Neutrino Physics and Experiments
2nd - Lecture

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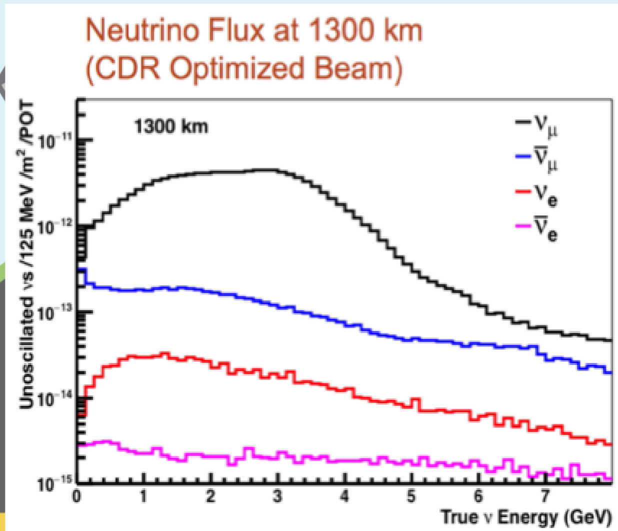
ICFA School 2023

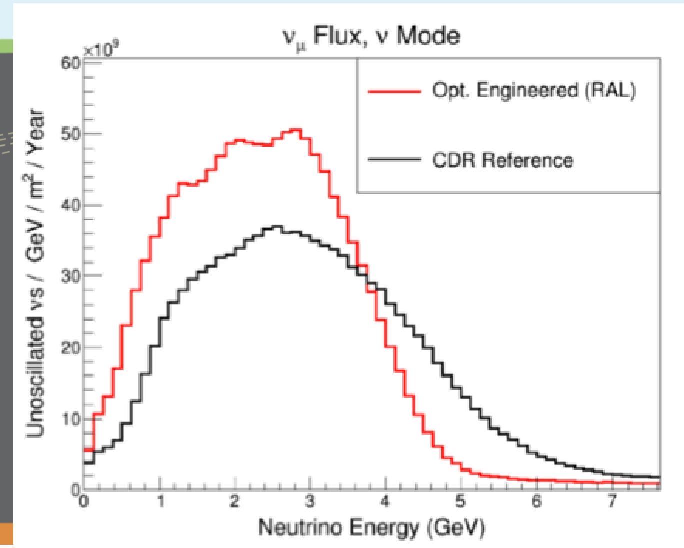
Tata institute of fundamental research

Three-neutrino oscillation:
Future

The DUNE experiment

Deep Underground Neutrino Experiment





- On-Axis Wide Band Beam (lower and higher energies) allows access to wide L/E range:

$$\frac{L}{E} = \frac{1300\text{ km}}{2.5\text{ GeV}} = 500\,\frac{\text{km}}{\text{GeV}}$$

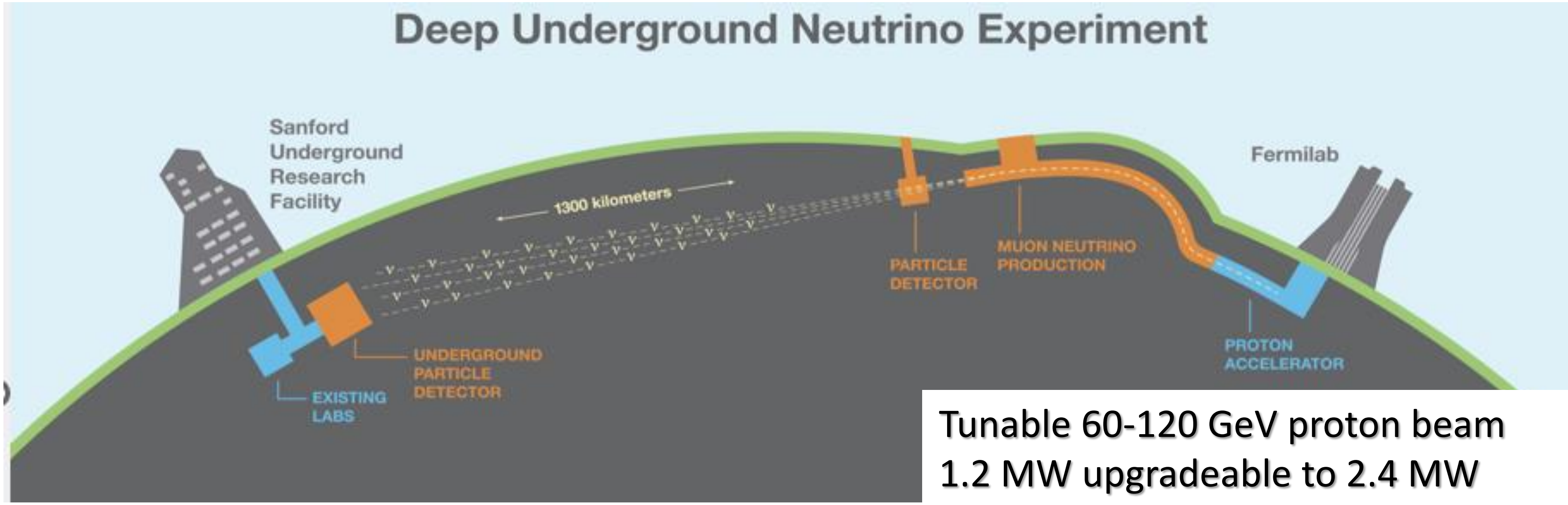
(1st Oscillation Maximum)

$$\frac{L}{E} = \frac{1300\text{ km}}{0.8\text{ GeV}} = 1700\,\frac{\text{km}}{\text{GeV}}$$

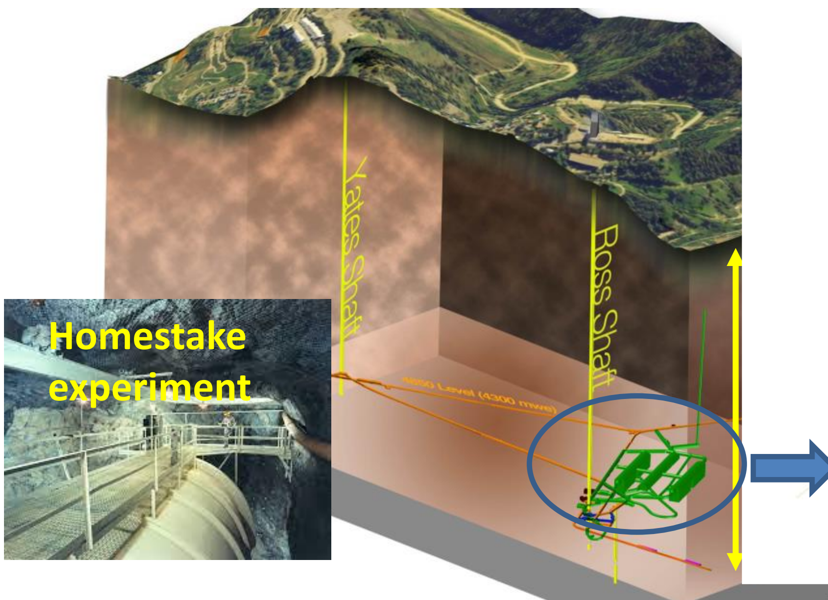
(2nd Oscillation Maximum)

- Separate neutrino and antineutrino modes

The DUNE experiment

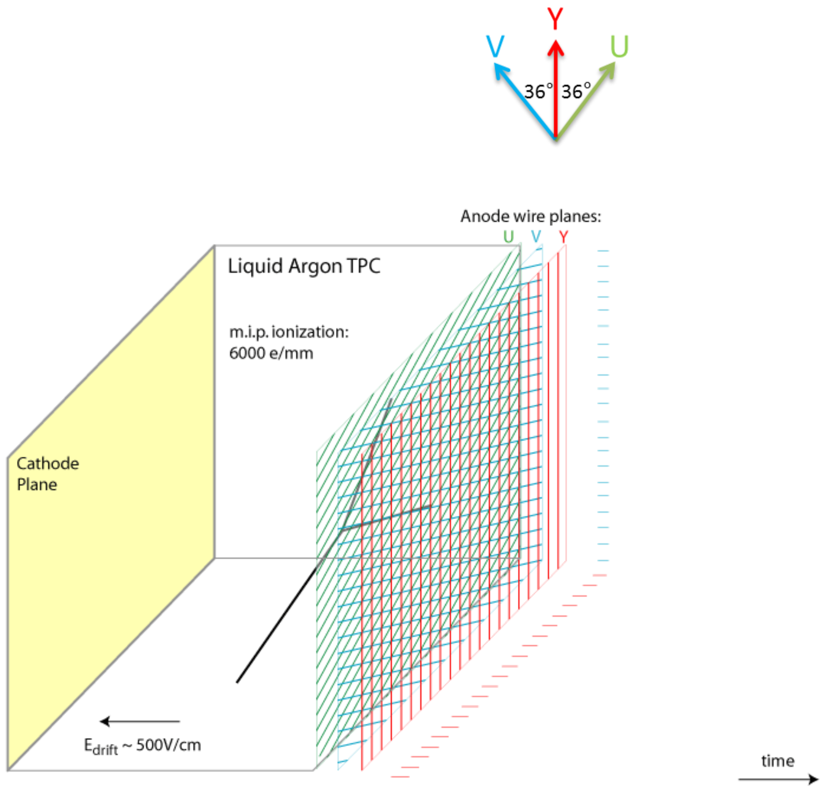


Tunable 60-120 GeV proton beam
1.2 MW upgradeable to 2.4 MW



Four 17 kton -mass Liquid Argon Time Projection Chamber (LArTPC) detectors.

LArTPC – Working Principle



Charged particles from ν-interactions release energy either **ionizing** (e- and Ar+) or **exciting** the Ar atoms (Ar*):

- **Ionized** electrons are drifted (~ms) by high electric field toward anode (TPC) 2D reconstruction of tracks/showers and calorimetry (dE/dx).
- **Excitation** produces prompt **scintillation** photons (~ns) establishing the t_0 of the interaction (Photon Detectors). $\mathrm{Ar}^*+\mathrm{Ar} \rightarrow \mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar} + \gamma$

LArTPC **critical features**:

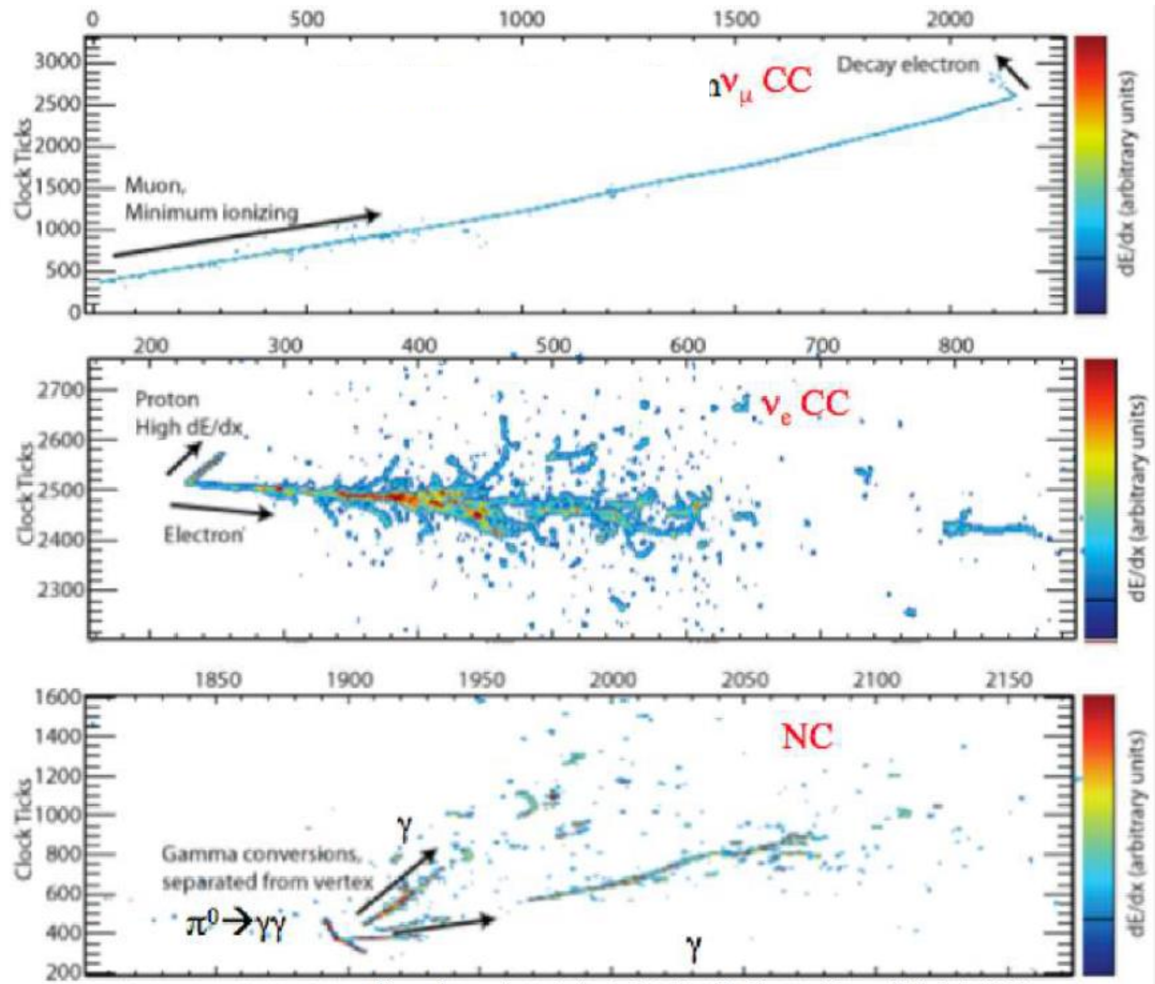
- LAr **ultra high purity**.
- **Uniformity** and **stability** of the Electric Field.

Combing ionization and scintillation signals :

- 3D imaging reconstruction of tracks and showers.

LArTPC –Capabilities

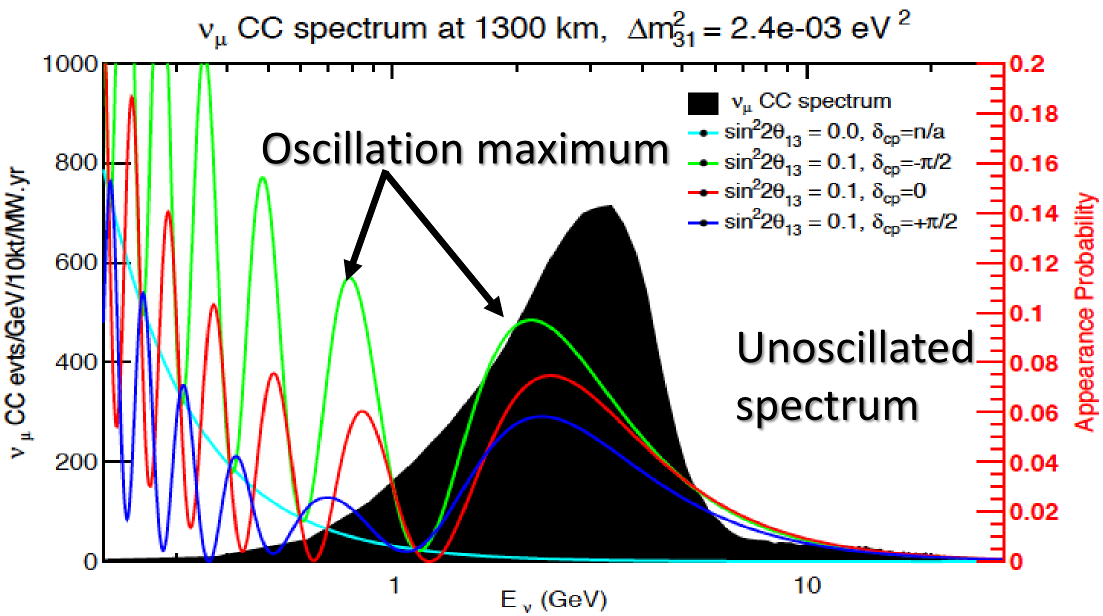
- Few mm resolution.
- Energy measurement.
- e-γ separation using distance from vertex and dE/dx.
- Particle identification through dE/dx.



Event display in LArTPC (MicroBooNE MC)

From Jianming Bian XIX International Workshop on Neutrino Telescopes (2021)

DUNE: Primary Physics Goals



Mass hierarchy

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$

$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}$$

$$\times \Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} + \delta)$$

$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

Matter effects

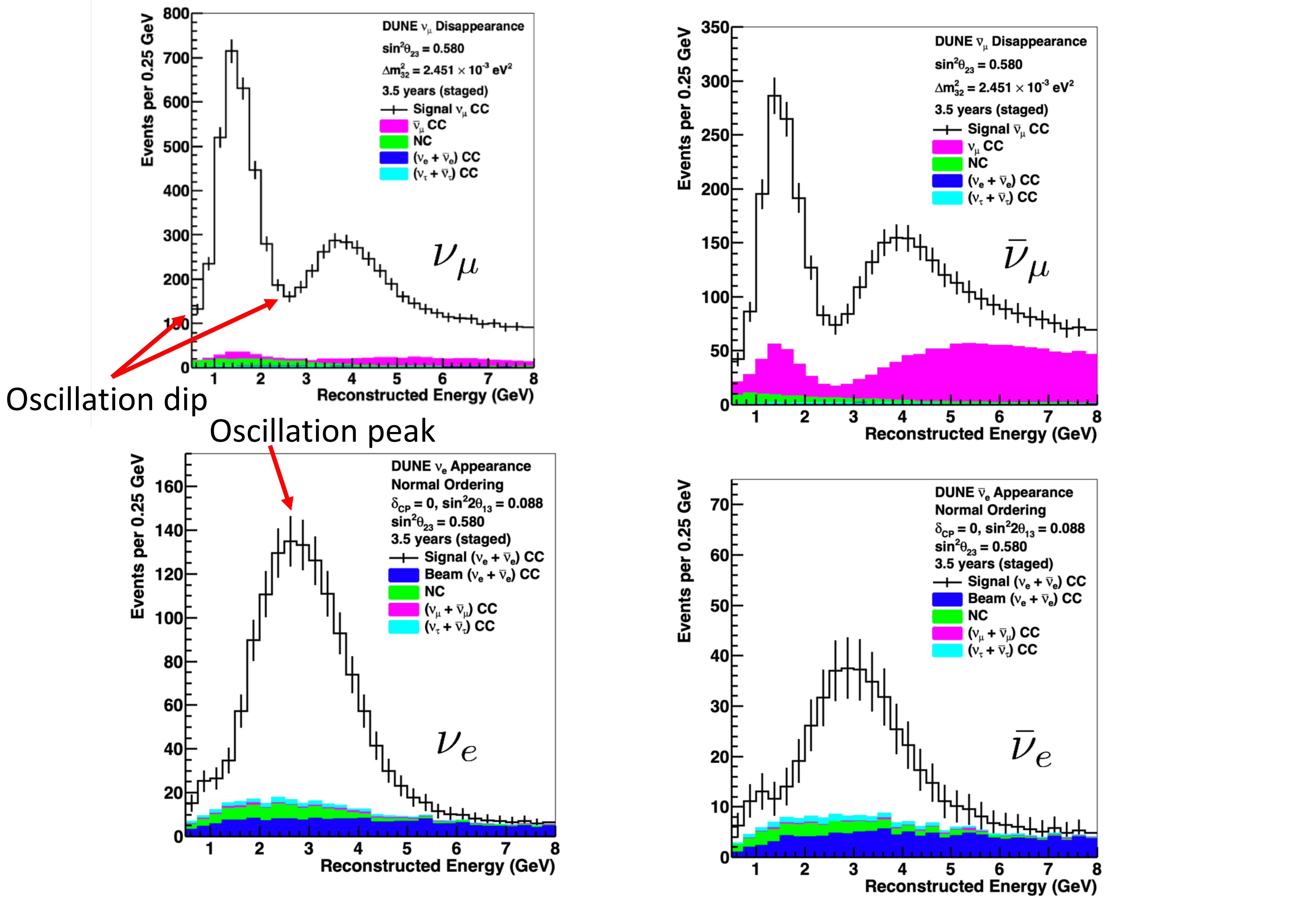
CP violation phase

$$a = \frac{G_F n_e}{\sqrt{2}}$$

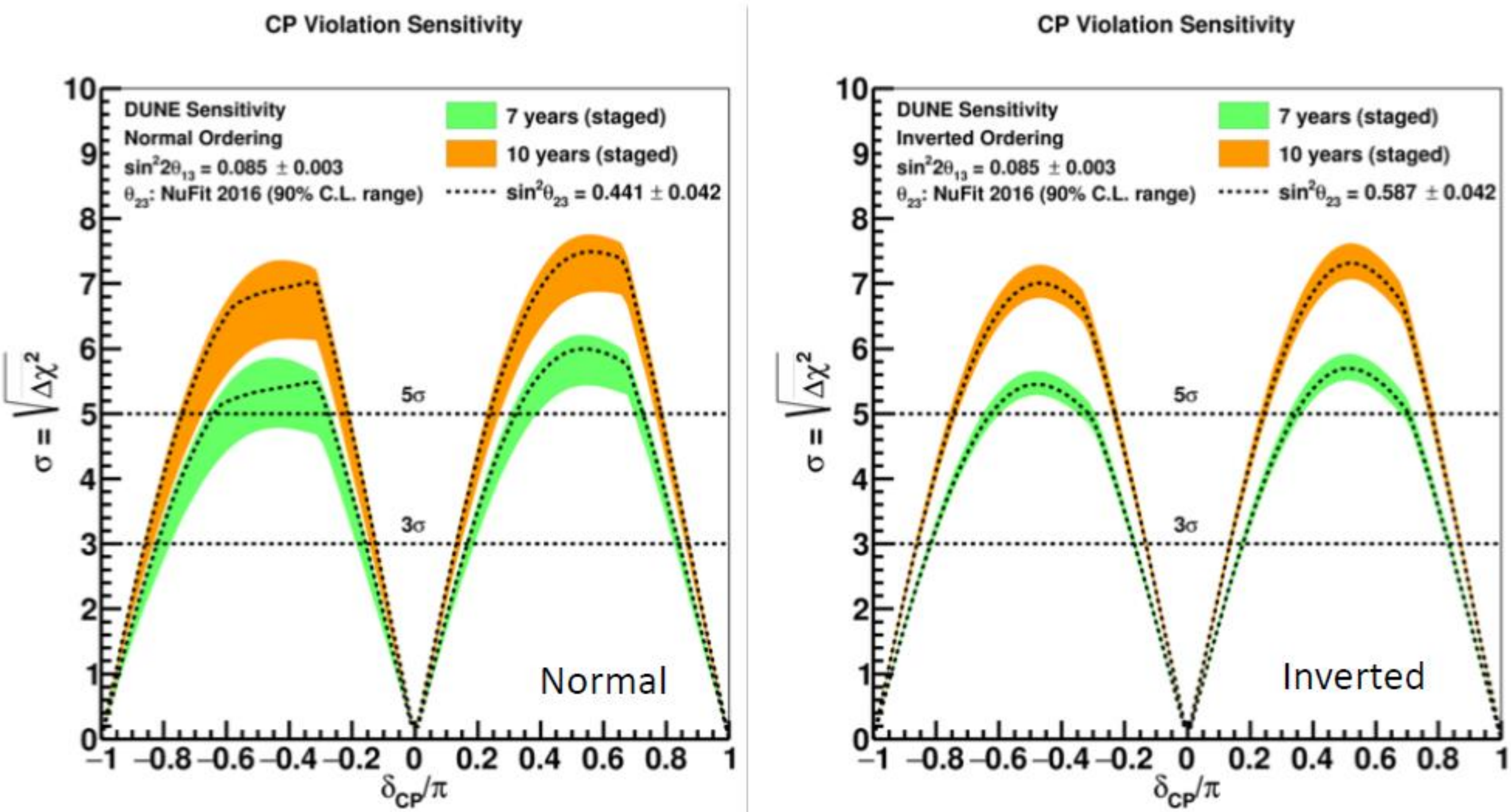
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

- Measure of the total rates and energy spectrum of ν_μ and ν_e at far detector.
- The peak of the ν_μ CC spectrum matches with the oscillation maximum.
- Unique capability for measuring with high sensitivity the **CP violation phase** and identifying the neutrino **mass hierarchy** at the same time.

DUNE: Oscillated energy spectrum



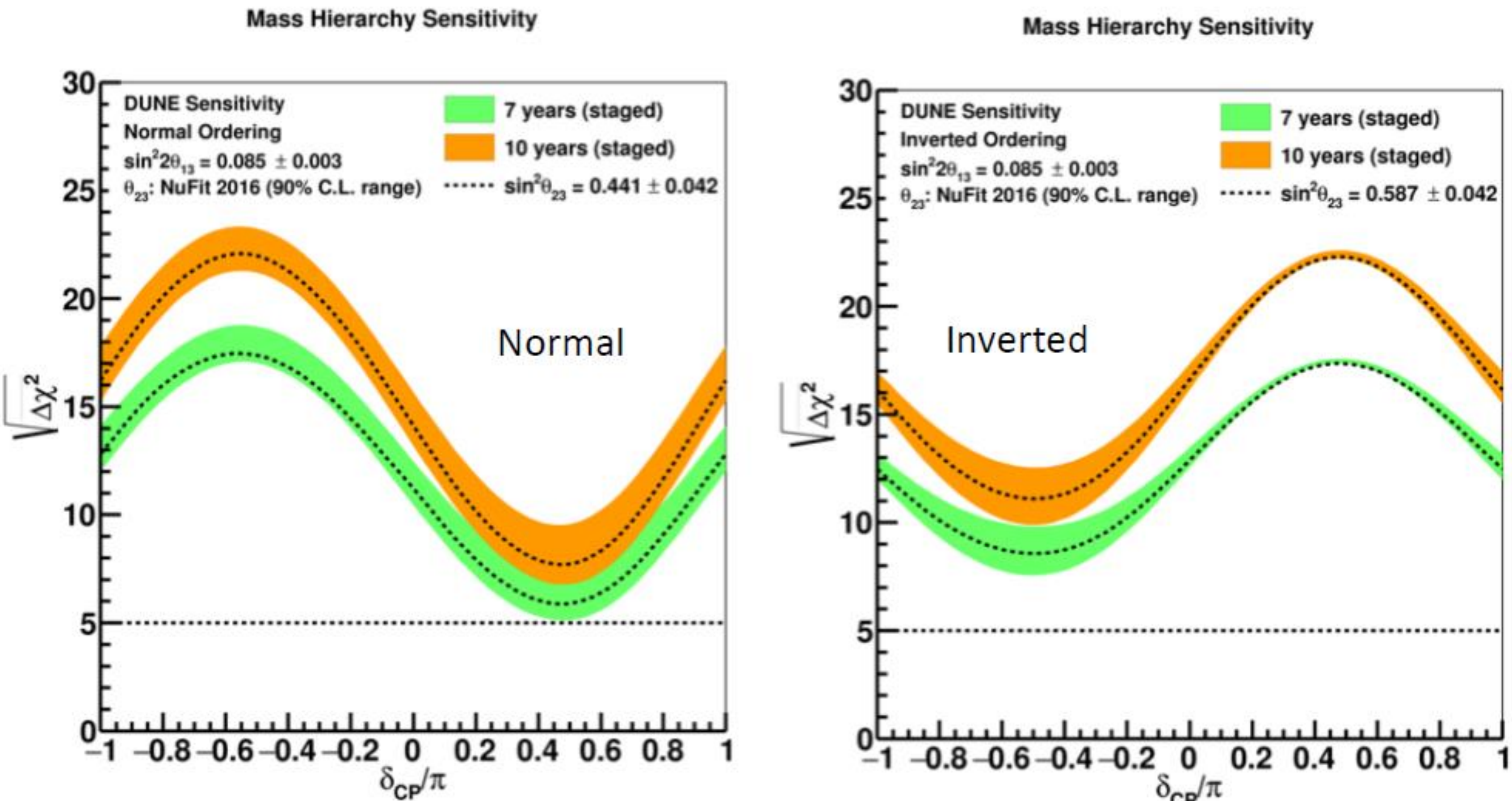
CP violation(CPV) Sensitivity



$$\delta_{\rm CP} \to \delta_{\rm CP}^{\rm true}$$

- The width of the band is the variation of 90%CL range values of θ_{23} given in NuFit 2016
- Equal running in the neutrino and antineutrino mode

Mass Hierarchy Sensitivity

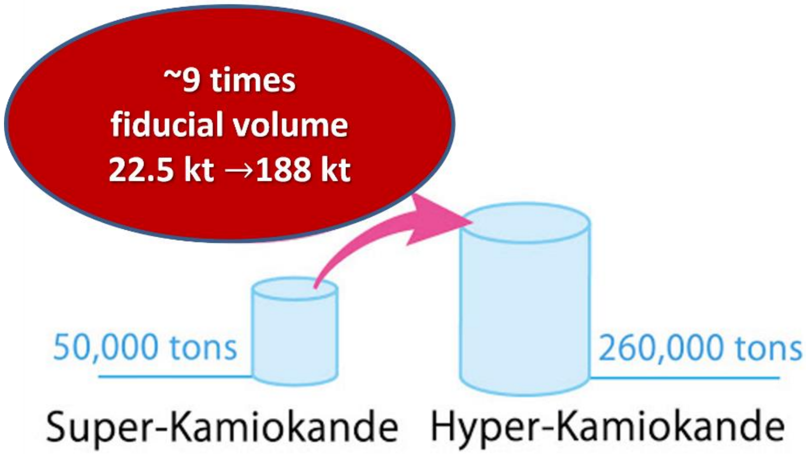


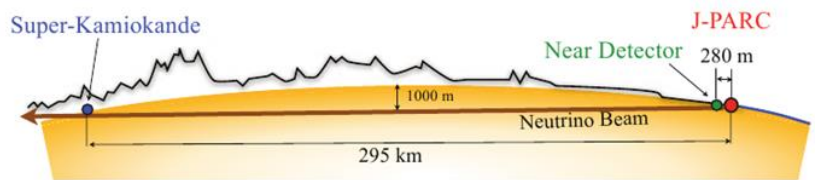
$$\delta_{\rm CP} \to \delta_{\rm CP}^{\rm true}$$

- The width of the band is the variation of 90%CL range values of θ_{23} given in NuFit 2016
- Equal running in the neutrino and antineutrino mode

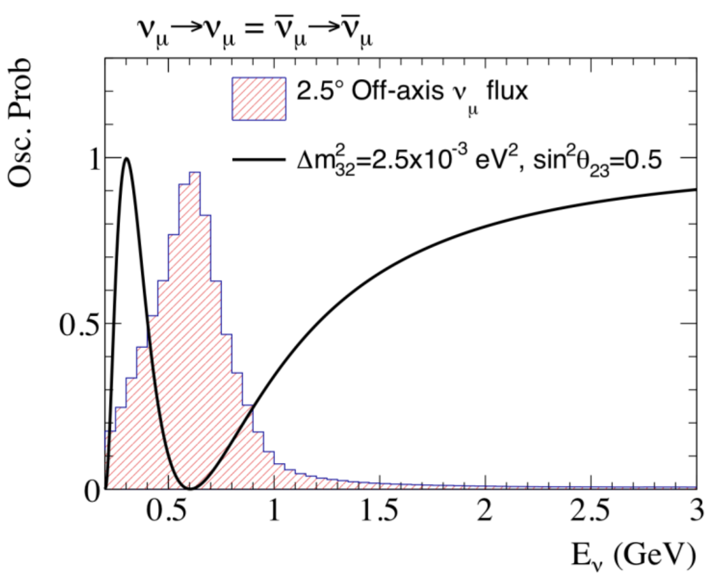
Tokai to HyperKamiokande (T2HK)

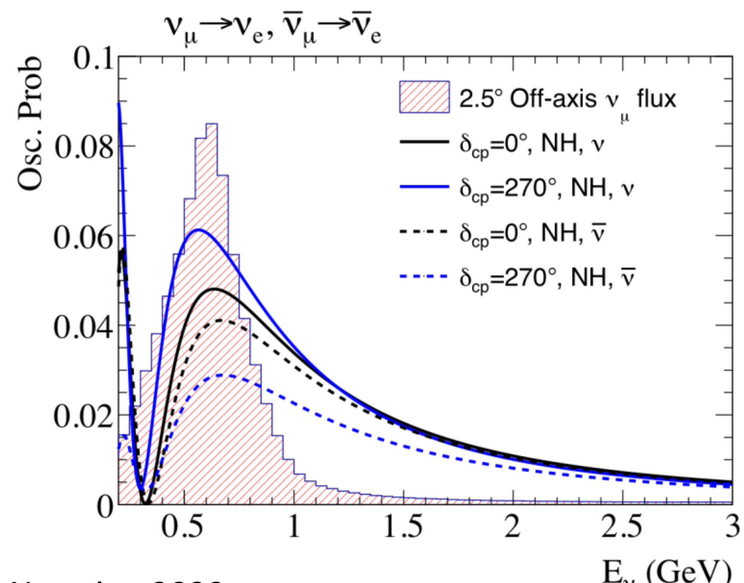
Water Cherenkov Experiment





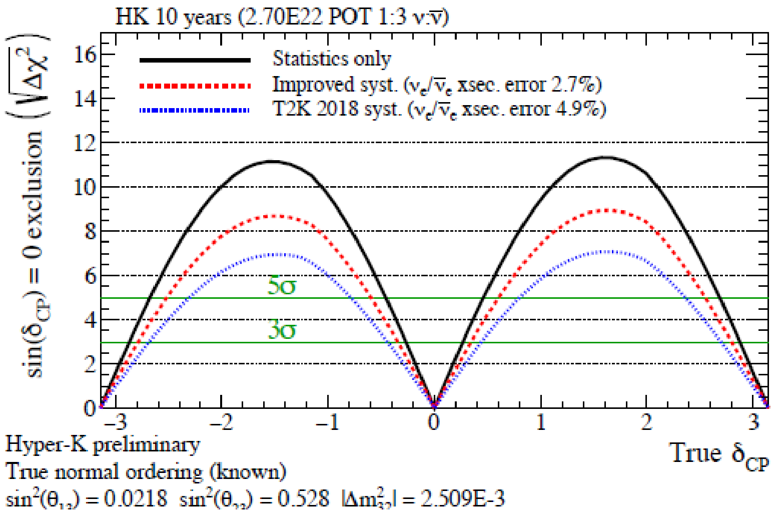
- 295 km Baseline
- 2.5 ° Off –axis beam peaked at 0.6 GeV
- $\nu_\mu / \bar{\nu}_\mu$ beam
- Near detector for constraining uncertainties on flux and neutrino interaction models.
- Start operation at 2027





T2HK: Oscillation Physics Goals

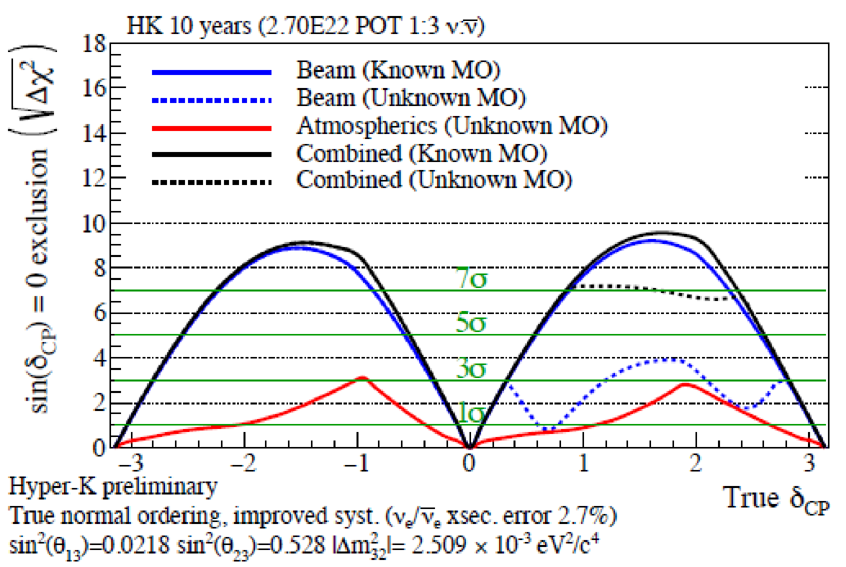
CP violation

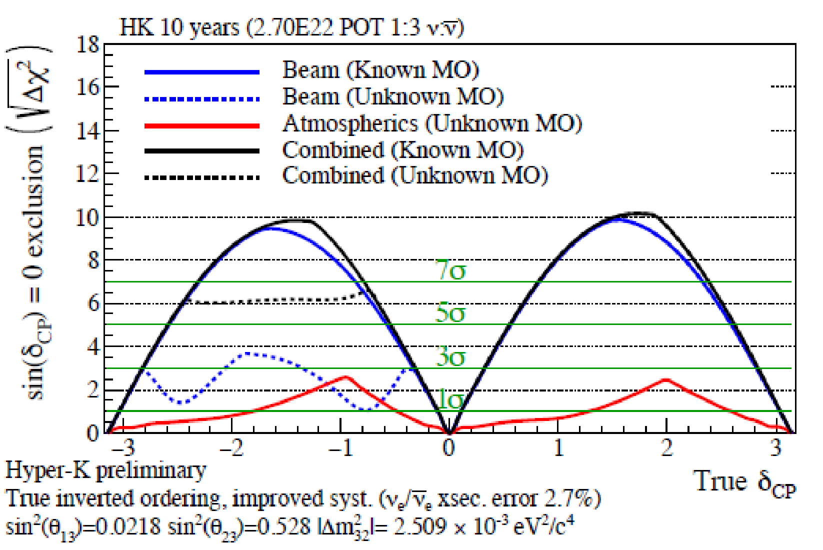


- **10 years running**
- **1: 3 $\nu/\bar{\nu}$ mode**

Jeanne Wilson Neutrino 2022

Mass Hierarchy (Ordering)

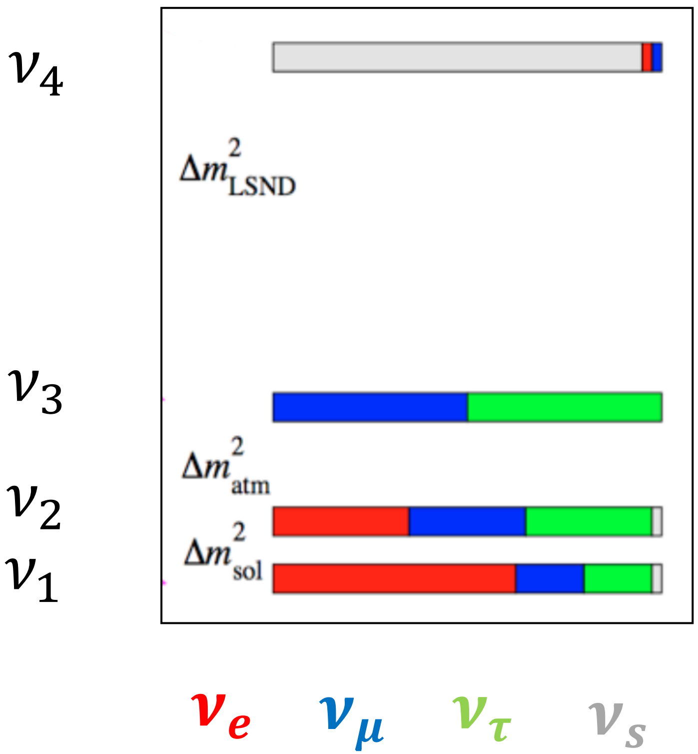




Beyond Three-neutrino oscillation: Sterile neutrino

Sterile neutrino 3+1

3+1



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$\nu_s = \nu_R^C$$

$$P_R \nu_R^C = 0 \quad P_L \nu_R^C = \nu_R^C \quad P_{R(L)} = \frac{1 \mp \gamma_5}{2}$$

Sterile neutrino does not feel Standard model interactions (right-handed singlet)

Oscillation probabilities in 3+1

In Short Baseline Experiments (SBL) we have:

$$\left\langle \frac{L}{E} \right\rangle_{\text{SBL}} \simeq \mathcal{O}(1) \equiv \Delta m^2 \sim \mathcal{O}(1\text{eV}^2) \Rightarrow \begin{cases} \Delta_{31} & \to 0 \\ \Delta_{21} & \to 0 \end{cases}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Only one oscillation frequency is present

⇓

two neutrino system

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2 \Delta_{41}^2 \ (\alpha \neq \beta)$$

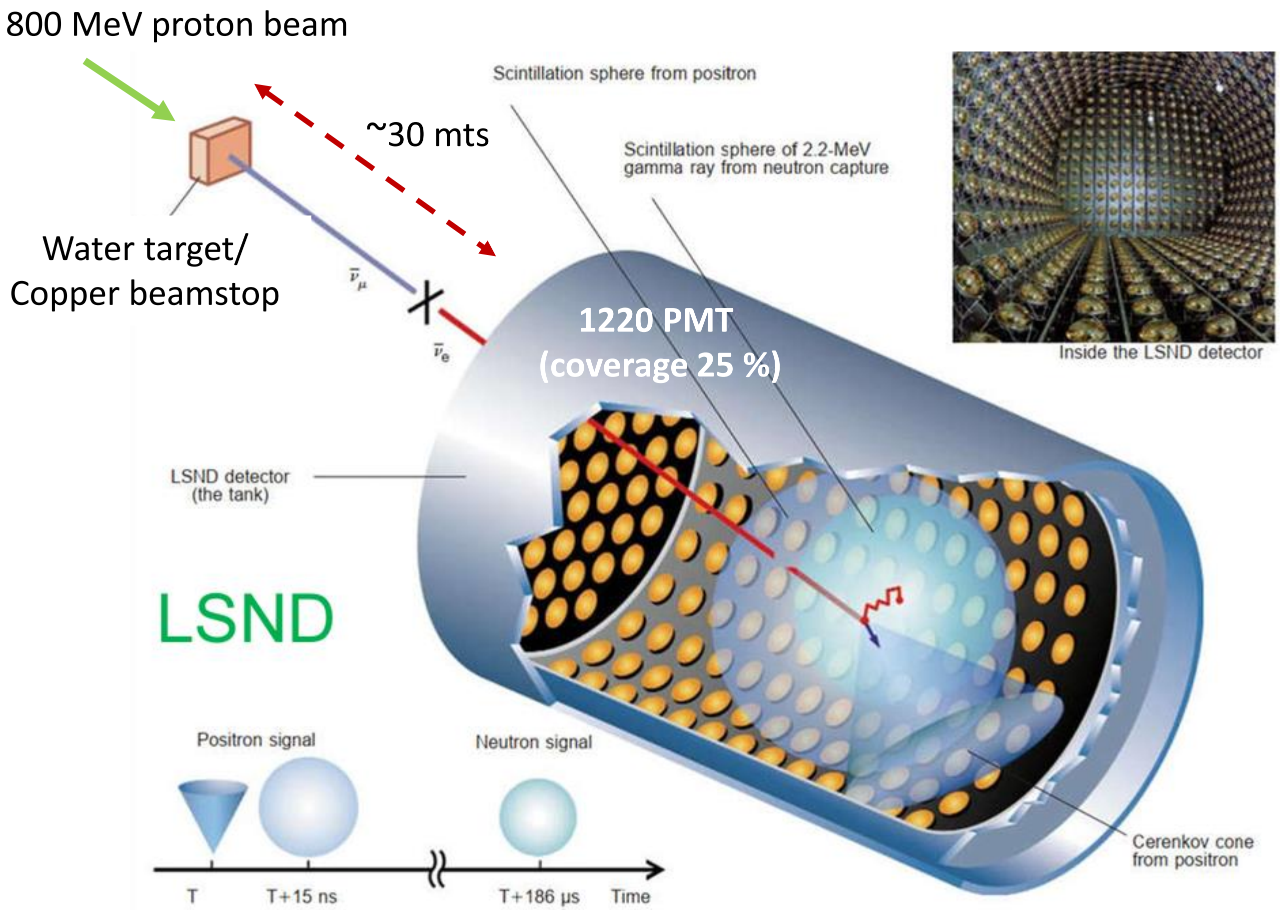
$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \Delta_{41}^2 \ (\alpha, \beta = e, \mu, \tau, s)$$

Where:

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

Liquid Scintillator Neutrino Detector (LSND)



Production

Protons on target (water) produces mostly π^+

$$\pi^+ \to \mu^+ \nu_\mu \quad \text{(Decay at rest)}$$

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

$$\bar{\nu}_e$$

Detection

Prompt scintillation signal

$$\bar{\nu}_e p \to e^+ n \quad \textbf{IBD}$$

$$np \to d\gamma$$

2.2 MeV photon

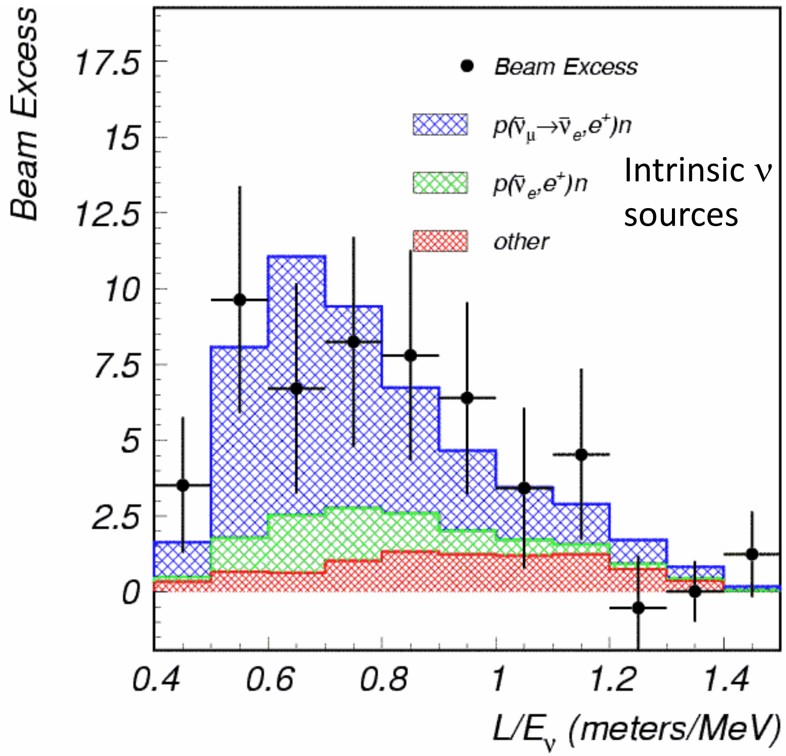
167 tons of Mineral Oil doped with fluorescent (Butyl –PBD)

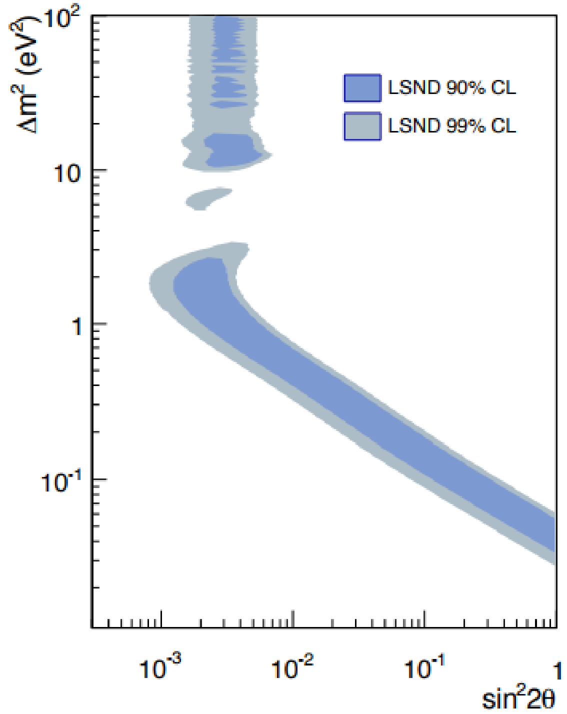
Neutrino Energy $\approx 20 - 55$ MeV

$$< \frac{L}{E} > \sim \frac{30}{40} \frac{\text{m}}{\text{MeV}}$$

π^- much less produced and absorbed before decaying (pion capture)

LSND Anomaly





A. Aguilar –Arevalo et al. PRD64, 112007 (2001)

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 0.245 \pm 0.067 \pm 0.045\%$$

$$\Delta m^2_{\rm LSND} \geq 0.02\,{\rm eV}^2$$

$\bar{\nu}_e$ appearance with 3.8 σ signal significance

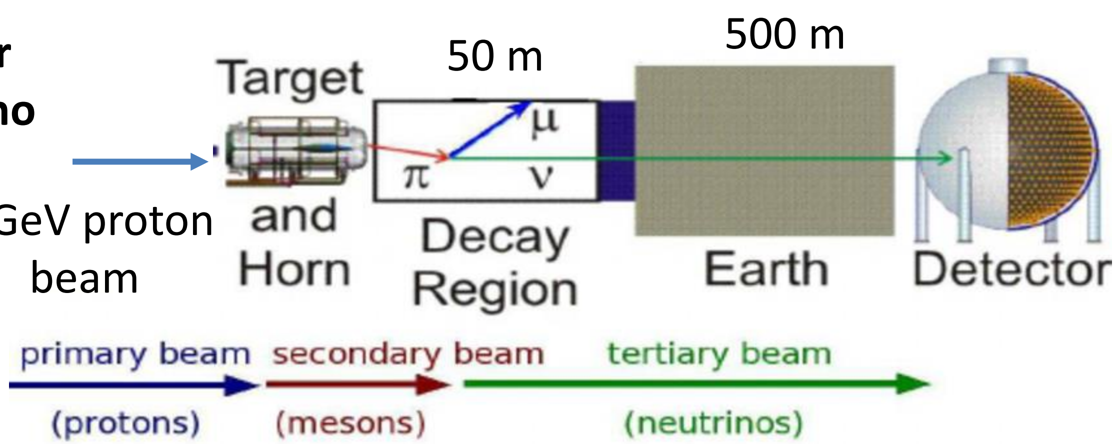
$$< \frac{L}{E} > \sim \mathcal{O}(1)$$

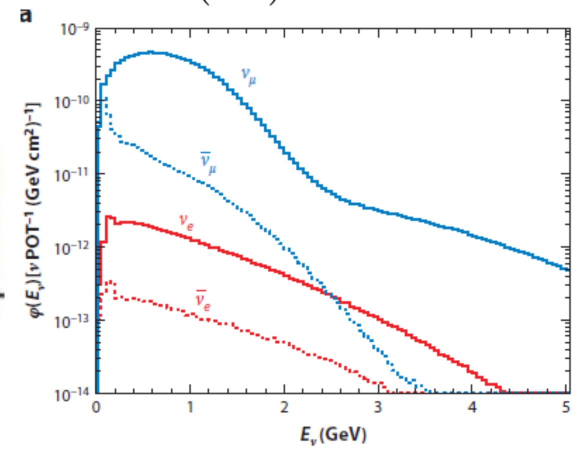
Mini Booster Neutrino Experiment (MiniBooNE)

$$\frac{L}{E} \sim \frac{0.5}{0.6(0.4)} \frac{\text{km}}{\text{GeV}} \sim \mathcal{O}(1)$$

Booster Neutrino Beam

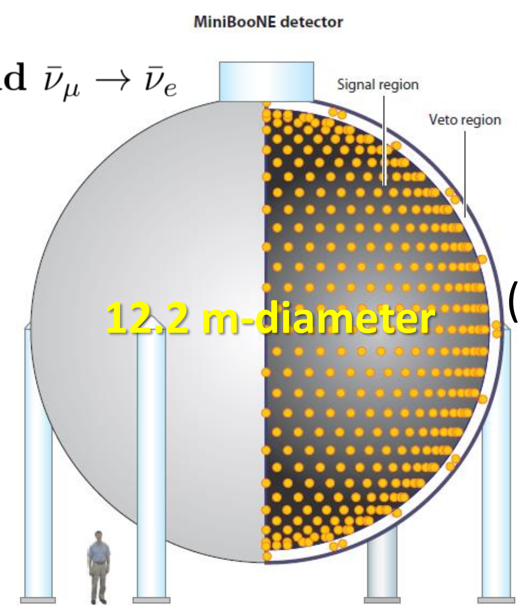
8 GeV proton beam



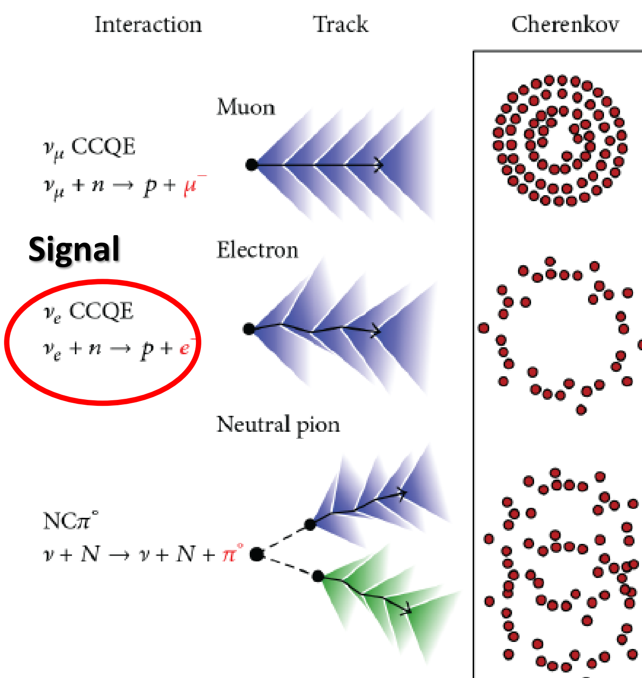


Search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

818 tons of mineral oil (CH_2) no scintillation doped

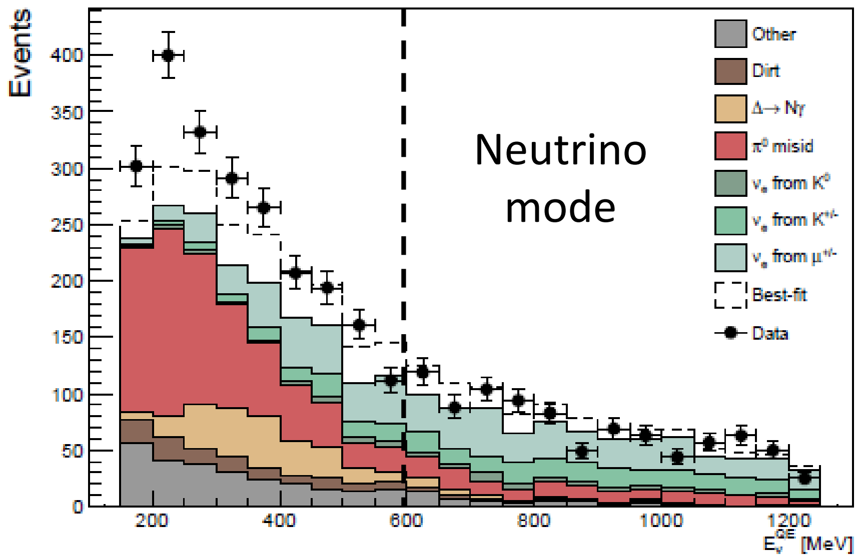


1280 8-inch PMTs (SR) (10 %coverage)

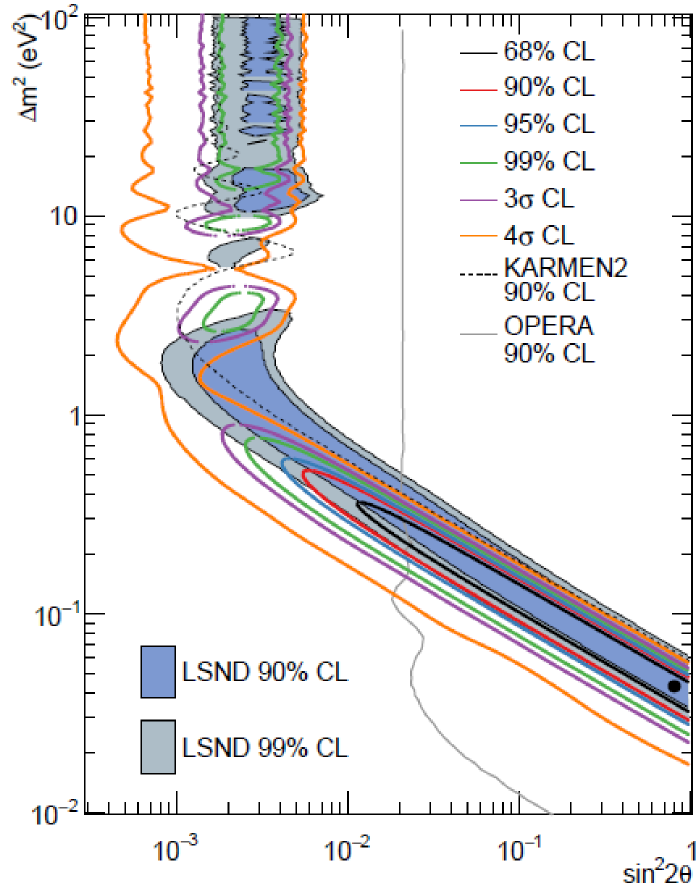


MiniBooNE Anomaly

Low-Energy Excess



4.8 σ overall significance (neutrino+antineutrino)



Neutrino + Antineutrino mode combined

Consistent with LSND

Main Backgrounds (limitations on e/γ separation)

$$\nu + N \rightarrow \nu + N + \pi^0$$

$$\hookrightarrow \gamma + \gamma$$

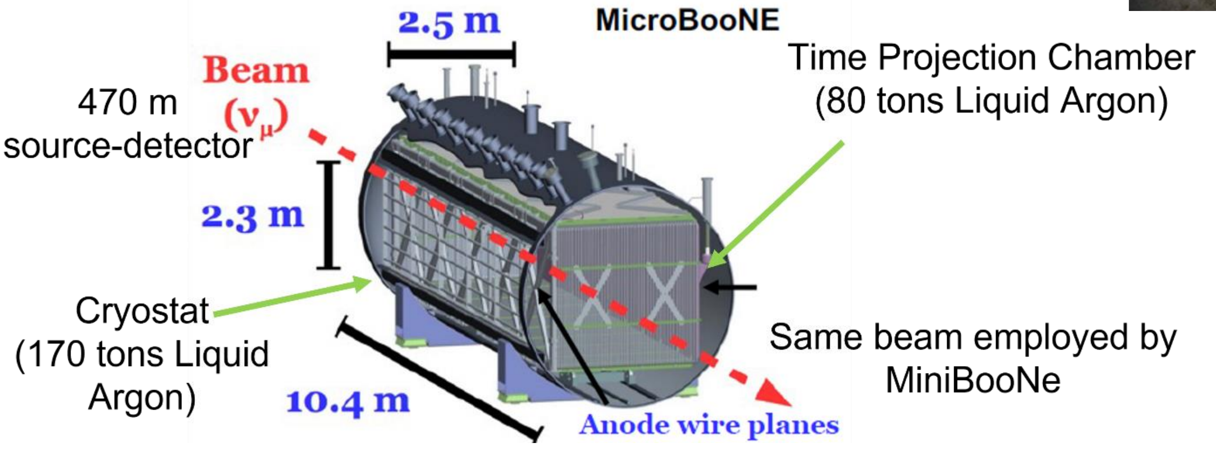
$$\nu + N \rightarrow \nu + \Delta$$

$$\hookrightarrow N + \gamma$$

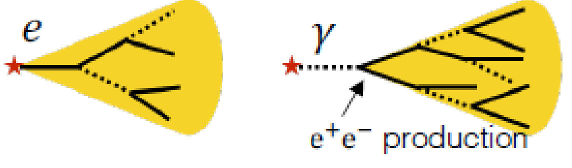
Micro Booster Neutrino Experiment (MicroBooNE)

(Main)Goal: Test MiniBooNE Anomaly (electron Low-Energy Excess)

Fully active Calorimetry + High-resolution Tracking



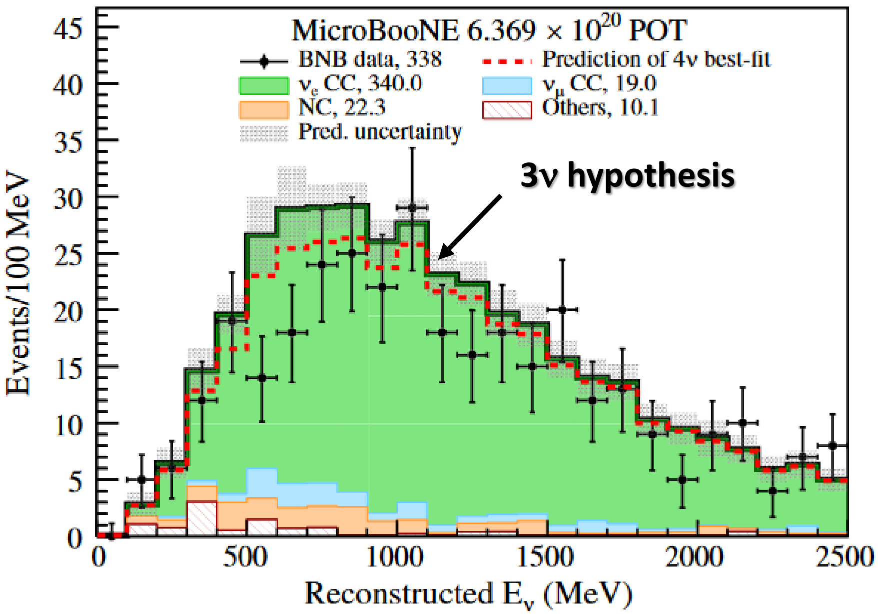
Key feature: e/γ separation

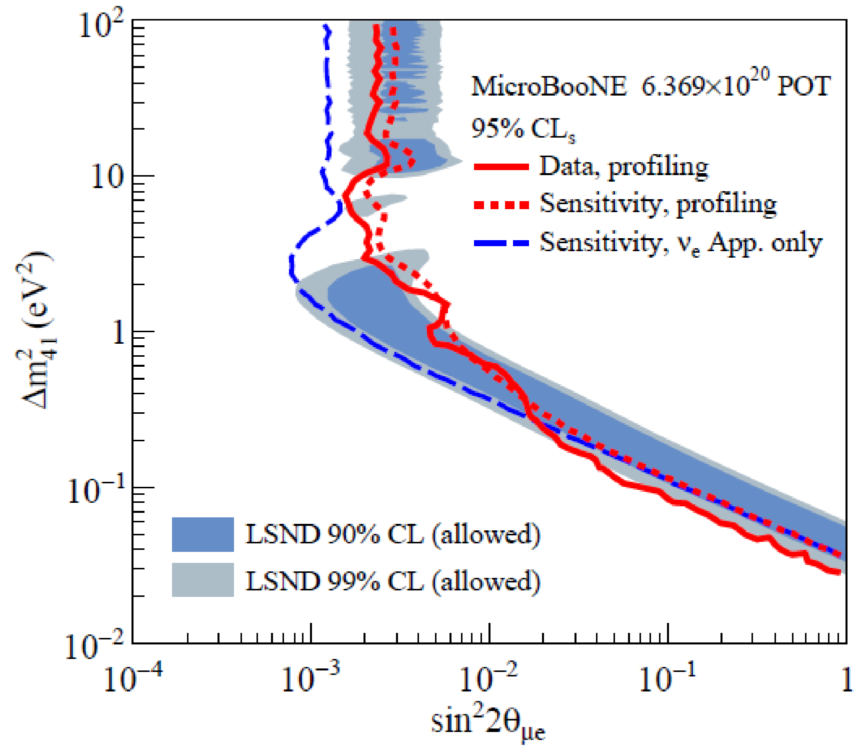


- Separation between interaction vertex and shower starting point
- Large opening angle ($e^+ e^-$)
- 1 MIP versus 2 MIP

Taken from Hanyu Wei (Neutrino 2022)

MicroBooNE - Results





3ν hypothesis consistent with data (absence of excess)

Exclusion limit

P. Abratenko et al, Phys.Rev.Lett. 130 (2023) 1, 011801

Gallium Anomaly

For calibration the solar ν_e -Gallium experiments (SAGE and GALLEX) used very intense (MCi) ν_e-radioactive sources of ^{37}Ar and ^{51}Cr :

$1\text{Ci} = 3.7 \times 10^{20}$ decays/s

ν_e-Radioactive sources $\sim \mathcal{O}(10)$ solar neutrinos

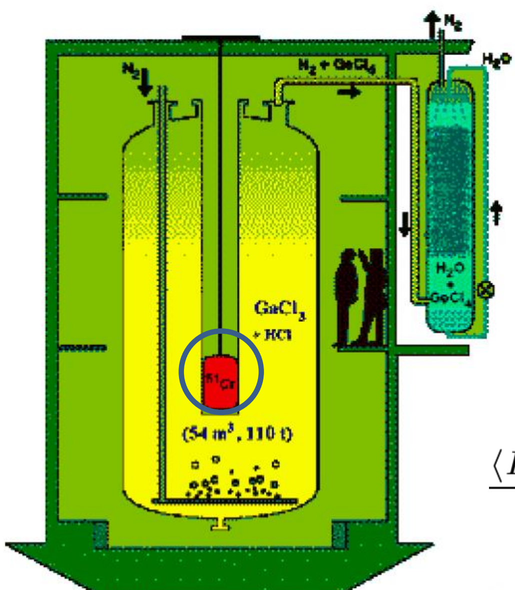
$$e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$$

$E \simeq 0.81$ MeV

$$e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$$

$E \simeq 0.75$ MeV

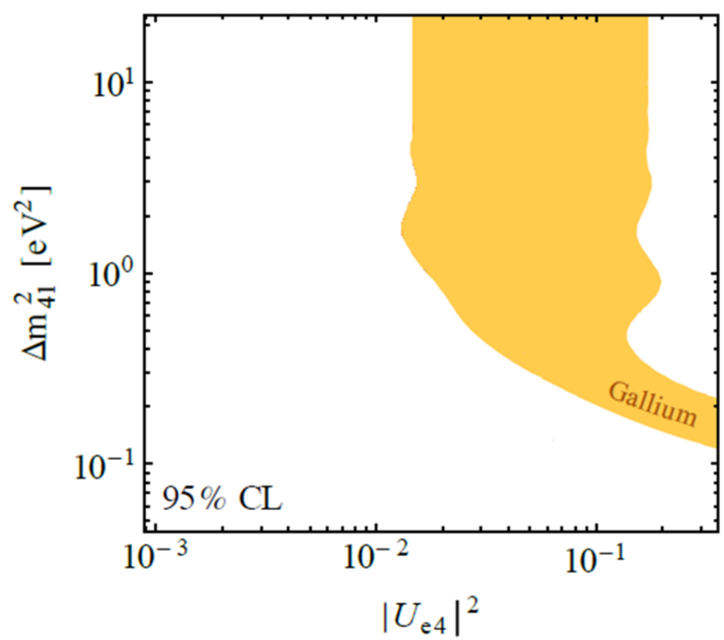
$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$



$$\frac{\langle L \rangle_{\text{SAGE}}}{E_{\nu_e}} \simeq \frac{0.60}{0.81} \frac{\text{m}}{\text{MeV}}$$

$$\frac{\langle L \rangle_{\text{GALLEX}}}{E_{\nu_e}} \simeq \frac{1.9}{0.75} \frac{\text{m}}{\text{MeV}}$$

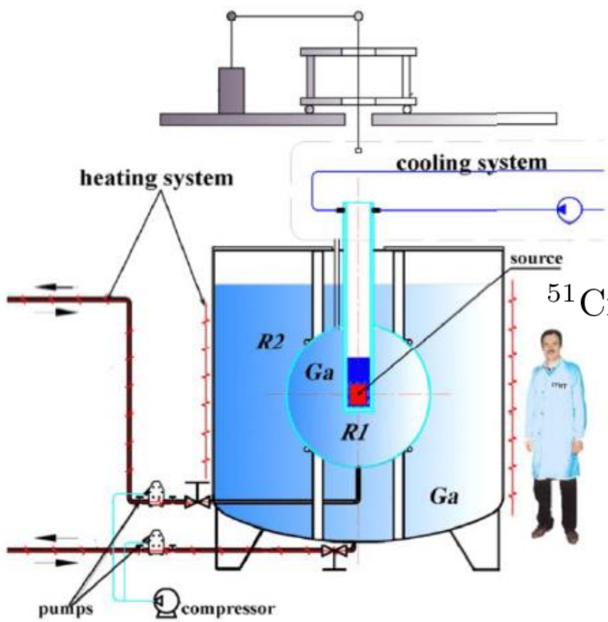
J. Kopp et al., JHEP 1305, 051 (2013)



Compatible with $\Delta m^2 \gtrsim \mathcal{O}(1\,\text{eV}^2)$

Baksan Experiment on Sterile Transitions BEST

Test of the Gallium Anomaly



^{51}Cr -3.28 MCi

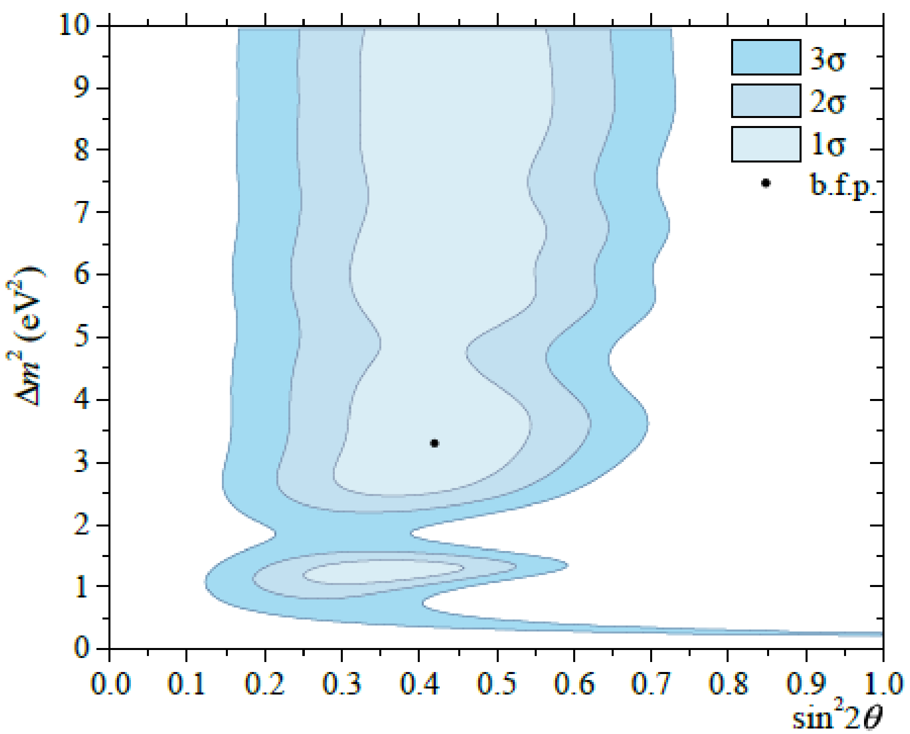
R_1 =0.66 m R_2 =1.096 m

Consistent between them

$$R_{inner} = 0.79 \pm 0.05$$

$$R_{out} = 0.77 \pm 0.05$$

V. V. Barinov et al., PRL. 128, 232501 (2022)

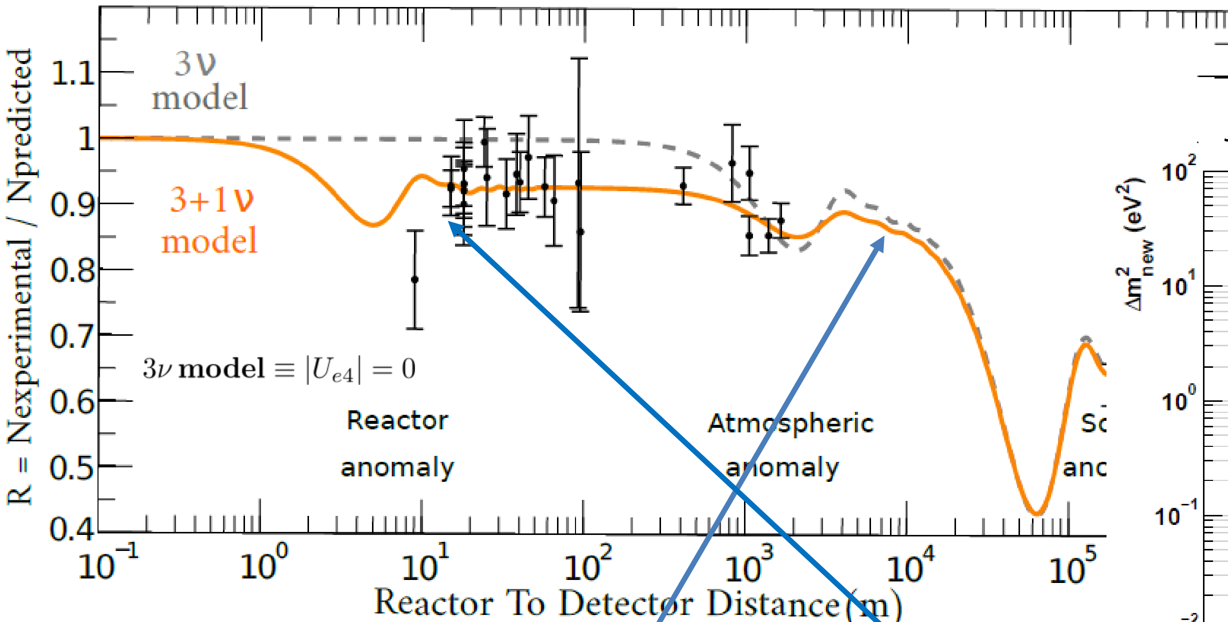


BEST result 4 σ deficit

Explained by $\Delta m^2 > 0.5\,\mathbf{eV}^2$

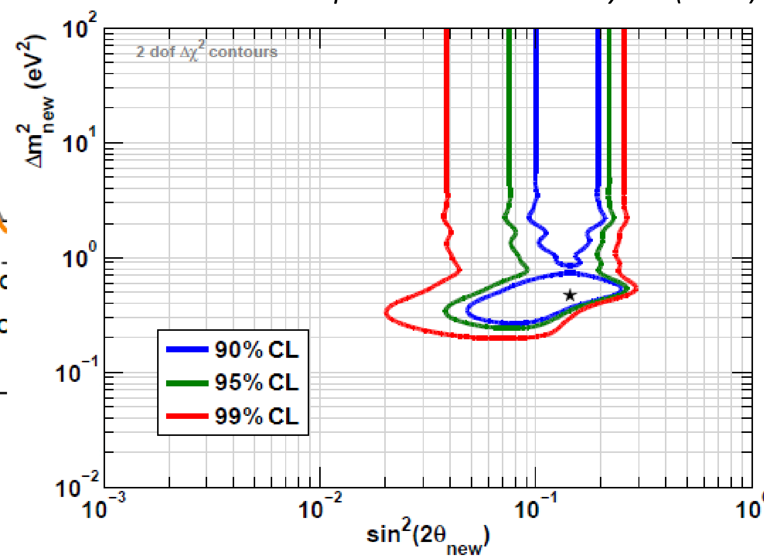
Reactor Antineutrino Anomaly (RAA)

A reevaluation of the reactor antineutrino fluxes (**Huber, PRC 84(2011) 024617, Mueller PRC 83(2011) 054615**) resulted in a 3.5 % increase in the flux, implying a 5.7% deficit in the average rate of reactor experiments (**G. Mention et al., PRD83, 073006 (2011)**).



Neutrino sterile oscillation proposed as solution

J. Link -Workshop on Fundamental Physics (2019)

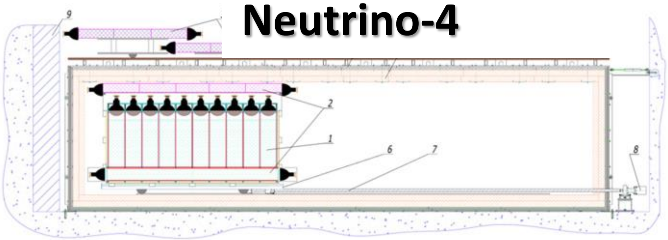


$$P^{3+1}_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1 - 4\left(1-|U_{e3}|^2-|U_{e4}|^2\right)|U_{e3}|^2\sin^2\Delta^2_{31} - \left(1-|U_{e4}|^2\right)|U_{e4}|^2\sin^2\Delta^2_{41}$$

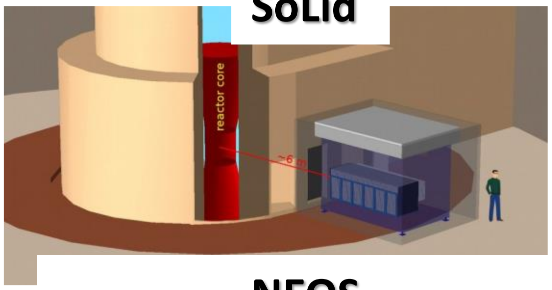
Very Short-baseline experiment (VSBL)

- Reactor experiments
- Distance to the reactor core $\mathcal{O}\,(10\,\mathrm{m})$
- To test the RAA (large $\Delta m^2 > 1\,\mathrm{eV}^2$)
- Large background (small overburden)
- S/B ratio at least $\mathcal{O}\,(1)$
- Extended core $(0.5 - 3.0)\,\mathrm{m}$

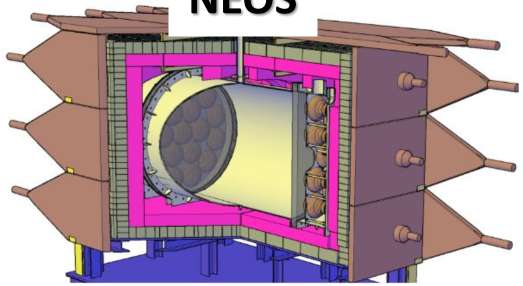
Neutrino-4



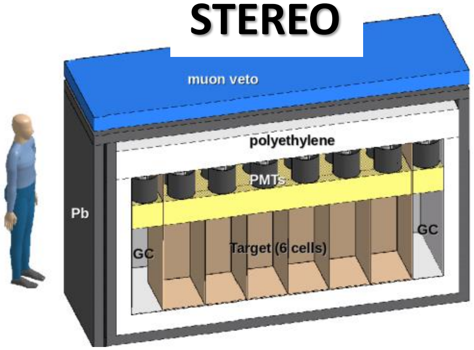
SoLid



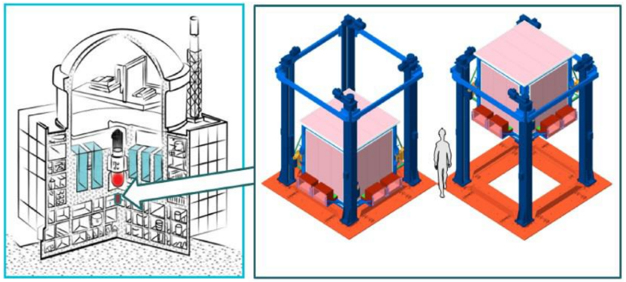
NEOS



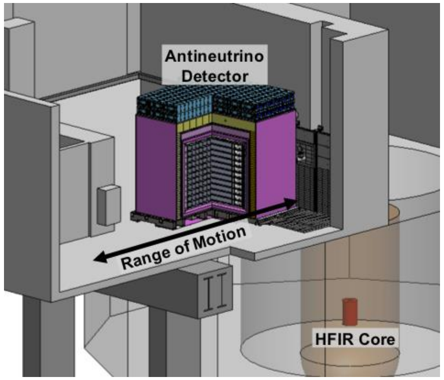
STEREO



DANSS

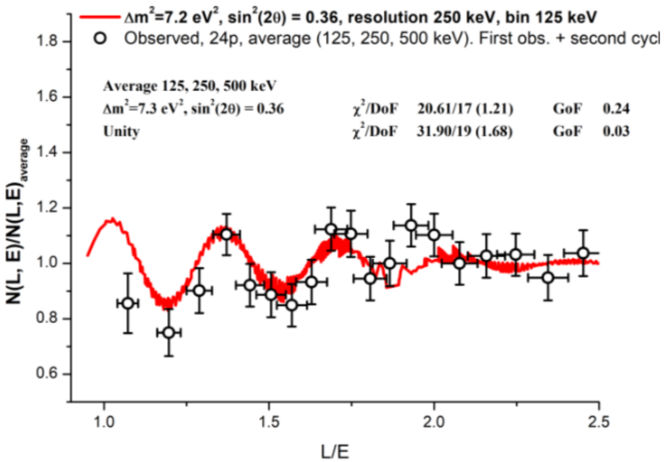


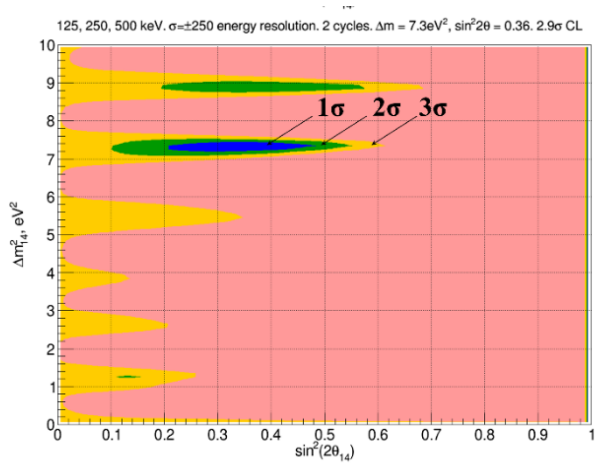
PROSPECT



VSBL results

Neutrino-4: 3.5σ oscillation effect $\Delta m^2_{41} \approx 7.3\,\mathrm{eV}^2\ \sin^2 2\theta_{14} \approx 0.36$





RENO-NEOS: from spectral comparison $\Delta m^2_{41} = 2.41\,\mathrm{eV}^2\ \sin^2 2\theta_{14} = 0.08$

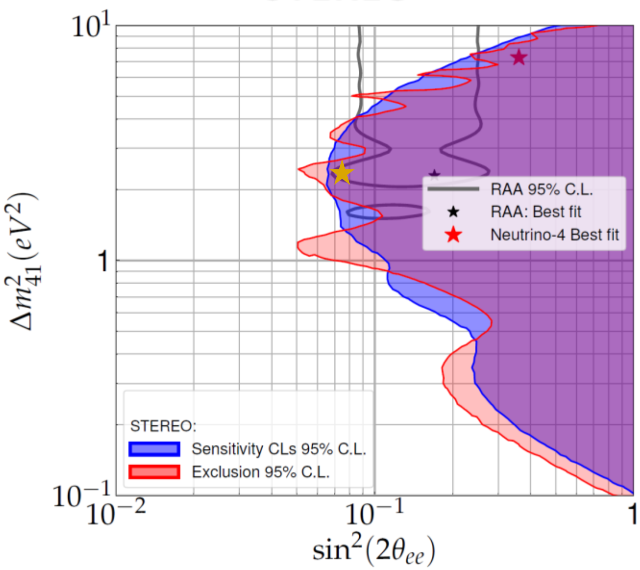
$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$$

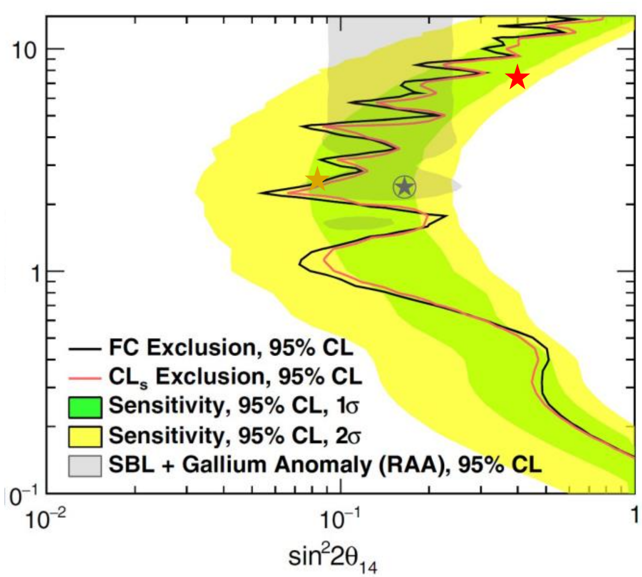
★ **Neutrino-4** best fit

★ **RENO-NEOS** best fit

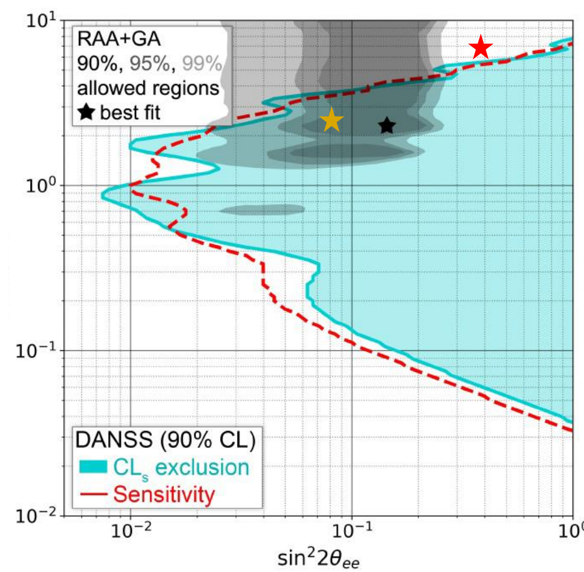
STEREO



PROSPECT



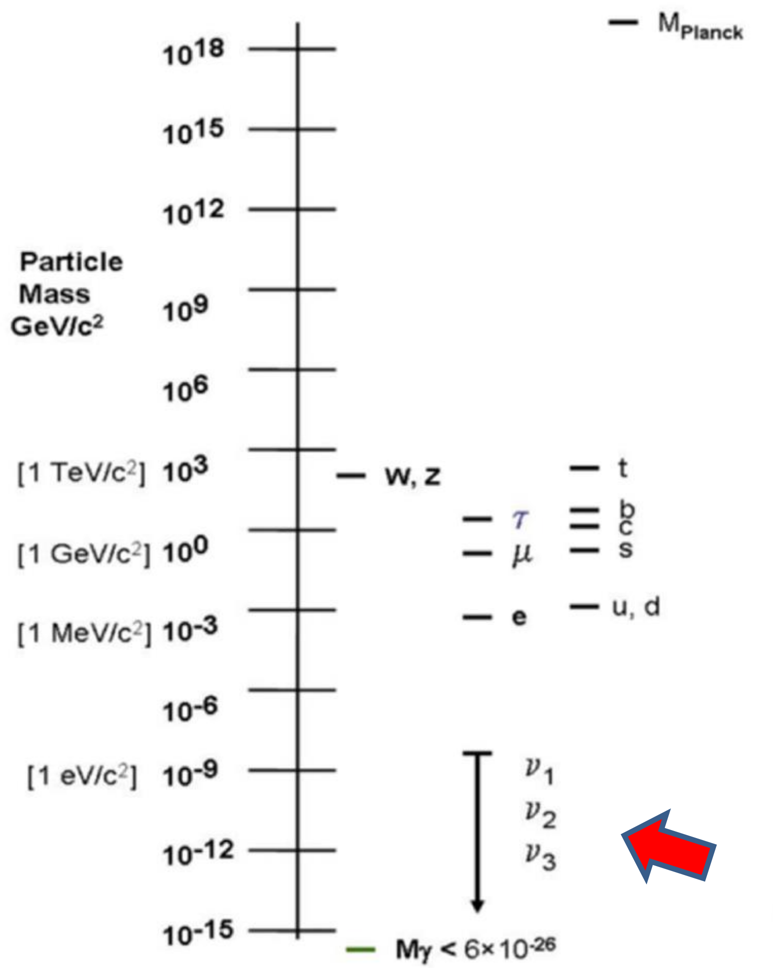
DANSS

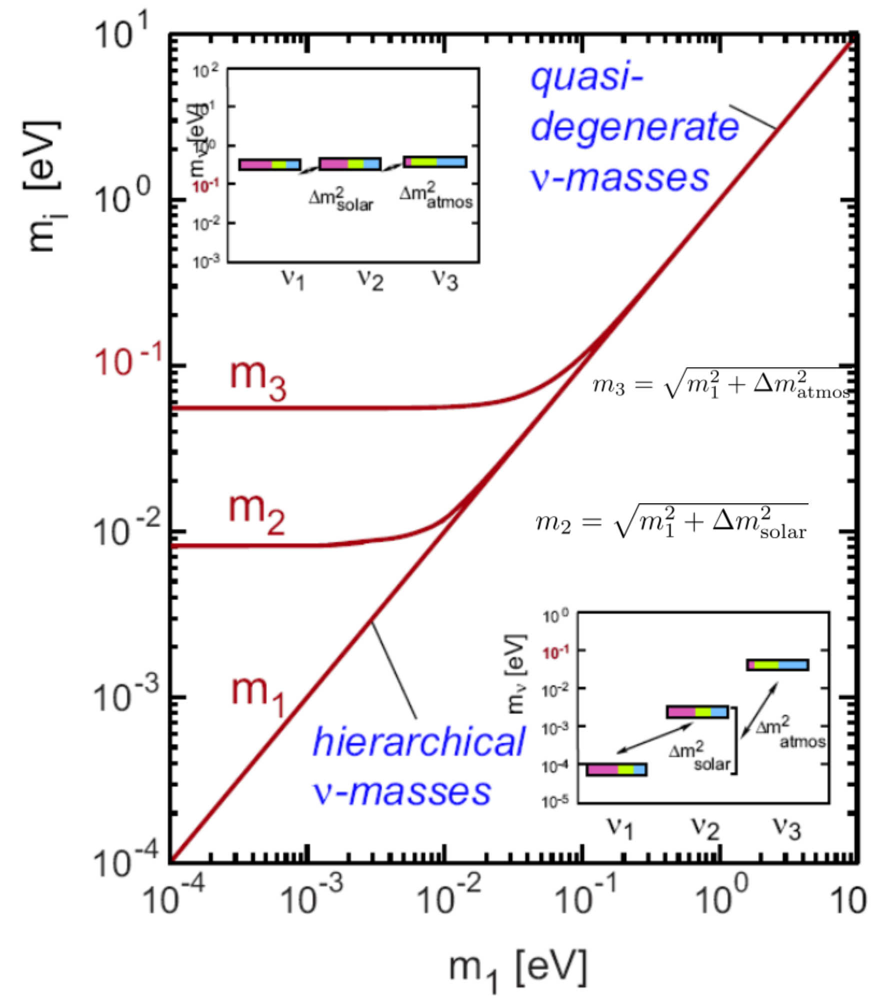


Absolute Neutrino Mass

Neutrino Mass

Standard Model Particle masses





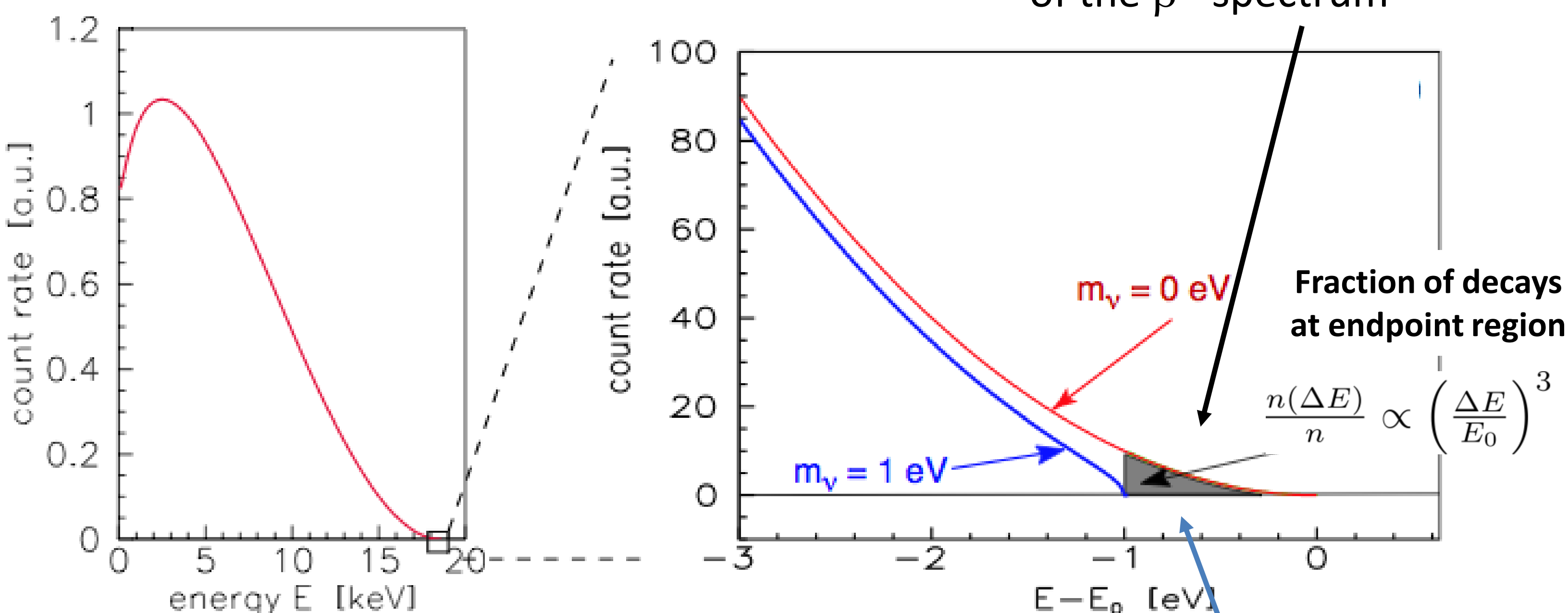
From Markus Steidl

Neutrino Mass Measurement -β decay

The way to measure the neutrino mass is via the electron spectrum from β–decay :

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e$$

A non-zero neutrino mass modifies the endpoint region of the β –spectrum



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

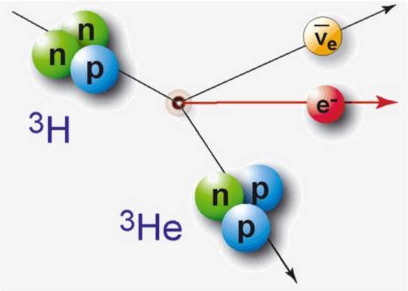
$$E = T_e$$

$$\frac{d\Gamma}{dE} \propto F(Z, E_e) E_e p_e (E_0 - E)\sqrt{(E_0 - E)^2 - m_\beta^2}$$

Neutrino Mass Measurement -β decay

The tritium β-decay is used for studying the endpoint of the electron energy spectrum:

$$^3H \rightarrow ^3 H_e^+ + e^- + \bar{\nu}_e$$



Why:

- Tritium has one of the lowest Q_β-values from β-decay 18.6 keV (i.e one of the smallest endpoint energy E_0). Then its fraction of decays at the endpoint are relatively high.

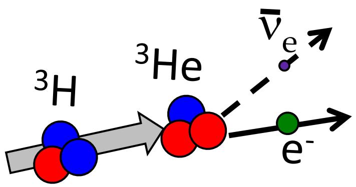
$$\frac{n(\Delta E)}{n} \sim \left(\frac{1}{Q_\beta}\right)^3$$

- It has high activity due its short half-life of 12.3 years.

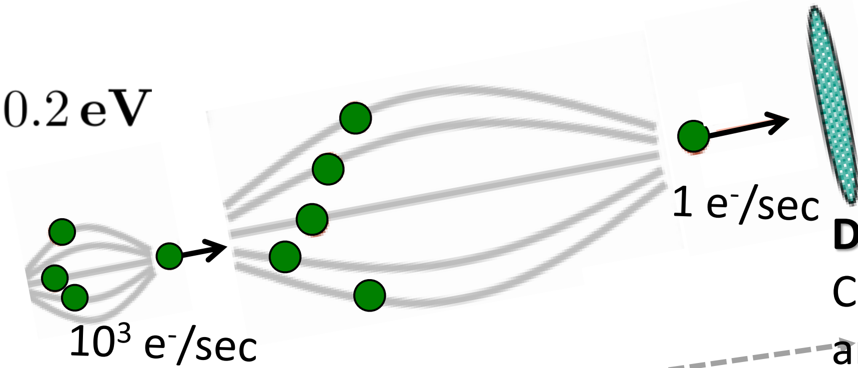
- A Hydrogen isotope and its daughter have a simple shell structure i.e simple and precise calculations involved.

Karlsruhe Tritium Neutrino Experiment- KATRIN

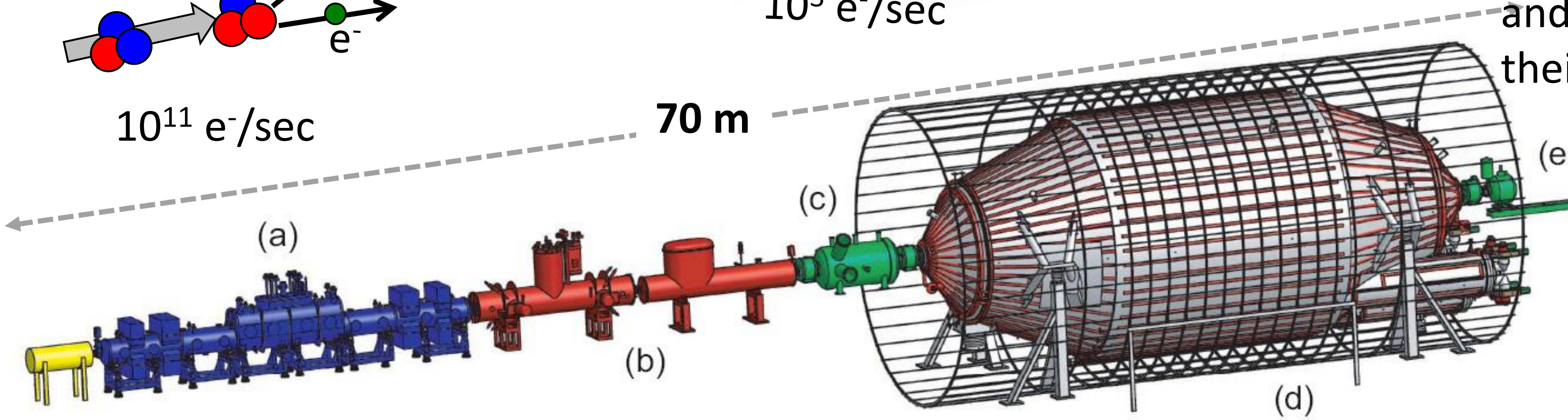
Target sensitivity: $m_{\beta\beta} > 0.2\,\mathrm{eV}$



10^{11} e$^-$/sec



Detector
Count electrons and measure their energy



Rear section
Calibration

Gaseous T_2 source
Provide Tritium column density

Transp-Pump System
Transport electrons adiabatically and reduce T_2 density

Pre-Spectrometer
Transmits only electrons with E> 10 keV

Main Spectrometer
Rejection of electrons with energy near below endpoint

$$\frac{\beta\text{−electron}}{\text{background}} = 9.9$$

Background

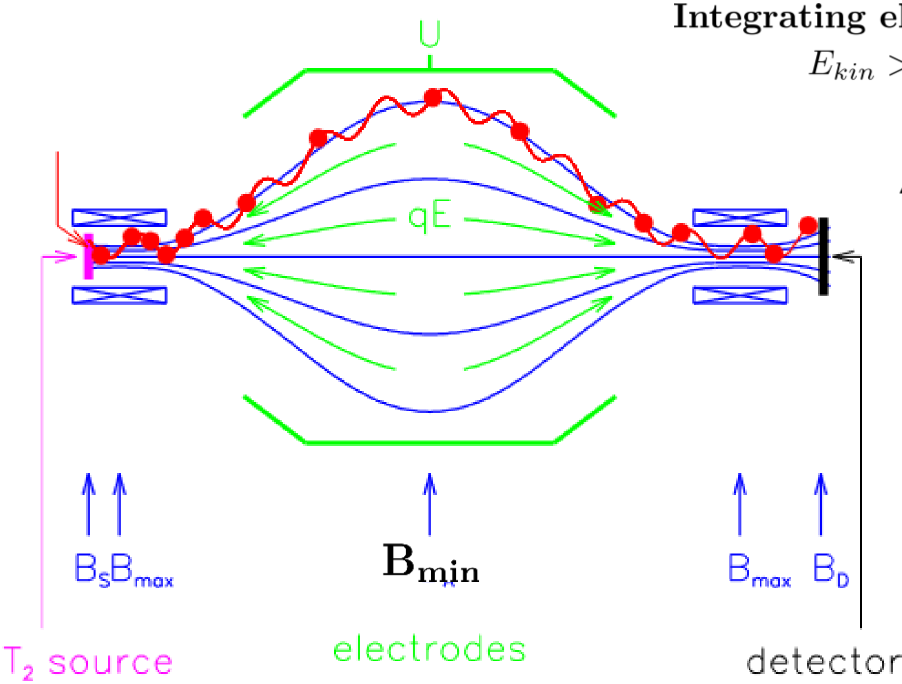
- originated in the spectrometer section
- Ionization of Rydberg states created from ^{210} Po α –decay (in the structural material)
- Residual gas ionization by electrons produced from Radon decay

MAC-E-Filter
Magnetic Adiabatic Collimation + Electrostatic Filter

- Two superconducting solenoids produce the guiding magnetic field. B_{max} = 2.5-4.2 T, and B_{min} < 0.63 mT.
- The decayed electrons travel on a cyclotron motion around the magnetic field lines.

Integrating electrostatic filter

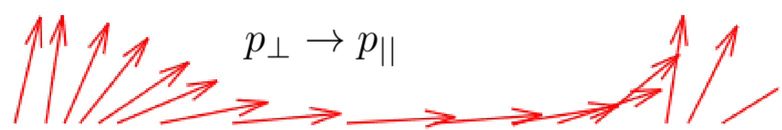
$$E_{kin} > qU(\int_{qU}^{E_0})$$



$$\Delta E = 0.93\,\mathrm{eV}$$

$$\frac{\Delta E}{E} = \frac{\mathrm{B_{min}}}{\mathrm{B_{max}}}$$

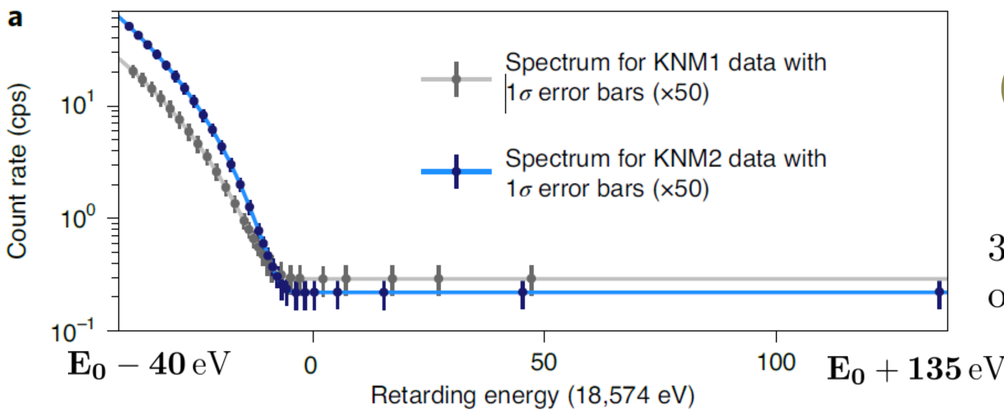
Adiabatic transformation



$$\gamma\mu = \frac{p_\perp^2}{B} = \mathrm{const}$$ **Under adiabatic conditions**

$\mu \rightarrow$ magnetic moment $p_\perp \rightarrow$ momentum component transverse to the B field

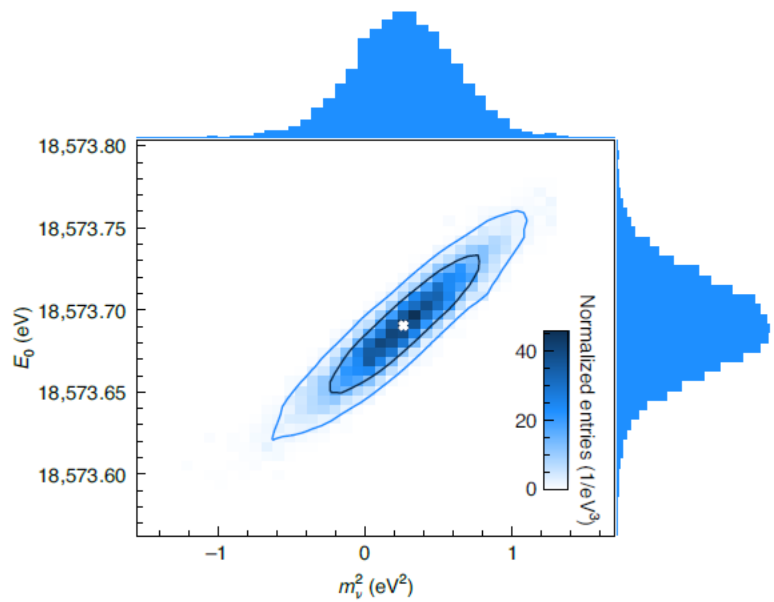
KATRIN -Results

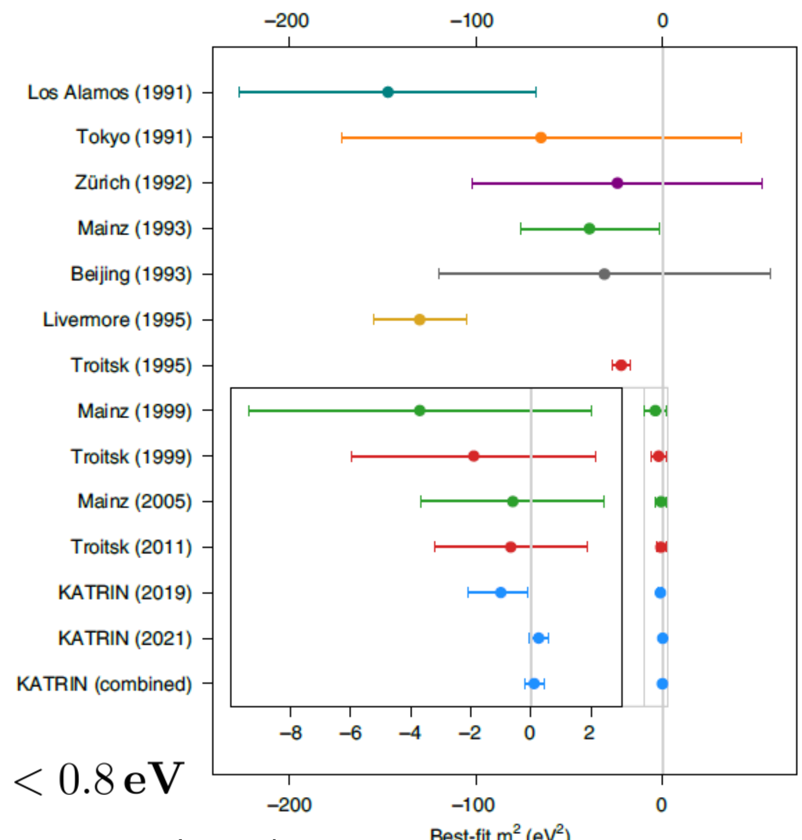


(KNM1) KATRIN neutrino-mass campaign (2019)

(KNM2) KATRIN neutrino-mass campaign (2022)

$3.6 \times 10^{6}\ \beta-$electrons collected in the last 40 eV of the integral spectrum.





$m_\nu^2 = 0.26 \pm 0.34\,\mathrm{eV}^2$ **(KMN2)** **Upper limit:** $m_\nu < 0.8\,\mathbf{eV}$

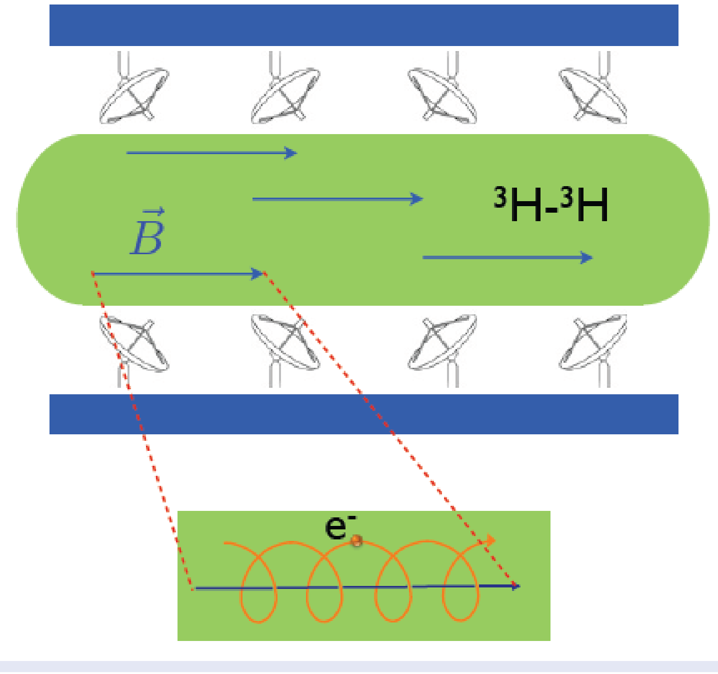
<u>Nature Physics</u> volume 18, 160–166 (2022)

Cyclotron Radiation Emission Spectroscopy (CRES)

Key points:

B. Monreal and J. Formaggio, PRD 80 (2009) 051301

- Trap a volume of atomic tritium
- Decay electrons process within a constant B-field.
- Measure the cyclotron frequency we get E_e
- Highest energy – lowest frequency signals



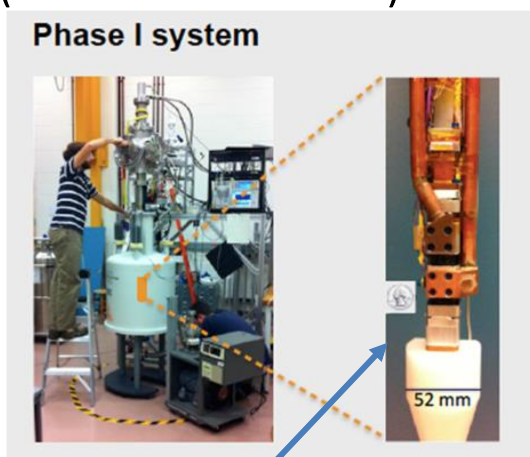
$$w(\gamma) = \frac{w_c}{\gamma} = \frac{eB}{E_{kin}+m}$$

Project 8

The Project 8
Neutrino Mass Experiment

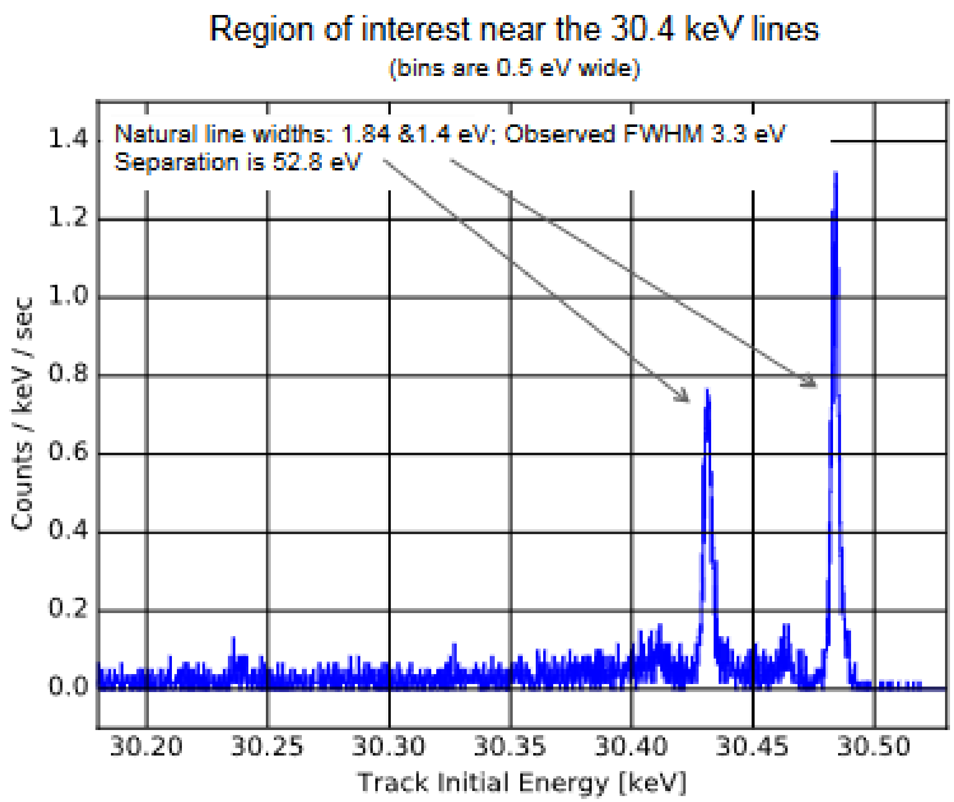
Proof of Principle – Project 8 (phase I results):

Test gas ^{83m}Kr (1.8 h half -life) provides several monoenergetic lines: 17.83 keV and 30.23 keV, 30.42 keV, 30.48 keV, 31.94 keV (internal conversion).



A waveguide insert in a superconducting solenoid B ~ 1 Tesla

Energy

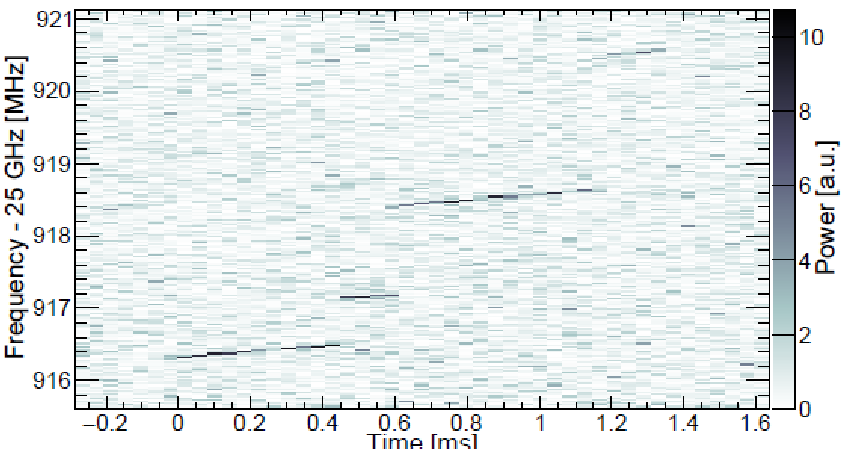


A. Ashtari Esfahani et al. , JPG 44, 054004 (2017)

The Project 8
Neutrino Mass Experiment

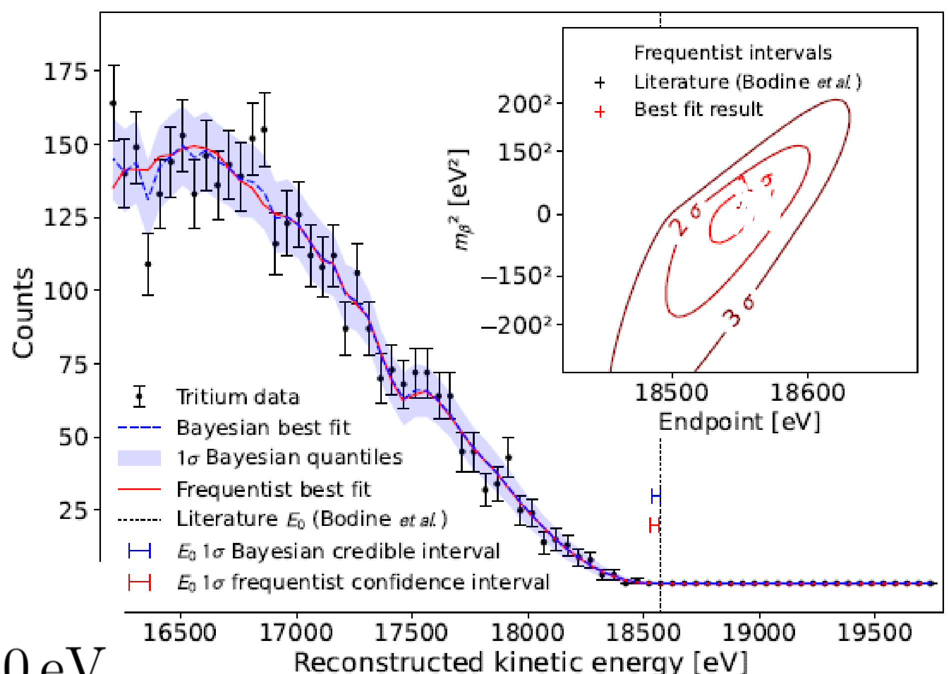
Project 8 (phase II: tritium results):

Spectrogram from a tritium beta decay electron



A. A. Ashtari Esfahani et al, arXiv:2212.05048

Extraction of continuous tritium beta spectrum



$$m_{\beta\beta} < 180\,\text{eV}$$

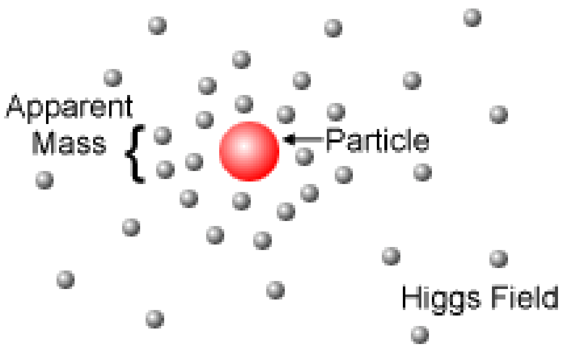
first mass upper limit with **CRES** technique

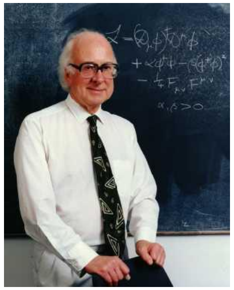
$$\textbf{Target sensitivity: } m_{\beta\beta} > 0.04\,\textbf{eV}$$

Nature of massive neutrinos

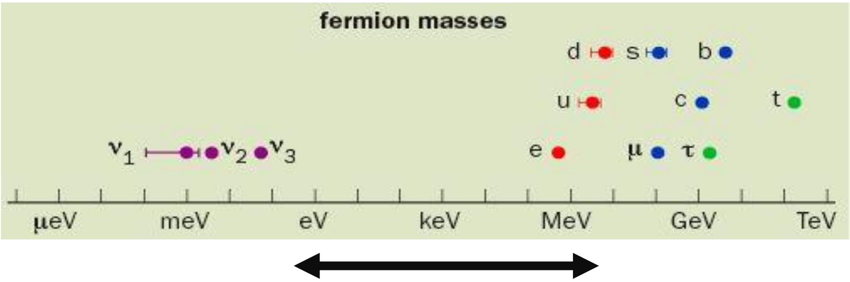
If the neutrino has mass then…

$$m_\nu^D = \frac{Y_\nu v}{\sqrt{2}} \simeq \mathcal{O}(\mathrm{eV})$$





Peter Higgs



six orders of magnitude

$$v = 246\,\mathrm{GeV}$$

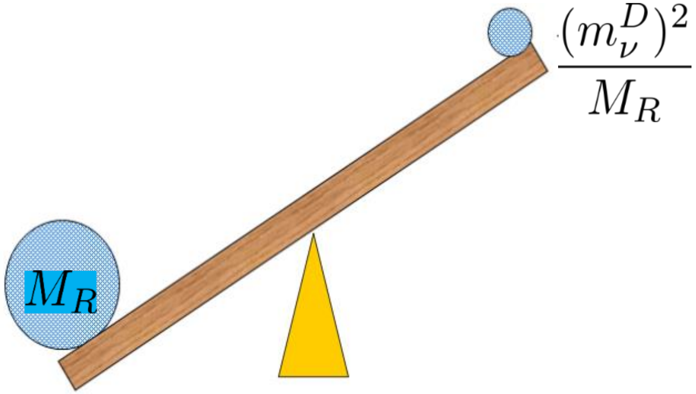
$$\frac{Y_e}{Y_\nu} = 10^6 \Rightarrow$$

Unnatural

Majorana condition

$$\nu = \nu^C = C\bar{\nu}^{\mathrm{T}}$$

Neutrino= Antineutrino

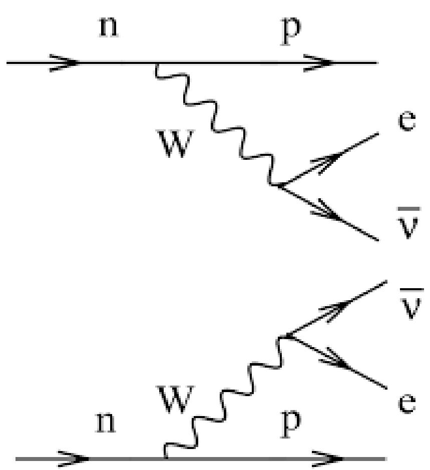


Seesaw mechanism

***Y** : intensity of the interaction of the massive particles with the Higgs*

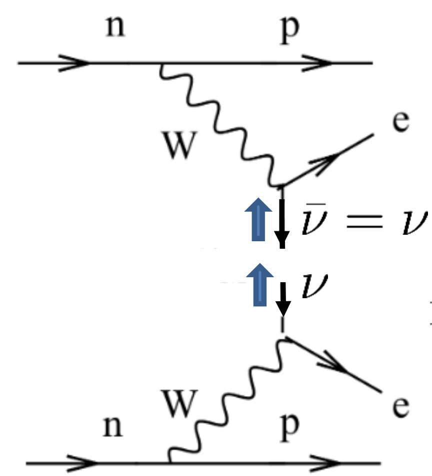
Double beta decay

Standard Model ($2\nu\beta\beta$)



$\Delta L = 0$

Beyond Standard Model ($0\nu\beta\beta$)

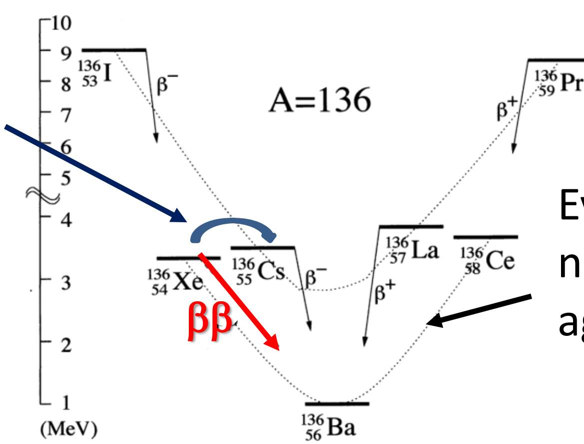


Majorana

$\Delta L = 2$

Lepton number violation

Single β-decay
energetically forbidden



Even-even
nuclei stable
against β–decay

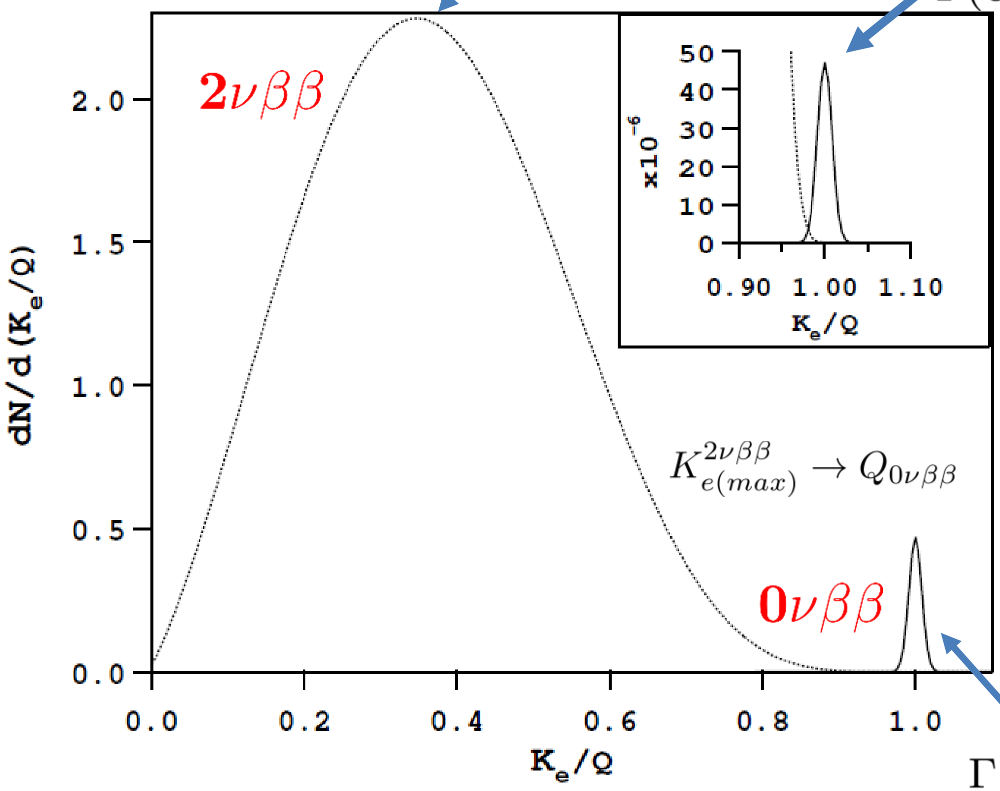
Second-order weak processes $\sim G_F^4$

$$T_{1/2}^{2\nu\beta\beta} > 10^{19}\text{years}$$

Neutrinoless double beta decay ($0\nu\beta\beta$)

normalized to 1

$$\frac{\Gamma(2\nu\beta\beta)}{\Gamma(0\nu\beta\beta)} \sim 10^6$$



$$\underbrace{K_e^{0\nu\beta\beta}}_{K_e^1+K_e^2} = Q_{0\nu\beta\beta}$$

smeared only by detector resolution (2%)

$$\frac{\Gamma(2\nu\beta\beta)}{\Gamma(0\nu\beta\beta)} \sim 10^2$$

Neutrinoless double beta decay (0νββ)

Nuclear Matrix Element

effective Majorana neutrino mass

half-life of 0νββ decay

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = G^{0\nu}(Q,Z)|\mathcal{M}^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2 \Rightarrow \langle m_{\beta\beta}\rangle^2 = \left[T_{1/2}^{0\nu\beta\beta} G^{0\nu}(Q,Z)|\mathcal{M}^{0\nu}|^2\right]^{-1}$$

Phase-space factor $\sim Q^5$

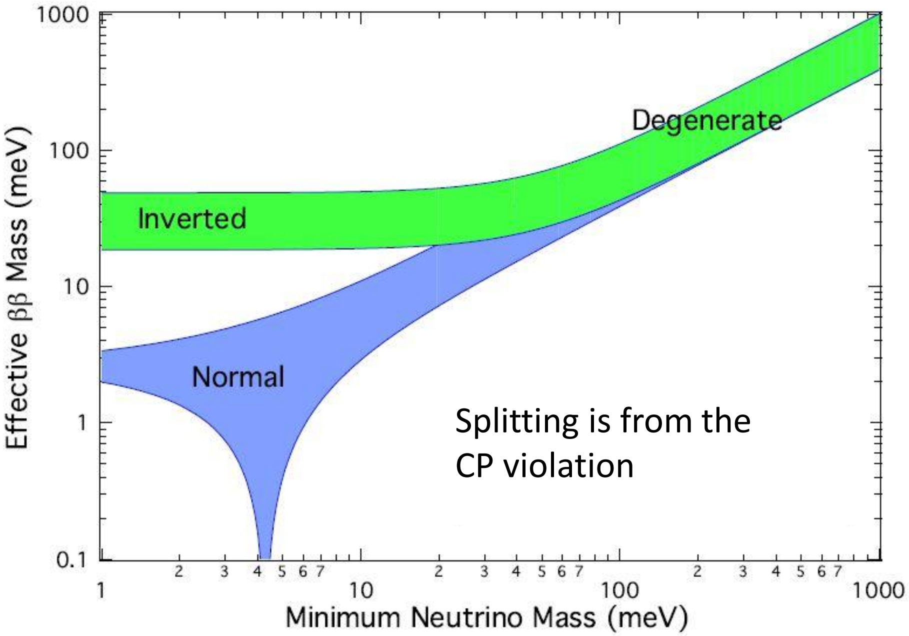
$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2$$

$$\langle m_{\beta\beta}\rangle = ||U_{e1}|^2 m_1 + e^{i(\alpha_1-\alpha_2)}|U_{e2}|^2 m_2 + e^{i(-\alpha_1-2\delta_{CP})}|U_{e3}|^2 m_3|$$

From Janet Conrad

α_1,α_2 Majorana CP-phases and δ_{CP} Dirac CP-phase

$$U_{PMNS}^{\text{Dirac}} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Splitting is from the CP violation

Experimental requirements-0νββ

Number of signal (S) and background (B) 0νββ events in the region of interest (a narrow window around $Q_{\beta\beta}$):

$$N_S^{0\nu} = \frac{\ln(2) N_A}{A} \left(\frac{a \epsilon M T}{T_{1/2}^{0\nu}} \right)$$

$$N_B^{0\nu} \propto B \Delta E M T$$

$T \rightarrow$ measured time $\epsilon \rightarrow$ efficieny $A \rightarrow$ atomic mass

$M \rightarrow$ detector mass $a \rightarrow$ isotope abundance $N_A \rightarrow$ Avogadro's number

$B \rightarrow$ backg. index $\left(\frac{1}{\text{mass-time-energy}}\right)$

$\Delta E \rightarrow$ energy res.

Sensitivity for non-zero **(zero)** background:

$$T_{1/2}^{0\nu} \propto \frac{a\epsilon}{n_\sigma} \sqrt{\frac{MT}{B\Delta E}} \left(\frac{a\epsilon MT}{n_\sigma} \right)$$

$$\Rightarrow \langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{G^{0\nu} |\mathcal{M}^{0\nu}|^2}} \left(\frac{A}{\epsilon} \right)^{1/2} \left(\frac{B\Delta E}{MT} \right)^{1/4} \sqrt{n_\sigma}$$

Derived from $n_\sigma = \frac{N_{Sig}^{0\nu}}{\sqrt{N_B^{0\nu}}}$

Ideally

- Large detector mass
- High-isotopic abundance
- Low background
  - Underground detector
- Good energy resolution
  - reduce 2νββ background.
  - resolve nearby peaks

Candidate nuclei - 0νββ decay

Peak Energy

Isotope	$G^{0\nu}$ (10^{-14} y^{-1})	$Q_{\beta\beta}$ (keV)	Nat. ab. (%)
^{48}Ca	6.35	4273.7	0.187
^{76}Ge	0.623	2039.1	7.8
^{82}Se	2.70	2995.5	9.2
^{96}Zr	5.63	3347.7	2.8
^{100}Mo	4.36	3035.0	9.6
^{110}Pd	1.40	2004.0	11.8
^{116}Cd	4.62	2809.1	7.6
^{124}Sn	2.55	2287.7	5.6
^{130}Te	4.09	2530.3	34.5
^{136}Xe	4.31	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

Phase - factor **Natural Abundances**

- Even-even nuclei
- High $Q_{\beta\beta}$ value help to mitigate background from natural radioactivity
- Low natural abundances.
- High cost (↑) –low natural abundance (↓)

Taken from B. Jones arXiv:2108.09364v2

Backgrounds - $0\nu\beta\beta$ decay

- **Natural radioactivity:** from ^{238}U and ^{232}Th decay chain ($T_{lifetime}$ ~10^9 yr).
  - The ^{208}Tl (^{232}Th decay chain) emits 2.615 MeV γ–ray line.
  - The ^{214}Bi (^{222} Rn's progeny- ^{238}U decay chain) emits β electron with energy up to 3.270 MeV.

- **Cosmic-ray muons:**
  - μ 's can produce cosmogenic radioactive isotopes and neutrons, which produce long-live radioisotope and secondary neutrons.
  - μ 's induce fast neutrons created in the external rock. Fast neutrons can induce more neutrons and γ via inelastic scattering and spallation products.

Classification by experimental technique

Bolometers

CUORE (^{130}Te)
CUPID (^{82}Se | ^{100} Mo | ^{130} Te)
AMORE ^{100} Mo

Semiconductors

GERDA (^{76}Ge)
Majorana Demonstrator (^{76}Ge)
LEGEND (^{76}Ge)

Scintillators

KamLAND-Zen (^{136}Xe)
SNO+ (^{130} Te)

Time –Projection Chambers

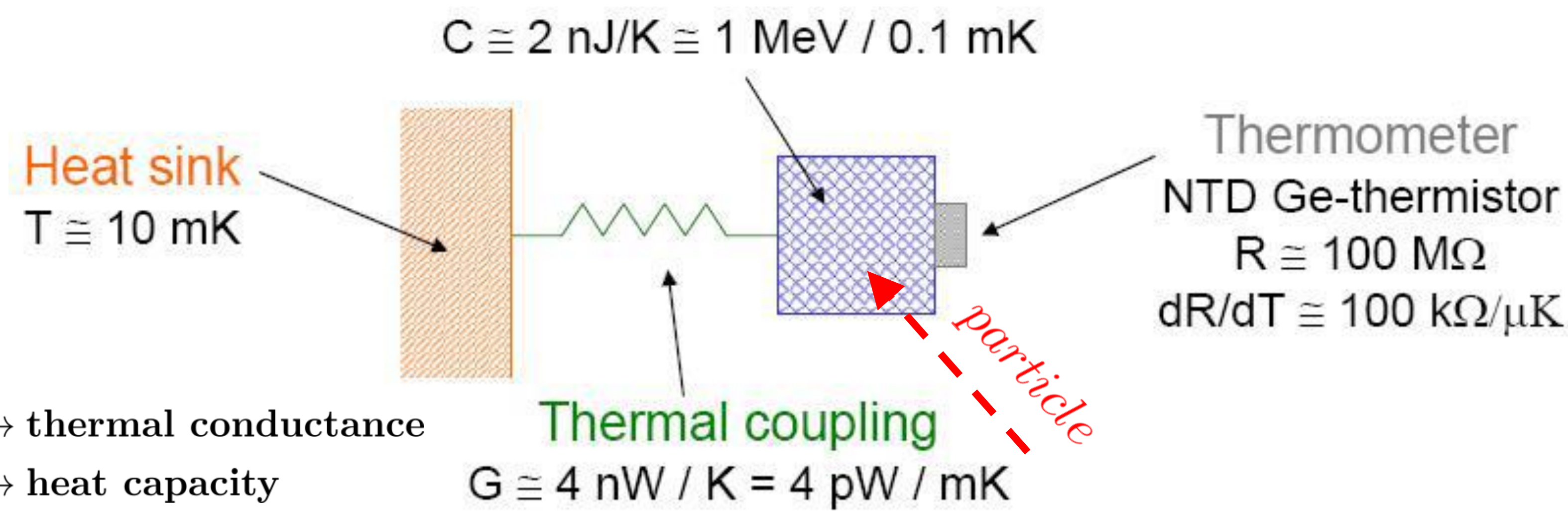
EXO-200 (^{136}Xe)
nEXO (^{136}Xe)
NEXT (^{136}Xe)

Tracking Calorimeters

NEMO -3 (^{100}Mo)
SuperNEMO (^{82}Se)

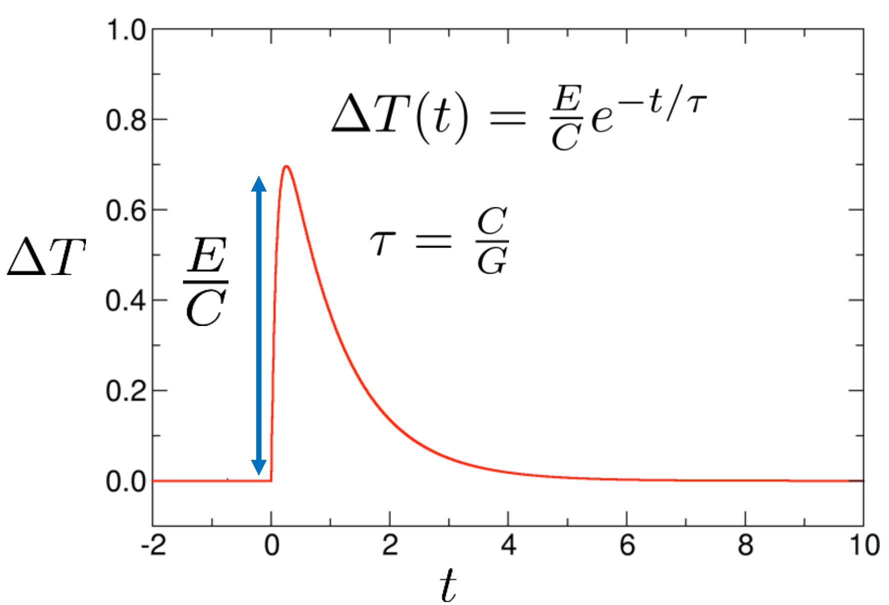
Not exhaustive list of experiments

Cryogenic Bolometer (^{130} Te)



$G \rightarrow$ **thermal conductance**

$C \rightarrow$ **heat capacity**

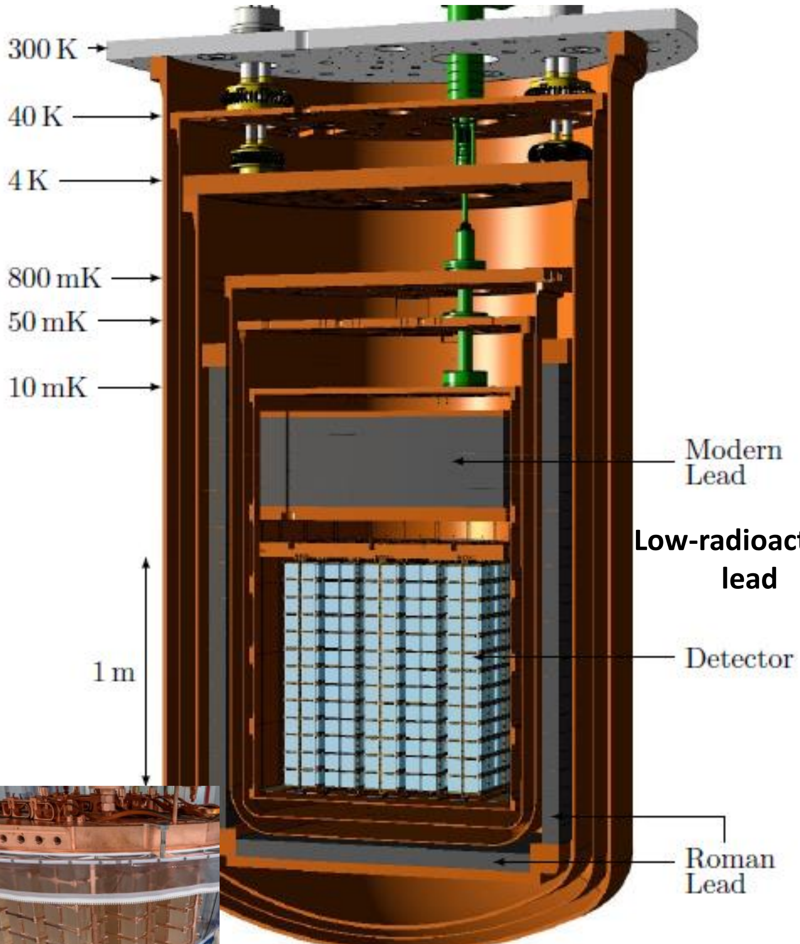


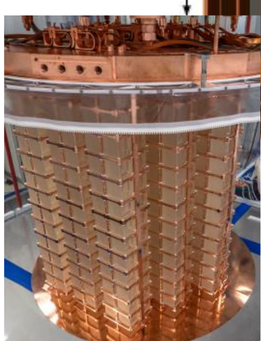
$E = \text{Energy deposited}$

- Measure total energy deposited
- No information about the particle ID, external γ and surface degraded α are major background concerns

Slide taken from Debbie Harris Invisibles 2014

Cryogenic Underground Observatory for Rare Events (CUORE)



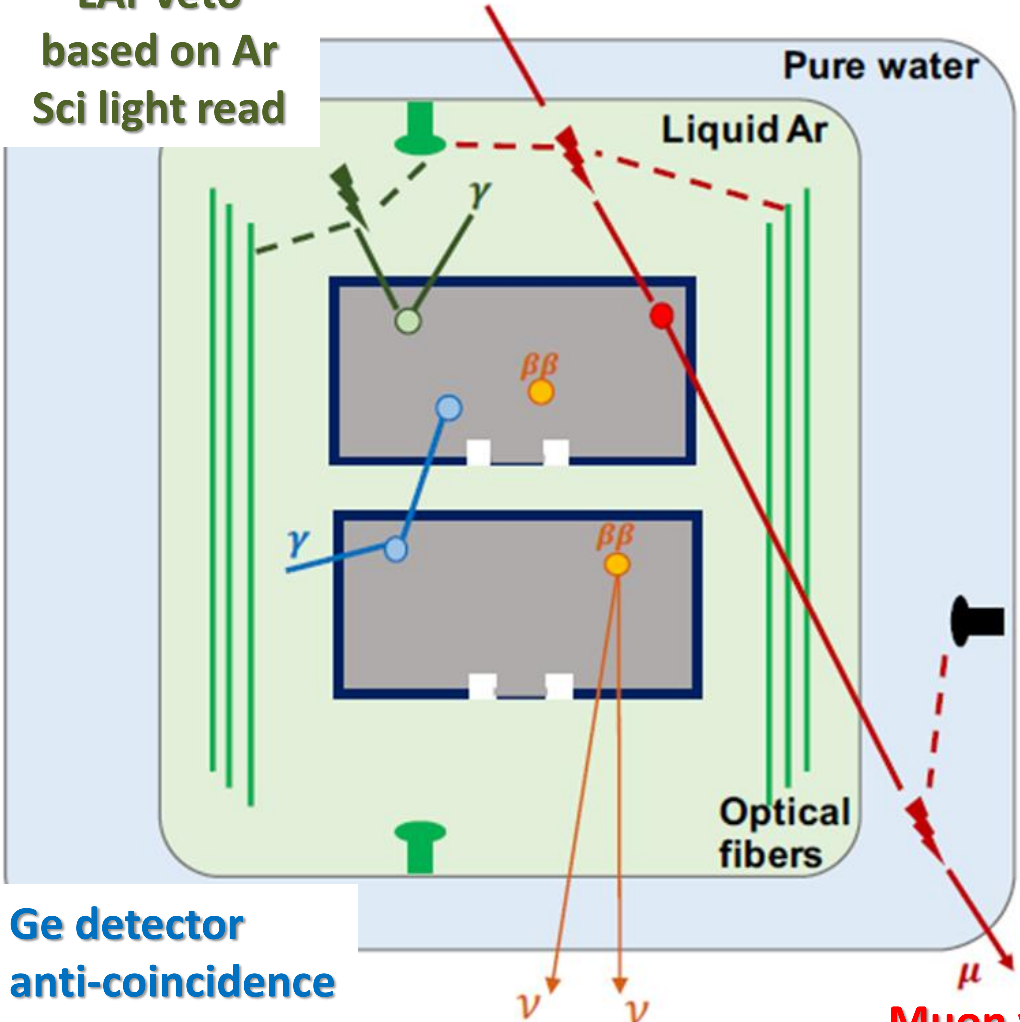


From Nature 604 (2022) 7904, 53-58

- Cryogenic Calorimeter (under 3600 m.w.e @Gran Sasso)
- ββ decay source is ^{130} Te high nat. abundance (34 %) with $Q_{\beta\beta}$ (2527.5 keV) above most nat. emitting lines.
- Resolution at FWHM: (7.8 ± 0.5) keV @ $Q_{\beta\beta}$.
- Array of 988 cubes of TeO_2 ($5 \times 5 \times 5\ cm^3$) - 206 kg ^{130}Te (288.8 kg-yr exposure).

Germanium Detector Array (GERDA)

LAr veto based on Ar Sci light read



Ge detector anti-coincidence

Muon veto Based on Cherenkov and Plastic Sci.

$\beta\beta$ decay source is ^{76}Ge $Q_{\beta\beta}$ (2039 keV)
Resolution at FWHM: (2.9 ± 0.1) keV @ $Q_{\beta\beta}$
41 high-purity germanium detectors made out of material enriched with ^{76}Ge
Exposure 127.2 kg-yr.
The two e^- from $0\nu\beta\beta$ deposit its energy a small volume (1 mm range).

Background :

- β-decay of ^{42}K progeny of the long-lived ^{42}Ar
- γ rays with similar energy (2e-) produce multi-site event.

Lic

Muon veto

O. Schulz, Lake Louise Winter Institute (2020)

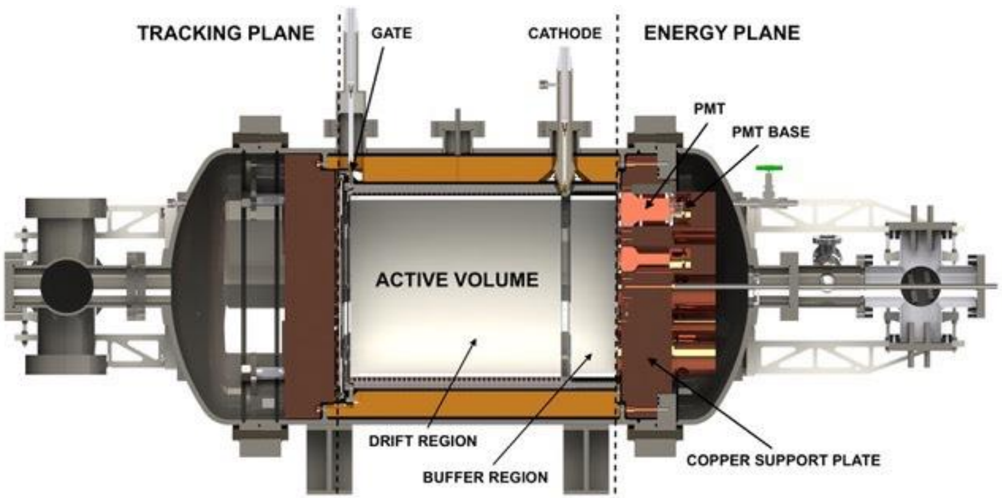
Current limits

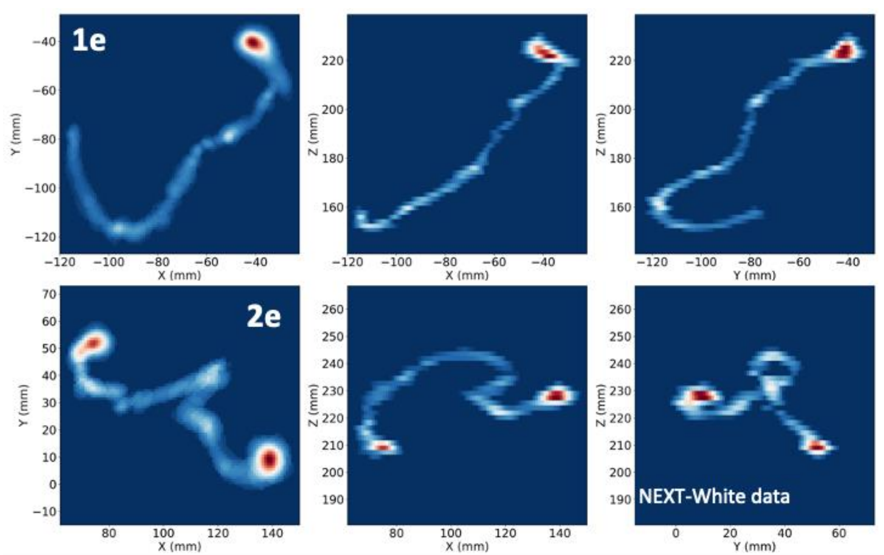
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

Fedor Šimkovic Neutrino 2022

NEXT-White

Proof of concept – NEXT-White





- 5 kg of Xenon gas enriched in the ^{136}Xe isotope.
- Energy resolution: $0.91 \pm 0.12\%$ FWHM at 2.6 MeV.

➢ 2 e^- event candidate has two blobs at the end of trail.

➢ 1 e^- event candidate has one blob.

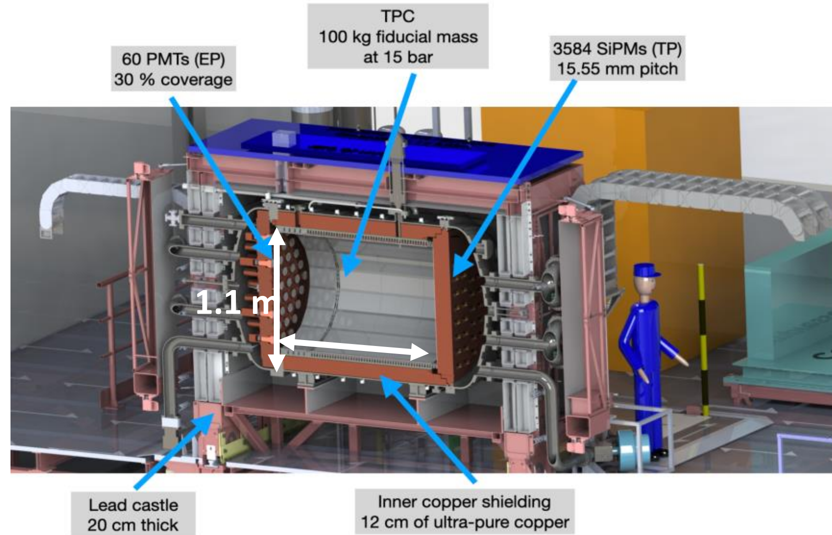
$$\frac{dE}{dx} \propto \frac{1}{v^2}$$

Taken from M. Sorel Neutrino 2022

NEXT Program - Future

NEXT -100 (2023-2025)

- Background free conditions 100 kg mass scale
- Status: ready to install soon



Taken from M. Sorel Neutrino 2022

NEXT –BOLD (2026-)

- 1109 kg of ^{136}Xe – energy resolution < 1 %
- S
- S
- E

dete

top

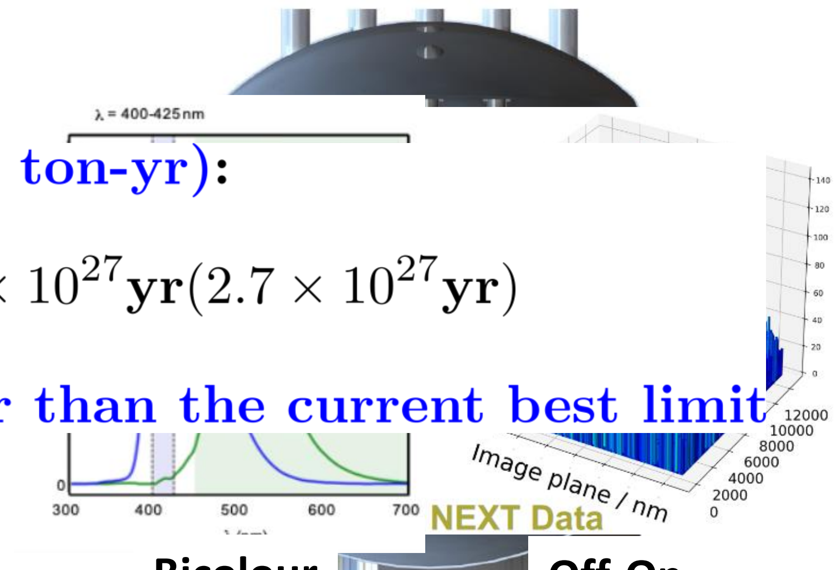
Sensitivity for 5 ton-yr (10 ton-yr):

$$T_{1/2}^{0\nu} > 1.4 \times 10^{27}\mathbf{yr}(2.7 \times 10^{27}\mathbf{yr})$$

one order of magnitude better than the current best limit

➢ Using single molecule fluor imaging for detect Ba^{2+}

JHEP 2021 (2021) 08, 164



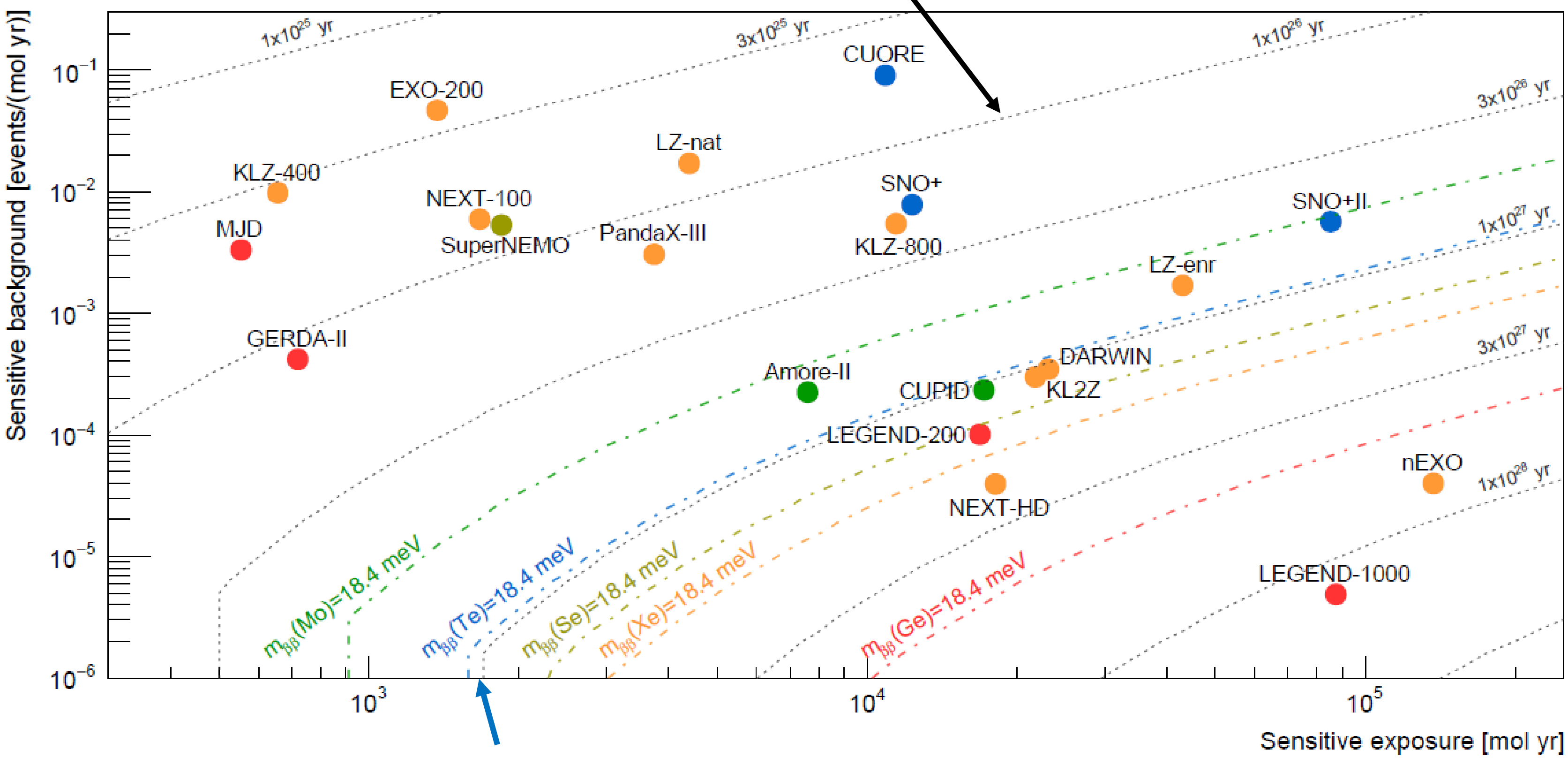
Bicolour **Off-On**

Landscape of $0\nu\beta\beta$ experiments

Discovery sensitivity values on the $0\nu\beta\beta$–decay half-life

Low Detector Mass

High Detector Mass



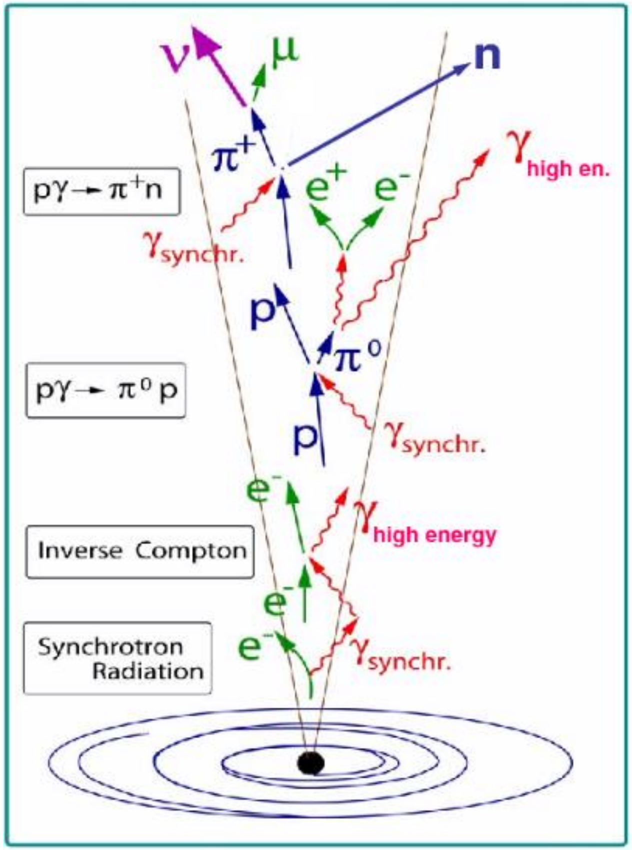
Sensitivities required to test the bottom of the inverted hierarchy,

T = 10 years (livetime)

Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787

Astrophysical Neutrinos

Astrophysical neutrinos



$$p + nucleus \rightarrow \pi + X\,(\pi = \pi^{\pm}, \pi^0)$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \\ \pi^+ + n \end{cases}$$

$$\pi^0 \rightarrow \gamma\gamma \quad \pi^{\pm} \rightarrow \mu^{\pm}\bar{\nu}_\mu$$
$$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e \text{ or } \mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$$

$$\Phi_\nu^{\rm prod} = (\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$$

After oscillations $P_{\nu_\alpha\nu_\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$

$$\Phi_\nu^{\rm earth} = (1 : 1 : 1)$$

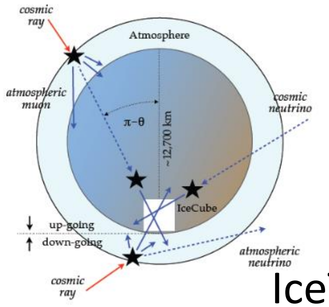
$$\Phi_\nu^{\rm prod} = (0 : 1 : 0) \Rightarrow \Phi_{\nu(\mu)}^{\rm earth} = (4 : 7 : 7)$$

Muon damped sources

$$\Phi_\nu^{\rm prod} = (1 : 0 : 0) \Rightarrow \Phi_{\nu(n)}^{\rm earth} = (5 : 2 : 2)$$

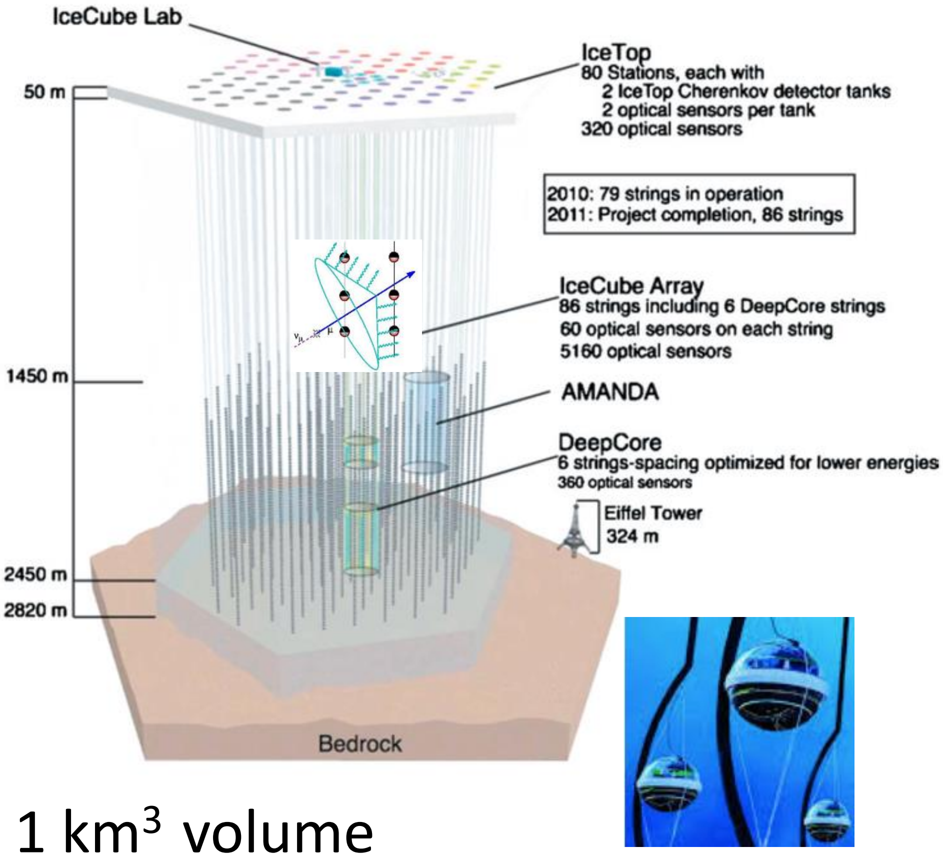
Neutron beam sources

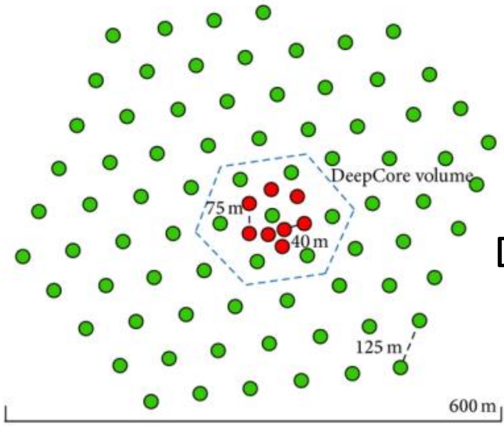
IceCube



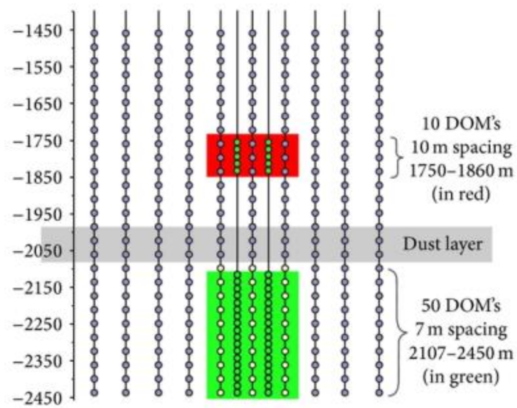
Std IceCube -Energy threshold 100 GeV Strings separation(H)~125, DOM separation(V~ 17 m)

IceTop veto for cosmic rays (CR)





Deep Core
8 strings

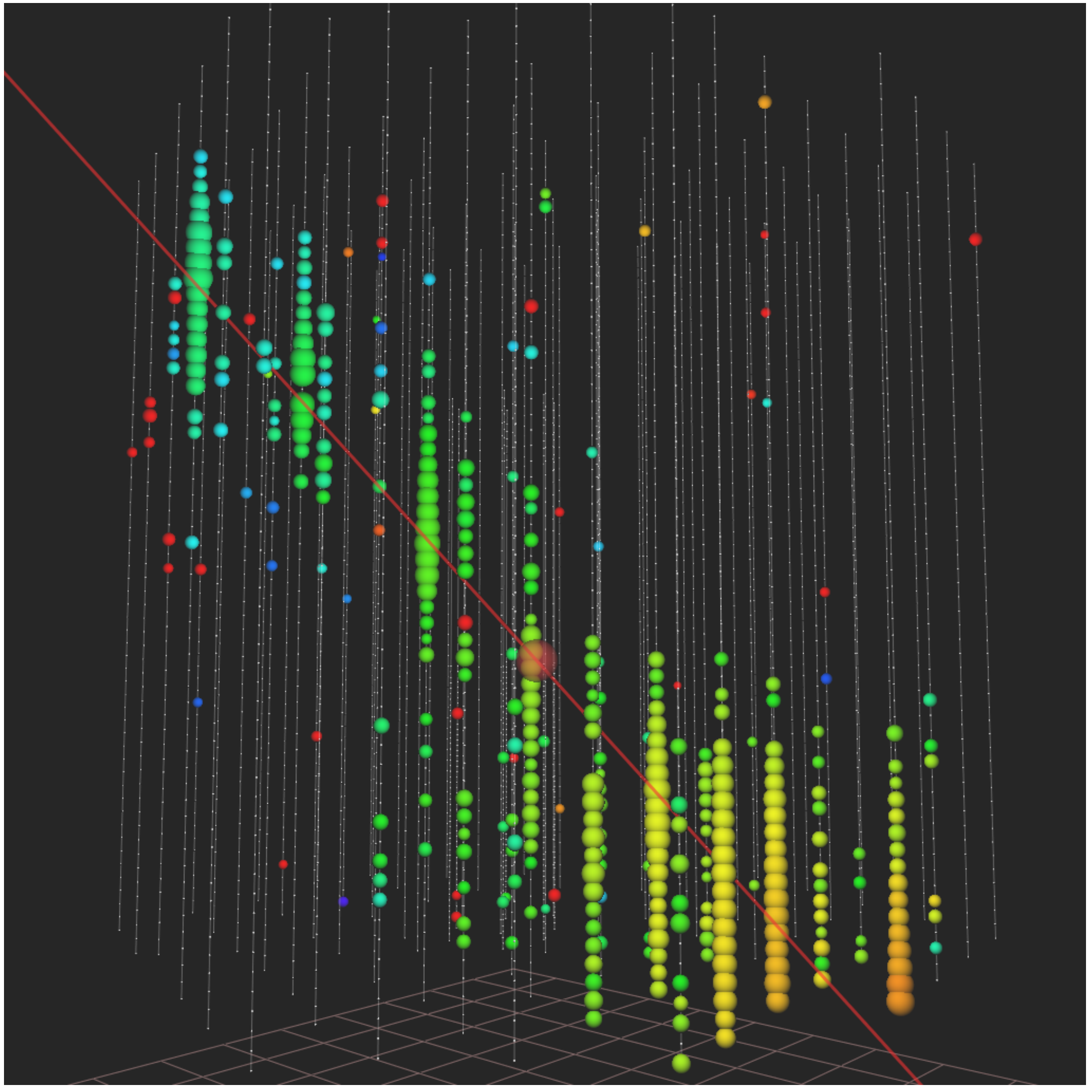


H ~55 m, V~ 7m

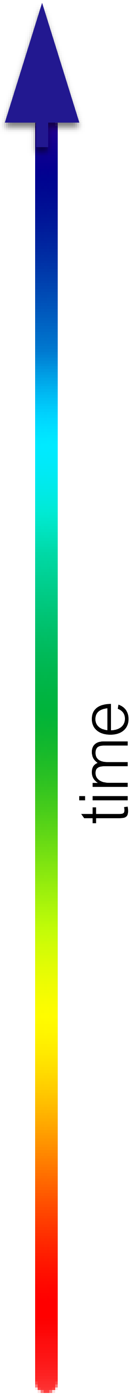
1 km^3 volume

Deep Core -Energy threshold 10 GeV
Lower spacing – lower energy threshold

IceCube – Event display

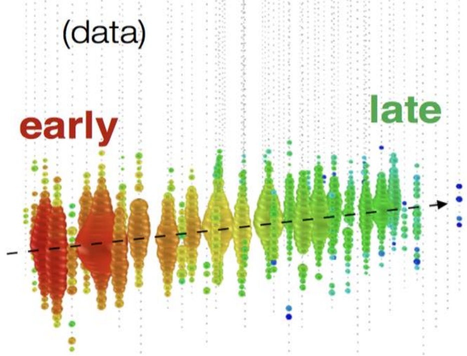


Size of spheres ~ amount of light collected



IceCube – event topologies

Charged-current ν_μ



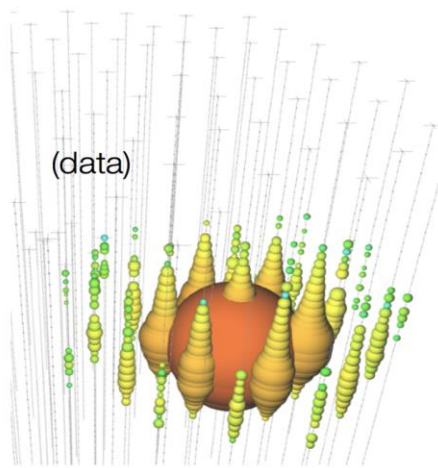
Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Res $\rightarrow$ 0.3 in $\log(E_\nu)$

$$\nu_\mu + N \rightarrow \mu + had$$

Neutral-current / ν_e

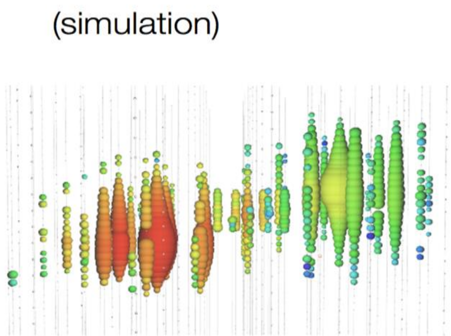


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

$$\nu_l + N \rightarrow \nu_l + had$$
$$\nu_e + N \rightarrow e + had$$

Charged-current ν_τ

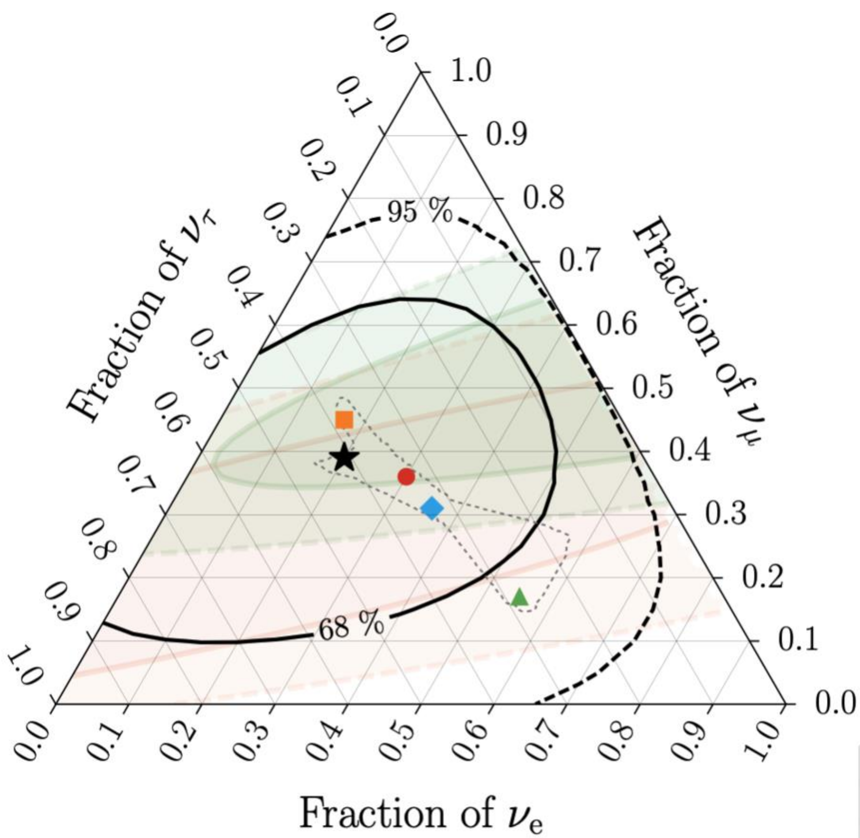


Double cascade

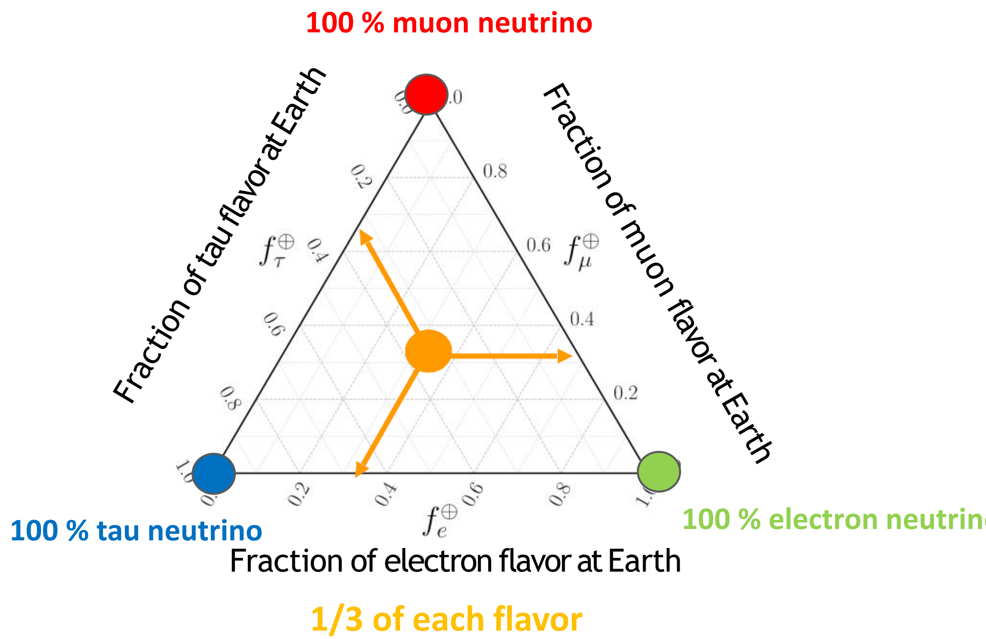
(resolvable above ~100 TeV deposited energy)

$$\nu_\tau + N \rightarrow \tau + had \rightarrow had$$

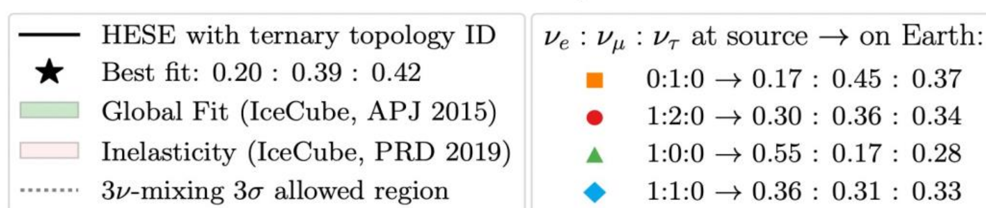
Astrophysical Neutrino Flavor Composition



IceCube Collaboration, arXiv:2011.03561



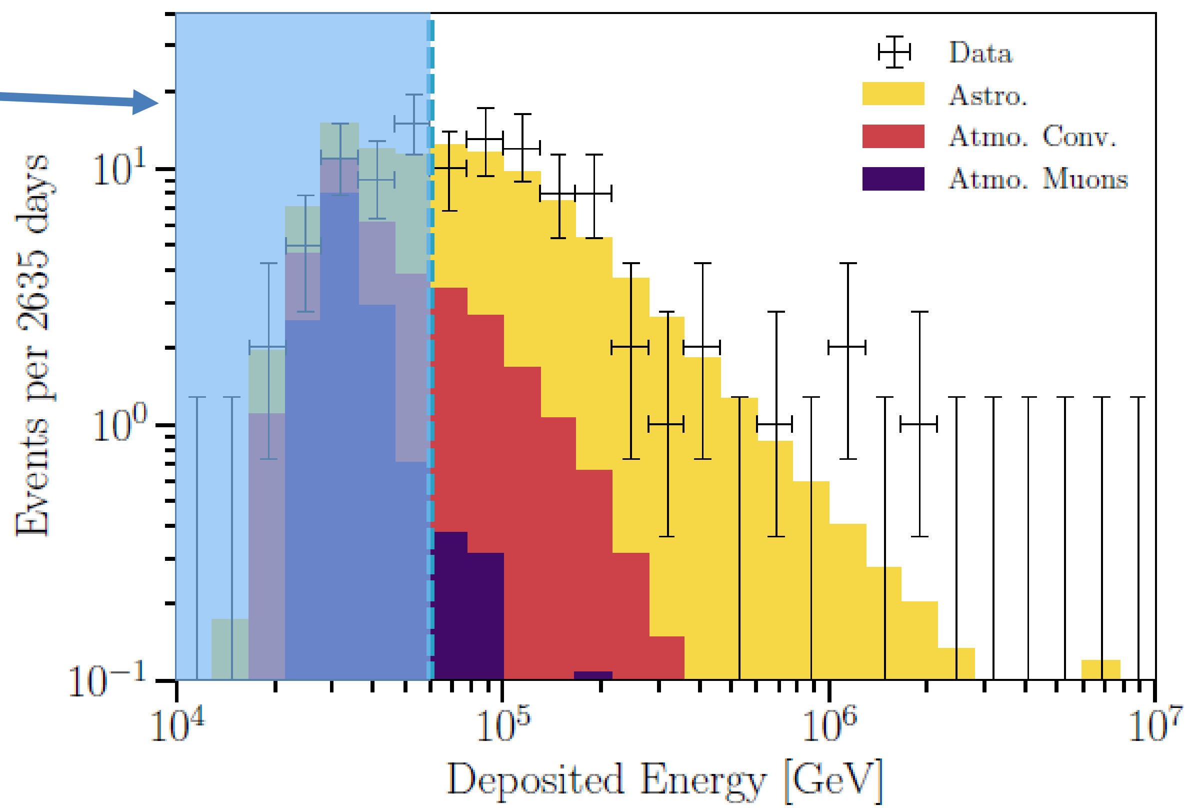
Courtesy of Carlos Arguelles



Astrophysical neutrinos spectra

$d\phi/dE = \Phi_{astro}(E/100\mathrm{TeV})^{-\gamma_{astro}}$ 10^{-18}[GeV cm^{-2} s^{-1} sr^{-1}]

Below 60TeV is excluded because of larger background uncertainties



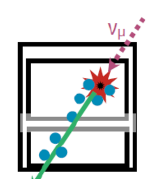
$\Phi_{\mathbf{astro}} = 6.37^{+1.47}_{-1.62}$

$\gamma_{\mathbf{astro}} = 2.87^{+0.20}_{-0.19}$

Above 60TeV: 60 HESE events

(HESE) High Energy Starting events:

interaction vertex within the detector

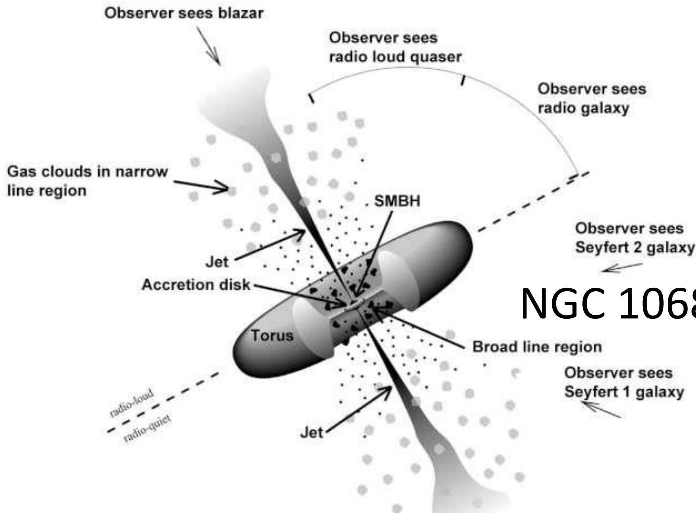


IceCube Collaboration, PhysRevD.104.022002

From Lu Lu, Christian Haack and TianluYuan,

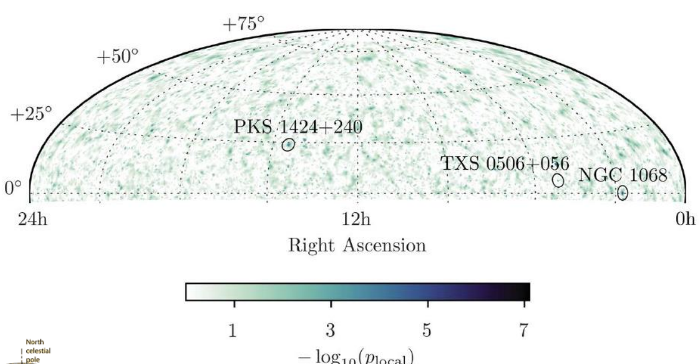
Astrophysical neutrinos

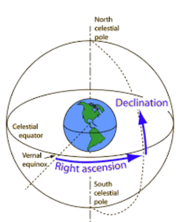
TXS 0506+056



Science, **378**, 6619 (2022)

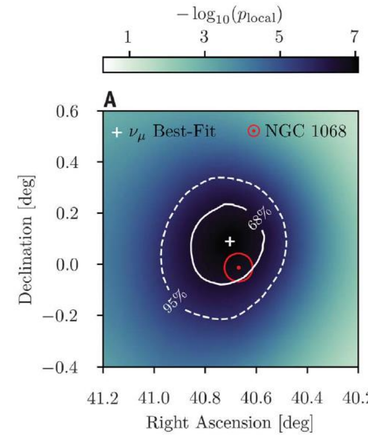
NGC 1068 4.2 σ significance



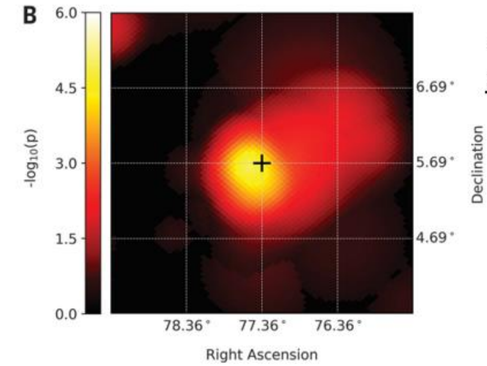


Science 378, 6619, 538-543 (2022)

NGC 1068

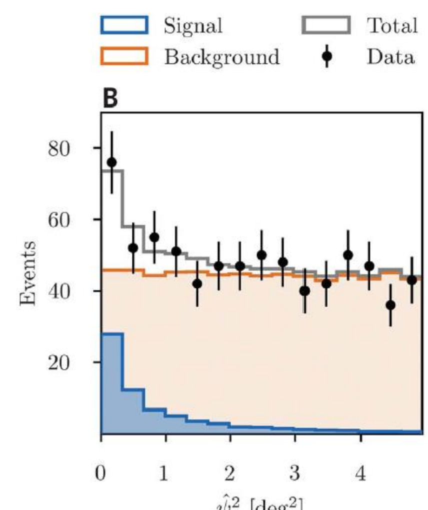


TXS 0506+056



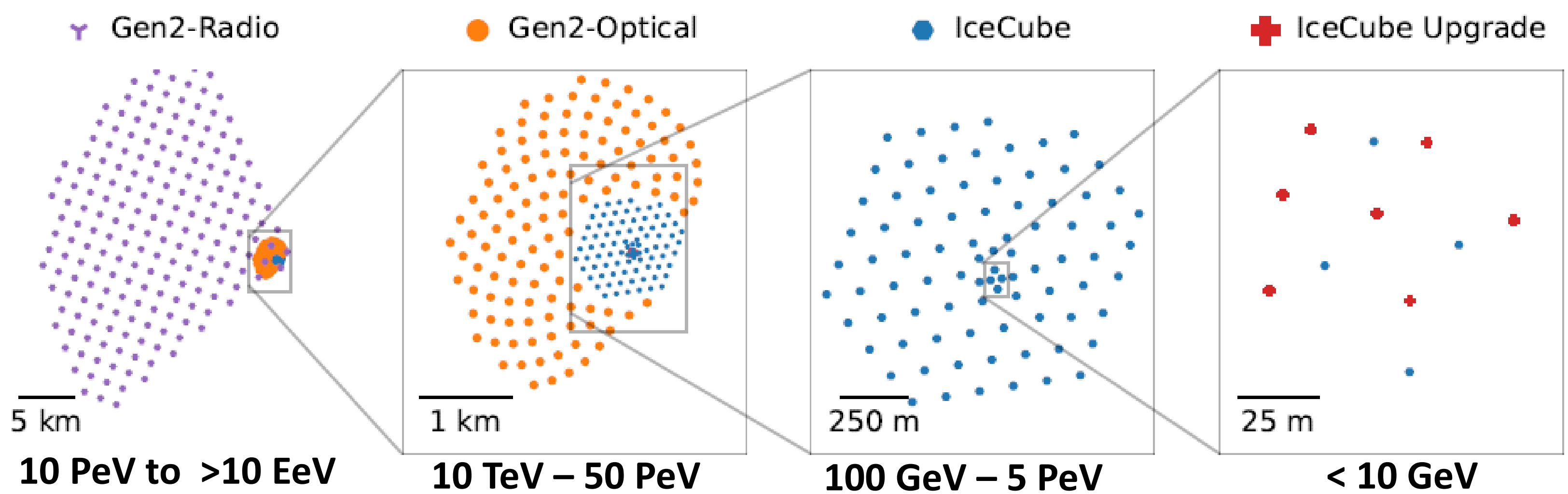
Science 361, 147-151 (2018)

NGC 1068 has an excess of 79^{+22}_{-20} neutrinos at TeV energies,



Squared angular distance between NGC 1068 and reconstructed event directions

IceCube-Gen2



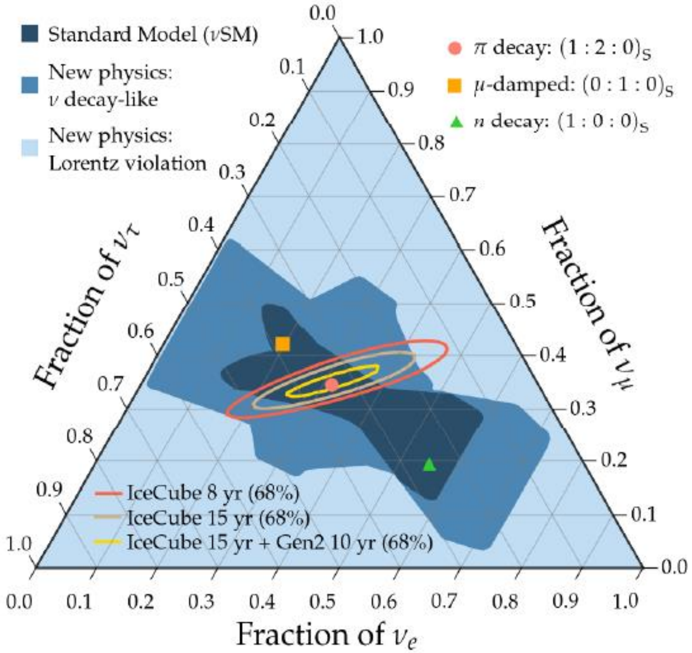
IceCube-Gen2 collaboration, arxiv:2008.04323

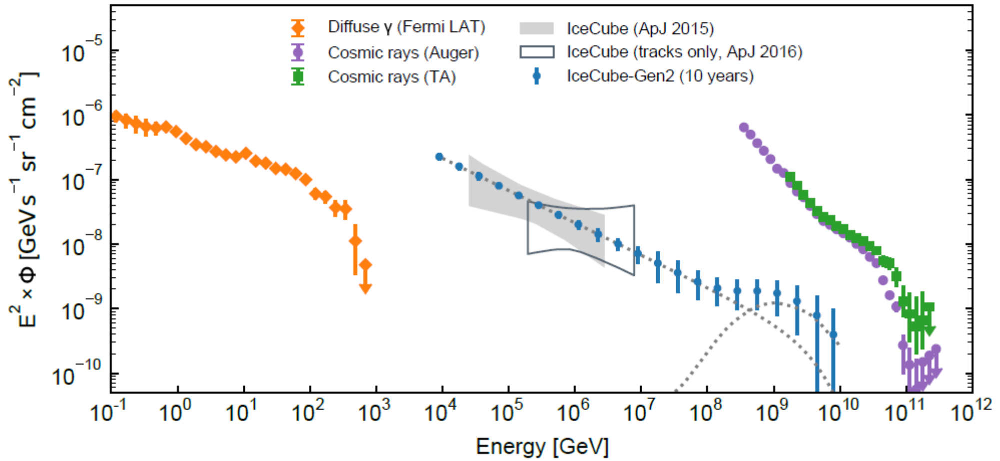
- Radio –Array 200 stations.
- Optical Array 120 strings (80 DOMs, H~240 m).
- DeepCore upgrade 7 new strings.

$V_{IceCube\text{-}Gen2} = 7.9\ V_{IceCube}$

Increases the neutrino event rate

IceCube-Gen2





IceCube-Gen2 collaboration, arxiv:2008.04323

Muchas gracias

Thank you!