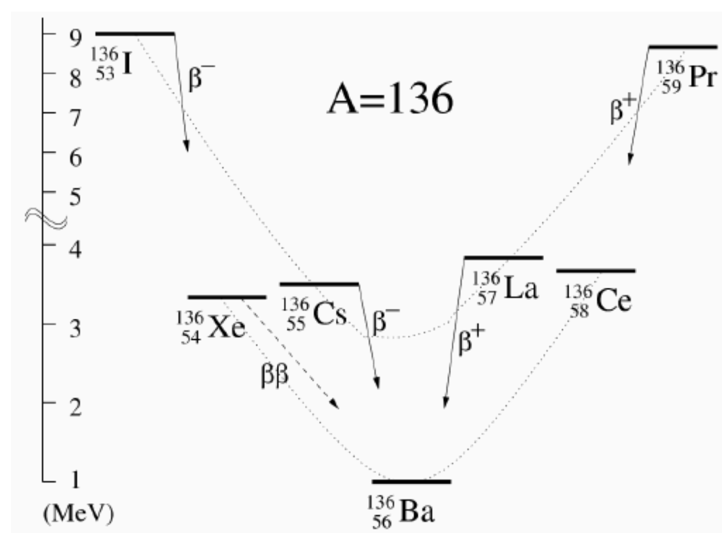
Reminder:

$$M(A,Z) = N \cdot M_n + Z \cdot M_p + Z \cdot m_e - |B|/c^2 \; ; \quad |B| = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_a \frac{(N-Z)^2}{4A} \pm \frac{\delta}{A^{1/2}}$$





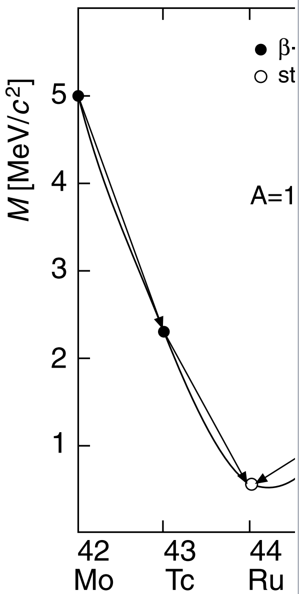




Beta-minus decay: M(A,Z) > M(A,Z+1)

Reminder:

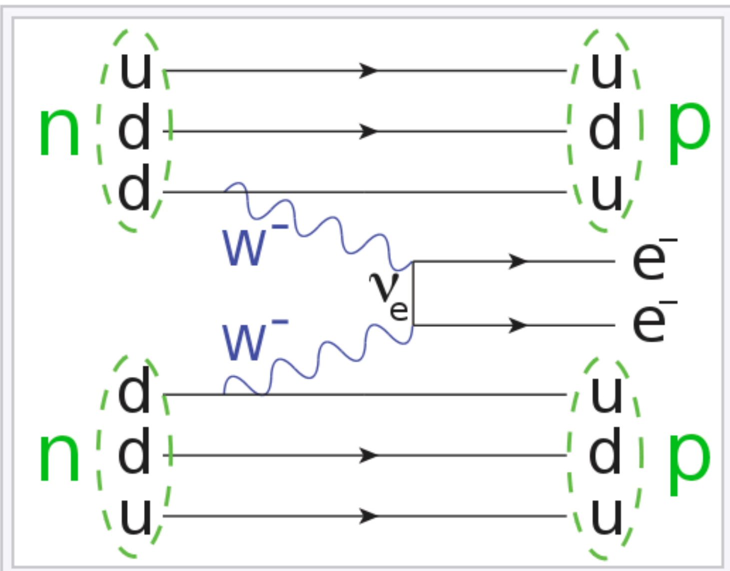
$M(A,Z) =$

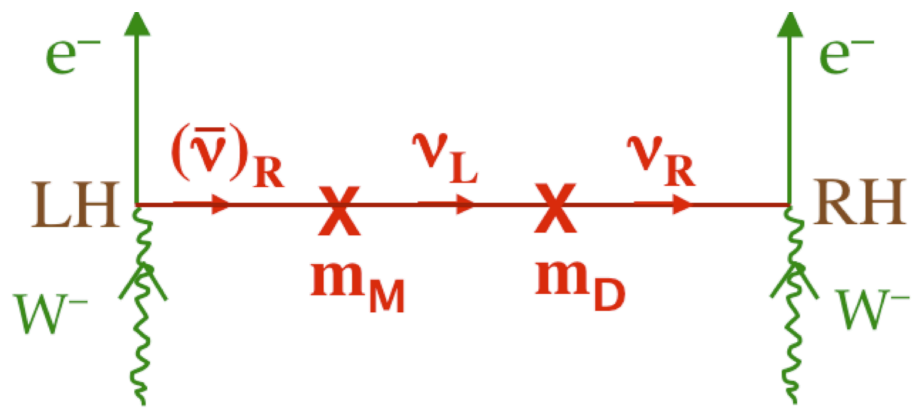


Nuclide	Half-life, 10^{21} years	Mode	Transition	Method	Experiment
^{48}Ca	$0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$	$\beta^-\beta^-$		direct	NEMO-3[10]
^{76}Ge	1.926 ± 0.094	$\beta^-\beta^-$		direct	GERDA[9]
^{78}Kr	$9.2^{+5.5}_{-2.6} \pm 1.3$	εε		direct	BAKSAN[9]
^{82}Se	$0.096 \pm 0.003 \pm 0.010$	$\beta^-\beta^-$		direct	NEMO-3[9]
^{96}Zr	$0.0235 \pm 0.0014 \pm 0.0016$	$\beta^-\beta^-$		direct	NEMO-3[9]
^{100}Mo	0.00693 ± 0.00004	$\beta^-\beta^-$		direct	NEMO-3[9]
	$0.69^{+0.10}_{-0.08} \pm 0.07$	$\beta^-\beta^-$	$0^+ \to 0^+_1$		Ge coincidence[9]
^{116}Cd	$0.028 \pm 0.001 \pm 0.003$ $0.026^{+0.009}_{-0.005}$	$\beta^-\beta^-$		direct	NEMO-3[9] ELLEGANT IV[9]
^{128}Te	7200 ± 400 1800 ± 700	$\beta^-\beta^-$		geochemical	[9]
^{130}Te	$0.82 \pm 0.02 \pm 0.06$	$\beta^-\beta^-$		direct	CUORE-0[11]
^{136}Xe	$2.165 \pm 0.016 \pm 0.059$	$\beta^-\beta^-$		direct	EXO-200[9]
^{130}Ba	(0.5 – 2.7)	εε		geochemical	[12][13]
^{150}Nd	$0.00911^{+0.00025}_{-0.00022} \pm 0.00063$	$\beta^-\beta^-$		direct	NEMO-3[9]
	$0.107^{+0.046}_{-0.026}$	$\beta^-\beta^-$	$0^+ \to 0^+_1$		Ge coincidence[9]
^{238}U	2.0 ± 0.6	$\beta^-\beta^-$		radiochemical	[9]

Beta-minu

NeutrinoLESS double beta decay



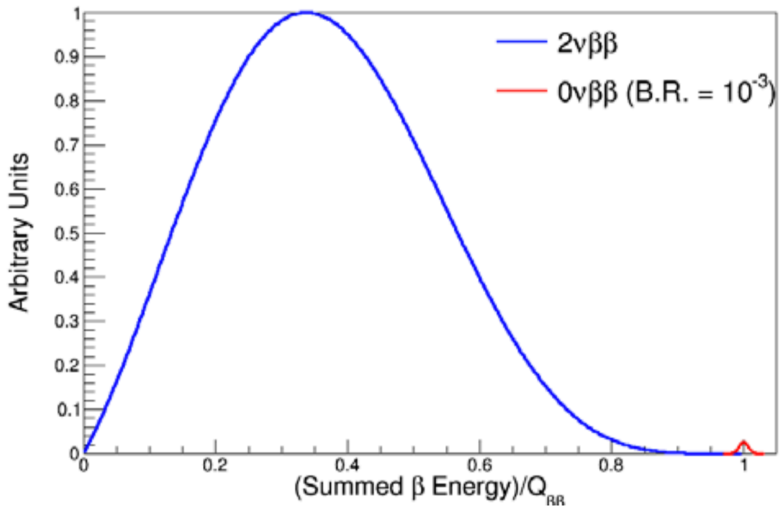


$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$ (of order 10^{25} years)

where $G^{0\nu}$ is the exactly calculable phase space integral, $<m_{\beta\beta}>$ is the effective neutrino mass and $M^{0\nu}$ is the nuclear matrix element. The effective neutrino mass is

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 \; m_{\nu i}|^2$$

Detection

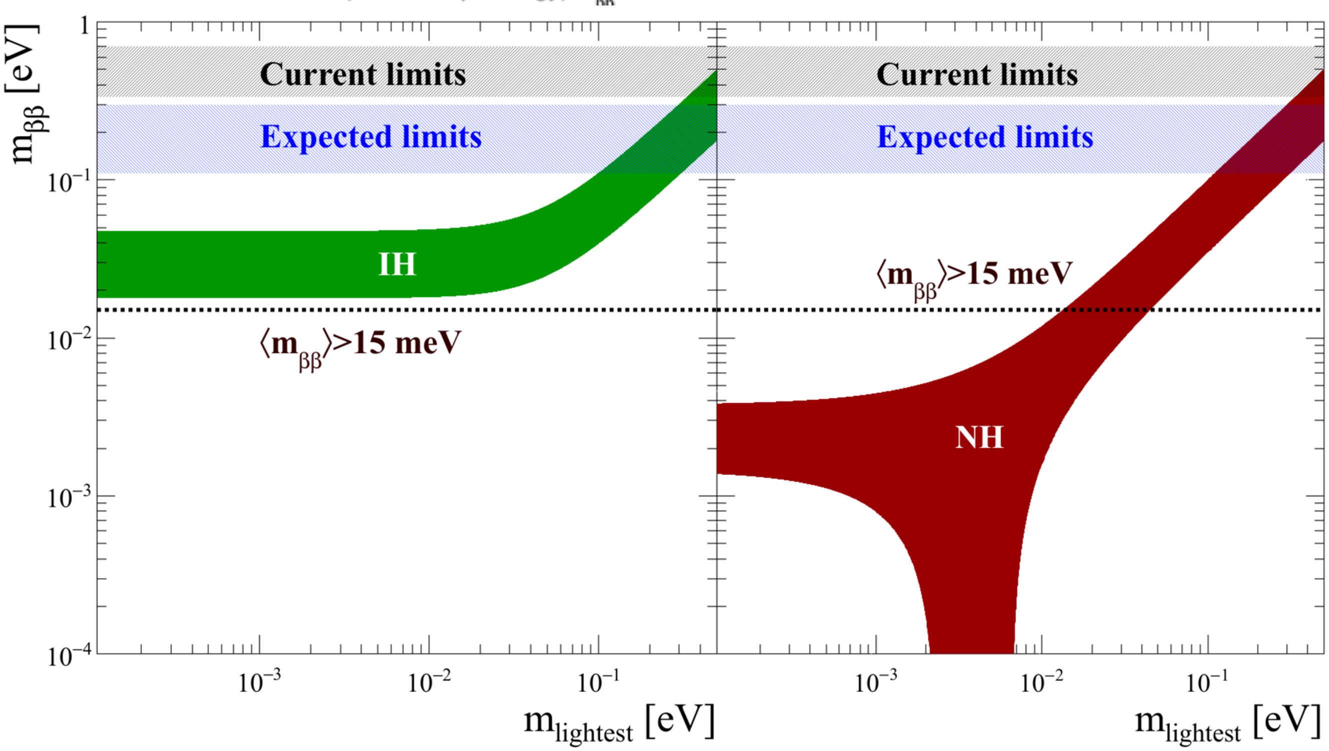


Reminder: Ordinary beta-decay

$$\mathrm{d}W(E_\mathrm{e}) = \frac{2\pi}{\hbar}\,|\mathcal{M}_{fi}|^2\,\frac{\mathrm{d}\varrho_f(E_0,E_\mathrm{e})}{\mathrm{d}E_\mathrm{e}}\mathrm{d}E_\mathrm{e}$$

$$\mathrm{d}\varrho_f(E_0,E_\mathrm{e}) = (4\pi)^2\,V^2\,\frac{E_\mathrm{e}\sqrt{E_\mathrm{e}^2 - m_\mathrm{e}^2c^4}\cdot(E_0-E_\mathrm{e})^2}{(2\pi\hbar c)^6}\,\mathrm{d}E_\mathrm{e}$$

Similar shape for 2β2ν decay



Sensitivity:

Effective average neutrino mass from neutrinoless double beta decay vs. the mass of the lightest neutrino. Current limits and expected limits from ongoing experiments are shown as gray and blue horizontal bands. The green (for inverted hierarchy) and red (for normal hierarchy) bands show the expected ranges within the light Majorana neutrino exchange mechanism. Next-generation ton-scale experiments aim to probe effective Majorana neutrino masses down to 15 meV, shown as the horizontal dashed line.

NeutrinoLESS double beta decay

Experiments taking data as of November 2017:

- COBRA, ^{116}Cd in room temperature CdZnTe crystals
- CUORE, ^{130}Te in ultracold TeO_2 crystals
- EXO, a ^{136}Xe and ^{134}Xe search
- GERDA, a ^{76}Ge detector
- KamLAND-Zen, a ^{136}Xe search. Data collection from 2011.[20]
- Majorana, using high purity ^{76}Ge p-type point-contact detectors.[21]
- XMASS using liquid Xe

Proposed/future experiments:

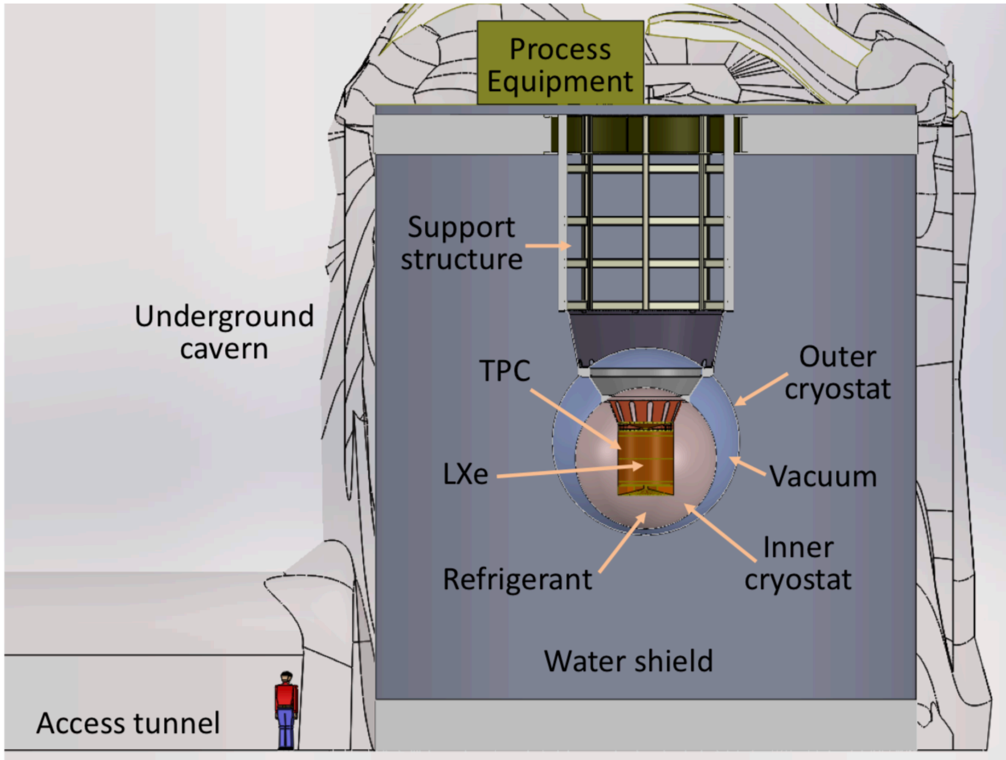
- CANDLES, ^{48}Ca in CaF_2, at Kamioka Observatory
- MOON, developing ^{100}Mo detectors
- AMoRE, ^{100}Mo enriched $CaMoO_4$ crystals at YangYang[22]
- nEXO, using liquid ^{136}Xe in a time projection chamber[23]
- LEGEND, Neutrinoless Double-beta Decay of ^{76}Ge.
- LUMINEU, exploring ^{100}Mo enriched $ZnMoO_4$ crystals at LSM, France.
- NEXT, a Xenon TPC. NEXT-DEMO ran and NEXT-100 will run in 2016.
- SNO+, a liquid scintillator, will study ^{130}Te
- SuperNEMO, a NEMO upgrade, will study ^{82}Se
- TIN.TIN, a ^{124}Sn detector at INO
- PandaX-III, an experiment with 200 kg to 1000 kg of 90% enriched ^{136}Xe

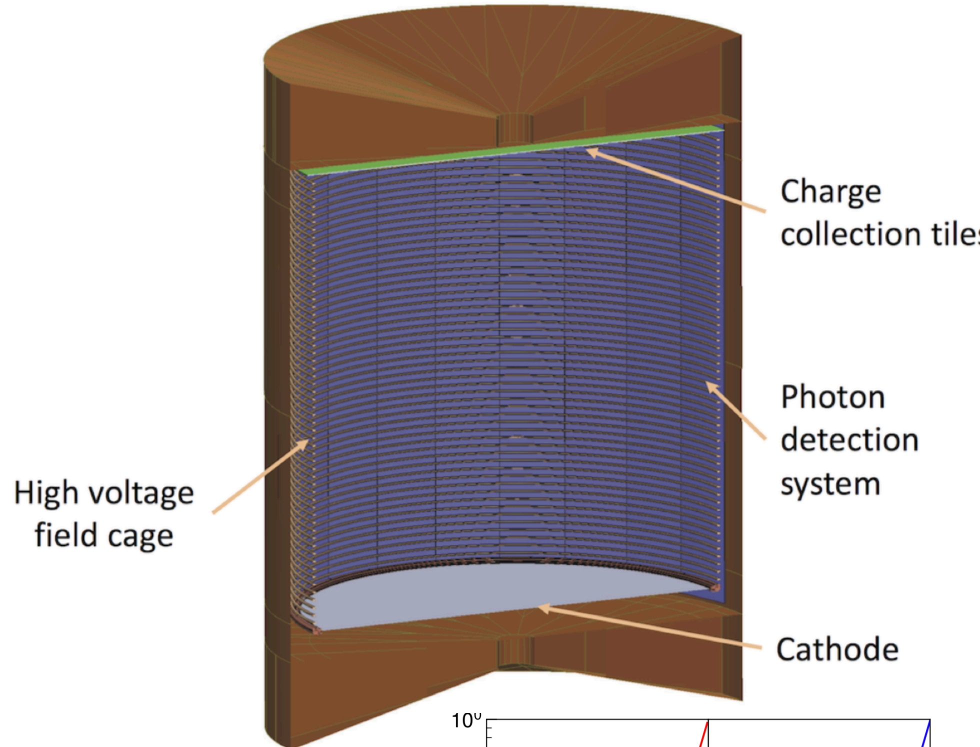
In the U.S. the Enriched Xenon Observatory (EXO-200) is currently operational at WIPP in New Mexico using 3D/time imaging in a liquid 136Xe chamber, while the Majorana Demonstrator at the Sanford laboratory in South Dakota using p-type point-contact 76Ge detectors is about to come on line. The Cryogenic Underground Observatory for Rare Events (CUORE) located at Gran Sasso National Laboratory in Italy is being assembled and commissioned using TeO2 crystals in a bolometric detector configuration. SNO+ at SNOLAB in Canada is a large-volume, loaded-scintillator detector under construction using 130Te. Other experiments, with some U.S. involvement, using 136Xe are KamLAND-Zen at the Kamioka mine in Japan, NEXT at the Canfranc Laboratory in Spain, and PANDAX-III at the JinPing Laboratory in China.

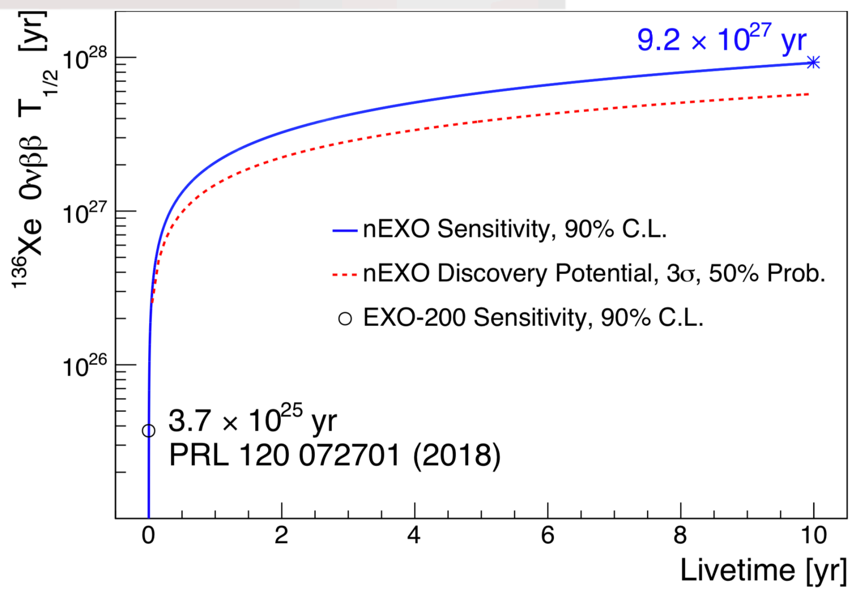
Running Experiments

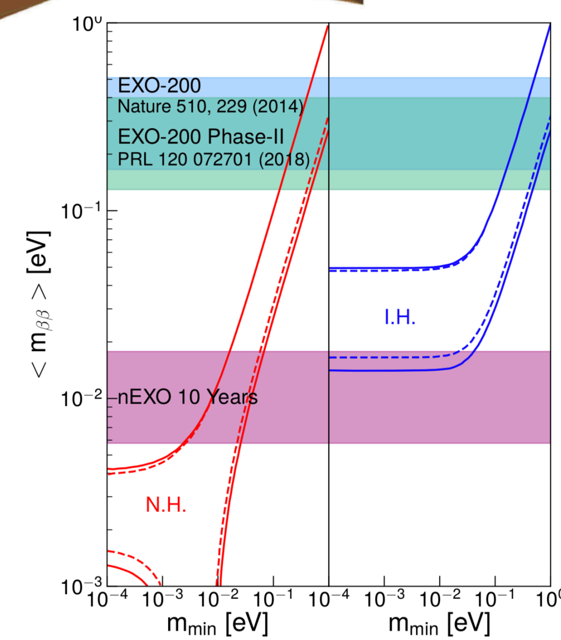
Experiment	BI	Median Sensitivity	$T_{1/2}$ Limit	$\langle m_{\beta\beta} \rangle$
KamLAND-Zen	~20×10^{-3} c/(keV kg yr)	5.6×10^{25} yr	1.1×10^{26} yr	61-165meV
EXO-200	1.5×10^{-3} c/(keV kg yr)	3.7×10^{25} yr	1.8×10^{25} yr	147-398meV
CUORE	14×10^{-3} c/(keV kg yr)	7×10^{24} yr	1.5×10^{25} yr	140-400meV
GERDA	$1.0^{+0.6}_{-0.4}\times10^{-3}$ c/(keV kg yr)	4.0×10^{25} yr	5.3×10^{25} yr	150-330meV
MJD	$1.6^{+1.2}_{-1.0}\times10^{-3}$ c/(keV kg yr)	2.1×10^{25} yr	1.9×10^{25} yr	240-520meV

Example: nEXO (Snolab?)





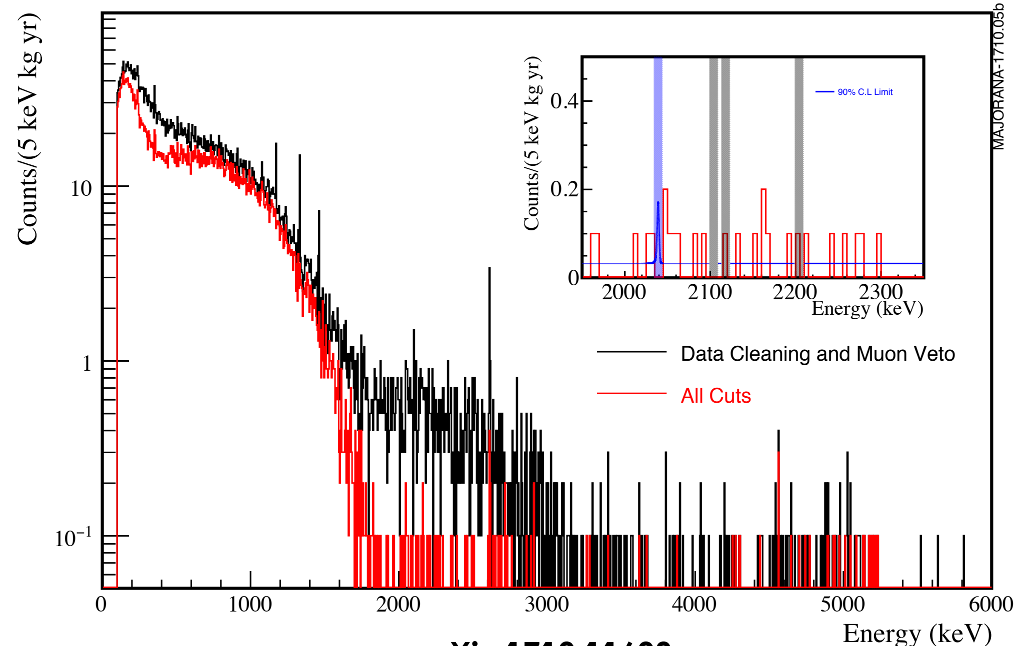




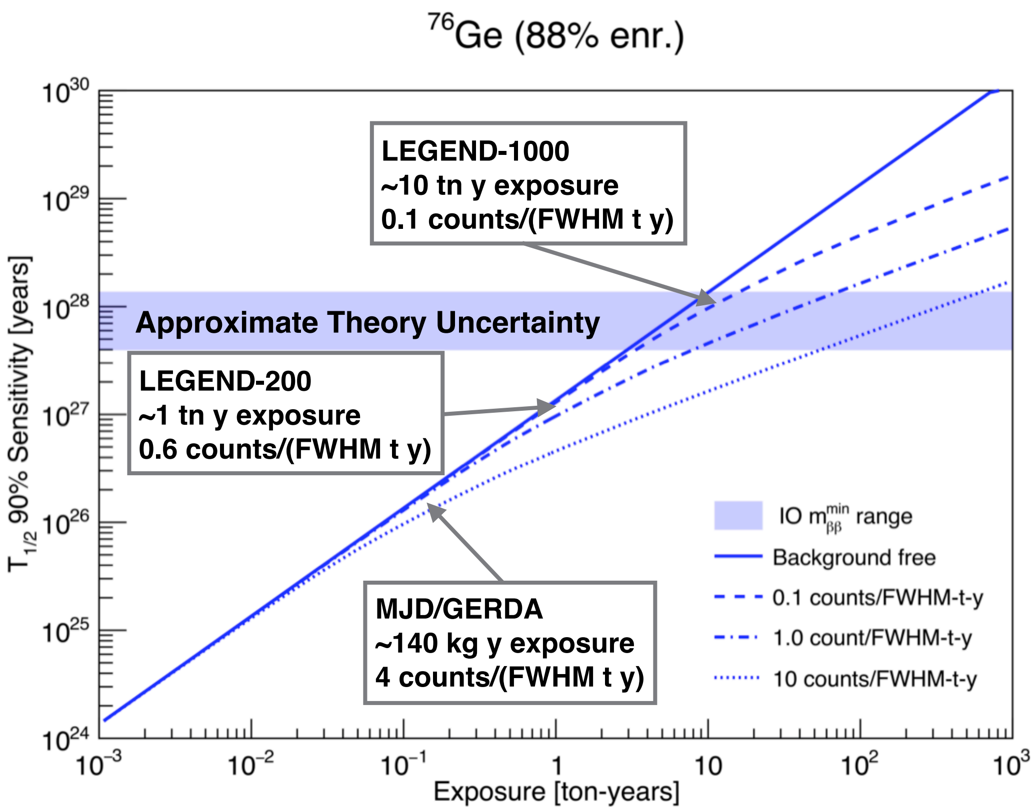
Majorana Demo

MJD Accomplishments - 2015-201

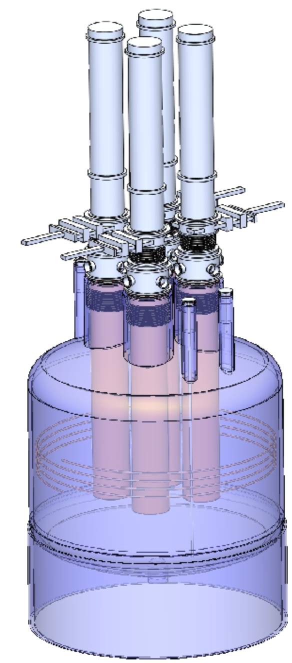
Demonstrated the best en
(**2.4keV FWHM** at 2039keV)
experiment to date.



arXiv:1710.11608



LEGEND-200

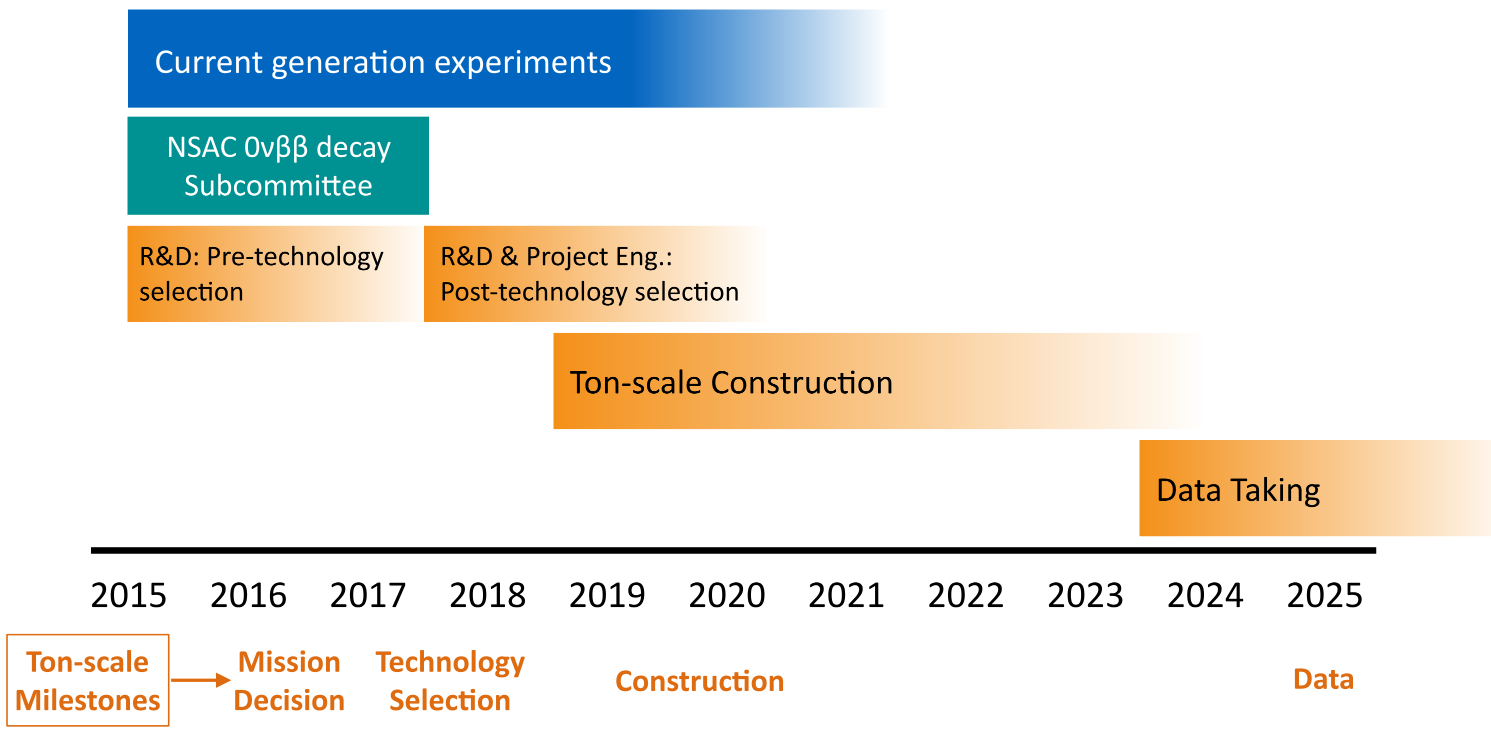


LEGEND-1000

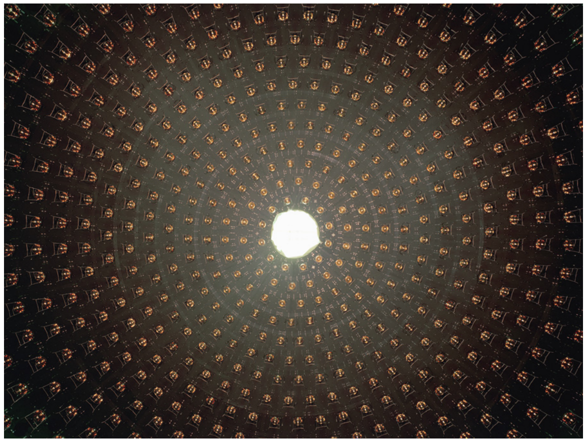
Timeline

<u>Ton-scale Neutrinoless Double Beta Decay ($0\nu\beta\beta$) - A Notional Timeline</u>

Search for Lepton Number Violation



Sterile Neutrinos?



miniBooNE

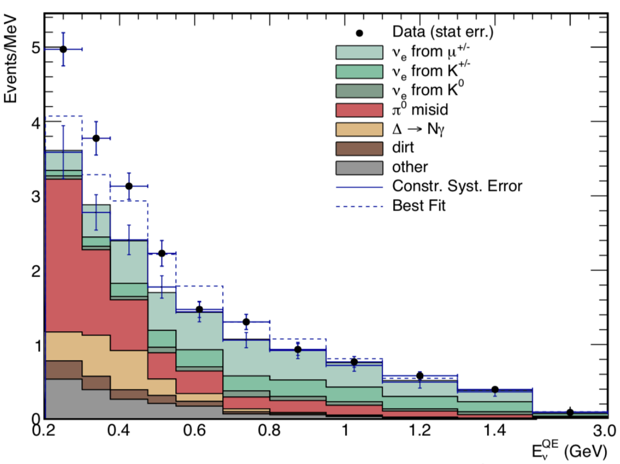
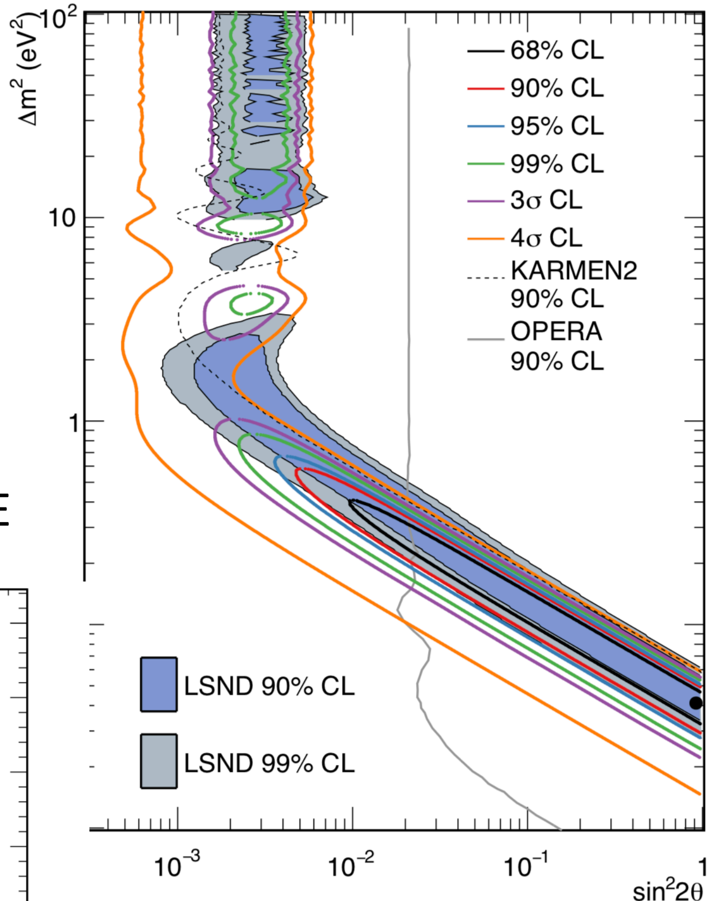
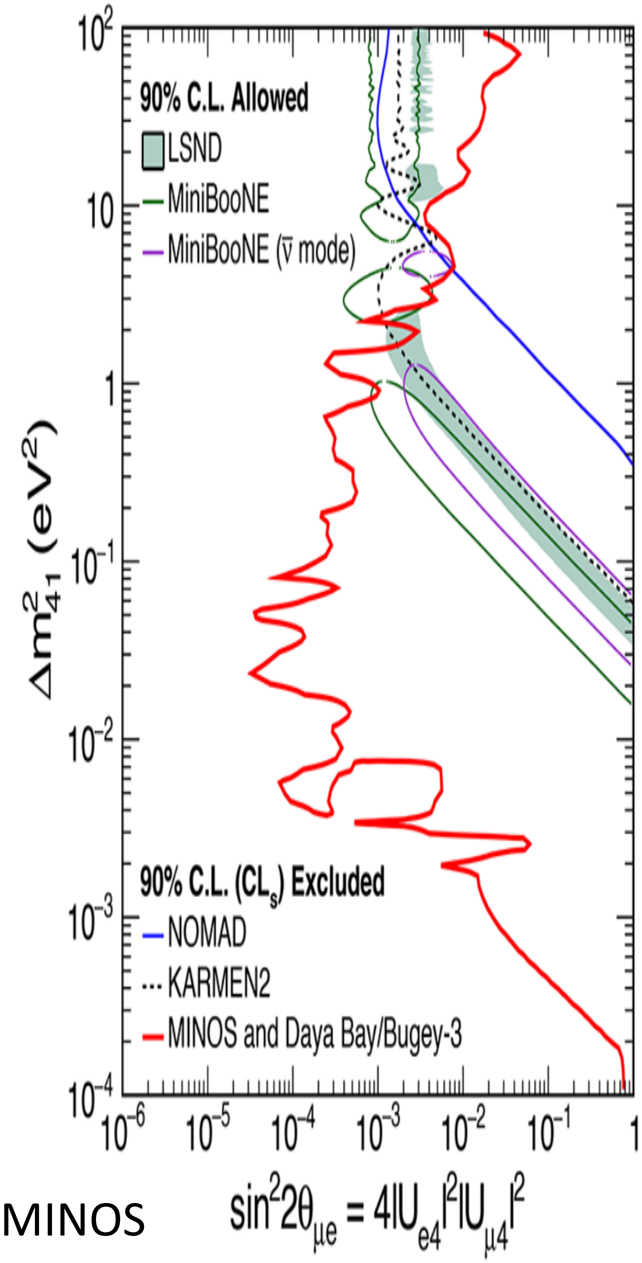


FIG. 1: The MiniBooNE neutrino mode E_ν^{QE} distributions, corresponding to the total 12.84×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and background (histogram with systematic errors). The dashed curve shows the best fit to the neutrino-mode data assuming two-neutrino oscillations. The last bin is for the energy interval from 1500-3000 MeV.





Daya Bay/Bugey/MINOS

…and the fun continues…

- Ice Cube
- Underwater ν detectors
- Coherent ν scattering
- Nuclear/particle physics with ν (MINERνA)
- Supernova ν hunting (Super-K with Gd)
- …