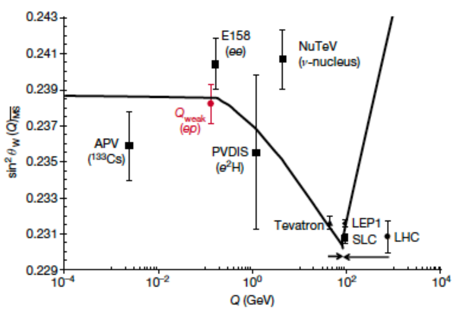
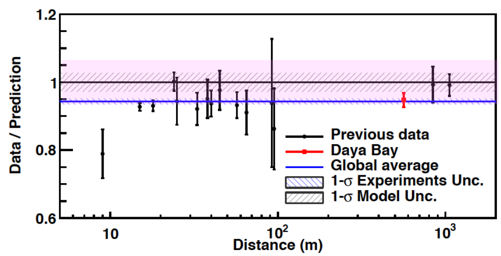
Fundamental Symmetries and Neutrinos in Nuclear Physics

Center for Frontiers in Nuclear Science

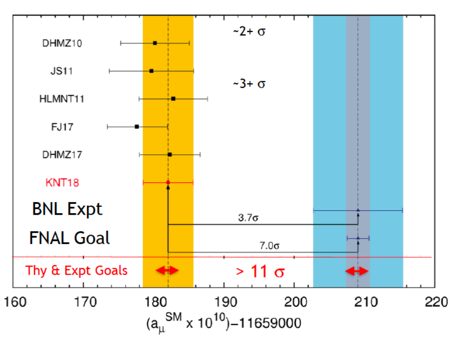


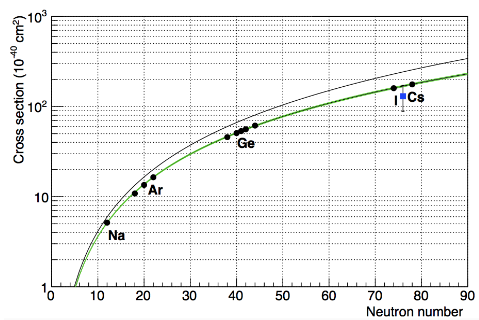


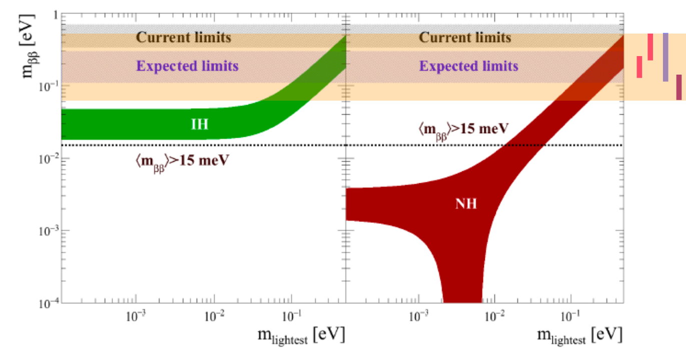
Inaugural Symposium

Stony Brook University / Brookhaven National Laboratory

November 28, 2018







J. F. Wilkerson

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

TUNL

COSMS INSTITUTE

OAK RIDGE National Laboratory

What lies beyond the Standard Model?

- The SM of subatomic matter has been amazingly successful.
- But we know the SM is incomplete
  - Neutrinos have mass
  - Dark Matter
  - Matter vs. Antimatter Asymmetry
  - Dark Energy
  - Origin of mass

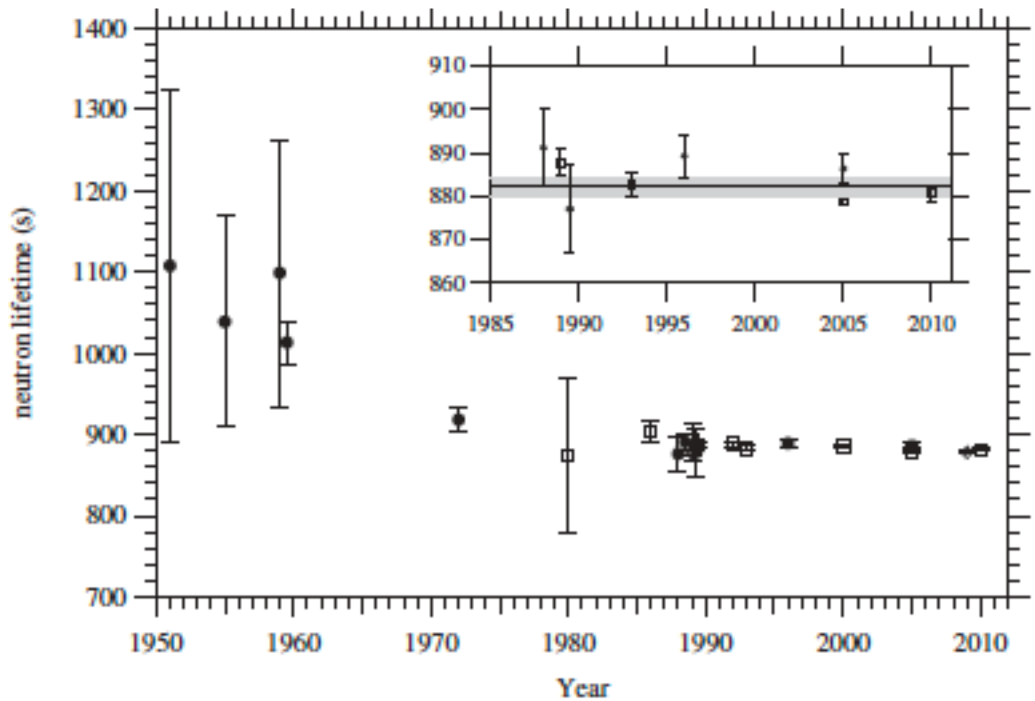
Precision Fundamental Symmetry and Neutrino measurements aim to guide us to better understanding of the fundamental particles and interactions and a new standard model.

Fundamental Symmetries and Nuclear Physics

- Neutron Lifetime
  - Determination of Weak coupling constants
  - Important to a number of weak interaction processes
- Parity Violating electron - proton scattering
  - Measure Weak charge of the proton
  - Complementary to Atomic and HEP measurements
  - Probes BSM physics models
- Anomalous magnetic moment of the muon
  - Direct comparison to standard model theoretical predictions
- neutron Electric Dipole Moment
  - Sensitive prove of time violation invariance
  - Probes BSM physics models
  - Could offer an explanation of matter - antimatter asymmetry

neutron lifetime

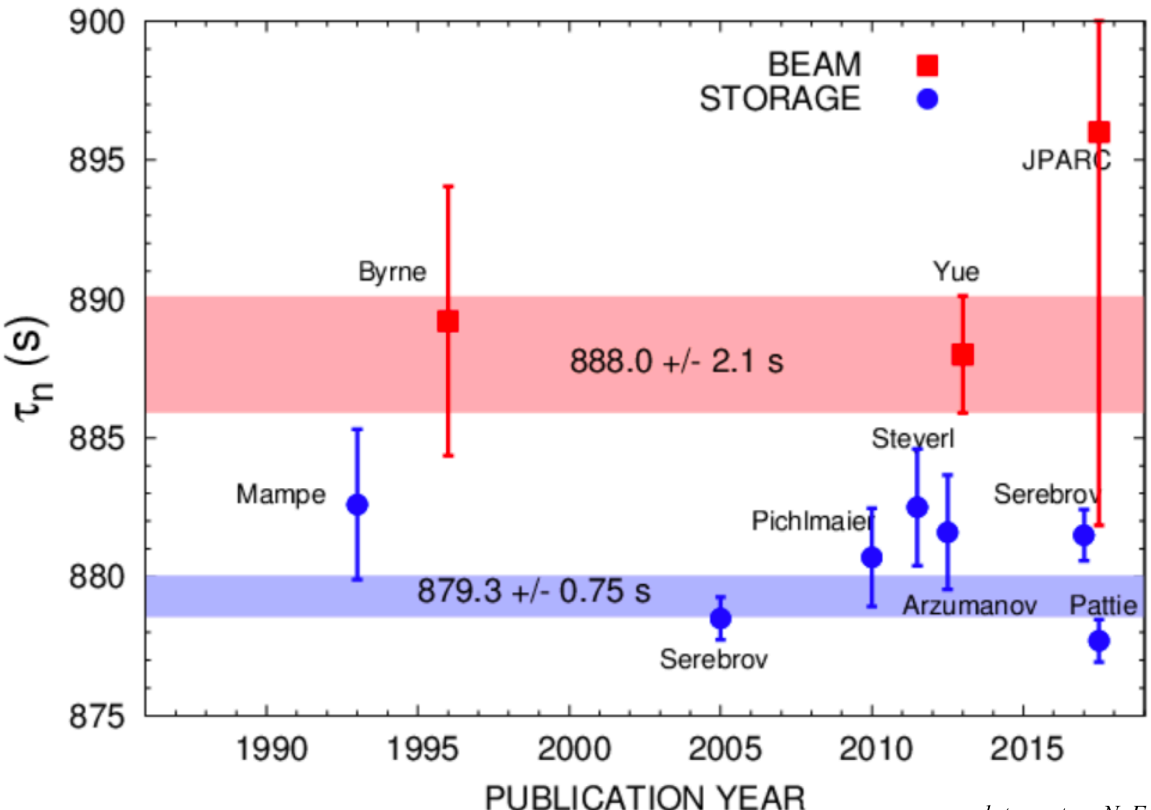
- Important parameter in nuclear physics
  - Big Bang nucleosynthesis
  - nuclear fusion
  - reactor antineutrinos detection
- Value depends on weak coupling constants (G_A & G_V)
- Comparison with other measurements, provides unitarity test of quark-mixing matrix



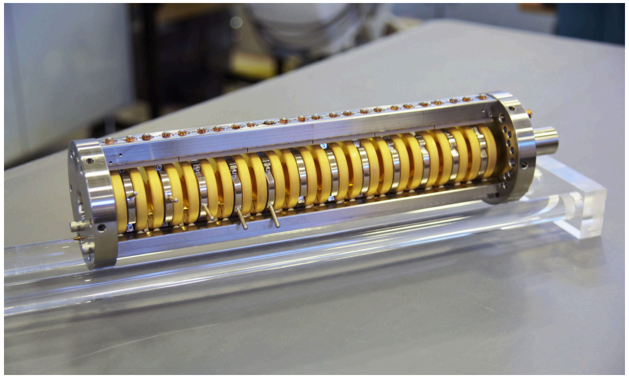
Wietfeldt and Greene, RMP 2011 DOI: 10.1103/RevModPhys.83.1173

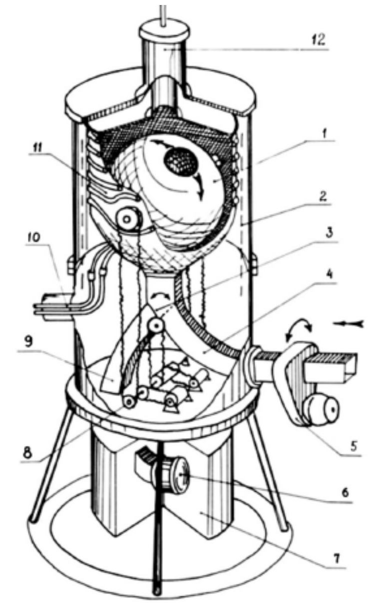
neutron lifetime Puzzle

Measurements at 0.1% level
but 4 σ difference between techniques



plot courtesy N. Fomin





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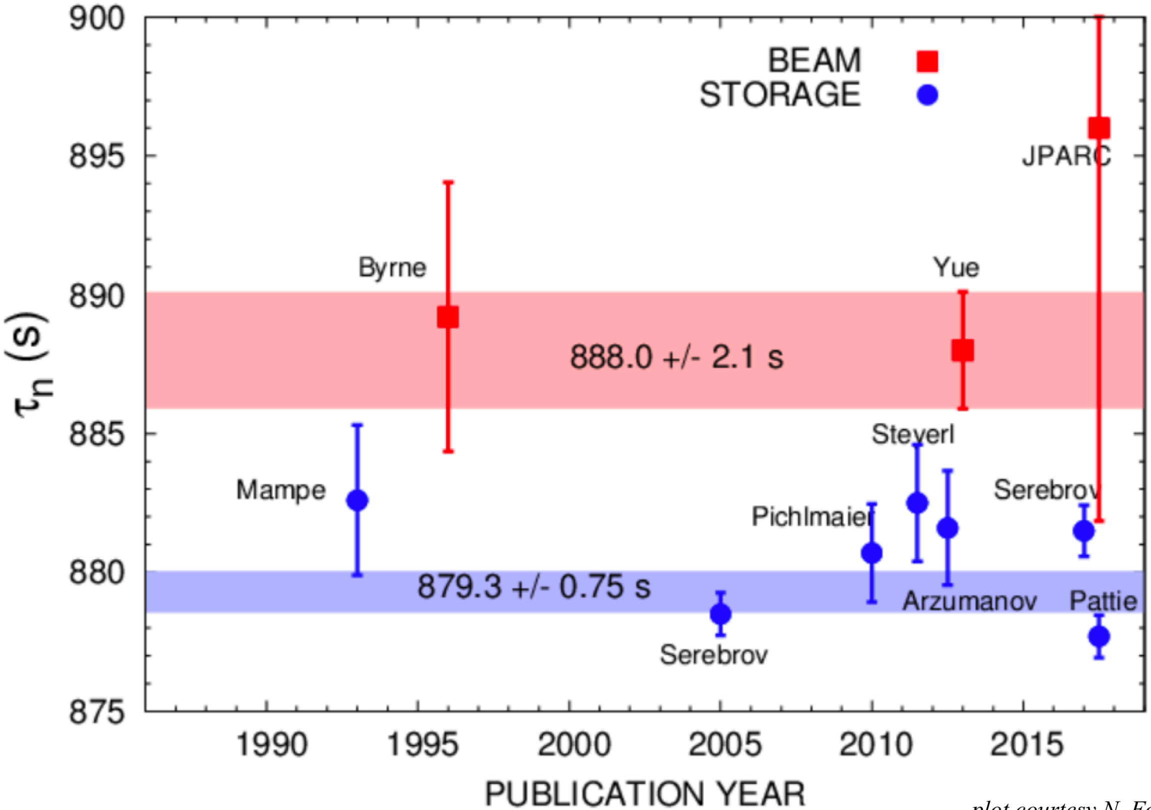
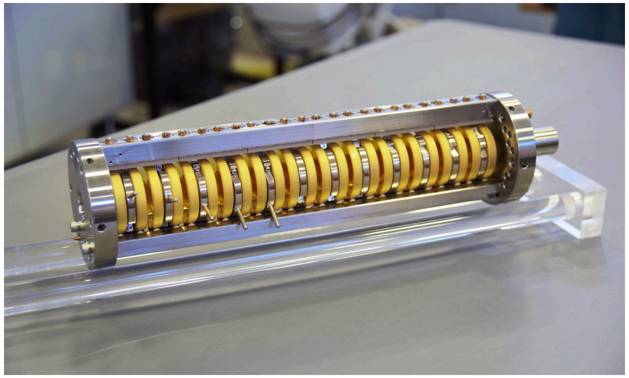
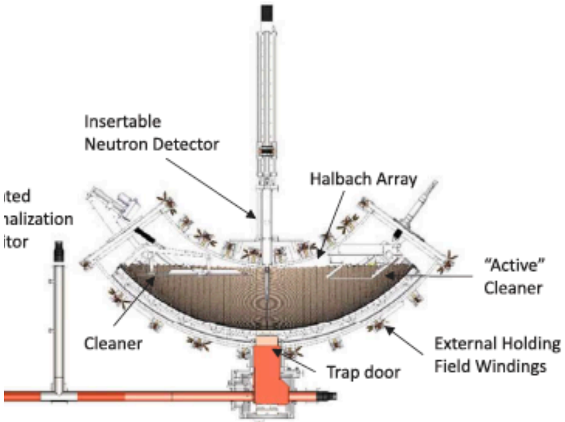


plot courtesy N. Fomin



R. W. Pattie Jr. et al., Science 360, 627 (2018).



Tension between determinations of G_V and G_A

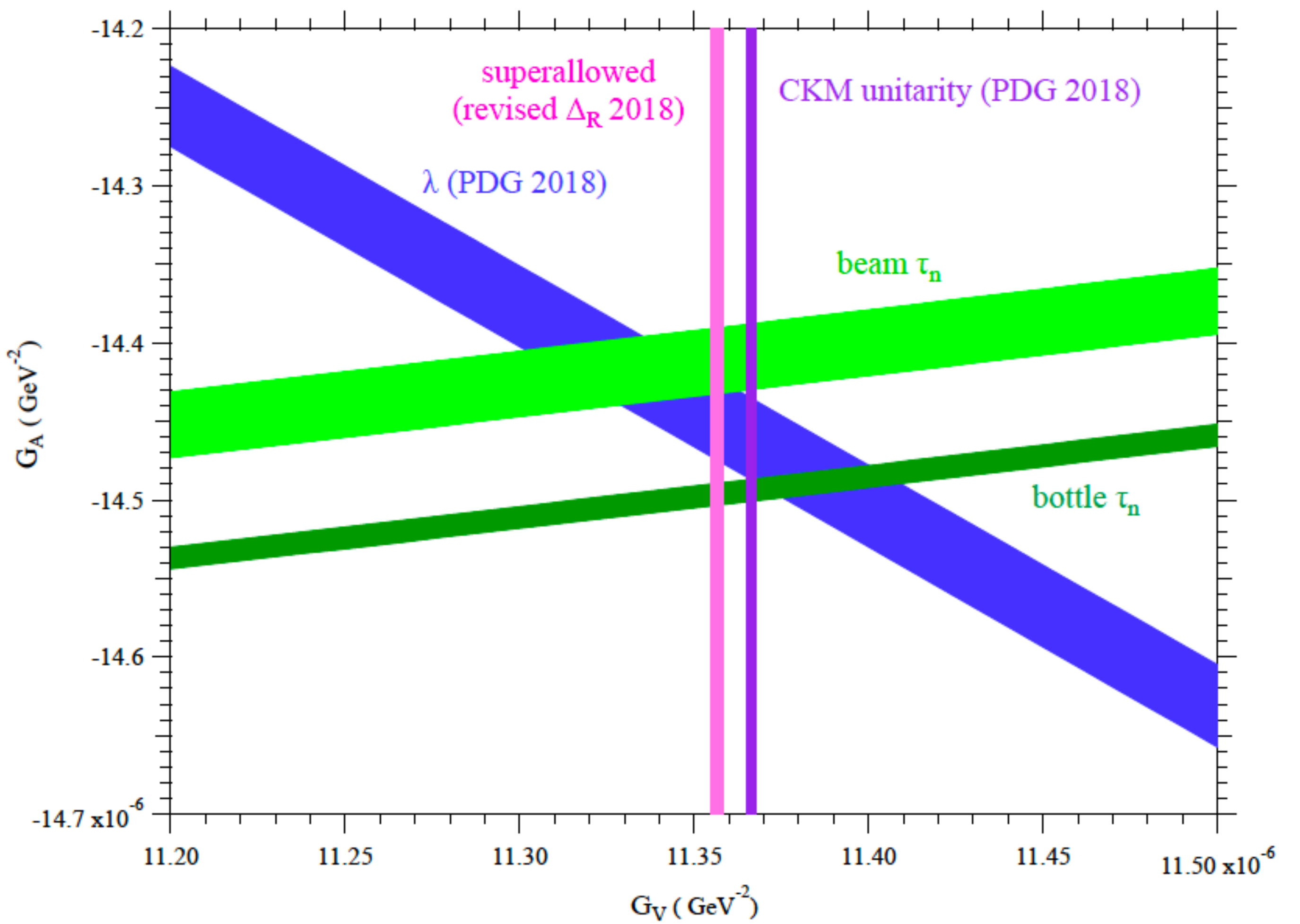
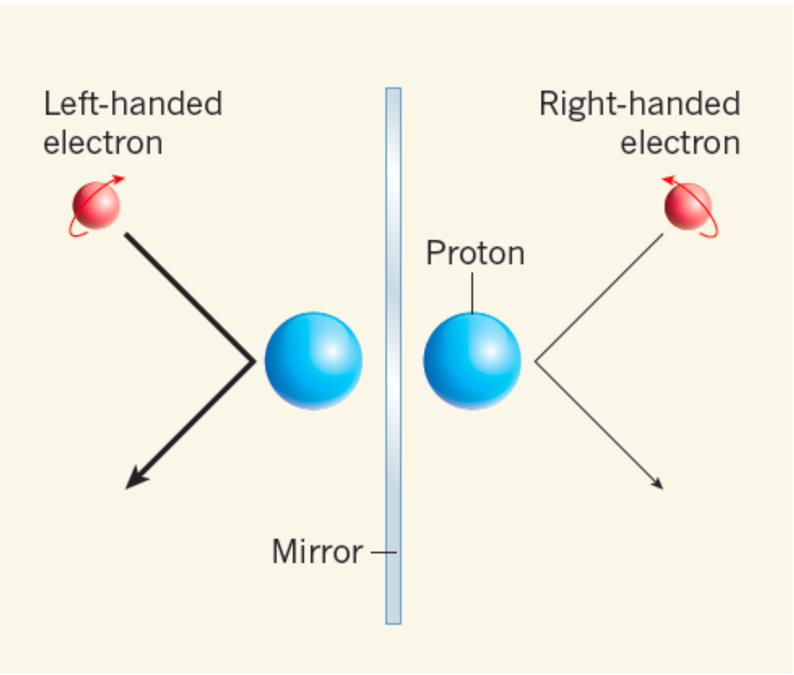
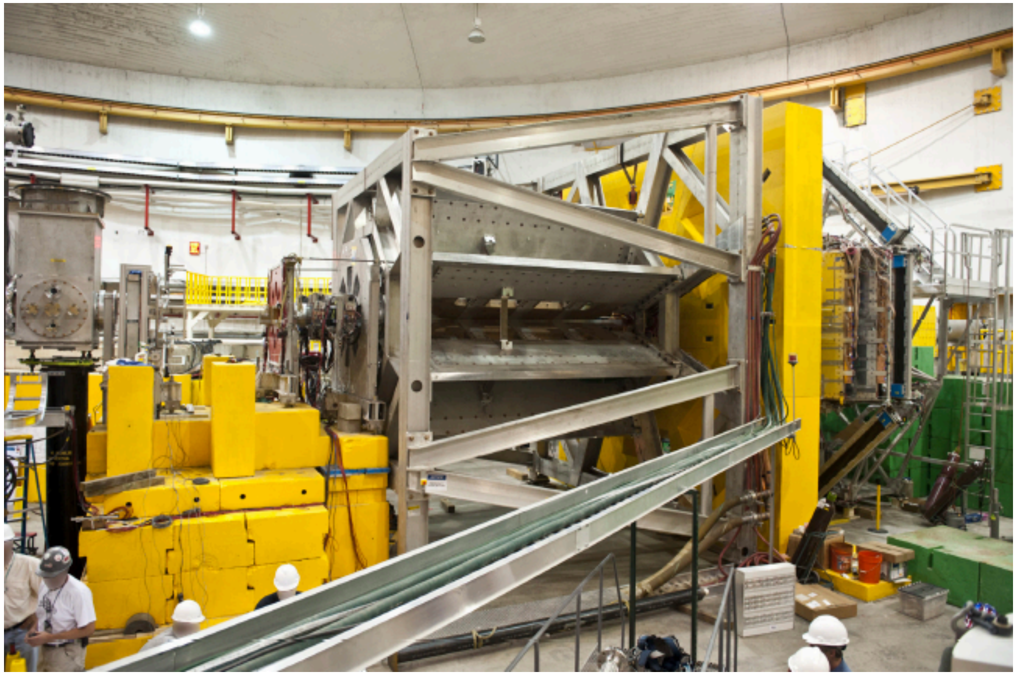


Image courtesy Fred Weidtfeldt

Weak Charge of the proton

- Measure parity violation of electrons scattering on protons



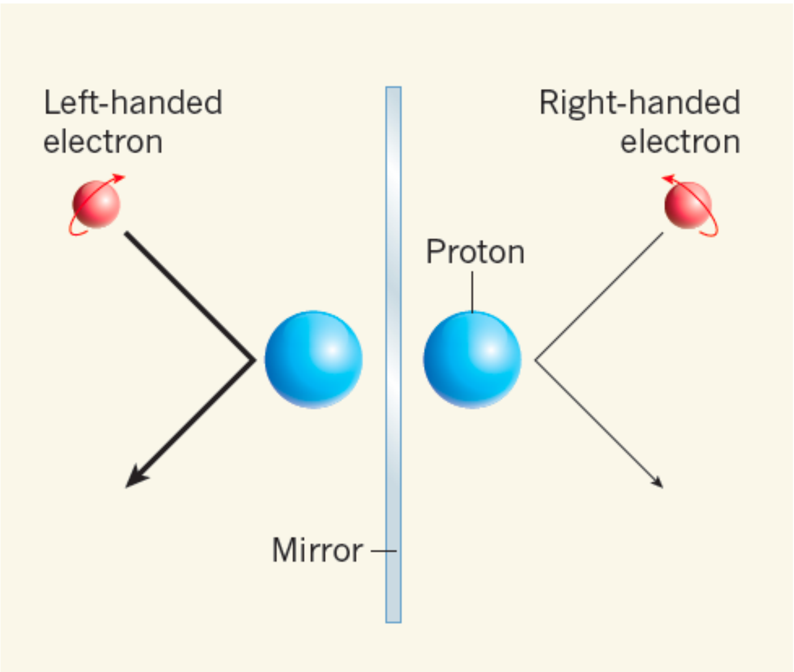


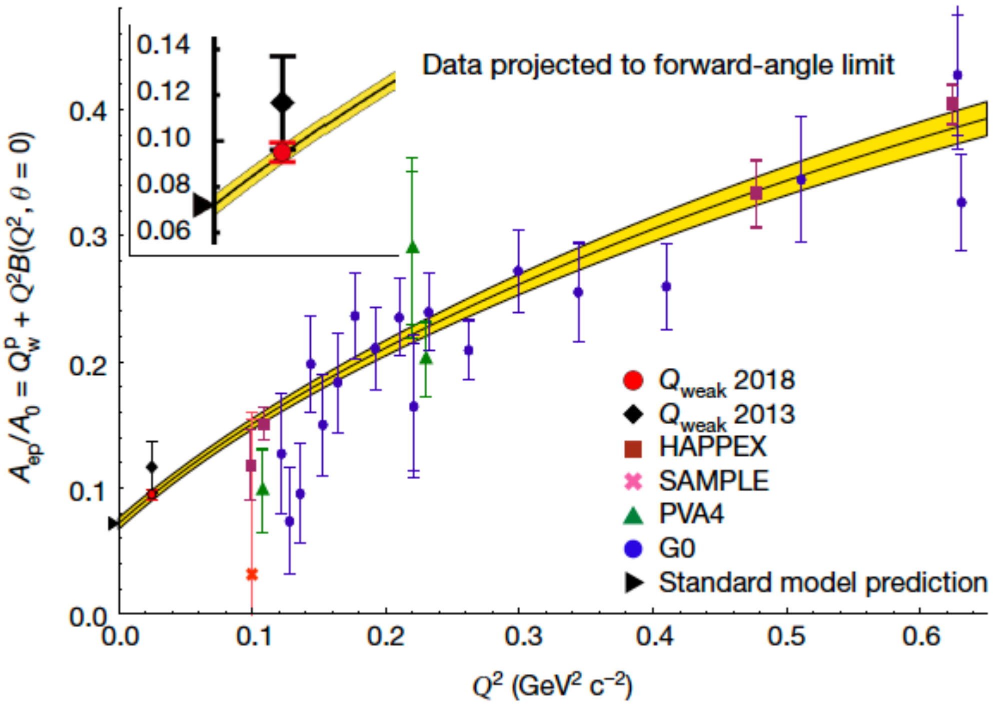
Q_{Weak} Experiment at JLab

The Jefferson Lab Q_{weak} Collaboration. *Nature* **557**, 207–211 (2018).

Weak Charge of the proton

- Measure parity violation of electrons scattering on protons





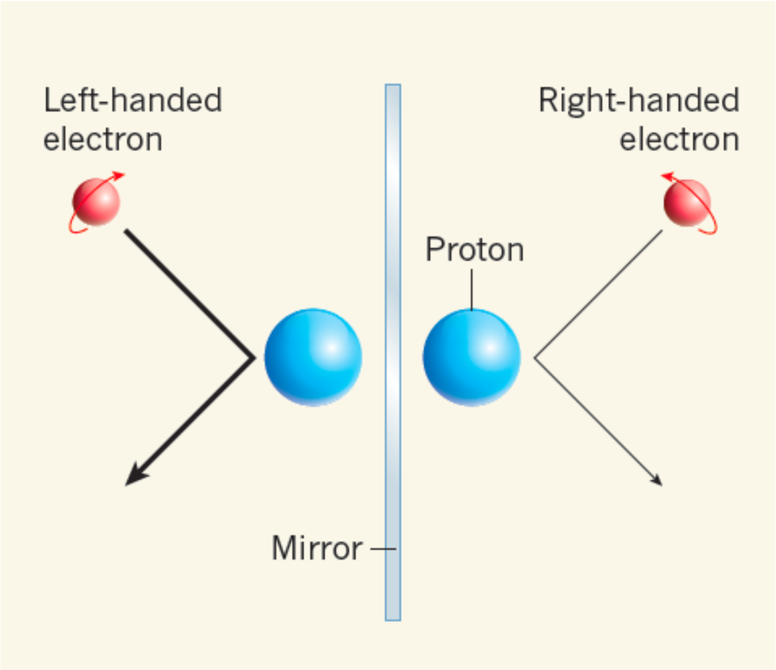
QWeak Experiment at JLab

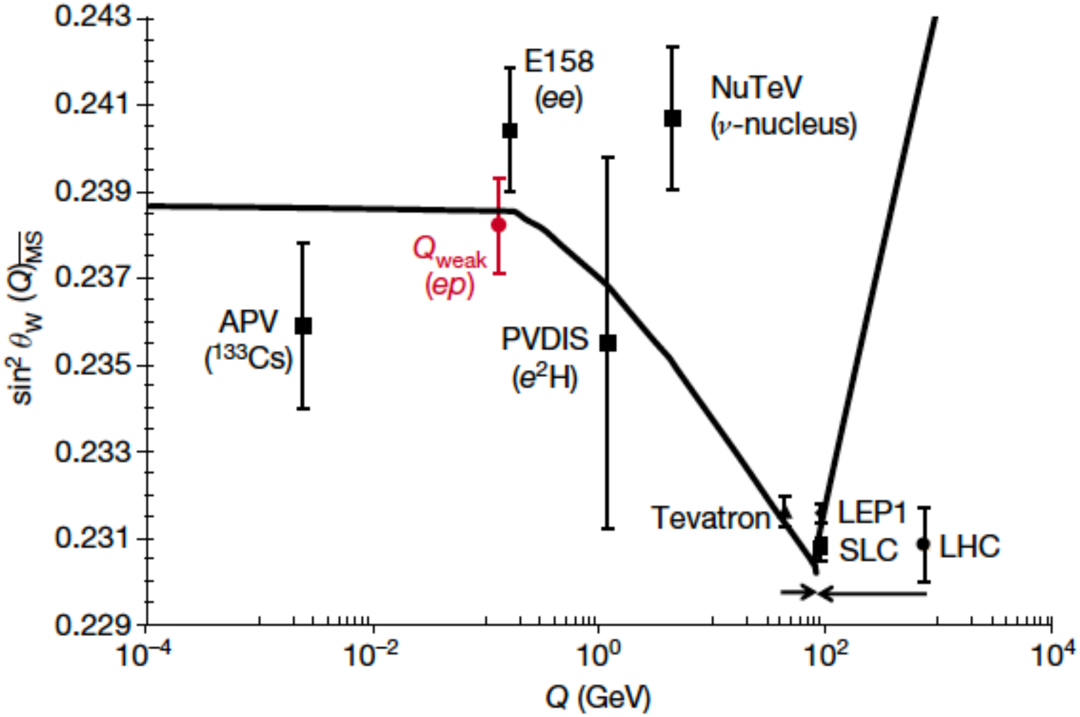
A_{ep} = –226.5 ± 9.3 parts per billion

The Jefferson Lab Q_{weak} Collaboration. *Nature* **557**, 207–211 (2018).

Weak Charge of the proton

- Measure parity violation of electrons scattering on protons





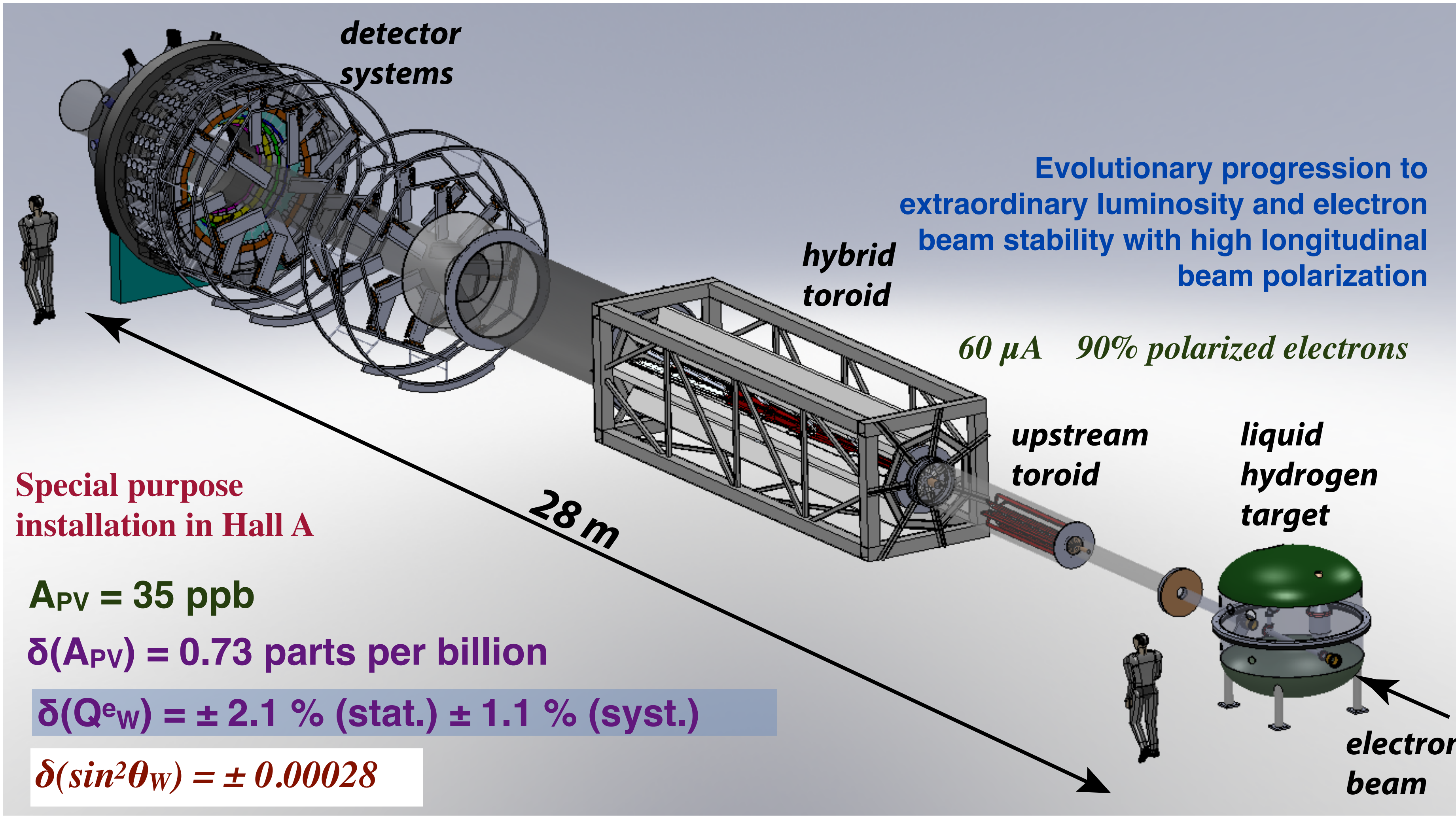
Q_{Weak} Experiment at JLab

0.0719 ± 0.0045

The Jefferson Lab $Q_{\rm weak}$ Collaboration. *Nature* **557**, 207–211 (2018).

MOLLER at JLab

Parity-Violating Fixed Target 11 GeV electron-electron (Møller) scattering



Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

60 μA   90% polarized electrons

Special purpose installation in Hall A

A_{PV} = 35 ppb

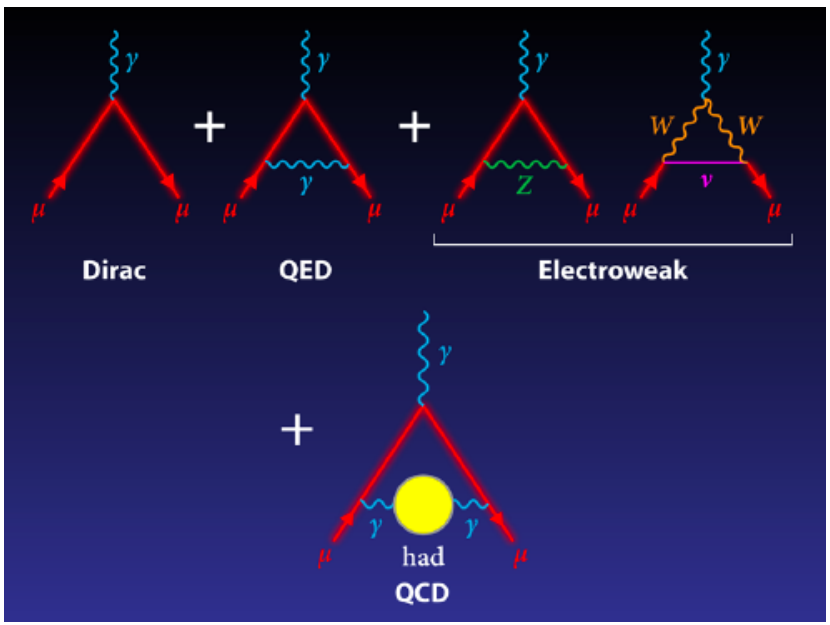
$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm$ 2.1 % (stat.) $\pm$ 1.1 % (syst.)

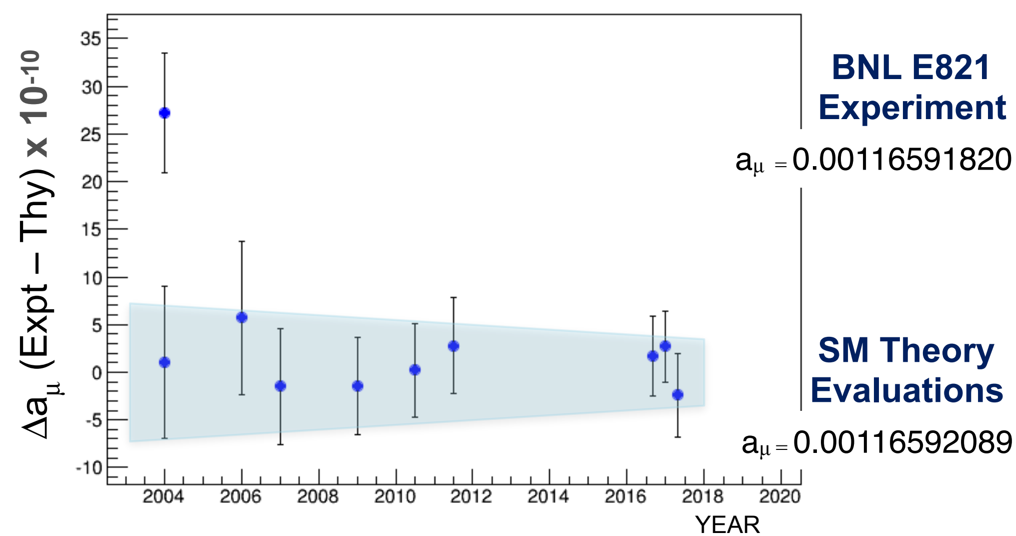
$\delta(\sin^2\theta_W) = \pm 0.00028$

μ Magnetic Moment (g-2)

- Calculation of the anomalous magnetic moment, a_μ, of the muon includes all known SM physics.
- Experimental measurement (BNL E821) differs from the theoretical calculation by 3.7 σ
- Is this a hint of new BSM physics?



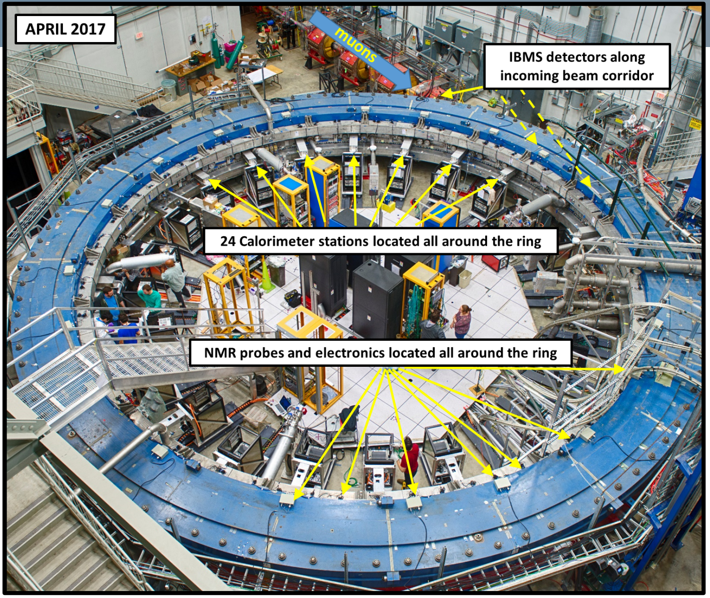
APS/Alan Stonebraker

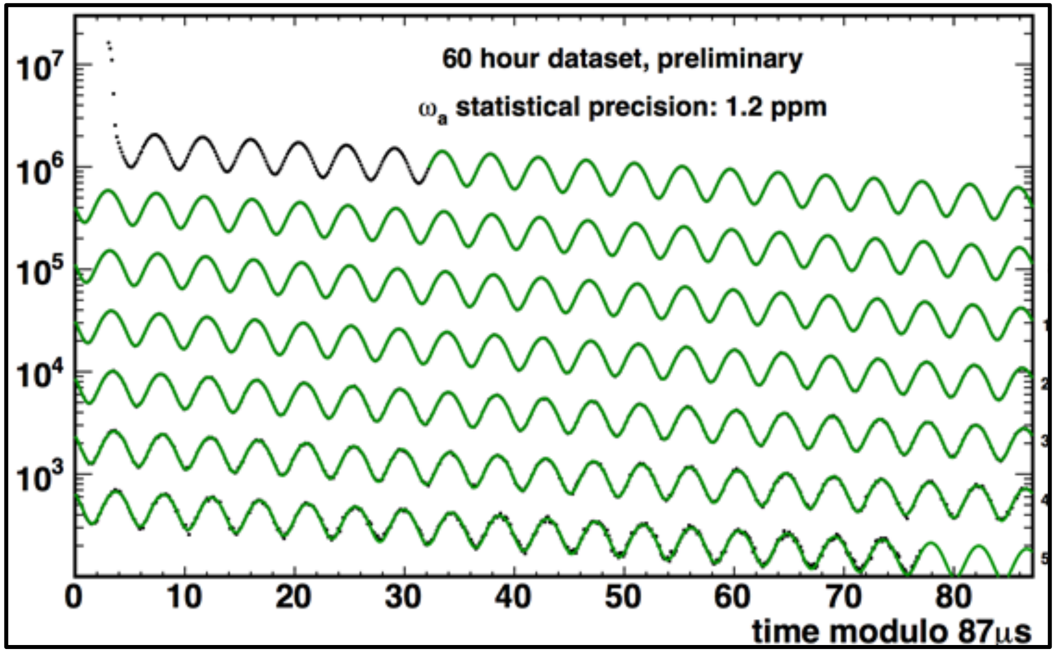


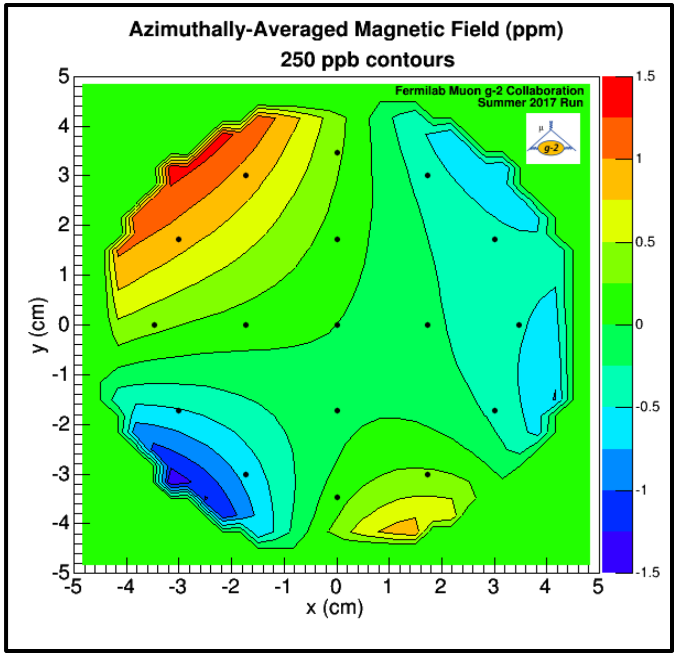
Muon g-2 at Fermilab

- Experiment up and running
- Analysis of Run1 data in progress
- Aim for 2019 1st result
- Precision expected to be ~better than BNL

Example fit of subset of data: 1.2 ppm in just 60 hours of data taking in Spring 2018
(10x more in production)

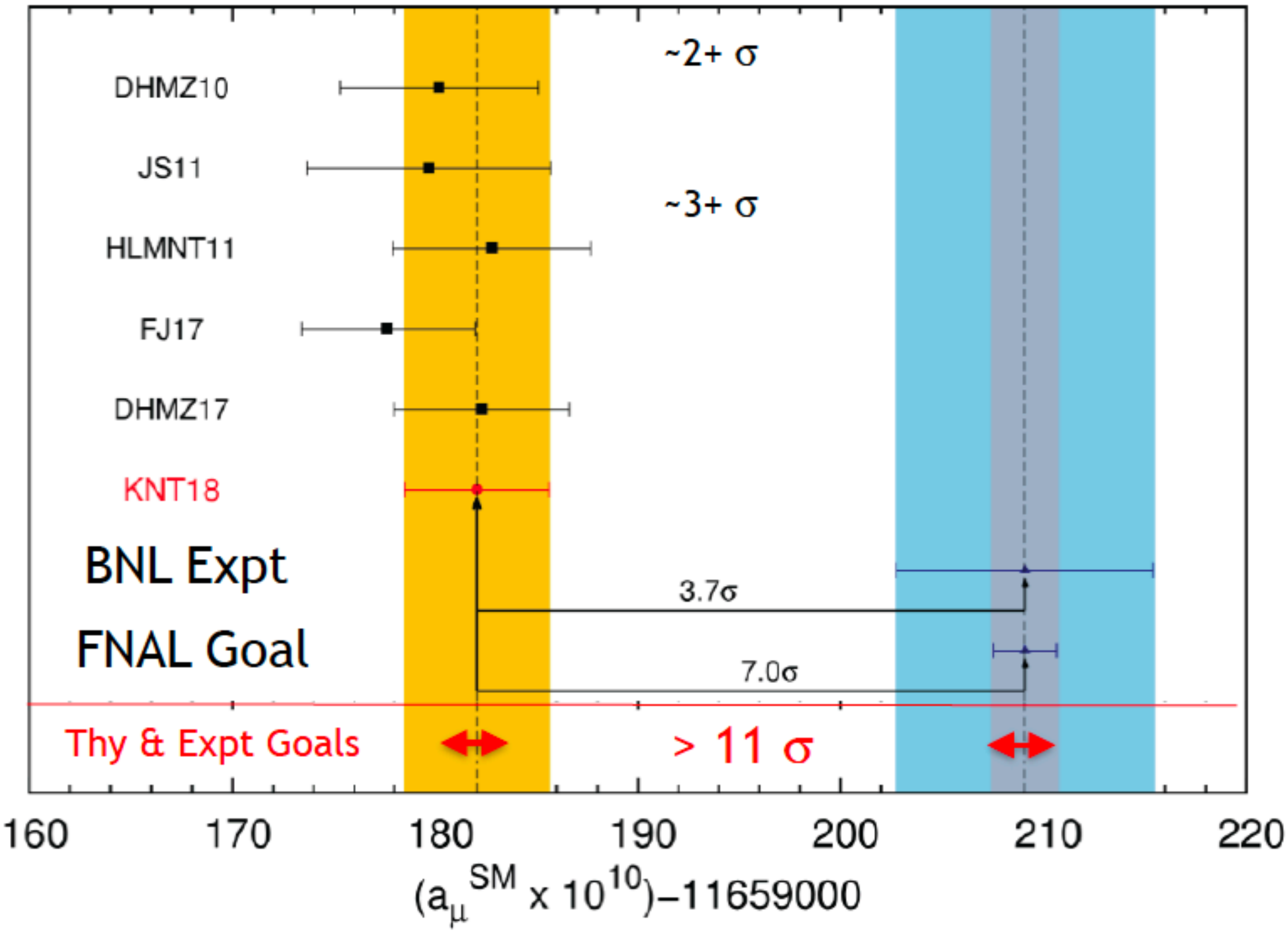






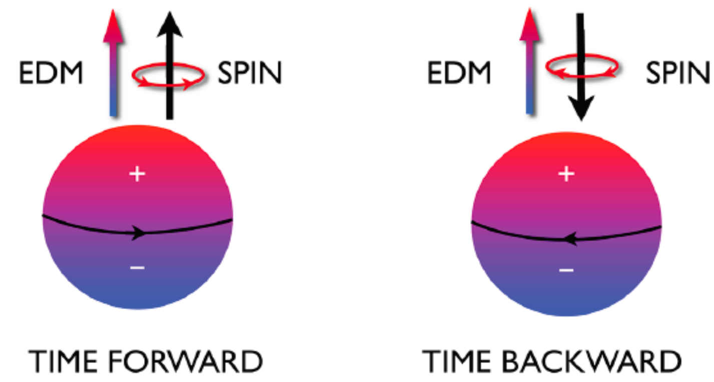
g-2 Prospects

- Improved calculations Muon g-2 Theory Initiative. (2019)
- New experimental results (2019)



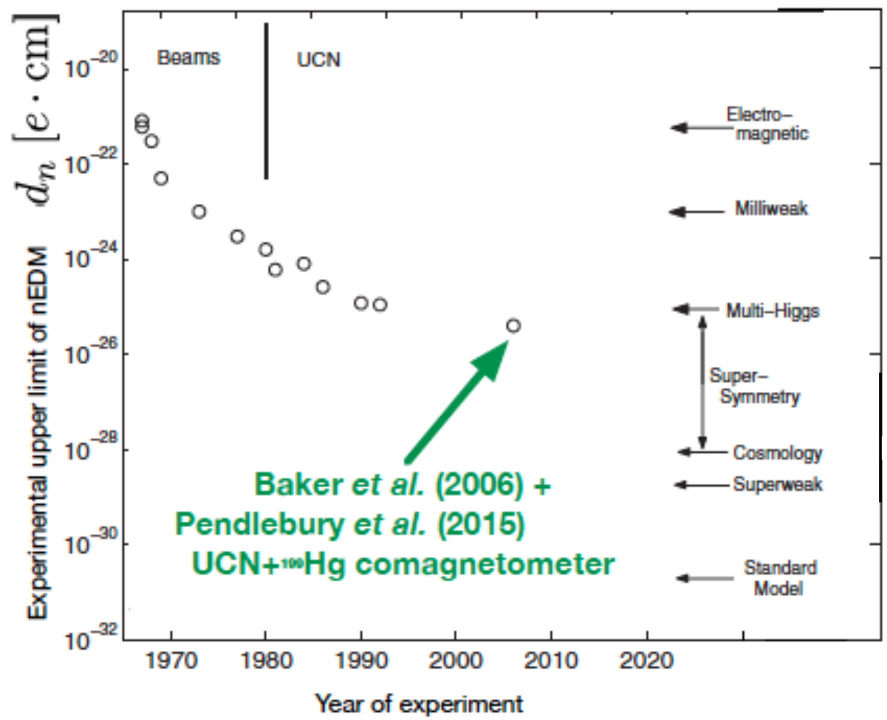
neutron Electric Dipole Moment (nEDM)

- If the neutron has an EDM
  - Violates time reversal invariance (and if CPT conserved, then CP)
  - Might offer an explanation of Matter - Antimatter asymmetry



- Limit on nEDM has improved by 10^9 in 60 years since Smith, Purcell, and Ramsey expt.

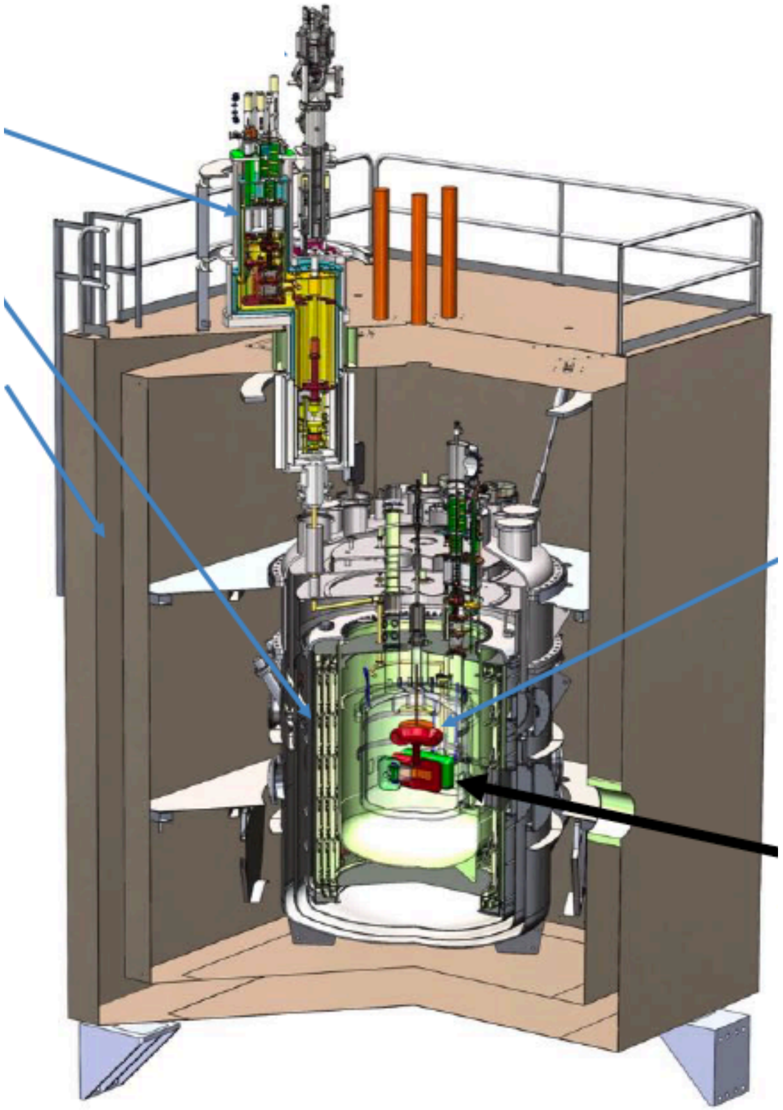
- Many BSM models predict an observable nEDM



nEDM prospects

In coming decade experiments aim to reach a sensitivity of 10^{-28} e·cm

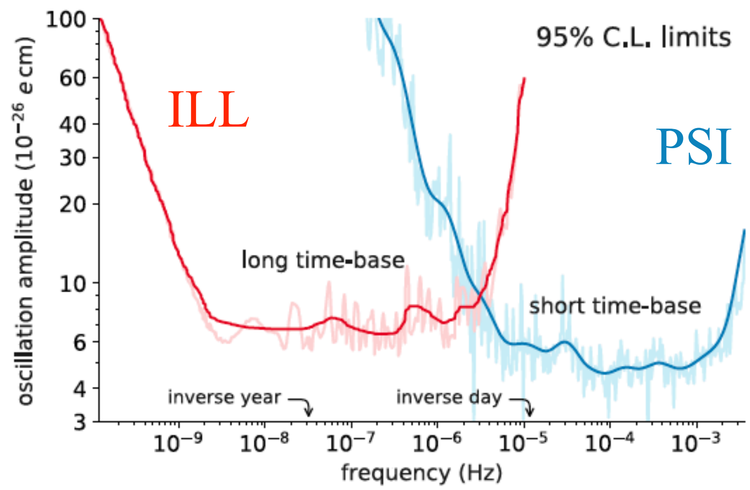
- nEDM expt. **running** at the UCN source at the Paul Scherrer Institute
- UCN nEDM expt. at TRIUMF (Const.)
- Cryogenic nEDM expt. at Institute Laue-Langevin (Const.)
- nEDM expt. Forschungsreaktor München II (Const.)
- nEDM experiment at Oak Ridge National Laboratory (figure)
  - past 4 years "Critical Component Demonstration"
  - 2018-2019: transition to "Large Scale Integration" phase
  - 2023 Data taking

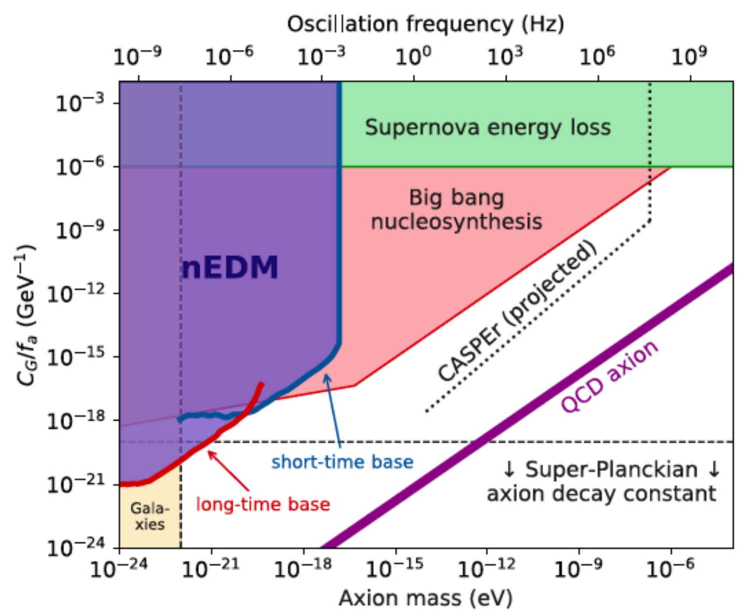


BSM nEDM Time Variation

Phys. Rev. **7**, 041034 (2017)

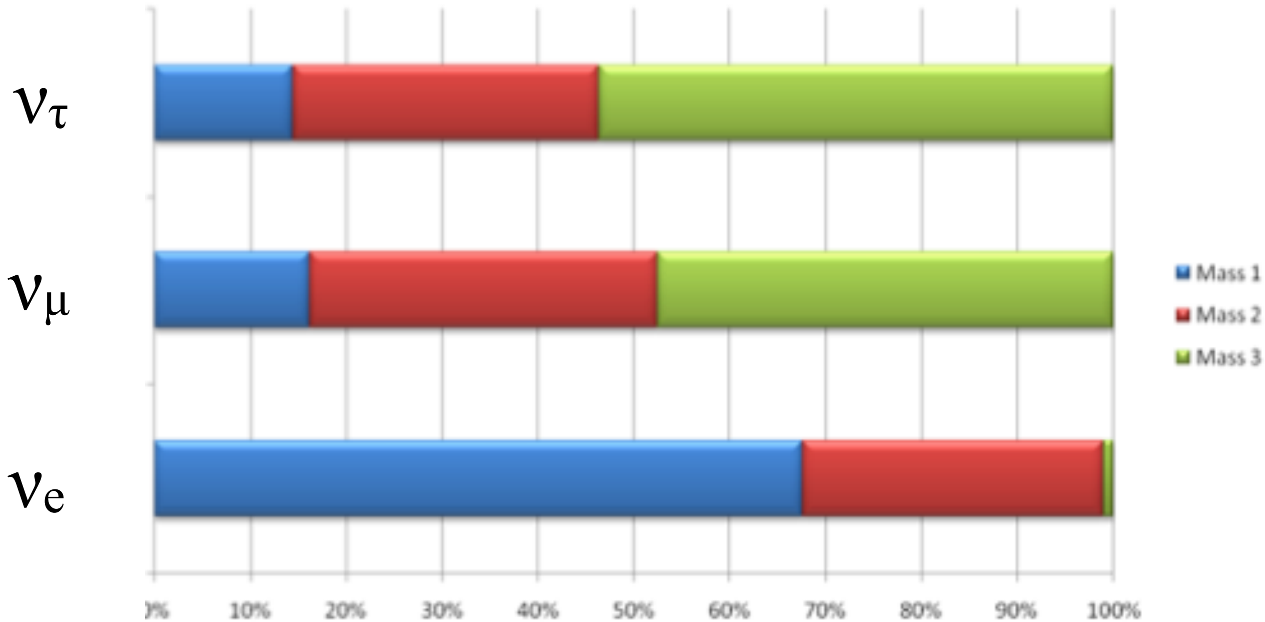
- Search for ultra light axion induced nEDM oscillations
- Sets limits on axion - gluon coupling





What we know about neutrinos (brief)

We have discovered that neutrinos have mass and that flavor states (ν_e, ν_μ, ν_τ) are admixtures of mass eigenstates

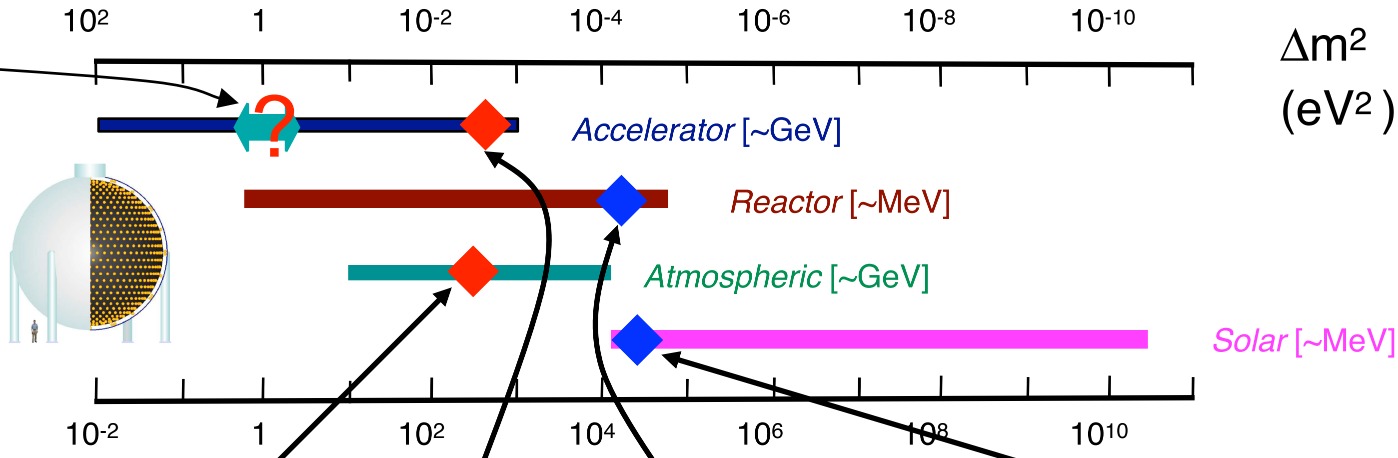


Our Standard Model (SM) of fundamental interactions is incomplete.

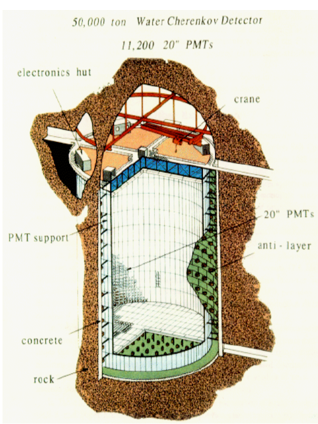
Expt. Observations of ν oscillations

LSND

miniBoone

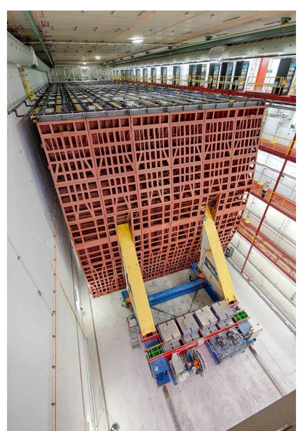


Atm. ν's
SuperKamiokande

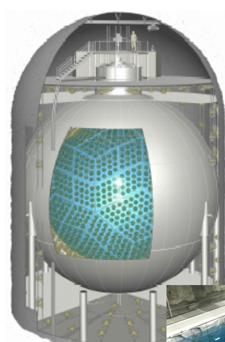


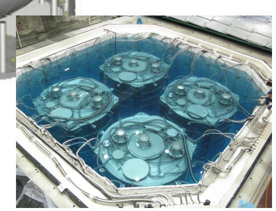
IceCube DeepCore, ANTARES

K2K, T2K, MINOS, NOνA

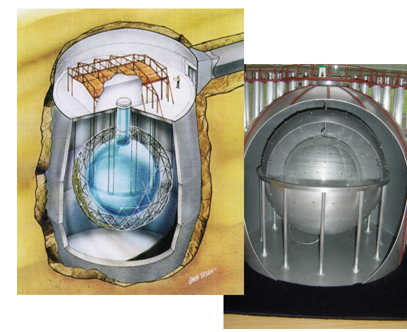


KamLAND





Solar ν's



SNO, SuperK, BOREXINO, Cl, Ga

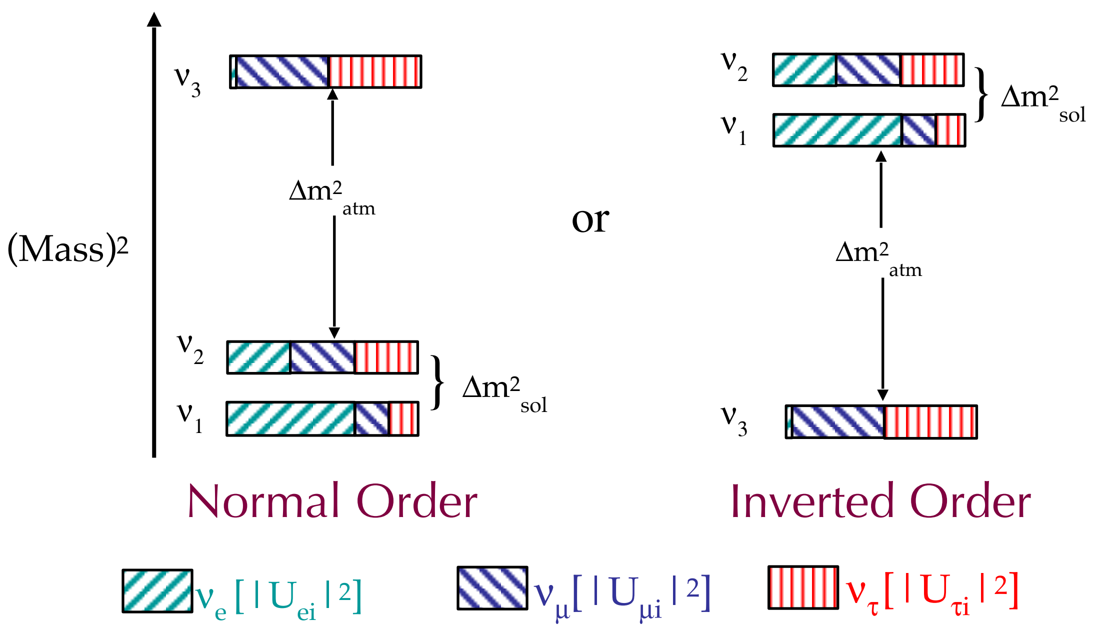
θ_{13} : SBL - Daya Bay, RENO, Double Chooz

What we know about neutrinos (3-flavor model)

Maki Nakagawa Sakata Pontecorvo 3x3 mixing matrix (analog to CKM)

$$
\begin{array}{cccccc}
 & & \text{Atmospheric} & \text{Cross-Mixing} & \text{Solar} & \text{Majorana phases} & \\
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} & = &
\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} &
\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} &
\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} &
\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} &
\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
\end{array}
$$

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$



Par.	Value (NO)	Unc. (1σ)
θ_{12}	34	5.5%
θ_{23}	47.7	4.7%
θ_{13}	8.4	3.5%
Δm_{sol}	7.5 x 10^{-5} eV^2	2.4%
Δm_{atm}	2.5 x 10^{-3} eV^2	1.3%

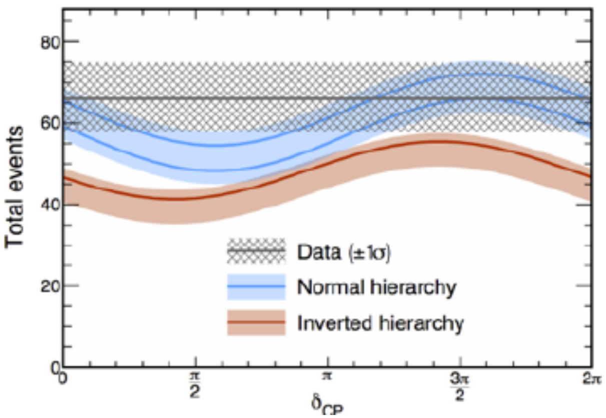
$\Delta m_{sol} \sim \Delta m_{21}$ $\Delta m_{atm} \sim \Delta m_{32}$

ν mysteries (what we don't know)

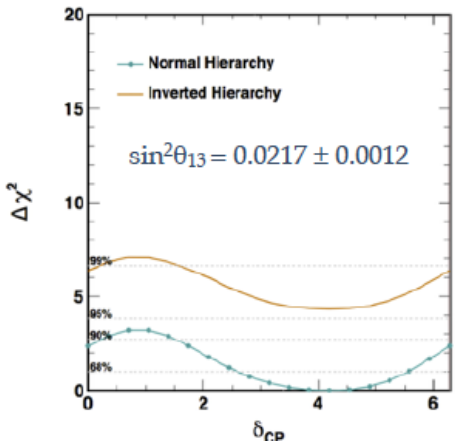
- What is the mass ordering — normal or inverted
  - Reactor measurements, Long baseline oscillation measurements
- Is CP violated (δ)?
  - Long baseline oscillation measurements
- Are there additional neutrino flavors — Sterile neutrinos?
  - reactor short baseline, accelerator searches, and intense sources
- What do neutrinos weigh and why are they so light?
  - Cosmology, direct kinematic searches, neutrinoless double beta decay
- Are neutrinos Majorana particles?
  - Neutrinoless double beta decay
- Are there additional non-standard neutrino interactions?
  - Coherent neutrino scattering, searches for rare decays

Searching for CP (δ) violation

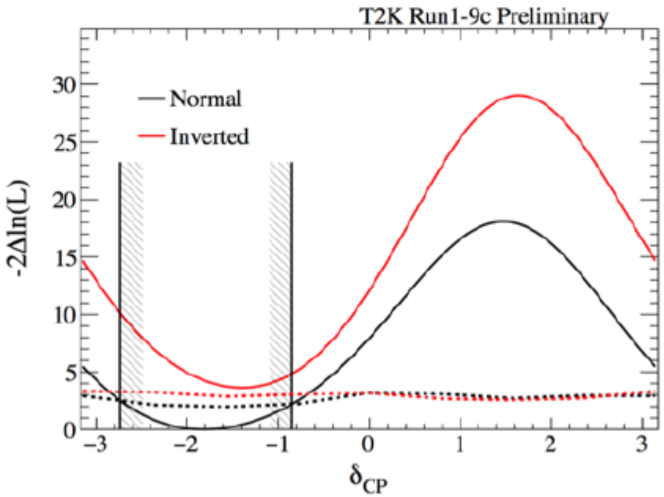
NOνA (1806.00096)



SuperK PRD97 (2018)

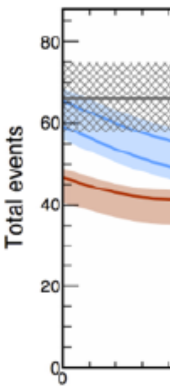


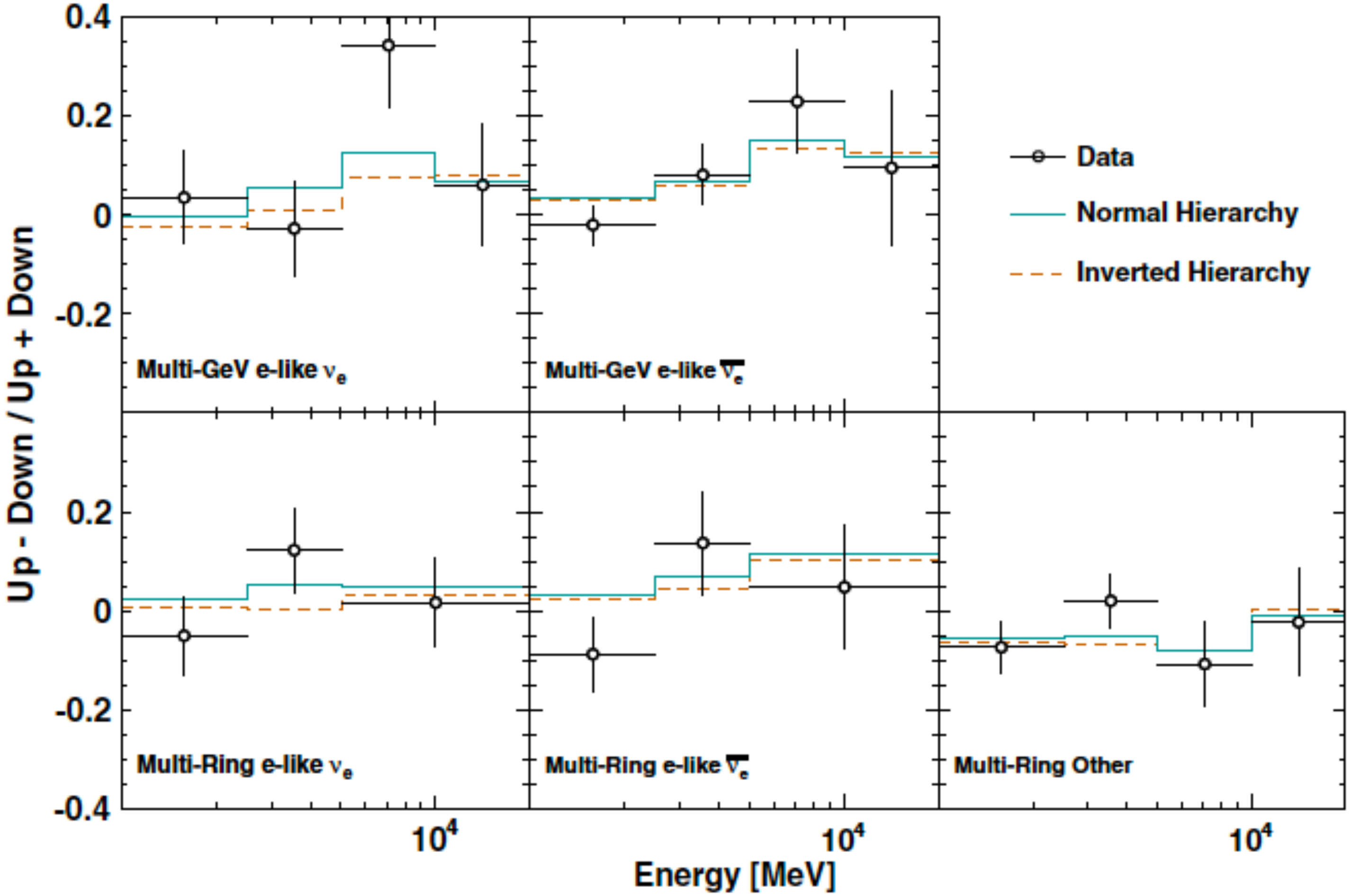
T2K Neutrino 2018

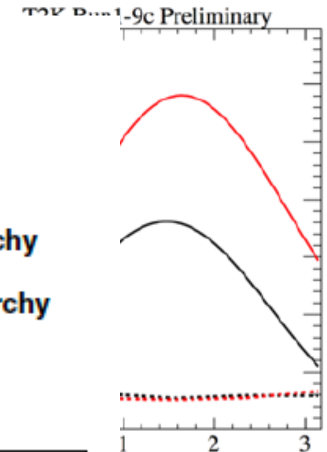


Searching for CP (δ) violation

NOνA (1806.00096) SuperK PRD97 (2018) T2K Neutrino 2018

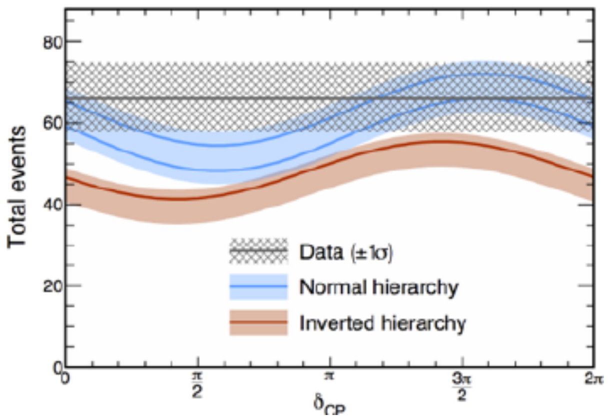




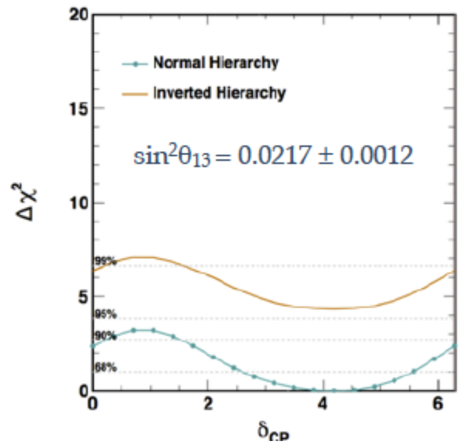


Searching for CP (δ) violation

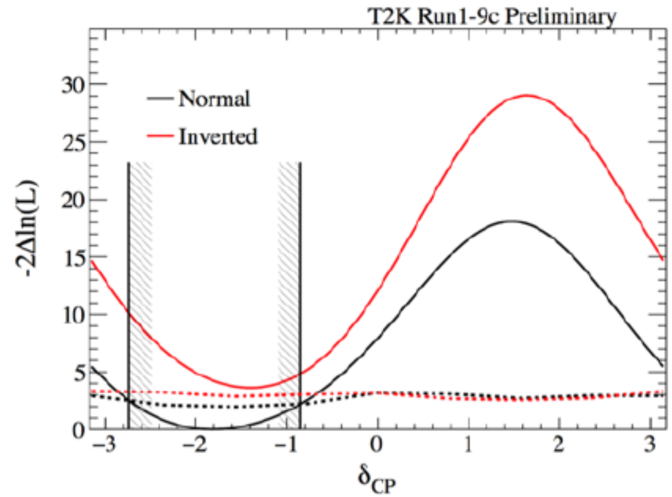
NOνA (1806.00096)



SuperK PRD97 (2018)

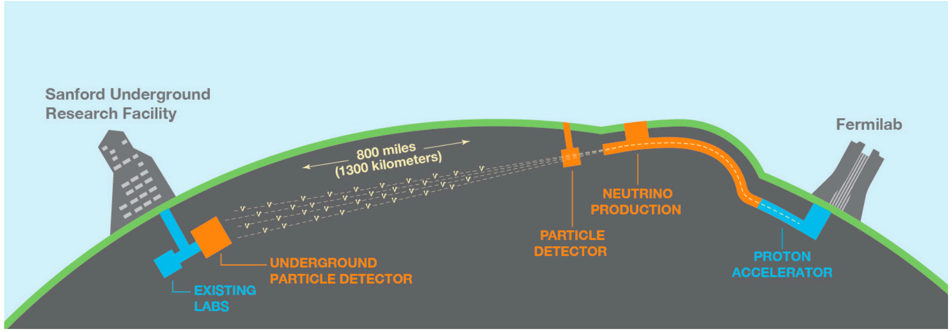


T2K Neutrino 2018

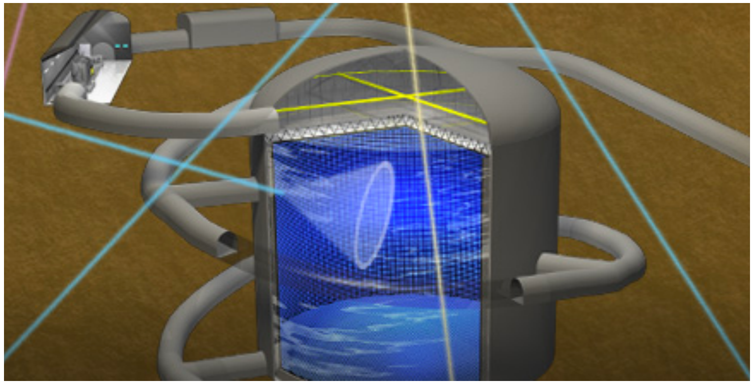


Future

DUNE



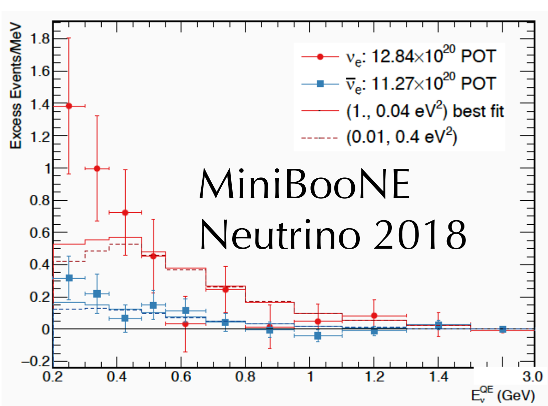
Hyper Kamiokande

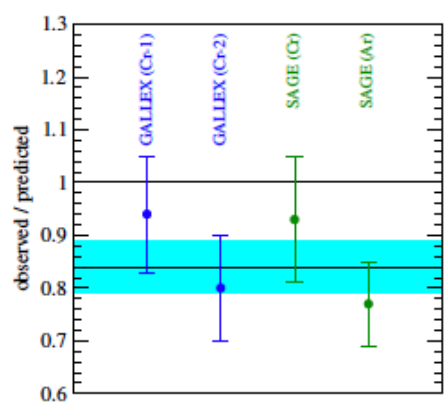


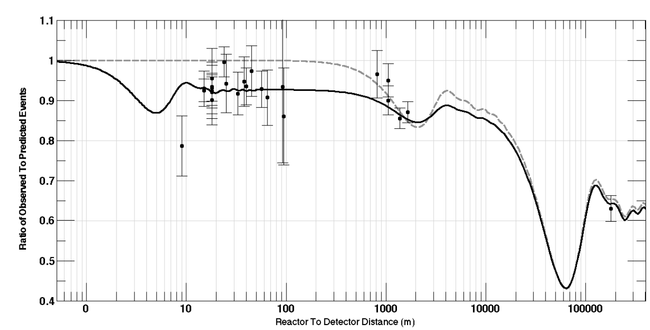
Are there additional neutrino flavors?

- Anomalies have been independently observed in three "classes" of neutrino oscillation experiments.
- Sterile neutrinos, with $\Delta m^2 \sim eV^2$, can offer an explanation for each of these anomalies. (Not consistent with 3 neutrino model.)
- But sterile neutrino models are unable to simultaneously accommodate all of the observed data.
- All the observations require confirmation.

Accelerator (Appearance)	Source (Cr, Ar) ν (Disappearance)	SBL Reactor anti-ν (Disappearance)

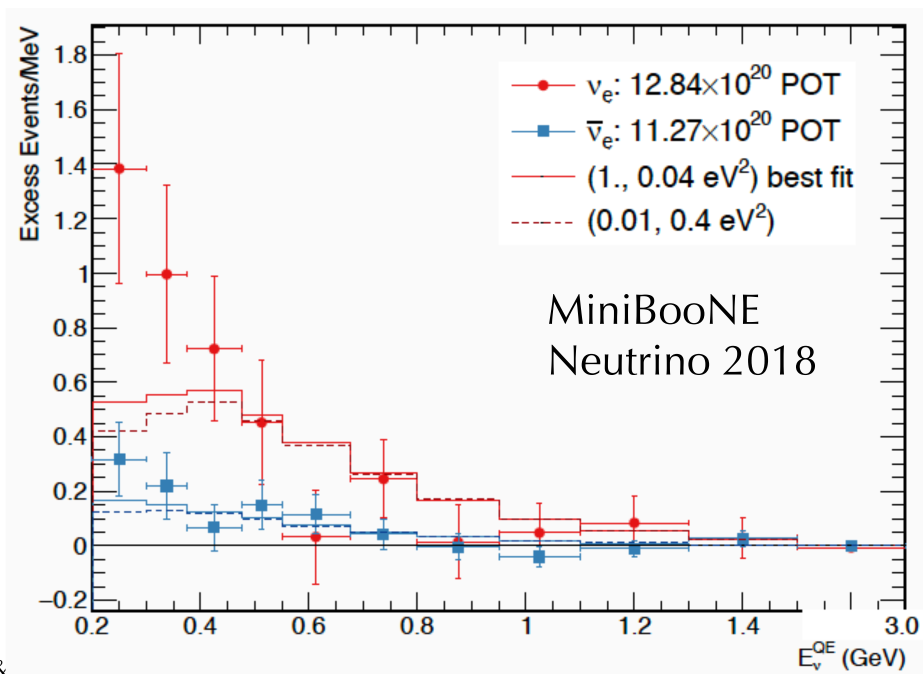


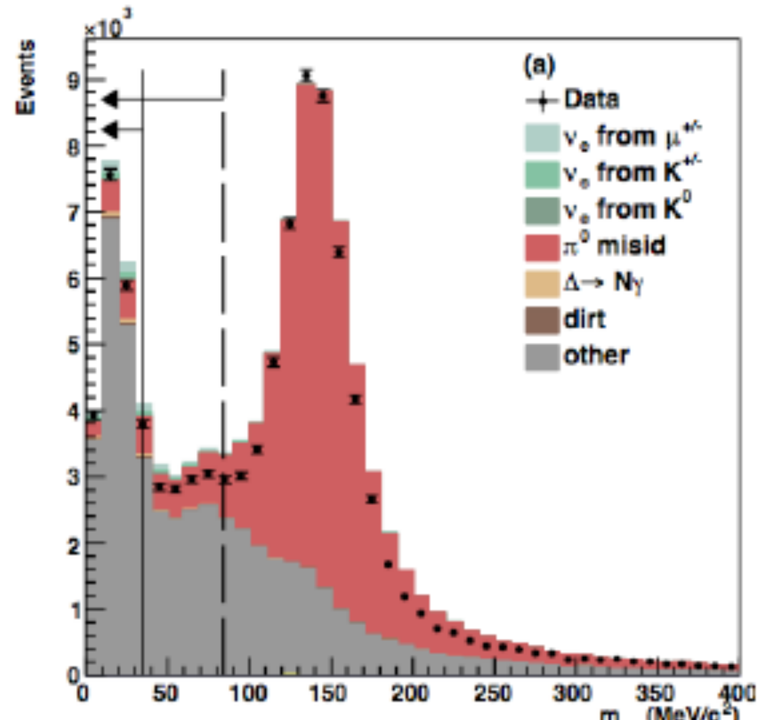




Oscillation anomalies: $\nu_\mu \rightarrow \nu_e$ appearance

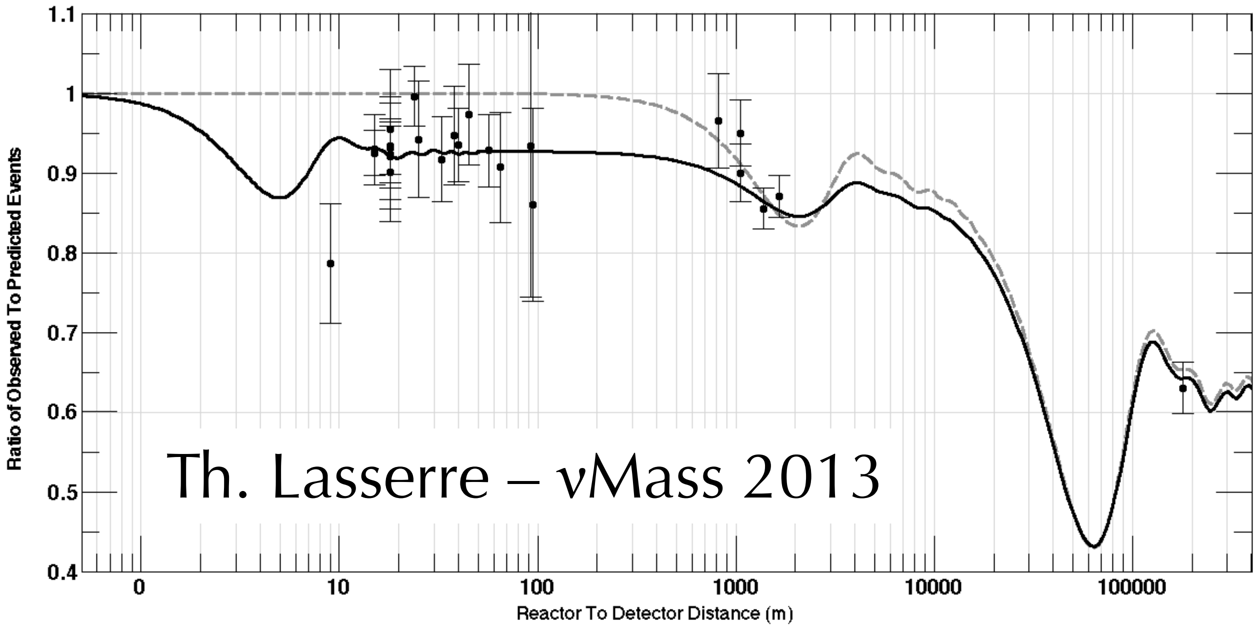
- MiniBooNE experiment sees excess counts for both neutrino and anti-neutrino data. (Approaching 5 σ) Sterile neutrino with $\Delta m^2 \sim eV^2$
- MiniBooNE and LSND together have > 6σ (DOI: 10.1103/PhysRevLett.121.221801) (Karmen did not see an excess, but insufficient sensitivity to rule out LSND observations).
- Some backgrounds have similar spectral shape to signal.
- MicroBooNE will test if excess is photons or electrons





Oscillation anomalies: $\overline{\nu}_e \rightarrow \overline{\nu}_e$ disappearance

- Mueller et al. and Huber in 2011 pointed out that improvements in the nuclear data for the reactor $\overline{\nu}_e$ spectra increased the expected number of $\overline{\nu}_e$ by 5-6%, resulting in a corresponding shortfall in the observed flux. Could be explained by sterile neutrino with $\Delta m^2 \sim eV^2$



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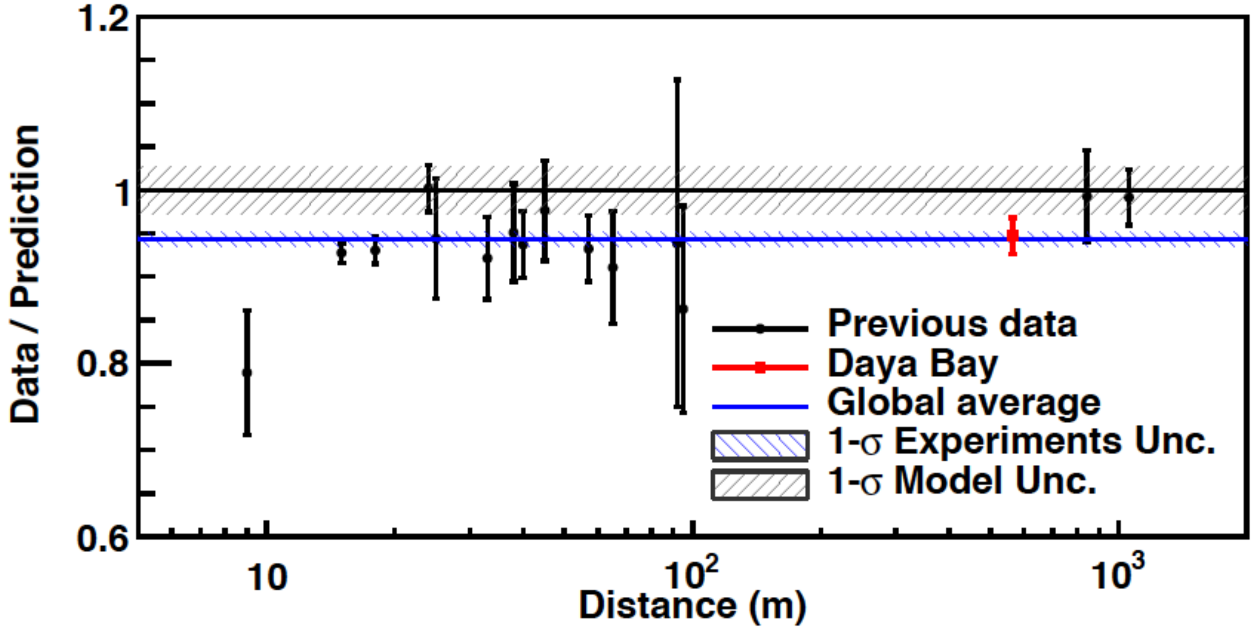

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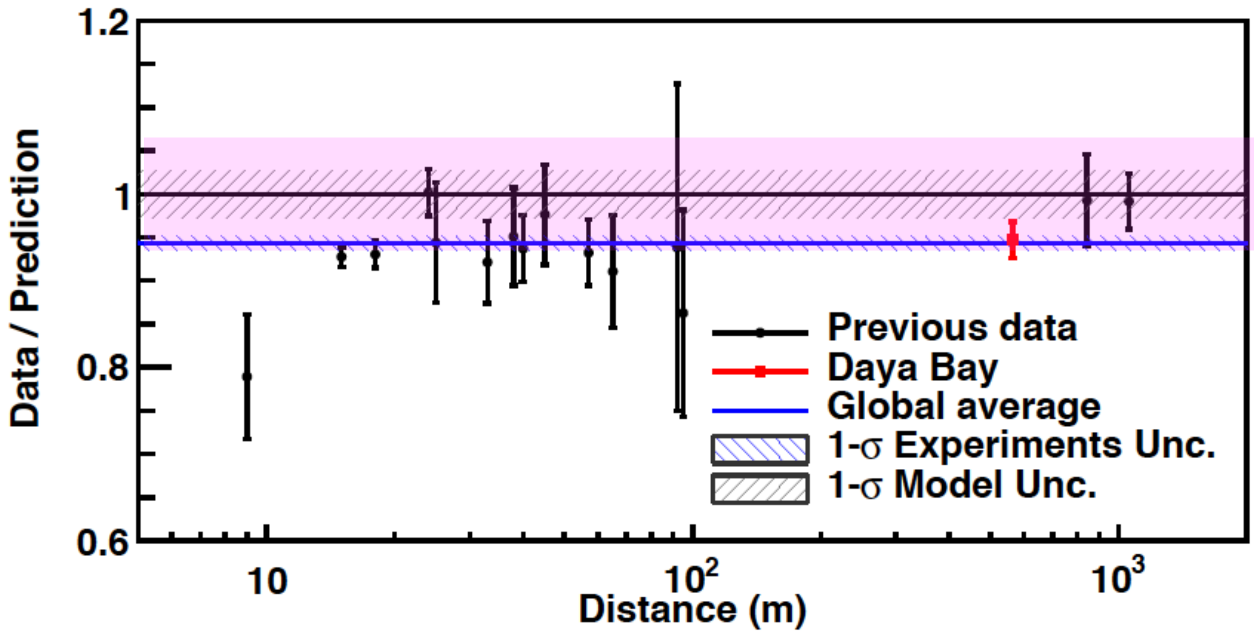
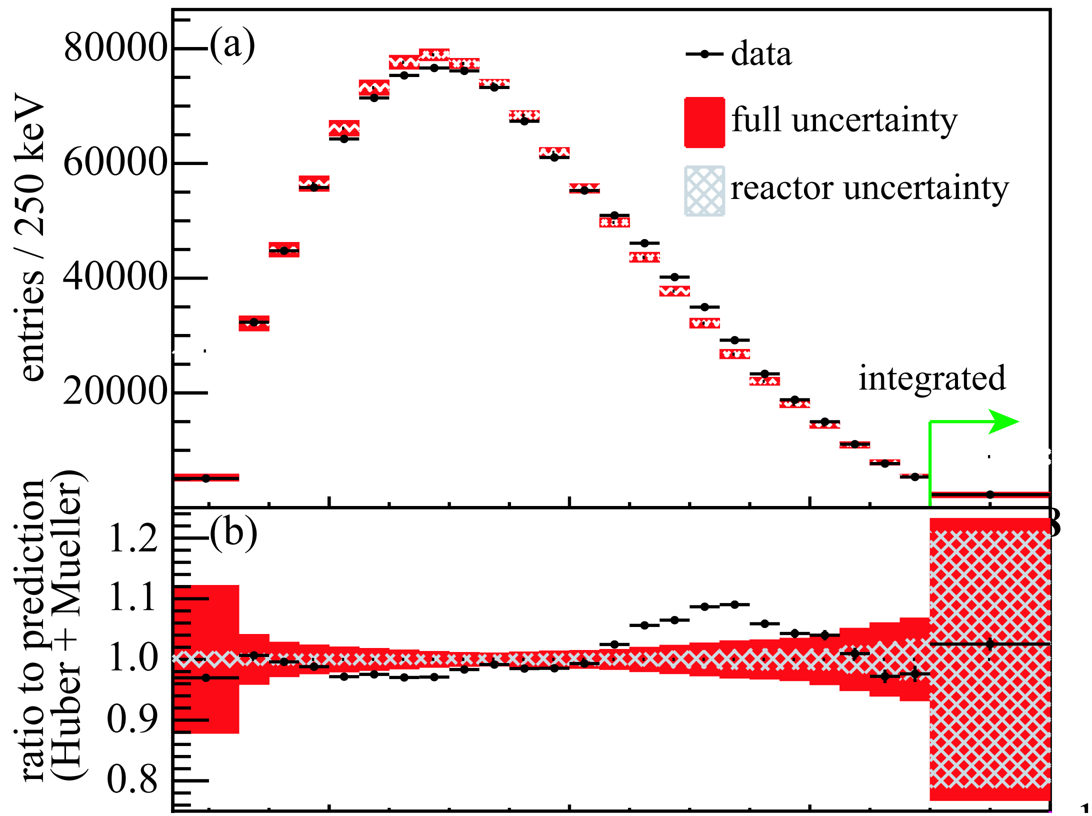


- Anna Hayes and her collaborators pointed out that one must take into account significant nuclear physics uncertainties. For example 30% of the β-decays are forbidden, with large uncertainties in rates.
- When you include NP uncertainties, not really an anomaly.

Oscillation anomalies: $\bar{\nu}_e \to \bar{\nu}_e$ disappearance

- Daya Bay, RENO, and Double Chooz all observe an excess in their spectra around 5 MeV
- Independent of distance L, hence cannot be sterile neutrino
- Conclusion: Uncertainties in understanding reactor flux predictions at the requisite precision.

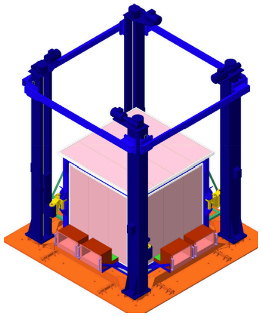
Daya Bay

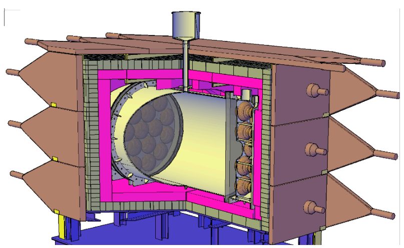


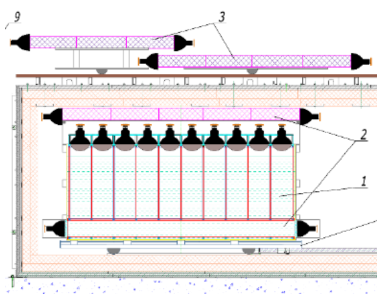
Precision Short Baseline Experiments

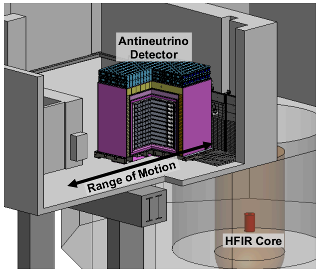
- The reactor anomaly has stimulated a new generation of precision short baseline experiments.
- Starting to exclude "best fit" value from Reactor anomaly.

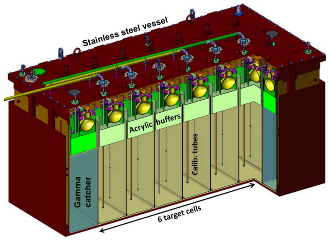
Collaboration	Distance (m)	Reactor	Detector	Status
DANSS	10.7-12.7	100 MW Power Reactor, Russia	plastic scint. + Gd layers	Operating
NEOS	24	2.8 GW Power Reactor, Korea	Gd loaded LS	Operating
Neutrino-4	6-12	100 MW, HEU, SM-3, Russia	Gd loaded LS	Operating
PROSPECT	7-12	85 MW, HEU, HIFR, ORNL	6Li doped LS	Operating
STEREO	9-11	58 MW, HEU, ILL	Gd loaded LS	Operating







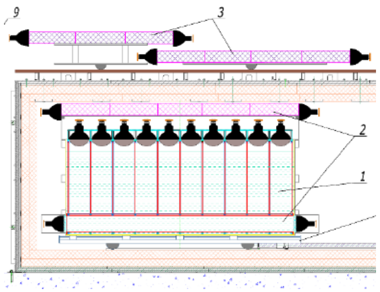


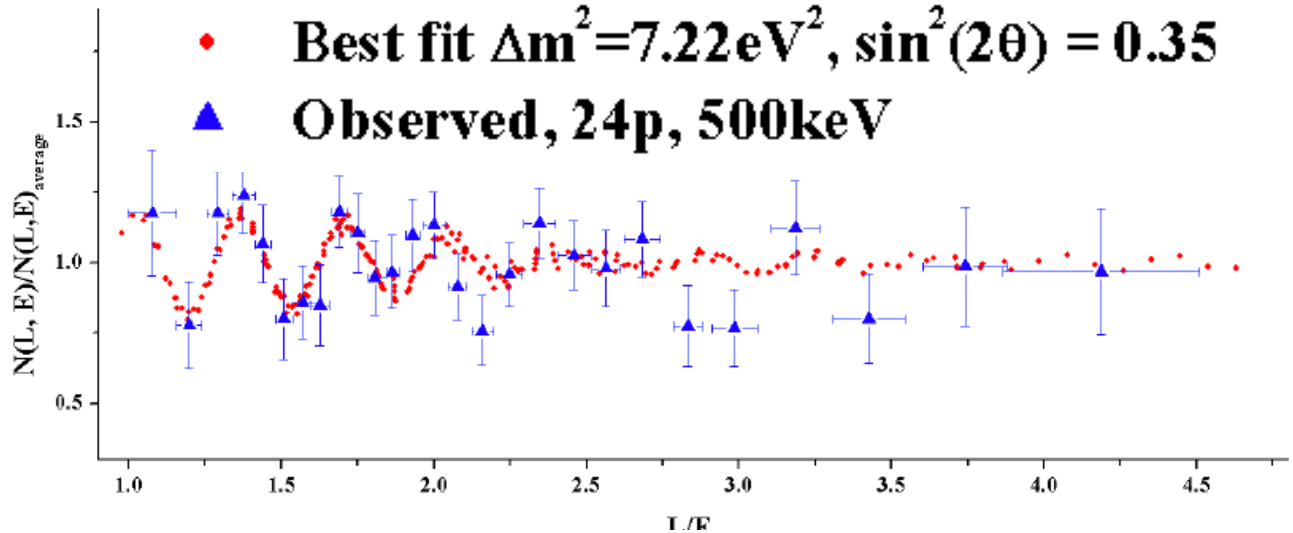


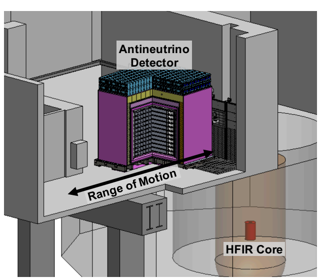
Precision SBL Recent Results

Neutrino-4

arXiv:1809.10561

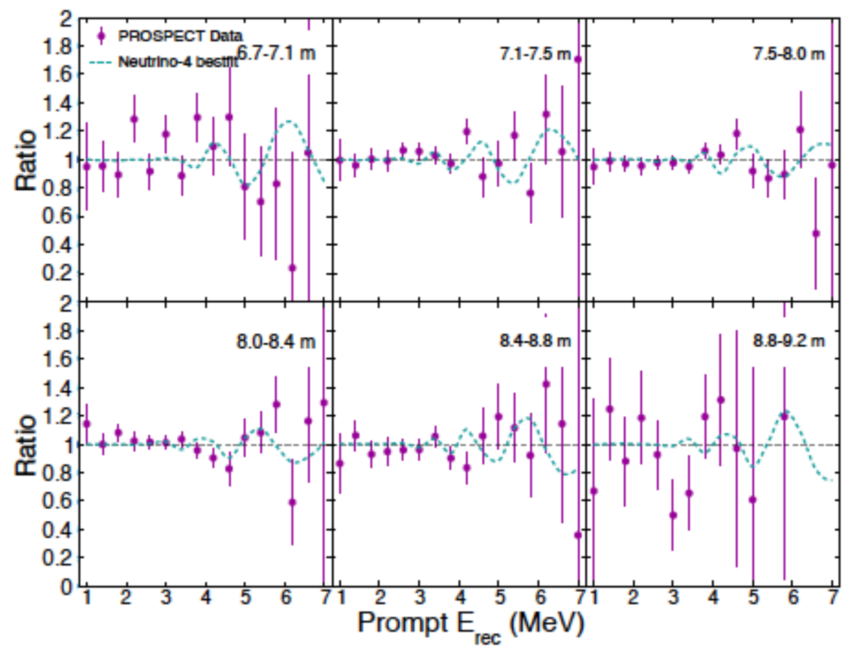






PROSPECT result (v2018)

- spectra from 6 baselines/ full spectrum
- Null-oscillation would yield a flat ratio for all baselines
- Direct ratio search for oscillations, reactor model independent



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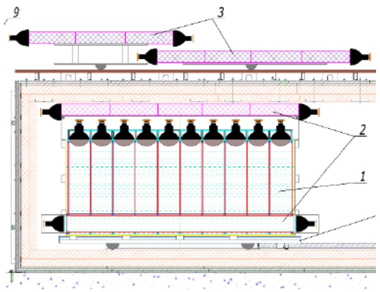
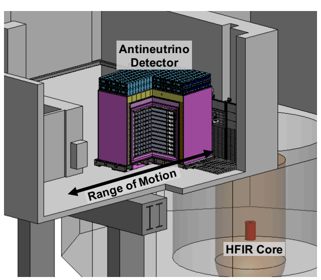
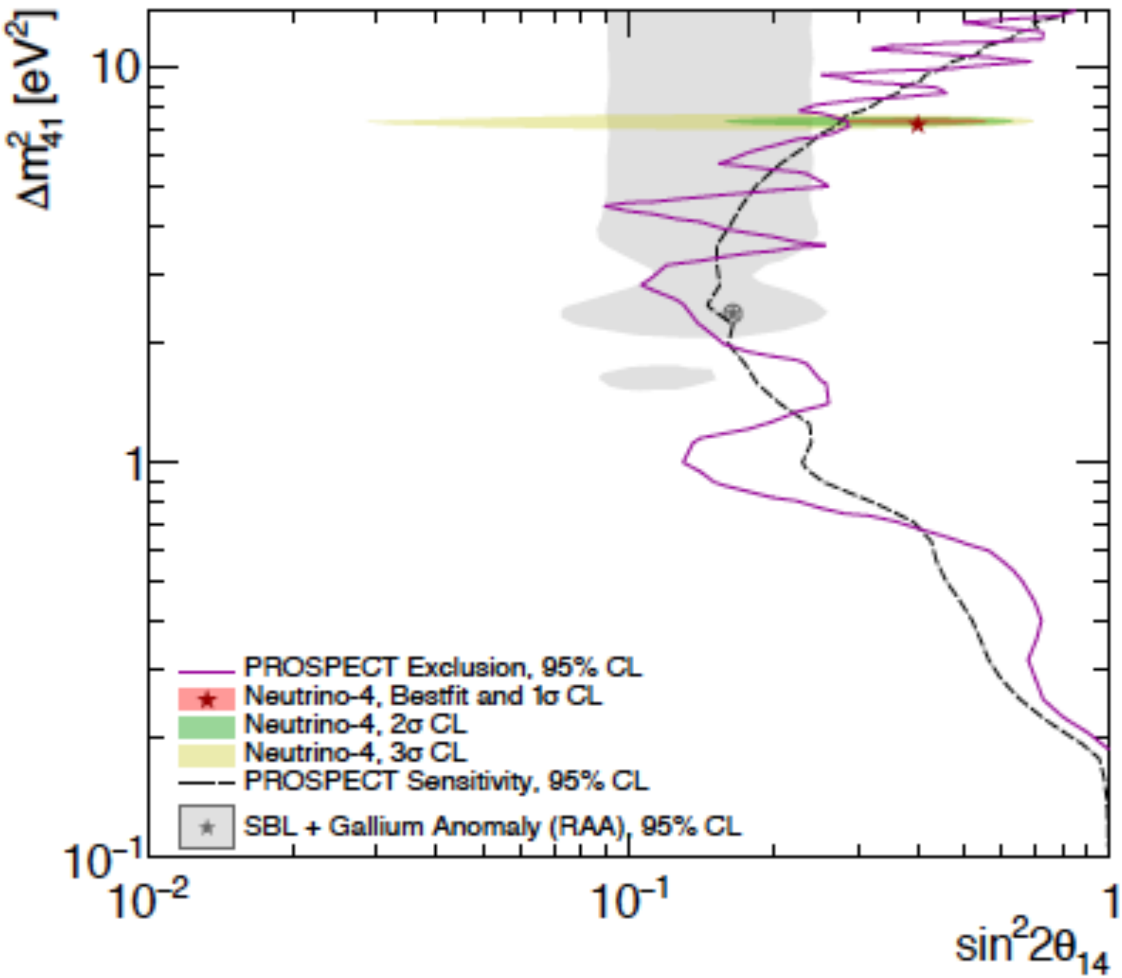


PROSPECT





Techniques to probe ν mass

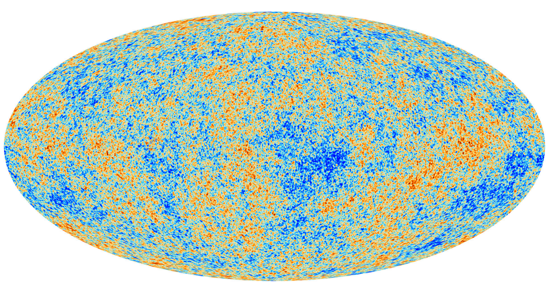
- Oscillation measurements set a lower bound under the assumption that the lightest neutrino mass eigenstate has a mass of zero.
- Three methods to probe mass : Cosmology, Decay kinematics, and neutrinoless double beta decay (0νββ)

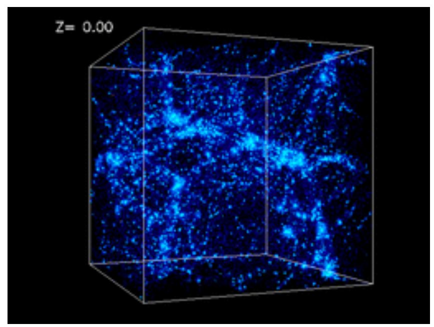
	ν oscillation	Cosmology	Decay kinematics	0νββ
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$	$M_\nu = \sum_i m_i$	$m_{\nu\beta}^2 = \sum_i \lvert U_{ei}^2 \rvert m_i^2$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert^2$
Present	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\mathrm{eV}^2$	$M_\nu < 0.23$ eV	$m_{\nu\beta} < 2$ eV	$m_{\beta\beta} < (0.1\text{-}0.4)$ eV
Next Gen		0.01 – 0.05 eV	0.2 eV	0.01 – 0.05 eV
Model dependences	No mass-scale information	ΛCDM - Only fit to 7 parameters - tension with H_0	Energy conservation	- Majorana vs - δ_1, δ_2 phases - L viol. mech. - NME, g_A

Table follows D. Parno, APS April 2018

Cosmology Sensitivity to ν mass

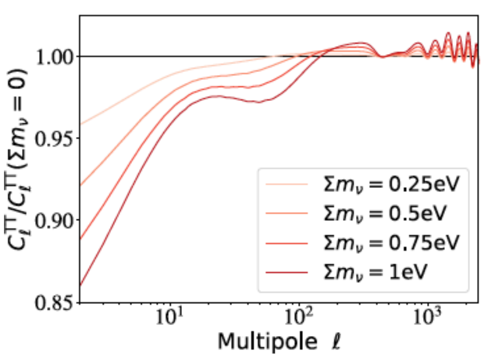
- Neutrinos with mass influence cosmological and astrophysical observables
- Using cosmological models (ΛCDM) one can extract information on the sum of neutrino masses. Model dependencies.
- Fits to CMB (Planck) only, CMB+LSS, CMB+LSS+Lyman α, independent data from Dark Energy Survey (DES).

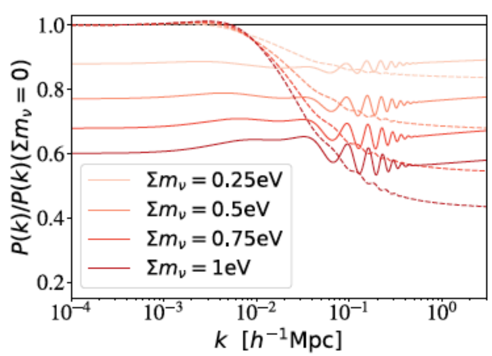




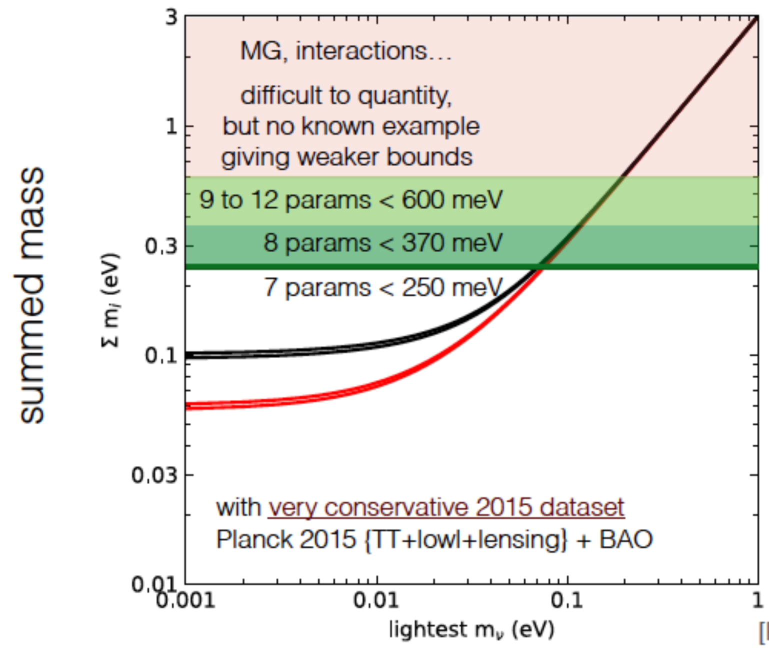
CMB spectrum LSS

LSS (Large Scale Structure) spectrum





PDG Neutrinos in Cosmology



Julien Lesgourgues, Neutrino 2018

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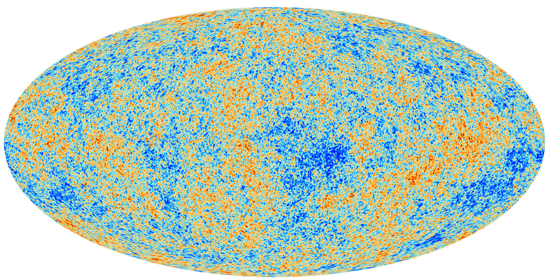

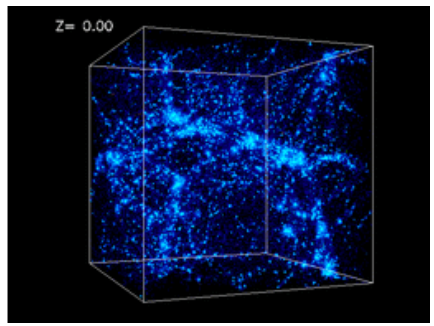

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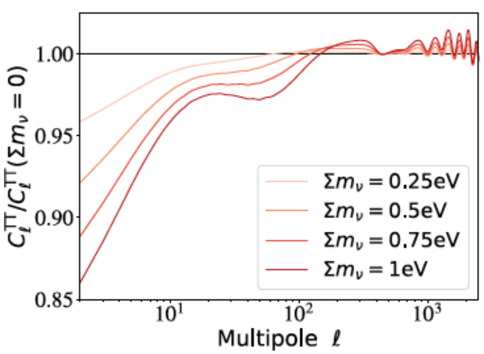
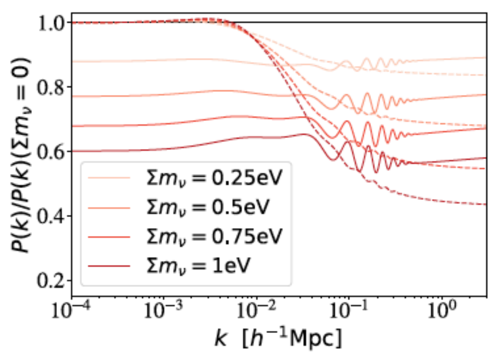
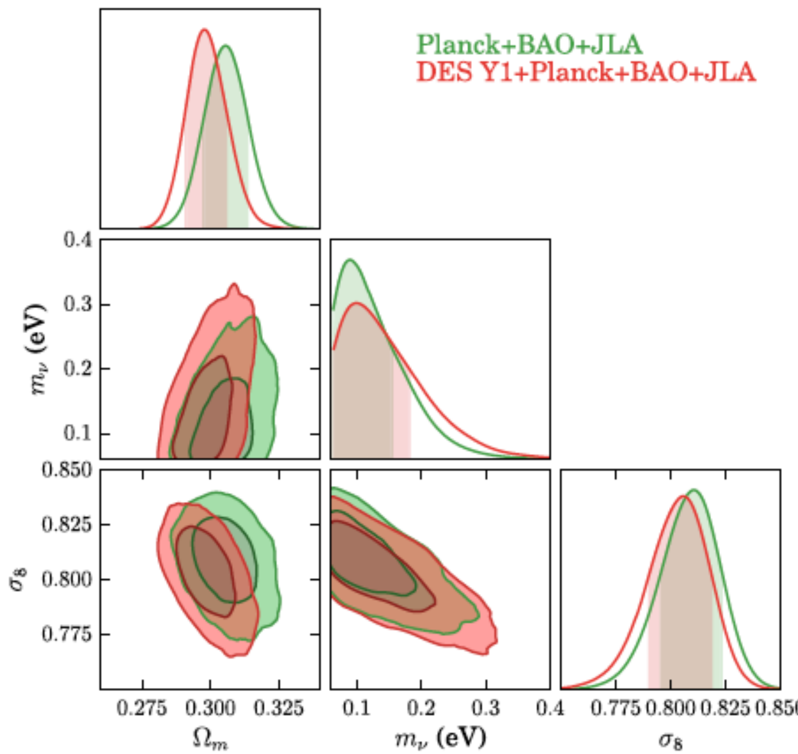




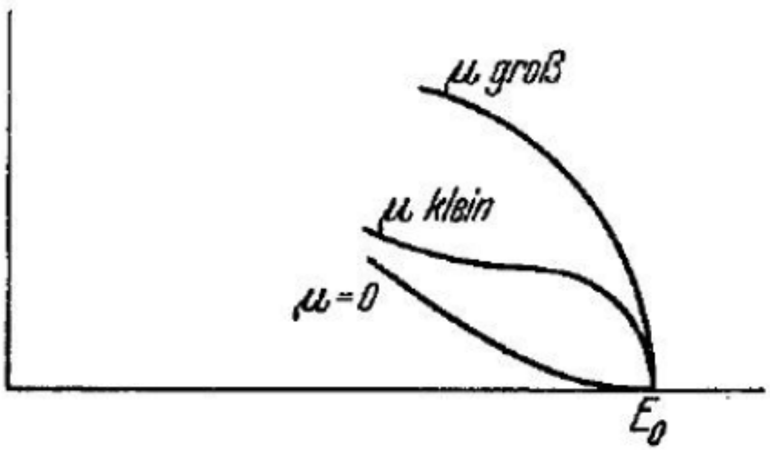
PDG Neutrinos in Cosmology

PHYSICAL REVIEW D 98, 043526 (2018)



Direct Kinematics: β-decay (or EC)

Fermi realized that one could measure the shape of the β-decay spectrum near the endpoint where the electron carries away the maximum energy to deduce the neutrino mass



$$dN(E) = K|M|^2 F(Z,R,E)\, p_e E\, (E_0 - E)\, \{(E_0-E)^2 - m^2_{\nu_e} c^4\}^{1/2}\, dE$$

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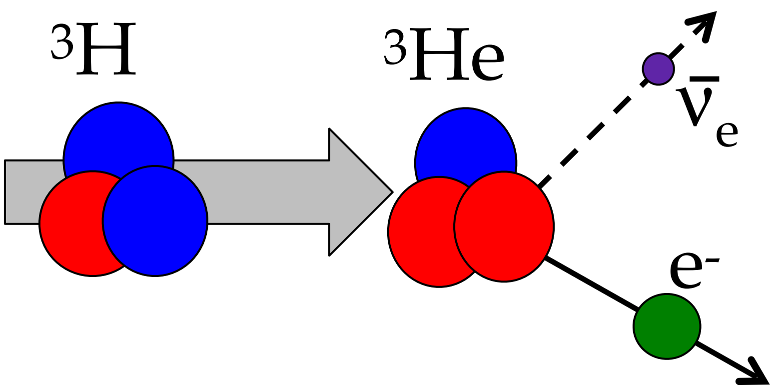

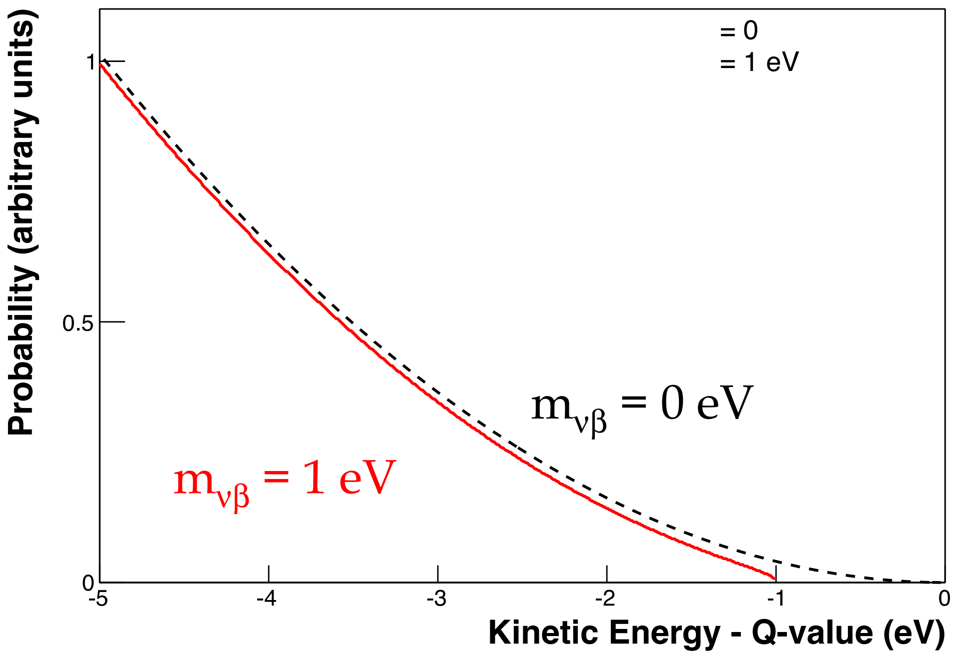

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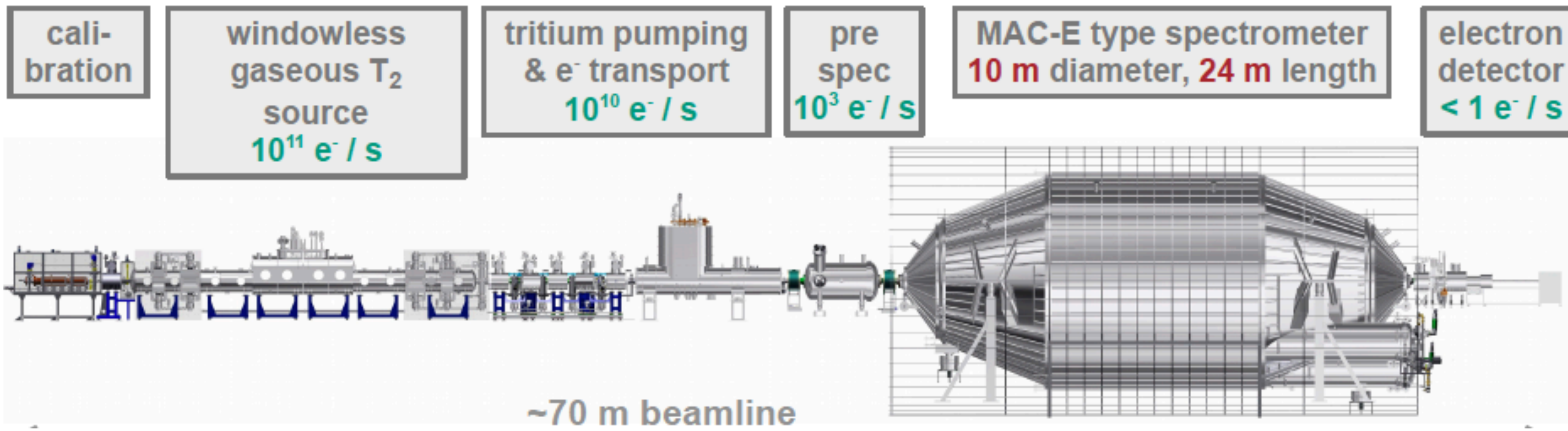
KATRIN Neutrino Mass Experiment

- Intense T_2 source (10^{11} decays/second)
- Spectrum analysis with electromagnetic filter



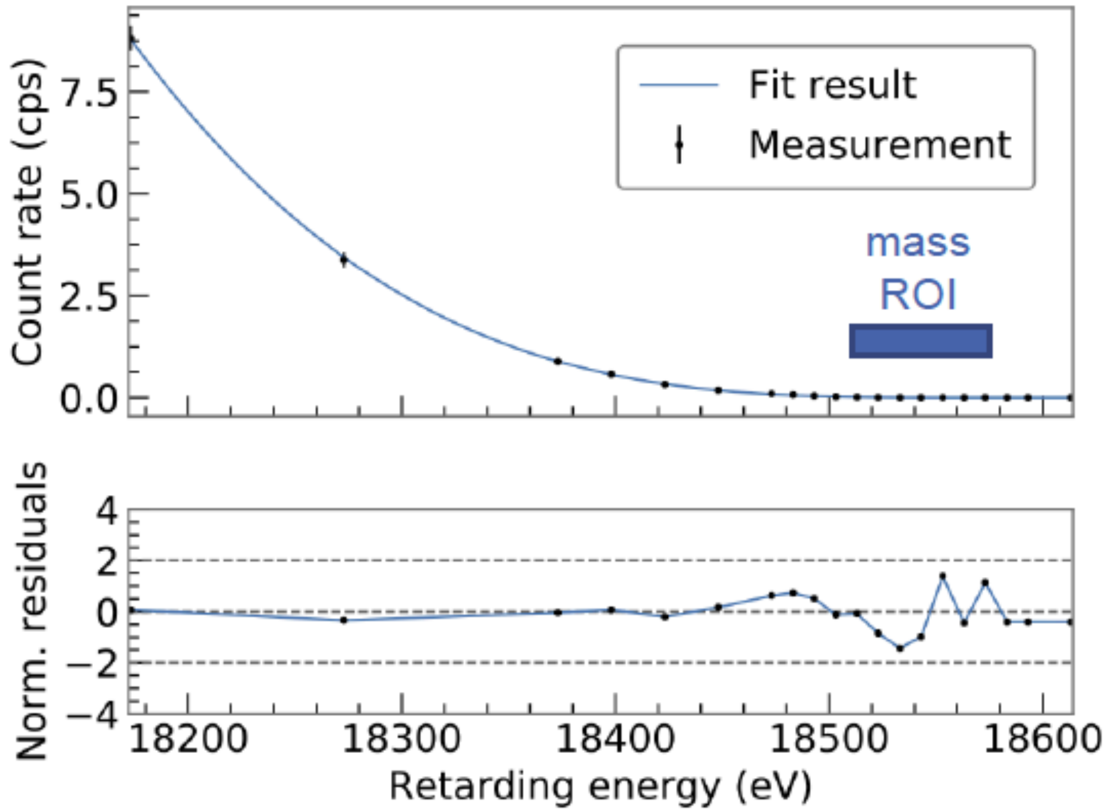
- Design resolution: 0.93 eV
- Design $m_{\nu\beta}$ sensitivity: 0.2 eV/c^2 at 90% CL

KATRIN First Tritium Run (May/June 2018)

- Goal: verify functionality of all system components and demonstrate 0.1% global stability
- Method: inject known gas mix from prepared cylinders (80% of nominal ρd, ~1% DT and ~99% D2 corresponds to <1% of nominal activity ≈ 500 MBq
- Study beta spectrum for systematic effects and test analysis strategies

Single run (3h), analysis of single detector pixel

- ROI extended to 400 eV
- Statistics only errors



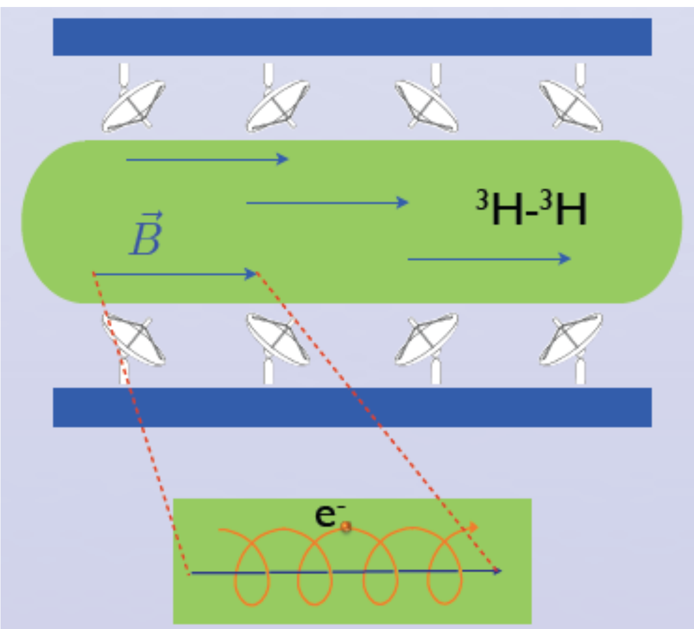
Project 8 - measure β frequency

Cyclotron Radiation Emission Spectroscopy (CRES)

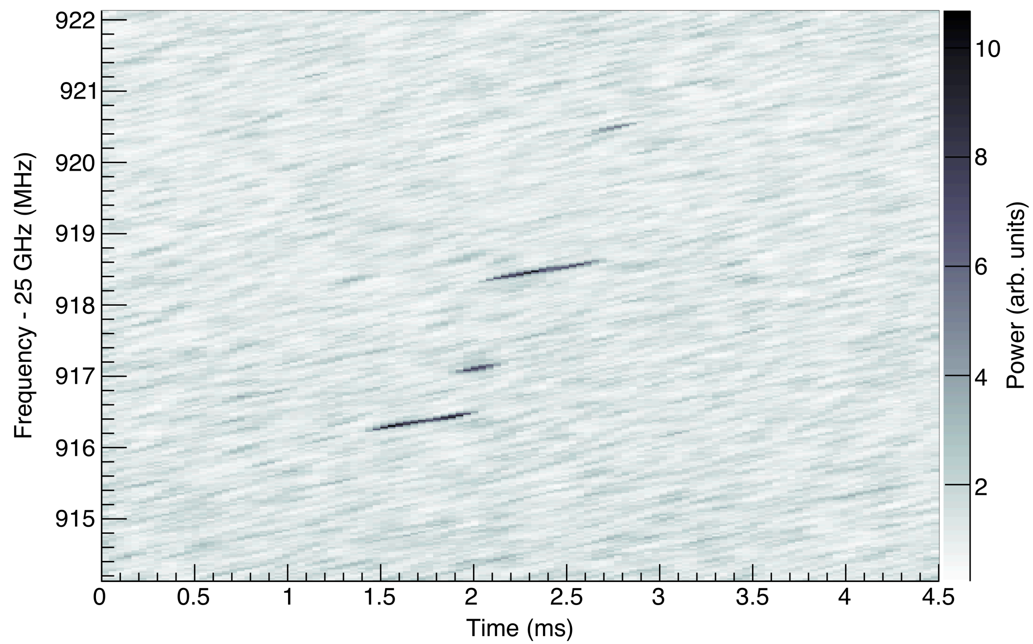
Cyclotron motion:

$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{kin}/c^2}$$

$$f_c = 27\,992.491\,10(6)\ \mathrm{MHz\,T^{-1}}$$



Decay Signal from T_2 source
(APS DNP/PSJ Hawaii Meeting)

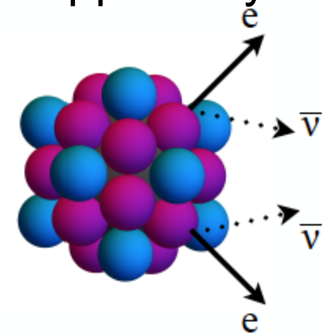


B. Monreal and J. Formaggio, PRD 80:051301, 2009

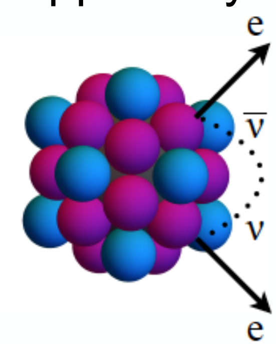
Are ν's Majorana Particles?

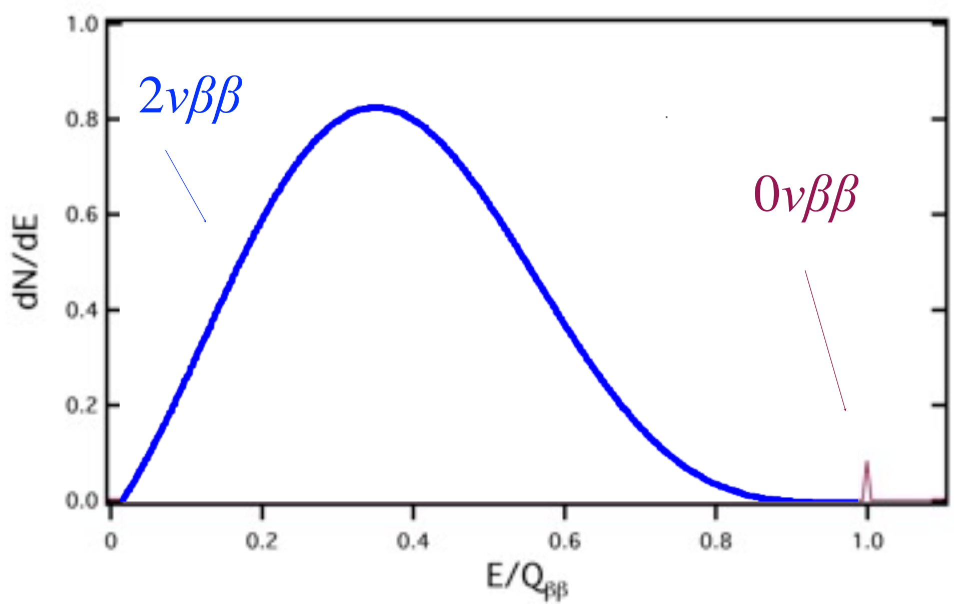
In a number of even-even nuclei, β-decay is energetically forbidden, while double-beta decay, from a nucleus of (A,Z) to (A,Z+2), is energetically allowed.

2νββ-decay



0νββ-decay





($2\nu\beta\beta$ $T_{1/2}$ ~ 10^{19} - 10^{21} years)

Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05

0νββ decay

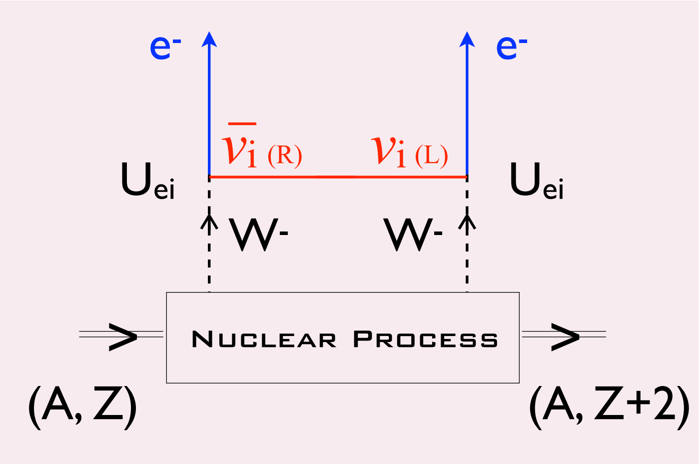
Requires:

- neutrino to have non-zero mass
  - "wrong-handed" helicity admixture ~ m_i/E_{ν_i}

Any process that allows 0νββ to occur requires Majorana neutrinos with non-zero mass. Schechter and Valle, 1982

- Lepton number violation
  - No experimental evidence that Lepton number must be conserved

  (i.e. allowed based on general SM principles, such as electroweak-isospin conservation and renormalizability)
  - Potential explanation for observed matter - antimatter asymmetry.



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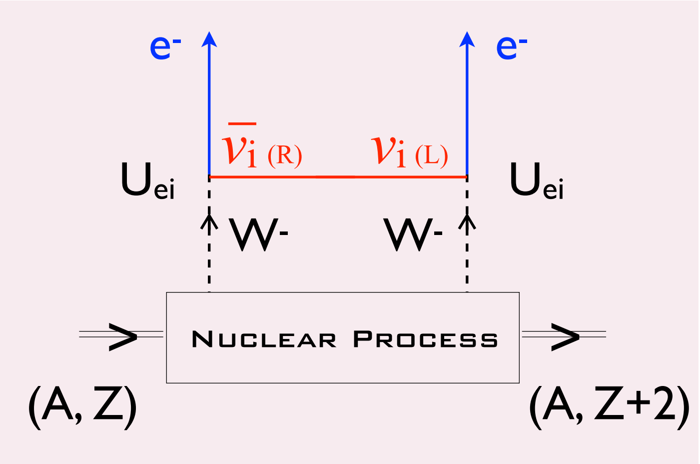


If 0νββ decay is observed ⇒

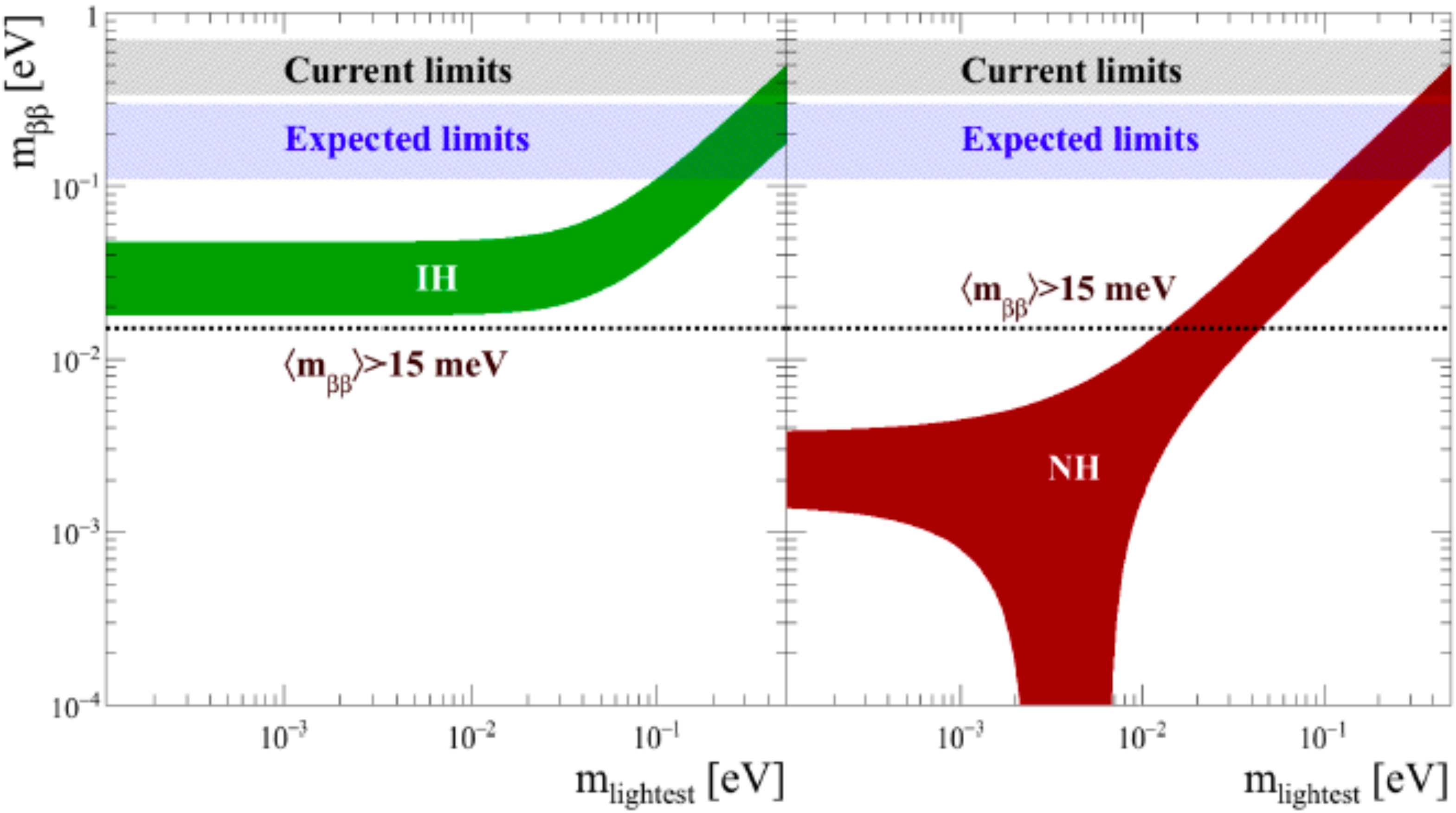
neutrinos are Majorana particles,
lepton number is violated,
sheds light on neutrino mass mechanism (does not arise standard Higgs)

0νββ Decay and <mββ>

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



2015 NSAC Long Range Plan for Nuclear Science

0νββ Decay and <mββ>

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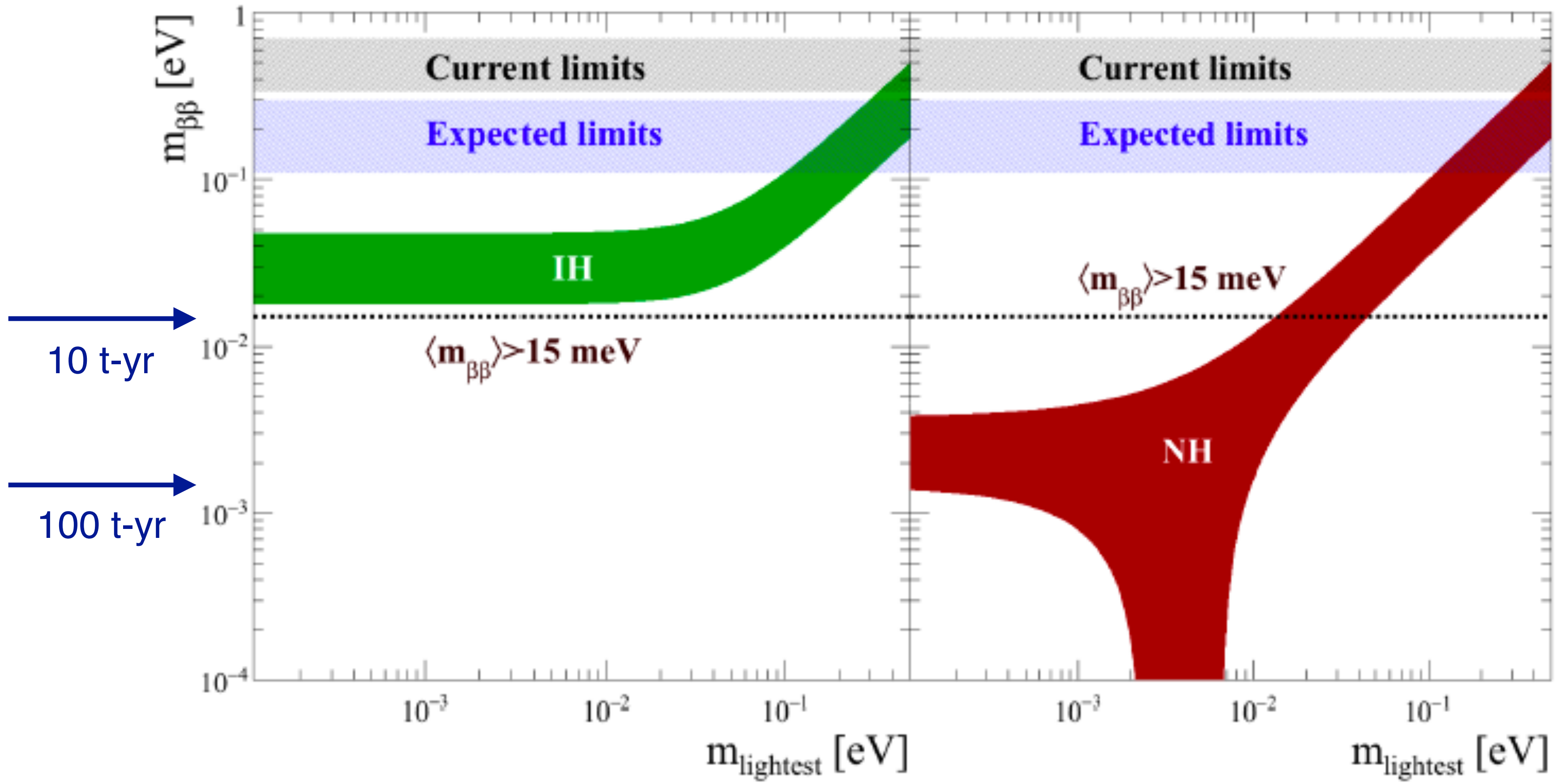
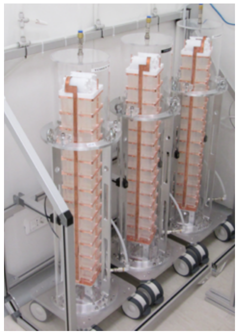


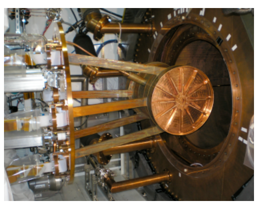
2015 NSAC Long Range Plan for Nuclear Science

0νββ decay Experiments - Efforts Underway

CUORE



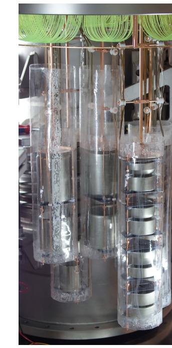
EXO200



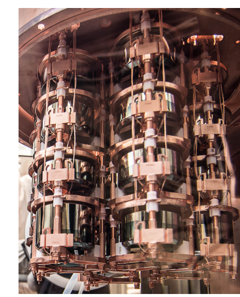
KamLAND Zen

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

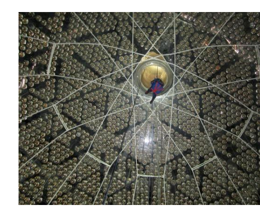
GERDA



MAJORANA



SNO+

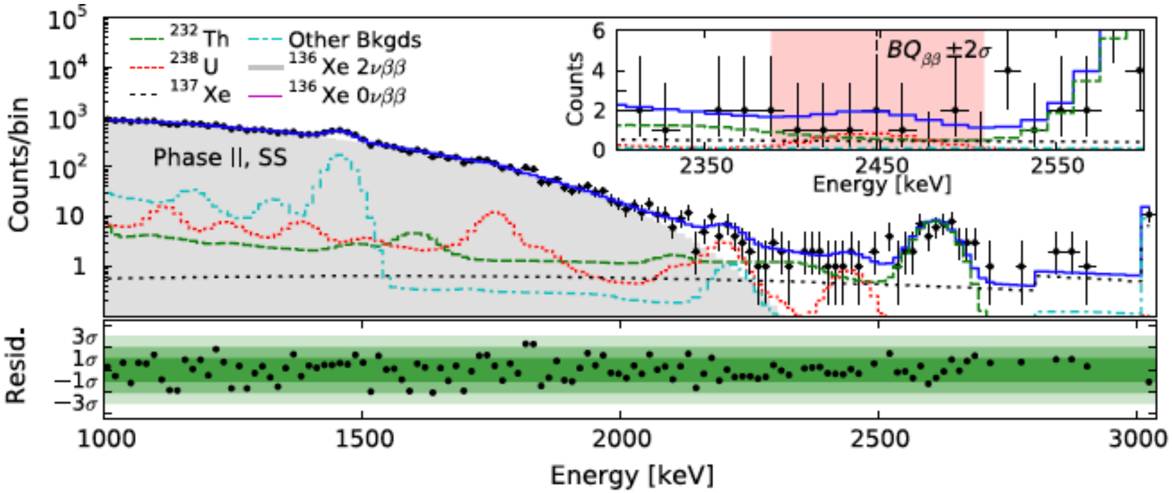


0νββ Status : Significant Progress !

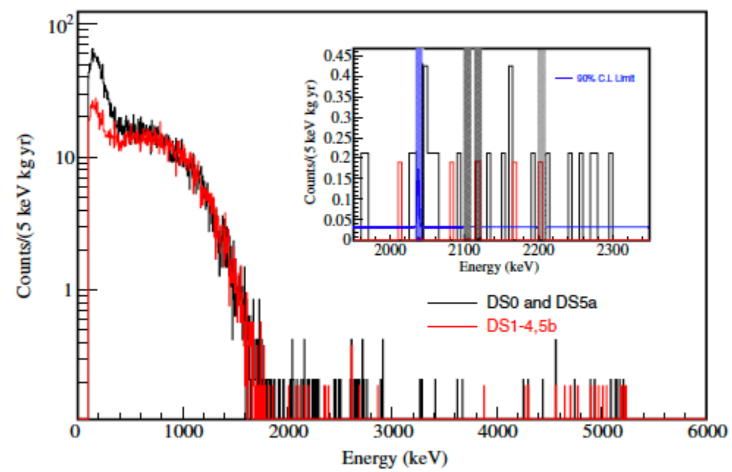
		Half-life (y)	$m_{\beta\beta}$ (meV)
PRL **117,** 082503 (2016) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2016 — **Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen**	^{136}Xe	$> 1.07 \cdot 10^{26}$	< 61-165
PHYSICAL REVIEW LETTERS **120,** 072701 (2018) — **Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector**	^{136}Xe	$> 0.18 \cdot 10^{26}$	< 147-398
PHYSICAL REVIEW LETTERS **120,** 132501 (2018) — Editors' Suggestion, Featured in Physics — **First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te**	^{130}Te	$> 0.15 \cdot 10^{26}$	< 110-520
PHYSICAL REVIEW LETTERS **120,** 132503 (2018) — Editors' Suggestion, Featured in Physics — **Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II**	^{76}Ge	$> 0.8 \cdot 10^{26}$	< 120-260
PHYSICAL REVIEW LETTERS **120,** 132502 (2018) — Editors' Suggestion, Featured in Physics — **Search for Neutrinoless Double-β Decay in ^{76}Ge with the MAJORANA DEMONSTRATOR**	^{76}Ge	$> 0.19 \cdot 10^{26}$	< 240-520

0νββ Current Results

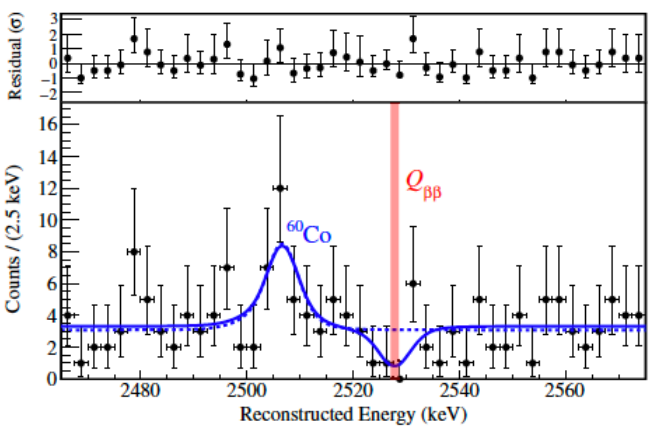
EXO-200 ^{136}Xe



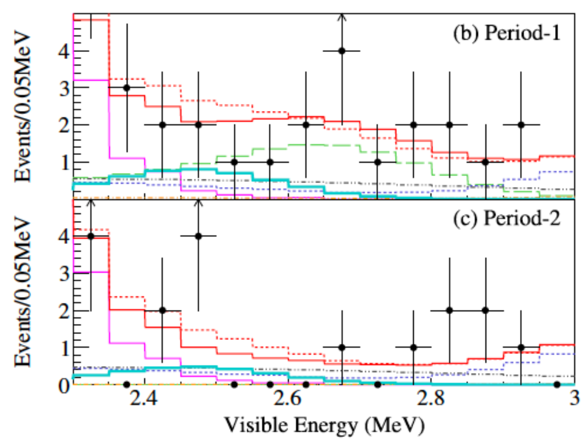
MAJORANA DEMONSTRATOR ^{76}Ge



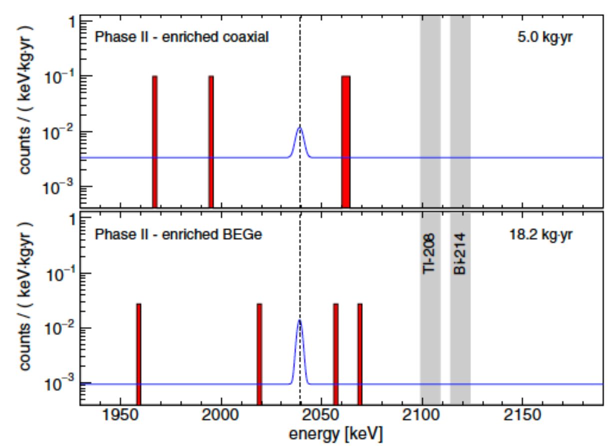
CUORE ^{130}Te



KamLAND Zen ^{136}Xe



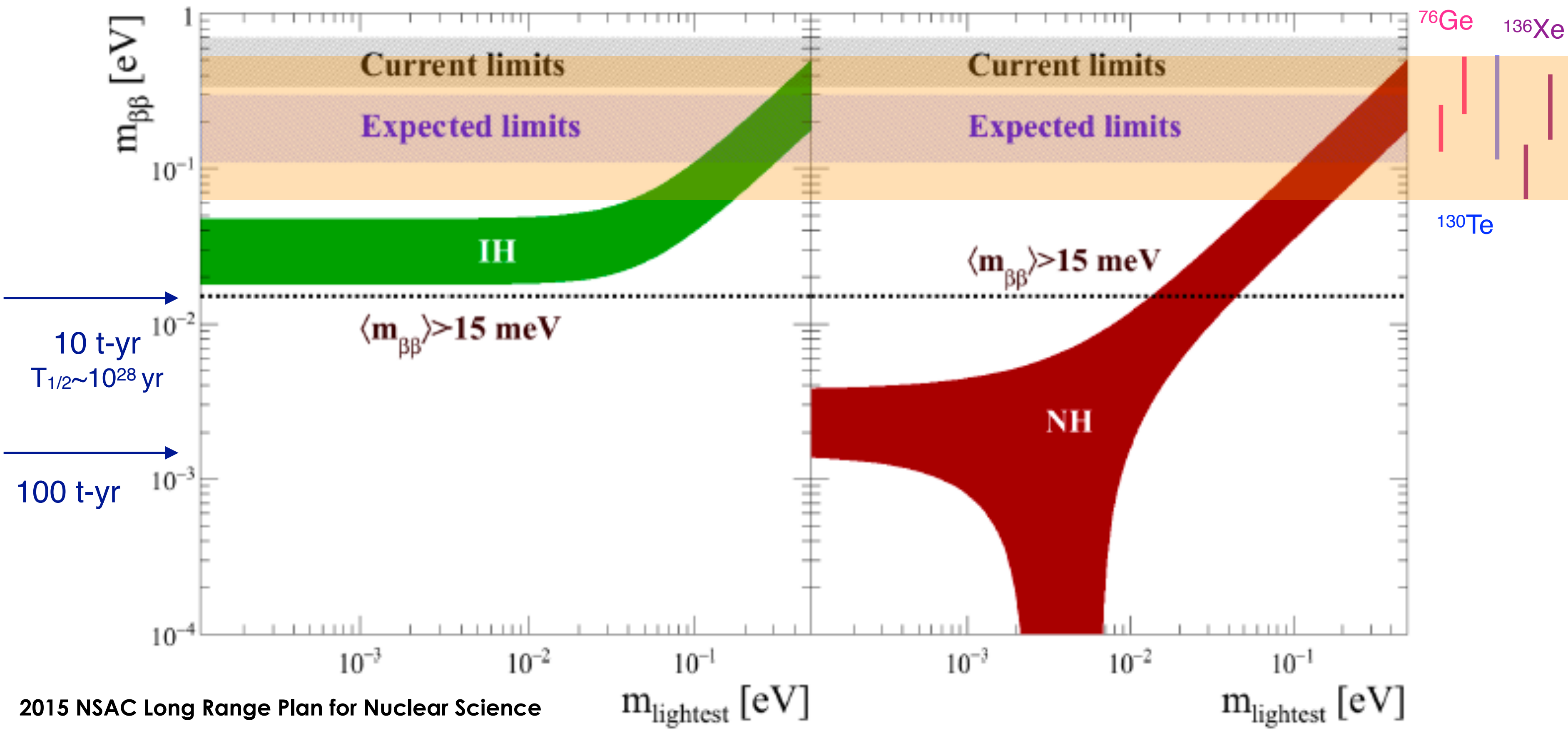
GERDA ^{76}Ge



Searching for 0νββ Decay

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



2015 NSAC Long Range Plan for Nuclear Science

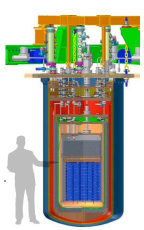
Next Generation $0\nu\beta\beta$ Considerations

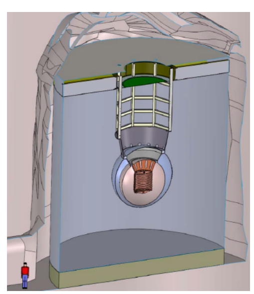
- Is there a preferred $0\nu\beta\beta$ isotope?
  – *No preferred isotope in terms of per unit mass - within current uncertainties on NME and g_A.*
- What evidence is needed to claim the observation of $0\nu\beta\beta$
  - *Measurement of a peak (or excess) at the correct energy at 3σ.*
  - *Observation in two different isotopes.*
- What is required to cover Inverted Ordering masses? ($T_{1/2}$ approaching 10^{28} years)
  - *For a nearly ideal, background free experiment ~ 10 t-y.*
- What are the critical experimental considerations?
  - *Availability of ton quantity of (enriched) isotopes.*
  - *Reduction of backgrounds (and/or effective discrimination)*
    - ✦ *$2\nu\beta\beta$ rate (irreducible background) - ^{76}Ge ^{130}Te, ^{136}Xe are the best (longest $T_{1/2}$), but impact depends on resolution.*
  - *Resolution.*

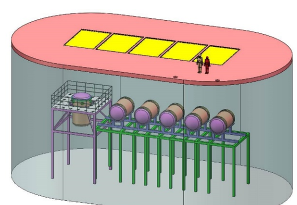
$0\nu\beta\beta$ decay Experiments - ton scale

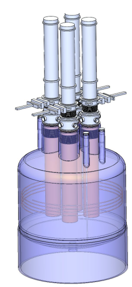
Collaboration	**Isotope**	**Technique**	**mass ($0\nu\beta\beta$ isotope)**	**Status**
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	Const. LEGEND-200
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Constr./Commish
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**400, 800 kg**	Complete,
KamLAND2-Zen	Xe-136	Improved light coll, disc	**800 kg**	Upgrade
NEXT	Xe-136	High pressure Xe TPC	**~ton**	Const. NEXT-100
PandaX - III	Xe-136	High pressure Xe TPC	**~ ton**	

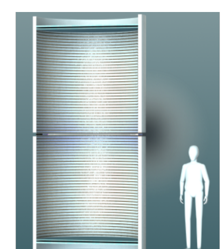

KamLAND Zen

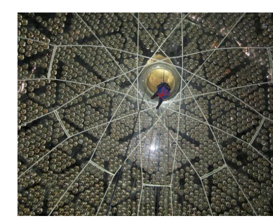

CUPID


nEXO


PandaX-III


LEGEND

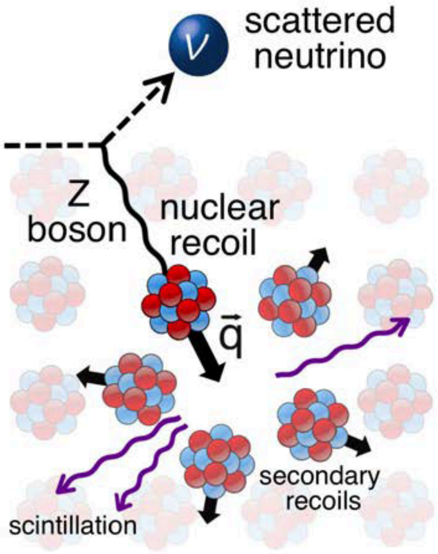

NEXT


SNO+

Summary: 0νββ-decay Status and Future Prospects

- Significant experimental progress since the 2015 long range plan.
  - Experiments have attained or are approaching sensitivities of $T_{1/2} > 10^{26}$ years, with substantially reduced backgrounds.
  - "Background free" measurements have been achieved as have detectors with masses >200 kg.
  - Theory progress should soon provide NME with realistic uncertainties and will likely reduce uncertainties associated with g_A .This will have a critical impact on understanding sensitivity and discovery potential
- Large international 0νββ collaborations are moving forward with designs for next generation experiments based on lessons learned from the current measurements.
  - All aim for sensitivity & discovery levels at $T_{1/2}$ approaching 10^{28} years
- The ability to discover 0νββ will require excellent energy resolution, low backgrounds ("background free") and large exposures (t-y) as well as observation by independent experiments, using different isotopes.

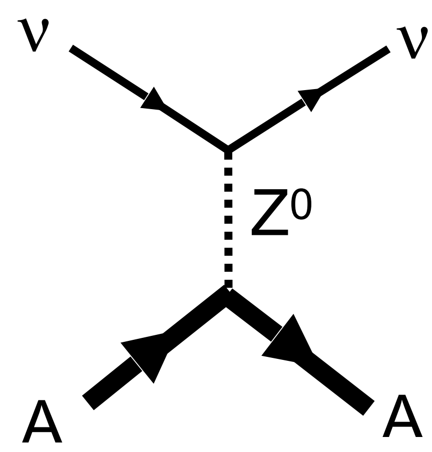
Coherent elastic ν-nucleus scattering (CEνNS)



$$\nu + A \rightarrow \nu + A$$

D. Z. Freedman, Coherent effects of a weak neutral current, Phys. Rev. D **9**, 1389 (1974).

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$



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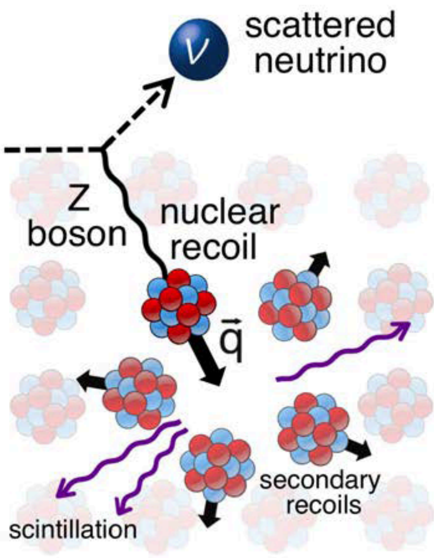

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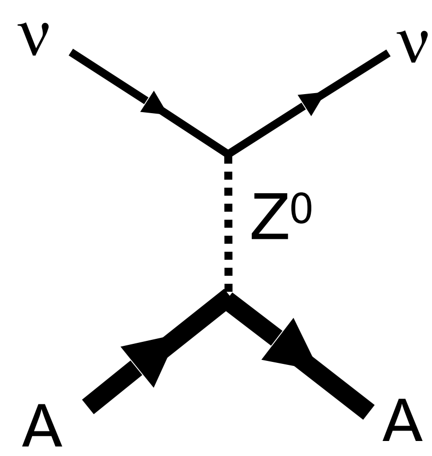
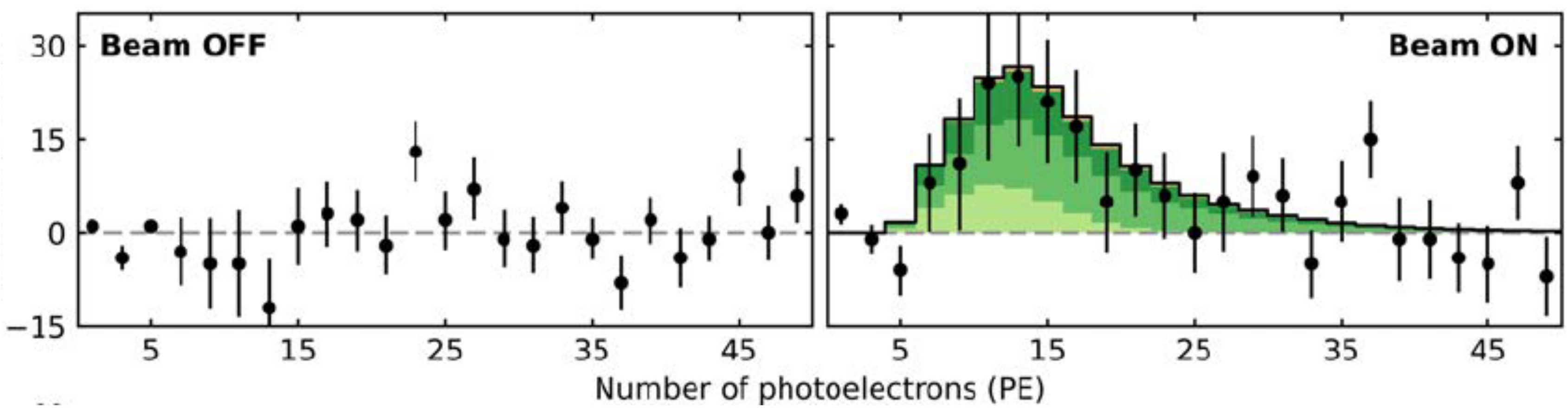


COHERENT

SNS SPALLATION NEUTRON SOURCE

Spallation Neutron Source (ORNL) w/ 14.6 kg CsI[Na]

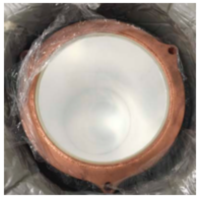
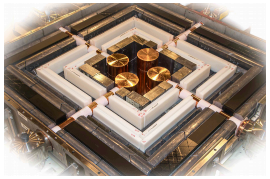
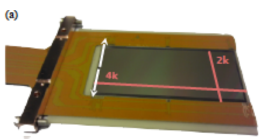


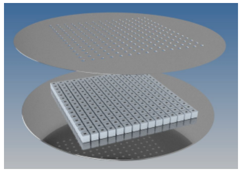
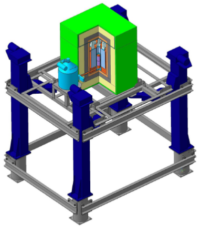
D. Akimov et al., *Science*, 2017 http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

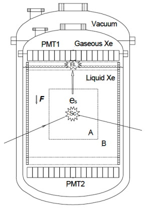
CEνENS Experiments and Prospects

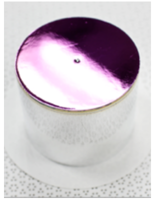
- A powerful tool to study fundamental physics — BSM interactions, ν magnetic moment, weak mixing angle, nuclear form factor, neutron radius and skin, …
- Impacts models for nuclear and particle astrophysics
- Potential applications — reactor monitoring, nonproliferation, …

Collaboration	Detector	Source	Status
COHERENT	14.6 kg CsI (Tl)	SNS, ORNL	Observed
	NaI, LAr, Ge	SNS, ORNL	Const.
CONNIE	Si CCD	3.9 GW Power Reactor, Brazil	Operating
COνUS	4 kg Ge	3.9 GW, Power React., Germany	Operating
MINER	Ge, Si bolometers	TRIGA Res. Reactora, Texas A&M	R&D
ν-CLEUS	$CaWO_4$ and Al_2O_3 calorimeter	Power reactor	R&D
ν-GeN	HPGe	Kalinin Power reactor	Operating
Ricochet	Zn, Ge, or $CaWO_4$ bolometer	Chooz reactor, France	R&D
RED	large mass LXe	3.2 GW Kalinin Plant or SNS	R&D
TEXONO	~ kg Ge	Kuo-Sheng Reactor Neutrino Laboratory, Taiwan	R&D





Fundamental Symmetries & Neutrinos Summary

- Fundamental Symmetry measurements with increasing complexity continue to push the sensitivity frontier
  - No significant deviations from the SM.
  - Promising prospects for progress.
- Neutrino oscillations demonstrate that SM is incomplete. But important questions remain.
  - Sterile neutrinos claims require confirmation. Understanding NP is crucial.
  - Major advances for $0\nu\beta\beta$ experiments, ready to go to ton scale
- Potential issues with limitations from NP uncertainties and estimation of systematics.

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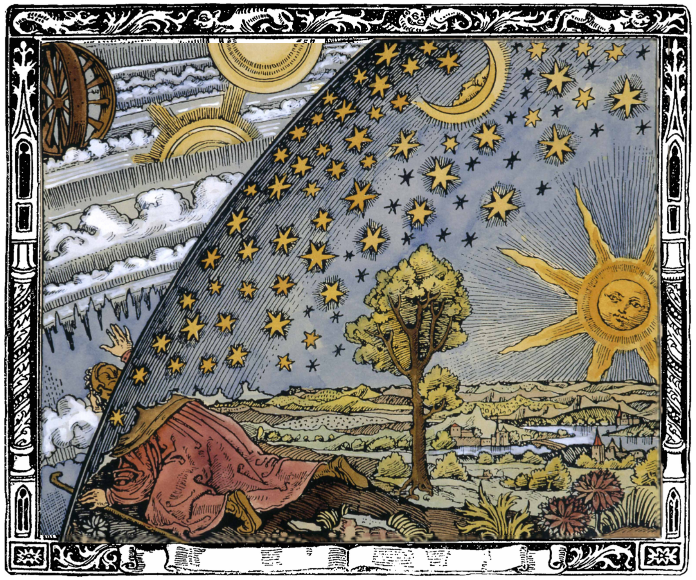
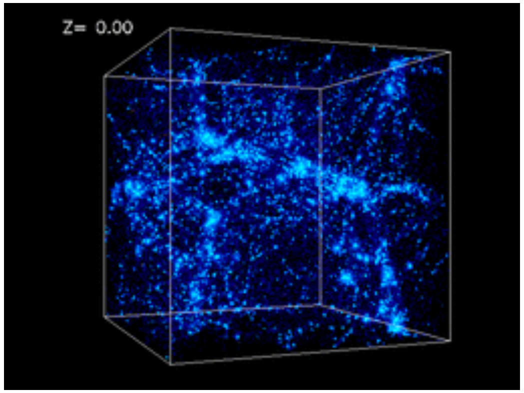


Why it matters

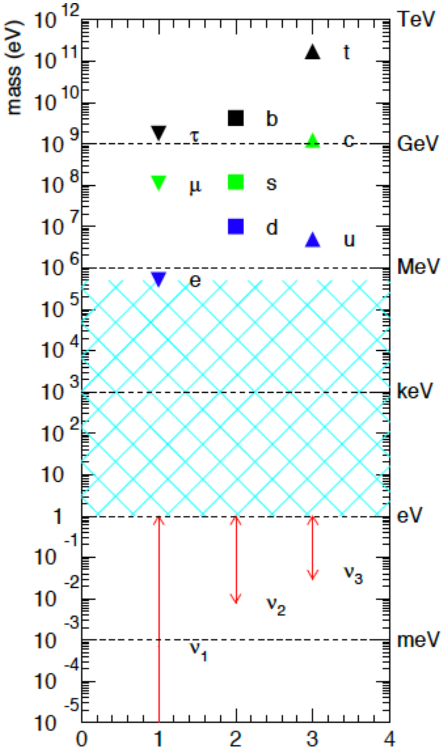
- ν's influence the evolution of the early universe an the growth of large scale structure in the universe (Cosmology)
  - Need to know the masses and number of neutrino flavors



- Raises the questions of how neutrinos fit into electroweak symmetry breaking (Higgs) and understanding the origin of mass

  Dirac — then neutrinos must have extremely weak coupling with Higgs

  Majorana — additional Higgs particles or another source of mass (See-saw and additional heavy neutrinos)
  - Need to know the masses
  - Are neutrinos Majorana particles?



André de Gouvêa

Why it matters

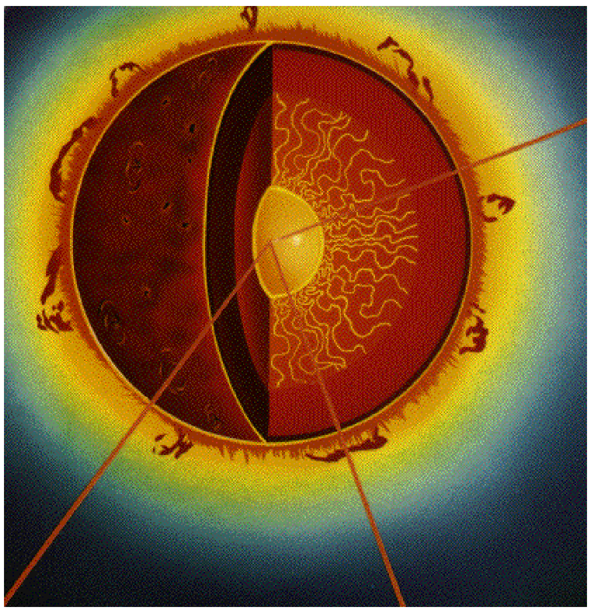
Sakharov Conditions
- Baryon # violation
- CP violation
- Out of equilibrium (sphaleron process)

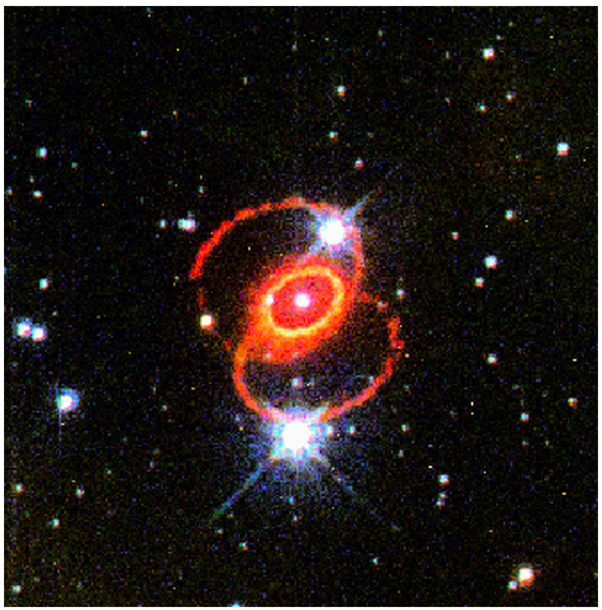
- May offer an explanation of the observed excess of matter to anti-matter (Leptogenesis)
  - Are neutrinos Majorana particles?
  - Is CP is violated in the lepton sector?

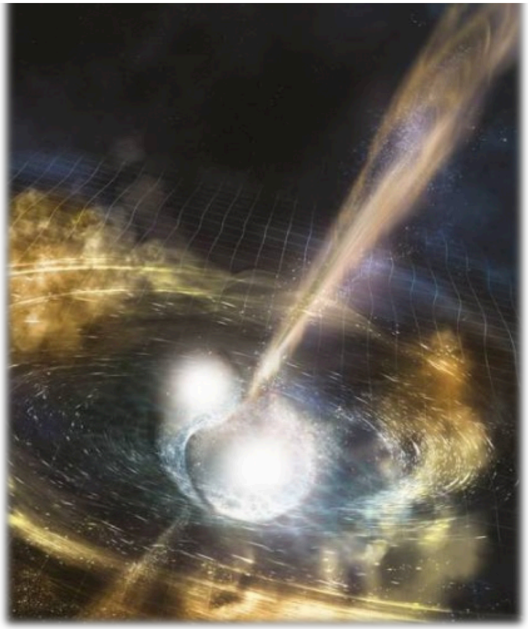
- Opens the questions of additional physics beyond the standard model?
  - additional neutrino flavors (Sterile neutrinos)?
  - non-standard neutrino interactions?

Why it matters

- Modify numerous mechanisms and processes in nuclear and particle astrophysics (Stellar burning, supernovae explosions, elemental abundances, blazers, …)
    - Need precise knowledge of mixing angles, mass ordering, cross-sections, …







- Using neutrinos to probe other physics: geoneutrinos, stellar burning, supernovae, neutrino astronomy, …

Oscillation Measurement Prospects - 3 flavor model

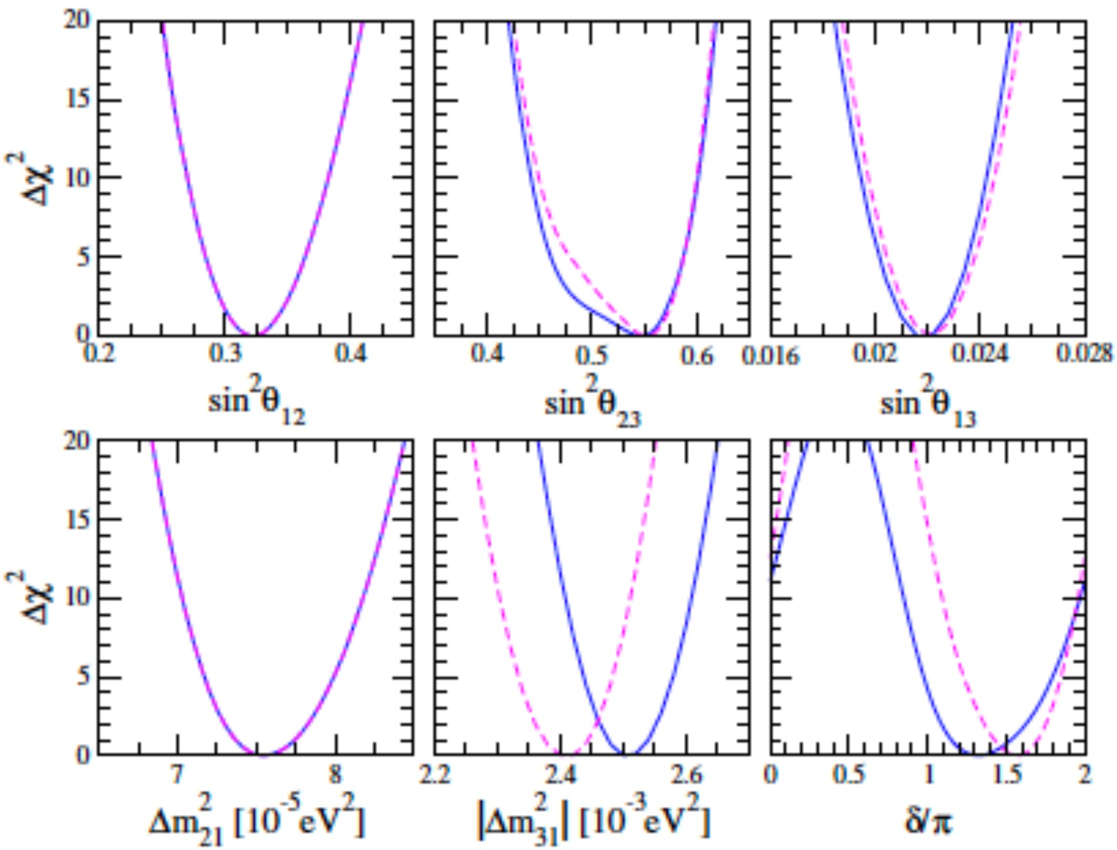
Three areas of emphasis:

- maximality/octant of θ_{23}
- neutrino mass ordering
- leptonic CP violation

Global fits to all available oscillation data finds ~3 σ preference for Normal Ordering

Phys.Lett. B782 (2018) 633-640

https://globalfit.astroparticles.es/



Operating

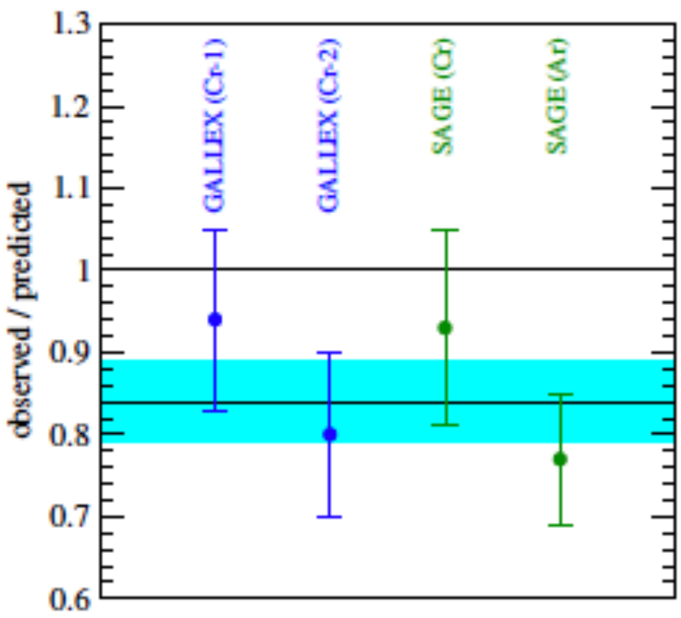
- T2K, NOνA, SuperK, IceCube DeepCore, ANTARES, Daya Bay, RENO, Double Chooz,

Near-future

- JUNO, RENO-50 ORCA, PINGU

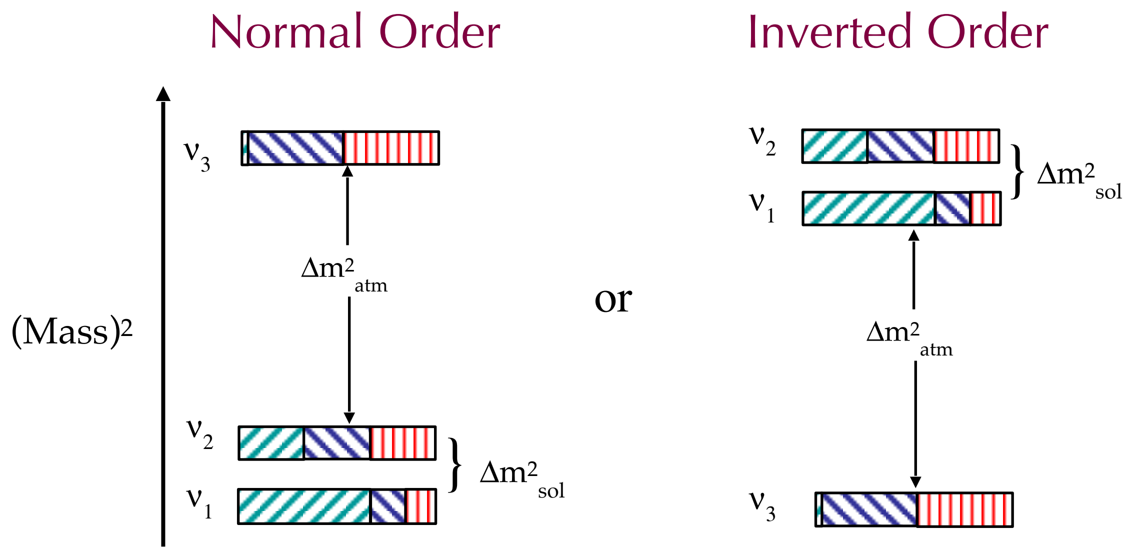
Oscillation anomalies: $\nu_e \rightarrow \nu_e$ disappearance

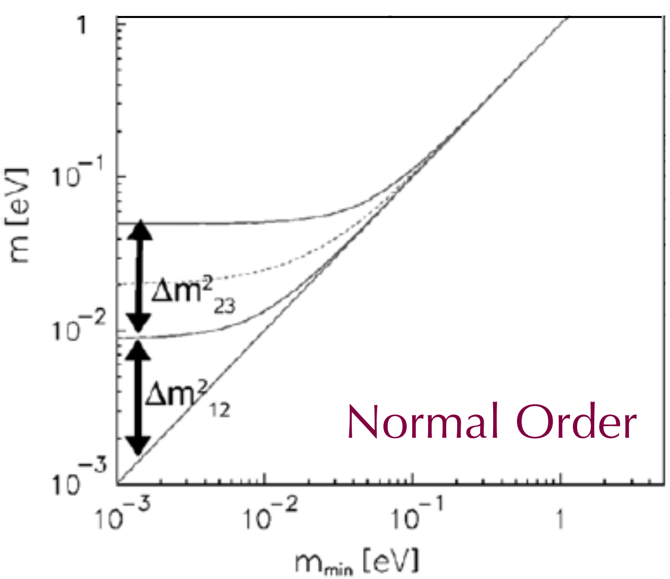
- Radiochemical Solar neutrino gallium experiments, SAGE and GALLEX, used intense sources to check their extraction efficiencies.
- Combine data from GALLEX (2 runs with ^{51}Cr) and SAGE (runs with ^{51}Cr and ^{37}Ar) give a ratio of detected/predicted of 0.85 ± 0.05.
- If neutrino oscillation, deficit consistent with sterile neutrino with $\Delta m^2 \sim eV^2$
- Concerns with correlated errors and systematic uncertainties.

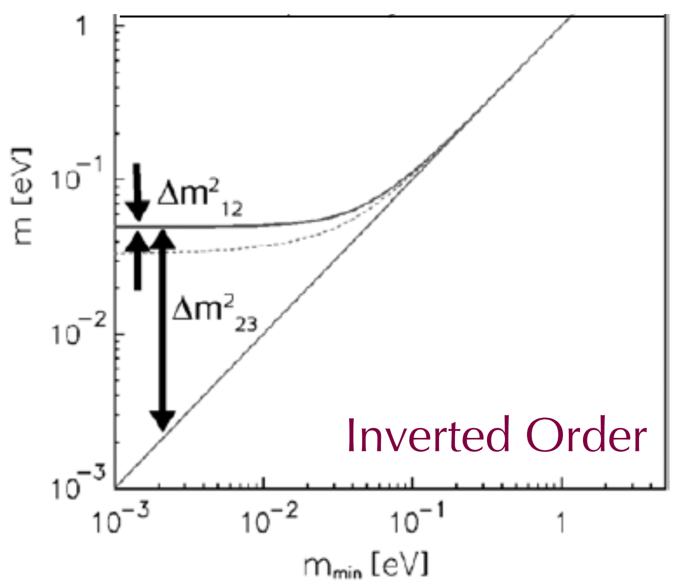


- Planned SOX experiment with ^{144}Ce source canceled.
  (Science 359 (6377), 729 DOI: 10.1126/science.359.6377.729)

Weighing the ν







$0\nu\beta\beta$ decay and Lepton Number Violation

(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale ($\Lambda \gg$ TeV)

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

- LNV dynamics at lower scale ($\Lambda \sim$ TeV)

$$\frac{1}{\Lambda^5}\,\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

- LNV dynamics at very low energy (e.g. low-scale seesaw)

$$-\frac{1}{2}M_R\,\overline{\nu_R^c}\nu_R \;+\; Y_\nu\,\bar{\ell}\nu_R\,H$$

Affects $0\nu\beta\beta$ in significant ways, depending on mass scale M_R: eV $\rightarrow$ 100 GeV

NSAC 2015 Long Range Plan

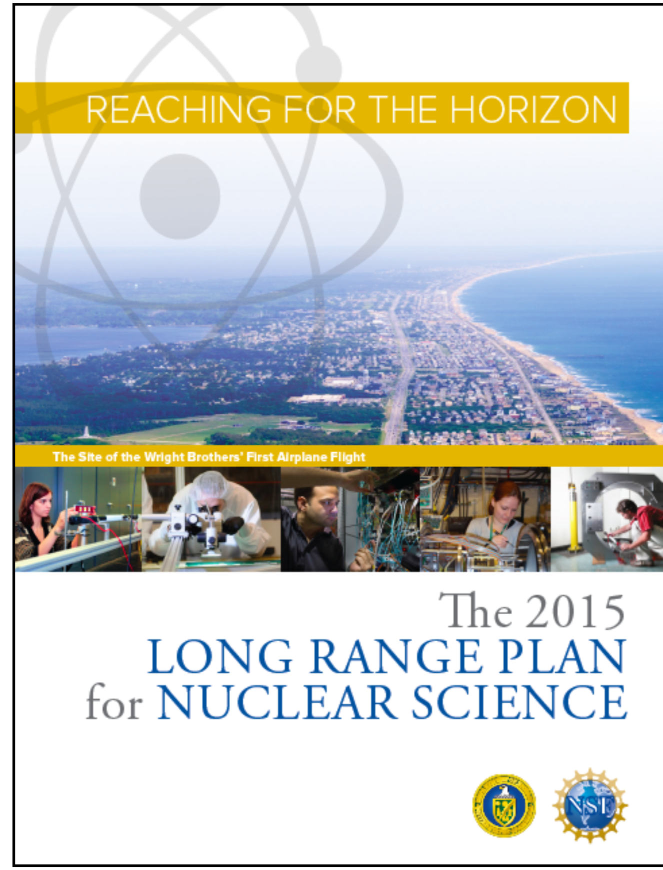
RECOMMENDATION II

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.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

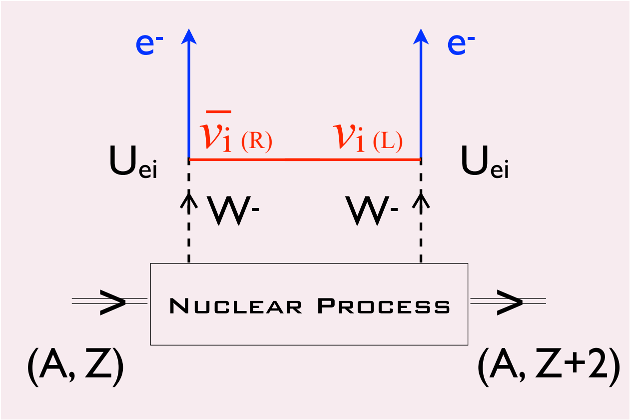
A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.



0νββ and ν mass

Observable (decay rate) depends on nuclear processes & nature of lepton number violating interactions (η).



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}(\eta)\right|^2 \eta^2$$

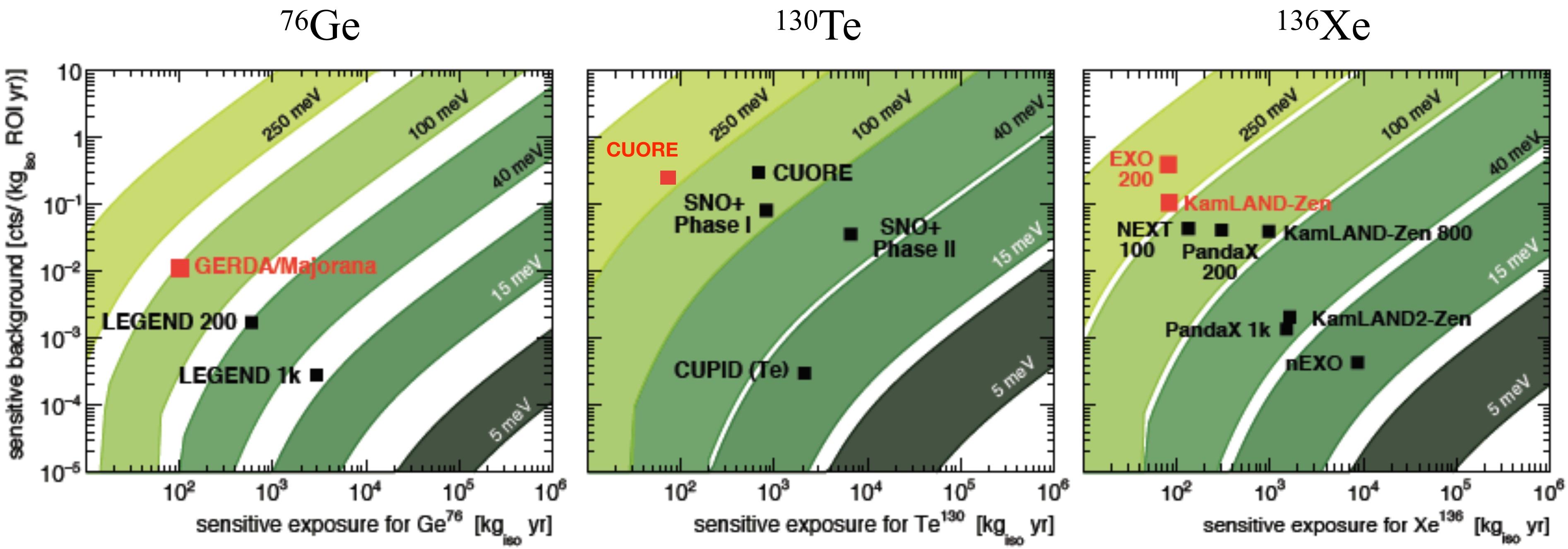
$$\Downarrow$$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

- Phase space, $G_{0\nu}$ is calculable.
- Nuclear matrix elements (NME) via theory.
- Effective neutrino mass, $\langle m_{\beta\beta}\rangle$, depends directly on the assumed form of lepton number violating (LNV) interactions.

Discovery Sensitivity Comparison

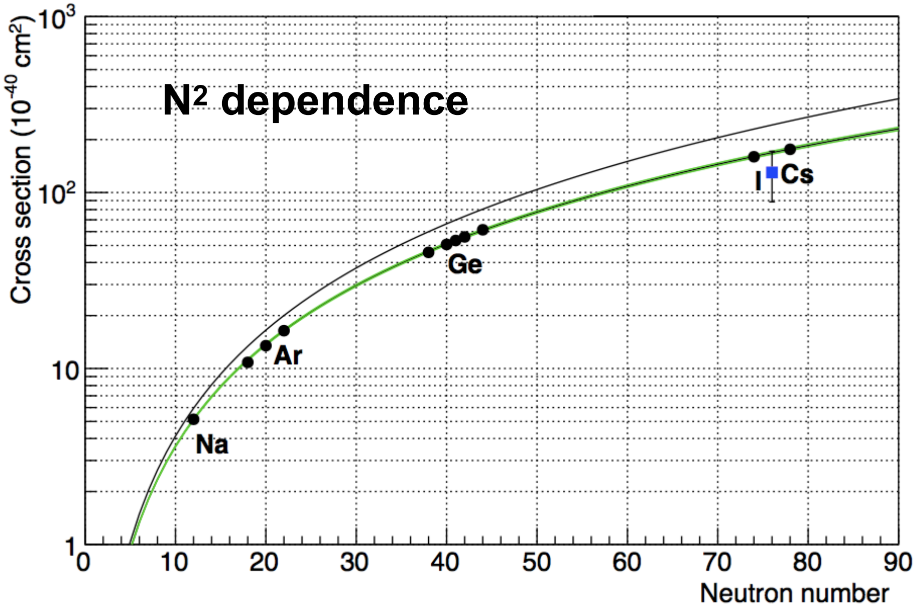
Discovery probability of next-generation neutrinoless double-beta decay experiments
Matteo Agostini, Giovanni Benato, and Jason Detwiler arXiv:1705.02996v1

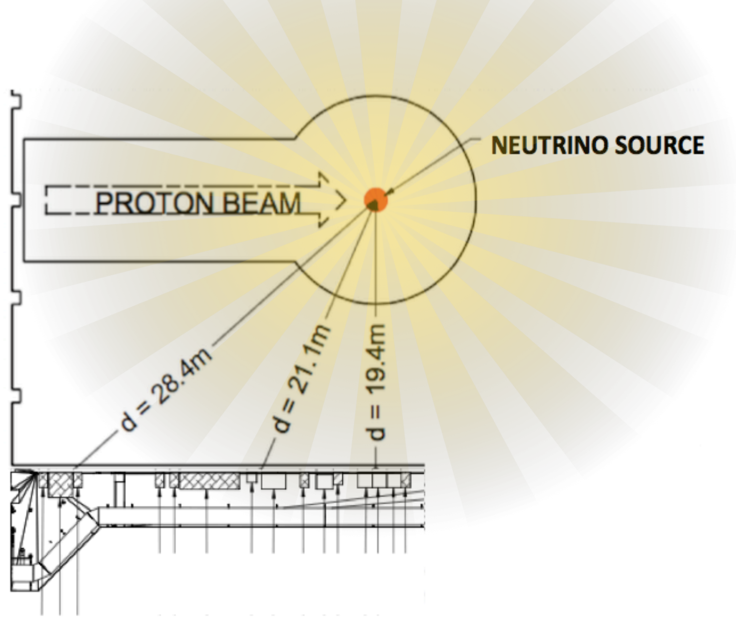


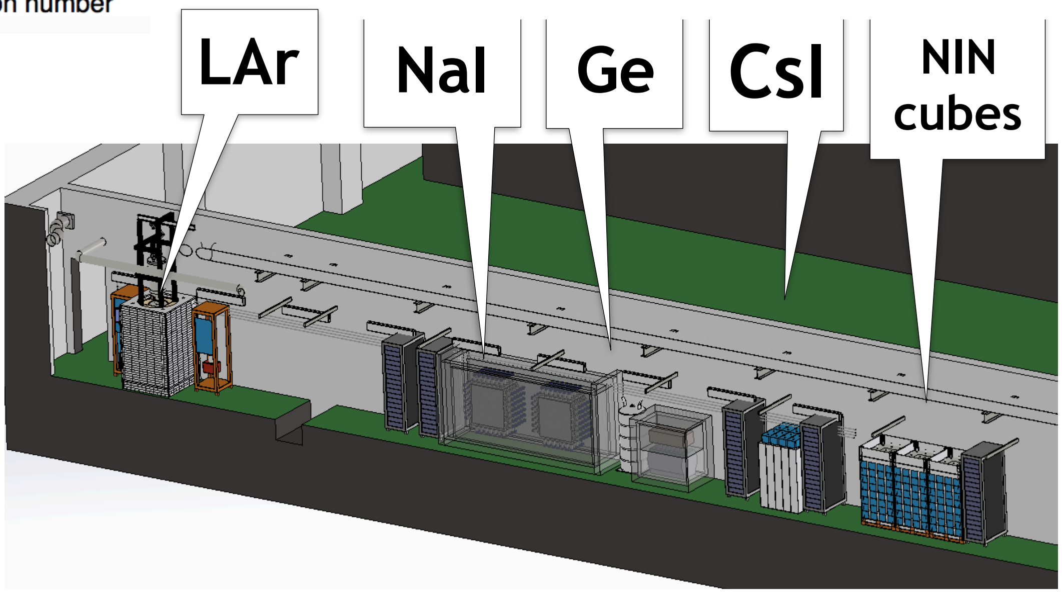
Red : Achieved Backgrounds; Black : Projected Backgrounds

Width of bands based on range of NME values

Comprehensive CEνNS Program







Located in SNS basement (measured neutron backgrounds low, ~ 8 mwe overburden)

Backgrounds resolution, discovery

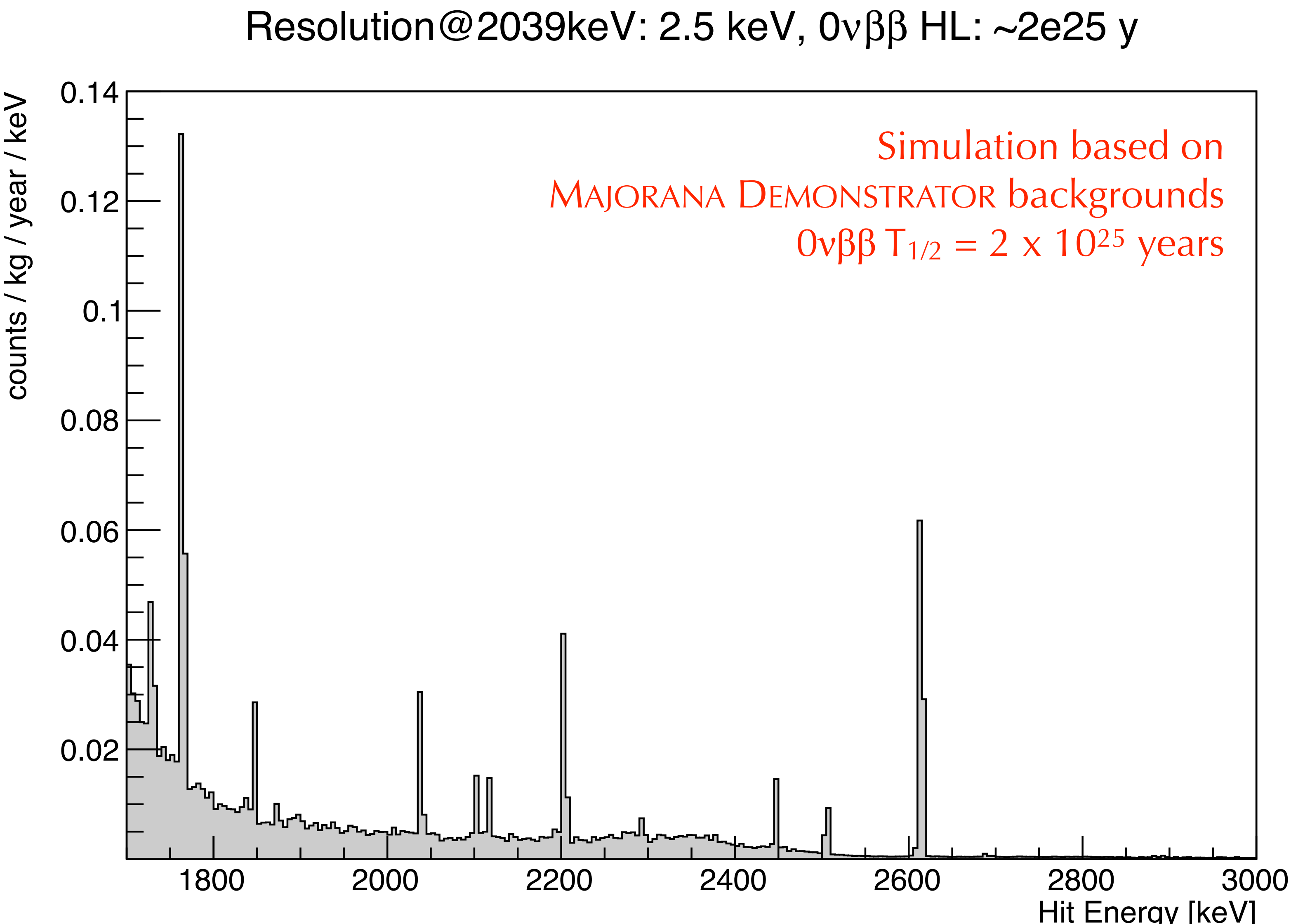
Experiment	Background (counts/FWHM t y)	Width (1 FWHM)
CUORE	108	8 keV
GERDA-II	2.9	2.9 keV
MAJORANA DEM.	4.0	2.5 keV
EXO-200	111	71 keV
KamLAND-Zen	~3.5(~120 per t(Xe))	272 keV

S. Elliott

Background is per tonne of material, not isotope
– an important distinction for KamLAND-Zen.

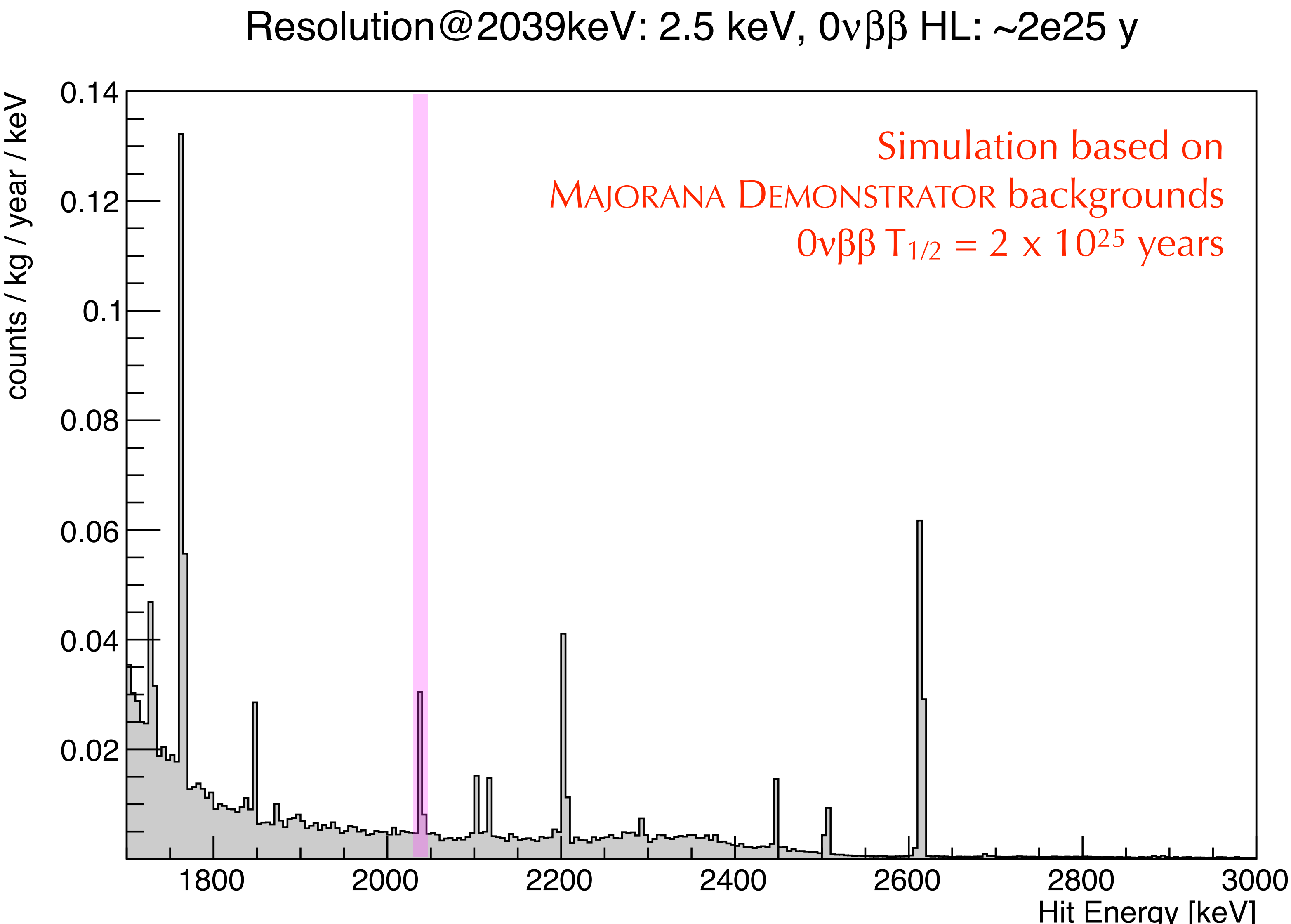
Requirement for a ton scale experiment is ~ 0.1 or less.

Backgrounds, resolution, discovery



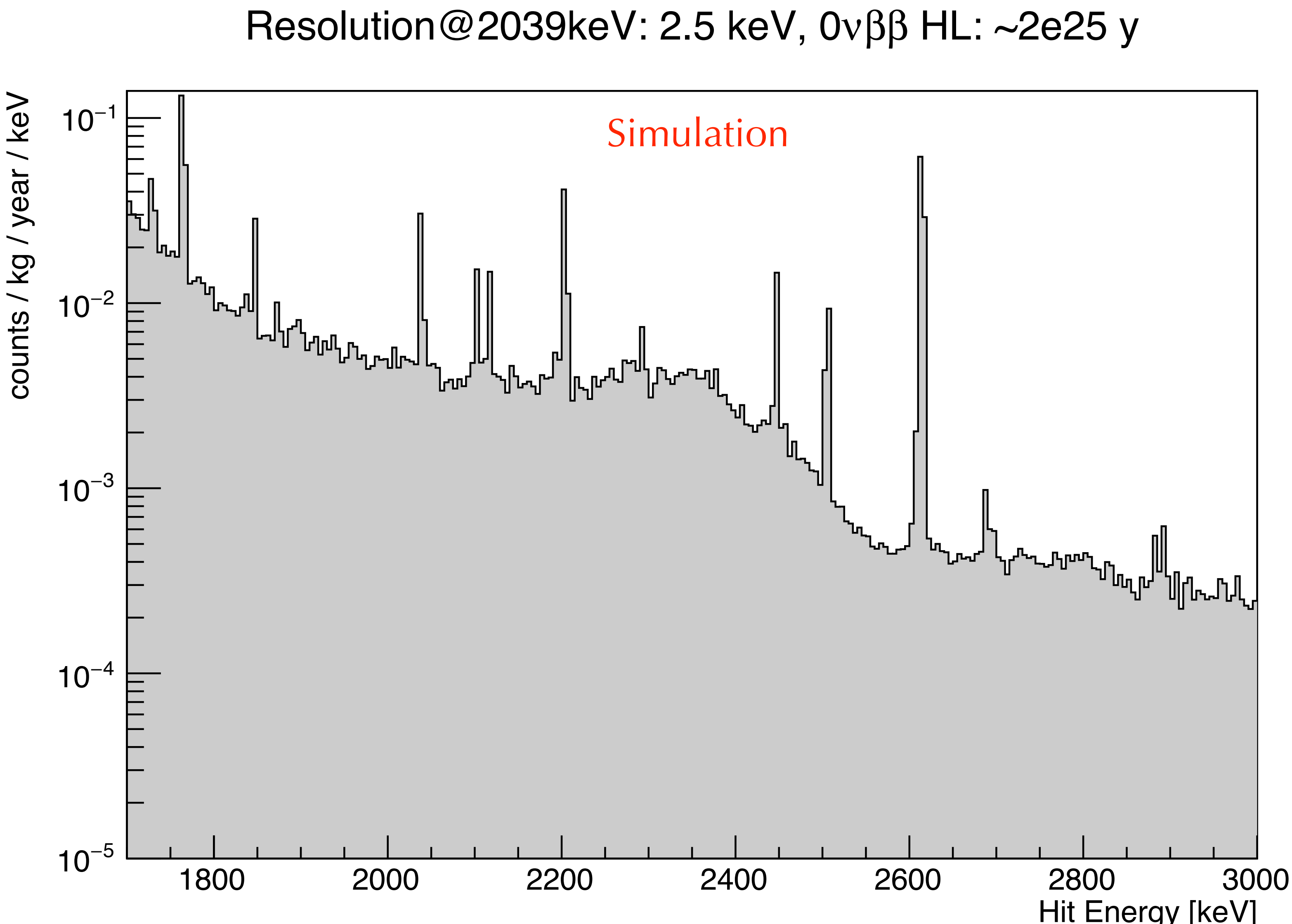
M. Buuck

Backgrounds, resolution, discovery



M. Buuck

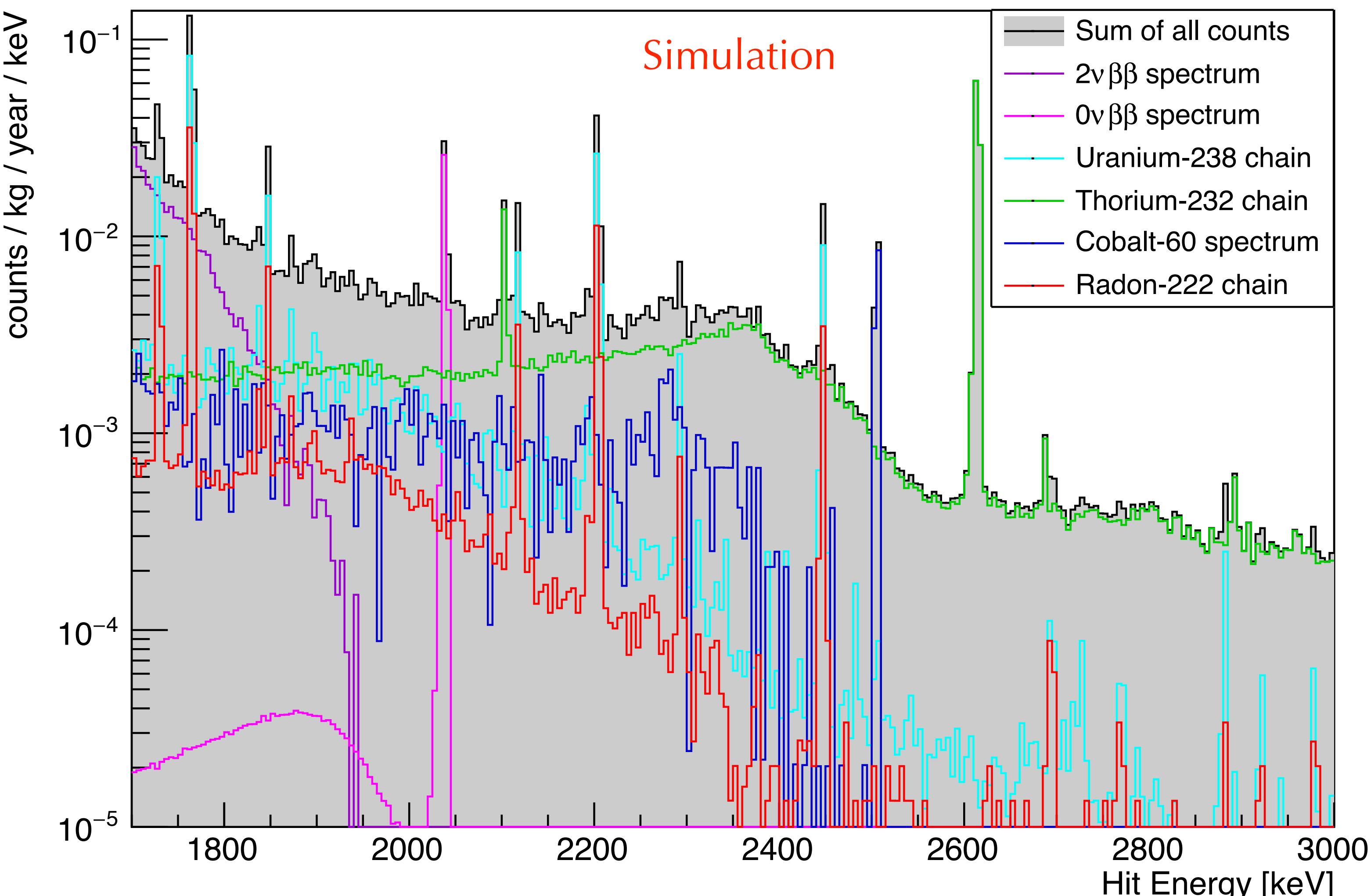
Backgrounds, resolution, discovery



M. Buuck

Backgrounds, resolution, discovery

Resolution@2039keV: 2.5 keV, 0νββ HL: ~2e25 y



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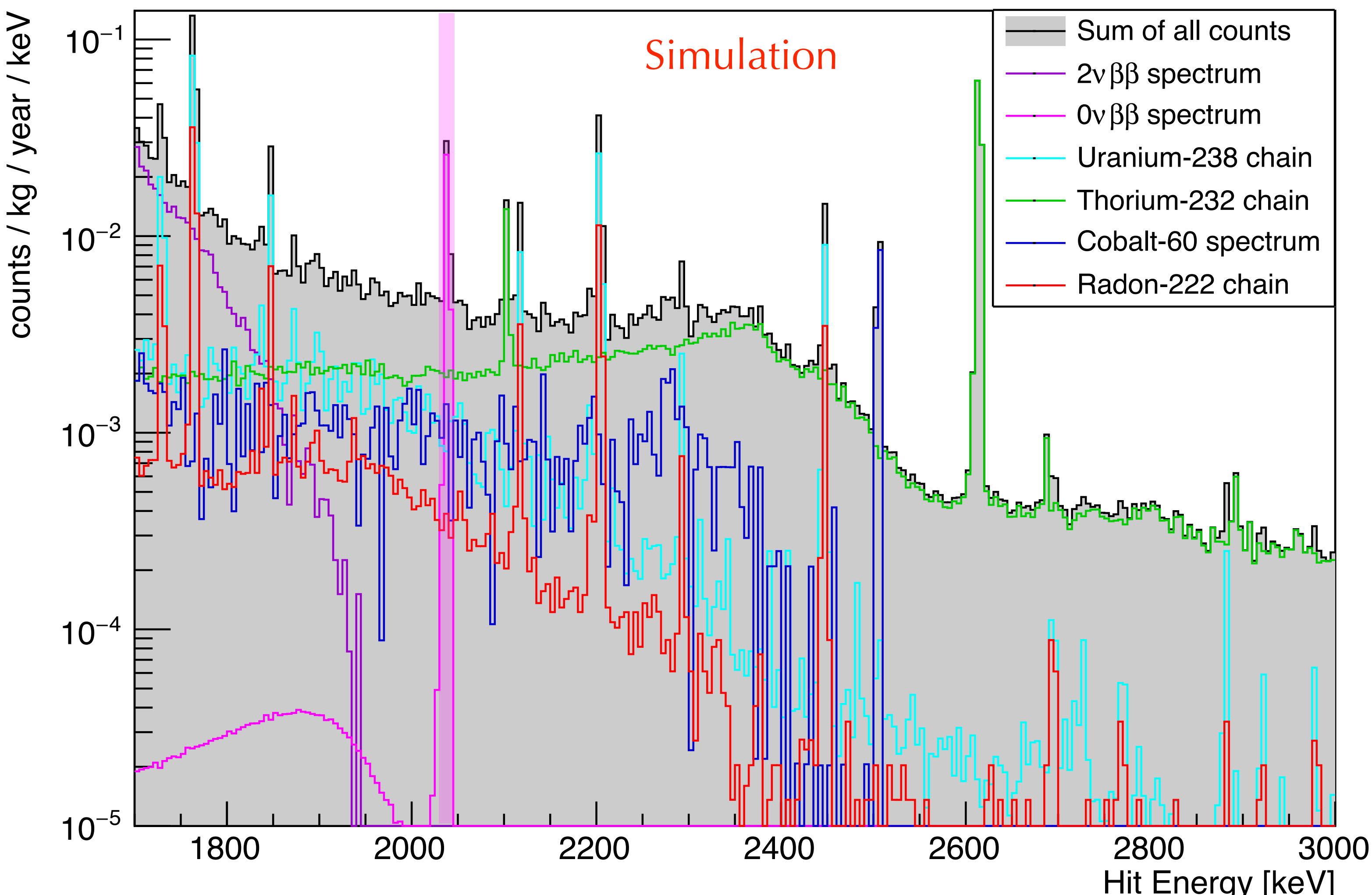
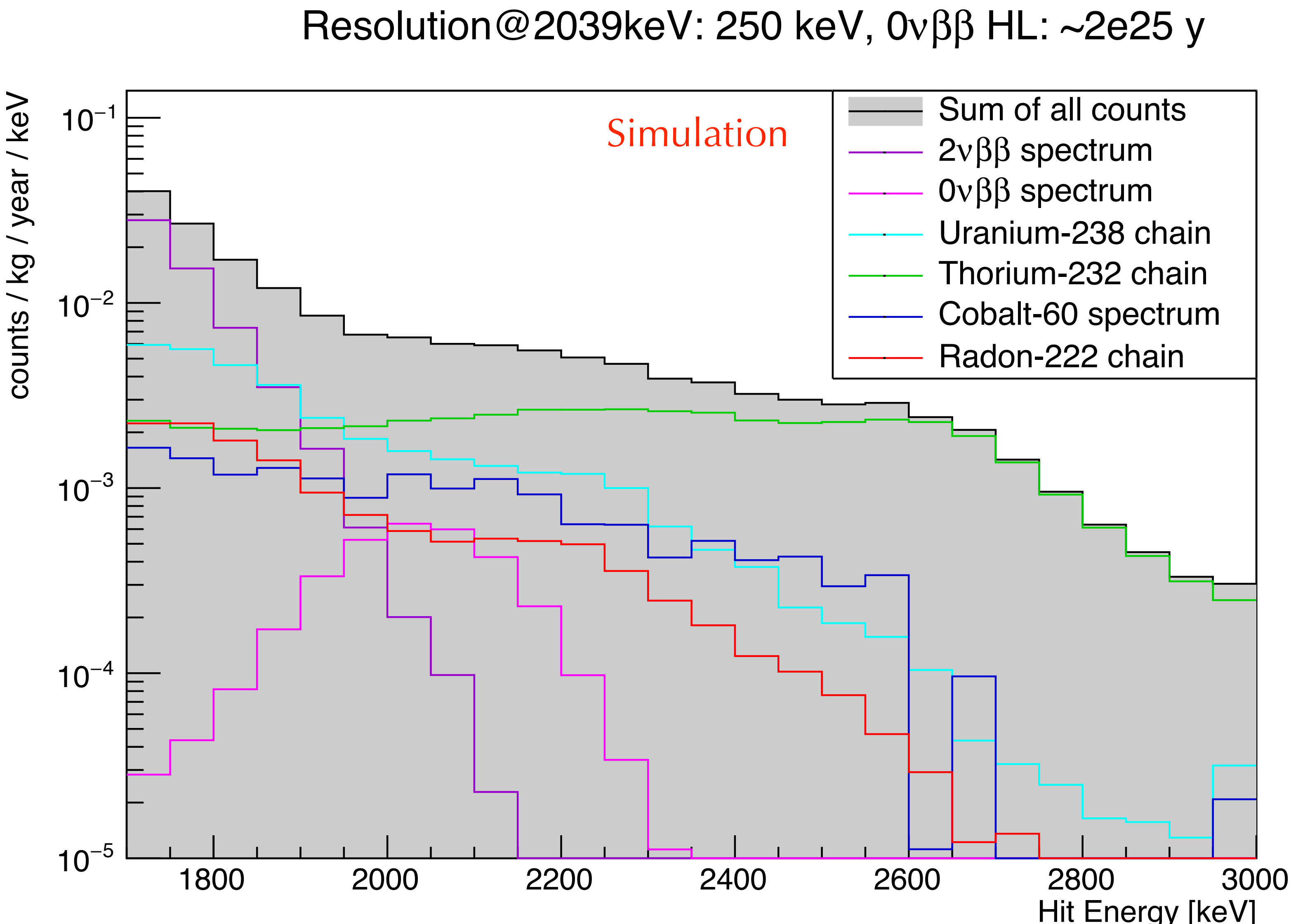
Backgrounds, resolution, discovery

Resolution@2039keV: 2.5 keV, 0νββ HL: ~2e25 y



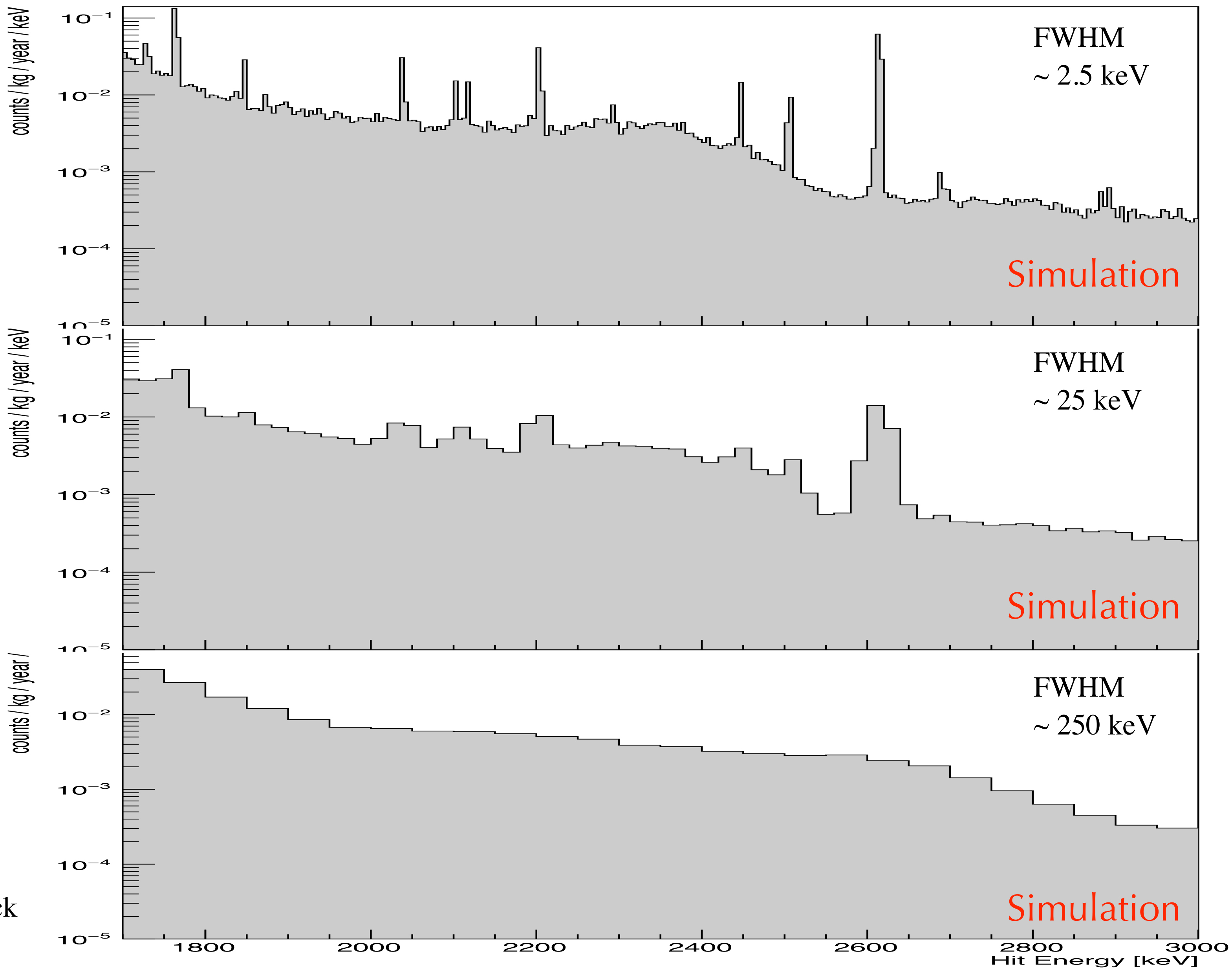
M. Buuck

Backgrounds, resolution, discovery



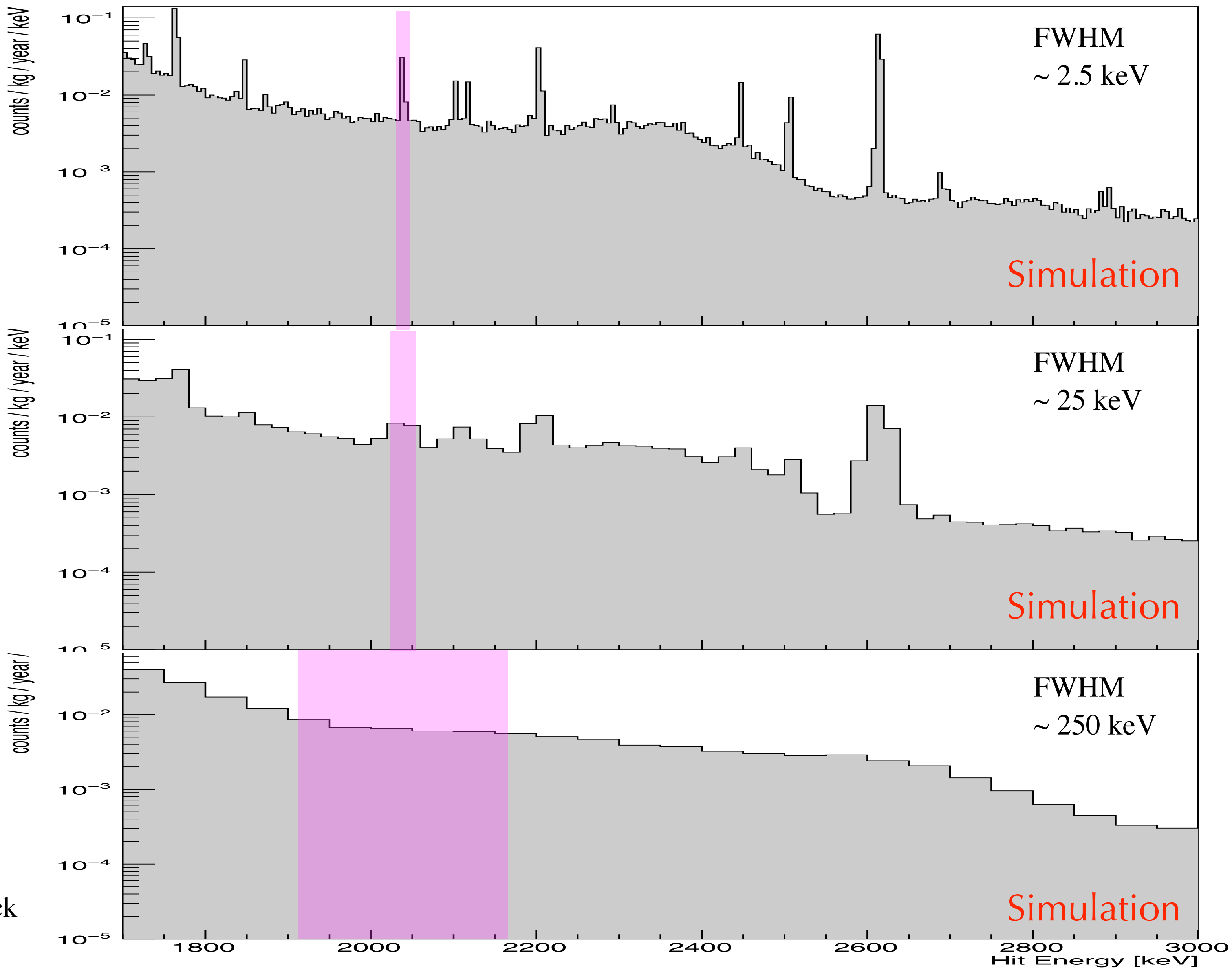
M. Buuck

Backgrounds, resolution, discovery



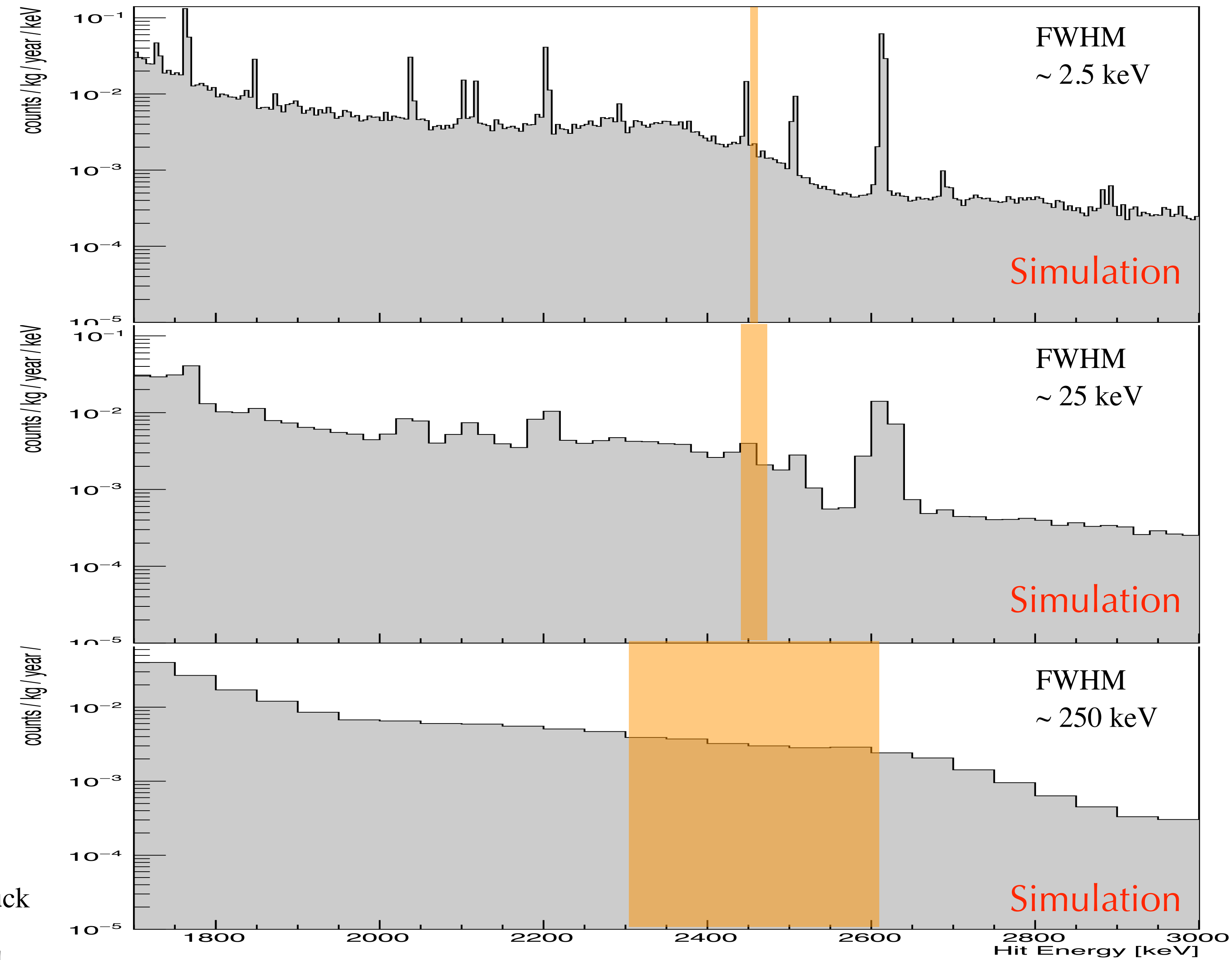
M. Buuck

Backgrounds, resolution, discovery



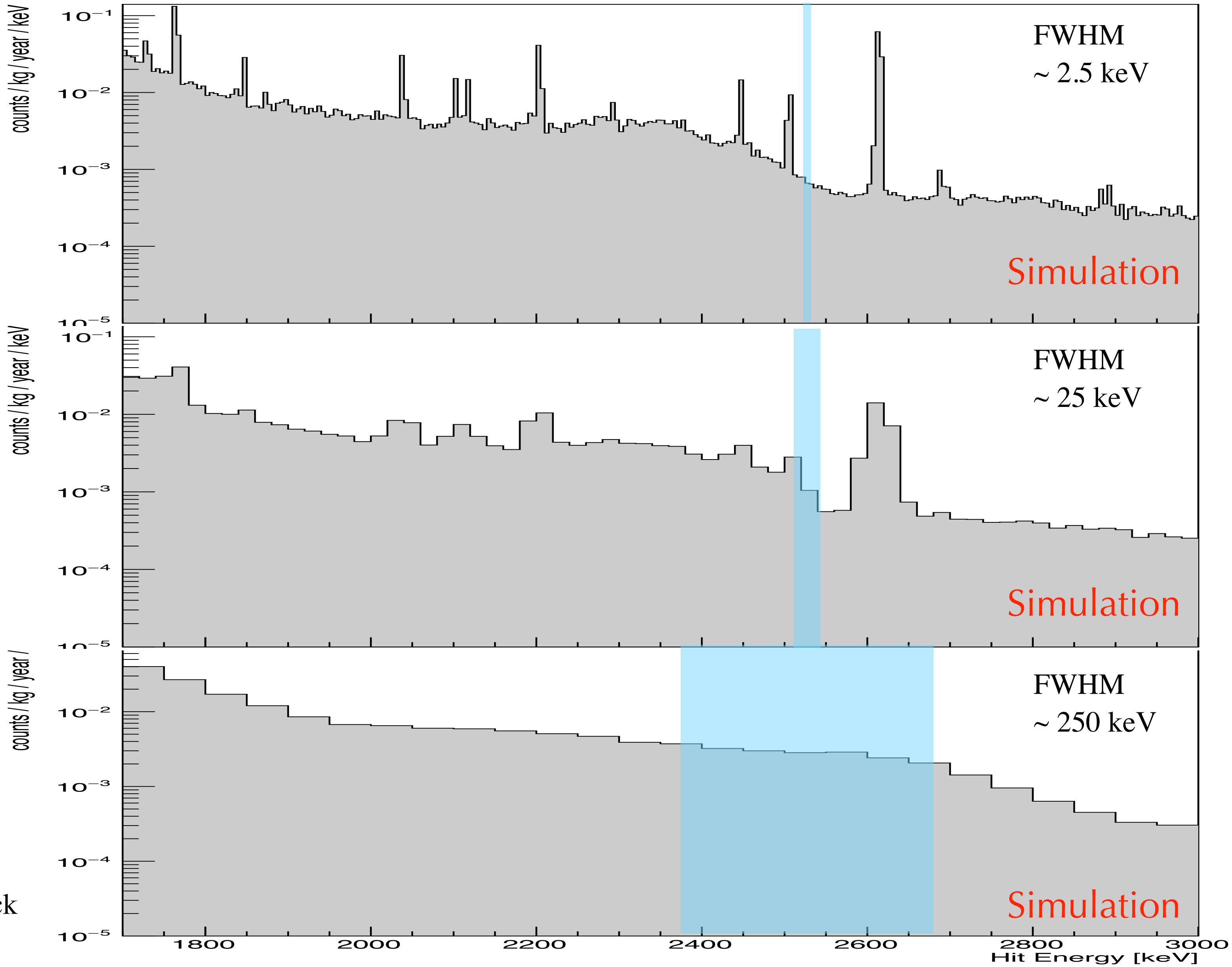
M. Buuck

Backgrounds, resolution, discovery



M. Buuck

Backgrounds, resolution, discovery



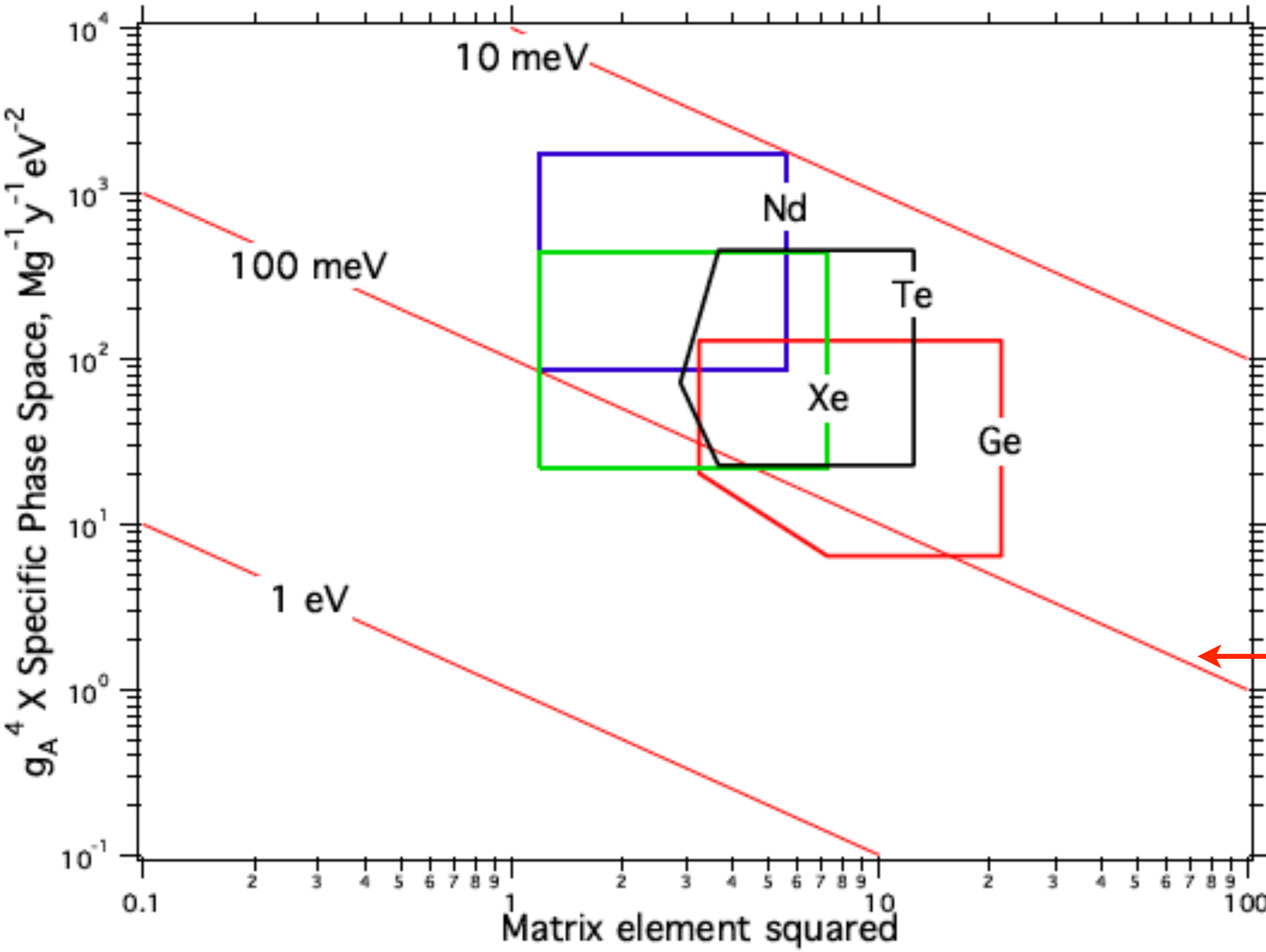
M. Buuck

Sensitivity to <$m_{\beta\beta}$> per unit mass

For Ge, Te, Xe, Nd

uncertainty on NME^2

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

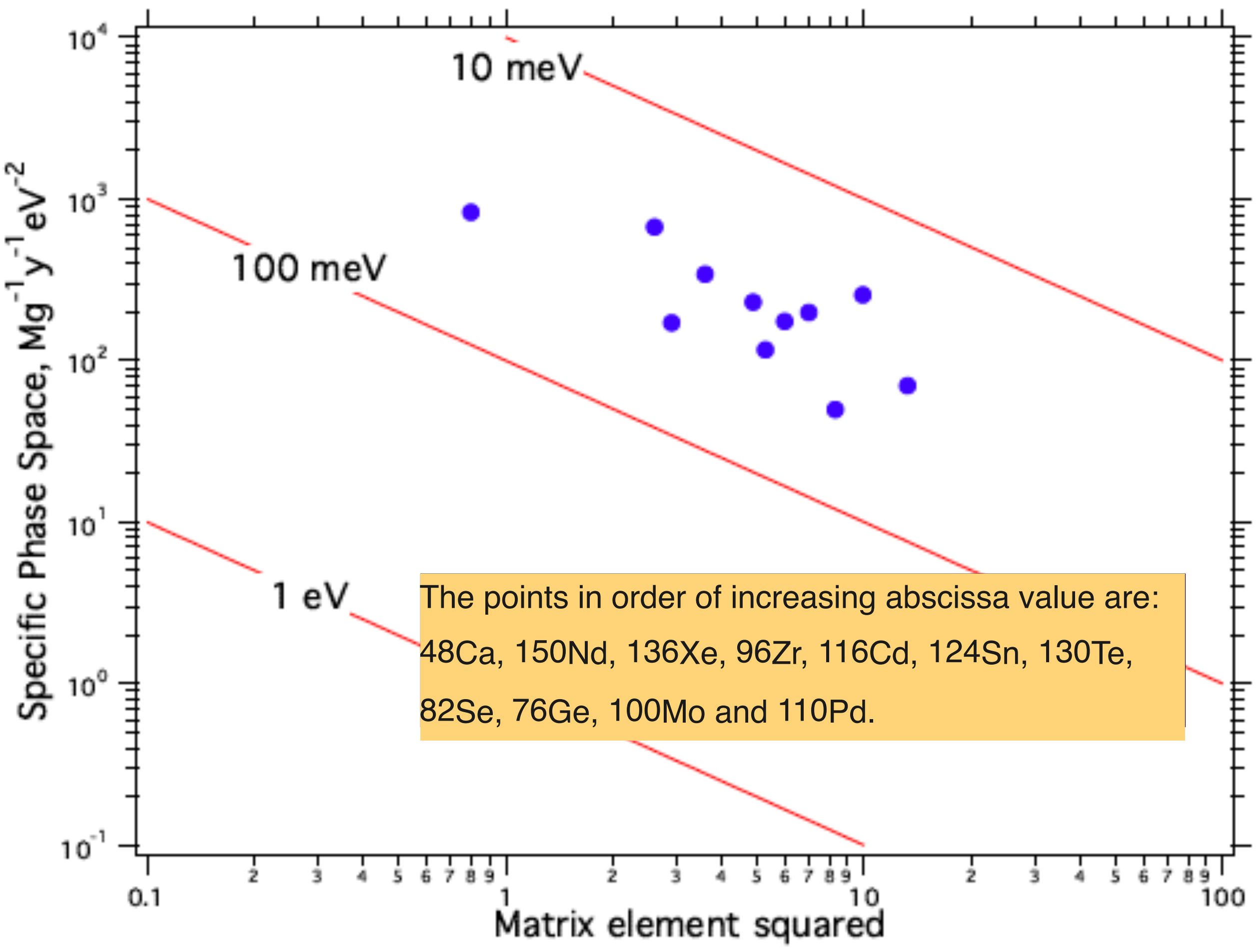


uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

Sensitivity per unit mass of isotope

➡ Isotopes have comparable sensitivities in terms of rate per unit mass



R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Inverse correlation observed between phase space and the square of the nuclear matrix element .

geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

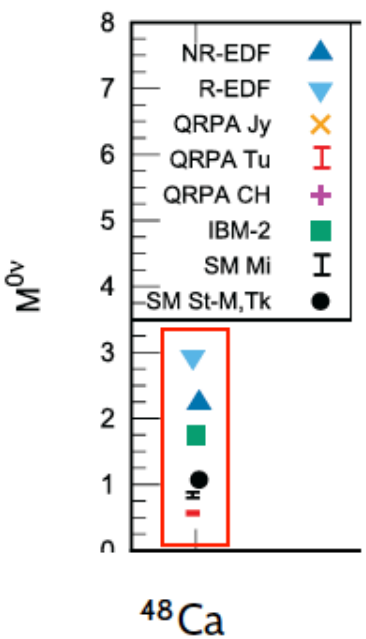
Progress with 0νββ Theory

Topical Nuclear Theory Collaboration for Double-Beta Decay and Fundamental Symmetries

Goals are calculated nuclear matrix elements that:

1. Are more accurate.
2. Carry a quantified uncertainty.

Goal 1 involves the development and application of powerful many-body techniques, e.g. the Coupled-Clusters Method, and the In-Medium Similarity Renormalization Group.



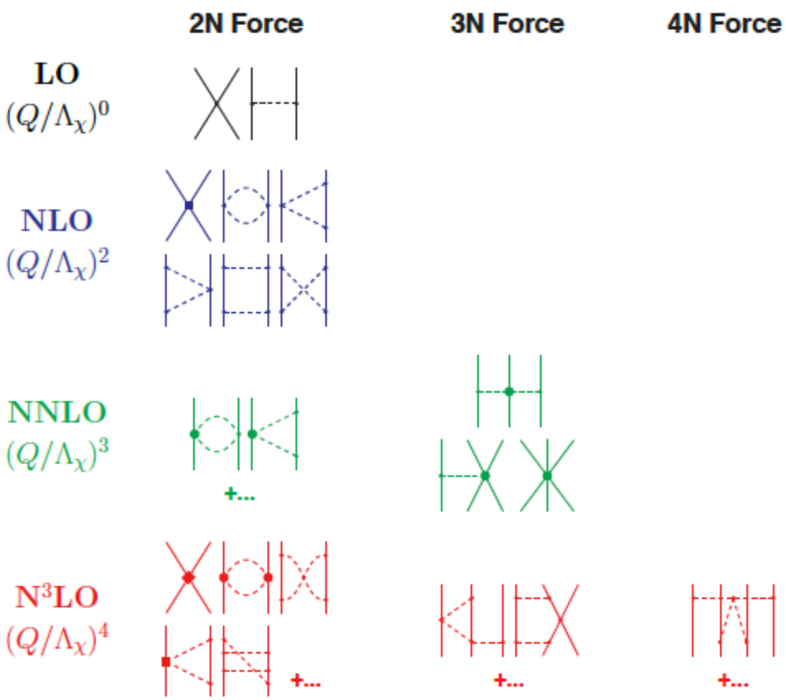
Red bar at bottom is coupled cluster calculation (Hagen et al).

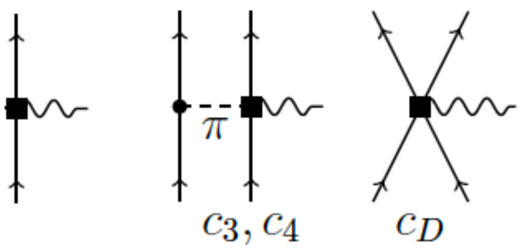
(We don't believe the small value is generic).

^{76}Ge in progress, ^{136}Xe in next couple of years.

Progress with 0νββ Theory

Goal 2 requires a first-principles framework of interactions and currents: Chiral Effective Field Theory.





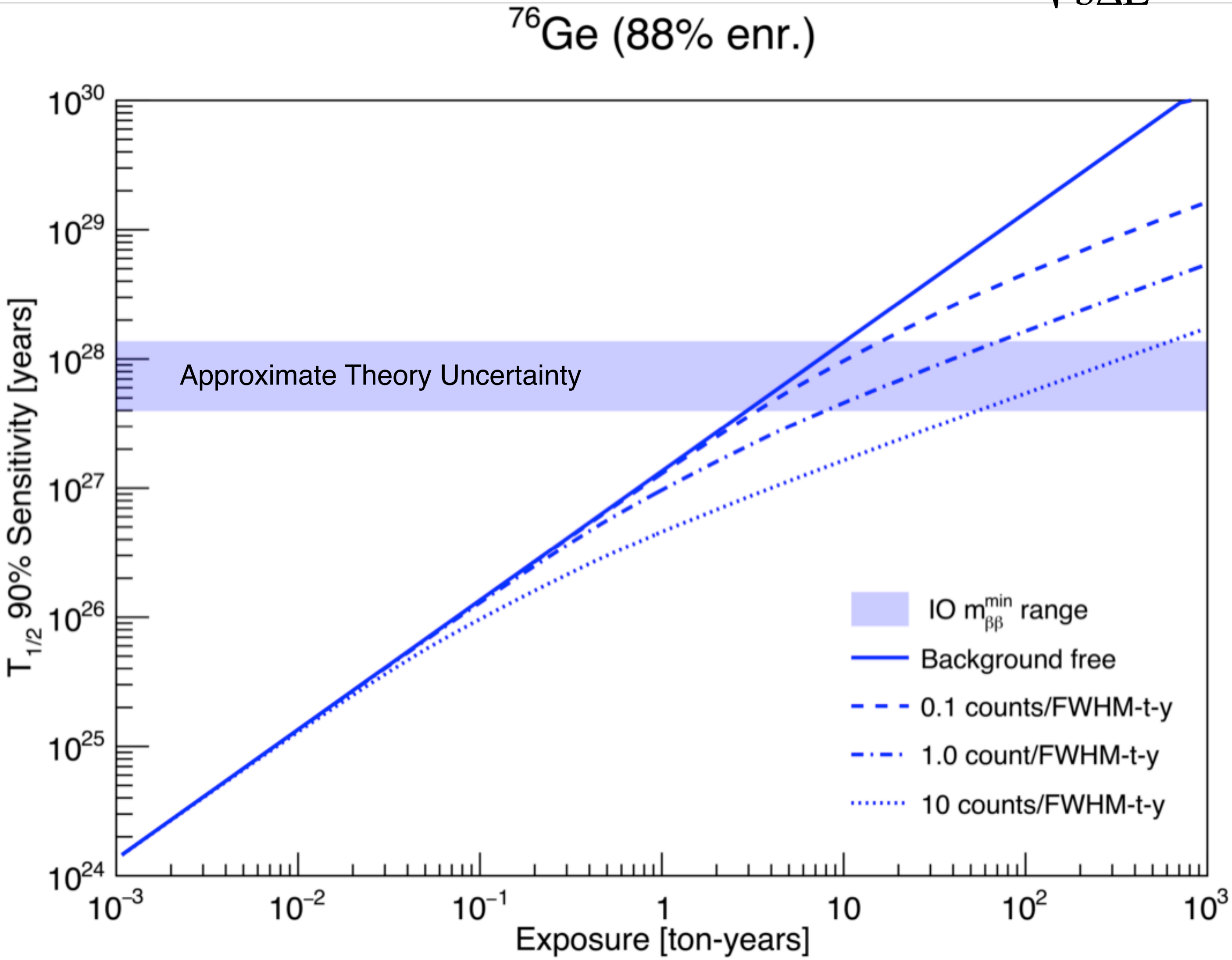
Comes with consistent weak current.

Cirigliano et al. recently found that we need new short-range operator, even when underlying mechanism is light-ν exchange. May increase uncertainty.

Along the way, have explained most of quenching in β decay, are currently exploring effects on ββ decay.

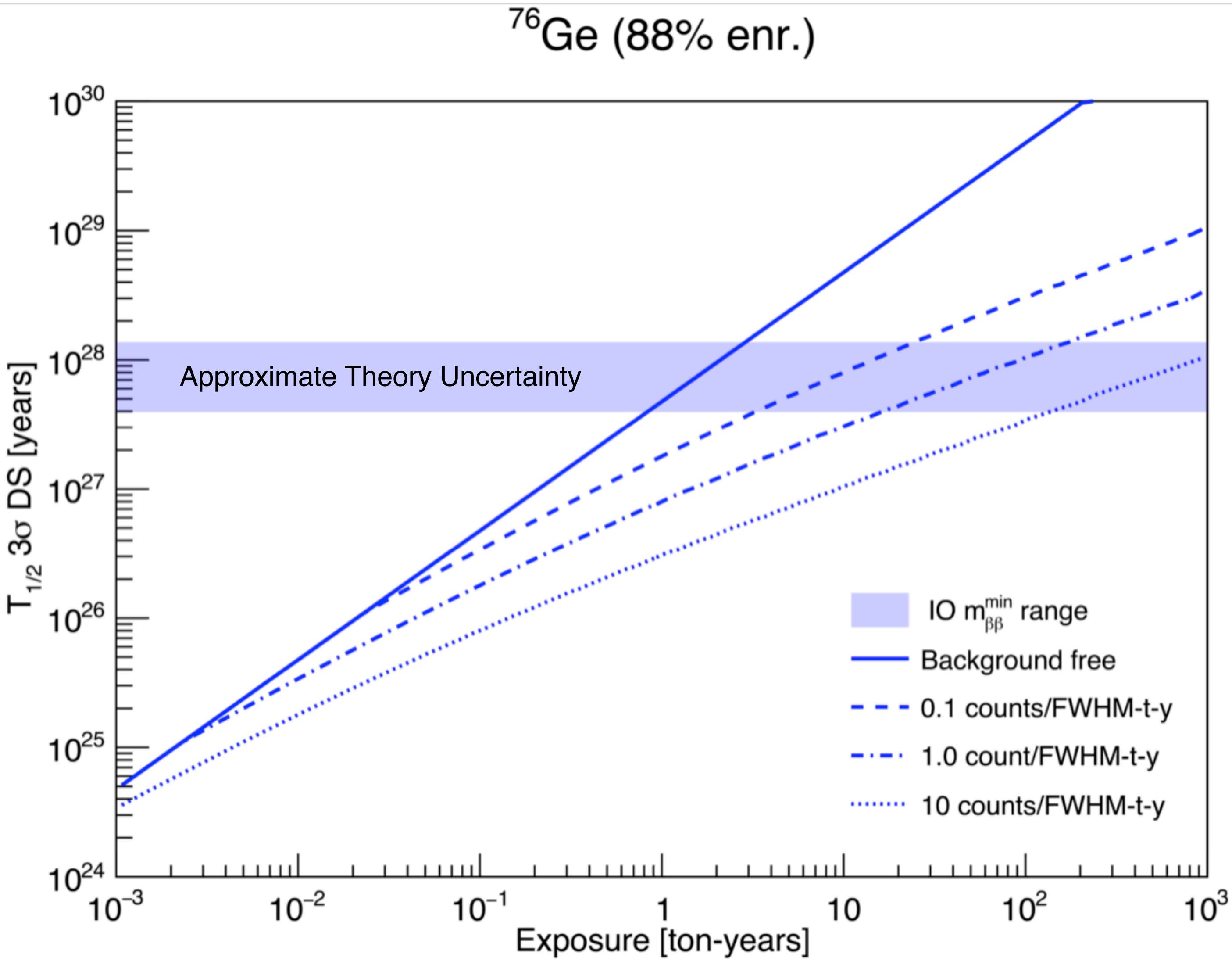
Sensitivity vs. Exposure

$$T^{0\nu}_{1/2}(\text{background free}) \propto \text{MT} \qquad T^{0\nu}_{1/2}(\text{backgrounds}) \propto \sqrt{\frac{\text{MT}}{\text{b}\Delta\text{E}}}$$



J. Detwiler

3σ Discovery vs. Exposure



J. Detwiler

Potential contributions to the background

- Primordial, natural radioactivity in the detector and array components: U, Th, K
- Backgrounds from cosmogenic activation while material is above ground (ββ-isotope or shield specific, ^{60}Co, ^{3}H, ^{39}Ar, ^{42}Ar, …)
- Backgrounds from the surrounding environment:
  external γ, (α,n), (n,α), Rn plate-out, etc.
- μ-induced backgrounds generated at depth:
  Cu, Pb(n,n' γ), ββ-decay specific(n,n),(n,γ), direct μ
- 2 neutrino double beta decay (for 1000 kg, impact depends on resolution)
- neutrino backgrounds (for 1000 kg, can be a contribution)

Reducing Backgrounds - Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non “source” materials
  - Clean (low-activity) shielding
  - Fabricate ultra-clean materials (underground fab in some cases)
  - Go deep — reduced μ’s & related induced activities
- Utilize background measurement & discrimination techniques

$0\nu\beta\beta$ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions

- Energy resolution
- Active veto detector
- Tracking (topology)
- Particle ID, angular, spatial, & time correlations
- Fiducial self-consistent fits
- Single site / multi site fitting
- Granularity [multiple detectors]
- Pulse shape discrimination (PSD)
- Ion Identification

GERDA & MAJORANA ^{76}Ge

Ionization

MAJORANA DEMONSTRATOR

Vacuum cryostats in a passive graded shield with ultra-clean materials

- Module 1 (June 2015 - ongoing)
- Module 2 (August 2015 - ongoing)
- 29.7 kg of 88% enriched ^{76}Ge crystals
  - 35 PPC detectors
  - + 23 ^{nat}Ge BEGe detectors (14.4 kg)
- 2.5 keV FWHM @ 2039 keV
- BG goal: 1 cts/(keV t yr):

GERDA

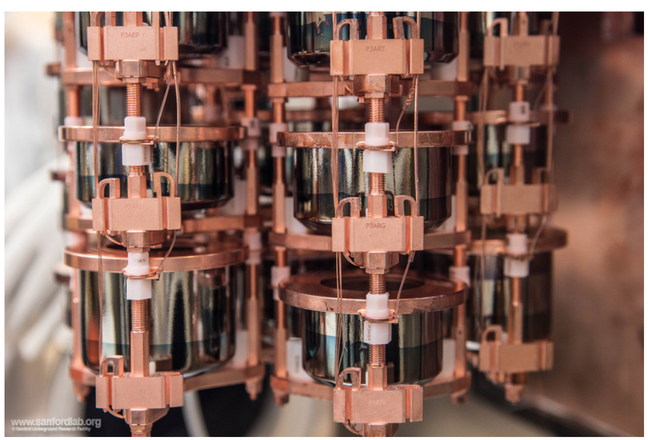
Direct immersion in active LAr shield

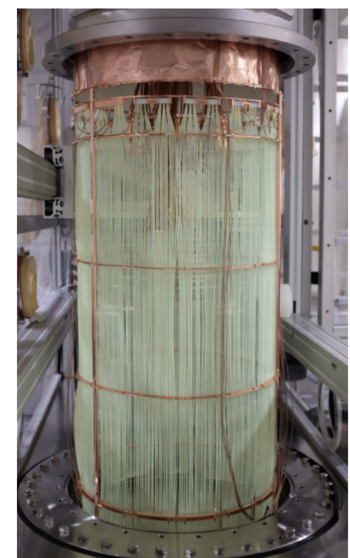
- Phase I (Nov 2011- May 2013)
- Phase II (Dec 2015- ongoing):
- 35.6 kg of 87% enriched ^{76}Ge crystals
  - 30 BEGe detectors (20.0 kg)
  - 7 coaxial HdM and IGEX (18 kg)
- 2.9 keV FWHM @ 2039 keV
- BG goal: 1 cts / (keV t yr)

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Target of 100 kg yr



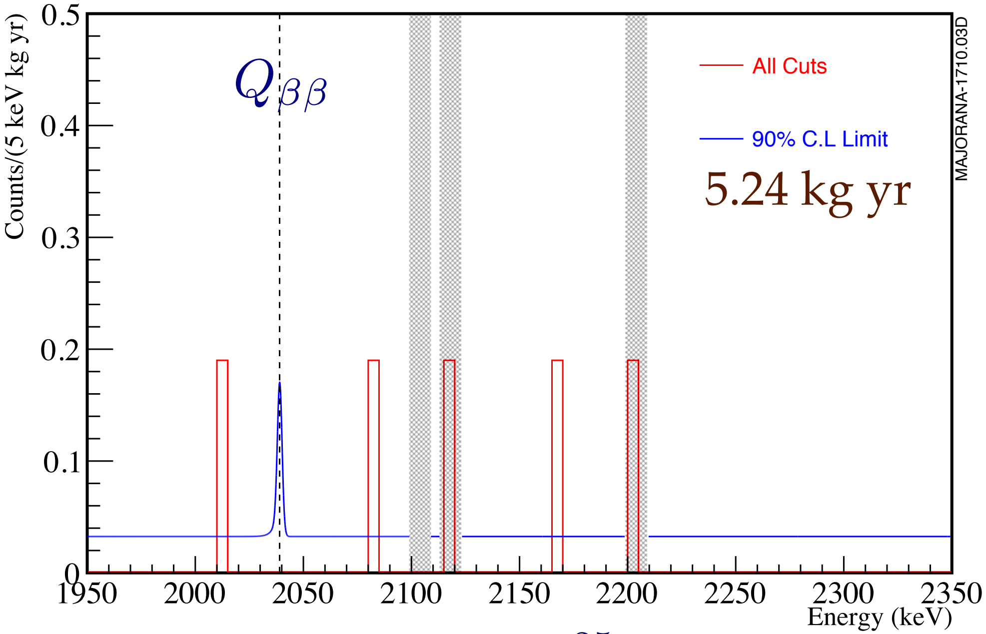


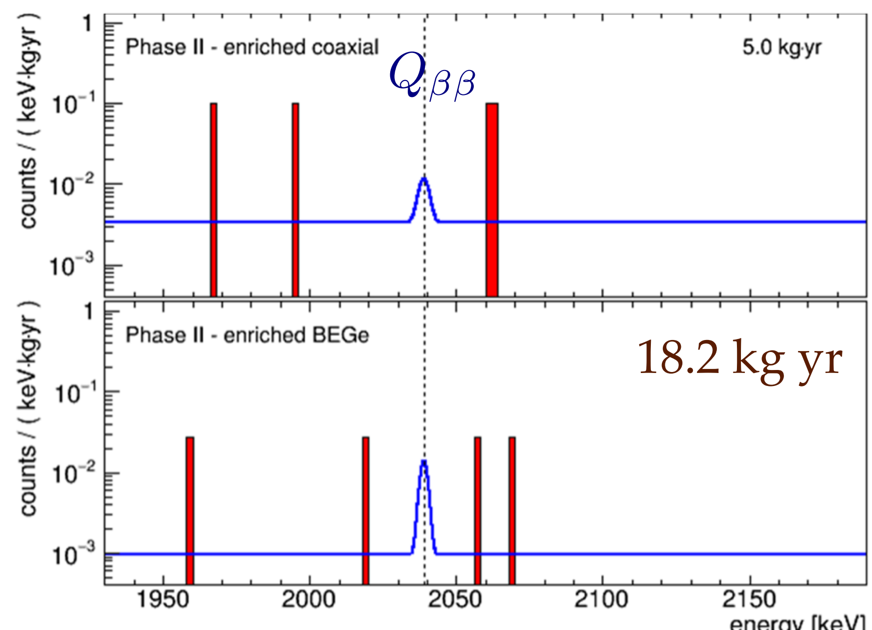
GERDA & MAJORANA ^{76}Ge

Ionization

Both experiments are presently operating in a “background free” regime and benefiting from excellent energy resolution: Best $Q_{\beta\beta}$ fractional resolution and lowest background in the region of interest with respect to other isotopes

MAJORANA DEMONSTRATOR		GERDA
$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)	Full Exposure Limits	$T^{0\nu}_{1/2} > 8.0 \times 10^{25}$ yr (90% CL)
9.95 kg yr — PRL **120** 132502 (2018)		PRL **120** 132503 (2018) — 46.7 kg yr
$1.6^{+1.2}_{-1.0}$ cts/(keV t yr)	Low BG Operation	$1.0^{+0.6}_{-0.4}$ cts/(keV t yr)





2.1×10^{25} yr	Median Sensitivities	5.8×10^{25} yr

LEGEND ^{76}Ge

Ionization

Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay

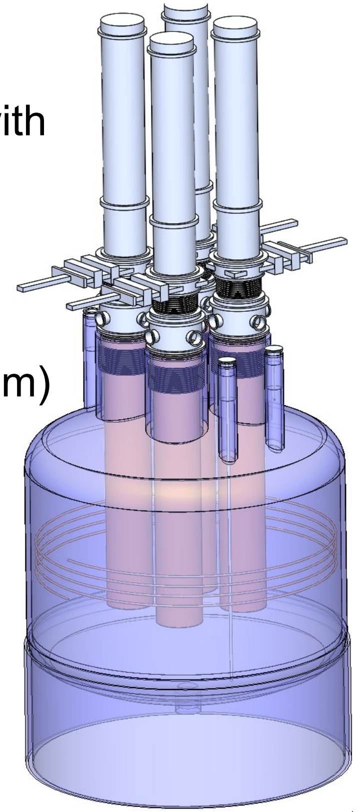
LEGEND mission: "The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results."

First Stage:

- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal
  0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use existing MAJORANA & GERDA detectors
- Proposal submitted to LNGS in March 2018
- Have funding for 130 of the 200 kg in place.

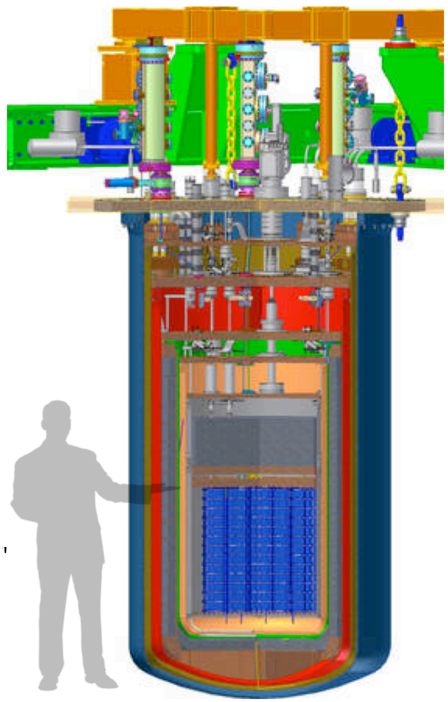
Subsequent Stages:

- 1000 kg ^{76}Ge (staged)
- Timeline coordinated with First Stage
- BG goal
  0.1 cts/(FWHM t yr)
- Location tbd
- Required depth (Ge-77m) under investigation

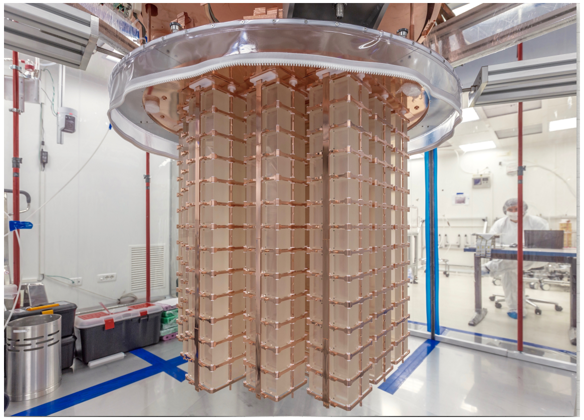


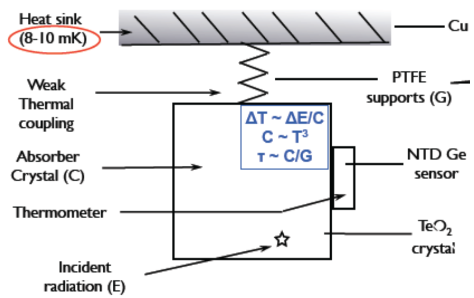
CUORE ^{130}Te

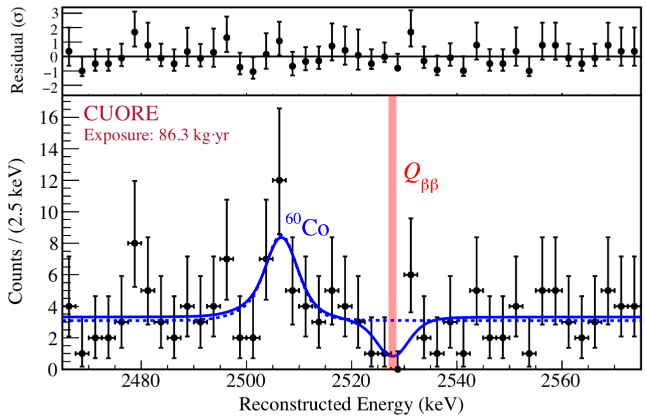
Phonons



- First ton-scale bolometric detector: 988 TeO_2 detectors operating at ~10 mK temperature
  - 742 kg of TeO_2 → 206 kg of ^{130}Te
- Excellent cryogenic performance
- Energy resolution 7.7 keV with improvements underway
- Background in ROI (0.014±0.002) counts/(kg*keV*year), consistent with design goal of 0.01 counts/(kg*keV*year)
- First results after 2 months of data taking in 2017:
  - $T_{1/2}^{0\nu\beta\beta}(^{130}Te) > 1.5\times10^{25}$ years (with CUORE-0/Cuoricino)
  - $m_{\beta\beta}$<110-520 meV [PRL **120**, 132501 (2018)]
  - 5-year sensitivity: $T_{1/2} > 9\times10^{25}$ years; $m_{\beta\beta}$<140-400 meV





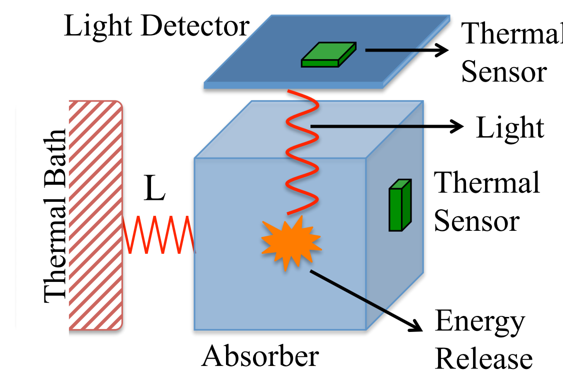


CUORE Upgrade with Particle ID (CUPID)

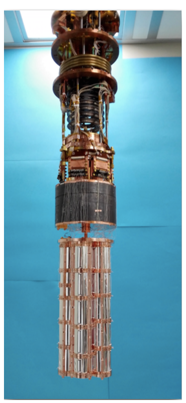
Scintillator - Phonons

- Next-generation bolometric tonne-scale experiment
- CUORE design, proven CUORE cryogenics
- 988 enriched (90%) crystals, α rejection by detecting light (Cherenkov, scintillation)
  - Goal: nearly zero background measurement: background goal < 0.1 events / (ROI ton*year)
  - Sensitivity to the bottom of IH region

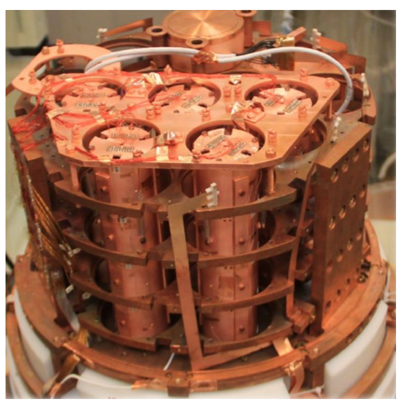
R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
White papers: arXiv:1504.03599 & arXiv:1504.03612



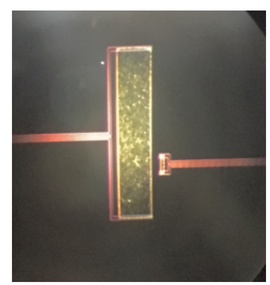
Worldwide R&D, pilot experiments to demonstrate readiness to construct a tonne-scale experiment



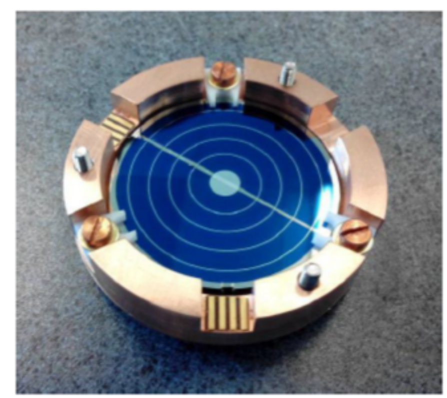
CUPID-0/Se at LNGS
$Zn^{82}Se$ crystals



CUPID-Mo at Modane
$Li_2{}^{100}MoO_4$ crystals



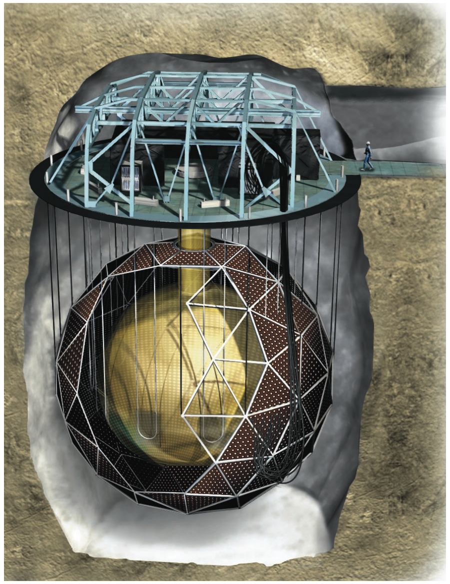
Luke-Neganov and TES-based Cherenkov light detectors for TeO_2

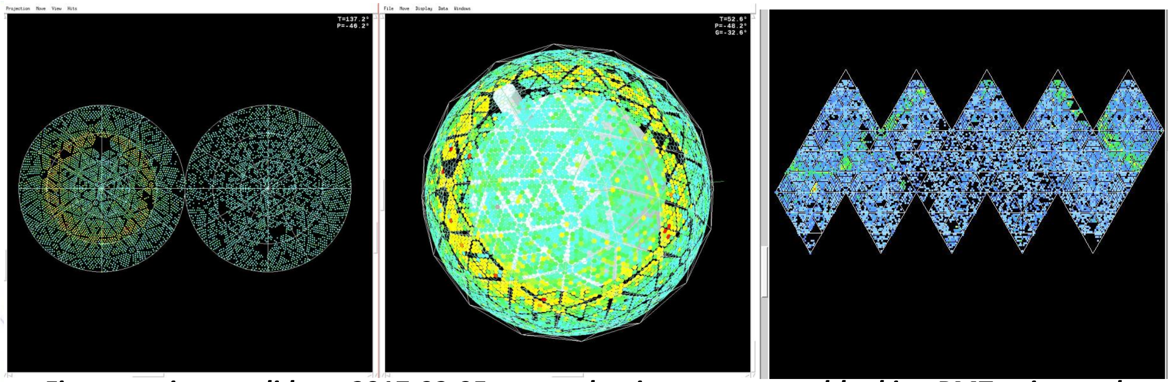


SNO+ ^{130}Te (Phase I)

Scintillation

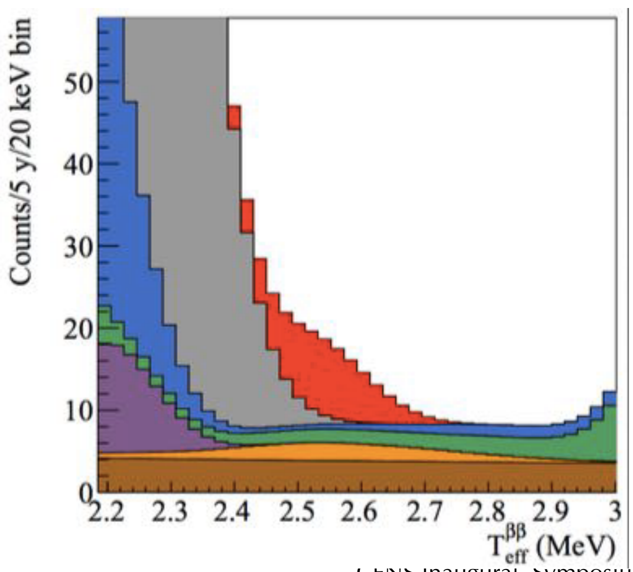
- Phase-I: 3.9 t Te @0.5% loading in liquid scintillator → 1300 kg ^{130}Te (20% FV); Planned phase-II 3% loading
- $Q_{\beta\beta}$=2530.3 keV ; $\sigma \sim$ 82 keV (4.6%)
- All detector engineering complete: **water data taking started May 2017**
- Objective is 780 tonnes linear alkyl benzene (+PPO+Te-ButaneDiol)
- LAB purification plant in final commissioning, **fill August 2018**
- 3.8 tonnes TeA underground cooling; 4 tonnes en route from China
- Te and butane-diol plant in construction, **expected loading 2019**
- Phase-I: $T_{1/2} > 1.96 \times 10^{26}$ yr (90% CL); $m_{\beta\beta} <$ 36-90 meV





First neutrino candidate: 2017-02-05, upward-going, no outward-looking PMTs triggered

3.8 tonnes Telluric acid UG (half since 01/15); cosmogenic activity decaying



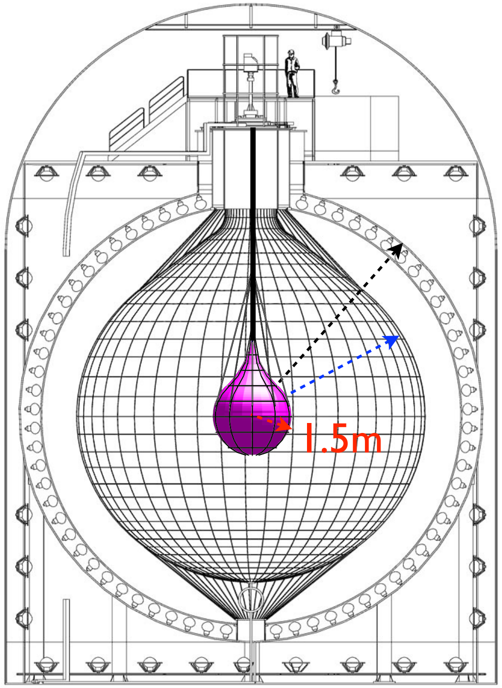
KamLAND-ZEN ^{136}Xe

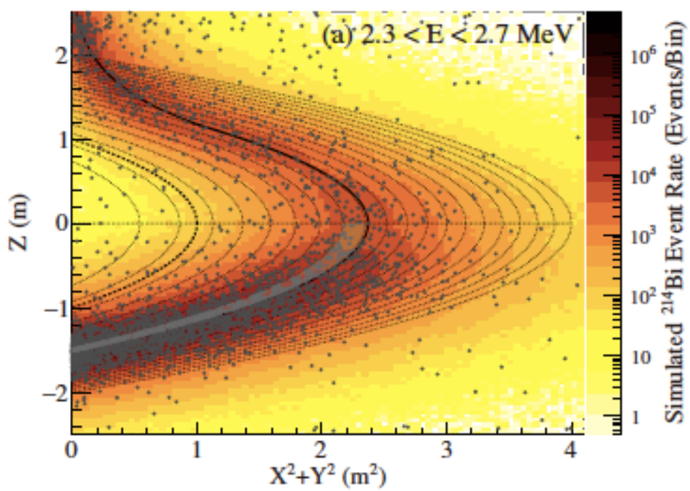
Scintillation

- 90% enr ^{136}Xe in liquid scint. balloon R=1.5 m
- $Q_{\beta\beta}$=2457.8 keV ; σ ~ 114 keV (4.6%)
- Phase II (PRL **117** 082503 (2016))
  - 380 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 534.5 days, with 126 kg y exposure
  - ^{110m}Ag contamination reduced by x10

$T_{1/2} > 1.07 \times 10^{26}$ y (90% CL)

Sensitivity $T_{1/2} > 5.6 \times 10^{25}$ y (90% CL)





- Unsuccessful new larger mini balloon deployment - 2016
- Next phase: data taking 750 kg enriched Xe starting summer 2018 (new balloon to be installed April)
- KamLAND2-Zen with 1000kg+ proposed with improved light collection efficiency

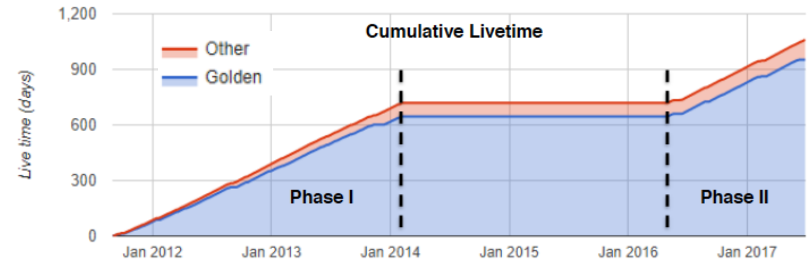
EXO-200 ^{136}Xe

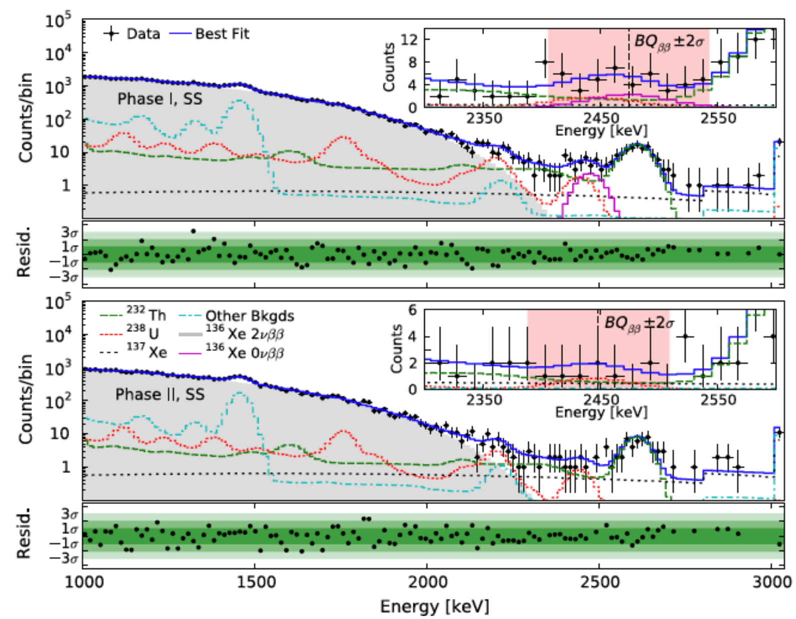
Scintillation - Ionization

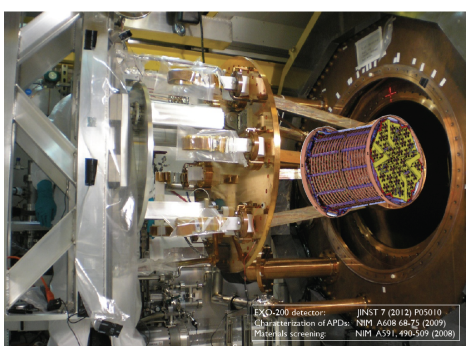
- Enriched Liquid Xe in TPC
  - $Q_{\beta\beta}$=2457.8 keV
  - 200 kg of 80.6 % enriched ^{136}Xe
  - 75.6 kg fiducial mass,
  - 177.6 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution (71 keV FWHM @ $Q_{\beta\beta}$)
  - Phase II improved resolution : 1.23%
  - Single site - Multisite discrimination

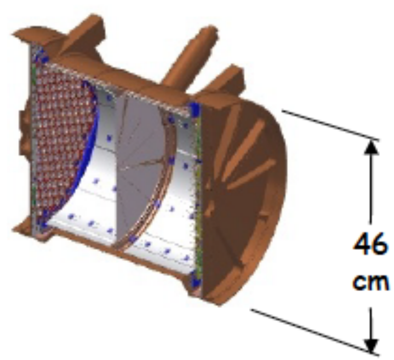
$T_{1/2} > 1.8 \times 10^{25}$ y (90% CL)

Sensitivity 3.5×10^{25} y (90% CL)





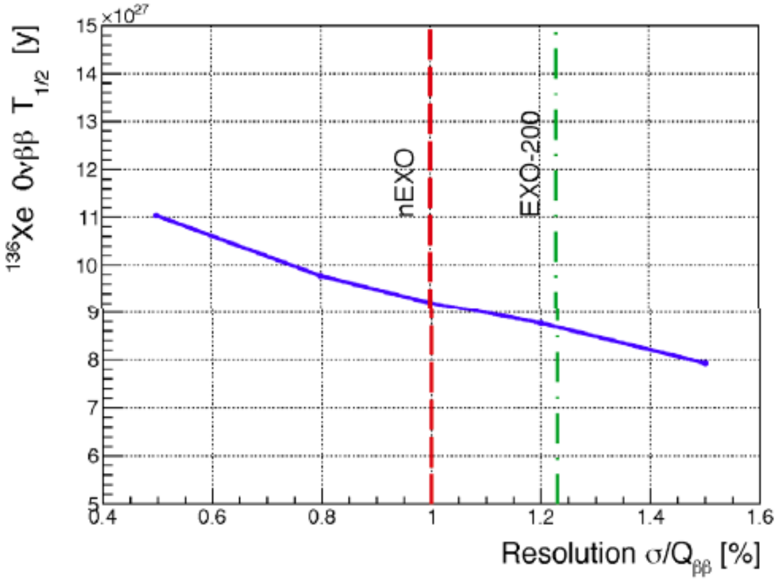


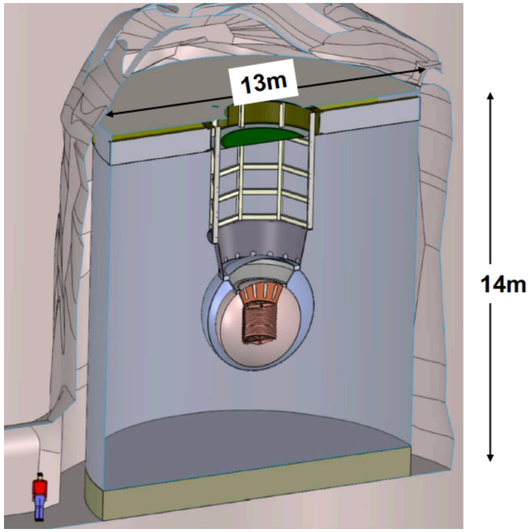


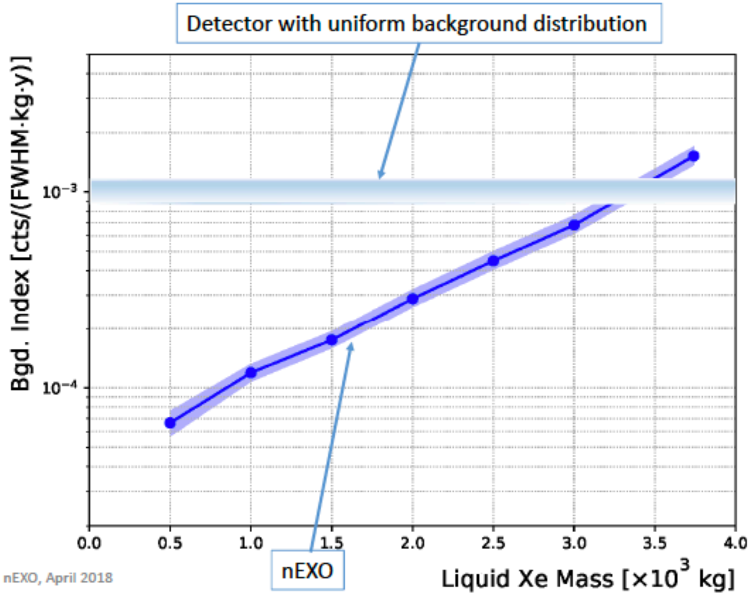
nEXO ^{136}Xe

Scintillation - Ionization

- 5 tonnes of ^{enr}Xe
- LXe homogeneous imaging TPC similar to EXO-200:
- nEXO 10 yr 90% CL sensitivity: $T_{1/2} > 5 \cdot 10^{27}$ yr
- Improvements and R&D focussed:
  - Light collection (SiPM)
  - Charge collection (tiles)
  - HV stability
  - Background controls sensitivity



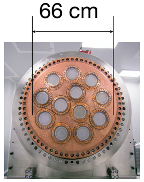


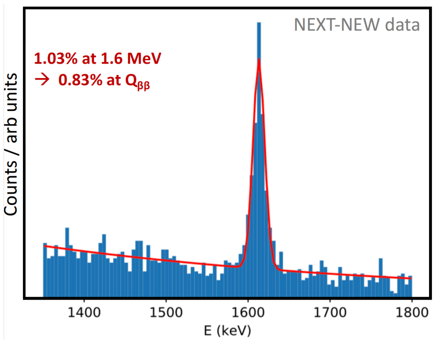


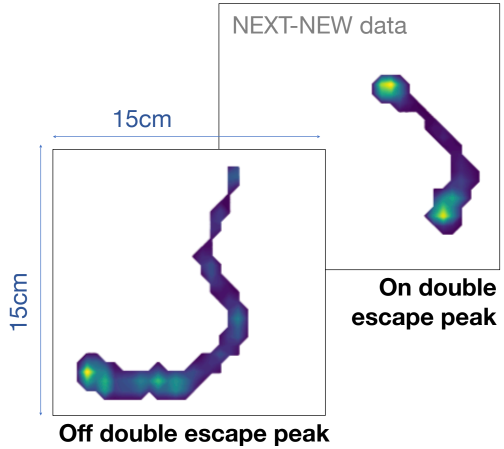
NEXT ^{136}Xe

Scintillation - Ionization

- High pressure (10-15 bar) ^{136}Xe TPC for high E- resolution + tracking capability
- $Q_{\beta\beta}$=2457.8 keV ; σ ~ 7.3 keV (0.3%)
- NEXT-NEW
  - 4.5 kg_{iso}, operating at Canfranc
  - Energy resolutions extrapolating to substantially better than 1%

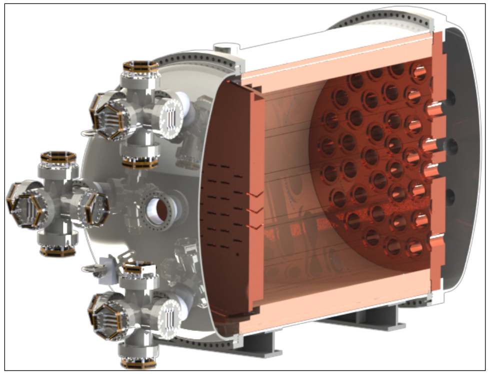




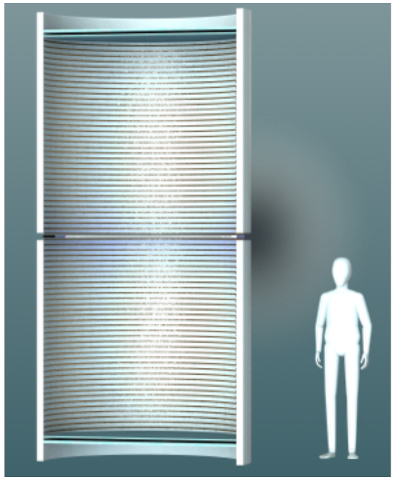


- NEXT-100
  - NEXT-100 in construction now thru 2019.
  - Demonstrate "background free@100kg-scale" technology by 2021

NEXT-100 (~100 kg)
[2018 - 2020's]



NEXT-500
[future generation]



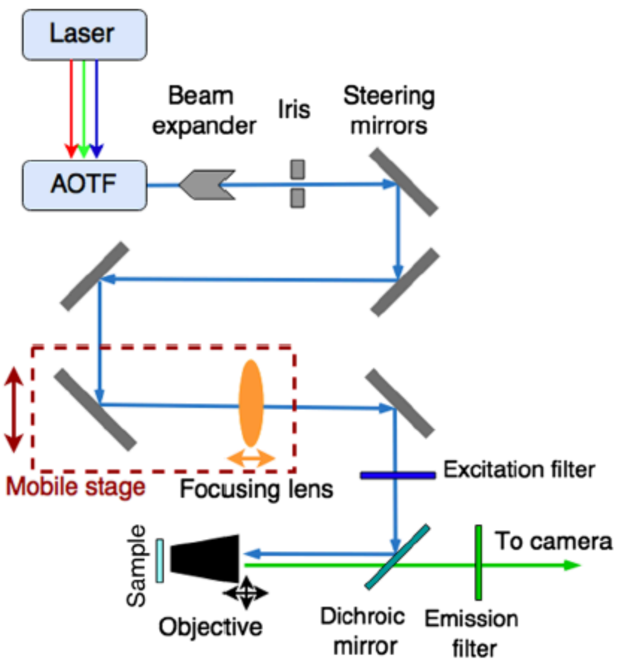
Scintillation - Ionization

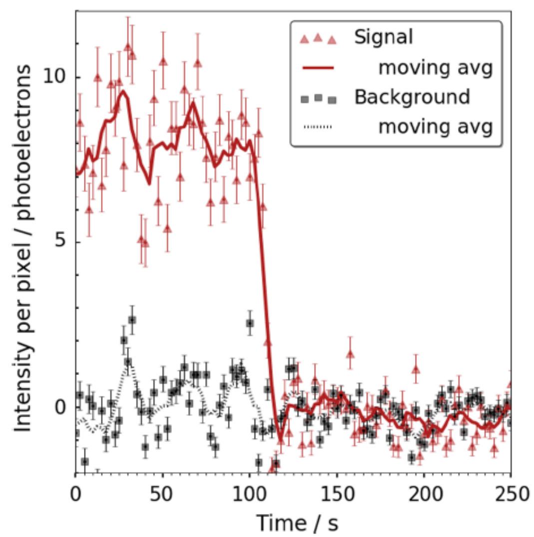
PHYSICAL REVIEW LETTERS **120,** 132504 (2018)

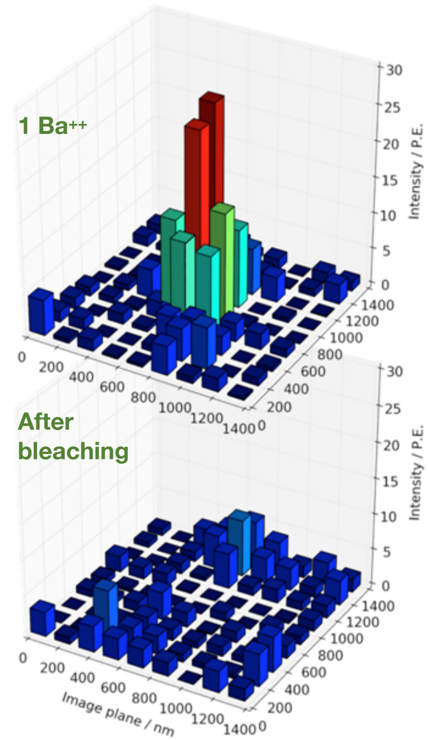
Editors' Suggestion **Featured in Physics**

Demonstration of Single-Barium-Ion Sensitivity for Neutrinoless Double-Beta Decay Using Single-Molecule Fluorescence Imaging

TARGET*: *Single barium ion sensitivity to completely reject non ββ backgrounds





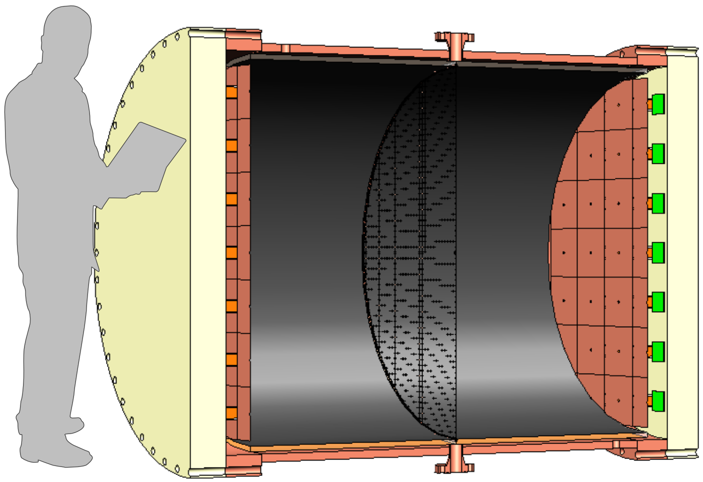


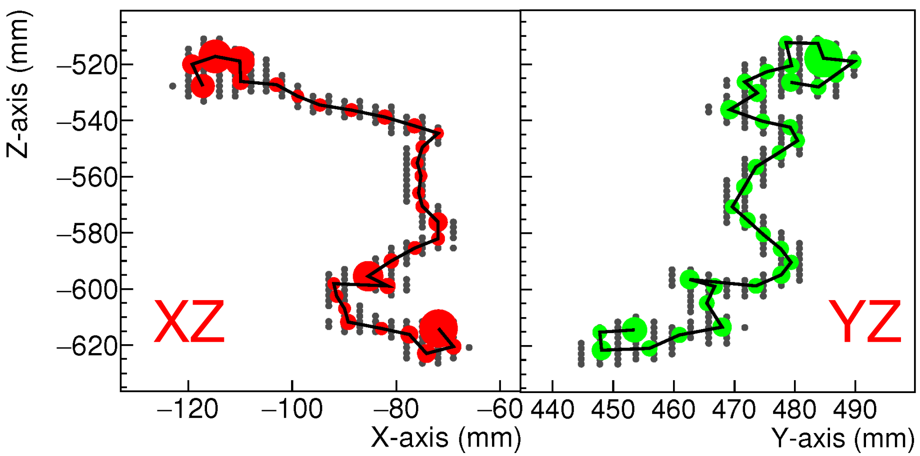
Single barium ion sensitivity demonstrated with SMFI

PandaX-III ^{136}Xe

Ionization

- High pressure gas TPC, phased approach with multiple 200-kg enriched xenon gas TPC for a ton-scale 0νββ experiment [arXiv:1610.08883]
- Prototype being commissioned.
- First 200 kg detector: construction starts summer 2018. Located at CJPL.
- TPC with two charge readout planes on two ends
- 4 m^3 inner volume and 10 bar working pressure
- Main design features: Micromegas modules for charge readout. Good energy resolution and background suppression with tracking [arXiv:1802.03489]





0νββ event with a Bragg peak at each end of the track